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Chapter 1

Introduction

IDA is part of a software family called SUNDIALS: SUite of Nonlinear and Differential/ALgebraic equation Solvers [26]. This suite consists of CVODE, ARKODE, KINSOL, and IDA, and variants of these with sensitivity analysis capabilities, CVODES and IDAS.

IDA is a general purpose solver for the initial value problem (IVP) for systems of differential-algebraic equations (DAEs). The name IDA stands for Implicit Differential-Algebraic solver. IDA is based on DASPK [9, 10], but is written in ANSI-standard C rather than FORTRAN77. Its most notable features are that, (1) in the solution of the underlying nonlinear system at each time step, it offers a choice of Newton/direct methods and a choice of Inexact Newton/Krylov (iterative) methods; and (2) it is written in a data-independent manner in that it acts on generic vectors and matrices without any assumptions on the underlying organization of the data. Thus IDA shares significant modules previously written within CASC at LLNL to support the ordinary differential equation (ODE) solvers CVODE [27, 15] and PVODE [13, 14], and also the nonlinear system solver KINSOL [16].

At present, IDA may utilize a variety of Krylov methods provided in SUNDIALS that can be used in conjunction with Newton iteration: these include the GMRES (Generalized Minimal RESidual) [38], FGMRES (Flexible Generalized Minimum RESidual) [37], Bi-CGStab (Bi-Conjugate Gradient Stabilized) [39], TFQMR (Transpose-Free Quasi-Minimal Residual) [21], and PCG (Preconditioned Conjugate Gradient) [23] linear iterative methods. As Krylov methods, these require little matrix storage for solving the Newton equations as compared to direct methods. However, the algorithms allow for a user-supplied preconditioner matrix, and, for most problems, preconditioning is essential for an efficient solution.

For very large DAE systems, the Krylov methods are preferable over direct linear solver methods, and are often the only feasible choice. Among the Krylov methods in SUNDIALS, we recommend GMRES as the best overall choice. However, users are encouraged to compare all options, especially if encountering convergence failures with GMRES. Bi-CGStab and TFQMR have an advantage in storage requirements, in that the number of workspace vectors they require is fixed, while that number for GMRES depends on the desired Krylov subspace size. FGMRES has an advantage in that it is designed to support preconditioners that vary between iterations (e.g. iterative methods). PCG exhibits rapid convergence and minimal workspace vectors, but only works for symmetric linear systems.

There are several motivations for choosing the C language for IDA. First, a general movement away from FORTRAN and toward C in scientific computing was apparent. Second, the pointer, structure, and dynamic memory allocation features in C are extremely useful in software of this complexity, with the great variety of method options offered. Finally, we prefer C over C++ for IDA because of the wider availability of C compilers, the potentially greater efficiency of C, and the greater ease of interfacing the solver to applications written in extended FORTRAN.
1.1 Changes from previous versions

Changes in v5.1.0

Fixed a build system bug related to finding LAPACK/BLAS.
Fixed a build system bug related to checking if the KLU library works.
Fixed a build system bug related to finding PETSc when using the CMake variables `PETSC_INCLUDES` and `PETSC_LIBRARIES` instead of `PETSC_DIR`.
Added a new build system option, `CUDA_ARCH`, that can be used to specify the CUDA architecture to compile for.
Added two utility functions, `SUNDIALSFileOpen` and `SUNDIALSFileClose` for creating/destroying file pointers that are useful when using the Fortran 2003 interfaces.

Changes in v5.0.0

Build system changes

- Increased the minimum required CMake version to 3.5 for most SUNDIALS configurations, and 3.10 when CUDA or OpenMP with device offloading are enabled.

- The CMake option `BLAS_ENABLE` and the variable `BLAS_LIBRARIES` have been removed to simplify builds as SUNDIALS packages do not use BLAS directly. For third party libraries that require linking to BLAS, the path to the BLAS library should be included in the `_LIBRARIES` variable for the third party library e.g., `SUPERLUDIST_LIBRARIES` when enabling SuperLU_DIST.

- Fixed a bug in the build system that prevented the `NVVECTOR_PTHREADS` module from being built.

NVVECTOR module changes

- Two new functions were added to aid in creating custom NVVECTOR objects. The constructor `NVNewEmpty` allocates an “empty” generic NVVECTOR with the object’s content pointer and the function pointers in the operations structure initialized to `NULL`. When used in the constructor for custom objects this function will ease the introduction of any new optional operations to the NVVECTOR API by ensuring only required operations need to be set. Additionally, the function `NVCopyOps(u, v)` has been added to copy the operation function pointers between vector objects. When used in clone routines for custom vector objects these functions also will ease the introduction of any new optional operations to the NVVECTOR API by ensuring all operations are copied when cloning objects. See §6.1.5 for more details.

- Two new NVVECTOR implementations, NVVECTOR_MANYVECTOR and NVVECTOR_MPI manyVECTOR, have been created to support flexible partitioning of solution data among different processing elements (e.g., CPU + GPU) or for multi-physics problems that couple distinct MPI-based simulations together. This implementation is accompanied by additions to user documentation and SUNDIALS examples. See §6.13 and §6.14 for more details.

- One new required vector operation and ten new optional vector operations have been added to the NVVECTOR API. The new required operation, `NGetLength`, returns the global length of an NVVECTOR. The optional operations have been added to support the new NVVECTOR_MPI manyVECTOR implementation. The operation `NGetCommunicator` must be implemented by subvectors that are combined to create an NVVECTOR_MPI manyVECTOR, but is not used outside of this context. The remaining nine operations are optional local reduction operations intended to eliminate unnecessary latency when performing vector reduction operations (norms, etc.) on distributed memory systems. The optional local reduction vector operations are `NVDotProdLocal`, `NVMaxNormLocal`, `NVMinLocal`, `NVL1NormLocal`, `NVWSqrSumLocal`, `NVWSqrSumMaskLocal`, `NVInvTestLocal`, `NVConstrMaskLocal`, and `NVMinQuotientLocal`. 
1.1 Changes from previous versions

If an NVECTOR implementation defines any of the local operations as NULL, then the NVECTOR_MPIMANYVECTOR will call standard NVECTOR operations to complete the computation. See §6.1.4 for more details.

- An additional NVECTOR implementation, NVECTOR_MPIPLUSX, has been created to support the MPI+X paradigm where X is a type of on-node parallelism (e.g., OpenMP, CUDA). The implementation is accompanied by additions to user documentation and SUNDIALS examples. See §6.15 for more details.

- The _MPIcuda and _MPIRaja functions have been removed from the NVECTOR_CUDA and NVECTOR_RAJA implementations respectively. Accordingly, the nvector_mpiCUDA.h, nvector_mpiRaja.h, libsundials_nvecmpicuda.lib, and libsundials_nvecmpicudaraja.lib files have been removed. Users should use the NVECTOR_MPIPLUSX module coupled in conjunction with the NVECTOR_CUDA or NVECTOR_RAJA modules to replace the functionality. The necessary changes are minimal and should require few code modifications. See the programs in examples/ida/mpicuda and examples/ida/mpiraja for examples of how to use the NVECTOR_MPIPLUSX module with the NVECTOR_CUDA and NVECTOR_RAJA modules respectively.

- Fixed a memory leak in the NVECTOR_PETSC module clone function.

- Made performance improvements to the NVECTOR_CUDA module. Users who utilize a non-default stream should no longer see default stream synchronizations after memory transfers.

- Added a new constructor to the NVECTOR_CUDA module that allows a user to provide custom allocate and free functions for the vector data array and internal reduction buffer. See §6.9.1 for more details.

- Added new Fortran 2003 interfaces for most NVECTOR modules. See Chapter 6 for more details on how to use the interfaces.

- Added three new NVECTOR utility functions, FN_VGetVecAtIndexVectorArray, FN_VSetVecAtIndexVectorArray, and FN_VNewVectorArray, for working with N_Vector arrays when using the Fortran 2003 interfaces. See §6.1.5 for more details.

SUNMatrix module changes

- Two new functions were added to aid in creating custom SUNMATRIX objects. The constructor SUNMatNewEmpty allocates an “empty” generic SUNMATRIX with the object’s content pointer and the function pointers in the operations structure initialized to NULL. When used in the constructor for custom objects this function will ease the introduction of any new optional operations to the SUNMATRIX API by ensuring only required operations need to be set. Additionally, the function SUNMatCopyOps(A, B) has been added to copy the operation function pointers between matrix objects. When used in clone routines for custom matrix objects these functions also will ease the introduction of any new optional operations to the SUNMATRIX API by ensuring all operations are copied when cloning objects. See §7.1.2 for more details.

- A new operation, SUNMatMatvecSetup, was added to the SUNMATRIX API to perform any setup necessary for computing a matrix-vector product. This operation is useful for SUNMATRIX implementations which need to prepare the matrix itself, or communication structures before performing the matrix-vector product. Users who have implemented custom SUNMATRIX modules will need to at least update their code to set the corresponding ops structure member, matvecsetup, to NULL. See §7.1.1 for more details.

- The generic SUNMATRIX API now defines error codes to be returned by SUNMATRIX operations. Operations which return an integer flag indicating success/failure may return different values than previously. See §7.1.3 for more details.
• A new SUNMATRIX (and SUNLINSOL) implementation was added to facilitate the use of the SuperLU_DIST library with SUNDIALS. See §7.6 for more details.

• Added new Fortran 2003 interfaces for most SUNMATRIX modules. See Chapter 7 for more details on how to use the interfaces.

SUNLinearSolver module changes

• A new function was added to aid in creating custom SUNLINSOL objects. The constructor SUNLinSolNewEmpty allocates an “empty” generic SUNLINSOL with the object’s content pointer and the function pointers in the operations structure initialized to NULL. When used in the constructor for custom objects this function will ease the introduction of any new optional operations to the SUNLINSOL API by ensuring only required operations need to be set. See §8.3 for more details.

• The return type of the SUNLINSOL API function SUNLinSolLastFlag has changed from long int to sunindextype to be consistent with the type used to store row indices in dense and banded linear solver modules.

• Added a new optional operation to the SUNLINSOL API, SUNLinSolGetID, that returns a SUNLinearSolver_ID for identifying the linear solver module.

• The SUNLINSOL API has been updated to make the initialize and setup functions optional.

• A new SUNLINSOL (and SUNMATRIX) implementation was added to facilitate the use of the SuperLU_DIST library with SUNDIALS. See §8.10 for more details.

• Added a new SUNLINSOL implementation, SUNLinearSolver_cuSolverSp_batchQR, which leverages the NVIDIA cuSOLVER sparse batched QR method for efficiently solving block diagonal linear systems on NVIDIA GPUs. See §8.12 for more details.

• Added three new accessor functions to the SUNLINSOL_KLU module, SUNLinSol_KLUGetSymbolic, SUNLinSol_KLUGetNumeric, and SUNLinSol_KLUGetCommon, to provide user access to the underlying KLU solver structures. See §8.9.2 for more details.

• Added new Fortran 2003 interfaces for most SUNLINSOL modules. See Chapter 8 for more details on how to use the interfaces.

SUNNonlinearSolver module changes

• A new function was added to aid in creating custom SUNNONLINSOL objects. The constructor SUNNonlinSolNewEmpty allocates an “empty” generic SUNNONLINSOL with the object’s content pointer and the function pointers in the operations structure initialized to NULL. When used in the constructor for custom objects this function will ease the introduction of any new optional operations to the SUNNONLINSOL API by ensuring only required operations need to be set. See §9.1.8 for more details.

• To facilitate the use of user supplied nonlinear solver convergence test functions the SUNNonlinSolSetConvTestFn function in the SUNNONLINSOL API has been updated to take a void* data pointer as input. The supplied data pointer will be passed to the nonlinear solver convergence test function on each call.

• The inputs values passed to the first two inputs of the SUNNonlinSolSolve function in the SUNNONLINSOL have been changed to be the predicted state and the initial guess for the correction to that state. Additionally, the definitions of SUNNonlinSolLSetupFn and SUNNonlinSolLSolveFn in the SUNNONLINSOL API have been updated to remove unused input parameters. For more information on the nonlinear system formulation see §9.2 and for more details on the API functions see Chapter 9.
1.1 Changes from previous versions

- Added a new SUNNONLINSOL implementation, SUNNONLINSOL_PETSCSNES, which interfaces to the PETSc SNES nonlinear solver API. See §9.4 for more details.
- Added new Fortran 2003 interfaces for most SUNNONLINSOL modules. See Chapter 9 for more details on how to use the interfaces.

IDA changes

- A bug was fixed in the IDA linear solver interface where an incorrect Jacobian-vector product increment was used with iterative solvers other than SUNLINSOL_SPGMR and SUNLINSOL_SPFGMR.
- Fixed a memory leak in FIDA when not using the default nonlinear solver.
- Removed extraneous calls to N_VMin for simulations where the scalar valued absolute tolerance, or all entries of the vector-valued absolute tolerance array, are strictly positive. In this scenario, IDA will remove at least one global reduction per time step.
- The IDALS interface has been updated to only zero the Jacobian matrix before calling a user-supplied Jacobian evaluation function when the attached linear solver has type SUNLINEARSOLVER_DIRECT.
- Added the new functions, IDAGetCurrentCj, IDAGetCurrentY, IDAGetCurrentYp, IDAComputeCurrentY, and IDAComputeCurrentYp which may be useful to users who choose to provide their own nonlinear solver implementations.
- Added a Fortran 2003 interface to IDA. See Chapter 5 for more details.

Changes in v4.1.0

An additional nvector implementation was added for the Tpetra vector from the Trilinos library to facilitate interoperability between SUNDIALS and Trilinos. This implementation is accompanied by additions to user documentation and SUNDIALS examples.

A bug was fixed where a nonlinear solver object could be freed twice in some use cases.

The EXAMPLES_ENABLE_CUDA CMake option has been removed. The option EXAMPLES_ENABLE_CUDA enables all examples that use CUDA including the RAJA examples with a CUDA back end (if the RAJA nvector is enabled).

The implementation header file ida_impl.h is no longer installed. This means users who are directly manipulating the IDAMem structure will need to update their code to use IDA’s public API.

Python is no longer required to run make test and make test_install.

Changes in v4.0.2

Added information on how to contribute to SUNDIALS and a contributing agreement.

Moved definitions of DLS and SPILS backwards compatibility functions to a source file. The symbols are now included in the IDA library, libsundials_ida.

Changes in v4.0.1

No changes were made in this release.

Changes in v4.0.0

IDA’s previous direct and iterative linear solver interfaces, IDADLS and IDESPILS, have been merged into a single unified linear solver interface, IDALS, to support any valid SUNLINSOL module. This includes the “DIRECT” and “ITERATIVE” types as well as the new “MATRIX_ITERATIVE” type. Details regarding how IDALS utilizes linear solvers of each type as well as discussion regarding intended use cases for user-supplied SUNLINSOL implementations are included in Chapter 8. All IDA example
programs and the standalone linear solver examples have been updated to use the unified linear solver interface.

The unified interface for the new IDALS module is very similar to the previous IDADLS and IDASPILS interfaces. To minimize challenges in user migration to the new names, the previous C and FORTRAN routine names may still be used; these will be deprecated in future releases, so we recommend that users migrate to the new names soon. Additionally, we note that FORTRAN users, however, may need to enlarge their iout array of optional integer outputs, and update the indices that they query for certain linear-solver-related statistics.

The names of all constructor routines for SUNDIALS-provided SUNLINSOL implementations have been updated to follow the naming convention SUNLinSol* where * is the name of the linear solver. The new names are SUNLinSolBand, SUNLinSol_Dense, SUNLinSol_KLU, SUNLinSol_LapackBand, SUNLinSol_LapackDense, SUNLinSol_PCG, SUNLinSol_SPBCGS, SUNLinSol_SPFGMR, SUNLinSol_SPGMR, SUNLinSol_SPTFQMR, and SUNLinSol_SuperLUMT. Solver-specific “set” routine names have been similarly standardized. To minimize challenges in user migration to the new names, the previous routine names may still be used; these will be deprecated in future releases, so we recommend that users migrate to the new names soon. All IDA example programs and the standalone linear solver examples have been updated to use the new naming convention.

The SUNBandMatrix constructor has been simplified to remove the storage upper bandwidth argument.

SUNDIALS integrators have been updated to utilize generic nonlinear solver modules defined through the SUNNONLINSOL API. This API will ease the addition of new nonlinear solver options and allow for external or user-supplied nonlinear solvers. The SUNNONLINSOL API and SUNDIALS provided modules are described in Chapter 9 and follow the same object oriented design and implementation used by the nvector, sunmatrix, and SUNLINSOL modules. Currently two SUNNONLINSOL implementations are provided, SUNNONLINSOL_NEWTON and SUNNONLINSOL_FIXEDPOINT. These replicate the previous integrator specific implementations of a Newton iteration and a fixed-point iteration (previously referred to as a functional iteration, respectively). Note the SUNNONLINSOL_FIXEDPOINT module can optionally utilize Anderson’s method to accelerate convergence. Example programs using each of these nonlinear solver modules in a standalone manner have been added and all IDA example programs have been updated to use generic SUNNONLINSOL modules.

By default IDA uses the SUNNONLINSOL_NEWTON module. Since IDA previously only used an internal implementation of a Newton iteration no changes are required to user programs and functions for setting the nonlinear solver options (e.g., IDASetMaxNonlinIters) or getting nonlinear solver statistics (e.g., IDAGetNumNonlinSolvIters) remain unchanged and internally call generic SUNNONLINSOL functions as needed. While SUNDIALS includes a fixed-point nonlinear solver module, it is not currently supported in IDA. For details on attaching a user-supplied nonlinear solver to IDA see Chapter 4. Additionally, the example program idaRoberts_dns.c explicitly creates an attaches a SUNNONLINSOL_NEWTON object to demonstrate the process of creating and attaching a nonlinear solver module (note this is not necessary in general as IDA uses the SUNNONLINSOL_NEWTON module by default).

Three fused vector operations and seven vector array operations have been added to the NVECTOR API. These optional operations are disabled by default and may be activated by calling vector specific routines after creating an NVECTOR (see Chapter 6 for more details). The new operations are intended to increase data reuse in vector operations, reduce parallel communication on distributed memory systems, and lower the number of kernel launches on systems with accelerators. The fused operations are N_VLinearCombination, N_VScaleAddMulti, and N_VDotProdMulti and the vector array operations are N_VLinearCombinationVectorArray, N_VScaleVectorArray, N_VConstVectorArray, N_VWrmsNormVectorArray, N_VWrmsNormMaskVectorArray, N_VScaleAddMultiVectorArray, and N_VLinearCombinationVectorArray. If an NVECTOR implementation defines any of these operations as NULL, then standard NVECTOR operations will automatically be called as necessary to complete the computation.

Multiple updates to nvector_cuda were made:

- Changed N_VGetLength_Cuda to return the global vector length instead of the local vector length.
1.1 Changes from previous versions

- Added `N_VGetLocalLength_Cuda` to return the local vector length.
- Added `N_VGetMPIComm_Cuda` to return the MPI communicator used.
- Removed the accessor functions in the namespace suncudavec.
- Changed the `N_VMake_Cuda` function to take a host data pointer and a device data pointer instead of an `N_VectorContent_Cuda` object.
- Added the ability to set the `cudaStream_t` used for execution of the `NVECTOR_CUDA` kernels. See the function `N_VSetCudaStreams_Cuda`.
- Added `N_VNewManaged_Cuda`, `N_VMakeManaged_Cuda`, and `N_VIsManagedMemory_Cuda` functions to accommodate using managed memory with the `NVECTOR_CUDA`.

Multiple changes to `NVECTOR_RAJA` were made:

- Changed `N_VGetLength_Raja` to return the global vector length instead of the local vector length.
- Added `N_VGetLocalLength_Raja` to return the local vector length.
- Added `N_VGetMPIComm_Raja` to return the MPI communicator used.
- Removed the accessor functions in the namespace suncudavec.

A new `NVECTOR` implementation for leveraging OpenMP 4.5+ device offloading has been added, `NVECTOR_OPENMPDEV`. See §6.11 for more details.

Changes in v3.2.1

The changes in this minor release include the following:

- Fixed a bug in the CUDA NVECTOR where the `N_VInvTest` operation could write beyond the allocated vector data.
- Fixed library installation path for multiarch systems. This fix changes the default library installation path to `CMAKE_INSTALL_PREFIX/CMAKE_INSTALL_LIBDIR` from `CMAKE_INSTALL_PREFIX/lib`. `CMAKE_INSTALL_LIBDIR` is automatically set, but is available as a CMake option that can modified.

Changes in v3.2.0

Fixed a problem with setting `sunindextype` which would occur with some compilers (e.g. armclang) that did not define `_STDC_VERSION_`.

Added hybrid MPI/CUDA and MPI/RAJA vectors to allow use of more than one MPI rank when using a GPU system. The vectors assume one GPU device per MPI rank.

Changed the name of the RAJA NVECTOR library to `libsundials_nveccudaraja.lib` from `libsundials_nvecraja.lib` to better reflect that we only support CUDA as a backend for RAJA currently.

Several changes were made to the build system:

- CMake 3.1.3 is now the minimum required CMake version.
- Deprecate the behavior of the `SUNDIALS_INDEX_TYPE` CMake option and added the `SUNDIALS_INDEX_SIZE` CMake option to select the `sunindextype` integer size.
- The native CMake FindMPI module is now used to locate an MPI installation.
• If MPI is enabled and MPI compiler wrappers are not set, the build system will check if 
CMAKE_<language>_COMPILER can compile MPI programs before trying to locate and use an 
MPI installation.

• The previous options for setting MPI compiler wrappers and the executable for running MPI 
programs have been deprecated. The new options that align with those used in native 
CMake FindMPI module are MPI_C_COMPILER, MPI_CXX_COMPILER, MPI_Fortran_COMPILER, and 
MPIEXEC_EXECUTABLE.

• When a Fortran name-mangling scheme is needed (e.g., LAPACK_ENABLE is ON) the build system 
will infer the scheme from the Fortran compiler. If a Fortran compiler is not available or the in-
ferred or default scheme needs to be overridden, the advanced options SUNDIALS_F77_FUNC_CASE 
and SUNDIALS_F77_FUNC_UNDERSCORES can be used to manually set the name-mangling scheme 
and bypass trying to infer the scheme.

• Parts of the main CMakeLists.txt file were moved to new files in the src and example directories 
to make the CMake configuration file structure more modular.

Changes in v3.1.2

The changes in this minor release include the following:

• Updated the minimum required version of CMake to 2.8.12 and enabled using rpath by default 
to locate shared libraries on OSX.

• Fixed Windows specific problem where sunindextype was not correctly defined when using 
64-bit integers for the sundials index type. On Windows sunindextype is now defined as the 
MSVC basic type _int64.

• Added sparse SUNMatrix “Reallocate” routine to allow specification of the nonzero storage.

• Updated the KLU SUNLinearSolver module to set constants for the two reinitialization types, 
and fixed a bug in the full reinitialization approach where the sparse SUNMatrix pointer would 
go out of scope on some architectures.

• Updated the “ScaleAdd” and “ScaleAddI” implementations in the sparse SUNMatrix module 
to more optimally handle the case where the target matrix contained sufficient storage for the 
sum, but had the wrong sparsity pattern. The sum now occurs in-place, by performing the sum 
backwards in the existing storage. However, it is still more efficient if the user-supplied Jacobian 
routine allocates storage for the sum $I + \gamma J$ manually (with zero entries if needed).

• Changed the LICENSE install path to instdir/include/sundials.

Changes in v3.1.1

The changes in this minor release include the following:

• Fixed a potential memory leak in the spgmr and spfgmr linear solvers: if “Initialize” was 
called multiple times then the solver memory was reallocated (without being freed).

• Updated KLU SUNLINSOL module to use a typedef for the precision-specific solve function to 
be used (to avoid compiler warnings).

• Added missing typecasts for some (void*) pointers (again, to avoid compiler warnings).

• Bugfix in sunmatrix_sparse.c where we had used int instead of sunindextype in one location.

• Added missing #include <stdio.h> in NVECTOR and SUNMATRIX header files.

• Added missing prototype for IDASpilsGetNumJTEvals.
1.1 Changes from previous versions

- Fixed an indexing bug in the CUDA NVVECTOR implementation of NVWrmsNormMask and revised the RAJA NVVECTOR implementation of NVWrmsNormMask to work with mask arrays using values other than zero or one. Replaced double with realtype in the RAJA vector test functions.
- Fixed compilation issue with GCC 7.3.0 and Fortran programs that do not require a SUNMATRIX module (e.g., iterative linear solvers).

In addition to the changes above, minor corrections were also made to the example programs, build system, and user documentation.

Changes in v3.1.0

Added NVVECTOR print functions that write vector data to a specified file (e.g., NVPrintFile_Serial).

Added make test and make test_install options to the build system for testing SUNDIALS after building with make and installing with make install respectively.

Changes in v3.0.0

All interfaces to matrix structures and linear solvers have been reworked, and all example programs have been updated. The goal of the redesign of these interfaces was to provide more encapsulation and to ease interfacing of custom linear solvers and interoperability with linear solver libraries. Specific changes include:

- Added generic SUNMATRIX module with three provided implementations: dense, banded and sparse. These replicate previous SUNDIALS Dls and Sls matrix structures in a single object-oriented API.
- Added example problems demonstrating use of generic SUNMATRIX modules.
- Added generic SUNLinearSolver module with eleven provided implementations: SUNDIALS native dense, SUNDIALS native banded, LAPACK dense, LAPACK band, KLU, SuperLU_MT, SPGMR, SPBCGS, SPTFQMR, SPFGMR, and PCG. These replicate previous SUNDIALS generic linear solvers in a single object-oriented API.
- Added example problems demonstrating use of generic SUNLinearSolver modules.
- Expanded package-provided direct linear solver (Dls) interfaces and scaled, preconditioned, iterative linear solver (Spils) interfaces to utilize generic SUNMATRIX and SUNLinearSolver objects.
- Removed package-specific, linear solver-specific, solver modules (e.g. CVDENSE, KINBAND, IDAKLU, ARKSPGMR) since their functionality is entirely replicated by the generic Dls/Spils interfaces and SUNLinearSolver/SUNMATRIX modules. The exception is CVDIAG, a diagonal approximate Jacobian solver available to CVODE and CVODES.
- Converted all SUNDIALS example problems and files to utilize the new generic SUNMATRIX and SUNLinearSolver objects, along with updated Dls and Spils linear solver interfaces.
- Added Spils interface routines to ARKODE, CVODE, CVODES, IDA, and IDAS to allow specification of a user-provided "JTSetup" routine. This change supports users who wish to set up data structures for the user-provided Jacobian-times-vector ("JTimes") routine, and where the cost of one JTSetup setup per Newton iteration can be amortized between multiple JTimes calls.

Two additional NVVECTOR implementations were added – one for CUDA and one for RAJA vectors. These vectors are supplied to provide very basic support for running on GPU architectures. Users are advised that these vectors both move all data to the GPU device upon construction, and speedup will only be realized if the user also conducts the right-hand-side function evaluation on the device. In addition, these vectors assume the problem fits on one GPU. Further information about RAJA, users are referred to the web site, https://software.llnl.gov/RAJA/. These additions are accompanied by additions to various interface functions and to user documentation.
All indices for data structures were updated to a new `sunindextype` that can be configured to be a 32- or 64-bit integer data index type. `sunindextype` is defined to be `int32_t` or `int64_t` when portable types are supported, otherwise it is defined as `int` or `long int`. The Fortran interfaces continue to use `long int` for indices, except for their sparse matrix interface that now uses the new `sunindextype`. This new flexible capability for index types includes interfaces to PETSc, hypre, SuperLU_MT, and KLU with either 32-bit or 64-bit capabilities depending how the user configures SUNDIALS.

To avoid potential namespace conflicts, the macros defining `boolean` values `TRUE` and `FALSE` have been changed to `SUNTRUE` and `SUNFALSE` respectively.

Temporary vectors were removed from preconditioner setup and solve routines for all packages. It is assumed that all necessary data for user-provided preconditioner operations will be allocated and stored in user-provided data structures.

The file `include/sundials_fconfig.h` was added. This file contains SUNDIALS type information for use in Fortran programs.

The build system was expanded to support many of the xSDK-compliant keys. The xSDK is a movement in scientific software to provide a foundation for the rapid and efficient production of high-quality, sustainable extreme-scale scientific applications. More information can be found at, https://xsdk.info.

Added functions `SUNDIALSGetVersion` and `SUNDIALSGetVersionNumber` to get SUNDIALS release version information at runtime.

In addition, numerous changes were made to the build system. These include the addition of separate `BLAS_ENABLE` and `BLAS_LIBRARIES` CMake variables, additional error checking during CMake configuration, minor bug fixes, and renaming CMake options to enable/disable examples for greater clarity and an added option to enable/disable Fortran 77 examples. These changes included changing `EXAMPLES_ENABLE` to `EXAMPLES_ENABLE_C`, changing `CXX_ENABLE` to `EXAMPLES_ENABLE_CXX`, changing `F90_ENABLE` to `EXAMPLES_ENABLE_F90`, and adding an `EXAMPLES_ENABLE_F77` option.

A bug fix was done to add a missing prototype for `IDASetMaxBacksIC` in `ida.h`.

Corrections and additions were made to the examples, to installation-related files, and to the user documentation.

**Changes in v2.9.0**

Two additional `NVECTOR` implementations were added – one for Hypre (parallel) ParVector vectors, and one for PETSc vectors. These additions are accompanied by additions to various interface functions and to user documentation.

Each `NVECTOR` module now includes a function, `NVGetVectorID`, that returns the `NVECTOR` module name.

An optional input function was added to set a maximum number of linesearch backtracks in the initial condition calculation. Also, corrections were made to three Fortran interface functions.

For each linear solver, the various solver performance counters are now initialized to 0 in both the solver specification function and in solver `linit` function. This ensures that these solver counters are initialized upon linear solver instantiation as well as at the beginning of the problem solution.

A memory leak was fixed in the banded preconditioner interface. In addition, updates were done to return integers from linear solver and preconditioner 'free' functions.

The Krylov linear solver Bi-CGstab was enhanced by removing a redundant dot product. Various additions and corrections were made to the interfaces to the sparse solvers KLU and SuperLU_MT, including support for CSR format when using KLU.

New examples were added for use of the OpenMP vector.

Minor corrections and additions were made to the `IDA` solver, to the Fortran interfaces, to the examples, to installation-related files, and to the user documentation.
Changes in v2.8.0

Two major additions were made to the linear system solvers that are available for use with the IDA solver. First, in the serial case, an interface to the sparse direct solver KLU was added. Second, an interface to SuperLU_MT, the multi-threaded version of SuperLU, was added as a thread-parallel sparse direct solver option, to be used with the serial version of the nvector module. As part of these additions, a sparse matrix (CSC format) structure was added to IDA.

Otherwise, only relatively minor modifications were made to IDA:

In IDARootfind, a minor bug was corrected, where the input array rootdir was ignored, and a line was added to break out of root-search loop if the initial interval size is below the tolerance ttol.

In IDALapackBand, the line \texttt{smu = MIN(N-1,mu+ml)} was changed to \texttt{smu = mu + ml} to correct an illegal input error for \texttt{DGBTRF/DGBTRS}.

A minor bug was fixed regarding the testing of the input \texttt{tstop} on the first call to \texttt{IDASolve}.

In order to avoid possible name conflicts, the mathematical macro and function names MIN, MAX, SQR, RAbs, RSqrt, RExp, RPowerI, and RPowerR were changed to SUNMIN, SUNMAX, SUNSQR, SUNRabs, SUNRsqrt, SUNRExp, SRpowerI, and SUNRpowerR, respectively. These names occur in both the solver and in various example programs.

In the FIDA optional input routines \texttt{FIDASETIIN}, \texttt{FIDASETRIN}, and \texttt{FIDASETVIN}, the optional fourth argument \texttt{key_length} was removed, with hardcoded key string lengths passed to all \texttt{strncpy} tests.

In all FIDA examples, integer declarations were revised so that those which must match a C type \texttt{long int} are declared \texttt{INTEGER*8}, and a comment was added about the type match. All other integer declarations are just \texttt{INTEGER}. Corresponding minor corrections were made to the user guide.

Two new nvector modules have been added for thread-parallel computing environments — one for OpenMP, denoted \texttt{NVECTOR\_OPENMP}, and one for Pthreads, denoted \texttt{NVECTOR\_PTHREADS}.

With this version of Sundials, support and documentation of the Autotools mode of installation is being dropped, in favor of the CMake mode, which is considered more widely portable.

Changes in v2.7.0

One significant design change was made with this release: The problem size and its relatives, bandwidth parameters, related internal indices, pivot arrays, and the optional output \texttt{lsflag} have all been changed from type \texttt{int} to type \texttt{long int}, except for the problem size and bandwidths in user calls to routines specifying BLAS/LAPACK routines for the dense/band linear solvers. The function \texttt{NewIntArray} is replaced by a pair \texttt{NewIntArray/NewLintArray}, for \texttt{int} and \texttt{long int} arrays, respectively.

A large number of minor errors have been fixed. Among these are the following: After the solver memory is created, it is set to zero before being filled. To be consistent with IDAS, IDA uses the function \texttt{IDAGetDky} for optional output retrieval. In each linear solver interface function, the linear solver memory is freed on an error return, and the \texttt{**Free} function now includes a line setting to NULL the main memory pointer to the linear solver memory. A memory leak was fixed in two of the \texttt{IDASp***Free} functions. In the rootfinding functions \texttt{IDARcheck1/IDARcheck2}, when an exact zero is found, the array \texttt{glo} of \texttt{g} values at the left endpoint is adjusted, instead of shifting the \texttt{t} location \texttt{tlo} slightly. In the installation files, we modified the treatment of the macro \texttt{SUNDIALS\_USE\_GENERIC\_MATH}, so that the parameter \texttt{GENERIC\_MATH\_LIB} is either defined (with no value) or not defined.

Changes in v2.6.0

Two new features were added in this release: (a) a new linear solver module, based on BLAS and LAPACK for both dense and banded matrices, and (b) option to specify which direction of zero-crossing is to be monitored while performing rootfinding.

The user interface has been further refined. Some of the API changes involve: (a) a reorganization of all linear solver modules into two families (besides the already present family of scaled preconditioned iterative linear solvers, the direct solvers, including the new LAPACK-based ones, were also
organized into a direct family); (b) maintaining a single pointer to user data, optionally specified through a Set-type function; (c) a general streamlining of the band-block-diagonal preconditioner module distributed with the solver.

Changes in v2.5.0

The main changes in this release involve a rearrangement of the entire SUNDIALS source tree (see §3.1). At the user interface level, the main impact is in the mechanism of including SUNDIALS header files which must now include the relative path (e.g. \#include <cvode/cvode.h>). Additional changes were made to the build system: all exported header files are now installed in separate subdirectories of the installation include directory.

A bug was fixed in the internal difference-quotient dense and banded Jacobian approximations, related to the estimation of the perturbation (which could have led to a failure of the linear solver when zero components with sufficiently small absolute tolerances were present).

The user interface to the consistent initial conditions calculations was modified. The IDACalcIC arguments t0, yy0, and yp0 were removed and a new function, IDAGetconsistentIC is provided (see §4.5.5 and §4.5.10.3 for details).

The functions in the generic dense linear solver (sundials_dense and sundials_smalldense) were modified to work for rectangular $m \times n$ matrices ($m \leq n$), while the factorization and solution functions were renamed to DenseGETRF/denGETRF and DenseGETRS/denGETRS, respectively. The factorization and solution functions in the generic band linear solver were renamed BandGBTF and BandGBTRS, respectively.

Changes in v2.4.0

FIDA, a Fortran-C interface module, was added (for details see Chapter 5.2).

IDASPBBCG and IDASPTFQMR modules have been added to interface with the Scaled Preconditioned Bi-CGstab (SPBCGS) and Scaled Preconditioned Transpose-Free Quasi-Minimal Residual (SPTFQMR) linear solver modules, respectively (for details see Chapter 4). At the same time, function type names for Scaled Preconditioned Iterative Linear Solvers were added for the user-supplied Jacobian-times-vector and preconditioner setup and solve functions.

The rootfinding feature was added, whereby the roots of a set of given functions may be computed during the integration of the DAE system.

A user-callable routine was added to access the estimated local error vector.

The deallocation functions now take as arguments the address of the respective memory block pointer.

To reduce the possibility of conflicts, the names of all header files have been changed by adding unique prefixes (ida_ and sundials_). When using the default installation procedure, the header files are exported under various subdirectories of the target include directory. For more details see Appendix A.

Changes in v2.3.0

The user interface has been further refined. Several functions used for setting optional inputs were combined into a single one. An optional user-supplied routine for setting the error weight vector was added. Additionally, to resolve potential variable scope issues, all SUNDIALS solvers release user data right after its use. The build systems has been further improved to make it more robust.

Changes in v2.2.2

Minor corrections and improvements were made to the build system. A new chapter in the User Guide was added — with constants that appear in the user interface.
Changes in v2.2.1

The changes in this minor SUNDIALS release affect only the build system.

Changes in v2.2.0

The major changes from the previous version involve a redesign of the user interface across the entire SUNDIALS suite. We have eliminated the mechanism of providing optional inputs and extracting optional statistics from the solver through the \texttt{iopt} and \texttt{ropt} arrays. Instead, IDA now provides a set of routines (with prefix \texttt{IDASet}) to change the default values for various quantities controlling the solver and a set of extraction routines (with prefix \texttt{IDAGet}) to extract statistics after return from the main solver routine. Similarly, each linear solver module provides its own set of \texttt{Set}- and \texttt{Get}-type routines. For more details see §4.5.8 and §4.5.10.

Additionally, the interfaces to several user-supplied routines (such as those providing Jacobians and preconditioner information) were simplified by reducing the number of arguments. The same information that was previously accessible through such arguments can now be obtained through \texttt{Get}-type functions.

Installation of IDA (and all of SUNDIALS) has been completely redesigned and is now based on configure scripts.

1.2 Reading this User Guide

The structure of this document is as follows:

- In Chapter 2, we give short descriptions of the numerical methods implemented by IDA for the solution of initial value problems for systems of DAEs, along with short descriptions of preconditioning (§2.2) and rootfinding (§2.3).

- The following chapter describes the structure of the SUNDIALS suite of solvers (§3.1) and the software organization of the IDA solver (§3.2).

- Chapter 4 is the main usage document for IDA for C applications. It includes a complete description of the user interface for the integration of DAE initial value problems.

- In Chapter 5.2, we describe FIDA, an interface module for the use of IDA with FORTRAN applications.

- Chapter 6 gives a brief overview of the generic NVVECTOR module shared among the various components of SUNDIALS, as well as details on the NVVECTOR implementations provided with SUNDIALS.

- Chapter 7 gives a brief overview of the generic SUNMATRIX module shared among the various components of SUNDIALS, and details on the SUNMATRIX implementations provided with SUNDIALS: a dense implementation (§7.3), a banded implementation (§7.4) and a sparse implementation (§7.5).

- Chapter 8 gives a brief overview of the generic SUNLINSOL module shared among the various components of SUNDIALS. This chapter contains details on the SUNLINSOL implementations provided with SUNDIALS. The chapter also contains details on the SUNLINSOL implementations provided with SUNDIALS that interface with external linear solver libraries.

- Chapter 9 describes the SUNNONLINSOL API and nonlinear solver implementations shared among the various components of SUNDIALS.

- Finally, in the appendices, we provide detailed instructions for the installation of IDA, within the structure of SUNDIALS (Appendix A), as well as a list of all the constants used for input to and output from IDA functions (Appendix B).
Finally, the reader should be aware of the following notational conventions in this user guide: program listings and identifiers (such as `IDAInit`) within textual explanations appear in typewriter type style; fields in C structures (such as `content`) appear in italics; and packages or modules, such as `idadls`, are written in all capitals. Usage and installation instructions that constitute important warnings are marked with a triangular symbol in the margin.

**Acknowledgments.** We wish to acknowledge the contributions to previous versions of the IDA code and user guide of Allan G. Taylor.

### 1.3 SUNDIALS Release License

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1.3.3 SUNDIALS Release Numbers

- LLNL-CODE-667205 (ARKODE)
- UCRL-CODE-155951 (CVODE)
- UCRL-CODE-155950 (CVODES)
- UCRL-CODE-155952 (IDA)
- UCRL-CODE-237203 (IDAS)
- LLNL-CODE-665877 (KINSOL)
Chapter 2
Mathematical Considerations

IDA solves the initial-value problem (IVP) for a DAE system of the general form

\[ F(t, y, \dot{y}) = 0, \quad y(t_0) = y_0, \quad \dot{y}(t_0) = \dot{y}_0, \quad (2.1) \]

where \( y, \dot{y}, \) and \( F \) are vectors in \( \mathbb{R}^N, \) \( t \) is the independent variable, \( \dot{y} = dy/dt, \) and initial values \( y_0, \dot{y}_0 \) are given. (Often \( t \) is time, but it certainly need not be.)

2.1 IVP solution

Prior to integrating a DAE initial-value problem, an important requirement is that the pair of vectors \( y_0 \) and \( \dot{y}_0 \) are both initialized to satisfy the DAE residual \( F(t_0, y_0, \dot{y}_0) = 0. \) For a class of problems that includes so-called semi-explicit index-one systems, IDA provides a routine that computes consistent initial conditions from a user’s initial guess \([10]\). For this, the user must identify sub-vectors of \( y \) (not necessarily contiguous), denoted \( y_d \) and \( y_a, \) which are its differential and algebraic parts, respectively, such that \( F \) depends on \( y_d \) but not on any components of \( y_a. \) The assumption that the system is “index one” means that for a given \( t \) and \( y_d, \) the system \( F(t, y, \dot{y}) = 0 \) defines \( y_a \) uniquely. In this case, a solver within IDA computes \( y_a \) and \( \dot{y}_d \) at \( t = t_0, \) given \( y_d \) and an initial guess for \( y_a. \) A second available option with this solver also computes all of \( y(t_0) \) given \( \dot{y}(t_0); \) this is intended mainly for quasi-steady-state problems, where \( \dot{y}(t_0) = 0 \) is given. In both cases, IDA solves the system \( F(t_0, y_0, \dot{y}_0) = 0 \) for the unknown components of \( y_0 \) and \( \dot{y}_0, \) using Newton iteration augmented with a line search global strategy. In doing this, it makes use of the existing machinery that is to be used for solving the linear systems during the integration, in combination with certain tricks involving the step size (which is set artificially for this calculation). For problems that do not fall into either of these categories, the user is responsible for passing consistent values, or risks failure in the numerical integration.

The integration method used in IDA is the variable-order, variable-coefficient BDF (Backward Differentiation Formula), in fixed-leading-coefficient form \([6]\). The method order ranges from 1 to 5, with the BDF of order \( q \) given by the multistep formula

\[ \sum_{i=0}^{q} \alpha_{n,i} y_{n-i} = h_n \dot{y}_n, \quad (2.2) \]

where \( y_n \) and \( \dot{y}_n \) are the computed approximations to \( y(t_n) \) and \( \dot{y}(t_n), \) respectively, and the step size is \( h_n = t_n - t_{n-1}. \) The coefficients \( \alpha_{n,i} \) are uniquely determined by the order \( q, \) and the history of the step sizes. The application of the BDF (2.2) to the DAE system (2.1) results in a nonlinear algebraic system to be solved at each step:

\[ G(y_n) = F \left( t_n, y_n, h_n^{-1} \sum_{i=0}^{q} \alpha_{n,i} y_{n-i} \right) = 0. \quad (2.3) \]
By default IDA solves (2.3) with a Newton iteration but IDA also allows for user-defined nonlinear solvers (see Chapter 9). Each Newton iteration requires the solution of a linear system of the form

\[ J[y_{n(m+1)} - y_{n(m)}] = -G(y_{n(m)}) , \]  

where \( y_{n(m)} \) is the \( m \)-th approximation to \( y_n \). Here \( J \) is some approximation to the system Jacobian \( \frac{\partial G}{\partial y} = \frac{\partial F}{\partial y} + \frac{\partial F}{\partial \dot{y}} \), \( \alpha = \alpha_{n,0}/h_n \). The scalar \( \alpha \) changes whenever the step size or method order changes.

For the solution of the linear systems within the Newton iteration, IDA provides several choices, including the option of a user-supplied linear solver module (see Chapter 8). The linear solver modules distributed with SUNDIALS are organized in two families, a direct family comprising direct linear solvers for dense, banded, or sparse matrices and a spils family comprising scaled preconditioned iterative (Krylov) linear solvers. The methods offered through these modules are as follows:

- dense direct solvers, using either an internal implementation or a BLAS/LAPACK implementation (serial or threaded vector modules only),
- band direct solvers, using either an internal implementation or a BLAS/LAPACK implementation (serial or threaded vector modules only),
- sparse direct solver interfaces, using either the KLU sparse solver library \([17, 1]\), or the thread-enabled SuperLU_MT sparse solver library \([33, 19, 4]\) (serial or threaded vector modules only) [Note that users will need to download and install the KLU or SuperLU_MT packages independent of IDA],
- SPGMR, a scaled preconditioned GMRES (Generalized Minimal Residual method) solver with or without restarts,
- SPFgmr, a scaled preconditioned FGMRES (Flexible Generalized Minimal Residual method) solver with or without restarts,
- SPBcgs, a scaled preconditioned Bi-CGStab (Bi-Conjugate Gradient Stable method) solver,
- SPTFqmr, a scaled preconditioned TFQMR (Transpose-Free Quasi-Minimal Residual method) solver, or
- PCG, a scaled preconditioned CG (Conjugate Gradient method) solver.

For large stiff systems, where direct methods are not feasible, the combination of a BDF integrator and a preconditioned Krylov method yields a powerful tool because it combines established methods for stiff integration, nonlinear iteration, and Krylov (linear) iteration with a problem-specific treatment of the dominant source of stiffness, in the form of the user-supplied preconditioner matrix \([8]\). For the spils linear solvers with IDA, preconditioning is allowed only on the left (see §2.2). Note that the dense, band, and sparse direct linear solvers can only be used with serial and threaded vector representations.

In the process of controlling errors at various levels, IDA uses a weighted root-mean-square norm, denoted \( \| \cdot \|_{\text{WRMS}} \), for all error-like quantities. The multiplicative weights used are based on the current solution and on the relative and absolute tolerances input by the user, namely

\[ W_i = 1 / \left[ r\text{tol} \cdot |y_i| + a\text{tol}_i \right] . \]  

Because \( 1/W_i \) represents a tolerance in the component \( y_i \), a vector whose norm is 1 is regarded as “small.” For brevity, we will usually drop the subscript WRMS on norms in what follows.

In the case of a matrix-based linear solver, the default Newton iteration is a Modified Newton iteration, in that the Jacobian \( J \) is fixed (and usually out of date) throughout the nonlinear iterations, with a coefficient \( \bar{\alpha} \) in place of \( \alpha \) in \( J \). However, in the case that a matrix-free iterative linear solver is
used, the default Newton iteration is an Inexact Newton iteration, in which $J$ is applied in a matrix-free manner, with matrix-vector products $Jv$ obtained by either difference quotients or a user-supplied routine. In this case, the linear residual $J\Delta y + G$ is nonzero but controlled. With the default Newton iteration, the matrix $J$ and preconditioner matrix $P$ are updated as infrequently as possible to balance the high costs of matrix operations against other costs. Specifically, this matrix update occurs when:

- starting the problem,
- the value $\bar{\alpha}$ at the last update is such that $\alpha/\bar{\alpha} < 3/5$ or $\alpha/\bar{\alpha} > 5/3$, or
- a non-fatal convergence failure occurred with an out-of-date $J$ or $P$.

The above strategy balances the high cost of frequent matrix evaluations and preprocessing with the slow convergence due to infrequent updates. To reduce storage costs on an update, Jacobian information is always reevaluated from scratch.

The default stopping test for nonlinear solver iterations in IDA ensures that the iteration error $y_n - y_{n(m)}$ is small relative to $y$ itself. For this, we estimate the linear convergence rate at all iterations $m > 1$ as

$$ R = \left( \frac{\delta_m}{\delta_1} \right)^{\frac{1}{m-1}}, $$

where the $\delta_m = y_{n(m)} - y_{n(m-1)}$ is the correction at iteration $m = 1, 2, \ldots$. The nonlinear solver iteration is halted if $R > 0.9$. The convergence test at the $m$-th iteration is then

$$ S\|\delta_m\| < 0.33, \quad \text{(2.7)} $$

where $S = R/(R-1)$ whenever $m > 1$ and $R \leq 0.9$. The user has the option of changing the constant in the convergence test from its default value of 0.33. The quantity $S$ is set to $S = 20$ initially and whenever $J$ or $P$ is updated, and it is reset to $S = 100$ on a step with $\alpha \neq \bar{\alpha}$. Note that at $m = 1$, the convergence test (2.7) uses an old value for $S$. Therefore, at the first nonlinear solver iteration, we make an additional test and stop the iteration if $\|\delta_1\| < 0.33 \cdot 10^{-4}$ (since such a $\delta_1$ is probably just noise and therefore not appropriate for use in evaluating $R$). We allow only a small number (default value 4) of nonlinear iterations. If convergence fails with $J$ or $P$ current, we are forced to reduce the step size $h_n$, and we replace $h_n$ by $h_n/4$. The integration is halted after a preset number (default value 10) of convergence failures. Both the maximum number of allowable nonlinear iterations and the maximum number of nonlinear convergence failures can be changed by the user from their default values.

When an iterative method is used to solve the linear system, to minimize the effect of linear iteration errors on the nonlinear and local integration error controls, we require the preconditioned linear residual to be small relative to the allowed error in the nonlinear iteration, i.e., $\|P^{-1}(Jx+G)\| < 0.05 \cdot 0.33$. The safety factor 0.05 can be changed by the user.

When the Jacobian is stored using either dense or band SUNMATRIX objects, the Jacobian $J$ defined in (2.5) can be either supplied by the user or have IDA compute one internally by difference quotients. In the latter case, we use the approximation

$$ J_{ij} = \left[ F_i(t, y + \sigma_j e_j, \dot{y} + \alpha \sigma_j e_j) - F_i(t, y, \dot{y}) \right]/\sigma_j, \text{ with} $$

$$ \sigma_j = \sqrt{U} \max \{|y_j|, |h\dot{y}_j|, 1/W_j \} \text{sign}(h\dot{y}_j), $$

where $U$ is the unit roundoff, $h$ is the current step size, and $W_j$ is the error weight for the component $y_j$ defined by (2.6). We note that with sparse and user-supplied SUNMATRIX objects, the Jacobian must be supplied by a user routine.

In the case of an iterative linear solver, if a routine for $Jv$ is not supplied, such products are approximated by

$$ Jv = [F(t, y + \sigma v, \dot{y} + \alpha \sigma v) - F(t, y, \dot{y})]/\sigma, $$

where the increment $\sigma = 1/\|v\|$. As an option, the user can specify a constant factor that is inserted into this expression for $\sigma$. 
During the course of integrating the system, IDA computes an estimate of the local truncation error, LTE, at the \( n \)-th time step, and requires this to satisfy the inequality

\[
\|\text{LTE}\|_{\text{WRMS}} \leq 1.
\]

Asymptotically, LTE varies as \( h^{q+1} \) at step size \( h \) and order \( q \), as does the predictor-corrector difference \( \Delta_n \equiv y_n - y_{n(0)} \). Thus there is a constant \( C \) such that

\[
\text{LTE} = C\Delta_n + O(h^{q+2}),
\]

and so the norm of LTE is estimated as \( |C| \cdot \|\Delta_n\| \). In addition, IDA requires that the error in the associated polynomial interpolant over the current step be bounded by 1 in norm. The leading term of the norm of this error is bounded by \( \bar{C}\|\Delta_n\| \) for another constant \( \bar{C} \). Thus the local error test in IDA is

\[
\max\{|C|, \bar{C}\}\|\Delta_n\| \leq 1. \quad (2.8)
\]

A user option is available by which the algebraic components of the error vector are omitted from the test (2.8), if these have been so identified.

In IDA, the local error test is tightly coupled with the logic for selecting the step size and order. First, there is an initial phase that is treated specially; for the first few steps, the step size is doubled and the order raised (from its initial value of 1) on every step, until (a) the local error test (2.8) fails, (b) the order is reduced (by the rules given below), or (c) the order reaches 5 (the maximum). For step and order selection on the general step, IDA uses a different set of local error estimates, based on the asymptotic behavior of the local error in the case of fixed step sizes. At each of the orders \( q' \) equal to \( q \), \( q - 1 \) (if \( q > 1 \)), \( q - 2 \) (if \( q > 2 \)), or \( q + 1 \) (if \( q < 5 \)), there are constants \( C(q') \) such that the norm of the local truncation error at order \( q' \) satisfies

\[
\text{LTE}(q') = C(q')\|\phi(q' + 1)\| + O(h^{q'+2}),
\]

where \( \phi(k) \) is a modified divided difference of order \( k \) that is retained by IDA (and behaves asymptotically as \( h^k \)). Thus the local truncation errors are estimated as \( \text{ELTE}(q') = C(q')\|\phi(q' + 1)\| \) to select step sizes. But the choice of order in IDA is based on the requirement that the scaled derivative norms, \( \|h^k y(k)\| \), are monotonically decreasing with \( k \), for \( k \) near \( q \). These norms are again estimated using the \( \phi(k) \), and in fact

\[
\|h^{q'+1} y(q'+1)\| \approx T(q') \equiv (q' + 1)\text{ELTE}(q').
\]

The step/order selection begins with a test for monotonicity that is made even before the local error test is performed. Namely, the order is reset to \( q' = q - 1 \) if (a) \( q = 2 \) and \( T(1) \leq T(2)/2 \), or (b) \( q > 2 \) and \( \max\{T(q-1), T(q-2)\} \leq T(q) \); otherwise \( q' = q \). Next the local error test (2.8) is performed, and if it fails, the step is redone at order \( q ← q' \) and a new step size \( h' \). The latter is based on the \( h^{q+1} \) asymptotic behavior of \( \text{ELTE}(q) \), and, with safety factors, is given by

\[
\eta = h'/h = 0.9/[2\text{ELTE}(q)]^{1/(q+1)}.
\]

The value of \( \eta \) is adjusted so that 0.25 ≤ \( \eta \) ≤ 0.9 before setting \( h ← h' = \eta h \). If the local error test fails a second time, IDA uses \( \eta = 0.25 \), and on the third and subsequent failures it uses \( q = 1 \) and \( \eta = 0.25 \). After 10 failures, IDA returns with a give-up message.

As soon as the local error test has passed, the step and order for the next step may be adjusted. No such change is made if \( q' = q - 1 \) from the prior test, if \( q = 5 \), or if \( q \) was increased on the previous step. Otherwise, if the last \( q + 1 \) steps were taken at a constant order \( q < 5 \) and a constant step size, IDA considers raising the order to \( q + 1 \). The logic is as follows: (a) If \( q = 1 \), then reset \( q = 2 \) if \( T(2) < T(1)/2 \). (b) If \( q > 1 \) then

- reset \( q ← q - 1 \) if \( T(q - 1) \leq \min\{T(q), T(q + 1)\} \);
- else reset \( q ← q + 1 \) if \( T(q + 1) < T(q) \);
• leave \( q \) unchanged otherwise [then \( T(q - 1) > T(q) \leq T(q + 1) \)].

In any case, the new step size \( h' \) is set much as before:

\[
\eta = h'/h = 1/[2 \cdot \text{ELTE}(q)]^{1/(q+1)}.
\]

The value of \( \eta \) is adjusted such that (a) if \( \eta > 2 \), \( \eta \) is reset to 2; (b) if \( \eta \leq 1 \), \( \eta \) is restricted to \( 0.5 \leq \eta \leq 0.9 \); and (c) if \( 1 < \eta < 2 \) we use \( \eta = 1 \). Finally, \( h \) is reset to \( h' = \eta h \). Thus we do not increase the step size unless it can be doubled. See [6] for details.

IDA permits the user to impose optional inequality constraints on individual components of the solution vector \( y \). Any of the following four constraints can be imposed: \( y_i > 0 \), \( y_i < 0 \), \( y_i \geq 0 \), or \( y_i \leq 0 \). The constraint satisfaction is tested after a successful nonlinear system solution. If any constraint fails, we declare a convergence failure of the nonlinear iteration and reduce the step size. Rather than cutting the step size by some arbitrary factor, IDA estimates a new step size \( h' \) using a linear approximation of the components in \( y \) that failed the constraint test (including a safety factor of 0.9 to cover the strict inequality case). These additional constraints are also imposed during the calculation of consistent initial conditions. If a step fails to satisfy the constraints repeatedly within a step attempt then the integration is halted and an error is returned. In this case the user may need to employ other strategies as discussed in §4.5.2 to satisfy the inequality constraints.

Normally, IDA takes steps until a user-defined output value \( t = t_{\text{out}} \) is overtaken, and then computes \( y(t_{\text{out}}) \) by interpolation. However, a “one step” mode option is available, where control returns to the calling program after each step. There are also options to force IDA not to integrate past a given stopping point \( t = t_{\text{stop}} \).

2.2 Preconditioning

When using a nonlinear solver that requires the solution of a linear system of the form \( J\Delta y = -G \) (e.g., the default Newton iteration), IDA makes repeated use of a linear solver. If this linear system solve is done with one of the scaled preconditioned iterative linear solvers supplied with SUNDIALS, these solvers are rarely successful if used without preconditioning; it is generally necessary to precondition the system in order to obtain acceptable efficiency. A system \( Ax = b \) can be preconditioned on the left, on the right, or on both sides. The Krylov method is then applied to a system with the matrix \( P^{-1}A \), \( AP^{-1} \), or \( P_L^{-1}AP_R^{-1} \), instead of \( A \). However, within IDA, preconditioning is allowed only on the left, so that the iterative method is applied to systems \( (P^{-1}J)\Delta y = -P^{-1}G \). Left preconditioning is required to make the norm of the linear residual in the nonlinear iteration meaningful; in general, \( \|J\Delta y + G\| \) is meaningless, since the weights used in the WRMS-norm correspond to \( y \).

In order to improve the convergence of the Krylov iteration, the preconditioner matrix \( P \) should in some sense approximate the system matrix \( A \). Yet at the same time, in order to be cost-effective, the matrix \( P \) should be reasonably efficient to evaluate and solve. Finding a good point in this tradeoff between rapid convergence and low cost can be very difficult. Good choices are often problem-dependent (for example, see [8] for an extensive study of preconditioners for reaction-transport systems).

Typical preconditioners used with IDA are based on approximations to the iteration matrix of the systems involved; in other words, \( P \approx \frac{\partial F}{\partial y} + \alpha \frac{\partial F}{\partial y} \), where \( \alpha \) is a scalar inversely proportional to the integration step size \( h \). Because the Krylov iteration occurs within a nonlinear solver iteration and further also within a time integration, and since each of these iterations has its own test for convergence, the preconditioner may use a very crude approximation, as long as it captures the dominant numerical feature(s) of the system. We have found that the combination of a preconditioner with the Newton-Krylov iteration, using even a fairly poor approximation to the Jacobian, can be surprisingly superior to using the same matrix without Krylov acceleration (i.e., a modified Newton iteration), as well as to using the Newton-Krylov method with no preconditioning.

2.3 Rootfinding

The IDA solver has been augmented to include a rootfinding feature. This means that, while integrating the Initial Value Problem (2.1), IDA can also find the roots of a set of user-defined functions \( g_i(t, y, \dot{y}) \)
that depend on \( t \), the solution vector \( y = y(t) \), and its \( t \)-derivative \( \dot{y}(t) \). The number of these root functions is arbitrary, and if more than one \( g_i \) is found to have a root in any given interval, the various root locations are found and reported in the order that they occur on the \( t \) axis, in the direction of integration.

Generally, this rootfinding feature finds only roots of odd multiplicity, corresponding to changes in sign of \( g_i(t, y(t), \dot{y}(t)) \), denoted \( g_i(t) \) for short. If a user root function has a root of even multiplicity (no sign change), it will probably be missed by \textsc{id}a. If such a root is desired, the user should reformulate the root function so that it changes sign at the desired root.

The basic scheme used is to check for sign changes of any \( g_i(t) \) over each time step taken, and then (when a sign change is found) to home in on the root (or roots) with a modified secant method \cite{24}. In addition, each time \( g \) is computed, \textsc{id}a checks to see if \( g(t) = 0 \) exactly, and if so it reports this as a root. However, if an exact zero of any \( g \) is found at a point \( t \), \textsc{id}a computes \( g \) at \( t + \delta \) for a small increment \( \delta \), slightly further in the direction of integration, and if any \( g(t + \delta) = 0 \) also, \textsc{id}a stops and reports an error. This way, each time \textsc{id}a takes a time step, it is guaranteed that the values of all \( g \) are nonzero at some past value of \( t \), beyond which a search for roots is to be done.

At any given time in the course of the time-stepping, after suitable checking and adjusting has been done, \textsc{id}a has an interval \((t_{lo}, t_{hi})\) in which roots of the \( g_i(t) \) are to be sought, such that \( t_{hi} \) is further ahead in the direction of integration, and all \( g_i(t_{lo}) \neq 0 \). The endpoint \( t_{hi} \) is either \( t_n \), the end of the time step last taken, or the next requested output time \( t_{out} \) if this comes sooner. The endpoint \( t_{lo} \) is either \( t_{n-1} \), or the last output time \( t_{out} \) (if this occurred within the last step), or the last root location (if a root was just located within this step), possibly adjusted slightly toward \( t_n \) if an exact zero was found. The algorithm checks \( g \) at \( t_{hi} \) for zeros and for sign changes in \((t_{lo}, t_{hi})\). If no sign changes are found, then either a root is reported (if some \( g_i(t_{hi}) = 0 \) or we proceed to the next time interval (starting at \( t_{hi} \)). If one or more sign changes were found, then a loop is entered to locate the root to within a rather tight tolerance, given by

\[
\tau = 100 * U * (|t_n| + |h|) \quad (U = \text{unit roundoff})
\]

Whenever sign changes are seen in two or more root functions, the one deemed most likely to have its root occur first is the one with the largest value of \(|g_i(t_{hi})|/|g_i(t_{hi}) - g_i(t_{lo})|\), corresponding to the closest to \( t_{lo} \) of the secant method values. At each pass through the loop, a new value \( t_{mid} \) is set, strictly within the search interval, and the values of \( g_i(t_{mid}) \) are checked. Then either \( t_{lo} \) or \( t_{hi} \) is reset to \( t_{mid} \) according to which subinterval is found to have the sign change. If there is none in \((t_{lo}, t_{mid})\) but some \( g_i(t_{mid}) = 0 \), then that root is reported. The loop continues until \(|t_{hi} - t_{lo}| < \tau \), and then the reported root location is \( t_{hi} \).

In the loop to locate the root of \( g_i(t) \), the formula for \( t_{mid} \) is

\[
t_{mid} = t_{hi} - (t_{hi} - t_{lo})g_i(t_{hi})/[g_i(t_{hi}) - \alpha g_i(t_{lo})],
\]

where \( \alpha \) a weight parameter. On the first two passes through the loop, \( \alpha \) is set to 1, making \( t_{mid} \) the secant method value. Thereafter, \( \alpha \) is reset according to the side of the subinterval (low vs high, i.e. toward \( t_{lo} \) vs toward \( t_{hi} \)) in which the sign change was found in the previous two passes. If the two sides were opposite, \( \alpha \) is set to 1. If the two sides were the same, \( \alpha \) is halved (if on the low side) or doubled (if on the high side). The value of \( t_{mid} \) is closer to \( t_{lo} \) when \( \alpha < 1 \) and closer to \( t_{hi} \) when \( \alpha > 1 \). If the above value of \( t_{mid} \) is within \( \tau/2 \) of \( t_{lo} \) or \( t_{hi} \), it is adjusted inward, such that its fractional distance from the endpoint (relative to the interval size) is between .1 and .5 (.5 being the midpoint), and the actual distance from the endpoint is at least \( \tau/2 \).
Chapter 3

Code Organization

3.1 SUNDIALS organization

The family of solvers referred to as SUNDIALS consists of the solvers CVODE and ARKODE (for ODE systems), KINSOL (for nonlinear algebraic systems), and IDA (for differential-algebraic systems). In addition, SUNDIALS also includes variants of CVODE and IDA with sensitivity analysis capabilities (using either forward or adjoint methods), called CVODES and IDAS, respectively.

The various solvers of this family share many subordinate modules. For this reason, it is organized as a family, with a directory structure that exploits that sharing (see Figures 3.1 and 3.2).

Figure 3.1: High-level diagram of the SUNDIALS suite.
following is a list of the solver packages presently available, and the basic functionality of each:

- **cvode**, a solver for stiff and nonstiff ODE systems $dy/dt = f(t,y)$ based on Adams and BDF methods;
- **cvodes**, a solver for stiff and nonstiff ODE systems with sensitivity analysis capabilities;
- **arkode**, a solver for stiff, nonstiff, mixed stiff-nonstiff, and multirate ODE systems $Mdy/dt = f_1(t,y) + f_2(t,y)$ based on Runge-Kutta methods;
- **ida**, a solver for differential-algebraic systems $F(t,y,\dot{y}) = 0$ based on BDF methods;
- **idas**, a solver for differential-algebraic systems with sensitivity analysis capabilities;
- **kinsol**, a solver for nonlinear algebraic systems $F(u) = 0$.

Note for modules that provide interfaces to third-party libraries (i.e., LAPACK, KLU, SUPERLUMT, SuperLU_DIST, hypre, PETSC, Trilinos, and RAJA) users will need to download and compile those packages independently.

### 3.2 IDA organization

The IDA package is written in the ANSI C language. The following summarizes the basic structure of the package, although knowledge of this structure is not necessary for its use.

The overall organization of the IDA package is shown in Figure 3.3. The central integration module, implemented in the files `ida.h`, `ida_impl.h`, and `ida.c`, deals with the evaluation of integration
coefficients, estimation of local error, selection of stepsize and order, and interpolation to user output points, among other issues.

IDA utilizes generic linear and nonlinear solver modules defined by the SUNLINSOL API (see Chapter 8) and SUNNONLINSOL API (see Chapter 9) respectively. As such, IDA has no knowledge of the method being used to solve the linear and nonlinear systems that arise in each time step. For any given user problem, there exists a single nonlinear solver interface and, if necessary, a linear system solver interface is specified, and invoked as needed during the integration. While SUNDIALS includes a fixed-point nonlinear solver module, it is not currently supported in IDA (note the fixed-point module is listed in Figure 3.1 but not Figure 3.3).

IDA now has a single unified linear solver interface, IDALS, supporting both direct and iterative linear solvers built using the generic SUNLINSOL API (see Chapter 8). These solvers may utilize a SUNMATRIX object (see Chapter 7) for storing Jacobian information, or they may be matrix-free. Since IDA can operate on any valid SUNLINSOL implementation, the set of linear solver modules available to IDA will expand as new SUNLINSOL modules are developed.

For users employing dense or banded Jacobian matrices, IDALS includes algorithms for their approximation through difference quotients, but the user also has the option of supplying the Jacobian (or an approximation to it) directly. This user-supplied routine is required when using sparse or user-supplied Jacobian matrices.

For users employing matrix-free iterative linear solvers, IDALS includes an algorithm for the approximation by difference quotients of the product between the Jacobian matrix and a vector, Jv. Again, the user has the option of providing routines for this operation, in two phases: setup (preprocessing of Jacobian data) and multiplication.

For preconditioned iterative methods, the preconditioning must be supplied by the user, again in two phases: setup and solve. While there is no default choice of preconditioner analogous to the difference-quotient approximation in the direct case, the references [8, 12], together with the example and demonstration programs included with IDA, offer considerable assistance in building preconditioners.

IDA’s linear solver interface consists of four primary routines, devoted to (1) memory allocation and initialization, (2) setup of the matrix data involved, (3) solution of the system, and (4) freeing of memory. The setup and solution phases are separate because the evaluation of Jacobians and preconditioners is done only periodically during the integration, as required to achieve convergence.
The call list within the central IDA module to each of the four associated functions is fixed, thus allowing the central module to be completely independent of the linear system method.

IDA also provides a preconditioner module, IDABBDPRE, for use with any of the Krylov iterative linear solvers. It works in conjunction with NVECTOR_PARALLEL and generates a preconditioner that is a block-diagonal matrix with each block being a banded matrix.

All state information used by IDA to solve a given problem is saved in a structure, and a pointer to that structure is returned to the user. There is no global data in the IDA package, and so, in this respect, it is reentrant. State information specific to the linear solver is saved in a separate structure, a pointer to which resides in the IDA memory structure. The reentrancy of IDA was motivated by the situation where two or more problems are solved by intermixed calls to the package from one user program.
Chapter 4

Using IDA for C Applications

This chapter is concerned with the use of IDA for the integration of DAEs in a C language setting. The following sections treat the header files, the layout of the user’s main program, description of the IDA user-callable functions, and description of user-supplied functions.

The sample programs described in the companion document [28] may also be helpful. Those codes may be used as templates (with the removal of some lines involved in testing), and are included in the IDA package.

Users with applications written in FORTRAN should see Chapter 5.2, which describes the FORTRAN/C interface module.

The user should be aware that not all SUNLINSOL and SUNMATRIX modules are compatible with all nVECTOR implementations. Details on compatibility are given in the documentation for each SUNMATRIX module (Chapter 7) and each SUNLINSOL module (Chapter 8). For example, nVECTOR_PARALLEL is not compatible with the dense, banded, or sparse SUNMATRIX types, or with the corresponding dense, banded, or sparse SUNLINSOL modules. Please check Chapters 7 and 8 to verify compatibility between these modules. In addition to that documentation, we note that the preconditioner module IDABBDPRE can only be used with nVECTOR_PARALLEL. It is not recommended to use a threaded vector module with SuperLU_MT unless it is the nVECTOR_OPENMP module, and SuperLU_MT is also compiled with OpenMP.

IDA uses various constants for both input and output. These are defined as needed in this chapter, but for convenience are also listed separately in Appendix B.

4.1 Access to library and header files

At this point, it is assumed that the installation of IDA, following the procedure described in Appendix A, has been completed successfully.

Regardless of where the user’s application program resides, its associated compilation and load commands must make reference to the appropriate locations for the library and header files required by IDA. The relevant library files are

- `libdir/libsundials_ida.lib`
- `libdir/libsundials_nvec*.lib`

where the file extension .lib is typically .so for shared libraries and .a for static libraries. The relevant header files are located in the subdirectories

- `incdir/include/id`a
- `incdir/include/sundials`
- `incdir/include/nvector`
• `incdir/include/sunmatrix`
• `incdir/include/sunlinsol`
• `incdir/include/sunnonlinsol`

The directories `libdir` and `incdir` are the install library and include directories, respectively. For a default installation, these are `instdir/lib` and `instdir/include`, respectively, where `instdir` is the directory where SUNDIALS was installed (see Appendix A).

Note that an application cannot link to both the IDA and IDAS libraries because both contain user-callable functions with the same names (to ensure that IDAS is backward compatible with IDA). Therefore, applications that contain both DAE problems and DAEs with sensitivity analysis, should use IDAS.

4.2 Data types

The `sundials_types.h` file contains the definition of the type `realtype`, which is used by the SUNDIALS solvers for all floating-point data, the definition of the integer type `sunindextype`, which is used for vector and matrix indices, and `booleantype`, which is used for certain logic operations within SUNDIALS.

4.2.1 Floating point types

The type `realtype` can be `float`, `double`, or `long double`, with the default being `double`. The user can change the precision of the SUNDIALS solvers arithmetic at the configuration stage (see §A.1.2).

Additionally, based on the current precision, `sundials_types.h` defines `BIG_REAL` to be the largest value representable as a `realtype`, `SMALL_REAL` to be the smallest value representable as a `realtype`, and `UNIT_ROUNDOFF` to be the difference between 1.0 and the minimum `realtype` greater than 1.0.

Within SUNDIALS, real constants are set by way of a macro called `RCONST`. It is this macro that needs the ability to branch on the definition `realtype`. In ANSI C, a floating-point constant with no suffix is stored as a `double`. Placing the suffix “F” at the end of a floating point constant makes it a `float`, whereas using the suffix “L” makes it a `long double`. For example,

```c
#define A 1.0
#define B 1.0F
#define C 1.0L
```

defines `A` to be a `double` constant equal to 1.0, `B` to be a `float` constant equal to 1.0, and `C` to be a `long double` constant equal to 1.0. The macro call `RCONST(1.0)` automatically expands to 1.0 if `realtype` is `double`, to 1.0F if `realtype` is `float`, or to 1.0L if `realtype` is `long double`. SUNDIALS uses the `RCONST` macro internally to declare all of its floating-point constants.

Additionally, SUNDIALS defines several macros for common mathematical functions e.g., `fabs`, `sqrt`, `exp`, etc. in `sundials_math.h`. The macros are prefixed with `SUNR` and expand to the appropriate C function based on the `realtype`. For example, the macro `SUNRabs` expands to the C function `fabs` when `realtype` is `double`, `fabsf` when `realtype` is `float`, and `fabsl` when `realtype` is `long double`.

A user program which uses the type `realtype`, the `RCONST` macro, and the `SUNR` mathematical function macros is precision-independent except for any calls to precision-specific library functions. Our example programs use `realtype`, `RCONST`, and the `SUNR` macros. Users can, however, use the type `double`, `float`, or `long double` in their code (assuming that this usage is consistent with the typedef for `realtype`) and call the appropriate math library functions directly. Thus, a previously existing piece of ANSI C code can use SUNDIALS without modifying the code to use `realtype`, `RCONST`, or the `SUNR` macros so long as the SUNDIALS libraries use the correct precision (for details see §A.1.2).
4.2.2 Integer types used for indexing

The type sunindextype is used for indexing array entries in SUNDIALS modules (e.g., vectors lengths and matrix sizes) as well as for storing the total problem size. During configuration sunindextype may be selected to be either a 32- or 64-bit signed integer with the default being 64-bit. See §A.1.2 for the configuration option to select the desired size of sunindextype. When using a 32-bit integer the total problem size is limited to $2^{31} - 1$ and with 64-bit integers the limit is $2^{63} - 1$. For users with problem sizes that exceed the 64-bit limit an advanced configuration option is available to specify the type used for sunindextype.

A user program which uses sunindextype to handle indices will work with both index storage types except for any calls to index storage-specific external libraries. Our C and C++ example programs use sunindextype. Users can, however, use any compatible type (e.g., int, long int, int32_t, int64_t, or long long int) in their code, assuming that this usage is consistent with the typedef for sunindextype on their architecture. Thus, a previously existing piece of ANSI C code can use SUNDIALS without modifying the code to use sunindextype, so long as the SUNDIALS libraries use the appropriate index storage type (for details see §A.1.2).

4.3 Header files

The calling program must include several header files so that various macros and data types can be used. The header file that is always required is:

- ida/idah.h, the header file for IDA, which defines the several types and various constants, and includes function prototypes. This includes the header file for IDALS, ida/idals.h.

Note that idah.h includes sundials_types.h, which defines the types realtype, sunindextype, and booleantype and the constants SUNFALSE and SUNTRUE.

The calling program must also include an NVECTOR implementation header file, of the form nvector/nvector_***.h. See Chapter 6 for the appropriate name. This file in turn includes the header file sundials_nvector.h which defines the abstract N_Vector data type.

If using a non-default nonlinear solver module, or when interacting with a SUNNONLINSOL module directly, the calling program must also include a SUNNONLINSOL implementation header file, of the form sundials/nonlinsol_***.h where *** is the name of the nonlinear solver module (see Chapter 9 for more information). This file in turn includes the header file sundials_nonlinear_solver.h which defines the abstract SUNNonlinearSolver data type.

If using a nonlinear solver that requires the solution of a linear system of the form (2.4) (e.g., the default Newton iteration), a linear solver module header file is also required. The header files corresponding to the various SUNDIALS-provided linear solver modules available for use with IDA are:

- sundilsol/sundilsol_dense.h, which is used with the dense linear solver module, SUNLINSOL_DENSE;
- sundilsol/sundilsol_band.h, which is used with the banded linear solver module, SUNLINSOL_BAND;
- sundilsol/sundilsol_lapackdense.h, which is used with the LAPACK dense linear solver module, SUNLINSOL_LAPACKDENSE;
- sundilsol/sundilsol_lapackband.h, which is used with the LAPACK banded linear solver module, SUNLINSOL_LAPACKBAND;
- sundilsol/sundilsol_klu.h, which is used with the KLU sparse linear solver module, SUNLINSOL_KLU;
- sundilsol/sundilsol_superlumt.h, which is used with the SUPERLUMT sparse linear solver module, SUNLINSOL_SUPERLUMT;
• Iterative linear solvers:
  - `sunlinsol/sunlinsol_spgmr.h`, which is used with the scaled, preconditioned GMRES Krylov linear solver module, SUNLINSOL_SPGMR;
  - `sunlinsol/sunlinsol_spfgmr.h`, which is used with the scaled, preconditioned FGMRES Krylov linear solver module, SUNLINSOL_SPFGMR;
  - `sunlinsol/sunlinsol_spbcgs.h`, which is used with the scaled, preconditioned Bi-CGStab Krylov linear solver module, SUNLINSOL_SPBCGS;
  - `sunlinsol/sunlinsol_sptfqmr.h`, which is used with the scaled, preconditioned TFQMR Krylov linear solver module, SUNLINSOL_SPTFQMR;
  - `sunlinsol/sunlinsol_pcg.h`, which is used with the scaled, preconditioned CG Krylov linear solver module, SUNLINSOL_PCG;

The header files for the SUNLINSOL_DENSE and SUNLINSOL_LAPACKDENSE linear solver modules include the file `sunmatrix/sunmatrix_dense.h`, which defines the SUNMATRIX_DENSE matrix module, as well as various functions and macros acting on such matrices.

The header files for the SUNLINSOL_BAND and SUNLINSOL_LAPACKBAND linear solver modules include the file `sunmatrix/sunmatrix_band.h`, which defines the SUNMATRIX_BAND matrix module, as well as various functions and macros acting on such matrices.

The header files for the SUNLINSOL_KLU and SUNLINSOL_SUPERLUMT sparse linear solvers include the file `sunmatrix/sunmatrix_sparse.h`, which defines the SUNMATRIX_SPARSE matrix module, as well as various functions and macros acting on such matrices.

The header files for the Krylov iterative solvers include the file `sundials/sundials_iterative.h`, which enumerates the kind of preconditioning, and (for the SPGMR and SPFGMR solvers) the choices for the Gram-Schmidt process.

Other headers may be needed, according to the choice of preconditioner, etc. For example, in the IDA_FoodWeb_kryp example (see [28]), preconditioning is done with a block-diagonal matrix. For this, even though the SUNLINSOL_SPGMR linear solver is used, the header `sundials/sundials_dense.h` is included for access to the underlying generic dense matrix arithmetic routines.

### 4.4 A skeleton of the user’s main program

The following is a skeleton of the user’s main program (or calling program) for the integration of a DAE IVP. Most of the steps are independent of the NVECTOR, SUNMATRIX, SUNLINSOL, and SUNNONLINSOL implementations used. For the steps that are not, refer to Chapter 6, 7, 8, and 9 for the specific name of the function to be called or macro to be referenced.

1. **Initialize parallel or multi-threaded environment, if appropriate**
   
   For example, call `MPI_Init` to initialize MPI if used, or set `num_threads`, the number of threads to use within the threaded vector functions, if used.

2. **Set problem dimensions etc.**
   
   This generally includes the problem size `N`, and may include the local vector length `Nlocal`.
   
   Note: The variables `N` and `Nlocal` should be of type `sunindextype`.

3. **Set vectors of initial values**
   
   To set the vectors `y0` and `yp0` to initial values for `y` and `ŷ`, use the appropriate functions defined by the particular NVECTOR implementation.

   For native SUNDIALS vector implementations (except the CUDA and RAJA-based ones), use a call of the form `y = N_VMake(..., ydata)` if the `realtype` array `ydata` containing the initial values of `y` already exists. Otherwise, create a new vector by making a call of the form `y0 =`
4.4 A skeleton of the user’s main program

\( N_{VNew}(...) \), and then set its elements by accessing the underlying data with a call of the form \( ydata = N_{VGetArrayPointer}(y0) \). See §6.3-6.6 for details.

For the hypre and PETSc vector wrappers, first create and initialize the underlying vector and then create an NVVECTOR wrapper with a call of the form \( y0 = N_{VMake}(yvec) \), where \( yvec \) is a hypre or PETSc vector. Note that calls like \( N_{VNew}(...) \) and \( N_{VGetArrayPointer}(...) \) are not available for these vector wrappers. See §6.7 and §6.8 for details.

If using either the CUDA- or RAJA-based vector implementations use a call of the form \( y0 = N_{VMake}(..., c) \) where \( c \) is a pointer to a suncudavec or sunrajavec vector class if this class already exists. Otherwise, create a new vector by making a call of the form \( y0 = N_{VNew}(...) \), and then set its elements by accessing the underlying data where it is located with a call of the form \( N_{VGetDeviceArrayPointer}(...) \) or \( N_{VGetHostArrayPointer}(...) \). Note that the vector class will allocate memory on both the host and device when instantiated. See §6.9-6.10 for details.

Set the vector \( y_p0 \) of initial conditions for \( \dot{y} \) similarly.

4. Create IDA object

Call \( ida\_mem = IDACreate() \) to create the IDA memory block. IDACreate returns a pointer to the IDA memory structure. See §4.5.1 for details. This \( \text{void } * \) pointer must then be passed as the first argument to all subsequent IDA function calls.

5. Initialize IDA solver

Call IDAInit(...) to provide required problem specifications (residual function, initial time, and initial conditions), allocate internal memory for IDA, and initialize IDA. IDAInit returns an error flag to indicate success or an illegal argument value. See §4.5.1 for details.

6. Specify integration tolerances

Call IDASSTolerances(...) or IDASVtolerances(...) to specify, respectively, a scalar relative tolerance and scalar absolute tolerance, or a scalar relative tolerance and a vector of absolute tolerances. Alternatively, call IDAWFtolerances to specify a function which sets directly the weights used in evaluating WRMS vector norms. See §4.5.2 for details.

7. Create matrix object

If a nonlinear solver requiring a linear solver will be used (e.g., the default Newton iteration) and the linear solver will be a matrix-based linear solver, then a template Jacobian matrix must be created by calling the appropriate constructor function defined by the particular SUNMATRIX implementation.

For the SUNDIALS-supplied SUNMATRIX implementations, the matrix object may be created using a call of the form

\[ \text{SUNMatrix } J = \text{SUNBandMatrix}(...); \]

or

\[ \text{SUNMatrix } J = \text{SUNDenseMatrix}(...); \]

or

\[ \text{SUNMatrix } J = \text{SUNSparseMatrix}(...); \]

NOTE: The dense, banded, and sparse matrix objects are usable only in a serial or threaded environment.

8. Create linear solver object

If a nonlinear solver requiring a linear solver is chosen (e.g., the default Newton iteration), then the desired linear solver object must be created by calling the appropriate constructor function...
defined by the particular SUNLINSOL implementation.

For any of the SUNDIALS-supplied SUNLINSOL implementations, the linear solver object may be created using a call of the form

\[
\text{SUNLinearSolver } LS = \text{SUNLinSol}_*(...);
\]

where * can be replaced with “Dense”, “SPGMR”, or other options, as discussed in §4.5.3 and Chapter 8.

9. **Set linear solver optional inputs**

   Call \*Set\* functions from the selected linear solver module to change optional inputs specific to that linear solver. See the documentation for each SUNLINSOL module in Chapter 8 for details.

10. **Attach linear solver module**

    If a nonlinear solver requiring a linear solver is chosen (e.g., the default Newton iteration), then initialize the IDALS linear solver interface by attaching the linear solver object (and matrix object, if applicable) with the following call (for details see §4.5.3):

\[
\text{ier} = \text{IDASetLinearSolver}(...);
\]

11. **Set optional inputs**

    Optionally, call IDASet\* functions to change from their default values any optional inputs that control the behavior of IDA. See §4.5.8.1 and §4.5.8 for details.

12. **Create nonlinear solver object** *(optional)*

    If using a non-default nonlinear solver (see §4.5.4), then create the desired nonlinear solver object by calling the appropriate constructor function defined by the particular SUNNONLINSOL implementation (e.g., \text{NLS} = \text{SUNNonlinSol}_***(...); where ** is the name of the nonlinear solver (see Chapter 9 for details).

13. **Attach nonlinear solver module** *(optional)*

    If using a non-default nonlinear solver, then initialize the nonlinear solver interface by attaching the nonlinear solver object by calling \text{ier} = \text{IDASetNonlinearSolver(ida_mem, NLS)}; (see §4.5.4 for details).

14. **Set nonlinear solver optional inputs** *(optional)*

    Call the appropriate set functions for the selected nonlinear solver module to change optional inputs specific to that nonlinear solver. These \textit{must} be called after IDAInit if using the default nonlinear solver or after attaching a new nonlinear solver to IDA, otherwise the optional inputs will be overridden by IDA defaults. See Chapter 9 for more information on optional inputs.

15. **Correct initial values**

    Optionally, call IDACalcIC to correct the initial values \(y_0\) and \(y'0\) passed to IDAInit. See §4.5.5. Also see §4.5.8.3 for relevant optional input calls.

16. **Specify rootfinding problem**

    Optionally, call IDARootInit to initialize a rootfinding problem to be solved during the integration of the DAE system. See §4.5.6 for details, and see §4.5.8.4 for relevant optional input calls.

17. **Advance solution in time**

    For each point at which output is desired, call \text{flag} = IDASolve(ida_mem, tout, \&tret, yret, ypret, itask). Here itask specifies the return mode. The vector \text{yret} (which can be the same as the vector \text{y0} above) will contain \(y(t)\), while the vector \text{ypret} (which can be the same as the vector \text{yp0} above) will contain \(\dot{y}(t)\). See §4.5.7 for details.
4.4 A skeleton of the user’s main program

18. **Get optional outputs**
   Call `IDA*Get*` functions to obtain optional output. See §4.5.10 for details.

19. **Deallocate memory for solution vectors**
   Upon completion of the integration, deallocate memory for the vectors `yret` and `ypret` (or `y` and `yp`) by calling the appropriate destructor function defined by the `NVECTOR` implementation:
   ```c
   N_VDestroy(yret);
   ```
   and similarly for `ypret`.

20. **Free solver memory**
   ```c
   IDAFree(&ida_mem)
   ```
   to free the memory allocated for IDA.

21. **Free nonlinear solver memory** *(optional)*
   If a non-default nonlinear solver was used, then call `SUNNonlinSolFree(NLS)` to free any memory allocated for the `SUNNONLINSOL` object.

22. **Free linear solver and matrix memory**
   Call `SUNLinSolFree` and `SUNMatDestroy` to free any memory allocated for the linear solver and matrix objects created above.

23. **Finalize MPI, if used**
   ```c
   MPI_Finalize()
   ```
   to terminate MPI.

**sundials** provides some linear solvers only as a means for users to get problems running and not as highly efficient solvers. For example, if solving a dense system, we suggest using the LAPACK solvers if the size of the linear system is > 50,000. (Thanks to A. Nicolai for his testing and recommendation.) Table 4.1 shows the linear solver interfaces available as `SUNLINSOL` modules and the vector implementations required for use. As an example, one cannot use the dense direct solver interfaces with the MPI-based vector implementation. However, as discussed in Chapter 8 the **sundials** packages operate on generic `SUNLINSOL` objects, allowing a user to develop their own solvers should they so desire.

Table 4.1: **sundials** linear solver interfaces and vector implementations that can be used for each.

<table>
<thead>
<tr>
<th>Linear Solver</th>
<th>Serial</th>
<th>Parallel (MPI)</th>
<th>OpenMP</th>
<th>pThreads</th>
<th>hypre</th>
<th>PETSc</th>
<th>CUDA</th>
<th>RAJA</th>
<th>User Supp.</th>
</tr>
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<tr>
<td>Dense</td>
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<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>LapackDense</td>
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<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>LapackBand</td>
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<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>KLU</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>SUPERLUMUT</td>
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<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>SPGMR</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td>✓</td>
<td>✓</td>
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<tr>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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</tr>
</tbody>
</table>
4.5 User-callable functions

This section describes the IDA functions that are called by the user to set up and solve a DAE. Some of these are required. However, starting with §4.5.8, the functions listed involve optional inputs/outputs or restarting, and those paragraphs can be skipped for a casual use of IDA. In any case, refer to §4.4 for the correct order of these calls.

On an error, each user-callable function returns a negative value and sends an error message to the error handler routine, which prints the message on stderr by default. However, the user can set a file as error output or can provide his own error handler function (see §4.5.8.1).

4.5.1 IDA initialization and deallocation functions

The following three functions must be called in the order listed. The last one is to be called only after the DAE solution is complete, as it frees the IDA memory block created and allocated by the first two calls.

**IDACreate**

Call ida_mem = IDACreate();

Description The function IDACreate instantiates an IDA solver object.

Arguments IDACreate has no arguments.

Return value If successful, IDACreate returns a pointer to the newly created IDA memory block (of type void *). Otherwise it returns NULL.

**IDAInit**

Call flag = IDAInit(ida_mem, res, t0, y0, yp0);

Description The function IDAInit provides required problem and solution specifications, allocates internal memory, and initializes IDA.

Arguments ida_mem (void *) pointer to the IDA memory block returned by IDACreate.

res (IDAResFn) is the C function which computes the residual function $F$ in the DAE. This function has the form res(t, yy, yp, resval, user_data). For full details see §4.6.1.

$\text{t0}$ (realtype) is the initial value of $t$.

$\text{y0}$ (N_Vector) is the initial value of $y$.

$\text{yp0}$ (N_Vector) is the initial value of $\dot{y}$.

Return value The return value flag (of type int) will be one of the following:

- **IDA_SUCCESS** The call to IDAInit was successful.
- **IDA_MEM_NULL** The IDA memory block was not initialized through a previous call to IDACreate.
- **IDA_MEM_FAIL** A memory allocation request has failed.
- **IDA_ILL_INPUT** An input argument to IDAInit has an illegal value.

Notes If an error occurred, IDAInit also sends an error message to the error handler function.

**IDAFree**

Call IDAFree(&ida_mem);

Description The function IDAFree frees the pointer allocated by a previous call to IDACreate.

Arguments The argument is the pointer to the IDA memory block (of type void *).

Return value The function IDAFree has no return value.
4.5 User-callable functions

4.5.2 IDA tolerance specification functions

One of the following three functions must be called to specify the integration tolerances (or directly specify the weights used in evaluating WRMS vector norms). Note that this call must be made after the call to IDAInit.

**IDASStolerances**

Call `flag = IDASStolerances(ida_mem, reltol, abstol);`

Description The function `IDASStolerances` specifies scalar relative and absolute tolerances.

Arguments `ida_mem (void *)` pointer to the IDA memory block returned by `IDACreate`.

`reltol (realtype)` is the scalar relative error tolerance.

`abstol (realtype)` is the scalar absolute error tolerance.

Return value The return value `flag` (of type `int`) will be one of the following:

- `IDA_SUCCESS` The call to `IDASStolerances` was successful.
- `IDA_MEM_NULL` The IDA memory block was not initialized through a previous call to `IDACreate`.
- `IDA_NO_MALLOC` The allocation function `IDAInit` has not been called.
- `IDA_ILL_INPUT` One of the input tolerances was negative.

**IDASVtolerances**

Call `flag = IDASVtolerances(ida_mem, reltol, abstol);`

Description The function `IDASVtolerances` specifies scalar relative tolerance and vector absolute tolerances.

Arguments `ida_mem (void *)` pointer to the IDA memory block returned by `IDACreate`.

`reltol (realtype)` is the scalar relative error tolerance.

`abstol (N_Vector)` is the vector of absolute error tolerances.

Return value The return value `flag` (of type `int`) will be one of the following:

- `IDA_SUCCESS` The call to `IDASVtolerances` was successful.
- `IDA_MEM_NULL` The IDA memory block was not initialized through a previous call to `IDACreate`.
- `IDA_NO_MALLOC` The allocation function `IDAInit` has not been called.
- `IDA_ILL_INPUT` The relative error tolerance was negative or the absolute tolerance had a negative component.

Notes This choice of tolerances is important when the absolute error tolerance needs to be different for each component of the state vector \( y \).

**IDAWFtolerances**

Call `flag = IDAWFtolerances(ida_mem, efun);`

Description The function `IDAWFtolerances` specifies a user-supplied function `efun` that sets the multiplicative error weights \( W_i \) for use in the weighted RMS norm, which are normally defined by Eq. (2.6).

Arguments `ida_mem (void *)` pointer to the IDA memory block returned by `IDACreate`.

`efun (IDAEwtFn)` is the C function which defines the `ewt` vector (see §4.6.3).

Return value The return value `flag` (of type `int`) will be one of the following:

- `IDA_SUCCESS` The call to `IDAWFtolerances` was successful.
- `IDA_MEM_NULL` The IDA memory block was not initialized through a previous call to `IDACreate`.
IDA_NO_MALLOC The allocation function IDAInit has not been called.

General advice on choice of tolerances. For many users, the appropriate choices for tolerance values in reltol and abstol are a concern. The following pieces of advice are relevant.

(1) The scalar relative tolerance reltol is to be set to control relative errors. So \( \text{reltol} = 10^{-4} \) means that errors are controlled to .01%. We do not recommend using \( \text{reltol} \) larger than \( 10^{-3} \). On the other hand, \( \text{reltol} \) should not be so small that it is comparable to the unit roundoff of the machine arithmetic (generally around \( 10^{-15} \)).

(2) The absolute tolerances \( \text{abstol} \) (whether scalar or vector) need to be set to control absolute errors when any components of the solution vector \( y \) may be so small that pure relative error control is meaningless. For example, if \( y[i] \) starts at some nonzero value, but in time decays to zero, then pure relative error control on \( y[i] \) makes no sense (and is overly costly) after \( y[i] \) is below some noise level. Then \( \text{abstol} \) (if scalar) or \( \text{abstol}[i] \) (if a vector) needs to be set to that noise level. If the different components have different noise levels, then \( \text{abstol} \) should be a vector. See the example idaRoberts_dns in the IDA package, and the discussion of it in the IDA Examples document [28]. In that problem, the three components vary between 0 and 1, and have different noise levels; hence the \( \text{abstol} \) vector. It is impossible to give any general advice on \( \text{abstol} \) values, because the appropriate noise levels are completely problem-dependent. The user or modeler hopefully has some idea as to what those noise levels are.

(3) Finally, it is important to pick all the tolerance values conservatively, because they control the error committed on each individual time step. The final (global) errors are a sort of accumulation of those per-step errors. A good rule of thumb is to reduce the tolerances by a factor of .01 from the actual desired limits on errors. So if you want .01% accuracy (globally), a good choice is \( \text{reltol} = 10^{-6} \). But in any case, it is a good idea to do a few experiments with the tolerances to see how the computed solution values vary as tolerances are reduced.

Advice on controlling unphysical negative values. In many applications, some components in the true solution are always positive or non-negative, though at times very small. In the numerical solution, however, small negative (hence unphysical) values can then occur. In most cases, these values are harmless, and simply need to be controlled, not eliminated. The following pieces of advice are relevant.

(1) The way to control the size of unwanted negative computed values is with tighter absolute tolerances. Again this requires some knowledge of the noise level of these components, which may or may not be different for different components. Some experimentation may be needed.

(2) If output plots or tables are being generated, and it is important to avoid having negative numbers appear there (for the sake of avoiding a long explanation of them, if nothing else), then eliminate them, but only in the context of the output medium. Then the internal values carried by the solver are unaffected. Remember that a small negative value in \( y_{\text{ret}} \) returned by IDA, with magnitude comparable to \( \text{abstol} \) or less, is equivalent to zero as far as the computation is concerned.

(3) The user’s residual routine \( \text{res} \) should never change a negative value in the solution vector \( yy \) to a non-negative value, as a ”solution” to this problem. This can cause instability. If the \( \text{res} \) routine cannot tolerate a zero or negative value (e.g. because there is a square root or log of it), then the offending value should be changed to zero or a tiny positive number in a temporary variable (not in the input \( yy \) vector) for the purposes of computing \( F(t,y,\dot{y}) \).

(4) IDA provides the option of enforcing positivity or non-negativity on components. Also, such constraints can be enforced by use of the recoverable error return feature in the user-supplied residual function. However, because these options involve some extra overhead cost, they should only be exercised if the use of absolute tolerances to control the computed values is unsuccessful.

4.5.3 Linear solver interface functions

As previously explained, a if the nonlinear solver requires the solution of linear systems of the from (2.4) (e.g., the default Newton iteration, then solution of these linear systems is handled with the idals linear solver interface. This interface supports all valid sunlinsol modules. Here, matrix-based sunlinsol modules utilize sunmatrix objects to store the Jacobian matrix \( J = \partial F/\partial y + \alpha \partial F/\partial \dot{y} \).
and factorizations used throughout the solution process. Conversely, matrix-free SUNLINSOL modules instead use iterative methods to solve the linear systems of equations, and only require the action of the Jacobian on a vector, \( Jv \).

With most iterative linear solvers, preconditioning can be done on the left only, on the right only, on both the left and the right, or not at all. The exceptions to this rule are SPFGMR that supports right preconditioning only and PCG that performs symmetric preconditioning. However, in IDA only left preconditioning is supported. For the specification of a preconditioner, see the iterative linear solver sections in §4.5.8 and §4.6. A preconditioner matrix \( P \) must approximate the Jacobian \( J \), at least crudely.

To specify a generic linear solver to IDA, after the call to IDACreate but before any calls to IDASolve, the user’s program must create the appropriate SUNLINSOL object and call the function IDASetLinearSolver, as documented below. To create the SUNLinearSolver object, the user may call one of the Sundials-packaged SUNLINSOL module constructor routines via a call of the form

\[
\text{SUNLinearSolver } LS = \text{SUNLinSol}_*(...);
\]

The current list of such constructor routines includes SUNLinSol_Dense, SUNLinSol_Band, SUNLinSol_LapackDense, SUNLinSol_LapackBand, SUNLinSol_KLU, SUNLinSol_SuperLUMT, SUNLinSol_SPGMR, SUNLinSol_SPFGMR, SUNLinSol_SPBCGS, SUNLinSol_SPTFQMR, and SUNLinSol_PCG.

Alternately, a user-supplied SUNLinearSolver module may be created and used instead. The use of each of the generic linear solvers involves certain constants, functions and possibly some macros, that are likely to be needed in the user code. These are available in the corresponding header file associated with the specific SUNMATRIX or SUNLINSOL module in question, as described in Chapters 7 and 8.

Once this solver object has been constructed, the user should attach it to IDA via a call to IDASetLinearSolver. The first argument passed to this function is the IDA memory pointer returned by IDACreate; the second argument is the desired SUNLINSOL object to use for solving systems. The third argument is an optional SUNMATRIX object to accompany matrix-based SUNLINSOL inputs (for matrix-free linear solvers, the third argument should be NULL). A call to this function initializes the IDALS linear solver interface, linking it to the main IDA integrator, and allows the user to specify additional parameters and routines pertinent to their choice of linear solver.

**IDASetLinearSolver**

**Call**

\[
\text{flag} = \text{IDASetLinearSolver}(\text{ida\_mem}, LS, J);
\]

**Description**
The function IDASetLinearSolver attaches a generic SUNLINSOL object \( LS \) and corresponding template Jacobian SUNMATRIX object \( J \) (if applicable) to IDA, initializing the IDALS linear solver interface.

**Arguments**
- \( ida\_mem \) (void *) pointer to the IDA memory block.
- \( LS \) (SUNLinearSolver) SUNLINSOL object to use for solving linear systems of the form (2.4).
- \( J \) (SUNMatrix) SUNMATRIX object for used as a template for the Jacobian (or NULL if not applicable).

**Return value**
The return value \( \text{flag} \) (of type \( \text{int} \)) is one of

- IDALS_SUCCESS The IDALS initialization was successful.
- IDALS_MEM_NULL The \( ida\_mem \) pointer is NULL.
- IDALS_ILL_INPUT The IDALS interface is not compatible with the \( LS \) or \( J \) input objects or is incompatible with the current NVECTOR module.
- IDALS_SUNLS_FAIL A call to the \( LS \) object failed.
- IDALS_MEM_FAIL A memory allocation request failed.

**Notes**
If \( LS \) is a matrix-based linear solver, then the template Jacobian matrix \( J \) will be used in the solve process, so if additional storage is required within the SUNMATRIX object (e.g. for factorization of a banded matrix), ensure that the input object is allocated
with sufficient size (see the documentation of the particular SUNMATRIX type in Chapter 7 for further information).

The previous routines IDADlsSetLinearSolver and IDASpilsSetLinearSolver are now wrappers for this routine, and may still be used for backward-compatibility. However, these will be deprecated in future releases, so we recommend that users transition to the new routine name soon.

### 4.5.4 Nonlinear solver interface function

By default IDA uses the SUNNONLINSOL implementation of Newton’s method defined by the SUNNONLINSOL_{NEWTON} module (see §9.3). To specify a different nonlinear solver in IDA, the user’s program must create a SUNNONLINSOL object by calling the appropriate constructor routine. The user must then attach the SUNNONLINSOL object to IDA by calling IDASetNonlinearSolver, as documented below.

When changing the nonlinear solver in IDA, IDASetNonlinearSolver must be called after IDAINit. If any calls to IDASolve have been made, then IDA will need to be reinitialized by calling IDAREInit to ensure that the nonlinear solver is initialized correctly before any subsequent calls to IDASolve.

The first argument passed to the routine IDASetNonlinearSolver is the IDA memory pointer returned by IDACreate and the second argument is the SUNNONLINSOL object to use for solving the nonlinear system 2.3. A call to this function attaches the nonlinear solver to the main IDA integrator. We note that at present, the SUNNONLINSOL object must be of type SUNNONLINEARSOLVER_ROOTFIND.

#### IDASetNonlinearSolver

Call

```c
flag = IDASetNonlinearSolver(ida_mem, NLS);
```

Description The function IDASetNonlinearSolver attaches a SUNNONLINSOL object (NLS) to IDA.

Arguments

- `ida_mem` (void *) pointer to the IDA memory block.
- `NLS` (SUNNonlinearSolver) SUNNONLINSOL object to use for solving nonlinear systems.

Return value The return value `flag` (of type int) is one of

- `IDA_SUCCESS` The nonlinear solver was successfully attached.
- `IDA_MEM_NULL` The `ida_mem` pointer is NULL.
- `IDA_ILL_INPUT` The SUNNONLINSOL object is NULL, does not implement the required nonlinear solver operations, is not of the correct type, or the residual function, convergence test function, or maximum number of nonlinear iterations could not be set.

### 4.5.5 Initial condition calculation function

IDACalcIC calculates corrected initial conditions for the DAE system for certain index-one problems including a class of systems of semi-implicit form. (See §2.1 and Ref. [10].) It uses Newton iteration combined with a linesearch algorithm. Calling IDACalcIC is optional. It is only necessary when the initial conditions do not satisfy the given system. Thus if $y_0$ and $y_0'$ are known to satisfy $F(t_0, y_0, y_0') = 0$, then a call to IDACalcIC is generally not necessary.

A call to the function IDACalcIC must be preceded by successful calls to IDACreate and IDAINit (or IDAREInit), and by a successful call to the linear system solver specification function. The call to IDACalcIC should precede the call(s) to IDASolve for the given problem.

#### IDACalcIC

Call

```c
flag = IDACalcIC(ida_mem, icopt, tout1);
```

Description The function IDACalcIC corrects the initial values $y_0$ and $y_0'$ at time $t_0$.

Arguments

- `ida_mem` (void *) pointer to the IDA memory block.
icot (int) is one of the following two options for the initial condition calculation.

icot=IDA_YA_YDP_INIT directs IDACalcIC to compute the algebraic components of \( y \) and differential components of \( \dot{y} \), given the differential components of \( y \). This option requires that the N_Vector id was set through IDASetId, specifying the differential and algebraic components.

icot=IDA_Y_INIT directs IDACalcIC to compute all components of \( y \), given \( \dot{y} \). In this case, id is not required.

tout1 (realtype) is the first value of \( t \) at which a solution will be requested (from IDASolve). This value is needed here only to determine the direction of integration and rough scale in the independent variable \( t \).

Return value The return value flag (of type int) will be one of the following:

IDA_SUCCESS IDASolve succeeded.
IDA_MEM_NULL The argument ida_mem was NULL.
IDA_NO_MALLOC The allocation function IDAInit has not been called.
IDA_ILL_INPUT One of the input arguments was illegal.
IDA_LSETUP_FAIL The linear solver’s setup function failed in an unrecoverable manner.
IDA_LINIT_FAIL The linear solver’s initialization function failed.
IDA_LSOLVE_FAIL The linear solver’s solve function failed in an unrecoverable manner.
IDA_BAD_EWT Some component of the error weight vector is zero (illegal), either for the input value of \( y_0 \) or a corrected value.
IDA_FIRST_RES_FAIL The user’s residual function returned a recoverable error flag on the first call, but IDACalcIC was unable to recover.
IDA_RES_FAIL The user’s residual function returned a nonrecoverable error flag.
IDA_NO_RECOVERY The user’s residual function, or the linear solver’s setup or solve function had a recoverable error, but IDACalcIC was unable to recover.
IDA_CONSTR_FAIL IDACalcIC was unable to find a solution satisfying the inequality constraints.
IDA_LINESEARCH_FAIL The linesearch algorithm failed to find a solution with a step larger than steptol in weighted RMS norm, and within the allowed number of backtracks.
IDA_CONV_FAIL IDACalcIC failed to get convergence of the Newton iterations.

Notes All failure return values are negative and therefore a test flag < 0 will trap all IDACalcIC failures.

Note that IDACalcIC will correct the values of \( y(t_0) \) and \( \dot{y}(t_0) \) which were specified in the previous call to IDAInit or IDAReInit. To obtain the corrected values, call IDAGetconsistentIC (see §4.5.10.3).

4.5.6 Rootfinding initialization function

While integrating the IVP, IDA has the capability of finding the roots of a set of user-defined functions. To activate the rootfinding algorithm, call the following function. This is normally called only once, prior to the first call to IDASolve, but if the rootfinding problem is to be changed during the solution, IDARootInit can also be called prior to a continuation call to IDASolve.

IDARootInit

Call flag = IDARootInit(ida_mem, nrtfn, g);
Description

The function \texttt{IDARootInit} specifies that the roots of a set of functions \( g_i(t, y, \dot{y}) \) are to be found while the IVP is being solved.

Arguments

- \texttt{ida_mem} (\texttt{void *}) pointer to the IDA memory block returned by \texttt{IDACreate}.
- \texttt{nrtfn} (\texttt{int}) is the number of root functions \( g_i \).
- \texttt{g} (\texttt{IDARootFn}) is the C function which defines the \texttt{nrtfn} functions \( g_i(t, y, \dot{y}) \) whose roots are sought. See §4.6.4 for details.

Return value

The return value \texttt{flag} (of type \texttt{int}) is one of:

- \texttt{IDA_SUCCESS} The call to \texttt{IDARootInit} was successful.
- \texttt{IDA_MEM_NULL} The \texttt{ida_mem} argument was NULL.
- \texttt{IDA_MEM_FAIL} A memory allocation failed.
- \texttt{IDA_Ill_INPUT} The function \texttt{g} is NULL, but \texttt{nrtfn} > 0.

Notes

If a new IVP is to be solved with a call to \texttt{IDAReInit}, where the new IVP has no rootfinding problem but the prior one did, then call \texttt{IDARootInit} with \texttt{nrtfn} = 0.

### 4.5.7 IDA solver function

This is the central step in the solution process, the call to perform the integration of the DAE. One of the input arguments (\texttt{itask}) specifies one of two modes as to where IDA is to return a solution. But these modes are modified if the user has set a stop time (with \texttt{IDASetStopTime}) or requested rootfinding.

#### IDASolve

Call

\begin{verbatim}
flag = IDASolve(ida_mem, tout, &tret, yret, ypret, itask);
\end{verbatim}

Description

The function \texttt{IDASolve} integrates the DAE over an interval in \( t \).

Arguments

- \texttt{ida_mem} (\texttt{void *}) pointer to the IDA memory block.
- \texttt{tout} (\texttt{realtype}) the next time at which a computed solution is desired.
- \texttt{tret} (\texttt{realtype}) the time reached by the solver (output).
- \texttt{yret} (\texttt{N_Vector}) the computed solution vector \( y \).
- \texttt{ypret} (\texttt{N_Vector}) the computed solution vector \( \dot{y} \).
- \texttt{itask} (\texttt{int}) a flag indicating the job of the solver for the next user step. The \texttt{IDA_NORMAL} task is to have the solver take internal steps until it has reached or just passed the user specified \texttt{tout} parameter. The solver then interpolates in order to return approximate values of \( y(tout) \) and \( \dot{y}(tout) \). The \texttt{IDA_ONE_STEP} option tells the solver to just take one internal step and return the solution at the point reached by that step.

Return value

\texttt{IDASolve} returns vectors \texttt{yret} and \texttt{ypret} and a corresponding independent variable value \( t = tret \), such that \( (yret, ypret) \) are the computed values of \( (y(t), \dot{y}(t)) \).

In \texttt{IDA_NORMAL} mode with no errors, \texttt{tret} will be equal to \texttt{tout} and \texttt{yret} = \( y(tout) \), \texttt{ypret} = \( \dot{y}(tout) \).

The return value \texttt{flag} (of type \texttt{int}) will be one of the following:

- \texttt{IDA_SUCCESS} \texttt{IDASolve} succeeded.
- \texttt{IDA_TSTOP_RETURN} \texttt{IDASolve} succeeded by reaching the stop point specified through the optional input function \texttt{IDASetStopTime}. See §4.5.8.1 for more information.
- \texttt{IDA_ROOT_RETURN} \texttt{IDASolve} succeeded and found one or more roots. In this case, \texttt{tret} is the location of the root. If \texttt{nrtfn} > 1, call \texttt{IDAGetRootInfo} to see which \( g_i \) were found to have a root. See §4.5.10.4 for more information.
- \texttt{IDA_MEM_NULL} The \texttt{ida_mem} argument was NULL.
4.5 User-callable functions

IDA_ILI_INPUT  One of the inputs to IDASolve was illegal, or some other input to the solver was either illegal or missing. The latter category includes the following situations: (a) The tolerances have not been set. (b) A component of the error weight vector became zero during internal time-stepping. (c) The linear solver initialization function (called by the user after calling IDACreate) failed to set the linear solver-specific lsolve field in ida_mem. (d) A root of one of the root functions was found both at a point $t$ and also very near $t$. In any case, the user should see the printed error message for details.

IDA_TOO MUCH WORK  The solver took mxstep internal steps but could not reach tout. The default value for mxstep is MXSTEP_DEFAULT = 500.

IDA_TOO MUCH ACC  The solver could not satisfy the accuracy demanded by the user for some internal step.

IDA_ERR FAIL  Error test failures occurred too many times (MXNEF = 10) during one internal time step or occurred with $|h| = h_{\text{min}}$.

IDA_CONV FAIL  Convergence test failures occurred too many times (MXNCF = 10) during one internal time step or occurred with $|h| = h_{\text{min}}$.

IDA_LINIT FAIL  The linear solver’s initialization function failed.

IDA_LSETUP FAIL  The linear solver’s setup function failed in an unrecoverable manner.

IDA_LSOLVE FAIL  The linear solver’s solve function failed in an unrecoverable manner.

IDA_CONSTR FAIL  The inequality constraints were violated and the solver was unable to recover.

IDA_REP_RES_ERR  The user’s residual function repeatedly returned a recoverable error flag, but the solver was unable to recover.

IDA_RES FAIL  The user’s residual function returned a nonrecoverable error flag.

IDA_RTFUNC FAIL  The rootfinding function failed.

Notes  The vector $y_{\text{ret}}$ can occupy the same space as the vector $y_0$ of initial conditions that was passed to IDAInit, and the vector $yp_{\text{ret}}$ can occupy the same space as $yp_0$.

In the IDA_ONE_STEP mode, tout is used on the first call only, and only to get the direction and rough scale of the independent variable.

If a stop time is enabled (through a call to IDASetStopTime), then IDASolve returns the solution at tstop. Once the integrator returns at a stop time, any future testing for tstop is disabled (and can be reenabled only though a new call to IDASetStopTime).

All failure return values are negative and therefore a test flag < 0 will trap all IDASolve failures.

On any error return in which one or more internal steps were taken by IDASolve, the returned values of tret, yret, and yp_{\text{ret}} correspond to the farthest point reached in the integration. On all other error returns, these values are left unchanged from the previous IDASolve return.

4.5.8 Optional input functions

There are numerous optional input parameters that control the behavior of the IDA solver. IDA provides functions that can be used to change these optional input parameters from their default values. Table 4.2 lists all optional input functions in IDA which are then described in detail in the remainder of this section. For the most casual use of IDA, the reader can skip to §4.6.

We note that, on an error return, all these functions also send an error message to the error handler function. We also note that all error return values are negative, so a test flag < 0 will catch any error.
### Table 4.2: Optional inputs for IDA and IDALS

<table>
<thead>
<tr>
<th>Optional input</th>
<th>Function name</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pointer to an error file</td>
<td>IDASetErrFile</td>
<td>stderr</td>
</tr>
<tr>
<td>Error handler function</td>
<td>IDASetErrHandlerFn</td>
<td>internal fn.</td>
</tr>
<tr>
<td>User data</td>
<td>IDASetUserData</td>
<td>NULL</td>
</tr>
<tr>
<td>Maximum order for BDF method</td>
<td>IDASetMaxOrd</td>
<td>5</td>
</tr>
<tr>
<td>Maximum no. of internal steps before ( t_{out} )</td>
<td>IDASetMaxNumSteps</td>
<td>500</td>
</tr>
<tr>
<td>Initial step size</td>
<td>IDASetInitStep</td>
<td>estimated</td>
</tr>
<tr>
<td>Maximum absolute step size</td>
<td>IDASetMaxStep</td>
<td>∞</td>
</tr>
<tr>
<td>Value of ( t_{stop} )</td>
<td>IDASetStopTime</td>
<td>∞</td>
</tr>
<tr>
<td>Maximum no. of error test failures</td>
<td>IDASetMaxErrTestFails</td>
<td>10</td>
</tr>
<tr>
<td>Maximum no. of nonlinear iterations</td>
<td>IDASetMaxNonlinIters</td>
<td>4</td>
</tr>
<tr>
<td>Maximum no. of convergence failures</td>
<td>IDASetMaxConvFails</td>
<td>10</td>
</tr>
<tr>
<td>Coeff. in the nonlinear convergence test</td>
<td>IDASetNonlinConvCoef</td>
<td>0.33</td>
</tr>
<tr>
<td>Supress alg. vars. from error test</td>
<td>IDASetSuppressAlg</td>
<td>SUNFALSE</td>
</tr>
<tr>
<td>Variable types (differential/algebraic)</td>
<td>IDASetId</td>
<td>NULL</td>
</tr>
<tr>
<td>Inequality constraints on solution</td>
<td>IDASetConstraints</td>
<td>NULL</td>
</tr>
<tr>
<td>Direction of zero-crossing</td>
<td>IDASetRootDirection</td>
<td>both</td>
</tr>
<tr>
<td>Disable rootfinding warnings</td>
<td>IDASetNoInactiveRootWarn</td>
<td>none</td>
</tr>
</tbody>
</table>

#### IDA initial conditions calculation

<table>
<thead>
<tr>
<th>Optional input</th>
<th>Function name</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coeff. in the nonlinear convergence test</td>
<td>IDASetNonlinConvCoefIC</td>
<td>0.0033</td>
</tr>
<tr>
<td>Maximum no. of steps</td>
<td>IDASetMaxNumStepsIC</td>
<td>5</td>
</tr>
<tr>
<td>Maximum no. of Jacobian/precond. evals.</td>
<td>IDASetMaxNumJacsIC</td>
<td>4</td>
</tr>
<tr>
<td>Maximum no. of Newton iterations</td>
<td>IDASetMaxNumItersIC</td>
<td>10</td>
</tr>
<tr>
<td>Max. linesearch backtracks per Newton iter.</td>
<td>IDASetMaxBacksIC</td>
<td>100</td>
</tr>
<tr>
<td>Turn off linesearch</td>
<td>IDASetLineSearchOffIC</td>
<td>SUNFALSE</td>
</tr>
<tr>
<td>Lower bound on Newton step</td>
<td>IDASetStepToleranceIC</td>
<td>uround^{2/3}</td>
</tr>
</tbody>
</table>

#### IDALS linear solver interface

<table>
<thead>
<tr>
<th>Optional input</th>
<th>Function name</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jacobian function</td>
<td>IDASetJacFn</td>
<td>DQ</td>
</tr>
<tr>
<td>Jacobian-times-vector function</td>
<td>IDASetJacTimes</td>
<td>NULL, DQ</td>
</tr>
<tr>
<td>Preconditioner functions</td>
<td>IDASetPreconditioner</td>
<td>NULL, NULL</td>
</tr>
<tr>
<td>Ratio between linear and nonlinear tolerances</td>
<td>IDASetEpsLin</td>
<td>0.05</td>
</tr>
<tr>
<td>Increment factor used in DQ ( Jv ) approx.</td>
<td>IDASetIncrementFactor</td>
<td>1.0</td>
</tr>
</tbody>
</table>
4.5 User-callable functions

4.5.8.1 Main solver optional input functions

The calls listed here can be executed in any order. However, if the user's program calls either IDASetErrFile or IDASetErrHandlerFn, then that call should appear first, in order to take effect for any later error message.

**IDASetErrFile**

Call

\[
\text{flag} = \text{IDASetErrFile}(\text{ida_mem}, \text{errfp});
\]

Description

The function IDASetErrFile specifies the pointer to the file where all IDA messages should be directed when the default IDA error handler function is used.

Arguments

- `ida_mem` (void *) pointer to the IDA memory block.
- `errfp` (FILE *) pointer to output file.

Return value

The return value `flag` (of type `int`) is one of

- `IDA_SUCCESS` The optional value has been successfully set.
- `IDA_MEM_NULL` The `ida_mem` pointer is NULL.

Notes

The default value for `errfp` is stderr.

Passing a value NULL disables all future error message output (except for the case in which the IDA memory pointer is NULL). This use of IDASetErrFile is strongly discouraged.

If IDASetErrFile is to be called, it should be called before any other optional input functions, in order to take effect for any later error message.

**IDASetErrHandlerFn**

Call

\[
\text{flag} = \text{IDASetErrHandlerFn}(\text{ida_mem}, \text{ehfun}, \text{eh_data});
\]

Description

The function IDASetErrHandlerFn specifies the optional user-defined function to be used in handling error messages.

Arguments

- `ida_mem` (void *) pointer to the IDA memory block.
- `ehfun` (IDAErrHandlerFn) is the user's C error handler function (see §4.6.2).
- `eh_data` (void *) pointer to user data passed to `ehfun` every time it is called.

Return value

The return value `flag` (of type `int`) is one of

- `IDA_SUCCESS` The function `ehfun` and data pointer `eh_data` have been successfully set.
- `IDA_MEM_NULL` The `ida_mem` pointer is NULL.

Notes

Error messages indicating that the IDA solver memory is NULL will always be directed to stderr.

**IDASetUserData**

Call

\[
\text{flag} = \text{IDASetUserData}(\text{ida_mem}, \text{user_data});
\]

Description

The function IDASetUserData specifies the user data block `user_data` and attaches it to the main IDA memory block.

Arguments

- `ida_mem` (void *) pointer to the IDA memory block.
- `user_data` (void *) pointer to the user data.

Return value

The return value `flag` (of type `int`) is one of

- `IDA_SUCCESS` The optional value has been successfully set.
- `IDA_MEM_NULL` The `ida_mem` pointer is NULL.
Notes If specified, the pointer to user_data is passed to all user-supplied functions that have it as an argument. Otherwise, a NULL pointer is passed.

If user_data is needed in user linear solver or preconditioner functions, the call to IDASetUserData must be made before the call to specify the linear solver.

**IDASetMaxOrd**

Call `flag = IDASetMaxOrd(ida_mem, maxord);`

Description The function IDASetMaxOrd specifies the maximum order of the linear multistep method.

Arguments ida_mem (void *) pointer to the IDA memory block.

maxord (int) value of the maximum method order. This must be positive.

Return value The return value flag (of type int) is one of

- **IDA_SUCCESS** The optional value has been successfully set.
- **IDA_MEM_NULL** The ida_mem pointer is NULL.
- **IDA_IILL_INPUT** The input value maxord is ≤ 0, or larger than its previous value.

Notes The default value is 5. If the input value exceeds 5, the value 5 will be used. Since maxord affects the memory requirements for the internal IDA memory block, its value cannot be increased past its previous value.

**IDASetMaxNumSteps**

Call `flag = IDASetMaxNumSteps(ida_mem, mxsteps);`

Description The function IDASetMaxNumSteps specifies the maximum number of steps to be taken by the solver in its attempt to reach the next output time.

Arguments ida_mem (void *) pointer to the IDA memory block.

mxsteps (long int) maximum allowed number of steps.

Return value The return value flag (of type int) is one of

- **IDA_SUCCESS** The optional value has been successfully set.
- **IDA_MEM_NULL** The ida_mem pointer is NULL.

Notes Passing `mxsteps = 0` results in IDA using the default value (500).

Passing `mxsteps < 0` disables the test (not recommended).

**IDASetInitStep**

Call `flag = IDASetInitStep(ida_mem, hin);`

Description The function IDASetInitStep specifies the initial step size.

Arguments ida_mem (void *) pointer to the IDA memory block.

hin (realtype) value of the initial step size to be attempted. Pass 0.0 to have IDA use the default value.

Return value The return value flag (of type int) is one of

- **IDA_SUCCESS** The optional value has been successfully set.
- **IDA_MEM_NULL** The ida_mem pointer is NULL.

Notes By default, IDA estimates the initial step as the solution of \( \|h\dot{y}\|_{WRMS} = 1/2 \), with an added restriction that \( |h| \leq .001|t_{out} - t_{0}| \).
4.5 User-callable functions

IDASetMaxStep

Call flag = IDASetMaxStep(ida_mem, hmax);

Description The function IDASetMaxStep specifies the maximum absolute value of the step size.

Arguments ida_mem (void *) pointer to the IDA memory block.

hmax (realtype) maximum absolute value of the step size.

Return value The return value flag (of type int) is one of

- IDA_SUCCESS The optional value has been successfully set.
- IDA_MEM_NULL The ida_mem pointer is NULL.
- IDA_ILL_INPUT Either hmax is not positive or it is smaller than the minimum allowable step.

Notes Pass hmax = 0 to obtain the default value ∞.

IDASetStopTime

Call flag = IDASetStopTime(ida_mem, tstop);

Description The function IDASetStopTime specifies the value of the independent variable t past which the solution is not to proceed.

Arguments ida_mem (void *) pointer to the IDA memory block.

tstop (realtype) value of the independent variable past which the solution should not proceed.

Return value The return value flag (of type int) is one of

- IDA_SUCCESS The optional value has been successfully set.
- IDA_MEM_NULL The ida_mem pointer is NULL.
- IDA_ILL_INPUT The value of tstop is not beyond the current t value, t_n.

Notes The default, if this routine is not called, is that no stop time is imposed.

Once the integrator returns at a stop time, any future testing for tstop is disabled (and can be reenabled only though a new call to IDASetStopTime).

IDASetMaxErrTestFails

Call flag = IDASetMaxErrTestFails(ida_mem, maxnef);

Description The function IDASetMaxErrTestFails specifies the maximum number of error test failures in attempting one step.

Arguments ida_mem (void *) pointer to the IDA memory block.

maxnef (int) maximum number of error test failures allowed on one step (> 0).

Return value The return value flag (of type int) is one of

- IDA_SUCCESS The optional value has been successfully set.
- IDA_MEM_NULL The ida_mem pointer is NULL.

Notes The default value is 10.

IDASetMaxNonlinIters

Call flag = IDASetMaxNonlinIters(ida_mem, maxcor);

Description The function IDASetMaxNonlinIters specifies the maximum number of nonlinear solver iterations at one step.

Arguments ida_mem (void *) pointer to the IDA memory block.
maxcor (int) maximum number of nonlinear solver iterations allowed on one step (> 0).

Return value The return value flag (of type int) is one of

IDA_SUCCESS The optional value has been successfully set.
IDA_MEM_NULL The ida_mem pointer is NULL.
IDA_MEM_FAIL The sunnonlinsol module is NULL.

Notes The default value is 4.

**IDASetMaxConvFails**

**Call**

flag = IDASetMaxConvFails(ida_mem, maxncf);

**Description**
The function IDASetMaxConvFails specifies the maximum number of nonlinear solver convergence failures at one step.

**Arguments**

ida_mem (void *) pointer to the IDA memory block.
maxncf (int) maximum number of allowable nonlinear solver convergence failures on one step (> 0).

**Return value**
The return value flag (of type int) is one of

IDA_SUCCESS The optional value has been successfully set.
IDA_MEM_NULL The ida_mem pointer is NULL.

Notes The default value is 10.

**IDASetNonlinConvCoef**

**Call**

flag = IDASetNonlinConvCoef(ida_mem, nlscoef);

**Description**
The function IDASetNonlinConvCoef specifies the safety factor in the nonlinear convergence test; see Chapter 2, Eq. (2.7).

**Arguments**

ida_mem (void *) pointer to the IDA memory block.
nlscoef (realtype) coefficient in nonlinear convergence test (> 0).

**Return value**
The return value flag (of type int) is one of

IDA_SUCCESS The optional value has been successfully set.
IDA_MEM_NULL The ida_mem pointer is NULL.
IDA_Ill_INPUT The value of nlscoef is <= 0.

Notes The default value is 0.33.

**IDASetSuppressAlg**

**Call**

flag = IDASetSuppressAlg(ida_mem, suppressalg);

**Description**
The function IDASetSuppressAlg indicates whether or not to suppress algebraic variables in the local error test.

**Arguments**

ida_mem (void *) pointer to the IDA memory block.
suppressalg (booleantype) indicates whether to suppress (SUNTRUE) or not (SUNFALSE) the algebraic variables in the local error test.

**Return value**
The return value flag (of type int) is one of

IDA_SUCCESS The optional value has been successfully set.
IDA_MEM_NULL The ida_mem pointer is NULL.
4.5 User-callable functions

Notes

The default value is SUNFALSE.

If suppressalg=SUNTRUE is selected, then the id vector must be set (through IDASetId) to specify the algebraic components.

In general, the use of this option (with suppressalg = SUNTRUE) is discouraged when solving DAE systems of index 1, whereas it is generally encouraged for systems of index 2 or more. See pp. 146-147 of Ref. [6] for more on this issue.

**IDASetId**

Call

```
flag = IDASetId(ida_mem, id);
```

Description

The function IDASetId specifies algebraic/differential components in the y vector.

Arguments

`ida_mem` (void *) pointer to the IDA memory block.

`id` (N_Vector) state vector. A value of 1.0 indicates a differential variable, while 0.0 indicates an algebraic variable.

Return value

The return value `flag` (of type int) is one of

- IDA_SUCCESS The optional value has been successfully set.
- IDA_MEM.NULL The ida_mem pointer is NULL.

Notes

The vector id is required if the algebraic variables are to be suppressed from the local error test (see IDASetSuppressAlg) or if IDACalcIC is to be called with icopt = IDA_YA_YDP_INIT (see §4.5.5).

**IDASetConstraints**

Call

```
flag = IDASetConstraints(ida_mem, constraints);
```

Description

The function IDASetConstraints specifies a vector defining inequality constraints for each component of the solution vector y.

Arguments

`ida_mem` (void *) pointer to the IDA memory block.

`constraints` (N_Vector) vector of constraint flags. If `constraints[i]` is

- 0.0 then no constraint is imposed on \( y_i \).
- 1.0 then \( y_i \) will be constrained to be \( y_i \geq 0.0 \).
- -1.0 then \( y_i \) will be constrained to be \( y_i \leq 0.0 \).
- 2.0 then \( y_i \) will be constrained to be \( y_i > 0.0 \).
- -2.0 then \( y_i \) will be constrained to be \( y_i < 0.0 \).

Return value

The return value `flag` (of type int) is one of

- IDA_SUCCESS The optional value has been successfully set.
- IDA_MEM.NULL The ida_mem pointer is NULL.
- IDA_ILL.INPUT The constraints vector contains illegal values.

Notes

The presence of a non-NULL constraints vector that is not 0.0 in all components will cause constraint checking to be performed. However, a call with 0.0 in all components of `constraints` will result in an illegal input return.

4.5.8.2 Linear solver interface optional input functions

The mathematical explanation of the linear solver methods available to IDA is provided in §2.1. We group the user-callable routines into four categories: general routines concerning the overall IDALS linear solver interface, optional inputs for matrix-based linear solvers, optional inputs for matrix-free linear solvers, and optional inputs for iterative linear solvers. We note that the matrix-based and matrix-free groups are mutually exclusive, whereas the “iterative” tag can apply to either case.
When using matrix-based linear solver modules, the IDALS solver interface needs a function to compute an approximation to the Jacobian matrix $J(t,y,\dot{y})$. This function must be of type IDALSJacFn. The user can supply a Jacobian function, or if using a dense or banded matrix $J$ can use the default internal difference quotient approximation that comes with the IDALS interface. To specify a user-supplied Jacobian function $jac$, IDALS provides the function IDASetJacFn. The IDALS interface passes the pointer $user\_data$ to the Jacobian function. This allows the user to create an arbitrary structure with relevant problem data and access it during the execution of the user-supplied Jacobian function, without using global data in the program. The pointer $user\_data$ may be specified through IDASetUserData.

```
IDASetJacFn
Call flag = IDASetJacFn(ida_mem, jac);
```

**Description** The function IDASetJacFn specifies the Jacobian approximation function to be used for a matrix-based solver within the IDALS interface.

**Arguments**
- ida_mem (void *) pointer to the IDA memory block.
- jac (IDALSJacFn) user-defined Jacobian approximation function.

**Return value** The return value $flag$ (of type int) is one of:
- IDALS_SUCCESS The optional value has been successfully set.
- IDALS_MEM_NULL The $ida\_mem$ pointer is NULL.
- IDALS_LMEM_NULL The IDALS linear solver interface has not been initialized.

**Notes**
This function must be called after the IDALS linear solver interface has been initialized through a call to IDASetLinearSolver.

By default, IDALS uses an internal difference quotient function for dense and band matrices. If NULL is passed to $jac$, this default function is used. An error will occur if no $jac$ is supplied when using other matrix types.

The function type IDALSJacFn is described in §4.6.5.

The previous routine IDADlsSetJacFn is now a wrapper for this routine, and may still be used for backward-compatibility. However, this will be deprecated in future releases, so we recommend that users transition to the new routine name soon.

When using matrix-free linear solver modules, the IDALS solver interface requires a function to compute an approximation to the product between the Jacobian matrix $J(t,y)$ and a vector $v$. The user can supply a Jacobian-times-vector approximation function, or use the default internal difference quotient function that comes with the IDALS solver interface. A user-defined Jacobian-vector function must be of type IDALSJacTimesVecFn and can be specified through a call to IDASetJacTimes (see §4.6.6 for specification details). The evaluation and processing of any Jacobian-related data needed by the user's Jacobian-times-vector function may be done in the optional user-supplied function $jtsetup$ (see §4.6.7 for specification details). The pointer $user\_data$ received through IDASetUserData (or a pointer to NULL if $user\_data$ was not specified) is passed to the Jacobian-times-vector setup and product functions, $jtsetup$ and $jtimes$, each time they are called. This allows the user to create an arbitrary structure with relevant problem data and access it during the execution of the user-supplied functions without using global data in the program.

```
IDASetJacTimes
Call flag = IDASetJacTimes(ida_mem, jsetup, jtimes);
```

**Description** The function IDASetJacTimes specifies the Jacobian-vector setup and product functions.

**Arguments**
- ida_mem (void *) pointer to the IDA memory block.
- jsetup (IDALSJacTimesSetupFn) user-defined function to set up the Jacobian-vector product. Pass NULL if no setup is necessary.
4.5 User-callable functions

`jtimes` (IDALsJacTimesVecFn) user-defined Jacobian-vector product function.

Return value

The return value `flag` (of type `int`) is one of

- **IDALS_SUCCESS**: The optional value has been successfully set.
- **IDALS_MEM_NULL**: The `ida_mem` pointer is NULL.
- **IDALS_LMEM_NULL**: The IDALS linear solver has not been initialized.
- **IDALS_SUNLS_FAIL**: An error occurred when setting up the system matrix-times-vector routines in the SUNLINSOL object used by the IDALS interface.

Notes

The default is to use an internal finite difference quotient for `jtimes` and to omit `jtsetup`. If NULL is passed to `jtimes`, these defaults are used. A user may specify non-NULL `jtimes` and NULL `jtsetup` inputs.

This function must be called after the IDALS linear solver interface has been initialized through a call to `IDASetLinearSolver`.

The function type `IDALsJacTimesSetupFn` is described in §4.6.7.

The function type `IDALsJacTimesVecFn` is described in §4.6.6.

The previous routine `IDASpilsSetJacTimes` is now a wrapper for this routine, and may still be used for backward-compatibility. However, this will be deprecated in future releases, so we recommend that users transition to the new routine name soon.

Alternately, when using the default difference-quotient approximation to the Jacobian-vector product, the user may specify the factor to use in setting increments for the finite-difference approximation, via a call to `IDASetIncrementFactor`:

```c
flag = IDASetIncrementFactor(ida_mem, dqincfac);
```

**Description**

The function `IDASetIncrementFactor` specifies the increment factor to be used in the difference-quotient approximation to the product $Jv$. Specifically, $Jv$ is approximated via the formula

$$Jv = \frac{1}{\sigma} [F(t, \tilde{y}, \tilde{y}') - F(t, y, y')]$$

where $\tilde{y} = y + \sigma v$, $\tilde{y}' = y' + c_j \sigma v$, $c_j$ is a BDF parameter proportional to the step size, $\sigma = \sqrt{N \ dqincfac}$, and $N$ is the number of equations in the DAE system.

**Arguments**

- `ida_mem` (void *) pointer to the IDA memory block.
- `dqincfac` (realtype) user-specified increment factor (positive).

**Return value**

The return value `flag` (of type `int`) is one of

- **IDALS_SUCCESS**: The optional value has been successfully set.
- **IDALS_MEM_NULL**: The `ida_mem` pointer is NULL.
- **IDALS_LMEM_NULL**: The IDALS linear solver has not been initialized.
- **IDALS_IILL_INPUT**: The specified value of `dqincfac` is $\leq 0$.

**Notes**

This function must be called after the IDALS linear solver interface has been initialized through a call to `IDASetLinearSolver`.

The previous routine `IDASpilsSetIncrementFactor` is now a wrapper for this routine, and may still be used for backward-compatibility. However, this will be deprecated in future releases, so we recommend that users transition to the new routine name soon.

When using an iterative linear solver, the user may supply a preconditioning operator to aid in solution of the system. This operator consists of two user-supplied functions, `psetup` and `psolve`, that are supplied to IDA using the function `IDASetPreconditioner`. The `psetup` function supplied to this routine should handle evaluation and preprocessing of any Jacobian data needed by the user's
preconditioner solve function, \texttt{psolve}. Both of these functions are fully specified in §4.6. The user data pointer received through \texttt{IDASetUserData} (or a pointer to \texttt{NULL} if user data was not specified) is passed to the \texttt{psetup} and \texttt{psolve} functions. This allows the user to create an arbitrary structure with relevant problem data and access it during the execution of the user-supplied preconditioner functions without using global data in the program.

Also, as described in §2.1, the \texttt{idals} interface requires that iterative linear solvers stop when the norm of the preconditioned residual satisfies

\[ \|r\| \leq \frac{\epsilon_L \epsilon}{10} \]

where \(\epsilon\) is the nonlinear solver tolerance, and the default \(\epsilon_L = 0.05\); this value may be modified by the user through the \texttt{IDASetEpsLin} function.

\[\text{IDASetPreconditioner}\]
\begin{verbatim}
Call flag = IDASetPreconditioner(ida_mem, psetup, psolve);
Description The function \texttt{IDASetPreconditioner} specifies the preconditioner setup and solve functions.
Arguments ida_mem (void *) pointer to the IDA memory block.
psetup (IDALSPrecSetupFn) user-defined function to set up the preconditioner. Pass \texttt{NULL} if no setup is necessary.
psolve (IDALSPrecSolveFn) user-defined preconditioner solve function.
Return value The return value \texttt{flag} (of type \texttt{int}) is one of
\begin{itemize}
  \item \texttt{IDALS\_SUCCESS} The optional values have been successfully set.
  \item \texttt{IDALS\_MEM\_NULL} The \texttt{ida_mem} pointer is \texttt{NULL}.
  \item \texttt{IDALS\_LMEM\_NULL} The \texttt{idals} linear solver has not been initialized.
  \item \texttt{IDALS\_SUNLS\_FAIL} An error occurred when setting up preconditioning in the \texttt{SUNLINSOL} object used by the \texttt{idals} interface.
\end{itemize}
Notes The default is \texttt{NULL} for both arguments (i.e., no preconditioning).
This function must be called \textit{after} the \texttt{idals} linear solver interface has been initialized through a call to \texttt{IDASetLinearSolver}.
The function type \texttt{IDALS\_PrecSolveFn} is described in §4.6.8.
The function type \texttt{IDALS\_PrecSetupFn} is described in §4.6.9.
The previous routine \texttt{IDASpilsSetPreconditioner} is now a wrapper for this routine, and may still be used for backward-compatibility. However, this will be deprecated in future releases, so we recommend that users transition to the new routine name soon.
\end{verbatim}

\[\text{IDASetsEpsLin}\]
\begin{verbatim}
Call flag = IDASetsEpsLin(ida_mem, eplifac);
Description The function \texttt{IDASetsEpsLin} specifies the factor by which the Krylov linear solver's convergence test constant is reduced from the nonlinear iteration test constant.
Arguments ida_mem (void *) pointer to the IDA memory block.
eplifac (realtype) linear convergence safety factor (\(\geq 0.0\)).
Return value The return value \texttt{flag} (of type \texttt{int}) is one of
\begin{itemize}
  \item \texttt{IDALS\_SUCCESS} The optional value has been successfully set.
  \item \texttt{IDALS\_MEM\_NULL} The \texttt{ida_mem} pointer is \texttt{NULL}.
  \item \texttt{IDALS\_LMEM\_NULL} The \texttt{idals} linear solver has not been initialized.
  \item \texttt{IDALS\_ILL\_INPUT} The factor \texttt{eplifac} is negative.
\end{itemize}
\end{verbatim}
4.5 User-callable functions

Notes

The default value is 0.05.

This function must be called after the IDALS linear solver interface has been initialized through a call to IDASetLinearSolver.

If eplifac = 0.0 is passed, the default value is used.

The previous routine IDASpilsSetEpsLin is now a wrapper for this routine, and may still be used for backward-compatibility. However, this will be deprecated in future releases, so we recommend that users transition to the new routine name soon.

4.5.8.3 Initial condition calculation optional input functions

The following functions can be called just prior to calling IDACalcIC to set optional inputs controlling the initial condition calculation.

### IDASetNonlinConvCoefIC

**Call**

```c
flag = IDASetNonlinConvCoefIC(ida_mem, epiccon);
```

**Description**

The function IDASetNonlinConvCoefIC specifies the positive constant in the Newton iteration convergence test within the initial condition calculation.

**Arguments**

- `ida_mem` (void *) pointer to the ida memory block.
- `epiccon` (realtype) coefficient in the Newton convergence test (> 0).

**Return value**

The return value `flag` (of type `int`) is one of

- `IDA_SUCCESS` The optional value has been successfully set.
- `IDA_MEM_NULL` The `ida_mem` pointer is NULL.
- `IDA_Ill_INPUT` The `epiccon` factor is <= 0.0.

**Notes**

The default value is 0.01 · 0.33.

This test uses a weighted RMS norm (with weights defined by the tolerances). For new initial value vectors \( y \) and \( \dot{y} \) to be accepted, the norm of \( J^{-1}F(t_0, y, \dot{y}) \) must be \( \leq \) `epiccon`, where \( J \) is the system Jacobian.

### IDASetMaxNumStepsIC

**Call**

```c
flag = IDASetMaxNumStepsIC(ida_mem, maxnh);
```

**Description**

The function IDASetMaxNumStepsIC specifies the maximum number of steps allowed when `icpt` = IDA_YA_YDP_INIT in IDACalcIC, where \( h \) appears in the system Jacobian, \( J = \partial F/\partial y + (1/h)\partial F/\partial \dot{y} \).

**Arguments**

- `ida_mem` (void *) pointer to the ida memory block.
- `maxnh` (int) maximum allowed number of values for \( h \).

**Return value**

The return value `flag` (of type `int`) is one of

- `IDA_SUCCESS` The optional value has been successfully set.
- `IDA_MEM_NULL` The `ida_mem` pointer is NULL.
- `IDA_Ill_INPUT` `maxnh` is non-positive.

**Notes**

The default value is 5.

### IDASetMaxNumJacsIC

**Call**

```c
flag = IDASetMaxNumJacsIC(ida_mem, maxnj);
```

**Description**

The function IDASetMaxNumJacsIC specifies the maximum number of the approximate Jacobian or preconditioner evaluations allowed when the Newton iteration appears to be slowly converging.
Arguments  ida_mem (void *) pointer to the IDA memory block.
maxnj (int) maximum allowed number of Jacobian or preconditioner evaluations.

Return value The return value flag (of type int) is one of
IDA_SUCCESS The optional value has been successfully set.
IDA_MEM_NULL The ida_mem pointer is NULL.
IDA_I LL_INPUT maxnj is non-positive.

Notes The default value is 4.

**IDASetMaxNumItersIC**

Call flag = IDASetMaxNumItersIC(ida_mem, maxnit);

Description The function IDASetMaxNumItersIC specifies the maximum number of Newton iterations allowed in any one attempt to solve the initial conditions calculation problem.

Arguments ida_mem (void *) pointer to the IDA memory block.
maxnit (int) maximum number of Newton iterations.

Return value The return value flag (of type int) is one of
IDA_SUCCESS The optional value has been successfully set.
IDA_MEM_NULL The ida_mem pointer is NULL.
IDA_I LL_INPUT maxnit is non-positive.

Notes The default value is 10.

**IDASetMaxBacksIC**

Call flag = IDASetMaxBacksIC(ida_mem, maxbacks);

Description The function IDASetMaxBacksIC specifies the maximum number of linesearch backtracks allowed in any Newton iteration, when solving the initial conditions calculation problem.

Arguments ida_mem (void *) pointer to the IDA memory block.
maxbacks (int) maximum number of linesearch backtracks per Newton step.

Return value The return value flag (of type int) is one of
IDA_SUCCESS The optional value has been successfully set.
IDA_MEM_NULL The ida_mem pointer is NULL.
IDA_I LL_INPUT maxbacks is non-positive.

Notes The default value is 100.

**IDASetLineSearchOffIC**

Call flag = IDASetLineSearchOffIC(ida_mem, lsoff);

Description The function IDASetLineSearchOffIC specifies whether to turn on or off the linesearch algorithm.

Arguments ida_mem (void *) pointer to the IDA memory block.
lsoff (booleantype) a flag to turn off (SUNTRUE) or keep (SUNFALSE) the linesearch algorithm.

Return value The return value flag (of type int) is one of
IDA_SUCCESS The optional value has been successfully set.
IDA_MEM_NULL The ida_mem pointer is NULL.

Notes The default value is SUNFALSE.
4.5 User-callable functions

IDASetStepToleranceIC

Call flag = IDASetStepToleranceIC(ida_mem, steptol);

Description The function IDASetStepToleranceIC specifies a positive lower bound on the Newton step.

Arguments ida_mem (void *) pointer to the IDA memory block.
steptol (int) Minimum allowed WRMS-norm of the Newton step (> 0.0).

Return value The return value flag (of type int) is one of
IDA_SUCCESS The optional value has been successfully set.
IDA_MEM_NULL The ida_mem pointer is NULL.
IDA_Ill_INPUT The steptol tolerance is <= 0.0.

Notes The default value is (unit roundoff)\(^{2/3}\).

4.5.8.4 Rootfinding optional input functions

The following functions can be called to set optional inputs to control the rootfinding algorithm.

IDASetRootDirection

Call flag = IDASetRootDirection(ida_mem, rootdir);

Description The function IDASetRootDirection specifies the direction of zero-crossings to be located and returned to the user.

Arguments ida_mem (void *) pointer to the IDA memory block.
rootdir (int *) state array of length nrtfn, the number of root functions \(g_i\), as specified in the call to the function IDARootInit. A value of 0 for rootdir[\(i\)] indicates that crossing in either direction should be reported for \(g_i\). A value of +1 or −1 indicates that the solver should report only zero-crossings where \(g_i\) is increasing or decreasing, respectively.

Return value The return value flag (of type int) is one of
IDA_SUCCESS The optional value has been successfully set.
IDA_MEM_NULL The ida_mem pointer is NULL.
IDA_Ill_INPUT rootfinding has not been activated through a call to IDARootInit.

Notes The default behavior is to locate both zero-crossing directions.

IDASetNoInactiveRootWarn

Call flag = IDASetNoInactiveRootWarn(ida_mem);

Description The function IDASetNoInactiveRootWarn disables issuing a warning if some root function appears to be identically zero at the beginning of the integration.

Arguments ida_mem (void *) pointer to the IDA memory block.

Return value The return value flag (of type int) is one of
IDA_SUCCESS The optional value has been successfully set.
IDA_MEM_NULL The ida_mem pointer is NULL.

Notes IDA will not report the initial conditions as a possible zero-crossing (assuming that one or more components \(g_i\) are zero at the initial time). However, if it appears that some \(g_i\) is identically zero at the initial time (i.e., \(g_i\) is zero at the initial time and after the first step), IDA will issue a warning which can be disabled with this optional input function.
## 4.5.9 Interpolated output function

An optional function `IDAGetDky` is available to obtain additional output values. This function must be called after a successful return from `IDASolve` and provides interpolated values of $y$ or its derivatives of order up to the last internal order used for any value of $t$ in the last internal step taken by IDA.

The call to the `IDAGetDky` function has the following form:

```c
IDAGetDky
Call
flag = IDAGetDky(ida_mem, t, k, dky);
```

**Description**
The function `IDAGetDky` computes the interpolated values of the $k^{th}$ derivative of $y$ for any value of $t$ in the last internal step taken by IDA. The value of $k$ must be non-negative and smaller than the last internal order used. A value of 0 for $k$ means that the $y$ is interpolated. The value of $t$ must satisfy $t_n - h_u \leq t \leq t_n$, where $t_n$ denotes the current internal time reached, and $h_u$ is the last internal step size used successfully.

**Arguments**
- `ida_mem` (void *) pointer to the IDA memory block.
- `t` (realtype) time at which to interpolate.
- `k` (int) integer specifying the order of the derivative of $y$ wanted.
- `dky` (N_Vector) vector containing the interpolated $k^{th}$ derivative of $y(t)$.

**Return value**
The return value `flag` (of type `int`) is one of
- `IDA_SUCCESS` `IDAGetDky` succeeded.
- `IDA_MEM_NULL` The `ida_mem` argument was `NULL`.
- `IDA_BAD_T` $t$ is not in the interval $[t_n - h_u, t_n]$.
- `IDA_BAD_K` $k$ is not one of $\{0, 1, \ldots, klast\}$.
- `IDA_BAD_DKY` `dky` is `NULL`.

**Notes**
It is only legal to call the function `IDAGetDky` after a successful return from `IDASolve`. Functions `IDAGetCurrentTime`, `IDAGetLastStep` and `IDAGetLastOrder` (see §4.5.10.2) can be used to access $t_n$, $h_u$ and $klast$.

## 4.5.10 Optional output functions

IDA provides an extensive list of functions that can be used to obtain solver performance information. Table 4.3 lists all optional output functions in IDA, which are then described in detail in the remainder of this section.

Some of the optional outputs, especially the various counters, can be very useful in determining how successful the IDA solver is in doing its job. For example, the counters `nsteps` and `nrevals` provide a rough measure of the overall cost of a given run, and can be compared among runs with differing input options to suggest which set of options is most efficient. The ratio `nniters/nsteps` measures the performance of the nonlinear solver in solving the nonlinear systems at each time step; typical values for this range from 1.1 to 1.8. The ratio `njevals/nniters` (in the case of a matrix-based linear solver), and the ratio `npevals/nniters` (in the case of an iterative linear solver) measure the overall degree of nonlinearity in these systems, and also the quality of the approximate Jacobian or preconditioner being used. Thus, for example, `njevals/nniters` can indicate if a user-supplied Jacobian is inaccurate, if this ratio is larger than for the case of the corresponding internal Jacobian. The ratio `nliters/nniters` measures the performance of the Krylov iterative linear solver, and thus (indirectly) the quality of the preconditioner.

### 4.5.10.1 SUNDIALS version information

The following functions provide a way to get SUNDIALS version information at runtime.
### 4.5 User-callable functions

Table 4.3: Optional outputs from IDA and IDALS

<table>
<thead>
<tr>
<th>Optional output</th>
<th>Function name</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IDA main solver</strong></td>
<td></td>
</tr>
<tr>
<td>Size of IDA real and integer workspace</td>
<td>IDAGetWorkspace</td>
</tr>
<tr>
<td>Cumulative number of internal steps</td>
<td>IDAGetNumSteps</td>
</tr>
<tr>
<td>No. of calls to residual function</td>
<td>IDAGetNumResEvals</td>
</tr>
<tr>
<td>No. of calls to linear solver setup function</td>
<td>IDAGetNumLinSolvSetups</td>
</tr>
<tr>
<td>No. of local error test failures that have occurred</td>
<td>IDAGetNumErrTestFails</td>
</tr>
<tr>
<td>Order used during the last step</td>
<td>IDAGetLastOrder</td>
</tr>
<tr>
<td>Order to be attempted on the next step</td>
<td>IDAGetCurrentOrder</td>
</tr>
<tr>
<td>Order reductions due to stability limit detection</td>
<td>IDAGetNumStabLimOrderReds</td>
</tr>
<tr>
<td>Actual initial step size used</td>
<td>IDAGetActualInitStep</td>
</tr>
<tr>
<td>Step size used for the last step</td>
<td>IDAGetLastStep</td>
</tr>
<tr>
<td>Step size to be attempted on the next step</td>
<td>IDAGetCurrentStep</td>
</tr>
<tr>
<td>Current internal time reached by the solver</td>
<td>IDAGetCurrentTime</td>
</tr>
<tr>
<td>Suggested factor for tolerance scaling</td>
<td>IDAGetTolScaleFactor</td>
</tr>
<tr>
<td>Error weight vector for state variables</td>
<td>IDAGetErrWeights</td>
</tr>
<tr>
<td>Estimated local errors</td>
<td>IDAGetEstLocalErrors</td>
</tr>
<tr>
<td>No. of nonlinear solver iterations</td>
<td>IDAGetNumNonlinSolvIters</td>
</tr>
<tr>
<td>No. of nonlinear convergence failures</td>
<td>IDAGetNumNonlinSolvConvFails</td>
</tr>
<tr>
<td>Array showing roots found</td>
<td>IDAGetRootInfo</td>
</tr>
<tr>
<td>No. of calls to user root function</td>
<td>IDAGetNumGEvals</td>
</tr>
<tr>
<td>Name of constant associated with a return flag</td>
<td>IDAGetReturnFlagName</td>
</tr>
<tr>
<td><strong>IDA initial conditions calculation</strong></td>
<td></td>
</tr>
<tr>
<td>Number of backtrack operations</td>
<td>IDAGetNumBacktrackops</td>
</tr>
<tr>
<td>Corrected initial conditions</td>
<td>IDAGetConsistentIC</td>
</tr>
<tr>
<td><strong>IDALS linear solver interface</strong></td>
<td></td>
</tr>
<tr>
<td>Size of real and integer workspace</td>
<td>IDAGetLinWorkSpace</td>
</tr>
<tr>
<td>No. of Jacobian evaluations</td>
<td>IDAGetNumJacEvals</td>
</tr>
<tr>
<td>No. of residual calls for finite diff. Jacobian[-vector] evals.</td>
<td>IDAGetNumLinResEvals</td>
</tr>
<tr>
<td>No. of linear iterations</td>
<td>IDAGetNumLinIters</td>
</tr>
<tr>
<td>No. of linear convergence failures</td>
<td>IDAGetNumLinConvFails</td>
</tr>
<tr>
<td>No. of preconditioner evaluations</td>
<td>IDAGetNumPrecEvals</td>
</tr>
<tr>
<td>No. of preconditioner solves</td>
<td>IDAGetNumPrecSolves</td>
</tr>
<tr>
<td>No. of Jacobian-vector setup evaluations</td>
<td>IDAGetNumJTSetupEvals</td>
</tr>
<tr>
<td>No. of Jacobian-vector product evaluations</td>
<td>IDAGetNumJtimesEvals</td>
</tr>
<tr>
<td>Last return from a linear solver function</td>
<td>IDAGetLastLinFlag</td>
</tr>
<tr>
<td>Name of constant associated with a return flag</td>
<td>IDAGetLinReturnFlagName</td>
</tr>
</tbody>
</table>
Using IDA for C Applications

### SUNDIALSGetVersion

**Call**

```c
flag = SUNDIALSGetVersion(version, len);
```

**Description**
The function `SUNDIALSGetVersion` fills a character array with SUNDIALS version information.

**Arguments**
- `version` (char *) character array to hold the SUNDIALS version information.
- `len` (int) allocated length of the `version` character array.

**Return value**
If successful, `SUNDIALSGetVersion` returns 0 and `version` contains the SUNDIALS version information. Otherwise, it returns −1 and `version` is not set (the input character array is too short).

**Notes**
A string of 25 characters should be sufficient to hold the version information. Any trailing characters in the `version` array are removed.

### SUNDIALSGetVersionNumber

**Call**

```c
flag = SUNDIALSGetVersionNumber(&major, &minor, &patch, label, len);
```

**Description**
The function `SUNDIALSGetVersionNumber` sets integers for the SUNDIALS major, minor, and patch release numbers and fills a character array with the release label if applicable.

**Arguments**
- `major` (int) SUNDIALS release major version number.
- `minor` (int) SUNDIALS release minor version number.
- `patch` (int) SUNDIALS release patch version number.
- `label` (char *) character array to hold the SUNDIALS release label.
- `len` (int) allocated length of the `label` character array.

**Return value**
If successful, `SUNDIALSGetVersionNumber` returns 0 and the `major`, `minor`, `patch`, and `label` values are set. Otherwise, it returns −1 and the values are not set (the input character array is too short).

**Notes**
A string of 10 characters should be sufficient to hold the label information. If a label is not used in the release version, no information is copied to `label`. Any trailing characters in the `label` array are removed.

#### 4.5.10.2 Main solver optional output functions

IDA provides several user-callable functions that can be used to obtain different quantities that may be of interest to the user, such as solver workspace requirements, solver performance statistics, as well as additional data from the IDA memory block (a suggested tolerance scaling factor, the error weight vector, and the vector of estimated local errors). Also provided are functions to extract statistics related to the performance of the SUNNONLINSOL nonlinear solver being used. As a convenience, additional extraction functions provide the optional outputs in groups. These optional output functions are described next.

### IDAGetWorkSpace

**Call**

```c
flag = IDAGetWorkSpace(ida_mem, &lenrw, &leniw);
```

**Description**
The function `IDAGetWorkSpace` returns the IDA real and integer workspace sizes.

**Arguments**
- `ida_mem` (void *) pointer to the IDA memory block.
- `lenrw` (long int) number of real values in the IDA workspace.
- `leniw` (long int) number of integer values in the IDA workspace.

**Return value**
The return value `flag` (of type `int`) is one of

- `IDA_SUCCESS` The optional output value has been successfully set.
- `IDA_MEM_NULL` The `ida_mem` pointer is NULL.
Notes

In terms of the problem size $N$, the maximum method order $\text{maxord}$, and the number $\text{nrtfn}$ of root functions (see §4.5.6), the actual size of the real workspace, in $\text{realtype}$ words, is given by the following:

- base value: $\text{lenrw} = 55 + (m + 6) \times N_r + 3\times\text{nrtfn}$;
- with $\text{IDASVtolerances}$: $\text{lenrw} = \text{lenrw} + N_r$;
- with constraint checking (see $\text{IDASetConstraints}$): $\text{lenrw} = \text{lenrw} + N_r$;
- with $\text{id}$ specified (see $\text{IDASetId}$): $\text{lenrw} = \text{lenrw} + N_r$;

where $m = \max(\text{maxord}, 3)$, and $N_r$ is the number of real words in one $\text{N_Vector} (\approx N)$.

The size of the integer workspace (without distinction between $\text{int}$ and $\text{long int}$ words) is given by:

- base value: $\text{leniw} = 38 + (m + 6) \times N_i + \text{nrtfn}$;
- with $\text{IDASVtolerances}$: $\text{leniw} = \text{leniw} + N_i$;
- with constraint checking: $\text{leniw} = \text{lenrw} + N_i$;
- with $\text{id}$ specified: $\text{leniw} = \text{lenrw} + N_i$;

where $N_i$ is the number of integer words in one $\text{N_Vector}$ ($= 1$ for $\text{NVECTOR_SERIAL}$ and $2^n\text{npes}$ for $\text{NVECTOR_PARALLEL}$ on $\text{npes}$ processors).

For the default value of $\text{maxord}$, with no rootfinding, no $\text{id}$, no constraints, and with no call to $\text{IDASVtolerances}$, these lengths are given roughly by: $\text{lenrw} = 55 + 11N$, $\text{leniw} = 49$.

**IDAGetNumSteps**

Call 

```c
flag = IDAGetNumSteps(ida_mem, &nsteps);
```

Description The function $\text{IDAGetNumSteps}$ returns the cumulative number of internal steps taken by the solver (total so far).

Arguments 

- `ida_mem` (void *) pointer to the IDA memory block.
- `nsteps` (long int) number of steps taken by IDA.

Return value The return value $\text{flag}$ (of type `int`) is one of

- $\text{IDA\_SUCCESS}$ The optional output value has been successfully set.
- $\text{IDA\_MEM\_NULL}$ The `ida_mem` pointer is NULL.

**IDAGetNumResEvals**

Call 

```c
flag = IDAGetNumResEvals(ida_mem, &nrevals);
```

Description The function $\text{IDAGetNumResEvals}$ returns the number of calls to the user’s residual evaluation function.

Arguments 

- `ida_mem` (void *) pointer to the IDA memory block.
- `nrevals` (long int) number of calls to the user’s $\text{res}$ function.

Return value The return value $\text{flag}$ (of type `int`) is one of

- $\text{IDA\_SUCCESS}$ The optional output value has been successfully set.
- $\text{IDA\_MEM\_NULL}$ The `ida_mem` pointer is NULL.

Notes The $\text{nrevals}$ value returned by $\text{IDAGetNumResEvals}$ does not account for calls made to $\text{res}$ from a linear solver or preconditioner module.
### IDAGetNumLinSolvSetups

**Call**

```c
flag = IDAGetNumLinSolvSetups(ida_mem, &nlinsetups);
```

**Description**
The function `IDAGetNumLinSolvSetups` returns the cumulative number of calls made to the linear solver’s setup function (total so far).

**Arguments**
- `ida_mem` ((void *) pointer to the IDA memory block.)
- `nlinsetups` (long int) number of calls made to the linear solver setup function.

**Return value**
The return value `flag` (of type int) is one of:
- `IDA_SUCCESS` The optional output value has been successfully set.
- `IDA_MEM_NULL` The `ida_mem` pointer is NULL.

### IDAGetNumErrTestFails

**Call**

```c
flag = IDAGetNumErrTestFails(ida_mem, &netfails);
```

**Description**
The function `IDAGetNumErrTestFails` returns the cumulative number of local error test failures that have occurred (total so far).

**Arguments**
- `ida_mem` ((void *) pointer to the IDA memory block.)
- `netfails` (long int) number of error test failures.

**Return value**
The return value `flag` (of type int) is one of:
- `IDA_SUCCESS` The optional output value has been successfully set.
- `IDA_MEM_NULL` The `ida_mem` pointer is NULL.

### IDAGetLastOrder

**Call**

```c
flag = IDAGetLastOrder(ida_mem, &klast);
```

**Description**
The function `IDAGetLastOrder` returns the integration method order used during the last internal step.

**Arguments**
- `ida_mem` (void *) pointer to the IDA memory block.
- `klast` (int) method order used on the last internal step.

**Return value**
The return value `flag` (of type int) is one of:
- `IDA_SUCCESS` The optional output value has been successfully set.
- `IDA_MEM_NULL` The `ida_mem` pointer is NULL.

### IDAGetCurrentOrder

**Call**

```c
flag = IDAGetCurrentOrder(ida_mem, &kcur);
```

**Description**
The function `IDAGetCurrentOrder` returns the integration method order to be used on the next internal step.

**Arguments**
- `ida_mem` (void *) pointer to the IDA memory block.
- `kcur` (int) method order to be used on the next internal step.

**Return value**
The return value `flag` (of type int) is one of:
- `IDA_SUCCESS` The optional output value has been successfully set.
- `IDA_MEM_NULL` The `ida_mem` pointer is NULL.
### IDAGetLastStep

**Call**

\[
\text{flag} = \text{IDAGetLastStep}(\text{ida\_mem, } \&\text{hlast});
\]

**Description**
The function \(\text{IDAGetLastStep}\) returns the integration step size taken on the last internal step (if from \(\text{IDASolve}\), or the last value of the artificial step size \(h\) (if from \(\text{IDACalcIC}\)).

**Arguments**
- \(\text{ida\_mem}\) (void *) pointer to the IDA memory block.
- \(\text{hlast}\) (realtype) step size taken on the last internal step by IDA, or last artificial step size used in \(\text{IDACalcIC}\), whichever was called last.

**Return value**
The return value \(\text{flag}\) (of type \(\text{int}\)) is one of:
- \(\text{IDA\_SUCCESS}\): The optional output value has been successfully set.
- \(\text{IDA\_MEM\_NULL}\): The \(\text{ida\_mem}\) pointer is NULL.

### IDAGetCurrentStep

**Call**

\[
\text{flag} = \text{IDAGetCurrentStep}(\text{ida\_mem, } \&\text{hcur});
\]

**Description**
The function \(\text{IDAGetCurrentStep}\) returns the integration step size to be attempted on the next internal step.

**Arguments**
- \(\text{ida\_mem}\) (void *) pointer to the IDA memory block.
- \(\text{hcur}\) (realtype) step size to be attempted on the next internal step.

**Return value**
The return value \(\text{flag}\) (of type \(\text{int}\)) is one of:
- \(\text{IDA\_SUCCESS}\): The optional output value has been successfully set.
- \(\text{IDA\_MEM\_NULL}\): The \(\text{ida\_mem}\) pointer is NULL.

### IDAGetActualInitStep

**Call**

\[
\text{flag} = \text{IDAGetActualInitStep}(\text{ida\_mem, } \&\text{hinused});
\]

**Description**
The function \(\text{IDAGetActualInitStep}\) returns the value of the integration step size used on the first step.

**Arguments**
- \(\text{ida\_mem}\) (void *) pointer to the IDA memory block.
- \(\text{hinused}\) (realtype) actual value of initial step size.

**Return value**
The return value \(\text{flag}\) (of type \(\text{int}\)) is one of:
- \(\text{IDA\_SUCCESS}\): The optional output value has been successfully set.
- \(\text{IDA\_MEM\_NULL}\): The \(\text{ida\_mem}\) pointer is NULL.

**Notes**
Even if the value of the initial integration step size was specified by the user through a call to \(\text{IDASetInitStep}\), this value might have been changed by IDA to ensure that the step size is within the prescribed bounds \((h_{\text{min}} \leq h_0 \leq h_{\text{max}})\), or to meet the local error test.

### IDAGetCurrentTime

**Call**

\[
\text{flag} = \text{IDAGetCurrentTime}(\text{ida\_mem, } \&\text{tcur});
\]

**Description**
The function \(\text{IDAGetCurrentTime}\) returns the current internal time reached by the solver.

**Arguments**
- \(\text{ida\_mem}\) (void *) pointer to the IDA memory block.
- \(\text{tcur}\) (realtype) current internal time reached.

**Return value**
The return value \(\text{flag}\) (of type \(\text{int}\)) is one of:
- \(\text{IDA\_SUCCESS}\): The optional output value has been successfully set.
- \(\text{IDA\_MEM\_NULL}\): The \(\text{ida\_mem}\) pointer is NULL.
**IDAGetTolScaleFactor**

Call: `flag = IDAGetTolScaleFactor(ida_mem, &tolsfac);`

Description: The function `IDAGetTolScaleFactor` returns a suggested factor by which the user's tolerances should be scaled when too much accuracy has been requested for some internal step.

Arguments:
- `ida_mem` (void *) pointer to the IDA memory block.
- `tolsfac` (realtype) suggested scaling factor for user tolerances.

Return value: The return value `flag` (of type `int`) is one of:
- `IDA_SUCCESS` The optional output value has been successfully set.
- `IDA_MEM_NULL` The `ida_mem` pointer is NULL.

**IDAGetErrWeights**

Call: `flag = IDAGetErrWeights(ida_mem, eweight);`

Description: The function `IDAGetErrWeights` returns the solution error weights at the current time. These are the $W_i$ given by Eq. (2.6) (or by the user's `IDAEwtFn`).

Arguments:
- `ida_mem` (void *) pointer to the IDA memory block.
- `eweight` (N_Vector) solution error weights at the current time.

Return value: The return value `flag` (of type `int`) is one of:
- `IDA_SUCCESS` The optional output value has been successfully set.
- `IDA_MEM_NULL` The `ida_mem` pointer is NULL.

Notes: The user must allocate space for `eweight`.

**IDAGetEstLocalErrors**

Call: `flag = IDAGetEstLocalErrors(ida_mem, ele);`

Description: The function `IDAGetEstLocalErrors` returns the estimated local errors.

Arguments:
- `ida_mem` (void *) pointer to the IDA memory block.
- `ele` (N_Vector) estimated local errors at the current time.

Return value: The return value `flag` (of type `int`) is one of:
- `IDA_SUCCESS` The optional output value has been successfully set.
- `IDA_MEM_NULL` The `ida_mem` pointer is NULL.

Notes: The user must allocate space for `ele`. The values returned in `ele` are only valid if `IDASolve` returned a non-negative value. The `ele` vector, together with the `eweight` vector from `IDAGetErrWeights`, can be used to determine how the various components of the system contributed to the estimated local error test. Specifically, that error test uses the RMS norm of a vector whose components are the products of the components of these two vectors. Thus, for example, if there were recent error test failures, the components causing the failures are those with largest values for the products, denoted loosely as `eweight[i]*ele[i]`.

**IDAGetIntegratorStats**

Call: `flag = IDAGetIntegratorStats(ida_mem, &nsteps, &nrevals, &nlinsetsups, &netfails, &klast, &kcur, &hinused, &hlast, &hcur, &tcur);`

Description: The function `IDAGetIntegratorStats` returns the IDA integrator statistics as a group.

Arguments:
- `ida_mem` (void *) pointer to the IDA memory block.
nsteps  (long int) cumulative number of steps taken by IDA.
nrevals (long int) cumulative number of calls to the user's res function.
nlinsetups (long int) cumulative number of calls made to the linear solver setup function.
netfails (long int) cumulative number of error test failures.
klast (int) method order used on the last internal step.
kcur (int) method order to be used on the next internal step.
hinused (realtype) actual value of initial step size.
hlast (realtype) step size taken on the last internal step.
hcur (realtype) step size to be attempted on the next internal step.
tcur (realtype) current internal time reached.

Return value The return value flag (of type int) is one of
IDA_SUCCESS the optional output values have been successfully set.
IDA_MEM_NULL the ida_mem pointer is NULL.

IDAGetNumNonlinSolvIters
Call flag = IDAGetNumNonlinSolvIters(ida_mem, &nniters);
Description The function IDAGetNumNonlinSolvIters returns the cumulative number of nonlinear iterations performed.
Arguments ida_mem (void *) pointer to the IDA memory block.
niters (long int) number of nonlinear iterations performed.
Return value The return value flag (of type int) is one of
IDA_SUCCESS The optional output value has been successfully set.
IDA_MEM_NULL The ida_mem pointer is NULL.

IDAGetNumNonlinSolvConvFails
Call flag = IDAGetNumNonlinSolvConvFails(ida_mem, &nncfails);
Description The function IDAGetNumNonlinSolvConvFails returns the cumulative number of nonlinear convergence failures that have occurred.
Arguments ida_mem (void *) pointer to the IDA memory block.
nncfails (long int) number of nonlinear convergence failures.
Return value The return value flag (of type int) is one of
IDA_SUCCESS The optional output value has been successfully set.
IDA_MEM_NULL The ida_mem pointer is NULL.

IDAGetNonlinSolvStats
Call flag = IDAGetNonlinSolvStats(ida_mem, &nniters, &nncfails);
Description The function IDAGetNonlinSolvStats returns the IDA nonlinear solver statistics as a group.
Arguments ida_mem (void *) pointer to the IDA memory block.
niters (long int) cumulative number of nonlinear iterations performed.
nncfails (long int) cumulative number of nonlinear convergence failures.
Return value The return value flag (of type int) is one of
IDA_SUCCESS The optional output value has been successfully set.
IDA_MEM_NULL The ida_mem pointer is NULL.
IDA_MEM_FAIL The SUNNONLINSOL module is NULL.

**IDAGetReturnFlagName**

Call: `name = IDAGetReturnFlagName(flag);`

Description: The function `IDAGetReturnFlagName` returns the name of the IDA constant corresponding to `flag`.

Arguments: The only argument, of type `int`, is a return flag from an IDA function.

Return value: The return value is a string containing the name of the corresponding constant.

**4.5.10.3 Initial condition calculation optional output functions**

**IDAGetNumBacktrackOps**

Call: `flag = IDAGetNumBacktrackOps(ida_mem, &nbacktr);`

Description: The function `IDAGetNumBacktrackOps` returns the number of backtrack operations done in the linesearch algorithm in `IDACalcIC`.

Arguments: `ida_mem` (void *) pointer to the IDA memory block.
`nbacktr` (long int) the cumulative number of backtrack operations.

Return value: The return value `flag` (of type `int`) is one of

- `IDA_SUCCESS` The optional output value has been successfully set.
- `IDA_MEM_NULL` The `ida_mem` pointer is NULL.

**IDAGetConsistentIC**

Call: `flag = IDAGetConsistentIC(ida_mem, yy0_mod, yp0_mod);`

Description: The function `IDAGetConsistentIC` returns the corrected initial conditions calculated by `IDACalcIC`.

Arguments: `ida_mem` (void *) pointer to the IDA memory block.
`yy0_mod` (N_Vector) consistent solution vector.
`yp0_mod` (N_Vector) consistent derivative vector.

Return value: The return value `flag` (of type `int`) is one of

- `IDA_SUCCESS` The optional output value has been successfully set.
- `IDA_ILLEGAL_INPUT` The function was not called before the first call to `IDASolve`.
- `IDA_MEM_NULL` The `ida_mem` pointer is NULL.

Notes: If the consistent solution vector or consistent derivative vector is not desired, pass NULL for the corresponding argument.

- The user must allocate space for `yy0_mod` and `yp0_mod` (if not NULL).

**4.5.10.4 Rootfinding optional output functions**

There are two optional output functions associated with rootfinding.
4.5 User-callable functions

**IDAGetRootInfo**

Call

```c
flag = IDAGetRootInfo(ida_mem, rootsfound);
```

Description

The function `IDAGetRootInfo` returns an array showing which functions were found to have a root.

Arguments

- `ida_mem` (void *) pointer to the IDA memory block.
- `rootsfound` (int *) array of length `nrtfn` with the indices of the user functions $g_i$ found to have a root. For $i = 0, \ldots, nrtfn - 1$, $rootsfound[i] \neq 0$ if $g_i$ has a root, and $= 0$ if not.

Return value

The return value `flag` (of type `int`) is one of

- `IDA_SUCCESS` The optional output values have been successfully set.
- `IDA_MEM_NULL` The `ida_mem` pointer is NULL.

Notes

Note that, for the components $g_i$ for which a root was found, the sign of $rootsfound[i]$ indicates the direction of zero-crossing. A value of $+1$ indicates that $g_i$ is increasing, while a value of $-1$ indicates a decreasing $g_i$.

The user must allocate memory for the vector `rootsfound`.

**IDAGetNumGEvals**

Call

```c
flag = IDAGetNumGEvals(ida_mem, &ngevals);
```

Description

The function `IDAGetNumGEvals` returns the cumulative number of calls to the user root function $g$.

Arguments

- `ida_mem` (void *) pointer to the IDA memory block.
- `ngevals` (long int) number of calls to the user’s function $g$ so far.

Return value

The return value `flag` (of type `int`) is one of

- `IDA_SUCCESS` The optional output value has been successfully set.
- `IDA_MEM_NULL` The `ida_mem` pointer is NULL.

**4.5.10.5 IDALS linear solver interface optional output functions**

The following optional outputs are available from the IDALS modules: workspace requirements, number of calls to the Jacobian routine, number of calls to the residual routine for finite-difference Jacobian or Jacobian-vector product approximation, number of linear iterations, number of linear convergence failures, number of calls to the preconditioner setup and solve routines, number of calls to the Jacobian-vector setup and product routines, and last return value from an IDALS function. Note that, where the name of an output would otherwise conflict with the name of an optional output from the main solver, a suffix `LS` (for Linear Solver) has been added (e.g. `lenrwLS`).

**IDAGetLinWorkSpace**

Call

```c
flag = IDAGetLinWorkSpace(ida_mem, &lenrwLS, &leniwLS);
```

Description

The function `IDAGetLinWorkSpace` returns the sizes of the real and integer workspaces used by the IDALS linear solver interface.

Arguments

- `ida_mem` (void *) pointer to the IDA memory block.
- `lenrwLS` (long int) the number of real values in the IDALS workspace.
- `leniwLS` (long int) the number of integer values in the IDALS workspace.

Return value

The return value `flag` (of type `int`) is one of

- `IDALS_SUCCESS` The optional output value has been successfully set.
- `IDALS_MEM_NULL` The `ida_mem` pointer is NULL.
- `IDALS_LMEM_NULL` The IDALS linear solver has not been initialized.
Notes

The workspace requirements reported by this routine correspond only to memory allocated within this interface and to memory allocated by the SUNLINSOL object attached to it. The template Jacobian matrix allocated by the user outside of IDALS is not included in this report.

The previous routines IDADlsGetWorkspace and IDASpilsGetWorkspace are now wrappers for this routine, and may still be used for backward-compatibility. However, these will be deprecated in future releases, so we recommend that users transition to the new routine name soon.

**IDAGetNumJacEvals**

Call

```c
flag = IDAGetNumJacEvals(ida_mem, &njevals);
```

Description

The function **IDAGetNumJacEvals** returns the cumulative number of calls to the IDALS Jacobian approximation function.

Arguments

- `ida_mem` (void *) pointer to the IDA memory block.
- `njevals` (long int) the cumulative number of calls to the Jacobian function (total so far).

Return value

The return value `flag` (of type `int`) is one of

- **IDALS_SUCCESS** The optional output value has been successfully set.
- **IDALS_MEM_NULL** The `ida_mem` pointer is NULL.
- **IDALS_LMEM_NULL** The IDALS linear solver has not been initialized.

Notes

The previous routine **IDADlsGetNumJacEvals** is now a wrapper for this routine, and may still be used for backward-compatibility. However, this will be deprecated in future releases, so we recommend that users transition to the new routine name soon.

**IDAGetNumLinResEvals**

Call

```c
flag = IDAGetNumLinResEvals(ida_mem, &nrevalsLS);
```

Description

The function **IDAGetNumLinResEvals** returns the cumulative number of calls to the user residual function due to the finite difference Jacobian approximation or finite difference Jacobian-vector product approximation.

Arguments

- `ida_mem` (void *) pointer to the IDA memory block.
- `nrevalsLS` (long int) the cumulative number of calls to the user residual function.

Return value

The return value `flag` (of type `int`) is one of

- **IDALS_SUCCESS** The optional output value has been successfully set.
- **IDALS_MEM_NULL** The `ida_mem` pointer is NULL.
- **IDALS_LMEM_NULL** The IDALS linear solver has not been initialized.

Notes

The value `nrevalsLS` is incremented only if one of the default internal difference quotient functions is used.

The previous routines **IDADlsGetNumRhsEvals** and **IDASpilsGetNumRhsEvals** are now wrappers for this routine, and may still be used for backward-compatibility. However, these will be deprecated in future releases, so we recommend that users transition to the new routine name soon.

**IDAGetNumLinIters**

Call

```c
flag = IDAGetNumLinIters(ida_mem, &nliters);
```

Description

The function **IDAGetNumLinIters** returns the cumulative number of linear iterations.

Arguments

- `ida_mem` (void *) pointer to the IDA memory block.
4.5 User-callable functions

nliters (long int) the current number of linear iterations.

Return value The return value flag (of type int) is one of

- IDALS_SUCCESS The optional output value has been successfully set.
- IDALS_MEM_NULL The ida_mem pointer is NULL.
- IDALS_LMEM_NULL The IDALS linear solver has not been initialized.

Notes The previous routine IDASpilsGetNumLinIters is now a wrapper for this routine, and may still be used for backward-compatibility. However, this will be deprecated in future releases, so we recommend that users transition to the new routine name soon.

IDAGetNumLinConvFails

Call flag = IDAGetNumLinConvFails(ida_mem, &nlcfails);

Description The function IDAGetNumLinConvFails returns the cumulative number of linear convergence failures.

Arguments ida_mem (void *) pointer to the IDA memory block.

nlcfails (long int) the current number of linear convergence failures.

Return value The return value flag (of type int) is one of

- IDALS_SUCCESS The optional output value has been successfully set.
- IDALS_MEM_NULL The ida_mem pointer is NULL.
- IDALS_LMEM_NULL The IDALS linear solver has not been initialized.

Notes The previous routine IDASpilsGetNumConvFails is now a wrapper for this routine, and may still be used for backward-compatibility. However, this will be deprecated in future releases, so we recommend that users transition to the new routine name soon.

IDAGetNumPrecEvals

Call flag = IDAGetNumPrecEvals(ida_mem, &npevals);

Description The function IDAGetNumPrecEvals returns the cumulative number of preconditioner evaluations, i.e., the number of calls made to psetup.

Arguments ida_mem (void *) pointer to the IDA memory block.

npevals (long int) the cumulative number of calls to psetup.

Return value The return value flag (of type int) is one of

- IDALS_SUCCESS The optional output value has been successfully set.
- IDALS_MEM_NULL The ida_mem pointer is NULL.
- IDALS_LMEM_NULL The IDALS linear solver has not been initialized.

Notes The previous routine IDASpilsGetNumPrecEvals is now a wrapper for this routine, and may still be used for backward-compatibility. However, this will be deprecated in future releases, so we recommend that users transition to the new routine name soon.

IDAGetNumPrecSolves

Call flag = IDAGetNumPrecSolves(ida_mem, &npsolves);

Description The function IDAGetNumPrecSolves returns the cumulative number of calls made to the preconditioner solve function, psolve.

Arguments ida_mem (void *) pointer to the IDA memory block.

npsolves (long int) the cumulative number of calls to psolve.

Return value The return value flag (of type int) is one of

- IDALS_SUCCESS The optional output value has been successfully set.
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IDALS_MEM_NULL  The ida_mem pointer is NULL.
IDALS_LMEM_NULL The IDALS linear solver has not been initialized.

Notes  The previous routine IDASpilsGetNumPrecSolves is now a wrapper for this routine, and may still be used for backward-compatibility. However, this will be deprecated in future releases, so we recommend that users transition to the new routine name soon.

IDAGetNumJTSetupEvals

Call  flag = IDAGetNumJTSetupEvals(ida_mem, &njtsetup);

Description  The function IDAGetNumJTSetupEvals returns the cumulative number of calls made to the Jacobian-vector setup function jsetup.

Arguments  ida_mem (void *) pointer to the IDA memory block.
            njtsetup (long int) the current number of calls to jsetup.

Return value  The return value flag (of type int) is one of
              IDALS_SUCCESS  The optional output value has been successfully set.
              IDALS_MEM_NULL The ida_mem pointer is NULL.
              IDALS_LMEM_NULL The IDALS linear solver has not been initialized.

Notes  The previous routine IDASpilsGetNumJTSetupEvals is now a wrapper for this routine, and may still be used for backward-compatibility. However, this will be deprecated in future releases, so we recommend that users transition to the new routine name soon.

IDAGetNumJtimesEvals

Call  flag = IDAGetNumJtimesEvals(ida_mem, &njvevals);

Description  The function IDAGetNumJtimesEvals returns the cumulative number of calls made to the Jacobian-vector function, jtimes.

Arguments  ida_mem (void *) pointer to the IDA memory block.
            njvevals (long int) the cumulative number of calls to jtimes.

Return value  The return value flag (of type int) is one of
              IDALS_SUCCESS  The optional output value has been successfully set.
              IDALS_MEM_NULL The ida_mem pointer is NULL.
              IDALS_LMEM_NULL The IDALS linear solver has not been initialized.

Notes  The previous routine IDASpilsGetNumJtimesEvals is now a wrapper for this routine, and may still be used for backward-compatibility. However, this will be deprecated in future releases, so we recommend that users transition to the new routine name soon.

IDAGetLastLinFlag

Call  flag = IDAGetLastLinFlag(ida_mem, &lsflag);

Description  The function IDAGetLastLinFlag returns the last return value from an IDALS routine.

Arguments  ida_mem (void *) pointer to the IDA memory block.
            lsflag (long int) the value of the last return flag from an IDALS function.

Return value  The return value flag (of type int) is one of
              IDALS_SUCCESS  The optional output value has been successfully set.
              IDALS_MEM_NULL The ida_mem pointer is NULL.
              IDALS_LMEM_NULL The IDALS linear solver has not been initialized.
4.5 User-callable functions

Notes

If the idals setup function failed (i.e., IDASolve returned IDA_LSETUP_FAIL) when using the SUNLINSOL(Dense or SUNLINSOL_BAND modules), then the value of lsflag is equal to the column index (numbered from one) at which a zero diagonal element was encountered during the LU factorization of the (dense or banded) Jacobian matrix.

If the idals setup function failed when using another SUNLINSOL module, then lsflag will be SUNLS_PSET_FAIL_UNREC, SUNLS_ASET_FAIL_UNREC, or SUNLS_PACKAGE_FAIL_UNREC.

If the idals solve function failed (IDASolve returned IDA_LSOLVE_FAIL), lsflag contains the error return flag from the SUNLINSOL object, which will be one of: SUNLS_MEM_NULL, indicating that the SUNLINSOL memory is NULL; SUNLS_ATIMES_FAIL_UNREC, indicating an unrecoverable failure in the J*v function; SUNLS_PSOLVE_FAIL_UNREC, indicating that the preconditioner solve function psolve failed unrecoverably; SUNLS_GS_FAIL, indicating a failure in the Gram-Schmidt procedure (generated only in SPGMR or SPFGMR); SUNLS_QRSOL_FAIL, indicating that the matrix R was found to be singular during the QR solve phase (SPGMR and SPFGMR only); or SUNLS_PACKAGE_FAIL_UNREC, indicating an unrecoverable failure in an external iterative linear solver package.

The previous routines IDADlsGetLastFlag and IDASpilsGetLastFlag are now wrappers for this routine, and may still be used for backward-compatibility. However, these will be deprecated in future releases, so we recommend that users transition to the new routine name soon.

**IDAGetLinReturnFlagName**

**Call**

name = IDAGetLinReturnFlagName(lsflag);

**Description**
The function IDAGetLinReturnFlagName returns the name of the idals constant corresponding to lsflag.

**Arguments**
The only argument, of type long int, is a return flag from an IDALS function.

**Return value**
The return value is a string containing the name of the corresponding constant.

If $1 \leq \text{lsflag} \leq N$ (LU factorization failed), this function returns “NONE”.

**Notes**
The previous routines IDADlsGetReturnFlagName and IDASpilsGetReturnFlagName are now wrappers for this routine, and may still be used for backward-compatibility. However, these will be deprecated in future releases, so we recommend that users transition to the new routine name soon.

4.5.11 IDA reinitialization function

The function IDAREInit reinitializes the main IDA solver for the solution of a new problem, where a prior call to IDAINit has been made. The new problem must have the same size as the previous one. IDAREInit performs the same input checking and initializations that IDAINit does, but does no memory allocation, as it assumes that the existing internal memory is sufficient for the new problem. A call to IDAREInit deletes the solution history that was stored internally during the previous integration. Following a successful call to IDAREInit, call IDASolve again for the solution of the new problem.

The use of IDAREInit requires that the maximum method order, maxord, is no larger for the new problem than for the problem specified in the last call to IDAINit. In addition, the same NVECTOR module set for the previous problem will be reused for the new problem.

If there are changes to the linear solver specifications, make the appropriate calls to either the linear solver objects themselves, or to the IDALS interface routines, as described in §4.5.3.

If there are changes to any optional inputs, make the appropriate IDASet*** calls, as described in §4.5.8. Otherwise, all solver inputs set previously remain in effect.

One important use of the IDAREInit function is in the treating of jump discontinuities in the residual function. Except in cases of fairly small jumps, it is usually more efficient to stop at each point
of discontinuity and restart the integrator with a readjusted DAE model, using a call to IDAReInit. To stop when the location of the discontinuity is known, simply make that location a value of tout. To stop when the location of the discontinuity is determined by the solution, use the rootfinding feature. In either case, it is critical that the residual function not incorporate the discontinuity, but rather have a smooth extension over the discontinuity, so that the step across it (and subsequent rootfinding, if used) can be done efficiently. Then use a switch within the residual function (communicated through user_data) that can be flipped between the stopping of the integration and the restart, so that the restarted problem uses the new values (which have jumped). Similar comments apply if there is to be a jump in the dependent variable vector.

**IDAReInit**

Call

```c
flag = IDAReInit(ida_mem, t0, y0, yp0);
```

Description The function IDAReInit provides required problem specifications and reinitializes IDA.

Arguments

- `ida_mem` (void *) pointer to the IDA memory block.
- `t0` (realtype) is the initial value of \( t \).
- `y0` (N_Vector) is the initial value of \( y \).
- `yp0` (N_Vector) is the initial value of \( \dot{y} \).

Return value The return value `flag` (of type `int`) will be one of the following:

- **IDA_SUCCESS** The call to IDAReInit was successful.
- **IDA_MEM_NULL** The IDA memory block was not initialized through a previous call to IDACreate.
- **IDA_NO_MALLOC** Memory space for the IDA memory block was not allocated through a previous call to IDAInit.
- **IDA_Ill_INPUT** An input argument to IDAReInit has an illegal value.

Notes If an error occurred, IDAReInit also sends an error message to the error handler function.

### 4.6 User-supplied functions

The user-supplied functions consist of one function defining the DAE residual, (optionally) a function that handles error and warning messages, (optionally) a function that provides the error weight vector, (optionally) one or two functions that provide Jacobian-related information for the linear solver, and (optionally) one or two functions that define the preconditioner for use in any of the Krylov iteration algorithms.

#### 4.6.1 Residual function

The user must provide a function of type IDAResFn defined as follows:

**IDAResFn**

Definition

```c
typedef int (*IDAResFn)(realtype tt, N_Vector yy, N_Vector yp,
                         N_Vector rr, void *user_data);
```

Purpose This function computes the problem residual for given values of the independent variable \( t \), state vector \( y \), and derivative \( \dot{y} \).

Arguments

- `tt` is the current value of the independent variable.
- `yy` is the current value of the dependent variable vector, \( y(t) \).
- `yp` is the current value of \( \dot{y}(t) \).
- `rr` is the output residual vector \( F(t, y, \dot{y}) \).
user_data is a pointer to user data, the same as the user_data parameter passed to IDASetUserData.

Return value An IDAResFn function type should return a value of 0 if successful, a positive value if a recoverable error occurred (e.g. yy has an illegal value), or a negative value if a nonrecoverable error occurred. In the last case, the integrator halts. If a recoverable error occurred, the integrator will attempt to correct and retry.

Notes A recoverable failure error return from the IDAResFn is typically used to flag a value of the dependent variable y that is “illegal” in some way (e.g., negative where only a non-negative value is physically meaningful). If such a return is made, IDA will attempt to recover (possibly repeating the nonlinear solve, or reducing the step size) in order to avoid this recoverable error return.

For efficiency reasons, the DAE residual function is not evaluated at the converged solution of the nonlinear solver. Therefore, in general, a recoverable error in that converged value cannot be corrected. (It may be detected when the right-hand side function is called the first time during the following integration step, but a successful step cannot be undone.)

Allocation of memory for yp is handled within IDA.

4.6.2 Error message handler function

As an alternative to the default behavior of directing error and warning messages to the file pointed to by errfp (see IDASetErrFile), the user may provide a function of type IDAErrHandlerFn to process any such messages. The function type IDAErrHandlerFn is defined as follows:

**IDAErrHandlerFn**

Definition

```c
typedef void (*IDAErrHandlerFn)(int error_code, const char *module, const char *function, char *msg, void *eh_data);
```

Purpose

This function processes error and warning messages from IDA and its sub-modules.

Arguments

- **error_code** is the error code.
- **module** is the name of the IDA module reporting the error.
- **function** is the name of the function in which the error occurred.
- **msg** is the error message.
- **eh_data** is a pointer to user data, the same as the eh_data parameter passed to IDASetErrHandlerFn.

Return value

A IDAErrHandlerFn function has no return value.

Notes

**error_code** is negative for errors and positive (IDA_WARNING) for warnings. If a function that returns a pointer to memory encounters an error, it sets **error_code** to 0.

4.6.3 Error weight function

As an alternative to providing the relative and absolute tolerances, the user may provide a function of type IDAEwtFn to compute a vector ewt containing the multiplicative weights $W_i$ used in the WRMS norm $\| v \|_{\text{WRMS}} = \sqrt{(1/N) \sum_1^N (W_i \cdot v_i)^2}$. These weights will used in place of those defined by Eq. (2.6). The function type IDAEwtFn is defined as follows:

**IDAEwtFn**

Definition

```c
typedef int (*IDAEwtFn)(N_Vector y, N_Vector ewt, void *user_data);
```

Purpose

This function computes the WRMS error weights for the vector y.
Arguments

- \( y \) is the value of the dependent variable vector at which the weight vector is to be computed.
- \( \textbf{ewt} \) is the output vector containing the error weights.
- \( \textbf{user\_data} \) is a pointer to user data, the same as the \textbf{user\_data} parameter passed to \texttt{IDASetUserData}.

Return value

An \texttt{IDA\_Ewt\_Fn} function type must return 0 if it successfully set the error weights and \(-1\) otherwise.

Notes

- Allocation of memory for \( \textbf{ewt} \) is handled within IDA.
- The error weight vector must have all components positive. It is the user’s responsibility to perform this test and return \(-1\) if it is not satisfied.

4.6.4 Rootfinding function

If a rootfinding problem is to be solved during the integration of the DAE system, the user must supply a C function of type \texttt{IDA\_Root\_Fn}, defined as follows:

\[ \texttt{IDARootFn} \]

Definition

\[
\begin{align*}
typedef \texttt{int} \ast \texttt{IDARootFn}(\texttt{realtype} \ t, \ \texttt{N\_Vector} \ y, \ \texttt{N\_Vector} \ yp, \\
\texttt{realtype} \ast \texttt{gout}, \ \texttt{void} \ast \texttt{user\_data});
\end{align*}
\]

Purpose

This function computes a vector-valued function \( g(t, y, \dot{y}) \) such that the roots of the \( nrtfn \) components \( g_i(t, y, \dot{y}) \) are to be found during the integration.

Arguments

- \( t \) is the current value of the independent variable.
- \( y \) is the current value of the dependent variable vector, \( y(t) \).
- \( yp \) is the current value of \( \dot{y}(t) \), the \( t \)−derivative of \( y \).
- \( gout \) is the output array, of length \( nrtfn \), with components \( g_i(t, y, \dot{y}) \).
- \( \textbf{user\_data} \) is a pointer to user data, the same as the \textbf{user\_data} parameter passed to \texttt{IDA\_Set\_UserData}.

Return value

An \texttt{IDARootFn} should return 0 if successful or a non-zero value if an error occurred (in which case the integration is halted and \texttt{IDA\_Solve} returns \texttt{IDA\_RTFUNC\_FAIL}).

Notes

- Allocation of memory for \( \textbf{gout} \) is handled within IDA.

4.6.5 Jacobian construction (matrix-based linear solvers)

If a matrix-based linear solver module is used (i.e. a non-NULL \texttt{SUNMatrix} object was supplied to \texttt{IDA\_Set\_Linear\_Solver}), the user may provide a function of type \texttt{IDALs\_Jac\_Fn} defined as follows:

\[ \texttt{IDALs\_Jac\_Fn} \]

Definition

\[
\begin{align*}
typedef \texttt{int} \ast \texttt{IDALs\_Jac\_Fn}(\texttt{realtype} \ tt, \ \texttt{realtype} \ cj, \\
\texttt{N\_Vector} \ yy, \ \texttt{N\_Vector} \ yp, \ \texttt{N\_Vector} \ rr, \\
\texttt{SUNMatrix} \ \text{Jac}, \ \texttt{void} \ast \texttt{user\_data}, \\
\texttt{N\_Vector} \ \text{tmp1}, \ \texttt{N\_Vector} \ \text{tmp2}, \ \texttt{N\_Vector} \ \text{tmp3});
\end{align*}
\]

Purpose

This function computes the Jacobian matrix \( J \) of the DAE system (or an approximation to it), defined by Eq. (2.5).

Arguments

- \( tt \) is the current value of the independent variable \( t \).
- \( cj \) is the scalar in the system Jacobian, proportional to the inverse of the step size (\( \alpha \) in Eq. (2.5) ).
- \( yy \) is the current value of the dependent variable vector, \( y(t) \).
- \( yp \) is the current value of \( \dot{y}(t) \).
- \( rr \) is the current value of the residual vector \( F(t, y, \dot{y}) \).
**4.6 User-supplied functions**

| Jac | is the output (approximate) Jacobian matrix (of type SUNMatrix), $J = \frac{\partial F}{\partial y} + c_j \frac{\partial F}{\partial y_j}$. |
| user_data | is a pointer to user data, the same as the user_data parameter passed to IDASSetUserData. |
| tmp1 | tmp2 |
| tmp3 | are pointers to memory allocated for variables of type N_Vector which can be used by IDALsJacFn function as temporary storage or work space. |

**Return value** An IDALsJacFn should return 0 if successful, a positive value if a recoverable error occurred, or a negative value if a nonrecoverable error occurred.

**Notes** Information regarding the structure of the specific SUNMATRIX structure (e.g. number of rows, upper/lower bandwidth, sparsity type) may be obtained through using the implementation-specific SUNMATRIX interface functions (see Chapter 7 for details).

With direct linear solvers (i.e., linear solvers with type SUNLINEARSOLVER_DIRECT), the Jacobian matrix $J(t, y)$ is zeroed out prior to calling the user-supplied Jacobian function so only nonzero elements need to be loaded into Jac.

If the user’s IDALsJacFn function uses difference quotient approximations, it may need to access quantities not in the call list. These quantities may include the current stepsize, the error weights, etc. To obtain these, the user will need to add a pointer to $\text{ida}_\text{mem}$ to user_data and then use the IDAGet$\text{*}$ functions described in §4.5.10.2. The unit roundoff can be accessed as UNIT_ROUNDOFF defined in sundials_types.h.

**dense:**
A user-supplied dense Jacobian function must load the $\text{Neq} \times \text{Neq}$ dense matrix Jac with an approximation to the Jacobian matrix $J(t, y)$ at the point $(t, y, y')$. The accessor macros $\text{SM\_ELEMENT\_D}$ and $\text{SM\_COLUMN\_D}$ allow the user to read and write dense matrix elements without making explicit references to the underlying representation of the SUNMATRIX\_DENSE type. $\text{SM\_ELEMENT\_D}(J, i, j)$ references the $(i, j)$-th element of the dense matrix Jac (with $i, j = 0 \ldots \text{Neq} - 1$). This macro is meant for small problems for which efficiency of access is not a major concern. Thus, in terms of the indices $m$ and $n$ ranging from 1 to $\text{Neq}$, the Jacobian element $J_{m,n}$ can be set using the statement $\text{SM\_ELEMENT\_D}(J, m-1, n-1) = J_{m,n}$. Alternatively, $\text{SM\_COLUMN\_D}(J, j)$ returns a pointer to the first element of the $j$-th column of Jac (with $j = 0 \ldots \text{Neq} - 1$), and the elements of the $j$-th column can then be accessed using ordinary array indexing. Consequently, $J_{m,n}$ can be loaded using the statements $\text{col}\_n = \text{SM\_COLUMN\_D}(J, n-1)$; $\text{col}\_n[m-1] = J_{m,n}$. For large problems, it is more efficient to use $\text{SM\_COLUMN\_D}$ than to use $\text{SM\_ELEMENT\_D}$. Note that both of these macros number rows and columns starting from 0. The SUNMATRIX\_DENSE type and accessor macros are documented in §7.3.

**banded:**
A user-supplied banded Jacobian function must load the $\text{Neq} \times \text{Neq}$ banded matrix Jac with an approximation to the Jacobian matrix $J(t, y, y')$ at the point $(t, y, y')$. The accessor macros $\text{SM\_ELEMENT\_B}$, $\text{SM\_COLUMN\_B}$, and $\text{SM\_COLUMN\_ELEMENT\_B}$ allow the user to read and write banded matrix elements without making specific references to the underlying representation of the SUNMATRIX\_BAND type. $\text{SM\_ELEMENT\_B}(J, i, j)$ references the $(i, j)$-th element of the banded matrix Jac, counting from 0. This macro is meant for use in small problems for which efficiency of access is not a major concern. Thus, in terms of the indices $m$ and $n$ ranging from 1 to $\text{Neq}$ with $(m, n)$ within the band defined by $\text{mupper}$ and $\text{mlower}$, the Jacobian element $J_{m,n}$ can be loaded using the statement $\text{SM\_ELEMENT\_B}(J, m-1, n-1) = J_{m,n}$. The elements within the band are those with $\text{mupper} = m-\text{mlower} \leq m-\text{mlower}$. Alternatively, $\text{SM\_COLUMN\_B}(J,$
j) returns a pointer to the diagonal element of the j-th column of Jac, and if we assign this address to `realtype *col_j`, then the i-th element of the j-th column is given by `SM_COLUMN_ELEMENT_B(col_j, i, j)`, counting from 0. Thus, for \((m, n)\) within the band, \(J_{m,n}\) can be loaded by setting \(col_n = SM_COLUMN_B(J, n-1)\); and

\[
SM_COLUMN_ELEMENT_B(col_n, m-1, n-1) = J_{m,n}.
\]

The elements of the j-th column can also be accessed via ordinary array indexing, but this approach requires knowledge of the underlying storage for a band matrix of type `SUNMATRIX_BAND`. The array `col_n` can be indexed from \(-\text{mupper}\) to \(\text{mlower}\). For large problems, it is more efficient to use `SM_COLUMN_B` and `SM_COLUMN_ELEMENT_B` than to use the `SM_ELEMENT_B` macro. As in the dense case, these macros all number rows and columns starting from 0. The `SUNMATRIX_BAND` type and accessor macros are documented in §7.4.

**sparse:**

A user-supplied sparse Jacobian function must load the \(\text{Neq} \times \text{Neq}\) compressed-sparse-column or compressed-sparse-row matrix Jac with an approximation to the Jacobian matrix \(J(t, y, \dot{y})\) at the point \((tt, yy, yp)\). Storage for Jac already exists on entry to this function, although the user should ensure that sufficient space is allocated in Jac to hold the nonzero values to be set; if the existing space is insufficient the user may reallocate the data and index arrays as needed. The amount of allocated space in a `SUNMATRIX_SPARSE` object may be accessed using the macro `SM_NNZ_S` or the routine `SUNSparseMatrix_NNZ`. The `SUNMATRIX_SPARSE` type and accessor macros are documented in §7.5.

The previous function type `IDADlsJacFn` is identical to `IDALsJacFns`, and may still be used for backward-compatibility. However, this will be deprecated in future releases, so we recommend that users transition to the new function type name soon.

### 4.6.6 Jacobian-vector product (matrix-free linear solvers)

If a matrix-free linear solver is to be used (i.e., a `NULL`-valued `SUNMATRIX` was supplied to `IDASetLinearSolver`), the user may provide a function of type `IDALsJacTimesVecFn` in the following form, to compute matrix-vector products \(Jv\). If such a function is not supplied, the default is a difference quotient approximation to these products.

```c
typedef int (*IDALsJacTimesVecFn)(realtype tt, N_Vector yy, N_Vector yp, N_Vector rr, N_Vector v, N_Vector Jv, realtype cj, void *user_data, N_Vector tmp1, N_Vector tmp2);
```

**Definition**

This function computes the product \(Jv\) of the DAE system Jacobian \(J\) (or an approximation to it) and a given vector \(v\), where \(J\) is defined by Eq. (2.5).

**Purpose**

This function computes the product \(Jv\) of the DAE system Jacobian \(J\) (or an approximation to it) and a given vector \(v\), where \(J\) is defined by Eq. (2.5).

**Arguments**

- **tt** is the current value of the independent variable.
- **yy** is the current value of the dependent variable vector, \(y(t)\).
- **yp** is the current value of \(\dot{y}(t)\).
- **rr** is the current value of the residual vector \(F(t, y, \dot{y})\).
- **v** is the vector by which the Jacobian must be multiplied to the right.
- **Jv** is the computed output vector.
- **cj** is the scalar in the system Jacobian, proportional to the inverse of the step size (\(\alpha\) in Eq. (2.5)).
- **user_data** is a pointer to user data, the same as the `user_data` parameter passed to `IDASetUserData`.
- `tmp1`
4.6 User-supplied functions

...are pointers to memory allocated for variables of type N_Vector which can be used by IDALSJacTimesVecFn as temporary storage or work space.

Return value  The value returned by the Jacobian-times-vector function should be 0 if successful. A nonzero value indicates that a nonrecoverable error occurred.

Notes  This function must return a value of \( J \times v \) that uses the current value of \( J \), i.e. as evaluated at the current \((t, y, \dot{y})\).

If the user’s IDALSJacTimesVecFn function uses difference quotient approximations, it may need to access quantities not in the call list. These include the current stepsize, the error weights, etc. To obtain these, the user will need to add a pointer to ida_mem to user_data and then use the IDAGet* functions described in §4.5.10.2. The unit roundoff can be accessed as UNIT_ROUNDOFF defined in sundials_types.h.

The previous function type IDASpilsJacTimesVecFn is identical to IDALSJacTimesVecFn, and may still be used for backward-compatibility. However, this will be deprecated in future releases, so we recommend that users transition to the new function type name soon.

4.6.7 Jacobian-vector product setup (matrix-free linear solvers)

If the user’s Jacobian-times-vector requires that any Jacobian-related data be preprocessed or evaluated, then this needs to be done in a user-supplied function of type IDALSJacTimesSetupFn, defined as follows:

```
typedef int (*IDALSJacTimesSetupFn)(realtype tt, N_Vector yy,
                                   N_Vector yp, N_Vector rr,
                                   realtype cj, void *user_data);
```

Definition  This function preprocesses and/or evaluates Jacobian data needed by the Jacobian-times-vector routine.

Purpose  Arguments  
\( tt \)  is the current value of the independent variable.
\( yy \)  is the current value of the dependent variable vector, \( y(t) \).
\( yp \)  is the current value of \( \dot{y}(t) \).
\( rr \)  is the current value of the residual vector \( F(t, y, \dot{y}) \).
\( cj \)  is the scalar in the system Jacobian, proportional to the inverse of the step size \( (\alpha \text{ in Eq. (2.5)}) \).

user_data is a pointer to user data, the same as the user_data parameter passed to IDASetUserData.

Return value  The value returned by the Jacobian-vector setup function should be 0 if successful, positive for a recoverable error (in which case the step will be retried), or negative for an unrecoverable error (in which case the integration is halted).

Notes  Each call to the Jacobian-vector setup function is preceded by a call to the IDAResFn user function with the same \((t, y, \dot{y})\) arguments. Thus, the setup function can use any auxiliary data that is computed and saved during the evaluation of the DAE residual.

If the user’s IDALSJacTimesVecFn function uses difference quotient approximations, it may need to access quantities not in the call list. These include the current stepsize, the error weights, etc. To obtain these, the user will need to add a pointer to ida_mem to user_data and then use the IDAGet* functions described in §4.5.10.2. The unit roundoff can be accessed as UNIT_ROUNDOFF defined in sundials_types.h.

The previous function type IDASpilsJacTimesSetupFn is identical to IDALSJacTimesSetupFn, and may still be used for backward-compatibility. However, this will be deprecated in
future releases, so we recommend that users transition to the new function type name soon.

4.6.8 Preconditioner solve (iterative linear solvers)

If a user-supplied preconditioner is to be used with a SUNLINSOL solver module, then the user must provide a function to solve the linear system \( Pz = r \) where \( P \) is a left preconditioner matrix which approximates (at least crudely) the Jacobian matrix \( J = \partial F/\partial y + cj \partial F/\partial \dot{y} \). This function must be of type IDALSPrecSolveFn, defined as follows:

```c
typedef int (*IDALSPrecSolveFn)(realtype tt, N_Vector yy,
                               N_Vector yp, N_Vector rr,
                               N_Vector rvec, N_Vector zvec,
                               realtype cj, realtype delta,
                               void *user_data);
```

Purpose

This function solves the preconditioning system \( Pz = r \).

Arguments

- \( tt \) is the current value of the independent variable.
- \( yy \) is the current value of the dependent variable vector, \( y(t) \).
- \( yp \) is the current value of \( \dot{y}(t) \).
- \( rr \) is the current value of the residual vector \( F(t, y, \dot{y}) \).
- \( rvec \) is the right-hand side vector \( r \) of the linear system to be solved.
- \( zvec \) is the computed output vector.
- \( cj \) is the scalar in the system Jacobian, proportional to the inverse of the step size (\( \alpha \) in Eq. (2.5)).
- \( delta \) is an input tolerance to be used if an iterative method is employed in the solution. In that case, the residual vector \( Res = r - Pz \) of the system should be made less than \( delta \) in weighted \( l_2 \) norm, i.e., \( \sqrt{\sum_i (Res_i \cdot ewt_i)^2} < delta \). To obtain the \( N \_Vector ewt \), call IDAGetErrWeights (see §4.5.10.2).
- \( user \_data \) is a pointer to user data, the same as the \( user \_data \) parameter passed to the function IDASetUserData.

Return value

The value to be returned by the preconditioner solve function is a flag indicating whether it was successful. This value should be 0 if successful, positive for a recoverable error (in which case the step will be retried), negative for an unrecoverable error (in which case the integration is halted).

Notes

The previous function type IDASpilsPrecSolveFn is identical to IDALSPrecSolveFn, and may still be used for backward-compatibility. However, this will be deprecated in future releases, so we recommend that users transition to the new function type name soon.

4.6.9 Preconditioner setup (iterative linear solvers)

If the user’s preconditioner requires that any Jacobian-related data be evaluated or preprocessed, then this needs to be done in a user-supplied function of type IDALSPrecSetupFn, defined as follows:

```c
typedef int (*IDALSPrecSetupFn)(realtype tt, N_Vector yy,
                                N_Vector yp, N_Vector rr,
                                realtype cj, void *user_data);
```

Notes

The previous function type IDASpilsPrecSetupFn is identical to IDALSPrecSetupFn, and may still be used for backward-compatibility. However, this will be deprecated in future releases, so we recommend that users transition to the new function type name soon.
4.7 A parallel band-block-diagonal preconditioner module

Purpose This function evaluates and/or preprocesses Jacobian-related data needed by the preconditioner.

Arguments

- $tt$ is the current value of the independent variable.
- $yy$ is the current value of the dependent variable vector, $y(t)$.
- $yp$ is the current value of $\dot{y}(t)$.
- $rr$ is the current value of the residual vector $F(t, y, \dot{y})$.
- $cj$ is the scalar in the system Jacobian, proportional to the inverse of the step size ($\alpha$ in Eq. (2.5)).

User data is a pointer to user data, the same as the user_data parameter passed to the function IDASetUserData.

Return value The value returned by the preconditioner setup function is a flag indicating whether it was successful. This value should be 0 if successful, positive for a recoverable error (in which case the step will be retried), negative for an unrecoverable error (in which case the integration is halted).

Notes

The operations performed by this function might include forming a crude approximate Jacobian, and performing an LU factorization on the resulting approximation.

Each call to the preconditioner setup function is preceded by a call to the IDAResFn user function with the same ($tt$, $yy$, $yp$) arguments. Thus the preconditioner setup function can use any auxiliary data that is computed and saved during the evaluation of the DAE residual.

This function is not called in advance of every call to the preconditioner solve function, but rather is called only as often as needed to achieve convergence in the nonlinear solver.

If the user’s IDALSPrecSetupFn function uses difference quotient approximations, it may need to access quantities not in the call list. These include the current stepsize, the error weights, etc. To obtain these, the user will need to add a pointer to ida_mem to user_data and then use the IDAGet* functions described in §4.5.10.2. The unit roundoff can be accessed as UNIT_ROUNDOFF defined in sundials_types.h.

The previous function type IDASpilsPrecSetupFn is identical to IDALSPrecSetupFn, and may still be used for backward-compatibility. However, this will be deprecated in future releases, so we recommend that users transition to the new function type name soon.

4.7 A parallel band-block-diagonal preconditioner module

A principal reason for using a parallel DAE solver such as IDA lies in the solution of partial differential equations (PDEs). Moreover, the use of a Krylov iterative method for the solution of many such problems is motivated by the nature of the underlying linear system of equations (2.4) that must be solved at each time step. The linear algebraic system is large, sparse, and structured. However, if a Krylov iterative method is to be effective in this setting, then a nontrivial preconditioner needs to be used. Otherwise, the rate of convergence of the Krylov iterative method is usually unacceptably slow. Unfortunately, an effective preconditioner tends to be problem-specific.

However, we have developed one type of preconditioner that treats a rather broad class of PDE-based problems. It has been successfully used for several realistic, large-scale problems [30] and is included in a software module within the IDA package. This module works with the parallel vector module NVECTOR_PARALLEL and generates a preconditioner that is a block-diagonal matrix with each block being a band matrix. The blocks need not have the same number of super- and sub-diagonals, and these numbers may vary from block to block. This Band-Block-Diagonal Preconditioner module is called IDABBDPRE.

One way to envision these preconditioners is to think of the domain of the computational PDE problem as being subdivided into $M$ non-overlapping sub-domains. Each of these sub-domains is then
assigned to one of the $M$ processors to be used to solve the DAE system. The basic idea is to isolate the preconditioning so that it is local to each processor, and also to use a (possibly cheaper) approximate residual function. This requires the definition of a new function $G(t, y, ˙y)$ which approximates the function $F(t, y, ˙y)$ in the definition of the DAE system (2.1). However, the user may set $G = F$. Corresponding to the domain decomposition, there is a decomposition of the solution vectors $y$ and $˙y$ into $M$ disjoint blocks $y_m$ and $˙y_m$, and a decomposition of $G$ into blocks $G_m$. The block $G_m$ depends on $y_m$ and $˙y_m$, and also on components of $y_{m'}$ and $˙y_{m'}$ associated with neighboring sub-domains (so-called ghost-cell data). Let $y_m$ and $˙y_m$ denote $y_m$ and $˙y_m$ (respectively) augmented with those other components on which $G_m$ depends. Then we have

$$G(t, y, ˙y) = [G_1(t, ˙y_1, ˙y_1), G_2(t, ˙y_2, ˙y_2), \ldots, G_M(t, ˙y_M, ˙y_M)]^T,$$

(4.1)

and each of the blocks $G_m(t, ˙y_m, ˙y_m)$ is uncoupled from the others.

The preconditioner associated with this decomposition has the form

$$P = \text{diag}[P_1, P_2, \ldots, P_M]$$

(4.2)

where

$$P_m \approx \partial G_m / \partial y_m + \alpha \partial G_m / \partial ˙y_m$$

(4.3)

This matrix is taken to be banded, with upper and lower half-bandwidths $\text{mudq}$ and $\text{mldq}$ defined as the number of non-zero diagonals above and below the main diagonal, respectively. The difference quotient approximation is computed using $\text{mudq} + \text{mldq} + 2$ evaluations of $G_m$, but only a matrix of bandwidth $\text{mukeep} + \text{mlkeep} + 1$ is retained.

Neither pair of parameters need be the true half-bandwidths of the Jacobians of the local block of $G$, if smaller values provide a more efficient preconditioner. Such an efficiency gain may occur if the couplings in the DAE system outside a certain bandwidth are considerably weaker than those within the band. Reducing $\text{mukeep}$ and $\text{mlkeep}$ while keeping $\text{mudq}$ and $\text{mldq}$ at their true values, discards the elements outside the narrower band. Reducing both pairs has the additional effect of lumping the outer Jacobian elements into the computed elements within the band, and requires more caution and experimentation.

The solution of the complete linear system

$$Px = b$$

(4.4)

reduces to solving each of the equations

$$P_m x_m = b_m$$

(4.5)

and this is done by banded LU factorization of $P_m$ followed by a banded backsolve.

Similar block-diagonal preconditioners could be considered with different treatment of the blocks $P_m$. For example, incomplete LU factorization or an iterative method could be used instead of banded LU factorization.

The IDABBDPRE module calls two user-provided functions to construct $P$: a required function $\text{Gres}$ (of type IDABBDLocalFn) which approximates the residual function $G(t, y, ˙y) \approx F(t, y, ˙y)$ and which is computed locally, and an optional function $\text{Gcomm}$ (of type IDABBDCommFn) which performs all inter-process communication necessary to evaluate the approximate residual $G$. These are in addition to the user-supplied residual function $\text{res}$. Both functions take as input the same pointer $\text{user\_data}$ as passed by the user to IDASetUserData and passed to the user’s function $\text{res}$. The user is responsible for providing space (presumably within $\text{user\_data}$) for components of $yy$ and $yp$ that are communicated by $\text{Gcomm}$ from the other processors, and that are then used by $\text{Gres}$, which should not do any communication.

**IDABBDLocalFn**

**Definition**

```c
typedef int (*IDABBDLocalFn)(sunindextype Nlocal, realtime tt,
   N_Vector yy, N_Vector yp, N_Vector gval,
   void *user_data);
```
Purpose  This $G_\text{res}$ function computes $G(t, y, \dot{y})$. It loads the vector $g_{\text{val}}$ as a function of $tt$, $yy$, and $yp$.

Arguments  
- $N_{\text{local}}$ is the local vector length.
- $tt$ is the value of the independent variable.
- $yy$ is the dependent variable.
- $yp$ is the derivative of the dependent variable.
- $g_{\text{val}}$ is the output vector.
- $\text{user\_data}$ is a pointer to user data, the same as the $\text{user\_data}$ parameter passed to IDASetUserData.

Return value  
An IDABBDLocalFn function type should return 0 to indicate success, 1 for a recoverable error, or -1 for a non-recoverable error.

Notes  
This function must assume that all inter-processor communication of data needed to calculate $g_{\text{val}}$ has already been done, and this data is accessible within $\text{user\_data}$. The case where $G$ is mathematically identical to $F$ is allowed.

### IDABBDCommFn

**Definition**  
typedef int (*IDABBDCommFn)(sunindextype $N_{\text{local}}$, realtype $tt$, N_Vector yy, N_Vector yp, void *$\text{user\_data}$);

**Purpose**  
This $G_{\text{comm}}$ function performs all inter-processor communications necessary for the execution of the $G_{\text{res}}$ function above, using the input vectors $yy$ and $yp$.

**Arguments**  
- $N_{\text{local}}$ is the local vector length.
- $tt$ is the value of the independent variable.
- $yy$ is the dependent variable.
- $yp$ is the derivative of the dependent variable.
- $\text{user\_data}$ is a pointer to user data, the same as the $\text{user\_data}$ parameter passed to IDASetUserData.

**Return value**  
An IDABBDCommFn function type should return 0 to indicate success, 1 for a recoverable error, or -1 for a non-recoverable error.

**Notes**  
The $G_{\text{comm}}$ function is expected to save communicated data in space defined within the structure $\text{user\_data}$.

Each call to the $G_{\text{comm}}$ function is preceded by a call to the residual function $res$ with the same ($tt$, $yy$, $yp$) arguments. Thus $G_{\text{comm}}$ can omit any communications done by $res$ if relevant to the evaluation of $G_{\text{res}}$. If all necessary communication was done in $res$, then $G_{\text{comm}} = \text{NULL}$ can be passed in the call to IDABBDPrecInit (see below).

Besides the header files required for the integration of the DAE problem (see §4.3), to use the IDABBDPRE module, the main program must include the header file ida\_bbdpre.h which declares the needed function prototypes.

The following is a summary of the usage of this module and describes the sequence of calls in the user main program. Steps that are unchanged from the user main program presented in §4.4 are grayed-out.

1. Initialize MPI
2. Set problem dimensions etc.
3. Set vectors of initial values
4. Create IDA object
5. Initialize IDA solver
6. Specify integration tolerances

7. Create linear solver object
   When creating the iterative linear solver object, specify the use of left preconditioning (PRE_LEFT) as IDA only supports left preconditioning.

8. Set linear solver optional inputs

9. Attach linear solver module

10. Set optional inputs
    Note that the user should not overwrite the preconditioner setup function or solve function through calls to idIDASetPreconditioner optional input function.

11. Initialize the IDABBDPRE preconditioner module
    Specify the upper and lower bandwidths mudq, mldq and mukeep, mlkeep and call
    \[
    \text{flag} = \text{IDABBDPrecInit}(\text{ida\_mem}, \text{Nlocal}, \text{mudq}, \text{mldq}, \\
    \text{mukeep}, \text{mlkeep}, \text{dq\_rel\_yy}, \text{Gres}, \text{Gcomm});
    \]
    to allocate memory and initialize the internal preconditioner data. The last two arguments of IDABBDPrecInit are the two user-supplied functions described above.

12. Create nonlinear solver object

13. Attach nonlinear solver module

14. Set nonlinear solver optional inputs

15. Correct initial values

16. Specify rootfinding problem

17. Advance solution in time

18. Get optional outputs
    Additional optional outputs associated with IDABBDPRE are available by way of two routines described below, IDABBDPrecGetWorkSpace and IDABBDPrecGetNumGfnEvals.

19. Deallocate memory for solution vectors

20. Free solver memory

21. Free nonlinear solver memory

22. Free linear solver memory

23. Finalize MPI

The user-callable functions that initialize (step 11 above) or re-initialize the IDABBDPRE preconditioner module are described next.

**IDABBDPrecInit**

Call \[
\text{flag} = \text{IDABBDPrecInit}(\text{ida\_mem}, \text{Nlocal}, \text{mudq}, \text{mldq}, \\
\text{mukeep}, \text{mlkeep}, \text{dq\_rel\_yy}, \text{Gres}, \text{Gcomm});
\]

Description The function IDABBDPrecInit initializes and allocates (internal) memory for the IDABBDPRE preconditioner.
4.7 A parallel band-block-diagonal preconditioner module

Arguments

ida_mem (void *) pointer to the IDA memory block.

Nlocal (sunindextype) local vector dimension.

mudq (sunindextype) upper half-bandwidth to be used in the difference-quotient Jacobian approximation.

mldq (sunindextype) lower half-bandwidth to be used in the difference-quotient Jacobian approximation.

mukeep (sunindextype) upper half-bandwidth of the retained banded approximate Jacobian block.

mlkeep (sunindextype) lower half-bandwidth of the retained banded approximate Jacobian block.

dq_rel_yy (realtype) the relative increment in components of y used in the difference quotient approximations. The default is \( dq\_rel\_yy = \sqrt{\text{unit roundoff}} \), which can be specified by passing \( dq\_rel\_yy = 0.0 \).

Gres (IDABBDLocalFn) the C function which computes the local residual approximation \( G(t, y, \dot{y}) \).

Gcomm (IDABBDCommFn) the optional C function which performs all inter-process communication required for the computation of \( G(t, y, \dot{y}) \).

Return value

The return value flag (of type int) is one of

IDALS_SUCCESS The call to IDABBDPrecInit was successful.

IDALS_MEM_NULL The ida_mem pointer was NULL.

IDALS_MEM_FAIL A memory allocation request has failed.

IDALS_LMEM_NULL An IDALS linear solver memory was not attached.

IDALS_IILL_INPUT The supplied vector implementation was not compatible with the block band preconditioner.

Notes

If one of the half-bandwidths \( \text{mudq} \) or \( \text{mldq} \) to be used in the difference-quotient calculation of the approximate Jacobian is negative or exceeds the value \( N\text{local} - 1 \), it is replaced by 0 or \( N\text{local} - 1 \) accordingly.

The half-bandwidths \( \text{mudq} \) and \( \text{mldq} \) need not be the true half-bandwidths of the Jacobian of the local block of \( G \), when smaller values may provide a greater efficiency.

Also, the half-bandwidths \( \text{mukeep} \) and \( \text{mlkeep} \) of the retained banded approximate Jacobian block may be even smaller, to reduce storage and computation costs further.

For all four half-bandwidths, the values need not be the same on every processor.

The IDABBDPRE module also provides a reinitialization function to allow for a sequence of problems of the same size, with the same linear solver choice, provided there is no change in \( N\text{local} \), \( \text{mukeep} \), or \( \text{mlkeep} \). After solving one problem, and after calling IDAReInit to re-initialize IDA for a subsequent problem, a call to IDABBDPrecReInit can be made to change any of the following: the half-bandwidths \( \text{mudq} \) and \( \text{mldq} \) used in the difference-quotient Jacobian approximations, the relative increment \( dq\_rel\_yy \), or one of the user-supplied functions \( G\text{res} \) and \( G\text{comm} \). If there is a change in any of the linear solver inputs, an additional call to the “Set” routines provided by the SUNLINSOL module, and/or one or more of the corresponding IDASet*** functions, must also be made (in the proper order).

[**IDABBDPrecReInit**]

Call flag = IDABBDPrecReInit(ida_mem, mudq, mldq, dq_rel_yy);

Description The function IDABBDPrecReInit reinitializes the IDABBDPRE preconditioner.

Arguments

ida_mem (void *) pointer to the IDA memory block.

mudq (sunindextype) upper half-bandwidth to be used in the difference-quotient Jacobian approximation.
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mldq  (sunindextype) lower half-bandwidth to be used in the difference-quotient Jacobian approximation.

dq_rel_yy (realtype) the relative increment in components of y used in the difference quotient approximations. The default is dq_rel_yy = √unit roundoff, which can be specified by passing dq_rel_yy = 0.0.

Return value The return value flag (of type int) is one of

| IDALS_SUCCESS | The call to IDABBDPRecReInit was successful. |
| IDALS_MEM_NULL | The ida_mem pointer was NULL. |
| IDALS_LMEM_NULL | An IDALS linear solver memory was not attached. |
| IDALS_PMEM_NULL | The function IDABBDPRecInit was not previously called. |

Notes If one of the half-bandwidths mudq or mldq is negative or exceeds the value Nlocal − 1, it is replaced by 0 or Nlocal − 1, accordingly.

The following two optional output functions are available for use with the IDABBDPRE module:

### IDABBDPrecGetWorkSpace

**Call**

flag = IDABBDPrecGetWorkSpace(ida_mem, &lenrwBBDP, &leniwBBDP);

**Description**
The function IDABBDPrecGetWorkSpace returns the local sizes of the IDABBDPRE real and integer workspaces.

**Arguments**

- ida_mem (void *) pointer to the IDA memory block.
- lenrwBBDP (long int) local number of real values in the IDABBDPRE workspace.
- leniwBBDP (long int) local number of integer values in the IDABBDPRE workspace.

**Return value**
The return value flag (of type int) is one of

| IDALS_SUCCESS | The optional output value has been successfully set. |
| IDALS_MEM_NULL | The ida_mem pointer was NULL. |
| IDALS_PMEM_NULL | The IDABBDPRE preconditioner has not been initialized. |

**Notes**
The workspace requirements reported by this routine correspond only to memory allocated within the IDABBDPRE module (the banded matrix approximation, banded SUNLINSOL object, temporary vectors). These values are local to each process.
The workspaces referred to here exist in addition to those given by the corresponding function IDAGetLinWorkSpace.

### IDABBDPrecGetNumGfnEvals

**Call**

flag = IDABBDPrecGetNumGfnEvals(ida_mem, &ngevalsBBDP);

**Description**
The function IDABBDPrecGetNumGfnEvals returns the cumulative number of calls to the user Gres function due to the finite difference approximation of the Jacobian blocks used within IDABBDPRE’s preconditioner setup function.

**Arguments**

- ida_mem (void *) pointer to the IDA memory block.
- ngevalsBBDP (long int) the cumulative number of calls to the user Gres function.

**Return value**
The return value flag (of type int) is one of

| IDALS_SUCCESS | The optional output value has been successfully set. |
| IDALS_MEM_NULL | The ida_mem pointer was NULL. |
| IDALS_PMEM_NULL | The IDABBDPRE preconditioner has not been initialized. |

In addition to the ngevalsBBDP Gres evaluations, the costs associated with IDABBDPRE also include nlinsetups LU factorizations, nlinsetups calls to Gcomm, npsolves banded backsolve calls, and nrevalsLS residual function evaluations, where nlinsetups is an optional IDA output (see §4.5.10.2), and npsolves and nrevalsLS are linear solver optional outputs (see §4.5.10.5).
Chapter 5

Using IDA for Fortran Applications

A Fortran 2003 module (fida.mod) as well as a Fortran 77 style interface (FIDA) are provided to support the use of IDA, for the solution of DAE systems in a mixed Fortran/C setting. While IDA is written in C, it is assumed here that the user’s calling program and user-supplied problem-defining routines are written in Fortran.

5.1 IDA Fortran 2003 Interface Module

The fida.mod Fortran module defines interfaces to most IDA C functions using the intrinsic iso_c_binding module which provides a standardized mechanism for interoperating with C. All interfaced functions are named after the corresponding C function, but with a leading ‘F’. For example, the IDA function IDACreate is interfaced as FIDACreate. Thus, the steps to use IDA and the function calls in Fortran 2003 are identical (ignoring language differences) to those in C. The C functions with Fortran 2003 interfaces indicate this in their description in Chapter 4. The Fortran 2003 IDA interface module can be accessed by the use statement, i.e. use fida.mod, and linking to the library libsundials_fida_mod.lib in addition to libsunслиals_ida.lib.

The Fortran 2003 interface modules were generated with SWIG Fortran, a fork of SWIG [31]. Users who are interested in the SWIG code used in the generation process should contact the SUNDIALS development team.

5.1.1 SUNDIALS Fortran 2003 Interface Modules

All of the generic SUNDIALS modules provide Fortran 2003 interface modules. Many of the generic module implementations provide Fortran 2003 interfaces (a complete list of modules with Fortran 2003 interfaces is given in Table 5.1). A module can be accessed with the use statement, e.g. use fnvector_openmp_mod, and linking to the Fortran 2003 library in addition to the C library, e.g. libsunслиals_fnvecopenmp_mod.lib and libsunслиals_nvecopenmp.lib.

The Fortran 2003 interfaces leverage the iso_c_binding module and the bind(C) attribute to closely follow the SUNDIALS C API (ignoring language differences). The generic SUNDIALS structures, e.g. N_Vector, are interfaced as Fortran derived types, and function signatures are matched but with an F prepending the name, e.g. FN_VConst instead of N_VConst. Constants are named exactly as they are in the C API. Accordingly, using SUNDIALS via the Fortran 2003 interfaces looks just like using it in C. Some caveats stemming from the language differences are discussed in the section 5.1.3. A discussion on the topic of equivalent data types in C and Fortran 2003 is presented in section 5.1.2.

Further information on the Fortran 2003 interfaces specific to modules is given in the NVECTOR, SUNMATRIX, SUNLINSOL, and SUNNONLINSOL alongside the C documentation (chapters 6, 7, 8, and 9 respectively). For details on where the Fortran 2003 module (.mod) files and libraries are installed see Appendix A.
Table 5.1: Summary of Fortran 2003 interfaces for shared SUNDIALS modules.

<table>
<thead>
<tr>
<th>Module</th>
<th>Fortran 2003 Module Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>NVECTOR</td>
<td>fsundials_nvector_mod</td>
</tr>
<tr>
<td>NVECTOR_SERIAL</td>
<td>fnvector_serial_mod</td>
</tr>
<tr>
<td>NVECTOR_PARALLEL</td>
<td>fnvector_parallel_mod</td>
</tr>
<tr>
<td>NVECTOR_OPENMP</td>
<td>fnvector_openmp_mod</td>
</tr>
<tr>
<td>NVECTOR_PTHREADS</td>
<td>fnvector_pthreads_mod</td>
</tr>
<tr>
<td>NVECTOR_PARHYPERP</td>
<td>Not interfaced</td>
</tr>
<tr>
<td>NVECTOR_PETSC</td>
<td>Not interfaced</td>
</tr>
<tr>
<td>NVECTOR_CUDA</td>
<td>Not interfaced</td>
</tr>
<tr>
<td>NVECTOR_RAJA</td>
<td>Not interfaced</td>
</tr>
<tr>
<td>NVECTOR_MANYVECTOR</td>
<td>fnvector_manyvector_mod</td>
</tr>
<tr>
<td>NVECTOR_MPIPLUSX</td>
<td>fnvector_mpiplusx_mod</td>
</tr>
<tr>
<td>SUNMatrix</td>
<td>fsundials_matrix_mod</td>
</tr>
<tr>
<td>SUNMATRIX_BAND</td>
<td>fsunmatrix_band_mod</td>
</tr>
<tr>
<td>SUNMATRIX_DENSE</td>
<td>fsunmatrix_dense_mod</td>
</tr>
<tr>
<td>SUNMATRIX_SPARSE</td>
<td>fsunmatrix_sparse_mod</td>
</tr>
<tr>
<td>SUNLinearSolver</td>
<td>fsundials_linearsolver_mod</td>
</tr>
<tr>
<td>SUNLINSOL_BAND</td>
<td>fsunlinsol_band_mod</td>
</tr>
<tr>
<td>SUNLINSOL_DENSE</td>
<td>fsunlinsol_dense_mod</td>
</tr>
<tr>
<td>SUNLINSOL_LAPACKBAND</td>
<td>Not interfaced</td>
</tr>
<tr>
<td>SUNLINSOL_LAPACKDENSE</td>
<td>Not interfaced</td>
</tr>
<tr>
<td>SUNLINSOL_KLU</td>
<td>fsunlinsol_klu_mod</td>
</tr>
<tr>
<td>SUNLINSOL_SUPERLU_MT</td>
<td>Not interfaced</td>
</tr>
<tr>
<td>SUNLINSOL_SUPERLUDIST</td>
<td>Not interfaced</td>
</tr>
<tr>
<td>SUNLINSOL_SPGMR</td>
<td>fsunlinsol_spgmr_mod</td>
</tr>
<tr>
<td>SUNLINSOL_SPFGRMR</td>
<td>fsunlinsol_spgmr_mod</td>
</tr>
<tr>
<td>SUNLINSOL_SPBCGS</td>
<td>fsunlinsol_spbcgs_mod</td>
</tr>
<tr>
<td>SUNLINSOL_SPTFQMR</td>
<td>fsunlinsol_sptfqmr_mod</td>
</tr>
<tr>
<td>SUNLINSOL_PCG</td>
<td>fsunlinsol_pcg_mod</td>
</tr>
<tr>
<td>SUNNonlinearSolver</td>
<td>fsundials_nonlinearsolver_mod</td>
</tr>
<tr>
<td>SUNLINSOL_NONLINEAR</td>
<td>fsunlinsol_nonlinear_mod</td>
</tr>
<tr>
<td>SUNLINSOL_FIXEDPOINT</td>
<td>fsunlinsol_fixedpoint_mod</td>
</tr>
</tbody>
</table>

5.1.2 Data Types

Generally, the Fortran 2003 type that is equivalent to the C type is what one would expect. Primitive types map to the iso_c_binding type equivalent. SUNDIALS generic types map to a Fortran derived type. However, the handling of pointer types is not always clear as they can depend on the parameter direction. Table 5.2 presents a summary of the type equivalencies with the parameter direction in mind.

Currently, the Fortran 2003 interfaces are only compatible with SUNDIALS builds where the realtype is double precision and the sunindextype size is 64-bits.

5.1.3 Notable Fortran/C usage differences

While the Fortran 2003 interface to SUNDIALS closely follows the C API, some differences are inevitable due to the differences between Fortran and C. In this section, we note the most critical differences. Additionally, section 5.1.2 discusses equivalencies of data types in the two languages.
Table 5.2: C/Fortran 2003 Equivalent Types

<table>
<thead>
<tr>
<th>C type</th>
<th>Parameter Direction</th>
<th>Fortran 2003 type</th>
</tr>
</thead>
<tbody>
<tr>
<td>double</td>
<td>in, inout, out, return</td>
<td>real(c_double)</td>
</tr>
<tr>
<td>int</td>
<td>in, inout, out, return</td>
<td>integer(c_int)</td>
</tr>
<tr>
<td>long</td>
<td>in, inout, out, return</td>
<td>integer(c_long)</td>
</tr>
<tr>
<td>booleantype</td>
<td>in, inout, out, return</td>
<td>integer(c_int)</td>
</tr>
<tr>
<td>realtype</td>
<td>in, inout, out, return</td>
<td>real(c_double)</td>
</tr>
<tr>
<td>sunindextype</td>
<td>in, inout, out, return</td>
<td>integer(c_long)</td>
</tr>
<tr>
<td>double*</td>
<td>in, inout, out</td>
<td>real(c_double), dimension(*)</td>
</tr>
<tr>
<td>double*</td>
<td>return</td>
<td>real(c_double), pointer, dimension(*)</td>
</tr>
<tr>
<td>int*</td>
<td>in, inout, out</td>
<td>integer(c_int), dimension(*)</td>
</tr>
<tr>
<td>int*</td>
<td>return</td>
<td>integer(c_int), pointer, dimension(*)</td>
</tr>
<tr>
<td>long*</td>
<td>in, inout, out</td>
<td>integer(c_long), dimension(*)</td>
</tr>
<tr>
<td>long*</td>
<td>return</td>
<td>integer(c_long), pointer, dimension(*)</td>
</tr>
<tr>
<td>realtype*</td>
<td>in, inout, out</td>
<td>real(c_double), pointer, dimension(*)</td>
</tr>
<tr>
<td>realtype*</td>
<td>return</td>
<td>real(c_double), pointer, dimension(*)</td>
</tr>
<tr>
<td>sunindextype*</td>
<td>in, inout, out</td>
<td>integer(c_long), dimension(*)</td>
</tr>
<tr>
<td>sunindextype*</td>
<td>return</td>
<td>integer(c_long), pointer, dimension(*)</td>
</tr>
<tr>
<td>realtype[]</td>
<td>in, inout, out</td>
<td>integer(c_long), dimension(*)</td>
</tr>
<tr>
<td>sunindextype[]</td>
<td>in, inout, out</td>
<td>integer(c_long), dimension(*)</td>
</tr>
<tr>
<td>N_Vector</td>
<td>in, inout, out</td>
<td>type(N_Vector)</td>
</tr>
<tr>
<td>N_Vector</td>
<td>return</td>
<td>type(N_Vector), pointer</td>
</tr>
<tr>
<td>SUNMatrix</td>
<td>in, inout, out</td>
<td>type(SUNMatrix)</td>
</tr>
<tr>
<td>SUNMatrix</td>
<td>return</td>
<td>type(SUNMatrix), pointer</td>
</tr>
<tr>
<td>SUNLinearSolver</td>
<td>in, inout, out</td>
<td>type(SUNLinearSolver)</td>
</tr>
<tr>
<td>SUNLinearSolver</td>
<td>return</td>
<td>type(SUNLinearSolver), pointer</td>
</tr>
<tr>
<td>SUNNonlinearSolver</td>
<td>in, inout, out</td>
<td>type(SUNNonlinearSolver)</td>
</tr>
<tr>
<td>SUNNonlinearSolver</td>
<td>return</td>
<td>type(SUNNonlinearSolver), pointer</td>
</tr>
<tr>
<td>FILE*</td>
<td>in, inout, out, return</td>
<td>type(c_ptr)</td>
</tr>
<tr>
<td>void*</td>
<td>in, inout, out, return</td>
<td>type(c_ptr)</td>
</tr>
<tr>
<td>T**</td>
<td>in, inout, out, return</td>
<td>type(c_ptr)</td>
</tr>
<tr>
<td>T***</td>
<td>in, inout, out, return</td>
<td>type(c_ptr)</td>
</tr>
<tr>
<td>T****</td>
<td>in, inout, out, return</td>
<td>type(c_ptr)</td>
</tr>
</tbody>
</table>

5.1.3.1 Creating generic SUNDEIALS objects

In the C API a generic SUNDEIALS object, such as an N_Vector, is actually a pointer to an underlying C struct. However, in the Fortran 2003 interface, the derived type is bound to the C struct, not the pointer to the struct. E.g., type(N_Vector) is bound to the C struct generic_N_Vector not the N_Vector type. The consequence of this is that creating and declaring SUNDEIALS objects in Fortran is nuanced. This is illustrated in the code snippets below:

**C code:**

```c
N_Vector x;
x = N_VNew_Serial(N);
```

**Fortran code:**

```fortran
type(N_Vector), pointer :: x
x => FN_VNew_Serial(N)
```

Note that in the Fortran declaration, the vector is a type(N_Vector), pointer, and that the pointer assignment operator is then used.
5.1.3.2 Arrays and pointers

Unlike in the C API, in the Fortran 2003 interface, arrays and pointers are treated differently when they are return values versus arguments to a function. Additionally, pointers which are meant to be out parameters, not arrays, in the C API must still be declared as a rank-1 array in Fortran. The reason for this is partially due to the Fortran 2003 standard for C bindings, and partially due to the tool used to generate the interfaces. Regardless, the code snippets below illustrate the differences.

C code:

```c
N_Vector x
realtype* xdata;
long int leniw, lenrw;

x = N_VNew_Serial(N);

/* capturing a returned array/pointer */
xdata = N_VGetArrayPointer(x)

/* passing array/pointer to a function */
N_VSetArrayPointer(xdata, x)

/* pointers that are out-parameters */
N_VSpace(x, &leniw, &lenrw);
```

Fortran code:

```fortran
type(N_Vector), pointer :: x
real(c_double), pointer :: xdataptr(:)
real(c_double) :: xdata(N)
integer(c_long) :: leniw(1), lenrw(1)

x => FN_VNew_Serial(x)

! capturing a returned array/pointer
xdataptr => FN_VGetArrayPointer(x)

! passing array/pointer to a function
call FN_VSetArrayPointer(xdata, x)

! pointers that are out-parameters
call FN_VSpace(x, leniw, lenrw)
```

5.1.3.3 Passing procedure pointers and user data

Since functions/subroutines passed to sundials will be called from within C code, the Fortran procedure must have the attribute bind(C). Additionally, when providing them as arguments to a Fortran 2003 interface routine, it is required to convert a procedure's Fortran address to C with the Fortran intrinsic c_funloc.

Typically when passing user data to a sundials function, a user may simply cast some custom data structure as a void*. When using the Fortran 2003 interfaces, the same thing can be achieved. Note, the custom data structure does not have to be bind(C) since it is never accessed on the C side.

C code:

```c
MyUserData* udata;
```
void *cvode_mem;

ierr = CVodeSetUserData(cvode_mem, udata);

Fortran code:

type(MyUserData) :: udata

type(c_ptr) :: cvode_mem

ierr = FCVodeSetUserData(cvode_mem, c_loc(udata))

On the other hand, Fortran users may instead choose to store problem-specific data, e.g. problem parameters, within modules, and thus do not need the SUNDIALS-provided user_data pointers to pass such data back to user-supplied functions. These users should supply the c_null_ptr input for user_data arguments to the relevant SUNDIALS functions.

5.1.3.4 Passing NULL to optional parameters

In the SUNDIALS C API some functions have optional parameters that a caller can pass NULL to. If the optional parameter is of a type that is equivalent to a Fortran type(c_ptr) (see section 5.1.2), then a Fortran user can pass the intrinsic c_null_ptr. However, if the optional parameter is of a type that is not equivalent to type(c_ptr), then a caller must provide a Fortran pointer that is dissociated. This is demonstrated in the code example below.

C code:

SUNLinearSolver LS;
N_Vector x, b;

! SUNLinSolSolve expects a SUNMatrix or NULL
! as the second parameter.
ierr = SUNLinSolSolve(LS, NULL, x, b);

Fortran code:

type(SUNLinearSolver), pointer :: LS

type(SUNMatrix), pointer :: A

type(N_Vector), pointer :: x, b

A => null()

! SUNLinSolSolve expects a type(SUNMatrix), pointer
! as the second parameter. Therefore, we cannot
! pass a c_null_ptr, rather we pass a disassociated A.
ierr = FSUNLinSolSolve(LS, A, x, b)

5.1.3.5 Working with N_Vector arrays

Arrays of N_Vector objects are interfaced to Fortran 2003 as opaque type(c_ptr). As such, it is not possible to directly index an array of N_Vector objects returned by the N_Vector “VectorArray” operations, or packages with sensitivity capabilities. Instead, SUNDIALS provides a utility function FN_VGetVecAtIndexVectorArray that can be called for accessing a vector in a vector array. The example below demonstrates this:

C code:
N_Vector x;
N_Vector* vecs;

vecs = N_VCloneVectorArray(count, x);
for (int i=0; i < count; ++i)
    N_VConst(vecs[i]);

Fortran code:

type(N_Vector), pointer :: x, xi
type(c_ptr) :: vecs

vecs = FN_VCloneVectorArray(count, x)
do index, count
    xi => FN_VGetVecAtIndexVectorArray(vecs, index)
    call FN_VConst(xi)
endo

SUNDIALS also provides the functions FN_VSetVecAtIndexVectorArray and FN_VNewVectorArray for working with N_Vector arrays. These functions are particularly useful for users of the Fortran interface to the NVVECTOR_MANYVECTOR or NVVECTOR_MPI_MANYVECTOR when creating the subvector array. Both of these functions along with FN_VGetVecAtIndexVectorArray are further described in Chapter 6.1.5.

5.1.3.6 Providing file pointers

Expert SUNDIALS users may notice that there are a few advanced functions in the SUNDIALS C API that take a FILE * argument. Since there is no portable way to convert between a Fortran file descriptor and a C file pointer, SUNDIALS provides two utility functions for creating a FILE * and destroying it. These functions are defined in the module fsundials_futils_mod.

FSUNDIALSFileOpen

Call fp = FSUNDIALSFileOpen(filename, mode)

Description The function allocates a FILE * by calling the C function fopen.

Arguments

filename (character(kind=C_CHAR, len=*)) - the path to the file to open
mode (character(kind=C_CHAR, len=*)) - the mode string given to fopen It should begin with one of the following characters:
    "r" - open text file for reading
    "r+" - open text file for reading and writing
    "w" - truncate text file to zero length or create it for writing
    "w+" - open text file for reading or writing, create it if it does not exist
    "a" - open for appending, see documentation of "fopen" for your system/compiler
    "a+" - open for reading and appending, see documentation for "fopen" for your system/compiler

Return value This returns a type(C_PTR) which is a FILE* in C. If it is NULL, then there was an error opening the file.
5.2 FIDA, an Interface Module for FORTRAN Applications

The fida interface module is a package of C functions which support the use of the ida solver, for the solution of DAE systems, in a mixed FORTRAN/C setting. While ida is written in C, it is assumed here that the user’s calling program and user-supplied problem-defining routines are written in FORTRAN. This package provides the necessary interface to ida for all supplied serial and parallel nvector implementations.

5.3 Important note on portability

In this package, the names of the interface functions, and the names of the FORTRAN user routines called by them, appear as dummy names which are mapped to actual values by a series of definitions in the header files. By default, those mapping definitions depend in turn on the C macro F77_FUNC defined in the header file sundials_config.h. The mapping defined by F77_FUNC in turn transforms the C interface names to match the name-mangling approach used by the supplied Fortran compiler.

By “name-mangling”, we mean that due to the case-independent nature of the FORTRAN language, FORTRAN compilers convert all subroutine and object names to use either all lower-case or all upper-case characters, and append either zero, one or two underscores as a prefix or suffix to the name. For example, the FORTRAN subroutine MyFunction() will be changed to one of myfunction, MYFUNCTION, myfunction_, MYFUNCTION_, and so on, depending on the FORTRAN compiler used.

SUNDIALS determines this name-mangling scheme at configuration time (see Appendix A).

5.4 Fortran Data Types

Throughout this documentation, we will refer to data types according to their usage in C. The equivalent types to these may vary, depending on your computer architecture and on how SUNDIALS was compiled (see Appendix A). A FORTRAN user should first determine the equivalent types for their architecture and compiler, and then take care that all arguments passed through this FORTRAN/C interface are declared of the appropriate type.

**Integers:** While SUNDIALS uses the configurable sunindextype type as the integer type for vector and matrix indices for its C code, the FORTRAN interfaces are more restricted. The sunindextype is only used for index values and pointers when filling sparse matrices. As for C, the sunindextype can be configured to be a 32- or 64-bit signed integer by setting the variable SUNDIALS_INDEX_TYPE at compile time (See Appendix A). The default value is int64_t. A FORTRAN user should set this variable based on the integer type used for vector and matrix indices in their FORTRAN code. The corresponding FORTRAN types are:
• int32_t – equivalent to an INTEGER or INTEGER*4 in FORTRAN
• int64_t – equivalent to an INTEGER*8 in FORTRAN

In general, for the FORTRAN interfaces in SUNDIALS, flags of type int, vector and matrix lengths, counters, and arguments to *SETIN() functions all have long int type, and sunindextype is only used for index values and pointers when filling sparse matrices. Note that if an F90 (or higher) user wants to find out the value of sunindextype, they can include sundials_fconfig.h.

Real numbers: As discussed in Appendix A, at compilation SUNDIALS allows the configuration option SUNDIALS_PRECISION, that accepts values of single, double or extended (the default is double). This choice dictates the size of a realtype variable. The corresponding FORTRAN types for these realtype sizes are:
• single – equivalent to a REAL or REAL*4 in FORTRAN
• double – equivalent to a DOUBLE PRECISION or REAL*8 in FORTRAN
• extended – equivalent to a REAL*16 in FORTRAN

5.4.1 FIDA routines
The user-callable functions, with the corresponding IDA functions, are as follows:
• Interface to the nvector modules
  – FNVINITS (defined by NVECTOR_SERIAL) interfaces to N_VNewEmpty_Serial.
  – FNVINITP (defined by NVECTOR_PARALLEL) interfaces to N_VNewEmpty_Parallel.
  – FNVINITOMP (defined by NVECTOR_OPENMP) interfaces to N_VNewEmpty_OpenMP.
  – FNVINITPTS (defined by NVECTOR_PTHREADS) interfaces to N_VNewEmpty_Pthreads.
• Interface to the sunmatrix modules
  – FSUNBANDMATINIT (defined by SUNMATRIX_BAND) interfaces to SUNBandMatrix.
  – FSUNDENSEMATINIT (defined by SUNMATRIX_DENSE) interfaces to SUNDenseMatrix.
  – FSUNSPARSEMATINIT (defined by SUNMATRIX_SPARSE) interfaces to SUNSparseMatrix.
• Interface to the sunlinsol modules
  – FSUNBANDLINSOLINIT (defined by SUNLINSOL_BAND) interfaces to SUNLinSol_Band.
  – FSUNDENSELINSOLINIT (defined by SUNLINSOL_DENSE) interfaces to SUNLinSol_Dense.
  – FSUNKLUINIT (defined by SUNLINSOL_KLU) interfaces to SUNLinSol_KLU.
  – FSUNKLUREINIT (defined by SUNLINSOL_KLU) interfaces to SUNLinSol_KLUReinit.
  – FSUNLAPACKBANDINIT (defined by SUNLINSOL_LAPACKBAND) interfaces to SUNLinSol_LapackBand.
  – FSUNLAPACKDENSEINIT (defined by SUNLINSOL_LAPACKDENSE) interfaces to SUNLinSol_LapackDense.
  – FSUNPCGINIT (defined by SUNLINSOL_PCG) interfaces to SUNLinSol_PCG.
  – FSUNSPBCGSINIT (defined by SUNLINSOL_SPBCGS) interfaces to SUNLinSol_SPBCGS.
  – FSUNSPFGMRINIT (defined by SUNLINSOL_SPFGMR) interfaces to SUNLinSol_SPFGMR.
  – FSUNSPGMRINIT (defined by SUNLINSOL_SPGMR) interfaces to SUNLinSol_SPGMR.
  – FSUNSPTFQMRINIT (defined by SUNLINSOL_SPTFQMR) interfaces to SUNLinSol_SPTFQMR.
  – FSUNSUPERLUMTINIT (defined by SUNLINSOL_SUPERLUMT) interfaces to SUNLinSol_SuperLUMT.
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- Interface to the main IDA module
  - FIDAMALLOC interfaces to IDACreate, IDASSetUserData, IDAInit, IDASStolerances, and IDASVtolerances.
  - FIDAREINIT interfaces to IDAREInit and IDASStolerances/IDASVtolerances.
  - FIDASETII, FIDASETVIN, and FIDASETTRIN interface to IDASet* functions.
  - FIDATOLREINIT interfaces to IDASStolerances/IDASVtolerances.
  - FIDACALCIC interfaces to IDACalcIC.
  - FIDAEWTSET interfaces to IDAWFtolerances.
  - FIDASOLVE interfaces to IDASolve, IDASolver, and to the optional output functions for the selected linear solver module.
  - FIDAGETDKY interfaces to IDAGetDky.
  - FIDAGETERRWEIGHTS interfaces to IDAGetErrWeights.
  - FIDAGETESTLOCALERR interfaces to IDAGetEstLocalErrors.
  - FIDAFREE interfaces to IDAFree.

- Interface to the IDALS module
  - FIDALSINIT interfaces to IDASSetLinearSolver.
  - FIDALSSETEPSLIN interfaces to IDASSetEpsLin
  - FIDALSSETJAC interfaces to IDASSetJacTimes.
  - FIDALSSETPREC interfaces to IDASSetPreconditioner.
  - FIDADENSESETJAC interfaces to IDASSetJacFn.
  - FIDABANDSETJAC interfaces to IDASSetJacFn.
  - FIDASPARSESETJAC interfaces to IDASSetJacFn.

The user-supplied functions, each listed with the corresponding internal interface function which calls it (and its type within IDA), are as follows:

<table>
<thead>
<tr>
<th>FIDA routine (Fortran, user-supplied)</th>
<th>IDA function (C, interface)</th>
<th>IDA type of interface function</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIDARESFUN</td>
<td>FIDaresfn</td>
<td>IDAResFn</td>
</tr>
<tr>
<td>FIDAEWT</td>
<td>FIDAEwtSet</td>
<td>IDAEwtFn</td>
</tr>
<tr>
<td>FIDADJAC</td>
<td>FIDADenseJac</td>
<td>IDALSJacFn</td>
</tr>
<tr>
<td>FIDABJAC</td>
<td>FIDABandJac</td>
<td>IDALSJacFn</td>
</tr>
<tr>
<td>FIDASPJAC</td>
<td>FIDASparseJac</td>
<td>IDALSJacFn</td>
</tr>
<tr>
<td>FIDAPSOl</td>
<td>FIDAPSol</td>
<td>IDALSPrecSolveFn</td>
</tr>
<tr>
<td>FIDAPSET</td>
<td>FIDAPSet</td>
<td>IDALSPrecSetupFn</td>
</tr>
<tr>
<td>FIDAJTIMES</td>
<td>FIDAjtimes</td>
<td>IDALSJacTimesVecFn</td>
</tr>
<tr>
<td>FIDAJTSETUP</td>
<td>FIDAJTSetup</td>
<td>IDALSJacTimesSetupFn</td>
</tr>
</tbody>
</table>

In contrast to the case of direct use of IDA, and of most Fortran DAE solvers, the names of all user-supplied routines here are fixed, in order to maximize portability for the resulting mixed-language program.
5.4.2 Usage of the FIDA interface module

The usage of FIDA requires calls to a variety of interface functions, depending on the method options selected, and one or more user-supplied routines which define the problem to be solved. These function calls and user routines are summarized separately below. Some details are omitted, and the user is referred to the description of the corresponding IDA functions for information on the arguments of any given user-callable interface routine, or of a given user-supplied function called by an interface function. The usage of FIDA for rootfinding, and usage of FIDA with preconditioner modules, are each described in later sections.

1. Residual function specification

   The user must, in all cases, supply the following FORTRAN routine

   ```fortran
   SUBROUTINE FIDARESFUN (T, Y, YP, R, IPAR, RPAR, IER)
   DIMENSION Y(*), YP(*), R(*), IPAR(*), RPAR(*)
   ...
   RETURN
   END
   ```

   It must set the R array to \( F(t, y, \dot{y}) \), the residual function of the DAE system, as a function of \( T = t \) and the arrays \( Y = y \) and \( YP = \dot{y} \). The arrays IPAR (of integers) and RPAR (of reals) contain user data and are the same as those passed to FIDAMALLOC. It should return IER = 0 if it was successful, IER = 1 if it had a recoverable failure, or IER = -1 if it had a non-recoverable failure.

2. NVECTOR module initialization

   If using one of the NVECTOR modules supplied with SUNDIALS, the user must make a call of the form

   ```fortran
   CALL FNVINIT***(...)
   ```

   in which the name and call sequence are as described in the appropriate section of Chapter 6.

3. SUNMATRIX module initialization

   In the case of a stiff system, the implicit BDF method involves the solution of linear systems related to the Jacobian of the DAE system. If using a Newton iteration with the direct SUNLINSOL linear solver module and one of the SUNMATRIX modules supplied with SUNDIALS, the user must make a call of the form

   ```fortran
   CALL FSUN***MATINIT(...)
   ```

   in which the name and call sequence are as described in the appropriate section of Chapter 7. Note that the dense, band, or sparse matrix options are usable only in a serial or multi-threaded environment.

4. SUNLINSOL module initialization

   If using a Newton iteration with one of the SUNLINSOL linear solver modules supplied with SUNDIALS, the user must make a call of the form

   ```fortran
   CALL FSUNBANDLINSOLINIT(...)  
   CALL FSUNDENSELINSOLINIT(...)  
   CALL FSUNKLUINIT(...)  
   CALL FSUNLAPACKBANDINIT(...)  
   CALL FSUNLAPACKDENSEINIT(...)  
   CALL FSUNPCGINIT(...)  
   CALL FSUNSPBCGSINIT(...)  
   CALL FSUNSPFGMRINIT(...)  
   CALL FSUNSPGMRINIT(...)  
   ```
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CALL FSUNSPTFQMRINIT(...)
CALL FSUNSUPERLUMTINIT(...)

in which the call sequence is as described in the appropriate section of Chapter 8. Note that the
dense, band, or sparse solvers are usable only in a serial or multi-threaded environment.

Once one of these solvers has been initialized, its solver parameters may be modified using a call
to the functions

CALL FSUNKLUSETORDERING(...)
CALL FSUNSUPERLUMTSETORDERING(...)
CALL FSUNPCGSETPRECTYPE(...)
CALL FSUNPCGSETMAXL(...)
CALL FSUNSPBCGSSETPRECTYPE(...)
CALL FSUNSPBCGSSETMAXL(...)
CALL FSUNSPFGMRSETGSTYPE(...)
CALL FSUNSPFGMRSETPRECTYPE(...) 
CALL FSUNSPTFQMRSETPRECTYPE(...) 
CALL FSUNSPTFQMRSETMAXL(...)

where again the call sequences are described in the appropriate sections of Chapter 8.

5. Problem specification

To set various problem and solution parameters and allocate internal memory, make the following
call:

FIDAMALLOC

Call
CALL FIDAMALLOC(T0, Y0, YPO, IATOL, RTOL, ATOL, 
&
   IOUT, ROUT, IPAR, RPAR, IER)

Description This function provides required problem and solution specifications, specifies op-
tional inputs, allocates internal memory, and initializes IDA.

Arguments
T0 is the initial value of \( t \).
Y0 is an array of initial conditions for \( y \).
YP0 is an array of initial conditions for \( \dot{y} \).
IATOL specifies the type for absolute tolerance \( ATOL \): 1 for scalar or 2 for array. If 
IATOL= 3, the arguments RTOL and ATOL are ignored and the user is expected 
to subsequently call FIDAECTSET and provide the function FIDAECT.
RTOL is the relative tolerance (scalar).
ATOL is the absolute tolerance (scalar or array).
IOUT is an integer array of length at least 21 for integer optional outputs.
ROUT is a real array of length at least 6 for real optional outputs.
IPAR is an integer array of user data which will be passed unmodified to all user-provided routines.
RPAR is a real array of user data which will be passed unmodified to all user-provided routines.

Return value IER is a return completion flag. Values are 0 for successful return and \(-1\) otherwise. 
See printed message for details in case of failure.

Notes The user integer data arrays IOUT and IPAR must be declared as \texttt{INTEGER*4} or \texttt{INTEGER*8} according to the C type \texttt{long int}.
Modifications to the user data arrays IPAR and RPAR inside a user-provided routine 
will be propagated to all subsequent calls to such routines.
The optional outputs associated with the main IDA integrator are listed in Table 5.4.

As an alternative to providing tolerances in the call to FIDAMALLOC, the user may provide a routine to compute the error weights used in the WRMS norm evaluations. If supplied, it must have the following form:

```fortran
SUBROUTINE FIDAETW (Y, EWT, IPAR, RPAR, IER)
  DIMENSION Y(*), EWT(*), IPAR(*), RPAR(*)
```

It must set the positive components of the error weight vector EWT for the calculation of the WRMS norm of Y. On return, set IER = 0 if FIDAETW was successful, and nonzero otherwise. The arrays IPAR (of integers) and RPAR (of reals) contain user data and are the same as those passed to FIDAMALLOC.

If the FIDAETW routine is provided, then, following the call to FIDAMALLOC, the user must make the call:

```fortran
CALL FIDAETWSET (FLAG, IER)
```

with FLAG ≠ 0 to specify use of the user-supplied error weight routine. The argument IER is an error return flag, which is 0 for success or non-zero if an error occurred.

6. Set optional inputs

Call FIDASETIN, FIDASETTRIN, and/or FIDASETVIN to set desired optional inputs, if any. See §5.5 for details.

7. Linear solver interface specification

The variable-order, variable-coefficient BDF method used by IDA involves the solution of linear systems related to the system Jacobian $J = \partial F/\partial y + \alpha \partial F/\partial \dot{y}$. See Eq. (2.4). To attach the linear solver (and optionally the matrix) objects initialized in steps 3 and 4 above, the user of IDA must initialize the IDALS linear solver interface. To attach any SUNLINSOL object (and optional SUNMATRIX object) to IDA, then following calls to initialize the SUNLINSOL (and SUNMATRIX) object(s) in steps 3 and 4 above, the user must make the call:

```fortran
CALL FIDALSINIT(IER)
```

IER is an error return flag set on 0 on success or −1 if a memory failure occurred.

The previous routines FIDADLSINIT and FIDASPINLSINIT are now wrappers for this routine, and may still be used for backward-compatibility. However, these will be deprecated in future releases, so we recommend that users transition to the new routine name soon.

IDALS with dense Jacobian matrix

As an option when using the IDALS interface with the SUNLINSOL_DENSE or SUNLINSOL_LAPACKDENSE linear solvers, the user may supply a routine that computes a dense approximation of the system Jacobian $J$. If supplied, it must have the following form:

```fortran
SUBROUTINE FIDADJAC (NEQ, T, Y, YP, R, DJAC, CJ, EWT, H,
  & IPAR, RPAR, WK1, WK2, WK3, IER)
  DIMENSION Y(*), YP(*), R(*), EWT(*), DJAC(NEQ,*),
  & IPAR(*), RPAR(*), WK1(*), WK2(*), WK3(*)
```

This routine must compute the Jacobian and store it columnwise in DJAC. The vectors WK1, WK2, and WK3 of length NEQ are provided as work space for use in FIDADJAC. The input arguments T, Y, YP, R, and CJ are the current values of $t$, $y$, $\dot{y}$, $F(t, y, \dot{y})$, and $\alpha$, respectively. The arrays IPAR (of
5.4 Fortran Data Types

integers) and RPAR (of reals) contain user data and are the same as those passed to FIDAMALLOC. 

NOTE: The argument NEQ has a type consistent with C type `long int` even in the case when the LAPACK dense solver is to be used.

If the user’s FIDADJAC uses difference quotient approximations, it may need to use the error weight array EWT and current stepsize H in the calculation of suitable increments. It may also need the unit roundoff, which can be obtained as the optional output ROUT(6), passed from the calling program to this routine using COMMON.

If the FIDADJAC routine is provided, then, following the call to FIDALSINIT the user must make the call:

```
CALL FIDADENSESETJAC (FLAG, IER)
```

with FLAG ≠ 0 to specify use of the user-supplied Jacobian approximation. The argument IER is an error return flag, which is 0 for success or non-zero if an error occurred.

**idals with band Jacobian matrix**

As an option when using the idals interface with the SUNLINSOL_BAND or SUNLINSOL_LAPACK_BAND linear solvers, the user may supply a routine that computes a band approximation of the system Jacobian J. If supplied, it must have the following form:

```
SUBROUTINE FIDABJAC(NEQ, MU, ML, MDIM, T, Y, YP, R, CJ, Bjac,
& EWT, H, IPAR, RPAR, WK1, WK2, WK3, IER)
```

This routine must load the MDIM by NEQ array Bjac with the Jacobian matrix at the current (t, y, y) in band form. Store in Bjac(k, j) the Jacobian element J_{i,j} with k = i - j + MU + 1 (k = 1 \cdots ML + MU + 1) and j = 1 \cdots N. The vectors WK1, WK2, and WK3 of length NEQ are provided as work space for use in FIDABJAC. The input arguments T, Y, YP, and CJ are the current values of t, y, y, F(t, y, y), and α, respectively. The arrays IPAR (of integers) and RPAR (of reals) contain user data and are the same as those passed to FIDAMALLOC. NOTE: The arguments NEQ, MU, ML, and MDIM have a type consistent with C type `long int` even in the case when the LAPACK band solver is to be used.

If the user’s FIDABJAC uses difference quotient approximations, it may need to use the error weight array EWT and current stepsize H in the calculation of suitable increments. It may also need the unit roundoff, which can be obtained as the optional output ROUT(6), passed from the calling program to this routine using COMMON.

If the FIDABJAC routine is provided, then, following the call to FIDALSINIT, the user must make the call:

```
CALL FIDABANDSETJAC (FLAG, IER)
```

with FLAG ≠ 0 to specify use of the user-supplied Jacobian approximation. The argument IER is an error return flag, which is 0 for success or non-zero if an error occurred.

**idals with sparse Jacobian matrix**

When using the idals interface with the SUNLINSOL_KLU or SUNLINSOL_SUPERLUMT linear solvers, the user must supply the FIDASPJAC routine that computes a compressed-sparse-column (CSC) or compressed-sparse-row (CSR) approximation of the system Jacobian J = ∂F/∂y + c_j ∂F/∂y. If supplied, it must have the following form:

```
SUBROUTINE FIDASPJAC(T, CJ, Y, YP, R, N, NNZ, JDATA, JINDEXVALS,
& JINDEXPTRS, H, IPAR, RPAR, WK1, WK2, WK3, IER)
```
It must load the \( N \) by \( N \) compressed sparse column [or compressed sparse row] matrix with storage for \( NNZ \) nonzeros, stored in the arrays \( JDATA \) (nonzero values), \( JINDEXVALS \) (row [or column] indices for each nonzero), \( JINDEXPTRS \) (indices for start of each column [or row]), with the Jacobian matrix at the current \((t,y)\) in CSC [or CSR] form (see \textit{sunmatrix\_sparse.h} for more information). The arguments are \( T \), the current time; \( CJ \), scalar in the system proportional to the inverse step size; \( Y \), an array containing state variables; \( YP \), an array containing state derivatives; \( R \), an array containing the system nonlinear residual; \( N \), the number of matrix rows/columns in the Jacobian; \( NNZ \), allocated length of nonzero storage; \( JDATA \), nonzero values in the Jacobian (of length \( NNZ \)); \( JINDEXVALS \), row [or column] indices for each nonzero in Jacobian (of length \( NNZ \)); \( JINDEXPTRS \), pointers to each Jacobian column [or row] in the two preceding arrays (of length \( N+1 \)); \( H \), the current step size; \( IPAR \), an array containing integer user data that was passed to \textit{FIDAMALLOC}; \( RPAR \), an array containing real user data that was passed to \textit{FIDAMALLOC}; \( WK* \), work arrays containing temporary workspace of same size as \( Y \); and \( IER \), error return code (0 if successful, > 0 if a recoverable error occurred, or < 0 if an unrecoverable error occurred.)

To indicate that the \texttt{FIDASPJAC} routine has been provided, then following the call to \texttt{FIDALSINIT}, the following call must be made

\begin{verbatim}
CALL FIDASPARSESETJAC (IER)
\end{verbatim}

The int return flag \( IER \) is an error return flag which is 0 for success or nonzero for an error.

\texttt{IDALS} with Jacobian-vector product

As an option when using the \texttt{IDALS} linear solver interface, the user may supply a routine that computes the product of the system Jacobian \( J = \partial F/\partial y + \alpha \partial F/\partial \dot{y} \) and a given vector \( v \). If supplied, it must have the following form:

\begin{verbatim}
SUBROUTINE FIDAJTIMES(T, Y, YP, R, V, FJV, CJ, EWT, H, & IPAR, RPAR, WK1, WK2, IER)
DIMENSION Y(*), YP(*), R(*), V(*), FJV(*), EWT(*), & IPAR(*), RPAR(*), WK1(*), WK2(*)
\end{verbatim}

This routine must compute the product vector \( Jv \), where the vector \( v \) is stored in \( V \), and store the product in \( FJV \). On return, set \( IER = 0 \) if \texttt{FIDAJTIMES} was successful, and nonzero otherwise. The vectors \( WK1 \) and \( WK2 \), of length \( NEQ \), are provided as work space for use in \texttt{FIDAJTIMES}. The input arguments \( T, Y, YP, R, \) and \( CJ \) are the current values of \( t, y, \dot{y}, F(t,y,\dot{y}), \) and \( \alpha \), respectively. The arrays \( IPAR \) (of integers) and \( RPAR \) (of reals) contain user data and are the same as those passed to \texttt{FIDAMALLOC}.

If the user’s \texttt{FIDAJTIMES} uses difference quotient approximations, it may need to use the error weight array \( EWT \) and current stepsize \( H \) in the calculation of suitable increments. It may also need the unit roundoff, which can be obtained as the optional output \texttt{ROUT(6)} , passed from the calling program to this routine using \texttt{COMMON}.

If the user’s Jacobian-times-vector product routine requires that any Jacobian related data be evaluated or preprocessed, then the following routine can be used for the evaluation and preprocessing of this data:

\begin{verbatim}
SUBROUTINE FIDAJTSETUP (T, Y, YP, R, CJ, EWT, H, IPAR, RPAR, IER)
DIMENSION Y(*), YP(*), R(*), EWT(*), IPAR(*), RPAR(*)
\end{verbatim}

Typically this routine will use only \( T, Y, \) and \texttt{IDAYP}. It should compute any necessary data for subsequent calls to \texttt{FIDAJTIMES}. On return, set \( IER = 0 \) if \texttt{FIDAJTSETUP} was successful, and nonzero otherwise. The arrays \( IPAR \) (of integers) and \( RPAR \) (of reals) contain user data and are the same as those passed to \texttt{FIDAMALLOC}.

To indicate that the \texttt{FIDAJTIMES} and \texttt{FIDAJTSETUP} routines have been provided, then following the call to \texttt{FIDALSINIT}, the following call must be made

\begin{verbatim}
CALL FIDASPARSESETJAC (IER)
\end{verbatim}
CALL FIDALSSETJAC (FLAG, IER)

with FLAG ≠ 0. The return flag IER is 0 if successful, or negative if a memory error occurred.

The previous routine FIDASPILSETJAC is now a wrapper for this routine, and may still be used for backward-compatibility. However, this will be deprecated in future releases, so we recommend that users transition to the new routine name soon.

If the user calls FIDALSSETJAC, the routine FIDAJTSETUP must be provided, even if it is not needed, and it must return IER=0.

**FIDALS with preconditioning**

If user-supplied preconditioning is to be performed, the following routine must be supplied for solution of the preconditioner linear system:

```fortran
SUBROUTINE FIDAPSOL(T, Y, YP, R, RV, ZV, CJ, DELTA, EWT,
                      & IPAR, RPAR, IER)
  DIMENSION Y(*), YP(*), R(*), RV(*), ZV(*), EWT(*),
                      & IPAR(*), RPAR(*)
```

It must solve the preconditioner linear system \( Pz = r \), where \( r = RV \) is input, and store the solution \( z \) in \( ZV \). Here \( P \) is the left preconditioner. The input arguments \( T, Y, YP, R, \text{ and } CJ \) are the current values of \( t, y, \dot{y}, F(t, y, \dot{y}), \text{ and } \alpha \), respectively. On return, set IER = 0 if FIDAPSOL was successful, set IER positive if a recoverable error occurred, and set IER negative if a non-recoverable error occurred.

The arguments EWT and DELTA are input and provide the error weight array and a scalar tolerance, respectively, for use by FIDAPSOL if it uses an iterative method in its solution. In that case, the residual vector \( \rho = r - Pz \) of the system should be made less than DELTA in weighted \( \ell_2 \) norm, i.e. \( \sqrt{\sum (\rho_i \ast EWT[i])^2} < \text{DELTA} \). The arrays IPAR (of integers) and RPAR (of reals) contain user data and are the same as those passed to FIDAMALLOC.

If the user’s preconditioner requires that any Jacobian-related data be evaluated or preprocessed, then the following routine is to be used for the evaluation and preprocessing of the preconditioner:

```fortran
SUBROUTINE FIDAPSET(T, Y, YP, R, CJ, EWT, H,
                      & IPAR, RPAR, IER)
  DIMENSION Y(*), YP(*), R(*), EWT(*),
                      & IPAR(*), RPAR(*)
```

It must perform any evaluation of Jacobian-related data and preprocessing needed for the solution of the preconditioner linear systems by FIDAPSOL. The input arguments \( T, Y, YP, R, \text{ and } CJ \) are the current values of \( t, y, \dot{y}, F(t, y, \dot{y}), \text{ and } \alpha \), respectively. On return, set IER = 0 if FIDAPSET was successful, set IER positive if a recoverable error occurred, and set IER negative if a non-recoverable error occurred. The arrays IPAR (of integers) and RPAR (of reals) contain user data and are the same as those passed to FIDAMALLOC.

If the user’s FIDAPSET uses difference quotient approximations, it may need to use the error weight array \( \text{EWT} \) and current stepsize \( H \) in the calculation of suitable increments. It may also need the unit roundoff, which can be obtained as the optional output ROUT(6), passed from the calling program to this routine using COMMON.

To indicate that the FIDAPSET and FIDAPSOL routines are supplied, then following the call to FIDALSINIT, the user must call

```fortran
CALL FIDALSSETPREC (FLAG, IER)
```
with \( \text{FLAG} \neq 0 \). The return flag \( \text{IER} \) is 0 if successful, or negative if a memory error occurred. In addition, the user must supply preconditioner routines \text{FIDAPSET} and \text{FIDAPSOl}.

The previous routine \text{FIDASPISELTPREC} is now a wrapper for this routine, and may still be used for backward-compatibility. However, this will be deprecated in future releases, so we recommend that users transition to the new routine name soon.

If the user calls \text{FIDALSSETPREC}, the subroutine \text{FIDAPSET} must be provided, even if it is not needed, and it must return \( \text{IER} = 0 \).

8. Correct initial values

Optionally, to correct the initial values \( y \) and/or \( \dot{y} \), make the call

\[
\text{CALL FIDACALCIC} \ (\text{ICOPT}, \text{TOUT1}, \text{IER})
\]

(See §2.1 for details.) The arguments are as follows: \( \text{ICOPT} \) is 1 for initializing the algebraic components of \( y \) and differential components of \( \dot{y} \), or 2 for initializing all of \( y \). \( \text{IER} \) is an error return flag, which is 0 for success, or negative for a failure (see \text{IDACalcIC} return values).

9. Problem solution

Carrying out the integration is accomplished by making calls as follows:

\[
\text{CALL FIDASOLVE} \ (\text{TOUT}, \text{T}, \text{Y}, \text{YP}, \text{ITASK}, \text{IER})
\]

The arguments are as follows. \( \text{TOUT} \) specifies the next value of \( t \) at which a solution is desired (input). \( \text{T} \) is the value of \( t \) reached by the solver on output. \( \text{Y} \) is an array containing the computed solution vector \( y \) on output. \( \text{YP} \) is an array containing the computed solution vector \( \dot{y} \) on output. \( \text{ITASK} \) is a task indicator and should be set to 1 for normal mode (overshoot \text{TOUT} and interpolate), or to 2 for one-step mode (return after each internal step taken). \( \text{IER} \) is a completion flag and will be set to a positive value upon successful return or to a negative value if an error occurred. These values correspond to the \text{IDASolve} returns (see §4.5.7 and §B.2). The current values of the optional outputs are available in \text{IOU}T and \text{ROU}T (see Table 5.4).

10. Additional solution output

After a successful return from \text{FIDASOLVE}, the routine \text{FIDAGETDKY} may be called to get interpolated values of \( y \) or any derivative \( \frac{d^k y}{dt^k} \) for \( k \) not exceeding the current method order, and for any value of \( t \) in the last internal step taken by \text{ida}. The call is as follows:

\[
\text{CALL FIDAGETDKY} \ (\text{T}, \text{K}, \text{DKY}, \text{IER})
\]

where \( \text{T} \) is the input value of \( t \) at which solution derivative is desired, \( \text{K} \) is the derivative order, and \( \text{DKY} \) is an array containing the computed vector \( y^{(K)}(t) \) on return. The value of \( \text{T} \) must lie between \( \text{TCUR} - \text{HLAST} \) and \( \text{TCUR} \). The value of \( \text{K} \) must satisfy \( 0 \leq \text{K} \leq \text{QLAST} \). (See the optional outputs for \text{TCUR}, \text{HLAST}, and \text{QLAST}.) The return flag \( \text{IER} \) is set to 0 upon successful return, or to a negative value to indicate an illegal input.

11. Problem reinitialization

To re-initialize the \text{ida} solver for the solution of a new problem of the same size as one already solved, make the following call:

\[
\text{CALL FIDAREINIT} \ (\text{TO}, \text{YO}, \text{YP0}, \text{IATOL}, \text{RTOL}, \text{ATOL}, \text{IER})
\]

The arguments have the same names and meanings as those of \text{FIDAMALLOC}. \text{FIDAREINIT} performs the same initializations as \text{FIDAMALLOC}, but does no memory allocation, using instead the existing internal memory created by the previous \text{FIDAMALLOC} call.
Following this call, if the choice of linear solver is being changed then a user must make a call to create the alternate SUNLINSOL module and then attach it to the IDALS interface, as shown above. If only linear solver parameters are being modified, then these calls may be made without re-attaching to the IDALS interface.

12. Memory deallocation

To free the internal memory created by the call to FIDAMALLOC, FIDALSINIT, FNVINIT* and FSUN***MATINIT, make the call

CALL FIDAFREE

5.5 FIDA optional input and output

In order to keep the number of user-callable FIDA interface routines to a minimum, optional inputs to the IDA solver are passed through only three routines: FIDASETIN for integer optional inputs, FIDASETрин for real optional inputs, and FIDASETVIN for real vector (array) optional inputs. These functions should be called as follows:

CALL FIDASETIN(KEY, IVAL, IER)
CALL FIDASETрин(KEY, RVAL, IER)
CALL FIDASETVIN(KEY, VVAL, IER)

where KEY is a quoted string indicating which optional input is set (see Table 5.3), IVAL is the input integer value, RVAL is the input real value (scalar), VVAL is the input real array, and IER is an integer return flag which is set to 0 on success and a negative value if a failure occurred. IVAL should be declared so as to match C type long int.

When using FIDASETVIN to specify the variable types (KEY = 'ID_VEC') the components in the array VVAL must be 1.0 to indicate a differential variable, or 0.0 to indicate an algebraic variable. Note that this array is required only if FIDACALCIC is to be called with ICOPT = 1, or if algebraic variables are suppressed from the error test (indicated using FIDASETIN with KEY = 'SUPPRESS_ALG'). When using FIDASETVIN to specify optional constraints on the solution vector (KEY = 'CONSTR_VEC') the components in the array VVAL should be one of −2.0, −1.0, 0.0, 1.0, or 2.0. See the description of IDASetConstraints (§4.5.8.1) for details.

The optional outputs from the IDA solver are accessed not through individual functions, but rather through a pair of arrays, IOUT (integer type) of dimension at least 21, and ROUT (real type) of dimension at least 6. These arrays are owned (and allocated) by the user and are passed as arguments to FIDAMALLOC. Table 5.4 lists the entries in these two arrays and specifies the optional variable as well as the IDA function which is actually called to extract the optional output.

For more details on the optional inputs and outputs, see §4.5.8 and §4.5.10.

In addition to the optional inputs communicated through FIDASET* calls and the optional outputs extracted from IOUT and ROUT, the following user-callable routines are available:

To reset the tolerances at any time, make the following call:

CALL FIDATOLREINIT (IATOL, RTOL, ATOL, IER)

The tolerance arguments have the same names and meanings as those of FIDAMALLOC. The error return flag IER is 0 if successful, and negative if there was a memory failure or illegal input.

To obtain the error weight array EWT, containing the multiplicative error weights used the WRMS norms, make the following call:

CALL FIDAGETERRWEIGHTS (EWT, IER)

This computes the EWT array, normally defined by Eq. (2.6). The array EWT, of length NEQ or NLOCAL, must already have been declared by the user. The error return flag IER is zero if successful, and negative if there was a memory error.
Table 5.3: Keys for setting FIDA optional inputs

<table>
<thead>
<tr>
<th>Key</th>
<th>Optional input</th>
<th>Default value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAX_ORD</td>
<td>Maximum LMM method order</td>
<td>5</td>
</tr>
<tr>
<td>MAX_NSTEPS</td>
<td>Maximum no. of internal steps before ( t_{\text{out}} )</td>
<td>500</td>
</tr>
<tr>
<td>MAX_ERRFAIL</td>
<td>Maximum no. of error test failures</td>
<td>10</td>
</tr>
<tr>
<td>MAX_NITERS</td>
<td>Maximum no. of nonlinear iterations</td>
<td>4</td>
</tr>
<tr>
<td>MAX_CONVFAIL</td>
<td>Maximum no. of convergence failures</td>
<td>10</td>
</tr>
<tr>
<td>SUPPRESS_ALG</td>
<td>Suppress alg. vars. from error test (1 = SUNTRUE)</td>
<td>0 (= SUNFALSE)</td>
</tr>
<tr>
<td>MAX_NSTEPS_IC</td>
<td>Maximum no. of steps for IC calc.</td>
<td>5</td>
</tr>
<tr>
<td>MAX_NITERS_IC</td>
<td>Maximum no. of Newton iterations for IC calc.</td>
<td>10</td>
</tr>
<tr>
<td>MAX,NJE_IC</td>
<td>Maximum no. of Jac. evals for IC calc.</td>
<td>4</td>
</tr>
<tr>
<td>LS_OFF_IC</td>
<td>Turn off line search (1 = SUNTRUE)</td>
<td>0 (= SUNFALSE)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Key</th>
<th>Optional input</th>
<th>Default value</th>
</tr>
</thead>
<tbody>
<tr>
<td>INIT_STEP</td>
<td>Initial step size</td>
<td>estimated</td>
</tr>
<tr>
<td>MAX_STEP</td>
<td>Maximum absolute step size</td>
<td>( \infty )</td>
</tr>
<tr>
<td>STOP_TIME</td>
<td>Value of ( t_{\text{stop}} )</td>
<td>undefined</td>
</tr>
<tr>
<td>NLCONV_COEF</td>
<td>Coeff. in the nonlinear conv. test</td>
<td>0.33</td>
</tr>
<tr>
<td>NLCONV_COEF_IC</td>
<td>Coeff. in the nonlinear conv. test for IC calc.</td>
<td>0.0033</td>
</tr>
<tr>
<td>STEP_TOL_IC</td>
<td>Lower bound on Newton step for IC calc.</td>
<td>( \text{uround}^{2/3} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Key</th>
<th>Optional input</th>
<th>Default value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID_VEC</td>
<td>Differential/algebraic component types</td>
<td>undefined</td>
</tr>
<tr>
<td>CONSTR_VEC</td>
<td>Inequality constraints on solution</td>
<td>undefined</td>
</tr>
</tbody>
</table>
Table 5.4: Description of the FIDA optional output arrays IOUT and ROUT

### Integer output array IOUT

<table>
<thead>
<tr>
<th>Index</th>
<th>Optional output</th>
<th>IDA function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LENRW</td>
<td>IDAGetWorkSpace</td>
</tr>
<tr>
<td>2</td>
<td>LENIW</td>
<td>IDAGetWorkSpace</td>
</tr>
<tr>
<td>3</td>
<td>NST</td>
<td>IDAGetNumSteps</td>
</tr>
<tr>
<td>4</td>
<td>NRE</td>
<td>IDAGetNumResEvals</td>
</tr>
<tr>
<td>5</td>
<td>NETF</td>
<td>IDAGetNumErrTestFails</td>
</tr>
<tr>
<td>6</td>
<td>NNCFAILS</td>
<td>IDAGetNonlinSolvConvFails</td>
</tr>
<tr>
<td>7</td>
<td>NNI</td>
<td>IDAGetNumNonlinSolvIters</td>
</tr>
<tr>
<td>8</td>
<td>NSETUPS</td>
<td>IDAGetNumLinSolvSetups</td>
</tr>
<tr>
<td>9</td>
<td>QLAST</td>
<td>IDAGetLastOrder</td>
</tr>
<tr>
<td>10</td>
<td>QCUR</td>
<td>IDAGetCurrentOrder</td>
</tr>
<tr>
<td>11</td>
<td>NBCKTRKOPS</td>
<td>IDAGetNumBacktrackOps</td>
</tr>
<tr>
<td>12</td>
<td>NGE</td>
<td>IDAGetNumGEvals</td>
</tr>
</tbody>
</table>

### IDALS linear solver interface

<table>
<thead>
<tr>
<th>Index</th>
<th>Optional output</th>
<th>IDA function</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>LENRWLS</td>
<td>IDAGetLinWorkSpace</td>
</tr>
<tr>
<td>14</td>
<td>LENIWLS</td>
<td>IDAGetLinWorkSpace</td>
</tr>
<tr>
<td>15</td>
<td>LS_FLAG</td>
<td>IDAGetLastLinFlag</td>
</tr>
<tr>
<td>16</td>
<td>NRELS</td>
<td>IDAGetNumLinResEvals</td>
</tr>
<tr>
<td>17</td>
<td>NJE</td>
<td>IDAGetNumJacEvals</td>
</tr>
<tr>
<td>18</td>
<td>NJETS</td>
<td>IDAGetNumJSetupEvals</td>
</tr>
<tr>
<td>19</td>
<td>NJT</td>
<td>IDAGetNumJtimesEvals</td>
</tr>
<tr>
<td>20</td>
<td>NPE</td>
<td>IDAGetNumPrecEvals</td>
</tr>
<tr>
<td>21</td>
<td>NPS</td>
<td>IDAGetNumPrecSolves</td>
</tr>
<tr>
<td>22</td>
<td>NLI</td>
<td>IDAGetNumLinIters</td>
</tr>
<tr>
<td>23</td>
<td>NCFL</td>
<td>IDAGetNumLinConvFails</td>
</tr>
</tbody>
</table>

### Real output array ROUT

<table>
<thead>
<tr>
<th>Index</th>
<th>Optional output</th>
<th>IDA function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H0_USED</td>
<td>IDAGetActualInitStep</td>
</tr>
<tr>
<td>2</td>
<td>HLAST</td>
<td>IDAGetLastStep</td>
</tr>
<tr>
<td>3</td>
<td>HCUR</td>
<td>IDAGetCurrentStep</td>
</tr>
<tr>
<td>4</td>
<td>TCUR</td>
<td>IDAGetCurrentTime</td>
</tr>
<tr>
<td>5</td>
<td>TOLFACT</td>
<td>IDAGetTolScaleFactor</td>
</tr>
<tr>
<td>6</td>
<td>UROUND</td>
<td>unit roundoff</td>
</tr>
</tbody>
</table>
To obtain the estimated local errors, following a successful call to FIDASOLVE, make the following call:

```fortran
CALL FIDAGETESTLOCALERR (ELE, IER)
```

This computes the ELE array of estimated local errors as of the last step taken. The array ELE must already have been declared by the user. The error return flag IER is zero if successful, and negative if there was a memory error.

### 5.5.1 Usage of the FIDAROOT interface to rootfinding

The FIDAROOT interface package allows programs written in FORTRAN to use the rootfinding feature of the IDA solver module. The user-callable functions in FIDAROOT, with the corresponding IDA functions, are as follows:

- **FIDAROOTINIT** interfaces to IDARootInit.
- **FIDAROOTINFO** interfaces to IDAGetRootInfo.
- **FIDAROOTFREE** interfaces to IDARootFree.

Note that, at this time FIDAROOT does not provide support to specify the direction of zero-crossing that is to be monitored. Instead, all roots are considered. However, the actual direction of zero-crossing is reported (through the sign of the non-zero elements in the array INFO returned by **FIDAROOTINFO**).

In order to use the rootfinding feature of IDA, the following call must be made, after calling **FIDAMALLOC** but prior to calling **FIDASOLVE**, to allocate and initialize memory for the FIDAROOT module:

```fortran
CALL FIDAROOTINIT (NRTFN, IER)
```

The arguments are as follows:

- **NRTFN** is the number of root functions. IER is a return completion flag; its values are 0 for success, −1 if the IDA memory was NULL, and −14 if a memory allocation failed.

To specify the functions whose roots are to be found, the user must define the following routine:

```fortran
SUBROUTINE FIDAROOTFN (T, Y, YP, G, IPAR, RPAR, IER)
DIMENSION Y(*), YP(*), G(*), IPAR(*), RPAR(*)
```

It must set the G array, of length NRTFN, with components \( g_i(t, y, \dot{y}) \), as a function of \( T = t \) and the arrays \( Y = y \) and \( YP = \dot{y} \). The arrays IPAR (of integers) and RPAR (of reals) contain user data and are the same as those passed to FIDAMALLOC. Set IER on 0 if successful, or on a non-zero value if an error occurred.

When making calls to FIDASOLVE to solve the DAE system, the occurrence of a root is flagged by the return value IER = 2. In that case, if NRTFN > 1, the functions \( g_i \) which were found to have a root can be identified by making the following call:

```fortran
CALL FIDAROOTINFO (NRTFN, INFO, IER)
```

The arguments are as follows:

- **NRTFN** is the number of root functions. INFO is an integer array of length NRTFN with root information. IER is a return completion flag; its values are 0 for success, negative if there was a memory failure. The returned values of INFO(i) \( (i = 1, \ldots, NRTFN) \) are 0 or ±1, such that INFO(i) = +1 if \( g_i \) was found to have a root and \( g_i \) is increasing, INFO(i) = −1 if \( g_i \) was found to have a root and \( g_i \) is decreasing, and INFO(i) = 0 otherwise.

The total number of calls made to the root function FIDAROOTFN, denoted NGE, can be obtained from IOUT(12). If the FIDA/IDA memory block is reinitialized to solve a different problem via a call to **FIDAREINIT**, then the counter NGE is reset to zero.

To free the memory resources allocated by a prior call to FIDAROOTINIT, make the following call:

```fortran
CALL FIDAROOTFREE
```

See §4.5.6 for additional information on the rootfinding feature.
5.5.2 Usage of the FIDABBD interface to IDABBDPRE

The FIDABBD interface sub-module is a package of C functions which, as part of the FIDA interface module, support the use of the IDA solver with the parallel NVECTOR_PARALLEL module, in a combination of any of the Krylov iterative solver modules with the IDABBDPRE preconditioner module (see §4.7).

The user-callable functions in this package, with the corresponding IDA and IDABBDPRE functions, are as follows:

- FIDABBDINIT interfaces to IDABBDPrecAlloc.
- FIDABBDREINIT interfaces to IDABBDPrecReInit.
- FIDABBDOPT interfaces to IDABBDPRE optional output functions.
- FIDABBDFREE interfaces to IDABBDPrecFree.

In addition to the FORTRAN residual function FIDARESFUN, the user-supplied functions used by this package, are listed below, each with the corresponding interface function which calls it (and its type within IDABBDPRE or IDA):

<table>
<thead>
<tr>
<th>FIDABBD routine (FORTRAN)</th>
<th>IDA function (C)</th>
<th>IDA function type</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIDACLOCFN</td>
<td>FIDAgloc</td>
<td>IDABBDLocalFn</td>
</tr>
<tr>
<td>FIDACOMMFN</td>
<td>FIDAcfn</td>
<td>IDABBDCommFn</td>
</tr>
<tr>
<td>FIDAJTIMES</td>
<td>FIDAJtimes</td>
<td>IDALSJacTimesVecFn</td>
</tr>
<tr>
<td>FIDAJTSETUP</td>
<td>FIDAJTSetup</td>
<td>IDALSJacTimesSetupFn</td>
</tr>
</tbody>
</table>

As with the rest of the FIDA routines, the names of all user-supplied routines here are fixed, in order to maximize portability for the resulting mixed-language program. Additionally, based on flags discussed above in §5.4.1, the names of the user-supplied routines are mapped to actual values through a series of definitions in the header file fidabbd.h.

The following is a summary of the usage of this module. Steps that are unchanged from the main program described in §5.4.2 are grayed-out.

1. Residual function specification
2. NVECTOR module initialization
3. SUNLINSOL module initialization
   - Initialize one of the iterative SUNLINSOL modules, by calling one of FSUNPCGINIT, FSUNSPBCGSINIT, FSUNSPFGMRINIT, FSUNSPGMRINIT or FSUNSPTFQMRINIT.
4. Problem specification
5. Set optional inputs
6. Linear solver interface specification
   - Initialize the IDALS iterative linear solver interface by calling FIDALSINIT.
7. BBD preconditioner initialization
   - To initialize the IDABBDPRE preconditioner, make the following call:

     CALL FIDABBDINIT (NLOCAL, MUDQ, MLDQ, MU, ML, DQRELY, IER)

The arguments are as follows. NLOCAL is the local size of vectors on this processor. MUDQ and MLDQ are the upper and lower half-bandwidths to be used in the computation of the local Jacobian blocks by difference quotients. These may be smaller than the true half-bandwidths of the Jacobian of the local block of $G$, when smaller values may provide greater efficiency. MU and ML are the upper
and lower half-bandwidths of the band matrix that is retained as an approximation of the local Jacobian block. These may be smaller than MUDQ and MLDQ. DQRELY is the relative increment factor in y for difference quotients (optional). A value of 0.0 indicates the default, √unit roundoff. IER is a return completion flag. A value of 0 indicates success, while a value of −1 indicates that a memory failure occurred or that an input had an illegal value.

8. Correct initial values

9. Problem solution

10. Additional solution output

11. IDABBBDPRE Optional outputs

Optional outputs specific to the spgmr, spbcgs, or sptfqmr solver are listed in Table 5.4. To obtain the optional outputs associated with the IDABBBDPRE module, make the following call:

\[
\text{CALL FIDABBDOPT (LENRWBBD, LENIWBBBD, NGEBBBD)}
\]

The arguments should be consistent with C type long int. Their returned values are as follows: LENRWBBD is the length of real preconditioner work space, in realltype words. LENIWBBBD is the length of integer preconditioner work space, in integer words. Both of these sizes are local to the current processor. NGEBBBD is the number of G(t, y, ˙y) evaluations (calls to FIDALOCFN) so far.

12. Problem reinitialization

If a sequence of problems of the same size is being solved using the same linear solver in combination with the IDABBBDPRE preconditioner, then the IDA package can be re-initialized for the second and subsequent problems by calling FIDAREINIT, following which a call to FIDABBBDINIT may or may not be needed. If the input arguments are the same, no FIDABBBDINIT call is needed. If there is a change in input arguments other than MU or ML, then the user program should make the call

\[
\text{CALL FIDABBBDREINIT (NLOCAL, MUDQ, MLDQ, DQRELY, IER)}
\]

This reinitializes the IDABBBDPRE preconditioner, but without reallocating its memory. The arguments of the FIDABBBDREINIT routine have the same names and meanings as those of FIDABBBDINIT. If the value of MU or ML is being changed, then a call to FIDABBBDINIT must be made. Finally, if there is a change in any of the linear solver inputs, then a call to one of FSUN****INIT, followed by a call to FIDALSINIT must also be made; in this case the linear solver memory is reallocated.

13. Memory deallocation

(The memory allocated for the FIDABBBD module is deallocated automatically by FIDAFREE.)

14. User-supplied routines

The following two routines must be supplied for use with the IDABBBDPRE module:

\[
\text{SUBROUTINE FIDAGLOCFN (NLOC, T, YLOC, YPLOC, GLOC, IPAR, RPAR, IER)}
\]

\[
\text{DIMENSION YLOC(*), YPLOC(*), GLOC(*), IPAR(*), RPAR(*)}
\]

This routine is to evaluate the function G(t, y, ˙y) approximating F (possibly identical to F), in terms of T = t, and the arrays YLOC and YPLOC (of length NLOC), which are the sub-vectors of y and ˙y local to this processor. The resulting (local) sub-vector is to be stored in the array GLOC. IER is a return flag that should be set to 0 if successful, to 1 (for a recoverable error), or to -1 (for a non-recoverable error). The arrays IPAR (of integers) and RPAR (of reals) contain user data and are the same as those passed to FIDAMALLOC.
5.5 FIDA optional input and output

SUBROUTINE FIDACOMMFN (NLOC, T, YLOC, YPLOC, IPAR, RPAR, IER)
DIMENSION YLOC(*), YPLOC(*), IPAR(*), RPAR(*)

This routine is to perform the inter-processor communication necessary for the FIDAGLOCFN routine. Each call to FIDACOMMFN is preceded by a call to the residual routine FIDARESFUN with the same arguments T, YLOC, and YPLOC. Thus FIDACOMMFN can omit any communications done by FIDARESFUN if relevant to the evaluation of GLOC. The arrays IPAR (of integers) and RPAR (of reals) contain user data and are the same as those passed to FIDAMALLOC. IER is a return flag that should be set to 0 if successful, to 1 (for a recoverable error), or to -1 (for a non-recoverable error).

The subroutine FIDACOMMFN must be supplied even if it is empty, and it must return IER = 0.

Optionally, the user can supply routines FIDAJTIMES and FIDAJTSETUP for the evaluation of Jacobian-vector products, as described above in step 7 in §5.4.2.
Chapter 6

Description of the NVECTOR module

The SUNDIALS solvers are written in a data-independent manner. They all operate on generic vectors (of type N_Vector) through a set of operations defined by the particular NVECTOR implementation. Users can provide their own specific implementation of the nvector module, or use one of the implementations provided with SUNDIALS. The generic nvector is described below and the implementations provided with SUNDIALS are described in the following sections.

6.1 The NVECTOR API

The generic nvector API can be broken down into five groups of functions: the core vector operations, the fused vector operations, the vector array operations, the local reduction operations, and finally some utility functions. The first four groups are defined by a particular nvector implementation. The utility functions are defined by the generic nvector itself.

6.1.1 NVECTOR core functions

\begin{verbatim}
N_VGetVectorID
\end{verbatim}

Call \texttt{id = N_VGetVectorID(w);}

Description Returns the vector type identifier for the vector \texttt{w}. It is used to determine the vector implementation type (e.g. serial, parallel, ...) from the abstract \texttt{N_Vector} interface.

Arguments \texttt{w} (N_Vector) a NVECTOR object

Return value This function returns an N_Vector_ID. Possible values are given in Table 6.1.

F2003 Name FN_VGetVectorID

\begin{verbatim}
N_VClone
\end{verbatim}

Call \texttt{v = N_VClone(w);}

Description Creates a new \texttt{N_Vector} of the same type as an existing vector \texttt{w} and sets the \texttt{ops} field. It does not copy the vector, but rather allocates storage for the new vector.

Arguments \texttt{w} (N_Vector) a NVECTOR object

Return value This function returns an \texttt{N_Vector} object. If an error occurs, then this routine will return NULL.

F2003 Name FN_VClone
**N_VCloneEmpty**

Call
\[
v = \text{N_VCloneEmpty}(w);
\]

Description
Creates a new N_Vector of the same type as an existing vector \( w \) and sets the \( \text{ops} \) field. It does not allocate storage for data.

Arguments
\( w \) (N_Vector) a NVECTOR object

Return value
This function returns an N_Vector object. If an error occurs, then this routine will return NULL.

F2003 Name  FN_VCloneEmpty

**N_VDestroy**

Call
\[
\text{N_VDestroy}(v);
\]

Description
Destroys the N_Vector \( v \) and frees memory allocated for its internal data.

Arguments
\( v \) (N_Vector) a NVECTOR object to destroy

Return value
None

F2003 Name  FN_VDestroy

**N_VSpace**

Call
\[
\text{N_VSpace}(v, \&\text{lrw}, \&\text{liw});
\]

Description
Returns storage requirements for one N_Vector. \( \text{lrw} \) contains the number of realtype words and \( \text{liw} \) contains the number of integer words. This function is advisory only, for use in determining a user's total space requirements; it could be a dummy function in a user-supplied NVECTOR module if that information is not of interest.

Arguments
\( v \) (N_Vector) a NVECTOR object
\( \text{lrw} \) (sunindextype*) out parameter containing the number of realtype words
\( \text{liw} \) (sunindextype*) out parameter containing the number of integer words

Return value
None

F2003 Name  FN_VSpace

F2003 Call
\[
\text{integer(c_long)} :: \text{lrw}(1), \text{liw}(1)
\]
\[
call \text{FN_VSpace.Serial}(v, \text{lrw}, \text{liw})
\]

**N_VGetArrayPointer**

Call
\[
vdata = \text{N_VGetArrayPointer}(v);
\]

Description
Returns a pointer to a realtype array from the N_Vector \( v \). Note that this assumes that the internal data in N_Vector is a contiguous array of realtype. This routine is only used in the solver-specific interfaces to the dense and banded (serial) linear solvers, the sparse linear solvers (serial and threaded), and in the interfaces to the banded (serial) and band-block-diagonal (parallel) preconditioner modules provided with SUNDIALS.

Arguments
\( v \) (N_Vector) a NVECTOR object

Return value
realtype*

F2003 Name  FN_VGetArrayPointer
6.1 The \texttt{NVECTOR} API

\textbf{\texttt{N_VSetArrayPointer}}

\textbf{Call} \quad \texttt{N_VSetArrayPointer(vdata, v);}

\textbf{Description} \quad Overwrites the pointer to the data in an \texttt{N_Vector} with a given \texttt{realtype*}. Note that this assumes that the internal data in \texttt{N_Vector} is a contiguous array of \texttt{realtype}. This routine is only used in the interfaces to the dense (serial) linear solver, hence need not exist in a user-supplied NVECTOR module for a parallel environment.

\textbf{Arguments} \quad v \ (\texttt{N_Vector}) \ a \ \texttt{NVECTOR} \ object

\textbf{Return value} \quad \texttt{None}

\textbf{F2003 Name} \quad \texttt{FN_VSetArrayPointer}

\textbf{\texttt{N_VGetCommunicator}}

\textbf{Call} \quad \texttt{N_VGetCommunicator(v);}

\textbf{Description} \quad Returns a pointer to the \texttt{MPI_Comm} object associated with the vector (if applicable). For MPI-unaware vector implementations, this should return \texttt{NULL}.

\textbf{Arguments} \quad v \ (\texttt{N_Vector}) \ a \ \texttt{NVECTOR} \ object

\textbf{Return value} \quad A \ \texttt{void*} \ pointer to the \texttt{MPI_Comm} object if the vector is MPI-aware, otherwise \texttt{NULL}.

\textbf{F2003 Name} \quad \texttt{FN_VGetCommunicator}

\textbf{\texttt{N_VGetLength}}

\textbf{Call} \quad \texttt{N_VGetLength(v);}

\textbf{Description} \quad Returns the global length (number of ‘active’ entries) in the \texttt{NVECTOR} v. This value should be cumulative across all processes if the vector is used in a parallel environment. If \(v\) contains additional storage, e.g., for parallel communication, those entries should not be included.

\textbf{Arguments} \quad v \ (\texttt{N_Vector}) \ a \ \texttt{NVECTOR} \ object

\textbf{Return value} \quad \texttt{sunindextype}

\textbf{F2003 Name} \quad \texttt{FN_VGetLength}

\textbf{\texttt{N_VLinearSum}}

\textbf{Call} \quad \texttt{N_VLinearSum(a, x, b, y, z);}

\textbf{Description} \quad Performs the operation \(z = ax + by\), where \(a\) and \(b\) are \texttt{realtype} scalars and \(x\) and \(y\) are of type \texttt{N_Vector}: \(z_i = ax_i + by_i, \ i = 0, \ldots, n-1\).

\textbf{Arguments} \quad a \ (\texttt{realtype}) \ constant \ that \ scales \ \texttt{x}

\quad x \ (\texttt{N_Vector}) \ a \ \texttt{NVECTOR} \ object

\quad b \ (\texttt{realtype}) \ constant \ that \ scales \ \texttt{y}

\quad y \ (\texttt{N_Vector}) \ a \ \texttt{NVECTOR} \ object

\quad z \ (\texttt{N_Vector}) \ a \ \texttt{NVECTOR} \ object \ containing \ the \ result

\textbf{Return value} \quad \texttt{None}

\textbf{F2003 Name} \quad \texttt{FN_VLinearSum}
**Description of the NV**ECTOR module

**N_VConst**

**Call**

\[ \text{N_VConst}(c, z); \]

**Description**
Sets all components of the \text{n_vector} \( z \) to \text{realtype} \( c \): \( z_i = c, \ i = 0, \ldots, n - 1. \)

**Arguments**
- \( c \) (\text{realtype}) constant to set all components of \( z \) to
- \( z \) (\text{n_vector}) a \text{NV}ECTOR object containing the result

**Return value** None

F2003 Name \text{FN_VConst}

**N_VProd**

**Call**

\[ \text{N_VProd}(x, y, z); \]

**Description**
Sets the \text{n_vector} \( z \) to be the component-wise product of the \text{n_vector} inputs \( x \) and \( y \):
\[ z_i = x_i y_i, \ i = 0, \ldots, n - 1. \]

**Arguments**
- \( x \) (\text{n_vector}) a \text{NV}ECTOR object
- \( y \) (\text{n_vector}) a \text{NV}ECTOR object
- \( z \) (\text{n_vector}) a \text{NV}ECTOR object containing the result

**Return value** None

F2003 Name \text{FN_VProd}

**N_VDiv**

**Call**

\[ \text{N_VDiv}(x, y, z); \]

**Description**
Sets the \text{n_vector} \( z \) to be the component-wise ratio of the \text{n_vector} inputs \( x \) and \( y \):
\[ z_i = x_i / y_i, \ i = 0, \ldots, n - 1. \] The \( y_i \) may not be tested for 0 values. It should only be called with a \( y \) that is guaranteed to have all nonzero components.

**Arguments**
- \( x \) (\text{n_vector}) a \text{NV}ECTOR object
- \( y \) (\text{n_vector}) a \text{NV}ECTOR object
- \( z \) (\text{n_vector}) a \text{NV}ECTOR object containing the result

**Return value** None

F2003 Name \text{FN_VDiv}

**N_VScale**

**Call**

\[ \text{N_VScale}(c, x, z); \]

**Description**
Scales the \text{n_vector} \( x \) by the \text{realtype} scalar \( c \) and returns the result in \( z \):
\[ z_i = cx_i, \ i = 0, \ldots, n - 1. \]

**Arguments**
- \( c \) (\text{realtype}) constant that scales the vector \( x \)
- \( x \) (\text{n_vector}) a \text{NV}ECTOR object
- \( z \) (\text{n_vector}) a \text{NV}ECTOR object containing the result

**Return value** None

F2003 Name \text{FN_VScale}
6.1 The NVIRTUAL API

\textbf{NVAbs} \newline
Call \[\text{NVAbs}(x, z);\] \newline
Description Sets the components of the NVIRTUAL \textit{z} to be the absolute values of the components of the NVIRTUAL \textit{x}: \[y_i = |x_i|, \quad i = 0, \ldots, n - 1.\] \newline
Arguments \textit{x} (NVIRTUAL) a NVIRTUAL object \newline
\textit{z} (NVIRTUAL) a NVIRTUAL object containing the result \newline
Return value None \newline
F2003 Name FN_VAbs \newline

\textbf{NVIInv} \newline
Call \[\text{NVIInv}(x, z);\] \newline
Description Sets the components of the NVIRTUAL \textit{z} to be the inverses of the components of the NVIRTUAL \textit{x}: \[z_i = 1.0/x_i, \quad i = 0, \ldots, n - 1.\] This routine may not check for division by 0. It should be called only with an \textit{x} which is guaranteed to have all nonzero components. \newline
Arguments \textit{x} (NVIRTUAL) a NVIRTUAL object \newline
\textit{z} (NVIRTUAL) a NVIRTUAL object containing the result \newline
Return value None \newline
F2003 Name FN_VInv \newline

\textbf{NVAddConst} \newline
Call \[\text{NVAddConst}(x, b, z);\] \newline
Description Adds the realtype scalar \textit{b} to all components of \textit{x} and returns the result in the NVIRTUAL \textit{z}: \[z_i = x_i + b, \quad i = 0, \ldots, n - 1.\] \newline
Arguments \textit{x} (NVIRTUAL) a NVIRTUAL object \newline
\textit{b} (realtype) constant added to all components of \textit{x} \newline
\textit{z} (NVIRTUAL) a NVIRTUAL object containing the result \newline
Return value None \newline
F2003 Name FN_NVAddConst \newline

\textbf{NVDotProd} \newline
Call \[d = \text{NVDotProd}(x, y);\] \newline
Description Returns the value of the ordinary dot product of \textit{x} and \textit{y}: \[d = \sum_{i=0}^{n-1} x_i y_i.\] \newline
Arguments \textit{x} (NVIRTUAL) a NVIRTUAL object with \textit{y} \newline
\textit{y} (NVIRTUAL) a NVIRTUAL object with \textit{x} \newline
Return value realtype \newline
F2003 Name FN_NVDotProd \newline

\textbf{NVMaxNorm} \newline
Call \[m = \text{NVMaxNorm}(x);\] \newline
Description Returns the maximum norm of the NVIRTUAL \textit{x}: \[m = \max_i |x_i|.\] \newline
Arguments \textit{x} (NVIRTUAL) a NVIRTUAL object \newline
Return value realtype \newline
F2003 Name FN_NVMaxNorm
**N_VWrmsNorm**

Call  
\[ m = \text{N_VWrmsNorm}(x, w) \]

Description  
Returns the weighted root-mean-square norm of the N_Vector \( x \) with realtype weight vector \( w \):  
\[ m = \sqrt{\left( \sum_{i=0}^{n-1} (x_i w_i)^2 \right) / n}. \]

Arguments  
- \( x \) (N_Vector) a NVECTOR object
- \( w \) (N_Vector) a NVECTOR object containing weights

Return value  
realtype

F2003 Name  
FN_VWrmsNorm

**N_VWrmsNormMask**

Call  
\[ m = \text{N_VWrmsNormMask}(x, w, id); \]

Description  
Returns the weighted root mean square norm of the N_Vector \( x \) with realtype weight vector \( w \) built using only the elements of \( x \) corresponding to positive elements of the N_Vector \( id \):  
\[ m = \sqrt{\left( \sum_{i=0}^{n-1} (x_i w_i H(id_i))^2 \right) / n}, \]  
where \( H(\alpha) = \begin{cases} 1 & \alpha > 0 \\ 0 & \alpha \leq 0 \end{cases} \)

Arguments  
- \( x \) (N_Vector) a NVECTOR object
- \( w \) (N_Vector) a NVECTOR object containing weights
- \( id \) (N_Vector) mask vector

Return value  
realtype

F2003 Name  
FN_VWrmsNormMask

**N_VMin**

Call  
\[ m = \text{N_VMin}(x); \]

Description  
Returns the smallest element of the N_Vector \( x \):  
\[ m = \min_i x_i. \]

Arguments  
- \( x \) (N_Vector) a NVECTOR object

Return value  
realtype

F2003 Name  
FN_VMin

**N_VWL2Norm**

Call  
\[ m = \text{N_VWL2Norm}(x, w); \]

Description  
Returns the weighted Euclidean \( \ell_2 \) norm of the N_Vector \( x \) with realtype weight vector \( w \):  
\[ m = \sqrt{\sum_{i=0}^{n-1} (x_i w_i)^2}. \]

Arguments  
- \( x \) (N_Vector) a NVECTOR object
- \( w \) (N_Vector) a NVECTOR object containing weights

Return value  
realtype

F2003 Name  
FN_VWL2Norm

**N_VL1Norm**

Call  
\[ m = \text{N_VL1Norm}(x); \]

Description  
Returns the \( \ell_1 \) norm of the N_Vector \( x \):  
\[ m = \sum_{i=0}^{n-1} |x_i|. \]

Arguments  
- \( x \) (N_Vector) a NVECTOR object to obtain the norm of

Return value  
realtype

F2003 Name  
FN_VL1Norm
6.1 The NVECTOR API

### N_VCompare

**Call**

N_VCompare(c, x, z);

**Description**

Compares the components of the N_Vector \( x \) to the \texttt{realtype} scalar \( c \) and returns an N_Vector \( z \) such that: \( z_i = 1.0 \) if \( |x_i| \geq c \) and \( z_i = 0.0 \) otherwise.

**Arguments**

- \( c \) (\texttt{realtype}) constant that each component of \( x \) is compared to
- \( x \) (N_Vector) a NVVECTOR object
- \( z \) (N_Vector) a NVVECTOR object containing the result

**Return value**

None

F2003 Name FN_VCompare

### N_VInvTest

**Call**

\[ t = N\_VInvTest(x, z); \]

**Description**

Sets the components of the N_Vector \( z \) to be the inverses of the components of the N_Vector \( x \), with prior testing for zero values: \( z_i = 1.0/x_i \), \( i = 0, \ldots, n - 1 \).

**Arguments**

- \( x \) (N_Vector) a NVVECTOR object
- \( z \) (N_Vector) an output NVVECTOR object

**Return value**

Returns a \texttt{booleantype} with value SUNTRUE if all components of \( x \) are nonzero (successful inversion) and returns SUNFALSE otherwise.

F2003 Name FN_VInvTest

### N_VConstrMask

**Call**

\[ t = N\_VConstrMask(c, x, m); \]

**Description**

Performs the following constraint tests: \( x_i > 0 \) if \( c_i = 2 \), \( x_i \geq 0 \) if \( c_i = 1 \), \( x_i \leq 0 \) if \( c_i = -1 \), \( x_i < 0 \) if \( c_i = -2 \). There is no constraint on \( x_i \) if \( c_i = 0 \). This routine returns a boolean assigned to SUNFALSE if any element failed the constraint test and assigned to SUNTRUE if all passed. It also sets a mask vector \( m \), with elements equal to 1.0 where the constraint test failed, and 0.0 where the test passed. This routine is used only for constraint checking.

**Arguments**

- \( c \) (\texttt{realtype}) scalar constraint value
- \( x \) (N_Vector) a NVVECTOR object
- \( m \) (N_Vector) output mask vector

**Return value**

Returns a \texttt{booleantype} with value SUNFALSE if any element failed the constraint test, and SUNTRUE if all passed.

F2003 Name FN_VConstrMask

### N_VMinQuotient

**Call**

\[ \text{minq} = N\_VMinQuotient(\text{num}, \text{denom}); \]

**Description**

This routine returns the minimum of the quotients obtained by term-wise dividing \texttt{num}, by \texttt{denom}. A zero element in \texttt{denom} will be skipped. If no such quotients are found, then the large value \texttt{BIG-REAL} (defined in the header file sundials_types.h) is returned.

**Arguments**

- \( \text{num} \) (N_Vector) a NVVECTOR object used as the numerator
- \( \text{denom} \) (N_Vector) a NVVECTOR object used as the denominator

**Return value**

\texttt{realtype}

F2003 Name FN_VMinQuotient
6.1.2 NVECTOR fused functions

Fused and vector array operations are intended to increase data reuse, reduce parallel communication on distributed memory systems, and lower the number of kernel launches on systems with accelerators. If a particular NVECTOR implementation defines a fused or vector array operation as NULL, the generic NVECTOR module will automatically call standard vector operations as necessary to complete the desired operation. In all SUNDIALS-provided NVECTOR implementations, all fused and vector array operations are disabled by default. However, these implementations provide additional user-callable functions to enable/disable any or all of the fused and vector array operations. See the following sections for the implementation specific functions to enable/disable operations.

**N_VLinearCombination**

Call `ier = N_VLinearCombination(nv, c, X, z);`

Description This routine computes the linear combination of `nv` vectors with `n` elements:

\[ z_i = \sum_{j=0}^{n_v-1} c_j x_{j,i}, \quad i = 0\ldots,n - 1, \]

where `c` is an array of `n_v` scalars, `X` is an array of `n_v` vectors, and `z` is the output vector.

Arguments
- `nv` (int) the number of vectors in the linear combination
- `c` (realtype*) an array of `n_v` scalars used to scale the corresponding vector in `X`
- `X` (N_Vector*) an array of `n_v` NVECTOR objects to be scaled and combined
- `z` (N_Vector) a NVECTOR object containing the result

Return value Returns an `int` with value 0 for success and a non-zero value otherwise.

Notes If the output vector `z` is one of the vectors in `X`, then it must be the first vector in the vector array.

F2003 Name FN_VLinearCombination

F2003 Call `real(c_double) :: c(nv)`
`type(c_ptr), target :: X(nv)`
`type(N_Vector), pointer :: z`
`ier = FN_VLinearCombination(nv, c, X, z)`

**N_VScaleAddMulti**

Call `ier = N_VScaleAddMulti(nv, c, x, Y, Z);`

Description This routine scales and adds one vector to `nv` vectors with `n` elements:

\[ z_{j,i} = c_j x_{i} + y_{j,i}, \quad j = 0\ldots,n_v - 1, \quad i = 0\ldots,n - 1, \]

where `c` is an array of `n_v` scalars, `x` is the vector to be scaled and added to each vector in the vector array of `n_v` vectors `Y`, and `Z` is a vector array of `n_v` output vectors.

Arguments
- `nv` (int) the number of scalars and vectors in `c`, `Y`, and `Z`
- `c` (realtype*) an array of `n_v` scalars
- `x` (N_Vector) a NVECTOR object to be scaled and added to each vector in `Y`
- `Y` (N_Vector*) an array of `n_v` NVECTOR objects where each vector `j` will have the vector `x` scaled by `c_j` added to it
- `Z` (N_Vector) an output array of `n_v` NVECTOR objects

Return value Returns an `int` with value 0 for success and a non-zero value otherwise.

F2003 Name FN_VScaleAddMulti
6.1 The NVECTOR API

F2003 Call
real(c_double) :: c(nv)
type(c_ptr), target :: Y(nv), Z(nv)
type(N_Vector), pointer :: x
ierr = FN_VScaleAddMulti(nv, c, x, Y, Z)

N_VDotProdMulti
Call
ier = N_VDotProdMulti(nv, x, Y, d);
Description
This routine computes the dot product of a vector with \( n_v \) other vectors:

\[
d_j = \sum_{i=0}^{n-1} x_i y_{j,i}, \quad j = 0, \ldots, n_v - 1,
\]

where \( d \) is an array of \( n_v \) scalars containing the dot products of the vector \( x \) with each of the \( n_v \) vectors in the vector array \( Y \).

Arguments
- \( nv \) (int) the number of vectors in \( Y \)
- \( x \) (N_Vector) a NVECTOR object to be used in a dot product with each of the vectors in \( Y \)
- \( Y \) (N_Vector*) an array of \( n_v \) NVECTOR objects to use in a dot product with \( x \)
- \( d \) (realtype*) an output array of \( n_v \) dot products

Return value
Returns an int with value 0 for success and a non-zero value otherwise.

F2003 Name FN_VDotProdMulti

6.1.3 NVECTOR vector array functions

N_VLinearSumVectorArray
Call
ier = N_VLinearSumVectorArray(nv, a, X, b, Y, Z);
Description
This routine computes the linear sum of two vector arrays containing \( n_v \) vectors of \( n \) elements:

\[
z_{j,i} = ax_{j,i} + by_{j,i}, \quad i = 0, \ldots, n - 1 \quad j = 0, \ldots, n_v - 1,
\]

where \( a \) and \( b \) are scalars and \( X, Y, \) and \( Z \) are arrays of \( n_v \) vectors.

Arguments
- \( nv \) (int) the number of vectors in the vector arrays
- \( a \) (realtype) constant to scale each vector in \( X \) by
- \( X \) (N_Vector*) an array of \( n_v \) NVECTOR objects
- \( Y \) (N_Vector*) an array of \( n_v \) NVECTOR objects
- \( Z \) (N_Vector*) an output array of \( n_v \) NVECTOR objects

Return value
Returns an int with value 0 for success and a non-zero value otherwise.

F2003 Name FN_VLinearSumVectorArray
**Description of the NVECTOR module**

### N_VScaleVectorArray

**Call**

```c
ier = N_VScaleVectorArray(nv, c, X, Z);
```

**Description**

This routine scales each vector of \( n \) elements in a vector array of \( nv \) vectors by a potentially different constant:

\[
z_{j,i} = c_{j} x_{j,i}, \quad i = 0, \ldots, n - 1 \quad j = 0, \ldots, nv - 1,
\]

where \( c \) is an array of \( nv \) scalars and \( X \) and \( Z \) are arrays of \( nv \) vectors.

**Arguments**

- \( nv \) (int) the number of vectors in the vector arrays
- \( c \) (realtype) constant to scale each vector in \( X \) by
- \( X \) (N_Vector*) an array of \( nv \) NVECTOR objects
- \( Z \) (N_Vector*) an output array of \( nv \) NVECTOR objects

**Return value**

Returns an int with value 0 for success and a non-zero value otherwise.

F2003 Name `FN_VScaleVectorArray`

### N_VConstVectorArray

**Call**

```c
ier = N_VConstVectorArray(nv, c, X);
```

**Description**

This routine sets each element in a vector of \( n \) elements in a vector array of \( nv \) vectors to the same value:

\[
z_{j,i} = c, \quad i = 0, \ldots, n - 1 \quad j = 0, \ldots, nv - 1,
\]

where \( c \) is a scalar and \( X \) is an array of \( nv \) vectors.

**Arguments**

- \( nv \) (int) the number of vectors in \( X \)
- \( c \) (realtype) constant to set every element in every vector of \( X \) to
- \( X \) (N_Vector*) an array of \( nv \) NVECTOR objects

**Return value**

Returns an int with value 0 for success and a non-zero value otherwise.

F2003 Name `FN_VConstVectorArray`

### N_VWrmNormVectorArray

**Call**

```c
ier = N_VWrmNormVectorArray(nv, X, W, m);
```

**Description**

This routine computes the weighted root mean square norm of \( nv \) vectors with \( n \) elements:

\[
m_{j} = \left( \frac{1}{n} \sum_{i=0}^{n-1} (x_{j,i}w_{j,i})^2 \right)^{1/2}, \quad j = 0, \ldots, nv - 1,
\]

where \( m \) contains the \( nv \) norms of the vectors in the vector array \( X \) with corresponding weight vectors \( W \).

**Arguments**

- \( nv \) (int) the number of vectors in the vector arrays
- \( X \) (N_Vector*) an array of \( nv \) NVECTOR objects
- \( W \) (N_Vector*) an array of \( nv \) NVECTOR objects
- \( m \) (realtype*) an output array of \( nv \) norms

**Return value**

Returns an int with value 0 for success and a non-zero value otherwise.

F2003 Name `FN_VWrmNormVectorArray`
6.1 The NVECTOR API

N_VWrmsNormMaskVectorArray

Call ier = N_VWrmsNormMaskVectorArray(nv, X, W, id, m);

Description This routine computes the masked weighted root mean square norm of \( n_v \) vectors with \( n \) elements:

\[
m_j = \left( \frac{1}{n} \sum_{i=0}^{n-1} (x_{j,i} w_{j,i} H(id_i))^2 \right)^{1/2}, \quad j = 0, \ldots, n_v - 1,
\]

\( H(id_i) = 1 \) for \( id_i > 0 \) and is zero otherwise, \( m \) contains the \( n_v \) norms of the vectors in the vector array \( X \) with corresponding weight vectors \( W \) and mask vector \( id \).

Arguments

- \( nv \) (int) the number of vectors in the vector arrays
- \( X \) (N_Vector*) an array of \( n_v \) NVECTOR objects
- \( W \) (N_Vector*) an array of \( n_v \) NVECTOR objects
- \( id \) (N_Vector) the mask vector
- \( m \) (realtype*) an output array of \( n_v \) norms

Return value Returns an int with value 0 for success and a non-zero value otherwise.

F2003 Name FN_VWrmsNormMaskVectorArray

N_VScaleAddMultiVectorArray

Call ier = N_VScaleAddMultiVectorArray(nv, ns, c, X, YY, ZZ);

Description This routine scales and adds a vector in a vector array of \( n_v \) vectors to the corresponding vector in \( n_s \) vector arrays:

\[
z_{j,i} = \sum_{k=0}^{n_s-1} c_k x_{k,j,i}, \quad i = 0, \ldots, n - 1 \quad j = 0, \ldots, n_v - 1,
\]

where \( c \) is an array of \( n_s \) scalars, \( X \) is a vector array of \( n_v \) vectors to be scaled and added to the corresponding vector in each of the \( n_s \) vector arrays in the array of vector arrays \( YY \) and stored in the output array of vector arrays \( ZZ \).

Arguments

- \( nv \) (int) the number of vectors in the vector arrays
- \( ns \) (int) the number of scalars in \( c \) and vector arrays in \( YY \) and \( ZZ \)
- \( c \) (realtype*) an array of \( n_s \) scalars
- \( X \) (N_Vector*) an array of \( n_v \) NVECTOR objects
- \( YY \) (N_Vector**) an array of \( n_s \) NVECTOR arrays
- \( ZZ \) (N_Vector**) an output array of \( n_s \) NVECTOR arrays

Return value Returns an int with value 0 for success and a non-zero value otherwise.

N_VLinearCombinationVectorArray

Call ier = N_VLinearCombinationVectorArray(nv, ns, c, XX, Z);

Description This routine computes the linear combination of \( n_s \) vector arrays containing \( n_v \) vectors with \( n \) elements:

\[
z_{j,i} = \sum_{k=0}^{n_s-1} c_k x_{k,j,i}, \quad i = 0, \ldots, n - 1 \quad j = 0, \ldots, n_v - 1,
\]

where \( c \) is an array of \( n_s \) scalars (type realtype*), \( XX \) (type N_Vector**) is an array of \( n_s \) vector arrays each containing \( n_v \) vectors to be summed into the output vector array of \( n_v \) vectors \( Z \) (type N_Vector*). If the output vector array \( Z \) is one of the vector arrays in \( XX \), then it must be the first vector array in \( XX \).
Description of the NVECTOR module

Arguments

- \texttt{nv} (int) the number of vectors in the vector arrays
- \texttt{ns} (int) the number of scalars in \texttt{c} and vector arrays in \texttt{YY} and \texttt{ZZ}
- \texttt{c} (realtype*) an array of \texttt{ns} scalars
- \texttt{XX} (N_Vector**) an array of \texttt{ns} NVECTOR arrays
- \texttt{Z} (N_Vector*) an output array NVECTOR objects

Return value

Returns an \texttt{int} with value 0 for success and a non-zero value otherwise.

6.1.4 NVECTOR local reduction functions

Local reduction operations are intended to reduce parallel communication on distributed memory systems, particularly when NVECTOR objects are combined together within a NVECTOR_MPI MANYVECTOR object (see Section 6.14). If a particular NVECTOR implementation defines a local reduction operation as NULL, the NVECTOR_MPI MANYVECTOR module will automatically call standard vector reduction operations as necessary to complete the desired operation. All SUNDIALS-provided NVECTOR implementations include these local reduction operations, which may be used as templates for user-defined NVECTOR implementations.

\begin{verbatim}
N_VDotProdLocal
Call   d = N_VDotProdLocal(x, y);
Description  This routine computes the MPI task-local portion of the ordinary dot product of \(x\) and \(y\):

\[
d = \sum_{i=0}^{n\text{local}-1} x_i y_i,
\]

where \(n\text{local}\) corresponds to the number of components in the vector on this MPI task (or \(n\text{local} = n\) for MPI-unaware applications).

Arguments

- \texttt{x} (N_Vector) a NVECTOR object
- \texttt{y} (N_Vector) a NVECTOR object

Return value \texttt{realtype}

F2003 Name \texttt{FN_VDotProdLocal}
\end{verbatim}

\begin{verbatim}
N_VMaxNormLocal
Call   m = N_VMaxNormLocal(x);
Description  This routine computes the MPI task-local portion of the maximum norm of the N_Vector \(x\):

\[
m = \max_{0 \leq i < n\text{local}} |x_i|,
\]

where \(n\text{local}\) corresponds to the number of components in the vector on this MPI task (or \(n\text{local} = n\) for MPI-unaware applications).

Arguments

- \texttt{x} (N_Vector) a NVECTOR object

Return value \texttt{realtype}

F2003 Name \texttt{FN_VMaxNormLocal}
\end{verbatim}

\begin{verbatim}
N_VMinLocal
Call   m = N_VMinLocal(x);
\end{verbatim}
6.1 The NVECTOR API

Description This routine computes the smallest element of the MPI task-local portion of the N_Vector:

\[ m = \min_{0 \leq i < n_{\text{local}}} x_i, \]

where \( n_{\text{local}} \) corresponds to the number of components in the vector on this MPI task (or \( n_{\text{local}} = n \) for MPI-unaware applications).

Arguments \( x \) (N_Vector) a NVECTOR object

Return value realtype

F2003 Name FN_VMinLocal

\[ \text{FN_VL1NormLocal} \]

Call \( n = \text{FN_VL1NormLocal}(x); \)

Description This routine computes the MPI task-local portion of the \( \ell_1 \) norm of the N_Vector \( x \):

\[ n = \sum_{i=0}^{n_{\text{local}}-1} |x_i|, \]

where \( n_{\text{local}} \) corresponds to the number of components in the vector on this MPI task (or \( n_{\text{local}} = n \) for MPI-unaware applications).

Arguments \( x \) (N_Vector) a NVECTOR object

Return value realtype

F2003 Name FN_VL1NormLocal

\[ \text{FN_VWSqrSumLocal} \]

Call \( s = \text{FN_VWSqrSumLocal}(x,w); \)

Description This routine computes the MPI task-local portion of the weighted squared sum of the N_Vector \( x \) with weight vector \( w \):

\[ s = \sum_{i=0}^{n_{\text{local}}-1} (x_iw_i)^2, \]

where \( n_{\text{local}} \) corresponds to the number of components in the vector on this MPI task (or \( n_{\text{local}} = n \) for MPI-unaware applications).

Arguments \( x \) (N_Vector) a NVECTOR object
\( w \) (N_Vector) a NVECTOR object containing weights

Return value realtype

F2003 Name FN_VWSqrSumLocal

\[ \text{FN_VWSqrSumMaskLocal} \]

Call \( s = \text{FN_VWSqrSumMaskLocal}(x,w,id); \)

Description This routine computes the MPI task-local portion of the weighted squared sum of the N_Vector \( x \) with weight vector \( w \) built using only the elements of \( x \) corresponding to positive elements of the N_Vector \( id \):

\[ m = \sum_{i=0}^{n_{\text{local}}-1} (x_iw_iH(id_i))^2, \quad \text{where} \quad H(\alpha) = \begin{cases} 1 & \alpha > 0 \\ 0 & \alpha \leq 0 \end{cases} \]

and \( n_{\text{local}} \) corresponds to the number of components in the vector on this MPI task (or \( n_{\text{local}} = n \) for MPI-unaware applications).
Description of the NVECTOR module

Arguments
- \( x \) (N_Vector) a NVECTOR object
- \( w \) (N_Vector) a NVECTOR object containing weights
- \( \text{id} \) (N_Vector) a NVECTOR object used as a mask

Return value: \text{realtype}

F2003 Name: \text{FN_VWSpSumMaskLocal}

\text{N_VInvTestLocal}

Call: \( t = \text{N_VInvTestLocal}(x, z) \);

Description: Sets the MPI task-local components of the N_Vector \( z \) to be the inverses of the components of the N_Vector \( x \), with prior testing for zero values:

\[ z_i = \frac{1.0}{x_i}, \quad i = 0, \ldots, n_{\text{local}} - 1, \]

where \( n_{\text{local}} \) corresponds to the number of components in the vector on this MPI task (or \( n_{\text{local}} = n \) for MPI-unaware applications).

Arguments
- \( x \) (N_Vector) a NVECTOR object
- \( z \) (N_Vector) an output NVECTOR object

Return value: Returns a \text{booleantype} with the value \text{SUNTRUE} if all task-local components of \( x \) are nonzero (successful inversion) and with the value \text{SUNFALSE} otherwise.

F2003 Name: \text{FN_VInvTestLocal}

\text{N_VConstrMaskLocal}

Call: \( t = \text{N_VConstrMaskLocal}(c, x, m) \);

Description: Performs the following constraint tests:

- \( x_i > 0 \) if \( c_i = 2 \),
- \( x_i \geq 0 \) if \( c_i = 1 \),
- \( x_i \leq 0 \) if \( c_i = -1 \),
- \( x_i < 0 \) if \( c_i = -2 \), and
- no test if \( c_i = 0 \),

for all MPI task-local components of the vectors. It sets a mask vector \( m \), with elements equal to 1.0 where the constraint test failed, and 0.0 where the test passed. This routine is used only for constraint checking.

Arguments
- \( c \) (realtype) scalar constraint value
- \( x \) (N_Vector) a NVECTOR object
- \( m \) (N_Vector) output mask vector

Return value: Returns a \text{booleantype} with the value \text{SUNFALSE} if any task-local element failed the constraint test and the value \text{SUNTRUE} if all passed.

F2003 Name: \text{FN_VConstrMaskLocal}

\text{N_VMinQuotientLocal}

Call: \( \text{minq} = \text{N_VMinQuotientLocal}(\text{num}, \text{denom}) \);

Description: This routine returns the minimum of the quotients obtained by term-wise dividing \( \text{num}_i \) by \( \text{denom}_i \), for all MPI task-local components of the vectors. A zero element in \text{denom} will be skipped. If no such quotients are found, then the large value \text{BIG_REAL} (defined in the header file \text{sundials_types.h}) is returned.
6.1 The NVECTOR API

Arguments  
\begin{itemize}
  \item num (N_Vector) a NVECTOR object used as the numerator
  \item denom (N_Vector) a NVECTOR object used as the denominator
\end{itemize}

Return value  realtype

F2003 Name  FN_VMinQuotientLocal

6.1.5 NVECTOR utility functions

To aid in the creation of custom NVECTOR modules the generic NVECTOR module provides three utility functions \texttt{N_VNewEmpty}, \texttt{N_VCopyOps} and \texttt{N_VFreeEmpty}. When used in custom NVECTOR constructors and clone routines these functions will ease the introduction of any new optional vector operations to the NVECTOR API by ensuring only required operations need to be set and all operations are copied when cloning a vector.

To aid the use of arrays of NVECTOR objects, the generic NVECTOR module also provides the utility functions \texttt{N_VCloneVectorArray}, \texttt{N_VCloneVectorArrayEmpty}, and \texttt{N_VDestroyVectorArray}.

\begin{verbatim}
N_VNewEmpty
\end{verbatim}

\begin{verbatim}
Call  \texttt{v = N_VNewEmpty();}
Description  The function \texttt{N_VNewEmpty} allocates a new generic NVECTOR object and initializes its content pointer and the function pointers in the operations structure to NULL.
Arguments  None
Return value  This function returns an \texttt{N_Vector} object. If an error occurs when allocating the object, then this routine will return NULL.
\end{verbatim}

F2003 Name  FN_VNewEmpty

\begin{verbatim}
N_VCopyOps
\end{verbatim}

\begin{verbatim}
Call  \texttt{retval = N_VCopyOps\texttt{(w, v);}\texttt{)}
Description  The function \texttt{N_VCopyOps} copies the function pointers in the ops structure of \texttt{w} into the ops structure of \texttt{v}.
Arguments  \texttt{w} (N_Vector) the vector to copy operations from \texttt{v} (N_Vector) the vector to copy operations to
Return value  This returns \texttt{0} if successful and a non-zero value if either of the inputs are NULL or the ops structure of either input is NULL.
\end{verbatim}

F2003 Name  FN_VCopyOps

\begin{verbatim}
N_VFreeEmpty
\end{verbatim}

\begin{verbatim}
Call  \texttt{N_VFreeEmpty(v);}\texttt{)
Description  This routine frees the generic \texttt{N_Vector} object, under the assumption that any implementation-specific data that was allocated within the underlying content structure has already been freed. It will additionally test whether the ops pointer is NULL, and, if it is not, it will free it as well.
Arguments  \texttt{v} (N_Vector)
Return value  None
\end{verbatim}

F2003 Name  FN_VFreeEmpty
Description of the NVECTOR module

**N_VCloneEmptyVectorArray**

Call

\[
\text{vecarray} = \text{N_VCloneEmptyVectorArray}(\text{count}, w);
\]

Description Creates an array of \(\text{count}\) variables of type \(\text{N_Vector}\), each of the same type as the existing \(\text{N_Vector}\) \(w\). It achieves this by calling the implementation-specific \(\text{N_VCloneEmpty}\) operation.

Arguments

- \(\text{count}\) (int) the size of the vector array
- \(w\) (\(\text{N_Vector}\)) the vector to clone

Return value Returns an array of \(\text{count}\) \(\text{N_Vector}\) objects if successful, or NULL if an error occurred while cloning.

**N_VCloneVectorArray**

Call

\[
\text{vecarray} = \text{N_VCloneVectorArray}(\text{count}, w);
\]

Description Creates an array of \(\text{count}\) variables of type \(\text{N_Vector}\), each of the same type as the existing \(\text{N_Vector}\) \(w\). It achieves this by calling the implementation-specific \(\text{N_VClone}\) operation.

Arguments

- \(\text{count}\) (int) the size of the vector array
- \(w\) (\(\text{N_Vector}\)) the vector to clone

Return value Returns an array of \(\text{count}\) \(\text{N_Vector}\) objects if successful, or NULL if an error occurred while cloning.

**N_VDestroyVectorArray**

Call

\[
\text{N_VDestroyVectorArray}(\text{count}, w);
\]

Description Destroys (frees) an array of variables of type \(\text{N_Vector}\). It depends on the implementation-specific \(\text{N_VDestroy}\) operation.

Arguments

- \(\text{vs}\) (\(\text{N_Vector}\)) the array of vectors to destroy
- \(\text{count}\) (int) the size of the vector array

Return value None

**N_VNewVectorArray**

Call

\[
\text{vecarray} = \text{N_VNewVectorArray}(\text{count});
\]

Description Returns an empty \(\text{N_Vector}\) array large enough to hold \(\text{count}\) \(\text{N_Vector}\) objects. This function is primarily meant for users of the Fortran 2003 interface.

Arguments

- \(\text{count}\) (int) the size of the vector array

Return value Returns a \(\text{N_Vector}\) if successful, Returns NULL if an error occurred.

Notes Users of the Fortran 2003 interface to the \(\text{N_VManyVector}\) or \(\text{N_VMPIManyVector}\) will need this to create an array to hold the subvectors. Note that this function does restrict the the max number of subvectors usable with the \(\text{N_VManyVector}\) and \(\text{N_VMPIManyVector}\) to the max size of an int despite the ManyVector implementations accepting a subvector count larger than this value.

F2003 Name \(\text{FN_VNewVectorArray}\)
Table 6.1: Vector Identifications associated with vector kernels supplied with Sundials.

<table>
<thead>
<tr>
<th>Vector ID</th>
<th>Vector type</th>
<th>ID Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUNDIALS_NVEC_SERIAL</td>
<td>Serial</td>
<td>0</td>
</tr>
<tr>
<td>SUNDIALS_NVEC_PARALLEL</td>
<td>Distributed memory parallel (MPI)</td>
<td>1</td>
</tr>
<tr>
<td>SUNDIALS_NVEC_OPENMP</td>
<td>OpenMP shared memory parallel</td>
<td>2</td>
</tr>
<tr>
<td>SUNDIALS_NVEC_PTHREADS</td>
<td>PThreads shared memory parallel</td>
<td>3</td>
</tr>
<tr>
<td>SUNDIALS_NVEC_PARHYP</td>
<td>hypre ParHyp parallel vector</td>
<td>4</td>
</tr>
<tr>
<td>SUNDIALS_NVEC_PETSC</td>
<td>PETSc parallel vector</td>
<td>5</td>
</tr>
<tr>
<td>SUNDIALS_NVEC_CUDA</td>
<td>CUDA parallel vector</td>
<td>6</td>
</tr>
<tr>
<td>SUNDIALS_NVEC_RAJA</td>
<td>RAJA parallel vector</td>
<td>7</td>
</tr>
<tr>
<td>SUNDIALS_NVEC_OPENMPDEV</td>
<td>OpenMP parallel vector with device offloading</td>
<td>8</td>
</tr>
<tr>
<td>SUNDIALS_NVEC_TRILINOS</td>
<td>Trilinos Tpetra vector</td>
<td>9</td>
</tr>
<tr>
<td>SUNDIALS_NVEC_MANYVECTOR</td>
<td>“ManyVector” vector</td>
<td>10</td>
</tr>
<tr>
<td>SUNDIALS_NVEC_MPI_MANYVECTOR</td>
<td>MPI-enabled “ManyVector” vector</td>
<td>11</td>
</tr>
<tr>
<td>SUNDIALS_NVEC_MPIPLUSX</td>
<td>MPI+X vector</td>
<td>12</td>
</tr>
<tr>
<td>SUNDIALS_NVEC_CUSTOM</td>
<td>User-provided custom vector</td>
<td>13</td>
</tr>
</tbody>
</table>

N_VGetVecAtIndexVectorArray

Call

\[ v = N_{\text{VGetVecAtIndexVectorArray}}(\text{vecs, index}); \]

Description

Returns the N_Vector object stored in the vector array at the provided index. This function is primarily meant for users of the Fortran 2003 interface.

Arguments

- \text{vecs} (N_Vector*) the array of vectors to index
- \text{index} (int) the index of the vector to return

Return value

Returns the N_Vector object stored in the vector array at the provided index. Returns NULL if an error occurred.

F2003 Name \text{FN_{VGetVecAtIndexVectorArray}}

N_VSetVecAtIndexVectorArray

Call

\[ N_{\text{VSetVecAtIndexVectorArray}}(\text{vecs, index, v}); \]

Description

Sets the N_Vector object stored in the vector array at the provided index. This function is primarily meant for users of the Fortran 2003 interface.

Arguments

- \text{vecs} (N_Vector*) the array of vectors to index
- \text{index} (int) the index of the vector to return
- \text{v} (N_Vector) the vector to store at the index

Return value

None

F2003 Name \text{FN_{VSetVecAtIndexVectorArray}}

### 6.1.6 NVECTOR identifiers

Each NVECTOR implementation included in Sundials has a unique identifier specified in enumeration and shown in Table 6.1.

### 6.1.7 The generic NVECTOR module implementation

The generic N_Vector type is a pointer to a structure that has an implementation-dependent content field containing the description and actual data of the vector, and an ops field pointing to a structure with generic vector operations. The type N_Vector is defined as
typedef struct _generic_N_Vector *N_Vector;

struct _generic_N_Vector {
    void *content;
    struct _generic_N_Vector_Ops *ops;
};

The _generic_N_Vector_Ops structure is essentially a list of pointers to the various actual vector operations, and is defined as

struct _generic_N_Vector_Ops {
    N_Vector_ID (*nvgetvectorid)(N_Vector);
    N_Vector (*nvclone)(N_Vector);
    N_Vector (*nvcloneempty)(N_Vector);
    void (*nvdestroy)(N_Vector);
    void (*nvspace)(N_Vector, sunindextype *, sunindextype *);
    realtype* (*nvgetarraypointer)(N_Vector);
    void (*nvsetarraypointer)(realtype *, N_Vector);
    void* (*nvgetcommunicator)(N_Vector);
    sunindextype (*nvgetlength)(N_Vector);
    void (*nvlinearsum)(realtype, N_Vector, realtype, N_Vector, N_Vector);
    void (*nvconst)(realtype, N_Vector);
    void (*nvprod)(N_Vector, N_Vector, N_Vector);
    void (*nvdiv)(N_Vector, N_Vector, N_Vector);
    void (*nyscale)(realtype, N_Vector, N_Vector);
    void (*nvabs)(N_Vector, N_Vector);
    void (*ninv)(N_Vector, N_Vector);
    void (*nvaddconst)(N_Vector, realtype, N_Vector);
    realtype (*nvdotprod)(N_Vector, N_Vector);
    realtype (*nvmaxnorm)(N_Vector);
    realtype (*nvwrmsnorm)(N_Vector, N_Vector);
    realtype (*nvwrmsnormmask)(N_Vector, N_Vector, N_Vector);
    realtype (*nvmin)(N_Vector);
    realtype (*nvwl2norm)(N_Vector, N_Vector);
    realtype (*nvl1norm)(N_Vector);
    realtype (*nvcompare)(realtype, N_Vector, N_Vector);
    booleantype (*nvinvtest)(N_Vector, N_Vector);
    booleantype (*nvconstrmask)(N_Vector, N_Vector);
    realtype (*nvminquotient)(N_Vector, N_Vector);
    int (*nvlinearcombination)(int, realtype*, N_Vector*, N_Vector);
    int (*nvscaleaddmulti)(int, realtype*, N_Vector, N_Vector*, N_Vector*);
    int (*nvdotprodmulti)(int, N_Vector, N_Vector*, realtype*);
    int (*nvlinearsumvectorarray)(int, realtype, N_Vector*, N_Vector*, N_Vector*);
    int (*nvwrmsnormvectorarray)(int, N_Vector*, N_Vector*);
    int (*nvwrmsnormmaskvectorarray)(int, N_Vector*, N_Vector*, N_Vector, realtype*);
    int (*nvscaleaddmultivectorarray)(int, int, realtype*, N_Vector*, N_Vector*, N_Vector**);
    int (*nvlinearcombinationvectorarray)(int, int, realtype*, N_Vector**, N_Vector*);
    realtype (*nvdotprodlocal)(N_Vector, N_Vector);
    realtype (*nvmaxnormlocal)(N_Vector);
The generic NVECTOR module defines and implements the vector operations acting on an N_Vector. These routines are nothing but wrappers for the vector operations defined by a particular NVECTOR implementation, which are accessed through the ops field of the N_Vector structure. To illustrate this point we show below the implementation of a typical vector operation from the generic NVECTOR module, namely N_VScale, which performs the scaling of a vector $x$ by a scalar $c$:

```c
void N_VScale(realtype c, N_Vector x, N_Vector z)
{
    z->ops->nvscale(c, x, z);
}
```

Section 6.1.1 defines a complete list of all standard vector operations defined by the generic NVECTOR module. Sections 6.1.2, 6.1.3 and 6.1.4 list optional fused, vector array and local reduction operations, respectively.

The Fortran 2003 interface provides a bind(C) derived-type for the generic N_Vector and the generic N_Vector_Ops structures. Their definition is given below.

```fortran
type, bind(C), public :: N_Vector
  type(C_PTR), public :: content
  type(C_PTR), public :: ops
end type N_Vector

type, bind(C), public :: N_Vector_Ops
  type(C_FUNPTR), public :: nvgetvectorid
  type(C_FUNPTR), public :: nvclone
  type(C_FUNPTR), public :: nvcloneempty
  type(C_FUNPTR), public :: nvdestroy
  type(C_FUNPTR), public :: nvspace
  type(C_FUNPTR), public :: nvgetarraypointer
  type(C_FUNPTR), public :: nvsetarraypointer
  type(C_FUNPTR), public :: nvgetcommunicator
  type(C_FUNPTR), public :: nvgetlength
  type(C_FUNPTR), public :: nvlinsum
  type(C_FUNPTR), public :: nvconst
  type(C_FUNPTR), public :: nvprod
  type(C_FUNPTR), public :: nvdiv
  type(C_FUNPTR), public :: nvscale
  type(C_FUNPTR), public :: nvabs
  type(C_FUNPTR), public :: nvinv
  type(C_FUNPTR), public :: nvaddconst
  type(C_FUNPTR), public :: nvdotprod
  type(C_FUNPTR), public :: nvmaxnorm
  type(C_FUNPTR), public :: nvwrmsnorm
  type(C_FUNPTR), public :: nvwrmsnormmask
  type(C_FUNPTR), public :: nvmin
  type(C_FUNPTR), public :: nvl2norm
```

Description of the NVECTOR module

6.1.8 Implementing a custom NVECTOR

A particular implementation of the NVECTOR module must:

- Specify the content field of N_Vector.
- Define and implement the vector operations. Note that the names of these routines should be unique to that implementation in order to permit using more than one NVECTOR module (each with different N_Vector internal data representations) in the same code.
- Define and implement user-callable constructor and destructor routines to create and free an N_Vector with the new content field and with ops pointing to the new vector operations.
- Optionally, define and implement additional user-callable routines acting on the newly defined N_Vector (e.g., a routine to print the content for debugging purposes).
- Optionally, provide accessor macros as needed for that particular implementation to be used to access different parts in the content field of the newly defined N_Vector.

It is recommended that a user-supplied NVECTOR implementation returns the SUNDIALS_NVEC_CUSTOM identifier from the N_VGetVectorID function.

To aid in the creation of custom NVECTOR modules the generic NVECTOR module provides two utility functions N_VNewEmpty and N_VCopyOps. When used in custom NVECTOR constructors and clone routines these functions will ease the introduction of any new optional vector operations to the NVECTOR API by ensuring only required operations need to be set and all operations are copied when cloning a vector.

6.1.8.1 Support for complex-valued vectors

While sundials itself is written under an assumption of real-valued data, it does provide limited support for complex-valued problems. However, since none of the built-in NVECTOR modules supports
complex-valued data, users must provide a custom NVECTOR implementation for this task. Many of the NVECTOR routines described in Sections 6.1.1-6.1.4 above naturally extend to complex-valued vectors; however, some do not. To this end, we provide the following guidance:

- **N_VMin** and **N_VMinLocal** should return the minimum of all real components of the vector, i.e., \( m = \min_i \text{real}(x_i) \).
- **N_VConst** (and similarly **N_VConstVectorArray**) should set the real components of the vector to the input constant, and set all imaginary components to zero, i.e., \( z_i = c + 0j, i = 0, \ldots, n-1 \).
- **N_VAddConst** should only update the real components of the vector with the input constant, leaving all imaginary components unchanged.
- **N_VWrmNorm**, **N_VWrmNormMask**, **N_VWsqSumLocal** and **N_VWsqSumMaskLocal** should assume that all entries of the weight vector \( w \) and the mask vector \( id \) are real-valued.
- **N_VDotProd** should mathematically return a complex number for complex-valued vectors; as this is not possible with SUNDIALS' current realtype, this routine should be set to NULL in the custom NVECTOR implementation.
- **N_VCompare**, **N_VConstrMask**, **N_VMinQuotient**, **N_VConstrMaskLocal** and **N_VMinQuotientLocal** are ill-defined due to the lack of a clear ordering in the complex plane. These routines should be set to NULL in the custom NVECTOR implementation.

While many SUNDIALS solver modules may be utilized on complex-valued data, others cannot. Specifically, although both SUNDNLS_NNOLNEW and SUNDNLS_FIXEP will be used with any of the IVP solvers (CVODE, CVODES, IDA, IDAS and ARKODE) for complex-valued problems, the Anderson-acceleration feature SUNDNLS_FIXEP cannot be used due to its reliance on N_VDotProd. By this same logic, the Anderson acceleration feature within KINSOL also will not work with complex-valued vectors.

Similarly, although each package’s linear solver interface (e.g., CVLS) may be used on complex-valued problems, none of the built-in SUNMATRIX or SUNLINSOL modules work. Hence a complex-valued user should provide a custom SUNLINSOL (and optionally a custom SUNMATRIX) implementation for solving linear systems, and then attach this module as normal to the package’s linear solver interface.

Finally, constraint-handling features of each package cannot be used for complex-valued data, due to the issue of ordering in the complex plane discussed above with N_VCompare, N_VConstrMask, N_VMinQuotient, N_VConstrMaskLocal and N_VMinQuotientLocal.

We provide a simple example of a complex-valued example problem, including a custom complex-valued Fortran 2003 NVECTOR module, in the files examples/arkode/F2003_custom/ark_analytic_complex_f2003.f90, examples/arkode/F2003_custom/fnvector_complex_mod.f90, and examples/arkode/F2003_custom/test_fnvector_complex_mod.f90.

### 6.2 NVECTOR functions used by IDA

In Table 6.2 below, we list the vector functions used in the NVECTOR module used by the IDA package. The table also shows, for each function, which of the code modules uses the function. The IDA column shows function usage within the main integrator module, while the remaining columns show function usage within the IDALS linear solvers interface, the IDABBDPRE preconditioner module, and the FIDA module.

At this point, we should emphasize that the IDA user does not need to know anything about the usage of vector functions by the IDA code modules in order to use IDA. The information is presented as an implementation detail for the interested reader.

Special cases (numbers match markings in table):
## Table 6.2: List of vector functions usage by IDA code modules

<table>
<thead>
<tr>
<th>Function</th>
<th>IDA</th>
<th>IDALS</th>
<th>IDABBDPR</th>
<th>FIDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>N_VGetVectorID</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N_VGetLength</td>
<td></td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N_VClone</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>N_VCloneEmpty</td>
<td></td>
<td>1</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>N_VDestroy</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>N_VSpace</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>N_VGetArrayPointer</td>
<td></td>
<td>1</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>N_VSetArrayPointer</td>
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<td>✓</td>
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<tr>
<td>N_VLinearSum</td>
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<td>N_VConst</td>
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<tr>
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<td></td>
</tr>
<tr>
<td>N_VAddConst</td>
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</tr>
<tr>
<td>N_VMaxNorm</td>
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<tr>
<td>N_VWrmsNorm</td>
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</tr>
<tr>
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<tr>
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<tr>
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<tr>
<td>N_VLinearCombination</td>
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</tr>
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</tr>
<tr>
<td>N_VScaleVectorArray</td>
<td>✓</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

1. These routines are only required if an internal difference-quotient routine for constructing dense or band Jacobian matrices is used.

2. This routine is optional, and is only used in estimating space requirements for IDA modules for user feedback.

3. The optional function \texttt{N_VDotProdMulti} is only used when Classical Gram-Schmidt is enabled with SPGMR or SPFMR. The remaining operations from Tables 6.1.2 and 6.1.3 not listed above are unused and a user-supplied NVVECTOR module for IDA could omit these operations.

4. This routine is only used when an iterative or matrix iterative SUNLINSOL module is supplied to IDA.

Of the functions listed in Table 6.1.1, \texttt{N_VWL2Norm}, \texttt{N_VL1Norm}, \texttt{N_VInvTest}, and \texttt{N_VGetCommunicator} are not used by IDA. Therefore a user-supplied NVVECTOR module for IDA could omit these functions (although some may be needed by SUNNONLINSOL or SUNLINSOL modules).
6.3 The NVECTOR_SERIAL implementation

The serial implementation of the NVVECTOR module provided with SUNDIALS, NVVECTOR_SERIAL, defines the content field of NV_VECTOR to be a structure containing the length of the vector, a pointer to the beginning of a contiguous data array, and a boolean flag own_data which specifies the ownership of data.

```c
struct _N_VectorContent_Serial {
    sunindextype length;
    booleantype own_data;
    realtype *data;
};
```

The header file to include when using this module is nvector_serial.h. The installed module library to link to is libsundials_nvecserial.lib where .lib is typically .so for shared libraries and .a for static libraries.

6.3.1 NVVECTOR_SERIAL accessor macros

The following macros are provided to access the content of an NVVECTOR_SERIAL vector. The suffix _S in the names denotes the serial version.

- **NV_CONTENT_S**
  
  This routine gives access to the contents of the serial vector NV_VECTOR.
  
  The assignment \( v\_cont = \text{NV\_CONTENT\_S}(v) \) sets \( v\_cont \) to be a pointer to the serial NV_VECTOR content structure.
  
  Implementation:
  ```c
  #define NV_CONTENT_S(v) ( (N_VectorContent_Serial)(v->content) )
  ```

- **NV_OWN_DATA_S, NV_DATA_S, NV_LENGTH_S**
  
  These macros give individual access to the parts of the content of a serial NV_VECTOR.
  
  The assignment \( v\_data = \text{NV\_DATA\_S}(v) \) sets \( v\_data \) to be a pointer to the first component of the data for the NV_VECTOR \( v \). The assignment \( \text{NV\_DATA\_S}(v) = v\_data \) sets the component array of \( v \) to be \( v\_data \) by storing the pointer \( v\_data \).
  
  The assignment \( v\_len = \text{NV\_LENGTH\_S}(v) \) sets \( v\_len \) to be the length of \( v \). On the other hand, the call \( \text{NV\_LENGTH\_S}(v) = \text{len\_v} \) sets the length of \( v \) to be \( \text{len\_v} \).
  
  Implementation:
  ```c
  #define NV_OWN_DATA_S(v) ( NV_CONTENT_S(v)->own_data )
  #define NV_DATA_S(v) ( NV_CONTENT_S(v)->data )
  #define NV_LENGTH_S(v) ( NV_CONTENT_S(v)->length )
  ```

- **NV_Ith_S**

  This macro gives access to the individual components of the data array of an NV_VECTOR.

  The assignment \( r = \text{NV\_Ith\_S}(v,i) \) sets \( r \) to be the value of the \( i \)-th component of \( v \). The assignment \( \text{NV\_Ith\_S}(v,i) = r \) sets the value of the \( i \)-th component of \( v \) to be \( r \).

  Here \( i \) ranges from 0 to \( n-1 \) for a vector of length \( n \).

  Implementation:
  ```c
  #define NV_Ith_S(v,i) ( NV_DATA_S(v)[i] )
  ```
6.3.2 NVECTOR_SERIAL functions

The NVECTOR_SERIAL module defines serial implementations of all vector operations listed in Tables 6.1.1, 6.1.2, 6.1.3 and 6.1.4. Their names are obtained from those in these tables by appending the suffix _Serial (e.g. N_VDestroy_Serial). All the standard vector operations listed in 6.1.1 with the suffix _Serial appended are callable via the FORTRAN 2003 interface by prepending an ‘F’ (e.g. FN_VDestroy_Serial).

The module NVECTOR_SERIAL provides the following additional user-callable routines:

**N_VNew_Serial**
Prototype: \( N\_Vector \ N\_VNew\_Serial(sunindextype \ vec\_length) \);
Description: This function creates and allocates memory for a serial \( N\_Vector \). Its only argument is the vector length.
F2003 Name: This function is callable as FN_VNew_Serial when using the Fortran 2003 interface module.

**N_VNewEmpty_Serial**
Prototype: \( N\_Vector \ N\_VNewEmpty\_Serial(sunindextype \ vec\_length) \);
Description: This function creates a new serial \( N\_Vector \) with an empty (NULL) data array.
F2003 Name: This function is callable as FN_VNewEmpty_Serial when using the Fortran 2003 interface module.

**N_VMake_Serial**
Prototype: \( N\_Vector \ N\_VMake\_Serial(sunindextype \ vec\_length, realtype \]* v\_data) \);
Description: This function creates and allocates memory for a serial vector with user-provided data array.
(This function does not allocate memory for v\_data itself.)
F2003 Name: This function is callable as FN_VMake_Serial when using the Fortran 2003 interface module.

**N_VCloneVectorArray_Serial**
Prototype: \( N\_Vector \ \ast N\_VCloneVectorArray\_Serial(int \ count, N\_Vector \ w) \);
Description: This function creates (by cloning) an array of count serial vectors.
F2003 Name: This function is callable as FN_VCloneVectorArray_Serial when using the Fortran 2003 interface module.

**N_VCloneVectorArrayEmpty_Serial**
Prototype: \( N\_Vector \ \ast N\_VCloneVectorArrayEmpty\_Serial(int \ count, N\_Vector \ w) \);
Description: This function creates (by cloning) an array of count serial vectors, each with an empty (NULL) data array.
F2003 Name: This function is callable as FN_VCloneVectorArrayEmpty_Serial when using the Fortran 2003 interface module.
6.3 The NVECTOR_SERIAL implementation

**N_VDestroyVectorArray_Serial**

Prototype: `void N_VDestroyVectorArray_Serial(N_Vector *vs, int count);`

Description: This function frees memory allocated for the array of `count` variables of type `N_Vector` created with `N_VCloneVectorArray_Serial` or with `N_VCloneVectorArrayEmpty_Serial`.

F2003 Name: This function is callable as `FN_VDestroyVectorArray_Serial` when using the Fortran 2003 interface module.

**N_VPrint_Serial**

Prototype: `void N_VPrint_Serial(N_Vector v);`

Description: This function prints the content of a serial vector to `stdout`.

F2003 Name: This function is callable as `FN_VPrint_Serial` when using the Fortran 2003 interface module.

**N_VPrintFile_Serial**

Prototype: `void N_VPrintFile_Serial(N_Vector v, FILE *outfile);`

Description: This function prints the content of a serial vector to `outfile`.

F2003 Name: This function is callable as `FN_VPrintFile_Serial` when using the Fortran 2003 interface module.

By default all fused and vector array operations are disabled in the NVECTOR_SERIAL module. The following additional user-callable routines are provided to enable or disable fused and vector array operations for a specific vector. To ensure consistency across vectors it is recommended to first create a vector with `N_VNew_Serial`, enable/disable the desired operations for that vector with the functions below, and create any additional vectors from that vector using `N_VClone`. This guarantees the new vectors will have the same operations enabled/disabled as cloned vectors inherit the same enable/disable options as the vector they are cloned from while vectors created with `N_VNew_Serial` will have the default settings for the NVECTOR_SERIAL module.

**N_VEnableFusedOps_Serial**

Prototype: `int N_VEnableFusedOps_Serial(N_Vector v, boolantype tf);`

Description: This function enables (SUNTRUE) or disables (SUNFALSE) all fused and vector array operations in the serial vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are `NULL`.

F2003 Name: This function is callable as `FN_VEnableFusedOps_Serial` when using the Fortran 2003 interface module.

**N_VEnableLinearCombination_Serial**

Prototype: `int N_VEnableLinearCombination_Serial(N_Vector v, boolantype tf);`

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination fused operation in the serial vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are `NULL`.

F2003 Name: This function is callable as `FN_VEnableLinearCombination_Serial` when using the Fortran 2003 interface module.
**N_EnableScaleAddMulti_Serial**

Prototype: `int N_EnableScaleAddMulti_Serial(N_Vector v, booleantype tf);`

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector to multiple vectors fused operation in the serial vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

F2003 Name: This function is callable as `FN_EnableScaleAddMulti_Serial` when using the Fortran 2003 interface module.

**N_EnableDotProdMulti_Serial**

Prototype: `int N_EnableDotProdMulti_Serial(N_Vector v, booleantype tf);`

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the multiple dot products fused operation in the serial vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

F2003 Name: This function is callable as `FN_EnableDotProdMulti_Serial` when using the Fortran 2003 interface module.

**N_EnableLinearSumVectorArray_Serial**

Prototype: `int N_EnableLinearSumVectorArray_Serial(N_Vector v, booleantype tf);`

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the linear sum operation for vector arrays in the serial vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

F2003 Name: This function is callable as `FN_EnableLinearSumVectorArray_Serial` when using the Fortran 2003 interface module.

**N_EnableScaleVectorArray_Serial**

Prototype: `int N_EnableScaleVectorArray_Serial(N_Vector v, booleantype tf);`

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the scale operation for vector arrays in the serial vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

F2003 Name: This function is callable as `FN_EnableScaleVectorArray_Serial` when using the Fortran 2003 interface module.

**N_EnableConstVectorArray_Serial**

Prototype: `int N_EnableConstVectorArray_Serial(N_Vector v, booleantype tf);`

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the const operation for vector arrays in the serial vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

F2003 Name: This function is callable as `FN_EnableConstVectorArray_Serial` when using the Fortran 2003 interface module.

**N_EnableWrmsNormVectorArray_Serial**

Prototype: `int N_EnableWrmsNormVectorArray_Serial(N_Vector v, booleantype tf);`

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the WRMS norm operation for vector arrays in the serial vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.
F2003 Name This function is callable as FN_VEnableWrmsNormVectorArray_Serial when using the Fortran 2003 interface module.

**N_VEnableWrmsNormMaskVectorArray_Serial**

Prototype
```
int N_VEnableWrmsNormMaskVectorArray_Serial(N_Vector v, booleantype tf);
```

Description This function enables (SUNTRUE) or disables (SUNFALSE) the masked WRMS norm operation for vector arrays in the serial vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

F2003 Name This function is callable as FN_VEnableWrmsNormMaskVectorArray_Serial when using the Fortran 2003 interface module.

**N_VEnableScaleAddMultiVectorArray_Serial**

Prototype
```
int N_VEnableScaleAddMultiVectorArray_Serial(N_Vector v,
                                           booleantype tf);
```

Description This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector array to multiple vector arrays operation in the serial vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**N_VEnableLinearCombinationVectorArray_Serial**

Prototype
```
int N_VEnableLinearCombinationVectorArray_Serial(N_Vector v,
                                           booleantype tf);
```

Description This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination operation for vector arrays in the serial vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

Notes

- When looping over the components of an N_Vector v, it is more efficient to first obtain the component array via `v_data = NV_DATA_S(v)` and then access `v_data[i]` within the loop than it is to use `NV_Ith_S(v,i)` within the loop.

- `N_VNewEmpty_Serial`, `N_VMake_Serial`, and `N_VCloneVectorArrayEmpty_Serial` set the field `own_data = SUNFALSE`. `N_VDestroy_Serial` and `N_VDestroyVectorArray_Serial` will not attempt to free the pointer `data` for any N_Vector with `own_data` set to SUNFALSE. In such a case, it is the user’s responsibility to deallocate the `data` pointer.

- To maximize efficiency, vector operations in the nvector_serial implementation that have more than one N_Vector argument do not check for consistent internal representation of these vectors. It is the user’s responsibility to ensure that such routines are called with N_Vector arguments that were all created with the same internal representations.

6.3.3 NVECTOR_SERIAL Fortran interfaces

The nvector_serial module provides a FORTRAN 2003 module as well as FORTRAN 77 style interface functions for use from FORTRAN applications.
**FORTRAN 2003 interface module**

The fnvector_serial_mod FORTRAN module defines interfaces to all nvector_serial C functions using the intrinsic iso_c_binding module which provides a standardized mechanism for interoperating with C. As noted in the C function descriptions above, the interface functions are named after the corresponding C function, but with a leading ‘F’. For example, the function N_VNew_Serial is interfaced as FN_VNew_Serial.

The FORTRAN 2003 nvector_serial interface module can be accessed with the use statement, i.e. use fnvector_serial_mod, and linking to the library libsundials_fnvector_serial_mod.lib in addition to the C library. For details on where the library and module file fnvector_serial_mod.mod are installed see Appendix A. We note that the module is accessible from the FORTRAN 2003 SUNDIALS integrators without separately linking to the libsundials_fnvector_serial_mod library.

**FORTRAN 77 interface functions**

For solvers that include a FORTRAN 77 interface module, the nvector_serial module also includes a FORTRAN-callable function FNVINITS(code, NEQ, IER), to initialize this nvector_serial module. Here code is an input solver id (1 for cvode, 2 for ida, 3 for kinsol, 4 for arkode); NEQ is the problem size (declared so as to match C type long int); and IER is an error return flag equal 0 for success and -1 for failure.

### 6.4 The NVECTOR_PARALLEL implementation

The NVECTOR_PARALLEL implementation of the NVECTOR module provided with SUNDIALS is based on MPI. It defines the content field of N_Vector to be a structure containing the global and local lengths of the vector, a pointer to the beginning of a contiguous local data array, an MPI communicator, and a boolean flag own_data indicating ownership of the data array data.

```c
struct _N_VectorContent_Parallel {
    sunindextype local_length;
    sunindextype global_length;
    booleantype own_data;
    realtype *data;
    MPI_Comm comm;
};
```

The header file to include when using this module is nvector_parallel.h. The installed module library to link to is libsundials_nvecparallel.lib where .lib is typically .so for shared libraries and .a for static libraries.

### 6.4.1 NVECTOR_PARALLEL accessor macros

The following macros are provided to access the content of a NVECTOR_PARALLEL vector. The suffix _P in the names denotes the distributed memory parallel version.

- **NV_CONTENT_P**
  
  This macro gives access to the contents of the parallel vector N_Vector.

  The assignment `v_cont = NV_CONTENT_P(v)` sets `v_cont` to be a pointer to the N_Vector content structure of type struct _N_VectorContent_Parallel.

  Implementation:
  ```c
  #define NV_CONTENT_P(v) ( (N_VectorContent_Parallel)(v->content) )
  ```


  These macros give individual access to the parts of the content of a parallel N_Vector.
The assignment \( v_{\text{data}} = \text{NV\_DATA\_P}(v) \) sets \( v_{\text{data}} \) to be a pointer to the first component of the local data for the N\_Vector \( v \). The assignment \( \text{NV\_DATA\_P}(v) = v_{\text{data}} \) sets the component array of \( v \) to be \( v_{\text{data}} \) by storing the pointer \( v_{\text{data}} \).

The assignment \( v_{\text{llen}} = \text{NV\_LOCLENGTH\_P}(v) \) sets \( v_{\text{llen}} \) to be the length of the local part of \( v \). The call \( \text{NV\_LENGTH\_P}(v) = v_{\text{llen}} \) sets the local length of \( v \) to be \( v_{\text{llen}} \).

The assignment \( v_{\text{glen}} = \text{NV\_GLOBLENGTH\_P}(v) \) sets \( v_{\text{glen}} \) to be the global length of the vector \( v \). The call \( \text{NV\_GLOBLENGTH\_P}(v) = v_{\text{glen}} \) sets the global length of \( v \) to be \( v_{\text{glen}} \).

### Implementation:

- **NV\_OWN\_DATA\_P**

  \[
  \text{define } \text{NV\_OWN\_DATA\_P}(v) \text{ ( } \text{NV\_CONTENT\_P}(v)\rightarrow\text{own\_data} \text{ )}
  \]

- **NV\_DATA\_P**

  \[
  \text{define } \text{NV\_DATA\_P}(v) \text{ ( } \text{NV\_CONTENT\_P}(v)\rightarrow\text{data} \text{ )}
  \]

- **NV\_LOCLENGTH\_P**

  \[
  \text{define } \text{NV\_LOCLENGTH\_P}(v) \text{ ( } \text{NV\_CONTENT\_P}(v)\rightarrow\text{local\_length} \text{ )}
  \]

- **NV\_GLOBLENGTH\_P**

  \[
  \text{define } \text{NV\_GLOBLENGTH\_P}(v) \text{ ( } \text{NV\_CONTENT\_P}(v)\rightarrow\text{global\_length} \text{ )}
  \]

• **NV\_COMM\_P**

  This macro provides access to the MPI communicator used by the NVECTOR\_PARALLEL vectors.

  Implementation:

  \[
  \text{define } \text{NV\_COMM\_P}(v) \text{ ( } \text{NV\_CONTENT\_P}(v)\rightarrow\text{comm} \text{ )}
  \]

• **NV\_Ith\_P**

  This macro gives access to the individual components of the local data array of an N\_Vector.

  The assignment \( r = \text{NV\_Ith\_P}(v,i) \) sets \( r \) to be the value of the \( i \)-th component of the local part of \( v \). The assignment \( \text{NV\_Ith\_P}(v,i) = r \) sets the value of the \( i \)-th component of the local part of \( v \) to be \( r \).

  Here \( i \) ranges from 0 to \( n - 1 \), where \( n \) is the local length.

  Implementation:

  \[
  \text{define } \text{NV\_Ith\_P}(v,i) \text{ ( } \text{NV\_DATA\_P}(v)[i] \text{ )}
  \]

### 6.4.2 NVECTOR\_PARALLEL functions

The NVECTOR\_PARALLEL module defines parallel implementations of all vector operations listed in Tables 6.1.1, 6.1.2, 6.1.3, and 6.1.4. Their names are obtained from those in these tables by appending the suffix \_Parallel (e.g. N\_VDestroy\_Parallel). The module NVECTOR\_PARALLEL provides the following additional user-callable routines:

**N\_VNew\_Parallel**

Prototype \( \text{N\_Vector N\_VNew\_Parallel(MPI\_Comm comm, sunindextype local\_length, sunindextype global\_length);} \)

Description This function creates and allocates memory for a parallel vector.

F2003 Name This function is callable as FN\_VNew\_Parallel when using the Fortran 2003 interface module.

**N\_VNewEmpty\_Parallel**

Prototype \( \text{N\_Vector N\_VNewEmpty\_Parallel(MPI\_Comm comm, sunindextype local\_length, sunindextype global\_length);} \)

Description This function creates a new parallel N\_Vector with an empty (NULL) data array.

F2003 Name This function is callable as FN\_VNewEmpty\_Parallel when using the Fortran 2003 interface module.
Description of the NVVECTOR module

N_VMake_Parallel
Prototype  N_Vector N_VMake_Parallel(MPI_Comm comm, sunindextype local_length,
                           sunindextype global_length, realtype *v_data);
Description  This function creates and allocates memory for a parallel vector with user-provided data
array. This function does not allocate memory for v_data itself.
F2003 Name  This function is callable as FN_VMake_Parallel when using the Fortran 2003 interface module.

N_VCloneVectorArray Parallel
Prototype  N_Vector *N_VCloneVectorArray_Parallel(int count, N_Vector w);
Description  This function creates (by cloning) an array of count parallel vectors.
F2003 Name  This function is callable as FN_VCloneVectorArray_Parallel when using the Fortran 2003 interface module.

N_VCloneVectorArrayEmpty_Parallel
Prototype  N_Vector *N_VCloneVectorArrayEmpty_Parallel(int count, N_Vector w);
Description  This function creates (by cloning) an array of count parallel vectors, each with an empty
(NULL) data array.
F2003 Name  This function is callable as FN_VCloneVectorArrayEmpty_Parallel when using the Fortran 2003 interface module.

N_VDestroyVectorArray_Parallel
Prototype  void N_VDestroyVectorArray_Parallel(N_Vector *vs, int count);
Description  This function frees memory allocated for the array of count variables of type N_Vector
created with N_VCloneVectorArray_Parallel or with N_VCloneVectorArrayEmpty_Parallel.
F2003 Name  This function is callable as FN_VDestroyVectorArray_Parallel when using the Fortran 2003 interface module.

N_VGetLocalLength_Parallel
Prototype  sunindextype N_VGetLocalLength_Parallel(N_Vector v);
Description  This function returns the local vector length.
F2003 Name  This function is callable as FN_VGetLocalLength_Parallel when using the Fortran 2003 interface module.

N_VPrint_Parallel
Prototype  void N_VPrint_Parallel(N_Vector v);
Description  This function prints the local content of a parallel vector to stdout.
F2003 Name  This function is callable as FN_VPrint_Parallel when using the Fortran 2003 interface module.
6.4 The NVVECTOR_PARALLEL implementation

**N.VPrintFile.Parallel**

Prototype: `void N_VPrintFile_Parallel(N_Vector v, FILE *outfile);`

Description: This function prints the local content of a parallel vector to `outfile`.

F2003 Name: This function is callable as `FN_VPrintFile_Parallel` when using the Fortran 2003 interface module.

By default all fused and vector array operations are disabled in the NVVECTOR_PARALLEL module. The following additional user-callable routines are provided to enable or disable fused and vector array operations for a specific vector. To ensure consistency across vectors it is recommended to first create a vector with `N_VNew_Parallel`, enable/disable the desired operations for that vector with the functions below, and create any additional vectors from that vector using `N_VClone` with that vector. This guarantees the new vectors will have the same operations enabled/disabled as cloned vectors inherit the same enable/disable options as the vector they are cloned from while vectors created with `N_VNew_Parallel` will have the default settings for the NVVECTOR_PARALLEL module.

**N.VEnableFusedOps_Parallel**

Prototype: `int N_VEnableFusedOps_Parallel(N_Vector v, booleantype tf);`

Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) all fused and vector array operations in the parallel vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are NULL.

F2003 Name: This function is callable as `FN_VEnableFusedOps_Parallel` when using the Fortran 2003 interface module.

**N.VEnableLinearCombination_Parallel**

Prototype: `int N_VEnableLinearCombination_Parallel(N_Vector v, booleantype tf);`

Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the linear combination fused operation in the parallel vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are NULL.

F2003 Name: This function is callable as `FN_VEnableLinearCombination_Parallel` when using the Fortran 2003 interface module.

**N.VEnableScaleAddMulti_Parallel**

Prototype: `int N_VEnableScaleAddMulti_Parallel(N_Vector v, booleantype tf);`

Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the scale and add a vector to multiple vectors fused operation in the parallel vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are NULL.

F2003 Name: This function is callable as `FN_VEnableScaleAddMulti_Parallel` when using the Fortran 2003 interface module.

**N.VEnableDotProdMulti_Parallel**

Prototype: `int N_VEnableDotProdMulti_Parallel(N_Vector v, booleantype tf);`

Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the multiple dot products fused operation in the parallel vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are NULL.

F2003 Name: This function is callable as `FN_VEnableDotProdMulti_Parallel` when using the Fortran 2003 interface module.
Description of the NVVECTOR module

**N_VEnableLinearSumVectorArray_Parallel**

Prototype: `int N_VEnableLinearSumVectorArray_Parallel(N_Vector v, booleantype tf);`

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the linear sum operation for vector arrays in the parallel vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

F2003 Name: This function is callable as FN_VEnableLinearSumVectorArray_Parallel when using the Fortran 2003 interface module.

**N_VEnableScaleVectorArray_Parallel**

Prototype: `int N_VEnableScaleVectorArray_Parallel(N_Vector v, booleantype tf);`

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the scale operation for vector arrays in the parallel vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

F2003 Name: This function is callable as FN_VEnableScaleVectorArray_Parallel when using the Fortran 2003 interface module.

**N_VEnableConstVectorArray_Parallel**

Prototype: `int N_VEnableConstVectorArray_Parallel(N_Vector v, booleantype tf);`

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the const operation for vector arrays in the parallel vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

F2003 Name: This function is callable as FN_VEnableConstVectorArray_Parallel when using the Fortran 2003 interface module.

**N_VEnableWrmsNormVectorArray_Parallel**

Prototype: `int N_VEnableWrmsNormVectorArray_Parallel(N_Vector v, booleantype tf);`

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the WRMS norm operation for vector arrays in the parallel vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

F2003 Name: This function is callable as FN_VEnableWrmsNormVectorArray_Parallel when using the Fortran 2003 interface module.

**N_VEnableWrmsNormMaskVectorArray_Parallel**

Prototype: `int N_VEnableWrmsNormMaskVectorArray_Parallel(N_Vector v, booleantype tf);`

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the masked WRMS norm operation for vector arrays in the parallel vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

F2003 Name: This function is callable as FN_VEnableWrmsNormMaskVectorArray_Parallel when using the Fortran 2003 interface module.

**N_VEnableScaleAddMultiVectorArray_Parallel**

Prototype: `int N_VEnableScaleAddMultiVectorArray_Parallel(N_Vector v, booleantype tf);`

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector array to multiple vector arrays operation in the parallel vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.
6.5 The NVVECTOR_OPENMP implementation

Prototype

```c
int N_VEnableLinearCombinationVectorArray_Parallel(N_Vector v, booleantype tf);
```

Description

This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination operation for vector arrays in the parallel vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

Notes

- When looping over the components of an N_Vector v, it is more efficient to first obtain the local component array via `v_data = NV_DATA_P(v)` and then access `v_data[i]` within the loop than it is to use `NV_Ith_P(v, i)` within the loop.

- N_VNewEmpty_Parallel, N_VMake_Parallel, and N_VCloneVectorArrayEmpty_Parallel set the field `own_data = SUNFALSE`. N_VDestroy_Parallel and N_VDestroyVectorArray_Parallel will not attempt to free the pointer data for any N_Vector with `own_data` set to SUNFALSE. In such a case, it is the user's responsibility to deallocate the data pointer.

- To maximize efficiency, vector operations in the NVVECTOR_PARALLEL implementation that have more than one N_Vector argument do not check for consistent internal representation of these vectors. It is the user's responsibility to ensure that such routines are called with N_Vector arguments that were all created with the same internal representations.

6.4.3 NVVECTOR_PARALLEL Fortran interfaces

For solvers that include a Fortran 77 interface module, the NVVECTOR_PARALLEL module also includes a Fortran-callable function FNVINITP(COMM, code, NLOCAL, NGLOBAL, IER), to initialize this NVVECTOR_PARALLEL module. Here COMM is the MPI communicator, code is an input solver id (1 for cvode, 2 for IDA, 3 for KINSOL, 4 for ARKODE); NLOCAL and NGLOBAL are the local and global vector sizes, respectively (declared so as to match C type long int); and IER is an error return flag equal 0 for success and -1 for failure. NOTE: If the header file sundials_config.h defines SUNDIALS_MPI_COMM_F2C to be 1 (meaning the MPI implementation used to build SUNDIALS includes the MPI_Comm_f2c function), then COMM can be any valid MPI communicator. Otherwise, MPI_COMM_WORLD will be used, so just pass an integer value as a placeholder.

6.5 The NVVECTOR_OPENMP implementation

In situations where a user has a multi-core processing unit capable of running multiple parallel threads with shared memory, SUNDIALS provides an implementation of NVVECTOR using OpenMP, called NVVECTOR_OPENMP, and an implementation using Pthreads, called NVVECTOR_PTHREADS. Testing has shown that vectors should be of length at least 100,000 before the overhead associated with creating and using the threads is made up by the parallelism in the vector calculations.

The OpenMP NVVECTOR implementation provided with SUNDIALS, NVVECTOR_OPENMP, defines the `content` field of N_Vector to be a structure containing the length of the vector, a pointer to the beginning of a contiguous data array, a boolean flag `own_data` which specifies the ownership of data, and the number of threads. Operations on the vector are threaded using OpenMP.

```c
struct _N_VectorContent_OpenMP {
    sunindextype length;
    booleantype own_data;
    realtype *data;
    int num_threads;
};
```
The header file to include when using this module is `nvector_openmp.h`. The installed module library to link to is `libsundials_nvecopemmp.lib` where `.lib` is typically `.so` for shared libraries and `.a` for static libraries. The FORTRAN module file to use when using the FORTRAN 2003 interface to this module is `fnvector_openmp.f90`.

### 6.5.1 NVECTOR_OPENMP accessor macros

The following macros are provided to access the content of an NVECTOR_OPENMP vector. The suffix `_OMP` in the names denotes the OpenMP version.

- **NV_CONTENT_OMP**
  This routine gives access to the contents of the OpenMP vector N_Vector.
  The assignment `v_cont = NV_CONTENT_OMP(v)` sets `v_cont` to be a pointer to the OpenMP N_Vector content structure.
  Implementation:
  ```c
  #define NV_CONTENT_OMP(v) ( (N_VectorContent_OpenMP)(v->content) )
  ```

- **NV_OWN_DATA_OMP, NV_DATA_OMP, NV_LENGTH_OMP, NV_NUM_THREADS_OMP**
  These macros give individual access to the parts of the content of a OpenMP N_Vector.
  The assignment `v_data = NV_DATA_OMP(v)` sets `v_data` to be a pointer to the first component of the data for the N_Vector `v`. The assignment `NV_DATA_OMP(v) = v_data` sets the component array of `v` to be `v_data` by storing the pointer `v_data`.
  The assignment `v_len = NV_LENGTH_OMP(v)` sets `v_len` to be the length of `v`. On the other hand, the call `NV_LENGTH_OMP(v) = len_v` sets the length of `v` to be `len_v`.
  The assignment `v.num_threads = NV_NUM_THREADS_OMP(v)` sets `v.num_threads` to be the number of threads from `v`. On the other hand, the call `NV_NUM_THREADS_OMP(v) = num_threads_v` sets the number of threads for `v` to be `num_threads_v`.
  Implementation:
  ```c
  #define NV_OWN_DATA_OMP(v) ( NV_CONTENT_OMP(v)->own_data )
  #define NV_DATA_OMP(v) ( NV_CONTENT_OMP(v)->data )
  #define NV_LENGTH_OMP(v) ( NV_CONTENT_OMP(v)->length )
  #define NV_NUM_THREADS_OMP(v) ( NV_CONTENT_OMP(v)->num_threads )
  ```

- **NV_Ith_OMP**
  This macro gives access to the individual components of the data array of an N_Vector.
  The assignment `r = NV_Ith_OMP(v,i)` sets `r` to be the value of the `i`-th component of `v`. The assignment `NV_Ith_OMP(v,i) = r` sets the value of the `i`-th component of `v` to be `r`.
  Here `i` ranges from `0` to `n−1` for a vector of length `n`.
  Implementation:
  ```c
  #define NV_Ith_OMP(v,i) ( NV_DATA_OMP(v)[i] )
  ```

### 6.5.2 NVECTOR_OPENMP functions

The NVECTOR_OPENMP module defines OpenMP implementations of all vector operations listed in Tables 6.1.1, 6.1.2, 6.1.3, and 6.1.4. Their names are obtained from those in these tables by appending the suffix `_OpenMP` (e.g. N_VDestroy_OpenMP). All the standard vector operations listed in 6.1.1 with the suffix `_OpenMP` appended are callable via the FORTRAN 2003 interface by prepending an ‘F’ (e.g. FN_VDestroy_OpenMP).

The module NVECTOR_OPENMP provides the following additional user-callable routines:
6.5 The NVECTOR_OPENMP implementation

**N_VNew_OpenMP**

Prototype: \( \text{N}_\text{Vector } \text{N}_\text{VNew}_\text{OpenMP}(\text{sunindextype vec\_length}, \text{int num\_threads}) \)

Description: This function creates and allocates memory for a OpenMP N_Vector. Arguments are the vector length and number of threads.

F2003 Name: This function is callable as \( \text{FN}_\text{VNew}_\text{OpenMP} \) when using the Fortran 2003 interface module.

**N_VNewEmpty_OpenMP**

Prototype: \( \text{N}_\text{Vector } \text{N}_\text{VNewEmpty}_\text{OpenMP}(\text{sunindextype vec\_length}, \text{int num\_threads}) \)

Description: This function creates a new OpenMP N_Vector with an empty (NULL) data array.

F2003 Name: This function is callable as \( \text{FN}_\text{VNewEmpty}_\text{OpenMP} \) when using the Fortran 2003 interface module.

**N_VMake_OpenMP**

Prototype: \( \text{N}_\text{Vector } \text{N}_\text{VMake}_\text{OpenMP}(\text{sunindextype vec\_length}, \text{realtype } *\text{v\_data}, \text{int num\_threads}); \)

Description: This function creates and allocates memory for a OpenMP vector with user-provided data array. This function does not allocate memory for \( \text{v\_data} \) itself.

F2003 Name: This function is callable as \( \text{FN}_\text{VMake}_\text{OpenMP} \) when using the Fortran 2003 interface module.

**N_VCloneVectorArray_OpenMP**

Prototype: \( \text{N}_\text{Vector } *\text{N}_\text{VCloneVectorArray}_\text{OpenMP}(\text{int count, N\_Vector } w) \)

Description: This function creates (by cloning) an array of count OpenMP vectors.

F2003 Name: This function is callable as \( \text{FN}_\text{VCloneVectorArray}_\text{OpenMP} \) when using the Fortran 2003 interface module.

**N_VCloneVectorArrayEmpty_OpenMP**

Prototype: \( \text{N}_\text{Vector } *\text{N}_\text{VCloneVectorArrayEmpty}_\text{OpenMP}(\text{int count, N\_Vector } w) \)

Description: This function creates (by cloning) an array of count OpenMP vectors, each with an empty (NULL) data array.

F2003 Name: This function is callable as \( \text{FN}_\text{VCloneVectorArrayEmpty}_\text{OpenMP} \) when using the Fortran 2003 interface module.

**N_VDestroyVectorArray_OpenMP**

Prototype: \( \text{void } \text{N}_\text{VDestroyVectorArray}_\text{OpenMP}(\text{N\_Vector } *\text{vs}, \text{int count}) \)

Description: This function frees memory allocated for the array of count variables of type N_Vector created with \( \text{N}_\text{VCloneVectorArray}_\text{OpenMP} \) or with \( \text{N}_\text{VCloneVectorArrayEmpty}_\text{OpenMP} \).

F2003 Name: This function is callable as \( \text{FN}_\text{VDestroyVectorArray}_\text{OpenMP} \) when using the Fortran 2003 interface module.
Description of the NVECTOR module

**N_VPrint_OpenMP**

Prototype: `void N_VPrint_OpenMP(N_Vector v)`  
Description: This function prints the content of an OpenMP vector to stdout.

F2003 Name: This function is callable as `FN_VPrint_OpenMP` when using the Fortran 2003 interface module.

**N_VPrintFile_OpenMP**

Prototype: `void N_VPrintFile_OpenMP(N_Vector v, FILE *outfile)`  
Description: This function prints the content of an OpenMP vector to `outfile`.

F2003 Name: This function is callable as `FN_VPrintFile_OpenMP` when using the Fortran 2003 interface module.

By default all fused and vector array operations are disabled in the `nvector_openmp` module. The following additional user-callable routines are provided to enable or disable fused and vector array operations for a specific vector. To ensure consistency across vectors it is recommended to first create a vector with `N_VNew_OpenMP`, enable/disable the desired operations for that vector with the functions below, and create any additional vectors from that vector using `N_VClone`. This guarantees the new vectors will have the same operations enabled/disabled as cloned vectors inherit the same enable/disable options as the vector they are cloned from while vectors created with `N_VNew_OpenMP` will have the default settings for the `nvector_openmp` module.

**N_VEnableFusedOps_OpenMP**

Prototype: `int N_VEnableFusedOps_OpenMP(N_Vector v, booleantype tf)`  
Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) all fused and vector array operations in the OpenMP vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are `NULL`.

F2003 Name: This function is callable as `FN_VEnableFusedOps_OpenMP` when using the Fortran 2003 interface module.

**N_VEnableLinearCombination_OpenMP**

Prototype: `int N_VEnableLinearCombination_OpenMP(N_Vector v, booleantype tf)`  
Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the linear combination fused operation in the OpenMP vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are `NULL`.

F2003 Name: This function is callable as `FN_VEnableLinearCombination_OpenMP` when using the Fortran 2003 interface module.

**N_VEnableScaleAddMulti_OpenMP**

Prototype: `int N_VEnableScaleAddMulti_OpenMP(N_Vector v, booleantype tf)`  
Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the scale and add a vector to multiple vectors fused operation in the OpenMP vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are `NULL`.

F2003 Name: This function is callable as `FN_VEnableScaleAddMulti_OpenMP` when using the Fortran 2003 interface module.
6.5 The NVECTOR_OPENMP implementation

**N_VEnableDotProdMulti_OpenMP**

**Prototype**

```c
int N_VEnableDotProdMulti_OpenMP(N_Vector v, booleantype tf)
```

**Description**

This function enables (SUNTRUE) or disables (SUNFALSE) the multiple dot products fused operation in the OpenMP vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**F2003 Name**

This function is callable as FN_VEnableDotProdMulti_OpenMP when using the Fortran 2003 interface module.

**N_VEnableLinearSumVectorArray_OpenMP**

**Prototype**

```c
int N_VEnableLinearSumVectorArray_OpenMP(N_Vector v, booleantype tf)
```

**Description**

This function enables (SUNTRUE) or disables (SUNFALSE) the linear sum operation for vector arrays in the OpenMP vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**F2003 Name**

This function is callable as FN_VEnableLinearSumVectorArray_OpenMP when using the Fortran 2003 interface module.

**N_VEnableScaleVectorArray_OpenMP**

**Prototype**

```c
int N_VEnableScaleVectorArray_OpenMP(N_Vector v, booleantype tf)
```

**Description**

This function enables (SUNTRUE) or disables (SUNFALSE) the scale operation for vector arrays in the OpenMP vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**F2003 Name**

This function is callable as FN_VEnableScaleVectorArray_OpenMP when using the Fortran 2003 interface module.

**N_VEnableConstVectorArray_OpenMP**

**Prototype**

```c
int N_VEnableConstVectorArray_OpenMP(N_Vector v, booleantype tf)
```

**Description**

This function enables (SUNTRUE) or disables (SUNFALSE) the const operation for vector arrays in the OpenMP vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**F2003 Name**

This function is callable as FN_VEnableConstVectorArray_OpenMP when using the Fortran 2003 interface module.

**N_VEnableWrmsNormVectorArray_OpenMP**

**Prototype**

```c
int N_VEnableWrmsNormVectorArray_OpenMP(N_Vector v, booleantype tf)
```

**Description**

This function enables (SUNTRUE) or disables (SUNFALSE) the WRMS norm operation for vector arrays in the OpenMP vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**F2003 Name**

This function is callable as FN_VEnableWrmsNormVectorArray_OpenMP when using the Fortran 2003 interface module.

**N_VEnableWrmsNormMaskVectorArray_OpenMP**

**Prototype**

```c
int N_VEnableWrmsNormMaskVectorArray_OpenMP(N_Vector v, booleantype tf)
```

**Description**

This function enables (SUNTRUE) or disables (SUNFALSE) the masked WRMS norm operation for vector arrays in the OpenMP vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.
F2003 Name This function is callable as FN_VEnableWrmsNormMaskVectorArray_OpenMP when using the Fortran 2003 interface module.

### N_VEnableScaleAddMultiVectorArray_OpenMP

**Prototype**
```c
int N_VEnableScaleAddMultiVectorArray_OpenMP(N_Vector v, booleantype tf)
```

**Description**
This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector array to multiple vector arrays operation in the OpenMP vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

### N_VEnableLinearCombinationVectorArray_OpenMP

**Prototype**
```c
int N_VEnableLinearCombinationVectorArray_OpenMP(N_Vector v, booleantype tf)
```

**Description**
This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination operation for vector arrays in the OpenMP vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**Notes**

- When looping over the components of an N_Vector v, it is more efficient to first obtain the component array via `v.data = NV_DATA_OMP(v)` and then access `v.data[i]` within the loop than it is to use `NV_Ith_OMP(v,i)` within the loop.

- N_VNewEmpty_OpenMP, N_VMake_OpenMP, and N_VCloneVectorArrayEmpty_OpenMP set the field `own_data = SUNFALSE`. N_VDestroy_OpenMP and N_VDestroyVectorArray_OpenMP will not attempt to free the pointer `data` for any N_Vector with `own_data` set to SUNFALSE. In such a case, it is the user’s responsibility to deallocate the `data` pointer.

- To maximize efficiency, vector operations in the NVECTOR_OPENMP implementation that have more than one N_Vector argument do not check for consistent internal representation of these vectors. It is the user’s responsibility to ensure that such routines are called with N_Vector arguments that were all created with the same internal representations.

### 6.5.3 NVECTOR_OPENMP Fortran interfaces

The NVECTOR_OPENMP module provides a FORTRAN 2003 module as well as FORTRAN 77 style interface functions for use from FORTRAN applications.

**FORTRAN 2003 interface module**

The nvector_openmp_mod FORTRAN module defines interfaces to most NVECTOR_OPENMP C functions using the intrinsic iso_c_binding module which provides a standardized mechanism for interoperating with C. As noted in the C function descriptions above, the interface functions are named after the corresponding C function, but with a leading ‘F’. For example, the function N_VNew_OpenMP is interfaced as FN_VNew_OpenMP.

The FORTRAN 2003 NVECTOR_OPENMP interface module can be accessed with the use statement, i.e. use fnvector_openmp_mod, and linking to the library libsundials_fnvectoropenmp_mod.lib in addition to the C library. For details on where the library and module file fnvector_openmp_mod.mod are installed see Appendix A.
6.6 The NVECTOR_PTHREADS implementation

FORTRAN 77 interface functions

For solvers that include a FORTRAN 77 interface module, the NVECTOR_OPENMP module also includes a FORTRAN-callable function FNVINITOMP(code, NEQ, NUMTHREADS, IER), to initialize this module. Here code is an input solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, 4 for ARKODE); NEQ is the problem size (declared so as to match C type long int); NUMTHREADS is the number of threads; and IER is an error return flag equal 0 for success and -1 for failure.

6.6 The NVECTOR_PTHREADS implementation

In situations where a user has a multi-core processing unit capable of running multiple parallel threads with shared memory, SUNDIALS provides an implementation of NVECTOR using OpenMP, called NVECTOR_OPENMP, and an implementation using Pthreads, called NVECTOR_PTHREADS. Testing has shown that vectors should be of length at least 100,000 before the overhead associated with creating and using the threads is made up by the parallelism in the vector calculations.

The Pthreads NVECTOR implementation provided with SUNDIALS, denoted NVECTOR_PTHREADS, defines the content field of N_Vector to be a structure containing the length of the vector, a pointer to the beginning of a contiguous data array, a boolean flag own_data which specifies the ownership of data, and the number of threads. Operations on the vector are threaded using POSIX threads (Pthreads).

```
struct _N_VectorContent_Pthreads {
  sunindextype length;
  booleantype own_data;
  realtype *data;
  int num_threads;
};
```

The header file to include when using this module is nvector_pthreads.h. The installed module library to link to is libsundials_nvecpthreads.lib where .lib is typically .so for shared libraries and .a for static libraries.

6.6.1 NVECTOR_PTHREADS accessor macros

The following macros are provided to access the content of an NVECTOR_PTHREADS vector. The suffix _PT in the names denotes the Pthreads version.

- **NV_CONTENT_PT**
  This routine gives access to the contents of the Pthreads vector N_Vector.
  The assignment \( v_{\text{cont}} = \text{NV\_CONTENT\_PT}(v) \) sets \( v_{\text{cont}} \) to be a pointer to the Pthreads N_Vector content structure.
  Implementation:
  ```c
  #define NV_CONTENT_PT(v) ( (N_VectorContent_Pthreads)(v->content) )
  ```

- **NV_OWN_DATA_PT, NV_DATA_PT, NV_LENGTH_PT, NV_NUM_THREADS_PT**
  These macros give individual access to the parts of the content of a Pthreads N_Vector.
  The assignment \( v_{\text{data}} = \text{NV\_DATA\_PT}(v) \) sets \( v_{\text{data}} \) to be a pointer to the first component of the data for the N_Vector \( v \). The assignment \( \text{NV\_DATA\_PT}(v) = v_{\text{data}} \) sets the component array of \( v \) to be \( v_{\text{data}} \) by storing the pointer \( v_{\text{data}} \).
  The assignment \( v_{\text{len}} = \text{NV\_LENGTH\_PT}(v) \) sets \( v_{\text{len}} \) to be the length of \( v \). On the other hand, the call \( \text{NV\_LENGTH\_PT}(v) = v_{\text{len}} \) sets the length of \( v \) to be \( v_{\text{len}} \).
  The assignment \( v_{\text{num\_threads}} = \text{NV\_NUM\_THREADS\_PT}(v) \) sets \( v_{\text{num\_threads}} \) to be the number of threads from \( v \). On the other hand, the call \( \text{NV\_NUM\_THREADS\_PT}(v) = v_{\text{num\_threads}} \) sets the number of threads for \( v \) to be \( v_{\text{num\_threads}} \).
Implementation:
#define NV_OWN_DATA_PT(v) ( NV_CONTENT_PT(v)->own_data )
#define NV_DATA_PT(v) ( NV_CONTENT_PT(v)->data )
#define NV_LENGTH_PT(v) ( NV_CONTENT_PT(v)->length )
#define NV_NUM_THREADS_PT(v) ( NV_CONTENT_PT(v)->num_threads )

• NV_Ith_PT
This macro gives access to the individual components of the data array of an N_Vector.
The assignment \( r = NV_Ith_PT(v, i) \) sets \( r \) to be the value of the \( i \)-th component of \( v \). The assignment \( NV_Ith_PT(v, i) = r \) sets the value of the \( i \)-th component of \( v \) to be \( r \).
Here \( i \) ranges from 0 to \( n - 1 \) for a vector of length \( n \).

Implementation:
#define NV_Ith_PT(v,i) ( NV_DATA_PT(v)[i] )

6.6.2 NVECTOR_PTHREADS functions
The nvector_pthreads module defines Pthreads implementations of all vector operations listed in Tables 6.1.1, 6.1.2, 6.1.3, and 6.1.4. Their names are obtained from those in these tables by appending the suffix _Pthreads (e.g. N_VDestroy_Pthreads). All the standard vector operations listed in 6.1.1 are callable via the FORTRAN 2003 interface by prepending an ‘F’ (e.g. FN_VDestroy_Pthreads). The module nvector_pthreads provides the following additional user-callable routines:

**N_VNew_Pthreads**

Prototype  
N_Vector N_VNew_Pthreads(sunindextype vec_length, int num_threads)

Description  
This function creates and allocates memory for a Pthreads N_Vector. Arguments are the vector length and number of threads.

F2003 Name  
This function is callable as FN_VNew_Pthreads when using the Fortran 2003 interface module.

**N_VNewEmpty_Pthreads**

Prototype  
N_Vector N_VNewEmpty_Pthreads(sunindextype vec_length, int num_threads)

Description  
This function creates a new Pthreads N_Vector with an empty (NULL) data array.

F2003 Name  
This function is callable as FN_VNewEmpty_Pthreads when using the Fortran 2003 interface module.

**N_VMake_Pthreads**

Prototype  
N_Vector N_VMake_Pthreads(sunindextype vec_length, realtype *v_data, int num_threads);

Description  
This function creates and allocates memory for a Pthreads vector with user-provided data array. This function does not allocate memory for v_data itself.

F2003 Name  
This function is callable as FN_VMake_Pthreads when using the Fortran 2003 interface module.
6.6 The NVECTOR_PTHREADS implementation

**N_VCloneVectorArray_Pthreads**

Prototype: `N_Vector *N_VCloneVectorArray_Pthreads(int count, N_Vector w)`

Description: This function creates (by cloning) an array of count Pthreads vectors.

F2003 Name: This function is callable as `FN_VCloneVectorArray_Pthreads` when using the Fortran 2003 interface module.

**N_VCloneVectorArrayEmpty_Pthreads**

Prototype: `N_Vector *N_VCloneVectorArrayEmpty_Pthreads(int count, N_Vector w)`

Description: This function creates (by cloning) an array of count Pthreads vectors, each with an empty (NULL) data array.

F2003 Name: This function is callable as `FN_VCloneVectorArrayEmpty_Pthreads` when using the Fortran 2003 interface module.

**N_VDestroyVectorArray_Pthreads**

Prototype: `void N_VDestroyVectorArray_Pthreads(N_Vector *vs, int count)`

Description: This function frees memory allocated for the array of count variables of type `N_Vector` created with `N_VCloneVectorArray_Pthreads` or with `N_VCloneVectorArrayEmpty_Pthreads`.

F2003 Name: This function is callable as `FN_VDestroyVectorArray_Pthreads` when using the Fortran 2003 interface module.

**N_VPrint_Pthreads**

Prototype: `void N_VPrint_Pthreads(N_Vector v)`

Description: This function prints the content of a Pthreads vector to `stdout`.

F2003 Name: This function is callable as `FN_VPrint_Pthreads` when using the Fortran 2003 interface module.

**N_VPrintFile_Pthreads**

Prototype: `void N_VPrintFile_Pthreads(N_Vector v, FILE *outfile)`

Description: This function prints the content of a Pthreads vector to `outfile`.

F2003 Name: This function is callable as `FN_VPrintFile_Pthreads` when using the Fortran 2003 interface module.

By default all fused and vector array operations are disabled in the `nvector_pthreads` module. The following additional user-callable routines are provided to enable or disable fused and vector array operations for a specific vector. To ensure consistency across vectors it is recommended to first create a vector with `N_VNew_Pthreads`, enable/disable the desired operations for that vector with the functions below, and create any additional vectors from that vector using `N_VClone`. This guarantees the new vectors will have the same operations enabled/disabled as cloned vectors inherit the same enable/disable options as the vector they are cloned from while vectors created with `N_VNew_Pthreads` will have the default settings for the `nvector_pthreads` module.

**N_VEnableFusedOps_Pthreads**

Prototype: `int N_VEnableFusedOps_Pthreads(N_Vector v, booleantype tf)`

Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) all fused and vector array operations in the Pthreads vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are NULL.
F2003 Name This function is callable as `FN_VEnableFusedOps_Pthreads` when using the Fortran 2003 interface module.

**N_VEnableLinearCombination_Pthreads**
Prototype: `int N_VEnableLinearCombination_Pthreads(N_Vector v, booleantype tf)`
Description: This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination fused operation in the Pthreads vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are NULL.

F2003 Name This function is callable as `FN_VEnableLinearCombination_Pthreads` when using the Fortran 2003 interface module.

**N_VEnableScaleAddMulti_Pthreads**
Prototype: `int N_VEnableScaleAddMulti_Pthreads(N_Vector v, booleantype tf)`
Description: This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector to multiple vectors fused operation in the Pthreads vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are NULL.

F2003 Name This function is callable as `FN_VEnableScaleAddMulti_Pthreads` when using the Fortran 2003 interface module.

**N_VEnableDotProdMulti_Pthreads**
Prototype: `int N_VEnableDotProdMulti_Pthreads(N_Vector v, booleantype tf)`
Description: This function enables (SUNTRUE) or disables (SUNFALSE) the multiple dot products fused operation in the Pthreads vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are NULL.

F2003 Name This function is callable as `FN_VEnableDotProdMulti_Pthreads` when using the Fortran 2003 interface module.

**N_VEnableLinearSumVectorArray_Pthreads**
Prototype: `int N_VEnableLinearSumVectorArray_Pthreads(N_Vector v, booleantype tf)`
Description: This function enables (SUNTRUE) or disables (SUNFALSE) the linear sum operation for vector arrays in the Pthreads vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are NULL.

F2003 Name This function is callable as `FN_VEnableLinearSumVectorArray_Pthreads` when using the Fortran 2003 interface module.

**N_VEnableScaleVectorArray_Pthreads**
Prototype: `int N_VEnableScaleVectorArray_Pthreads(N_Vector v, booleantype tf)`
Description: This function enables (SUNTRUE) or disables (SUNFALSE) the scale operation for vector arrays in the Pthreads vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are NULL.

F2003 Name This function is callable as `FN_VEnableScaleVectorArray_Pthreads` when using the Fortran 2003 interface module.
6.6 The NVECTOR_PTHREADS implementation

**N_VEnableConstVectorArray_Pthreads**

**Prototype**

```
int N_VEnableConstVectorArray_Pthreads(N_Vector v, booleantype tf)
```

**Description**

This function enables (SUNTRUE) or disables (SUNFALSE) the const operation for vector arrays in the Pthreads vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**F2003 Name**

This function is callable as FN_VEnableConstVectorArray_Pthreads when using the Fortran 2003 interface module.

**N_VEnableWrmsNormVectorArray_Pthreads**

**Prototype**

```
int N_VEnableWrmsNormVectorArray_Pthreads(N_Vector v, booleantype tf)
```

**Description**

This function enables (SUNTRUE) or disables (SUNFALSE) the WRMS norm operation for vector arrays in the Pthreads vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**F2003 Name**

This function is callable as FN_VEnableWrmsNormVectorArray_Pthreads when using the Fortran 2003 interface module.

**N_VEnableWrmsNormMaskVectorArray_Pthreads**

**Prototype**

```
int N_VEnableWrmsNormMaskVectorArray_Pthreads(N_Vector v, booleantype tf)
```

**Description**

This function enables (SUNTRUE) or disables (SUNFALSE) the masked WRMS norm operation for vector arrays in the Pthreads vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**F2003 Name**

This function is callable as FN_VEnableWrmsNormMaskVectorArray_Pthreads when using the Fortran 2003 interface module.

**N_VEnableScaleAddMultiVectorArray_Pthreads**

**Prototype**

```
int N_VEnableScaleAddMultiVectorArray_Pthreads(N_Vector v, booleantype tf)
```

**Description**

This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector array to multiple vector arrays operation in the Pthreads vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**N_VEnableLinearCombinationVectorArray_Pthreads**

**Prototype**

```
int N_VEnableLinearCombinationVectorArray_Pthreads(N_Vector v, booleantype tf)
```

**Description**

This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination operation for vector arrays in the Pthreads vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**Notes**

- When looping over the components of an N_Vector v, it is more efficient to first obtain the component array via `v_data = NV_DATA_PT(v)` and then access `v_data[i]` within the loop than it is to use `NV_Ith_PT(v,i)` within the loop.

- `N_VNewEmpty_Pthreads`, `N_VMake_Pthreads`, and `N_VCloneVectorArrayEmpty_Pthreads` set the field `own_data = SUNFALSE`. `N_Destroy_Pthreads` and `N_DestroyVectorArray_Pthreads` will not attempt to free the pointer `data` for any N_Vector with `own_data` set to SUNFALSE. In such a case, it is the user’s responsibility to deallocate the `data` pointer.
• To maximize efficiency, vector operations in the NVVECTOR_PTHREADS implementation that have more than one N_Vector argument do not check for consistent internal representation of these vectors. It is the user’s responsibility to ensure that such routines are called with N_Vector arguments that were all created with the same internal representations.

6.6.3 NVVECTOR_PTHREADS Fortran interfaces

The NVVECTOR_PTHREADS module provides a Fortran 2003 module as well as Fortran 77 style interface functions for use from Fortran applications.

**FORTRAN 2003 interface module**

The nvvector_pthreads_mod Fortran module defines interfaces to most NVVECTOR_PTHREADS C functions using the intrinsic iso_c_binding module which provides a standardized mechanism for interoperating with C. As noted in the C function descriptions above, the interface functions are named after the corresponding C function, but with a leading ‘F’. For example, the function N_VNew_Pthreads is interfaced as FN_VNew_Pthreads.

The Fortran 2003 NVVECTOR_PTHREADS interface module can be accessed with the use statement, i.e. use fnvector_pthreads_mod, and linking to the library libsundials_fnvectorpthreads_mod.lib in addition to the C library. For details on where the library and module file fnvector_pthreads_mod.mod are installed see Appendix A.

**FORTRAN 77 interface functions**

For solvers that include a Fortran interface module, the NVVECTOR_PTHREADS module also includes a Fortran-callable function FNVINITPTS(code, NEQ, NUMTHREADS, IER) to initialize this module. Here code is an input solver id (1 for cvode, 2 for ida, 3 for kinsol, 4 for arkode); NEQ is the problem size (declared so as to match C type long int); NUMTHREADS is the number of threads; and IER is an error return flag equal 0 for success and -1 for failure.

6.7 The NVVECTOR_PARHYP implementation

The NVVECTOR_PARHYP implementation of the NVVECTOR module provided with SUNDIALS is a wrapper around hypre’s ParVector class. Most of the vector kernels simply call hypre vector operations. The implementation defines the content field of N_Vector to be a structure containing the global and local lengths of the vector, a pointer to an object of type HYPRE_ParVector, an MPI communicator, and a boolean flag own_parvector indicating ownership of the hypre parallel vector object x.

```
struct _N_VectorContent_ParHyp {
    sunindextype local_length;
    sunindextype global_length;
    booleantype own_parvector;
    MPI_Comm comm;
    HYPRE_ParVector x;
};
```

The header file to include when using this module is nvvector_parhyp.h. The installed module library to link to is libsundials_nvecparhyp.lib where .lib is typically .so for shared libraries and .a for static libraries.

Unlike native SUNDIALS vector types, NVVECTOR_PARHYP does not provide macros to access its member variables. Note that NVVECTOR_PARHYP requires SUNDIALS to be built with MPI support.
6.7 The NVECTOR_PARHYP implementation

6.7.1 NVECTOR_PARHYP functions

The NVECTOR_PARHYP module defines implementations of all vector operations listed in Tables 6.1.1, 6.1.2, 6.1.3, and 6.1.4, except for N_VSetArrayPointer and N_VGetArrayPointer, because accessing raw vector data is handled by low-level hypre functions. As such, this vector is not available for use with sundials Fortran interfaces. When access to raw vector data is needed, one should extract the hypre vector first, and then use hypre methods to access the data. Usage examples of NVECTOR_PARHYP are provided in the cvAdvDiff_non_ph.c example program for CVODE [29] and the ark_diurnal_kry_ph.c example program for ARKODE [36].

The names of parhyp methods are obtained from those in Tables 6.1.1, 6.1.2, 6.1.3, and 6.1.4 by appending the suffix _ParHyp (e.g. N_VDestroy_ParHyp). The module NVECTOR_PARHYP provides the following additional user-callable routines:

N_VNewEmpty_ParHyp
Prototype: N_Vector N_VNewEmpty_ParHyp(MPI_Comm comm, sunindextype local_length, sunindextype global_length)
Description: This function creates a new parhyp N_Vector with the pointer to the hypre vector set to NULL.

N_VMake_ParHyp
Prototype: N_Vector N_VMake_ParHyp(HYPRE_ParVector x)
Description: This function creates an N_Vector wrapper around an existing hypre parallel vector. It does not allocate memory for x itself.

N_VGetVector_ParHyp
Prototype: HYPRE_ParVector N_VGetVector_ParHyp(N_Vector v)
Description: This function returns the underlying hypre vector.

N_VCloneVectorArray_ParHyp
Prototype: N_Vector *N_VCloneVectorArray_ParHyp(int count, N_Vector w)
Description: This function creates (by cloning) an array of count parallel vectors.

N_VCloneVectorArrayEmpty_ParHyp
Prototype: N_Vector *N_VCloneVectorArrayEmpty_ParHyp(int count, N_Vector w)
Description: This function creates (by cloning) an array of count parallel vectors, each with an empty (NULL) data array.

N_VDestroyVectorArray_ParHyp
Prototype: void N_VDestroyVectorArray_ParHyp(N_Vector *vs, int count)
Description: This function frees memory allocated for the array of count variables of type N_Vector created with N_VCloneVectorArray_ParHyp or with N_VCloneVectorArrayEmpty_ParHyp.

N_VPrint_ParHyp
Prototype: void N_VPrint_ParHyp(N_Vector v)
Description: This function prints the local content of a parhyp vector to stdout.
Description of the NVECTOR module

N_VPrintFile_ParHyp
Prototype    void N_VPrintFile_ParHyp(N_Vector v, FILE *outfile)
Description   This function prints the local content of a parhyp vector to outfile.

By default all fused and vector array operations are disabled in the NVECTOR_PARHYP module. The following additional user-callable routines are provided to enable or disable fused and vector array operations for a specific vector. To ensure consistency across vectors it is recommended to first create a vector with N_VMake_ParHyp, enable/disable the desired operations for that vector with the functions below, and create any additional vectors from that vector using N_VClone. This guarantees the new vectors will have the same operations enabled/disabled as cloned vectors inherit the same enable/disable options as the vector they are cloned from while vectors created with N_VMake_ParHyp will have the default settings for the NVECTOR_PARHYP module.

N_VEnableFusedOps_ParHyp
Prototype    int N_VEnableFusedOps_ParHyp(N_Vector v, booleantype tf)
Description   This function enables (SUNTRUE) or disables (SUNFALSE) all fused and vector array operations in the parhyp vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

N_VEnableLinearCombination_ParHyp
Prototype    int N_VEnableLinearCombination_ParHyp(N_Vector v, booleantype tf)
Description   This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination fused operation in the parhyp vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

N_VEnableScaleAddMulti_ParHyp
Prototype    int N_VEnableScaleAddMulti_ParHyp(N_Vector v, booleantype tf)
Description   This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector to multiple vectors fused operation in the parhyp vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

N_VEnableDotProdMulti_ParHyp
Prototype    int N_VEnableDotProdMulti_ParHyp(N_Vector v, booleantype tf)
Description   This function enables (SUNTRUE) or disables (SUNFALSE) the multiple dot products fused operation in the parhyp vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

N_VEnableLinearSumVectorArray_ParHyp
Prototype    int N_VEnableLinearSumVectorArray_ParHyp(N_Vector v, booleantype tf)
Description   This function enables (SUNTRUE) or disables (SUNFALSE) the linear sum operation for vector arrays in the parhyp vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

N_VEnableScaleVectorArray_ParHyp
Prototype    int N_VEnableScaleVectorArray_ParHyp(N_Vector v, booleantype tf)
6.7 The NVECTOR_PARHYP implementation

Description This function enables (SUNTRUE) or disables (SUNFALSE) the scale operation for vector arrays in the parhyp vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**N_VEnableConstVectorArray.ParHyp**

Prototype `int N_VEnableConstVectorArray.ParHyp(N_Vector v, booleantype tf)`

Description This function enables (SUNTRUE) or disables (SUNFALSE) the const operation for vector arrays in the parhyp vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**N_VEnableWrmsNormVectorArray.ParHyp**

Prototype `int N_VEnableWrmsNormVectorArray.ParHyp(N_Vector v, booleantype tf)`

Description This function enables (SUNTRUE) or disables (SUNFALSE) the WRMS norm operation for vector arrays in the parhyp vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**N_VEnableWrmsNormMaskVectorArray.ParHyp**

Prototype `int N_VEnableWrmsNormMaskVectorArray.ParHyp(N_Vector v, booleantype tf)`

Description This function enables (SUNTRUE) or disables (SUNFALSE) the masked WRMS norm operation for vector arrays in the parhyp vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**N_VEnableScaleAddMultiVectorArray.ParHyp**

Prototype `int N_VEnableScaleAddMultiVectorArray.ParHyp(N_Vector v, booleantype tf)`

Description This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector array to multiple vector arrays operation in the parhyp vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**N_VEnableLinearCombinationVectorArray.ParHyp**

Prototype `int N_VEnableLinearCombinationVectorArray.ParHyp(N_Vector v, booleantype tf)`

Description This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination operation for vector arrays in the parhyp vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

Notes

- When there is a need to access components of an `N_Vector.ParHyp`, `v`, it is recommended to extract the hypre vector via `x_vec = N_VGetVector.ParHyp(v)` and then access components using appropriate hypre functions.

- `N_VNewEmpty.ParHyp`, `N_VMake.ParHyp`, and `N_VCloneVectorArrayEmpty.ParHyp` set the field `own_parvector` to SUNFALSE. `N_VDestroy.ParHyp` and `N_VDestroyVectorArray.ParHyp` will not attempt to delete an underlying hypre vector for any `N_Vector` with `own_parvector` set to SUNFALSE. In such a case, it is the user’s responsibility to delete the underlying vector.
To maximize efficiency, vector operations in the NVECTOR_PARHYB implementation that have more than one \texttt{NVector} argument do not check for consistent internal representations of these vectors. It is the user’s responsibility to ensure that such routines are called with \texttt{NVector} arguments that were all created with the same internal representations.

### 6.8 The NVECTOR\_PETSC implementation

The NVECTOR\_PETSC module is an NVECTOR wrapper around the PETSc vector. It defines the \textit{content} field of a \texttt{NVector} to be a structure containing the global and local lengths of the vector, a pointer to the PETSc vector, an MPI communicator, and a boolean flag \textit{own data} indicating ownership of the wrapped PETSc vector.

```c
struct _N_VectorContent_Petsc {
    sunindextype local_length;
    sunindextype global_length;
    booleantype own_data;
    Vec *pvec;
    MPI_Comm comm;
};
```

The header file to include when using this module is \texttt{nvector\_petsc.h}. The installed module library to link to is \texttt{libsundials\_nvecpetsc.lib} where \texttt{.lib} is typically \texttt{.so} for shared libraries and \texttt{.a} for static libraries.

Unlike native SUNDIALS vector types, NVECTOR\_PETSC does not provide macros to access its member variables. Note that NVECTOR\_PETSC requires SUNDIALS to be built with MPI support.

#### 6.8.1 NVECTOR\_PETSC functions

The NVECTOR\_PETSC module defines implementations of all vector operations listed in Tables 6.1.1, 6.1.2, 6.1.3, and 6.1.4, except for \texttt{NGetArrayPointer} and \texttt{NSetArrayPointer}. As such, this vector cannot be used with SUNDIALS Fortran interfaces. When access to raw vector data is needed, it is recommended to extract the PETSc vector first, and then use PETSc methods to access the data. Usage examples of NVECTOR\_PETSC are provided in example programs for IDA [28].

The names of vector operations are obtained from those in Tables 6.1.1, 6.1.2, 6.1.3, and 6.1.4 by appending the suffix \_Petsc (e.g. \texttt{NDestroy\_Petsc}). The module NVECTOR\_PETSC provides the following additional user-callable routines:

**\texttt{NNewEmpty\_Petsc}**

Prototype \texttt{NVector NNewEmpty\_Petsc(MPI\_Comm comm, sunindextype local\_length, sunindextype global\_length)}

Description This function creates a new NVECTOR wrapper with the pointer to the wrapped PETSc vector set to (NULL). It is used by the \texttt{NMake\_Petsc} and \texttt{NClone\_Petsc} implementations.

**\texttt{NMake\_Petsc}**

Prototype \texttt{NVector NMake\_Petsc(Vec \*pvec)}

Description This function creates and allocates memory for an NVECTOR\_PETSC wrapper around a user-provided PETSc vector. It does \textit{not} allocate memory for the vector \texttt{pvec} itself.

**\texttt{NGetVector\_Petsc}**

Prototype \texttt{Vec \*NGetVector\_Petsc(N\_Vector v)}

Description This function returns a pointer to the underlying PETSc vector.
6.8 The NVECTOR_PETSC implementation

N_VCloneVectorArray_Petsc
Prototype  N_Vector *N_VCloneVectorArray_Petsc(int count, N_Vector w)
Description  This function creates (by cloning) an array of count NVECTOR_PETSC vectors.

N_VCloneVectorArrayEmpty_Petsc
Prototype  N_Vector *N_VCloneVectorArrayEmpty_Petsc(int count, N_Vector w)
Description  This function creates (by cloning) an array of count NVECTOR_PETSC vectors, each with pointers to PETSC vectors set to (NULL).

N_VDestroyVectorArray_Petsc
Prototype  void N_VDestroyVectorArray_Petsc(N_Vector *vs, int count)
Description  This function frees memory allocated for the array of count variables of type N_Vector created with N_VCloneVectorArray_Petsc or with N_VCloneVectorArrayEmpty_Petsc.

N_VPrint_Petsc
Prototype  void N_VPrint_Petsc(N_Vector v)
Description  This function prints the global content of a wrapped PETSC vector to stdout.

N_VPrintFile_Petsc
Prototype  void N_VPrintFile_Petsc(N_Vector v, const char fname[])
Description  This function prints the global content of a wrapped PETSC vector to fname.

By default all fused and vector array operations are disabled in the NVECTOR_PETSC module. The following additional user-callable routines are provided to enable or disable fused and vector array operations for a specific vector. To ensure consistency across vectors it is recommended to first create a vector with N_VMake_Petsc, enable/disable the desired operations for that vector with the functions below, and create any additional vectors from that vector using N_VClone. This guarantees the new vectors will have the same operations enabled/disabled as cloned vectors inherit the same enable/disable options as the vector they are cloned from while vectors created with N_VMake_Petsc will have the default settings for the NVECTOR_PETSC module.

N_VEnableFusedOps_Petsc
Prototype  int N_VEnableFusedOps_Petsc(N_Vector v, booleantype tf)
Description  This function enables (SUNTRUE) or disables (SUNFALSE) all fused and vector array operations in the PETSC vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

N_VEnableLinearCombination_Petsc
Prototype  int N_VEnableLinearCombination_Petsc(N_Vector v, booleantype tf)
Description  This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination fused operation in the PETSC vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.
N_VEnableScaleAddMulti_Petsc
Prototype int N_VEnableScaleAddMulti_Petsc(N_Vector v, booleantype tf)
Description This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector to multiple vectors fused operation in the PETSc vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

N_VEnableDotProdMulti_Petsc
 Prototype int N_VEnableDotProdMulti_Petsc(N_Vector v, booleantype tf)
Description This function enables (SUNTRUE) or disables (SUNFALSE) the multiple dot products fused operation in the PETSc vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

N_VEnableLinearSumVectorArray_Petsc
 Prototype int N_VEnableLinearSumVectorArray_Petsc(N_Vector v, booleantype tf)
Description This function enables (SUNTRUE) or disables (SUNFALSE) the linear sum operation for vector arrays in the PETSc vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

N_VEnableScaleVectorArray_Petsc
 Prototype int N_VEnableScaleVectorArray_Petsc(N_Vector v, booleantype tf)
Description This function enables (SUNTRUE) or disables (SUNFALSE) the scale operation for vector arrays in the PETSc vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

N_VEnableConstVectorArray_Petsc
 Prototype int N_VEnableConstVectorArray_Petsc(N_Vector v, booleantype tf)
Description This function enables (SUNTRUE) or disables (SUNFALSE) the const operation for vector arrays in the PETSc vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

N_VEnableWrmsNormVectorArray_Petsc
 Prototype int N_VEnableWrmsNormVectorArray_Petsc(N_Vector v, booleantype tf)
Description This function enables (SUNTRUE) or disables (SUNFALSE) the WRMS norm operation for vector arrays in the PETSc vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

N_VEnableWrmsNormMaskVectorArray_Petsc
 Prototype int N_VEnableWrmsNormMaskVectorArray_Petsc(N_Vector v, booleantype tf)
Description This function enables (SUNTRUE) or disables (SUNFALSE) the masked WRMS norm operation for vector arrays in the PETSc vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.
6.9 The NVECTOR_CUDA implementation

The NVECTOR_CUDA module is an experimental NVECTOR implementation in the CUDA language. The module allows for SUNDIALS vector kernels to run on GPU devices. It is intended for users who are already familiar with CUDA and GPU programming. Building this vector module requires a CUDA compiler and, by extension, a C++ compiler. The class Vector in the namespace suncudavec manages the vector data layout:

```cpp
template <class T, class I>
class Vector {
    I size_;           
    I mem_size_;       
    T* h_vec_;         
    T* d_vec_;         
    ThreadPartitioning<T, I>* partStream_; 
    ThreadPartitioning<T, I>* partReduce_; 
    bool ownPartitioning_; 
    bool ownData_;     
    bool managed_mem_; 
    ...
};
```

The class members are vector size (length), size of the vector data memory block, pointers to vector data on the host and the device, pointers to ThreadPartitioning implementations that handle thread

---

**N_VEnableScaleAddMultiVectorArray_Petsc**

Prototype: `int N_VEnableScaleAddMultiVectorArray_Petsc(N_Vector v, booleantype tf)`

Description: This function enables (`SUNTRUE`) or disables (`SUNTRUE`) the scale and add a vector array to multiple vector arrays operation in the PETSc vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are NULL.

**N_VEnableLinearCombinationVectorArray_Petsc**

Prototype: `int N_VEnableLinearCombinationVectorArray_Petsc(N_Vector v, booleantype tf)`

Description: This function enables (`SUNTRUE`) or disables (`SUNTRUE`) the linear combination operation for vector arrays in the PETSc vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are NULL.

Notes:

- When there is a need to access components of an N_Vector_Petsc, v, it is recommended to extract the PETSc vector via `x_vec = N_VGetVector_Petsc(v)` and then access components using appropriate PETSc functions.
- The functions N_VNewEmpty_Petsc, N_VMake_Petsc, and N_VCloneVectorArrayEmpty_Petsc set the field `own_data` to SUNFALSE. N_VDestroy_Petsc and N_VDestroyVectorArray_Petsc will not attempt to free the pointer `pvec` for any N_Vector with `own_data` set to SUNFALSE. In such a case, it is the user’s responsibility to deallocate the `pvec` pointer.
- To maximize efficiency, vector operations in the NVECTOR_PETSC implementation that have more than one N_Vector argument do not check for consistent internal representations of these vectors. It is the user’s responsibility to ensure that such routines are called with N_Vector arguments that were all created with the same internal representations.

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### 6.9 The NVECTOR_CUDA implementation

The NVECTOR_CUDA module is an experimental NVECTOR implementation in the CUDA language. The module allows for SUNDIALS vector kernels to run on GPU devices. It is intended for users who are already familiar with CUDA and GPU programming. Building this vector module requires a CUDA compiler and, by extension, a C++ compiler. The class `Vector` in the namespace `suncudavec` manages the vector data layout:
partitioning for streaming and reduction vector kernels, a boolean flag that signals if the vector owns the thread partitioning, a boolean flag that signals if the vector owns the data, and a boolean flag that signals if managed memory is used for the data arrays. The class Vector inherits from the empty structure

```c
struct _N_VectorContent_Cuda {};
```
to interface the C++ class with the NVECTOR C code. Due to the rapid progress of CUDA development, we expect that the suncudavec::Vector class will change frequently in future SUNDIALS releases. The code is structured so that it can tolerate significant changes in the suncudavec::Vector class without requiring changes to the user API.

When instantiated with N_VNew_Cuda, the class Vector will allocate memory on both the host and the device. Alternatively, a user can provide host and device data arrays by using the N_VMake_Cuda constructor. To use CUDA managed memory, the constructors N_VNewManaged_Cuda and N_VMakeManaged_Cuda are provided. Details on each of these constructors are provided below.

To use the NVECTOR_CUDA module, the header file to include is nvector_cuda.h, and the library to link to is libsundials_nveccuda.lib. The extension .lib is typically .so for shared libraries and .a for static libraries.

### 6.9.1 NVECTOR_CUDA functions

Unlike other native SUNDIALS vector types, NVVECTOR_CUDA does not provide macros to access its member variables. Instead, user should use the accessor functions:

#### N_VGetHostArrayPointer_Cuda

**Prototype**

```c
realtype *N_VGetHostArrayPointer_Cuda(N_Vector v)
```

**Description**

This function returns a pointer to the vector data on the host.

#### N_VGetDeviceArrayPointer_Cuda

**Prototype**

```c
realtype *N_VGetDeviceArrayPointer_Cuda(N_Vector v)
```

**Description**

This function returns a pointer to the vector data on the device.

#### N_VIsManagedMemory_Cuda

**Prototype**

```c
booleantype *N_VIsManagedMemory_Cuda(N_Vector v)
```

**Description**

This function returns a boolean flag indicating if the vector data is allocated in managed memory or not.

The NVVECTOR_CUDA module defines implementations of all vector operations listed in Tables 6.1.1, 6.1.2, 6.1.3 and 6.1.4, except for N_VSetArrayPointer, and, if using unmanaged memory, N_VGetArrayPointer. As such, this vector can only be used with the SUNDIALS Fortran interfaces, and the SUNDIALS direct solvers and preconditioners when using managed memory. The NVVECTOR_CUDA module provides separate functions to access data on the host and on the device for the unmanaged memory use case. It also provides methods for copying from the host to the device and vice versa. Usage examples of NVVECTOR_CUDA are provided in some example programs for CVODE [29].

The names of vector operations are obtained from those in Tables 6.1.1, 6.1.2, 6.1.3, and 6.1.4 by appending the suffix _Cuda (e.g. N_VDestroy_Cuda). The module NVVECTOR_CUDA provides the following functions:

#### N_VNew_Cuda

**Prototype**

```c
N_Vector N_VNew_Cuda(sunindextype length)
```

**Description**

This function creates and allocates memory for a CUDA N_Vector. The vector data array is allocated on both the host and device.
6.9 The NVECTOR_CUDA implementation

N_VNewManaged_Cuda
Prototype N_Vector N_VNewManaged_Cuda(sunindextype length)
Description This function creates and allocates memory for a CUDA N_Vector. The vector data array is allocated in managed memory.

N_VNewEmpty_Cuda
Prototype N_Vector N_VNewEmpty_Cuda()
Description This function creates a new NVECTOR wrapper with the pointer to the wrapped CUDA vector set to NULL. It is used by the N_VNew_Cuda, N_VMake_Cuda, and N_VClone_Cuda implementations.

N_VMake_Cuda
Prototype N_Vector N_VMake_Cuda(sunindextype length, realtype *h_data, realtype *dev_data)
Description This function creates an NVECTOR_CUDA with user-supplied vector data arrays h_vdata and d_vdata. This function does not allocate memory for data itself.

N_VMakeManaged_Cuda
Prototype N_Vector N_VMakeManaged_Cuda(sunindextype length, realtype *vdata)
Description This function creates an NVECTOR_CUDA with a user-supplied managed memory data array. This function does not allocate memory for data itself.

N_VMakeWithManagedAllocator_Cuda
Prototype N_Vector N_VMakeWithManagedAllocator_Cuda(sunindextype length, void* (*allocfn)(size_t size), void (*freefn)(void* ptr));
Description This function creates an NVECTOR_CUDA with a user-supplied memory allocator. It requires the user to provide a corresponding free function as well. The memory allocated by the allocator function must behave like CUDA managed memory.

The module NVECTOR_CUDA also provides the following user-callable routines:

N_VSetCudaStream_Cuda
Prototype void N_VSetCudaStream_Cuda(N_Vector v, cudaStream_t *stream)
Description This function sets the CUDA stream that all vector kernels will be launched on. By default an NVECTOR_CUDA uses the default CUDA stream.

Note: All vectors used in a single instance of a SUNDIALS solver must use the same CUDA stream, and the CUDA stream must be set prior to solver initialization. Additionally, if manually instantiating the stream and reduce ThreadPartitioning of a suncudavec::Vector, ensure that they use the same CUDA stream.

N_VCopyToDevice_Cuda
Prototype void N_VCopyToDevice_Cuda(N_Vector v)
Description This function copies host vector data to the device.
**N_VCopyFromDevice_Cuda**
Prototype: `void N_VCopyFromDevice_Cuda(N_Vector v)`
Description: This function copies vector data from the device to the host.

**N_VPrint_Cuda**
Prototype: `void N_VPrint_Cuda(N_Vector v)`
Description: This function prints the content of a CUDA vector to stdout.

**N_VPrintFile_Cuda**
Prototype: `void N_VPrintFile_Cuda(N_Vector v, FILE *outfile)`
Description: This function prints the content of a CUDA vector to outfile. By default all fused and vector array operations are disabled in the NVVECTOR_CUDA module. The following additional user-callable routines are provided to enable or disable fused and vector array operations for a specific vector. To ensure consistency across vectors it is recommended to first create a vector with `N_VNew_Cuda`, enable/disable the desired operations for that vector with the functions below, and create any additional vectors from that vector using `N_VClone`. This guarantees the new vectors will have the same operations enabled/disabled as cloned vectors inherit the same enable/disable options as the vector they are cloned from while vectors created with `N_VNew_Cuda` will have the default settings for the NVVECTOR_CUDA module.

**N_VEnableFusedOps_Cuda**
Prototype: `int N_VEnableFusedOps_Cuda(N_Vector v, boolean *tf)`
Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) all fused and vector array operations in the CUDA vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**N_VEnableLinearCombination_Cuda**
Prototype: `int N_VEnableLinearCombination_Cuda(N_Vector v, boolean *tf)`
Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the linear combination fused operation in the CUDA vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**N_VEnableScaleAddMulti_Cuda**
Prototype: `int N_VEnableScaleAddMulti_Cuda(N_Vector v, boolean *tf)`
Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the scale and add a vector to multiple vectors fused operation in the CUDA vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**N_VEnableDotProdMulti_Cuda**
Prototype: `int N_VEnableDotProdMulti_Cuda(N_Vector v, boolean *tf)`
Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the multiple dot products fused operation in the CUDA vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.
6.9 The NVECTOR_CUDA implementation

**N.VEnableLinearSumVectorArray_Cuda**

Prototype: `int N.VEnableLinearSumVectorArray_Cuda(N_Vector v, booleantype tf)`

Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the linear sum operation for vector arrays in the CUDA vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are `NULL`.

**N.VEnableScaleVectorArray_Cuda**

Prototype: `int N.VEnableScaleVectorArray_Cuda(N_Vector v, booleantype tf)`

Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the scale operation for vector arrays in the CUDA vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are `NULL`.

**N.VEnableConstVectorArray_Cuda**

Prototype: `int N.VEnableConstVectorArray_Cuda(N_Vector v, booleantype tf)`

Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the const operation for vector arrays in the CUDA vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are `NULL`.

**N.VEnableWrmsNormVectorArray_Cuda**

Prototype: `int N.VEnableWrmsNormVectorArray_Cuda(N_Vector v, booleantype tf)`

Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the WRMS norm operation for vector arrays in the CUDA vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are `NULL`.

**N.VEnableWrmsNormMaskVectorArray_Cuda**

Prototype: `int N.VEnableWrmsNormMaskVectorArray_Cuda(N_Vector v, booleantype tf)`

Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the masked WRMS norm operation for vector arrays in the CUDA vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are `NULL`.

**N.VEnableScaleAddMultiVectorArray_Cuda**

Prototype: `int N.VEnableScaleAddMultiVectorArray_Cuda(N_Vector v, booleantype tf)`

Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the scale and add a vector array to multiple vector arrays operation in the CUDA vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are `NULL`.

**N.VEnableLinearCombinationVectorArray_Cuda**

Prototype: `int N.VEnableLinearCombinationVectorArray_Cuda(N_Vector v, booleantype tf)`

Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the linear combination operation for vector arrays in the CUDA vector. The return value is 0 for success and -1 if the input vector or its `ops` structure are `NULL`. 
Notes

- When there is a need to access components of an NVector_Cuda, it is recommended to use functions N_VGetDeviceArrayPointer_Cuda or N_VGetHostArrayPointer_Cuda. However, when using managed memory, the function N_VGetArrayPointer may also be used.

- To maximize efficiency, vector operations in the NVECTOR_CUDA implementation that have more than one NVector argument do not check for consistent internal representations of these vectors. It is the user’s responsibility to ensure that such routines are called with NVector arguments that were all created with the same internal representations.

6.10 The NVECTOR_RAJA implementation

The NVECTOR_RAJA module is an experimental NVECTOR implementation using the RAJA hardware abstraction layer. In this implementation, RAJA allows for SUNDIALS vector kernels to run on GPU devices. The module is intended for users who are already familiar with RAJA and GPU programming. Building this vector module requires a C++11 compliant compiler and a CUDA software development toolkit. Besides the CUDA backend, RAJA has other backends such as serial, OpenMP, and OpenACC. These backends are not used in this SUNDIALS release. Class Vector in namespace sunrajavec manages the vector data layout:

```cpp
template <class T, class I>
class Vector {
    I size_; 
    I mem_size_; 
    T* h_vec_; 
    T* d_vec_; 
    ...
};
```

The class members are: vector size (length), size of the vector data memory block, the global vector size (length), a pointer to the vector data on the host, and a pointer to the vector data on the device. The class Vector inherits from an empty structure

```cpp
struct _N_VectorContent_Raja { };
```

to interface the C++ class with the NVECTOR C code. When instantiated, the class Vector will allocate memory on both the host and the device. Due to the rapid progress of RAJA development, we expect that the sunrajavec::Vector class will change frequently in future SUNDIALS releases. The code is structured so that it can tolerate significant changes in the sunrajavec::Vector class without requiring changes to the user API.

The header file to include when using this module is nvector_raja.h. The installed module library to link to are libsundials_nveccudaraja.lib. The extension .lib is typically .so for shared libraries and .a for static libraries.

6.10.1 NVECTOR_RAJA functions

Unlike other native SUNDIALS vector types, NVECTOR_RAJA does not provide macros to access its member variables. Instead, user should use the accessor functions:

```cpp
N_VGetHostArrayPointer_Raja
```

Prototype `realtype *N_VGetHostArrayPointer_Raja(N_Vector v)`

Description This function returns a pointer to the vector data on the host.
6.10 The NVVECTOR RAJA implementation

**N.VGetDeviceArrayPointer_Raja**

Prototype \( \text{realtype \ast \text{N.VGetDeviceArrayPointer_Raja}(\text{N.Vector } \text{v})} \)

Description This function returns a pointer to the vector data on the device.

The NVVECTOR RAJA module defines the implementations of all vector operations listed in Tables 6.1.1, 6.1.2, 6.1.3, and 6.1.4, except for N.VDotProdMulti, N.VWrmsNormVectorArray, and N.VWrmsNormMaskVectorArray as support for arrays of reduction vectors is not yet supported in RAJA. These functions will be added to the NVVECTOR RAJA implementation in the future. Additionally the vector operations N.VGetArrayPointer and N.VSetArrayPointer are not implemented by the RAJA vector. As such, this vector cannot be used with the SUNDIALS Fortran interfaces, nor with the SUNDIALS direct solvers and preconditioners. The NVVECTOR RAJA module provides separate functions to access data on the host and on the device. It also provides methods for copying data from the host to the device and vice versa. Usage examples of NVVECTOR RAJA are provided in some example programs for CVODE [29].

The names of vector operations are obtained from those in Tables 6.1.1, 6.1.2, 6.1.3, and 6.1.4 by appending the suffix _Raja (e.g. N.VDestroy_Raja). The module NVVECTOR RAJA provides the following additional user-callable routines:

**N.VNew_Raja**

Prototype \( \text{N.Vector \text{N.VNew_Raja}(\text{sunindextype length})} \)

Description This function creates and allocates memory for a CUDA N.Vector. The vector data array is allocated on both the host and device.

**N.VNewEmpty_Raja**

Prototype \( \text{N.Vector \text{N.VNewEmpty_Raja}()} \)

Description This function creates a new NVVECTOR wrapper with the pointer to the wrapped RAJA vector set to NULL. It is used by the N.VNew_Raja, N.VMake_Raja, and N.VClone_Raja implementations.

**N.VMake_Raja**

Prototype \( \text{N.Vector \text{N.VMake_Raja}(\text{N.VectorContent_Raja c})} \)

Description This function creates and allocates memory for an NVVECTOR RAJA wrapper around a user-provided sunrajavec::Vector class. Its only argument is of type N.VectorContent_Raja, which is the pointer to the class.

**N.VCopyToDevice_Raja**

Prototype \( \text{realtype \ast \text{N.VCopyToDevice_Raja}(\text{N.Vector } \text{v})} \)

Description This function copies host vector data to the device.

**N.VCopyFromDevice_Raja**

Prototype \( \text{realtype \ast \text{N.VCopyFromDevice_Raja}(\text{N.Vector } \text{v})} \)

Description This function copies vector data from the device to the host.

**N.VPrint_Raja**

Prototype \( \text{void \text{N.VPrint_Raja}(\text{N.Vector } \text{v})} \)

Description This function prints the content of a RAJA vector to stdout.
N_VPrintFile_Raja

Prototype: void N_VPrintFile_Raja(N_Vector v, FILE *outfile)

Description: This function prints the content of a RAJA vector to outfile.

By default all fused and vector array operations are disabled in the NVECTOR_RAJA module. The following additional user-callable routines are provided to enable or disable fused and vector array operations for a specific vector. To ensure consistency across vectors it is recommended to first create a vector with N_VNew_Raja, enable/disable the desired operations for that vector with the functions below, and create any additional vectors from that vector using N_VClone. This guarantees the new vectors will have the same operations enabled/disabled as cloned vectors inherit the same enable/disable options as the vector they are cloned from while vectors created with N_VNew_Raja will have the default settings for the NVECTOR_RAJA module.

N_VEnableFusedOps_Raja

Prototype: int N_VEnableFusedOps_Raja(N_Vector v, booleantype tf)

Description: This function enables (SUNTRUE) or disables (SUNFALSE) all fused and vector array operations in the RAJA vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

N_VEnableLinearCombination_Raja

Prototype: int N_VEnableLinearCombination_Raja(N_Vector v, booleantype tf)

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination fused operation in the RAJA vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

N_VEnableScaleAddMulti_Raja

Prototype: int N_VEnableScaleAddMulti_Raja(N_Vector v, booleantype tf)

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector to multiple vectors fused operation in the RAJA vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

N_VEnableLinearSumVectorArray_Raja

Prototype: int N_VEnableLinearSumVectorArray_Raja(N_Vector v, booleantype tf)

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the linear sum operation for vector arrays in the RAJA vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

N_VEnableScaleVectorArray_Raja

Prototype: int N_VEnableScaleVectorArray_Raja(N_Vector v, booleantype tf)

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the scale operation for vector arrays in the RAJA vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

N_VEnableConstVectorArray_Raja

Prototype: int N_VEnableConstVectorArray_Raja(N_Vector v, booleantype tf)
Description
This function enables (SUNTRUE) or disables (SUNFALSE) the const operation for vector arrays in the RAJA vector. The return value is 0 for success and −1 if the input vector or its ops structure are NULL.

Prototype
int N_VEnableScaleAddMultiVectorArray_Raja(N_Vector v, booleantype tf)

Description
This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector array to multiple vector arrays operation in the RAJA vector. The return value is 0 for success and −1 if the input vector or its ops structure are NULL.

Prototype
int N_VEnableLinearCombinationVectorArray_Raja(N_Vector v, booleantype tf)

Description
This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination operation for vector arrays in the RAJA vector. The return value is 0 for success and −1 if the input vector or its ops structure are NULL.

Notes

• When there is a need to access components of an N_Vector_Raja, v, it is recommended to use functions N_VGetDeviceArrayPointer_Raja or N_VGetHostArrayPointer_Raja.

• To maximize efficiency, vector operations in the NVECTOR_RAJA implementation that have more than one N_Vector argument do not check for consistent internal representations of these vectors. It is the user’s responsibility to ensure that such routines are called with N_Vector arguments that were all created with the same internal representations.

6.11 The NVECTOR_OPENMPDEV implementation

In situations where a user has access to a device such as a GPU for offloading computation, SUNDIALS provides an NVECTOR implementation using OpenMP device offloading, called NVECTOR_OPENMPDEV.

The NVECTOR_OPENMPDEV implementation defines the content field of the N_Vector to be a structure containing the length of the vector, a pointer to the beginning of a contiguous data array on the host, a pointer to the beginning of a contiguous data array on the device, and a boolean flag own_data which specifies the ownership of host and device data arrays.

struct _N_VectorContent_OpenMPDEV {
    sunindextype length;
    booleantype own_data;
    realtype *host_data;
    realtype *dev_data;
};

The header file to include when using this module is nvector_openmpdev.h. The installed module library to link to is libsundials_nvecopenmpdev.lib where .lib is typically .so for shared libraries and .a for static libraries.

6.11.1 NVECTOR_OPENMPDEV accessor macros

The following macros are provided to access the content of an NVECTOR_OPENMPDEV vector.
• NV_CONTENT_OMPDEV

This routine gives access to the contents of the NVECTOR_OPENMPDEV vector N_Vector.

The assignment v_cont = NV_CONTENT_OMPDEV(v) sets v_cont to be a pointer to the NVECTOR_OPENMPDEV N_Vector content structure.

Implementation:
#define NV_CONTENT_OMPDEV(v) ( (N_VectorContent_OpenMPDEV)(v->content) )

• NV_OWN_DATA_OMPDEV, NV_DATA_HOST_OMPDEV, NV_DATA_DEV_OMPDEV, NV_LENGTH_OMPDEV

These macros give individual access to the parts of the content of an NVECTOR_OPENMPDEV N_Vector.

The assignment v_data = NV_DATA_HOST_OMPDEV(v) sets v_data to be a pointer to the first component of the data on the host for the N_Vector v. The assignment NV_DATA_HOST_OMPDEV(v) = v_data sets the host component array of v to be v_data by storing the pointer v_data.

The assignment v_dev_data = NV_DATA_DEV_OMPDEV(v) sets v_dev_data to be a pointer to the first component of the data on the device for the N_Vector v. The assignment NV_DATA_DEV_OMPDEV(v) = v_dev_data sets the device component array of v to be v_dev_data by storing the pointer v_dev_data.

The assignment v_len = NV_LENGTH_OMPDEV(v) sets v_len to be the length of v. On the other hand, the call NV_LENGTH_OMPDEV(v) = len_v sets the length of v to be len_v.

Implementation:
#define NV_OWN_DATA_OMPDEV(v) ( NV_CONTENT_OMPDEV(v)->own_data )
#define NV_DATA_HOST_OMPDEV(v) ( NV_CONTENT_OMPDEV(v)->host_data )
#define NV_DATA_DEV_OMPDEV(v) ( NV_CONTENT_OMPDEV(v)->dev_data )
#define NV_LENGTH_OMPDEV(v) ( NV_CONTENT_OMPDEV(v)->length )

6.11.2 NVECTOR_OPENMPDEV functions

The NVECTOR_OPENMPDEV module defines OpenMP device offloading implementations of all vector operations listed in Tables 6.1.1, 6.1.2, 6.1.3, and 6.1.4, except for N_VGetArrayPointer and N_VSetArrayPointer. As such, this vector cannot be used with the SUNDIALS Fortran interfaces, nor with the SUNDIALS direct solvers and preconditioners. It also provides methods for copying from the host to the device and vice versa.

The names of vector operations are obtained from those in Tables 6.1.1, 6.1.2, 6.1.3, and 6.1.4 by appending the suffix _OpenMPDEV (e.g. N_VDestroy_OpenMPDEV). The module NVECTOR_OPENMPDEV provides the following additional user-callable routines:

**N_VNew_OpenMPDEV**

Prototype N_Vector N_VNew_OpenMPDEV(sunindextype vec_length)

Description This function creates and allocates memory for an NVECTOR_OPENMPDEV N_Vector.

**N_VNewEmpty_OpenMPDEV**

Prototype N_Vector N_VNewEmpty_OpenMPDEV(sunindextype vec_length)

Description This function creates a new NVECTOR_OPENMPDEV N_Vector with an empty (NULL) host and device data arrays.
6.11 The NVECTOR_OPENMPDEV implementation

**N_VECTOR_OPENMPDEV**

Prototype: `N_Vector N_VMake_OpenMPDEV(sunindextype vec_length, realtype *h_vdata, realtype *d_vdata)`

Description: This function creates an NVECTOR_OPENMPDEV vector with user-supplied vector data arrays h_vdata and d_vdata. This function does not allocate memory for data itself.

**N_VCloneVectorArray_OpenMPDEV**

Prototype: `N_Vector *N_VCloneVectorArray_OpenMPDEV(int count, N_Vector w)`

Description: This function creates (by cloning) an array of count NVVECTOR_OPENMPDEV vectors.

**N_VCloneVectorArrayEmpty_OpenMPDEV**

Prototype: `N_Vector *N_VCloneVectorArrayEmpty_OpenMPDEV(int count, N_Vector w)`

Description: This function creates (by cloning) an array of count NVVECTOR_OPENMPDEV vectors, each with an empty (NULL) data array.

**N_VDestroyVectorArray_OpenMPDEV**

Prototype: `void N_VDestroyVectorArray_OpenMPDEV(N_Vector *vs, int count)`

Description: This function frees memory allocated for the array of count variables of type N_Vector created with N_VCloneVectorArray_OpenMPDEV or with N_VCloneVectorArrayEmpty_OpenMPDEV.

**N_GetHostArrayPointer_OpenMPDEV**

Prototype: `realtype *N_GetHostArrayPointer_OpenMPDEV(N_Vector v)`

Description: This function returns a pointer to the host data array.

**N_GetDeviceArrayPointer_OpenMPDEV**

 Prototype: `realtype *N_GetDeviceArrayPointer_OpenMPDEV(N_Vector v)`

Description: This function returns a pointer to the device data array.

**N_Print_OpenMPDEV**

Prototype: `void N_Print_OpenMPDEV(N_Vector v)`

Description: This function prints the content of an NVVECTOR_OPENMPDEV vector to stdout.

**N_PrintFile_OpenMPDEV**

Prototype: `void N_PrintFile_OpenMPDEV(N_Vector v, FILE *outfile)`

Description: This function prints the content of an NVVECTOR_OPENMPDEV vector to outfile.

**N_CopyToDevice_OpenMPDEV**

Prototype: `void N_CopyToDevice_OpenMPDEV(N_Vector v)`

Description: This function copies the content of an NVVECTOR_OPENMPDEV vector’s host data array to the device data array.
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**N_VCopyFromDevice_OpenMPDEV**

Prototype  void N_VCopyFromDevice_OpenMPDEV(N_Vector v)

Description  This function copies the content of an NVVECTOR_OPENMPDEV vector’s device data array to the host data array.

By default all fused and vector array operations are disabled in the NVVECTOR_OPENMPDEV module. The following additional user-callable routines are provided to enable or disable fused and vector array operations for a specific vector. To ensure consistency across vectors it is recommended to first create a vector with N_VNew_OpenMPDEV, enable/disable the desired operations for that vector with the functions below, and create any additional vectors from that vector using N_VClone. This guarantees the new vectors will have the same operations enabled/disabled as cloned vectors inherit the same enable/disable options as the vector they are cloned from while vectors created with N_VNew_OpenMPDEV will have the default settings for the NVVECTOR_OPENMPDEV module.

**N_VEnableFusedOps_OpenMPDEV**

Prototype  int N_VEnableFusedOps_OpenMPDEV(N_Vector v, booleantype tf)

Description  This function enables (SUNTRUE) or disables (SUNFALSE) all fused and vector array operations in the NVVECTOR_OPENMPDEV vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**N_VEnableLinearCombination_OpenMPDEV**

Prototype  int N_VEnableLinearCombination_OpenMPDEV(N_Vector v, booleantype tf)

Description  This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination fused operation in the NVVECTOR_OPENMPDEV vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**N_VEnableScaleAddMulti_OpenMPDEV**

Prototype  int N_VEnableScaleAddMulti_OpenMPDEV(N_Vector v, booleantype tf)

Description  This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector to multiple vectors fused operation in the NVVECTOR_OPENMPDEV vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**N_VEnableDotProdMulti_OpenMPDEV**

Prototype  int N_VEnableDotProdMulti_OpenMPDEV(N_Vector v, booleantype tf)

Description  This function enables (SUNTRUE) or disables (SUNFALSE) the multiple dot products fused operation in the NVVECTOR_OPENMPDEV vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**N_VEnableLinearSumVectorArray_OpenMPDEV**

Prototype  int N_VEnableLinearSumVectorArray_OpenMPDEV(N_Vector v, booleantype tf)

Description  This function enables (SUNTRUE) or disables (SUNFALSE) the linear sum operation for vector arrays in the NVVECTOR_OPENMPDEV vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.
6.11 The NVECTOR_OPENMPDEV implementation

**N_VEnableScaleVectorArray_OpenMPDEV**

Prototype: `int N_VEnableScaleVectorArray_OpenMPDEV(N_Vector v, booleantype tf)`  
Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the scale operation for vector arrays in the NVECTOR_OPENMPDEV vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**N_VEnableConstVectorArray_OpenMPDEV**

Prototype: `int N_VEnableConstVectorArray_OpenMPDEV(N_Vector v, booleantype tf)`  
Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the const operation for vector arrays in the NVECTOR_OPENMPDEV vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**N_VEnableWrmsNormVectorArray_OpenMPDEV**

Prototype: `int N_VEnableWrmsNormVectorArray_OpenMPDEV(N_Vector v, booleantype tf)`  
Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the WRMS norm operation for vector arrays in the NVECTOR_OPENMPDEV vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**N_VEnableWrmsNormMaskVectorArray_OpenMPDEV**

Prototype: `int N_VEnableWrmsNormMaskVectorArray_OpenMPDEV(N_Vector v, booleantype tf)`  
Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the masked WRMS norm operation for vector arrays in the NVECTOR_OPENMPDEV vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**N_VEnableScaleAddMultiVectorArray_OpenMPDEV**

Prototype: `int N_VEnableScaleAddMultiVectorArray_OpenMPDEV(N_Vector v, booleantype tf)`  
Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the scale and add a vector array to multiple vector arrays operation in the NVECTOR_OPENMPDEV vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**N_VEnableLinearCombinationVectorArray_OpenMPDEV**

Prototype: `int N_VEnableLinearCombinationVectorArray_OpenMPDEV(N_Vector v, booleantype tf)`  
Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) the linear combination operation for vector arrays in the NVECTOR_OPENMPDEV vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**Notes**

- When looping over the components of an N_Vector v, it is most efficient to first obtain the component array via `h_data = NV_DATA_HOST_OPENMPDEV(v)` for the host array or `d_data = NV_DATA_DEV_OPENMPDEV(v)` for the device array and then access `h_data[i]` or `d_data[i]` within the loop.
• When accessing individual components of an N_Vector v on the host remember to first copy the array back from the device with N_VCopyFromDevice_OpenMPDEV(v) to ensure the array is up to date.

• N_VNewEmpty_OpenMPDEV, N_VMake_OpenMPDEV, and N_VCloneVectorArrayEmpty_OpenMPDEV set the field own_data = SUNFALSE. N_VDestroy_OpenMPDEV and N_VDestroyVectorArray_OpenMPDEV will not attempt to free the pointer data for any N_Vector with own_data set to SUNFALSE. In such a case, it is the user’s responsibility to deallocate the data pointer.

• To maximize efficiency, vector operations in the nvector_openmpdev implementation that have more than one N_Vector argument do not check for consistent internal representation of these vectors. It is the user’s responsibility to ensure that such routines are called with N_Vector arguments that were all created with the same internal representations.

6.12 The NVECTOR_TRILINOS implementation

The nvector_trilinos module is an nvector wrapper around the Trilinos Tpetra vector. The interface to Tpetra is implemented in the Sundials::TpetraVectorInterface class. This class simply stores a reference counting pointer to a Tpetra vector and inherits from an empty structure

struct _N_VectorContent_Trilinos {};

to interface the C++ class with the nvector C code. A pointer to an instance of this class is kept in the content field of the N_Vector object, to ensure that the Tpetra vector is not deleted for as long as the N_Vector object exists.

The Tpetra vector type in the Sundials::TpetraVectorInterface class is defined as:

typedef Tpetra::Vector<realtype, sunindextype, sunindextype> vector_type;

The Tpetra vector will use the sundials-specified realtype as its scalar type, and it will use sunindextype as the global and the local ordinal types. This type definition will use Tpetra’s default node type. Available Kokkos node types in Trilinos 12.14 release are serial (single thread), OpenMP, Pthread, and CUDA. The default node type is selected when building the Kokkos package. For example, the Tpetra vector will use a CUDA node if Tpetra was built with CUDA support and the CUDA node was selected as the default when Tpetra was built.

The header file to include when using this module is nvector_trilinos.h. The installed module library to link to is libsundials_nvectrilinos.lib where .lib is typically .so for shared libraries and .a for static libraries.

6.12.1 NVECTOR_TRILINOS functions

The nvector_trilinos module defines implementations of all vector operations listed in Tables 6.1.1, 6.1.4, and 6.1.4, except for N_VGetArrayPointer and N_VSetArrayPointer. As such, this vector cannot be used with SUNDIALS Fortran interfaces, nor with the SUNDIALS direct solvers and preconditioners. When access to raw vector data is needed, it is recommended to extract the Trilinos Tpetra vector first, and then use Tpetra vector methods to access the data. Usage examples of nvector_trilinos are provided in example programs for IDA [28].

The names of vector operations are obtained from those in Tables 6.1.1, 6.1.4, and 6.1.4 by appending the suffix _Trilinos (e.g. N_VDestroy_Trilinos). Vector operations call existing Tpetra::Vector methods when available. Vector operations specific to SUNDIALS are implemented as standalone functions in the namespace Sundials::TpetraVector, located in the file SundialsTpetraVectorKernels.hpp. The module nvector_trilinos provides the following additional user-callable functions:

• N_VGetVector_Trilinos

This C++ function takes an N_Vector as the argument and returns a reference counting pointer to the underlying Tpetra vector. This is a standalone function defined in the global namespace.
6.13 The NVECTOR_MANYVECTOR implementation

Teuchos::RCP<vector_type> N_VGetVector_Trilinos(N_Vector v);

- N_VMake_Trilinos
  This C++ function creates and allocates memory for an NVECTOR_TRILINOS wrapper around a user-provided Tpetra vector. This is a standalone function defined in the global namespace.

N_Vector N_VMake_Trilinos(Teuchos::RCP<vector_type> v);

Notes
- The template parameter vector_type should be set as:
  typedef Sundials::TpetraVectorInterface::vector_type vector_type
  This will ensure that data types used in Tpetra vector match those in SUNDIALS.
- When there is a need to access components of an N_Vector_Trilinos, v, it is recommended to extract the Trilinos vector object via x_vec = N_VGetVector_Trilinos(v) and then access components using the appropriate Trilinos functions.
- The functions N_VDestroy_Trilinos and N_VDestroyVectorArray_Trilinos only delete the N_Vector wrapper. The underlying Tpetra vector object will exist for as long as there is at least one reference to it.

6.13 The NVECTOR_MANYVECTOR implementation

The NVECTOR_MANYVECTOR implementation of the NVECTOR module provided with SUNDIALS is designed to facilitate problems with an inherent data partitioning for the solution vector within a computational node. These data partitions are entirely user-defined, through construction of distinct NVECTOR modules for each component, that are then combined together to form the NVECTOR_MANYVECTOR. We envision two generic use cases for this implementation:

A. **Heterogeneous computational architectures**: for users who wish to partition data on a node between different computing resources, they may create architecture-specific subvectors for each partition. For example, a user could create one serial component based on NVECTOR_SERIAL, another component for GPU accelerators based on NVECTOR_CUDA, and another threaded component based on NVECTOR_OPENMP.

B. **Structure of arrays (SOA) data layouts**: for users who wish to create separate subvectors for each solution component, e.g., in a Navier-Stokes simulation they could have separate subvectors for density, velocities and pressure, which are combined together into a single NVECTOR_MANYVECTOR for the overall “solution”.

We note that the above use cases are not mutually exclusive, and the NVECTOR_MANYVECTOR implementation should support arbitrary combinations of these cases.

The NVECTOR_MANYVECTOR implementation is designed to work with any NVECTOR subvectors that implement the minimum required set of operations. Additionally, NVECTOR_MANYVECTOR sets no limit on the number of subvectors that may be attached (aside from the limitations of using sunindextype for indexing, and standard per-node memory limitations). However, while this ostensibly supports subvectors with one entry each (i.e., one subvector for each solution entry), we anticipate that this extreme situation will hinder performance due to non-stride-one memory accesses and increased function call overhead. We therefore recommend a relatively coarse partitioning of the problem, although actual performance will likely be problem-dependent.

As a final note, in the coming years we plan to introduce additional algebraic solvers and time integration modules that will leverage the problem partitioning enabled by NVECTOR_MANYVECTOR. However, even at present we anticipate that users will be able to leverage such data partitioning in their problem-defining ODE right-hand side, DAE residual, or nonlinear solver residual functions.
6.13.1 NVECTOR_MANYVECTOR structure

The NVECTOR_MANYVECTOR implementation defines the content field of N_Vector to be a structure containing the number of subvectors comprising the ManyVector, the global length of the ManyVector (including all subvectors), a pointer to the beginning of the array of subvectors, and a boolean flag own_data indicating ownership of the subvectors that populate subvec_array.

```c
struct _N_VectorContent_ManyVector {
    sunindextype num_subvectors; /* number of vectors attached */
    sunindextype global_length; /* overall manyvector length */
    N_Vector* subvec_array; /* pointer to N_Vector array */
    booleantype own_data; /* flag indicating data ownership */
};
```

The header file to include when using this module is nvector_manyvector.h. The installed module library to link against is lib sundials_nvecmanyvector.lib where .lib is typically .so for shared libraries and .a for static libraries.

6.13.2 NVECTOR_MANYVECTOR functions

The NVECTOR_MANYVECTOR module implements all vector operations listed in Tables 6.1.1, 6.1.2, 6.1.3, and 6.1.4, except for NVGetArrayPointer, NVSetArrayPointer, NVScaleAddMultiVectorArray, and NVLinearCombinationVectorArray. As such, this vector cannot be used with the SUNDIALS Fortran-77 interfaces, nor with the SUNDIALS direct solvers and preconditioners. Instead, the NVECTOR_MANYVECTOR module provides functions to access subvectors, whose data may in turn be accessed according to their NVECTOR implementations.

The names of vector operations are obtained from those in Tables 6.1.1, 6.1.2, 6.1.3, and 6.1.4 by appending the suffix _ManyVector (e.g. NVDestroy_ManyVector). The module NVECTOR_MANYVECTOR provides the following additional user-callable routines:

**N_VNew_ManyVector**

Prototype  

```c
N_Vector N_VNew_ManyVector(sunindextype num_subvectors,
                            N_Vector *vec_array);
```

Description  

This function creates a ManyVector from a set of existing NVECTOR objects. This routine will copy all N_Vector pointers from the input vec_array, so the user may modify/free that pointer array after calling this function. However, this routine does not allocate any new subvectors, so the underlying NVECTOR objects themselves should not be destroyed before the ManyVector that contains them. Upon successful completion, the new ManyVector is returned; otherwise this routine returns NULL (e.g., a memory allocation failure occurred).

Users of the Fortran 2003 interface to this function will first need to use the generic N_Vector utility functions N_VNewVectorArray, and N_VSetVecAtIndexVectorArray to create the N_Vector* argument. This is further explained in Chapter 5.1.3.5, and the functions are documented in Chapter 6.1.5.

F2003 Name  

This function is callable as FN_VNew_ManyVector when using the Fortran 2003 interface module.

**N_VGetSubvector_ManyVector**

Prototype  

```c
N_Vector N_VGetSubvector_ManyVector(N_Vector v, sunindextype vec_num);
```

Description  

This function returns the vec_num subvector from the NVECTOR array.

F2003 Name  

This function is callable as FN_VGetSubvector_ManyVector when using the Fortran 2003 interface module.
6.13 The NVECTOR_MANYVECTOR implementation

N_VGetSubvectorArrayPointer_ManyVector
Prototype: `realtype *N_VGetSubvectorArrayPointer_ManyVector(N_Vector v, sunindextype vec_num);`
Description: This function returns the data array pointer for the `vec_num` subvector from the NVECTOR array.
If the input `vec_num` is invalid, or if the subvector does not support the `N_VGetArrayPointer` operation, then `NULL` is returned.
F2003 Name: This function is callable as `FN_VGetSubvectorArrayPointer_ManyVector` when using the Fortran 2003 interface module.

N_VSetSubvectorArrayPointer_ManyVector
Prototype: `int N_VSetSubvectorArrayPointer_ManyVector(realtype *v_data, N_Vector v, sunindextype vec_num);`
Description: This function sets the data array pointer for the `vec_num` subvector from the NVECTOR array.
If the input `vec_num` is invalid, or if the subvector does not support the `N_VSetArrayPointer` operation, then this routine returns -1; otherwise it returns 0.
F2003 Name: This function is callable as `FN_VSetSubvectorArrayPointer_ManyVector` when using the Fortran 2003 interface module.

N_VGetNumSubvectors_ManyVector
Prototype: `sunindextype N_VGetNumSubvectors_ManyVector(N_Vector v);`
Description: This function returns the overall number of subvectors in the ManyVector object.
F2003 Name: This function is callable as `FN_VGetNumSubvectors_ManyVector` when using the Fortran 2003 interface module.

By default all fused and vector array operations are disabled in the NVECTOR_MANYVECTOR module, except for `N_VWrmsNormVectorArray` and `N_VWrmsNormMaskVectorArray`, that are enabled by default. The following additional user-callable routines are provided to enable or disable fused and vector array operations for a specific vector. To ensure consistency across vectors it is recommended to first create a vector with `N_VNew_ManyVector`, enable/disable the desired operations for that vector with the functions below, and create any additional vectors from that vector using `N_VClone`. This guarantees that the new vectors will have the same operations enabled/disabled, since cloned vectors inherit those configuration options from the vector they are cloned from, while vectors created with `N_VNew_ManyVector` will have the default settings for the NVECTOR_MANYVECTOR module. We note that these routines do not call the corresponding routines on subvectors, so those should be set up as desired before attaching them to the ManyVector in `N_VNew_ManyVector`.

N_VEnableFusedOps_ManyVector
Prototype: `int N_VEnableFusedOps_ManyVector(N_Vector v, booleantype tf);`
Description: This function enables (`SUNTRUE`) or disables (`SUNFALSE`) all fused and vector array operations in the ManyVector. The return value is 0 for success and -1 if the input vector or its ops structure are `NULL`.
F2003 Name: This function is callable as `FN_VEnableFusedOps_ManyVector` when using the Fortran 2003 interface module.
N_VEnableLinearCombination_ManyVector
Prototype int N_VEnableLinearCombination_ManyVector(N_Vector v, booleantype tf);
Description This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination fused operation in the ManyVector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.
F2003 Name This function is callable as FN_VEnableLinearCombination_ManyVector when using the Fortran 2003 interface module.

N_VEnableScaleAddMulti_ManyVector
Prototype int N_VEnableScaleAddMulti_ManyVector(N_Vector v, booleantype tf);
Description This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector to multiple vectors fused operation in the ManyVector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.
F2003 Name This function is callable as FN_VEnableScaleAddMulti_ManyVector when using the Fortran 2003 interface module.

N_VEnableDotProdMulti_ManyVector
Prototype int N_VEnableDotProdMulti_ManyVector(N_Vector v, booleantype tf);
Description This function enables (SUNTRUE) or disables (SUNFALSE) the multiple dot products fused operation in the ManyVector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.
F2003 Name This function is callable as FN_VEnableDotProdMulti_ManyVector when using the Fortran 2003 interface module.

N_VEnableLinearSumVectorArray_ManyVector
Prototype int N_VEnableLinearSumVectorArray_ManyVector(N_Vector v, booleantype tf);
Description This function enables (SUNTRUE) or disables (SUNFALSE) the linear sum operation for vector arrays in the ManyVector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.
F2003 Name This function is callable as FN_VEnableLinearSumVectorArray_ManyVector when using the Fortran 2003 interface module.

N_VEnableScaleVectorArray_ManyVector
Prototype int N_VEnableScaleVectorArray_ManyVector(N_Vector v, booleantype tf);
Description This function enables (SUNTRUE) or disables (SUNFALSE) the scale operation for vector arrays in the ManyVector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.
F2003 Name This function is callable as FN_VEnableScaleVectorArray_ManyVector when using the Fortran 2003 interface module.

N_VEnableConstVectorArray_ManyVector
Prototype int N_VEnableConstVectorArray_ManyVector(N_Vector v, booleantype tf);
Description This function enables (SUNTRUE) or disables (SUNFALSE) the const operation for vector arrays in the ManyVector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.
F2003 Name This function is callable as \texttt{FN\_VEnableConstVectorArray\_ManyVector} when using the Fortran 2003 interface module.

\begin{verbatim}
N\_VEnableWrmsNormVectorArray\_ManyVector
Prototype \texttt{int N\_VEnableWrmsNormVectorArray\_ManyVector(N\_Vector v, boolean\_type tf);} \\
Description This function enables (\texttt{SUNTRUE}) or disables (\texttt{SUNFALSE}) the WRMS norm operation for vector arrays in the ManyVector. The return value is 0 for success and -1 if the input vector or its \texttt{ops} structure are NULL.
\end{verbatim}

F2003 Name This function is callable as \texttt{FN\_VEnableWrmsNormVectorArray\_ManyVector} when using the Fortran 2003 interface module.

\begin{verbatim}
N\_VEnableWrmsNormMaskVectorArray\_ManyVector
Prototype \texttt{int N\_VEnableWrmsNormMaskVectorArray\_ManyVector(N\_Vector v, boolean\_type tf);} \\
Description This function enables (\texttt{SUNTRUE}) or disables (\texttt{SUNFALSE}) the masked WRMS norm operation for vector arrays in the ManyVector. The return value is 0 for success and -1 if the input vector or its \texttt{ops} structure are NULL.
\end{verbatim}

F2003 Name This function is callable as \texttt{FN\_VEnableWrmsNormMaskVectorArray\_ManyVector} when using the Fortran 2003 interface module.

Notes

- \texttt{N\_VNew\_ManyVector} sets the field \texttt{own\_data = SUNFALSE}. \texttt{N\_VDestroy\_ManyVector} will not attempt to call \texttt{N\_VDestroy} on any subvectors contained in the subvector array for any \texttt{N\_Vector} with \texttt{own\_data} set to \texttt{SUNFALSE}. In such a case, it is the user’s responsibility to deallocate the subvectors.

- To maximize efficiency, arithmetic vector operations in the \texttt{NVECTOR\_MPIMANYVECTOR} implementation that have more than one \texttt{N\_Vector} argument do not check for consistent internal representation of these vectors. It is the user’s responsibility to ensure that such routines are called with \texttt{N\_Vector} arguments that were all created with the same subvector representations.

\section{6.14 The NV\texttt{ECTOR\_MPIMANYVECTOR} implementation}

The \texttt{NVECTOR\_MPIMANYVECTOR} implementation of the \texttt{NVECTOR} module provided with \texttt{SUNDIALS} is designed to facilitate problems with an inherent data partitioning for the solution vector, and when using distributed-memory parallel architectures. As such, the \texttt{MPI\_ManyVector} implementation supports all use cases allowed by the MPI-unaware \texttt{ManyVector} implementation, as well as partitioning data between nodes in a parallel environment. These data partitions are entirely user-defined, through construction of distinct \texttt{NVECTOR} modules for each component, that are then combined together to form the \texttt{NVECTOR\_MPIMANYVECTOR}. We envision three generic use cases for this implementation:

A. \textit{Heterogeneous computational architectures (single-node or multi-node)}: for users who wish to partition data on a node between different computing resources, they may create architecture-specific subvectors for each partition. For example, a user could create one MPI-parallel component based on \texttt{NVECTOR\_PARALLEL}, another single-node component for GPU accelerators based on \texttt{NVECTOR\_CUDA}, and another threaded single-node component based on \texttt{NVECTOR\_OPENMP}.

B. \textit{Process-based multiphysics decompositions (multi-node)}: for users who wish to combine separate simulations together, e.g., where one subvector resides on one subset of MPI processes, while another subvector resides on a different subset of MPI processes, and where the user has created a MPI intercommunicator to connect these distinct process sets together.
C. Structure of arrays (SOA) data layouts (single-node or multi-node): for users who wish to create separate subvectors for each solution component, e.g., in a Navier-Stokes simulation they could have separate subvectors for density, velocities and pressure, which are combined together into a single NVECTOR_MPIMANYVECTOR for the overall “solution”.

We note that the above use cases are not mutually exclusive, and the NVECTOR_MPIMANYVECTOR implementation should support arbitrary combinations of these cases.

The NVECTOR_MPIMANYVECTOR implementation is designed to work with any NVECTOR subvectors that implement the minimum required set of operations, however significant performance benefits may be obtained when subvectors additionally implement the optional local reduction operations listed in Table 6.1.4.

Additionally, NVECTOR_MPIMANYVECTOR sets no limit on the number of subvectors that may be attached (aside from the limitations of using sunindextype for indexing, and standard per-node memory limitations). However, while this ostensibly supports subvectors with one entry each (i.e., one subvector for each solution entry), we anticipate that this extreme situation will hinder performance due to non-stride-one memory accesses and increased function call overhead. We therefore recommend a relatively coarse partitioning of the problem, although actual performance will likely be problem-dependent.

As a final note, in the coming years we plan to introduce additional algebraic solvers and time integration modules that will leverage the problem partitioning enabled by NVECTOR_MPIMANYVECTOR. However, even at present we anticipate that users will be able to leverage such data partitioning in their problem-defining ODE right-hand side, DAE residual, or nonlinear solver residual functions.

6.14.1 NVECTOR_MPIMANYVECTOR structure

The NVECTOR_MPIMANYVECTOR implementation defines the content field of N_Vector to be a structure containing the MPI communicator (or MPI_COMM_NULL if running on a single-node), the number of subvectors comprising the MPIManyVector, the global length of the MPIManyVector (including all subvectors on all MPI tasks), a pointer to the beginning of the array of subvectors, and a boolean flag own_data indicating ownership of the subvectors that populate subvec_array.

```c
struct _N_VectorContent_MPIManyVector {
  MPI_Comm    comm; /* overall MPI communicator */
  sunindextype num_subvectors; /* number of vectors attached */
  sunindextype global_length; /* overall mpimanyvector length */
  N_Vector*  subvec_array; /* pointer to N_Vector array */
  booleantype own_data;  /* flag indicating data ownership */
};
```

The header file to include when using this module is nvector_mpimanyvector.h. The installed module library to link against is lib sundials_nvecmpimanyvector.lib where .lib is typically .so for shared libraries and .a for static libraries.

**Note:** If SUNDIALS is configured with MPI disabled, then the MPIManyVector library will not be built. Furthermore, any user codes that include nvector_mpimanyvector.h must be compiled using an MPI-aware compiler (whether the specific user code utilizes MPI or not). We note that the NVECTOR_MPIMANYVECTOR implementation is designed for ManyVector use cases in an MPI-unaware environment.

6.14.2 NVECTOR_MPIMANYVECTOR functions

The NVECTOR_MPIMANYVECTOR module implements all vector operations listed in Tables 6.1.1, 6.1.2, 6.1.3, and 6.1.4, except for NVGetArrayPointer, NVSetArrayPointer, NVScaleAddMultiVectorArray, and NVLinearCombinationVectorArray. As such, this vector cannot be used with the SUNDIALS Fortran-77 interfaces, nor with the SUNDIALS direct solvers and preconditioners. Instead, the NVECTOR_MPIMANYVECTOR module provides functions to access subvectors, whose data may in turn be accessed according to their NVECTOR implementations.
The names of vector operations are obtained from those in Tables 6.1.1, 6.1.2, 6.1.3, and 6.1.4 by appending the suffix \texttt{MPIManyVector} (e.g. \texttt{N_VDestroy\_MPIManyVector}). The module \texttt{NVECTOR\_MPI\_MANY\_VECTOR} provides the following additional user-callable routines:

\begin{verbatim}
N_VNew\_MPI\_Many\_Vector
Prototype N\_Vector N\_VNew\_MPI\_Many\_Vector(sunindextype num\_subvectors,
N\_Vector \*vec\_array);
Description This function creates an MPIManyVector from a set of existing nvector objects, under
the requirement that all MPI-aware subvectors use the same MPI communicator (this is
checked internally). If none of the subvectors are MPI-aware, then this may equivalently
be used to describe data partitioning within a single node. We note that this routine is
designed to support use cases A and C above.
This routine will copy all \texttt{N\_Vector} pointers from the input \texttt{vec\_array}, so the user may
modify/free that pointer array after calling this function. However, this routine does not
allocate any new subvectors, so the underlying \texttt{nvector} objects themselves should
not be destroyed before the MPIManyVector that contains them.
Upon successful completion, the new MPIManyVector is returned; otherwise this routine
returns \texttt{NULL} (e.g., if two MPI-aware subvectors use different MPI communicators).
Users of the Fortran 2003 interface to this function will first need to use the generic
\texttt{N\_Vector} utility functions \texttt{N\_VNew\_Vector\_Array}, and \texttt{N\_VSet\_Vec\_At\_Index\_Vector\_Array} to
create the \texttt{N\_Vector\*} argument. This is further explained in Chapter 5.1.3.5, and the
functions are documented in Chapter 6.1.5.
F2003 Name This function is callable as \texttt{FN\_VNew\_MPI\_Many\_Vector} when using the Fortran 2003 in-
terface module.
\end{verbatim}

\begin{verbatim}
N\_VMake\_MPI\_Many\_Vector
Prototype N\_Vector N\_VMake\_MPI\_Many\_Vector(MPI\_Comm comm, sunindextype num\_subvectors,
N\_Vector \*vec\_array);
Description This function creates an MPIManyVector from a set of existing nvector objects, and
a user-created MPI communicator that “connects” these subvectors. Any MPI-aware
subvectors may use different MPI communicators than the input \texttt{comm}. We note that
this routine is designed to support any combination of the use cases above.
The input \texttt{comm} should be this user-created MPI communicator. This routine will inter-
nally call \texttt{MPI\_Comm\_dup} to create a copy of the input \texttt{comm}, so the user-supplied \texttt{comm}
argument need not be retained after the call to \texttt{N\_VMake\_MPI\_Many\_Vector}.
If all subvectors are MPI-unaware, then the input \texttt{comm} argument should be \texttt{MPI\_COMM\_NULL},
although in this case, it would be simpler to call \texttt{N\_VNew\_MPI\_Many\_Vector} instead, or to
just use the \texttt{N\_Vector\_MANY\_VECTOR} module.
This routine will copy all \texttt{N\_Vector} pointers from the input \texttt{vec\_array}, so the user may
modify/free that pointer array after calling this function. However, this routine does not
allocate any new subvectors, so the underlying \texttt{nvector} objects themselves should
not be destroyed before the MPIManyVector that contains them.
Upon successful completion, the new MPIManyVector is returned; otherwise this routine
returns \texttt{NULL} (e.g., if the input \texttt{vec\_array} is \texttt{NULL}).
F2003 Name This function is callable as \texttt{FN\_VMake\_MPI\_Many\_Vector} when using the Fortran 2003 in-
terface module.
\end{verbatim}
**N_VGetSubvector_MPIManyVector**

Prototype: `N_Vector N_VGetSubvector_MPIManyVector(N_Vector v, sunindextype vec_num);`

Description: This function returns the `vec_num` subvector from the NVECTOR array.

F2003 Name: This function is callable as `FN_VGetSubvector_MPIManyVector` when using the Fortran 2003 interface module.

**N_VGetSubvectorArrayPointer_MPIManyVector**

Prototype: `realtype *N_VGetSubvectorArrayPointer_MPIManyVector(N_Vector v, sunindextype vec_num);`

Description: This function returns the data array pointer for the `vec_num` subvector from the NVECTOR array.

If the input `vec_num` is invalid, or if the subvector does not support the `N_VGetArrayPointer` operation, then NULL is returned.

F2003 Name: This function is callable as `FN_VGetSubvectorArrayPointer_MPIManyVector` when using the Fortran 2003 interface module.

**N_VSetSubvectorArrayPointer_MPIManyVector**

Prototype: `int N_VSetSubvectorArrayPointer_MPIManyVector(realtype *v_data, N_Vector v, sunindextype vec_num);`

Description: This function sets the data array pointer for the `vec_num` subvector from the NVECTOR array.

If the input `vec_num` is invalid, or if the subvector does not support the `N_VSetArrayPointer` operation, then this routine returns -1; otherwise it returns 0.

F2003 Name: This function is callable as `FN_VSetSubvectorArrayPointer_MPIManyVector` when using the Fortran 2003 interface module.

**N_VGetNumSubvectors_MPIManyVector**

Prototype: `sunindextype N_VGetNumSubvectors_MPIManyVector(N_Vector v);`

Description: This function returns the overall number of subvectors in the MPIManyVector object.

F2003 Name: This function is callable as `FN_VGetNumSubvectors_MPIManyVector` when using the Fortran 2003 interface module.

By default all fused and vector array operations are disabled in the NVECTOR_MPI MANYVECTOR module, except for `N_VWrmsNormVectorArray` and `N_VWrmsNormMaskVectorArray`, that are enabled by default. The following additional user-callable routines are provided to enable or disable fused and vector array operations for a specific vector. To ensure consistency across vectors it is recommended to first create a vector with `N_VNew_MPIManyVector` or `N_VMMake_MPIManyVector`, enable/disable the desired operations for that vector with the functions below, and create any additional vectors from that vector using `N_VClone`. This guarantees that the new vectors will have the same operations enabled/disabled, since cloned vectors inherit those configuration options from the vector they are cloned from, while vectors created with `N_VNew_MPIManyVector` and `N_VMMake_MPIManyVector` will have the default settings for the NVECTOR_MPI MANYVECTOR module. We note that these routines do not call the corresponding routines on subvectors, so those should be set up as desired before attaching them to the MPIManyVector in `N_VNew_MPIManyVector` or `N_VMMake_MPIManyVector`. 
6.14 The NVECTOR_MPMANYVECTOR implementation

**N_VEnableFusedOps_MPIManyVector**

Prototype: int N_VEnableFusedOps_MPIManyVector(N_Vector v, booleantype tf);

Description: This function enables (SUNTRUE) or disables (SUNFALSE) all fused and vector array operations in the MPIManyVector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

F2003 Name: This function is callable as FN_VEnableFusedOps_MPIManyVector when using the Fortran 2003 interface module.

**N_VEnableLinearCombination_MPIManyVector**

Prototype: int N_VEnableLinearCombination_MPIManyVector(N_Vector v, booleantype tf);

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination fused operation in the MPIManyVector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

F2003 Name: This function is callable as FN_VEnableLinearCombination_MPIManyVector when using the Fortran 2003 interface module.

**N_VEnableScaleAddMulti_MPIManyVector**

Prototype: int N_VEnableScaleAddMulti_MPIManyVector(N_Vector v, booleantype tf);

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector to multiple vectors fused operation in the MPIManyVector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

F2003 Name: This function is callable as FN_VEnableScaleAddMulti_MPIManyVector when using the Fortran 2003 interface module.

**N_VEnableDotProdMulti_MPIManyVector**

Prototype: int N_VEnableDotProdMulti_MPIManyVector(N_Vector v, booleantype tf);

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the multiple dot products fused operation in the MPIManyVector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

F2003 Name: This function is callable as FN_VEnableDotProdMulti_MPIManyVector when using the Fortran 2003 interface module.

**N_VEnableLinearSumVectorArray_MPIManyVector**

Prototype: int N_VEnableLinearSumVectorArray_MPIManyVector(N_Vector v, booleantype tf);

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the linear sum operation for vector arrays in the MPIManyVector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

F2003 Name: This function is callable as FN_VEnableLinearSumVectorArray_MPIManyVector when using the Fortran 2003 interface module.

**N_VEnableScaleVectorArray_MPIManyVector**

Prototype: int N_VEnableScaleVectorArray_MPIManyVector(N_Vector v, booleantype tf);

Description: This function enables (SUNTRUE) or disables (SUNFALSE) the scale operation for vector arrays in the MPIManyVector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.
F2003 Name This function is callable as FN_VEnableScaleVectorArray_MPIManyVector when using the Fortran 2003 interface module.

\[ N_VEnableConstVectorArray_MPIManyVector \]

Prototype \[ \text{int } N_{\text{VEnableConstVectorArray}} \text{\_MPIManyVector(N\_Vector } v, \text{ booleantype } tf); \]

Description This function enables (SUNTRUE) or disables (SUNFALSE) the const operation for vector arrays in the MPIManyVector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

F2003 Name This function is callable as FN_VEnableConstVectorArray_MPIManyVector when using the Fortran 2003 interface module.

\[ N_{\text{VEnableWrmsNormVectorArray}} \text{\_MPIManyVector} \]

Prototype \[ \text{int } N_{\text{VEnableWrmsNormVectorArray}} \text{\_MPIManyVector(N\_Vector } v, \text{ booleantype } tf); \]

Description This function enables (SUNTRUE) or disables (SUNFALSE) the WRMS norm operation for vector arrays in the MPIManyVector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

F2003 Name This function is callable as FN_VEnableWrmsNormVectorArray_MPIManyVector when using the Fortran 2003 interface module.

\[ N_{\text{VEnableWrmsNormMaskVectorArray}} \text{\_MPIManyVector} \]

Prototype \[ \text{int } N_{\text{VEnableWrmsNormMaskVectorArray}} \text{\_MPIManyVector(N\_Vector } v, \text{ booleantype } tf); \]

Description This function enables (SUNTRUE) or disables (SUNFALSE) the masked WRMS norm operation for vector arrays in the MPIManyVector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

F2003 Name This function is callable as FN_VEnableWrmsNormMaskVectorArray_MPIManyVector when using the Fortran 2003 interface module.

Notes

- \text{N\_New\_MPIManyVector} and \text{N\_Make\_MPIManyVector} set the field own\_data = SUNTRUE. \text{N\_Destroy\_MPIManyVector} will not attempt to call \text{N\_Destroy} on any subvectors contained in the subvector array for any \text{N\_Vector} with own\_data set to SUNFALSE. In such a case, it is the user’s responsibility to deallocate the subvectors.

- To maximize efficiency, arithmetic vector operations in the NV\_MPIManyVector implementation that have more than one \text{N\_Vector} argument do not check for consistent internal representation of these vectors. It is the user’s responsibility to ensure that such routines are called with \text{N\_Vector} arguments that were all created with the same subvector representations.

6.15 The NV\_MPIPLUSX implementation

The NV\_MPIPLUSX implementation of the NV\_VECTOR module provided with SUNDIALS is designed to facilitate the MPI+X paradigm, where X is some form of on-node (local) parallelism (e.g. OpenMP, CUDA). This paradigm is becoming increasingly popular with the rise of heterogeneous computing architectures.

The NV\_MPIPLUSX implementation is designed to work with any NV\_VECTOR that implements the minimum required set of operations. However, it is not recommended to use the NV\_VECTOR\_PARALLEL, NV\_VECTOR\_PARHYYP, NV\_VECTOR\_PETSC, or NV\_VECTOR\_TRILINOS implementations underneath the NV\_MPIPLUSX module since they already provide MPI capabilities.
6.15 The NVECTOR_MPIPLUSX implementation

6.15.1 NVECTOR_MPIPLUSX structure

The NVECTOR_MPIPLUSX implementation is a thin wrapper around the NVECTOR_MPMANYVECTOR. Accordingly, it adopts the same content structure as defined in Section 6.14.1.

The header file to include when using this module is nvector_mpiplusx.h. The installed module library to link against is libsundials_nvecmpiplusx.lib where .lib is typically .so for shared libraries and .a for static libraries.

**Note:** If SUNDIALS is configured with MPI disabled, then the mpiplusx library will not be built. Furthermore, any user codes that include nvector_mpiplusx.h must be compiled using an MPI-aware compiler.

6.15.2 NVECTOR_MPIPLUSX functions

The NVECTOR_MPIPLUSX module adopts all vector operations listed in Tables 6.1.1, 6.1.2, 6.1.3, and 6.1.4, from the NVECTOR_MPMANYVECTOR (see section 6.14.2) except for N_VGetArrayPointer and N_VSetArrayPointer; the module provides its own implementation of these functions that call the local vector implementations. Therefore, the NVECTOR_MPIPLUSX module implements all of the operations listed in the referenced sections except for N_VScaleAddMultiVectorArray, and N_VLinearCombinationVectorArray. Accordingly, it’s compatibility with the SUNDIALS Fortran-77 interface, and with the SUNDIALS direct solvers and preconditioners depends on the local vector implementation.

The module NVECTOR_MPIPLUSX provides the following additional user-callable routines:

### N_VMake_MPIPlusX

**Prototype**

```c
N_Vector N_VMake_MPIPlusX(MPI_Comm comm,
                         N_Vector *local_vector);
```

**Description**

This function creates an MPIPlusX vector from an existing local (i.e. on-node) NVECTOR object, and a user-created MPI communicator.

The input `comm` should be this user-created MPI communicator. This routine will internally call `MPI_Comm_dup` to create a copy of the input `comm`, so the user-supplied `comm` argument need not be retained after the call to `N_VMake_MPIPlusX`.

This routine will copy the N_Vector pointer to the input `local_vector`, so the underlying local NVECTOR object should not be destroyed before the mpiplusx that contains it.

Upon successful completion, the new MPIPlusX is returned; otherwise this routine returns NULL (e.g., if the input `local_vector` is NULL).

**F2003 Name**

This function is callable as FN_VMake_MPIPlusX when using the Fortran 2003 interface module.

### N_VGetLocalVector_MPIPlusX

**Prototype**

```c
N_Vector N_VGetLocalVector_MPIPlusX(N_Vector v);
```

**Description**

This function returns the local vector underneath the the MPIPlusX NVECTOR.

**F2003 Name**

This function is callable as FN_VGetLocalVector_MPIPlusX when using the Fortran 2003 interface module.

### N_VGetArrayPointer_MPIPlusX

**Prototype**

```c
realtype* N_VGetArrayPointer_MPIPlusX(N_Vector v);
```

**Description**

This function returns the data array pointer for the local vector if the local vector implements the N_VGetArrayPointer operation; otherwise it returns NULL.

**F2003 Name**

This function is callable as FN_VGetArrayPointer_MPIPlusX when using the Fortran 2003 interface module.
Description of the NVVECTOR module

Prototype    void N_VSetArrayPointer_MPIPlusX(realtype *data, N_Vector v);

Description    This function sets the data array pointer for the local vector if the local vector implements the N_VSetArrayPointer operation.

F2003 Name    This function is callable as FN_VSetArrayPointer_MPIPlusX when using the Fortran 2003 interface module.

The NVVECTOR_MPIPLUSX module does not implement any fused or vector array operations. Instead users should enable/disable fused operations on the local vector.

Notes

- N_VMake_MPIPlusX sets the field own_data = SUNFALSE.
  and N_VDestroy_MPIPlusX will not call N_VDestroy on the local vector. In this case, it is the user’s responsibility to deallocate the local vector.

- To maximize efficiency, arithmetic vector operations in the NVVECTOR_MPIPLUSX implementation that have more than one N_Vector argument do not check for consistent internal representation of these vectors. It is the user’s responsibility to ensure that such routines are called with N_Vector arguments that were all created with the same local vector representations.

6.16 NVVECTOR Examples

There are NVector examples that may be installed for the implementations provided with SUNDIALS. Each implementation makes use of the functions in test_nvector.c. These example functions show simple usage of the NVector family of functions. The input to the examples are the vector length, number of threads (if threaded implementation), and a print timing flag.

The following is a list of the example functions in test_nvector.c:

- Test_N_VClone: Creates clone of vector and checks validity of clone.
- Test_N_VCloneEmpty: Creates clone of empty vector and checks validity of clone.
- Test_N_VCloneVectorArray: Creates clone of vector array and checks validity of cloned array.
- Test_N_VCloneVectorArray: Creates clone of empty vector array and checks validity of cloned array.
- Test_N_VGetArrayPointer: Get array pointer.
- Test_N_VSetArrayPointer: Allocate new vector, set pointer to new vector array, and check values.
- Test_N_VGetLength: Compares self-reported length to calculated length.
- Test_N_VGetCommunicator: Compares self-reported communicator to the one used in constructor; or for MPI-unaware vectors it ensures that NULL is reported.
- Test_N_VLinearSum Case 1a: Test y = x + y
- Test_N_VLinearSum Case 1b: Test y = -x + y
- Test_N_VLinearSum Case 1c: Test y = ax + y
- Test_N_VLinearSum Case 2a: Test x = x + y
- Test_N_VLinearSum Case 2b: Test x = x - y
- Test_N_VLinearSum Case 2c: Test x = x + by
• Test_NVLinearSum Case 3: Test $z = x + y$
• Test_NVLinearSum Case 4a: Test $z = x - y$
• Test_NVLinearSum Case 4b: Test $z = -x + y$
• Test_NVLinearSum Case 5a: Test $z = x + by$
• Test_NVLinearSum Case 5b: Test $z = ax + y$
• Test_NVLinearSum Case 6a: Test $z = -x + by$
• Test_NVLinearSum Case 6b: Test $z = ax - y$
• Test_NVLinearSum Case 7: Test $z = a(x + y)$
• Test_NVLinearSum Case 8: Test $z = a(x - y)$
• Test_NVLinearSum Case 9: Test $z = ax + by$
• Test_NVConst: Fill vector with constant and check result.
• Test_NVProd: Test vector multiply: $z = x \times y$
• Test_NVDiv: Test vector division: $z = x / y$
• Test_NVScale: Case 1: scale: $x = cx$
• Test_NVScale: Case 2: copy: $z = x$
• Test_NVScale: Case 3: negate: $z = -x$
• Test_NVScale: Case 4: combination: $z = cx$
• Test_NVAbs: Create absolute value of vector.
• Test_NVAddConst: add constant vector: $z = c + x$
• Test_NVDotProd: Calculate dot product of two vectors.
• Test_NVMaxNorm: Create vector with known values, find and validate the max norm.
• Test_NVWtRmsNorm: Create vector of known values, find and validate the weighted root mean square.
• Test_NVWtRmsNormMask: Create vector of known values, find and validate the weighted root mean square using all elements except one.
• Test_NVMin: Create vector, find and validate the min.
• Test_NVWtL2Norm: Create vector, find and validate the weighted Euclidean L2 norm.
• Test_NVWtL1Norm: Create vector, find and validate the L1 norm.
• Test_NVCompare: Compare vector with constant returning and validating comparison vector.
• Test_NVInvTest: Test $z[i] = 1 / x[i]$
• Test_NVConstrMask: Test mask of vector x with vector c.
• Test_NVMinQuotient: Fill two vectors with known values. Calculate and validate minimum quotient.
• Test_NVLinearCombination Case 1a: Test $x = a x$
Description of the NVECTOR module

- Test\_N\_VLinearCombination Case 1b: Test $z = a \ x$
- Test\_N\_VLinearCombination Case 2a: Test $x = a \ x + b \ y$
- Test\_N\_VLinearCombination Case 2b: Test $z = a \ x + b \ y$
- Test\_N\_VLinearCombination Case 3a: Test $x = x + a \ y + b \ z$
- Test\_N\_VLinearCombination Case 3b: Test $x = a \ x + b \ y + c \ z$
- Test\_N\_VLinearCombination Case 3c: Test $w = a \ x + b \ y + c \ z$
- Test\_N\_VScaleAddMulti Case 1a: $y = a \ x + y$
- Test\_N\_VScaleAddMulti Case 1b: $z = a \ x + y$
- Test\_N\_VScaleAddMulti Case 2a: $Y[i] = c[i] \ x + Y[i]$, $i = 1,2,3$
- Test\_N\_VScaleAddMulti Case 2b: $Z[i] = c[i] \ x + Y[i]$, $i = 1,2,3$
- Test\_N\_VDotProdMulti Case 1: Calculate the dot product of two vectors
- Test\_N\_VDotProdMulti Case 2: Calculate the dot product of one vector with three other vectors in a vector array.
- Test\_N\_VLinearSumVectorArray Case 1: $z = a \ x + b \ y$
- Test\_N\_VLinearSumVectorArray Case 2a: $Z[i] = a \ X[i] + b \ Y[i]$
- Test\_N\_VLinearSumVectorArray Case 2b: $X[i] = a \ X[i] + b \ Y[i]$
- Test\_N\_VLinearSumVectorArray Case 2c: $Y[i] = a \ X[i] + b \ Y[i]$
- Test\_N\_VScaleVectorArray Case 1a: $y = c \ y$
- Test\_N\_VScaleVectorArray Case 1b: $z = c \ y$
- Test\_N\_VScaleVectorArray Case 2a: $Y[i] = c[i] \ Y[i]$
- Test\_N\_VScaleVectorArray Case 2b: $Z[i] = c[i] \ Y[i]$
- Test\_N\_VScaleVectorArray Case 1a: $z = c$
- Test\_N\_VScaleVectorArray Case 1b: $Z[i] = c$
- Test\_N\_VWrmsNormVectorArray Case 1a: Create a vector of know values, find and validate the weighted root mean square norm.
- Test\_N\_VWrmsNormVectorArray Case 1b: Create a vector array of three vectors of know values, find and validate the weighted root mean square norm of each.
- Test\_N\_VWrmsNormMaskVectorArray Case 1a: Create a vector of know values, find and validate the weighted root mean square norm using all elements except one.
- Test\_N\_VWrmsNormMaskVectorArray Case 1b: Create a vector array of three vectors of know values, find and validate the weighted root mean square norm of each using all elements except one.
- Test\_N\_VScaleAddMultiVectorArray Case 1a: $y = a \ x + y$
- Test\_N\_VScaleAddMultiVectorArray Case 1b: $z = a \ x + y$
- Test\_N\_VScaleAddMultiVectorArray Case 2a: $Y[j][0] = a[j] \ X[0] + Y[j][0]$
• Test_N_VScaleAddMultiVectorArray Case 2b: $Z[j][0] = a[j] \times X[0] + Y[j][0]$
• Test_N_VScaleAddMultiVectorArray Case 3a: $Y[0][i] = a[0] \times X[i] + Y[0][i]$
• Test_N_VScaleAddMultiVectorArray Case 3b: $Z[0][i] = a[0] \times X[i] + Y[0][i]$
• Test_N_VScaleAddMultiVectorArray Case 4a: $Y[j][i] = a[j] \times X[i] + Y[j][i]$
• Test_N_VScaleAddMultiVectorArray Case 4b: $Z[j][i] = a[j] \times X[i] + Y[j][i]$
• Test_N_VLinearCombinationVectorArray Case 1a: $x = a \times x$
• Test_N_VLinearCombinationVectorArray Case 1b: $z = a \times x$
• Test_N_VLinearCombinationVectorArray Case 2a: $x = a \times x + b \times y$
• Test_N_VLinearCombinationVectorArray Case 2b: $z = a \times x + b \times y$
• Test_N_VLinearCombinationVectorArray Case 3a: $x = a \times x + b \times y + c \times z$
• Test_N_VLinearCombinationVectorArray Case 3b: $w = a \times x + b \times y + c \times z$
• Test_N_VLinearCombinationVectorArray Case 4a: $X[0][i] = c[0] \times X[0][i]$
• Test_N_VLinearCombinationVectorArray Case 4b: $Z[i] = c[0] \times X[0][i]$
• Test_N_VLinearCombinationVectorArray Case 5a: $X[0][i] = c[0] \times X[0][i] + c[1] \times X[1][i]$
• Test_N_VLinearCombinationVectorArray Case 5b: $Z[i] = c[0] \times X[0][i] + c[1] \times X[1][i]$
• Test_N_VLinearCombinationVectorArray Case 6a: $X[0][i] = X[0][i] + c[1] \times X[1][i] + c[2] \times X[2][i]$
• Test_N_VLinearCombinationVectorArray Case 6b: $X[0][i] = c[0] \times X[0][i] + c[1] \times X[1][i] + c[2] \times X[2][i]$
• Test_N_VDotProdLocal: Calculate MPI task-local portion of the dot product of two vectors.
• Test_N_VMaxNormLocal: Create vector with known values, find and validate the MPI task-local portion of the max norm.
• Test_N_VMinLocal: Create vector, find and validate the MPI task-local min.
• Test_N_VL1NormLocal: Create vector, find and validate the MPI task-local portion of the L1 norm.
• Test_N_VWSqrSumLocal: Create vector of known values, find and validate the MPI task-local portion of the weighted squared sum of two vectors.
• Test_N_VWSqrSumMaskLocal: Create vector of known values, find and validate the MPI task-local portion of the weighted squared sum of two vectors, using all elements except one.
• Test_N_VInvTestLocal: Test the MPI task-local portion of $z[i] = 1 / x[i]$
• Test_N_VConstrMaskLocal: Test the MPI task-local portion of the mask of vector $x$ with vector $c$.
• Test_N_VMinQuotientLocal: Fill two vectors with known values. Calculate and validate the MPI task-local minimum quotient.
Chapter 7

Description of the SUNMatrix module

For problems that involve direct methods for solving linear systems, the SUNDIALS solvers not only operate on generic vectors, but also on generic matrices (of type SUNMatrix), through a set of operations defined by the particular SUNMATRIX implementation. Users can provide their own specific implementation of the SUNMATRIX module, particularly in cases where they provide their own NVECTOR and/or linear solver modules, and require matrices that are compatible with those implementations. Alternately, we provide three SUNMATRIX implementations: dense, banded, and sparse. The generic operations are described below, and descriptions of the implementations provided with SUNDIALS follow.

7.1 The SUNMatrix API

The SUNMATRIX API can be grouped into two sets of functions: the core matrix operations, and utility functions. Section 7.1.1 lists the core operations, while Section 7.1.2 lists the utility functions.

7.1.1 SUNMatrix core functions

The generic SUNMatrix object defines the following set of core operations:

- **SUNMatGetID**
  
  Call `id = SUNMatGetID(A);`
  
  Description Returns the type identifier for the matrix A. It is used to determine the matrix implementation type (e.g. dense, banded, sparse,...) from the abstract SUNMatrix interface. This is used to assess compatibility with SUNDIALS-provided linear solver implementations.
  
  Arguments `A` (SUNMatrix) a SUNMATRIX object
  
  Return value A SUNMATRIX_ID, possible values are given in the Table 7.2.
  
  F2003 Name FSUNMatGetID

- **SUNMatClone**
  
  Call `B = SUNMatClone(A);`
  
  Description Creates a new SUNMatrix of the same type as an existing matrix A and sets the ops field. It does not copy the matrix, but rather allocates storage for the new matrix.
  
  Arguments `A` (SUNMatrix) a SUNMATRIX object
Description of the SUNMatrix module

Return value SUNMatrix

F2003 Name FSUNMatClone

F2003 Call type(SUNMatrix), pointer :: B
B => FSUNMatClone(A)

Call SUNMatDestroy(A);
Description Destroys A and frees memory allocated for its internal data.
Arguments A (SUNMatrix) a SUNMATRIX object
Return value None
F2003 Name FSUNMatDestroy

Call ier = SUNMatSpace(A, &lrw, &liw);
Description Returns the storage requirements for the matrix A. lrw is a long int containing the number of realtype words and liw is a long int containing the number of integer words.
Arguments A (SUNMatrix) a SUNMATRIX object
lrw (sunindextype*) the number of realtype words
liw (sunindextype*) the number of integer words
Return value None
Notes This function is advisory only, for use in determining a user’s total space requirements; it could be a dummy function in a user-supplied SUNMATRIX module if that information is not of interest.
F2003 Name FSUNMatSpace
F2003 Call integer(c_long) :: lrw(1), liw(1)
ier = FSUNMatSpace(A, lrw, liw)

Call ier = SUNMatZero(A);
Description Performs the operation $A_{ij} = 0$ for all entries of the matrix $A$.
Arguments A (SUNMatrix) a SUNMATRIX object
Return value A SUNMATRIX return code of type int denoting success/failure
F2003 Name FSUNMatZero

Call ier = SUNMatCopy(A,B);
Description Performs the operation $B_{ij} = A_{i,j}$ for all entries of the matrices $A$ and $B$.
Arguments A (SUNMatrix) a SUNMATRIX object
B (SUNMatrix) a SUNMATRIX object
Return value A SUNMATRIX return code of type int denoting success/failure
F2003 Name FSUNMatCopy
7.1 The SUNMatrix API

**SUNMatScaleAdd**

Call: `ier = SUNMatScaleAdd(c, A, B);

Description: Performs the operation $A = cA + B$.

Arguments:
- `c` (realtype) constant that scales $A$
- `A` (SUNMatrix) a SUNMATRIX object
- `B` (SUNMatrix) a SUNMATRIX object

Return value: A SUNMATRIX return code of type `int` denoting success/failure.

F2003 Name: FSUNMatScaleAdd

**SUNMatScaleAddI**

Call: `ier = SUNMatScaleAddI(c, A);

Description: Performs the operation $A = cA + I$.

Arguments:
- `c` (realtype) constant that scales $A$
- `A` (SUNMatrix) a SUNMATRIX object

Return value: A SUNMATRIX return code of type `int` denoting success/failure.

F2003 Name: FSUNMatScaleAddI

**SUNMatMatvecSetup**

Call: `ier = SUNMatMatvecSetup(A);

Description: Performs any setup necessary to perform a matrix-vector product. It is useful for SUNMatrix implementations which need to prepare the matrix itself, or communication structures before performing the matrix-vector product.

Arguments:
- `A` (SUNMatrix) a SUNMATRIX object

Return value: A SUNMATRIX return code of type `int` denoting success/failure.

F2003 Name: FSUNMatMatvecSetup

**SUNMatMatvec**

Call: `ier = SUNMatMatvec(A, x, y);

Description: Performs the matrix-vector product operation, $y = Ax$. It should only be called with vectors `x` and `y` that are compatible with the matrix `A` – both in storage type and dimensions.

Arguments:
- `A` (SUNMatrix) a SUNMATRIX object
- `x` (N_Vector) a NVECTOR object
- `y` (N_Vector) an output NVECTOR object

Return value: A SUNMATRIX return code of type `int` denoting success/failure.

F2003 Name: FSUNMatMatvec

### 7.1.2 SUNMatrix utility functions

To aid in the creation of custom SUNMATRIX modules the generic SUNMATRIX module provides two utility functions `SUNMatNewEmpty` and `SUNMatVCopyOps`. 
### Description of the SUNMatrix module

**SUNMatNewEmpty**

**Call**

```c
A = SUNMatNewEmpty();
```

**Description**
The function **SUNMatNewEmpty** allocates a new generic **SUNMatrix** object and initializes its content pointer and the function pointers in the operations structure to **NULL**.

**Arguments**
None

**Return value**
This function returns a **SUNMatrix** object. If an error occurs when allocating the object, then this routine will return **NULL**.

F2003 Name \( \text{FSUNMatNewEmpty} \)

---

**SUNMatFreeEmpty**

**Call**

```c
SUNMatFreeEmpty(A);
```

**Description**
This routine frees the generic **SUNMatrix** object, under the assumption that any implementation-specific data that was allocated within the underlying content structure has already been freed. It will additionally test whether the ops pointer is **NULL**, and, if it is not, it will free it as well.

**Arguments**
\( A \) (**SUNMatrix**) a **SUNMatrix** object

**Return value**
None

F2003 Name \( \text{FSUNMatFreeEmpty} \)

---

**SUNMatCopyOps**

**Call**

```c
retval = SUNMatCopyOps(A, B);
```

**Description**
The function **SUNMatCopyOps** copies the function pointers in the **ops** structure of **A** into the **ops** structure of **B**.

**Arguments**
\( A \) (**SUNMatrix**) the matrix to copy operations from

\( B \) (**SUNMatrix**) the matrix to copy operations to

**Return value**
This returns 0 if successful and a non-zero value if either of the inputs are **NULL** or the **ops** structure of either input is **NULL**.

F2003 Name \( \text{FSUNMatCopyOps} \)

### 7.1.3 SUNMatrix return codes

The functions provided to **SUNMatrix** modules within the sundials-provided **SUNMatrix** implementations utilize a common set of return codes, shown in Table 7.1. These adhere to a common pattern: 0 indicates success, and a negative value indicates a failure. The actual values of each return code are primarily to provide additional information to the user in case of a failure.

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUNMAT_SUCCESS</td>
<td>0</td>
<td>successful call or converged solve</td>
</tr>
</tbody>
</table>

*continued on next page*
Table 7.2: Identifiers associated with matrix kernels supplied with Sundials.

<table>
<thead>
<tr>
<th>Matrix ID</th>
<th>Matrix type</th>
<th>ID Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUNMATRIX_DENSE</td>
<td>Dense ( M \times N ) matrix</td>
<td>0</td>
</tr>
<tr>
<td>SUNMATRIX_BAND</td>
<td>Band ( M \times M ) matrix</td>
<td>1</td>
</tr>
<tr>
<td>SUNMATRIX_SPARSE</td>
<td>Sparse (CSR or CSC) ( M \times N ) matrix</td>
<td>2</td>
</tr>
<tr>
<td>SUNMATRIX_SLUNRLOC</td>
<td>Adapter for the SuperLU_DIST SuperMatrix</td>
<td>3</td>
</tr>
<tr>
<td>SUNMATRIX_CUSTOM</td>
<td>User-provided custom matrix</td>
<td>4</td>
</tr>
</tbody>
</table>

Name       | Value  | Description                                                   |
-----------|--------|--------------------------------------------------------------|
SUNMAT_ILL_INPUT    | -701   | an illegal input has been provided to the function           |
SUNMAT_MEM_FAIL     | -702   | failed memory access or allocation                            |
SUNMAT_OPERATION_FAIL | -703  | a SUNMatrix operation returned nonzero                        |
SUNMAT_MATVEC_SETUP_REQUIRED | -704 | the SUNMatMatvecSetup routine needs to be called before calling SUNMatMatvec |

7.1.4 SUNMatrix identifiers

Each SUNMATRIX implementation included in Sundials has a unique identifier specified in enumeration and shown in Table 7.2. It is recommended that a user-supplied SUNMATRIX implementation use the SUNMATRIX_CUSTOM identifier.

7.1.5 Compatibility of SUNMatrix modules

We note that not all SUNMATRIX types are compatible with all NVECTOR types provided with Sundials. This is primarily due to the need for compatibility within the SUNMatMatvec routine; however, compatibility between SUNMATRIX and NVECTOR implementations is more crucial when considering their interaction within SUNLINSOL objects, as will be described in more detail in Chapter 8. More specifically, in Table 7.3 we show the matrix interfaces available as SUNMATRIX modules, and the compatible vector implementations.

Table 7.3: Sundials matrix interfaces and vector implementations that can be used for each.

<table>
<thead>
<tr>
<th>Matrix Interface</th>
<th>Serial (MPI)</th>
<th>Parallel</th>
<th>OpenMP</th>
<th>pThreads</th>
<th>hypre Vec.</th>
<th>PETSc Vec.</th>
<th>CUDA</th>
<th>RAJA</th>
<th>User Suppl.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Band</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Sparse</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>SLUNRloc</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>User supplied</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

7.1.6 The generic SUNMatrix module implementation

The generic SUNMatrix type has been modeled after the object-oriented style of the generic N_Vector type. Specifically, a generic SUNMatrix is a pointer to a structure that has an implementation-dependent content field containing the description and actual data of the matrix, and an ops field pointing to a structure with generic matrix operations. The type SUNMatrix is defined as

typedef struct _generic_SUNMatrix *SUNMatrix;
The _generic_SUNMatrix_Ops structure is essentially a list of pointers to the various actual matrix operations, and is defined as

```c
struct _generic_SUNMatrix_Ops {
    SUNMatrix_ID (*getid)(SUNMatrix);
    SUNMatrix (*)(clone)(SUNMatrix);
    void (*)(destroy)(SUNMatrix);
    int (*)(zero)(SUNMatrix);
    int (*)(copy)(SUNMatrix, SUNMatrix);
    int (*)(scaleadd)(realtype, SUNMatrix, SUNMatrix);
    int (*)(scaleaddi)(realtype, SUNMatrix);
    int (*)(matvecsetup)(SUNMatrix);
    int (*)(matvec)(SUNMatrix, N_Vector, N_Vector);
    int (*)(space)(SUNMatrix, long int*, long int*);
};
```

The generic SUNMATRIX module defines and implements the matrix operations acting on SUNMatrix objects. These routines are nothing but wrappers for the matrix operations defined by a particular SUNMATRIX implementation, which are accessed through the `ops` field of the SUNMatrix structure. To illustrate this point we show below the implementation of a typical matrix operation from the generic SUNMATRIX module, namely SUNMatZero, which sets all values of a matrix A to zero, returning a flag denoting a successful/failed operation:

```c
int SUNMatZero(SUNMatrix A)
{
    return((int) A->ops->zero(A));
}
```

Section 7.1.1 contains a complete list of all matrix operations defined by the generic SUNMATRIX module.

The Fortran 2003 interface provides a bind(C) derived-type for the _generic_SUNMatrix and the _generic_SUNMatrix_Ops structures. Their definition is given below.

```fortran
type, bind(C), public :: SUNMatrix
    type(C_PTR), public :: content
    type(C_PTR), public :: ops
end type SUNMatrix

type, bind(C), public :: SUNMatrix_Ops
    type(C_FUNPTR), public :: getid
    type(C_FUNPTR), public :: clone
    type(C_FUNPTR), public :: destroy
    type(C_FUNPTR), public :: zero
    type(C_FUNPTR), public :: copy
    type(C_FUNPTR), public :: scaleadd
    type(C_FUNPTR), public :: scaleaddi
    type(C_FUNPTR), public :: matvecsetup
    type(C_FUNPTR), public :: matvec
    type(C_FUNPTR), public :: space
end type SUNMatrix_Ops
```
7.1.7 Implementing a custom SUNMatrix

A particular implementation of the SUNMATRIX module must:

- Specify the content field of the SUNMatrix object.

- Define and implement a minimal subset of the matrix operations. See the documentation for each SUNDIALS solver to determine which SUNMATRIX operations they require.

  Note that the names of these routines should be unique to that implementation in order to permit using more than one SUNMATRIX module (each with different SUNMatrix internal data representations) in the same code.

- Define and implement user-callable constructor and destructor routines to create and free a SUNMatrix with the new content field and with ops pointing to the new matrix operations.

- Optionally, define and implement additional user-callable routines acting on the newly defined SUNMatrix (e.g., a routine to print the content for debugging purposes).

- Optionally, provide accessor macros or functions as needed for that particular implementation to access different parts of the content field of the newly defined SUNMatrix.

It is recommended that a user-supplied SUNMATRIX implementation use the SUNMATRIX_CUSTOM identifier.

To aid in the creation of custom SUNMATRIX modules the generic SUNMATRIX module provides two utility functions SUNMatNewEmpty and SUNMatVCopyOps. When used in custom SUNMATRIX constructors and clone routines these functions will ease the introduction of any new optional matrix operations to the SUNMATRIX API by ensuring only required operations need to be set and all operations are copied when cloning a matrix. These functions are described in Section 7.1.2.

7.2 SUNMatrix functions used by IDA

In Table 7.4, we list the matrix functions in the SUNMATRIX module used within the IDA package. The table also shows, for each function, which of the code modules uses the function. The main IDA integrator does not call any SUNMATRIX functions directly, so the table columns are specific to the IDALS interface and the IDABBDPRE preconditioner module. We further note that the IDALS interface only utilizes these routines when supplied with a matrix-based linear solver, i.e., the SUNMATRIX object passed to IDASetLinearSolver was not NULL.

At this point, we should emphasize that the IDA user does not need to know anything about the usage of matrix functions by the IDA code modules in order to use IDA. The information is presented as an implementation detail for the interested reader.

Table 7.4: List of matrix functions usage by IDA code modules

<table>
<thead>
<tr>
<th>Function</th>
<th>IDALS</th>
<th>IDABBDPRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUNMatGetID</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>SUNMatDestroy</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>SUNMatZero</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SUNMatSpace</td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

The matrix functions listed in Section 7.1.1 with a † symbol are optionally used, in that these are only called if they are implemented in the SUNMATRIX module that is being used (i.e. their function pointers are non-NULL). The matrix functions listed in Section 7.1.1 that are not used by IDA
are: SUNMatCopy, SUNMatClone, SUNMatScaleAdd, SUNMatScaleAddI and SUNMatMatvec. Therefore a user-supplied SUNMATRIX module for IDA could omit these functions.

### 7.3 The SUNMatrix_Dense implementation

The dense implementation of the SUNMATRIX module provided with SUNDIALS, SUNMATRIX_DENSE, defines the `content` field of SUNMatrix to be the following structure:

```c
struct _SUNMatrixContent_Dense {
    sunindextype M;
    sunindextype N;
    realtype *data;
    sunindextype ldata;
    realtype **cols;
};
```

These entries of the `content` field contain the following information:

- **M** - number of rows
- **N** - number of columns
- **data** - pointer to a contiguous block of realtype variables. The elements of the dense matrix are stored columnwise, i.e. the (i,j)-th element of a dense SUNMATRIX A (with 0 ≤ i < M and 0 ≤ j < N) may be accessed via `data[j*M+i]`.
- **ldata** - length of the data array (= M*N).
- **cols** - array of pointers. `cols[j]` points to the first element of the j-th column of the matrix in the array `data`. The (i,j)-th element of a dense SUNMATRIX A (with 0 ≤ i < M and 0 ≤ j < N) may be accessed via `cols[j][i]`.

The header file to include when using this module is `sunmatrix/sunmatrix_dense.h`. The SUNMATRIX_DENSE module is accessible from all SUNDIALS solvers without linking to the `libsundials_sunmatrixdense` module library.

#### 7.3.1 SUNMatrix_Dense accessor macros

The following macros are provided to access the content of a SUNMATRIX_DENSE matrix. The prefix `SM_` in the names denotes that these macros are for SUNMatrix implementations, and the suffix `_D` denotes that these are specific to the dense version.

- **SM_CONTENT_D**
  
  This macro gives access to the contents of the dense SUNMatrix.

  The assignment `A_cont = SM_CONTENT_D(A)` sets `A_cont` to be a pointer to the dense SUNMatrix content structure.

  Implementation:
  ```c
  #define SM_CONTENT_D(A) ( (SUNMatrixContent_Dense)(A->content) )
  ```

- **SM_ROWS_D, SM_COLUMNS_D, and SM_LDATA_D**

  These macros give individual access to various lengths relevant to the content of a dense SUNMatrix.

  These may be used either to retrieve or to set these values. For example, the assignment `A_rows = SM_ROWS_D(A)` sets `A_rows` to be the number of rows in the matrix A. Similarly, the assignment `SM_COLUMNS_D(A) = A_cols` sets the number of columns in A to equal `A_cols`.

  Implementation:
  ```c
  #define SM_ROWS_D(A) ( SM_CONTENT_D(A)->M )
  ```
#define SM_COLUMNS_D(A) ( SM_CONTENT_D(A)->N )
#define SM_LDATA_D(A) ( SM_CONTENT_D(A)->ldata )

- SM_DATA_D and SM_COLS_D

These macros give access to the data and cols pointers for the matrix entries.
The assignment A_data = SM_DATA_D(A) sets A_data to be a pointer to the first component of
the data array for the dense SUNMatrix A. The assignment SM_DATA_D(A) = A_data sets the data
array of A to be A_data by storing the pointer A_data.

Similarly, the assignment A.cols = SM_COLS_D(A) sets A.cols to be a pointer to the array of
column pointers for the dense SUNMatrix A. The assignment SM_COLS_D(A) = A.cols sets the
column pointer array of A to be A.cols by storing the pointer A.cols.

Implementation:
#define SM_DATA_D(A) ( SM_CONTENT_D(A)->data )
#define SM_COLS_D(A) ( SM_CONTENT_D(A)->cols )

- SM_COLUMN_D and SM_ELEMENT_D

These macros give access to the individual columns and entries of the data array of a dense
SUNMatrix.

The assignment col_j = SM_COLUMN_D(A,j) sets col_j to be a pointer to the first entry of
the j-th column of the M × N dense matrix A (with 0 ≤ j < N). The type of the expression
SM_COLUMN_D(A,j) is realtype *. The pointer returned by the call SM_COLUMN_D(A,j) can be
treated as an array which is indexed from 0 to M − 1.

The assignments SM_ELEMENT_D(A,i,j) = a_ij and a_ij = SM_ELEMENT_D(A,i,j) reference the
(i,j)-th element of the M × N dense matrix A (with 0 ≤ i < M and 0 ≤ j < N).

Implementation:
#define SM_COLUMN_D(A,j) ( (SM_CONTENT_D(A)->cols)[j] )
#define SM_ELEMENT_D(A,i,j) ( (SM_CONTENT_D(A)->cols)[j][i] )

7.3.2 SUNMatrix_Dense functions

The SUNMATRIX_DENSE module defines dense implementations of all matrix operations listed in Section 7.1.1. Their names are obtained from those in Section 7.1.1 by appending the suffix _Dense
(e.g. SUNMatCopy_Dense). All the standard matrix operations listed in Section 7.1.1 with the
suffix _Dense appended are callable via the FORTRAN 2003 interface by prepending an ‘F’ (e.g.
FSUNMatCopy_Dense).

The module SUNMATRIX_DENSE provides the following additional user-callable routines:

### SUNDenseMatrix
Prototype SUNMatrix SUNDenseMatrix(sunindextype M, sunindextype N)
Description This constructor function creates and allocates memory for a dense SUNMatrix. Its
arguments are the number of rows, M, and columns, N, for the dense matrix.
F2003 Name This function is callable as FSUNDenseMatrix when using the Fortran 2003 interface module.

### SUNDenseMatrix_Print
Prototype void SUNDenseMatrix_Print(SUNMatrix A, FILE* outfile)
Description This function prints the content of a dense SUNMatrix to the output stream specified
by outfile. Note: stdout or stderr may be used as arguments for outfile to print
directly to standard output or standard error, respectively.
Description of the SUNMatrix module

\textbf{SUNDenseMatrix\_Rows}

Prototype \texttt{sunindextype SUNDenseMatrix\_Rows(SUNMatrix A)}

Description This function returns the number of rows in the dense SUNMatrix.

F2003 Name This function is callable as \texttt{FSUNDenseMatrix\_Rows} when using the Fortran 2003 interface module.

\textbf{SUNDenseMatrix\_Columns}

Prototype \texttt{sunindextype SUNDenseMatrix\_Columns(SUNMatrix A)}

Description This function returns the number of columns in the dense SUNMatrix.

F2003 Name This function is callable as \texttt{FSUNDenseMatrix\_Columns} when using the Fortran 2003 interface module.

\textbf{SUNDenseMatrix\_LData}

Prototype \texttt{sunindextype SUNDenseMatrix\_LData(SUNMatrix A)}

Description This function returns the length of the data array for the dense SUNMatrix.

F2003 Name This function is callable as \texttt{FSUNDenseMatrix\_LData} when using the Fortran 2003 interface module.

\textbf{SUNDenseMatrix\_Data}

Prototype \texttt{realtype* SUNDenseMatrix\_Data(SUNMatrix A)}

Description This function returns a pointer to the data array for the dense SUNMatrix.

F2003 Name This function is callable as \texttt{FSUNDenseMatrix\_Data} when using the Fortran 2003 interface module.

\textbf{SUNDenseMatrix\_Cols}

Prototype \texttt{realtype** SUNDenseMatrix\_Cols(SUNMatrix A)}

Description This function returns a pointer to the cols array for the dense SUNMatrix.

\textbf{SUNDenseMatrix\_Column}

Prototype \texttt{realtype* SUNDenseMatrix\_Column(SUNMatrix A, sunindextype j)}

Description This function returns a pointer to the first entry of the jth column of the dense SUNMatrix. The resulting pointer should be indexed over the range 0 to M − 1.

F2003 Name This function is callable as \texttt{FSUNDenseMatrix\_Column} when using the Fortran 2003 interface module.

Notes

- When looping over the components of a dense SUNMatrix \texttt{A}, the most efficient approaches are to:
  - First obtain the component array via \texttt{A\_data = SM\_DATA\_D(A)} or \texttt{A\_data = SUNDenseMatrix\_Data(A)} and then access \texttt{A\_data[i]} within the loop.
  - First obtain the array of column pointers via \texttt{A\_cols = SM\_COLS\_D(A)} or \texttt{A\_cols = SUNDenseMatrix\_Cols(A)}, and then access \texttt{A\_cols[j][i]} within the loop.
  - Within a loop over the columns, access the column pointer via \texttt{A\_colj = SUNDenseMatrix\_Column(A, j)} and then to access the entries within that column using \texttt{A\_colj[i]} within the loop.
All three of these are more efficient than using `SM_ELEMENT_D(A,i,j)` within a double loop.

- Within the `SUNMatMatvec_Dense` routine, internal consistency checks are performed to ensure that the matrix is called with consistent `nvector` implementations. These are currently limited to: `nvector_serial`, `nvector_openmp`, and `nvector_pthreads`. As additional compatible vector implementations are added to Sundials, these will be included within this compatibility check.

### 7.3.3 SUNMatrix_Dense Fortran interfaces

The `sunmatrix_dense` module provides a FORTRAN 2003 module as well as FORTRAN 77 style interface functions for use from FORTRAN applications.

**FORTRAN 2003 interface module**

The `fsunmatrix_dense_mod` FORTRAN module defines interfaces to most `sunmatrix_dense` C functions using the intrinsic `iso_c_binding` module which provides a standardized mechanism for interoperating with C. As noted in the C function descriptions above, the interface functions are named after the corresponding C function, but with a leading ‘F’. For example, the function `SUNDenseMatrix` is interfaced as `FSUNDenseMatrix`.

The FORTRAN 2003 `sunmatrix_dense` interface module can be accessed with the `use` statement, i.e. `use fsunmatrix_dense_mod`, and linking to the library `libsundials_fsunmatrixdense_mod.lib` in addition to the C library. For details on where the library and module file `fsunmatrix_dense_mod.mod` are installed see Appendix A. We note that the module is accessible from the FORTRAN 2003 Sundials integrators without separately linking to the `libsundials_fsunmatrixdense_mod` library.

**FORTRAN 77 interface functions**

For solvers that include a FORTRAN interface module, the `sunmatrix_dense` module also includes the FORTRAN-callable function `FSUNDenseMatInit(code, M, N, ier)` to initialize this `sunmatrix_dense` module for a given Sundials solver. Here `code` is an integer input solver id (1 for cvode, 2 for ida, 3 for kinsol, 4 for arkode); `M` and `N` are the corresponding dense matrix construction arguments (declared to match C type `long int`); and `ier` is an error return flag equal to 0 for success and -1 for failure. Both `code` and `ier` are declared to match C type `int`. Additionally, when using ARKODE with a non-identity mass matrix, the FORTRAN-callable function `FSUNDenseMassMatInit(M, N, ier)` initializes this `sunmatrix_dense` module for storing the mass matrix.

### 7.4 The SUNMatrix_Band implementation

The banded implementation of the `sunmatrix` module provided with Sundials, `sunmatrix_band`, defines the `content` field of `SUNMatrix` to be the following structure:

```c
struct _SUNMatrixContent_Band {
    sunindextype M;
    sunindextype N;
    sunindextype mu;
    sunindextype ml;
    sunindextype s_mu;
    sunindextype ldim;
    realtype *data;
    sunindextype ldata;
    realtype **cols;
};
```

A diagram of the underlying data representation in a banded matrix is shown in Figure 7.1. A more complete description of the parts of this `content` field is given below:
Description of the SUNMatrix module

- **M** - number of rows
- **N** - number of columns ($N = M$)
- **mu** - upper half-bandwidth, $0 \leq \mu < N$
- **ml** - lower half-bandwidth, $0 \leq ml < N$

$s_{\mu}$ - storage upper bandwidth, $\mu \leq s_{\mu} < N$. The LU decomposition routines in the associated SUNLINSOL_BAND and SUNLINSOL_LAPACK_BAND modules write the LU factors into the storage for $A$. The upper triangular factor $U$, however, may have an upper bandwidth as big as $\min(N-1, \mu+ml)$ because of partial pivoting. The $s_{\mu}$ field holds the upper half-bandwidth allocated for $A$.

- **ldim** - leading dimension ($ldim \geq s_{\mu}+ml+1$)
- **data** - pointer to a contiguous block of `realtype` variables. The elements of the banded matrix are stored columnwise (i.e. columns are stored one on top of the other in memory). Only elements within the specified half-bandwidths are stored. `data` is a pointer to `ldata` contiguous locations which hold the elements within the band of $A$.

- **ldata** - length of the data array ($= ldim \cdot N$)
- **cols** - array of pointers. `cols[j]` is a pointer to the uppermost element within the band in the $j$-th column. This pointer may be treated as an array indexed from $s_{\mu} - \mu$ (to access the uppermost element within the band in the $j$-th column) to $s_{\mu} + ml$ (to access the lowest element within the band in the $j$-th column). Indices from $0$ to $s_{\mu} - \mu - 1$ give access to extra storage elements required by the LU decomposition function. Finally, `cols[j][i-j+s_{\mu}]` is the $(i,j)$-th element with $j-\mu \leq i \leq j+ml$.

The header file to include when using this module is `sunmatrix/sunmatrix_band.h`. The SUNMATRIX_BAND module is accessible from all SUNDIALS solvers without linking to the LIBSUNDIALS_SUNMATRIX_BAND module library.

### 7.4.1 SUNMatrix_Band accessor macros

The following macros are provided to access the content of a SUNMATRIX_BAND matrix. The prefix `SM_` in the names denotes that these macros are for SUNMatrix implementations, and the suffix `_B` denotes that these are specific to the banded version.

- **SM_CONTENT_B**
  This routine gives access to the contents of the banded SUNMatrix.
  
  The assignment $A_{\text{cont}} = \text{SM\_CONTENT\_B}(A)$ sets $A_{\text{cont}}$ to be a pointer to the banded SUNMatrix content structure.
  
  Implementation:
  ```
  #define SM_CONTENT_B(A) ( (SUNMatrixContent_Band)(A->content) )
  ```

- **SM_ROWS_B, SM_COLUMNS_B, SM_UBAND_B, SM_LBAND_B, SM_SUBAND_B, SM_LDIM_B, and SM_LDATA_B**
  These macros give individual access to various lengths relevant to the content of a banded SUNMatrix.
  
  These may be used either to retrieve or to set these values. For example, the assignment $A_{\text{rows}} = \text{SM\_ROWS\_B}(A)$ sets $A_{\text{rows}}$ to be the number of rows in the matrix $A$. Similarly, the assignment $\text{SM\_COLUMNS\_B}(A) = A_{\text{cols}}$ sets the number of columns in $A$ to equal $A_{\text{cols}}$.
  
  Implementation:
  ```
  #define SM_ROWS_B(A) ( SM_CONTENT_B(A)->M )
  #define SM_COLUMNS_B(A) ( SM_CONTENT_B(A)->N )
  #define SM_UBAND_B(A) ( SM_CONTENT_B(A)->mu )
  #define SM_LBAND_B(A) ( SM_CONTENT_B(A)->ml )
  ```
Figure 7.1: Diagram of the storage for the SUNMATRIX_BAND module. Here $A$ is an $N \times N$ band matrix with upper and lower half-bandwidths $\mu$ and $m_l$, respectively. The rows and columns of $A$ are numbered from 0 to $N - 1$ and the $(i,j)$-th element of $A$ is denoted $A(i,j)$. The greyed out areas of the underlying component storage are used by the associated SUNLINSOL_BAND linear solver.
#define SM_SUBAND_B(A) ( SM_CONTENT_B(A)->s_mu )
#define SM_LDIM_B(A) ( SM_CONTENT_B(A)->ldim )
#define SM_LDATA_B(A) ( SM_CONTENT_B(A)->ldata )

- **SM_DATA_B** and **SM_COLS_B**

  These macros give access to the data and cols pointers for the matrix entries.

  The assignment \( A_{\text{data}} = \text{SM_DATA_B}(A) \) sets \( A_{\text{data}} \) to be a pointer to the first component of the data array for the banded SUNMatrix \( A \). The assignment \( \text{SM_DATA_B}(A) = A_{\text{data}} \) sets the data array of \( A \) to be \( A_{\text{data}} \) by storing the pointer \( A_{\text{data}} \).

  Similarly, the assignment \( A_{\text{cols}} = \text{SM_COLS_B}(A) \) sets \( A_{\text{cols}} \) to be a pointer to the array of column pointers for the banded SUNMatrix \( A \). The assignment \( \text{SM_COLS_B}(A) = A_{\text{cols}} \) sets the column pointer array of \( A \) to be \( A_{\text{cols}} \) by storing the pointer \( A_{\text{cols}} \).

  Implementation:

  ```c
  #define SM_DATA_B(A) ( SM_CONTENT_B(A)->data )
  #define SM_COLS_B(A) ( SM_CONTENT_B(A)->cols )
  ``

- **SM_COLUMN_B**, **SM_COLUMN_ELEMENT_B**, and **SM_ELEMENT_B**

  These macros give access to the individual columns and entries of the data array of a banded SUNMatrix.

  The assignments \( \text{SM_ELEMENT_B}(A,i,j) = a_{ij} \) and \( a_{ij} = \text{SM_ELEMENT_B}(A,i,j) \) reference the \((i,j)\)-th element of the \( N \times N \) band matrix \( A \), where \( 0 \leq i, j \leq N - 1 \). The location \((i,j)\) should further satisfy \( j - \mu \leq i \leq j + ml \).

  The assignment \( \text{col}_j = \text{SM_COLUMN_B}(A,j) \) sets \( \text{col}_j \) to be a pointer to the diagonal element of the \( j \)-th column of the \( N \times N \) band matrix \( A \), \( 0 \leq j \leq N - 1 \). The type of the expression \( \text{SM_COLUMN_B}(A,j) \) is \text{realtype} * . The pointer returned by the call \( \text{SM_COLUMN_B}(A,j) \) can be treated as an array which is indexed from \( -\mu \) to \( ml \).

  The assignments \( \text{SM_COLUMN_ELEMENT_B}(\text{col}_j,i,j) = a_{ij} \) and \( a_{ij} = \text{SM_COLUMN_ELEMENT_B}(\text{col}_j,i,j) \) reference the \((i,j)\)-th entry of the band matrix \( A \) when used in conjunction with \( \text{SM_COLUMN_B}(A,j) \) to reference the \( j \)-th column through \( \text{col}_j \). The index \((i,j)\) should satisfy \( j - \mu \leq i \leq j + ml \).

  Implementation:

  ```c
  #define SM_COLUMN_B(A,j) ( ((SM_CONTENT_B(A)->cols)[j])+SM_SUBAND_B(A) )
  #define SM_COLUMN_ELEMENT_B(col_j,i,j) (col_j[(i)-(j)])
  #define SM_ELEMENT_B(A,i,j) ( (SM_CONTENT_B(A)->cols)[j][(i)-(j)]+SM_SUBAND_B(A) )
  ``

### 7.4.2 SUNMatrix_Band functions

The SUNMATRIX_BAND module defines banded implementations of all matrix operations listed in Section 7.1.1. Their names are obtained from those in Section 7.1.1 by appending the suffix _Band_ (e.g. SUNMatCopy_Band). All the standard matrix operations listed in Section 7.1.1 with the suffix _Band_ appended are callable via the FORTRAN 2003 interface by prepending an ‘F’ (e.g. FSUNMatCopy_Band).

The module SUNMATRIX_BAND provides the following additional user-callable routines:

```c
SUNBandMatrix
Prototype
SUNMatrix SUNBandMatrix(sunindextype N, sunindextype mu, sunindextype ml)
```
Description This constructor function creates and allocates memory for a banded SUNMatrix. Its arguments are the matrix size, $N$, and the upper and lower half-bandwidths of the matrix, $\mu$ and $\ml$. The stored upper bandwidth is set to $\mu+\ml$ to accommodate subsequent factorization in the SUNLINSOL_BAND and SUNLINSOL_LAPACK_BAND modules.

F2003 Name This function is callable as FSUNBandMatrix when using the Fortran 2003 interface module.

**SUNBandMatrixStorage**

Prototype `SUNMatrix SUNBandMatrixStorage(sunindextype N, sunindextype mu, sunindextype ml, sunindextype smu)`

Description This constructor function creates and allocates memory for a banded SUNMatrix. Its arguments are the matrix size, $N$, the upper and lower half-bandwidths of the matrix, $\mu$ and $\ml$, and the stored upper bandwidth, $\smu$. When creating a band SUNMatrix, this value should be

- at least min($N-1,\mu+\ml$) if the matrix will be used by the SUNLINSOL_BAND module;
- exactly equal to $\mu+\ml$ if the matrix will be used by the SUNLINSOL_LAPACK_BAND module;
- at least $\mu$ if used in some other manner.

*Note: it is strongly recommended that users call the default constructor, SUNBandMatrix, in all standard use cases. This advanced constructor is used internally within SUNDIALS solvers, and is provided to users who require banded matrices for non-default purposes.*

**SUNBandMatrix_Print**

Prototype `void SUNBandMatrix_Print(SUNMatrix A, FILE* outfile)`

Description This function prints the content of a banded SUNMatrix to the output stream specified by `outfile`. Note: `stdout` or `stderr` may be used as arguments for `outfile` to print directly to standard output or standard error, respectively.

**SUNBandMatrix_Rows**

Prototype `sunindextype SUNBandMatrix_Rows(SUNMatrix A)`

Description This function returns the number of rows in the banded SUNMatrix.

F2003 Name This function is callable as FSUNBandMatrix_Rows when using the Fortran 2003 interface module.

**SUNBandMatrix_Columns**

Prototype `sunindextype SUNBandMatrix_Columns(SUNMatrix A)`

Description This function returns the number of columns in the banded SUNMatrix.

F2003 Name This function is callable as FSUNBandMatrix_Columns when using the Fortran 2003 interface module.

**SUNBandMatrix_LowerBandwidth**

Prototype `sunindextype SUNBandMatrix_LowerBandwidth(SUNMatrix A)`

Description This function returns the lower half-bandwidth of the banded SUNMatrix.

F2003 Name This function is callable as FSUNBandMatrix_LowerBandwidth when using the Fortran 2003 interface module.
Description of the SUNMatrix module

**SUNBandMatrix_UpperBandwidth**

Prototype: `sunindextype SUNBandMatrix_UpperBandwidth(SUNMatrix A)`

Description: This function returns the upper half-bandwidth of the banded SUNMatrix.

F2003 Name: This function is callable as `FSUNBandMatrix_UpperBandwidth` when using the Fortran 2003 interface module.

**SUNBandMatrix_StoredUpperBandwidth**

Prototype: `sunindextype SUNBandMatrix_StoredUpperBandwidth(SUNMatrix A)`

Description: This function returns the stored upper half-bandwidth of the banded SUNMatrix.

F2003 Name: This function is callable as `FSUNBandMatrix_StoredUpperBandwidth` when using the Fortran 2003 interface module.

**SUNBandMatrix_LDim**

Prototype: `sunindextype SUNBandMatrix_LDim(SUNMatrix A)`

Description: This function returns the length of the leading dimension of the banded SUNMatrix.

F2003 Name: This function is callable as `FSUNBandMatrix_LDim` when using the Fortran 2003 interface module.

**SUNBandMatrix_Data**

Prototype: `realtype* SUNBandMatrix_Data(SUNMatrix A)`

Description: This function returns a pointer to the data array for the banded SUNMatrix.

F2003 Name: This function is callable as `FSUNBandMatrix_Data` when using the Fortran 2003 interface module.

**SUNBandMatrix_Cols**

Prototype: `realtype** SUNBandMatrix_Cols(SUNMatrix A)`

Description: This function returns a pointer to the cols array for the banded SUNMatrix.

**SUNBandMatrix_Column**

Prototype: `realtype* SUNBandMatrix_Column(SUNMatrix A, sunindextype j)`

Description: This function returns a pointer to the diagonal entry of the j-th column of the banded SUNMatrix. The resulting pointer should be indexed over the range $-\text{mu}$ to $\text{ml}$.

F2003 Name: This function is callable as `FSUNBandMatrix_Column` when using the Fortran 2003 interface module.

Notes

- When looping over the components of a banded SUNMatrix $A$, the most efficient approaches are to:
  - First obtain the component array via $A\_\text{data} = \text{SM\_DATA\_B}(A)$ or $A\_\text{data} = \text{SUNBandMatrix\_Data}(A)$ and then access $A\_\text{data}[i]$ within the loop.
  - First obtain the array of column pointers via $A\_\text{cols} = \text{SM\_COLS\_B}(A)$ or $A\_\text{cols} = \text{SUNBandMatrix\_Cols}(A)$, and then access $A\_\text{cols}[j][i]$ within the loop.
  - Within a loop over the columns, access the column pointer via $A\_\text{col}_j = \text{SUNBandMatrix\_Column}(A, j)$ and then to access the entries within that column using $\text{SM\_COLUMN\_ELEMENT\_B}(A\_\text{col}_j, i, j)$. 

7.5 The SUNMatrix Sparse implementation

All three of these are more efficient than using $\text{SM}_\text{ELEMENT}_B(A, i, j)$ within a double loop.

- Within the SUNMatMatvec_Band routine, internal consistency checks are performed to ensure that the matrix is called with consistent NVVECTOR implementations. These are currently limited to NVVECTOR_SERIAL, NVVECTOR_OPENMP, and NVVECTOR_PTHREADS. As additional compatible vector implementations are added to SUNDIALS, these will be included within this compatibility check.

### 7.4.3 SUNMatrix_Band Fortran interfaces

The SUNMATRIX_BAND module provides a FORTRAN 2003 module as well as FORTRAN 77 style interface functions for use from FORTRAN applications.

#### FORTRAN 2003 interface module

The fsunmatrix_band_mod FORTRAN module defines interfaces to most SUNMATRIX_BAND C functions using the intrinsic iso_c_binding module which provides a standardized mechanism for interoperating with C. As noted in the C function descriptions above, the interface functions are named after the corresponding C function, but with a leading ‘F’. For example, the function SUNBandMatrix is interfaced as FSUNBandMatrix.

The FORTRAN 2003 SUNMATRIX_BAND interface module can be accessed with the use statement, i.e. use fsunmatrix_band_mod, and linking to the library lib sundials_fsunmatrixband_mod.lib in addition to the C library. For details on where the library and module file fsunmatrix_band_mod are installed see Appendix A. We note that the module is accessible from the FORTRAN 2003 SUNDIALS integrators without separately linking to the lib sundials_fsunmatrixband_mod library.

#### FORTRAN 77 interface functions

For solvers that include a FORTRAN interface module, the SUNMATRIX_BAND module also includes the FORTRAN-callable function FSUNBandMatInit(code, N, mu, ml, ier) to initialize this SUNMATRIX_BAND module for a given SUNDIALS solver. Here code is an integer input solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, 4 for ARKODE); N, mu, and ml are the corresponding band matrix construction arguments (declared to match C type long int); and ier is an error return flag equal to 0 for success and -1 for failure. Both code and ier are declared to match C type int. Additionally, when using ARKODE with a non-identity mass matrix, the FORTRAN-callable function FSUNBandMassMatInit(N, mu, ml, ier) initializes this SUNMATRIX_BAND module for storing the mass matrix.

### 7.5 The SUNMatrix Sparse implementation

The sparse implementation of the SUNMATRIX module provided with SUNDIALS, SUNMATRIX_SPARSE, is designed to work with either compressed-sparse-column (CSC) or compressed-sparse-row (CSR) sparse matrix formats. To this end, it defines the content field of SUNMatrix to be the following structure:

```c
struct _SUNMatrixContent_Sparse {
    sunindextype M;
    sunindextype N;
    sunindextype NNZ;
    sunindextype NP;
    realtype *data;
    int sparsetype;
    sunindextype *indexvals;
    sunindextype *indexptrs;
    /* CSC indices */
    sunindextype **rowvals;
    ...
}
```
sunindextype **colptrs;
/* CSR indices */
sunindextype **colvals;
sunindextype **rowptrs;
};

A diagram of the underlying data representation for a CSC matrix is shown in Figure 7.2 (the CSR format is similar). A more complete description of the parts of this content field is given below:

- \( M \) - number of rows
- \( N \) - number of columns
- \( NNZ \) - maximum number of nonzero entries in the matrix (allocated length of data and indexvals arrays)
- \( NP \) - number of index pointers (e.g. number of column pointers for CSC matrix). For CSC matrices \( NP = N \), and for CSR matrices \( NP = M \). This value is set automatically based on the input for sparsetype.
- data - pointer to a contiguous block of realtype variables (of length NNZ), containing the values of the nonzero entries in the matrix
- sparsetype - type of the sparse matrix (CSC_MAT or CSR_MAT)
- indexvals - pointer to a contiguous block of int variables (of length NNZ), containing the row indices (if CSC) or column indices (if CSR) of each nonzero matrix entry held in data
- indexptrs - pointer to a contiguous block of int variables (of length \( NP+1 \)). For CSC matrices each entry provides the index of the first column entry into the data and indexvals arrays, e.g. if indexptr[3]=7, then the first nonzero entry in the fourth column of the matrix is located in data[7], and is located in row indexvals[7] of the matrix. The last entry contains the total number of nonzero values in the matrix and hence points one past the end of the active data in the data and indexvals arrays. For CSR matrices, each entry provides the index of the first row entry into the data and indexvals arrays.

The following pointers are added to the SlsMat type for user convenience, to provide a more intuitive interface to the CSC and CSR sparse matrix data structures. They are set automatically when creating a sparse SUNMATRIX, based on the sparse matrix storage type.

- rowvals - pointer to indexvals when sparsetype is CSC_MAT, otherwise set to NULL.
- colptrs - pointer to indexptrs when sparsetype is CSC_MAT, otherwise set to NULL.
- colvals - pointer to indexvals when sparsetype is CSR_MAT, otherwise set to NULL.
- rowptrs - pointer to indexptrs when sparsetype is CSR_MAT, otherwise set to NULL.

For example, the 5 × 4 CSC matrix

\[
\begin{bmatrix}
0 & 3 & 1 & 0 \\
3 & 0 & 0 & 2 \\
0 & 7 & 0 & 0 \\
1 & 0 & 0 & 9 \\
0 & 0 & 0 & 5 \\
\end{bmatrix}
\]

could be stored in this structure as either

\[
\begin{align*}
M &= 5; \\
N &= 4; \\
NNZ &= 8; \\
NP &= N; \\
data &= \{3.0, 1.0, 3.0, 7.0, 1.0, 2.0, 9.0, 5.0\}; \\
sparsetype &= \text{CSC\_MAT}; \\
indexvals &= \{1, 3, 0, 2, 0, 1, 3, 4\}; \\
indexptrs &= \{0, 2, 4, 5, 8\};
\end{align*}
\]

or
7.5 The SUNMatrix_Sparse implementation

\begin{verbatim}
M = 5;
N = 4;
NNZ = 10;
NP = N;
data = {3.0, 1.0, 3.0, 7.0, 1.0, 2.0, 9.0, 5.0, *, *};
sparsetype = CSC_MAT;
indexvals = {1, 3, 0, 2, 0, 1, 3, 4, *, *};
indexptrs = {0, 2, 4, 5, 8};
\end{verbatim}

where the first has no unused space, and the second has additional storage (the entries marked with * may contain any values). Note in both cases that the final value in indexptrs is 8, indicating the total number of nonzero entries in the matrix.

Similarly, in CSR format, the same matrix could be stored as

\begin{verbatim}
M = 5;
N = 4;
NNZ = 8;
NP = N;
data = {3.0, 1.0, 3.0, 2.0, 7.0, 1.0, 9.0, 5.0};
sparsetype = CSR_MAT;
indexvals = {1, 2, 0, 3, 1, 0, 3, 3};
indexptrs = {0, 2, 4, 5, 7, 8};
\end{verbatim}

The header file to include when using this module is sunmatrix/sunmatrix_sparse.h. The SUNMATRIX_SPARSE module is accessible from all SUNDIALS solvers without linking to the libsundials_sunmatrixsparse module library.

7.5.1 SUNMatrix_Sparse accessor macros

The following macros are provided to access the content of a SUNMATRIX_SPARSE matrix. The prefix SM_ in the names denotes that these macros are for SUNMatrix implementations, and the suffix _S denotes that these are specific to the sparse version.

- **SM_CONTENT_S**

  This routine gives access to the contents of the sparse SUNMatrix.

  The assignment \( A_{\text{cont}} = \text{SM\_CONTENT\_S}(A) \) sets \( A_{\text{cont}} \) to be a pointer to the sparse SUNMatrix content structure.

  Implementation:

  \[
  \text{#define SM\_CONTENT\_S(A) \hspace{1em} \left( \text{SUNMatrixContent\_Sparse}(A->\text{content}) \right) }
  \]

- **SM_ROWS_S, SM_COLUMNS_S, SM_NNZ_S, SM_NP_S, and SM_SPARSETYPE_S**

  These macros give individual access to various lengths relevant to the content of a sparse SUNMatrix.

  These may be used either to retrieve or to set these values. For example, the assignment \( A_{\text{rows}} = \text{SM\_ROWS\_S}(A) \) sets \( A_{\text{rows}} \) to be the number of rows in the matrix \( A \). Similarly, the assignment \( \text{SM\_COLUMNS\_S}(A) = A_{\text{cols}} \) sets the number of columns in \( A \) to equal \( A_{\text{cols}} \).

  Implementation:

  \[
  \text{#define SM\_ROWS\_S(A) \hspace{1em} \left( \text{SM\_CONTENT\_S}(A)\rightarrow M \right) }
  \]
  \[
  \text{#define SM\_COLUMNS\_S(A) \hspace{1em} \left( \text{SM\_CONTENT\_S}(A)\rightarrow N \right) }
  \]
  \[
  \text{#define SM\_NNZ\_S(A) \hspace{1em} \left( \text{SM\_CONTENT\_S}(A)\rightarrow \text{NNZ} \right) }
  \]
  \[
  \text{#define SM\_NP\_S(A) \hspace{1em} \left( \text{SM\_CONTENT\_S}(A)\rightarrow \text{NP} \right) }
  \]
  \[
  \text{#define SM\_SPARSETYPE\_S(A) \hspace{1em} \left( \text{SM\_CONTENT\_S}(A)\rightarrow \text{sparsetype} \right) }
  \]
Figure 7.2: Diagram of the storage for a compressed-sparse-column matrix. Here $A$ is an $M \times N$ sparse matrix with storage for up to $\text{NNZ}$ nonzero entries (the allocated length of both $\text{data}$ and $\text{indexvals}$). The entries in $\text{indexvals}$ may assume values from 0 to $M - 1$, corresponding to the row index (zero-based) of each nonzero value. The entries in $\text{data}$ contain the values of the nonzero entries, with the row $i$, column $j$ entry of $A$ (again, zero-based) denoted as $A(i,j)$. The $\text{indexptrs}$ array contains $N + 1$ entries; the first $N$ denote the starting index of each column within the $\text{indexvals}$ and $\text{data}$ arrays, while the final entry points one past the final nonzero entry. Here, although $\text{NNZ}$ values are allocated, only $\text{nz}$ are actually filled in; the greyed-out portions of $\text{data}$ and $\text{indexvals}$ indicate extra allocated space.
• SM_DATA_S, SM_INDEXVALS_S, and SM_INDEXPTRS_S

These macros give access to the data and index arrays for the matrix entries.

The assignment $A_{\text{data}} = \text{SM\_DATA\_S}(A)$ sets $A_{\text{data}}$ to be a pointer to the first component of the data array for the sparse SUNMatrix $A$. The assignment $\text{SM\_DATA\_S}(A) = A_{\text{data}}$ sets the data array of $A$ to be $A_{\text{data}}$ by storing the pointer $A_{\text{data}}$.

Similarly, the assignment $A_{\text{indexvals}} = \text{SM\_INDEXVALS\_S}(A)$ sets $A_{\text{indexvals}}$ to be a pointer to the array of index values (i.e. row indices for a CSC matrix, or column indices for a CSR matrix) for the sparse SUNMatrix $A$. The assignment $A_{\text{indexptrs}} = \text{SM\_INDEXPTRS\_S}(A)$ sets $A_{\text{indexptrs}}$ to be a pointer to the array of index pointers (i.e. the starting indices in the data/indexvals arrays for each row or column in CSR or CSC formats, respectively).

Implementation:

```c
#define SM_DATA_S(A) ((SM.CONTENT.S(A))->data)
#define SM_INDEXVALS_S(A) ((SM.CONTENT.S(A))->indexvals)
#define SM_INDEXPTRS_S(A) ((SM.CONTENT.S(A))->indexptrs)
```

### 7.5.2 SUNMatrix_Sparse functions

The SUNMATRIX_SPARSE module defines sparse implementations of all matrix operations listed in Section 7.1.1. Their names are obtained from those in Section 7.1.1 by appending the suffix _Sparse (e.g. SUNMatCopy_Sparse). All the standard matrix operations listed in Section 7.1.1 with the suffix _Sparse appended are callable via the FORTRAN 2003 interface by prepending an ‘F’ (e.g. FSUNMatCopy_Sparse).

The module SUNMATRIX_SPARSE provides the following additional user-callable routines:

**SUNSparseMatrix**

Prototype

```c
SUNMatrix SUNSparseMatrix(sunindextype M, sunindextype N, sunindextype NNZ, int sparsetype);
```

Description

This function creates and allocates memory for a sparse SUNMatrix. Its arguments are the number of rows and columns of the matrix, $M$ and $N$, the maximum number of nonzeros to be stored in the matrix, NNZ, and a flag sparsetype indicating whether to use CSR or CSC format (valid arguments are CSR_MAT or CSC_MAT).

F2003 Name

This function is callable as FSUNSparseMatrix when using the Fortran 2003 interface module.

**SUNSparseFromDenseMatrix**

Prototype

```c
SUNMatrix SUNSparseFromDenseMatrix(SUNMatrix A, realtype droptol, int sparsetype);
```

Description

This function creates a new sparse matrix from an existing dense matrix by copying all values with magnitude larger than $\text{droptol}$ into the sparse matrix structure.

Requirements:

- $A$ must have type SUNMATRIX_DENSE;
- $\text{droptol}$ must be non-negative;
- sparsetype must be either CSC_MAT or CSR_MAT.

The function returns NULL if any requirements are violated, or if the matrix storage request cannot be satisfied.

F2003 Name

This function is callable as FSUNSparseFromDenseMatrix when using the Fortran 2003 interface module.
SUNSparseFromBandMatrix
Prototype: SUNMatrix SUNSparseFromBandMatrix(SUNMatrix A, realtype droptol, int sparsetype);
Description: This function creates a new sparse matrix from an existing band matrix by copying all values with magnitude larger than droptol into the sparse matrix structure.
Requirements:
- A must have type SUNMATRIX_BAND;
- droptol must be non-negative;
- sparsetype must be either CSC_MAT or CSR_MAT.
The function returns NULL if any requirements are violated, or if the matrix storage request cannot be satisfied.
F2003 Name: This function is callable as FSUNSparseFromBandMatrix when using the Fortran 2003 interface module.

SUNSparseMatrix_Realloc
Prototype: int SUNSparseMatrix_Realloc(SUNMatrix A);
Description: This function reallocates internal storage arrays in a sparse matrix so that the resulting sparse matrix has no wasted space (i.e. the space allocated for nonzero entries equals the actual number of nonzeros, indexptrs[NP]). Returns 0 on success and 1 on failure (e.g. if the input matrix is not sparse).
F2003 Name: This function is callable as FSUNSparseMatrix_Realloc when using the Fortran 2003 interface module.

SUNSparseMatrix_Reallocate
Prototype: int SUNSparseMatrix_Reallocate(SUNMatrix A, sunindextype NNZ);
Description: This function reallocates internal storage arrays in a sparse matrix so that the resulting sparse matrix has storage for a specified number of nonzeros. Returns 0 on success and 1 on failure (e.g. if the input matrix is not sparse or if NNZ is negative).
F2003 Name: This function is callable as FSUNSparseMatrix_Reallocate when using the Fortran 2003 interface module.

SUNSparseMatrix_Print
Prototype: void SUNSparseMatrix_Print(SUNMatrix A, FILE* outfile);
Description: This function prints the content of a sparse SUNMatrix to the output stream specified by outfile. Note: stdout or stderr may be used as arguments for outfile to print directly to standard output or standard error, respectively.

SUNSparseMatrix_Rows
Prototype: sunindextype SUNSparseMatrix_Rows(SUNMatrix A);
Description: This function returns the number of rows in the sparse SUNMatrix.
F2003 Name: This function is callable as FSUNSparseMatrix_Rows when using the Fortran 2003 interface module.
7.5 The SUNMatrix_Sparse implementation

SUNSparseMatrix_Columns
Prototype  
\texttt{sunindextype SUNSparseMatrix\_Columns(SUNMatrix A)}
Description  This function returns the number of columns in the sparse SUNMatrix.
F2003 Name  This function is callable as \texttt{FSUNSparseMatrix\_Columns} when using the Fortran 2003 interface module.

SUNSparseMatrix_NNZ
Prototype  
\texttt{sunindextype SUNSparseMatrix\_NNZ(SUNMatrix A)}
Description  This function returns the number of entries allocated for nonzero storage for the sparse matrix SUNMatrix.
F2003 Name  This function is callable as \texttt{FSUNSparseMatrix\_NNZ} when using the Fortran 2003 interface module.

SUNSparseMatrix_NP
Prototype  
\texttt{sunindextype SUNSparseMatrix\_NP(SUNMatrix A)}
Description  This function returns the number of columns/rows for the sparse SUNMatrix, depending on whether the matrix uses CSC/CSR format, respectively. The \texttt{indexptrs} array has \texttt{NP+1} entries.
F2003 Name  This function is callable as \texttt{FSUNSparseMatrix\_NP} when using the Fortran 2003 interface module.

SUNSparseMatrix_SparseType
Prototype  
\texttt{int SUNSparseMatrix\_SparseType(SUNMatrix A)}
Description  This function returns the storage type (CSR\_MAT or CSC\_MAT) for the sparse SUNMatrix.
F2003 Name  This function is callable as \texttt{FSUNSparseMatrix\_SparseType} when using the Fortran 2003 interface module.

SUNSparseMatrix_Data
Prototype  
\texttt{realtype* SUNSparseMatrix\_Data(SUNMatrix A)}
Description  This function returns a pointer to the data array for the sparse SUNMatrix.
F2003 Name  This function is callable as \texttt{FSUNSparseMatrix\_Data} when using the Fortran 2003 interface module.

SUNSparseMatrix_IndexValues
Prototype  
\texttt{sunindextype* SUNSparseMatrix\_IndexValues(SUNMatrix A)}
Description  This function returns a pointer to index value array for the sparse SUNMatrix: for CSR format this is the column index for each nonzero entry, for CSC format this is the row index for each nonzero entry.
F2003 Name  This function is callable as \texttt{FSUNSparseMatrix\_IndexValues} when using the Fortran 2003 interface module.
208 Description of the SUNMatrix module

Prototype  `sunindextype* SUNSparseMatrix_IndexPointers(SUNMatrix A)`

Description  This function returns a pointer to the index pointer array for the sparse SUNMatrix: for CSR format this is the location of the first entry of each row in the data and indexvalues arrays, for CSC format this is the location of the first entry of each column.

F2003 Name  This function is callable as `FSUNSparseMatrix_IndexPointers` when using the Fortran 2003 interface module.

Within the SUNMatMatvec_Sparse routine, internal consistency checks are performed to ensure that the matrix is called with consistent NVECTOR implementations. These are currently limited to: NVECTOR_SERIAL, NVECTOR_OPENMP, NVECTOR_PTHREADS, and NVECTOR_CUDA when using managed memory. As additional compatible vector implementations are added to SUNDIALS, these will be included within this compatibility check.

7.5.3 SUNMatrix_Sparse Fortran interfaces

The SUNMATRIX_SPARSE module provides a FORTRAN 2003 module as well as FORTRAN 77 style interface functions for use from FORTRAN applications.

FORTRAN 2003 interface module

The F_SUNMATRIX_SPARSE module defines interfaces to most SUNMATRIX_SPARSE C functions using the intrinsic iso_c_binding module which provides a standardized mechanism for interoperating with C. As noted in the C function descriptions above, the interface functions are named after the corresponding C function, but with a leading ‘F’. For example, the function SUNSparseMatrix is interfaced as FSUNSparseMatrix.

The Fortran 2003 SUNMATRIX_SPARSE interface module can be accessed with the `use` statement, i.e. use f_sunmatrix_sparse_mod, and linking to the library libsundials_fsunmatrixsparse_mod.lib in addition to the C library. For details on where the library and module file f_sunmatrix_sparse_mod.mod are installed see Appendix A. We note that the module is accessible from the Fortran 2003 SUNDIALS integrators without separately linking to the libsundials_fsunmatrixsparse_mod library.

FORTRAN 77 interface functions

For solvers that include a Fortran interface module, the SUNMATRIX_SPARSE module also includes the Fortran-callable function FSUNSparseMatInit(code, M, N, NNZ, sparsetype, ier) to initialize this SUNMATRIX_SPARSE module for a given SUNDIALS solver. Here code is an integer input for the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, 4 for ARKODE); M, N and NNZ are the corresponding sparse matrix construction arguments (declared to match C type long int); sparsetype is an integer flag indicating the sparse storage type (0 for CSC, 1 for CSR); and ier is an error return flag equal to 0 for success and -1 for failure. Each of code, sparsetype and ier are declared so as to match C type int. Additionally, when using ARKODE with a non-identity mass matrix, the Fortran-callable function FSUNSparseMassMatInit(M, N, NNZ, sparsetype, ier) initializes this SUNMATRIX_SPARSE module for storing the mass matrix.

7.6 The SUNMatrix_SLUNRloc implementation

The SUNMATRIX_SLUNRLOC implementation of the SUNMATRIX module provided with SUNDIALS is an adapter for the SuperMatrix structure provided by the SuperLU_DIST sparse matrix factorization and solver library written by X. Sherry Li [3, 22, 34, 35]. It is designed to be used with the SUNLINSOL_SUPERLUDIST linear solver discussed in Section 8.10. To this end, it defines the content field of SUNMatrix to be the following structure:
7.6 The SUNMatrix_SLUNRloc implementation

struct _SUNMatrixContent_SLUNRloc {
    bool own_data;
    gridinfo_t *grid;
    sunindextype *row_to_proc;
    pdgsmv_comm_t *gsmv_comm;
    SuperMatrix *A_super;
    SuperMatrix *ACS_super;
};

A more complete description of the this content field is given below:

own_data - a flag which indicates if the SUNMatrix is responsible for freeing A_super
grid - pointer to the SuperLU_DIST structure that stores the 2D process grid
row_to_proc - a mapping between the rows in the matrix and the process it resides on; will be NULL until the SUNMatMatvecSetup routine is called
gsmv_comm - pointer to the SuperLU_DIST structure that stores the communication information needed for matrix-vector multiplication; will be NULL until the SUNMatMatvecSetup routine is called
A_super - pointer to the underlying SuperLU_DIST SuperMatrix with Stype = SLU_NR_loc, Dtype = SLU_D, Mtype = SLU_GE; must have the full diagonal present to be used with SUNMatScaleAddI routine
ACS_super - a column-sorted version of the matrix needed to perform matrix-vector multiplication; will be NULL until the routine SUNMatMatvecSetup routine is called

The header file to include when using this module is sunmatrix/sunmatrix_slunrloc.h. The installed module library to link to is libsundials_sunmatrixslunrloc.lib where .lib is typically .so for shared libraries and .a for static libraries.

7.6.1 SUNMatrix_SLUNRloc functions

The module SUNMATRIX_SLUNRLOC provides the following user-callable routines:

SUNMatrix_SLUNRloc
Call
A = SUNMatrix_SLUNRloc(Asuper, grid);
Description The function SUNMatrix_SLUNRloc creates and allocates memory for a SUNMATRIX_SLUNRLOC object.
Arguments Asuper (SuperMatrix*) a fully-allocated SuperLU_DIST SuperMatrix that the SUNMatrix will wrap; must have Stype = SLU_NR_loc, Dtype = SLU_D, Mtype = SLU_GE to be compatible
grid (gridinfo_t*) the initialized SuperLU_DIST 2D process grid structure
Return value a SUNMatrix object if Asuper is compatible else NULL
Notes

SUNMatrix_SLUNRloc_Print
Call
SUNMatrix_SLUNRloc_Print(A, fp);
Description The function SUNMatrix_SLUNRloc_Print prints the underlying SuperMatrix content.
Arguments A (SUNMatrix) the matrix to print
fp (FILE) the file pointer used for printing
Return value void
Notes
The SUNMatrix module defines implementations of all generic SUNMatrix operations listed in Section 7.1.1:

- **SUNMatGetID_SLUNRloc** - returns SUNMATRIX_SLUNRLOC
- **SUNMatClone_SLUNRloc**
- **SUNMatDestroy_SLUNRloc**
- **SUNMatSpace_SLUNRloc** - this only returns information for the storage within the matrix interface, i.e. storage for row_to_proc
- **SUNMatZero_SLUNRloc**
- **SUNMatCopy_SLUNRloc**
- **SUNMatScaleAdd_SLUNRloc** - performs $A = cA + B$, but $A$ and $B$ must have the same sparsity pattern
- **SUNMatScaleAddI_SLUNRloc** - performs $A = cA + I$, but the diagonal of $A$ must be present
- **SUNMatMatvecSetup_SLUNRloc** - initializes the SuperLU_DIST parallel communication structures needed to perform a matrix-vector product; only needs to be called before the first call to SUNMatMatvec or if the matrix changed since the last setup
- **SUNMatMatvec_SLUNRloc**

The SUNMatrix module requires that the complete diagonal, i.e. nonzeros and zeros, is present in order to use the SUNMatScaleAddI operation.
Chapter 8

Description of the SUNLinearSolver module

For problems that involve the solution of linear systems of equations, the SUNDIALS packages operate using generic linear solver modules defined through the SUNLINSOL API. This allows SUNDIALS packages to utilize any valid SUNLINSOL implementation that provides a set of required functions. These functions can be divided into three categories. The first are the core linear solver functions. The second group consists of "set" routines to supply the linear solver object with functions provided by the SUNDIALS package, or for modification of solver parameters. The last group consists of "get" routines for retrieving artifacts (statistics, residual vectors, etc.) from the linear solver. All of these functions are defined in the header file sundials/sundials_linearsolver.h.

The implementations provided with SUNDIALS work in coordination with the SUNDIALS generic NVECTOR and SUNMATRIX modules to provide a set of compatible data structures and solvers for the solution of linear systems using direct or iterative (matrix-based or matrix-free) methods. Moreover, advanced users can provide a customized SUNLinearSolver implementation to any SUNDIALS package, particularly in cases where they provide their own NVECTOR and/or SUNMATRIX modules.

Historically, the SUNDIALS packages have been designed to specifically leverage the use of either direct linear solvers or matrix-free, scaled, preconditioned, iterative linear solvers. However, matrix-based iterative linear solvers are also supported.

The iterative linear solvers packaged with SUNDIALS leverage scaling and preconditioning, as applicable, to balance error between solution components and to accelerate convergence of the linear solver. To this end, instead of solving the linear system $Ax = b$ directly, these apply the underlying iterative algorithm to the transformed system

$$\tilde{A}\tilde{x} = \tilde{b}$$

where

$$\tilde{A} = S_1P_1^{-1}AP_2^{-1}S_2^{-1},$$
$$\tilde{b} = S_1P_1^{-1}b,$$
$$\tilde{x} = S_2P_2x,$$

and where

- $P_1$ is the left preconditioner,
- $P_2$ is the right preconditioner,
- $S_1$ is a diagonal matrix of scale factors for $P_1^{-1}b$,
- $S_2$ is a diagonal matrix of scale factors for $P_2x$. 
The scaling matrices are chosen so that $S_1 P_1^{-1} b$ and $S_2 P_2 x$ have dimensionless components. If preconditioning is done on the left only ($P_2 = I$), by a matrix $P$, then $S_2$ must be a scaling for $x$, while $S_1$ is a scaling for $P^{-1} b$, and so may also be taken as a scaling for $x$. Similarly, if preconditioning is done on the right only ($P_1 = I$ and $P_2 = P$), then $S_1$ must be a scaling for $b$, while $S_2$ is a scaling for $P x$, and may also be taken as a scaling for $b$.

SUNDIALS packages request that iterative linear solvers stop based on the 2-norm of the scaled preconditioned residual meeting a prescribed tolerance

$$\| \tilde{b} - \tilde{A} \tilde{x} \|_2 < \text{tol}. $$

When provided an iterative SUNLINSOL implementation that does not support the scaling matrices $S_1$ and $S_2$, SUNDIALS’ packages will adjust the value of tol accordingly (see §8.4.2 for more details). In this case, they instead request that iterative linear solvers stop based on the criteria

$$\| P_1^{-1} b - P_1^{-1} A x \|_2 < \text{tol}. $$

We note that the corresponding adjustments to tol in this case are non-optimal, in that they cannot balance error between specific entries of the solution $x$, only the aggregate error in the overall solution vector.

We further note that not all of the SUNDIALS-provided iterative linear solvers support the full range of the above options (e.g., separate left/right preconditioning), and that some of the SUNDIALS packages only utilize a subset of these options. Further details on these exceptions are described in the documentation for each SUNLINSOL implementation, or for each SUNDIALS package.

For users interested in providing their own SUNLINSOL module, the following section presents the SUNLINSOL API and its implementation beginning with the definition of SUNLINSOL functions in sections 8.1.1 – 8.1.3. This is followed by the definition of functions supplied to a linear solver implementation in section 8.1.4. A table of linear solver return codes is given in section 8.1.5. The SUNLinearSolver type and the generic SUNLINSOL module are defined in section 8.1.6. The section 8.2 discusses compatibility between the SUNDIALS-provided SUNLINSOL modules and SUNMATRIX modules. Section 8.3 lists the requirements for supplying a custom SUNLINSOL module and discusses some intended use cases. Users wishing to supply their own SUNLINSOL module are encouraged to use the SUNLINSOL implementations provided with SUNDIALS as a template for supplying custom linear solver modules. The SUNLINSOL functions required by this SUNDIALS package as well as other package specific details are given in section 8.4. The remaining sections of this chapter present the SUNLINSOL modules provided with SUNDIALS.

8.1 The SUNLinearSolver API

The SUNLINSOL API defines several linear solver operations that enable SUNDIALS packages to utilize any SUNLINSOL implementation that provides the required functions. These functions can be divided into three categories. The first are the core linear solver functions. The second group of functions consists of set routines to supply the linear solver with functions provided by the SUNDIALS time integrators and to modify solver parameters. The final group consists of get routines for retrieving linear solver statistics. All of these functions are defined in the header file sundials/sundials_linear solver.h.

8.1.1 SUNLinearSolver core functions

The core linear solver functions consist of two required functions to get the linear solver type (SUNLinSolGetType) and solve the linear system $Ax = b$ (SUNLinSolSolve). The remaining functions are for getting the solver ID (SUNLinSolGetID), initializing the linear solver object once all solver-specific options have been set (SUNLinSolInitialize), setting up the linear solver object to utilize an updated matrix $A$ (SUNLinSolSetup), and for destroying the linear solver object (SUNLinSolFree) are optional.
8.1 The SUNLinearSolver API

**SUNLinSolGetType**

**Call**

\[
\text{type} = \text{SUNLinSolGetType}(\text{LS});
\]

**Description**

The *required* function `SUNLinSolGetType` returns the type identifier for the linear solver `LS`. It is used to determine the solver type (direct, iterative, or matrix-iterative) from the abstract `SUNLinearSolver` interface.

**Arguments**

- `LS` (SUNLinearSolver) a `SUNLINSOL` object.

**Return value**

The return value `type` (of type `int`) will be one of the following:

- **SUNLINEARSOLVER_DIRECT** – 0, the `SUNLINSOL` module requires a matrix, and computes an 'exact' solution to the linear system defined by that matrix.

- **SUNLINEARSOLVER_ITERATIVE** – 1, the `SUNLINSOL` module does not require a matrix (though one may be provided), and computes an inexact solution to the linear system using a matrix-free iterative algorithm. That is it solves the linear system defined by the package-supplied `ATimes` routine (see `SUNLinSolSetATimes` below), even if that linear system differs from the one encoded in the matrix object (if one is provided). As the solver computes the solution only inexactly (or may diverge), the linear solver should check for solution convergence/accuracy as appropriate.

- **SUNLINEARSOLVER_MATRIX_ITERATIVE** – 2, the `SUNLINSOL` module requires a matrix, and computes an inexact solution to the linear system defined by that matrix using an iterative algorithm. That is it solves the linear system defined by the matrix object even if that linear system differs from that encoded in the matrix object (if one is provided). As the solver computes the solution only inexactly (or may diverge), the linear solver should check for solution convergence/accuracy as appropriate.

**Notes**

See section 8.3.1 for more information on intended use cases corresponding to the linear solver type.

F2003 Name `FSUNLinSolGetType`

**SUNLinSolGetID**

**Call**

\[
\text{id} = \text{SUNLinSolGetID}(\text{LS});
\]

**Description**

The *optional* function `SUNLinSolGetID` returns the identifier for the linear solver `LS`.

**Arguments**

- `LS` (SUNLinearSolver) a `SUNLINSOL` object.

**Return value**

The return value `id` (of type `int`) will be a non-negative value defined by the enumeration `SUNLinearSolver_ID`.

**Notes**

It is recommended that a user-supplied `SUNLinearSolver` return the `SUNLINEARSOLVER_CUSTOM` identifier.

F2003 Name `FSUNLinSolGetID`

**SUNLinSolInitialize**

**Call**

\[
\text{retval} = \text{SUNLinSolInitialize}(\text{LS});
\]

**Description**

The *optional* function `SUNLinSolInitialize` performs linear solver initialization (assuming that all solver-specific options have been set).

**Arguments**

- `LS` (SUNLinearSolver) a `SUNLINSOL` object.

**Return value**

This should return zero for a successful call, and a negative value for a failure, ideally returning one of the generic error codes listed in Table 8.1.

F2003 Name `FSUNLinSolInitialize`
Description of the SUNLinearSolver module

**SUNLinSolSetup**

Call
\[
\text{retval} = \text{SUNLinSolSetup}(\text{LS}, A);
\]

Description
The *optional* function SUNLinSolSetup performs any linear solver setup needed, based on an updated system SUNMATRIX A. This may be called frequently (e.g., with a full Newton method) or infrequently (for a modified Newton method), based on the type of integrator and/or nonlinear solver requesting the solves.

Arguments
- \( \text{LS} \) (SUNLinearSolver) a SUNLINSOL object.
- \( A \) (SUNMatrix) a SUNMATRIX object.

Return value
This should return zero for a successful call, a positive value for a recoverable failure and a negative value for an unrecoverable failure, ideally returning one of the generic error codes listed in Table 8.1.

F2003 Name FSUNLinSolSetup

**SUNLinSolSolve**

Call
\[
\text{retval} = \text{SUNLinSolSolve}(\text{LS}, A, x, b, \text{tol});
\]

Description
The *required* function SUNLinSolSolve solves a linear system \( Ax = b \).

Arguments
- \( \text{LS} \) (SUNLinearSolver) a SUNLINSOL object.
- \( A \) (SUNMatrix) a SUNMATRIX object.
- \( x \) (N_Vector) a NVECTOR object containing the initial guess for the solution of the linear system, and the solution to the linear system upon return.
- \( b \) (N_Vector) a NVECTOR object containing the linear system right-hand side.
- \( \text{tol} \) (realtype) the desired linear solver tolerance.

Return value
This should return zero for a successful call, a positive value for a recoverable failure and a negative value for an unrecoverable failure, ideally returning one of the generic error codes listed in Table 8.1.

Notes
- **Direct solvers**: can ignore the \( \text{tol} \) argument.
- **Matrix-free solvers**: (those that identify as SUNLINEARSOLVER_ITERATIVE) can ignore the SUNMATRIX input \( A \), and should instead rely on the matrix-vector product function supplied through the routine SUNLinSolSetATimes.
- **Iterative solvers**: (those that identify as SUNLINEARSOLVER_ITERATIVE or SUNLINEARSOLVER_MATRIX_ITERATIVE) should attempt to solve to the specified tolerance \( \text{tol} \) in a weighted 2-norm. If the solver does not support scaling then it should just use a 2-norm.

F2003 Name FSUNLinSolSolve

**SUNLinSolFree**

Call
\[
\text{retval} = \text{SUNLinSolFree}(\text{LS});
\]

Description
The *optional* function SUNLinSolFree frees memory allocated by the linear solver.

Arguments
- \( \text{LS} \) (SUNLinearSolver) a SUNLINSOL object.

Return value
This should return zero for a successful call and a negative value for a failure.

F2003 Name FSUNLinSolFree
8.1.2 SUNLinearSolver set functions

The following set functions are used to supply linear solver modules with functions defined by the SUNDIALS packages and to modify solver parameters. Only the routine for setting the matrix-vector product routine is required, and that is only for matrix-free linear solver modules. Otherwise, all other set functions are optional. SUNLINSOL implementations that do not provide the functionality for any optional routine should leave the corresponding function pointer NULL instead of supplying a dummy routine.

**SUNLinSolSetATimes**

**Call**
```
retval = SUNLinSolSetATimes(LS, A_data, ATimes);
```

**Description**
The function `SUNLinSolSetATimes` is required for matrix-free linear solvers; otherwise it is optional. This routine provides an ATimesFn function pointer, as well as a void* pointer to a data structure used by this routine, to a linear solver object. SUNDIALS packages will call this function to set the matrix-vector product function to either a solver-provided difference-quotient via vector operations or a user-supplied solver-specific routine.

**Arguments**
- `LS` (SUNLinearSolver) a SUNLINSOL object.
- `A_data` (void*) data structure passed to ATimes.
- `ATimes` (ATimesFn) function pointer implementing the matrix-vector product routine.

**Return value**
This routine should return zero for a successful call, and a negative value for a failure, ideally returning one of the generic error codes listed in Table 8.1.

**F2003 Name** FSUNLinSolSetATimes

**SUNLinSolSetPreconditioner**

**Call**
```
retval = SUNLinSolSetPreconditioner(LS, Pdata, Pset, Psol);
```

**Description**
The optional function `SUNLinSolSetPreconditioner` provides PSetupFn and PSolveFn function pointers that implement the preconditioner solves $P^{-1}_1$ and $P^{-1}_2$ from equations (8.1)-(8.2). This routine will be called by a SUNDIALS package, which will provide translation between the generic Pset and Psol calls and the package- or user-supplied routines.

**Arguments**
- `LS` (SUNLinearSolver) a SUNLINSOL object.
- `Pdata` (void*) data structure passed to both Pset and Psol.
- `Pset` (PSetupFn) function pointer implementing the preconditioner setup.
- `Psol` (PSolveFn) function pointer implementing the preconditioner solve.

**Return value**
This routine should return zero for a successful call, and a negative value for a failure, ideally returning one of the generic error codes listed in Table 8.1.

**F2003 Name** FSUNLinSolSetPreconditioner

**SUNLinSolSetScalingVectors**

**Call**
```
retval = SUNLinSolSetScalingVectors(LS, s1, s2);
```

**Description**
The optional function `SUNLinSolSetScalingVectors` provides left/right scaling vectors for the linear system solve. Here, `s1` and `s2` are NVECTOR of positive scale factors containing the diagonal of the matrices $S_1$ and $S_2$ from equations (8.1)-(8.2), respectively. Neither of these vectors need to be tested for positivity, and a NULL argument for either indicates that the corresponding scaling matrix is the identity.

**Arguments**
- `LS` (SUNLinearSolver) a SUNLINSOL object.
- `s1` (N_Vector) diagonal of the matrix $S_1$
s2 (N_Vector) diagonal of the matrix $S_2$

Return value This routine should return zero for a successful call, and a negative value for a failure, ideally returning one of the generic error codes listed in Table 8.1.

F2003 Name FSUNLinSolSetScalingVectors

8.1.3 SUNLinearSolver get functions

The following get functions allow SUNDIALS packages to retrieve results from a linear solve. All routines are optional.

**SUNLinSolNumIters**

Call 
\[ \text{its} = \text{SUNLinSolNumIters}(\text{LS}); \]

Description The *optional* function SUNLinSolNumIters should return the number of linear iterations performed in the last ‘solve’ call.

Arguments LS (SUNLinearSolver) a SUNLINSOL object.

Return value int containing the number of iterations

F2003 Name FSUNLinSolNumIters

**SUNLinSolResNorm**

Call 
\[ \text{rnorm} = \text{SUNLinSolResNorm}(\text{LS}); \]

Description The *optional* function SUNLinSolResNorm should return the final residual norm from the last ‘solve’ call.

Arguments LS (SUNLinearSolver) a SUNLINSOL object.

Return value realltype containing the final residual norm

F2003 Name FSUNLinSolResNorm

**SUNLinSolResid**

Call 
\[ \text{rvec} = \text{SUNLinSolResid}(\text{LS}); \]

Description If an iterative method computes the preconditioned initial residual and returns with a successful solve without performing any iterations (i.e., either the initial guess or the preconditioner is sufficiently accurate), then this *optional* routine may be called by the SUNDIALS package. This routine should return the NVECTOR containing the preconditioned initial residual vector.

Arguments LS (SUNLinearSolver) a SUNLINSOL object.

Return value N_Vector containing the final residual vector

Notes Since N_Vector is actually a pointer, and the results are not modified, this routine should *not* require additional memory allocation. If the SUNLINSOL object does not retain a vector for this purpose, then this function pointer should be set to NULL in the implementation.

F2003 Name FSUNLinSolResid

**SUNLinSolLastFlag**

Call 
\[ \text{lflag} = \text{SUNLinSolLastFlag}(\text{LS}); \]

Description The *optional* function SUNLinSolLastFlag should return the last error flag encountered within the linear solver. This is not called by the SUNDIALS packages directly; it allows the user to investigate linear solver issues after a failed solve.
8.1 The SUNLinearSolver API

Arguments

- LS (SUNLinearSolver) a SUNLINSOL object.

Return value

sunindextype containing the most recent error flag

F2003 Name  FSUNLinSolLastFlag

SUNLinSolSpace

Call  

retval = SUNLinSolSpace(LS, &lrw, &liw);

Description

The optional function SUNLinSolSpace should return the storage requirements for the linear solver LS.

Arguments

- LS (SUNLinearSolver) a SUNLINSOL object.
- lrw (long int*) the number of realtype words stored by the linear solver.
- liw (long int*) the number of integer words stored by the linear solver.

Return value

This should return zero for a successful call, and a negative value for a failure, ideally returning one of the generic error codes listed in Table 8.1.

Notes

This function is advisory only, for use in determining a user’s total space requirements.

F2003 Name  FSUNLinSolSpace

8.1.4 Functions provided by SUNDIALS packages

To interface with the SUNLINSOL modules, the SUNDIALS packages supply a variety of routines for evaluating the matrix-vector product, and setting up and applying the preconditioner. These package-provided routines translate between the user-supplied ODE, DAE, or nonlinear systems and the generic interfaces to the linear systems of equations that result in their solution. The types for functions provided to a SUNLINSOL module are defined in the header file sundials/sundials_iterative.h, and are described below.

ATimesFn

Definition  

typedef int (*ATimesFn)(void *A_data, N_Vector v, N_Vector z);

Purpose

These functions compute the action of a matrix on a vector, performing the operation \( z = Av \). Memory for \( z \) should already be allocated prior to calling this function. The vector \( v \) should be left unchanged.

Arguments

- A_data is a pointer to client data, the same as that supplied to SUNLinSolSetATimes.
- v is the input vector to multiply.
- z is the output vector computed.

Return value

This routine should return 0 if successful and a non-zero value if unsuccessful.

PSetupFn

Definition  

typedef int (*PSetupFn)(void *P_data)

Purpose

These functions set up any requisite problem data in preparation for calls to the corresponding PSolveFn.

Arguments

- P_data is a pointer to client data, the same pointer as that supplied to the routine SUNLinSolSetPreconditioner.

Return value

This routine should return 0 if successful and a non-zero value if unsuccessful.
PSolveFn

Definition typedef int (*PSolveFn)(void *P_data, N_Vector r, N_Vector z, realtype tol, int lr)

Purpose These functions solve the preconditioner equation $Pz = r$ for the vector $z$. Memory for $z$ should already be allocated prior to calling this function. The parameter $P\_data$ is a pointer to any information about $P$ which the function needs in order to do its job (set up by the corresponding PSetupFn). The parameter $lr$ is input, and indicates whether $P$ is to be taken as the left preconditioner or the right preconditioner: $lr = 1$ for left and $lr = 2$ for right. If preconditioning is on one side only, $lr$ can be ignored. If the preconditioner is iterative, then it should strive to solve the preconditioner equation so that

$$\|Pz - r\|_{\text{wrms}} < tol$$

where the weight vector for the WRMS norm may be accessed from the main package memory structure. The vector $r$ should not be modified by the PSolveFn.

Arguments $P\_data$ is a pointer to client data, the same pointer as that supplied to the routine SUNLinSolSetPreconditioner.

$r$ is the right-hand side vector for the preconditioner system.

$z$ is the solution vector for the preconditioner system.

$tol$ is the desired tolerance for an iterative preconditioner.

$lr$ is flag indicating whether the routine should perform left (1) or right (2) preconditioning.

Return value This routine should return 0 if successful and a non-zero value if unsuccessful. On a failure, a negative return value indicates an unrecoverable condition, while a positive value indicates a recoverable one, in which the calling routine may reattempt the solution after updating preconditioner data.

8.1.5 SUNLinearSolver return codes

The functions provided to SUNLINSOL modules by each SUNDIALS package, and functions within the SUNDIALS-provided SUNLINSOL implementations utilize a common set of return codes, shown in Table 8.1. These adhere to a common pattern: 0 indicates success, a positive value corresponds to a recoverable failure, and a negative value indicates a non-recoverable failure. Aside from this pattern, the actual values of each error code are primarily to provide additional information to the user in case of a linear solver failure.

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUNLS_SUCCESS</td>
<td>0</td>
<td>successful call or converged solve</td>
</tr>
<tr>
<td>SUNLS_MEM_NULL</td>
<td>-801</td>
<td>the memory argument to the function is NULL</td>
</tr>
<tr>
<td>SUNLS_Ill_INPUT</td>
<td>-802</td>
<td>an illegal input has been provided to the function</td>
</tr>
<tr>
<td>SUNLS_MEM_FAIL</td>
<td>-803</td>
<td>failed memory access or allocation</td>
</tr>
<tr>
<td>SUNLS_ATIMES_FAIL_UNREC</td>
<td>-804</td>
<td>an unrecoverable failure occurred in the ATimes routine</td>
</tr>
</tbody>
</table>

continued on next page
### 8.1 The SUNLinearSolver API

SUNDIALS packages interact with specific SUNLINSOL implementations through the generic SUNLINSOL module on which all other SUNLINSOL implementations are built. The **SUNLinearSolver** type is a pointer to a structure containing an implementation-dependent *content* field, and an *ops* field. The type **SUNLinearSolver** is defined as

```c
typedef struct _generic_SUNLinearSolver *SUNLinearSolver;

struct _generic_SUNLinearSolver {
    void *content;
    struct _generic_SUNLinearSolver_Ops *ops;
};
```

where the **_generic_SUNLinearSolver_Ops** structure is a list of pointers to the various actual linear solver operations provided by a specific implementation. The **_generic_SUNLinearSolver_Ops** structure is defined as

```c
struct _generic_SUNLinearSolver_Ops {
    SUNLinearSolver_Type (*gettype)(SUNLinearSolver);
    SUNLinearSolver_ID (*getid)(SUNLinearSolver);
    int (*setatimes)(SUNLinearSolver, void*, ATimesFn);
    int (*setpreconditioner)(SUNLinearSolver, void*,
                             PSetupFn, PSolveFn);
    int (*setscalingvectors)(SUNLinearSolver,
                              N_Vector, N_Vector);
    int (*initialize)(SUNLinearSolver);
};
```

#### 8.1.6 The generic SUNLinearSolver module

**SUNLINSOL** packages interact with specific SUNLINSOL implementations through the generic SUNLINSOL module on which all other SUNLINSOL implementations are built. The **SUNLinearSolver** type is a pointer to a structure containing an implementation-dependent *content* field, and an *ops* field. The type **SUNLinearSolver** is defined as

```c
typedef struct _generic_SUNLinearSolver *SUNLinearSolver;

struct _generic_SUNLinearSolver {
    void *content;
    struct _generic_SUNLinearSolver_Ops *ops;
};
```

where the **_generic_SUNLinearSolver_Ops** structure is a list of pointers to the various actual linear solver operations provided by a specific implementation. The **_generic_SUNLinearSolver_Ops** structure is defined as

```c
struct _generic_SUNLinearSolver_Ops {
    SUNLinearSolver_Type (*gettype)(SUNLinearSolver);
    SUNLinearSolver_ID (*getid)(SUNLinearSolver);
    int (*setatimes)(SUNLinearSolver, void*, ATimesFn);
    int (*setpreconditioner)(SUNLinearSolver, void*,
                             PSetupFn, PSolveFn);
    int (*setscalingvectors)(SUNLinearSolver,
                              N_Vector, N_Vector);
    int (*initialize)(SUNLinearSolver);
};
```
The generic SUNLINSOL module defines and implements the linear solver operations defined in Sections 8.1.1-8.1.3. These routines are in fact only wrappers to the linear solver operations defined by a particular SUNLINSOL implementation, which are accessed through the ops field of the SUNLinearSolver structure. To illustrate this point we show below the implementation of a typical linear solver operation from the generic SUNLINSOL module, namely SUNLinSolInitialize, which initializes a SUNLINSOL object for use after it has been created and configured, and returns a flag denoting a successful/failed operation:

```c
int SUNLinSolInitialize(SUNLinearSolver S)
{
    return ((int) S->ops->initialize(S));
}
```

The Fortran 2003 interface provides a bind(C) derived-type for the _generic_SUNLinearSolver and the _generic_SUNLinearSolver_Ops structures. Their definition is given below.

```c
  type, bind(C), public :: SUNLinearSolver
  type(C_PTR), public :: content
  type(C_PTR), public :: ops
end type SUNLinearSolver

  type, bind(C), public :: SUNLinearSolver_Ops
  type(C_FUNPTR), public :: gettype
  type(C_FUNPTR), public :: setatimes
  type(C_FUNPTR), public :: setpreconditioner
  type(C_FUNPTR), public :: setscalingvectors
  type(C_FUNPTR), public :: initialize
  type(C_FUNPTR), public :: setup
  type(C_FUNPTR), public :: solve
  type(C_FUNPTR), public :: numiters
  type(C_FUNPTR), public :: resnorm
  type(C_FUNPTR), public :: lastflag
  type(C_FUNPTR), public :: space
  type(C_FUNPTR), public :: resid
  type(C_FUNPTR), public :: free
end type SUNLinearSolver_Ops
```

### 8.2 Compatibility of SUNLinearSolver modules

We note that not all SUNLINSOL types are compatible with all SUNMATRIX and NVECTOR types provided with SUNDIALS. In Table 8.2 we show the matrix-based linear solvers available as SUNLINSOL modules, and the compatible matrix implementations. Recall that Table 4.1 shows the compatibility between all SUNLINSOL modules and vector implementations.
### 8.3 Implementing a custom SUNLinearSolver module

A particular implementation of the SUNLINSOL module must:

- Specify the `content` field of the `SUNLinearSolver` object.

- Define and implement a minimal subset of the linear solver operations. See the section 8.4 to determine which SUNLINSOL operations are required for this SUNDIALS package.

Note that the names of these routines should be unique to that implementation in order to permit using more than one SUNLINSOL module (each with different `SUNLinearSolver` internal data representations) in the same code.

- Define and implement user-callable constructor and destructor routines to create and free a `SUNLinearSolver` with the new `content` field and with `ops` pointing to the new linear solver operations.

We note that the function pointers for all unsupported optional routines should be set to `NULL` in the `ops` structure. This allows the SUNDIALS package that is using the SUNLINSOL object to know that the associated functionality is not supported.

To aid in the creation of custom SUNLINSOL modules the generic SUNLINSOL module provides the utility functions `SUNLinSolNewEmpty` and `SUNLinSolFreeEmpty`. When used in custom SUNLINSOL constructors the function `SUNLinSolNewEmpty` will ease the introduction of any new optional linear solver operations to the SUNLINSOL API by ensuring only required operations need to be set.

**SUNLinSolNewEmpty**

```
Call LS = SUNLinSolNewEmpty();
```

**Description**
The function `SUNLinSolNewEmpty` allocates a new generic SUNLINSOL object and initializes its content pointer and the function pointers in the operations structure to `NULL`.

**Arguments**
None

**Return value**
This function returns a `SUNLinearSolver` object. If an error occurs when allocating the object, then this routine will return `NULL`.

F2003 Name `FSUNLinSolNewEmpty`

**SUNLinSolFreeEmpty**

```
Call SUNLinSolFreeEmpty(LS);
```
Description of the SUNLinearSolver module

Description  This routine frees the generic SUNLinSolFreeEmpty object, under the assumption that any implementation-specific data that was allocated within the underlying content structure has already been freed. It will additionally test whether the ops pointer is NULL, and, if it is not, it will free it as well.

Arguments  LS (SUNLinearSolver)

Return value  None

F2003 Name  FSUNLinSolFreeEmpty

Additionally, a SUNLINSOL implementation may do the following:

- Define and implement additional user-callable “set” routines acting on the SUNLinearSolver, e.g., for setting various configuration options to tune the linear solver to a particular problem.
- Provide additional user-callable “get” routines acting on the SUNLinearSolver object, e.g., for returning various solve statistics.

8.3.1 Intended use cases

The SUNLINSOL (and SUNMATRIX) APIs are designed to require a minimal set of routines to ease interfacing with custom or third-party linear solver libraries. External solvers provide similar routines with the necessary functionality and thus will require minimal effort to wrap within custom SUNMATRIX and SUNLINSOL implementations. Sections 7.2 and 8.4 include a list of the required set of routines that compatible SUNMATRIX and SUNLINSOL implementations must provide. As SUNDIALS packages utilize generic SUNLINSOL modules allowing for user-supplied SUNLinearSolver implementations, there exists a wide range of possible linear solver combinations. Some intended use cases for both the SUNDIALS-provided and user-supplied SUNLINSOL modules are discussed in the following sections.

Direct linear solvers

Direct linear solver modules require a matrix and compute an ‘exact’ solution to the linear system defined by the matrix. Multiple matrix formats and associated direct linear solvers are supplied with SUNDIALS through different SUNMATRIX and SUNLINSOL implementations. SUNDIALS packages strive to amortize the high cost of matrix construction by reusing matrix information for multiple nonlinear iterations. As a result, each package’s linear solver interface recomputes Jacobian information as infrequently as possible.

Alternative matrix storage formats and compatible linear solvers that are not currently provided by, or interfaced with, SUNDIALS can leverage this infrastructure with minimal effort. To do so, a user must implement custom SUNMATRIX and SUNLINSOL wrappers for the desired matrix format and/or linear solver following the APIs described in Chapters 7 and 8. This user-supplied SUNLINSOL module must then self-identify as having SUNLINEARSOLVER_DIRECT type.

Matrix-free iterative linear solvers

Matrix-free iterative linear solver modules do not require a matrix and compute an inexact solution to the linear system defined by the package-supplied ATimes routine. SUNDIALS supplies multiple scaled, preconditioned iterative linear solver (spils) SUNLINSOL modules that support scaling to allow users to handle non-dimensionalization (as best as possible) within each SUNDIALS package and retain variables and define equations as desired in their applications. For linear solvers that do not support left/right scaling, the tolerance supplied to the linear solver is adjusted to compensate (see section 8.4.2 for more details); however, this use case may be non-optimal and cannot handle situations where the magnitudes of different solution components or equations vary dramatically within a single problem.

To utilize alternative linear solvers that are not currently provided by, or interfaced with, SUNDIALS a user must implement a custom SUNLINSOL wrapper for the linear solver following the API described in Chapter 8. This user-supplied SUNLINSOL module must then self-identify as having SUNLINEARSOLVER_ITERATIVE type.
Matrix-based iterative linear solvers (reusing $A$)

Matrix-based iterative linear solver modules require a matrix and compute an inexact solution to the linear system defined by the matrix. This matrix will be updated infrequently and reused across multiple solves to amortize cost of matrix construction. As in the direct linear solver case, only wrappers for the matrix and linear solver in SUNMATRIX and SUNLINSOL implementations need to be created to utilize a new linear solver. This user-supplied SUNLINSOL module must then self-identify as having SUNLINEARSOLVER_MATRIX_ITERATIVE type.

At present, SUNDIALS has one example problem that uses this approach for wrapping a structured-grid matrix, linear solver, and preconditioner from the hypre library that may be used as a template for other customized implementations (see examples/arkode/CXX_parhyp/ark_heat2D_hypre.cpp).

Matrix-based iterative linear solvers (current $A$)

For users who wish to utilize a matrix-based iterative linear solver module where the matrix is purely for preconditioning and the linear system is defined by the package-supplied ATimes routine, we envision two current possibilities.

The preferred approach is for users to employ one of the SUNDIALS spils SUNLINSOL implementations (SUNLINSOL_SPGMR, SUNLINSOL_SPGMRES, SUNLINSOL_SPBCGS, SUNLINSOL_SPTFQMR, or SUNLINSOL_PCG) as the outer solver. The creation and storage of the preconditioner matrix, and interfacing with the corresponding linear solver, can be handled through a package’s preconditioner ‘setup’ and ‘solve’ functionality (see §4.5.8.2) without creating SUNMATRIX and SUNLINSOL implementations. This usage mode is recommended primarily because the SUNDIALS-provided spils modules support the scaling as described above.

A second approach supported by the linear solver APIs is as follows. If the SUNLINSOL implementation is matrix-based, self-identifies as having SUNLINEARSOLVER_ITERATIVE type, and also provides a non-NULL SUNLinSolSetATimes routine, then each SUNDIALS package will call that routine to attach its package-specific matrix-vector product routine to the SUNLINSOL object. The SUNDIALS package will then call the SUNLINSOL-provided SUNLinSolSetup routine (infrequently) to update matrix information, but will provide current matrix-vector products to the SUNLINSOL implementation through the package-supplied ATimesFn routine.

8.4 IDA SUNLinearSolver interface

Table 8.3 below lists the SUNLINSOL module linear solver functions used within the IDALS interface. As with the SUNMATRIX module, we emphasize that the IDA user does not need to know detailed usage of linear solver functions by the IDA code modules in order to use IDA. The information is presented as an implementation detail for the interested reader.

The linear solver functions listed below are marked with ✓ to indicate that they are required, or with † to indicate that they are only called if they are non-NULL in the SUNLINSOL implementation that is being used. Note:

1. Although IDALS does not call SUNLinSolLastFlag directly, this routine is available for users to query linear solver issues directly.

2. Although IDALS does not call SUNLinSolFree directly, this routine should be available for users to call when cleaning up from a simulation.

Since there are a wide range of potential SUNLINSOL use cases, the following subsections describe some details of the IDALS interface, in the case that interested users wish to develop custom SUNLINSOL modules.

8.4.1 Lagged matrix information

If the SUNLINSOL object self-identifies as having type SUNLINEARSOLVER_DIRECT or
Table 8.3: List of linear solver function usage in the idals interface

<table>
<thead>
<tr>
<th>Function</th>
<th>DIRECT</th>
<th>ITERATIVE</th>
<th>MATRIX-ITERATIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUNLinSolGetType</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SUNLinSolSetATimes</td>
<td>†</td>
<td>✓</td>
<td>†</td>
</tr>
<tr>
<td>SUNLinSolSetPreconditioner</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>SUNLinSolSetScalingVectors</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>SUNLinSolInitialize</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SUNLinSolSetup</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SUNLinSolSolve</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SUNLinSolNumIters</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SUNLinSolResid</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>'SUNLinSolLastFlag</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>^SUNLinSolFree</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUNLinSolSpace</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
</tbody>
</table>

\[ x = \frac{2}{1 + \alpha/\bar{\alpha}} \bar{x}. \] (8.3)

The motivation for this selection of the scaling factor \( c = \frac{2}{1 + \alpha/\bar{\alpha}} \) is discussed in detail in [6, 25]. In short, if we consider a stationary iteration for the linear system as consisting of a solve with \( \bar{M} \) followed by scaling by \( c \), then for a linear constant-coefficient problem, the error in the solution vector will be reduced at each iteration by the error matrix \( E = I - c\bar{M}^{-1}M \), with a convergence rate given by the spectral radius of \( E \). Assuming that stiff systems have a spectrum spread widely over the left half-plane, \( c \) is chosen to minimize the magnitude of the eigenvalues of \( E \).

### 8.4.2 Iterative linear solver tolerance

If the sunlinsol object self-identifies as having type SUNLINEARSOLVER ITERATIVE or SUNLINEARSOLVER MATRIX ITERATIVE then idals will set the input tolerance \( \text{delta} \) as described in §2.1. However, if the iterative linear solver does not support scaling matrices (i.e., the SUNLinSolSetScalingVectors routine is NULL), then idals will attempt to adjust the linear solver tolerance to account for this lack of functionality. To this end, the following assumptions are made:

1. All solution components have similar magnitude; hence the error weight vector \( W \) used in the WRMS norm (see §2.1) should satisfy the assumption
   \[ W_i \approx W_{\text{mean}}, \quad \text{for} \quad i = 0, \ldots, n-1. \]

2. The sunlinsol object uses a standard 2-norm to measure convergence.
Since IDA uses identical left and right scaling matrices, \( S_1 = S_2 = S = \text{diag}(W) \), then the linear solver convergence requirement is converted as follows (using the notation from equations (8.1)-(8.2)):

\[
\begin{align*}
\|\tilde{b} - \tilde{A}x\|_2 < \text{tol} &\iff \|SP_1^{-1}b - SP_1^{-1}Ax\|_2 < \text{tol} \\
&\iff \sum_{i=0}^{n-1} \left[ W_i (P_1^{-1}(b - Ax))_i \right]^2 < \text{tol}^2 \\
&\iff W_{\text{mean}}^2 \sum_{i=0}^{n-1} \left[ (P_1^{-1}(b - Ax))_i \right]^2 < \text{tol}^2 \\
&\iff \sum_{i=0}^{n-1} \left[ (P_1^{-1}(b - Ax))_i \right]^2 < \left( \frac{\text{tol}}{W_{\text{mean}}} \right)^2 \\
&\iff \|P_1^{-1}(b - Ax)\|_2 < \frac{\text{tol}}{W_{\text{mean}}} 
\end{align*}
\]

Therefore the tolerance scaling factor

\[ W_{\text{mean}} = \|W\|_2 / \sqrt{n} \]

is computed and the scaled tolerance \( \text{delta} = \text{tol}/W_{\text{mean}} \) is supplied to the SUNLINSOL object.

### 8.5 The SUNLinearSolver_Dense implementation

This section describes the SUNLINSOL implementation for solving dense linear systems. The SUNLINSOL_DENSE module is designed to be used with the corresponding SUNMATRIX_DENSE matrix type, and one of the serial or shared-memory NVECTOR implementations (NVECTOR_SERIAL, NVECTOR_OPENMP, or NVECTOR_PTHREADS).

To access the SUNLINSOL_DENSE module, include the header file `sunlinsol/sunlinsol_dense.h`. We note that the SUNLINSOL_DENSE module is accessible from SUNDIALS packages without separately linking to the `libsundials_sunlinsoldense` module library.

#### 8.5.1 SUNLinearSolver_Dense description

This solver is constructed to perform the following operations:

- The “setup” call performs a \( LU \) factorization with partial (row) pivoting (\( O(N^3) \) cost), \( PA = LU \), where \( P \) is a permutation matrix, \( L \) is a lower triangular matrix with 1’s on the diagonal, and \( U \) is an upper triangular matrix. This factorization is stored in-place on the input SUNMATRIX_DENSE object \( A \), with pivoting information encoding \( P \) stored in the pivots array.

- The “solve” call performs pivoting and forward and backward substitution using the stored pivots array and the \( LU \) factors held in the SUNMATRIX_DENSE object (\( O(N^2) \) cost).

#### 8.5.2 SUNLinearSolver_Dense functions

The SUNLINSOL_DENSE module provides the following user-callable constructor for creating a SUNLinearSolver object.

```
SUNLinSol_Dense
Call LS = SUNLinSol_Dense(y, A);
Description The function SUNLinSol_Dense creates and allocates memory for a dense SUNLinearSolver object.
```
Description of the SUNLinearSolver module

Arguments

- \( y (N\_\text{Vector}) \): a template for cloning vectors needed within the solver.
- \( A (\text{SUNMatrix}) \): a SUNMATRIX\_DENSE matrix template for cloning matrices needed within the solver.

Return value

This returns a SUNLinearSolver object. If either \( A \) or \( y \) are incompatible then this routine will return NULL.

Notes

This routine will perform consistency checks to ensure that it is called with consistent NVECTOR and SUNMATRIX implementations. These are currently limited to the SUNMATRIX\_DENSE matrix type and the NVECTOR\_SERIAL, NVECTOR\_OPENMP, and NVECTOR\_PTHREADS vector types. As additional compatible matrix and vector implementations are added to SUNDIALS, these will be included within this compatibility check.

Deprecated Name

For backward compatibility, the wrapper function SUNDenseLinearSolver with identical input and output arguments is also provided.

F2003 Name

FSUNLinSol\_Dense

The SUNLINSOL\_DENSE module defines implementations of all “direct” linear solver operations listed in Sections 8.1.1 – 8.1.3:

- SUNLinSolGetType\_Dense
- SUNLinSolInitialize\_Dense – this does nothing, since all consistency checks are performed at solver creation.
- SUNLinSolSetup\_Dense – this performs the \( LU \) factorization.
- SUNLinSolSolve\_Dense – this uses the \( LU \) factors and pivots array to perform the solve.
- SUNLinSolLastFlag\_Dense
- SUNLinSolSpace\_Dense – this only returns information for the storage within the solver object, i.e. storage for \( \text{N, last\_flag, and pivots} \).
- SUNLinSolFree\_Dense

All of the listed operations are callable via the FORTRAN 2003 interface module by prepending an ‘F’ to the function name.

8.5.3 SUNLinearSolver\_Dense Fortran interfaces

The SUNLINSOL\_DENSE module provides a FORTRAN 2003 module as well as FORTRAN 77 style interface functions for use from FORTRAN applications.

FORTRAN 2003 interface module

The fsunlinsol\_dense\_mod FORTRAN module defines interfaces to all SUNLINSOL\_DENSE C functions using the intrinsic iso\_c\_binding module which provides a standardized mechanism for interoperating with C. As noted in the C function descriptions above, the interface functions are named after the corresponding C function, but with a leading ‘F’. For example, the function SUNLinSol\_Dense is interfaced as FSUNLinSol\_Dense.

The FORTRAN 2003 SUNLINSOL\_DENSE interface module can be accessed with the use statement, i.e. use fsunlinsol\_dense\_mod, and linking to the library libsundials_fsunlinsoldense\_mod\_lib in addition to the C library. For details on where the library and module file fsunlinsol\_dense\_mod\_mod are installed see Appendix A. We note that the module is accessible from the FORTRAN 2003 SUNDIALS integrators without separately linking to the libsundials_fsunlinsoldense\_mod library.
8.6 The SUNLinearSolver_Band implementation

FORTRAN 77 interface functions

For solvers that include a FORTRAN 77 interface module, the SUNLINSOL_DENSE module also includes a Fortran-callable function for creating a SUNLinearSolver object.

### FSUNDENSELINSOLINIT

<table>
<thead>
<tr>
<th>Call</th>
<th>FSUNDENSELINSOLINIT(code, ier)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>The function FSUNDENSELINSOLINIT can be called for Fortran programs to create a dense SUNLinearSolver object.</td>
</tr>
<tr>
<td>Arguments</td>
<td>code (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).</td>
</tr>
<tr>
<td>Return value</td>
<td>ier is a return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.</td>
</tr>
<tr>
<td>Notes</td>
<td>This routine must be called after both the NVECTOR and SUNMATRIX objects have been initialized. Additionally, when using ARKODE with a non-identity mass matrix, the SUNLINSOL_DENSE module includes a Fortran-callable function for creating a SUNLinearSolver mass matrix solver object.</td>
</tr>
</tbody>
</table>

### FSUNMASSDENSELINSOLINIT

<table>
<thead>
<tr>
<th>Call</th>
<th>FSUNMASSDENSELINSOLINIT(ier)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>The function FSUNMASSDENSELINSOLINIT can be called for Fortran programs to create a dense SUNLinearSolver object for mass matrix linear systems.</td>
</tr>
<tr>
<td>Arguments</td>
<td>None</td>
</tr>
<tr>
<td>Return value</td>
<td>ier is an int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.</td>
</tr>
<tr>
<td>Notes</td>
<td>This routine must be called after both the NVECTOR and SUNMATRIX mass-matrix objects have been initialized.</td>
</tr>
</tbody>
</table>

8.5.4 SUNLinearSolver_Dense content

The SUNLINSOL_DENSE module defines the content field of a SUNLinearSolver as the following structure:

```c
struct _SUNLinearSolverContent_Dense {
    sunindextype N;
    sunindextype *pivots;
    sunindextype last_flag;
};
```

These entries of the content field contain the following information:

- `N` - size of the linear system,
- `pivots` - index array for partial pivoting in LU factorization,
- `last_flag` - last error return flag from internal function evaluations.

8.6 The SUNLinearSolver_Band implementation

This section describes the SUNLINSOL implementation for solving banded linear systems. The SUNLINSOL_BAND module is designed to be used with the corresponding SUNMATRIX_BAND matrix type, and one of the serial or shared-memory NVECTOR implementations (NVECTOR_SERIAL, NVECTOR_OPENMP, or NVECTOR_PTHREADS).
To access the sunlinsol_band module, include the header file sunlinsol/sunlinsol_band.h. We note that the sunlinsol_band module is accessible from SUNDIALS packages without separately linking to the libsundials_sunlinsolband module library.

### 8.6.1 SUNLinearSolver_Band description

This solver is constructed to perform the following operations:

- The “setup” call performs a LU factorization with partial (row) pivoting, \( PA = LU \), where \( P \) is a permutation matrix, \( L \) is a lower triangular matrix with 1’s on the diagonal, and \( U \) is an upper triangular matrix. This factorization is stored in-place on the input sunmatrix_band object \( A \), with pivoting information encoding \( P \) stored in the pivots array.

- The “solve” call performs pivoting and forward and backward substitution using the stored pivots array and the LU factors held in the sunmatrix_band object.

- \( A \) must be allocated to accommodate the increase in upper bandwidth that occurs during factorization. More precisely, if \( A \) is a band matrix with upper bandwidth \( \mu \) and lower bandwidth \( \mu_l \), then the upper triangular factor \( U \) can have upper bandwidth as big as \( \mu_{su} = \min(N-1,\mu+\mu_l) \). The lower triangular factor \( L \) has lower bandwidth \( \mu_l \).

### 8.6.2 SUNLinearSolver_Band functions

The sunlinsol_band module provides the following user-callable constructor for creating a SUNLinearSolver object.

```c
SUNLinSolBand LS = SUNLinSolBand(y, A);
```

**Description**
The function `SUNLinSolBand` creates and allocates memory for a band SUNLinearSolver object.

**Arguments**
- \( y \) (N_Vector) a template for cloning vectors needed within the solver
- \( A \) (SUNMatrix) a SUNMATRIX_BAND matrix template for cloning matrices needed within the solver

**Return value**
This returns a SUNLinearSolver object. If either \( A \) or \( y \) are incompatible then this routine will return NULL.

**Notes**
This routine will perform consistency checks to ensure that it is called with consistent NVVECTOR and SUNMATRIX implementations. These are currently limited to the SUNMATRIX_BAND matrix type and the NVVECTOR_SERIAL, NVVECTOR_OPENMP, and NVVECTOR_PTHREADS vector types. As additional compatible matrix and vector implementations are added to SUNDIALS, these will be included within this compatibility check.

Additionally, this routine will verify that the input matrix \( A \) is allocated with appropriate upper bandwidth storage for the LU factorization.

**Deprecated Name**
For backward compatibility, the wrapper function `SUNBandLinearSolver` with identical input and output arguments is also provided.

**F2003 Name**
FSUNLinSolBand

The sunlinsol_band module defines band implementations of all “direct” linear solver operations listed in Sections 8.1.1 – 8.1.3:

- SUNLinSolGetType_Band
- SUNLinSolInitialize_Band – this does nothing, since all consistency checks are performed at solver creation.
• **SUNLinSolSetup_Band** – this performs the *LU* factorization.

• **SUNLinSolSolve_Band** – this uses the *LU* factors and *pivots* array to perform the solve.

• **SUNLinSolLastFlag_Band**

• **SUNLinSolSpace_Band** – this only returns information for the storage *within* the solver object, i.e. storage for *N*, *last_flag*, and *pivots*.

• **SUNLinSolFree_Band**

All of the listed operations are callable via the FORTRAN 2003 interface module by prepending an ‘F’ to the function name.

### 8.6.3 SUNLinearSolver_Band Fortran interfaces

The SUNLINSOL_BAND module provides a FORTRAN 2003 module as well as FORTRAN 77 style interface functions for use from FORTRAN applications.

**FORTRAN 2003 interface module**

The *fsunlinsol_band_mod* FORTRAN module defines interfaces to all SUNLINSOL_BAND C functions using the intrinsic *iso_c_binding* module which provides a standardized mechanism for interoperating with C. As noted in the C function descriptions above, the interface functions are named after the corresponding C function, but with a leading ‘F’. For example, the function *SUNLinSol_Band* is interfaced as *FSUNLinSol_Band*.

The FORTRAN 2003 SUNLINSOL_BAND interface module can be accessed with the `use` statement, i.e. `use fsunlinsol_band_mod`, and linking to the library *libsundials_fsunlinsolband_mod.lib* in addition to the C library. For details on where the library and module file *fsunlinsol_band_mod.mod* are installed see Appendix A. We note that the module is accessible from the FORTRAN 2003 SUNDIALS integrators *without* separately linking to the *libsundials_fsunlinsolband_mod* library.

**FORTRAN 77 interface functions**

For solvers that include a FORTRAN 77 interface module, the SUNLINSOL_BAND module also includes a Fortran-callable function for creating a SUNLinearSolver object.

```fortran
FSUNBANDLINSOLINIT
Call                  FSUNBANDLINSOLINIT(code, ier)
Description          The function FSUNBANDLINSOLINIT can be called for Fortran programs to create a band SUNLinearSolver object.
Arguments            code (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).
Return value         ier is a return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.
Notes                This routine must be called *after* both the NVECTOR and SUNMATRIX objects have been initialized.
```

Additionally, when using ARKODE with a non-identity mass matrix, the SUNLINSOL_BAND module includes a Fortran-callable function for creating a SUNLinearSolver mass matrix solver object.
**FSUNMASSBANDLINSOLINIT**

Call | FSUNMASSBANDLINSOLINIT(ier)
--- | ---
Description | The function FSUNMASSBANDLINSOLINIT can be called for Fortran programs to create a band SUNLinearSolver object for mass matrix linear systems.
Arguments | None
Return value | ier is an int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.
Notes | This routine must be called after both the NVECTOR and SUNMATRIX mass-matrix objects have been initialized.

### 8.6.4 SUNLinearSolver_Band content

The SUNLINSOL_BAND module defines the content field of a SUNLinearSolver as the following structure:

```c
struct _SUNLinearSolverContent_Band {
  sunindextype N;
  sunindextype *pivots;
  sunindextype last_flag;
};
```

These entries of the content field contain the following information:

- **N** - size of the linear system,
- **pivots** - index array for partial pivoting in LU factorization,
- **last_flag** - last error return flag from internal function evaluations.

### 8.7 The SUNLinearSolver_LapackDense implementation

This section describes the SUNLINSOL implementation for solving dense linear systems with LAPACK. The SUNLINSOL_LAPACKDENSE module is designed to be used with the corresponding SUNMATRIX_DENSE matrix type, and one of the serial or shared-memory NVECTOR implementations (NVECTOR_SERIAL, NVECTOR_OPENMP, or NVECTOR_PTHREADS).

To access the SUNLINSOL_LAPACKDENSE module, include the header file `sunlinsol/sunlinsol_lapackdense.h`. The installed module library to link to is `libsundials_sunlinsollapackdense.lib` where `.lib` is typically `.so` for shared libraries and `.a` for static libraries.

The SUNLINSOL_LAPACKDENSE module is a SUNLINSOL wrapper for the LAPACK dense matrix factorization and solve routines, *GETRF* and *GETRS*, where * is either D or S, depending on whether SUNDIALS was configured to have realtype set to double or single, respectively (see Section 4.2). In order to use the SUNLINSOL_LAPACKDENSE module it is assumed that LAPACK has been installed on the system prior to installation of SUNDIALS, and that SUNDIALS has been configured appropriately to link with LAPACK (see Appendix A for details). We note that since there do not exist 128-bit floating-point factorization and solve routines in LAPACK, this interface cannot be compiled when using extended precision for realtype. Similarly, since there do not exist 64-bit integer LAPACK routines, the SUNLINSOL_LAPACKDENSE module also cannot be compiled when using 64-bit integers for the sunindextype.

### 8.7.1 SUNLinearSolver_LapackDense description

This solver is constructed to perform the following operations:
- The “setup” call performs a $LU$ factorization with partial (row) pivoting ($O(N^3)$ cost), $PA = LU$, where $P$ is a permutation matrix, $L$ is a lower triangular matrix with 1’s on the diagonal, and $U$ is an upper triangular matrix. This factorization is stored in-place on the input SUNMATRIX_DENSE object $A$, with pivoting information encoding $P$ stored in the pivots array.

- The “solve” call performs pivoting and forward and backward substitution using the stored pivots array and the $LU$ factors held in the SUNMATRIX_DENSE object ($O(N^2)$ cost).

### 8.7.2 SUNLinearSolver_LapackDense functions

The SUNLINSOL_LAPACKDENSE module provides the following user-callable constructor for creating a SUNLinearSolver object.

```c
SUNLinSol_LapackDense
```

**Call**

```c
LS = SUNLinSol_LapackDense(y, A);
```

**Description**
The function SUNLinSol_LapackDense creates and allocates memory for a LAPACK-based, dense SUNLinearSolver object.

**Arguments**
- $y$ ($N$ Vector): a template for cloning vectors needed within the solver
- $A$ (SUNMatrix): a SUNMATRIX_DENSE matrix template for cloning matrices needed within the solver

**Return value**
This returns a SUNLinearSolver object. If either $A$ or $y$ are incompatible then this routine will return NULL.

**Notes**
This routine will perform consistency checks to ensure that it is called with consistent NVECTOR and SUNMATRIX implementations. These are currently limited to the SUNMATRIX_DENSE matrix type and the NVECTOR_SERIAL, NVECTOR_OPENMP, and NVECTOR_PTHREADS vector types. As additional compatible matrix and vector implementations are added to SUNDIALS, these will be included within this compatibility check.

**Deprecated Name**
For backward compatibility, the wrapper function SUNLapackDense with identical input and output arguments is also provided.

The SUNLINSOL_LAPACKDENSE module defines dense implementations of all “direct” linear solver operations listed in Sections 8.1.1 – 8.1.3:

- SUNLinSolGetType_LapackDense
- SUNLinSolInitialize_LapackDense – this does nothing, since all consistency checks are performed at solver creation.
- SUNLinSolSetup_LapackDense – this calls either DGETRF or SGETRF to perform the $LU$ factorization.
- SUNLinSolSolve_LapackDense – this calls either DGETRS or SGETRS to use the $LU$ factors and pivots array to perform the solve.
- SUNLinSolLastFlag_LapackDense
- SUNLinSolSpace_LapackDense – this only returns information for the storage within the solver object, i.e. storage for $N$, last_flag, and pivots.
- SUNLinSolFree_LapackDense

### 8.7.3 SUNLinearSolver_LapackDense Fortran interfaces

For solvers that include a FORTRAN 77 interface module, the SUNLINSOL_LAPACKDENSE module also includes a Fortran-callable function for creating a SUNLinearSolver object.
Description of the SUNLinearSolver module

**FSUNLAPACKDENSEINIT**

Call: \texttt{FSUNLAPACKDENSEINIT(code, ier)}

Description: The function \texttt{FSUNLAPACKDENSEINIT} can be called for Fortran programs to create a LAPACK-based dense \texttt{SUNLinearSolver} object.

Arguments: \texttt{code} (int*) is an integer input specifying the solver id (1 for \texttt{cvode}, 2 for \texttt{ida}, 3 for \texttt{kinsol}, and 4 for \texttt{arkode}).

Return value: \texttt{ier} is a return completion flag equal to 0 for a success return and \texttt{-1} otherwise. See printed message for details in case of failure.

Notes: This routine must be called \textit{after} both the nvector and sunmatrix objects have been initialized.

Additionally, when using \texttt{arkode} with a non-identity mass matrix, the SUNLINSOL_LAPACKDENSE module includes a Fortran-callable function for creating a \texttt{SUNLinearSolver} mass matrix solver object.

**FSUNMASSLAPACKDENSEINIT**

Call: \texttt{FSUNMASSLAPACKDENSEINIT(ier)}

Description: The function \texttt{FSUNMASSLAPACKDENSEINIT} can be called for Fortran programs to create a LAPACK-based, dense \texttt{SUNLinearSolver} object for mass matrix linear systems.

Arguments: None

Return value: \texttt{ier} is an int return completion flag equal to 0 for a success return and \texttt{-1} otherwise. See printed message for details in case of failure.

Notes: This routine must be called \textit{after} both the nvector and sunmatrix mass-matrix objects have been initialized.

### 8.7.4 SUNLinearSolver_LapackDense content

The SUNLINSOL_LAPACKDENSE module defines the \textit{content} field of a \texttt{SUNLinearSolver} as the following structure:

```c
struct _SUNLinearSolverContent_Dense {
    sunindextype N;
    sunindextype *pivots;
    sunindextype last_flag;
};
```

These entries of the \textit{content} field contain the following information:

- \texttt{N} - size of the linear system,
- \texttt{pivots} - index array for partial pivoting in LU factorization,
- \texttt{last_flag} - last error return flag from internal function evaluations.

### 8.8 The SUNLinearSolver_LapackBand implementation

This section describes the SUNLINSOL implementation for solving banded linear systems with LAPACK. The SUNLINSOL_LAPACKBAND module is designed to be used with the corresponding SUNMATRIX_BAND matrix type, and one of the serial or shared-memory NVECTOR implementations (NVECTOR_SERIAL, NVECTOR_OPENMP, or NVECTOR_PTHREADS).

To access the SUNLINSOL_LAPACKBAND module, include the header file `sunlinsol/sunlinsol_lapackband.h`. The installed module library to link to is `libsundials_sunlinsollapackband.lib` where `.lib` is typically `.so` for shared libraries and `.a` for static libraries.
The SUNLINSOL_LAPACKBAND module is a SUNLINSOL wrapper for the LAPACK band matrix factorization and solve routines, *GBTRF and *GBTRS, where * is either D or S, depending on whether SUNDIALS was configured to have realtype set to double or single, respectively (see Section 4.2). In order to use the SUNLINSOL_LAPACKBAND module it is assumed that LAPACK has been installed on the system prior to installation of SUNDIALS, and that SUNDIALS has been configured appropriately to link with LAPACK (see Appendix A for details). We note that since there do not exist 128-bit floating-point factorization and solve routines in LAPACK, this interface cannot be compiled when using extended precision for realtype. Similarly, since there do not exist 64-bit integer LAPACK routines, the SUNLINSOL_LAPACKBAND module also cannot be compiled when using 64-bit integers for the sunindextype.

8.8.1 SUNLinearSolver_LapackBand description

This solver is constructed to perform the following operations:

- The “setup” call performs a LU factorization with partial (row) pivoting, \( PA = LU \), where \( P \) is a permutation matrix, \( L \) is a lower triangular matrix with 1’s on the diagonal, and \( U \) is an upper triangular matrix. This factorization is stored in-place on the input SUNMATRIX_BAND object \( A \), with pivoting information encoding \( P \) stored in the pivots array.

- The “solve” call performs pivoting and forward and backward substitution using the stored pivots array and the LU factors held in the SUNMATRIX_BAND object.

- \( A \) must be allocated to accommodate the increase in upper bandwidth that occurs during factorization. More precisely, if \( A \) is a band matrix with upper bandwidth \( mu \) and lower bandwidth \( ml \), then the upper triangular factor \( U \) can have upper bandwidth as big as \( smu = \min(N-1, mu+ml) \). The lower triangular factor \( L \) has lower bandwidth \( ml \).

8.8.2 SUNLinearSolver_LapackBand functions

The SUNLINSOL_LAPACKBAND module provides the following user-callable constructor for creating a SUNLinearSolver object.

```
SUNLinSol_LapackBand
Call LS = SUNLinSol_LapackBand(y, A);
Description The function SUNLinSol_LapackBand creates and allocates memory for a LAPACK-based, band SUNLinearSolver object.
Arguments y (N_Vector) a template for cloning vectors needed within the solver
          A (SUNMatrix) a SUNMATRIX_BAND matrix template for cloning matrices needed within the solver
Return value This returns a SUNLinearSolver object. If either A or y are incompatible then this routine will return NULL.
Notes This routine will perform consistency checks to ensure that it is called with consistent NVECTOR and SUNMATRIX implementations. These are currently limited to the SUNMATRIX_BAND matrix type and the NVECTOR_SERIAL, NVECTOR_OPENMP, and NVECTOR_PTHREADS vector types. As additional compatible matrix and vector implementations are added to SUNDIALS, these will be included within this compatibility check.
          Additionally, this routine will verify that the input matrix A is allocated with appropriate upper bandwidth storage for the LU factorization.
Deprecated Name For backward compatibility, the wrapper function SUNLapackBand with identical input and output arguments is also provided.
```
The SUNLINSOL_LAPACKBAND module defines band implementations of all “direct” linear solver operations listed in Sections 8.1.1 – 8.1.3:

- **SUNLinSolGetType** (*LapackBand*)

- **SUNLinSolInitialize** (*LapackBand*) – this does nothing, since all consistency checks are performed at solver creation.

- **SUNLinSolSetup** (*LapackBand*) – this calls either DGBTRF or SGBTRF to perform the $LU$ factorization.

- **SUNLinSolSolve** (*LapackBand*) – this calls either DGBTRS or SGBTRS to use the $LU$ factors and pivots array to perform the solve.

- **SUNLinSolLastFlag** (*LapackBand*)

- **SUNLinSolSpace** (*LapackBand*) – this only returns information for the storage within the solver object, i.e. storage for $N$, last_flag, and pivots.

- **SUNLinSolFree** (*LapackBand*)

### 8.8.3 SUNLinearSolver_LapackBand Fortran interfaces

For solvers that include a FORTRAN 77 interface module, the SUNLINSOL_LAPACKBAND module also includes a Fortran-callable function for creating a SUNLinearSolver object.

**FSUNLAPACKDENSEINIT**

*Call*  
FSUNLAPACKBANDINIT(code, ier)

*Description*  
The function FSUNLAPACKBANDINIT can be called for Fortran programs to create a LAPACK-based band SUNLinearSolver object.

*Arguments*  
code (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSSOL, and 4 for ARKODE).

*Return value*  
ier is a return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

*Notes*  
This routine must be called after both the NVECTOR and SUNMATRIX objects have been initialized.

Additionally, when using ARKODE with a non-identity mass matrix, the SUNLINSOL_LAPACKBAND module includes a Fortran-callable function for creating a SUNLinearSolver mass matrix solver object.

**FSUNMASSLAPACKBANDINIT**

*Call*  
FSUNMASSLAPACKBANDINIT(ier)

*Description*  
The function FSUNMASSLAPACKBANDINIT can be called for Fortran programs to create a LAPACK-based, band SUNLinearSolver object for mass matrix linear systems.

*Arguments*  
None

*Return value*  
ier is an int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

*Notes*  
This routine must be called after both the NVECTOR and SUNMATRIX mass-matrix objects have been initialized.
8.8.4 SUNLinearSolver_LapackBand content

The SUNLINSOL_LAPACKBAND module defines the content field of a SUNLinearSolver as the following structure:

```c
struct _SUNLinearSolverContent_Band {
    sunindextype N;
    sunindextype *pivots;
    sunindextype last_flag;
};
```

These entries of the content field contain the following information:

- **N** - size of the linear system,
- **pivots** - index array for partial pivoting in LU factorization,
- **last_flag** - last error return flag from internal function evaluations.

8.9 The SUNLinearSolver_KLU implementation

This section describes the SUNLINSOL implementation for solving sparse linear systems with KLU. The SUNLINSOL_KLU module is designed to be used with the corresponding SUNMATRIX_SPARSE matrix type, and one of the serial or shared-memory NVECTOR implementations (NVECTOR_SERIAL, NVECTOR_OPENMP, or NVECTOR_PTHREADS).

The header file to include when using this module is sunlinsol/sunlinsol_klu.h. The installed module library to link to is libsundials_sunlinsolklu.lib where.lib is typically .so for shared libraries and .a for static libraries.

The SUNLINSOL_KLU module is a SUNLINSOL wrapper for the KLU sparse matrix factorization and solver library written by Tim Davis [1, 17]. In order to use the SUNLINSOL_KLU interface to KLU, it is assumed that KLU has been installed on the system prior to installation of SUNDIALS, and that SUNDIALS has been configured appropriately to link with KLU (see Appendix A for details). Additionally, this wrapper only supports double-precision calculations, and therefore cannot be compiled if SUNDIALS is configured to have realtype set to either extended or single (see Section 4.2). Since the KLU library supports both 32-bit and 64-bit integers, this interface will be compiled for either of the available sunindextype options.

8.9.1 SUNLinearSolver_KLU description

The KLU library has a symbolic factorization routine that computes the permutation of the linear system matrix to block triangular form and the permutations that will pre-order the diagonal blocks (the only ones that need to be factored) to reduce fill-in (using AMD, COLAMD, CHOLAMD, natural, or an ordering given by the user). Of these ordering choices, the default value in the SUNLINSOL_KLU module is the COLAMD ordering.

KLU breaks the factorization into two separate parts. The first is a symbolic factorization and the second is a numeric factorization that returns the factored matrix along with final pivot information. KLU also has a refactor routine that can be called instead of the numeric factorization. This routine will reuse the pivot information. This routine also returns diagnostic information that a user can examine to determine if numerical stability is being lost and a full numerical factorization should be done instead of the refactor.

Since the linear systems that arise within the context of SUNDIALS calculations will typically have identical sparsity patterns, the SUNLINSOL_KLU module is constructed to perform the following operations:

- The first time that the “setup” routine is called, it performs the symbolic factorization, followed by an initial numerical factorization.
On subsequent calls to the “setup” routine, it calls the appropriate KLU “refactor” routine, followed by estimates of the numerical conditioning using the relevant “rcond”, and if necessary “condest”, routine(s). If these estimates of the condition number are larger than $\varepsilon^{-2/3}$ (where $\varepsilon$ is the double-precision unit roundoff), then a new factorization is performed.

- The module includes the routine SUNKLUReInit, that can be called by the user to force a full or partial refactorization at the next “setup” call.

- The “solve” call performs pivoting and forward and backward substitution using the stored KLU data structures. We note that in this solve KLU operates on the native data arrays for the right-hand side and solution vectors, without requiring costly data copies.

### 8.9.2 SUNLinearSolver_KLU functions

The SUNLINSOL_KLU module provides the following user-callable constructor for creating a SUNLinearSolver object.

```c
SUNLinSol_KLU
```

**Call**

```c
LS = SUNLinSol_KLU(y, A);
```

**Description**

The function SUNLinSol_KLU creates and allocates memory for a KLU-based SUNLinearSolver object.

**Arguments**

- `y` (N_Vector) a template for cloning vectors needed within the solver
- `A` (SUNMatrix) a SUNMATRIX_SPARSE matrix template for cloning matrices needed within the solver

**Return value**

This returns a SUNLinearSolver object. If either `A` or `y` are incompatible then this routine will return NULL.

**Notes**

This routine will perform consistency checks to ensure that it is called with consistent NVECTOR and SUNMATRIX implementations. These are currently limited to the SUNMATRIX_SPARSE matrix type (using either CSR or CSC storage formats) and the NVECTOR_SERIAL, NVECTOR_OPENMP, and NVECTOR_PTHREADS vector types. As additional compatible matrix and vector implementations are added to Sundials, these will be included within this compatibility check.

**Deprecated Name**

For backward compatibility, the wrapper function SUNKLU with identical input and output arguments is also provided.

**F2003 Name**

FSUNLinSol_KLU

The SUNLINSOL_KLU module defines implementations of all “direct” linear solver operations listed in Sections 8.1.1 – 8.1.3:

- **SUNLinSolGetType_KLU**
- **SUNLinSolInitialize_KLU** – this sets the first_factorize flag to 1, forcing both symbolic and numerical factorizations on the subsequent “setup” call.
- **SUNLinSolSetup_KLU** – this performs either a LU factorization or refactorization of the input matrix.
- **SUNLinSolSolve_KLU** – this calls the appropriate KLU solve routine to utilize the LU factors to solve the linear system.
- **SUNLinSolLastFlag_KLU**
- **SUNLinSolSpace_KLU** – this only returns information for the storage within the solver interface, i.e. storage for the integers last_flag and first_factorize. For additional space requirements, see the KLU documentation.
8.9 The SUNLinearSolver_KLU implementation

- SUNLinSolFree_KLU

All of the listed operations are callable via the FORTRAN 2003 interface module by prepending an ‘F’ to the function name.

The SUNLINSOL_KLU module also defines the following additional user-callable functions.

### SUNLinSol_KLUREInit

**Call**
```
retval = SUNLinSol_KLUREInit(LS, A, nnz, reinit_type);
```

**Description**
The function SUNLinSol_KLUREInit reinitializes memory and flags for a new factorization (symbolic and numeric) to be conducted at the next solver setup call. This routine is useful in the cases where the number of nonzeroes has changed or if the structure of the linear system has changed which would require a new symbolic (and numeric factorization).

**Arguments**
- **LS** (SUNLinearSolver) a template for cloning vectors needed within the solver
- **A** (SUNMatrix) a SUNMATRIX_SPARSE matrix template for cloning matrices needed within the solver
- **nnz** (sunindextype) the new number of nonzeros in the matrix
- **reinit_type** (int) flag governing the level of reinitialization. The allowed values are:
  - **SUNKLU_REINIT_FULL** – The Jacobian matrix will be destroyed and a new one will be allocated based on the nnz value passed to this call. New symbolic and numeric factorizations will be completed at the next solver setup.
  - **SUNKLU_REINIT_PARTIAL** – Only symbolic and numeric factorizations will be completed. It is assumed that the Jacobian size has not exceeded the size of nnz given in the sparse matrix provided to the original constructor routine (or the previous SUNLinSol_KLUREInit call).

**Return value**
The return values from this function are SUNLS_MEM_NULL (either S or A are NULL), SUNLS_ILL_INPUT (A does not have type SUNMATRIX_SPARSE or reinit_type is invalid), SUNLS_MEM_FAIL (reallocation of the sparse matrix failed) or SUNLS_SUCCESS.

**Notes**
This routine will perform consistency checks to ensure that it is called with consistent NVECTOR and SUNMATRIX implementations. These are currently limited to the SUNMATRIX_SPARSE matrix type (using either CSR or CSC storage formats) and the NVECTOR_SERIAL, NVECTOR_OPENMP, and NVECTOR_PTHREADS vector types. As additional compatible matrix and vector implementations are added to Sundials, these will be included within this compatibility check.

This routine assumes no other changes to solver use are necessary.

**Deprecated Name**
For backward compatibility, the wrapper function SUNKLUReInit with identical input and output arguments is also provided.

**F2003 Name**
FSUNLinSol_KLUREInit

### SUNLinSol_KLUSetOrdering

**Call**
```
retval = SUNLinSol_KLUSetOrdering(LS, ordering);
```

**Description**
This function sets the ordering used by KLU for reducing fill in the linear solve.

**Arguments**
- **LS** (SUNLinearSolver) the SUNLINSOL_KLU object
- **ordering** (int) flag indicating the reordering algorithm to use, the options are:
  - 0 AMD,
1 COLAMD, and 2 the natural ordering. The default is 1 for COLAMD.

Return value The return values from this function are SUNLS_MEM_NULL (S is NULL), SUNLS_ILL_INPUT (invalid ordering choice), or SUNLS_SUCCESS.

 Deprecated Name For backward compatibility, the wrapper function SUNKLUSetOrdering with identical input and output arguments is also provided.

 F2003 Name FSUNLinSol_KLUSetOrdering

 SUNLinSol_KLUGetSymbolic

 Call symbolic = SUNLinSol_KLUGetSymbolic(LS);

 Description This function returns a pointer to the KLU symbolic factorization stored in the SUNLIN-SOL_KLU content structure.

 Arguments LS (SUNLinearSolver) the SUNLINSOL_KLU object

 Return value The return type from this function is sun_klu_symbolic.

 Notes When SUNDIALS is compiled with 32-bit indices (SUNDIALS_INDEX_SIZE=32), sun_klu_symbolic is mapped to the KLU type klu_symbolic; when SUNDIALS is compiled with 64-bit indices (SUNDIALS_INDEX_SIZE=64) this is mapped to the KLU type klu_l_symbolic.

 SUNLinSol_KLUGetNumeric

 Call numeric = SUNLinSol_KLUGetNumeric(LS);

 Description This function returns a pointer to the KLU numeric factorization stored in the SUNLIN-SOL_KLU content structure.

 Arguments LS (SUNLinearSolver) the SUNLINSOL_KLU object

 Return value The return type from this function is sun_klu_numeric.

 Notes When SUNDIALS is compiled with 32-bit indices (SUNDIALS_INDEX_SIZE=32), sun_klu_numeric is mapped to the KLU type klu_numeric; when SUNDIALS is compiled with 64-bit indices (SUNDIALS_INDEX_SIZE=64), this is mapped to the KLU type klu_l_numeric.

 SUNLinSol_KLUGetCommon

 Call common = SUNLinSol_KLUGetCommon(LS);

 Description This function returns a pointer to the KLU common structure stored within in the SUNLINSOL_KLU content structure.

 Arguments LS (SUNLinearSolver) the SUNLINSOL_KLU object

 Return value The return type from this function is sun_klu_common.

 Notes When SUNDIALS is compiled with 32-bit indices (SUNDIALS_INDEX_SIZE=32), sun_klu_common is mapped to the KLU type klu_common; when SUNDIALS is compiled with 64-bit indices (SUNDIALS_INDEX_SIZE=64), this is mapped to the KLU type klu_l_common.

 8.9.3 SUNLinearSolver_KLU Fortran interfaces

 The SUNLINSOL_KLU module provides a FORTRAN 2003 module as well as FORTRAN 77 style interface functions for use from FORTRAN applications.
8.9 The SU NLinSol_ KLU implementation

FORTRAN 2003 interface module

The fsunlinsol_klu_mod FORTRAN module defines interfaces to all SUNLINSOL_KLU C functions using the intrinsic iso_c_binding module which provides a standardized mechanism for interoperating with C. As noted in the C function descriptions above, the interface functions are named after the corresponding C function, but with a leading ‘F’. For example, the function SUNLinSol_klu is interfaced as FSUNLinSol_klu.

The FORTRAN 2003 SUNLINSOL_KLU interface module can be accessed with the use statement, i.e. use fsunlinsol_klu_mod, and linking to the library libsundials_fsunlinsolklu_mod.lib in addition to the C library. For details on where the library and module file fsunlinsol_klu_mod.mod are installed see Appendix A.

FORTRAN 77 interface functions

For solvers that include a FORTRAN 77 interface module, the SUNLINSOL_KLU module also includes a Fortran-callable function for creating a SUNLinearSolver object.

FSUNKLUINIT

Call
FSUNKLUINIT(code, ier)

Description The function FSUNKLUINIT can be called for Fortran programs to create a SUNLINSOL_KLU object.

Arguments code (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).

Return value ier is a return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes This routine must be called after both the NVVECTOR and SUNMATRIX objects have been initialized.

Additionally, when using ARKODE with a non-identity mass matrix, the SUNLINSOL_KLU module includes a Fortran-callable function for creating a SUNLinearSolver mass matrix solver object.

FSUNMASSKLUINIT

Call
FSUNMASSKLUINIT(ier)

Description The function FSUNMASSKLUINIT can be called for Fortran programs to create a KLU-based SUNLinearSolver object for mass matrix linear systems.

Arguments None

Return value ier is an int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes This routine must be called after both the NVVECTOR and SUNMATRIX mass-matrix objects have been initialized.

The SUNLinSol_KLUReInit and SUNLinSol_KLUSetOrdering routines also support FORTRAN interfaces for the system and mass matrix solvers:

FSUNKLUREINIT

Call
FSUNKLUREINIT(code, nnz, reinit_type, ier)

Description The function FSUNKLUREINIT can be called for Fortran programs to re-initialize a SUNLINSOL_KLU object.

Arguments code (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).

nnz (sunindextype*) the new number of nonzeros in the matrix
reinit_type (int*) flag governing the level of reinitialization. The allowed values are:
1 – The Jacobian matrix will be destroyed and a new one will be allocated based on the nnz value passed to this call. New symbolic and numeric factorizations will be completed at the next solver setup.
2 – Only symbolic and numeric factorizations will be completed. It is assumed that the Jacobian size has not exceeded the size of nnz given in the sparse matrix provided to the original constructor routine (or the previous SUNLinSol_KLUReInit call).

Return value ier is a int return completion flag equal to 0 for a success return and −1 otherwise. See printed message for details in case of failure.

Notes See SUNLinSol_KLUReInit for complete further documentation of this routine.

FSUNMASSKLUReInit
Call FSUNMASSKLUReInit(nnz, reinit_type, ier)
Description The function FSUNMASSKLUReInit can be called for Fortran programs to re-initialize a sunlinsol_klu object for mass matrix linear systems.
Arguments The arguments are identical to FSUNKLUReInit above, except that code is not needed since mass matrix linear systems only arise in ARKODE.
Return value ier is a int return completion flag equal to 0 for a success return and −1 otherwise. See printed message for details in case of failure.
Notes See SUNLinSol_KLUReInit for complete further documentation of this routine.

FSUNKLUSetOrdering
Call FSUNKLUSetOrdering(code, ordering, ier)
Description The function FSUNKLUSetOrdering can be called for Fortran programs to change the reordering algorithm used by KLU.
Arguments code (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).
ordering (int*) flag indication the reordering algorithm to use. Options include:
0 AMD,
1 COLAMD, and
2 the natural ordering.
The default is 1 for COLAMD.
Return value ier is a int return completion flag equal to 0 for a success return and −1 otherwise. See printed message for details in case of failure.
Notes See SUNLinSol_KLUSetOrdering for complete further documentation of this routine.

FSUNMASSKLUSetOrdering
Call FSUNMASSKLUSetOrdering(ier)
Description The function FSUNMASSKLUSetOrdering can be called for Fortran programs to change the reordering algorithm used by KLU for mass matrix linear systems.
Arguments The arguments are identical to FSUNKLUSetOrdering above, except that code is not needed since mass matrix linear systems only arise in ARKODE.
Return value ier is a int return completion flag equal to 0 for a success return and −1 otherwise. See printed message for details in case of failure.
Notes See SUNLinSol_KLUSetOrdering for complete further documentation of this routine.
8.9.4 SUNLinearSolver_KLU content

The SUNLINSOL_KLU module defines the content field of a SUNLinearSolver as the following structure:

```c
struct _SUNLinearSolverContent_KLU {
    int last_flag;
    int first_factorize;
    sun_klu_symbolic *symbolic;
    sun_klu_numeric *numeric;
    sun_klu_common common;
    sunindextype (*klu_solver)(sun_klu_symbolic*, sun_klu_numeric*,
        sunindextype, sunindextype,
        double*, sun_klu_common*);
};
```

These entries of the content field contain the following information:

- **last_flag** - last error return flag from internal function evaluations,
- **first_factorize** - flag indicating whether the factorization has ever been performed,
- **symbolic** - KLU storage structure for symbolic factorization components, with underlying type `klu_symbolic` or `klu_l_symbolic`, depending on whether SUNDIALS was installed with 32-bit versus 64-bit indices, respectively,
- **numeric** - KLU storage structure for numeric factorization components, with underlying type `klu_numeric` or `klu_l_numeric`, depending on whether SUNDIALS was installed with 32-bit versus 64-bit indices, respectively.
- **common** - storage structure for common KLU solver components, with underlying type `klu_common` or `klu_l_common`, depending on whether SUNDIALS was installed with 32-bit versus 64-bit indices, respectively,
- **klu_solver** - pointer to the appropriate KLU solver function (depending on whether it is using a CSR or CSC sparse matrix, and on whether SUNDIALS was installed with 32-bit or 64-bit indices).

8.10 The SUNLinearSolver_SuperLUDIST implementation

The SuperLU_DIST implementation of the SUNLINSOL module provided with SUNDIALS, SUNLINSOL_SUPERLUDIST, is designed to be used with the corresponding SUNMATRIX_SLUNRLOC matrix type, and one of the serial, threaded or parallel NVECTOR implementations (NVECTOR_SERIAL, NVECTOR_OPENMP, NVECTOR_PTHREADS, NVECTOR_PARALLEL, or NVECTOR_PARHYP).

The header file to include when using this module is `sunlinsol/sunlinsol_superludist.h`. The installed module library to link to is `libsundials_sunlinsolsuperludist.lib` where `.lib` is typically `.so` for shared libraries and `.a` for static libraries.

8.10.1 SUNLinearSolver_SuperLUDIST description

The SUNLINSOL_SUPERLUDIST module is a SUNLINSOL adapter for the SuperLU_DIST sparse matrix factorization and solver library written by X. Sherry Li [3, 22, 34, 35]. The package uses a SPMD parallel programming model and multithreading to enhance efficiency in distributed-memory parallel environments with multicore nodes and possibly GPU accelerators. It uses MPI for communication, OpenMP for threading, and CUDA for GPU support. In order to use the SUNLINSOL_SUPERLUDIST interface to SuperLU_DIST, it is assumed that SuperLU_DIST has been installed on the system prior to installation of SUNDIALS, and that SUNDIALS has been configured appropriately to link with SuperLU_DIST (see Appendix A for details). Additionally, the adapter only supports double-precision calculations, and therefore cannot be compiled if SUNDIALS is configured to use single or extended precision. Moreover, since the SuperLU_DIST library may be installed to support either 32-bit or
64-bit integers, it is assumed that the SuperLU_DIST library is installed using the same integer size as SUNDIALS.

The SuperLU_DIST library provides many options to control how a linear system will be solved. These options may be set by a user on an instance of the superlu_dist_options_t struct, and then it may be provided as an argument to the SUNLINSOL_SUPERLUDIST constructor. The SUNLINSOL_SUPERLUDIST module will respect all options set except for Fact – this option is necessarily modified by the SUNLINSOL_SUPERLUDIST module in the setup and solve routines.

Since the linear systems that arise within the context of SUNDIALS calculations will typically have identical sparsity patterns, the SUNLINSOL_SUPERLUDIST module is constructed to perform the following operations:

- The first time that the “setup” routine is called, it sets the SuperLU_DIST option Fact to DOFACT so that a subsequent call to the “solve” routine will perform a symbolic factorization, followed by an initial numerical factorization before continuing to solve the system.

- On subsequent calls to the “setup” routine, it sets the SuperLU_DIST option Fact to SamePattern so that a subsequent call to “solve” will perform factorization assuming the same sparsity pattern as prior, i.e. it will reuse the column permutation vector.

- If “setup” is called prior to the “solve” routine, then the “solve” routine will perform a symbolic factorization, followed by an initial numerical factorization before continuing to the sparse triangular solves, and, potentially, iterative refinement. If “setup” is not called prior, “solve” will skip to the triangular solve step. We note that in this solve SuperLU_DIST operates on the native data arrays for the right-hand side and solution vectors, without requiring costly data copies.

### 8.10.2 SUNLinearSolver_SuperLUDIST functions

The SUNLINSOL_SUPERLUDIST module defines implementations of all “direct” linear solver operations listed in Sections 8.1.1-8.1.3:

- SUNLinSolGetType_SuperLUDIST

- SUNLinSolInitialize_SuperLUDIST – this sets the first_factorize flag to 1 and resets the internal SuperLU_DIST statistics variables.

- SUNLinSolSetup_SuperLUDIST – this sets the appropriate SuperLU_DIST options so that a subsequent solve will perform a symbolic and numerical factorization before proceeding with the triangular solves

- SUNLinSolSolve_SuperLUDIST – this calls the SuperLU_DIST solve routine to perform factorization (if the setup routine was called prior) and then use the LU factors to solve the linear system.

- SUNLinSolLastFlag_SuperLUDIST

- SUNLinSolSpace_SuperLUDIST – this only returns information for the storage within the solver interface, i.e. storage for the integers last_flag and first_factorize. For additional space requirements, see the SuperLU_DIST documentation.

- SUNLinSolFree_SuperLUDIST

In addition, the module SUNLINSOL_SUPERLUDIST provides the following user-callable routines:
Call:  
\[
\text{LS} = \text{SUNLinSol\_SuperLUDIST}(y, A, \text{grid}, \text{lu}, \text{scaleperm}, \text{solve}, \text{stat}, \text{options});
\]

Description:  
The function \text{SUNLinSol\_SuperLUDIST} creates and allocates memory for a \text{SUNLinearSolver} object.

Arguments:  
y \quad (\text{N\_Vector}) a template for cloning vectors needed within the solver
A \quad (\text{SUNMatrix}) a \text{SUNMatrix\_SLUNRLOC} matrix template for cloning matrices needed within the solver
\text{grid} \quad (\text{gridinfo\_t*})
\text{lu} \quad (\text{LUstruct\_t*})
\text{scaleperm} \quad (\text{ScalePermstruct\_t*})
\text{solve} \quad (\text{SOLVEstruct\_t*})
\text{stat} \quad (\text{SuperLUStat\_t*})
\text{options} \quad (\text{superlu\_dist\_options\_t*})

Return value:  
This returns a \text{SUNLinearSolver} object. If either \text{A} or \text{y} are incompatible then this routine will return NULL.

Notes:  
This routine analyzes the input matrix and vector to determine the linear system size and to assess compatibility with the SuperLU DIST library.

This routine will perform consistency checks to ensure that it is called with consistent \text{NVECTOR} and \text{SUNMATRIX} implementations. These are currently limited to the \text{SUNMATRIX\_SLUNRLOC} matrix type and the \text{NVECTOR\_SERIAL}, \text{NVECTOR\_PARALLEL}, \text{NVECTOR\_PARHYMP}, \text{NVECTOR\_OPENMP}, and \text{NVECTOR\_PTHREADS} vector types. As additional compatible matrix and vector implementations are added to SUNDIALS, these will be included within this compatibility check.

The \text{grid}, \text{lu}, \text{scaleperm}, \text{solve}, and \text{options} arguments are not checked and are passed directly to SuperLU DIST routines.

Some struct members of the \text{options} argument are modified internally by the \text{SUNLinearSolver\_SuperLUDIST} solver. Specifically the member \text{Fact}, is modified in the setup and solve routines.

Call:  
\[
\text{realtype} \ berr = \text{SUNLinSol\_SuperLUDIST\_GetBerr}(\text{LS});
\]

Description:  
The function \text{SUNLinSol\_SuperLUDIST\_GetBerr} returns the componentwise relative backward error of the computed solution.

Arguments:  
\text{LS} \quad (\text{SUNLinearSolver}) the \text{SUNLinearSolver\_SuperLUDIST} object

Return value:  
\text{realtype}

Notes

Call:  
\[
\text{gridinfo\_t*} \ \text{grid} = \text{SUNLinSol\_SuperLUDIST\_GetGridinfo}(\text{LS});
\]

Description:  
The function \text{SUNLinSol\_SuperLUDIST\_GetGridinfo} returns the SuperLU DIST structure that contains the 2D process grid.

Arguments:  
\text{LS} \quad (\text{SUNLinearSolver}) the \text{SUNLinearSolver\_SuperLUDIST} object

Return value:  
\text{gridinfo\_t*}

Notes
Description of the SUNLinearSolver module

SUNLinSol_SuperLUDIST_GetLUstruct

Call  

\[ \text{LUstruct}_t\ast lu = \text{SUNLinSol\_SuperLUDIST\_GetLUstruct}(\text{LS}); \]

Description  
The function SUNLinSol_SuperLUDIST_GetLUstruct returns the SuperLU_DIST structure that contains the distributed \( L \) and \( U \) factors.

Arguments  
\( \text{LS} \) (SUNLinearSolver) the SUNLINSOL\_SUPERLUDIST object

Return value  
\( \text{LUstruct}_t\ast \)

Notes

SUNLinSol_SuperLUDIST_GetSuperLUOptions

Call  

\[ \text{superlu\_dist\_options}_t\ast opts = \text{SUNLinSol\_SuperLUDIST\_GetSuperLUOptions}(\text{LS}); \]

Description  
The function SUNLinSol_SuperLUDIST_GetSuperLUOptions returns the SuperLU_DIST structure that contains the options which control how the linear system is factorized and solved.

Arguments  
\( \text{LS} \) (SUNLinearSolver) the SUNLINSOL\_SUPERLUDIST object

Return value  
\( \text{superlu\_dist\_options}_t\ast \)

Notes

SUNLinSol_SuperLUDIST_GetScalePermstruct

Call  

\[ \text{ScalePermstruct}_t\ast sp = \text{SUNLinSol\_SuperLUDIST\_GetScalePermstruct}(\text{LS}); \]

Description  
The function SUNLinSol_SuperLUDIST_GetScalePermstruct returns the SuperLU_DIST structure that contains the vectors that describe the transformations done to the matrix, \( A \).

Arguments  
\( \text{LS} \) (SUNLinearSolver) the SUNLINSOL\_SUPERLUDIST object

Return value  
\( \text{ScalePermstruct}_t\ast \)

Notes

SUNLinSol_SuperLUDIST_GetSOLVEstruct

Call  

\[ \text{SOLVEstruct}_t\ast solve = \text{SUNLinSol\_SuperLUDIST\_GetSOLVEstruct}(\text{LS}); \]

Description  
The function SUNLinSol_SuperLUDIST_GetSOLVEstruct returns the SuperLU_DIST structure that contains information for communication during the solution phase.

Arguments  
\( \text{LS} \) (SUNLinearSolver) the SUNLINSOL\_SUPERLUDIST object

Return value  
\( \text{SOLVEstruct}_t\ast \)

Notes

SUNLinSol_SuperLUDIST_GetSuperLUStat

Call  

\[ \text{SuperLUStat}_t\ast stat = \text{SUNLinSol\_SuperLUDIST\_GetSuperLUStat}(\text{LS}); \]

Description  
The function SUNLinSol_SuperLUDIST_GetSuperLUStat returns the SuperLU_DIST structure that stores information about runtime and flop count.

Arguments  
\( \text{LS} \) (SUNLinearSolver) the SUNLINSOL\_SUPERLUDIST object

Return value  
\( \text{SuperLUStat}_t\ast \)

Notes
8.10.3 SUNLinearSolver_SuperLUDIST content

The SUNLINSOLSUPERLUDIST module defines the content field of a SUNLinearSolver to be the following structure:

```c
struct _SUNLinearSolverContent_SuperLUDIST {
    boolean type first_factorize;
    int last_flag;
    realtype berr;
    gridinfo_t *grid;
    LUstruct_t *lu;
    superlu_dist_options_t *options;
    ScalePermstruct_t *scaleperm;
    SOLVEstruct_t *solve;
    SuperLUSStat_t *stat;
    sunindextype N;
};
```

These entries of the content field contain the following information:

- **first_factorize** - flag indicating whether the factorization has ever been performed,
- **last_flag** - last error return flag from calls to internal routines,
- **berr** - the componentwise relative backward error of the computed solution,
- **grid** - pointer to the SuperLU_DIST structure that stores the 2D process grid,
- **lu** - pointer to the SuperLU_DIST structure that stores the distributed $L$ and $U$ factors,
- **options** - pointer to SuperLU_DIST options structure,
- **scaleperm** - pointer to the SuperLU_DIST structure that stores vectors describing the transformations done to the matrix, $A$,
- **solve** - pointer to the SuperLU_DIST solve structure,
- **stat** - pointer to the SuperLU_DIST structure that stores information about runtime and flop count,
- **N** - the number of equations in the system

8.11 The SUNLinearSolver_SuperLUMT implementation

This section describes the SUNLINSOL implementation for solving sparse linear systems with SuperLU_MT. The SUPERLUMT module is designed to be used with the corresponding SUNMATRIX_SPARSE matrix type, and one of the serial or shared-memory NVECTOR implementations (NVECTOR_SERIAL, NVECTOR_OPENMP, or NVECTOR_PTHREADS). While these are compatible, it is not recommended to use a threaded vector module with SUNLINSOL_SUPERLUMT unless it is the NVECTOR_OPENMP module and the SUPERLUMT library has also been compiled with OpenMP.

The header file to include when using this module is sunlinsol/sunlinsol_superlumt.h. The installed module library to link to is libsundials_sunlinsolsuperlumt.lib where .lib is typically .so for shared libraries and .a for static libraries.

The SUNLINSOL_SUPERLUMT module is a SUNLINSOL wrapper for the SUPERLUMT sparse matrix factorization and solver library written by X. Sherry Li [4, 33, 19]. The package performs matrix factorization using threads to enhance efficiency in shared memory parallel environments. It should be noted that threads are only used in the factorization step. In order to use the SUNLINSOL_SUPERLUMT interface to SUPERLUMT, it is assumed that SUPERLUMT has been installed on the system prior to installation of SUNDIALS, and that SUNDIALS has been configured appropriately to link with SUPERLUMT.
(see Appendix A for details). Additionally, this wrapper only supports single- and double-precision calculations, and therefore cannot be compiled if SUNDIALS is configured to have realtype set to extended (see Section 4.2). Moreover, since the SUPERLUMT library may be installed to support either 32-bit or 64-bit integers, it is assumed that the SUPERLUMT library is installed using the same integer precision as the SUNDIALS sunindextype option.

8.11.1 SUNLinearSolver_SuperLUMT description

The SUPERLUMT library has a symbolic factorization routine that computes the permutation of the linear system matrix to reduce fill-in on subsequent LU factorizations (using COLAMD, minimal degree ordering on $A^T \cdot A$, minimal degree ordering on $A^T + A$, or natural ordering). Of these ordering choices, the default value in the SUNLINSOL_SUPERLUMT module is the COLAMD ordering.

Since the linear systems that arise within the context of SUNDIALS calculations will typically have identical sparsity patterns, the SUNLINSOL_SUPERLUMT module is constructed to perform the following operations:

- The first time that the “setup” routine is called, it performs the symbolic factorization, followed by an initial numerical factorization.
- On subsequent calls to the “setup” routine, it skips the symbolic factorization, and only refactors the input matrix.
- The “solve” call performs pivoting and forward and backward substitution using the stored SUPERLUMT data structures. We note that in this solve SUPERLUMT operates on the native data arrays for the right-hand side and solution vectors, without requiring costly data copies.

8.11.2 SUNLinearSolver_SuperLUMT functions

The module SUNLINSOL_SUPERLUMT provides the following user-callable constructor for creating a SUNLinearSolver object.

```
SUNLinSol_SuperLUMT
Call LS = SUNLinSol_SuperLUMT(y, A, num_threads);
Description The function SUNLinSol_SuperLUMT creates and allocates memory for a SuperLU_MT-based SUNLinearSolver object.
Arguments y (N_Vector) a template for cloning vectors needed within the solver
A (SUNMatrix) a SUNMATRIX_SPARSE matrix template for cloning matrices needed within the solver
num_threads (int) desired number of threads (OpenMP or Pthreads, depending on how SUPERLUMT was installed) to use during the factorization steps
Return value This returns a SUNLinearSolver object. If either A or y are incompatible then this routine will return NULL.
Notes This routine analyzes the input matrix and vector to determine the linear system size and to assess compatibility with the SUPERLUMT library.
This routine will perform consistency checks to ensure that it is called with consistent NVECTOR and SUNMATRIX implementations. These are currently limited to the SUNMATRIX_SPARSE matrix type (using either CSR or CSC storage formats) and the NVECTOR_SERIAL, NVECTOR_OPENMP, and NVECTOR_PTHREADS vector types. As additional compatible matrix and vector implementations are added to SUNDIALS, these will be included within this compatibility check.
The num_threads argument is not checked and is passed directly to SUPERLUMT routines.
```
8.11 The SUNLinearSolver_SuperLUMT implementation

Deprecated Name For backward compatibility, the wrapper function SUNSuperLUMT with identical input and output arguments is also provided.

The SUNLINSOL SUPERLUMT module defines implementations of all “direct” linear solver operations listed in Sections 8.1.1 – 8.1.3:

- SUNLinSolGetType_SuperLUMT
- SUNLinSolInitialize_SuperLUMT – this sets the first_factorize flag to 1 and resets the internal SUPERLUMT statistics variables.
- SUNLinSolSetup_SuperLUMT – this performs either a LU factorization or refactorization of the input matrix.
- SUNLinSolSolve_SuperLUMT – this calls the appropriate SUPERLUMT solve routine to utilize the LU factors to solve the linear system.
- SUNLinSolLastFlag_SuperLUMT
- SUNLinSolSpace_SuperLUMT – this only returns information for the storage within the solver interface, i.e. storage for the integers last_flag and first_factorize. For additional space requirements, see the SUPERLUMT documentation.
- SUNLinSolFree_SuperLUMT

The SUNLINSOL SUPERLUMT module also defines the following additional user-callable function.

```c
SUNLinSol_SuperLUMTSetOrdering
```

Call `retval = SUNLinSol_SuperLUMTSetOrdering(LS, ordering);`

Description This function sets the ordering used by SUPERLUMT for reducing fill in the linear solve.

Arguments
- LS (SUNLinearSolver) the SUNLINSOL SUPERLUMT object
- ordering (int) a flag indicating the ordering algorithm to use, the options are:
  0 natural ordering
  1 minimal degree ordering on \( A^T A \)
  2 minimal degree ordering on \( A^T + A \)
  3 COLAMD ordering for unsymmetric matrices

The default is 3 for COLAMD.

Return value The return values from this function are SUNLS_MEM_NULL (S is NULL), SUNLS_ILL_INPUT (invalid ordering choice), or SUNLS_SUCCESS.

Deprecated Name For backward compatibility, the wrapper function SUNSuperLUMTSetOrdering with identical input and output arguments is also provided.

8.11.3 SUNLinearSolver_SuperLUMT Fortran interfaces

For solvers that include a Fortran interface module, the SUNLINSOL SUPERLUMT module also includes a Fortran-callable function for creating a SUNLinearSolver object.

```fortran
FSUNSUPERLUMTINIT
```

Call `FSUNSUPERLUMTINIT(code, num_threads, ier)`

Description The function FSUNSUPERLUMTINIT can be called for Fortran programs to create a SUNLINSOL_KLU object.

Arguments
- code (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).
num_threads (int*) desired number of threads (OpenMP or Pthreads, depending on how SUPERLUMT was installed) to use during the factorization steps

Return value ier is a return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes This routine must be called after both the NVECTOR and SUNMATRIX objects have been initialized.

Additionally, when using ARKODE with a non-identity mass matrix, the SUNLINSOL_SUPERLUMT module includes a Fortran-callable function for creating a SUNLinearSolver mass matrix solver object.

FSUNMASSUPERLUMTINIT

Call FSUNMASSUPERLUMTINIT(num_threads, ier)

Description The function FSUNMASSUPERLUMTINIT can be called for Fortran programs to create a SuperLU_MT-based SUNLinearSolver object for mass matrix linear systems.

Arguments num_threads (int*) desired number of threads (OpenMP or Pthreads, depending on how SUPERLUMT was installed) to use during the factorization steps.

Return value ier is an int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes This routine must be called after both the NVECTOR and SUNMATRIX mass-matrix objects have been initialized.

The SUNLinSol_SuperLUMTSetOrdering routine also supports Fortran interfaces for the system and mass matrix solvers:

FSUNSUPERLUMTSETORDERING

Call FSUNSUPERLUMTSETORDERING(code, ordering, ier)

Description The function FSUNSUPERLUMTSETORDERING can be called for Fortran programs to update the ordering algorithm in a SUNLINSOL_SUPERLUMT object.

Arguments code (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).

ordering (int*) a flag indicating the ordering algorithm, options are:

0 natural ordering
1 minimal degree ordering on $A^T A$
2 minimal degree ordering on $A^T + A$
3 COLAMD ordering for unsymmetric matrices

The default is 3 for COLAMD.

Return value ier is an int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes See SUNLinSol_SuperLUMTSetOrdering for complete further documentation of this routine.

FSUNMASSUPERLUMTSETORDERING

Call FSUNMASSUPERLUMTSETORDERING(ordering, ier)

Description The function FSUNMASSUPERLUMTSETORDERING can be called for Fortran programs to update the ordering algorithm in a SUNLINSOL_SUPERLUMT object for mass matrix linear systems.

Arguments ordering (int*) a flag indicating the ordering algorithm, options are:

0 natural ordering
8.12 The SUNLinearSolver_cuSolverSp_batchQR implementation

1 minimal degree ordering on \(A^TA\)
2 minimal degree ordering on \(A^T + A\)
3 COLAMD ordering for unsymmetric matrices

The default is 3 for COLAMD.

Return value \(\text{ier}\) is a \(\text{int}\) return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes See SUNLinSol_SuperLUMTSetOrdering for complete further documentation of this routine.

8.11.4 SUNLinearSolver_SuperLUMT content

The SUNLINSOL_SUPERLUMT module defines the content field of a SUNLinearSolver as the following structure:

```c
struct _SUNLinearSolverContent_SuperLUMT {
    int last_flag;
    int first_factorize;
    Gstat_t *Gstat;
    sunindextype *perm_r, *perm_c;
    sunindextype N;
    int num_threads;
    realtype diag_pivot_thresh;
    int ordering;
    superlumt_options_t *options;
};
```

These entries of the content field contain the following information:

- last_flag - last error return flag from internal function evaluations,
- first_factorize - flag indicating whether the factorization has ever been performed,
- A, AC, L, U, B - SuperMatrix pointers used in solve,
- Gstat - GStat_t object used in solve,
- perm_r, perm_c - permutation arrays used in solve,
- N - size of the linear system,
- num_threads - number of OpenMP/Pthreads threads to use,
- diag_pivot_thresh - threshold on diagonal pivoting,
- ordering - flag for which reordering algorithm to use,
- options - pointer to SUPERLUMT options structure.

8.12 The SUNLinearSolver_cuSolverSp_batchQR implementation

The SUNLinearSolver_cuSolverSp_batchQR implementation of the SUNLINSOL API is designed to be used with the SUNMATRIX_SPARSE matrix type, and the SUNVECTOR_CUDA vector type with managed memory. The header file to include when using this module is sunlinsol/sunlinsol_cusolversp_batchqr.h. The installed library to link to is libsundials_sunlinsol_cusolversp_batchqr.lib where .lib is typically .so for shared libraries and .a for static libraries.

The SUNLinearSolver_cuSolverSp_batchQR module is experimental and subject to change.
8.12.1 SUNLinearSolver_cuSolverSp_batchQR description

The SUNLinearSolver_cuSolverSp_batchQR implementation provides an interface to the batched sparse QR factorization method provided by the NVIDIA cuSOLVER library [2]. The module is designed for solving block diagonal linear systems of the form

\[
A = \begin{bmatrix}
A_1 & 0 & \cdots & 0 \\
0 & A_2 & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & A_n
\end{bmatrix}
\]

where all block matrices \( A_j \) share the same sparsity pattern. The matrix must be in the CSR storage format. For further details about the method itself, review the NVIDIA documentation.

8.12.2 SUNLinearSolver_cuSolverSp_batchQR functions

The SUNLinearSolver_cuSolverSp_batchQR module defines implementations of all “direct” linear solver operations listed in Sections 8.1.1-8.1.3:

- SUNLinSolGetType_cuSolverSp_batchQR
- SUNLinSolInitialize_cuSolverSp_batchQR – this sets the first_factorize flag to 1
- SUNLinSolSetup_cuSolverSp_batchQR – this always copies the relevant SUNMATRIX_SPARSE data to the GPU; if this is the first setup it will perform symbolic analysis on the system
- SUNLinSolSolve_cuSolverSp_batchQR – this calls the cusolverSpXcsrqrsvBatched routine to perform factorization
- SUNLinSolLastFlag_cuSolverSp_batchQR
- SUNLinSolFree_cuSolverSp_batchQR

In addition, the module provides the following user-callable routines:

```c
SUNLinSol_cuSolverSp_batchQR
```

Call

```c
LS = SUNLinSol_cuSolverSp_batchQR(y, A, nsubsys, subsys_size, subsys_nnz);
```

Description

The function SUNLinSol_cuSolverSp_batchQR creates and allocates memory for a SUNLINSOL object.

Arguments

- \( y \) (N_Vector) a NVECTOR_CUDA vector for checking compatibility with the solver
- \( A \) (SUNMatrix) a SUNMATRIX_SPARSE matrix for checking compatibility with the solver
- \( nsubsys \) (int) the number of subsystems, i.e., the number of blocks in the matrix
- \( subsys_size \) (int) the number of rows/columns in a block
- \( subsys_nnz \) (int) the number of nonzeros in a block

Return value

This returns a SUNLinearSolver object. If either \( A \) or \( y \) are incompatible then this routine will return NULL.

Notes

This routine analyzes the input matrix and vector to determine the linear system size and to assess compatibility with the solver.

This routine will perform consistency checks to ensure that it is called with consistent NVECTOR and SUNMATRIX implementations. These are currently limited to the SUNMATRIX_SPARSE matrix type and the NVECTOR_CUDA vector type. Since the SUNMATRIX_SPARSE matrix type is only compatible with the NVECTOR_CUDA when using
managed memory, the restriction is also in place for the linear solver. As additional compatible matrix and vector implementations are added to SUNDIALS, these will be included within this compatibility check.

```c
SUNLinSol_cuSolverSp_batchQR_GetDescription
Call SUNLinSol_cuSolverSp_batchQR_GetDescription(LS, &desc);
Description The function SUNLinSol_cuSolverSp_batchQR_GetDescription accesses the string description of the object (empty by default).
Arguments LS (SUNLinearSolver) a SUNLinSol_cuSolverSp_batchQR object
desc (char **) the string description of the linear solver
Return value None
```

```c
SUNLinSol_cuSolverSp_batchQR_SetDescription
Call SUNLinSol_cuSolverSp_batchQR_SetDescription(LS, desc);
Description The function SUNLinSol_cuSolverSp_batchQR_SetDescription sets the string description of the object (empty by default).
Arguments LS (SUNLinearSolver) a SUNLinSol_cuSolverSp_batchQR object
desc (const char *) the string description of the linear solver
Return value None
```

### 8.12.3 SUNLinearSolver_cuSolverSp_batchQR content

The SUNLinearSolver_cuSolverSp_batchQR module defines the content field of a SUNLinearSolver to be the following structure:

```c
struct _SUNLinearSolverContent_cuSolverSp_batchQR {
    int nsubsys; /* number of subsystems */
    int subsys_size; /* size of each subsystem */
    int subsys_nnz; /* number of nonzeros per subsystem */
    int last_flag; /* last return flag */
    booleantype first_factorize; /* is this the first factorization? */
    size_t internal_size; /* size of cusolver internal buffer for Q and R */
    size_t workspace_size; /* size of cusolver memory block for num. factorization */
    cusolverSpHandle_t cusolver_handle; /* cuSolver context */
    cusparseMatDescr_t system_description; /* matrix description */
    realtype* d_values; /* device array of matrix A values */
    int* d_rowptr; /* device array of rowptrs for a subsystem */
    int* d_colind; /* device array of column indices for a subsystem */
    csrqrInfo_t info; /* opaque cusolver data structure */
    void* workspace; /* memory block used by cusolver */
    const char* desc; /* description of this linear solver */
};
```

### 8.13 The SUNLinearSolver_SPGMR implementation

This section describes the SUNLINSOL implementation of the SPGMR (Scaled, Preconditioned, Generalized Minimum Residual [38]) iterative linear solver. The SUNLINSOL_SPGMR module is designed to be compatible with any NVector implementation that supports a minimal subset of operations (N_VClone, N_VDotProd, N_VScale, N_VLinearSum, N_VProd, N_VConst, N_VDiv, and N_VDestroy).
When using Classical Gram-Schmidt, the optional function $N_VDotProdMulti$ may be supplied for increased efficiency.

To access the SUNLINSOL_SPGMR module, include the header file `sunlinsol/sunlinsol_spgmr.h`. We note that the SUNLINSOL_SPGMR module is accessible from SUNDIALS packages without separately linking to the `libsundials_sunlinsolspgmr` module library.

### 8.13.1 SUNLinearSolver_SPGMR description

This solver is constructed to perform the following operations:

- During construction, the $xcor$ and $vtemp$ arrays are cloned from a template $NVECTOR$ that is input, and default solver parameters are set.
- User-facing “set” routines may be called to modify default solver parameters.
- Additional “set” routines are called by the SUNDIALS solver that interfaces with SUNLINSOL_SPGMR to supply the $ATimes$, $PSetup$, and $Psolve$ function pointers and $s1$ and $s2$ scaling vectors.
- In the “initialize” call, the remaining solver data is allocated ($V$, $Hes$, $givens$, and $yg$)
- In the “setup” call, any non-$NULL$ $PSetup$ function is called. Typically, this is provided by the SUNDIALS solver itself, that translates between the generic $PSetup$ function and the solver-specific routine (solver-supplied or user-supplied).
- In the “solve” call, the GMRES iteration is performed. This will include scaling, preconditioning, and restarts if those options have been supplied.

### 8.13.2 SUNLinearSolver_SPGMR functions

The SUNLINSOL_SPGMR module provides the following user-callable constructor for creating a SUNLinearSolver object.

```
SUNLinSol_SPGMR
Call 
LS = SUNLinSol_SPGMR(y, pretype, maxl);
```

**Description**
The function SUNLinSol_SPGMR creates and allocates memory for a SPGMR SUNLinearSolver object.

**Arguments**
- $y$ ($NVector$) a template for cloning vectors needed within the solver
- pretype ($int$) flag indicating the desired type of preconditioning, allowed values are:
  - PREC_NONE (0)
  - PREC_LEFT (1)
  - PREC_RIGHT (2)
  - PREC_BOTH (3)
- Any other integer input will result in the default (no preconditioning).
- maxl ($int$) the number of Krylov basis vectors to use. Values $\leq 0$ will result in the default value (5).

**Return value**
This returns a SUNLinearSolver object. If either $y$ is incompatible then this routine will return NULL.

**Notes**
This routine will perform consistency checks to ensure that it is called with a consistent $NVECTOR$ implementation (i.e. that it supplies the requisite vector operations). If $y$ is incompatible, then this routine will return NULL.

We note that some SUNDIALS solvers are designed to only work with left preconditioning (IDA and IDAS) and others with only right preconditioning (KINSOL). While
it is possible to configure a SUNLINSOLSPGMR object to use any of the preconditioning options with these solvers, this use mode is not supported and may result in inferior performance.

Deprecated Name For backward compatibility, the wrapper function SUNSPGMR with identical input and output arguments is also provided.

F2003 Name FSUNLinSolSPGMR

The SUNLINSOLSPGMR module defines implementations of all “iterative” linear solver operations listed in Sections 8.1.1 – 8.1.3:

- SUNLinSolGetTypeSPGMR
- SUNLinSolInitializeSPGMR
- SUNLinSolSetATimesSPGMR
- SUNLinSolSetPreconditionerSPGMR
- SUNLinSolSetScalingVectorsSPGMR
- SUNLinSolSetupSPGMR
- SUNLinSolSolveSPGMR
- SUNLinSolNumItersSPGMR
- SUNLinSolResNormSPGMR
- SUNLinSolResidSPGMR
- SUNLinSolLastFlagSPGMR
- SUNLinSolSpaceSPGMR
- SUNLinSolFreeSPGMR

All of the listed operations are callable via the FORTRAN 2003 interface module by prepending an ‘F’ to the function name.

The SUNLINSOLSPGMR module also defines the following additional user-callable functions.

```c
SUNLinSolSPGMRSetPrecType
```

Call `retval = SUNLinSolSPGMRSetPrecType(LS, pretype);`

Description The function SUNLinSolSPGMRSetPrecType updates the type of preconditioning to use in the SUNLINSOLSPGMR object.

Arguments

- LS (`SUNLinearSolver`) the SUNLINSOLSPGMR object to update
- pretype (`int`) flag indicating the desired type of preconditioning, allowed values match those discussed in SUNLinSolSPGMR.

Return value This routine will return with one of the error codes SUNLS_ILLEGAL_INPUT (illegal pretype), SUNLS_MEM_NULL (S is NULL) or SUNLS_SUCCESS.

Deprecated Name For backward compatibility, the wrapper function SUNSPGMRSetPrecType with identical input and output arguments is also provided.

F2003 Name FSUNLinSolSPGMRSetPrecType
SUNLinSol_SPGMRSetGSType

Call
retval = SUNLinSol_SPGMRSetGSType(LS, gstype);

Description
The function SUNLinSol_SPGMRSetGSType sets the type of Gram-Schmidt orthogonalization to use in the SUNLINSOL_SPGMR object.

Arguments
LS (SUNLinearSolver) the SUNLINSOL_SPGMR object to update

gstype (int) flag indicating the desired orthogonalization algorithm; allowed values are:

- MODIFIED_GS (1)
- CLASSICAL_GS (2)

Any other integer input will result in a failure, returning error code SUNLS_Ill_INPUT.

Return value
This routine will return with one of the error codes SUNLS_Ill_INPUT (illegal pretype), SUNLS_MEM_NULL (S is NULL) or SUNLS_SUCCESS.

Deprecated Name
For backward compatibility, the wrapper function SUNSPGMRSetGSType with identical input and output arguments is also provided.

F2003 Name
FSUNLinSol_SPGMRSetGSType

SUNLinSol_SPGMRSetMaxRestarts

Call
retval = SUNLinSol_SPGMRSetMaxRestarts(LS, maxrs);

Description
The function SUNLinSol_SPGMRSetMaxRestarts sets the number of GMRES restarts to allow in the SUNLINSOL_SPGMR object.

Arguments
LS (SUNLinearSolver) the SUNLINSOL_SPGMR object to update

maxrs (int) integer indicating number of restarts to allow. A negative input will result in the default of 0.

Return value
This routine will return with one of the error codes SUNLS_MEM_NULL (S is NULL) or SUNLS_SUCCESS.

Deprecated Name
For backward compatibility, the wrapper function SUNSPGMRSetMaxRestarts with identical input and output arguments is also provided.

F2003 Name
FSUNLinSol_SPGMRSetMaxRestarts

8.13.3 SUNLinearSolver_SPGMR Fortran interfaces

The SUNLINSOL_SPGMR module provides a Fortran 2003 module as well as Fortran 77 style interface functions for use from Fortran applications.

FORTRAN 2003 interface module

The fsunlinsol_spgrm_mod Fortran module defines interfaces to all SUNLINSOL_SPGMR C functions using the intrinsic iso_c_binding module which provides a standardized mechanism for interoperating with C. As noted in the C function descriptions above, the interface functions are named after the corresponding C function, but with a leading ‘F’. For example, the function SUNLinSol_SPGMR is interfaced as FSUNLinSol_SPGMR.

The Fortran 2003 SUNLINSOL_SPGMR interface module can be accessed with the use statement, i.e. use fsunlinsol_spgrm_mod, and linking to the library libsundials_fsunlinsolspgmr_mod.lib in addition to the C library. For details on where the library and module file fsunlinsol_spgrm_mod.mod are installed see Appendix A. We note that the module is accessible from the Fortran 2003 Sundials integrators without separately linking to the libsundials_fsunlinsolspgmr_mod library.
FORTRAN 77 interface functions

For solvers that include a FORTRAN 77 interface module, the SUNLINSOL SPGMR module also includes a Fortran-callable function for creating a SUNLinearSolver object.

**FSUNSPGMRINIT**

Call

FSUNSPGMRINIT(code, pretype, maxl, ier)

Description
The function FSUNSPGMRINIT can be called for Fortran programs to create a SUNLINSOL SPGMR object.

Arguments
- code (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).
- pretype (int*) flag indicating desired preconditioning type
- maxl (int*) flag indicating Krylov subspace size

Return value
- ier is a return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes
- This routine must be called after the NVECTOR object has been initialized.
- Allowable values for pretype and maxl are the same as for the C function SUNLinSol SPGMR.

Additionally, when using ARKODE with a non-identity mass matrix, the SUNLINSOL SPGMR module includes a Fortran-callable function for creating a SUNLinearSolver mass matrix solver object.

**FSUNMASSSPGMRINIT**

Call

FSUNMASSSPGMRINIT(pretype, maxl, ier)

Description
The function FSUNMASSSPGMRINIT can be called for Fortran programs to create a SUNLINSOL SPGMR object for mass matrix linear systems.

Arguments
- pretype (int*) flag indicating desired preconditioning type
- maxl (int*) flag indicating Krylov subspace size

Return value
- ier is an int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes
- This routine must be called after the NVECTOR object has been initialized.
- Allowable values for pretype and maxl are the same as for the C function SUNLinSol SPGMR.

The SUNLinSol SPGMRSetPrecType, SUNLinSol SPGMRSetGSType and SUNLinSol SPGMRSetMaxRestarts routines also support Fortran interfaces for the system and mass matrix solvers.

**FSUNSPGMRSETGSTYPE**

Call

FSUNSPGMRSETGSTYPE(code, gstype, ier)

Description
The function FSUNSPGMRSETGSTYPE can be called for Fortran programs to change the Gram-Schmidt orthogonalization algorithm.

Arguments
- code (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).
- gstype (int*) flag indicating the desired orthogonalization algorithm.

Return value
- ier is an int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes
- See SUNLinSol SPGMRSetGSType for complete further documentation of this routine.
FSUNMASSSPGMRSETGSTYPE

Call            FSUNMASSSPGMRSETGSTYPE(gstype, ier)

Description    The function FSUNMASSSPGMRSETGSTYPE can be called for Fortran programs to change the Gram-Schmidt orthogonalization algorithm for mass matrix linear systems.

Arguments      The arguments are identical to FSUNSPGMRSETGSTYPE above, except that code is not needed since mass matrix linear systems only arise in ARKODE.

Return value   ier is a int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes          See SUNLinSol_SPGMRSewtGSType for complete further documentation of this routine.

FSUNSPGMRSETPRECTYPE

Call            FSUNSPGMRSETPRECTYPE(code, pretype, ier)

Description    The function FSUNSPGMRSETPRECTYPE can be called for Fortran programs to change the type of preconditioning to use.

Arguments      code (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).
                 pretype (int*) flag indicating the type of preconditioning to use.

Return value   ier is a int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes          See SUNLinSol_SPGMRSewtPrecType for complete further documentation of this routine.

FSUNMASSSPGMRSETPRECTYPE

Call            FSUNMASSSPGMRSETPRECTYPE(pretype, ier)

Description    The function FSUNMASSSPGMRSETPRECTYPE can be called for Fortran programs to change the type of preconditioning for mass matrix linear systems.

Arguments      The arguments are identical to FSUNSPGMRSETPRECTYPE above, except that code is not needed since mass matrix linear systems only arise in ARKODE.

Return value   ier is a int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes          See SUNLinSol_SPGMRSewtPrecType for complete further documentation of this routine.

FSUNSPGMRSETMAXRS

Call            FSUNSPGMRSETMAXRS(code, maxrs, ier)

Description    The function FSUNSPGMRSETMAXRS can be called for Fortran programs to change the maximum number of restarts allowed for SPGMR.

Arguments      code (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).
                 maxrs (int*) maximum allowed number of restarts.

Return value   ier is a int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes          See SUNLinSol_SPGMRSewtMaxRestarts for complete further documentation of this routine.
8.13 The SUNLinearSolver\_SPGMR implementation

### FSUNMASSSPGMRSETMAXRS

**Call**

FSUNMASSSPGMRSETMAXRS(maxrs, ier)

**Description**

The function FSUNMASSSPGMRSETMAXRS can be called for Fortran programs to change the maximum number of restarts allowed for SPGMR for mass matrix linear systems.

**Arguments**

The arguments are identical to FSUNSPGMRSETMAXRS above, except that code is not needed since mass matrix linear systems only arise in ARKode.

**Return value**

ier is a int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

**Notes**

See SUNLinSol\_SPGMRSetMaxRestarts for complete further documentation of this routine.

### 8.13.4 SUNLinearSolver\_SPGMR content

The SUNLINSOL\_SPGMR module defines the content field of a SUNLinearSolver as the following structure:

```c
struct _SUNLinearSolverContent_SPGMR {
    int maxl;
    int pretype;
    int gstype;
    int max_restarts;
    int numiters;
    realtype resnorm;
    int last_flag;
    ATimesFn ATimes;
    void* ATData;
    PSetupFn Psetup;
    PSolveFn Psolve;
    void* PData;
    N_Vector s1;
    N_Vector s2;
    N_Vector *V;
    realtype **Hes;
    realtype *givens;
    N_Vector xcor;
    realtype *yg;
    N_Vector vtemp;
};
```

These entries of the content field contain the following information:

- **maxl** - number of GMRES basis vectors to use (default is 5),
- **pretype** - flag for type of preconditioning to employ (default is none),
- **gstype** - flag for type of Gram-Schmidt orthogonalization (default is modified Gram-Schmidt),
- **max_restarts** - number of GMRES restarts to allow (default is 0),
- **numiters** - number of iterations from the most-recent solve,
- **resnorm** - final linear residual norm from the most-recent solve,
- **last_flag** - last error return flag from an internal function,
- **ATimes** - function pointer to perform $Av$ product,
- **ATData** - pointer to structure for ATimes,
- **Psetup** - function pointer to preconditioner setup routine,
Description of the SUNLinearSolver module

Psolve - function pointer to preconditioner solve routine,
PData - pointer to structure for Psetup and Psolve,
s1, s2 - vector pointers for supplied scaling matrices (default is NULL),
V - the array of Krylov basis vectors \(v_1, \ldots, v_{\text{maxl}+1}\), stored in \(V[0], \ldots, V[\text{maxl}]\). Each \(v_i\) is a vector of type nvector.,
Hes - the \((\text{maxl} + 1) \times \text{maxl}\) Hessenberg matrix. It is stored row-wise so that the \((i,j)\)th element is given by \(\text{Hes}[i][j]\),
givens - a length \(2 \times \text{maxl}\) array which represents the Givens rotation matrices that arise in the GMRES algorithm. These matrices are \(F_0, F_1, \ldots, F_j\), where

\[
F_i = \begin{bmatrix}
1 & & & & c_i & -s_i \\
& \ddots & & & & \\
& & \ddots & & & \\
& & & 1 & c_i & s_i \\
s_i & s_i & c_i & & & \\
& & & & & 1
\end{bmatrix},
\]

are represented in the givens vector as \(\text{givens}[0] = c_0, \text{givens}[1] = s_0, \text{givens}[2] = c_1, \text{givens}[3] = s_1, \ldots, \text{givens}[2j] = c_j, \text{givens}[2j+1] = s_j\),
xcor - a vector which holds the scaled, preconditioned correction to the initial guess,
 yg - a length \((\text{maxl}+1)\) array of realtype values used to hold “short” vectors (e.g. \(y\) and \(g\)),
 vtemp - temporary vector storage.

8.14 The SUNLinearSolver_SPFGMR implementation

This section describes the SUNLINSOL implementation of the SPFGMR (Scaled, Preconditioned, Flexible, Generalized Minimum Residual [37]) iterative linear solver. The SUNLINSOL_SPFGMR module is designed to be compatible with any NVECTOR implementation that supports a minimal subset of operations (\(\text{NClone}, \text{NDotProd}, \text{NScale}, \text{NLinearSum}, \text{NProd}, \text{NConst}, \text{NDiv}, \text{NDestroy}\)). When using Classical Gram-Schmidt, the optional function \(\text{NVDotProdMulti}\) may be supplied for increased efficiency. Unlike the other Krylov iterative linear solvers supplied with SUNDIALS, SPFGMR is specifically designed to work with a changing preconditioner (e.g. from an iterative method).

To access the SUNLINSOL_SPFGMR module, include the header file sunlinsol/sunlinsol_spfgmr.h. We note that the SUNLINSOL_SPFGMR module is accessible from SUNDIALS packages without separately linking to the lib sundials sunlinsolspfgmr module library.

8.14.1 SUNLinearSolver_SPFGMR description

This solver is constructed to perform the following operations:

- During construction, the xcor and vtemp arrays are cloned from a template NVECTOR that is input, and default solver parameters are set.
- User-facing “set” routines may be called to modify default solver parameters.
- Additional “set” routines are called by the SUNDIALS solver that interfaces with SUNLINSOL_SPFGMR to supply the ATimes, PSetup, and Psolve function pointers and s1 and s2 scaling vectors.
• In the “initialize” call, the remaining solver data is allocated \((V, Hes, givens, \text{and } yg)\).

• In the “setup” call, any non-NULL \texttt{PSetup} function is called. Typically, this is provided by the \texttt{sundials} solver itself, that translates between the generic \texttt{PSetup} function and the solver-specific routine (solver-supplied or user-supplied).

• In the “solve” call, the FGMRES iteration is performed. This will include scaling, preconditioning, and restarts if those options have been supplied.

### 8.14.2 SUNLinearSolver\_SPFGMR functions

The \texttt{sunlinsol\_spfgmr} module provides the following user-callable constructor for creating a \texttt{SUNLinearSolver} object.

```c
SUNLinSol\_SPFGMR
Call
\texttt{LS = SUNLinSol\_SPFGMR(y, pretype, maxl);}  

Description
The function \texttt{SUNLinSol\_SPFGMR} creates and allocates memory for a \texttt{SPFGMR SUNLinearSolver} object.

Arguments
\texttt{y} (\texttt{NVector}) a template for cloning vectors needed within the solver
\texttt{pretype} (\texttt{int}) flag indicating the desired type of preconditioning, allowed values are:
  - \texttt{PREC\_NONE} (0)
  - \texttt{PREC\_LEFT} (1)
  - \texttt{PREC\_RIGHT} (2)
  - \texttt{PREC\_BOTH} (3)
Any other integer input will result in the default (no preconditioning).
\texttt{maxl} (\texttt{int}) the number of Krylov basis vectors to use. Values \(\leq 0\) will result in the default value (5).

Return value
This returns a \texttt{SUNLinearSolver} object. If either \texttt{y} is incompatible then this routine will return \texttt{NULL}.

Notes
This routine will perform consistency checks to ensure that it is called with a consistent \texttt{NVECTOR} implementation (i.e. that it supplies the requisite vector operations). If \texttt{y} is incompatible, then this routine will return \texttt{NULL}.

We note that some \texttt{sundials} solvers are designed to only work with left preconditioning (IDA and IDAS) and others with only right preconditioning (KINSOL). While it is possible to configure a \texttt{sunlinsol\_spfgmr} object to use any of the preconditioning options with these solvers, this use mode is not supported and may result in inferior performance.

F2003 Name \texttt{FSUNLinSol\_SPFGMR}

\texttt{SUNSPFGMR} The \texttt{sunlinsol\_spfgmr} module defines implementations of all “iterative” linear solver operations listed in Sections 8.1.1 – 8.1.3:

- \texttt{SUNLinSol\_Get\_Type\_SPFGMR}
- \texttt{SUNLinSol\_Initialize\_SPFGMR}
- \texttt{SUNLinSol\_Set\_ATimes\_SPFGMR}
- \texttt{SUNLinSol\_Set\_Preconditioner\_SPFGMR}
- \texttt{SUNLinSol\_Set\_Scaling\_Vectors\_SPFGMR}
- \texttt{SUNLinSol\_Setup\_SPFGMR}
- \texttt{SUNLinSol\_Solve\_SPFGMR}
• SUNLinSolNumIters_SPFGMR
• SUNLinSolResNorm_SPFGMR
• SUNLinSolResid_SPFGMR
• SUNLinSolLastFlag_SPFGMR
• SUNLinSolSpace_SPFGMR
• SUNLinSolFree_SPFGMR

All of the listed operations are callable via the FORTRAN 2003 interface module by prepending an ‘F’ to the function name.

The SUNLINSOL_SPFGMR module also defines the following additional user-callable functions.

**SUNLinSol_SPFGMRSetPrecType**

Call

```
retval = SUNLinSol_SPFGMRSetPrecType(LS, pretype);
```

Description

The function `SUNLinSol_SPFGMRSetPrecType` updates the type of preconditioning to use in the SUNLINSOL_SPFGMR object.

Arguments

- `LS` (SUNLinearSolver) the SUNLINSOL_SPFGMR object to update
- `pretype` (int) flag indicating the desired type of preconditioning, allowed values match those discussed in SUNLinSol_SPFGMR.

Return value

This routine will return with one of the error codes SUNLS_ILL_INPUT (illegal pretype), SUNLS_MEM_NULL (S is NULL) or SUNLS_SUCCESS.

Deprecated Name

For backward compatibility, the wrapper function `SUNSPFGMRSetPrecType` with identical input and output arguments is also provided.

F2003 Name

FSUNLinSol_SPFGMRSetPrecType

**SUNLinSol_SPFGMRSetGSType**

Call

```
retval = SUNLinSol_SPFGMRSetGSType(LS, gstype);
```

Description

The function `SUNLinSol_SPFGMRSetGSType` sets the type of Gram-Schmidt orthogonalization to use in the SUNLINSOL_SPFGMR object.

Arguments

- `LS` (SUNLinearSolver) the SUNLINSOL_SPFGMR object to update
- `gstype` (int) flag indicating the desired orthogonalization algorithm; allowed values are:
  - `MODIFIED_GS` (1)
  - `CLASSICAL_GS` (2)

Any other integer input will result in a failure, returning error code SUNLS_ILL_INPUT.

Return value

This routine will return with one of the error codes SUNLS_ILL_INPUT (illegal pretype), SUNLS_MEM_NULL (S is NULL) or SUNLS_SUCCESS.

Deprecated Name

For backward compatibility, the wrapper function `SUNSPFGMRSetGSType` with identical input and output arguments is also provided.

F2003 Name

FSUNLinSol_SPFGMRSetGSType
8.14 The SUNLinearSolver_SPFGMR implementation

```
SUNLinSol_SPFGMRSetMaxRestarts
```

Call `retval = SUNLinSol_SPFGMRSetMaxRestarts(LS, maxrs);`

Description The function `SUNLinSol_SPFGMRSetMaxRestarts` sets the number of GMRES restarts to allow in the `SUNLinSol_SPFGMR` object.

Arguments
- `LS` (SUNLinearSolver) the `SUNLinSol_SPFGMR` object to update
- `maxrs` (int) integer indicating number of restarts to allow. A negative input will result in the default of 0.

Return value This routine will return with one of the error codes `SUNLS_MEM_NULL` (S is NULL) or `SUNLS_SUCCESS`.

Deprecated Name For backward compatibility, the wrapper function `SUNSPFGMRSetMaxRestarts` with identical input and output arguments is also provided.

F2003 Name `FSUNLinSol_SPFGMRSetMaxRestarts`

8.14.3 SUNLinearSolver_SPFGMR Fortran interfaces

The `SUNLinSol_SPFGMR` module provides a Fortran 2003 module as well as Fortran 77 style interface functions for use from Fortran applications.

FORTRAN 2003 interface module

The `fsunlinsol_spfgmr_mod` Fortran module defines interfaces to all `SUNLinSol_SPFGMR` C functions using the intrinsic `iso_c_binding` module which provides a standardized mechanism for interoperating with C. As noted in the C function descriptions above, the interface functions are named after the corresponding C function, but with a leading 'F'. For example, the function `SUNLinSol_SPFGMR` is interfaced as `FSUNLinSol_SPFGMR`.

The Fortran 2003 `SUNLinSol_SPFGMR` interface module can be accessed with the `use` statement, i.e. `use fsunlinsol_spfgmr_mod`, and linking to the library `libsundials_fsunlinsolspfgmr_mod.lib` in addition to the C library. For details on where the library and module file `fsunlinsol_spfgmr_mod.mod` are installed see Appendix A. We note that the module is accessible from the Fortran 2003 Sundials integrators without separately linking to the `libsundials_fsunlinsolspfgmr_mod` library.

FORTRAN 77 interface functions

For solvers that include a Fortran 77 interface module, the `SUNLinSol_SPFGMR` module also includes a Fortran-callable function for creating a `SUNLinearSolver` object.

```
FSUNSPFGMRINIT
```

Call `FSUNSPFGMRINIT(code, pretype, maxl, ier)`

Description The function `FSUNSPFGMRINIT` can be called for Fortran programs to create a `SUNLinSol_SPFGMR` object.

Arguments
- `code` (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).
- `pretype` (int*) flag indicating desired preconditioning type
- `maxl` (int*) flag indicating Krylov subspace size

Return value `ier` is a return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes This routine must be called after the `NVECTOR` object has been initialized.

Allowable values for `pretype` and `maxl` are the same as for the C function `SUNLinSol_SPFGMR`.
Additionally, when using ARKODE with a non-identity mass matrix, the SUNLINSOL_SPFGMR module includes a Fortran-callable function for creating a SUNLinearSolver mass matrix solver object.

**FSUNMASSSPFGMRINIT**

Call: `FSUNMASSSPFGMRINIT(pretype, maxl, ier)`

Description: The function `FSUNMASSSPFGMRINIT` can be called for Fortran programs to create a SUNLINSOL_SPFGMR object for mass matrix linear systems.

Arguments:
- `pretype` (int*) flag indicating desired preconditioning type
- `maxl` (int*) flag indicating Krylov subspace size

Return value: `ier` is an int return completion flag equal to 0 for a success return and ~1 otherwise. See printed message for details in case of failure.

Notes: This routine must be called after the nvector object has been initialized. Allowable values for `pretype` and `maxl` are the same as for the C function SUNLinSol_SPFGMR.

The SUNLinSol_SPFGMRSetPrecType, SUNLinSol_SPFGMRSetGSType and SUNLinSol_SPFGMRSetMaxRestarts routines also support Fortran interfaces for the system and mass matrix solvers.

**FSUNSPFGMRSETGSTYPE**

Call: `FSUNSPFGMRSETGSTYPE(code, gstype, ier)`

Description: The function `FSUNSPFGMRSETGSTYPE` can be called for Fortran programs to change the Gram-Schmidt orthogonalization algorithm.

Arguments:
- `code` (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).
- `gstype` (int*) flag indicating the desired orthogonalization algorithm.

Return value: `ier` is an int return completion flag equal to 0 for a success return and ~1 otherwise. See printed message for details in case of failure.

Notes: See SUNLinSol_SPFGMRSetGSType for complete further documentation of this routine.

**FSUNMASSSPFGMRSETGSTYPE**

Call: `FSUNMASSSPFGMRSETGSTYPE(gstype, ier)`

Description: The function `FSUNMASSSPFGMRSETGSTYPE` can be called for Fortran programs to change the Gram-Schmidt orthogonalization algorithm for mass matrix linear systems.

Arguments: The arguments are identical to `FSUNSPFGMRSETGSTYPE` above, except that `code` is not needed since mass matrix linear systems only arise in ARKODE.

Return value: `ier` is an int return completion flag equal to 0 for a success return and ~1 otherwise. See printed message for details in case of failure.

Notes: See SUNLinSol_SPFGMRSetGSType for complete further documentation of this routine.

**FSUNSPFGMRSETPRECTYPE**

Call: `FSUNSPFGMRSETPRECTYPE(code, pretype, ier)`

Description: The function `FSUNSPFGMRSETPRECTYPE` can be called for Fortran programs to change the type of preconditioning to use.

Arguments:
- `code` (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).
- `pretype` (int*) flag indicating the type of preconditioning to use.
8.14 The SUNLinearSolver_SPFGMR implementation

Return value `ier` is an integer return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes See SUNLinSol_SPFGMRSSetPrecType for complete further documentation of this routine.

---

**SUNMASSSPFGMRSETPRECTYPE**

Call `FSUNMASSSPFGMRSETPRECTYPE(pretype, ier)`

Description The function `FSUNMASSSPFGMRSETPRECTYPE` can be called for Fortran programs to change the type of preconditioning for mass matrix linear systems.

Arguments The arguments are identical to `FSUNSPPGMRSSETPRECTYPE` above, except that `code` is not needed since mass matrix linear systems only arise in ARKODE.

Return value `ier` is an integer return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes See SUNLinSol_SPFGMRSSetPrecType for complete further documentation of this routine.

---

**SUNSPFGMRSETMAXRS**

Call `FSUNSPFGMRSETMAXRS(code, maxrs, ier)`

Description The function `FSUNSPFGMRSETMAXRS` can be called for Fortran programs to change the maximum number of restarts allowed for SPFGMR.

Arguments `code` (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).

`maxrs` (int*) maximum allowed number of restarts.

Return value `ier` is an integer return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes See SUNLinSol_SPFGMRSSetMaxRestarts for complete further documentation of this routine.

---

**SUNMASSSPFGMRSETMAXRS**

Call `FSUNMASSSPFGMRSETMAXRS(maxrs, ier)`

Description The function `FSUNMASSSPFGMRSETMAXRS` can be called for Fortran programs to change the maximum number of restarts allowed for SPFGMR for mass matrix linear systems.

Arguments The arguments are identical to `FSUNSPFGMRSETMAXRS` above, except that `code` is not needed since mass matrix linear systems only arise in ARKODE.

Return value `ier` is an integer return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes See SUNLinSol_SPFGMRSSetMaxRestarts for complete further documentation of this routine.

8.14.4 SUNLinearSolver_SPFGMR content

The SUNLINSOL_SPFGMR module defines the `content` field of a SUNLinearSolver as the following structure:

```c
struct _SUNLinearSolverContent_SPFGMR {
    int maxl;
    int pretype;
    int gstype;
    int max_restarts;
    int numiters;
};
```
realtype resnorm;
int last_flag;
ATimesFn ATimes;
void* ATData;
PSetupFn Psetup;
PSolveFn Psolve;
void* PData;
N_Vector s1;
N_Vector s2;
N_Vector *V;
N_Vector *Z;
realtype **Hes;
realtype *givens;
N_Vector xcor;
realtype *yg;
N_Vector vtemp;
};

These entries of the content field contain the following information:

- number of FGMRES basis vectors to use (default is 5),
- flag for type of preconditioning to employ (default is none),
- flag for type of Gram-Schmidt orthogonalization (default is modified Gram-Schmidt),
- number of FGMRES restarts to allow (default is 0),
- number of iterations from the most-recent solve,
- final linear residual norm from the most-recent solve,
- last error return flag from an internal function,
- function pointer to perform \( Av \) product,
- pointer to structure for ATimes,
- function pointer to preconditioner setup routine,
- function pointer to preconditioner solve routine,
- pointer to structure for Psetup and Psolve,
- vector pointers for supplied scaling matrices (default is NULL),
- the array of Krylov basis vectors \( v_1, \ldots, v_{\text{maxl}+1} \), stored in \( V[0], \ldots, V[\text{maxl}] \). Each \( v_i \) is a vector of type NVECTOR.,
- the array of preconditioned Krylov basis vectors \( z_1, \ldots, z_{\text{maxl}+1} \), stored in \( Z[0], \ldots, Z[\text{maxl}] \). Each \( z_i \) is a vector of type NVECTOR.,
- the \((\text{maxl} + 1) \times \text{maxl}\) Hessenberg matrix. It is stored row-wise so that the \((i,j)\)th element is given by \( \text{Hes}[i][j] \),
- a length \( 2 \times \text{maxl} \) array which represents the Givens rotation matrices that arise in the FGMRES algorithm. These matrices are \( F_0, F_1, \ldots, F_j \), where

\[
F_i = \begin{bmatrix}
1 & \cdots & 1 \\
\vdots & \ddots & \vdots \\
0 & \cdots & 0 \\
& c_i & -s_i \\
& s_i & c_i \\
& \cdots & \cdots \\
& 1 & \cdots \\
\end{bmatrix},
\]
are represented in the \texttt{givens} vector as \( givens[0] = c_0, givens[1] = s_0, givens[2] = c_1, givens[3] = s_1, \ldots givens[2j] = c_j, givens[2j+1] = s_j. \)

\begin{itemize}
  \item \texttt{xcor} - a vector which holds the scaled, preconditioned correction to the initial guess,
  \item \texttt{yg} - a length \((\text{maxl}+1)\) array of \texttt{realtype} values used to hold “short” vectors (e.g. \texttt{y} and \texttt{g}),
  \item \texttt{vtemp} - temporary vector storage.
\end{itemize}

### 8.15 The SUNLinearSolver_SPBCGS implementation

This section describes the \texttt{SUNLinearSolver_SPBCGS} implementation of the SPBCGS (Scaled, Preconditioned, Bi-Conjugate Gradient, Stabilized [39]) iterative linear solver. The \texttt{SUNLinearSolver_SPBCGS} module is designed to be compatible with any \texttt{NVector} implementation that supports a minimal subset of operations (\texttt{N_VClone}, \texttt{N_VDotProd}, \texttt{N_VScale}, \texttt{N_VLinearSum}, \texttt{N_VProd}, \texttt{N_VDiv}, and \texttt{N_VDestroy}). Unlike the \texttt{SPGMR} and \texttt{SPFGMR} algorithms, SPBCGS requires a fixed amount of memory that does not increase with the number of allowed iterations.

To access the \texttt{SUNLinearSolver_SPBCGS} module, include the header file \texttt{sunlinsol/sunlinsol_spbcgs.h}. We note that the \texttt{SUNLinearSolver_SPBCGS} module is accessible from \texttt{SUNDIALS} packages without separately linking to the \texttt{libsundials_sunlinsolspbcgs} module library.

#### 8.15.1 SUNLinearSolver_SPBCGS description

This solver is constructed to perform the following operations:

- During construction all \texttt{NVector} solver data is allocated, with vectors cloned from a template \texttt{NVector} that is input, and default solver parameters are set.
- User-facing “set” routines may be called to modify default solver parameters.
- Additional “set” routines are called by the \texttt{SUNDIALS} solver that interfaces with \texttt{SUNLinearSolver_SPBCGS} to supply the \texttt{ATimes}, \texttt{PSetup}, and \texttt{Psolve} function pointers and \texttt{s1} and \texttt{s2} scaling vectors.
- In the “initialize” call, the solver parameters are checked for validity.
- In the “setup” call, any non-\texttt{NULL} \texttt{PSetup} function is called. Typically, this is provided by the \texttt{SUNDIALS} solver itself, that translates between the generic \texttt{PSetup} function and the solver-specific routine (solver-supplied or user-supplied).
- In the “solve” call the SPBCGS iteration is performed. This will include scaling and preconditioning if those options have been supplied.

#### 8.15.2 SUNLinearSolver_SPBCGS functions

The \texttt{SUNLinearSolver_SPBCGS} module provides the following user-callable constructor for creating a \texttt{SUNLinearSolver} object.

\begin{verbatim}
SUNLinSol_SPBCGS
Call  LS = SUNLinSol_SPBCGS(y, pretype, maxl);
Description The function SUNLinSol_SPBCGS creates and allocates memory for a SPBCGS SUNLinearSolver object.
Arguments y (N_Vector) a template for cloning vectors needed within the solver
       pretype (int) flag indicating the desired type of preconditioning, allowed values are:
       \begin{itemize}
         \item PREC_NONE (0)
\end{itemize}
\end{verbatim}
Description of the SUNLinearSolver module

- PREC_LEFT (1)
- PREC_RIGHT (2)
- PREC_BOTH (3)

Any other integer input will result in the default (no preconditioning).

\[ \text{maxl} \quad (\text{int}) \] the number of linear iterations to allow. Values \( \leq 0 \) will result in the default value (5).

Return value
This returns a SUNLinearSolver object. If either \( y \) is incompatible then this routine will return NULL.

Notes
This routine will perform consistency checks to ensure that it is called with a consistent nvector implementation (i.e. that it supplies the requisite vector operations). If \( y \) is incompatible, then this routine will return NULL.

We note that some sundials solvers are designed to only work with left preconditioning (IDA and IDAS) and others with only right preconditioning (KINSOL). While it is possible to configure a SUNLINSOL_SPBCGS object to use any of the preconditioning options with these solvers, this use mode is not supported and may result in inferior performance.

Deprecated Name
For backward compatibility, the wrapper function SUNSPBCGS with identical input and output arguments is also provided.

F2003 Name
FSUNLinSol_SPBCGS

The SUNLINSOL_SPBCGS module defines implementations of all “iterative” linear solver operations listed in Sections 8.1.1 – 8.1.3:

- SUNLinSolGetType_SPBCGS
- SUNLinSolInitialize_SPBCGS
- SUNLinSolSetATimes_SPBCGS
- SUNLinSolSetPreconditioner_SPBCGS
- SUNLinSolSetScalingVectors_SPBCGS
- SUNLinSolSetup_SPBCGS
- SUNLinSolSolve_SPBCGS
- SUNLinSolNumIters_SPBCGS
- SUNLinSolResNorm_SPBCGS
- SUNLinSolResid_SPBCGS
- SUNLinSolLastFlag_SPBCGS
- SUNLinSolSpace_SPBCGS
- SUNLinSolFree_SPBCGS

All of the listed operations are callable via the FORTRAN 2003 interface module by prepending an ‘F’ to the function name.

The SUNLINSOL_SPBCGS module also defines the following additional user-callable functions.
8.15 The SUNLinearSolver_SPBCGS implementation

**SUNLinSol_SPBCGSSetPrecType**

Call

```c
retval = SUNLinSol_SPBCGSSetPrecType(LS, pretype);
```

Description

The function `SUNLinSol_SPBCGSSetPrecType` updates the type of preconditioning to use in the `SUNLINSOL_SPBCGS` object.

Arguments

- `LS` ([SUNLinearSolver](https://example.com)) the `SUNLINSOL_SPBCGS` object to update
- `pretype` ([int](https://example.com)) flag indicating the desired type of preconditioning, allowed values match those discussed in `SUNLinSol_SPBCGS`.

Return value

This routine will return with one of the error codes `SUNLS_Ill_INPUT` (illegal `pretype`), `SUNLS_MEM_NULL` (`S` is `NULL`) or `SUNLS_SUCCESS`.

Deprecated Name

For backward compatibility, the wrapper function `SUNSPBCGSSetPrecType` with identical input and output arguments is also provided.

F2003 Name

`FSUNLinSol_SPBCGSSetPrecType`

**SUNLinSol_SPBCGSSetMaxl**

Call

```c
retval = SUNLinSol_SPBCGSSetMaxl(LS, maxl);
```

Description

The function `SUNLinSol_SPBCGSSetMaxl` updates the number of linear solver iterations to allow.

Arguments

- `LS` ([SUNLinearSolver](https://example.com)) the `SUNLINSOL_SPBCGS` object to update
- `maxl` ([int](https://example.com)) flag indicating the number of iterations to allow. Values ≤ 0 will result in the default value (5).

Return value

This routine will return with one of the error codes `SUNLS_MEM_NULL` (`S` is `NULL`) or `SUNLS_SUCCESS`.

Deprecated Name

For backward compatibility, the wrapper function `SUNSPBCGSSetMaxl` with identical input and output arguments is also provided.

F2003 Name

`FSUNLinSol_SPBCGSSetMaxl`

8.15.3 SUNLinearSolver_SPBCGS Fortran interfaces

The `SUNLINSOL_SPBCGS` module provides a [FORTRAN](https://example.com) 2003 module as well as [FORTRAN](https://example.com) 77 style interface functions for use from [FORTRAN](https://example.com) applications.

**FORTRAN 2003 interface module**

The `fsunlinsol_spbcgs_mod` [FORTRAN](https://example.com) module defines interfaces to all `SUNLINSOL_SPBCGS` C functions using the intrinsic [iso_c_binding](https://example.com) module which provides a standardized mechanism for interoperating with C. As noted in the C function descriptions above, the interface functions are named after the corresponding C function, but with a leading ‘F’. For example, the function `SUNLinSol_SPBCGS` is interfaced as `FSUNLinSol_SPBCGS`.

The [FORTRAN](https://example.com) 2003 `SUNLINSOL_SPBCGS` interface module can be accessed with the `use` statement, i.e. `use fsunlinsol_spbcgs_mod`, and linking to the library `libsundials_fsunlinsolspbcgs_mod.lib` in addition to the C library. For details on where the library and module file `fsunlinsol_spbcgs_mod.mod` are installed see Appendix A. We note that the module is accessible from the [FORTRAN](https://example.com) 2003 SUNDIALS integrators without separately linking to the `libsundials_fsunlinsolspbcgs_mod.lib` library.

**FORTRAN 77 interface functions**

For solvers that include a [FORTRAN](https://example.com) 77 interface module, the `SUNLINSOL_SPBCGS` module also includes a Fortran-callable function for creating a `SUNLinearSolver` object.
**FSUNSPBCGSINIT**

**Call**

FSUNSPBCGSINIT(code, pretype, maxl, ier)

**Description**
The function FSUNSPBCGSINIT can be called for Fortran programs to create a SUNLIN-SOL_SPBCGS object.

**Arguments**
- **code** (int*) is an integer input specifying the solver id (1 for cvode, 2 for ida, 3 for kinsol, and 4 for arkode).
- **pretype** (int*) flag indicating desired preconditioning type
- **maxl** (int*) flag indicating number of iterations to allow

**Return value**
- **ier** is a return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

**Notes**
- This routine must be called after the NVECTOR object has been initialized.
- Allowable values for `pretype` and `maxl` are the same as for the C function SUNLinSol_SPBCGS.

Additionally, when using arkode with a non-identity mass matrix, the SUNLINSOL_SPBCGS module includes a Fortran-callable function for creating a SUNLinearSolver mass matrix solver object.

**FSUNMASSSPBCGSINIT**

**Call**

FSUNMASSSPBCGSINIT(pretype, maxl, ier)

**Description**
The function FSUNMASSSPBCGSINIT can be called for Fortran programs to create a SUNLINSOL_SPBCGS object for mass matrix linear systems.

**Arguments**
- **pretype** (int*) flag indicating desired preconditioning type
- **maxl** (int*) flag indicating number of iterations to allow

**Return value**
- **ier** is an int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

**Notes**
- This routine must be called after the NVECTOR object has been initialized.
- Allowable values for `pretype` and `maxl` are the same as for the C function SUNLinSol_SPBCGS.

The SUNLinSol_SPBCGSSetPrecType and SUNLinSol_SPBCGSSetMaxl routines also support Fortran interfaces for the system and mass matrix solvers.

**FSUNSPBCGSSETPRECTYPE**

**Call**

FSUNSPBCGSSETPRECTYPE(code, pretype, ier)

**Description**
The function FSUNSPBCGSSETPRECTYPE can be called for Fortran programs to change the type of preconditioning to use.

**Arguments**
- **code** (int*) is an integer input specifying the solver id (1 for cvode, 2 for ida, 3 for kinsol, and 4 for arkode).
- **pretype** (int*) flag indicating the type of preconditioning to use.

**Return value**
- **ier** is an int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

**Notes**
- See SUNLinSol_SPBCGSSetPrecType for complete further documentation of this routine.

**FSUNMASSSPBCGSSETPRECTYPE**

**Call**

FSUNMASSSPBCGSSETPRECTYPE(pretype, ier)

**Description**
The function FSUNMASSSPBCGSSETPRECTYPE can be called for Fortran programs to change the type of preconditioning for mass matrix linear systems.
Arguments The arguments are identical to `FSUNSPBCGSSETPRECTYPE` above, except that `code` is not needed since mass matrix linear systems only arise in ARKODE.

Return value `ier` is an int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes See `SUNLinSol_SPCGSSetPrecType` for complete further documentation of this routine.

**FSUNSPBCGSSETMAXL**

Call `FSUNSPBCGSSETMAXL(code, maxl, ier)`

Description The function `FSUNSPBCGSSETMAXL` can be called for Fortran programs to change the maximum number of iterations to allow.

Arguments `code` (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).

`maxl` (int*) the number of iterations to allow.

Return value `ier` is an int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes See `SUNLinSol_SPCGSSetMaxl` for complete further documentation of this routine.

**FSUNMASSSPBCGSSETMAXL**

Call `FSUNMASSSPBCGSSETMAXL(maxl, ier)`

Description The function `FSUNMASSSPBCGSSETMAXL` can be called for Fortran programs to change the type of preconditioning for mass matrix linear systems.

Arguments The arguments are identical to `FSUNSPBCGSSETMAXL` above, except that `code` is not needed since mass matrix linear systems only arise in ARKODE.

Return value `ier` is an int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes See `SUNLinSol_SPCGSSetMaxl` for complete further documentation of this routine.

### 8.15.4 SUNLinearSolver_SPBCGS content

The `sunlinsol_spbcgs` module defines the `content` field of a `SUNLinearSolver` as the following structure:

```c
struct _SUNLinearSolverContent_SPBCGS {
    int maxl;
    int pretype;
    int numiters;
    realtype resnorm;
    int last_flag;
    ATimesFn ATimes;
    void* ATData;
    PSetupFn Psetup;
    PSolveFn Psolve;
    void* PData;
    N_Vector s1;
    N_Vector s2;
    N_Vector r;
    N_Vector r_star;
    N_Vector p;
    N_Vector q;
    N_Vector u;
};
```
N_Vector Ap;
N_Vector vtemp;
};

These entries of the content field contain the following information:
maxl - number of SPBCGS iterations to allow (default is 5),
pretype - flag for type of preconditioning to employ (default is none),
umiters - number of iterations from the most-recent solve,
resnorm - final linear residual norm from the most-recent solve,
last_flag - last error return flag from an internal function,
ATimes - function pointer to perform \( Av \) product,
ATData - pointer to structure for ATimes,
Psetup - function pointer to preconditioner setup routine,
Psolve - function pointer to preconditioner solve routine,
PData - pointer to structure for Psetup and Psolve,
s1, s2 - vector pointers for supplied scaling matrices (default is NULL),
r - a NVVECTOR which holds the current scaled, preconditioned linear system residual,
r_star - a NVVECTOR which holds the initial scaled, preconditioned linear system residual,
p, q, u, Ap, vtemp - NVECTORS used for workspace by the SPBCGS algorithm.

8.16 The SUNLinearSolver_SPTFQMR implementation

This section describes the SUNLINSOL implementation of the SPTFQMR (Scaled, Preconditioned, Transpose-Free Quasi-Minimum Residual [21]) iterative linear solver. The SUNLINSOL_SPTFQMR module is designed to be compatible with any NVVECTOR implementation that supports a minimal subset of operations (\( N\_VClone \), \( N\_VDotProd \), \( N\_VScale \), \( N\_VLinearSum \), \( N\_VProd \), \( N\_VConst \), \( N\_VDiv \), and \( N\_VDestroy \)). Unlike the SPGMR and SPFGMR algorithms, SPTFQMR requires a fixed amount of memory that does not increase with the number of allowed iterations.

To access the SUNLINSOL_SPTFQMR module, include the header file sunlinsol/sunlinsol_sptfqmr.h. We note that the SUNLINSOL_SPTFQMR module is accessible from SUNDIALS packages without separately linking to the libsundials_sunlinsolsptfqmr module library.

8.16.1 SUNLinearSolver_SPTFQMR description

This solver is constructed to perform the following operations:

- During construction all NVVECTOR solver data is allocated, with vectors cloned from a template NVVECTOR that is input, and default solver parameters are set.
- User-facing “set” routines may be called to modify default solver parameters.
- Additional “set” routines are called by the SUNDIALS solver that interfaces with SUNLINSOL_SPTFQMR to supply the ATimes, PSet, and Psolve function pointers and s1 and s2 scaling vectors.
- In the “initialize” call, the solver parameters are checked for validity.
- In the “setup” call, any non-NULL PSet function is called. Typically, this is provided by the SUNDIALS solver itself, that translates between the generic PSet function and the solver-specific routine (solver-supplied or user-supplied).
- In the “solve” call the TFQMR iteration is performed. This will include scaling and preconditioning if those options have been supplied.
8.16.2 SUNLinearSolver_SPTFQMR functions

The SUNLINSOL_SPTFQMR module provides the following user-callable constructor for creating a SUNLinearSolver object.

---

**SUNLinSol_SPTFQMR**

Call

```c
LS = SUNLinSol_SPTFQMR(y, pretype, maxl);
```

Description

The function SUNLinSol_SPTFQMR creates and allocates memory for a SPTFQMR SUNLinearSolver object.

Arguments

- `y` (N_Vector) a template for cloning vectors needed within the solver
- `pretype` (int) flag indicating the desired type of preconditioning, allowed values are:
  - `PREC_NONE` (0)
  - `PREC_LEFT` (1)
  - `PREC_RIGHT` (2)
  - `PREC_BOTH` (3)

Any other integer input will result in the default (no preconditioning).

- `maxl` (int) the number of linear iterations to allow. Values ≤ 0 will result in the default value (5).

Return value

This returns a SUNLinearSolver object. If either `y` is incompatible then this routine will return `NULL`.

Notes

This routine will perform consistency checks to ensure that it is called with a consistent NVECTOR implementation (i.e. that it supplies the requisite vector operations). If `y` is incompatible, then this routine will return `NULL`.

We note that some SUNDIALS solvers are designed to only work with left preconditioning (IDA and IDAS) and others with only right preconditioning (KINSOL). While it is possible to configure a SUNLINSOL_SPTFQMR object to use any of the preconditioning options with these solvers, this use mode is not supported and may result in inferior performance.

Deprecated Name

For backward compatibility, the wrapper function SUNSPTFQMR with identical input and output arguments is also provided.

F2003 Name

FSUNLinSol_SPTFQMR

The SUNLINSOL_SPTFQMR module defines implementations of all “iterative” linear solver operations listed in Sections 8.1.1 – 8.1.3:

- SUNLinSolGetType_SPTFQMR
- SUNLinSolInitialize_SPTFQMR
- SUNLinSolSetATimes_SPTFQMR
- SUNLinSolSetPreconditioner_SPTFQMR
- SUNLinSolSetScalingVectors_SPTFQMR
- SUNLinSolSetup_SPTFQMR
- SUNLinSolSolve_SPTFQMR
- SUNLinSolNumIters_SPTFQMR
- SUNLinSolResNorm_SPTFQMR
- SUNLinSolResid_SPTFQMR
272 Description of the SUNLinearSolver module

- SUNLinSolLastFlag_SPTFQMR
- SUNLinSolSpace_SPTFQMR
- SUNLinSolFree_SPTFQMR

All of the listed operations are callable via the FORTRAN 2003 interface module by prepending an ‘F’ to the function name.

The SUNLINSOL_SPTFQMR module also defines the following additional user-callable functions.

```fortran
SUNLinSol_SPTFQMRSetPrecType
Call    retval = SUNLinSol_SPTFQMRSetPrecType(LS, pretype);
Description The function SUNLinSol_SPTFQMRSetPrecType updates the type of preconditioning to use in the SUNLINSOL_SPTFQMR object.
Arguments  LS (SUNLinearSolver) the SUNLINSOL_SPTFQMR object to update
            pretype (int) flag indicating the desired type of preconditioning, allowed values match those discussed in SUNLinSol_SPTFQMR.
Return value This routine will return with one of the error codes SUNLS_ILL_INPUT (illegal pretype), SUNLS_MEM_NULL (S is NULL) or SUNLS_SUCCESS.
Deprecated Name For backward compatibility, the wrapper function SUNSPTFQMRSetPrecType with identical input and output arguments is also provided.
F2003 Name  FSUNLinSol_SPTFQMRSetPrecType
```

```fortran
SUNLinSol_SPTFQMRSetMaxl
Call    retval = SUNLinSol_SPTFQMRSetMaxl(LS, maxl);
Description The function SUNLinSol_SPTFQMRSetMaxl updates the number of linear solver iterations to allow.
Arguments  LS (SUNLinearSolver) the SUNLINSOL_SPTFQMR object to update
            maxl (int) flag indicating the number of iterations to allow; values ≤ 0 will result in the default value (5)
Return value This routine will return with one of the error codes SUNLS_MEM_NULL (S is NULL) or SUNLS_SUCCESS.
F2003 Name  FSUNLinSol_SPTFQMRSetMaxl
```

8.16.3 SUNLinearSolver_SPTFQMR Fortran interfaces

The SUNLINSOL_SPTFQMR module provides a FORTRAN 2003 module as well as FORTRAN 77 style interface functions for use from FORTRAN applications.

FORTRAN 2003 interface module

The fsunlinsol_sptfqmr_mod FORTRAN module defines interfaces to all SUNLINSOL_SPTFQMR C functions using the intrinsic iso_c_binding module which provides a standardized mechanism for interoperating with C. As noted in the C function descriptions above, the interface functions are named after the corresponding C function, but with a leading ‘F’. For example, the function SUNLinSol_SPTFQMR is interfaced as FSUNLinSol_SPTFQMR.

The FORTRAN 2003 SUNLINSOL_SPTFQMR interface module can be accessed with the use statement, i.e. use fsunlinsol_sptfqmr_mod, and linking to the library libsundials_fsunlinsol_sptfqmr_mod.lib in addition to the C library. For details on where the library and module file fsunlinsol_sptfqmr_mod.mod are installed see Appendix A. We note that the module is accessible...
from the FORTRAN 2003 SUNDIALS integrators without separately linking to the 
libsundials_fsunlinsolsptfqmr_mod library.

**FORTRAN 77 interface functions**

For solvers that include a FORTRAN 77 interface module, the SUNLINSOL_SPTFQMR module also includes a Fortran-callable function for creating a SUNLinearSolver object.

**FSUNSPFQMRINIT**

Call

FSUNSPFQMRINIT(code, pretype, maxl, ier)

Description The function FSUNSPFQMRINIT can be called for Fortran programs to create a SUNLINSOL_SPTFQMR object.

Arguments

- **code** (int*) is an integer input specifying the solver id (1 for cvode, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).
- **pretype** (int*) flag indicating desired preconditioning type
- **maxl** (int*) flag indicating number of iterations to allow

Return value **ier** is a return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes This routine must be called after the nvector object has been initialized.

Allowable values for **pretype** and **maxl** are the same as for the C function SUNLinSol_SPTFQMR.

Additionally, when using ARKODE with a non-identity mass matrix, the SUNLINSOL_SPTFQMR module includes a Fortran-callable function for creating a SUNLinearSolver mass matrix solver object.

**FSUMASSSPFQMRINIT**

Call

FSUMASSSPFQMRINIT(pretype, maxl, ier)

Description The function FSUMASSSPFQMRINIT can be called for Fortran programs to create a SUNLINSOL_SPTFQMR object for mass matrix linear systems.

Arguments

- **pretype** (int*) flag indicating desired preconditioning type
- **maxl** (int*) flag indicating number of iterations to allow

Return value **ier** is an int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes This routine must be called after the nvector object has been initialized.

Allowable values for **pretype** and **maxl** are the same as for the C function SUNLinSol_SPTFQMR.

The SUNLinSol_SPTFQMRSetPrecType and SUNLinSol_SPTFQMRSetMaxl routines also support Fortran interfaces for the system and mass matrix solvers.

**FSUNSPFQMRSETPRECTYPE**

Call

FSUNSPFQMRSETPRECTYPE(code, pretype, ier)

Description The function FSUNSPFQMRSETPRECTYPE can be called for Fortran programs to change the type of preconditioning to use.

Arguments

- **code** (int*) is an integer input specifying the solver id (1 for cvode, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).
- **pretype** (int*) flag indicating the type of preconditioning to use.

Return value **ier** is an int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.
Notes See SUNLinSol_SPTFQMRSetPrecType for complete further documentation of this routine.

**FSUNMASSSPTFQMRSETPRECTYPE**

Call FSUNMASSSPTFQMRSETPRECTYPE(pretype, ier)

Description The function FSUNMASSSPTFQMRSETPRECTYPE can be called for Fortran programs to change the type of preconditioning for mass matrix linear systems.

Arguments The arguments are identical to FSUNSPTFQMRSETPRECTYPE above, except that code is not needed since mass matrix linear systems only arise in ARKODE.

Return value ier is a int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes See SUNLinSol_SPTFQMRSetPrecType for complete further documentation of this routine.

**FSUNSPTFQMRSETMAXL**

Call FSUNSPTFQMRSETMAXL(code, maxl, ier)

Description The function FSUNSPTFQMRSETMAXL can be called for Fortran programs to change the maximum number of iterations to allow.

Arguments code (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).

maxl (int*) the number of iterations to allow.

Return value ier is a int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes See SUNLinSol_SPTFQMRSetMaxl for complete further documentation of this routine.

**FSUNMASSSPTFQMRSETMAXL**

Call FSUNMASSSPTFQMRSETMAXL(maxl, ier)

Description The function FSUNMASSSPTFQMRSETMAXL can be called for Fortran programs to change the type of preconditioning for mass matrix linear systems.

Arguments The arguments are identical to FSUNSPTFQMRSETMAXL above, except that code is not needed since mass matrix linear systems only arise in ARKODE.

Return value ier is a int return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

Notes See SUNLinSol_SPTFQMRSetMaxl for complete further documentation of this routine.

### 8.16.4 SUNLinearSolver_SPTFQMR content

The SUNLinSol_SPTFQMR module defines the content field of a SUNLinearSolver as the following structure:

```c
struct _SUNLinearSolverContent_SPTFQMR {
    int maxl;
    int pretype;
    int numiters;
    realtype resnorm;
    int last_flag;
    ATimesFn ATimes;
    void* ATData;
};
```
PSolverFn Psolve;

void* PData;
N_Vector s1;
N_Vector s2;
N_Vector r_star;
N_Vector q;
N_Vector d;
N_Vector v;
N_Vector p;
N_Vector *r;
N_Vector u;
N_Vector vtemp1;
N_Vector vtemp2;
N_Vector vtemp3;

};

These entries of the `content` field contain the following information:

- `maxl` - number of TFQMR iterations to allow (default is 5),
- `pretype` - flag for type of preconditioning to employ (default is none),
- `numiters` - number of iterations from the most-recent solve,
- `resnorm` - final linear residual norm from the most-recent solve,
- `last_flag` - last error return flag from an internal function,
- `ATimes` - function pointer to perform $Av$ product,
- `ATData` - pointer to structure for `ATimes`,
- `Psetup` - function pointer to preconditioner setup routine,
- `Psolve` - function pointer to preconditioner solve routine,
- `PData` - pointer to structure for `Psetup` and `Psolve`,
- `s1`, `s2` - vector pointers for supplied scaling matrices (default is NULL),
- `r_star` - a NVECTOR which holds the initial scaled, preconditioned linear system residual,
- `q`, `d`, `v`, `p`, `u` - NVECTORS used for workspace by the SPTFQMR algorithm,
- `r` - array of two NVECTORS used for workspace within the SPTFQMR algorithm,
- `vtemp1`, `vtemp2`, `vtemp3` - temporary vector storage.

### 8.17 The SUNLinearSolver_PCg implementation

This section describes the SUNLINSOL implementation of the PCG (Preconditioned Conjugate Gradient [23]) iterative linear solver. The SUNLINSOL_PCg module is designed to be compatible with any NVECTOR implementation that supports a minimal subset of operations (N_VClone, N_VDotProd, N_VScale, N_VLinearSum, N_VProd, and N_VDestroy). Unlike the SPGMR and SPFGMR algorithms, PCG requires a fixed amount of memory that does not increase with the number of allowed iterations.

To access the SUNLINSOL_PCg module, include the header file `sunlinsol/sunlinsol_pcg.h`. We note that the SUNLINSOL_PCg module is accessible from SUNDIALS packages without separately linking to the `libsundials_sunlinsolpcg` module library.

#### 8.17.1 SUNLinearSolver_PCg description

Unlike all of the other iterative linear solvers supplied with SUNDIALS, PCG should only be used on symmetric linear systems (e.g. mass matrix linear systems encountered in ARKODE). As a result, the
Explanation of the role of scaling and preconditioning matrices given in general must be modified in this scenario. The PCG algorithm solves a linear system $Ax = b$ where $A$ is a symmetric ($A^T = A$), real-valued matrix. Preconditioning is allowed, and is applied in a symmetric fashion on both the right and left. Scaling is also allowed and is applied symmetrically. We denote the preconditioner and scaling matrices as follows:

- $P$ is the preconditioner (assumed symmetric),
- $S$ is a diagonal matrix of scale factors.

The matrices $A$ and $P$ are not required explicitly; only routines that provide $A$ and $P^{-1}$ as operators are required. The diagonal of the matrix $S$ is held in a single nvector, supplied by the user.

In this notation, PCG applies the underlying CG algorithm to the equivalent transformed system

$$\tilde{A}\tilde{x} = \tilde{b}$$

where

$$\tilde{A} = SP^{-1}AP^{-1}S,$$
$$\tilde{b} = SP^{-1}b,$$
$$\tilde{x} = S^{-1}Px.$$  

The scaling matrix must be chosen so that the vectors $SP^{-1}b$ and $S^{-1}Px$ have dimensionless components.

The stopping test for the PCG iterations is on the L2 norm of the scaled preconditioned residual:

$$\|\tilde{b} - \tilde{A}\tilde{x}\|_2 < \delta$$
$$\Leftrightarrow$$
$$\|SP^{-1}b - SP^{-1}Ax\|_2 < \delta$$
$$\Leftrightarrow$$
$$\|P^{-1}b - P^{-1}Ax\|_S < \delta$$

where $\|v\|_S = \sqrt{v^T S^T Sv}$, with an input tolerance $\delta$.

This solver is constructed to perform the following operations:

- During construction all nvector solver data is allocated, with vectors cloned from a template nvector that is input, and default solver parameters are set.
- User-facing “set” routines may be called to modify default solver parameters.
- Additional “set” routines are called by the Sundials solver that interfaces with SUNLINSOL_PCG to supply the ATimes, PSetup, and Psolve function pointers and s scaling vector.
- In the “initialize” call, the solver parameters are checked for validity.
- In the “setup” call, any non-NULL PSetup function is called. Typically, this is provided by the Sundials solver itself, that translates between the generic PSetup function and the solver-specific routine (solver-supplied or user-supplied).
- In the “solve” call the PCG iteration is performed. This will include scaling and preconditioning if those options have been supplied.

### 8.17.2 SUNLinearSolver_PCG functions

The SUNLINSOL_PCG module provides the following user-callable constructor for creating a SUNLinearSolver object.
8.17 The SUNLinearSolver_PCG implementation

Call

\[ LS = \text{SUNLinSol_PCG}(y, \text{pretype}, \text{maxl}); \]

Description

The function SUNLinSol_PCG creates and allocates memory for a PCG SUNLinearSolver object.

Arguments

- \( y \) (N_Vector) a template for cloning vectors needed within the solver
- \( \text{pretype} \) (int) flag indicating whether to use preconditioning. Since the PCG algorithm is designed to only support symmetric preconditioning, then any of the \( \text{pretype} \) inputs \text{PREC_LEFT} (1), \text{PREC_RIGHT} (2), or \text{PREC_BOTH} (3) will result in use of the symmetric preconditioner; any other integer input will result in the default (no preconditioning).
- \( \text{maxl} \) (int) the number of linear iterations to allow; values \( \leq 0 \) will result in the default value (5).

Return value

This returns a \text{SUNLinearSolver} object. If either \( y \) is incompatible then this routine will return NULL.

Notes

This routine will perform consistency checks to ensure that it is called with a consistent NVECTOR implementation (i.e. that it supplies the requisite vector operations). If \( y \) is incompatible, then this routine will return NULL.

Although some SUNDIALS solvers are designed to only work with left preconditioning (IDA and IDAS) and others with only right preconditioning (KINSOL), PCG should only be used with these packages when the linear systems are known to be symmetric. Since the scaling of matrix rows and columns must be identical in a symmetric matrix, symmetric preconditioning should work appropriately even for packages designed with one-sided preconditioning in mind.

Deprecated Name

For backward compatibility, the wrapper function \text{SUNPCG} with identical input and output arguments is also provided.

F2003 Name

FSUNLinSol_PCG

The SUNLINSOL_PCG module defines implementations of all “iterative” linear solver operations listed in Sections 8.1.1 – 8.1.3:

- \text{SUNLinSolGetType_PCG}
- \text{SUNLinSolInitialize_PCG}
- \text{SUNLinSolSetATimes_PCG}
- \text{SUNLinSolSetPreconditioner_PCG}
- \text{SUNLinSolSetScalingVectors_PCG} – since PCG only supports symmetric scaling, the second NVECTOR argument to this function is ignored
- \text{SUNLinSolSetup_PCG}
- \text{SUNLinSolSolve_PCG}
- \text{SUNLinSolNumIters_PCG}
- \text{SUNLinSolResNorm_PCG}
- \text{SUNLinSolResid_PCG}
- \text{SUNLinSolLastFlag_PCG}
- \text{SUNLinSolSpace_PCG}
- \text{SUNLinSolFree_PCG}

All of the listed operations are callable via the FORTRAN 2003 interface module by prepending an ‘F’ to the function name.

The SUNLINSOL_PCG module also defines the following additional user-callable functions.
The function SUNLinSol_PCSetPrecType updates the flag indicating use of preconditioning in the SUNLINSOL_PCG object.

Arguments

- LS (SUNLinearSolver) the SUNLINSOL_PCG object to update
- pretype (int) flag indicating use of preconditioning, allowed values match those discussed in SUNLinSol_PCG.

Return value

This routine will return with one of the error codes SUNLS_ILL_INPUT (illegal pretype), SUNLS_MEM_NULL (S is NULL) or SUNLS_SUCCESS.

Deprecated Name

For backward compatibility, the wrapper function SUNPCGSetPrecType with identical input and output arguments is also provided.

F2003 Name

FSUNLinSol_PCSetPrecType

The function SUNLinSol_PCSetMaxl updates the number of linear solver iterations to allow.

Arguments

- LS (SUNLinearSolver) the SUNLINSOL_PCG object to update
- maxl (int) flag indicating the number of iterations to allow; values ≤ 0 will result in the default value (5)

Return value

This routine will return with one of the error codes SUNLS_MEM_NULL (S is NULL) or SUNLS_SUCCESS.

Deprecated Name

For backward compatibility, the wrapper function SUNPCGSetMaxl with identical input and output arguments is also provided.

F2003 Name

FSUNLinSol_PCSetMaxl

8.17.3 SUNLinearSolver_PCG Fortran interfaces

The SUNLINSOL_PCG module provides a FORTRAN 2003 module as well as FORTRAN 77 style interface functions for use from FORTRAN applications.

FORTRAN 2003 interface module

The fsunlinsol.pcg_mod FORTRAN module defines interfaces to all SUNLINSOL_PCG C functions using the intrinsic iso_c_binding module which provides a standardized mechanism for interoperating with C. As noted in the C function descriptions above, the interface functions are named after the corresponding C function, but with a leading 'F'. For example, the function SUNLinSol_PCG is interfaced as FSUNLinSol_PCG.

The FORTRAN 2003 SUNLINSOL_PCG interface module can be accessed with the use statement, i.e. use fsunlinsol_pcg_mod, and linking to the library libsundials_fsunlinsolpcg_mod.lib in addition to the C library. For details on where the library and module file fsunlinsol.pcg_mod.mod are installed see Appendix A. We note that the module is accessible from the FORTRAN 2003 SUNDIALS integrators without separately linking to the libsundials_fsunlinsolpcg_mod library.

FORTRAN 77 interface functions

For solvers that include a FORTRAN 77 interface module, the SUNLINSOL_PCG module also includes a Fortran-callable function for creating a SUNLinearSolver object.
The function `FSUNPCGINIT` can be called for Fortran programs to create a SUNLinearSolver object.

**Arguments**
- `code` (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).
- `pretype` (int*) flag indicating desired preconditioning type
- `maxl` (int*) flag indicating number of iterations to allow

**Return value** `ier` is a return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

**Notes** This routine must be called after the NVECTOR object has been initialized.
Allowable values for `pretype` and `maxl` are the same as for the C function SUNLinSol_PCG.

Additionally, when using ARKODE with a non-identity mass matrix, the SUNLINSOL_PCG module includes a Fortran-callable function for creating a SUNLinearSolver mass matrix solver object.

The SUNLinSol_PCGSetPrecType and SUNLinSol_PCGSetMax1 routines also support Fortran interfaces for the system and mass matrix solvers.

The function `FSUNMASSPCGINIT` can be called for Fortran programs to create a SUNLinearSolver object for mass matrix linear systems.

**Arguments**
- `pretype` (int*) flag indicating desired preconditioning type
- `maxl` (int*) flag indicating number of iterations to allow

**Return value** `ier` is a return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

**Notes** This routine must be called after the NVECTOR object has been initialized.
Allowable values for `pretype` and `maxl` are the same as for the C function SUNLinSol_PCG.

The SUNLinSol_PCGSetPrecType and SUNLinSol_PCGSetMax1 routines also support Fortran interfaces for the system and mass matrix solvers.

The function `FSUNPCGSETPRECTYPE` can be called for Fortran programs to change the type of preconditioning to use.

**Arguments**
- `code` (int*) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).
- `pretype` (int*) flag indicating the type of preconditioning to use.

**Return value** `ier` is a return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

**Notes** See SUNLinSol_PCGSetPrecType for complete further documentation of this routine.

The function `FSUNMASSPCGSETPRECTYPE` can be called for Fortran programs to change the type of preconditioning for mass matrix linear systems.

The arguments are identical to `FSUNPCGSETPRECTYPE` above, except that `code` is not needed since mass matrix linear systems only arise in ARKODE.
Return value \( ier \) is an int return completion flag equal to 0 for a success return and \(-1\) otherwise. See printed message for details in case of failure.

Notes See SUNLinSol\_PCGSetPrecType for complete further documentation of this routine.

\[ \text{FSUNPCGSETMAXL} \]
Call \( \text{FSUNPCGSETMAXL}(\text{code, maxl, ier}) \)
Description The function FSUNPCGSETMAXL can be called for Fortran programs to change the maximum number of iterations to allow.
Arguments \( \text{code (int*)} \) is an integer input specifying the solver id (1 for cvode, 2 for IDA, 3 for KINSOL, and 4 for ARKODE).
\( \text{maxl (int*)} \) the number of iterations to allow.
Return value \( ier \) is an int return completion flag equal to 0 for a success return and \(-1\) otherwise. See printed message for details in case of failure.
Notes See SUNLinSol\_PCGSetMaxl for complete further documentation of this routine.

\[ \text{FSUNMASSPCGSETMAXL} \]
Call \( \text{FSUNMASSPCGSETMAXL}(\text{maxl, ier}) \)
Description The function FSUNMASSPCGSETMAXL can be called for Fortran programs to change the type of preconditioning for mass matrix linear systems.
Arguments The arguments are identical to FSUNPCGSETMAXL above, except that \( \text{code} \) is not needed since mass matrix linear systems only arise in ARKODE.
Return value \( ier \) is an int return completion flag equal to 0 for a success return and \(-1\) otherwise. See printed message for details in case of failure.
Notes See SUNLinSol\_PCGSetMaxl for complete further documentation of this routine.

8.17.4 SUNLinearSolver\_PCG content

The SUNLINSOL\_PCG module defines the \textit{content} field of a SUNLinearSolver as the following structure:

```c
struct _SUNLinearSolverContent_PCG {
    int maxl;
    int pretype;
    int numiters;
    realtype resnorm;
    int last_flag;
    ATimesFn ATimes;
    void* ATData;
    PSetupFn Psetup;
    PSolveFn Psolve;
    void* PData;
    N_Vector s;
    N_Vector r;
    N_Vector p;
    N_Vector z;
    N_Vector Ap;
};
```

These entries of the \textit{content} field contain the following information:
- \( \text{maxl} \) - number of PCG iterations to allow (default is 5),
- \( \text{pretype} \) - flag for use of preconditioning (default is none),
numiters  - number of iterations from the most-recent solve,
resnorm  - final linear residual norm from the most-recent solve,
last_flag - last error return flag from an internal function,
ATimes   - function pointer to perform $Av$ product,
ATData   - pointer to structure for ATimes,
Psetup   - function pointer to preconditioner setup routine,
Psolve   - function pointer to preconditioner solve routine,
PData    - pointer to structure for Psetup and Psolve,
s       - vector pointer for supplied scaling matrix (default is NULL),
r       - an nvector which holds the preconditioned linear system residual,
p, z, Ap - nVECTORS used for workspace by the PCG algorithm.

8.18 SUNLinearSolver Examples

There are SUNLinearSolver examples that may be installed for each implementation; these make use of the functions in test_sunlinsol.c. These example functions show simple usage of the SUNLinearSolver family of functions. The inputs to the examples depend on the linear solver type, and are output to stdout if the example is run without the appropriate number of command-line arguments.

The following is a list of the example functions in test_sunlinsol.c:

- Test_SUNLinSolGetType: Verifies the returned solver type against the value that should be returned.
- Test_SUNLinSolInitialize: Verifies that SUNLinSolInitialize can be called and returns successfully.
- Test_SUNLinSolSetup: Verifies that SUNLinSolSetup can be called and returns successfully.
- Test_SUNLinSolSolve: Given a sunmatrix object $A$, nVECTOR objects $x$ and $b$ (where $Ax = b$) and a desired solution tolerance $tol$, this routine clones $x$ into a new vector $y$, calls SUNLinSolSolve to fill $y$ as the solution to $Ay = b$ (to the input tolerance), verifies that each entry in $x$ and $y$ match to within $10 \times tol$, and overwrites $x$ with $y$ prior to returning (in case the calling routine would like to investigate further).
- Test_SUNLinSolSetATimes (iterative solvers only): Verifies that SUNLinSolSetATimes can be called and returns successfully.
- Test_SUNLinSolSetPreconditioner (iterative solvers only): Verifies that SUNLinSolSetPreconditioner can be called and returns successfully.
- Test_SUNLinSolSetScalingVectors (iterative solvers only): Verifies that SUNLinSolSetScalingVectors can be called and returns successfully.
- Test_SUNLinSolLastFlag: Verifies that SUNLinSolLastFlag can be called, and outputs the result to stdout.
- Test_SUNLinSolNumIters (iterative solvers only): Verifies that SUNLinSolNumIters can be called, and outputs the result to stdout.
- Test_SUNLinSolResNorm (iterative solvers only): Verifies that SUNLinSolResNorm can be called, and that the result is non-negative.
- Test_SUNLinSolResid (iterative solvers only): Verifies that SUNLinSolResid can be called.
• Test_SUNLinSolSpace verifies that SUNLinSolSpace can be called, and outputs the results to stdout.

We’ll note that these tests should be performed in a particular order. For either direct or iterative linear solvers, Test_SUNLinSolInitialize must be called before Test_SUNLinSolSetup, which must be called before Test_SUNLinSolSolve. Additionally, for iterative linear solvers Test_SUNLinSolSetATimes, Test_SUNLinSolSetPreconditioner and Test_SUNLinSolSetScalingVectors should be called before Test_SUNLinSolInitialize; similarly Test_SUNLinSolNumIters, Test_SUNLinSolResNorm and Test_SUNLinSolResid should be called after Test_SUNLinSolSolve. These are called in the appropriate order in all of the example problems.
Chapter 9

Description of the SUNNonlinearSolver module

SUNDIALS time integration packages are written in terms of generic nonlinear solver operations defined by the SUNNONLINSOL API and implemented by a particular SUNNONLINSOL module of type SUNNonlinearSolver. Users can supply their own SUNNONLINSOL module, or use one of the modules provided with SUNDIALS. Depending on the package, nonlinear solver modules can either target system presented in a rootfinding \(F(y) = 0\) or fixed-point \(G(y) = y\) formulation. For more information on the formulation of the nonlinear system(s) see section 9.2.

The time integrators in SUNDIALS specify a default nonlinear solver module and as such this chapter is intended for users that wish to use a non-default nonlinear solver module or would like to provide their own nonlinear solver implementation. Users interested in using a non-default solver module may skip the description of the SUNNONLINSOL API in section 9.1 and proceed to the subsequent sections in this chapter that describe the SUNNONLINSOL modules provided with SUNDIALS.

For users interested in providing their own SUNNONLINSOL module, the following section presents the SUNNONLINSOL API and its implementation beginning with the definition of SUNNONLINSOL functions in sections 9.1.1 – 9.1.3. This is followed by the definition of functions supplied to a nonlinear solver implementation in section 9.1.4. A table of nonlinear solver return codes is given in section 9.1.5. The SUNNonlinearSolver type and the generic SUNNONLINSOL module are defined in section 9.1.6. Section 9.1.7 describes how SUNNONLINSOL models interface with SUNDIALS integrators providing sensitivity analysis capabilities (CVODES and IDAS). Finally, section 9.1.8 lists the requirements for supplying a custom SUNNONLINSOL module. Users wishing to supply their own SUNNONLINSOL module are encouraged to use the SUNNONLINSOL implementations provided with SUNDIALS as a template for supplying custom nonlinear solver modules.

9.1 The SUNNonlinearSolver API

The SUNNONLINSOL API defines several nonlinear solver operations that enable SUNDIALS integrators to utilize any SUNNONLINSOL implementation that provides the required functions. These functions can be divided into three categories. The first are the core nonlinear solver functions. The second group of functions consists of set routines to supply the nonlinear solver with functions provided by the SUNDIALS time integrators and to modify solver parameters. The final group consists of get routines for retrieving nonlinear solver statistics. All of these functions are defined in the header file sundials/sundials_nonlinear_solver.h.

9.1.1 SUNNonlinearSolver core functions

The core nonlinear solver functions consist of two required functions to get the nonlinear solver type (SUNNonlinSolGetType) and solve the nonlinear system (SUNNonlinSolSolve). The remaining three
Description of the SUNNonlinearSolver module

functions for nonlinear solver initialization (SUNNonlinSolInitialization), setup
(SUNNonlinSolSetup), and destruction (SUNNonlinSolFree) are optional.

```
SUNNonlinSolGetType
Call type = SUNNonlinSolGetType(NLS);
Description The \textit{required} function SUNNonlinSolGetType returns nonlinear solver type.
Arguments NLS (SUNNonlinearSolver) a SUNNONLINSOL object.
Return value The return value \textit{type} (of type \texttt{int}) will be one of the following:
- SUNNONLINEARSOLVER_ROOTFIND 0, the SUNNONLINSOL module solves $F(y) = 0$.
- SUNNONLINEARSOLVER_FIXEDPOINT 1, the SUNNONLINSOL module solves $G(y) = y$.
```

```
SUNNonlinSolInitialize
Call retval = SUNNonlinSolInitialize(NLS);
Description The \textit{optional} function SUNNonlinSolInitialize performs nonlinear solver initialization
and may perform any necessary memory allocations.
Arguments NLS (SUNNonlinearSolver) a SUNNONLINSOL object.
Return value The return value \textit{retval} (of type \texttt{int}) is zero for a successful call and a negative value
for a failure.
Notes It is assumed all solver-specific options have been set prior to calling
SUNNonlinSolInitialize. SUNNONLINSOL implementations that do not require initialization
may set this operation to NULL.
```

```
SUNNonlinSolSetup
Call retval = SUNNonlinSolSetup(NLS, y, mem);
Description The \textit{optional} function SUNNonlinSolSetup performs any solver setup needed for a non-
linear solve.
Arguments NLS (SUNNonlinearSolver) a SUNNONLINSOL object.
y (N_Vector) the initial iteration passed to the nonlinear solver.
mem (void *) the SUNDIALS integrator memory structure.
Return value The return value \textit{retval} (of type \texttt{int}) is zero for a successful call and a negative value
for a failure.
Notes SUNDIALS integrators call SUNNonlinSolSetup before each step attempt. SUNNONLINSOL
implementations that do not require setup may set this operation to NULL.
```

```
SUNNonlinSolSolve
Call retval = SUNNonlinSolSolve(NLS, y0, ycor, w, tol, callLSetup, mem);
Description The \textit{required} function SUNNonlinSolSolve solves the nonlinear system $F(y) = 0$ or
$G(y) = y$.
Arguments NLS (SUNNonlinearSolver) a SUNNONLINSOL object.
y0 (N_Vector) the predicted value for the new solution state. This \textit{must} remain unchanged throughout the solution process. See section 9.2 for more
detail on the nonlinear system formulation.
```

F2003 Name FSUNNonlinSolGetType
F2003 Name FSUNNonlinSolInitialize
F2003 Name FSUNNonlinSolSetup
F2003 Name FSUNNonlinSolSolve
ycor \text{(N\_Vector)} on input the initial guess for the correction to the predicted state (zero) and on output the final correction to the predicted state. See section 9.2 for more detail on the nonlinear system formulation.

\( w \) \text{(N\_Vector)} the solution error weight vector used for computing weighted error norms.

tol \text{(realtype)} the requested solution tolerance in the weighted root-mean-squared norm.

callLSetup \text{(boolantype)} a flag indicating that the integrator recommends for the linear solver setup function to be called.

\text{mem} \text{(void \*)} the SUNDIALS integrator memory structure.

Return value The return value \text{retval} (of type int) is zero for a successful solve, a positive value for a recoverable error (i.e., the solve failed and the integrator should reduce the step size and reattempt the step), and a negative value for an unrecoverable error (i.e., the solve failed and the integrator should halt and return an error to the user).

F2003 Name FSUNNonlinSolSolve

\textbf{SUNNonlinSolFree}

\textbf{Call} \quad \text{retval} = \text{SUNNonlinSolFree}(\text{NLS});

\textbf{Description} \quad The \textit{optional} function \text{SUNNonlinSolFree} frees any memory allocated by the nonlinear solver.

\textbf{Arguments} \quad \text{NLS} \text{ (SUNNonlinearSolver)} a SUNNONLINSOL object.

\textbf{Return value} \quad The return value \text{retval} (of type int) should be zero for a successful call, and a negative value for a failure. SUNNONLINSOL implementations that do not allocate data may set this operation to NULL.

F2003 Name FSUNNonlinSolFree

9.1.2 SUNNonlinearSolver set functions

The following set functions are used to supply nonlinear solver modules with functions defined by the SUNDIALS integrators and to modify solver parameters. Only the routine for setting the nonlinear system defining function (\text{SUNNonlinSolSetSysFn} is required. All other set functions are optional.

\textbf{SUNNonlinSolSetSysFn}

\textbf{Call} \quad \text{retval} = \text{SUNNonlinSolSetSysFn}(\text{NLS}, \text{SysFn});

\textbf{Description} \quad The \textit{required} function \text{SUNNonlinSolSetSysFn} is used to provide the nonlinear solver with the function defining the nonlinear system. This is the function \( F(y) \) in \( F(y) = 0 \) for SUNNONLINEARSOLVER\_ROOTFIND modules or \( G(y) \) in \( G(y) = y \) for SUNNONLINEARSOLVER\_FIXEDPOINT modules.

\textbf{Arguments} \quad \text{NLS} \text{ (SUNNonlinearSolver)} a SUNNONLINSOL object.

\text{SysFn} \text{ (SUNNonlinSolSysFn)} the function defining the nonlinear system. See section 9.1.4 for the definition of SUNNonlinSolSysFn.

\textbf{Return value} \quad The return value \text{retval} (of type int) should be zero for a successful call, and a negative value for a failure.

F2003 Name FSUNNonlinSolSetSysFn
Description of the SUNNonlinearSolver module

**SUNNonlinSolSetLSetupFn**

Call
\[
\text{retval} = \text{SUNNonlinSolSetLSetupFn}(\text{NLS}, \text{LSetupFn});
\]

Description The *optional* function SUNNonlinSolSetLSetupFn is called by SUNDIALS integrators to provide the nonlinear solver with access to its linear solver setup function.

Arguments
- **NLS** (SUNNonlinearSolver) a SUNNONLINSOL object.
- **LSetupFn** (SUNNonlinSolLSetupFn) a wrapper function to the SUNDIALS integrator’s linear solver setup function. See section 9.1.4 for the definition of SUNNonlinLSetupFn.

Return value The return value *retval* (of type int) should be zero for a successful call, and a negative value for a failure.

Notes The SUNNonlinLSetupFn function sets up the linear system \( Ax = b \) where \( A = \frac{\partial F}{\partial y} \) is the linearization of the nonlinear residual function \( F(y) = 0 \) (when using SUNLINSOL direct linear solvers) or calls the user-defined preconditioner setup function (when using SUNLINSOL iterative linear solvers). SUNNONLINSOL implementations that do not require solving this system, do not utilize SUNLINSOL linear solvers, or use SUNLINSOL linear solvers that do not require setup may set this operation to NULL.

F2003 Name FSUNNonlinSolSetLSetupFn

**SUNNonlinSolSetLSolveFn**

Call
\[
\text{retval} = \text{SUNNonlinSolSetLSolveFn}(\text{NLS}, \text{LSolveFn});
\]

Description The *optional* function SUNNonlinSolSetLSolveFn is called by SUNDIALS integrators to provide the nonlinear solver with access to its linear solver solve function.

Arguments
- **NLS** (SUNNonlinearSolver) a SUNNONLINSOL object
- **LSolveFn** (SUNNonlinSolLSolveFn) a wrapper function to the SUNDIALS integrator’s linear solver solve function. See section 9.1.4 for the definition of SUNNonlinSolLSolveFn.

Return value The return value *retval* (of type int) should be zero for a successful call, and a negative value for a failure.

Notes The SUNNonlinLSolveFn function solves the linear system \( Ax = b \) where \( A = \frac{\partial F}{\partial y} \) is the linearization of the nonlinear residual function \( F(y) = 0 \). SUNNONLINSOL implementations that do not require solving this system or do not use SUNLINSOL linear solvers may set this operation to NULL.

F2003 Name FSUNNonlinSolSetLSolveFn

**SUNNonlinSolSetConvTestFn**

Call
\[
\text{retval} = \text{SUNNonlinSolSetConvTestFn}(\text{NLS}, \text{CTestFn}, \text{ctest\_data});
\]

Description The *optional* function SUNNonlinSolSetConvTestFn is used to provide the nonlinear solver with a function for determining if the nonlinear solver iteration has converged. This is typically called by SUNDIALS integrators to define their nonlinear convergence criteria, but may be replaced by the user.

Arguments
- **NLS** (SUNNonlinearSolver) a SUNNONLINSOL object.
- **CTestFn** (SUNNonlineSolConvTestFn) a SUNDIALS integrator’s nonlinear solver convergence test function. See section 9.1.4 for the definition of SUNNonlinSolConvTestFn.
- **ctest\_data** (void*) is a data pointer passed to CTestFn every time it is called.

Return value The return value *retval* (of type int) should be zero for a successful call, and a negative value for a failure.
Notes SUNNONLINSOL implementations utilizing their own convergence test criteria may set this function to NULL.

F2003 Name FSUNNonlinSolSetConvTestFn

*SUNNonlinSolSetMaxIters*

Call \( \text{retval} = \text{SUNNonlinSolSetMaxIters}(\text{NLS}, \text{maxiters}); \)

Description The optional function SUNNonlinSolSetMaxIters sets the maximum number of nonlinear solver iterations. This is typically called by SUNDIALS integrators to define their default iteration limit, but may be adjusted by the user.

Arguments \( \text{NLS} \) (SUNNonlinearSolver) a SUNNONLINSOL object.
\( \text{maxiters} \) (int) the maximum number of nonlinear iterations.

Return value The return value \( \text{retval} \) (of type int) should be zero for a successful call, and a negative value for a failure (e.g., \( \text{maxiters} < 1 \)).

F2003 Name FSUNNonlinSolSetMaxIters

9.1.3 SUNNonlinearSolver get functions

The following get functions allow SUNDIALS integrators to retrieve nonlinear solver statistics. The routines to get the current total number of iterations (SUNNonlinSolGetNumIters) and number of convergence failures (SUNNonlinSolGetNumConvFails) are optional. The routine to get the current nonlinear solver iteration (SUNNonlinSolGetCurIter) is required when using the convergence test provided by the SUNDIALS integrator or by the ARKODE and CVODE linear solver interfaces. Otherwise, SUNNonlinSolGetCurIter is optional.

*SUNNonlinSolGetNumIters*

Call \( \text{retval} = \text{SUNNonlinSolGetNumIters}(\text{NLS}, \text{numiters}); \)

Description The optional function SUNNonlinSolGetNumIters returns the total number of nonlinear solver iterations. This is typically called by the SUNDIALS integrator to store the nonlinear solver statistics, but may also be called by the user.

Arguments \( \text{NLS} \) (SUNNonlinearSolver) a SUNNONLINSOL object
\( \text{numiters} \) (long int*) the total number of nonlinear solver iterations.

Return value The return value \( \text{retval} \) (of type int) should be zero for a successful call, and a negative value for a failure.

F2003 Name FSUNNonlinSolGetNumIters

*SUNNonlinSolGetCurIter*

Call \( \text{retval} = \text{SUNNonlinSolGetCurIter}(\text{NLS}, \text{iter}); \)

Description The function SUNNonlinSolGetCurIter returns the iteration index of the current nonlinear solve. This function is required when using SUNDIALS integrator-provided convergence tests or when using a SUNLINSOL spils linear solver; otherwise it is optional.

Arguments \( \text{NLS} \) (SUNNonlinearSolver) a SUNNONLINSOL object
\( \text{iter} \) (int*) the nonlinear solver iteration in the current solve starting from zero.

Return value The return value \( \text{retval} \) (of type int) should be zero for a successful call, and a negative value for a failure.

F2003 Name FSUNNonlinSolGetCurIter
Description of the SUNNonlinearSolver module

**SUNNonlinSolGetNumConvFails**

Call

\[
\text{retval} = \text{SUNNonlinSolGetNumConvFails}(\text{NLS}, \text{nconvfails});
\]

Description The *optional* function `SUNNonlinSolGetNumConvFails` returns the total number of nonlinear solver convergence failures. This may be called by the SUNDIALS integrator to store the nonlinear solver statistics, but may also be called by the user.

Arguments

- `NLS` (SUNNonlinearSolver) a SUNNOLINSOL object
- `nconvfails` (long int*) the total number of nonlinear solver convergence failures.

Return value The return value `retval` (of type int) should be zero for a successful call, and a negative value for a failure.

F2003 Name `FSUNNonlinSolGetNumConvFails`

### 9.1.4 Functions provided by SUNDIALS integrators

To interface with SUNNOLINSOL modules, the SUNDIALS integrators supply a variety of routines for evaluating the nonlinear system, calling the SUNLINSOL setup and solve functions, and testing the nonlinear iteration for convergence. These integrator-provided routines translate between the user-supplied ODE or DAE systems and the generic interfaces to the nonlinear or linear systems of equations that result in their solution. The types for functions provided to a SUNNOLINSOL module are defined in the header file `sundials/sundials_nonlinearsolver.h`, and are described below.

**SUNNonlinSolSysFn**

Definition

\[
\text{typedef int (*SUNNonlinSolSysFn)(N\text{Vector} \ ycor, N\text{Vector} \ F, \ void* \ mem);
\]

Purpose

These functions evaluate the nonlinear system \( F(y) \) for SUNNONLINEARSOLVER_ROOTFIND type modules or \( G(y) \) for SUNNONLINEARSOLVER_FIXEDPOINT type modules. Memory for \( F \) must by be allocated prior to calling this function. The vector \( ycor \) will be left unchanged.

Arguments

- `ycor` is the current correction to the predicted state at which the nonlinear system should be evaluated. See section 9.2 for more detail on the nonlinear system formulation.
- `F` is the output vector containing \( F(y) \) or \( G(y) \), depending on the solver type.
- `mem` is the SUNDIALS integrator memory structure.

Return value

The return value `retval` (of type int) is zero for a successful solve, a positive value for a recoverable error, and a negative value for an unrecoverable error.

Notes

As discussed in section 9.2, SUNDIALS integrators formulate nonlinear systems as a function of the correction to the predicted solution. On each call to the nonlinear system function the integrator will compute and store the current solution based on the input correction. Additionally, the residual will store the value of the ODE right-hand side function or DAE residual used in computing the nonlinear system residual. These stored values are then directly used in the integrator-supplied linear solver setup and solve functions as applicable.

**SUNNonlinSolLSetupFn**

Definition

\[
\text{typedef int (*SUNNonlinSolLSetupFn)(boolantype \ jbad, boolantype* \ jcur, \ void* \ mem);
\]

Purpose

These functions are wrappers to the SUNDIALS integrator's function for setting up linear solves with SUNLINSOL modules.

Arguments

- `jbad` is an input indicating whether the nonlinear solver believes that \( A \) has gone stale (SUNTRUE) or not (SUNFALSE).
The `SUNNonlinearSolver` API

`jcur` is an output indicating whether the routine has updated the Jacobian $A$ (`SUNTRUE`) or not (`SUNFALSE`).

`mem` is the SUNDIALS integrator memory structure.

**Return value**
The return value `retval` (of type `int`) is zero for a successful solve, a positive value for a recoverable error, and a negative value for an unrecoverable error.

**Notes**
The `SUNNonlinLSetupFn` function sets up the linear system $Ax = b$ where $A = \frac{\partial F}{\partial y}$ is the linearization of the nonlinear residual function $F(y) = 0$ (when using SUNLINSOL direct linear solvers) or calls the user-defined preconditioner setup function (when using SUNLINSOL iterative linear solvers). SUNNONLINSOL implementations that do not require solving this system, do not utilize SUNLINSOL linear solvers, or use SUNLINSOL linear solvers that do not require setup may ignore these functions.

As discussed in the description of `SUNNonlinSolSysFn`, the linear solver setup function assumes that the nonlinear system function has been called prior to the linear solver setup function as the setup will utilize saved values from the nonlinear system evaluation (e.g., the updated solution).

### SUNNonlinSolveFn

**Definition**
```c
typedef int (*SUNNonlinSolveFn)(N_Vector b, void* mem);
```

**Purpose**
These functions are wrappers to the SUNDIALS integrator’s function for solving linear systems with SUNLINSOL modules.

**Arguments**
- `b` contains the right-hand side vector for the linear solve on input and the solution to the linear system on output.
- `mem` is the SUNDIALS integrator memory structure.

**Return value**
The return value `retval` (of type `int`) is zero for a successful solve, a positive value for a recoverable error, and a negative value for an unrecoverable error.

**Notes**
The `SUNNonlinLSolveFn` function solves the linear system $Ax = b$ where $A = \frac{\partial F}{\partial y}$ is the linearization of the nonlinear residual function $F(y) = 0$. SUNNONLINSOL implementations that do not require solving this system or do not use SUNLINSOL linear solvers may ignore these functions.

As discussed in the description of `SUNNonlinSolSysFn`, the linear solver solve function assumes that the nonlinear system function has been called prior to the linear solver solve function as the solve may utilize saved values from the nonlinear system evaluation (e.g., the updated solution).

### SUNNonlinConvTestFn

**Definition**
```c
typedef int (*SUNNonlinConvTestFn)(SUNNonlinearSolver NLS, N_Vector ycor, N_Vector del, realtype tol, N_Vector ewt, void* ctest_data);
```

**Purpose**
These functions are SUNDIALS integrator-specific convergence tests for nonlinear solvers and are typically supplied by each SUNDIALS integrator, but users may supply custom problem-specific versions as desired.

**Arguments**
- `NLS` is the SUNNONLINSOL object.
- `ycor` is the current correction (nonlinear iterate).
- `del` is the difference between the current and prior nonlinear iterates.
- `tol` is the nonlinear solver tolerance.
- `ewt` is the weight vector used in computing weighted norms.
- `ctest_data` is the data pointer provided to `SUNNonlinSolSetConvTestFn`. 
Return value  The return value of this routine will be a negative value if an unrecoverable error occurred or one of the following:

- `SUN_NLS_SUCCESS`  the iteration is converged.
- `SUN_NLS_CONTINUE` the iteration has not converged, keep iterating.
- `SUN_NLS_CONV_RECVR` the iteration appears to be diverging, try to recover.

Notes  The tolerance passed to this routine by SUNDIALS integrators is the tolerance in a weighted root-mean-squared norm with error weight vector `ewt`. SUNNONLINSOL modules utilizing their own convergence criteria may ignore these functions.

9.1.5 SUNNonlinearSolver return codes

The functions provided to SUNNONLINSOL modules by each SUNDIALS integrator, and functions within the SUNDIALS-provided SUNNONLINSOL implementations utilize a common set of return codes, shown below in Table 9.1. Here, negative values correspond to non-recoverable failures, positive values to recoverable failures, and zero to a successful call.

Table 9.1: Description of the SUNNonlinearSolver return codes

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUN_NLS_SUCCESS</td>
<td>0</td>
<td>successful call or converged solve</td>
</tr>
<tr>
<td>SUN_NLS_CONTINUE</td>
<td>901</td>
<td>the nonlinear solver is not converged, keep iterating</td>
</tr>
<tr>
<td>SUN_NLS_CONV_RECVR</td>
<td>902</td>
<td>the nonlinear solver appears to be diverging, try to recover</td>
</tr>
<tr>
<td>SUN_NLS_MEM_NULL</td>
<td>-901</td>
<td>a memory argument is NULL</td>
</tr>
<tr>
<td>SUN_NLS_MEM_FAIL</td>
<td>-902</td>
<td>a memory access or allocation failed</td>
</tr>
<tr>
<td>SUN_NLS_ILL_INPUT</td>
<td>-903</td>
<td>an illegal input option was provided</td>
</tr>
<tr>
<td>SUN_NLS_VECTOROP_ERR</td>
<td>-904</td>
<td>a nVECTOR operation failed</td>
</tr>
<tr>
<td>SUN_NLS_EXT_FAIL</td>
<td>-905</td>
<td>an external library call returned an error</td>
</tr>
</tbody>
</table>

9.1.6 The generic SUNNonlinearSolver module

SUNDIALS integrators interact with specific SUNNONLINSOL implementations through the generic SUNNONLINSOL module on which all other SUNNONLINSOL implementations are built. The SUNNonlinearSolver type is a pointer to a structure containing an implementation-dependent content field and an ops field. The type SUNNonlinearSolver is defined as follows:

typedef struct _generic_SUNNonlinearSolver *SUNNonlinearSolver;

struct _generic_SUNNonlinearSolver {
    void *content;
    struct _generic_SUNNonlinearSolver_Ops *ops;
};

where the _generic_SUNNonlinearSolver_Ops structure is a list of pointers to the various actual nonlinear solver operations provided by a specific implementation. The _generic_SUNNonlinearSolver_Ops structure is defined as

struct _generic_SUNNonlinearSolver_Ops {
    SUNNonlinearSolver_Type (*gettype)(SUNNonlinearSolver);
    int (*initialize)(SUNNonlinearSolver);
    int (*setup)(SUNNonlinearSolver, N_Vector, void*);
    int (*solve)(SUNNonlinearSolver, N_Vector, N_Vector,
                 N_Vector, realtype, booleantype, void*);
The SUNNonlinearSolver API

```c
int (*free)(SUNNonlinearSolver);
int (*setsysfn)(SUNNonlinearSolver, SUNNonlinSolSysFn);
int (*setlsetupfn)(SUNNonlinearSolver, SUNNonlinSolLSetupFn);
int (*setlsolvefn)(SUNNonlinearSolver, SUNNonlinSolLSolveFn);
int (*setctestfn)(SUNNonlinearSolver, SUNNonlinSolConvTestFn, void*);
int (*setmaxiters)(SUNNonlinearSolver, int);
int (*getnumiters)(SUNNonlinearSolver, long int*);
int (*getcuriter)(SUNNonlinearSolver, int*);
int (*getnumconvfails)(SUNNonlinearSolver, long int*);
};
```

The generic SUNNONLINSOL module defines and implements the nonlinear solver operations defined in Sections 9.1.1 – 9.1.3. These routines are in fact only wrappers to the nonlinear solver operations provided by a particular SUNNONLINSOL implementation, which are accessed through the ops field of the SUNNonlinearSolver structure. To illustrate this point we show below the implementation of a typical nonlinear solver operation from the generic SUNNONLINSOL module, namely SUNNonlinSolSolve, which solves the nonlinear system and returns a flag denoting a successful or failed solve:

```c
int SUNNonlinSolSolve(SUNNonlinearSolver NLS,
    N_Vector y0, N_Vector y,
    N_Vector w, realtype tol,
    booleantype callLSetup, void* mem)
{
    return((int) NLS->ops->solve(NLS, y0, y, w, tol, callLSetup, mem));
}
```

The Fortran 2003 interface provides a bind(C) derived-type for the _generic_SUNNonlinearSolver and the _generic_SUNNonlinearSolver_Ops structures. Their definition is given below.

```fortran
type, bind(C), public :: SUNNonlinearSolver
  type(C_PTR), public :: content
  type(C_PTR), public :: ops
end type SUNNonlinearSolver

type, bind(C), public :: SUNNonlinearSolver_Ops
  type(C_FUNPTR), public :: gettype
  type(C_FUNPTR), public :: initialize
  type(C_FUNPTR), public :: setup
  type(C_FUNPTR), public :: solve
  type(C_FUNPTR), public :: free
  type(C_FUNPTR), public :: setsysfn
  type(C_FUNPTR), public :: setlsetupfn
  type(C_FUNPTR), public :: setlsolvefn
  type(C_FUNPTR), public :: setctestfn
  type(C_FUNPTR), public :: setmaxiters
  type(C_FUNPTR), public :: getnumiters
  type(C_FUNPTR), public :: getcuriter
  type(C_FUNPTR), public :: getnumconvfails
end type SUNNonlinearSolver_Ops
```

### 9.1.7 Usage with sensitivity enabled integrators

When used with SUNDIALS packages that support sensitivity analysis capabilities (e.g., CVODES and IDAS) a special NVECTOR module is used to interface with SUNNONLINSOL modules for solves involving sensitivity vectors stored in an NVECTOR array. As described below, the NVECTOR_SENSWRAPPER
module is an NV ECTOR implementation where the vector content is an NV ECTOR array. This wrapper vector allows SUNNONLINSOL modules to operate on data stored as a collection of vectors.

For all SUNDIALS-provided SUNNONLINSOL modules a special constructor wrapper is provided so users do not need to interact directly with the NV ECTOR_SENSWRAPPER module. These constructors follow the naming convention SUNNonlinSol_***Sens(count,...) where *** is the name of the SUNNONLINSOL module, count is the size of the vector wrapper, and ... are the module-specific constructor arguments.

The NV ECTOR_SENSWRAPPER module

This section describes the NV ECTOR_SENSWRAPPER implementation of an NV ECTOR. To access the NV ECTOR_SENSWRAPPER module, include the header file sundials/sundials_nv ector_senswrapper.h.

The NV ECTOR_SENSWRAPPER module defines an N Vector implementing all of the standard vectors operations defined in Table 6.1.1 but with some changes to how operations are computed in order to accommodate operating on a collection of vectors.

1. Element-wise vector operations are computed on a vector-by-vector basis. For example, the linear sum of two wrappers containing \( n_v \) vectors of length \( n \), \( NVLinearSum(a,x,b,y,z) \), is computed as

\[
  z_{j,i} = ax_{j,i} + by_{j,i}, \quad i = 0, \ldots, n - 1, \quad j = 0, \ldots, n_v - 1.
\]

2. The dot product of two wrappers containing \( n_v \) vectors of length \( n \) is computed as if it were the dot product of two vectors of length \( nn_v \). Thus \( d = NVDotProd(x,y) \) is

\[
  d = \sum_{j=0}^{n_v-1} \sum_{i=0}^{n-1} x_{j,i}y_{j,i}.
\]

3. All norms are computed as the maximum of the individual norms of the \( n_v \) vectors in the wrapper. For example, the weighted root mean square norm \( m = NVWrmsNorm(x, w) \) is

\[
  m = \max_j \left( \frac{1}{n} \sum_{i=0}^{n-1} (x_{j,i}w_{j,i})^2 \right)^{1/2}
\]

To enable usage alongside other NV ECTOR modules the NV ECTOR_SENSWRAPPER functions implementing vector operations have _SensWrapper appended to the generic vector operation name.

The NV ECTOR_SENSWRAPPER module provides the following constructors for creating an NV ECTOR_SENSWRAPPER:

\[
\text{N_VNewEmpty_SensWrapper}
\]

Call \( w = N\_VNewEmpty\_SensWrapper(count) \);

Description The function N_VNewEmpty_SensWrapper creates an empty NV ECTOR_SENSWRAPPER wrapper with space for count vectors.

Arguments count (int) the number of vectors the wrapper will contain.

Return value The return value \( w \) (of type N_Vector) will be a NV ECTOR object if the constructor exits successfully, otherwise \( w \) will be NULL.

F2003 Name FN_VNewEmpty_SensWrapper
The SUNNonlinearSolver API creates an \texttt{NVectorSensWrapper} wrapper containing \texttt{count} vectors cloned from \texttt{y}.

**Arguments**
- \texttt{count} (\texttt{int}) the number of vectors the wrapper will contain.
- \texttt{y} (\texttt{NVector}) the template vectors to use in creating the vector wrapper.

**Return value**
The return value \texttt{w} (of type \texttt{NVector}) will be a \texttt{NVector} object if the constructor exits successfully, otherwise \texttt{w} will be \texttt{NULL}.

The \texttt{NVectorSensWrapper} implementation of the \texttt{NVector} module defines the \texttt{content} field of the \texttt{NVector} to be a structure containing an \texttt{NVector} array, the number of vectors in the vector array, and a boolean flag indicating ownership of the vectors in the vector array.

\begin{verbatim}
struct _N_VectorContent_SensWrapper {
    N_Vector* vecs;
    int nvecs;
    boolean own_vecs;
};
\end{verbatim}

The following macros are provided to access the content of an \texttt{NVectorSensWrapper} vector.

- \texttt{NV_CONTENT_SW(v)} - provides access to the content structure
- \texttt{NV_VECs_SW(v)} - provides access to the vector array
- \texttt{NV_NVECS_SW(v)} - provides access to the number of vectors
- \texttt{NV_OWN_VECs_SW(v)} - provides access to the ownership flag
- \texttt{NV_VEC_Sw(v,i)} - provides access to the \texttt{i}-th vector in the vector array

### 9.1.8 Implementing a Custom SUNNonlinearSolver Module

A \texttt{SUNNonlinearSolver} implementation must do the following:

1. Specify the content of the \texttt{SUNNonlinearSolver} module.
2. Define and implement the required nonlinear solver operations defined in Sections 9.1.1 – 9.1.3.
   - Note that the names of the module routines should be unique to that implementation in order to permit using more than one \texttt{SUNNonlinearSolver} module (each with different \texttt{SUNNonlinearSolver} internal data representations) in the same code.
3. Define and implement a user-callable constructor to create a \texttt{SUNNonlinearSolver} object.

Additionally, a \texttt{SUNNonlinearSolver} implementation may do the following:

1. Define and implement additional user-callable “set” routines acting on the \texttt{SUNNonlinearSolver} object, e.g., for setting various configuration options to tune the performance of the nonlinear solve algorithm.
2. Provide additional user-callable “get” routines acting on the \texttt{SUNNonlinearSolver} object, e.g., for returning various solve statistics.

To aid in the creation of custom \texttt{SUNNonlinearSolver} modules the generic \texttt{SUNNonlinearSolver} module provides the utility functions \texttt{SUNNonlinSolNewEmpty} and \texttt{SUNNonlinSolFreeEmpty}. When used in custom \texttt{SUNNonlinearSolver} constructors, the function \texttt{SUNNonlinSolNewEmpty} will ease the introduction of any new optional nonlinear solver operations to the \texttt{SUNNonlinearSolver} API by ensuring only required operations need to be set.
Description of the SUNNonlinearSolver module

SUNNonlinSolNewEmpty

Call NLS = SUNNonlinSolNewEmpty();

Description The function SUNNonlinSolNewEmpty allocates a new generic SUNNONLINSOL object and initializes its content pointer and the function pointers in the operations structure to NULL.

Arguments None

Return value This function returns a SUNNonlinearSolver object. If an error occurs when allocating the object, then this routine will return NULL.

F2003 Name FSUNNonlinSolNewEmpty

SUNNonlinSolFreeEmpty

Call SUNNonlinSolFreeEmpty(NLS);

Description This routine frees the generic SUNNonlinearSolver object, under the assumption that any implementation-specific data that was allocated within the underlying content structure has already been freed. It will additionally test whether the ops pointer is NULL, and, if it is not, it will free it as well.

Arguments NLS (SUNNonlinearSolver)

Return value None

F2003 Name FSUNNonlinSolFreeEmpty

9.2 IDA SUNNonlinearSolver interface

As discussed in Chapter 2 each integration step requires the (approximate) solution of the nonlinear system

\[ G(y_n) = F \left( t_n, y_n, h_n^{-1} \sum_{i=0}^{q} \alpha_n,i y_{n-i} \right) = 0. \]  

(9.1)

Rather than solving this system for the new state \( y_n \) IDA reformulates the system to solve for the correction \( y_{cor} \) to the predicted new state \( y_{pred} \) and its derivative \( \dot{y}_{pred} \) so that \( y_n = y_{pred} + y_{cor} \) and \( \dot{y}_n = \dot{y}_{pred} + h_n^{-1} \alpha_{n,0} y_{cor} \). The nonlinear system rewritten in terms of \( y_{cor} \) is

\[ G(y_{cor}) = F \left( t_n, y_{pred} + y_{cor}, \dot{y}_{pred} + \alpha y_{cor} \right) = 0. \]  

(9.2)

where \( \alpha = h_n^{-1} \alpha_{n,0} \).

The nonlinear system function provided by IDA to the nonlinear solver module internally updates the current value of the new state and its derivative based on the input correction vector. The updated vectors are used when calling the DAE residual function and when setting up linear solves (e.g., for updating the Jacobian or preconditioner).

IDA provides several advanced functions that will not be needed by most users, but might be useful for users who choose to provide their own implementation of the SUNNonlinearSolver API. For example, such a user might need access to the current \( y \) and \( \dot{y} \) vectors to compute Jacobian data.

IDAGetCurrentCj

Call flag = IDAGetCurrentCj(ida_mem, &cj);

Description The function IDAGetCurrentCj returns the scalar \( c_j \) which is proportional to the inverse of the step size (\( \alpha \) in Eq. (2.5)).

Arguments ida_mem (void *) pointer to the IDA memory block.

cj (realtyle) the value of \( c_j \).
Return value The return value flag (of type int) is one of

IDA_SUCCESS The optional output value has been successfully set.
IDA_MEM_NULL The ida_mem pointer is NULL.

**IDAGetCurrentY**

Call flag = IDAGetCurrentY(ida_mem, &y);

Description The function IDAGetCurrentY returns the current $y$ vector.

Arguments ida_mem (void *) pointer to the IDA memory block.
y (N_Vector *) the current $y$ vector

Return value The return value flag (of type int) is one of

IDA_SUCCESS The optional output value has been successfully set.
IDA_MEM_NULL The ida_mem pointer is NULL.

**IDAGetCurrentYp**

Call flag = IDAGetCurrentYp(ida_mem, &yp);

Description The function IDAGetCurrentYp returns the current $\dot{y}$ vector.

Arguments ida_mem (void *) pointer to the IDA memory block.
yp (N_Vector *) the current $\dot{y}$ vector

Return value The return value flag (of type int) is one of

IDA_SUCCESS The optional output value has been successfully set.
IDA_MEM_NULL The ida_mem pointer is NULL.

**IDAComputeY**

Call flag = IDAComputeY(ida_mem, ycor, y);

Description The function computes the current $y$ vector based on the given correction vector from the nonlinear solver.

Arguments ida_mem - (void *) pointer to the IDA memory block
ycor - (N_Vector) the correction
y - (N_Vector) the output vector

Return value The return value flag (of type int) is one of

IDA_SUCCESS The optional output value has been successfully set.
IDA_MEM_NULL The ida_mem pointer is NULL.

**IDAComputeYp**

Call flag = IDAComputeYp(ida_mem, ycor, yp);

Description The function computes $\dot{y}$.

Arguments ida_mem - (void *) pointer to the IDA memory block
ycor - (N_Vector) the correction
yp - (N_Vector) the output vector array

Return value The return value flag (of type int) is one of

IDA_SUCCESS The optional output value has been successfully set.
IDA_MEM_NULL The ida_mem pointer is NULL.
9.3 The SUNNonlinearSolver_Newton implementation

This section describes the SUNNONLINSOL implementation of Newton’s method. To access the SUNNONLINSOL_NEWTON module, include the header file sunnonlinsol/sunnonlinsol_newton.h. We note that the SUNNONLINSOL_NEWTON module is accessible from SUNDIALS integrators without separately linking to the libsundials_sunnonlinsolnewton module library.

9.3.1 SUNNonlinearSolver_Newton description

To find the solution to
\[ F(y) = 0 \]  
(9.3)
given an initial guess \( y^{(0)} \), Newton’s method computes a series of approximate solutions
\[ y^{(m+1)} = y^{(m)} + \delta^{(m+1)} \]  
(9.4)
where \( m \) is the Newton iteration index, and the Newton update \( \delta^{(m+1)} \) is the solution of the linear system
\[ A(y^{(m)})\delta^{(m+1)} = -F(y^{(m)}) , \]  
(9.5)
in which \( A \) is the Jacobian matrix
\[ A \equiv \frac{\partial F}{\partial y} . \]  
(9.6)

Depending on the linear solver used, the SUNNONLINSOL_NEWTON module will employ either a Modified Newton method, or an Inexact Newton method [7, 11, 18, 20, 32]. When used with a direct linear solver, the Jacobian matrix \( A \) is held constant during the Newton iteration, resulting in a Modified Newton method. With a matrix-free iterative linear solver, the iteration is an Inexact Newton method.

In both cases, calls to the integrator-supplied SUNNonlinSolLSetupFn function are made infrequently to amortize the increased cost of matrix operations (updating \( A \) and its factorization within direct linear solvers, or updating the preconditioner within iterative linear solvers). Specifically, SUNNONLINSOL_NEWTON will call the SUNNonlinSolLSetupFn function in two instances:

(a) when requested by the integrator (the input callLSetSetup is SUNTRUE) before attempting the Newton iteration, or

(b) when reattempting the nonlinear solve after a recoverable failure occurs in the Newton iteration with stale Jacobian information (jcur is SUNFALSE). In this case, SUNNONLINSOL_NEWTON will set jbad to SUNTRUE before calling the SUNNonlinSolLSetupFn function.

Whether the Jacobian matrix \( A \) is fully or partially updated depends on logic unique to each integrator-supplied SUNNonlinSolLSetupFn routine. We refer to the discussion of nonlinear solver strategies provided in Chapter 2 for details on this decision.

The default maximum number of iterations and the stopping criteria for the Newton iteration are supplied by the SUNDIALS integrator when SUNNONLINSOL_NEWTON is attached to it. Both the maximum number of iterations and the convergence test function may be modified by the user by calling the SUNNonlinSolSetMaxIters and/or SUNNonlinSolSetConvTestFn functions after attaching the SUNNONLINSOL_NEWTON object to the integrator.

9.3.2 SUNNonlinearSolver_Newton functions

The SUNNONLINSOL_NEWTON module provides the following constructors for creating a SUNNonlinearSolver object.
9.3 The SUNNonlinearSolver_Newton implementation

**SUNNonlinSol_Newton**

Call

NLS = SUNNonlinSol_Newton(y);

Description

The function SUNNonlinSol_Newton creates a SUNNonlinearSolver object for use with SUNDIALS integrators to solve nonlinear systems of the form \( F(y) = 0 \) using Newton’s method.

Arguments

\( y \) (N_Vector) a template for cloning vectors needed within the solver.

Return value

The return value NLS (of type SUNNonlinearSolver) will be a SUNNONLINSOL object if the constructor exits successfully, otherwise NLS will be NULL.

F2003 Name  FSUNNonlinSol_Newton

**SUNNonlinSolNewtionsens**

Call

NLS = SUNNonlinSolNewtionsens(count, y);

Description

The function SUNNonlinSolNewtionsens creates a SUNNonlinearSolver object for use with SUNDIALS sensitivity enabled integrators (CVODES and IDAS) to solve nonlinear systems of the form \( F(y) = 0 \) using Newton’s method.

Arguments

\( count \) (int) the number of vectors in the nonlinear solve. When integrating a system containing \( Ns \) sensitivities the value of \( count \) is:

- \( Ns+1 \) if using a simultaneous corrector approach.
- \( Ns \) if using a staggered corrector approach.

\( y \) (N_Vector) a template for cloning vectors needed within the solver.

Return value

The return value NLS (of type SUNNonlinearSolver) will be a SUNNONLINSOL object if the constructor exits successfully, otherwise NLS will be NULL.

F2003 Name  FSUNNonlinSolNewtionsens

The SUNNONLINSOL_Newton module implements all of the functions defined in sections 9.1.1 – 9.1.3 except for the SUNNonlinSolSetup function. The SUNNONLINSOL_Newton functions have the same names as those defined by the generic SUNNONLINSOL API with _Newton appended to the function name. Unless using the SUNNONLINSOL_Newton module as a standalone nonlinear solver the generic functions defined in sections 9.1.1 – 9.1.3 should be called in favor of the SUNNONLINSOL_Newton-specific implementations.

The SUNNONLINSOL_Newton module also defines the following additional user-callable function.

**SUNNonlinSolGetSysFn_Newton**

Call

retval = SUNNonlinSolGetSysFn_Newton(NLS, SysFn);

Description

The function SUNNonlinSolGetSysFn_Newton returns the residual function that defines the nonlinear system.

Arguments

\( NLS \) (SUNNonlinearSolver) a SUNNONLINSOL object

\( SysFn \) (SUNNonlinSolSysFn*) the function defining the nonlinear system.

Return value

The return value retval (of type int) should be zero for a successful call, and a negative value for a failure.

Notes

This function is intended for users that wish to evaluate the nonlinear residual in a custom convergence test function for the SUNNONLINSOL_Newton module. We note that SUNNONLINSOL_Newton will not leverage the results from any user calls to SysFn.

F2003 Name  FSUNNonlinSolGetSysFn_Newton

9.3.3 SUNNonlinearSolver_Newton Fortran interfaces

The SUNNONLINSOL_Newton module provides a FORTRAN 2003 module as well as FORTRAN 77 style interface functions for use from FORTRAN applications.
FORTRAN 2003 interface module

The `fsunnonlinsol_newton_mod` FORTRAN module defines interfaces to all `SUNNONLINSOL_NEWTON` C functions using the intrinsic `iso_c_binding` module which provides a standardized mechanism for interoperating with C. As noted in the C function descriptions above, the interface functions are named after the corresponding C function, but with a leading ‘F’. For example, the function `SUNNonlinSol_Newton` is interfaced as `FSUNNonlinSol_Newton`.

The FORTRAN 2003 `SUNNONLINSOL_NEWTON` interface module can be accessed with the `use` statement, i.e. `use fsunnonlinsol_newton_mod`, and linking to the library `libsundials_fsunnonlinsolnewton_mod.lib` in addition to the C library. For details on where the library and module file `fsunnonlinsol_newton_mod.mod` are installed see Appendix A. We note that the module is accessible from the FORTRAN 2003 SUNDIALS integrators without separately linking to the `libsundials_fsunnonlinsolnewton_mod` library.

FORTRAN 77 interface functions

For SUNDIALS integrators that include a FORTRAN 77 interface, the `SUNNONLINSOL_NEWTON` module also includes a Fortran-callable function for creating a SUNNonlinearSolver object.

```fortran
FSUNNEWTONINIT(code, ier);
```

**Description** The function `FSUNNEWTONINIT` can be called for Fortran programs to create a SUNNonlinearSolver object for use with SUNDIALS integrators to solve nonlinear systems of the form \( F(y) = 0 \) with Newton’s method.

**Arguments**
- `code` (`int*`) is an integer input specifying the solver id (1 for CVODE, 2 for IDA, and 4 for ARKODE).

**Return value** `ier` is a return completion flag equal to 0 for a success return and -1 otherwise. See printed message for details in case of failure.

### 9.3.4 SUNNonlinearSolver_Newton content

The `SUNNONLINSOL_NEWTON` module defines the `content` field of a SUNNonlinearSolver as the following structure:

```c
struct _SUNNonlinearSolverContent_Newton {
    SUNNonlinSolSysFn Sys;
    SUNNonlinSolLSetupFn LSetup;
    SUNNonlinSolLSolveFn LSolve;
    SUNNonlinSolConvTestFn CTest;
    N_Vector delta;
    booleantype jcur;
    int curiter;
    int maxiters;
    long int niters;
    long int nconvfails;
    void* ctest_data;
};
```

These entries of the `content` field contain the following information:
- `Sys` - the function for evaluating the nonlinear system,
- `LSetup` - the package-supplied function for setting up the linear solver,
- `LSolve` - the package-supplied function for performing a linear solve,
9.4 The SUNNonlinearSolver_PetscSNES implementation

The SUNNonlinearSolver_PetscSNES implementation is a part of the PETSc SNES nonlinear solver(s). To enable the SUNNonlinearSolver_PetscSNES module, SUNDIALS must be configured to use PETSc. Instructions on how to do this are given in Chapter A.1.4. To access the module, users must include the header file `sunnonlinsol/sunnonlinsol_petscsnes.h`. The library to link to is `libsundials_sunnonlinsol_petsc.lib` where `.lib` is `.so` for shared libraries and `.a` for static libraries. Users of the SUNNonlinearSolver_PetscSNES should also see the section `nvector_petsc` 6.8 which discusses the nvector interface to the PETSc Vec API.

9.4.1 SUNNonlinearSolver_PetscSNES description

The SUNNonlinearSolver_PetscSNES implementation allows users to utilize a PETSc SNES nonlinear solver to solve the nonlinear systems that arise in the SUNDIALS integrators. Since SNES uses the KSP linear solver interface underneath it, the SUNNonlinearSolver_PetscSNES implementation does not interface with SUNDIALS linear solvers. Instead, users should set nonlinear solver options, linear solver options, and preconditioner options through the PETSc SNES, KSP, and PC APIs [5].

Important usage notes for the SUNNonlinearSolver_PetscSNES implementation are provided below:

- The SUNNonlinearSolver_PetscSNES implementation handles calling SNESetFunction at construction. The actual residual function $F(y)$ is set by the SUNDIALS integrator when the SUNNonlinearSolver_PetscSNES object is attached to it. Therefore, a user should not call SNESetFunction on a SNES object that is being used with SUNNonlinearSolver_PetscSNES. For these reasons, it is recommended, although not always necessary, that the user calls SUNNonlinSol_PetscSNES with the new SNES object immediately after calling.

- The number of nonlinear iterations is tracked by SUNDIALS separately from the count kept by SNES. As such, the function SUNNonlinSolGetNumIters reports the cumulative number of iterations across the lifetime of the SUNNonlinearSolver object.

- Some “converged” and “diverged” convergence reasons returned by SNES are treated as recoverable convergence failures by SUNDIALS. Therefore, the count of convergence failures returned by SUNNonlinSolGetNumConvFails will reflect the number of recoverable convergence failures as determined by SUNDIALS, and may differ from the count returned by SNESGetNonlinearStepFailures.

- The SUNNonlinearSolver_PetscSNES module is not currently compatible with the CVODES or IDAS staggered or simultaneous sensitivity strategies.

9.4.2 SUNNonlinearSolver_PetscSNES functions

The SUNNonlinearSolver_PetscSNES module provides the following constructor for creating a SUNNonlinearSolver object.

- `CTest` - the function for checking convergence of the Newton iteration,
- `delta` - the Newton iteration update vector,
- `jcur` - the Jacobian status (`SUNTRUE` = current, `SUNFALSE` = stale),
- `curiter` - the current number of iterations in the solve attempt,
- `maxiters` - the maximum number of Newton iterations allowed in a solve,
- `niters` - the total number of nonlinear iterations across all solves,
- `nconvfails` - the total number of nonlinear convergence failures across all solves, and
- `ctest_data` - the data pointer passed to the convergence test function.
SUNNonlinSol_PetscSNES

Call
NLS = SUNNonlinSol_PetscSNES(y, snes);

Description
The function SUNNonlinSol_PetscSNES creates a SUNNonlinearSolver object that wraps a PETSc SNES object for use with SUNDIALS. This will call SNESSetFunction on the provided SNES object.

Arguments
snes (SNES) a PETSc SNES object
y (N_Vector) a N_Vector object of type NVECTOR_PETSC that used as a template for the residual vector

Return value
A SUNNONLINSOL object if the constructor exits successfully, otherwise NLS will be NULL.

Notes
This function calls SNESSetFunction and will overwrite whatever function was previously set. Users should not call SNESSetFunction on the SNES object provided to the constructor.

The SUNNONLINSOL_PETSCSNES module implements all of the functions defined in sections 9.1.1 – 9.1.3 except for SUNNonlinSolSetup, SUNNonlinSolSetLSetupFn, SUNNonlinSolSetLSolveFn, SUNNonlinSolSetConvTestFn, and SUNNonlinSolSetMaxIters.

The SUNNONLINSOL_PETCSNES functions have the same names as those defined by the generic SUNNONLINSOL API with _PetscSNES appended to the function name. Unless using the SUNNONLINSOL_PETCSNES module as a standalone nonlinear solver the generic functions defined in sections 9.1.1 – 9.1.3 should be called in favor of the SUNNONLINSOL_PETCSNES-specific implementations.

The SUNNONLINSOL_PETCSNES module also defines the following additional user-callable functions.

SUNNonlinSolGetSNES_PetscSNES

Call
retval = SUNNonlinSolGetSNES_PetscSNES(NLS, SNES* snes);

Description
The function SUNNonlinSolGetSNES_PetscSNES gets the SNES context that was wrapped.

Arguments
NLS (SUNNonlinearSolver) a SUNNONLINSOL object
snes (SNES*) a pointer to a PETSc SNES object that will be set upon return

Return value
The return value retval (of type int) should be zero for a successful call, and a negative value for a failure.

SUNNonlinSolGetPetcError_PetscSNES

Call
retval = SUNNonlinSolGetPetcError_PetscSNES(NLS, PestcErrorCode* error);

Description
The function SUNNonlinSolGetPetcError_PetscSNES gets the last error code returned by the last internal call to a PETSc API function.

Arguments
NLS (SUNNonlinearSolver) a SUNNONLINSOL object
error (PestcErrorCode*) a pointer to a PETSc error integer that will be set upon return

Return value
The return value retval (of type int) should be zero for a successful call, and a negative value for a failure.

SUNNonlinSolGetSysFn_PetscSNES

Call
retval = SUNNonlinSolGetSysFn_PetscSNES(NLS, SysFn);

Description
The function SUNNonlinSolGetSysFn_PetscSNES returns the residual function that defines the nonlinear system.

Arguments
NLS (SUNNonlinearSolver) a SUNNONLINSOL object
SysFn (SUNNonlinSolSysFn*) the function defining the nonlinear system

Return value
The return value retval (of type int) should be zero for a successful call, and a negative value for a failure.
9.4.3 SUNNonlinearSolver_PetscSNES content

The SUNNONLINSOL_PETSCSNES module defines the content field of a SUNNonlinearSolver as the following structure:

```c
struct _SUNNonlinearSolverContent_PetscSNES {
    int sysfn_last_err;
    PetscErrorCode petsc_last_err;
    long int nconvfails;
    long int nni;
    void *imem;
    SNES snes;
    Vec r;
    N_Vector y, f;
    SUNNonlinSolSysFn Sys;
};
```

These entries of the content field contain the following information:
- `sysfn_last_err` - last error returned by the system defining function,
- `petsc_last_err` - last error returned by PETSc
- `nconvfails` - number of nonlinear converge failures (recoverable or not),
- `nni` - number of nonlinear iterations,
- `imem` - SUNDIALS integrator memory,
- `snes` - PETSc SNES context,
- `r` - the nonlinear residual,
- `y` - wrapper for PETSc vectors used in the system function,
- `f` - wrapper for PETSc vectors used in the system function,
- `Sys` - nonlinear system defining function.
Appendix A

SUNDIALS Package Installation Procedure

The installation of any SUNDIALS package is accomplished by installing the SUNDIALS suite as a whole, according to the instructions that follow. The same procedure applies whether or not the downloaded file contains one or all solvers in SUNDIALS.

The SUNDIALS suite (or individual solvers) are distributed as compressed archives (.tar.gz). The name of the distribution archive is of the form solver-x.y.z.tar.gz, where solver is one of: sundials, cvode, cvodes, arkode, ida, idas, or kinsol, and x.y.z represents the version number (of the SUNDIALS suite or of the individual solver). To begin the installation, first uncompress and expand the sources, by issuing

```
% tar xzf solver-x.y.z.tar.gz
```

This will extract source files under a directory solver-x.y.z.

Starting with version 2.6.0 of SUNDIALS, CMake is the only supported method of installation. The explanations of the installation procedure begins with a few common observations:

- The remainder of this chapter will follow these conventions:
  - **solverdir** is the directory solver-x.y.z created above; i.e., the directory containing the SUNDIALS sources.
  - **builddir** is the (temporary) directory under which SUNDIALS is built.
  - **instdir** is the directory under which the SUNDIALS exported header files and libraries will be installed. Typically, header files are exported under a directory instdir/include while libraries are installed under instdir/CMAKE_INSTALL_LIBDIR, with instdir and CMAKE_INSTALL_LIBDIR specified at configuration time.

- For SUNDIALS CMake-based installation, in-source builds are prohibited; in other words, the build directory builddir can not be the same as solverdir and such an attempt will lead to an error. This prevents “polluting” the source tree and allows efficient builds for different configurations and/or options.

- The installation directory instdir can not be the same as the source directory solverdir.

- By default, only the libraries and header files are exported to the installation directory instdir. If enabled by the user (with the appropriate toggle for CMake), the examples distributed with SUNDIALS will be built together with the solver libraries but the installation step will result in exporting (by default in a subdirectory of the installation directory) the example sources and sample outputs together with automatically generated configuration files that reference the installed SUNDIALS headers and libraries. As such, these configuration files for the SUNDIALS examples can be used as “templates” for your own problems. CMake installs CMakeLists.txt files
and also (as an option available only under Unix/Linux) Makefile files. Note this installation approach also allows the option of building the SUNDIALS examples without having to install them. (This can be used as a sanity check for the freshly built libraries.)

- Even if generation of shared libraries is enabled, only static libraries are created for the FCMIX modules. (Because of the use of fixed names for the Fortran user-provided subroutines, FCMIX shared libraries would result in “undefined symbol” errors at link time.)

## A.1 CMake-based installation

CMake-based installation provides a platform-independent build system. CMake can generate Unix and Linux Makefiles, as well as KDevelop, Visual Studio, and (Apple) XCode project files from the same configuration file. In addition, CMake also provides a GUI front end and which allows an interactive build and installation process.

The SUNDIALS build process requires CMake version 3.1.3 or higher and a working C compiler. On Unix-like operating systems, it also requires Make (and curses, including its development libraries, for the GUI front end to CMake, ccmake), while on Windows it requires Visual Studio. CMake is continually adding new features, and the latest version can be downloaded from http://www.cmake.org. Build instructions for CMake (only necessary for Unix-like systems) can be found on the CMake website. Once CMake is installed, Linux/Unix users will be able to use ccmake, while Windows users will be able to use CMakeSetup.

As previously noted, when using CMake to configure, build and install SUNDIALS, it is always required to use a separate build directory. While in-source builds are possible, they are explicitly prohibited by the SUNDIALS CMake scripts (one of the reasons being that, unlike autotools, CMake does not provide a make distclean procedure and it is therefore difficult to clean-up the source tree after an in-source build). By ensuring a separate build directory, it is an easy task for the user to clean-up all traces of the build by simply removing the build directory. CMake does generate a make clean which will remove files generated by the compiler and linker.

### A.1.1 Configuring, building, and installing on Unix-like systems

The default CMake configuration will build all included solvers and associated examples and will build static and shared libraries. The instdir defaults to /usr/local and can be changed by setting the CMAKE_INSTALL_PREFIX variable. Support for FORTRAN and all other options are disabled.

CMake can be used from the command line with the cmake command, or from a curses-based GUI by using the ccmake command. Examples for using both methods will be presented. For the examples shown it is assumed that there is a top level SUNDIALS directory with appropriate source, build and install directories:

```bash
% mkdir (...)sundials/instdir
% mkdir (...)sundials/builddir
% cd (...)sundials/builddir
```

**Building with the GUI**

Using CMake with the GUI follows this general process:

- Select and modify values, run configure (c key)
- New values are denoted with an asterisk
- To set a variable, move the cursor to the variable and press enter
  - If it is a boolean (ON/OFF) it will toggle the value
  - If it is string or file, it will allow editing of the string
-- For file and directories, the <tab> key can be used to complete

- Repeat until all values are set as desired and the generate option is available (g key)
- Some variables (advanced variables) are not visible right away
- To see advanced variables, toggle to advanced mode (t key)
- To search for a variable press / key, and to repeat the search, press the n key

To build the default configuration using the GUI, from the builddir enter the ccmake command and point to the solverdir:

% ccmake ../solverdir

The default configuration screen is shown in Figure A.1.

The default instdir for both sundials and corresponding examples can be changed by setting the CMAKE_INSTALL_PREFIX and the EXAMPLES_INSTALL_PATH as shown in figure A.2.

Pressing the (g key) will generate makefiles including all dependencies and all rules to build Sundials on this system. Back at the command prompt, you can now run:
To install SUNDIALS in the installation directory specified in the configuration, simply run:

% make install

Building from the command line

Using CMake from the command line is simply a matter of specifying CMake variable settings with the `make` command. The following will build the default configuration:

% make

A.1.2 Configuration options (Unix/Linux)

A complete list of all available options for a CMake-based SUNDIALS configuration is provide below. Note that the default values shown are for a typical configuration on a Linux system and are provided as illustration only.
BUILD_ARKODE - Build the ARKODE library
   Default: ON

BUILD_CVODE - Build the CVODE library
   Default: ON

BUILD_CVODES - Build the CVODES library
   Default: ON

BUILD_IDA - Build the IDA library
   Default: ON

BUILD_IDAS - Build the IDAS library
   Default: ON

BUILD_KINSOL - Build the KINSOL library
   Default: ON

BUILD_SHARED_LIBS - Build shared libraries
   Default: ON

BUILD_STATIC_LIBS - Build static libraries
   Default: ON

CMAKE_BUILD_TYPE - Choose the type of build, options are: None (CMAKE_C_FLAGS used), Debug, Release, RelWithDebInfo, and MinSizeRel
   Default:
   Note: Specifying a build type will trigger the corresponding build type specific compiler flag options below which will be appended to the flags set by CMAKE_<language>_FLAGS.

CMAKE_C_COMPILER - C compiler
   Default: /usr/bin/cc

CMAKE_C_FLAGS - Flags for C compiler
   Default:

CMAKE_C_FLAGS_DEBUG - Flags used by the C compiler during debug builds
   Default: -g

CMAKE_C_FLAGS_MINSIZEREL - Flags used by the C compiler during release minsize builds
   Default: -Os -DNDEBUG

CMAKE_C_FLAGS_RELEASE - Flags used by the C compiler during release builds
   Default: -O3 -DNDEBUG

CMAKE_CXX_COMPILER - C++ compiler
   Default: /usr/bin/c++
   Note: A C++ compiler (and all related options) are only triggered if C++ examples are enabled (EXAMPLES_ENABLE_CXX is ON). All sundials solvers can be used from C++ applications by default without setting any additional configuration options.

CMAKE_CXX_FLAGS - Flags for C++ compiler
   Default:

CMAKE_CXX_FLAGS_DEBUG - Flags used by the C++ compiler during debug builds
   Default: -g

CMAKE_CXX_FLAGS_MINSIZEREL - Flags used by the C++ compiler during release minsize builds
   Default: -Os -DNDEBUG
CMAKE_CXX_FLAGS_RELEASE - Flags used by the C++ compiler during release builds
   Default: -O3 -DNDEBUG

CMAKE_Fortran_COMPILER - Fortran compiler
   Default: /usr/bin/gfortran
   Note: Fortran support (and all related options) are triggered only if either Fortran-C support is enabled (FCMIX_ENABLE is ON) or LAPACK support is enabled (LAPACK_ENABLE is ON).

CMAKE_Fortran_FLAGS - Flags for Fortran compiler
   Default:

CMAKE_Fortran_FLAGS_DEBUG - Flags used by the Fortran compiler during debug builds
   Default: -g

CMAKE_Fortran_FLAGS_MINSIZEREL - Flags used by the Fortran compiler during release minsize builds
   Default: -Os

CMAKE_Fortran_FLAGS_RELEASE - Flags used by the Fortran compiler during release builds
   Default: -O3

CMAKE_INSTALL_PREFIX - Install path prefix, prepended onto install directories
   Default: /usr/local
   Note: The user must have write access to the location specified through this option. Exported SUNDIALS header files and libraries will be installed under subdirectories include and CMAKE_INSTALL_LIBDIR of CMAKE_INSTALL_PREFIX, respectively.

CMAKE_INSTALL_LIBDIR - Library installation directory
   Default:
   Note: This is the directory within CMAKE_INSTALL_PREFIX that the SUNDIALS libraries will be installed under. The default is automatically set based on the operating system using the GNUInstallDirs CMake module.

Fortran_INSTALL_MODDIR - Fortran module installation directory
   Default: fortran

CUDA_ENABLE - Build the SUNDIALS CUDA modules.
   Default: OFF

CUDA_ARCH - Specifies the CUDA architecture to compile for.
   Default: sm_30

EXAMPLES_ENABLE_C - Build the SUNDIALS C examples
   Default: ON

EXAMPLES_ENABLE_CUDA - Build the SUNDIALS CUDA examples
   Default: OFF
   Note: You need to enable CUDA support to build these examples.

EXAMPLES_ENABLE_CXX - Build the SUNDIALS C++ examples
   Default: OFF unless Trilinos_ENABLE is ON.

EXAMPLES_ENABLE_F77 - Build the SUNDIALS Fortran77 examples
   Default: ON (if F77_INTERFACE_ENABLE is ON)

EXAMPLES_ENABLE_F90 - Build the SUNDIALS Fortran90 examples
   Default: ON (if F77_INTERFACE_ENABLE is ON)

EXAMPLES_ENABLE_F2003 - Build the SUNDIALS Fortran2003 examples
   Default: ON (if F2003_INTERFACE_ENABLE is ON)
**EXAMPLES_INSTALL** - Install example files
Default: ON
Note: This option is triggered when any of the SUNDIALS example programs are enabled (EXAMPLES_ENABLE_<language> is ON). If the user requires installation of example programs then the sources and sample output files for all SUNDIALS modules that are currently enabled will be exported to the directory specified by EXAMPLES_INSTALL_PATH. A CMake configuration script will also be automatically generated and exported to the same directory. Additionally, if the configuration is done under a Unix-like system, makefiles for the compilation of the example programs (using the installed SUNDIALS libraries) will be automatically generated and exported to the directory specified by EXAMPLES_INSTALL_PATH.

**EXAMPLES_INSTALL_PATH** - Output directory for installing example files
Default: /usr/local/examples
Note: The actual default value for this option will be an examples subdirectory created under CMAKE_INSTALL_PREFIX.

**F77_INTERFACE_ENABLE** - Enable Fortran-C support via the Fortran 77 interfaces
Default: OFF

**F2003_INTERFACE_ENABLE** - Enable Fortran-C support via the Fortran 2003 interfaces
Default: OFF

**HYPRE_ENABLE** - Enable hypre support
Default: OFF
Note: See additional information on building with hypre enabled in A.1.4.

**HYPRE_INCLUDE_DIR** - Path to hypre header files

**HYPRE_LIBRARY_DIR** - Path to hypre installed library files

**KLU_ENABLE** - Enable KLU support
Default: OFF
Note: See additional information on building with KLU enabled in A.1.4.

**KLU_INCLUDE_DIR** - Path to SuiteSparse header files

**KLU_LIBRARY_DIR** - Path to SuiteSparse installed library files

**LAPACK_ENABLE** - Enable LAPACK support
Default: OFF
Note: Setting this option to ON will trigger additional CMake options. See additional information on building with LAPACK enabled in A.1.4.

**LAPACK_LIBRARIES** - LAPACK (and BLAS) libraries
Default: /usr/lib/liblapack.so;/usr/lib/libblas.so
Note: CMake will search for libraries in your LD_LIBRARY_PATH prior to searching default system paths.

**MPI_ENABLE** - Enable MPI support. This will build the parallel NVVECTOR and the MPI-aware version of the ManyVector library.
Default: OFF
Note: Setting this option to ON will trigger several additional options related to MPI.

**MPI_C_COMPILER** - mpicc program
Default:

**MPI_CXX_COMPILER** - mpicxx program
Default:
SUNDIALS Package Installation Procedure

Note: This option is triggered only if MPI is enabled (MPI_ENABLE is ON) and C++ examples are enabled (EXAMPLES_ENABLE_CXX is ON). All SUNDIALS solvers can be used from C++ MPI applications by default without setting any additional configuration options other than MPI_ENABLE.

**MPI_Fortran_COMPILER** - mpif77 or mpif90 program
Default:
Note: This option is triggered only if MPI is enabled (MPI_ENABLE is ON) and Fortran-C support is enabled (F77_INTERFACE_ENABLE or F2003_INTERFACE_ENABLE is ON).

**MPIEXEC_EXECUTABLE** - Specify the executable for running MPI programs
Default: mpirun
Note: This option is triggered only if MPI is enabled (MPI_ENABLE is ON).

**OPENMP_ENABLE** - Enable OpenMP support (build the OpenMP nvector).
Default: OFF

**OPENMP_DEVICE_ENABLE** - Enable OpenMP device offloading (build the OpenMPDEV nvector) if supported by the provided compiler.
Default: OFF

**SKIP_OPENMP_DEVICE_CHECK** - advanced option - Skip the check done to see if the OpenMP provided by the compiler supports OpenMP device offloading.
Default: OFF

**PETSC_ENABLE** - Enable PETSc support
Default: OFF
Note: See additional information on building with PETSc enabled in ??.

**PETSC_DIR** - Path to PETSc installation
Default:

**PETSC_LIBRARIES** - advanced option - Semi-colon separated list of PETSc link libraries. Unless provided by the user, this is autopopulated based on the PETSc installation found in PETSC_DIR.
Default:

**PETSC_INCLUDES** - advanced option - Semi-colon separated list of PETSc include directories. Unless provided by the user, this is autopopulated based on the PETSc installation found in PETSC_DIR.
Default:

**PTHREAD_ENABLE** - Enable Pthreads support (build the Pthreads nvector).
Default: OFF

**RAJA_ENABLE** - Enable RAJA support (build the RAJA nvector).
Default: OFF
Note: You need to enable CUDA in order to build the RAJA vector module.

**SUNDIALS_F77_FUNC_CASE** - advanced option - Specify the case to use in the Fortran name-mangling scheme, options are: lower or upper
Default:
Note: The build system will attempt to infer the Fortran name-mangling scheme using the Fortran compiler. This option should only be used if a Fortran compiler is not available or to override the inferred or default (lower) scheme if one can not be determined. If used, SUNDIALS_F77_FUNC_UNDERSCORES must also be set.

**SUNDIALS_F77_FUNC_UNDERSCORES** - advanced option - Specify the number of underscores to append in the Fortran name-mangling scheme, options are: none, one, or two
Default:
Note: The build system will attempt to infer the Fortran name-mangling scheme using the Fortran compiler. This option should only be used if a Fortran compiler is not available
or to override the inferred or default (one) scheme if one can not be determined. If used, 
SUNDIALS_F77_FUNC_CASE must also be set.

SUNDIALS_INDEX_TYPE - advanced option - Integer type used for SUNDIALS indices. The size must
match the size provided for the
SUNDIALS_INDEX_SIZE option.
Default:
Note: In past SUNDIALS versions, a user could set this option to INT64_T to use 64-bit integers,
or INT32_T to use 32-bit integers. Starting in SUNDIALS 3.2.0, these special values are dep-
recated. For SUNDIALS 3.2.0 and up, a user will only need to use the SUNDIALS_INDEX_SIZE
option in most cases.

SUNDIALS_INDEX_SIZE - Integer size (in bits) used for indices in SUNDIALS, options are: 32 or 64
Default: 64
Note: The build system tries to find an integer type of appropriate size. Candidate 64-bit
integer types are (in order of preference): int64_t, __int64, long long, and long. Candidate
32-bit integers are (in order of preference): int32_t, int, and long. The advanced option,
SUNDIALS_INDEX_TYPE can be used to provide a type not listed here.

SUNDIALS_PRECISION - Precision used in SUNDIALS, options are: double, single, or extended
Default: double

SUPERLUDIST_ENABLE - Enable SuperLU_DIST support
Default: OFF
Note: See additional information on building with SuperLU_DIST enabled in A.1.4.

SUPERLUDIST_INCLUDE_DIR - Path to SuperLU_DIST header files (typically SRC directory)

SUPERLUDIST_LIBRARY_DIR - Path to SuperLU_DIST installed library files

SUPERLUDIST_LIBRARIES - Semi-colon separated list of libraries needed for SuperLU_DIST

SUPERLUDIST_OpenMP - Enable SUNDIALS support for SuperLU_DIST built with OpenMP
Default: OFF
Note: SuperLU_DIST must be built with OpenMP support for this option to function properly.
Additionally the environment variable OMP_NUM_THREADS must be set to the desired number of
threads.

SUPERLUMT_ENABLE - Enable SUPERLUMT support
Default: OFF
Note: See additional information on building with SUPERLUMT enabled in A.1.4.

SUPERLUMT_INCLUDE_DIR - Path to SuperLU_MT header files (typically SRC directory)

SUPERLUMT_LIBRARY_DIR - Path to SuperLU_MT installed library files

SUPERLUMT_LIBRARIES - Semi-colon separated list of libraries needed for SuperLU_MT

SUPERLUMT_THREAD_TYPE - Must be set to Pthread or OpenMP
Default: Pthread

Trilinos_ENABLE - Enable Trilinos support (build the Tpetra NVVECTOR).
Default: OFF

Trilinos_DIR - Path to the Trilinos install directory.
Default:
TRILINOS_INTERFACE_C_COMPILER - advanced option - Set the C compiler for building the Trilinos interface (i.e., nvector_trilinos and the examples that use it).
Default: The C compiler exported from the found Trilinos installation if USE_XSDK_DEFAULTS=OFF.
CMAKE_C_COMPILER or MPI_C_COMPILER if USE_XSDK_DEFAULTS=ON.
Note: It is recommended to use the same compiler that was used to build the Trilinos library.

TRILINOS_INTERFACE_C_COMPILER_FLAGS - advanced option - Set the C compiler flags for Trilinos interface (i.e., nvector_trilinos and the examples that use it).
Default: The C compiler flags exported from the found Trilinos installation if USE_XSDK_DEFAULTS=OFF.
CMAKE_C_FLAGS if USE_XSDK_DEFAULTS=ON.
Note: It is recommended to use the same flags that were used to build the Trilinos library.

TRILINOS_INTERFACE_CXX_COMPILER - advanced option - Set the C++ compiler for building Trilinos interface (i.e., nvector_trilinos and the examples that use it).
Default: The C++ compiler exported from the found Trilinos installation if USE_XSDK_DEFAULTS=OFF.
CMAKE_CXX_COMPILER or MPI_CXX_COMPILER if USE_XSDK_DEFAULTS=ON.
Note: It is recommended to use the same compiler that was used to build the Trilinos library.

TRILINOS_INTERFACE_CXX_COMPILER_FLAGS - advanced option - Set the C++ compiler flags for Trilinos interface (i.e., nvector_trilinos and the examples that use it).
Default: The C++ compiler flags exported from the found Trilinos installation if USE_XSDK_DEFAULTS=OFF.
CMAKE_CXX_FLAGS if USE_XSDK_DEFAULTS=ON.
Note: It is recommended to use the same flags that were used to build the Trilinos library.

USE_GENERIC_MATH - Use generic (stdc) math libraries
Default: ON

xSDK Configuration Options

SUNDIALS supports CMake configuration options defined by the Extreme-scale Scientific Software Development Kit (xSDK) community policies (see https://xsdk.info for more information). xSDK CMake options are unused by default but may be activated by setting USE_XSDK_DEFAULTS to ON.

When xSDK options are active, they will overwrite the corresponding SUNDIALS option and may have different default values (see details below). As such the equivalent SUNDIALS options should not be used when configuring with xSDK options. In the GUI front end to CMake (ccmake), setting USE_XSDK_DEFAULTS to ON will hide the corresponding SUNDIALS options as advanced CMake variables. During configuration, messages are output detailing which xSDK flags are active and the equivalent SUNDIALS options that are replaced. Below is a complete list xSDK options and the corresponding SUNDIALS options if applicable.

TPL_ENABLE_HYPRE - Enable hypre support
Default: OFF
SUNDIALS equivalent: HYPRE_ENABLE

TPL_ENABLE_KLU - Enable KLU support
Default: OFF
SUNDIALS equivalent: KLU_ENABLE

TPL_ENABLE_PETSC - Enable PETSc support
Default: OFF
SUNDIALS equivalent: PETSC_ENABLE

TPL_ENABLE_LAPACK - Enable LAPACK support
Default: OFF
SUNDIALS equivalent: LAPACK_ENABLE
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TPL_ENABLE_SUPERLUDIST - Enable SuperLU_DIST support
   Default: OFF
   SUNDIALS equivalent: SUPERLUDIST_ENABLE

TPL_ENABLE_SUPERLUMT - Enable SuperLU_MT support
   Default: OFF
   SUNDIALS equivalent: SUPERLUMT_ENABLE

TPL_HYPRE_INCLUDE_DIRS - Path to hypre header files
   SUNDIALS equivalent: HYPRE_INCLUDE_DIR

TPL_HYPRE_LIBRARIES - hypre library
   SUNDIALS equivalent: N/A

TPL_KLU_INCLUDE_DIRS - Path to KLU header files
   SUNDIALS equivalent: KLU_INCLUDE_DIR

TPL_KLU_LIBRARIES - KLU library
   SUNDIALS equivalent: N/A

TPL_LAPACK_LIBRARIES - LAPACK (and BLAS) libraries
   Default: /usr/lib/liblapack.so:/usr/lib/libblas.so
   SUNDIALS equivalent: LAPACK_LIBRARIES
   Note: CMake will search for libraries in your LD_LIBRARY_PATH prior to searching default system paths.

TPL_PETSC_DIR - Path to PETSc installation
   SUNDIALS equivalent: PETSC_DIR

TPL_SUPERLUDIST_INCLUDE_DIRS - Path to SuperLU_DIST header files
   SUNDIALS equivalent: SUPERLUDIST_INCLUDE_DIR

TPL_SUPERLUDIST_LIBRARIES - Semi-colon separated list of libraries needed for SuperLU_DIST including the SuperLU_DIST library itself
   SUNDIALS equivalent: SUPERLUDIST_LIBRARIES

TPL_SUPERLUDIST_OPENMP - Enable SUNDIALS support for SuperLU_DIST built with OpenMP
   SUNDIALS equivalent: SUPERLUDIST_OPENMP

TPL_SUPERLUMT_LIBRARIES - SuperLU_MT library
   SUNDIALS equivalent: N/A

TPL_SUPERLUMT_THREAD_TYPE - SuperLU_MT library thread type
   SUNDIALS equivalent: SUPERLUMT_THREAD_TYPE

USE_XSDK_DEFAULTS - Enable xSDK default configuration settings
   Default: OFF
   SUNDIALS equivalent: N/A
   Note: Enabling xSDK defaults also sets CMAKE_BUILD_TYPE to Debug

XSDK_ENABLE_FORTRAN - Enable SUNDIALS Fortran interfaces
   Default: OFF
   SUNDIALS equivalent: F77_INTERFACE_ENABLE/F2003_INTERFACE_ENABLE

XSDK_INDEX_SIZE - Integer size (bits) used for indices in SUNDIALS, options are: 32 or 64
   Default: 32
   SUNDIALS equivalent: SUNDIALS_INDEX_SIZE

XSDK_PRECISION - Precision used in SUNDIALS, options are: double, single, or quad
   Default: double
   SUNDIALS equivalent: SUNDIALS_PRECISION
A.1.3 Configuration examples

The following examples will help demonstrate usage of the CMake configure options.
To configure SUNDIALS using the default C and Fortran compilers, and default mpicc and mpif77 parallel compilers, enable compilation of examples, and install libraries, headers, and example sources under subdirectories of /home/myname/sundials/, use:

```
% cmake \\
> -DCMAKE_INSTALL_PREFIX=/home/myname/sundials/instdir \\
> -DEXAMPLES_INSTALL_PATH=/home/myname/sundials/instdir/examples \\
> -DMPI_ENABLE=ON \\
> -DFCMIX_ENABLE=ON \\
>/home/myname/sundials/solverdir \\
%
% make install \\
%
```

To disable installation of the examples, use:

```
% cmake \\
> -DCMAKE_INSTALL_PREFIX=/home/myname/sundials/instdir \\
> -DEXAMPLES_INSTALL_PATH=/home/myname/sundials/instdir/examples \\
> -DMPI_ENABLE=ON \\
> -DFCMIX_ENABLE=ON \\
> -DEXAMPLES_INSTALL=OFF \\
>/home/myname/sundials/solverdir \\
%
% make install \\
%
```

A.1.4 Working with external Libraries

The SUNDIALS suite contains many options to enable implementation flexibility when developing solutions. The following are some notes addressing specific configurations when using the supported third party libraries. When building SUNDIALS as a shared library any external libraries used with SUNDIALS must also be build as a shared library or as a static library compiled with the -fPIC flag.

Building with LAPACK

To enable LAPACK, set the LAPACK_ENABLE option to ON. If the directory containing the LAPACK library is in the LD_LIBRARY_PATH environment variable, CMake will set the LAPACK_LIBRARIES variable accordingly, otherwise CMake will attempt to find the LAPACK library in standard system locations. To explicitly tell CMake what library to use, the LAPACK_LIBRARIES variable can be set to the desired libraries required for LAPACK.

```
% cmake \\
> -DCMAKE_INSTALL_PREFIX=/home/myname/sundials/instdir \\
> -DEXAMPLES_INSTALL_PATH=/home/myname/sundials/instdir/examples \\
> -DLAPACK_ENABLE=ON \\
> -DLAPACK_LIBRARIES=/mylapackpath/lib/libblas.so;/mylapackpath/lib/liblapack.so \\
>/home/myname/sundials/solverdir \\
%
% make install \\
%
```
If a working Fortran compiler is not available to infer the Fortran name-mangling scheme, the options `SUNDIALS_F77_FUNC_CASE` and `SUNDIALS_F77_FUNC_UNDERSCORES` must be set in order to bypass the check for a Fortran compiler and define the name-mangling scheme. The defaults for these options in earlier versions of SUNDIALS were `lower` and `one` respectively.

### Building with KLU

The KLU libraries are part of SuiteSparse, a suite of sparse matrix software, available from the Texas A&M University website: [http://faculty.cse.tamu.edu/davis/suitesparse.html](http://faculty.cse.tamu.edu/davis/suitesparse.html). SUNDIALS has been tested with KLU, set `KLU_ENABLE` to ON, set `KLU_INCLUDE_DIR` to the include path of the KLU installation and set `KLU_LIBRARY_DIR` to the lib path of the KLU installation. The CMake configure will result in populating the following variables: `AMD_LIBRARY`, `AMD_LIBRARY_DIR`, `BTF_LIBRARY`, `BTF_LIBRARY_DIR`, `COLAMD_LIBRARY`, `COLAMD_LIBRARY_DIR`, and `KLU_LIBRARY`.

### Building with SuperLU_MT

The SuperLU_MT libraries are available for download from the Lawrence Berkeley National Laboratory website: [http://crd-legacy.lbl.gov/~xiaoye/SuperLU/#superlu_mt](http://crd-legacy.lbl.gov/~xiaoye/SuperLU/#superlu_mt). SUNDIALS has been tested with SuperLU_MT version 3.1. To enable SuperLU_MT, set `SUPERLUMT_ENABLE` to ON, set `SUPERLUMT_INCLUDE_DIR` to the SRC path of the SuperLU_MT installation, and set the variable `SUPERLUMT_LIBRARY_DIR` to the lib path of the SuperLU_MT installation. At the same time, the variable `SUPERLUMT_LIBRARIES` must be set to a semi-colon separated list of other libraries SuperLU_MT depends on. For example, if SuperLU_MT was build with an external blas library, then include the full path to the blas library in this list. Additionally, the variable `SUPERLUMT_THREAD_TYPE` must be set to either Pthread or OpenMP.

Do not mix thread types when building SUNDIALS solvers. If threading is enabled for SUNDIALS by having either `OPENMP_ENABLE` or `PTHREAD_ENABLE` set to ON then SuperLU_MT should be set to use the same threading type.

### Building with SuperLU_DIST

The SuperLU_DIST libraries are available for download from the Lawrence Berkeley National Laboratory website: [http://crd-legacy.lbl.gov/~xiaoye/SuperLU/#superlu_dist](http://crd-legacy.lbl.gov/~xiaoye/SuperLU/#superlu_dist). SUNDIALS has been tested with SuperLU_DIST 6.1.1. To enable SuperLU_DIST, set `SUPERLUDIST_ENABLE` to ON, set `SUPERLUDIST_INCLUDE_DIR` to the include directory of the SuperLU_DIST installation (typically SRC), and set the variable `SUPERLUDIST_LIBRARY_DIR` to the path to library directory of the SuperLU_DIST installation (typically lib). At the same time, the variable `SUPERLUDIST_LIBRARIES` must be set to a semi-colon separated list of other libraries SuperLU_DIST depends on. For example, if SuperLU_DIST was built with LAPACK, then include the LAPACK library in this list. If SuperLU_DIST was built with OpenMP support, then you may set `SUPERLUDIST_OPENMP` to ON to utilize the OpenMP functionality of SuperLU_DIST.

Do not mix thread types when building SUNDIALS solvers. If threading is enabled for SUNDIALS by having `PTHREAD_ENABLE` set to ON then SuperLU_DIST should not be set to use OpenMP.

### Building with PETSc

The PETSc libraries are available for download from the Argonne National Laboratory website: [http://www.mcs.anl.gov/petsc](http://www.mcs.anl.gov/petsc). SUNDIALS has been tested with PETSc version 3.10.0–3.12.1. To enable PETSc, set `PETSC_ENABLE` to ON and then set `PETSC_DIR` to the path of the PETSc installation. Alternatively, a user can provide a list of include paths in `PETSC_INCLUDES`, and a list of complete paths to the libraries needed in `PETSC_LIBRARIES`.
Building with hypre

The hypre libraries are available for download from the Lawrence Livermore National Laboratory website: http://computing.llnl.gov/projects/hypre. SUNDIALS has been tested with hypre version 2.14.0–2.18.0. To enable hypre, set HYPRE_ENABLE to ON, set HYPRE_INCLUDE_DIR to the include path of the hypre installation, and set the variable HYPRE_LIBRARY_DIR to the lib path of the hypre installation.

Note: SUNDIALS must be configured so that SUNDIALS_INDEX_SIZE (or equivalently, XSDK_INDEX_SIZE) equals the precision of HYPRE_BigInt in the corresponding hypre installation.

Building with CUDA

SUNDIALS CUDA modules and examples have been tested with versions 9 through 10.1 of the CUDA toolkit. To build them, you need to install the Toolkit and compatible NVIDIA drivers. Both are available for download from the NVIDIA website: https://developer.nvidia.com/cuda-downloads. To enable CUDA, set CUDA_ENABLE to ON. If CUDA is installed in a nonstandard location, you may be prompted to set the variable CUDA_TOOLKIT_ROOT_DIR with your CUDA Toolkit installation path. To enable CUDA examples, set EXAMPLES_ENABLE_CUDA to ON.

Building with RAJA

RAJA is a performance portability layer developed by Lawrence Livermore National Laboratory and can be obtained from https://github.com/LLNL/RAJA. SUNDIALS RAJA modules and examples have been tested with RAJA up to version 0.9. Building SUNDIALS RAJA modules requires a CUDA-enabled RAJA installation. To enable RAJA, set CUDA_ENABLE and RAJA_ENABLE to ON. If RAJA is installed in a nonstandard location you will be prompted to set the variable RAJA_DIR with the path to the RAJA CMake configuration file. To enable building the RAJA examples set EXAMPLES_ENABLE_CUDA to ON.

Building with Trilinos

Trilinos is a suite of numerical libraries developed by Sandia National Laboratories. It can be obtained at https://github.com/trilinos/Trilinos. SUNDIALS Trilinos modules and examples have been tested with Trilinos version 12.14.1. To enable Trilinos, set Trilinos_ENABLE to ON. If Trilinos is installed in a nonstandard location you will be prompted to set the variable Trilinos_DIR with the path to the Trilinos CMake configuration file. It is desirable to build the Trilinos vector interface with same compiler and options that were used to build Trilinos. CMake will try to find the correct compiler settings automatically from the Trilinos configuration file. If that is not successful, the compilers and options can be manually set with the following CMake variables:

- Trilinos_INTERFACE_C_COMPILER
- Trilinos_INTERFACE_C_COMPILER_FLAGS
- Trilinos_INTERFACE_CXX_COMPILER
- Trilinos_INTERFACE_CXX_COMPILER_FLAGS

A.1.5 Testing the build and installation

If SUNDIALS was configured with EXAMPLES_ENABLE_<language> options to ON, then a set of regression tests can be run after building with the make command by running:

% make test

Additionally, if EXAMPLES_INSTALL was also set to ON, then a set of smoke tests can be run after installing with the make install command by running:

% make test_install
A.2 Building and Running Examples

Each of the SUNDIALS solvers is distributed with a set of examples demonstrating basic usage. To build and install the examples, set at least one of the EXAMPLES_ENABLE_<language> options to ON, and set EXAMPLES_INSTALL to ON. Specify the installation path for the examples with the variable EXAMPLES_INSTALL_PATH. CMake will generate CMakeLists.txt configuration files (and Makefile files if on Linux/Unix) that reference the installed SUNDIALS headers and libraries.

Either the CMakeLists.txt file or the traditional Makefile may be used to build the examples as well as serve as a template for creating user developed solutions. To use the supplied Makefile simply run make to compile and generate the executables. To use CMake from within the installed example directory, run cmake (or ccmake to use the GUI) followed by make to compile the example code. Note that if CMake is used, it will overwrite the traditional Makefile with a new CMake-generated Makefile. The resulting output from running the examples can be compared with example output bundled in the SUNDIALS distribution.

NOTE: There will potentially be differences in the output due to machine architecture, compiler versions, use of third party libraries etc.

A.3 Configuring, building, and installing on Windows

CMake can also be used to build SUNDIALS on Windows. To build SUNDIALS for use with Visual Studio the following steps should be performed:

1. Unzip the downloaded tar file(s) into a directory. This will be the solverdir
2. Create a separate builddir
3. Open a Visual Studio Command Prompt and cd to builddir
4. Run cmake-gui ../solverdir
   (a) Hit Configure
   (b) Check/Uncheck solvers to be built
   (c) Change CMAKE_INSTALL_PREFIX to instdir
   (d) Set other options as desired
   (e) Hit Generate
5. Back in the VS Command Window:
   (a) Run msbuild ALL_BUILD.vcxproj
   (b) Run msbuild INSTALL.vcxproj

The resulting libraries will be in the instdir. The SUNDIALS project can also now be opened in Visual Studio. Double click on the ALL_BUILD.vcxproj file to open the project. Build the whole solution to create the SUNDIALS libraries. To use the SUNDIALS libraries in your own projects, you must set the include directories for your project, add the SUNDIALS libraries to your project solution, and set the SUNDIALS libraries as dependencies for your project.

A.4 Installed libraries and exported header files

Using the CMake SUNDIALS build system, the command

% make install
will install the libraries under `libdir` and the public header files under `includedir`. The values for these directories are `instdir/CMAKE_INSTALL_LIBDIR` and `instdir/include`, respectively. The location can be changed by setting the CMake variable `CMAKE_INSTALL_PREFIX`. Although all installed libraries reside under `libdir/CMAKE_INSTALL_LIBDIR`, the public header files are further organized into subdirectories under `includedir/include`.

The installed libraries and exported header files are listed for reference in Table A.1. The file extension `.lib` is typically `.so` for shared libraries and `.a` for static libraries. Note that, in the Tables, names are relative to `libdir` for libraries and to `includedir` for header files.

A typical user program need not explicitly include any of the shared SUNDIALS header files from under the `includedir/include/sundials` directory since they are explicitly included by the appropriate solver header files (e.g., `cvode_dense.h` includes `sundials_dense.h`). However, it is both legal and safe to do so, and would be useful, for example, if the functions declared in `sundials_dense.h` are to be used in building a preconditioner.
### Table A.1: **SUNDIALS** libraries and header files

<table>
<thead>
<tr>
<th>Shared</th>
<th>Libraries</th>
<th>Header files</th>
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<td>n/a</td>
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<th><strong>Libraries</strong></th>
<th><strong>Header files</strong></th>
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<td>n/a</td>
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<table>
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<th>nvector/nvector_serial.h</th>
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<th>Header files</th>
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<td>libsundials_nvecserial.lib</td>
<td>nvector/nvector_serial.h</td>
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<tr>
<td></td>
<td>libsundials_fnvecserial_mod.lib</td>
<td>nvector/nvector_serial.h</td>
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<tr>
<td></td>
<td>libsundials_fnvecserial.a</td>
<td>nvector/nvector_serial.h</td>
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<th>Header files</th>
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<td>nvector/nvector_parallel.h</td>
</tr>
<tr>
<td></td>
<td>libsundials_fnvecparallel.a</td>
<td>nvector/nvector_parallel.h</td>
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<tr>
<td></td>
<td>libsundials_fnvecparallel_mod.lib</td>
<td>nvector/nvector_parallel.h</td>
</tr>
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<thead>
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<th><strong>Module files</strong></th>
<th>fnvector_parallel_mod.mod</th>
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<thead>
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<td>nvector/nvector_manyvector.h</td>
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<th><strong>Module files</strong></th>
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## A.4 Installed libraries and exported header files

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<td><strong>Header files</strong></td>
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<td><strong>SUNLINSOL_SPBCGS</strong></td>
<td><strong>Libraries</strong></td>
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### SUNLINSOL_LIBSUNDIALS_FSUNLINSOLSPBCGS
- **Libraries**: libsundials_fsunlinsolspbcgs.lib
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  - libsundials_fsunlinsolspbcgs.a
- **Header files**: sunlinsol/sunlinsol_spbcgs.h
- **Module files**: fsunlinsol_spbcgs_mod.mod

### SUNLINSOL_SPFGMR
- **Libraries**: libsundials_sunlinsolspfgmr.lib
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  - libsundials_sunlinsolspfgmr.a
- **Header files**: sunlinsol/sunlinsol_spfgmr.h
- **Module files**: fsunlinsol_spfgmr_mod.mod

### SUNLINSOL_SPGMR
- **Libraries**: libsundials_sunlinsolspgmr.lib
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  - libsundials_sunlinsolspgmr.a
- **Header files**: sunlinsol/sunlinsol_spgmr.h
- **Module files**: fsunlinsol_spgmr_mod.mod

### SUNLINSOL_SPTFQMR
- **Libraries**: libsundials_sunlinsolsptfqmr.lib
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  - libsundials_sunlinsolsptfqmr.a
- **Header files**: sunlinsol/sunlinsol_sptfqmr.h
- **Module files**: fsunlinsol_sptfqmr_mod.mod

### SUNLINSOL_SUPERLUMT
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- **Header files**: sunlinsol/sunlinsol_superlumt.h

### SUNLINSOL_SUPERLUDIST
- **Libraries**: libsundials_sunlinsolsuperludist.lib
  - libsundials_sunlinsolsuperludist.a
- **Header files**: sunlinsol/sunlinsol_superludist.h

### SUNLINSOL_CUSOVELSP_BATCHQ
- **Libraries**: libsundials_sunlinsolcusolversp.lib
- **Header files**: sunlinsol/sunlinsolcusolversp_batchqr.h

### SUNNONLINSOL_NEWTON
- **Libraries**: libsundials_sunnloninsolnewton.lib
  - libsundials_sunnloninsolnewton_mod.lib
  - libsundials_sunnloninsolnewton.a
- **Header files**: sunnonlinsol/sunnloninsol_newton.h
- **Module files**: fsunnloninsol_newton_mod.mod

### SUNNONLINSOL_FIXEDPOINT
- **Libraries**: libsundials_sunnloninsolfixedpoint.lib
  - libsundials_sunnloninsolfixedpoint_mod.lib
  - libsundials_sunnloninsolfixedpoint.a
- **Header files**: sunnonlinsol/sunnloninsol_fixedpoint.h
- **Module files**: fsunnloninsol_fixedpoint_mod.mod

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<table>
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<tr>
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<td>sunnonsol/sunnonsol_petcsnes.h</td>
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| CVODE                  | Libraries                           | Header files                      |
|                        | libsundials_cvode.lib               | cvode/cvode.h cvode/cvode_impl.h  |
|                        | libsundials_fcvode.a                | cvode/cvode_direct.h cvode/cvode_ls.h |
|                        | libsundials_fcvode_mod.lib          | cvode/cvode_spils.h cvode/cvode_bandpre.h |
|                        |                                      | cvode/cvode_bbdpre.h             |
|                        |                                      |                                  |
|                        | cvode/cvode.h                       | cvode/cvode_impl.h               |
|                        | cvode/cvode_direct.h                | cvode/cvode_ls.h                 |
|                        | cvode/cvode_spils.h                 | cvode/cvode_bandpre.h            |
|                        | cvode/cvode_bbdpre.h                |                                  |
|                        |                                      |                                  |
|                        | fcvode_mod.mod                      |                                  |

| CVODES                 | Libraries                           | Header files                      |
|                        | libsundials_cvodes.lib              | cvodes/cvodes.h cvodes/cvodes_impl.h |
|                        | libsundials_fcvodes_mod.lib         | cvodes/cvodes_direct.h cvodes/cvodes_ls.h |
|                        |                                      | cvodes/cvodes_spils.h cvodes/cvodes_bandpre.h |
|                        |                                      | cvodes/cvodes_bbdpre.h           |
|                        |                                      |                                  |
|                        | cvodes/cvodes.h                     | cvodes/cvodes_impl.h             |
|                        | cvodes/cvodes_direct.h              | cvodes/cvodes_ls.h               |
|                        | cvodes/cvodes_spils.h               | cvodes/cvodes_bandpre.h          |
|                        | cvodes/cvodes_bbdpre.h              |                                  |
|                        |                                      |                                  |
|                        | fcvodes_mod.mod                     |                                  |

| ARKODE                 | Libraries                           | Header files                      |
|                        | libsundials_arkode.lib              | arkode/arkode.h arkode/arkode_impl.h |
|                        | libsundials_farkode.a               | arkode/arkode_ls.h arkode/arkode_bandpre.h |
|                        | libsundials_farkode_mod.lib         | arkode/arkode_bbdpre.h           |
|                        |                                      |                                  |
|                        | arkode/arkode.h                     | arkode/arkode_impl.h             |
|                        | arkode/arkode_ls.h                  | arkode/arkode_bandpre.h          |
|                        | arkode/arkode_bbdpre.h              |                                  |
|                        |                                      |                                  |
|                        | farkode_mod.mod                     | farkode_arkstep_mod.mod          |
|                        | farkode_erkstep_mod.mod             | farkode_mristep_mod.mod          |

| IDA                    | Libraries                           | Header files                      |
|                        | libsundials_ida.lib                 | ida/ida.h ida/ida_impl.h          |
|                        | libsundials_fida.a                  | ida/ida_direct.h ida/ida_ls.h     |
|                        | libsundials_fida_mod.lib            | ida/ida_spils.h ida/ida_bbdpre.h  |
|                        |                                      |                                  |
|                        | ida/ida.h                           | ida/ida_impl.h                   |
|                        | ida/ida_direct.h                    | ida/ida_ls.h                     |
|                        | ida/ida_spils.h                     | ida/ida_bbdpre.h                 |
|                        |                                      |                                  |
|                        | fida_mod.mod                        |                                  |

| IDAS                   | Libraries                           | Header files                      |
|                        | libsundials_idas.lib                | idas/idas.h idas/idas_impl.h      |
|                        | libsundials_fidas_mod.lib           | idas/idas_direct.h idas/idas_ls.h |
|                        |                                      | idas/idas_spils.h idas/idas_bbdpre.h |
|                        |                                      |                                  |
|                        | idas/idas.h                         | idas/idas_impl.h                 |
|                        | idas/idas_direct.h                  | idas/idas_ls.h                   |
|                        | idas/idas_spils.h                   | idas/idas_bbdpre.h               |
|                        |                                      |                                  |
|                        | fidas_mod.mod                       |                                  |

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| KINSOL | Libraries | libsundials_kinsol.lib  |
|        |          | libsundials_fkinsol.a   |
|        |          | libsundials_fkinsol_mod.lib |
|        | Header files | kinsol/kinsol.h  |
|        |          | kinsol/kinsol_direct.h |
|        |          | kinsol/kinsol_spils.h |
|        |          | kinsol/kinsol_impl.h |
|        |          | kinsol/kinsol_ls.h     |
|        |          | kinsol/kinsol_bbdpre.h |
|        | Module files | fkinsol_mod.mod       |
Appendix B

IDA Constants

Below we list all input and output constants used by the main solver and linear solver modules, together with their numerical values and a short description of their meaning.

B.1 IDA input constants

<table>
<thead>
<tr>
<th>IDA main solver module</th>
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<tbody>
<tr>
<td>IDA_NORMAL</td>
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<tr>
<td>IDA_ONE_STEP</td>
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<td>IDA_YA_YDP_INIT</td>
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<table>
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<tr>
<th>Iterative linear solver module</th>
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<tr>
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B.2 IDA output constants

<table>
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<tr>
<th>IDA main solver module</th>
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<tr>
<td>IDA_SUCCESS</td>
</tr>
<tr>
<td>IDA_TSTOP_RETURN</td>
</tr>
<tr>
<td>IDA_ROOT_RETURN</td>
</tr>
<tr>
<td>IDA_WARNING</td>
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<tr>
<td>IDA_TOO_MUCH_WORK</td>
</tr>
<tr>
<td>IDA_TOO_MUCH_ACC</td>
</tr>
<tr>
<td>IDA_ERR_FAIL</td>
</tr>
</tbody>
</table>
IDA, Conv. Fail: Convergence test failures occurred too many times during one internal time step or minimum step size was reached.

IDA, Linit Fail: The linear solver's initialization function failed.

IDA, Lsetup Fail: The linear solver's setup function failed in an unrecoverable manner.

IDA, Lsolve Fail: The linear solver's solve function failed in an unrecoverable manner.

IDA, Res Fail: The user-provided residual function failed in an unrecoverable manner.

IDA, Rep Res Fail: The user-provided residual function repeatedly returned a recoverable error flag, but the solver was unable to recover.

IDA, Rtfunc Fail: The rootfinding function failed in an unrecoverable manner.

IDA, Constr Fail: The inequality constraints were violated and the solver was unable to recover.

IDA, First Res Fail: The user-provided residual function failed recoverably on the first call.

IDA, Linesearch Fail: The line search failed.

IDA, No Recovery: The residual function, linear solver setup function, or linear solver solve function had a recoverable failure, but IDACalcIC could not recover.

IDA, Nls Init Fail: The nonlinear solver's init routine failed.

IDA, Nls Setup Fail: The nonlinear solver's setup routine failed.

IDA, Mem Null: The ida_mem argument was NULL.

IDA, Mem Fail: A memory allocation failed.

IDA, Ill Input: One of the function inputs is illegal.

IDA, No Malloc: The IDA memory was not allocated by a call to IDAInit.

IDA, Bad Ewt: Zero value of some error weight component.

IDA, Bad K: The k-th derivative is not available.

IDA, Bad T: The time t is outside the last step taken.

IDA, Bad Dky: The vector argument where derivative should be stored is NULL.

IDALS, Linear Solver Interface

IDALS, Success: Successful function return.

IDALS, Mem Null: The ida_mem argument was NULL.

IDALS, Lmem Null: The IDALS linear solver has not been initialized.

IDALS, Ill Input: The IDALS solver is not compatible with the current NVECTOR module.

IDALS, Mem Fail: A memory allocation request failed.

IDALS, Pmem Null: The preconditioner module has not been initialized.

IDALS, JACFUNC UNRECVR: The Jacobian function failed in an unrecoverable manner.

IDALS, JACFUNC RECVR: The Jacobian function had a recoverable error.

IDALS, SUNMAT Fail: An error occurred with the current SUNMATRIX module.

IDALS, SUNLS Fail: An error occurred with the current SUNLINSOL module.
### Appendix C

#### SUNDIALS Release History

Table C.1: Release History

<table>
<thead>
<tr>
<th>Date</th>
<th>SUNDIALS</th>
<th>ARKODE</th>
<th>CVODE</th>
<th>CVODES</th>
<th>IDA</th>
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<th>KINSOL</th>
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<sup>1</sup>CVOODE written, <sup>2</sup>PVODE written, <sup>3</sup>CVOODE and PVODE combined, <sup>4</sup>IDA written, <sup>5</sup>KINSOL written
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