

# User Documentation for ARKODE v5.0.0

SUNDIALS v6.0.0

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January 05, 2022



LLNL-SM-668082

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This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

## CONTRIBUTORS

The SUNDIALS library has been developed over many years by a number of contributors. The current SUNDIALS team consists of Cody J. Balos, David J. Gardner, Alan C. Hindmarsh, Daniel R. Reynolds, and Carol S. Woodward. We thank Radu Serban for significant and critical past contributions.

Other contributors to SUNDIALS include: James Almgren-Bell, Lawrence E. Banks, Peter N. Brown, George Byrne, Rujeko Chinomona, Scott D. Cohen, Aaron Collier, Keith E. Grant, Steven L. Lee, Shelby L. Lockhart, John Loffeld, Daniel McGreer, Slaven Peles, Cosmin Petra, H. Hunter Schwartz, Jean M. Sexton, Dan Shumaker, Steve G. Smith, Allan G. Taylor, Hilari C. Tiedeman, Chris White, Ting Yan, and Ulrike M. Yang.



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This is the documentation for ARKODE, an adaptive step time integration package for stiff, nonstiff and mixed stiff/nonstiff systems of ordinary differential equations (ODEs) using Runge–Kutta (i.e. one-step, multi-stage) methods. The ARKODE solver is a component of the [SUNDIALS](#) suite of nonlinear and differential/algebraic equation solvers. It is designed to have a similar user experience to the [CVODE](#) solver, including user modes to allow adaptive integration to specified output times, return after each internal step and root-finding capabilities, and for calculations in serial, using shared-memory parallelism (via OpenMP, Pthreads, CUDA, Raja) or distributed-memory parallelism (via MPI). The default integration and solver options should apply to most users, though control over nearly all internal parameters and time adaptivity algorithms is enabled through optional interface routines.

ARKODE is written in C, with C++ and Fortran interfaces.

ARKODE is developed by [Southern Methodist University](#), with support by the US Department of Energy, Office of Science, Office of Advanced Scientific Computing Research, Scientific Discovery through Advanced Computing (SciDAC) Program through the [FASTMath](#) Institute, under subcontracts B598130 and B626484 from [Lawrence Livermore National Laboratory](#), and under DOE award DE-SC0021354.



# Chapter 1

## Introduction

The ARKODE infrastructure provides adaptive-step time integration modules for stiff, nonstiff and mixed stiff/nonstiff systems of ordinary differential equations (ODEs). ARKODE itself is structured to support a wide range of one-step (but multi-stage) methods, allowing for rapid development of parallel implementations of state-of-the-art time integration methods. At present, ARKODE is packaged with two time-stepping modules, *ARKStep* and *ERKStep*.

*ARKStep* supports ODE systems posed in split, linearly-implicit form,

$$M(t) \dot{y} = f^E(t, y) + f^I(t, y), \quad y(t_0) = y_0, \quad (1.1)$$

where  $t$  is the independent variable,  $y$  is the set of dependent variables (in  $\mathbb{R}^N$ ),  $M$  is a user-specified, nonsingular operator from  $\mathbb{R}^N$  to  $\mathbb{R}^N$ , and the right-hand side function is partitioned into up to two components:

- $f^E(t, y)$  contains the “nonstiff” time scale components to be integrated explicitly, and
- $f^I(t, y)$  contains the “stiff” time scale components to be integrated implicitly.

Either of these operators may be disabled, allowing for fully explicit, fully implicit, or combination implicit-explicit (ImEx) time integration.

The algorithms used in ARKStep are adaptive- and fixed-step additive Runge–Kutta methods. Such methods are defined through combining two complementary Runge–Kutta methods: one explicit (ERK) and the other diagonally implicit (DIRK). Through appropriately partitioning the ODE right-hand side into explicit and implicit components (1.1), such methods have the potential to enable accurate and efficient time integration of stiff, nonstiff, and mixed stiff/nonstiff systems of ordinary differential equations. A key feature allowing for high efficiency of these methods is that only the components in  $f^I(t, y)$  must be solved implicitly, allowing for splittings tuned for use with optimal implicit solver algorithms.

This framework allows for significant freedom over the constitutive methods used for each component, and ARKODE is packaged with a wide array of built-in methods for use. These built-in Butcher tables include adaptive explicit methods of orders 2-8, adaptive implicit methods of orders 2-5, and adaptive ImEx methods of orders 3-5.

*ERKStep* focuses specifically on problems posed in explicit form,

$$\dot{y} = f(t, y), \quad y(t_0) = y_0. \quad (1.2)$$

allowing for increased computational efficiency and memory savings. The algorithms used in ERKStep are adaptive- and fixed-step explicit Runge–Kutta methods. As with ARKStep, the ERKStep module is packaged with adaptive explicit methods of orders 2-8.

*MRISStep* focuses specifically on problems posed in additive form,

$$\dot{y} = f^E(t, y) + f^I(t, y) + f^F(t, y), \quad y(t_0) = y_0. \quad (1.3)$$

where here the right-hand side function is additively split into three components:

- $f^E(t, y)$  contains the “slow-nonstiff” components of the system (this will be integrated using an explicit method and a large time step  $h^S$ ),
- $f^I(t, y)$  contains the “slow-stiff” components of the system (this will be integrated using an implicit method and a large time step  $h^S$ ), and
- $f^F(t, y)$  contains the “fast” components of the system (this will be integrated using a possibly different method than the slow time scale and a small time step  $h^F \ll h^S$ ).

For such problems, MRIStep provides fixed-step slow step multirate infinitesimal step (MIS), multirate infinitesimal GARK (MRI-GARK), and implicit-explicit MRI-GARK (IMEX-MRI-GARK) methods, allowing for evolution of the problem (1.3) using multirate methods having orders of accuracy 2-4.

For ARKStep or MRIStep problems that include nonzero implicit term  $f^I(t, y)$ , the resulting implicit system (assumed nonlinear, unless specified otherwise) is solved approximately at each integration step, using a SUNNonlinearSolver module, supplied either by the user or from the underlying SUNDIALS infrastructure. For nonlinear solver algorithms that internally require a linear solver, ARKODE may use a variety of SUNLinearSolver modules provided with SUNDIALS, or again may utilize a user-supplied module.

## 1.1 Changes from previous versions

### 1.1.1 Changes in vx.x.x

Additionally export `SUNDIALS::<lib>` targets with no static/shared suffix for use within the build directory (this mirrors how the targets are exported upon installation).

Fixed memory leaks in the `SUNLINSOL_SUPERLUMT` linear solver.

Added new reduction implementations for the CUDA and HIP NVECTORS that use shared memory (local data storage) instead of atomics. These new implementations are recommended when the target hardware does not provide atomic support for the floating point precision that SUNDIALS is being built with. The HIP vector uses these by default, but the `N_VSetKernelExecPolicy_Cuda()` and `N_VSetKernelExecPolicy_Hip()` functions can be used to choose between different reduction implementations.

`CMAKE_C_STANDARD` is now set to 99 by default.

Fixed `sundials_export.h` include in `sundials_config.h`.

Fixed exported `SUNDIALSConfig.cmake` when profiling is enabled without Caliper.

### 1.1.2 Changes in v5.0.0

#### SUNContext

SUNDIALS v6.0.0 introduces a new `SUNContext` object on which all other SUNDIALS objects depend. As such, the constructors for all SUNDIALS packages, vectors, matrices, linear solvers, nonlinear solvers, and memory helpers have been updated to accept a context as the last input. Users upgrading to SUNDIALS v6.0.0 will need to call `SUNContext_Create()` to create a context object with before calling any other SUNDIALS library function, and then provide this object to other SUNDIALS constructors. The context object has been introduced to allow SUNDIALS to provide new features, such as the profiling/instrumentation also introduced in this release, while maintaining thread-safety. See the documentation section on the `SUNContext` for more details.

A script `upgrade-to-sundials-6-from-5.sh` has been provided with the release (obtainable from the GitHub release page) to help ease the transition to SUNDIALS v6.0.0. The script will add a `SUNCTX_PLACEHOLDER` argument to all of the calls to SUNDIALS constructors that now require a `SUNContext` object. It can also update deprecated SUNDIALS constants/types to the new names. It can be run like this:

```
> ./upgrade-to-sundials-6-from-5.sh <files to update>
```

## SUNProfiler

A capability to profile/instrument SUNDIALS library code has been added. This can be enabled with the CMake option `SUNDIALS_BUILD_WITH_PROFILING`. A built-in profiler will be used by default, but the `Caliper` library can also be used instead with the CMake option `ENABLE_CALIPER`. See the documentation section on profiling for more details.

**WARNING:** Profiling will impact performance, and should be enabled judiciously.

## SUNMemoryHelper

The `SUNMemoryHelper` functions `SUNMemoryHelper_Alloc()`, `SUNMemoryHelper_Dealloc()`, and `SUNMemoryHelper_Copy()` have been updated to accept an opaque handle as the last input. At a minimum, user-defined `SUNMemoryHelper` implementations will need to update these functions to accept the additional argument. Typically, this handle is the execution stream (e.g., a CUDA/HIP stream or SYCL queue) for the operation. The `CUDA`, `HIP`, and `SYCL` implementations have been updated accordingly. Additionally, the constructor `SUNMemoryHelper_Sycl()` has been updated to remove the SYCL queue as an input.

## NVector

Two new optional vector operations, `N_VDotProdMultiLocal()` and `N_VDotProdMultiAllReduce()`, have been added to support low-synchronization methods for Anderson acceleration.

The CUDA, HIP, and SYCL execution policies have been moved from the `sundials` namespace to the `sundials::cuda`, `sundials::hip`, and `sundials::sycl` namespaces respectively. Accordingly, the prefixes “Cuda”, “Hip”, and “Sycl” have been removed from the execution policy classes and methods.

The Sundials namespace used by the Trilinos Tpetra NVector has been replaced with the `sundials::trilinos::nvector_tpetra` namespace.

The serial, PThreads, PETSc, *hypre*, Parallel, OpenMP\_DEV, and OpenMP vector functions `N_VCloneVectorArray_*` and `N_VDestroyVectorArray_*` have been deprecated. The generic `N_VCloneVectorArray()` and `N_VDestroyVectorArray()` functions should be used instead.

The previously deprecated constructor `N_VMakeWithManagedAllocator_Cuda` and the function `N_VSetCudaStream_Cuda` have been removed and replaced with `N_VNewWithMemHelp_Cuda()` and `N_VSetKernelExecPolicy_Cuda()` respectively.

The previously deprecated macros `PVEC_REAL_MPI_TYPE` and `PVEC_INTEGER_MPI_TYPE` have been removed and replaced with `MPI_SUNREALTYPE` and `MPI_SUNINDEXTYPE` respectively.

## SUNLinearSolver

The following previously deprecated functions have been removed:

Removed	Replacement
SUNBandLinearSolver	<code>SUNLinSol_Band()</code>
SUNDenseLinearSolver	<code>SUNLinSol_Dense()</code>
SUNKLU	<code>SUNLinSol_KLU()</code>
SUNKLUReInit	<code>SUNLinSol_KLUReInit()</code>
SUNKLUSetOrdering	<code>SUNLinSol_KLUSetOrdering()</code>
SUNLapackBand	<code>SUNLinSol_LapackBand()</code>
SUNLapackDense	<code>SUNLinSol_LapackDense()</code>
SUNPCG	<code>SUNLinSol_PCG()</code>
SUNPCGSetPrecType	<code>SUNLinSol_PCGSetPrecType()</code>
SUNPCGSetMaxl	<code>SUNLinSol_PCGSetMaxl()</code>
SUNSPBCGS	<code>SUNLinSol_SPBCGS()</code>
SUNSPBCGSSetPrecType	<code>SUNLinSol_SPBCGSSetPrecType()</code>
SUNSPBCGSSetMaxl	<code>SUNLinSol_SPBCGSSetMaxl()</code>
SUNSPFGMR	<code>SUNLinSol_SPFGMR()</code>
SUNSPFGMRSetPrecType	<code>SUNLinSol_SPFGMRSetPrecType()</code>
SUNSPFGMRSetGSType	<code>SUNLinSol_SPFGMRSetGSType()</code>
SUNSPFGMRSetMaxRestarts	<code>SUNLinSol_SPFGMRSetMaxRestarts()</code>
SUNSPGMR	<code>SUNLinSol_SPGMR()</code>
SUNSPGMRSetPrecType	<code>SUNLinSol_SPGMRSetPrecType()</code>
SUNSPGMRSetGSType	<code>SUNLinSol_SPGMRSetGSType()</code>
SUNSPGMRSetMaxRestarts	<code>SUNLinSol_SPGMRSetMaxRestarts()</code>
SUNSPTFQMR	<code>SUNLinSol_SPTFQMR()</code>
SUNSPTFQMRSetPrecType	<code>SUNLinSol_SPTFQMRSetPrecType()</code>
SUNSPTFQMRSetMaxl	<code>SUNLinSol_SPTFQMRSetMaxl()</code>
SUNSuperLUMT	<code>SUNLinSol_SuperLUMT()</code>
SUNSuperLUMTSetOrdering	<code>SUNLinSol_SuperLUMTSetOrdering()</code>

## ARKODE

The MRIStep module has been extended to support implicit-explicit (IMEX) multirate infinitesimal generalized additive Runge–Kutta (MRI-GARK) methods. As such, `MRISetCreate()` has been updated to include arguments for the slow explicit and slow implicit ODE right-hand side functions. `MRISetCreate()` has also been updated to require attaching an MRIStepInnerStepper for evolving the fast time scale. `MRISetReInit()` has been similarly updated to take explicit and implicit right-hand side functions as input. Codes using explicit or implicit MRI methods will need to update `MRISetCreate()` and `MRISetReInit()` calls to pass NULL for either the explicit or implicit right-hand side function as appropriate. If ARKStep is used as the fast time scale integrator, codes will need to call `ARKStepCreateMRIStepInnerStepper()` to wrap the ARKStep memory as an MRIStepInnerStepper object. Additionally, `MRISetGetNumRhsEvals()` has been updated to return the number of slow implicit and explicit function evaluations. The coupling table structure `MRISetCouplingMem` and the functions `MRISetCoupling_Alloc()` and `MRISetCoupling_Create()` have also been updated to support IMEX-MRI-GARK methods.

The deprecated functions `MRISetGetCurrentButcherTables` and `MRISetWriteButcher` and the utility functions `MRISetSetTable` and `MRISetSetTableNum` have been removed. Users wishing to create an MRI-GARK method from a Butcher table should use `MRISetCoupling_MISoMRI()` to create the corresponding MRI coupling table and attach it with `MRISetSetCoupling()`.

The implementation of solve-decoupled implicit MRI-GARK methods has been updated to remove extraneous slow implicit function calls and reduce the memory requirements.

The previously deprecated functions `ARKStepSetMaxStepsBetweenLSet` and `ARKStepSetMaxStepsBetweenJac` have been removed and replaced with `ARKStepSetLSetupFrequency()` and `ARKStepSetMaxStepsBetweenJac()` respectively.

The ARKODE Fortran 77 interface has been removed. See §4.4 and the F2003 example programs for more details using the SUNDIALS Fortran 2003 module interfaces.

## Deprecations

In addition to the deprecations noted elsewhere, many constants, types, and functions have been renamed so that they are properly namespaced. The old names have been deprecated and will be removed in SUNDIALS v7.0.0.

The following constants, macros, and typedefs are now deprecated:

Deprecated Name	New Name
realtype	sunrealtype
booleantype	sunbooleantype
RCONST	SUN_RCONST
BIG_REAL	SUN_BIG_REAL
SMALL_REAL	SUN_SMALL_REAL
UNIT_ROUNDOFF	SUN_UNIT_ROUNDOFF
PREC_NONE	SUN_PREC_NONE
PREC_LEFT	SUN_PREC_LEFT
PREC_RIGHT	SUN_PREC_RIGHT
PREC_BOTH	SUN_PREC_BOTH
MODIFIED_GS	SUN_MODIFIED_GS
CLASSICAL_GS	SUN_CLASSICAL_GS
ATimesFn	SUNATimesFn
PSetupFn	SUNPSetupFn
PSolveFn	SUNPSolveFn
DlsMat	SUNDlsMat
DENSE_COL	SUNDLS_DENSE_COL
DENSE_ELEM	SUNDLS_DENSE_ELEM
BAND_COL	SUNDLS_BAND_COL
BAND_COL_ELEM	SUNDLS_BAND_COL_ELEM
BAND_ELEM	SUNDLS_BAND_ELEM
SDIRK_2_1_2	ARKODE_SDIRK_2_1_2
BILLINGTON_3_3_2	ARKODE_BILLINGTON_3_3_2
TRBDF2_3_3_2	ARKODE_TRBDF2_3_3_2
KVAERNO_4_2_3	ARKODE_KVAERNO_4_2_3
ARK324L2SA_DIRK_4_2_3	ARKODE_ARK324L2SA_DIRK_4_2_3
CASH_5_2_4	ARKODE_CASH_5_2_4
CASH_5_3_4	ARKODE_CASH_5_3_4
SDIRK_5_3_4	ARKODE_SDIRK_5_3_4
KVAERNO_5_3_4	ARKODE_KVAERNO_5_3_4
ARK436L2SA_DIRK_6_3_4	ARKODE_ARK436L2SA_DIRK_6_3_4
KVAERNO_7_4_5	ARKODE_KVAERNO_7_4_5
ARK548L2SA_DIRK_8_4_5	ARKODE_ARK548L2SA_DIRK_8_4_5
ARK437L2SA_DIRK_7_3_4	ARKODE_ARK437L2SA_DIRK_7_3_4
ARK548L2SAb_DIRK_8_4_5	ARKODE_ARK548L2SAb_DIRK_8_4_5
MIN_DIRK_NUM	ARKODE_MIN_DIRK_NUM
MAX_DIRK_NUM	ARKODE_MAX_DIRK_NUM
MIS_KW3	ARKODE_MIS_KW3
MRI_GARK_ERK33a	ARKODE_MRI_GARK_ERK33a
MRI_GARK_ERK45a	ARKODE_MRI_GARK_ERK45a
MRI_GARK_IRK21a	ARKODE_MRI_GARK_IRK21a
MRI_GARK_ESDIRK34a	ARKODE_MRI_GARK_ESDIRK34a

continues on next page

Table 1.1 – continued from previous page

Deprecated Name	New Name
MRI_GARK_ESDIRK46a	ARKODE_MRI_GARK_ESDIRK46a
IMEX_MRI_GARK3a	ARKODE_IMEX_MRI_GARK3a
IMEX_MRI_GARK3b	ARKODE_IMEX_MRI_GARK3b
IMEX_MRI_GARK4	ARKODE_IMEX_MRI_GARK4
MIN_MRI_NUM	ARKODE_MIN_MRI_NUM
MAX_MRI_NUM	ARKODE_MAX_MRI_NUM
DEFAULT_MRI_TABLE_3	MRISTEP_DEFAULT_TABLE_3
DEFAULT_EXPL_MRI_TABLE_3	MRISTEP_DEFAULT_EXPL_TABLE_3
DEFAULT_EXPL_MRI_TABLE_4	MRISTEP_DEFAULT_EXPL_TABLE_4
DEFAULT_IMPL_SD_TABLE_2	MRISTEP_DEFAULT_IMPL_SD_TABLE_2
DEFAULT_IMPL_SD_TABLE_3	MRISTEP_DEFAULT_IMPL_SD_TABLE_3
DEFAULT_IMPL_SD_TABLE_4	MRISTEP_DEFAULT_IMPL_SD_TABLE_4
DEFAULT_IMEX_SD_TABLE_3	MRISTEP_DEFAULT_IMEX_SD_TABLE_3
DEFAULT_IMEX_SD_TABLE_4	MRISTEP_DEFAULT_IMEX_SD_TABLE_4
HEUN_EULER_2_1_2	ARKODE_HEUN_EULER_2_1_2
BOGACKI_SHAMPINE_4_2_3	ARKODE_BOGACKI_SHAMPINE_4_2_3
ARK324L2SA_ERK_4_2_3	ARKODE_ARK324L2SA_ERK_4_2_3
ZONNEVELD_5_3_4	ARKODE_ZONNEVELD_5_3_4
ARK436L2SA_ERK_6_3_4	ARKODE_ARK436L2SA_ERK_6_3_4
SAYFY_ABURUB_6_3_4	ARKODE_SAYFY_ABURUB_6_3_4
CASH_KARP_6_4_5	ARKODE_CASH_KARP_6_4_5
FEHLBERG_6_4_5	ARKODE_FEHLBERG_6_4_5
DORMAND_PRINCE_7_4_5	ARKODE_DORMAND_PRINCE_7_4_5
ARK548L2SA_ERK_8_4_5	ARKODE_ARK548L2SA_ERK_8_4_5
VERNER_8_5_6	ARKODE_VERNER_8_5_6
FEHLBERG_13_7_8	ARKODE_FEHLBERG_13_7_8
KNOTH_WOLKE_3_3	ARKODE_KNOTH_WOLKE_3_3
ARK437L2SA_ERK_7_3_4	ARKODE_ARK437L2SA_ERK_7_3_4
ARK548L2Sab_ERK_8_4_5	ARKODE_ARK548L2Sab_ERK_8_4_5
MIN_ERK_NUM	ARKODE_MIN_ERK_NUM
MAX_ERK_NUM	ARKODE_MAX_ERK_NUM
DEFAULT_ERK_2	ARKSTEP_DEFAULT_ERK_2
DEFAULT_ERK_3	ARKSTEP_DEFAULT_ERK_3
DEFAULT_ERK_4	ARKSTEP_DEFAULT_ERK_4
DEFAULT_ERK_5	ARKSTEP_DEFAULT_ERK_5
DEFAULT_ERK_6	ARKSTEP_DEFAULT_ERK_6
DEFAULT_ERK_8	ARKSTEP_DEFAULT_ERK_8
DEFAULT_DIRK_2	ARKSTEP_DEFAULT_DIRK_2
DEFAULT_DIRK_3	ARKSTEP_DEFAULT_DIRK_3
DEFAULT_DIRK_4	ARKSTEP_DEFAULT_DIRK_4
DEFAULT_DIRK_5	ARKSTEP_DEFAULT_DIRK_5
DEFAULT_ARK_ETABLE_3	ARKSTEP_DEFAULT_ARK_ETABLE_3
DEFAULT_ARK_ETABLE_4	ARKSTEP_DEFAULT_ARK_ETABLE_4
DEFAULT_ARK_ETABLE_5	ARKSTEP_DEFAULT_ARK_ETABLE_4
DEFAULT_ARK_ITABLE_3	ARKSTEP_DEFAULT_ARK_ITABLE_3
DEFAULT_ARK_ITABLE_4	ARKSTEP_DEFAULT_ARK_ITABLE_4
DEFAULT_ARK_ITABLE_5	ARKSTEP_DEFAULT_ARK_ITABLE_5
DEFAULT_ERK_2	ERKSTEP_DEFAULT_2
DEFAULT_ERK_3	ERKSTEP_DEFAULT_3

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Table 1.1 – continued from previous page

Deprecated Name	New Name
DEFAULT_ERK_4	ERKSTEP_DEFAULT_4
DEFAULT_ERK_5	ERKSTEP_DEFAULT_5
DEFAULT_ERK_6	ERKSTEP_DEFAULT_6
DEFAULT_ERK_8	ERKSTEP_DEFAULT_8

In addition, the following functions are now deprecated (compile-time warnings will be thrown if supported by the compiler):

Deprecated Name	New Name
DenseGETRF	SUNDlsMat_DenseGETRF
DenseGETRS	SUNDlsMat_DenseGETRS
denseGETRF	SUNDlsMat_denseGETRF
denseGETRS	SUNDlsMat_denseGETRS
DensePOTRF	SUNDlsMat_DensePOTRF
DensePOTRS	SUNDlsMat_DensePOTRS
densePOTRF	SUNDlsMat_densePOTRF
densePOTRS	SUNDlsMat_densePOTRS
DenseGEQRF	SUNDlsMat_DenseGEQRF
DenseORMQR	SUNDlsMat_DenseORMQR
denseGEQRF	SUNDlsMat_denseGEQRF
denseORMQR	SUNDlsMat_denseORMQR
DenseCopy	SUNDlsMat_DenseCopy
denseCopy	SUNDlsMat_denseCopy
DenseScale	SUNDlsMat_DenseScale
denseScale	SUNDlsMat_denseScale
denseAddIdentity	SUNDlsMat_denseAddIdentity
DenseMatvec	SUNDlsMat_DenseMatvec
denseMatvec	SUNDlsMat_denseMatvec
BandGBTRF	SUNDlsMat_BandGBTRF
bandGBTRF	SUNDlsMat_bandGBTRF
BandGBTRS	SUNDlsMat_BandGBTRS
bandGBTRS	SUNDlsMat_bandGBTRS
BandCopy	SUNDlsMat_BandCopy
bandCopy	SUNDlsMat_bandCopy
BandScale	SUNDlsMat_BandScale
bandScale	SUNDlsMat_bandScale
bandAddIdentity	SUNDlsMat_bandAddIdentity
BandMatvec	SUNDlsMat_BandMatvec
bandMatvec	SUNDlsMat_bandMatvec
ModifiedGS	SUNModifiedGS
ClassicalGS	SUNClassicalGS
QRfact	SUNQRFact
QRsol	SUNQRsol
DlsMat_NewDenseMat	SUNDlsMat_NewDenseMat
DlsMat_NewBandMat	SUNDlsMat_NewBandMat
DestroyMat	SUNDlsMat_DestroyMat
NewIntArray	SUNDlsMat_NewIntArray
NewIndexArray	SUNDlsMat_NewIndexArray
NewRealArray	SUNDlsMat_NewRealArray

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Table 1.2 – continued from previous page

Deprecated Name	New Name
DestroyArray	SUNDlsMat_DestroyArray
AddIdentity	SUNDlsMat_AddIdentity
SetToZero	SUNDlsMat_SetToZero
PrintMat	SUNDlsMat_PrintMat
newDenseMat	SUNDlsMat_newDenseMat
newBandMat	SUNDlsMat_newBandMat
destroyMat	SUNDlsMat_destroyMat
newIntArray	SUNDlsMat_newIntArray
newIndexArray	SUNDlsMat_newIndexArray
newRealArray	SUNDlsMat_newRealArray
destroyArray	SUNDlsMat_destroyArray

In addition, the entire `sundials_lapack.h` header file is now deprecated for removal in SUNDIALS v7.0.0. Note, this header file is not needed to use the SUNDIALS LAPACK linear solvers.

### 1.1.3 Changes in v4.8.0

The RAJA NVECTOR implementation has been updated to support the SYCL backend in addition to the CUDA and HIP backend. Users can choose the backend when configuring SUNDIALS by using the `SUNDIALS_RAJA_BACKENDS` CMake variable. This module remains experimental and is subject to change from version to version.

A new SUNMatrix and SUNLinearSolver implementation were added to interface with the Intel oneAPI Math Kernel Library (oneMKL). Both the matrix and the linear solver support general dense linear systems as well as block diagonal linear systems. See §9.9 for more details. This module is experimental and is subject to change from version to version.

Added a new *optional* function to the SUNLinearSolver API, `SUNLinSolSetZeroGuess()`, to indicate that the next call to `SUNLinSolSolve()` will be made with a zero initial guess. SUNLinearSolver implementations that do not use the `SUNLinSolNewEmpty()` constructor will, at a minimum, need set the `setzeroguess` function pointer in the linear solver ops structure to NULL. The SUNDIALS iterative linear solver implementations have been updated to leverage this new set function to remove one dot product per solve.

ARKODE now supports a new “matrix-embedded” SUNLinearSolver type. This type supports user-supplied SUNLinearSolver implementations that set up and solve the specified linear system at each linear solve call. Any matrix-related data structures are held internally to the linear solver itself, and are not provided by the SUNDIALS package.

Support for user-defined inner (fast) integrators has been to the MRIStep module. See §5.4.8 for more information on providing a user-defined integration method.

Added the functions `ARKStepSetNlsRhsFn()` and `MRIStepSetNlsRhsFn()` to supply an alternative implicit right-hand side function for use within nonlinear system function evaluations.

The installed SUNDIALSConfig.cmake file now supports the `COMPONENTS` option to `find_package`. The exported targets no longer have `IMPORTED_GLOBAL` set.

A bug was fixed in `SUNMatCopyOps()` where the matrix-vector product setup function pointer was not copied.

A bug was fixed in the SPBCGS and SPTFQMR solvers for the case where a non-zero initial guess and a solution scaling vector are provided. This fix only impacts codes using SPBCGS or SPTFQMR as standalone solvers as all SUNDIALS packages utilize a zero initial guess.

A bug was fixed in the ARKODE stepper modules where the stop time may be passed after resetting the integrator.

### 1.1.4 Changes in v4.7.0

A new NVECTOR implementation based on the SYCL abstraction layer has been added targeting Intel GPUs. At present the only SYCL compiler supported is the DPC++ (Intel oneAPI) compiler. See §7.13 for more details. This module is considered experimental and is subject to major changes even in minor releases.

A new SUNMatrix and SUNLinearSolver implementation were added to interface with the MAGMA linear algebra library. Both the matrix and the linear solver support general dense linear systems as well as block diagonal linear systems, and both are targeted at GPUs (AMD or NVIDIA). See §9.8 for more details.

### 1.1.5 Changes in v4.6.1

Fixed a bug in the SUNDIALS CMake which caused an error if the CMAKE\_CXX\_STANDARD and SUNDIALS\_RAJA\_BACKENDS options were not provided.

Fixed some compiler warnings when using the IBM XL compilers.

### 1.1.6 Changes in v4.6.0

A new NVECTOR implementation based on the AMD ROCm HIP platform has been added. This vector can target NVIDIA or AMD GPUs. See §7.11 for more details. This module is considered experimental and is subject to change from version to version.

The RAJA NVECTOR implementation has been updated to support the HIP backend in addition to the CUDA backend. Users can choose the backend when configuring SUNDIALS by using the SUNDIALS\_RAJA\_BACKENDS CMake variable. This module remains experimental and is subject to change from version to version.

A new optional operation, `N_VGetDeviceArrayPointer()`, was added to the N\_Vector API. This operation is useful for N\_Vectors that utilize dual memory spaces, e.g. the native SUNDIALS CUDA N\_Vector.

The SUNMATRIX\_CUSPARSE and SUNLINEARSOLVER\_CUSOLVERS\_P\_BATQR implementations no longer require the SUNDIALS CUDA N\_Vector. Instead, they require that the vector utilized provides the `N_VGetDeviceArrayPointer()` operation, and that the pointer returned by `N_VGetDeviceArrayPointer()` is a valid CUDA device pointer.

### 1.1.7 Changes in v4.5.0

Refactored the SUNDIALS build system. CMake 3.12.0 or newer is now required. Users will likely see deprecation warnings, but otherwise the changes should be fully backwards compatible for almost all users. SUNDIALS now exports CMake targets and installs a SUNDIALSConfig.cmake file.

Added support for SuperLU DIST 6.3.0 or newer.

### 1.1.8 Changes in v4.4.0

Added full support for time-dependent mass matrices in ARKStep, and expanded existing non-identity mass matrix infrastructure to support use of the fixed point nonlinear solver. Fixed bug for ERK method integration with static mass matrices.

An interface between ARKStep and the XBraid multigrid reduction in time (MGRIT) library [1] has been added to enable parallel-in-time integration. See the §5.2.4 section for more information and the example codes in examples/arkode/CXX\_xbraid. This interface required the addition of three new N\_Vector operations to exchange vector data between computational nodes, see `N_VBufSize()`, `N_VBufPack()`, and `N_VBufUnpack()`. These N\_Vector operations are only used within the XBraid interface and need not be implemented for any other context.

Updated the MRIStep time-stepping module in ARKODE to support higher-order MRI-GARK methods [51], including methods that involve solve-decoupled, diagonally-implicit treatment of the slow time scale.

Added the functions `ARKStepSetLSNormFactor()`, `ARKStepSetMassLSNormFactor()`, and `MRIStepSetLSNormFactor()` to specify the factor for converting between integrator tolerances (WRMS norm) and linear solver tolerances (L2 norm) i.e., `tol_L2 = nrmfac * tol_WRMS`.

Added new reset functions `ARKStepReset()`, `ERKStepReset()`, and `MRIStepReset()` to reset the stepper time and state vector to user-provided values for continuing the integration from that point while retaining the integration history. These function complement the reinitialization functions `ARKStepReInit()`, `ERKStepReInit()`, and `MRIStepReInit()` which reinitialize the stepper so that the problem integration should resume as if started from scratch.

Added new functions `ARKStepComputeState()`, `ARKStepGetNonlinearSystemData()`, `MRIStepComputeState()`, and `MRIStepGetNonlinearSystemData()` which advanced users might find useful if providing a custom `SUNNonlinSolSysFn()`.

The expected behavior of `SUNNonlinSolGetNumIters()` and `SUNNonlinSolGetNumConvFails()` in the SUNNonlinearSolver API have been updated to specify that they should return the number of nonlinear solver iterations and convergence failures in the most recent solve respectively rather than the cumulative number of iterations and failures across all solves respectively. The API documentation and SUNDIALS provided SUNNonlinearSolver implementations have been updated accordingly. As before, the cumulative number of nonlinear iterations may be retrieved by calling `ARKStepGetNumNonlinSolvIters()`, the cumulative number of failures with `ARKStepGetNumNonlinSolvConvFails()`, or both with `ARKStepGetNonlinSolvStats()`.

A minor bug in checking the Jacobian evaluation frequency has been fixed. As a result codes using using a non-default Jacobian update frequency through a call to `ARKStepSetMaxStepsBetweenJac()` will need to increase the provided value by 1 to achieve the same behavior as before. Additionally, for greater clarity the functions `ARKStepSetMaxStepsBetweenLSet()` and `ARKStepSetMaxStepsBetweenJac()` have been deprecated and replaced with `ARKStepSetLSetupFrequency()` and `ARKStepSetJacEvalFrequency()` respectively.

The NVECTOR\_RAJA module has been updated to mirror the NVECTOR\_CUDA module. Notably, the update adds managed memory support to the NVECTOR\_RAJA module. Users of the module will need to update any calls to the `N_VMake_Raja` function because that signature was changed. This module remains experimental and is subject to change from version to version.

The NVECTOR\_TRILINOS module has been updated to work with Trilinos 12.18+. This update changes the local ordinal type to always be an `int`.

Added support for CUDA v11.

### 1.1.9 Changes in v4.3.0

Fixed a bug in ARKODE where the prototypes for `ERKStepSetMinReduction()` and `ARKStepSetMinReduction()` were not included in `arkode_erkstep.h` and `arkode_arkstep.h` respectively.

Fixed a bug where inequality constraint checking would need to be disabled and then re-enabled to update the inequality constraint values after resizing a problem. Resizing a problem will now disable constraints and a call to `ARKStepSetConstraints()` or `ERKStepSetConstraints()` is required to re-enable constraint checking for the new problem size.

Fixed a bug in the iterative linear solver modules where an error is not returned if the `Atimes` function is `NULL` or, if preconditioning is enabled, the `PSolve` function is `NULL`.

Added the ability to control the CUDA kernel launch parameters for the NVECTOR\_CUDA and SUNMATRIX\_CUSPARSE modules. These modules remain experimental and are subject to change from version to version. In addition, the NVECTOR\_CUDA kernels were rewritten to be more flexible. Most users should see equivalent performance or some improvement, but a select few may observe minor performance degradation with the default settings. Users are encouraged to contact the SUNDIALS team about any performance changes that they notice.

Added the optional function `ARKStepSetJacTimesRhsFn()` to specify an alternative implicit right-hand side function for computing Jacobian-vector products with the internal difference quotient approximation.

Added new capabilities for monitoring the solve phase in the `SUNNONLINSOL_NEWTON` and `SUNNONLINSOL_FIXED-POINT` modules, and the SUNDIALS iterative linear solver modules. SUNDIALS must be built with the CMake option `SUNDIALS_BUILD_WITH_MONITORING` to use these capabilities.

### 1.1.10 Changes in v4.2.0

Fixed a build system bug related to the Fortran 2003 interfaces when using the IBM XL compiler. When building the Fortran 2003 interfaces with an XL compiler it is recommended to set `CMAKE_Fortran_COMPILER` to `f2003`, `xlf2003`, or `xlf2003_r`.

Fixed a bug in how ARKODE interfaces with a user-supplied, iterative, unscaled linear solver. In this case, ARKODE adjusts the linear solver tolerance in an attempt to account for the lack of support for left/right scaling matrices. Previously, ARKODE computed this scaling factor using the error weight vector, `ewt`; this fix changes that to the residual weight vector, `rwt`, that can differ from `ewt` when solving problems with non-identity mass matrix.

Fixed a similar bug in how ARKODE interfaces with scaled linear solvers when solving problems with non-identity mass matrices. Here, the left scaling matrix should correspond with `rwt` and the right scaling matrix with `ewt`; these were reversed but are now correct.

Fixed a bug where a non-default value for the maximum allowed growth factor after the first step would be ignored.

The function `ARKStepSetLinearSolutionScaling()` was added to enable or disable the scaling applied to linear system solutions with matrix-based linear solvers to account for a lagged value of  $\gamma$  in the linear system matrix e.g.,  $M - \gamma J$  or  $I - \gamma J$ . Scaling is enabled by default when using a matrix-based linear solver.

Added two new functions, `ARKStepSetMinReduction()` and `ERKStepSetMinReduction()`, to change the minimum allowed step size reduction factor after an error test failure.

Added a new `SUNMatrix` implementation, §8.7, that interfaces to the sparse matrix implementation from the NVIDIA cuSPARSE library. In addition, the §9.17 `SUNLinearSolver` has been updated to use this matrix, as such, users of this module will need to update their code. These modules are still considered to be experimental, thus they are subject to breaking changes even in minor releases.

Added a new “stiff” interpolation module, based on Lagrange polynomial interpolation, that is accessible to each of the ARKStep, ERKStep and MRIStep time-stepping modules. This module is designed to provide increased interpolation accuracy when integrating stiff problems, as opposed to the ARKODE-standard Hermite interpolation module that can suffer when the IVP right-hand side has large Lipschitz constant. While the Hermite module remains the default, the new Lagrange module may be enabled using one of the routines `ARKStepSetInterpolantType()`, `ERKStepSetInterpolantType()`, or `MRIStepSetInterpolantType()`. The serial example problem `ark_brusselator.c` has been converted to use this Lagrange interpolation module. Created accompanying routines `ARKStepSetInterpolantDegree()`, `ARKStepSetInterpolantDegree()` and `ARKStepSetInterpolantDegree()` to provide user control over these interpolating polynomials. While the routines `ARKStepSetDenseOrder()`, `ARKStepSetDenseOrder()` and `ARKStepSetDenseOrder()` still exist, these have been deprecated and will be removed in a future release.

### 1.1.11 Changes in v4.1.0

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.

Fixed a bug in the Fortran 2003 interfaces to the ARKODE Butcher table routines and structure. This includes changing the ARKodeButcherTable type to be a type(c\_ptr) in Fortran.

Added two utility functions, SUNDIALSFileOpen and SUNDIALSfileClose for creating/destroying file pointers that are useful when using the Fortran 2003 interfaces.

Added support for a user-supplied function to update the prediction for each implicit stage solution in ARKStep. If supplied, this routine will be called *after* any existing ARKStep predictor algorithm completes, so that the predictor may be modified by the user as desired. The new user-supplied routine has type ARKStepStagePredictFn, and may be set by calling [ARKStepSetStagePredictFn\(\)](#).

The MRIStep module has been updated to support attaching different user data pointers to the inner and outer integrators. If applicable, user codes will need to add a call to [ARKStepSetUserData\(\)](#) to attach their user data pointer to the inner integrator memory as [MRIStepSetUserData\(\)](#) will not set the pointer for both the inner and outer integrators. The MRIStep examples have been updated to reflect this change.

Added support for constant damping to the SUNNonlinearSolver\_FixedPoint module when using Anderson acceleration. See §10.4.1 and the [SUNNonlinSolSetDamping\\_FixedPoint\(\)](#) for more details.

### 1.1.12 Changes in v4.0.0

#### 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 PThreads NVECTOR module from being built.

#### NVECTOR module changes

Two new functions were added to aid in creating custom NVECTOR objects. The constructor [N\\_VNewEmpty\(\)](#) allocates an “empty” generic NVECTOR 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 NVECTOR API by ensuring only required operations need to be set. Additionally, the function [N\\_VCopyOps\(\)](#) 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 NVECTOR API by ensuring all operations are copied when cloning objects.

Two new NVECTOR implementations, NVECTOR\_MANYVECTOR and NVECTOR\_MPIMANYVECTOR, 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.

One new required vector operation and ten new optional vector operations have been added to the NVECTOR API. The new required operation, [N\\_VGetLength\(\)](#), returns the global length of an N\_Vector. The optional operations

have been added to support the new NVECTOR\_MPIANYVECTOR implementation. The operation [N\\_VGetCommunicator\(\)](#) must be implemented by subvectors that are combined to create an NVECTOR\_MPIANYVECTOR, 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 [N\\_VDotProdLocal\(\)](#), [N\\_VMaxNormLocal\(\)](#), [N\\_VMinLocal\(\)](#), [N\\_VL1NormLocal\(\)](#), [N\\_VWSqrSumLocal\(\)](#), [N\\_VWSqrSumMaskLocal\(\)](#), [N\\_VInvTestLocal\(\)](#), [N\\_VConstrMaskLocal\(\)](#), and [N\\_VMinQuotientLocal\(\)](#). If an NVECTOR implementation defines any of the local operations as NULL, then the NVECTOR\_MPIANYVECTOR will call standard NVECTOR operations to complete the computation.

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.

The \*\_MPICu<sub>a</sub>d and \*\_MPIRaja functions have been removed from the NVECTOR\_CUDA and NVECTOR\_RAJA implementations respectively. Accordingly, the nvector\_mpicuda.h, nvector\_mpiraja.h, lib sundials\_nvecmpicuda.lib, and lib sundials\_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.

Added new Fortran 2003 interfaces for most NVECTOR modules. See the §4.4 section for more details.

Added three new NVECTOR utility functions, [N\\_VGetVecAtIndexVectorArray\(\)](#) [N\\_VSetVecAtIndexVectorArray\(\)](#), and [N\\_VNewVectorArray\(\)](#), for working with N\_Vector arrays when using the Fortran 2003 interfaces.

### 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\(\)](#) 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.

A new operation, [SUNMatMatvecSetup\(\)](#), was added to the SUNMATRIX API. 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.

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.

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.

A new SUNMATRIX (and SUNLINEARSOLVER) implementation was added to facilitate the use of the SuperLU-DIST library with SUNDIALS.

Added new Fortran 2003 interfaces for most SUNMATRIX modules. See the §4.4 section for more details.

### SUNLinearSolver module changes

A new function was added to aid in creating custom SUNLINEARSOLVER objects. The constructor [`SUNLinSolNewEmpty\(\)`](#) allocates an “empty” generic SUNLINEARSOLVER 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 SUNLINEARSOLVER API by ensuring only required operations need to be set.

The return type of the SUNLINEARSOLVER 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 SUNLINEARSOLVER API, [`SUNLinSolGetID\(\)`](#), that returns a `SUNLinearSolver_ID` for identifying the linear solver module.

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

A new SUNLINEARSOLVER (and SUNMATRIX) implementation was added to facilitate the use of the SuperLU-DIST library with SUNDIALS.

Added a new SUNLinearSolver implementation, `SUNLinearSolver_cuSolverSp_batchQR`, which leverages the NVIDIA cuSOLVER sparse batched QR method for efficiently solving block diagonal linear systems on NVIDIA GPUs.

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.

Added new Fortran 2003 interfaces for most SUNLINEARSOLVER modules. See the §4.4 section for more details.

### SUNNonlinearSolver module changes

A new function was added to aid in creating custom SUNNONLINEARSOLVER objects. The constructor [`SUNNonlinSolNewEmpty\(\)`](#) allocates an “empty” generic SUNNONLINEARSOLVER 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 SUNNONLINEARSOLVER API by ensuring only required operations need to be set.

To facilitate the use of user supplied nonlinear solver convergence test functions the [`SUNNonlinSolSetConvTestFn\(\)`](#) function in the SUNNONLINEARSOLVER 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 SUNNONLINEARSOLVER have been changed to be the predicted state and the initial guess for the correction to that state. Additionally, the definitions of `SUNNonlinSolvLSetupFn` and `SUNNonlinSolvLSolveFn` in the SUNNONLINEARSOLVER API have been updated to remove unused input parameters.

Added a new SUNNonlinearSolver implementation, `SUNNonlinsol_PetscSNES`, which interfaces to the PETSc SNES nonlinear solver API.

Added new Fortran 2003 interfaces for most SUNNONLINEARSOLVER modules. See the §4.4 section for more details.

### ARKODE changes

The MRIStep module has been updated to support explicit, implicit, or ImEx methods as the fast integrator using the ARKStep module. As a result some function signatures have been changed including [`MRIStepCreate\(\)`](#) which now takes an ARKStep memory structure for the fast integration as an input.

Fixed a bug in the ARKStep time-stepping module that would result in an infinite loop if the nonlinear solver failed to converge more than the maximum allowed times during a single step.

Fixed a bug that would result in a “too much accuracy requested” error when using fixed time step sizes with explicit methods in some cases.

Fixed a bug in ARKStep where the mass matrix linear solver setup function was not called in the Matrix-free case.

Fixed a minor bug in ARKStep where an incorrect flag is reported when an error occurs in the mass matrix setup or Jacobian-vector product setup functions.

Fixed a memory leak in FARKODE when not using the default nonlinear solver.

The reinitialization functions `ERKStepReInit()`, `ARKStepReInit()`, and `MRISetReInit()` have been updated to retain the minimum and maximum step size values from before reinitialization rather than resetting them to the default values.

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, ARKODE will remove at least one global reduction per time step.

The ARKLS 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`.

A new linear solver interface function `ARKLsLinSysFn()` was added as an alternative method for evaluating the linear system  $A = M - \gamma J$ .

Added two new embedded ARK methods of orders 4 and 5 to ARKODE (from [41]).

Support for optional inequality constraints on individual components of the solution vector has been added the ARKODE ERKStep and ARKStep modules. See the descriptions of `ERKStepSetConstraints()` and `ARKStepSetConstraints()` for more details. Note that enabling constraint handling requires the NVECTOR operations `N_VMinQuotient()`, `N_VConstrMask()`, and `N_VCompare()` that were not previously required by ARKODE.

Added two new ‘Get’ functions to ARKStep, `ARKStepGetCurrentGamma()`, and `ARKStepGetCurrentState()`, that may be useful to users who choose to provide their own nonlinear solver implementation.

Add two new ‘Set’ functions to MRISet, `MRISetPreInnerFn()` and `MRISetPostInnerFn()` for performing communication or memory transfers needed before or after the inner integration.

A new Fortran 2003 interface to ARKODE was added. This includes Fortran 2003 interfaces to the ARKStep, ERKStep, and MRISet time-stepping modules. See the §4.4 section for more details.

### 1.1.13 Changes in v3.1.0

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_RAJA` 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 `arkode_impl.h` is no longer installed. This means users who are directly manipulating the `ARKodeMem` structure will need to update their code to use ARKODE’s public API.

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

Fixed a bug in `ARKodeButcherTable_Write` when printing a Butcher table without an embedding.

### 1.1.14 Changes in v3.0.2

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

### 1.1.15 Changes in v3.0.1

A bug in ARKODE where single precision builds would fail to compile has been fixed.

### 1.1.16 Changes in v3.0.0

The ARKODE library has been entirely rewritten to support a modular approach to one-step methods, which should allow rapid research and development of novel integration methods without affecting existing solver functionality. To support this, the existing ARK-based methods have been encapsulated inside the new ARKStep time-stepping module. Two new time-stepping modules have been added:

- The ERKStep module provides an optimized implementation for explicit Runge–Kutta methods with reduced storage and number of calls to the ODE right-hand side function.
- The MRIStep module implements two-rate explicit-explicit multirate infinitesimal step methods utilizing different step sizes for slow and fast processes in an additive splitting.

This restructure has resulted in numerous small changes to the user interface, particularly the suite of “Set” routines for user-provided solver parameters and “Get” routines to access solver statistics, that are now prefixed with the name of time-stepping module (e.g., ARKStep or ERKStep) instead of ARKODE. Aside from affecting the names of these routines, user-level changes have been kept to a minimum. However, we recommend that users consult both this documentation and the ARKODE example programs for further details on the updated infrastructure.

As part of the ARKODE restructuring an *ARKodeButcherTable* structure has been added for storing Butcher tables. Functions for creating new Butcher tables and checking their analytic order are provided along with other utility routines. For more details see §6.

Two changes were made in the initial step size algorithm:

- Fixed an efficiency bug where an extra call to the right hand side function was made.
- Changed the behavior of the algorithm if the max-iterations case is hit. Before the algorithm would exit with the step size calculated on the penultimate iteration. Now it will exit with the step size calculated on the final iteration.

ARKODE’s dense output infrastructure has been improved to support higher-degree Hermite polynomial interpolants (up to degree 5) over the last successful time step.

ARKODE’s previous direct and iterative linear solver interfaces, ARKDLS and ARKSPILS, have been merged into a single unified linear solver interface, ARKLS, to support any valid SUNLINSOL module. This includes DIRECT and ITERATIVE types as well as the new MATRIX\_ITERATIVE type. Details regarding how ARKLS utilizes linear solvers of each type as well as discussion regarding intended use cases for user-supplied SUNLinSol implementations are included in the chapter §9. All ARKODE examples programs and the standalone linear solver examples have been updated to use the unified linear solver interface.

The user interface for the new ARKLS module is very similar to the previous ARKDLS and ARKSPILS interfaces. Additionally, we note that Fortran users will 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 `SUNLinSol_Band`, `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 ARKODE 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 §10 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 an accelerated fixed-point iteration, respectively. Example programs using each of these nonlinear solver modules in a standalone manner have been added and all ARKODE example programs have been updated to use generic `SUNNonlinSol` modules.

As with previous versions, ARKODE will use the Newton solver (now provided by `SUNNonlinSol_Newton`) by default. Use of the `ARKStepSetLinear()` routine (previously named `ARKodeSetLinear`) will indicate that the problem is linearly-implicit, using only a single Newton iteration per implicit stage. Users wishing to switch to the accelerated fixed-point solver are now required to create a `SUNNonlinSol_FixedPoint` object and attach that to ARKODE, instead of calling the previous `ARKodeSetFixedPoint` routine. See the documentation sections §5.2.1, §5.2.2.5, and §10.4 for further details, or the serial C example program `ark_brusselator_fp.c` for an example.

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 §7.1 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 changes to the CUDA NVECTOR were made:

- Changed the `N_VMake_Cuda` function to take a host data pointer and a device data pointer instead of an `N_VectorContent_Cuda` object.
- Changed `N_VGetLength_Cuda` to return the global vector length instead of the local vector length.
- 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`.
- Added the ability to set the `cudaStream_t` used for execution of the CUDA NVECTOR 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 CUDA NVECTOR.

Multiple changes to the RAJA NVECTOR 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 `sunrajavec`.

A new NVECTOR implementation for leveraging OpenMP 4.5+ device offloading has been added, NVECTOR\_OpenMPDEV. See §7.14 for more details.

### 1.1.17 Changes in v2.2.1

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.

### 1.1.18 Changes in v2.2.0

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 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., `ENABLE_LAPACK` is ON) the build system will infer the scheme from the Fortran compiler. If a Fortran compiler is not available or the inferred 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.

### 1.1.19 Changes in v2.1.2

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  $I + \gamma J$  or  $M + \gamma J$  manually (with zero entries if needed).

---

Changed LICENSE install path to `instdir/include/sundials`.

### 1.1.20 Changes in v2.1.1

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

Fixed a minor bug in the ARKReInit routine, where a flag was incorrectly set to indicate that the problem had been resized (instead of just re-initialized).

Fixed C++11 compiler errors/warnings about incompatible use of string literals.

Updated KLU SUNLinearSolver 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 `ARKSpilsGetNumMTSetups`.

Fixed an indexing bug in the CUDA NVECTOR implementation of `N_VWrmsNormMask` and revised the RAJA NVECTOR implementation of `N_VWrmsNormMask` 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 or SUNLinearSolver module (e.g. iterative linear solvers, explicit methods, fixed point solver, etc.).

### 1.1.21 Changes in v2.1.0

Added NVECTOR print functions that write vector data to a specified file (e.g. `N_VPrintFile_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.

### 1.1.22 Changes in v2.0.0

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 ease in interfacing 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: dense, banded, LAPACK dense, LAPACK band, KLU, SuperLU\_MT, SPGMR, SPBCGS, SPTFQMR, SPFQMR, 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 to utilize 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 NVECTOR 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 `booleantype` 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.

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

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>.

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 `ENABLE_EXAMPLES` to `ENABLE_EXAMPLES_C`, changing `CXX_ENABLE` to `EXAMPLES_ENABLE_CXX`, changing `F90_ENABLE` to `EXAMPLES_ENABLE_F90`, and adding an `EXAMPLES_ENABLE_F77` option.

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

### 1.1.23 Changes in v1.1.0

We have included numerous bugfixes and enhancements since the v1.0.2 release.

The bugfixes include:

- For each linear solver, the various solver performance counters are now initialized to 0 in both the solver specification function and in the solver’s `linit` function. This ensures that these solver counters are initialized upon linear solver instantiation as well as at the beginning of the problem solution.
- The choice of the method vs embedding the Billington and TRBDF2 explicit Runge–Kutta methods were swapped, since in those the lower-order coefficients result in an A-stable method, while the higher-order coefficients do not. This change results in significantly improved robustness when using those methods.
- A bug was fixed for the situation where a user supplies a vector of absolute tolerances, and also uses the vector `Resize()` functionality.
- A bug was fixed wherein a user-supplied Butcher table without an embedding is supplied, and the user is running with either fixed time steps (or they do adaptivity manually); previously this had resulted in an error since the embedding order was below 1.
- Numerous aspects of the documentation were fixed and/or clarified.

The feature changes/enhancements include:

- 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, `N_VGetVectorID`, that returns the NVECTOR module name.
- A memory leak was fixed in the banded preconditioner and banded-block-diagonal preconditioner interfaces. In addition, updates were done to return integers from linear solver and preconditioner ‘free’ routines.
- 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.
- The ARKODE implicit predictor algorithms were updated: methods 2 and 3 were improved slightly, a new predictor approach was added, and the default choice was modified.
- The underlying sparse matrix structure was enhanced to allow both CSR and CSC matrices, with CSR supported by the KLU linear solver interface. ARKODE interfaces to the KLU solver from both C and Fortran were updated to enable selection of sparse matrix type, and a Fortran-90 CSR example program was added.
- The missing `ARKSpilsGetNumMtimesEvals()` function was added – this had been included in the previous documentation but had not been implemented.
- The handling of integer codes for specifying built-in ARKODE Butcher tables was enhanced. While a global numbering system is still used, methods now have #defined names to simplify the user interface and to streamline incorporation of new Butcher tables into ARKODE.
- The maximum number of Butcher table stages was increased from 8 to 15 to accommodate very high order methods, and an 8th-order adaptive ERK method was added.
- Support was added for the explicit and implicit methods in an additive Runge–Kutta method to utilize different stage times, solution and embedding coefficients, to support new SSP-ARK methods.
- The FARKODE interface was extended to include a routine to set scalar/array-valued residual tolerances, to support Fortran applications with non-identity mass-matrices.

## 1.2 Reading this User Guide

This user guide is a combination of general usage instructions and specific example programs. We expect that some readers will want to concentrate on the general instructions, while others will refer mostly to the examples, and the organization is intended to accommodate both styles.

The structure of this document is as follows:

- In the next section we provide a thorough presentation of the underlying *mathematical algorithms* used within the ARKODE family of solvers.
- We follow this with an overview of how the source code for both SUNDIALS and ARKODE are *organized*.
- The largest section follows, providing a full account of how to use ARKODE’s time-stepping modules, *ARKStep*, *ERKStep*, and *MRIStep*, within C and C++ applications. This section then includes additional information on how to use ARKODE from applications written in *Fortran*, as well as information on how to leverage *GPU accelerators within ARKODE*.
- A much smaller section follows, describing ARKODE’s *Butcher table structure*, that is used by both ARKStep and ERKStep.
- Subsequent sections discuss shared SUNDIALS features that are used by ARKODE: *vector data structures*, *matrix data structures*, *linear solver data structures*, *nonlinear solver data structures*, *memory management utilities*, and the *installation procedure*.
- The final sections catalog the full set of *ARKODE constants*, that are used for both input specifications and return codes, and the full set of *Butcher tables* that are packaged with ARKODE.

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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

ARKODE solves ODE initial value problems (IVP) in  $\mathbb{R}^N$  posed in the form

$$M(t)\dot{y} = f(t, y), \quad y(t_0) = y_0. \quad (2.1)$$

Here,  $t$  is the independent variable (e.g. time), and the dependent variables are given by  $y \in \mathbb{R}^N$ , where we use the notation  $\dot{y}$  to denote  $dy/dt$ .

For each value of  $t$ ,  $M(t)$  is a user-specified linear operator from  $\mathbb{R}^N \rightarrow \mathbb{R}^N$ . This operator is assumed to be nonsingular and independent of  $y$ . For standard systems of ordinary differential equations and for problems arising from the spatial semi-discretization of partial differential equations using finite difference, finite volume, or spectral finite element methods,  $M$  is typically the identity matrix,  $I$ . For PDEs using standard finite-element spatial semi-discretizations,  $M$  is typically a well-conditioned mass matrix that is fixed throughout a simulation (or at least fixed between spatial rediscritization events).

The ODE right-hand side is given by the function  $f(t, y)$  – in general we make no assumption that the problem (2.1) is autonomous (i.e.,  $f = f(y)$ ) or linear ( $f = Ay$ ). In general, the time integration methods within ARKODE support additive splittings of this right-hand side function, as described in the subsections that follow. Through these splittings, the time-stepping methods currently supplied with ARKODE are designed to solve stiff, nonstiff, mixed stiff/nonstiff, and multirate problems. As per Ascher and Petzold [3], a problem is “stiff” if the stepsize needed to maintain stability of the forward Euler method is much smaller than that required to represent the solution accurately.

In the sub-sections that follow, we elaborate on the numerical methods utilized in ARKODE. We first discuss the “single-step” nature of the ARKODE infrastructure, including its usage modes and approaches for interpolated solution output. We then discuss the current suite of time-stepping modules supplied with ARKODE, including the ARKStep module for *additive Runge–Kutta methods*, the ERKStep module that is optimized for *explicit Runge–Kutta methods*, and the MRIStep module for *multirate infinitesimal step (MIS)*, *multirate infinitesimal GARK (MRI-GARK)*, and *implicit-explicit MRI-GARK (IMEX-MRI-GARK) methods*. We then discuss the *adaptive temporal error controllers* shared by the time-stepping modules, including discussion of our choice of norms for measuring errors within various components of the solver.

We then discuss the nonlinear and linear solver strategies used by ARKODE’s time-stepping modules for solving implicit algebraic systems that arise in computing each stage and/or step: *nonlinear solvers*, *linear solvers*, *preconditioners*, *error control* within iterative nonlinear and linear solvers, algorithms for *initial predictors* for implicit stage solutions, and approaches for handling *non-identity mass-matrices*.

We conclude with a section describing ARKODE’s *rootfinding capabilities*, that may be used to stop integration of a problem prematurely based on traversal of roots in user-specified functions.

## 2.1 Adaptive single-step methods

The ARKODE infrastructure is designed to support single-step, IVP integration methods, i.e.

$$y_n = \varphi(y_{n-1}, h_n)$$

where  $y_{n-1}$  is an approximation to the solution  $y(t_{n-1})$ ,  $y_n$  is an approximation to the solution  $y(t_n)$ ,  $t_n = t_{n-1} + h_n$ , and the approximation method is represented by the function  $\varphi$ .

The choice of step size  $h_n$  is determined by the time-stepping method (based on user-provided inputs, typically accuracy requirements). However, users may place minimum/maximum bounds on  $h_n$  if desired.

ARKODE's time stepping modules may be run in a variety of "modes":

- **NORMAL** – The solver will take internal steps until it has just overtaken a user-specified output time,  $t_{\text{out}}$ , in the direction of integration, i.e.  $t_{n-1} < t_{\text{out}} \leq t_n$  for forward integration, or  $t_n \leq t_{\text{out}} < t_{n-1}$  for backward integration. It will then compute an approximation to the solution  $y(t_{\text{out}})$  by interpolation (using one of the dense output routines described in the section §2.2).
- **ONE-STEP** – The solver will only take a single internal step  $y_{n-1} \rightarrow y_n$  and then return control back to the calling program. If this step will overtake  $t_{\text{out}}$  then the solver will again return an interpolated result; otherwise it will return a copy of the internal solution  $y_n$ .
- **NORMAL-TSTOP** – The solver will take internal steps until the next step will overtake  $t_{\text{out}}$ . It will then limit this next step so that  $t_n = t_{n-1} + h_n = t_{\text{out}}$ , and once the step completes it will return a copy of the internal solution  $y_n$ .
- **ONE-STEP-TSTOP** – The solver will check whether the next step will overtake  $t_{\text{out}}$  – if not then this mode is identical to "one-step" above; otherwise it will limit this next step so that  $t_n = t_{n-1} + h_n = t_{\text{out}}$ . In either case, once the step completes it will return a copy of the internal solution  $y_n$ .

We note that interpolated solutions may be slightly less accurate than the internal solutions produced by the solver. Hence, to ensure that the returned value has full method accuracy one of the "tstop" modes may be used.

## 2.2 Interpolation

As mentioned above, the time-stepping modules in ARKODE support interpolation of solutions  $y(t_{\text{out}})$  and derivatives  $y^{(d)}(t_{\text{out}})$ , where  $t_{\text{out}}$  occurs within a completed time step from  $t_{n-1} \rightarrow t_n$ . Additionally, this module supports extrapolation of solutions and derivatives for  $t$  outside this interval (e.g. to construct predictors for iterative nonlinear and linear solvers). To this end, ARKODE currently supports construction of polynomial interpolants  $p_q(t)$  of polynomial degree up to  $q = 5$ , although users may select interpolants of lower degree.

ARKODE provides two complementary interpolation approaches, both of which are accessible from any of the time-stepping modules: "Hermite" and "Lagrange". The former approach has been included with ARKODE since its inception, and is more suitable for non-stiff problems; the latter is a new approach that is designed to provide increased accuracy when integrating stiff problems. Both are described in detail below.

### 2.2.1 Hermite interpolation module

For non-stiff problems, polynomial interpolants of Hermite form are provided. Rewriting the IVP (2.1) in standard form,

$$\dot{y} = \hat{f}(t, y), \quad y(t_0) = y_0.$$

we typically construct temporal interpolants using the data  $\{y_{n-1}, \hat{f}_{n-1}, y_n, \hat{f}_n\}$ , where here we use the simplified notation  $\hat{f}_k$  to denote  $\hat{f}(t_k, y_k)$ . Defining a normalized “time” variable,  $\tau$ , for the most-recently-computed solution interval  $t_{n-1} \rightarrow t_n$  as

$$\tau(t) = \frac{t - t_n}{h_n},$$

we then construct the interpolants  $p_q(t)$  as follows:

- $q = 0$ : constant interpolant

$$p_0(\tau) = \frac{y_{n-1} + y_n}{2}.$$

- $q = 1$ : linear Lagrange interpolant

$$p_1(\tau) = -\tau y_{n-1} + (1 + \tau) y_n.$$

- $q = 2$ : quadratic Hermite interpolant

$$p_2(\tau) = \tau^2 y_{n-1} + (1 - \tau^2) y_n + h_n(\tau + \tau^2) \hat{f}_n.$$

- $q = 3$ : cubic Hermite interpolant

$$p_3(\tau) = (3\tau^2 + 2\tau^3) y_{n-1} + (1 - 3\tau^2 - 2\tau^3) y_n + h_n(\tau^2 + \tau^3) \hat{f}_{n-1} + h_n(\tau + 2\tau^2 + \tau^3) \hat{f}_n.$$

- $q = 4$ : quartic Hermite interpolant

$$\begin{aligned} p_4(\tau) = & (-6\tau^2 - 16\tau^3 - 9\tau^4) y_{n-1} + (1 + 6\tau^2 + 16\tau^3 + 9\tau^4) y_n + \frac{h_n}{4} (-5\tau^2 - 14\tau^3 - 9\tau^4) \hat{f}_{n-1} \\ & + h_n(\tau + 2\tau^2 + \tau^3) \hat{f}_n + \frac{27h_n}{4} (-\tau^4 - 2\tau^3 - \tau^2) \hat{f}_a, \end{aligned}$$

where  $\hat{f}_a = \hat{f}\left(t_n - \frac{h_n}{3}, p_3\left(-\frac{1}{3}\right)\right)$ . We point out that interpolation at this degree requires an additional evaluation of the full right-hand side function  $\hat{f}(t, y)$ , thereby increasing its cost in comparison with  $p_3(t)$ .

- $q = 5$ : quintic Hermite interpolant

$$\begin{aligned} p_5(\tau) = & (54\tau^5 + 135\tau^4 + 110\tau^3 + 30\tau^2) y_{n-1} + (1 - 54\tau^5 - 135\tau^4 - 110\tau^3 - 30\tau^2) y_n \\ & + \frac{h_n}{4} (27\tau^5 + 63\tau^4 + 49\tau^3 + 13\tau^2) \hat{f}_{n-1} + \frac{h_n}{4} (27\tau^5 + 72\tau^4 + 67\tau^3 + 26\tau^2 + \tau) \hat{f}_n \\ & + \frac{h_n}{4} (81\tau^5 + 189\tau^4 + 135\tau^3 + 27\tau^2) \hat{f}_a + \frac{h_n}{4} (81\tau^5 + 216\tau^4 + 189\tau^3 + 54\tau^2) \hat{f}_b, \end{aligned}$$

where  $\hat{f}_a = \hat{f}\left(t_n - \frac{h_n}{3}, p_4\left(-\frac{1}{3}\right)\right)$  and  $\hat{f}_b = \hat{f}\left(t_n - \frac{2h_n}{3}, p_4\left(-\frac{2}{3}\right)\right)$ . We point out that interpolation at this degree requires four additional evaluations of the full right-hand side function  $\hat{f}(t, y)$ , thereby significantly increasing its cost over  $p_4(t)$ .

We note that although interpolants of order  $q > 5$  are possible, these are not currently implemented due to their increased computing and storage costs.

## 2.2.2 Lagrange interpolation module

For stiff problems where  $\hat{f}$  may have large Lipschitz constant, polynomial interpolants of Lagrange form are provided. These interpolants are constructed using the data  $\{y_n, y_{n-1}, \dots, y_{n-\nu}\}$  where  $0 \leq \nu \leq 5$ . These polynomials have the form

$$p(t) = \sum_{j=0}^{\nu} y_{n-j} p_j(t), \quad \text{where}$$

$$p_j(t) = \prod_{\substack{l=0 \\ l \neq j}}^{\nu} \left( \frac{t - t_l}{t_j - t_l} \right), \quad j = 0, \dots, \nu.$$

Since we assume that the solutions  $y_{n-j}$  have length much larger than  $\nu \leq 5$  in ARKODE-based simulations, we evaluate  $p$  at any desired  $t \in \mathbb{R}$  by first evaluating the Lagrange polynomial basis functions at the input value for  $t$ , and then performing a simple linear combination of the vectors  $\{y_k\}_{k=0}^{\nu}$ . Derivatives  $p^{(d)}(t)$  may be evaluated similarly as

$$p^{(d)}(t) = \sum_{j=0}^{\nu} y_{n-j} p_j^{(d)}(t),$$

however since the algorithmic complexity involved in evaluating derivatives of the Lagrange basis functions increases dramatically as the derivative order grows, our Lagrange interpolation module currently only provides derivatives up to  $d = 3$ .

We note that when using this interpolation module, during the first  $(\nu - 1)$  steps of integration we do not have sufficient solution history to construct the full  $\nu$ -degree interpolant. Therefore during these initial steps, we construct the highest-degree interpolants that are currently available at the moment, achieving the full  $\nu$ -degree interpolant once these initial steps have completed.

## 2.3 ARKStep – Additive Runge–Kutta methods

The ARKStep time-stepping module in ARKODE is designed for IVPs of the form

$$M(t) \dot{y} = f^E(t, y) + f^I(t, y), \quad y(t_0) = y_0, \tag{2.2}$$

i.e. the right-hand side function is additively split into two components:

- $f^E(t, y)$  contains the “nonstiff” components of the system (this will be integrated using an explicit method);
- $f^I(t, y)$  contains the “stiff” components of the system (this will be integrated using an implicit method);

and the left-hand side may include a nonsingular, possibly time-dependent, matrix  $M(t)$ .

In solving the IVP (2.2), we first consider the corresponding problem in standard form,

$$\dot{y} = \hat{f}^E(t, y) + \hat{f}^I(t, y), \quad y(t_0) = y_0, \tag{2.3}$$

where  $\hat{f}^E(t, y) = M(t)^{-1} f^E(t, y)$  and  $\hat{f}^I(t, y) = M(t)^{-1} f^I(t, y)$ . ARKStep then utilizes variable-step, embedded, additive Runge–Kutta methods (ARK), corresponding to algorithms of the form

$$z_i = y_{n-1} + h_n \sum_{j=1}^{i-1} A_{i,j}^E \hat{f}^E(t_{n,j}^E, z_j) + h_n \sum_{j=1}^i A_{i,j}^I \hat{f}^I(t_{n,j}^I, z_j), \quad i = 1, \dots, s,$$

$$y_n = y_{n-1} + h_n \sum_{i=1}^s \left( b_i^E \hat{f}^E(t_{n,i}^E, z_i) + b_i^I \hat{f}^I(t_{n,i}^I, z_i) \right),$$

$$\tilde{y}_n = y_{n-1} + h_n \sum_{i=1}^s \left( \tilde{b}_i^E \hat{f}^E(t_{n,i}^E, z_i) + \tilde{b}_i^I \hat{f}^I(t_{n,i}^I, z_i) \right). \tag{2.4}$$

Here  $\tilde{y}_n$  are embedded solutions that approximate  $y(t_n)$  and are used for error estimation; these typically have slightly lower accuracy than the computed solutions  $y_n$ . The internal stage times are abbreviated using the notation  $t_{n,j}^E = t_{n-1} + c_j^E h_n$  and  $t_{n,j}^I = t_{n-1} + c_j^I h_n$ . The ARK method is primarily defined through the coefficients  $A^E \in \mathbb{R}^{s \times s}$ ,  $A^I \in \mathbb{R}^{s \times s}$ ,  $b^E \in \mathbb{R}^s$ ,  $b^I \in \mathbb{R}^s$ ,  $c^E \in \mathbb{R}^s$  and  $c^I \in \mathbb{R}^s$ , that correspond with the explicit and implicit Butcher tables. Additional coefficients  $\tilde{b}^E \in \mathbb{R}^s$  and  $\tilde{b}^I \in \mathbb{R}^s$  are used to construct the embedding  $\tilde{y}_n$ . We note that ARKStep currently enforces the constraint that the explicit and implicit methods in an ARK pair must share the same number of stages,  $s$ . We note that except when the problem has a time-independent mass matrix  $M$ , ARKStep allows the possibility for different explicit and implicit abscissae, i.e.  $c^E$  need not equal  $c^I$ .

The user of ARKStep must choose appropriately between one of three classes of methods: *ImEx*, *explicit*, and *implicit*. All of the built-in Butcher tables encoding the coefficients  $c^E$ ,  $c^I$ ,  $A^E$ ,  $A^I$ ,  $b^E$ ,  $b^I$ ,  $\tilde{b}^E$  and  $\tilde{b}^I$  are further described in the section §14.

For mixed stiff/nonstiff problems, a user should provide both of the functions  $f^E$  and  $f^I$  that define the IVP system. For such problems, ARKStep currently implements the ARK methods proposed in [40], allowing for methods having order of accuracy  $q = \{3, 4, 5\}$  and embeddings with orders  $p = \{2, 3, 4\}$ ; the tables for these methods are given in section §14.3. Additionally, user-defined ARK tables are supported.

For nonstiff problems, a user may specify that  $f^I = 0$ , i.e. the equation (2.2) reduces to the non-split IVP

$$M(t) \dot{y} = f^E(t, y), \quad y(t_0) = y_0. \quad (2.5)$$

In this scenario, the coefficients  $A^I = 0$ ,  $c^I = 0$ ,  $b^I = 0$  and  $\tilde{b}^I = 0$  in (2.4), and the ARK methods reduce to classical explicit Runge–Kutta methods (ERK). For these classes of methods, ARKODE provides coefficients with orders of accuracy  $q = \{2, 3, 4, 5, 6, 8\}$ , with embeddings of orders  $p = \{1, 2, 3, 4, 5, 7\}$ . These default to the methods in sections §14.1.1, §14.1.2, §14.1.5, §14.1.9, §14.1.14, and §14.1.15, respectively. As with ARK methods, user-defined ERK tables are supported.

Alternately, for stiff problems the user may specify that  $f^E = 0$ , so the equation (2.2) reduces to the non-split IVP

$$M(t) \dot{y} = f^I(t, y), \quad y(t_0) = y_0. \quad (2.6)$$

Similarly to ERK methods, in this scenario the coefficients  $A^E = 0$ ,  $c^E = 0$ ,  $b^E = 0$  and  $\tilde{b}^E = 0$  in (2.4), and the ARK methods reduce to classical diagonally-implicit Runge–Kutta methods (DIRK). For these classes of methods, ARKODE provides tables with orders of accuracy  $q = \{2, 3, 4, 5\}$ , with embeddings of orders  $p = \{1, 2, 3, 4\}$ . These default to the methods §14.2.1, §14.2.5, §14.2.8, and §14.2.13, respectively. Again, user-defined DIRK tables are supported.

## 2.4 ERKStep – Explicit Runge–Kutta methods

The ERKStep time-stepping module in ARKODE is designed for IVP of the form

$$\dot{y} = f(t, y), \quad y(t_0) = y_0, \quad (2.7)$$

i.e., unlike the more general problem form (2.2), ERKStep requires that problems have an identity mass matrix (i.e.,  $M(t) = I$ ) and that the right-hand side function is not split into separate components.

For such problems, ERKStep provides variable-step, embedded, explicit Runge–Kutta methods (ERK), corresponding to algorithms of the form

$$\begin{aligned} z_i &= y_{n-1} + h_n \sum_{j=1}^{i-1} A_{i,j} f(t_{n,j}, z_j), \quad i = 1, \dots, s, \\ y_n &= y_{n-1} + h_n \sum_{i=1}^s b_i f(t_{n,i}, z_i), \\ \tilde{y}_n &= y_{n-1} + h_n \sum_{i=1}^s \tilde{b}_i f(t_{n,i}, z_i), \end{aligned} \quad (2.8)$$

where the variables have the same meanings as in the previous section.

Clearly, the problem (2.7) is fully encapsulated in the more general problem (2.5), and the algorithm (2.8) is similarly encapsulated in the more general algorithm (2.4). While it therefore follows that ARKStep can be used to solve every problem solvable by ERKStep, using the same set of methods, we include ERKStep as a distinct time-stepping module since this simplified form admits a more efficient and memory-friendly implementation than the more general form (2.7).

## 2.5 MRIStep – Multirate infinitesimal step methods

The MRIStep time-stepping module in ARKODE is designed for IVPs of the form

$$\dot{y} = f^E(t, y) + f^I(t, y) + f^F(t, y), \quad y(t_0) = y_0. \quad (2.9)$$

i.e., the right-hand side function is additively split into three components:

- $f^E(t, y)$  contains the “slow-nonstiff” components of the system (this will be integrated using an explicit method and a large time step  $h^S$ ),
- $f^I(t, y)$  contains the “slow-stiff” components of the system (this will be integrated using an implicit method and a large time step  $h^S$ ), and
- $f^F(t, y)$  contains the “fast” components of the system (this will be integrated using a possibly different method than the slow time scale and a small time step  $h^F \ll h^S$ ).

As with ERKStep, MRIStep currently requires that problems be posed with an identity mass matrix,  $M(t) = I$ . The slow time scale may consist of only nonstiff terms ( $f^I \equiv 0$ ), only stiff terms ( $f^E \equiv 0$ ), or both nonstiff and stiff terms.

For cases with only a single slow right-hand side function (i.e.,  $f^E \equiv 0$  or  $f^I \equiv 0$ ), MRIStep provides fixed-slow-step multirate infinitesimal step (MIS) [53, 54, 55] and multirate infinitesimal GARK (MRI-GARK) [51] methods. For problems with an additively split slow right-hand side MRIStep provides fixed-slow-step implicit-explicit MRI-GARK (IMEX-MRI-GARK) [17] methods. The slow (outer) method derives from an  $s$  stage Runge–Kutta method for MIS and MRI-GARK methods or an additive Runge–Kutta method for IMEX-MRI-GARK methods. In either case, the stage values and the new solution are computed by solving an auxiliary ODE with a fast (inner) time integration method. This corresponds to the following algorithm for a single step:

1. Set  $z_1 = y_{n-1}$ .
2. For  $i = 2, \dots, s+1$  do:
  1. Let  $t_{n,i-1}^S = t_{n-1} + c_{i-1}^S h^S$  and  $v(t_{n,i-1}^S) = z_{i-1}$ .
  2. Let  $r_i(t) = \frac{1}{\Delta c_i^S} \sum_{j=1}^{i-1} \omega_{i,j}(\tau) f^E(t_{n,j}^I, z_j) + \frac{1}{\Delta c_i^S} \sum_{j=1}^i \gamma_{i,j}(\tau) f^I(t_{n,j}^I, z_j)$  where  $\Delta c_i^S = (c_i^S - c_{i-1}^S)$  and the normalized time is  $\tau = (t - t_{n,i-1}^S)/(h^S \Delta c_i^S)$ .
  3. For  $t \in [t_{n,i-1}^S, t_{n,i}^S]$  solve  $\dot{v}(t) = f^F(t, v) + r_i(t)$ .
  4. Set  $z_i = v(t_{n,i}^S)$ .
3. Set  $y_n = z_{s+1}$ .

The fast (inner) IVP solve can be carried out using either the ARKStep module (allowing for explicit, implicit, or ImEx treatments of the fast time scale with fixed or adaptive steps), or a user-defined integration method (see section §5.4.8).

The final abscissa is  $c_{s+1}^S = 1$  and the coefficients  $\omega_{i,j}$  and  $\gamma_{i,j}$  are polynomials in time that dictate the couplings from the slow to the fast time scale; these can be expressed as in [17] and [51] as

$$\omega_{i,j}(\tau) = \sum_{k \geq 0} \omega_{i,j}^{\{k\}} \tau^k \quad \text{and} \quad \gamma_{i,j}(\tau) = \sum_{k \geq 0} \gamma_{i,j}^{\{k\}} \tau^k, \quad (2.10)$$

and where the tables  $\Omega^{\{k\}} \in \mathbb{R}^{(s+1) \times (s+1)}$  and  $\Gamma^{\{k\}} \in \mathbb{R}^{(s+1) \times (s+1)}$  define the slow-to-fast coupling for the explicit and implicit components respectively.

For traditional MIS methods, the coupling coefficients are uniquely defined based on a slow Butcher table  $(A^S, b^S, c^S)$  having an explicit first stage (i.e.,  $c_1^S = 0$  and  $A_{1,j}^S = 0$  for  $1 \leq j \leq s$ ), sorted abscissae (i.e.,  $c_i^S \geq c_{i-1}^S$  for  $2 \leq i \leq s$ ), and the final abscissa is  $c_s^S \leq 1$ . With these properties met, the coupling coefficients for an explicit-slow method are given as

$$\omega_{i,j}^{\{0\}} = \begin{cases} 0, & \text{if } i = 1, \\ A_{i,j}^S - A_{i-1,j}^S, & \text{if } 2 \leq i \leq s, \\ b_j^S - A_{s,j}^S, & \text{if } i = s + 1. \end{cases} \quad (2.11)$$

For general slow tables  $(A^S, b^S, c^S)$  with at least second-order accuracy, the corresponding MIS method will be second order. However, if this slow table is at least third order and satisfies the additional condition

$$\sum_{i=2}^s (c_i^S - c_{i-1}^S) (\mathbf{e}_i + \mathbf{e}_{i-1})^T A^S c^S + (1 - c_s^S) \left( \frac{1}{2} + \mathbf{e}_s^T A^S c^S \right) = \frac{1}{3}, \quad (2.12)$$

where  $\mathbf{e}_j$  corresponds to the  $j$ -th column from the  $s \times s$  identity matrix, then the overall MIS method will be third order.

In the above algorithm, when the slow (outer) method has repeated abscissa, i.e.  $\Delta c_i^S = 0$  for stage  $i$ , the fast (inner) IVP can be rescaled and integrated analytically. In this case the stage is computed as

$$z_i = z_{i-1} + h^S \sum_{j=1}^{i-1} \left( \sum_{k \geq 0} \frac{\omega_{i,j}^{\{k\}}}{k+1} \right) f^E(t_{n,j}^S, z_j) + h^S \sum_{j=1}^i \left( \sum_{k \geq 0} \frac{\gamma_{i,j}^{\{k\}}}{k+1} \right) f^I(t_{n,j}^S, z_j), \quad (2.13)$$

which corresponds to a standard ARK, DIRK, or ERK stage computation depending on whether the summations over  $k$  are zero or nonzero.

As with standard ARK and DIRK methods, implicitness at the slow time scale is characterized by nonzero values on or above the diagonal of the matrices  $\Gamma^{\{k\}}$ . Typically, MRI-GARK and IMEX-MRI-GARK methods are at most diagonally-implicit (i.e.,  $\gamma_{i,j}^{\{k\}} = 0$  for all  $j > i$ ). Furthermore, diagonally-implicit stages are characterized as being “solve-decoupled” if  $\Delta c_i^S = 0$  when  $\text{gamma}_{\{i,i\}\wedge\{k\}} \neq 0$ , in which case the stage is computed as standard ARK or DIRK update. Alternately, a diagonally-implicit stage  $i$  is considered “solve-coupled” if  $\Delta c_i^S \gamma_{i,j}^{\{k\}} \neq 0$ , in which case the stage solution  $z_i$  is *both* an input to  $r(t)$  and the result of time-evolution of the fast IVP, necessitating an implicit solve that is coupled to the fast (inner) solver. At present, only “solve-decoupled” diagonally-implicit MRI-GARK and IMEX-MRI-GARK methods are supported.

For problems with only a slow-nonstiff term ( $f^I \equiv 0$ ), MRIStep provides third and fourth order explicit MRI-GARK methods. In cases with only a slow-stiff term ( $f^E \equiv 0$ ), MRIStep supplies second, third, and fourth order implicit solve-decoupled MRI-GARK methods. For applications with both stiff and nonstiff slow terms, MRIStep implements third and fourth order IMEX-MRI-GARK methods. For a complete list of the methods available in MRIStep see §5.4.7.2. Additionally, users may supply their own method by defining and attaching a coupling table, see §5.4.7 for more information.

## 2.6 Error norms

In the process of controlling errors at various levels (time integration, nonlinear solution, linear solution), the methods in ARKODE use a weighted root-mean-square norm, denoted  $\|\cdot\|_{\text{WRMS}}$ , for all error-like quantities,

$$\|v\|_{\text{WRMS}} = \left( \frac{1}{N} \sum_{i=1}^N (v_i w_i)^2 \right)^{1/2}. \quad (2.14)$$

The utility of this norm arises in the specification of the weighting vector  $w$ , that combines the units of the problem with user-supplied values that specify an “acceptable” level of error. To this end, we construct an error weight vector using the most-recent step solution and user-supplied relative and absolute tolerances, namely

$$w_i = (RTOL \cdot |y_{n-1,i}| + ATOL_i)^{-1}. \quad (2.15)$$

Since  $1/w_i$  represents a tolerance in the  $i$ -th component of the solution vector  $y$ , a vector whose WRMS norm is 1 is regarded as “small.” For brevity, unless specified otherwise we will drop the subscript WRMS on norms in the remainder of this section.

Additionally, for problems involving a non-identity mass matrix,  $M \neq I$ , the units of equation (2.2) may differ from the units of the solution  $y$ . In this case, we may additionally construct a residual weight vector,

$$w_i = \left( RTOL \cdot \left| (M(t_{n-1}) y_{n-1})_i \right| + ATOL'_i \right)^{-1}, \quad (2.16)$$

where the user may specify a separate absolute residual tolerance value or array,  $ATOL'$ . The choice of weighting vector used in any given norm is determined by the quantity being measured: values having “solution” units use (2.15), whereas values having “equation” units use (2.16). Obviously, for problems with  $M = I$ , the solution and equation units are identical, in which case the solvers in ARKODE will use (2.15) when computing all error norms.

## 2.7 Time step adaptivity

A critical component of IVP “solvers” (rather than just time-steppers) is their adaptive control of local truncation error (LTE). At every step, we estimate the local error, and ensure that it satisfies tolerance conditions. If this local error test fails, then the step is recomputed with a reduced step size. To this end, the Runge–Kutta methods packaged within both the ARKStep and ERKStep modules admit an embedded solution  $\tilde{y}_n$ , as shown in equations (2.4) and (2.8). Generally, these embedded solutions attain a slightly lower order of accuracy than the computed solution  $y_n$ . Denoting the order of accuracy for  $y_n$  as  $q$  and for  $\tilde{y}_n$  as  $p$ , most of these embedded methods satisfy  $p = q - 1$ . These values of  $q$  and  $p$  correspond to the *global* orders of accuracy for the method and embedding, hence each admit local truncation errors satisfying [31]

$$\begin{aligned} \|y_n - y(t_n)\| &= Ch_n^{q+1} + \mathcal{O}(h_n^{q+2}), \\ \|\tilde{y}_n - y(t_n)\| &= Dh_n^{p+1} + \mathcal{O}(h_n^{p+2}), \end{aligned} \quad (2.17)$$

where  $C$  and  $D$  are constants independent of  $h_n$ , and where we have assumed exact initial conditions for the step, i.e.  $y_{n-1} = y(t_{n-1})$ . Combining these estimates, we have

$$\|y_n - \tilde{y}_n\| = \|y_n - y(t_n) - \tilde{y}_n + y(t_n)\| \leq \|y_n - y(t_n)\| + \|\tilde{y}_n - y(t_n)\| \leq Dh_n^{p+1} + \mathcal{O}(h_n^{p+2}).$$

We therefore use the norm of the difference between  $y_n$  and  $\tilde{y}_n$  as an estimate for the LTE at the step  $n$

$$T_n = \beta (y_n - \tilde{y}_n) = \beta h_n \sum_{i=1}^s \left[ \left( b_i^E - \tilde{b}_i^E \right) \hat{f}^E(t_{n,i}^E, z_i) + \left( b_i^I - \tilde{b}_i^I \right) \hat{f}^I(t_{n,i}^I, z_i) \right] \quad (2.18)$$

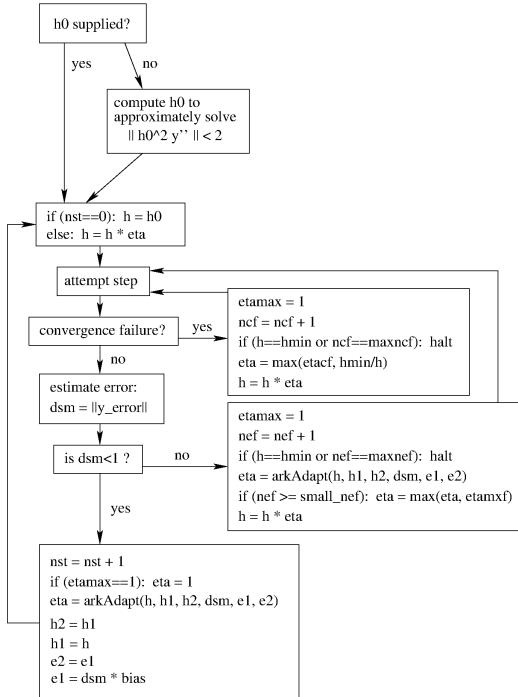
for ARK methods, and similarly for ERK methods. Here,  $\beta > 0$  is an error *bias* to help account for the error constant  $D$ ; the default value of this constant is  $\beta = 1.5$ , which may be modified by the user.

With this LTE estimate, the local error test is simply  $\|T_n\| < 1$  since this norm includes the user-specified tolerances. If this error test passes, the step is considered successful, and the estimate is subsequently used to determine the next step size, the algorithms used for this purpose are described in §2.7. If the error test fails, the step is rejected and a new step size  $h'$  is then computed using the same error controller as for successful steps. A new attempt at the step is made, and the error test is repeated. If the error test fails twice, then  $h'/h$  is limited above to 0.3, and limited below to 0.1 after an additional step failure. After seven error test failures, control is returned to the user with a failure message. We note that all of the constants listed above are only the default values; each may be modified by the user.

We define the step size ratio between a prospective step  $h'$  and a completed step  $h$  as  $\eta$ , i.e.  $\eta = h'/h$ . This value is subsequently bounded from above by  $\eta_{\max}$  to ensure that step size adjustments are not overly aggressive. This upper bound changes according to the step and history,

$$\eta_{\max} = \begin{cases} \text{etamx1}, & \text{on the first step (default is 10000),} \\ \text{growth}, & \text{on general steps (default is 20),} \\ 1, & \text{if the previous step had an error test failure.} \end{cases}$$

A flowchart detailing how the time steps are modified at each iteration to ensure solver convergence and successful steps is given in the figure below. Here, all norms correspond to the WRMS norm, and the error adaptivity function **arkAdapt** is supplied by one of the error control algorithms discussed in the subsections below.



For some problems it may be preferable to avoid small step size adjustments. This can be especially true for problems that construct a Newton Jacobian matrix or a preconditioner for a nonlinear or an iterative linear solve, where this construction is computationally expensive, and where convergence can be seriously hindered through use of an inaccurate matrix. To accommodate these scenarios, the step is left unchanged when  $\eta \in [\eta_L, \eta_U]$ . The default values for this interval are  $\eta_L = 1$  and  $\eta_U = 1.5$ , and may be modified by the user.

We note that any choices for  $\eta$  (or equivalently,  $h'$ ) are subsequently constrained by the optional user-supplied bounds  $h_{\min}$  and  $h_{\max}$ . Additionally, the time-stepping algorithms in ARKODE may similarly limit  $h'$  to adhere to a user-provided “TSTOP” stopping point,  $t_{\text{stop}}$ .

The time-stepping modules in ARKODE adapt the step size in order to attain local errors within desired tolerances of the true solution. These adaptivity algorithms estimate the prospective step size  $h'$  based on the asymptotic local error estimates (2.17). We define the values  $\varepsilon_n$ ,  $\varepsilon_{n-1}$  and  $\varepsilon_{n-2}$  as

$$\varepsilon_k \equiv \|T_k\| = \beta \|y_k - \tilde{y}_k\|,$$

corresponding to the local error estimates for three consecutive steps,  $t_{n-3} \rightarrow t_{n-2} \rightarrow t_{n-1} \rightarrow t_n$ . These local error history values are all initialized to 1 upon program initialization, to accommodate the few initial time steps of a calculation where some of these error estimates have not yet been computed. With these estimates, ARKODE supports a variety of error control algorithms, as specified in the subsections below.

## 2.7.1 PID controller

This is the default time adaptivity controller used by the ARKStep and ERKStep modules. It derives from those found in [40], [56], [57] and [58], and uses all three of the local error estimates  $\varepsilon_n$ ,  $\varepsilon_{n-1}$  and  $\varepsilon_{n-2}$  in determination of a prospective step size,

$$h' = h_n \varepsilon_n^{-k_1/p} \varepsilon_{n-1}^{k_2/p} \varepsilon_{n-2}^{-k_3/p},$$

where the constants  $k_1$ ,  $k_2$  and  $k_3$  default to 0.58, 0.21 and 0.1, respectively, and may be modified by the user. In this estimate, a floor of  $\varepsilon > 10^{-10}$  is enforced to avoid division-by-zero errors.

## 2.7.2 PI controller

Like with the previous method, the PI controller derives from those found in [40], [56], [57] and [58], but it differs in that it only uses the two most recent step sizes in its adaptivity algorithm,

$$h' = h_n \varepsilon_n^{-k_1/p} \varepsilon_{n-1}^{k_2/p}.$$

Here, the default values of  $k_1$  and  $k_2$  default to 0.8 and 0.31, respectively, though they may be changed by the user.

## 2.7.3 I controller

This is the standard time adaptivity control algorithm in use by most publicly-available ODE solver codes. It bases the prospective time step estimate entirely off of the current local error estimate,

$$h' = h_n \varepsilon_n^{-k_1/p}.$$

By default,  $k_1 = 1$ , but that may be modified by the user.

## 2.7.4 Explicit Gustafsson controller

This step adaptivity algorithm was proposed in [29], and is primarily useful with explicit Runge–Kutta methods. In the notation of our earlier controllers, it has the form

$$h' = \begin{cases} h_1 \varepsilon_1^{-1/p}, & \text{on the first step,} \\ h_n \varepsilon_n^{-k_1/p} \left( \frac{\varepsilon_n}{\varepsilon_{n-1}} \right)^{k_2/p}, & \text{on subsequent steps.} \end{cases} \quad (2.19)$$

The default values of  $k_1$  and  $k_2$  are 0.367 and 0.268, respectively, and may be modified by the user.

## 2.7.5 Implicit Gustafsson controller

A version of the above controller suitable for implicit Runge–Kutta methods was introduced in [30], and has the form

$$h' = \begin{cases} h_1 \varepsilon_1^{-1/p}, & \text{on the first step,} \\ h_n \left( \frac{h_n}{h_{n-1}} \right) \varepsilon_n^{-k_1/p} \left( \frac{\varepsilon_n}{\varepsilon_{n-1}} \right)^{-k_2/p}, & \text{on subsequent steps.} \end{cases} \quad (2.20)$$

The algorithm parameters default to  $k_1 = 0.98$  and  $k_2 = 0.95$ , but may be modified by the user.

## 2.7.6 ImEx Gustafsson controller

An ImEx version of these two preceding controllers is also available. This approach computes the estimates  $h'_1$  arising from equation (2.19) and the estimate  $h'_2$  arising from equation (2.20), and selects

$$h' = \frac{h}{|h|} \min \{|h'_1|, |h'_2|\}.$$

Here, equation (2.19) uses  $k_1$  and  $k_2$  with default values of 0.367 and 0.268, while equation (2.20) sets both parameters to the input  $k_3$  that defaults to 0.95. All of these values may be modified by the user.

## 2.7.7 User-supplied controller

Finally, ARKODE's time-stepping modules allow the user to define their own time step adaptivity function,

$$h' = H(y, t, h_n, h_{n-1}, h_{n-2}, \varepsilon_n, \varepsilon_{n-1}, \varepsilon_{n-2}, q, p),$$

to allow for problem-specific choices, or for continued experimentation with temporal error controllers.

## 2.8 Explicit stability

For problems that involve a nonzero explicit component, i.e.  $f^E(t, y) \neq 0$  in ARKStep or for any problem in ERKStep, explicit and ImEx Runge–Kutta methods may benefit from additional user-supplied information regarding the explicit stability region. All ARKODE adaptivity methods utilize estimates of the local error, and it is often the case that such local error control will be sufficient for method stability, since unstable steps will typically exceed the error control tolerances. However, for problems in which  $f^E(t, y)$  includes even moderately stiff components, and especially for higher-order integration methods, it may occur that a significant number of attempted steps will exceed the error tolerances. While these steps will automatically be recomputed, such trial-and-error can result in an unreasonable number of failed steps, increasing the cost of the computation. In these scenarios, a stability-based time step controller may also be useful.

Since the maximum stable explicit step for any method depends on the problem under consideration, in that the value  $(h_n, \lambda)$  must reside within a bounded stability region, where  $\lambda$  are the eigenvalues of the linearized operator  $\partial f^E / \partial y$ , information on the maximum stable step size is not readily available to ARKODE's time-stepping modules. However, for many problems such information may be easily obtained through analysis of the problem itself, e.g. in an advection-diffusion calculation  $f^I$  may contain the stiff diffusive components and  $f^E$  may contain the comparably nonstiff advection terms. In this scenario, an explicitly stable step  $h_{\text{exp}}$  would be predicted as one satisfying the Courant-Friedrichs-Lowy (CFL) stability condition for the advective portion of the problem,

$$|h_{\text{exp}}| < \frac{\Delta x}{|\lambda|}$$

where  $\Delta x$  is the spatial mesh size and  $\lambda$  is the fastest advective wave speed.

In these scenarios, a user may supply a routine to predict this maximum explicitly stable step size,  $|h_{\text{exp}}|$ . If a value for  $|h_{\text{exp}}|$  is supplied, it is compared against the value resulting from the local error controller,  $|h_{\text{acc}}|$ , and the eventual time step used will be limited accordingly,

$$h' = \frac{h}{|h|} \min\{c|h_{\text{exp}}|, |h_{\text{acc}}|\}.$$

Here the explicit stability step factor  $c > 0$  (often called the “CFL number”) defaults to 1/2 but may be modified by the user.

## 2.9 Fixed time stepping

While both the ARKStep and ERKStep time-stepping modules are designed for tolerance-based time step adaptivity, they additionally support a “fixed-step” mode (*note: fixed-step mode is currently required for the slow time scale in the MRIStep module*). This mode is typically used for debugging purposes, for verification against hand-coded Runge–Kutta methods, or for problems where the time steps should be chosen based on other problem-specific information. In this mode, all internal time step adaptivity is disabled:

- temporal error control is disabled,
- nonlinear or linear solver non-convergence will result in an error (instead of a step size adjustment),
- no check against an explicit stability condition is performed.

Additional information on this mode is provided in the sections [ARKStep Optional Inputs](#), [ERKStep Optional Inputs](#), and [MRIStep Optional Inputs](#).

## 2.10 Algebraic solvers

When solving a problem involving either an implicit component (e.g., in ARKStep with  $f^I(t, y) \neq 0$ , or in MRIStep with a solve-decoupled implicit slow stage), or a non-identity mass matrix ( $M(t) \neq I$  in ARKStep), systems of linear or nonlinear algebraic equations must be solved at each stage and/or step of the method. This section therefore focuses on the variety of mathematical methods provided in the ARKODE infrastructure for such problems, including [nonlinear solvers](#), [linear solvers](#), [preconditioners](#), [iterative solver error control](#), [implicit predictors](#), and techniques used for simplifying the above solves when using different classes of [mass-matrices](#).

### 2.10.1 Nonlinear solver methods

For the DIRK and ARK methods corresponding to (2.2) and (2.6) in ARKStep, and the solve-decoupled implicit slow stages (2.13) in MRIStep, an implicit system

$$G(z_i) = 0 \quad (2.21)$$

must be solved for each implicit stage  $z_i$ . In order to maximize solver efficiency, we define this root-finding problem differently based on the type of mass-matrix supplied by the user.

- In the case that  $M = I$  within ARKStep, we define the residual as

$$G(z_i) \equiv z_i - h_n A_{i,i}^I f^I(t_{n,i}^I, z_i) - a_i, \quad (2.22)$$

where we have the data

$$a_i \equiv y_{n-1} + h_n \sum_{j=1}^{i-1} [A_{i,j}^E f^E(t_{n,j}^E, z_j) + A_{i,j}^I f^I(t_{n,j}^I, z_j)].$$

- In the case of non-identity mass matrix  $M \neq I$  within ARKStep, but where  $M$  is independent of  $t$ , we define the residual as

$$G(z_i) \equiv M z_i - h_n A_{i,i}^I f^I(t_{n,i}^I, z_i) - a_i, \quad (2.23)$$

where we have the data

$$a_i \equiv M y_{n-1} + h_n \sum_{j=1}^{i-1} [A_{i,j}^E f^E(t_{n,j}^E, z_j) + A_{i,j}^I f^I(t_{n,j}^I, z_j)].$$

**Note:** This form of residual, as opposed to  $G(z_i) = z_i - h_n A_{i,i}^I \hat{f}^I(t_{n,i}^I, z_i) - a_i$  (with  $a_i$  defined appropriately), removes the need to perform the nonlinear solve with right-hand side function  $\hat{f}^I = M^{-1} f^I$ , as that would require a linear solve with  $M$  at *every evaluation* of the implicit right-hand side routine.

- In the case of ARKStep with  $M$  dependent on  $t$ , we define the residual as

$$G(z_i) \equiv M(t_{n,i}^I)(z_i - a_i) - h_n A_{i,i}^I f^I(t_{n,i}^I, z_i) \quad (2.24)$$

where we have the data

$$a_i \equiv y_{n-1} + h_n \sum_{j=1}^{i-1} \left[ A_{i,j}^E \hat{f}^E(t_{n,j}^E, z_j) + A_{i,j}^I \hat{f}^I(t_{n,j}^I, z_j) \right].$$

**Note:** As above, this form of the residual is chosen to remove excessive mass-matrix solves from the nonlinear solve process.

- Similarly, in MRIStep (that always assumes  $M = I$ ), we have the residual

$$G(z_i) \equiv z_i - h^S \left( \sum_{k \geq 0} \frac{\gamma_{i,i}^{\{k\}}}{k+1} \right) f^I(t_{n,i}^S, z_i) - a_i = 0 \quad (2.25)$$

where

$$a_i \equiv z_{i-1} + h^S \sum_{j=1}^{i-1} \left( \sum_{k \geq 0} \frac{\gamma_{i,j}^{\{k\}}}{k+1} \right) f^I(t_{n,j}^S, z_j).$$

In each of the above nonlinear residual functions, if  $f^I(t, y)$  depends nonlinearly on  $y$  then (2.21) corresponds to a nonlinear system of equations; if instead  $f^I(t, y)$  depends linearly on  $y$  then this is a linear system of equations.

To solve each of the above root-finding problems ARKODE leverages SUNNonlinearSolver modules from the underlying SUNDIALS infrastructure (see section §10). By default, ARKODE selects a variant of Newton's method,

$$z_i^{(m+1)} = z_i^{(m)} + \delta^{(m+1)}, \quad (2.26)$$

where  $m$  is the Newton iteration index, and the Newton update  $\delta^{(m+1)}$  in turn requires the solution of the Newton linear system

$$\mathcal{A}\left(t_{n,i}^I, z_i^{(m)}\right) \delta^{(m+1)} = -G\left(z_i^{(m)}\right), \quad (2.27)$$

in which

$$\mathcal{A}(t, z) \approx M(t) - \gamma J(t, z), \quad J(t, z) = \frac{\partial f^I(t, z)}{\partial z}, \quad \text{and} \quad \gamma = h_n A_{i,i}^I \quad (2.28)$$

within ARKStep, or

$$\mathcal{A}(t, z) \approx I - \gamma J(t, z), \quad J(t, z) = \frac{\partial f^I(t, z)}{\partial z}, \quad \text{and} \quad \gamma = h^S \sum_{k \geq 0} \frac{\gamma_{i,i}^{\{k\}}}{k+1} \quad (2.29)$$

within MRIStep.

In addition to Newton-based nonlinear solvers, the SUNDIALS SUNNonlinearSolver interface allows solvers of fixed-point type. These generally implement a fixed point iteration for solving an implicit stage  $z_i$ ,

$$z_i^{(m+1)} = \Phi(z_i^{(m)}) \equiv z_i^{(m)} - M(t_{n,i}^I)^{-1} G(z_i^{(m)}), \quad m = 0, 1, \dots \quad (2.30)$$

Unlike with Newton-based nonlinear solvers, fixed-point iterations generally *do not* require the solution of a linear system involving the Jacobian of  $f$  at each iteration.

Finally, if the user specifies that  $f^I(t, y)$  depends linearly on  $y$  in ARKStep or MRIStep and if the Newton-based SUNNonlinearSolver module is used, then the problem (2.21) will be solved using only a single Newton iteration. In this case, an additional user-supplied argument indicates whether this Jacobian is time-dependent or not, signaling whether the Jacobian or preconditioner needs to be recomputed at each stage or time step, or if it can be reused throughout the full simulation.

The optimal choice of solver (Newton vs fixed-point) is highly problem dependent. Since fixed-point solvers do not require the solution of linear systems involving the Jacobian of  $f$ , each iteration may be significantly less costly than their Newton counterparts. However, this can come at the cost of slower convergence (or even divergence) in comparison with Newton-like methods. While a Newton-based iteration is the default solver in ARKODE due to its increased robustness on very stiff problems, we strongly recommend that users also consider the fixed-point solver when attempting a new problem.

For either the Newton or fixed-point solvers, it is well-known that both the efficiency and robustness of the algorithm intimately depend on the choice of a good initial guess. The initial guess for these solvers is a prediction  $z_i^{(0)}$  that is computed explicitly from previously-computed data (e.g.  $y_{n-2}$ ,  $y_{n-1}$ , and  $z_j$  where  $j < i$ ). Additional information on the specific predictor algorithms is provided in section §2.10.5.

## 2.10.2 Linear solver methods

When a Newton-based method is chosen for solving each nonlinear system, a linear system of equations must be solved at each nonlinear iteration. For this solve ARKODE leverages another component of the shared SUNDIALS infrastructure, the “SUNLinearSolver,” described in section §9. These linear solver modules are grouped into two categories: matrix-based linear solvers and matrix-free iterative linear solvers. ARKODE’s interfaces for linear solves of these types are described in the subsections below.

### 2.10.2.1 Matrix-based linear solvers

In the case that a matrix-based linear solver is selected, a *modified Newton iteration* is utilized. In a modified Newton iteration, the matrix  $\mathcal{A}$  is held fixed for multiple Newton iterations. More precisely, each Newton iteration is computed from the modified equation

$$\tilde{\mathcal{A}}(\tilde{t}, \tilde{z}) \delta^{(m+1)} = -G(z_i^{(m)}), \quad (2.31)$$

in which

$$\tilde{\mathcal{A}}(\tilde{t}, \tilde{z}) \approx M(\tilde{t}) - \tilde{\gamma} J(\tilde{t}, \tilde{z}), \quad \text{and} \quad \tilde{\gamma} = \tilde{h} A_{i,i}^I \quad (\text{ARKStep}) \quad (2.32)$$

or

$$\tilde{\mathcal{A}}(\tilde{t}, \tilde{z}) \approx I - \tilde{\gamma} J(\tilde{t}, \tilde{z}), \quad \text{and} \quad \tilde{\gamma} = \tilde{h} \sum_{k \geq 0} \frac{\gamma_{i,i}^{\{k\}}}{k+1} \quad (\text{MRIStep}). \quad (2.33)$$

Here, the solution  $\tilde{z}$ , time  $\tilde{t}$ , and step size  $\tilde{h}$  upon which the modified equation rely, are merely values of these quantities from a previous iteration. In other words, the matrix  $\tilde{\mathcal{A}}$  is only computed rarely, and reused for repeated solves. As

described below in section §2.10.2.3, the frequency at which  $\tilde{\mathcal{A}}$  is recomputed defaults to 20 time steps, but may be modified by the user.

When using the dense and band SUNMatrix objects for the linear systems (2.31), the Jacobian  $J$  may be supplied by a user routine, or approximated internally by finite-differences. In the case of differencing, we use the standard approximation

$$J_{i,j}(t, z) \approx \frac{f_i^I(t, z + \sigma_j e_j) - f_i^I(t, z)}{\sigma_j},$$

where  $e_j$  is the  $j$ -th unit vector, and the increments  $\sigma_j$  are given by

$$\sigma_j = \max \left\{ \sqrt{U} |z_j|, \frac{\sigma_0}{w_j} \right\}.$$

Here  $U$  is the unit roundoff,  $\sigma_0$  is a small dimensionless value, and  $w_j$  is the error weight defined in (2.15). In the dense case, this approach requires  $N$  evaluations of  $f^I$ , one for each column of  $J$ . In the band case, the columns of  $J$  are computed in groups, using the Curtis-Powell-Reid algorithm, with the number of  $f^I$  evaluations equal to the matrix bandwidth.

We note that with sparse and user-supplied SUNMatrix objects, the Jacobian *must* be supplied by a user routine.

### 2.10.2.2 Matrix-free iterative linear solvers

In the case that a matrix-free iterative linear solver is chosen, an *inexact Newton iteration* is utilized. Here, the matrix  $\mathcal{A}$  is not itself constructed since the algorithms only require the product of this matrix with a given vector. Additionally, each Newton system (2.27) is not solved completely, since these linear solvers are iterative (hence the “inexact” in the name). As a result, for these linear solvers  $\mathcal{A}$  is applied in a matrix-free manner,

$$\mathcal{A}(t, z) v = M(t) v - \gamma J(t, z) v.$$

The mass matrix-vector products  $Mv$  *must* be provided through a user-supplied routine; the Jacobian matrix-vector products  $Jv$  are obtained by either calling an optional user-supplied routine, or through a finite difference approximation to the directional derivative:

$$J(t, z) v \approx \frac{f^I(t, z + \sigma v) - f^I(t, z)}{\sigma},$$

where we use the increment  $\sigma = 1/\|v\|$  to ensure that  $\|\sigma v\| = 1$ .

As with the modified Newton method that reused  $\mathcal{A}$  between solves, the inexact Newton iteration may also recompute the preconditioner  $P$  infrequently to balance the high costs of matrix construction and factorization against the reduced convergence rate that may result from a stale preconditioner.

### 2.10.2.3 Updating the linear solver

In cases where recomputation of the Newton matrix  $\tilde{\mathcal{A}}$  or preconditioner  $P$  is lagged, these structures will be recomputed only in the following circumstances:

- when starting the problem,
- when more than  $msbp = 20$  steps have been taken since the last update (this value may be modified by the user),
- when the value  $\tilde{\gamma}$  of  $\gamma$  at the last update satisfies  $|\gamma/\tilde{\gamma} - 1| > \Delta\gamma_{max} = 0.2$  (this value may be modified by the user),
- when a non-fatal convergence failure just occurred,
- when an error test failure just occurred, or

- if the problem is linearly implicit and  $\gamma$  has changed by a factor larger than 100 times machine epsilon.

When an update is forced due to a convergence failure, an update of  $\tilde{\mathcal{A}}$  or  $P$  may or may not involve a re-evaluation of  $J$  (in  $\tilde{\mathcal{A}}$ ) or of Jacobian data (in  $P$ ), depending on whether errors in the Jacobian were the likely cause of the failure. More generally, the decision is made to re-evaluate  $J$  (or instruct the user to update  $P$ ) when:

- starting the problem,
- more than  $msbj = 50$  steps have been taken since the last evaluation,
- a convergence failure occurred with an outdated matrix, and the value  $\tilde{\gamma}$  of  $\gamma$  at the last update satisfies  $|\gamma/\tilde{\gamma} - 1| > 0.2$ ,
- a convergence failure occurred that forced a step size reduction, or
- if the problem is linearly implicit and  $\gamma$  has changed by a factor larger than 100 times machine epsilon.

However, for linear solvers and preconditioners that do not rely on costly matrix construction and factorization operations (e.g. when using a geometric multigrid method as preconditioner), it may be more efficient to update these structures more frequently than the above heuristics specify, since the increased rate of linear/nonlinear solver convergence may more than account for the additional cost of Jacobian/preconditioner construction. To this end, a user may specify that the system matrix  $\mathcal{A}$  and/or preconditioner  $P$  should be recomputed more frequently.

As will be further discussed in section §2.10.4, in the case of most Krylov methods, preconditioning may be applied on the left, right, or on both sides of  $\mathcal{A}$ , with user-supplied routines for the preconditioner setup and solve operations.

## 2.10.3 Iteration Error Control

### 2.10.3.1 Nonlinear iteration error control

ARKODE provides a customized stopping test to the SUNNonlinearSolver module used for solving equation (2.21). This test is related to the temporal local error test, with the goal of keeping the nonlinear iteration errors from interfering with local error control. Denoting the final computed value of each stage solution as  $z_i^{(m)}$ , and the true stage solution solving (2.21) as  $z_i$ , we want to ensure that the iteration error  $z_i - z_i^{(m)}$  is “small” (recall that a norm less than 1 is already considered within an acceptable tolerance).

To this end, we first estimate the linear convergence rate  $R_i$  of the nonlinear iteration. We initialize  $R_i = 1$ , and reset it to this value whenever  $\tilde{\mathcal{A}}$  or  $P$  are updated. After computing a nonlinear correction  $\delta^{(m)} = z_i^{(m)} - z_i^{(m-1)}$ , if  $m > 0$  we update  $R_i$  as

$$R_i \leftarrow \max \left\{ c_r R_i, \left\| \delta^{(m)} \right\| / \left\| \delta^{(m-1)} \right\| \right\}. \quad (2.34)$$

where the default factor  $c_r = 0.3$  is user-modifiable.

Let  $y_n^{(m)}$  denote the time-evolved solution constructed using our approximate nonlinear stage solutions,  $z_i^{(m)}$ , and let  $y_n^{(\infty)}$  denote the time-evolved solution constructed using *exact* nonlinear stage solutions. We then use the estimate

$$\left\| y_n^{(\infty)} - y_n^{(m)} \right\| \approx \max_i \left\| z_i^{(m+1)} - z_i^{(m)} \right\| \approx \max_i R_i \left\| z_i^{(m)} - z_i^{(m-1)} \right\| = \max_i R_i \left\| \delta^{(m)} \right\|.$$

Therefore our convergence (stopping) test for the nonlinear iteration for each stage is

$$R_i \left\| \delta^{(m)} \right\| < \epsilon, \quad (2.35)$$

where the factor  $\epsilon$  has default value 0.1. We default to a maximum of 3 nonlinear iterations. We also declare the nonlinear iteration to be divergent if any of the ratios

$${}^c \left\| \delta^{(m)} \right\| / \left\| \delta^{(m-1)} \right\| > r_{div} {}^c \quad (2.36)$$

with  $m > 0$ , where  $r_{div}$  defaults to 2.3. If convergence fails in the nonlinear solver with  $\mathcal{A}$  current (i.e., not lagged), we reduce the step size  $h_n$  by a factor of  $\eta_{cf} = 0.25$ . The integration will be halted after  $max_{ncf} = 10$  convergence failures, or if a convergence failure occurs with  $h_n = h_{\min}$ . However, since the nonlinearity of (2.21) may vary significantly based on the problem under consideration, these default constants may all be modified by the user.

### 2.10.3.2 Linear iteration error control

When a Krylov method is used to solve the linear Newton systems (2.27), its errors must also be controlled. To this end, we approximate the linear iteration error in the solution vector  $\delta^{(m)}$  using the preconditioned residual vector, e.g.  $r = P\mathcal{A}\delta^{(m)} + PG$  for the case of left preconditioning (the role of the preconditioner is further elaborated in the next section). In an attempt to ensure that the linear iteration errors do not interfere with the nonlinear solution error and local time integration error controls, we require that the norm of the preconditioned linear residual satisfies

$$\|r\| \leq \frac{\epsilon_L \epsilon}{10}. \quad (2.37)$$

Here  $\epsilon$  is the same value as that is used above for the nonlinear error control. The factor of 10 is used to ensure that the linear solver error does not adversely affect the nonlinear solver convergence. Smaller values for the parameter  $\epsilon_L$  are typically useful for strongly nonlinear or very stiff ODE systems, while easier ODE systems may benefit from a value closer to 1. The default value is  $\epsilon_L = 0.05$ , which may be modified by the user. We note that for linearly implicit problems the tolerance (2.37) is similarly used for the single Newton iteration.

## 2.10.4 Preconditioning

When using an inexact Newton method to solve the nonlinear system (2.21), an iterative method is used repeatedly to solve linear systems of the form  $\mathcal{A}x = b$ , where  $x$  is a correction vector and  $b$  is a residual vector. If this iterative method is one of the scaled preconditioned iterative linear solvers supplied with SUNDIALS, their efficiency may benefit tremendously from preconditioning. A system  $\mathcal{A}x = b$  can be preconditioned using any one of:

$$\begin{aligned} (P^{-1}\mathcal{A})x &= P^{-1}b && [\text{left preconditioning}], \\ (\mathcal{A}P^{-1})Px &= b && [\text{right preconditioning}], \\ (P_L^{-1}\mathcal{A}P_R^{-1})P_Rx &= P_L^{-1}b && [\text{left and right preconditioning}]. \end{aligned}$$

These Krylov iterative methods are then applied to a system with the matrix  $P^{-1}\mathcal{A}$ ,  $\mathcal{A}P^{-1}$ , or  $P_L^{-1}\mathcal{A}P_R^{-1}$ , instead of  $\mathcal{A}$ . In order to improve the convergence of the Krylov iteration, the preconditioner matrix  $P$ , or the product  $P_L P_R$  in the third case, should in some sense approximate the system matrix  $\mathcal{A}$ . Simultaneously, in order to be cost-effective the matrix  $P$  (or matrices  $P_L$  and  $P_R$ ) should be reasonably efficient to evaluate and solve. Finding an optimal point in this trade-off between rapid convergence and low cost can be quite challenging. Good choices are often problem-dependent (for example, see [11] for an extensive study of preconditioners for reaction-transport systems).

Most of the iterative linear solvers supplied with SUNDIALS allow for all three types of preconditioning (left, right or both), although for non-symmetric matrices  $\mathcal{A}$  we know of few situations where preconditioning on both sides is superior to preconditioning on one side only (with the product  $P = P_L P_R$ ). Moreover, for a given preconditioner matrix, the merits of left vs. right preconditioning are unclear in general, so we recommend that the user experiment with both choices. Performance can differ between these since the inverse of the left preconditioner is included in the linear system residual whose norm is being tested in the Krylov algorithm. As a rule, however, if the preconditioner is the product of two matrices, we recommend that preconditioning be done either on the left only or the right only, rather than using one factor on each side. An exception to this rule is the PCG solver, that itself assumes a symmetric matrix  $\mathcal{A}$ , since the PCG algorithm in fact applies the single preconditioner matrix  $P$  in both left/right fashion as  $P^{-1/2}\mathcal{A}P^{-1/2}$ .

Typical preconditioners are based on approximations to the system Jacobian,  $J = \partial f^I / \partial y$ . Since the Newton iteration matrix involved is  $\mathcal{A} = M - \gamma J$ , any approximation  $\bar{J}$  to  $J$  yields a matrix that is of potential use as a preconditioner, namely  $P = M - \gamma \bar{J}$ . Because the Krylov iteration occurs within a Newton 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 features of the system. We have found that the combination of a preconditioner with the Newton-Krylov iteration, using even a relatively 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.

## 2.10.5 Implicit predictors

For problems with implicit components, a prediction algorithm is employed for constructing the initial guesses for each implicit Runge–Kutta stage,  $z_i^{(0)}$ . As is well-known with nonlinear solvers, the selection of a good initial guess can have dramatic effects on both the speed and robustness of the solve, making the difference between rapid quadratic convergence versus divergence of the iteration. To this end, a variety of prediction algorithms are provided. In each case, the stage guesses  $z_i^{(0)}$  are constructed explicitly using readily-available information, including the previous step solutions  $y_{n-1}$  and  $y_{n-2}$ , as well as any previous stage solutions  $z_j$ ,  $j < i$ . In most cases, prediction is performed by constructing an interpolating polynomial through existing data, which is then evaluated at the desired stage time to provide an inexpensive but (hopefully) reasonable prediction of the stage solution. Specifically, for most Runge–Kutta methods each stage solution satisfies

$$z_i \approx y(t_{n,i}^I),$$

(similarly for MRI methods  $z_i \approx y(t_{n,i}^S)$ ), so by constructing an interpolating polynomial  $p_q(t)$  through a set of existing data, the initial guess at stage solutions may be approximated as

$$z_i^{(0)} = p_q(t_{n,i}^I). \quad (2.38)$$

As the stage times for MRI stages and implicit ARK and DIRK stages usually have non-negative abscissae (i.e.,  $c_j^I > 0$ ), it is typically the case that  $t_{n,j}^I$  (resp.,  $t_{n,j}^S$ ) is outside of the time interval containing the data used to construct  $p_q(t)$ , hence (2.38) will correspond to an extrapolant instead of an interpolant. The dangers of using a polynomial interpolant to extrapolate values outside the interpolation interval are well-known, with higher-order polynomials and predictions further outside the interval resulting in the greatest potential inaccuracies.

The prediction algorithms available in ARKODE therefore construct a variety of interpolants  $p_q(t)$ , having different polynomial order and using different interpolation data, to support “optimal” choices for different types of problems, as described below. We note that due to the structural similarities between implicit ARK and DIRK stages in ARKStep, and solve-decoupled implicit stages in MRIStep, we use the ARKStep notation throughout the remainder of this section, but each statement equally applies to MRIStep (unless otherwise noted).

### 2.10.5.1 Trivial predictor

The so-called “trivial predictor” is given by the formula

$$p_0(t) = y_{n-1}.$$

While this piecewise-constant interpolant is clearly not a highly accurate candidate for problems with time-varying solutions, it is often the most robust approach for highly stiff problems, or for problems with implicit constraints whose violation may cause illegal solution values (e.g. a negative density or temperature).

### 2.10.5.2 Maximum order predictor

At the opposite end of the spectrum, ARKODE's interpolation modules discussed in section §2.2 can be used to construct a higher-order polynomial interpolant,  $p_q(t)$ . The implicit stage predictor is computed through evaluating the highest-degree-available interpolant at each stage time  $t_{n,i}^I$ .

### 2.10.5.3 Variable order predictor

This predictor attempts to use higher-degree polynomials  $p_q(t)$  for predicting earlier stages, and lower-degree interpolants for later stages. It uses the same interpolation module as described above, but chooses the polynomial degree adaptively based on the stage index  $i$ , under the assumption that the stage times are increasing, i.e.  $c_j^I < c_k^I$  for  $j < k$ :

$$q_i = \max\{q_{\max} - i + 1, 1\}, \quad i = 1, \dots, s.$$

### 2.10.5.4 Cutoff order predictor

This predictor follows a similar idea as the previous algorithm, but monitors the actual stage times to determine the polynomial interpolant to use for prediction. Denoting  $\tau = c_i^I \frac{h_n}{h_{n-1}}$ , the polynomial degree  $q_i$  is chosen as:

$$q_i = \begin{cases} q_{\max}, & \text{if } \tau < \frac{1}{2}, \\ 1, & \text{otherwise.} \end{cases}$$

### 2.10.5.5 Bootstrap predictor ( $M = I$ only) – deprecated

This predictor does not use any information from the preceding step, instead using information only within the current step  $[t_{n-1}, t_n]$ . In addition to using the solution and ODE right-hand side function,  $y_{n-1}$  and  $f(t_{n-1}, y_{n-1})$ , this approach uses the right-hand side from a previously computed stage solution in the same step,  $f(t_{n-1} + c_j^I h, z_j)$  to construct a quadratic Hermite interpolant for the prediction. If we define the constants  $\tilde{h} = c_j^I h$  and  $\tau = c_i^I h$ , the predictor is given by

$$z_i^{(0)} = y_{n-1} + \left(\tau - \frac{\tau^2}{2\tilde{h}}\right) f(t_{n-1}, y_{n-1}) + \frac{\tau^2}{2\tilde{h}} f(t_{n-1} + \tilde{h}, z_j).$$

For stages without a nonzero preceding stage time, i.e.  $c_j^I \neq 0$  for  $j < i$ , this method reduces to using the trivial predictor  $z_i^{(0)} = y_{n-1}$ . For stages having multiple preceding nonzero  $c_j^I$ , we choose the stage having largest  $c_j^I$  value, to minimize the level of extrapolation used in the prediction.

We note that in general, each stage solution  $z_j$  has significantly worse accuracy than the time step solutions  $y_{n-1}$ , due to the difference between the *stage order* and the *method order* in Runge–Kutta methods. As a result, the accuracy of this predictor will generally be rather limited, but it is provided for problems in which this increased stage error is better than the effects of extrapolation far outside of the previous time step interval  $[t_{n-2}, t_{n-1}]$ .

Although this approach could be used with non-identity mass matrix, support for that mode is not currently implemented, so selection of this predictor in the case of a non-identity mass matrix will result in use of the trivial predictor.

---

**Note:** This predictor has been deprecated, and will be removed from a future release.

---

### 2.10.5.6 Minimum correction predictor (ARKStep, $M = I$ only) – deprecated

The final predictor is not interpolation based; instead it utilizes all existing stage information from the current step to create a predictor containing all but the current stage solution. Specifically, as discussed in equations (2.4) and (2.21), each stage solves a nonlinear equation

$$z_i = y_{n-1} + h_n \sum_{j=1}^{i-1} A_{i,j}^E f^E(t_{n,j}^E, z_j) + h_n \sum_{j=1}^i A_{i,j}^I f^I(t_{n,j}^I, z_j),$$

$$\Leftrightarrow$$

$$G(z_i) \equiv z_i - h_n A_{i,i}^I f^I(t_{n,i}^I, z_i) - a_i = 0.$$

This prediction method merely computes the predictor  $z_i$  as

$$z_i = y_{n-1} + h_n \sum_{j=1}^{i-1} A_{i,j}^E f^E(t_{n,j}^E, z_j) + h_n \sum_{j=1}^{i-1} A_{i,j}^I f^I(t_{n,j}^I, z_j),$$

$$\Leftrightarrow$$

$$z_i = a_i.$$

Again, although this approach could be used with non-identity mass matrix, support for that mode is not currently implemented, so selection of this predictor in the case of a non-identity mass matrix will result in use of the trivial predictor.

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**Note:** This predictor has been deprecated, and will be removed from a future release.

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### 2.10.6 Mass matrix solver (ARKStep only)

Within the ARKStep algorithms described above, there are multiple locations where a matrix-vector product

$$b = Mv \tag{2.39}$$

or a linear solve

$$x = M^{-1}b \tag{2.40}$$

is required.

Of course, for problems in which  $M = I$  both of these operators are trivial. However for problems with non-identity mass matrix, these linear solves (2.40) may be handled using any valid SUNLinearSolver module, in the same manner as described in the section §2.10.2 for solving the linear Newton systems.

For ERK methods involving non-identity mass matrix, even though calculation of individual stages does not require an algebraic solve, both of the above operations (matrix-vector product, and mass matrix solve) may be required within each time step. Therefore, for these users we recommend reading the rest of this section as it pertains to ARK methods, with the obvious simplification that since  $f^E = f$  and  $f^I = 0$  no Newton or fixed-point nonlinear solve, and no overall system linear solve, is involved in the solution process.

At present, for DIRK and ARK problems using a matrix-based solver for the Newton nonlinear iterations, the type of matrix (dense, band, sparse, or custom) for the Jacobian matrix  $J$  must match the type of mass matrix  $M$ , since these are combined to form the Newton system matrix  $\tilde{A}$ . When matrix-based methods are employed, the user must supply a routine to compute  $M(t)$  in the appropriate form to match the structure of  $\tilde{A}$ , with a user-supplied routine of type `ARKLsMassFn()`. This matrix structure is used internally to perform any requisite mass matrix-vector products (2.39).

When matrix-free methods are selected, a routine must be supplied to perform the mass-matrix-vector product,  $Mv$ . As with iterative solvers for the Newton systems, preconditioning may be applied to aid in solution of the mass matrix systems (2.40). When using an iterative mass matrix linear solver, we require that the norm of the preconditioned linear residual satisfies

$$\|r\| \leq \epsilon_L \epsilon, \quad (2.41)$$

where again,  $\epsilon$  is the nonlinear solver tolerance parameter from (2.35). When using iterative system and mass matrix linear solvers,  $\epsilon_L$  may be specified separately for both tolerances (2.37) and (2.41).

In the algorithmic descriptions above there are five locations where a linear solve of the form (2.40) is required: (a) at each iteration of a fixed-point nonlinear solve, (b) in computing the Runge–Kutta right-hand side vectors  $\hat{f}_i^E$  and  $\hat{f}_i^I$ , (c) in constructing the time-evolved solution  $y_n$ , (d) in estimating the local temporal truncation error, and (e) in constructing predictors for the implicit solver iteration (see section §2.10.5.2). We note that different nonlinear solver approaches (i.e., Newton vs fixed-point) and different types of mass matrices (i.e., time-dependent versus fixed) result in different subsets of the above operations. We discuss each of these in the bullets below.

- When using a fixed-point nonlinear solver, at each fixed-point iteration we must solve

$$M(t_{n,i}^I) z_i^{(m+1)} = G(z_i^{(m)}), \quad m = 0, 1, \dots$$

for the new fixed-point iterate,  $z_i^{(m+1)}$ .

- In the case of a time-dependent mass matrix, to construct the Runge–Kutta right-hand side vectors we must solve

$$M(t_{n,i}^E) \hat{f}_i^E = f^E(t_{n,i}^E, z_i) \quad \text{and} \quad M(t_{n,i}^I) \hat{f}_i^I = f^I(t_{n,i}^I, z_i)$$

for the vectors  $\hat{f}_i^E$  and  $\hat{f}_i^I$ .

- For fixed mass matrices, we construct the time-evolved solution  $y_n$  from equation (2.4) by solving

$$\begin{aligned} My_n &= My_{n-1} + h_n \sum_{i=1}^s (b_i^E f^E(t_{n,i}^E, z_i) + b_i^I f^I(t_{n,i}^I, z_i)), \\ &\Leftrightarrow \\ M(y_n - y_{n-1}) &= h_n \sum_{i=1}^s (b_i^E f^E(t_{n,i}^E, z_i) + b_i^I f^I(t_{n,i}^I, z_i)), \\ &\Leftrightarrow \\ M\nu &= h_n \sum_{i=1}^s (b_i^E f^E(t_{n,i}^E, z_i) + b_i^I f^I(t_{n,i}^I, z_i)), \end{aligned}$$

for the update  $\nu = y_n - y_{n-1}$ .

Similarly, we compute the local temporal error estimate  $T_n$  from equation (2.18) by solving systems of the form

$$M T_n = h \sum_{i=1}^s \left[ \left( b_i^E - \tilde{b}_i^E \right) f^E(t_{n,i}^E, z_i) + \left( b_i^I - \tilde{b}_i^I \right) f^I(t_{n,i}^I, z_i) \right]. \quad (2.42)$$

- For problems with either form of non-identity mass matrix, in constructing dense output and implicit predictors of degree 2 or higher (see the section §2.10.5.2 above), we compute the derivative information  $\hat{f}_k$  from the equation

$$M(t_n) \hat{f}_n = f^E(t_n, y_n) + f^I(t_n, y_n).$$

In total, for problems with fixed mass matrix, we require only two mass-matrix linear solves (2.40) per attempted time step, with one more upon completion of a time step that meets the solution accuracy requirements. When fixed time-stepping is used ( $h_n = h$ ), the solve (2.42) is not performed at each attempted step.

Similarly, for problems with time-dependent mass matrix, we require  $2s$  mass-matrix linear solves (2.40) per attempted step, where  $s$  is the number of stages in the ARK method (only half of these are required for purely explicit or purely implicit problems, (2.5) or (2.6)), with one more upon completion of a time step that meets the solution accuracy requirements.

In addition to the above totals, when using a fixed-point nonlinear solver (assumed to require  $m$  iterations), we will need an additional  $ms$  mass-matrix linear solves (2.40) per attempted time step (but zero linear solves with the system Jacobian).

## 2.11 Rootfinding

All of the time-stepping modules in ARKODE also support a rootfinding feature. This means that, while integrating the IVP (2.1), these can also find the roots of a set of user-defined functions  $g_i(t, y)$  that depend on  $t$  and the solution vector  $y = y(t)$ . 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  $g_i(t, y(t))$ , denoted  $g_i(t)$  for short. If a user root function has a root of even multiplicity (no sign change), it will almost certainly be missed due to the realities of floating-point arithmetic. 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 [34]. In addition, each time  $g$  is evaluated, ARKODE checks to see if  $g_i(t) = 0$  exactly, and if so it reports this as a root. However, if an exact zero of any  $g_i$  is found at a point  $t$ , ARKODE computes  $g(t + \delta)$  for a small increment  $\delta$ , slightly further in the direction of integration, and if any  $g_i(t + \delta) = 0$  also, ARKODE stops and reports an error. This way, each time ARKODE takes a time step, it is guaranteed that the values of all  $g_i$  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, ARKODE has an interval  $(t_{\text{lo}}, t_{\text{hi}}]$  in which roots of the  $g_i(t)$  are to be sought, such that  $t_{\text{hi}}$  is further ahead in the direction of integration, and all  $g_i(t_{\text{lo}}) \neq 0$ . The endpoint  $t_{\text{hi}}$  is either  $t_n$ , the end of the time step last taken, or the next requested output time  $t_{\text{out}}$  if this comes sooner. The endpoint  $t_{\text{lo}}$  is either  $t_{n-1}$ , or the last output time  $t_{\text{out}}$  (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  $g(t_{\text{hi}})$  for zeros, and it checks for sign changes in  $(t_{\text{lo}}, t_{\text{hi}})$ . If no sign changes are found, then either a root is reported (if some  $g_i(t_{\text{hi}}) = 0$ ) or we proceed to the next time interval (starting at  $t_{\text{hi}}$ ). 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

$$\tau = 100 U (|t_n| + |h|) \quad (\text{where } U = \text{unit roundoff}).$$

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  $|g_i(t_{\text{hi}})| / |g_i(t_{\text{hi}}) - g_i(t_{\text{lo}})|$ , corresponding to the closest to  $t_{\text{lo}}$  of the secant method values. At each pass through the loop, a new value  $t_{\text{mid}}$  is set, strictly within the search interval, and the values of  $g_i(t_{\text{mid}})$  are checked. Then either  $t_{\text{lo}}$  or  $t_{\text{hi}}$  is reset to  $t_{\text{mid}}$  according to which subinterval is found to have the sign change. If there is none in  $(t_{\text{lo}}, t_{\text{mid}})$  but some  $g_i(t_{\text{mid}}) = 0$ , then that root is reported. The loop continues until  $|t_{\text{hi}} - t_{\text{lo}}| < \tau$ , and then the reported root location is  $t_{\text{hi}}$ . In the loop to locate the root of  $g_i(t)$ , the formula for  $t_{\text{mid}}$  is

$$t_{\text{mid}} = t_{\text{hi}} - \frac{g_i(t_{\text{hi}})(t_{\text{hi}} - t_{\text{lo}})}{g_i(t_{\text{hi}}) - \alpha g_i(t_{\text{lo}})},$$

where  $\alpha$  is a weight parameter. On the first two passes through the loop,  $\alpha$  is set to 1, making  $t_{\text{mid}}$  the secant method value. Thereafter,  $\alpha$  is reset according to the side of the subinterval (low vs high, i.e. toward  $t_{\text{lo}}$  vs toward  $t_{\text{hi}}$ ) 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  $t_{\text{mid}}$  is closer to  $t_{\text{lo}}$  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 0.1 and 0.5 (with 0.5 being the midpoint), and the actual distance from the endpoint is at least  $\tau/2$ .

Finally, we note that when running in parallel, ARKODE's rootfinding module assumes that the entire set of root defining functions  $g_i(t, y)$  is replicated on every MPI rank. Since in these cases the vector  $y$  is distributed across ranks, it is the user's responsibility to perform any necessary communication to ensure that  $g_i(t, y)$  is identical on each rank.

## 2.12 Inequality Constraints

The ARKStep and ERKStep modules in ARKODE permit 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 step and before the error test. If any constraint fails, the step size is reduced and a flag is set to update the Jacobian or preconditioner if applicable. Rather than cutting the step size by some arbitrary factor, ARKODE 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). If a step fails to satisfy the constraints 10 times (a value which may be modified by the user) within a step attempt, or fails with the minimum step size, then the integration is halted and an error is returned. In this case the user may need to employ other strategies as discussed in §5.2.2.2 and §5.3.2.2 to satisfy the inequality constraints.



# Chapter 3

## Code Organization

SUNDIALS consists of the solvers CVODE and ARKODE for ordinary differential equation (ODE) systems, IDA for differential-algebraic (DAE) systems, and KINSOL for nonlinear 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 following is a list summarizes the basic functionality of each SUNDIALS package:

- CVODE, a solver for stiff and nonstiff ODE systems  $\dot{y} = f(t, y)$  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  $M(t)\dot{y} = f_1(t, y) + f_2(t, y)$  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  $F(u) = 0$ .

The various packages in the suite share many common components and are organized as a family. Fig. 3.1 gives a high-level overview of solver packages, the shared vector, matrix, linear solver, and nonlinear solver interfaces (abstract base classes), and the corresponding class implementations provided with SUNDIALS. For classes that provide interfaces to third-party libraries (i.e., LAPACK, KLU, SuperLU\_MT, SuperLU\_DIST, hypre, PETSc, Trilinos, and Raja) users will need to download and compile those packages independently of SUNDIALS. The directory structure is shown in Fig. 3.2.

### 3.1 ARKODE organization

The ARKODE 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 ARKODE package is shown in Fig. 3.3. The central integration modules, implemented in the files `arkode.h`, `arkode_impl.h`, `arkode_butcher.h`, `arkode.c`, `arkode_arkstep.c`, `arkode_erkstep.c`, `arkode_mristep.h`, and `arkode_butcher.c`, deal with the evaluation of integration stages, the nonlinear solvers, estimation of the local truncation error, selection of step size, and interpolation to user output points, among other issues. ARKODE supports SUNNonlinearSolver modules in either root-finding or fixed-point form (see section §10) for any nonlinearly implicit problems that arise in computing each internal stage. When using Newton-based nonlinear solvers, or when using a non-identity mass matrix  $M \neq I$ , ARKODE has flexibility in the choice of method used to solve the linear sub-systems that arise. Therefore, for any user problem invoking the Newton solvers, or any user

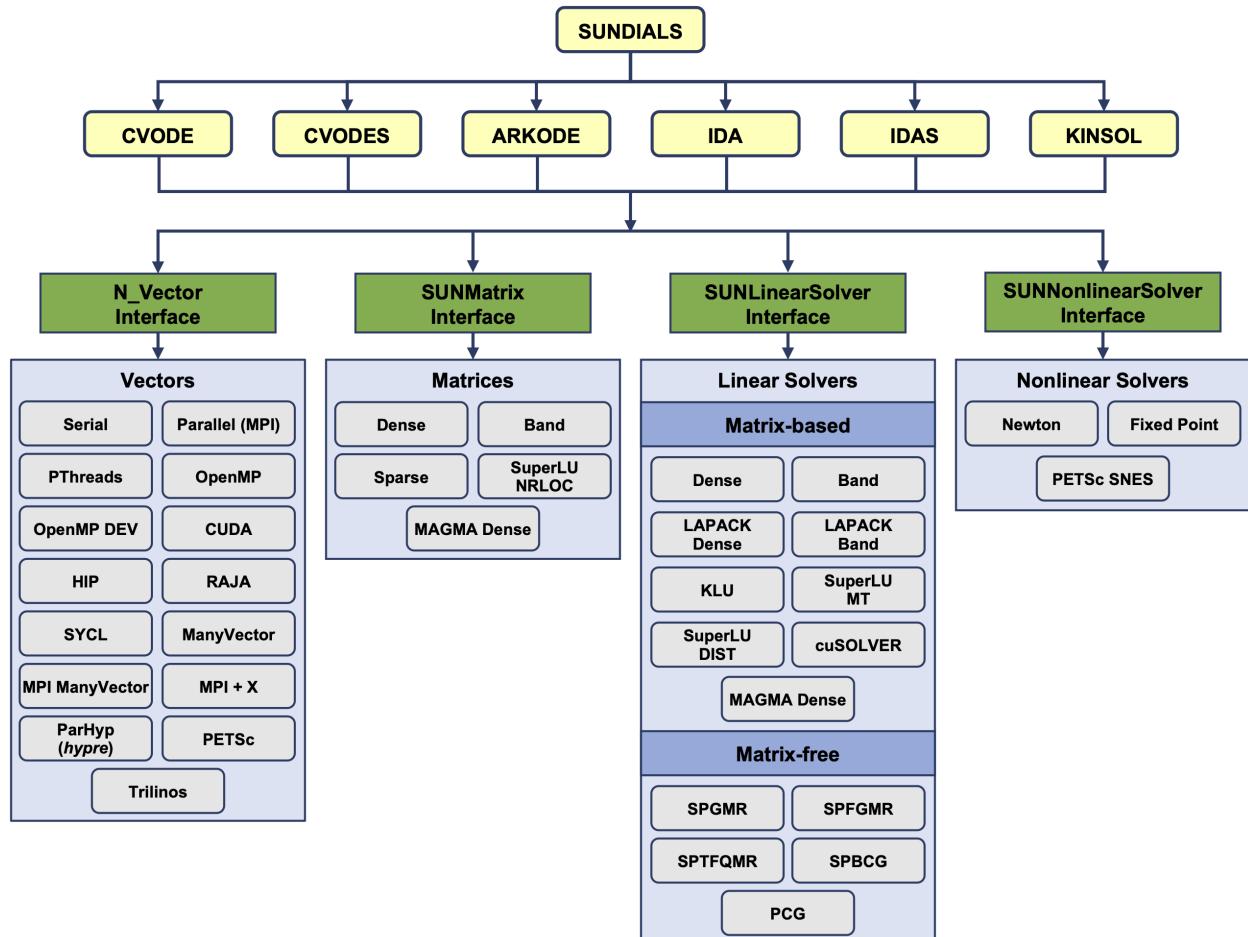


Fig. 3.1: High-level diagram of the SUNDIALS suite.

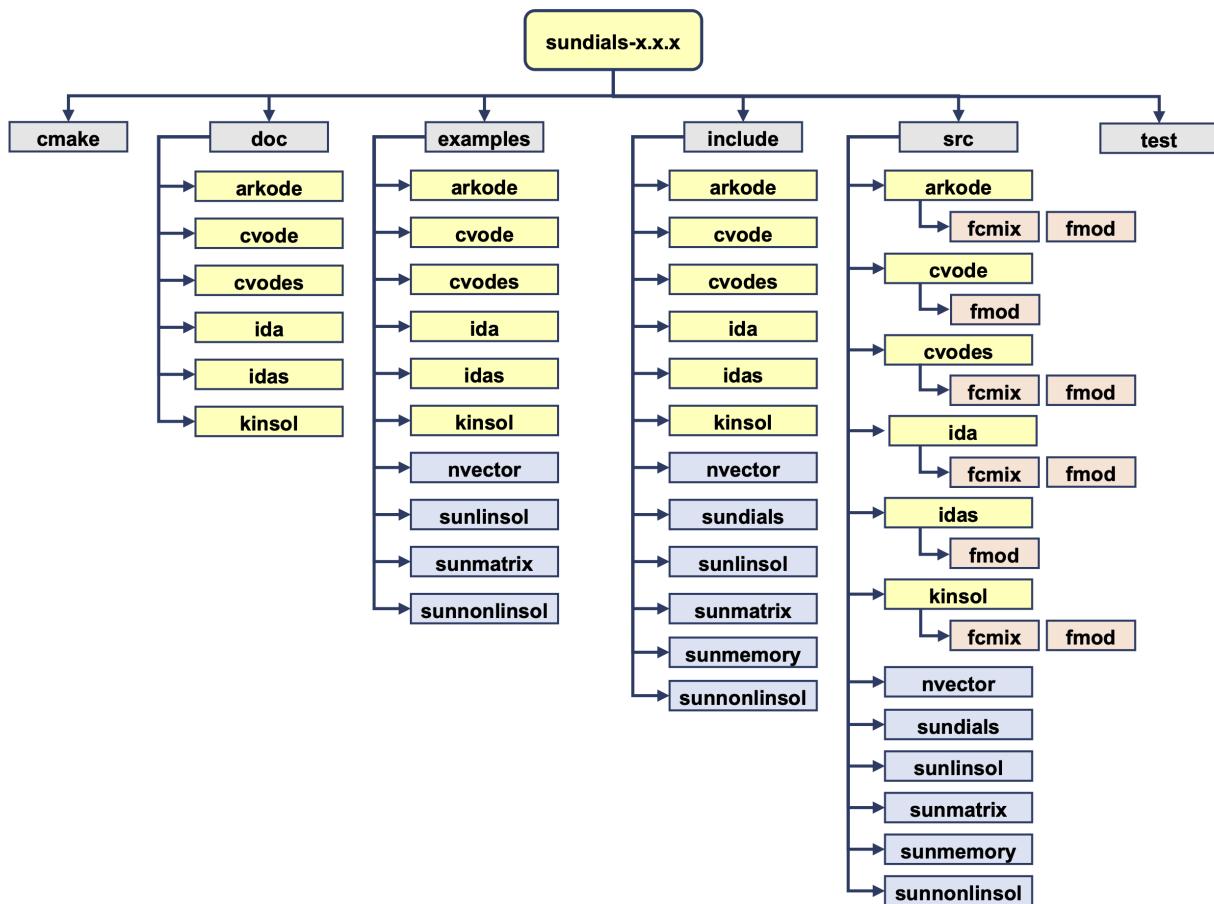


Fig. 3.2: Directory structure of the SUNDIALS source tree.

problem with  $M \neq I$ , one (or more) of the linear system solver modules should be specified by the user; this/these are then invoked as needed during the integration process.

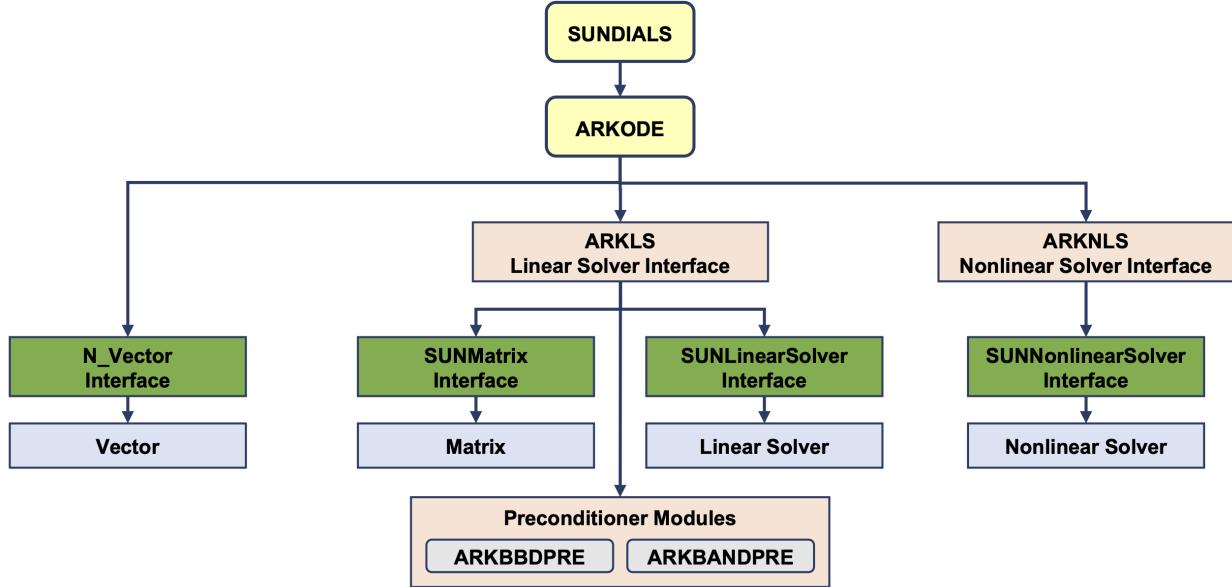


Fig. 3.3: *ARKODE organization*: Overall structure of the ARKODE package. Modules specific to ARKODE are the timesteppers (ARKODE), linear solver interfaces (ARKLS), nonlinear solver interfaces (ARKNLS), and preconditioners (ARKBANDPRE and ARKBBDPRE); all other items correspond to generic SUNDIALS vector, matrix, and solver modules.

For solving these linear systems, ARKODE’s linear solver interface supports both direct and iterative linear solvers adhering to the generic SUNLINSOL API (see §9). These solvers may utilize a SUNMATRIX object for storing Jacobian information, or they may be matrix-free. Since ARKODE can operate on any valid SUNLINSOL implementation, the set of linear solver modules available to ARKODE will expand as new SUNLINSOL modules are developed.

For preconditioned iterative methods with either the system or mass matrix solves, the preconditioning must be supplied by the user in two phases: setup and solve. While there is no default choice of preconditioner for generic problems, the references [11] and [14], together with the example and demonstration programs included with ARKODE and CVODE, offer considerable assistance in building simple preconditioners.

ARKODE also provides two rudimentary preconditioner modules, for use with any of the Krylov iterative linear solvers. The first, ARKBANDPRE is intended to be used with the serial or threaded vector data structures (NVECTOR\_SERIAL, NVECTOR\_OPENMP and NVECTOR\_PTHREADS), and provides a banded difference-quotient approximation to the Jacobian as the preconditioner, with corresponding setup and solve routines. The second preconditioner module, ARKBBDPRE, is intended to work with the parallel vector data structure, NVECTOR\_PARALLEL, and generates a preconditioner that is a block-diagonal matrix with each block being a band matrix owned by a single processor.

All state information used by ARKODE to solve a given problem is saved in a single opaque memory structure, and a pointer to that structure is returned to the user. For C, C++ and Fortran 2003 applications there is no global data in the ARKODE package, and so in this respect it is reentrant. State information specific to the linear solver interface is saved in a separate data structure, a pointer to which resides in the ARKODE memory structure. State information specific to the linear solver implementation (and matrix implementation, if applicable) are stored in their own data structures, that are returned to the user upon construction, and subsequently provided to ARKODE for use.

# Chapter 4

## Using SUNDIALS

As discussed in §3, the six solvers packages (CVODE(S), IDA(S), ARKODE, KINSOL) that make up SUNDIALS are built upon common classes/modules for vectors, matrices, and algebraic solvers. In addition, the six packages all leverage some other common infrastructure, which we discuss in this section.

### 4.1 The SUNContext Type

In SUNDIALS v6.0.0, the concept of a SUNDIALS simulation context was introduced, in particular the `SUNContext` class. All of the SUNDIALS objects (vectors, linear and nonlinear solvers, matrices, etc) that collectively form a SUNDIALS simulation, hold a reference to a common `SUNContext` object.

The `SUNContext` class/type is defined in the header file `sundials/sundials_context.h` as

```
typedef struct _SUNContext *SUNContext
```

Users should create a `SUNContext` object prior to any other calls to SUNDIALS library functions by calling:

```
int SUNContext_Create(void *comm, SUNContext *ctx)
```

Creates a `SUNContext` object associated with the thread of execution. The data of the `SUNContext` class is private.

#### Arguments:

- `comm` – a pointer to the MPI communicator or `NULL` if not using MPI.
- `ctx` – [in,out] upon successful exit, a pointer to the newly created `SUNContext` object.

#### Returns:

- Will return `< 0` if an error occurs, and zero otherwise.

The created `SUNContext` object should be provided to the constructor routines for different SUNDIALS classes/modules. E.g.,

```
SUNContext sunctx;  
void* package_mem;  
N_Vector x;  
  
SUNContext_Create(NULL, &sunctx);  
  
package_mem = CVodeCreate(..., sunctx);
```

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```
package_mem = IDACreate(..., sunctx);
package_mem = KINCreate(..., sunctx);
package_mem = ARKStepCreate(..., sunctx);

x = N_VNew_<SomeVector>(..., sunctx);
```

After all other SUNDIALS code, the SUNContext object should be freed with a call to:

```
int SUNContext_Free(SUNContext *ctx)
Frees the SUNContext object.
```

**Arguments:**

- ctx – pointer to a valid SUNContext object, NULL upon successful return.

**Returns:**

- Will return < 0 if an error occurs, and zero otherwise.

**Warning:** When MPI is being used, the `SUNContext_Free()` must be called prior to `MPI_Finalize`.

The SUNContext API further consists of the following functions:

```
int SUNContext_GetProfiler(SUNContext ctx, SUNProfiler *profiler)
Gets the SUNProfiler object associated with the SUNContext object.
```

**Arguments:**

- ctx – a valid SUNContext object.
- profiler – [in,out] a pointer to the SUNProfiler object associated with this context; will be NULL if profiling is not enabled.

**Returns:**

- Will return < 0 if an error occurs, and zero otherwise.

```
int SUNContext_SetProfiler(SUNContext ctx, SUNProfiler profiler)
Sets the SUNProfiler object associated with the SUNContext object.
```

**Arguments:**

- ctx – a valid SUNContext object.
- profiler – a SUNProfiler object to associate with this context; this is ignored if profiling is not enabled.

**Returns:**

- Will return < 0 if an error occurs, and zero otherwise.

### 4.1.1 Implications for task-based programming and multi-threading

Applications that need to have *concurrently initialized* SUNDIALS simulations need to take care to understand the following:

#. A SUNContext object must only be associated with *one* SUNDIALS simulation (a solver object and its associated vectors etc.) at a time.

- Concurrently initialized is not the same as concurrently executing. Even if two SUNDIALS simulations execute sequentially, if both are initialized at the same time with the same SUNContext, behavior is undefined.
- It is OK to reuse a SUNContext object with another SUNDIALS simulation after the first simulation has completed and all of the simulation's associated objects (vectors, matrices, algebraic solvers, etc.) have been destroyed.

#. The creation and destruction of a SUNContext object is cheap, especially in comparison to the cost of creating/destroying a SUNDIALS solver object.

The following (incomplete) code examples demonstrate these points using CVODE as the example SUNDIALS package.

```
SUNContext sunctxs[num_threads];
int cvode_initialized[num_threads];
void* cvode_mem[num_threads];

// Create
for (int i = 0; i < num_threads; i++) {
    sunctxs[i] = SUNContext_Create(...);
    cvode_mem[i] = CVodeCreate(..., sunctxs[i]);
    cvode_initialized[i] = 0; // not yet initialized
    // set optional cvode inputs...
}

// Solve
#pragma omp parallel for
for (int i = 0; i < num_problems; i++) {
    int retval = 0;
    int tid = omp_get_thread_num();
    if (!cvode_initialized[tid]) {
        retval = CVodeInit(cvode_mem[tid], ...);
        cvode_initialized[tid] = 1;
    } else {
        retval = CVodeReInit(cvode_mem[tid], ...);
    }
    CVode(cvode_mem[i], ...);
}

// Destroy
for (int i = 0; i < num_threads; i++) {
    // get optional cvode outputs...
    CVodeFree(&cvode_mem[i]);
    SUNContext_Free(&sunctxs[i]);
}
```

Since each thread has its own unique CVODE and SUNContext object pair, there should be no thread-safety issues. Users should be sure that you apply the same idea to the other SUNDIALS objects needed as well (e.g. an N\_Vector).

The variation of the above code example demonstrates another possible approach:

```
// Create, Solve, Destroy
#pragma omp parallel for
for (int i = 0; i < num_problems; i++) {
    int retval = 0;
    void* cvode_mem;
    SUNContext sunctx;

    sunctx = SUNContext_Create(...);
    cvode_mem = CVodeCreate(..., sunctx);
    retval = CVodeInit(cvode_mem, ...);

    // set optional cvode inputs...

    CVode(cvode_mem, ...);

    // get optional cvode outputs...

    CVodeFree(&cvode_mem);
    SUNContext_Free(&sunctx);
}
```

So long as the overhead of creating/destroying the CVODE object is small compared to the cost of solving the ODE, this approach is a fine alternative to the first approach since `SUNContext_Create()` and `SUNContext_Free()` are much cheaper than the CVODE create/free routines.

#### 4.1.2 Convenience class for C++ Users

For C++ users, a class, `sundials::Context`, that follows RAII is provided:

```
namespace sundials
{
    class Context
    {
        public:
            Context(void* comm = NULL)
            {
                SUNContext_Create(comm, &sunctx_);
            }

            operator SUNContext() { return sunctx_; }

            ~Context()
            {
                SUNContext_Free(&sunctx_);
            }

        private:
            SUNContext sunctx_;
    };
}
```

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```
} // namespace sundials
```

## 4.2 Performance Profiling

SUNDIALS includes a lightweight performance profiling layer that can be enabled at compile-time. Optionally, this profiling layer can leverage Caliper [7] for more advanced instrumentation and profiling. By default, only SUNDIALS library code is profiled. However, a public profiling API can be utilized to leverage the SUNDIALS profiler to time user code regions as well (see §4.2.2).

### 4.2.1 Enabling Profiling

To enable profiling, SUNDIALS must be built with the CMake option `SUNDIALS_BUILD_WITH_PROFILING` set to ON. To utilize Caliper support, the CMake option `ENABLE_CALIPER` must also be set to ON. More details in regards to configuring SUNDIALS with CMake can be found in §12.

When SUNDIALS is built with profiling enabled and **without Caliper**, then the environment variable `SUNPROFILER_PRINT` can be utilized to enable/disable the printing of profiler information. Setting `SUNPROFILER_PRINT=1` will cause the profiling information to be printed to stdout when the SUNDIALS simulation context is freed. Setting `SUNPROFILER_PRINT=0` will result in no profiling information being printed unless the `SUNProfiler_Print()` function is called explicitly. By default, `SUNPROFILER_PRINT` is assumed to be 0. `SUNPROFILER_PRINT` can also be set to a file path where the output should be printed.

If Caliper is enabled, then users should refer to the [Caliper documentation](#) for information on getting profiler output. In most cases, this involves setting the `CALI_CONFIG` environment variable.

**Warning:** While the SUNDIALS profiling scheme is relatively lightweight, enabling profiling can still negatively impact performance. As such, it is recommended that profiling is enabled judiciously.

### 4.2.2 Profiler API

The primary way of interacting with the SUNDIALS profiler is through the following macros:

```
SUNDIALS_MARK_FUNCTION_BEGIN(profobj)
SUNDIALS_MARK_FUNCTION_END(profobj)
SUNDIALS_WRAP_STATEMENT(profobj, name, stmt)
SUNDIALS_MARK_BEGIN(profobj, name)
SUNDIALS_MARK_END(profobj, name)
```

Additionally, in C++ applications, the follow macro is available:

```
SUNDIALS_CXX_MARK_FUNCTION(profobj)
```

These macros can be used to time specific functions or code regions. When using the \*\_BEGIN macros, it is important that a matching \*\_END macro is placed at all exit points for the scope/function. The `SUNDIALS_CXX_MARK_FUNCTION` macro only needs to be placed at the beginning of a function, and leverages RAII to implicitly end the region.

The `profobj` argument to the macro should be a `SUNProfiler` object, i.e. an instance of the struct

```
typedef struct _SUNProfiler *SUNProfiler
```

When SUNDIALS is built with profiling, a default profiling object is stored in the SUNContext object and can be accessed with a call to `SUNContext_GetProfiler()`.

The name argument should be a unique string indicating the name of the region/function. It is important that the name given to the \*\_BEGIN macros matches the name given to the \*\_END macros.

In addition to the macros, the following methods of the SUNProfiler class are available.

`int SUNProfiler_Create(void *comm, const char *title, SUNProfiler *p)`

Creates a new SUNProfiler object.

**Arguments:**

- `comm` – a pointer to the MPI communicator if MPI is enabled, otherwise can be NULL
- `title` – a title or description of the profiler
- `p` – [in,out] On input this is a pointer to a SUNProfiler, on output it will point to a new SUNProfiler instance

**Returns:**

- Returns zero if successful, or non-zero if an error occurred

`int SUNProfiler_Free(SUNProfiler *p)`

Frees a SUNProfiler object.

**Arguments:**

- `p` – [in,out] On input this is a pointer to a SUNProfiler, on output it will be NULL

**Returns:**

- Returns zero if successful, or non-zero if an error occurred

`int SUNProfiler_Begin(SUNProfiler p, const char *name)`

Starts timing the region indicated by the name.

**Arguments:**

- `p` – a SUNProfiler object
- `name` – a name for the profiling region

**Returns:**

- Returns zero if successful, or non-zero if an error occurred

`int SUNProfiler_End(SUNProfiler p, const char *name)`

Ends the timing of a region indicated by the name.

**Arguments:**

- `p` – a SUNProfiler object
- `name` – a name for the profiling region

**Returns:**

- Returns zero if successful, or non-zero if an error occurred

`int SUNProfiler_Print(SUNProfiler p, FILE *fp)`

Prints out a profiling summary. When constructed with an MPI comm the summary will include the average and maximum time per rank (in seconds) spent in each marked up region.

**Arguments:**

- `p` – a SUNProfiler object

- *fp* – the file handler to print to

**Returns:**

- Returns zero if successful, or non-zero if an error occurred

### 4.2.3 Example Usage

The following is an excerpt from the CVODE example code `examples/cvode/serial/cvAdvDiff_bnd.c`. It is applicable to any of the SUNDIALS solver packages.

```
SUNContext ctx;
SUNProfiler profobj;

/* Create the SUNDIALS context */
retval = SUNContext_Create(NULL, &ctx);

/* Get a reference to the profiler */
retval = SUNContext_GetProfiler(ctx, &profobj);

/* ... */

SUNDIALS_MARK_BEGIN(profobj, "Integration loop");
umax = N_VMaxNorm(u);
PrintHeader(reltol, abstol, umax);
for(iout=1, tout=T1; iout <= NOUT; iout++, tout += DTOUT) {
    retval = CVode(cvode_mem, tout, u, &t, CV_NORMAL);
    umax = N_VMaxNorm(u);
    retval = CVodeGetNumSteps(cvode_mem, &nst);
    PrintOutput(t, umax, nst);
}
SUNDIALS_MARK_END(profobj, "Integration loop");
PrintFinalStats(cvode_mem); /* Print some final statistics */
```

### 4.2.4 Other Considerations

If many regions are being timed, it may be necessary to increase the maximum number of profiler entries (the default is 2560). This can be done by setting the environment variable `SUNPROFILER_MAX_ENTRIES`.

## 4.3 SUNDIALS version information

SUNDIALS provides additional utilities to all packages, that may be used to retrieve SUNDIALS version information at runtime.

`int SUNDIALSGetVersion(char *version, int len)`

This routine fills a string with SUNDIALS version information.

**Arguments:**

- *version* – character array to hold the SUNDIALS version information.
- *len* – allocated length of the *version* character array.

**Return value:**

- 0 if successful
- -1 if the input string is too short to store the SUNDIALS version

**Notes:** An array of 25 characters should be sufficient to hold the version information.

**int SUNDIALSGetVersionNumber(int \*major, int \*minor, int \*patch, char \*label, int len)**

This routine sets integers for the SUNDIALS major, minor, and patch release numbers and fills a string with the release label if applicable.

**Arguments:**

- *major* – SUNDIALS release major version number.
- *minor* – SUNDIALS release minor version number.
- *patch* – SUNDIALS release patch version number.
- *label* – string to hold the SUNDIALS release label.
- *len* – allocated length of the *label* character array.

**Return value:**

- 0 if successful
- -1 if the input string is too short to store the SUNDIALS label

**Notes:** An array 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*.

## 4.4 SUNDIALS Fortran Interface

SUNDIALS provides modern, Fortran 2003 based, interfaces as Fortran modules to most of the C API including:

- All of the time-stepping modules in ARKODE:
  - The `farkode_arkstep_mod`, `farkode_erkstep_mod`, and `farkode_mristep_mod` modules provide interfaces to the ARKStep, ERKStep, and MRIStep integrators respectively.
  - The `farkode_mod` module interfaces to the components of ARKODE which are shared by the time-stepping modules.
- CVODE via the `fcvode_mod` module.
- CVODES via the `fcvodes_mod` module.
- IDA via the `fida_mod` module.
- IDAS via the `fidas_mod` module.
- KINSOL via the `fkinsol_mod` module.

Additionally, all of the SUNDIALS base classes (`N_Vector`, `SUNMatrix`, `SUNLinearSolver`, and `SUNNonlinearSolver`) include Fortran interface modules. A complete list of class implementations with Fortran 2003 interface modules is given in [Table 4.1](#).

An interface module can be accessed with the `use` statement, e.g.

```
use fcvode_mod
use fnvector_openmp_mod
```

and by linking to the Fortran 2003 library in addition to the C library, e.g. `libsundials_fnvecopenmp_mod.<so|a>`, `libsundials_nvecopenmp.<so|a>`, `libsundials_fckode_mod.<so|a>` and `libsundials_cvode.<so|a>`.

The Fortran 2003 interfaces leverage the `iso_c_binding` module and the `bind(C)` attribute to closely follow the SUNDIALS C API (modulo language differences). The SUNDIALS classes, 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()` or `FCVodeCreate` instead of `CVodeCreate`. 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 §4.4.2. A discussion on the topic of equivalent data types in C and Fortran 2003 is presented in §4.4.1.

Further information on the Fortran 2003 interfaces specific to the `N_Vector`, `SUNMatrix`, `SUNLinearSolver`, and `SUNNonlinearSolver` classes is given alongside the C documentation (§7, §8, §9, and §10 respectively). For details on where the Fortran 2003 module (.mod) files and libraries are installed see §12.

The Fortran 2003 interface modules were generated with SWIG Fortran [38], a fork of SWIG. Users who are interested in the SWIG code used in the generation process should contact the SUNDIALS development team.

Table 4.1: List of SUNDIALS Fortran 2003 interface modules

Class/Module	Fortran 2003 Module Name
ARKODE	farkode_mod
ARKODE::ARKSTEP	farkode_arkstep_mod
ARKODE::ERKSTEP	farkode_erkstep_mod
ARKODE::MRISTEP	farkode_mristep_mod
CVODE	fcvode_mod
CVODES	fcvodes_mod
IDA	fida_mod
IDAS	fidas_mod
KINSOL	fkinsol_mod
NVECTOR	fsundials_nvector_mod
NVECTOR_SERIAL	fnvector_serial_mod
NVECTOR_OPENMP	fnvector_openmp_mod
NVECTOR_PTHREADS	fnvector_pthreads_mod
NVECTOR_PARALLEL	fnvector_parallel_mod
NVECTOR_PARHYP	Not interfaced
NVECTOR_PETSC	Not interfaced
NVECTOR_CUDA	Not interfaced
NVECTOR_RAJA	Not interfaced
NVECTOR_SYCL	Not interfaced
NVECTOR_MANYVECTOR	fnvector_manyvector_mod
NVECTOR_MPIMANYVECTOR	fnvector_mpimanyvector_mod
NVECTOR_MPIPLUSX	fnvector_mpiplusx_mod
SUNMATRIX	fsundials_matrix_mod
SUNMATRIX_BAND	fsunmatrix_band_mod
SUNMATRIX_DENSE	fsunmatrix_dense_mod
SUNMATRIX_MAGMADENSE	Not interfaced
SUNMATRIX_ONEMKLDENSE	Not interfaced
SUNMATRIX_SPARSE	fsunmatrix_sparse_mod
SUNLINSOL	fsundials_linearsolver_mod
SUNLINSOL_BAND	fsunlinsol_band_mod
SUNLINSOL_DENSE	fsunlinsol_dense_mod
SUNLINSOL_LAPACKBAND	Not interfaced
SUNLINSOL_LAPACKDENSE	Not interfaced

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Table 4.1 – continued from previous page

Class/Module	Fortran 2003 Module Name
SUNLINSOL_MAGMADENSE	Not interfaced
SUNLINSOL_ONEMKLDENSE	Not interfaced
SUNLINSOL_KLU	fsunlinsol_klu_mod
SUNLINSOL_SLUMT	Not interfaced
SUNLINSOL_SLUDIST	Not interfaced
SUNLINSOL_SPGMR	fsunlinsol_spgmr_mod
SUNLINSOL_SPFGMR	fsunlinsol_spfgmr_mod
SUNLINSOL_SPBCGS	fsunlinsol_spbcgs_mod
SUNLINSOL_SPTFQMR	fsunlinsol_sptfqmr_mod
SUNLINSOL_PCG	fsunlinsol_pcg_mof
SUNNONLINSOL	fsundials_nonlinearsolver_mod
SUNNONLINSOL_NEWTON	fsunnnonlinsol_newton_mod
SUNNONLINSOL_FIXEDPOINT	fsunnnonlinsol_fixedpoint_mod
SUNNONLINSOL_PETSCSNES	Not interfaced

#### 4.4.1 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 classes 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 4.2 presents a summary of the type equivalencies with the parameter direction in mind.

**Warning:** Currently, the Fortran 2003 interfaces are only compatible with SUNDIALS builds where the `realtype` is double-precision the `sunindextype` size is 64-bits.

Table 4.2: C/Fortran-2003 Equivalent Types

C Type	Parameter Direction	Fortran 2003 type
<code>double</code>	in, inout, out, return	<code>real(c_double)</code>
<code>int</code>	in, inout, out, return	<code>integer(c_int)</code>
<code>long</code>	in, inout, out, return	<code>integer(c_long)</code>
<code>booleantype</code>	in, inout, out, return	<code>integer(c_int)</code>
<code>realtype</code>	in, inout, out, return	<code>real(c_double)</code>
<code>sunindextype</code>	in, inout, out, return	<code>integer(c_long)</code>
<code>double*</code>	in, inout, out	<code>real(c_double), dimension(*)</code>
<code>double*</code>	return	<code>real(c_double), pointer, dimension(:)</code>
<code>int*</code>	in, inout, out	<code>real(c_int), dimension(*)</code>
<code>int*</code>	return	<code>real(c_int), pointer, dimension(:)</code>
<code>long*</code>	in, inout, out	<code>real(c_long), dimension(*)</code>
<code>long*</code>	return	<code>real(c_long), pointer, dimension(:)</code>
<code>realtype*</code>	in, inout, out	<code>real(c_double), dimension(*)</code>
<code>realtype*</code>	return	<code>real(c_double), pointer, dimension(:)</code>
<code>sunindextype*</code>	in, inout, out	<code>real(c_long), dimension(*)</code>
<code>sunindextype*</code>	return	<code>real(c_long), pointer, dimension(:)</code>
<code>realtype[]</code>	in, inout, out	<code>real(c_double), dimension(*)</code>
<code>sunindextype[]</code>	in, inout, out	<code>integer(c_long), dimension(*)</code>
<code>N_Vector</code>	in, inout, out	<code>type(N_Vector)</code>

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Table 4.2 – continued from previous page

C Type	Parameter Direction	Fortran 2003 type
N_Vector	return	type(N_Vector), pointer
SUNMatrix	in, inout, out	type(SUNMatrix)
SUNMatrix	return	type(SUNMatrix), pointer
SUNLinearSolver	in, inout, out	type(SUNLinearSolver)
SUNLinearSolver	return	type(SUNLinearSolver), pointer
SUNNonlinearSolver	in, inout, out	type(SUNNonlinearSolver)
SUNNonlinearSolver	return	type(SUNNonlinearSolver), pointer
FILE*	in, inout, out, return	type(c_ptr)
void*	in, inout, out, return	type(c_ptr)
T**	in, inout, out, return	type(c_ptr)
T***	in, inout, out, return	type(c_ptr)
T****	in, inout, out, return	type(c_ptr)

## 4.4.2 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, §4.4.1 discusses equivalencies of data types in the two languages.

### 4.4.2.1 Creating generic SUNDIALS objects

In the C API a SUNDIALS class, 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. For example, `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 SUNDIALS objects in Fortran is nuanced. This is illustrated in the code snippets below:

C code:

```
N_Vector x;
x = N_VNew_Serial(N, sunctx);
```

Fortran code:

```
type(N_Vector), pointer :: x
x => FN_VNew_Serial(N, sunctx)
```

Note that in the Fortran declaration, the vector is a `type(N_Vector), pointer`, and that the pointer assignment operator is then used.

### 4.4.2.2 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:

```
N_Vector x;
realtype* xdata;
long int leniw, lenrw;

/* create a new serial vector */
x = N_VNew_Serial(N, sunctx);

/* 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:

```
type(N_Vector), pointer :: x
real(c_double), pointer :: xdataptr(:)
real(c_double)           :: xdata(N)
integer(c_long)          :: leniw(1), lenrw(1)

! create a new serial vector
x => FN_VNew_Serial(x, sunctx)

! 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)
```

#### 4.4.2.3 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:

```
MyUserData *udata;
void *cvode_mem;

ierr = CVodeSetUserData(cvode_mem, udata);
```

Fortran code:

```

type(MyUserData) :: udata
type(c_ptr)      :: arkode_mem

ierr = FARKStepSetUserData(arkode_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.

#### 4.4.2.4 Passing NULL to optional parameters

In the SUNDIALS C API some functions have optional parameters that a caller can pass as `NULL`. If the optional parameter is of a type that is equivalent to a Fortran `type(c_ptr)` (see §4.4.1), 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

! Disassociate A
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)

```

#### 4.4.2.5 Working with N\_Vector arrays

Arrays of `N_Vector` objects are interfaced to Fortran 2003 as an 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 (CVODES and IDAS). 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;

/* Create an array of N_Vectors */
vecs = N_VCloneVectorArray(count, x);

```

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```
/* Fill each array with ones */
for (int i = 0; i < count; ++i)
    N_VConst(vecs[i], 1.0);
```

Fortran code:

```
type(N_Vector), pointer :: x, xi
type(c_ptr)           :: vecs

! Create an array of N_Vectors
vecs = FN_VCloneVectorArray(count, x)

! Fill each array with ones
do index = 0, count-1
    xi => FN_VGetVecAtIndexVectorArray(vecs, index)
    call FN_VConst(xi, 1.d0)
enddo
```

SUNDIALS also provides the functions `N_VSetVecAtIndexVectorArray()` and `N_VNewVectorArray()` for working with `N_Vector` arrays, that have corresponding Fortran interfaces `FN_VSetVecAtIndexVectorArray` and `FN_VNewVectorArray`, respectively. These functions are particularly useful for users of the Fortran interface to the `NVECTOR_MANYVECTOR` or `NVECTOR_MPIMANYVECTOR` when creating the subvector array. Both of these functions along with `N_VGetVecAtIndexVectorArray()` (wrapped as `FN_VGetVecAtIndexVectorArray`) are further described in §7.1.1.

#### 4.4.2.6 Providing file pointers

There are a few functions in the SUNDIALS C API which 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`.

`FILE *SUNDIALSFileOpen(filename, mode)`

The function allocates a `FILE*` by calling the C function `fopen` with the provided filename and I/O mode.

**Arguments:**

- `filename` – the full path to the file, that should have Fortran type `character(kind=C_CHAR, len=*)`.
- `mode` – the I/O mode to use for the file. This should have the Fortran type `character(kind=C_CHAR, len=*)`. The string begins with one of the following characters:
  - `r` to open a text file for reading
  - `r+` to open a text file for reading/writing
  - `w` to truncate a text file to zero length or create it for writing
  - `w+` to open a text file for reading/writing or create it if it does not exist
  - `a` to open a text file for appending, see documentation of `fopen` for your system/compiler
  - `a+` to open a text file for reading/appending, see documentation for `fopen` for your system/compiler

**Return value:**

- The function returns a `type(C_PTR)` which holds a C `FILE*`.

---

```
void SUNDIALSFileClose(fp)
```

The function deallocates a C FILE\* by calling the C function `fclose` with the provided pointer.

**Arguments:**

- `fp` – the C FILE\* that was previously obtained from `fopen`. This should have the Fortran type `type(c_ptr)`.

#### 4.4.3 Important notes on portability

The SUNDIALS Fortran 2003 interface *should* be compatible with any compiler supporting the Fortran 2003 ISO standard. However, it has only been tested and confirmed to be working with GNU Fortran 4.9+ and Intel Fortran 18.0.1+.

Upon compilation of SUNDIALS, Fortran module (.mod) files are generated for each Fortran 2003 interface. These files are highly compiler specific, and thus it is almost always necessary to compile a consuming application with the same compiler that was used to generate the modules.

### 4.5 Features for GPU Accelerated Computing

In this section, we introduce the SUNDIALS GPU programming model and highlight SUNDIALS GPU features. The model leverages the fact that all of the SUNDIALS packages interact with simulation data either through the shared vector, matrix, and solver APIs (see Chapters §7, §8, §9, and §10) or through user-supplied callback functions. Thus, under the model, the overall structure of the user’s calling program, and the way users interact with the SUNDIALS packages is similar to using SUNDIALS in CPU-only environments.

#### 4.5.1 SUNDIALS GPU Programming Model

As described in [4], within the SUNDIALS GPU programming model, all control logic executes on the CPU, and all simulation data resides wherever the vector or matrix object dictates as long as SUNDIALS is in control of the program. That is, SUNDIALS will not migrate data (explicitly) from one memory space to another. Except in the most advanced use cases, it is safe to assume that data is kept resident in the GPU-device memory space. The consequence of this is that, when control is passed from the user’s calling program to SUNDIALS, simulation data in vector or matrix objects must be up-to-date in the device memory space. Similarly, when control is passed from SUNDIALS to the user’s calling program, the user should assume that any simulation data in vector and matrix objects are up-to-date in the device memory space. To put it succinctly, *it is the responsibility of the user’s calling program to manage data coherency between the CPU and GPU-device memory spaces* unless unified virtual memory (UVM), also known as managed memory, is being utilized. Typically, the GPU-enabled SUNDIALS modules provide functions to copy data from the host to the device and vice-versa as well as support for unmanaged memory or UVM. In practical terms, the way SUNDIALS handles distinct host and device memory spaces means that *users need to ensure that the user-supplied functions, e.g. the right-hand side function, only operate on simulation data in the device memory space* otherwise extra memory transfers will be required and performance will suffer. The exception to this rule is if some form of hybrid data partitioning (achievable with the NVECTOR\_MANYVECTOR, see §7.16) is utilized.

SUNDIALS provides many native shared features and modules that are GPU-enabled. Currently, these include the NVIDIA CUDA platform [67], AMD ROCm/HIP [64], and Intel oneAPI [65]. Table 4.3–Table 4.6 summarize the shared SUNDIALS modules that are GPU-enabled, what GPU programming environments they support, and what class of memory they support (unmanaged or UVM). Users may also supply their own GPU-enabled `N_Vector`, `SUNMatrix`, `SUNLinearSolver`, or `SUNNonlinearSolver` implementation, and the capabilities will be leveraged since SUNDIALS operates on data through these APIs.

In addition, SUNDIALS provides a memory management helper module (see §11) to support applications which implement their own memory management or memory pooling.

Table 4.3: List of SUNDIALS GPU-enabled N\_Vector Modules

Module	CUDA	ROCm/HIP	oneAPI	Unmanaged Memory	UVM
<i>NVECTOR_CUDA</i>	X			X	X
<i>NVECTOR_HIP</i>	X	X		X	X
<i>NVECTOR_RAJA</i>	X	X	X	X	X
<i>NVECTOR_SYCL</i>	X <sup>3</sup>	X <sup>3</sup>	X	X	X
<i>NVECTOR_OPENMPDEV</i>	X	X <sup>2</sup>	X <sup>2</sup>	X	

Table 4.4: List of SUNDIALS GPU-enabled SUNMatrix Modules

Module	CUDA	ROCm/HIP	oneAPI	Unmanaged Memory	UVM
<i>SUNMATRIX_CUSPARSE</i>	X			X	X
<i>SUNMATRIX_MAGMA Dense</i>	X	X		X	X
<i>SUNMATRIX_ONEMKLDENSE</i>	X <sup>3</sup>	X <sup>3</sup>	X	X	X

Table 4.5: List of SUNDIALS GPU-enabled SUNLinearSolver Modules

Module	CUDA	ROCm/HIP	oneAPI	Unmanaged Memory	UVM
<i>SUNLINSOL_CUSOLVERSP</i>	X			X	X
<i>SUNLINSOL_MAGMA Dense</i>	X			X	X
<i>SUNLINSOL_ONEMKLDENSE</i>	X <sup>3</sup>	X <sup>3</sup>	X	X	X
<i>SUNLINSOL_SPGMR</i>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>
<i>SUNLINSOL_SPGMRS</i>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>
<i>SUNLINSOL_SPTFQMR</i>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>
<i>SUNLINSOL_SPBCGS</i>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>
<i>SUNLINSOL_PCG</i>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>

Table 4.6: List of SUNDIALS GPU-enabled SUNNonlinearSolver Modules

Module	CUDA	ROCm/HIP	oneAPI	Unmanaged Memory	UVM
<i>SUNNONLINSOL_NEWTON</i>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>
<i>SUNNONLINSOL_FIXEDPOINT</i>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>	X <sup>1</sup>

Notes regarding the above tables:

1. This module inherits support from the NVECTOR module used
2. Support for ROCm/HIP and oneAPI are currently untested.
3. Support for CUDA and ROCm/HIP are currently untested.

In addition, note that implicit UVM (i.e. `malloc` returning UVM) is not accounted for.

## 4.5.2 Steps for Using GPU Accelerated SUNDIALS

For any SUNDIALS package, the generalized steps a user needs to take to use GPU accelerated SUNDIALS are:

1. Utilize a GPU-enabled `N_Vector` implementation. Initial data can be loaded on the host, but must be in the device memory space prior to handing control to SUNDIALS.
2. Utilize a GPU-enabled `SUNLinearSolver` linear solver (if applicable).
3. Utilize a GPU-enabled `SUNMatrix` implementation (if using a matrix-based linear solver).
4. Utilize a GPU-enabled `SUNNonlinearSolver` nonlinear solver (if applicable).
5. Write user-supplied functions so that they use data only in the device memory space (again, unless an atypical data partitioning is used). A few examples of these functions are the right-hand side evaluation function, the Jacobian evalution function, or the preconditioner evalution function. In the context of CUDA and the right-hand side function, one way a user might ensure data is accessed on the device is, for example, calling a CUDA kernel, which does all of the computation, from a CPU function which simply extracts the underlying device data array from the `N_Vector` object that is passed from SUNDIALS to the user-supplied function.

Users should refer to the above tables for a complete list of GPU-enabled native SUNDIALS modules.



# Chapter 5

## Using ARKODE

This chapter discusses usage for ARKODE from C, C++ and Fortran applications. The chapter builds upon §4. We first discuss commonalities to each of ARKODE’s time-stepping modules, including locations and naming conventions for the library and header files, and discussion of data types in SUNDIALS. We then separately discuss the C and C++ interfaces to each of ARKODE’s time stepping modules: *ARKStep*, *ERKStep*, and *MRIStep*. Following these, we describe set of *user-supplied routines* (both required and optional) that can be supplied to ARKODE.

### 5.1 Access to library and header files

At this point, it is assumed that the installation of ARKODE, following the procedure described in §12, 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 ARKODE. The relevant library files are

- libdir/libsundials\_arkode.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/arkode
- incdir/include/sundials
- incdir/include/nvector
- incdir/include/sunmatrix
- incdir/include/sunlinsol
- incdir/include/sunnonlinsol

The directories libdir and incdir are the installation 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 §12 for further details).

When using ARKODE, the calling program must include several header files so that various macros and data types can be used. One of the following header files is always required:

- arkode/arkode\_arkstep.h, the main header file for the ARKStep time-stepping module.

- `arkode/arkode_erkstep.h`, the main header file for the ERKStep time-stepping module.
- `arkode/arkode_mrstep.h`, the main header file for the MRIStep time-stepping module.

Each of these define several types and various constants, include function prototypes, and include the shared `arkode/arkode.h` and `arkode/arkode_ls.h` header files.

Note that `arkode.h` includes `sundials_types.h` directly, which defines the types `realtype`, `sunindextype`, and `booleantype` and the constants `SUNFALSE` and `SUNTRUE`, so a user program does not need to include `sundials-types.h` directly.

Additionally, the calling program must also include an NVECTOR implementation header file, of the form `nvector/nvector_***.h`, corresponding to the user's preferred data layout and form of parallelism. See §7 for details for the appropriate name. This file in turn includes the header file `sundials_nvector.h` which defines the abstract `N_Vector` data type.

If the user wishes to manually select between any of the pre-defined ERK or DIRK Butcher tables (for ARKStep, ERKStep, or as the basis for an MIS method), these are defined through a set of constants that are enumerated in the header files `arkode/arkode_butcher_erk.h` and `arkode/arkode_butcher_dirk.h`, or if a user wishes to manually specify one or more Butcher tables, the corresponding `ARKodeButcherTable` structure is defined in `arkode/arkode_butcher.h`. Alternatively, for MRIStep, slow-to-fast coupling coefficient tables are enumerated in the header file `arkode/arkode_mrstep.h`, or if a user wishes to manually specify a coupling table, the corresponding `MRISStepCouplingMem` structure is defined in `arkode/arkode_mrstep.h`.

If the user includes a non-trivial implicit component to their ODE system in ARKStep, or if the slow time scale for MRIStep should be treated implicitly, then each implicit stage will require a nonlinear solver for the resulting system of algebraic equations – the default for this is a modified or inexact Newton iteration, depending on the user's choice of linear solver. If using a non-default nonlinear solver module, or when interacting with a SUNNONLINSOL module directly, the calling program must also include a SUNNONLINSOL header file, of the form `sunnonlinsol/sunnonlinsol_***.h` where `***` is the name of the nonlinear solver module (see §10 for more information). This file in turn includes the header file `sundials_nonlinearSolver.h` which defines the abstract `SUNNonlinearSolver` data type.

If using a nonlinear solver that requires the solution of a linear system of the form  $\mathcal{A}x = b$  (e.g., the default Newton iteration), then a linear solver module header file will also be required. Similarly, if the ODE system in ARKStep involves a non-identity mass matrix  $M \neq I$ , then each time step will require a linear solver for systems of the form  $Mx = b$ . The header files corresponding to the SUNDIALS-provided linear solver modules available for use with ARKODE are:

- Direct linear solvers:
  - `sunlinsol/sunlinsol_dense.h`, which is used with the dense linear solver module, `SUNLINSOL_DENSE`;
  - `sunlinsol/sunlinsol_band.h`, which is used with the banded linear solver module, `SUNLINSOL_BAND`;
  - `sunlinsol/sunlinsol_lapackdense.h`, which is used with the LAPACK dense linear solver module, `SUNLINSOL_LAPACKDENSE`;
  - `sunlinsol/sunlinsol_lapackband.h`, which is used with the LAPACK banded linear solver module, `SUNLINSOL_LAPACKBAND`;
  - `sunlinsol/sunlinsol_klu.h`, which is used with the KLU sparse linear solver module, `SUNLINSOL_KLU`;
  - `sunlinsol/sunlinsol_superlumt.h`, which is used with the SuperLU\_MT sparse linear solver module, `SUNLINSOL_SUPERLUMT`;
  - `sunlinsol/sunlinsol_superludist.h`, which is used with the SuperLU\_DIST parallel sparse linear solver module, `SUNLINSOL_SUPERLUDIST`;

- `sunlinsol/sunlinsol_cusolversp_batchqr.h`, which is used with the batched sparse QR factorization method provided by the NVIDIA cuSOLVER library, SUNLINSOL\_CUSOLVERSP\_BATCHQR;
- 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 for 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 for acting on such matrices.

The header files for the SUNLINSOL\_KLU and SUNLINSOL\_SUPERLUMT linear solver modules include the file `sunmatrix/sunmatrix_sparse.h`, which defines the SUNMATRIX\_SPARSE matrix module, as well as various functions and macros for acting on such matrices.

The header file for the SUNLINSOL\_CUSOLVERSP\_BATCHQR linear solver module includes the file `sunmatrix/sunmatrix_cusparse.h`, which defines the SUNMATRIX\_CUSPARSE matrix module, as well as various functions for acting on such matrices.

The header file for the SUNLINSOL\_SUPERLUDIST linear solver module includes the file `sunmatrix/sunmatrix_slunrloc.h`, which defines the SUNMATRIX\_SLUNRLOC matrix module, as well as various functions for acting on such matrices.

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

Other headers may be needed, according to the choice of preconditioner, etc. For example, if preconditioning for an iterative linear solver were performed using the ARKBBDPRE module, the header `arkode/arkode_bbdpre.h` is needed to access the preconditioner initialization routines.

### 5.1.1 Data Types

The header file `sundials_types.h` contains the definition of the types:

- `realtype` – the floating-point type used by the SUNDIALS packages
- `sunindextype` – the integer type used for vector and matrix indices
- `booleantype` – the type used for logic operations within SUNDIALS

### 5.1.1.1 Floating point types

type **realtype**

The type **realtype** can be **float**, **double**, or **long double**, with the default being **double**. The user can change the precision of the arithmetic used in the SUNDIALS solvers at the configuration stage (see [SUNDIALS\\_PRECISION](#)).

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 of **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,

```
#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 C or C++ code can use SUNDIALS without modifying the code to use **realtype**, **RCONST**, or the **SUNR** macros so long as the SUNDIALS libraries are built to use the corresponding precision (see §12.1.2).

### 5.1.1.2 Integer types used for indexing

type **sunindextype**

The type **sunindextype** is used for indexing array entries in SUNDIALS modules as well as for storing the total problem size (*e.g.*, vector lengths and matrix sizes). During configuration **sunindextype** may be selected to be either a 32- or 64-bit *signed* integer with the default being 64-bit (see [SUNDIALS\\_INDEX\\_SIZE](#)).

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** (see [SUNDIALS\\_INDEX\\_TYPE](#)).

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 C or 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 §12.1.2).

### 5.1.1.3 Boolean type

type **booleantype**

As ANSI C89 (ISO C90) does not have a built-in boolean data type, SUNDIALS defines the type **booleantype** as an **int**.

The advantage of using the name **booleantype** (instead of **int**) is an increase in code readability. It also allows the programmer to make a distinction between **int** and boolean data. Variables of type **booleantype** are intended to have only the two values **SUNFALSE** (0) and **SUNTRUE** (1).

## 5.2 Using the ARKStep time-stepping module

This chapter is concerned with the use of the ARKStep time-stepping module for the solution of initial value problems (IVPs) in a C or C++ language setting. The following sections discuss the header files and the layout of the user's main program, and provide descriptions of the ARKStep user-callable functions and user-supplied functions.

The example programs located in the source code `examples/arkode` folder, including those described in the companion document [48], may be helpful as templates for new codes.

Users with applications written in Fortran should see the chapter §4.4, which describes the Fortran/C interface module for ARKStep, and may look to the Fortran example programs also provided in the ARKODE `examples` directory.

The user should be aware that not all SUNLINSOL, SUNMATRIX, and preconditioning modules are compatible with all NVECTOR implementations. Details on compatibility are given in the documentation for each SUNMATRIX (see §8) and each SUNLINSOL module (see §9). 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 §8 and §9 to verify compatibility between these modules. In addition to that documentation, we note that the ARKBANDPRE preconditioning module is only compatible with the NVECTOR\_SERIAL, NVECTOR\_OPENMP or NVECTOR\_PTHREADS vector implementations, and the preconditioner module ARKBDPRE can only be used with NVECTOR\_PARALLEL.

ARKStep uses various input and output constants from the shared ARKODE infrastructure. These are defined as needed in this chapter, but for convenience the full list is provided separately in §13.

The relevant information on using ARKStep's C and C++ interfaces is detailed in the following subsections.

### 5.2.1 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 an ODE IVP using the ARKStep module. Most of the steps are independent of the NVECTOR, SUNMATRIX, SUNLINSOL and SUNNONLINSOL implementations used. For the steps that are not, refer to §7, §8, §9, and §10 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. Create the SUNDIALS simulation context object.

Call `SUNContext_Create()` to allocate the `SUNContext` object.

3. 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.

---

#### 4. Set vector of initial values

To set the vector  $y_0$  of initial values, 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

```
y0 = 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 = N_VNew_***(...);
```

and then set its elements by accessing the underlying data where it is located with a call of the form

```
ydata = N_VGetArrayPointer_***(y0);
```

For details on each of SUNDIALS' provided vector implementations, see the corresponding sections in §7 for details.

#### 5. Create ARKStep object

Call `arkode_mem = ARKStepCreate(...)` to create the ARKStep memory block. `ARKStepCreate()` returns a `void*` pointer to this memory structure. See §5.2.2.1 for details.

#### 6. Specify integration tolerances

Call `ARKStepSStolerances()` or `ARKStepSVtolerances()` to specify either a scalar relative tolerance and scalar absolute tolerance, or a scalar relative tolerance and a vector of absolute tolerances, respectively. Alternatively, call `ARKStepWFtolerances()` to specify a function which sets directly the weights used in evaluating WRMS vector norms. See §5.2.2.2 for details.

If a problem with non-identity mass matrix is used, and the solution units differ considerably from the equation units, absolute tolerances for the equation residuals (nonlinear and linear) may be specified separately through calls to `ARKStepResStolerance()`, `ARKStepResVtolerance()`, or `ARKStepResFtolerance()`.

#### 7. Create matrix object

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

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

```
SUNMatrix A = SUNBandMatrix(..., sunctx);
```

or similar for the other matrix modules (see §8 for further information).

Similarly, if the problem involves a non-identity mass matrix, and the mass-matrix linear systems will be solved using a direct linear solver, then a template mass matrix must be created by using the appropriate functions defined by the particular SUNMATRIX implementation.

#### 8. Create linear solver object

If a nonlinear solver requiring a linear solver will be used (e.g., a Newton iteration), or if the problem involves a non-identity mass matrix, then the desired linear solver object(s) must be created by using the appropriate functions 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

```
SUNLinearSolver LS = SUNLinSol_*(...);
```

where \* can be replaced with “Dense”, “SPGMR”, or other options, as discussed in §9.

#### 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 §9 for details.

#### 10. Attach linear solver module

If a linear solver was created above for implicit stage solves, initialize the ARKLS linear solver interface by attaching the linear solver object (and Jacobian matrix object, if applicable) with the call (for details see §5.2.2.3):

```
ier = ARKStepSetLinearSolver(...);
```

Similarly, if the problem involves a non-identity mass matrix, initialize the ARKLS mass matrix linear solver interface by attaching the mass linear solver object (and mass matrix object, if applicable) with the call (for details see §5.2.2.3):

```
ier = ARKStepSetMassLinearSolver(...);
```

#### 11. Create nonlinear solver object

If the problem involves an implicit component, and if a non-default nonlinear solver object will be used for implicit stage solves (see §5.2.2.5), then the desired nonlinear solver object must be created by using the appropriate functions defined by the particular SUNNONLINSOL implementation (e.g., `NLS = SUNNonlinSol_***(...)`; where \*\*\* is the name of the nonlinear solver (see §10 for details).

For the SUNDIALS-supplied SUNNONLINSOL implementations, the nonlinear solver object may be created using a call of the form

```
SUNNonlinearSolver NLS = SUNNonlinSol_*(...);
```

where \* can be replaced with “Newton”, “FixedPoint”, or other options, as discussed in §10.

#### 12. Attach nonlinear solver module

If a nonlinear solver object was created above, then it must be attached to ARKStep using the call (for details see §5.2.2.5):

```
ier = ARKStepSetNonlinearSolver(...);
```

#### 13. Set nonlinear solver optional inputs

Call the appropriate set functions for the selected nonlinear solver module to change optional inputs specific to that nonlinear solver. These *must* be called after attaching the nonlinear solver to ARKStep, otherwise the optional inputs will be overridden by ARKStep defaults. See §10 for more information on optional inputs.

#### 14. Set optional inputs

Call ARKStepSet\* functions to change any optional inputs that control the behavior of ARKStep from their default values. See §5.2.2.8 for details.

15. Specify rootfinding problem

Optionally, call [ARKStepRootInit\(\)](#) to initialize a rootfinding problem to be solved during the integration of the ODE system. See §5.2.2.6 for general details, and §5.2.2.8 for relevant optional input calls.

16. Advance solution in time

For each point at which output is desired, call

```
ier = ARKStepEvolve(arkode_mem, tout, yout, &tret, itask);
```

Here, `itask` specifies the return mode. The vector `yout` (which can be the same as the vector `y0` above) will contain  $y(t_{\text{out}})$ . See §5.2.2.7 for details.

17. Get optional outputs

Call `ARKStepGet*` functions to obtain optional output. See §5.2.2.10 for details.

18. Deallocate memory for solution vector

Upon completion of the integration, deallocate memory for the vector `y` (or `yout`) by calling the destructor function:

```
N_VDestroy(y);
```

19. Free solver memory

Call [ARKStepFree\(\)](#) to free the memory allocated for the ARKStep module (and any nonlinear solver module).

20. Free linear solver and matrix memory

Call [SUNLinSolFree\(\)](#) and (possibly) [SUNMatDestroy\(\)](#) to free any memory allocated for the linear solver and matrix objects created above.

21. Free nonlinear solver memory

If a user-supplied `SUNNonlinearSolver` was provided to ARKStep, then call [SUNNonlinSolFree\(\)](#) to free any memory allocated for the nonlinear solver object created above.

22. Finalize MPI, if used

Call `MPI_Finalize` to terminate MPI.

## 5.2.2 ARKStep User-callable functions

This section describes the functions that are called by the user to setup and then solve an IVP using the ARKStep time-stepping module. Some of these are required; however, starting with §5.2.2.8, the functions listed involve optional inputs/outputs or restarting, and those paragraphs may be skipped for a casual use of ARKODE's ARKStep module. In any case, refer to the preceding section, §5.2.1, for the correct order of these calls.

On an error, each user-callable function returns a negative value (or NULL if the function returns a pointer) and sends an error message to the error handler routine, which prints the message to `stderr` by default. However, the user can set a file as error output or can provide her own error handler function (see §5.2.2.8 for details).

### 5.2.2.1 ARKStep initialization and deallocation functions

```
void *ARKStepCreate(ARKRhsFn fe, ARKRhsFn fi, realtype t0, N_Vector y0, SUNContext sunctx)
```

This function creates an internal memory block for a problem to be solved using the ARKStep time-stepping module in ARKODE.

#### Arguments:

- *fe* – the name of the C function (of type `ARKRhsFn()`) defining the explicit portion of the right-hand side function in  $M(t) y'(t) = f^E(t, y) + f^I(t, y)$ .
- *fi* – the name of the C function (of type `ARKRhsFn()`) defining the implicit portion of the right-hand side function in  $M(t) y'(t) = f^E(t, y) + f^I(t, y)$ .
- *t0* – the initial value of  $t$ .
- *y0* – the initial condition vector  $y(t_0)$ .
- *sunctx* – the `SUNContext` object (see §4.1)

**Return value:** If successful, a pointer to initialized problem memory of type `void*`, to be passed to all user-facing ARKStep routines listed below. If unsuccessful, a NULL pointer will be returned, and an error message will be printed to `stderr`.

```
void ARKStepFree(void **arkode_mem)
```

This function frees the problem memory *arkode\_mem* created by `ARKStepCreate()`.

#### Arguments:

- *arkode\_mem* – pointer to the ARKStep memory block.

**Return value:** None

### 5.2.2.2 ARKStep tolerance specification functions

These functions specify the integration tolerances. One of them **should** be called before the first call to `ARKStepEvolve()`; otherwise default values of `reltol = 1e-4` and `abstol = 1e-9` will be used, which may be entirely incorrect for a specific problem.

The integration tolerances `reltol` and `abstol` define a vector of error weights, `ewt`. In the case of `ARKStepSStolerances()`, this vector has components

```
ewt[i] = 1.0/(reltol*abs(y[i]) + abstol);
```

whereas in the case of `ARKStepSVtolerances()` the vector components are given by

```
ewt[i] = 1.0/(reltol*abs(y[i]) + abstol[i]);
```

This vector is used in all error and convergence tests, which use a weighted RMS norm on all error-like vectors *v*:

$$\|v\|_{WRMS} = \left( \frac{1}{N} \sum_{i=1}^N (v_i \text{ewt}_i)^2 \right)^{1/2},$$

where *N* is the problem dimension.

Alternatively, the user may supply a custom function to supply the `ewt` vector, through a call to `ARKStepWFtolerances()`.

```
int ARKStepSStolerances(void *arkode_mem, realtype reltol, realtype abstol)
```

This function specifies scalar relative and absolute tolerances.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *reltol* – scalar relative tolerance.
- *abstol* – scalar absolute tolerance.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL
- *ARK\_NO\_MALLOC* if the ARKStep memory was not allocated by the time-stepping module
- *ARK\_ILL\_INPUT* if an argument has an illegal value (e.g. a negative tolerance).

int **ARKStepSVtolerances**(void \*arkode\_mem, *realtype* reltol, *N\_Vecotr* abstol)

This function specifies a scalar relative tolerance and a vector absolute tolerance (a potentially different absolute tolerance for each vector component).

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *reltol* – scalar relative tolerance.
- *abstol* – vector containing the absolute tolerances for each solution component.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL
- *ARK\_NO\_MALLOC* if the ARKStep memory was not allocated by the time-stepping module
- *ARK\_ILL\_INPUT* if an argument has an illegal value (e.g. a negative tolerance).

int **ARKStepWFtolerances**(void \*arkode\_mem, *ARKEwtFn* efun)

This function specifies a user-supplied function *efun* to compute the error weight vector *ewt*.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *efun* – the name of the function (of type *ARKEwtFn()*) that implements the error weight vector computation.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL
- *ARK\_NO\_MALLOC* if the ARKStep memory was not allocated by the time-stepping module

Moreover, for problems involving a non-identity mass matrix  $M \neq I$ , the units of the solution vector  $y$  may differ from the units of the IVP, posed for the vector  $My$ . When this occurs, iterative solvers for the Newton linear systems and the mass matrix linear systems may require a different set of tolerances. Since the relative tolerance is dimensionless, but the absolute tolerance encodes a measure of what is “small” in the units of the respective quantity, a user may optionally define absolute tolerances in the equation units. In this case, ARKStep defines a vector of residual weights, *rwt* for measuring convergence of these iterative solvers. In the case of *ARKStepResStolerance()*, this vector has components

```
rwt[i] = 1.0/(reltol*abs(My[i]) + rabstol);
```

whereas in the case of `ARKStepResVtolerance()` the vector components are given by

```
rwt[i] = 1.0/(reltol*abs(My[i]) + rabstol[i]);
```

This residual weight vector is used in all iterative solver convergence tests, which similarly use a weighted RMS norm on all residual-like vectors  $v$ :

$$\|v\|_{WRMS} = \left( \frac{1}{N} \sum_{i=1}^N (v_i rwt_i)^2 \right)^{1/2},$$

where  $N$  is the problem dimension.

As with the error weight vector, the user may supply a custom function to supply the `rwt` vector, through a call to `ARKStepResFtolerance()`. Further information on all three of these functions is provided below.

`int ARKStepResStolerance(void *arkode_mem, realtype rabstol)`

This function specifies a scalar absolute residual tolerance.

#### Arguments:

- *arkode\_mem* – pointer to the ARKStep memory block.
- *rabstol* – scalar absolute residual tolerance.

#### Return value:

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL
- *ARK\_NO\_MALLOC* if the ARKStep memory was not allocated by the time-stepping module
- *ARK\_ILL\_INPUT* if an argument has an illegal value (e.g. a negative tolerance).

`int ARKStepResVtolerance(void *arkode_mem, N_Vector rabstol)`

This function specifies a vector of absolute residual tolerances.

#### Arguments:

- *arkode\_mem* – pointer to the ARKStep memory block.
- *rabstol* – vector containing the absolute residual tolerances for each solution component.

#### Return value:

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL
- *ARK\_NO\_MALLOC* if the ARKStep memory was not allocated by the time-stepping module
- *ARK\_ILL\_INPUT* if an argument has an illegal value (e.g. a negative tolerance).

`int ARKStepResFtolerance(void *arkode_mem, ARKRwtFn rfun)`

This function specifies a user-supplied function *rfun* to compute the residual weight vector `rwt`.

#### Arguments:

- *arkode\_mem* – pointer to the ARKStep memory block.
- *rfun* – the name of the function (of type `ARKRwtFn()`) that implements the residual weight vector computation.

#### Return value:

- *ARK\_SUCCESS* if successful

- *ARK\_MEM\_NULL* if the ARKStep memory was `NULL`
- *ARK\_NO\_MALLOC* if the ARKStep memory was not allocated by the time-stepping module

### General advice on the choice of tolerances

For many users, the appropriate choices for tolerance values in `reltol`, `abstol`, and `rabstol` 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 a value of  $10^{-4}$  means that errors are controlled to .01%. We do not recommend using `reltol` larger than  $10^{-3}$ . On the other hand, `reltol` should not be so small that it is comparable to the unit roundoff of the machine arithmetic (generally around  $10^{-15}$  for double-precision).
- (2) The absolute tolerances `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 `abstol` (if scalar) or `abstol[i]` (if a vector) needs to be set to that noise level. If the different components have different noise levels, then `abstol` should be a vector. For example, see the example problem `ark_robertson.c`, and the discussion of it in the ARKODE Examples Documentation [48]. In that problem, the three components vary between 0 and 1, and have different noise levels; hence the `atols` vector therein. It is impossible to give any general advice on `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) The residual absolute tolerances `rabstol` (whether scalar or vector) follow a similar explanation as for `abstol`, except that these should be set to the noise level of the equation components, i.e. the noise level of  $My$ . For problems in which  $M = I$ , it is recommended that `rabstol` be left unset, which will default to the already-supplied `abstol` values.
- (4) Finally, it is important to pick all the tolerance values conservatively, because they control the error committed on each individual step. The final (global) errors are an accumulation of those per-step errors, where that accumulation factor is problem-dependent. A general rule of thumb is to reduce the tolerances by a factor of 10 from the actual desired limits on errors. So if you want .01% relative accuracy (globally), a good choice for `reltol` is  $10^{-5}$ . 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 nonphysical 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 (nonphysical) values can then occur. In most cases, these values are harmless, and simply need to be controlled, not eliminated, but in other cases any value that violates a constraint may cause a simulation to halt. For both of these scenarios the following pieces of advice are relevant.

- (1) The best 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  $y$  returned by ARKStep, with magnitude comparable to `abstol` or less, is equivalent to zero as far as the computation is concerned.
- (3) The user's right-hand side routines  $f^E$  and  $f^I$  should never change a negative value in the solution vector  $y$  to a non-negative value in attempt to "fix" this problem, since this can lead to numerical instability. If the  $f^E$  or  $f^I$

routines cannot tolerate a zero or negative value (e.g. because there is a square root or log), then the offending value should be changed to zero or a tiny positive number in a temporary variable (not in the input  $y$  vector) for the purposes of computing  $f^E(t, y)$  or  $f^I(t, y)$ .

- (4) ARKStep supports component-wise constraints on solution components,  $y_i < 0$ ,  $y_i \leq 0$ , ,  $y_i > 0$ , or  $y_i \geq 0$ , through the user-callable function [ARKStepSetConstraints\(\)](#). At each internal time step, if any constraint is violated then ARKStep will attempt a smaller time step that should not violate this constraint. This reduced step size is chosen such that the step size is the largest possible but where the solution component satisfies the constraint.
- (5) Positivity and non-negativity constraints on components can also be enforced by use of the recoverable error return feature in the user-supplied right-hand side functions,  $f^E$  and  $f^I$ . When a recoverable error is encountered, ARKStep will retry the step with a smaller step size, which typically alleviates the problem. However, since this reduced step size is chosen without knowledge of the solution constraint, it may be overly conservative. Thus this option involves some additional overhead cost, and should only be exercised if the above recommendations are unsuccessful.

### 5.2.2.3 Linear solver interface functions

As previously explained, the Newton iterations used in solving implicit systems within ARKStep require the solution of linear systems of the form

$$\mathcal{A} \left( z_i^{(m)} \right) \delta^{(m+1)} = -G \left( z_i^{(m)} \right)$$

where

$$\mathcal{A} \approx M - \gamma J, \quad J = \frac{\partial f^I}{\partial y}.$$

ARKODE's ARKLS linear solver interface supports all valid `SUNLinearSolver` modules for this task.

Matrix-based `SUNLinearSolver` modules utilize `SUNMatrix` objects to store the approximate Jacobian matrix  $J$ , the Newton matrix  $\mathcal{A}$ , the mass matrix  $M$ , and, when using direct solvers, the factorizations used throughout the solution process.

Matrix-free `SUNLinearSolver` modules instead use iterative methods to solve the Newton systems of equations, and only require the *action* of the matrix on a vector,  $\mathcal{A}v$ . With most of these methods, 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. For the specification of a preconditioner, see the iterative linear solver portions of §5.2.2.8 and §5.5.

If preconditioning is done, user-supplied functions should be used to define left and right preconditioner matrices  $P_1$  and  $P_2$  (either of which could be the identity matrix), such that the product  $P_1P_2$  approximates the Newton matrix  $\mathcal{A} = M - \gamma J$ .

To specify a generic linear solver for ARKStep to use for the Newton systems, after the call to [ARKStepCreate\(\)](#) but before any calls to [ARKStepEvolve\(\)](#), the user's program must create the appropriate `SUNLinearSolver` object and call the function [ARKStepSetLinearSolver\(\)](#), 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

```
SUNLinearSolver LS = SUNLinSol_*(...);
```

The current list of SUNDIALS-packaged `SUNLinSol` modules, and their constructor routines, may be found in chapter §9. Alternately, a user-supplied `SUNLinearSolver` module may be created and used. Specific information on how to create such user-provided modules may be found in §9.1.8.

Once this solver object has been constructed, the user should attach it to ARKStep via a call to [ARKStepSetLinearSolver\(\)](#). The first argument passed to this function is the ARKStep memory pointer returned by [ARKStepCreate\(\)](#);

the second argument is the `SUNLinearSolver` object created above. The third argument is an optional `SUNMatrix` object to accompany matrix-based `SUNLinearSolver` inputs (for matrix-free linear solvers, the third argument should be `NULL`). A call to this function initializes the ARKLS linear solver interface, linking it to the ARKStep integrator, and allows the user to specify additional parameters and routines pertinent to their choice of linear solver.

```
int ARKStepSetLinearSolver(void *arkode_mem, SUNLinearSolver LS, SUNMatrix J)
```

This function specifies the `SUNLinearSolver` object that ARKStep should use, as well as a template Jacobian `SUNMatrix` object (if applicable).

**Arguments:**

- `arkode_mem` – pointer to the ARKStep memory block.
- `LS` – the `SUNLinearSolver` object to use.
- `J` – the template Jacobian `SUNMatrix` object to use (or `NULL` if not applicable).

**Return value:**

- `ARKLS_SUCCESS` if successful
- `ARKLS_MEM_NULL` if the ARKStep memory was `NULL`
- `ARKLS_MEM_FAIL` if there was a memory allocation failure
- `ARKLS_ILL_INPUT` if ARKLS is incompatible with the provided `LS` or `J` input objects, or the current `N_Vector` module.

**Notes:** If `LS` is a matrix-free linear solver, then the `J` argument should be `NULL`.

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 the §8 for further information).

When using sparse linear solvers, it is typically much more efficient to supply `J` so that it includes the full sparsity pattern of the Newton system matrices  $\mathcal{A} = M - \gamma J$ , even if `J` itself has zeros in nonzero locations of `M`. The reasoning for this is that  $\mathcal{A}$  is constructed in-place, on top of the user-specified values of `J`, so if the sparsity pattern in `J` is insufficient to store  $\mathcal{A}$  then it will need to be resized internally by ARKStep.

#### 5.2.2.4 Mass matrix solver specification functions

As discussed in §2.10.6, if the ODE system involves a non-identity mass matrix  $M \neq I$ , then ARKStep must solve linear systems of the form

$$Mx = b.$$

ARKODE's ARKLS mass-matrix linear solver interface supports all valid `SUNLinearSolver` modules for this task. For iterative linear solvers, user-supplied preconditioning can be applied. For the specification of a preconditioner, see the iterative linear solver portions of §5.2.2.8 and §5.5. If preconditioning is to be performed, user-supplied functions should be used to define left and right preconditioner matrices  $P_1$  and  $P_2$  (either of which could be the identity matrix), such that the product  $P_1 P_2$  approximates the mass matrix  $M$ .

To specify a generic linear solver for ARKStep to use for mass matrix systems, after the call to `ARKStepCreate()` but before any calls to `ARKStepEvolve()`, the user's program must create the appropriate `SUNLinearSolver` object and call the function `ARKStepSetMassLinearSolver()`, as documented below. The first argument passed to this function is the ARKStep memory pointer returned by `ARKStepCreate()`; the second argument is the desired `SUNLinearSolver` object to use for solving mass matrix systems. The third object is a template `SUNMatrix` to use with the provided `SUNLinearSolver` (if applicable). The fourth input is a flag to indicate whether the mass matrix is time-dependent, i.e.  $M = M(t)$ , or not. A call to this function initializes the ARKLS mass matrix linear solver interface,

linking this to the main ARKStep integrator, and allows the user to specify additional parameters and routines pertinent to their choice of linear solver.

Note: if the user program includes linear solvers for *both* the Newton and mass matrix systems, these must have the same type:

- If both are matrix-based, then they must utilize the same `SUNMatrix` type, since these will be added when forming the Newton system matrix  $\mathcal{A}$ . In this case, both the Newton and mass matrix linear solver interfaces can use the same `SUNLinearSolver` object, although different solver objects (e.g. with different solver parameters) are also allowed.
- If both are matrix-free, then the Newton and mass matrix `SUNLinearSolver` objects must be different. These may even use different solver algorithms (SPGMR, SPBCGS, etc.), if desired. For example, if the mass matrix is symmetric but the Jacobian is not, then PCG may be used for the mass matrix systems and SPGMR for the Newton systems.

```
int ARKStepSetMassLinearSolver(void *arkode_mem, SUNLinearSolver LS, SUNMatrix M, boolean type
                               time_dep)
```

This function specifies the `SUNLinearSolver` object that ARKStep should use for mass matrix systems, as well as a template `SUNMatrix` object.

#### Arguments:

- *arkode\_mem* – pointer to the ARKStep memory block.
- *LS* – the `SUNLinearSolver` object to use.
- *M* – the template mass `SUNMatrix` object to use.
- *time\_dep* – flag denoting whether the mass matrix depends on the independent variable ( $M = M(t)$ ) or not ( $M \neq M(t)$ ). `SUNTRUE` indicates time-dependence of the mass matrix.

#### Return value:

- `ARKLS_SUCCESS` if successful
- `ARKLS_MEM_NULL` if the ARKStep memory was `NULL`
- `ARKLS_MEM_FAIL` if there was a memory allocation failure
- `ARKLS_ILL_INPUT` if ARKLS is incompatible with the provided *LS* or *M* input objects, or the current `N_Vec` module.

**Notes:** If *LS* is a matrix-free linear solver, then the *M* argument should be `NULL`.

If *LS* is a matrix-based linear solver, then the template mass matrix *M* 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.

If called with *time\_dep* set to `SUNFALSE`, then the mass matrix is only computed and factored once (or when either `ARKStepReInit()` or `ARKStepResize()` are called), with the results reused throughout the entire ARKStep simulation.

Unlike the system Jacobian, the system mass matrix is not approximated using finite-differences of any functions provided to ARKStep. Hence, use of a matrix-based *LS* requires the user to provide a mass-matrix constructor routine (see `ARKLsMassFn` and `ARKStepSetMassFn()`).

Similarly, the system mass matrix-vector-product is not approximated using finite-differences of any functions provided to ARKStep. Hence, use of a matrix-free *LS* requires the user to provide a mass-matrix-times-vector product routine (see `ARKLsMassTimesVecFn` and `ARKStepSetMassTimes()`).

### 5.2.2.5 Nonlinear solver interface functions

When changing the nonlinear solver in ARKStep, after the call to `ARKStepCreate()` but before any calls to `ARKStepEvolve()`, the user's program must create the appropriate SUNNonlinearSolver object and call `ARKStepSetNonlinearSolver()`, as documented below. If any calls to `ARKStepEvolve()` have been made, then ARKStep will need to be reinitialized by calling `ARKStepReInit()` to ensure that the nonlinear solver is initialized correctly before any subsequent calls to `ARKStepEvolve()`.

The first argument passed to the routine `ARKStepSetNonlinearSolver()` is the ARKStep memory pointer returned by `ARKStepCreate()`; the second argument passed to this function is the desired SUNNonlinearSolver object to use for solving the nonlinear system for each implicit stage. A call to this function attaches the nonlinear solver to the main ARKStep integrator.

```
int ARKStepSetNonlinearSolver(void *arkode_mem, SUNNonlinearSolver NLS)
```

This function specifies the SUNNonlinearSolver object that ARKStep should use for implicit stage solves.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *NLS* – the SUNNonlinearSolver object to use.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL
- *ARK\_MEM\_FAIL* if there was a memory allocation failure
- *ARK\_ILL\_INPUT* if ARKStep is incompatible with the provided *NLS* input object.

**Notes:** ARKStep will use the Newton SUNNonlinearSolver module by default; a call to this routine replaces that module with the supplied *NLS* object.

### 5.2.2.6 Rootfinding initialization function

As described in §2.11, while solving the IVP, ARKODE's time-stepping modules have the capability to find the roots of a set of user-defined functions. To activate the root-finding algorithm, call the following function. This is normally called only once, prior to the first call to `ARKStepEvolve()`, but if the rootfinding problem is to be changed during the solution, `ARKStepRootInit()` can also be called prior to a continuation call to `ARKStepEvolve()`.

```
int ARKStepRootInit(void *arkode_mem, int nrtfn, ARKRootFn g)
```

Initializes a rootfinding problem to be solved during the integration of the ODE system. It must be called after `ARKStepCreate()`, and before `ARKStepEvolve()`.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nrtfn* – number of functions  $g_i$ , an integer  $\geq 0$ .
- *g* – name of user-supplied function, of type `ARKRootFn()`, defining the functions  $g_i$  whose roots are sought.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL
- *ARK\_MEM\_FAIL* if there was a memory allocation failure
- *ARK\_ILL\_INPUT* if *nrtfn* is greater than zero but *g* = NULL.

**Notes:** To disable the rootfinding feature after it has already been initialized, or to free memory associated with ARKStep's rootfinding module, call `ARKStepRootInit` with `nrtfn = 0`.

Similarly, if a new IVP is to be solved with a call to `ARKStepReInit()`, where the new IVP has no rootfinding problem but the prior one did, then call `ARKStepRootInit` with `nrtfn = 0`.

### 5.2.2.7 ARKStep solver function

This is the central step in the solution process – the call to perform the integration of the IVP. The input argument `itask` specifies one of two modes as to where ARKStep is to return a solution. These modes are modified if the user has set a stop time (with a call to the optional input function `ARKStepSetStopTime()`) or has requested rootfinding.

```
int ARKStepEvolve(void *arkode_mem, realtype tout, N_Vector yout, realtype *tret, int itask)
```

Integrates the ODE over an interval in  $t$ .

#### Arguments:

- `arkode_mem` – pointer to the ARKStep memory block.
- `tout` – the next time at which a computed solution is desired.
- `yout` – the computed solution vector.
- `tret` – the time corresponding to `yout` (output).
- `itask` – a flag indicating the job of the solver for the next user step.

The `ARK_NORMAL` option causes the solver to take internal steps until it has just overtaken a user-specified output time, `tout`, in the direction of integration, i.e.  $t_{n-1} < tout \leq t_n$  for forward integration, or  $t_n \leq tout < t_{n-1}$  for backward integration. It will then compute an approximation to the solution  $y(tout)$  by interpolation (as described in §2.2).

The `ARK_ONE_STEP` option tells the solver to only take a single internal step  $y_{n-1} \rightarrow y_n$  and then return control back to the calling program. If this step will overtake `tout` then the solver will again return an interpolated result; otherwise it will return a copy of the internal solution  $y_n$  in the vector `yout`.

#### Return value:

- `ARK_SUCCESS` if successful.
- `ARK_ROOT_RETURN` if `ARKStepEvolve()` succeeded, and found one or more roots. If the number of root functions, `nrtfn`, is greater than 1, call `ARKStepGetRootInfo()` to see which  $g_i$  were found to have a root at (`*tret`).
- `ARK_TSTOP_RETURN` if `ARKStepEvolve()` succeeded and returned at `tstop`.
- `ARK_MEM_NULL` if the `arkode_mem` argument was NULL.
- `ARK_NO_MALLOC` if `arkode_mem` was not allocated.
- `ARK_ILL_INPUT` if one of the inputs to `ARKStepEvolve()` is illegal, or some other input to the solver was either illegal or missing. Details will be provided in the error message. Typical causes of this failure:
  - (a) A component of the error weight vector became zero during internal time-stepping.
  - (b) The linear solver initialization function (called by the user after calling `ARKStepCreate()`) failed to set the linear solver-specific `lsolve` field in `arkode_mem`.
  - (c) A root of one of the root functions was found both at a point  $t$  and also very near  $t$ .
  - (d) The initial condition violates the inequality constraints.

- *ARK\_TOO MUCH\_WORK* if the solver took *mxstep* internal steps but could not reach *tout*. The default value for *mxstep* is *MXSTEP\_DEFAULT* = 500.
- *ARK\_TOO MUCH\_ACC* if the solver could not satisfy the accuracy demanded by the user for some internal step.
- *ARK\_ERR\_FAILURE* if error test failures occurred either too many times (*ark\_maxnef*) during one internal time step or occurred with  $|h| = h_{min}$ .
- *ARK\_CONV\_FAILURE* if either convergence test failures occurred too many times (*ark\_maxncf*) during one internal time step or occurred with  $|h| = h_{min}$ .
- *ARK\_INIT\_FAIL* if the linear solver's initialization function failed.
- *ARK\_LSETUP\_FAIL* if the linear solver's setup routine failed in an unrecoverable manner.
- *ARK\_LSOLVE\_FAIL* if the linear solver's solve routine failed in an unrecoverable manner.
- *ARK\_MASSINIT\_FAIL* if the mass matrix solver's initialization function failed.
- *ARK\_MASSSETUP\_FAIL* if the mass matrix solver's setup routine failed.
- *ARK\_MASSSOLVE\_FAIL* if the mass matrix solver's solve routine failed.
- *ARK\_VECTOROP\_ERR* a vector operation error occurred.

**Notes:** The input vector *yout* can use the same memory as the vector *y0* of initial conditions that was passed to [\*ARKStepCreate\(\)\*](#).

In *ARK\_ONE\_STEP* mode, *tout* is used only on the first call, and only to get the direction and a rough scale of the independent variable.

All failure return values are negative and so testing the return argument for negative values will trap all [\*ARKStepEvolve\(\)\*](#) failures.

Since interpolation may reduce the accuracy in the reported solution, if full method accuracy is desired the user should issue a call to [\*ARKStepSetStopTime\(\)\*](#) before the call to [\*ARKStepEvolve\(\)\*](#) to specify a fixed stop time to end the time step and return to the user. Upon return from [\*ARKStepEvolve\(\)\*](#), a copy of the internal solution *yn* will be returned in the vector *yout*. Once the integrator returns at a *tstop* time, any future testing for *tstop* is disabled (and can be re-enabled only though a new call to [\*ARKStepSetStopTime\(\)\*](#)).

On any error return in which one or more internal steps were taken by [\*ARKStepEvolve\(\)\*](#), the returned values of *tret* and *yout* correspond to the farthest point reached in the integration. On all other error returns, *tret* and *yout* are left unchanged from those provided to the routine.

### 5.2.2.8 Optional input functions

There are numerous optional input parameters that control the behavior of ARKStep, each of which may be modified from its default value through calling an appropriate input function. The following tables list all optional input functions, grouped by which aspect of ARKStep they control. Detailed information on the calling syntax and arguments for each function are then provided following each table.

The optional inputs are grouped into the following categories:

- General ARKStep options ([\*Optional inputs for ARKStep\*](#)),
- IVP method solver options ([\*Optional inputs for IVP method selection\*](#)),
- Step adaptivity solver options ([\*Optional inputs for time step adaptivity\*](#)),
- Implicit stage solver options ([\*Optional inputs for implicit stage solves\*](#)),
- Linear solver interface options ([\*Linear solver interface optional input functions\*](#)), and

- Rootfinding options (*Rootfinding optional input functions*).

For the most casual use of ARKStep, relying on the default set of solver parameters, the reader can skip to section on user-supplied functions, §5.5.

We note that, on an error return, all of the optional input functions send an error message to the error handler function. All error return values are negative, so a test on the return arguments for negative values will catch all errors. Finally, a call to an `ARKStepSet***` function can generally be made from the user's calling program at any time and, if successful, takes effect immediately. `ARKStepSet***` functions that cannot be called at any time note this in the “Notes:” section of the function documentation.

## Optional inputs for ARKStep

Optional input	Function name	Default
Return ARKStep parameters to their defaults	<code>ARKStepSetDefaults()</code>	internal
Set dense output interpolation type	<code>ARKStepSetInterpolantType()</code>	<code>ARK_INTERP_HERMITE</code>
Set dense output polynomial degree	<code>ARKStepSetInterpolantDegree()</code>	5
Supply a pointer to a diagnostics output file	<code>ARKStepSetDiagnostics()</code>	NULL
Supply a pointer to an error output file	<code>ARKStepSetErrFile()</code>	<code>stderr</code>
Supply a custom error handler function	<code>ARKStepSetErrorHandlerFn()</code>	internal fn
Disable time step adaptivity (fixed-step mode)	<code>ARKStepSetFixedStep()</code>	disabled
Supply an initial step size to attempt	<code>ARKStepSetInitStep()</code>	estimated
Maximum no. of warnings for $t_n + h = t_n$	<code>ARKStepSetMaxHnilWarns()</code>	10
Maximum no. of internal steps before $tout$	<code>ARKStepSetMaxNumSteps()</code>	500
Maximum absolute step size	<code>ARKStepSetMaxStep()</code>	$\infty$
Minimum absolute step size	<code>ARKStepSetMinStep()</code>	0.0
Set a value for $t_{stop}$	<code>ARKStepSetStopTime()</code>	N/A
Supply a pointer for user data	<code>ARKStepSetUserData()</code>	NULL
Maximum no. of ARKStep error test failures	<code>ARKStepSetMaxErrTestFails()</code>	7
Set ‘optimal’ adaptivity params. for a method	<code>ARKStepSetOptimalParams()</code>	internal
Set inequality constraints on solution	<code>ARKStepSetConstraints()</code>	NULL
Set max number of constraint failures	<code>ARKStepSetMaxNumConstrFails()</code>	10

`int ARKStepSetDefaults(void *arkode_mem)`

Resets all optional input parameters to ARKStep’s original default values.

### Arguments:

- `arkode_mem` – pointer to the ARKStep memory block.

### Return value:

- `ARK_SUCCESS` if successful
- `ARK_MEM_NULL` if the ARKStep memory is NULL
- `ARK_ILL_INPUT` if an argument has an illegal value

**Notes:** Does not change the `user_data` pointer or any parameters within the specified time-stepping module.

Also leaves alone any data structures or options related to root-finding (those can be reset using `ARKStepRootInit()`).

`int ARKStepSetInterpolantType(void *arkode_mem, int itype)`

Specifies use of the Lagrange or Hermite interpolation modules (used for dense output – interpolation of solution output values and implicit method predictors).

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *itype* – requested interpolant type (ARK\_INTERP\_HERMITE or ARK\_INTERP\_LAGRANGE)

**Return value:**

- ARK\_SUCCESS if successful
- ARK\_MEM\_NULL if the ARKStep memory is NULL
- ARK\_MEM\_FAIL if the interpolation module cannot be allocated
- ARK\_ILL\_INPUT if the *itype* argument is not recognized or the interpolation module has already been initialized

**Notes:** The Hermite interpolation module is described in §2.2.1, and the Lagrange interpolation module is described in §2.2.2.

This routine frees any previously-allocated interpolation module, and re-creates one according to the specified argument. Thus any previous calls to `ARKStepSetInterpolantDegree()` will be nullified.

This routine may only be called *after* the call to `ARKStepCreate()`. After the first call to `ARKStepEvolve()` the interpolation type may not be changed without first calling `ARKStepReInit()`.

If this routine is not called, the Hermite interpolation module will be used.

int **ARKStepSetInterpolantDegree**(void \*arkode\_mem, int degree)

Specifies the degree of the polynomial interpolant used for dense output (i.e. interpolation of solution output values and implicit method predictors).

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *degree* – requested polynomial degree.

**Return value:**

- ARK\_SUCCESS if successful
- ARK\_MEM\_NULL if the ARKStep memory or interpolation module are NULL
- ARK\_INTERP\_FAIL if this is called after `ARKStepEvolve()`
- ARK\_ILL\_INPUT if an argument has an illegal value or the interpolation module has already been initialized

**Notes:** Allowed values are between 0 and 5.

This routine should be called *after* `ARKStepCreate()` and *before* `ARKStepEvolve()`. After the first call to `ARKStepEvolve()` the interpolation degree may not be changed without first calling `ARKStepReInit()`.

If a user calls both this routine and `ARKStepSetInterpolantType()`, then `ARKStepSetInterpolantType()` must be called first.

Since the accuracy of any polynomial interpolant is limited by the accuracy of the time-step solutions on which it is based, the *actual* polynomial degree that is used by ARKStep will be the minimum of  $q - 1$  and the input *degree*, where  $q$  is the order of accuracy for the time integration method.

int **ARKStepSetDenseOrder**(void \*arkode\_mem, int dord)

*This function is deprecated, and will be removed in a future release. Users should transition to calling ARKStepSetInterpolantDegree() instead.*

int **ARKStepSetDiagnostics**(void \*arkode\_mem, FILE \*diagfp)

Specifies the file pointer for a diagnostics file where all ARKStep step adaptivity and solver information is written.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *diagfp* – pointer to the diagnostics output file.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** This parameter can be `stdout` or `stderr`, although the suggested approach is to specify a pointer to a unique file opened by the user and returned by `fopen`. If not called, or if called with a NULL file pointer, all diagnostics output is disabled.

When run in parallel, only one process should set a non-NUL value for this pointer, since statistics from all processes would be identical.

`int ARKStepSetErrFile(void *arkode_mem, FILE *errfp)`

Specifies a pointer to the file where all ARKStep warning and error messages will be written if the default internal error handling function is used.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *errfp* – pointer to the output file.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The default value for *errfp* is `stderr`.

Passing a NULL value disables all future error message output (except for the case wherein the ARKStep memory pointer is NULL). This use of the function is strongly discouraged.

If used, this routine should be called before any other optional input functions, in order to take effect for subsequent error messages.

`int ARKStepSetErrorHandlerFn(void *arkode_mem, ARKErrHandlerFn ehfun, void *eh_data)`

Specifies the optional user-defined function to be used in handling error messages.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *ehfun* – name of user-supplied error handler function.
- *eh\_data* – pointer to user data passed to *ehfun* every time it is called.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Error messages indicating that the ARKStep solver memory is NULL will always be directed to `stderr`.

```
int ARKStepSetFixedStep(void *arkode_mem, realtype hfixed)
```

Disables time step adaptivity within ARKStep, and specifies the fixed time step size to use for the following internal step(s).

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *hfixed* – value of the fixed step size to use.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Pass 0.0 to return ARKStep to the default (adaptive-step) mode.

Use of this function is not generally recommended, since it gives no assurance of the validity of the computed solutions. It is primarily provided for code-to-code verification testing purposes.

When using *ARKStepSetFixedStep()*, any values provided to the functions *ARKStepSetInitStep()*, *ARKStepSetAdaptivityFn()*, *ARKStepSetMaxErrTestFails()*, *ARKStepSetAdaptivityMethod()*, *ARKStepSetCFLFraction()*, *ARKStepsetErrorBias()*, *ARKStepSetFixedStepBounds()*, *ARKStepSetMaxCFailGrowth()*, *ARKStepSetMaxEfailGrowth()*, *ARKStepSetMaxFirstGrowth()*, *ARKStepSetMaxGrowth()*, *ARKStepSetMinReduction()*, *ARKStepSetSafetyFactor()*, *ARKStepSetSmallNumEFails()* and *ARKStepSetStabilityFn()* will be ignored, since temporal adaptivity is disabled.

If both *ARKStepSetFixedStep()* and *ARKStepSetStopTime()* are used, then the fixed step size will be used for all steps until the final step preceding the provided stop time (which may be shorter). To resume use of the previous fixed step size, another call to *ARKStepSetFixedStep()* must be made prior to calling *ARKStepEvolve()* to resume integration.

It is *not* recommended that *ARKStepSetFixedStep()* be used in concert with *ARKStepSetMaxStep()* or *ARKStepSetMinStep()*, since at best those latter two routines will provide no useful information to the solver, and at worst they may interfere with the desired fixed step size.

```
int ARKStepSetInitStep(void *arkode_mem, realtype hin)
```

Specifies the initial time step size ARKStep should use after initialization, re-initialization, or resetting.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *hin* – value of the initial step to be attempted ( $\neq 0$ ).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Pass 0.0 to use the default value.

By default, ARKStep estimates the initial step size to be  $h = \sqrt{\frac{2}{\|\ddot{y}\|}}$ , where  $\ddot{y}$  is estimate of the second derivative of the solution at  $t_0$ .

This routine will also reset the step size and error history.

---

**int `ARKStepSetMaxHnilWarns`**(void \*arkode\_mem, int mxhnil)

Specifies the maximum number of messages issued by the solver to warn that  $t + h = t$  on the next internal step, before ARKStep will instead return with an error.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *mxhnil* – maximum allowed number of warning messages ( $> 0$ ).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The default value is 10; set *mxhnil* to zero to specify this default.

A negative value indicates that no warning messages should be issued.

**int `ARKStepSetMaxNumSteps`**(void \*arkode\_mem, long int mxsteps)

Specifies the maximum number of steps to be taken by the solver in its attempt to reach the next output time, before ARKStep will return with an error.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *mxsteps* – maximum allowed number of internal steps.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Passing *mxsteps* = 0 results in ARKStep using the default value (500).

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

**int `ARKStepSetMaxStep`**(void \*arkode\_mem, *realtype* hmax)

Specifies the upper bound on the magnitude of the time step size.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *hmax* – maximum absolute value of the time step size ( $\geq 0$ ).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Pass *hmax*  $\leq 0.0$  to set the default value of  $\infty$ .

**int `ARKStepSetMinStep`**(void \*arkode\_mem, *realtype* hmin)

Specifies the lower bound on the magnitude of the time step size.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.

- $hmin$  – minimum absolute value of the time step size ( $\geq 0$ ).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Pass  $hmin \leq 0.0$  to set the default value of 0.

int **ARKStepSetStopTime**(void \*arkode\_mem, *realtype* tstop)

Specifies the value of the independent variable  $t$  past which the solution is not to proceed.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *tstop* – stopping time for the integrator.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The default is that no stop time is imposed.

int **ARKStepSetUserData**(void \*arkode\_mem, void \*user\_data)

Specifies the user data block *user\_data* and attaches it to the main ARKStep memory block.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *user\_data* – pointer to the user data.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** If specified, the pointer to *user\_data* is passed to all user-supplied functions for which it is an argument; otherwise NULL is passed.

If *user\_data* is needed in user preconditioner functions, the call to this function must be made *before* any calls to *ARKStepSetLinearSolver()* and/or *ARKStepSetMassLinearSolver()*.

int **ARKStepSetMaxErrTestFails**(void \*arkode\_mem, int maxnef)

Specifies the maximum number of error test failures permitted in attempting one step, before returning with an error.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *maxnef* – maximum allowed number of error test failures ( $> 0$ ).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL

- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The default value is 7; set  $\text{maxnef} \leq 0$  to specify this default.

**int *ARKStepSetOptimalParams*(void \*arkode\_mem)**

Sets all adaptivity and solver parameters to our “best guess” values for a given integration method type (ERK, DIRK, ARK) and a given method order.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Should only be called after the method order and integration method have been set. The “optimal” values resulted from repeated testing of ARKStep’s solvers on a variety of training problems. However, all problems are different, so these values may not be optimal for all users.

**int *ARKStepSetConstraints*(void \*arkode\_mem, *N\_Vector* constraints)**

Specifies a vector defining inequality constraints for each component of the solution vector  $y$ .

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *constraints* – vector of constraint flags. Each component specifies the type of solution constraint:

$$\text{constraints}[i] = \begin{cases} 0.0 & \Rightarrow \text{no constraint is imposed on } y_i, \\ 1.0 & \Rightarrow y_i \geq 0, \\ -1.0 & \Rightarrow y_i \leq 0, \\ 2.0 & \Rightarrow y_i > 0, \\ -2.0 & \Rightarrow y_i < 0. \end{cases}$$

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if the constraints vector contains illegal values

**Notes:** The presence of a non-NUL 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. A NULL constraints vector will disable constraint checking.

After a call to *ARKStepResize()* inequality constraint checking will be disabled and a call to *ARKStepSetConstraints()* is required to re-enable constraint checking.

Since constraint-handling is performed through cutting time steps that would violate the constraints, it is possible that this feature will cause some problems to fail due to an inability to enforce constraints even at the minimum time step size. Additionally, the features *ARKStepSetConstraints()* and *ARKStepSetFixedStep()* are incompatible, and should not be used simultaneously.

**int *ARKStepSetMaxNumConstrFails*(void \*arkode\_mem, int maxfails)**

Specifies the maximum number of constraint failures in a step before ARKStep will return with an error.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.

- *maxfails* – maximum allowed number of constrain failures.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL

**Notes:** Passing *maxfails*  $\leq 0$  results in ARKStep using the default value (10).

**Optional inputs for IVP method selection**

Optional input	Function name	Default
Set integrator method order	<a href="#">ARKStepSetOrder()</a>	4
Specify implicit/explicit problem	<a href="#">ARKStepSetImEx()</a>	SUNTRUE
Specify explicit problem	<a href="#">ARKStepSetExplicit()</a>	SUNFALSE
Specify implicit problem	<a href="#">ARKStepSetImplicit()</a>	SUNFALSE
Set additive RK tables	<a href="#">ARKStepSetTables()</a>	internal
Specify additive RK table numbers	<a href="#">ARKStepSetTableNum()</a>	internal

int **ARKStepSetOrder**(void \*arkode\_mem, int ord)

Specifies the order of accuracy for the ARK/DIRK/ERK integration method.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *ord* – requested order of accuracy.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** For explicit methods, the allowed values are  $2 \leq ord \leq 8$ . For implicit methods, the allowed values are  $2 \leq ord \leq 5$ , and for ImEx methods the allowed values are  $3 \leq ord \leq 5$ . Any illegal input will result in the default value of 4.

Since *ord* affects the memory requirements for the internal ARKStep memory block, it cannot be changed after the first call to [ARKStepEvolve\(\)](#), unless [ARKStepReInit\(\)](#) is called.

int **ARKStepSetImEx**(void \*arkode\_mem)

Specifies that both the implicit and explicit portions of problem are enabled, and to use an additive Runge–Kutta method.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** This is automatically deduced when neither of the function pointers *fe* or *fi* passed to [ARKStepCreate\(\)](#) are NULL, but may be set directly by the user if desired.

---

`int ARKStepSetExplicit(void *arkode_mem)`

Specifies that the implicit portion of problem is disabled, and to use an explicit RK method.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is *NULL*
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** This is automatically deduced when the function pointer *fi* passed to `ARKStepCreate()` is *NULL*, but may be set directly by the user if desired.

If the problem is posed in explicit form, i.e.  $\dot{y} = f(t, y)$ , then we recommend that the ERKStep time-stepper module be used instead.

`int ARKStepSetImplicit(void *arkode_mem)`

Specifies that the explicit portion of problem is disabled, and to use a diagonally implicit RK method.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is *NULL*
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** This is automatically deduced when the function pointer *fe* passed to `ARKStepCreate()` is *NULL*, but may be set directly by the user if desired.

`int ARKStepSetTables(void *arkode_mem, int q, int p, ARKodeButcherTable Bi, ARKodeButcherTable Be)`

Specifies a customized Butcher table (or pair) for the ERK, DIRK, or ARK method.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *q* – global order of accuracy for the ARK method.
- *p* – global order of accuracy for the embedded ARK method.
- *Bi* – the Butcher table for the implicit RK method.
- *Be* – the Butcher table for the explicit RK method.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is *NULL*
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** For a description of the `ARKodeButcherTable` type and related functions for creating Butcher tables, see §6.

To set an explicit table, *Bi* must be *NULL*. This automatically calls `ARKStepSetExplicit()`. However, if the problem is posed in explicit form, i.e.  $\dot{y} = f(t, y)$ , then we recommend that the ERKStep time-stepper module be used instead of ARKStep.

To set an implicit table,  $Be$  must be NULL. This automatically calls [`ARKStepSetImplicit\(\)`](#).

If both  $Bi$  and  $Be$  are provided, this routine automatically calls [`ARKStepSetImEx\(\)`](#).

When only one table is provided (i.e.,  $Bi$  or  $Be$  is NULL) then the input values of  $q$  and  $p$  are ignored and the global order of the method and embedding (if applicable) are obtained from the Butcher table structures. If both  $Bi$  and  $Be$  are non-NULL (e.g., an ImEx method is provided) then the input values of  $q$  and  $p$  are used as the order of the ARK method may be less than the orders of the individual tables. No error checking is performed to ensure that either  $p$  or  $q$  correctly describe the coefficients that were input.

Error checking is performed on  $Bi$  and  $Be$  (if non-NULL) to ensure that they specify DIRK and ERK methods, respectively.

If the inputs  $Bi$  or  $Be$  do not contain an embedding (when the corresponding explicit or implicit table is non-NULL), the user *must* call [`ARKStepSetFixedStep\(\)`](#) to enable fixed-step mode and set the desired time step size.

**int `ARKStepSetTableNum`(void \*arkode\_mem, `ARKODE_DIRKTableID` itable, `ARKODE_ERKTableID` etable)**

Indicates to use specific built-in Butcher tables for the ERK, DIRK or ARK method.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *itable* – index of the DIRK Butcher table.
- *etable* – index of the ERK Butcher table.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The allowable values for both the *itable* and *etable* arguments corresponding to built-in tables may be found in §14.

To choose an explicit table, set *itable* to a negative value. This automatically calls [`ARKStepSetExplicit\(\)`](#). However, if the problem is posed in explicit form, i.e.  $\dot{y} = f(t, y)$ , then we recommend that the ERKStep time-stepper module be used instead of ARKStep.

To select an implicit table, set *etable* to a negative value. This automatically calls [`ARKStepSetImplicit\(\)`](#).

If both *itable* and *etable* are non-negative, then these should match an existing implicit/explicit pair, listed in §14.3. This automatically calls [`ARKStepSetImEx\(\)`](#).

In all cases, error-checking is performed to ensure that the tables exist.

### Optional inputs for time step adaptivity

The mathematical explanation of ARKODE's time step adaptivity algorithm, including how each of the parameters below is used within the code, is provided in §2.7.

Optional input	Function name	Default
Set a custom time step adaptivity function	<code>ARKStepSetAdaptivityFn()</code>	internal
Choose an existing time step adaptivity method	<code>ARKStepSetAdaptivityMethod()</code>	0
Explicit stability safety factor	<code>ARKStepSetCFLFraction()</code>	0.5
Time step error bias factor	<code>ARKStepsetErrorBias()</code>	1.5
Bounds determining no change in step size	<code>ARKStepSetFixedStepBounds()</code>	1.0 1.5
Maximum step growth factor on convergence fail	<code>ARKStepSetMaxCFailGrowth()</code>	0.25
Maximum step growth factor on error test fail	<code>ARKStepSetMaxEFailGrowth()</code>	0.3
Maximum first step growth factor	<code>ARKStepSetMaxFirstGrowth()</code>	10000.0
Maximum allowed general step growth factor	<code>ARKStepSetMaxGrowth()</code>	20.0
Minimum allowed step reduction factor on error test fail	<code>ARKStepSetMinReduction()</code>	0.1
Time step safety factor	<code>ARKStepSetSafetyFactor()</code>	0.96
Error fails before MaxEFailGrowth takes effect	<code>ARKStepSetSmallNumEFails()</code>	2
Explicit stability function	<code>ARKStepSetStabilityFn()</code>	none

int **ARKStepSetAdaptivityFn**(void \*arkode\_mem, *ARKAdaptFn* hfun, void \*h\_data)

Sets a user-supplied time-step adaptivity function.

#### Arguments:

- *arkode\_mem* – pointer to the ARKStep memory block.
- *hfun* – name of user-supplied adaptivity function.
- *h\_data* – pointer to user data passed to *hfun* every time it is called.

#### Return value:

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** This function should focus on accuracy-based time step estimation; for stability based time steps the function `ARKStepSetStabilityFn()` should be used instead.

int **ARKStepSetAdaptivityMethod**(void \*arkode\_mem, int imethod, int idefault, int pq, *realtype* \*adapt\_params)

Specifies the method (and associated parameters) used for time step adaptivity.

#### Arguments:

- *arkode\_mem* – pointer to the ARKStep memory block.
- *imethod* – accuracy-based adaptivity method choice ( $0 \leq imethod \leq 5$ ): 0 is PID, 1 is PI, 2 is I, 3 is explicit Gustafsson, 4 is implicit Gustafsson, and 5 is the ImEx Gustafsson.
- *idefault* – flag denoting whether to use default adaptivity parameters (1), or that they will be supplied in the *adapt\_params* argument (0).
- *pq* – flag denoting whether to use the embedding order of accuracy *p* (0) or the method order of accuracy *q* (1) within the adaptivity algorithm. *p* is the default.
- *adapt\_params[0]* –  $k_1$  parameter within accuracy-based adaptivity algorithms.
- *adapt\_params[1]* –  $k_2$  parameter within accuracy-based adaptivity algorithms.
- *adapt\_params[2]* –  $k_3$  parameter within accuracy-based adaptivity algorithms.

#### Return value:

- *ARK\_SUCCESS* if successful

- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** If custom parameters are supplied, they will be checked for validity against published stability intervals. If other parameter values are desired, it is recommended to instead provide a custom function through a call to [ARKStepSetAdaptivityFn\(\)](#).

int **ARKStepSetCFLFraction**(void \*arkode\_mem, *realtype* cfl\_frac)

Specifies the fraction of the estimated explicitly stable step to use.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *cfl\_frac* – maximum allowed fraction of explicitly stable step (default is 0.5).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any non-positive parameter will imply a reset to the default value.

int **ARKStepsetErrorBias**(void \*arkode\_mem, *realtype* bias)

Specifies the bias to be applied to the error estimates within accuracy-based adaptivity strategies.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *bias* – bias applied to error in accuracy-based time step estimation (default is 1.5).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any value below 1.0 will imply a reset to the default value.

int **ARKStepSetFixedStepBounds**(void \*arkode\_mem, *realtype* lb, *realtype* ub)

Specifies the step growth interval in which the step size will remain unchanged.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *lb* – lower bound on window to leave step size fixed (default is 1.0).
- *ub* – upper bound on window to leave step size fixed (default is 1.5).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any interval *not* containing 1.0 will imply a reset to the default values.

---

```
int ARKStepSetMaxCFailGrowth(void *arkode_mem, realtype etacf)
```

Specifies the maximum step size growth factor upon an algebraic solver convergence failure on a stage solve within a step,  $\eta_{cf}$  from §2.10.3.1.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *etacf* – time step reduction factor on a nonlinear solver convergence failure (default is 0.25).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any value outside the interval (0, 1] will imply a reset to the default value.

```
int ARKStepSetMaxEfailGrowth(void *arkode_mem, realtype etamxf)
```

Specifies the maximum step size growth factor upon multiple successive accuracy-based error failures in the solver.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *etamxf* – time step reduction factor on multiple error fails (default is 0.3).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any value outside the interval (0, 1] will imply a reset to the default value.

```
int ARKStepSetMaxFirstGrowth(void *arkode_mem, realtype etamx1)
```

Specifies the maximum allowed growth factor in step size following the very first integration step.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *etamx1* – maximum allowed growth factor after the first time step (default is 10000.0).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any value  $\leq 1.0$  will imply a reset to the default value.

```
int ARKStepSetMaxGrowth(void *arkode_mem, realtype mx_growth)
```

Specifies the maximum allowed growth factor in step size between consecutive steps in the integration process.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *mx\_growth* – maximum allowed growth factor between consecutive time steps (default is 20.0).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any value  $\leq 1.0$  will imply a reset to the default value.

**int *ARKStepSetMinReduction*(void \*arkode\_mem, *realtyp* eta\_min)**

Specifies the minimum allowed reduction factor in step size between step attempts, resulting from a temporal error failure in the integration process.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *eta\_min* – minimum allowed reduction factor in time step after an error test failure (default is 0.1).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any value outside the interval (0, 1) will imply a reset to the default value.

**int *ARKStepSetSafetyFactor*(void \*arkode\_mem, *realtyp* safety)**

Specifies the safety factor to be applied to the accuracy-based estimated step.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *safety* – safety factor applied to accuracy-based time step (default is 0.96).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any value  $\leq 0$  will imply a reset to the default value.

**int *ARKStepSetSmallNumEfails*(void \*arkode\_mem, int small\_nef)**

Specifies the threshold for “multiple” successive error failures before the *etamxf* parameter from *ARKStepSetMaxEfailGrowth()* is applied.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *small\_nef* – bound to determine ‘multiple’ for *etamxf* (default is 2).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any value  $\leq 0$  will imply a reset to the default value.

**int *ARKStepSetStabilityFn*(void \*arkode\_mem, *ARKExpStabFn* EStab, void \*estab\_data)**

Sets the problem-dependent function to estimate a stable time step size for the explicit portion of the ODE system.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *EStab* – name of user-supplied stability function.
- *estab\_data* – pointer to user data passed to *EStab* every time it is called.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is **NULL**
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** This function should return an estimate of the absolute value of the maximum stable time step for the explicit portion of the ODE system. It is not required, since accuracy-based adaptivity may be sufficient for retaining stability, but this can be quite useful for problems where the explicit right-hand side function  $f^E(t, y)$  contains stiff terms.

**Optional inputs for implicit stage solves**

The mathematical explanation for the nonlinear solver strategies used by ARKStep, including how each of the parameters below is used within the code, is provided in §2.10.1.

Optional input	Function name	Default
Specify that $f^I$ is linearly implicit	<a href="#">ARKStepSetLinear()</a>	SUNFALSE
Specify that $f^I$ is nonlinearly implicit	<a href="#">ARKStepSetNonlinear()</a>	SUNTRUE
Implicit predictor method	<a href="#">ARKStepSetPredictorMethod()</a>	0
User-provided implicit stage predictor	<a href="#">ARKStepSetStagePredictFn()</a>	NULL
RHS function for nonlinear system evaluations	<a href="#">ARKStepSetNlRhsFn()</a>	NULL
Maximum number of nonlinear iterations	<a href="#">ARKStepSetMaxNonlinIters()</a>	3
Coefficient in the nonlinear convergence test	<a href="#">ARKStepSetNonlinConvCoef()</a>	0.1
Nonlinear convergence rate constant	<a href="#">ARKStepSetNonlinCRDown()</a>	0.3
Nonlinear residual divergence ratio	<a href="#">ARKStepSetNonlinRDiv()</a>	2.3
Maximum number of convergence failures	<a href="#">ARKStepSetMaxConvFails()</a>	10

int **ARKStepSetLinear**(void \*arkode\_mem, int timedepend)

Specifies that the implicit portion of the problem is linear.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *timedepend* – flag denoting whether the Jacobian of  $f^I(t, y)$  is time-dependent (1) or not (0).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is **NULL**
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Tightens the linear solver tolerances and takes only a single Newton iteration. Calls [ARKStepSetDeltaGammaMax\(\)](#) to enforce Jacobian recomputation when the step size ratio changes by more than 100 times the unit roundoff (since nonlinear convergence is not tested). Only applicable when used in combination with the modified or inexact Newton iteration (not the fixed-point solver).

When  $f^I(t, y)$  is time-dependent, all linear solver structures (Jacobian, preconditioner) will be updated preceding *each* implicit stage. Thus one must balance the relative costs of such recomputation against the benefits of requiring only a single Newton linear solve.

**int `ARKStepSetNonlinear`(void \*arkode\_mem)**  
Specifies that the implicit portion of the problem is nonlinear.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** This is the default behavior of ARKStep, so the function is primarily useful to undo a previous call to `ARKStepSetLinear()`. Calls `ARKStepSetDeltaGammaMax()` to reset the step size ratio threshold to the default value.

**int `ARKStepSetPredictorMethod`(void \*arkode\_mem, int method)**  
Specifies the method from §2.10.5 to use for predicting implicit solutions.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *method* – method choice ( $0 \leq method \leq 4$ ):
  - 0 is the trivial predictor,
  - 1 is the maximum order (dense output) predictor,
  - 2 is the variable order predictor, that decreases the polynomial degree for more distant RK stages,
  - 3 is the cutoff order predictor, that uses the maximum order for early RK stages, and a first-order predictor for distant RK stages,
  - 4 is the bootstrap predictor, that uses a second-order predictor based on only information within the current step. **deprecated**
  - 5 is the minimum correction predictor, that uses all preceding stage information within the current step for prediction. **deprecated**

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The default value is 0. If *method* is set to an undefined value, this default predictor will be used.

Options 4 and 5 are currently not supported when solving a problem involving a non-identity mass matrix. In that case, selection of *method* as 4 or 5 will instead default to the trivial predictor (*method* 0). **Both of these options have been deprecated, and will be removed from a future release.**

**int `ARKStepSetStagePredictFn`(void \*arkode\_mem, *ARKStagePredictFn* PredictStage)**  
Sets the user-supplied function to update the implicit stage predictor prior to execution of the nonlinear or linear solver algorithms that compute the implicit stage solution.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *PredictStage* – name of user-supplied predictor function. If NULL, then any previously-provided stage prediction function will be disabled.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL

**Notes:** See §5.5.7 for more information on this user-supplied routine.

**int *ARKStepSetNlsRhsFn*(void \*arkode\_mem, *ARKRhsFn* nls\_fi)**

Specifies an alternative implicit right-hand side function for evaluating  $f^I(t, y)$  within nonlinear system function evaluations (2.22) - (2.24).

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nls\_fi* – the alternative C function for computing the right-hand side function  $f^I(t, y)$  in the ODE.

**Return value:**

- *ARK\_SUCCESS* if successful.
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL.

**Notes:** The default is to use the implicit right-hand side function provided to *ARKStepCreate()* in nonlinear system functions. If the input implicit right-hand side function is NULL, the default is used.

When using a non-default nonlinear solver, this function must be called *after ARKStepSetNonlinear-Solver()*.

**int *ARKStepSetMaxNonlinIters*(void \*arkode\_mem, int maxcor)**

Specifies the maximum number of nonlinear solver iterations permitted per implicit stage solve within each time step.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *maxcor* – maximum allowed solver iterations per stage ( $> 0$ ).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value or if the SUNNONLINSOL module is NULL
- *ARK\_NLS\_OP\_ERR* if the SUNNONLINSOL object returned a failure flag

**Notes:** The default value is 3; set *maxcor*  $\leq 0$  to specify this default.

**int *ARKStepSetNonlinConvCoef*(void \*arkode\_mem, *realtype* nlscoef)**

Specifies the safety factor  $\epsilon$  used within the nonlinear solver convergence test (2.35).

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nlscoef* – coefficient in nonlinear solver convergence test ( $> 0.0$ ).

**Return value:**

- *ARK\_SUCCESS* if successful

- *ARK\_MEM\_NULL* if the ARKStep memory is **NULL**
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The default value is 0.1; set  $nlscoef \leq 0$  to specify this default.

int **ARKStepSetNonlinCRDown**(void \*arkode\_mem, *realtype* crdown)

Specifies the constant  $c_r$  used in estimating the nonlinear solver convergence rate (2.34).

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *crdown* – nonlinear convergence rate estimation constant (default is 0.3).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is **NULL**
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any non-positive parameter will imply a reset to the default value.

int **ARKStepSetNonlinRDiv**(void \*arkode\_mem, *realtype* rdiv)

Specifies the nonlinear correction threshold  $r_{div}$  from (2.36), beyond which the iteration will be declared divergent.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *rdiv* – tolerance on nonlinear correction size ratio to declare divergence (default is 2.3).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is **NULL**
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any non-positive parameter will imply a reset to the default value.

int **ARKStepSetMaxConvFails**(void \*arkode\_mem, int maxncf)

Specifies the maximum number of nonlinear solver convergence failures permitted during one step,  $max_{ncf}$  from §2.10.3.1, before ARKStep will return with an error.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *maxncf* – maximum allowed nonlinear solver convergence failures per step ( $> 0$ ).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is **NULL**
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The default value is 10; set  $max_{ncf} \leq 0$  to specify this default.

Upon each convergence failure, ARKStep will first call the Jacobian setup routine and try again (if a Newton method is used). If a convergence failure still occurs, the time step size is reduced by the factor *etacf* (set within *ARKStepSetMaxCFailGrowth()*).

## Linear solver interface optional input functions

The mathematical explanation of the linear solver methods available to ARKStep is provided in §2.10.2. We group the user-callable routines into four categories: general routines concerning the update frequency for matrices and/or preconditioners, 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.

### Optional inputs for the ARKLS linear solver interface

As discussed in §2.10.2.3, ARKODE strives to reuse matrix and preconditioner data for as many solves as possible to amortize the high costs of matrix construction and factorization. To that end, ARKStep provides user-callable routines to modify this behavior. Recall that the Newton system matrices that arise within an implicit stage solve are  $\mathcal{A}(t, z) \approx M(t) - \gamma J(t, z)$ , where the implicit right-hand side function has Jacobian matrix  $J(t, z) = \frac{\partial f^T(t, z)}{\partial z}$ .

The matrix or preconditioner for  $\mathcal{A}$  can only be updated within a call to the linear solver “setup” routine. In general, the frequency with which the linear solver setup routine is called may be controlled with the *msbp* argument to [ARKStepSetLSetupFrequency\(\)](#). When this occurs, the validity of  $\mathcal{A}$  for successive time steps intimately depends on whether the corresponding  $\gamma$  and  $J$  inputs remain valid.

At each call to the linear solver setup routine the decision to update  $\mathcal{A}$  with a new value of  $\gamma$ , and to reuse or reevaluate Jacobian information, depends on several factors including:

- the success or failure of previous solve attempts,
- the success or failure of the previous time step attempts,
- the change in  $\gamma$  from the value used when constructing  $\mathcal{A}$ , and
- the number of steps since Jacobian information was last evaluated.

The frequency with which to update Jacobian information can be controlled with the *msbj* argument to [ARKStepSetJacEvalFrequency\(\)](#). We note that this is only checked *within* calls to the linear solver setup routine, so values *msbj* < *msbp* do not make sense. For linear-solvers with user-supplied preconditioning the above factors are used to determine whether to recommend updating the Jacobian information in the preconditioner (i.e., whether to set *jok* to SUNFALSE in calling the user-supplied [ARKLsPrecSetupFn\(\)](#)). For matrix-based linear solvers these factors determine whether the matrix  $J(t, y) = \frac{\partial f^T(t, y)}{\partial y}$  should be updated (either with an internal finite difference approximation or a call to the user-supplied [ARKLsJacFn\(\)](#)); if not then the previous value is reused and the system matrix  $\mathcal{A}(t, y) \approx M(t) - \gamma J(t, y)$  is recomputed using the current  $\gamma$  value.

Table 5.1: Optional inputs for the ARKLS linear solver interface

Optional input	Function name	Default
Max change in step signaling new $J$	<a href="#">ARKStepSetDeltaGammaMax()</a>	0.2
Linear solver setup frequency	<a href="#">ARKStepSetLSetupFrequency()</a>	20
Jacobian / preconditioner update frequency	<a href="#">ARKStepSetJacEvalFrequency()</a>	51

int [ARKStepSetDeltaGammaMax](#)(void \*arkode\_mem, *realtype* dgmax)

Specifies a scaled step size ratio tolerance,  $\Delta\gamma_{max}$  from §2.10.2.3, beyond which the linear solver setup routine will be signaled.

#### Arguments:

- *arkode\_mem* – pointer to the ARKStep memory block.
- *dgmax* – tolerance on step size ratio change before calling linear solver setup routine (default is 0.2).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any non-positive parameter will imply a reset to the default value.

**int *ARKStepSetLSetupFrequency*(void \*arkode\_mem, int msbp)**

Specifies the frequency of calls to the linear solver setup routine, *msbp* from §2.10.2.3.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *msbp* – the linear solver setup frequency.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL

**Notes:** Positive values of **msbp** specify the linear solver setup frequency. For example, an input of 1 means the setup function will be called every time step while an input of 2 means it will be called every other time step. If **msbp** is 0, the default value of 20 will be used. A negative value forces a linear solver step at each implicit stage.

**int *ARKStepSetJacEvalFrequency*(void \*arkode\_mem, long int msbj)**

Specifies the frequency for recomputing the Jacobian or recommending a preconditioner update, *msbj* from §2.10.2.3.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *msbj* – the Jacobian re-computation or preconditioner update frequency.

**Return value:**

- *ARKLS\_SUCCESS* if successful.
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL.
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL.

**Notes:** The Jacobian update frequency is only checked *within* calls to the linear solver setup routine, as such values of  $msbj < msbp$  will result in recomputing the Jacobian every *msbp* steps. See *ARKStepSetLSetupFrequency()* for setting the linear solver steup frequency *msbp*.

Passing a value  $msbj \leq 0$  indicates to use the default value of 51.

This function must be called *after* the ARKLS system solver interface has been initialized through a call to *ARKStepSetLinearSolver()*.

## Optional inputs for matrix-based SUNLinearSolver modules

Optional input	Function name	Default
Jacobian function	<code>ARKStepSetJacFn()</code>	DQ
Linear system function	<code>ARKStepSetLinSysFn()</code>	internal
Mass matrix function	<code>ARKStepSetMassFn()</code>	none
Enable or disable linear solution scaling	<code>ARKStepSetLinearSolutionScaling()</code>	on

When using matrix-based linear solver modules, the ARKLS solver interface needs a function to compute an approximation to the Jacobian matrix  $J(t, y)$  or the linear system  $\mathcal{A}(t, y) = M(t) - \gamma J(t, y)$ .

For  $J(t, y)$ , the ARKLS interface is packaged with a routine that can approximate  $J$  if the user has selected either the `SUNMATRIX_DENSE` or `SUNMATRIX_BAND` objects. Alternatively, the user can supply a custom Jacobian function of type `ARKLsJacFn()` – this is *required* when the user selects other matrix formats. To specify a user-supplied Jacobian function, ARKStep provides the function `ARKStepSetJacFn()`.

Alternatively, a function of type `ARKLsLinSysFn()` can be provided to evaluate the matrix  $\mathcal{A}(t, y)$ . By default, ARKLS uses an internal linear system function leveraging the SUNMATRIX API to form the matrix  $\mathcal{A}(t, y)$  by combining the matrices  $M(t)$  and  $J(t, y)$ . To specify a user-supplied linear system function instead, ARKStep provides the function `ARKStepSetLinSysFn()`.

If the ODE system involves a non-identity mass matrix,  $M \neq I$ , matrix-based linear solver modules require a function to compute an approximation to the mass matrix  $M(t)$ . There is no default difference quotient approximation (for any matrix type), so this routine must be supplied by the user. This function must be of type `ARKLsMassFn()`, and should be set using the function `ARKStepSetMassFn()`.

In either case ( $J(t, y)$  versus  $\mathcal{A}(t, y)$  is supplied) the matrix information will be updated infrequently to reduce matrix construction and, with direct solvers, factorization costs. As a result the value of  $\gamma$  may not be current and a scaling factor is applied to the solution of the linear system to account for the lagged value of  $\gamma$ . See §9.2.1 for more details. The function `ARKStepSetLinearSolutionScaling()` can be used to disable this scaling when necessary, e.g., when providing a custom linear solver that updates the matrix using the current  $\gamma$  as part of the solve.

The ARKLS interface passes the user data pointer to the Jacobian, linear system, and mass matrix functions. This allows the user to create an arbitrary structure with relevant problem data and access it during the execution of the user-supplied Jacobian, linear system or mass matrix functions, without using global data in the program. The user data pointer may be specified through `ARKStepSetUserData()`.

`int ARKStepSetJacFn(void *arkode_mem, ARKLsJacFn jac)`

Specifies the Jacobian approximation routine to be used for the matrix-based solver with the ARKLS interface.

### Arguments:

- `arkode_mem` – pointer to the ARKStep memory block.
- `jac` – name of user-supplied Jacobian approximation function.

### Return value:

- `ARKLS_SUCCESS` if successful
- `ARKLS_MEM_NULL` if the ARKStep memory was NULL
- `ARKLS_LMEM_NULL` if the linear solver memory was NULL

**Notes:** This routine must be called after the ARKLS linear solver interface has been initialized through a call to `ARKStepSetLinearSolver()`.

By default, ARKLS uses an internal difference quotient function for the `SUNMATRIX_DENSE` and `SUNMATRIX_BAND` modules. If NULL is passed in for `jac`, this default is used. An error will occur if no `jac` is

supplied when using other matrix types.

The function type `ARKLsJacFn()` is described in §5.5.

`int ARKStepSetLinSysFn(void *arkode_mem, ARKLSLinSysFn linsys)`

Specifies the linear system approximation routine to be used for the matrix-based solver with the ARKLS interface.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *linsys* – name of user-supplied linear system approximation function.

**Return value:**

- `ARKLS_SUCCESS` if successful
- `ARKLS_MEM_NULL` if the ARKStep memory was NULL
- `ARKLS_LMEM_NULL` if the linear solver memory was NULL

**Notes:** This routine must be called after the ARKLS linear solver interface has been initialized through a call to `ARKStepSetLinearSolver()`.

By default, ARKLS uses an internal linear system function that leverages the SUNMATRIX API to form the system  $M - \gamma J$ . If NULL is passed in for *linsys*, this default is used.

The function type `ARKLsLinSysFn()` is described in §5.5.

`int ARKStepSetMassFn(void *arkode_mem, ARKLSMassFn mass)`

Specifies the mass matrix approximation routine to be used for the matrix-based solver with the ARKLS interface.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *mass* – name of user-supplied mass matrix approximation function.

**Return value:**

- `ARKLS_SUCCESS` if successful
- `ARKLS_MEM_NULL` if the ARKStep memory was NULL
- `ARKLS_MASSMEM_NULL` if the mass matrix solver memory was NULL
- `ARKLS_ILL_INPUT` if an argument has an illegal value

**Notes:** This routine must be called after the ARKLS mass matrix solver interface has been initialized through a call to `ARKStepSetMassLinearSolver()`.

Since there is no default difference quotient function for mass matrices, *mass* must be non-NUL.

The function type `ARKLsMassFn()` is described in §5.5.

`int ARKStepSetLinearSolutionScaling(void *arkode_mem, booleantype onoff)`

Enables or disables scaling the linear system solution to account for a change in  $\gamma$  in the linear system. For more details see §9.2.1.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *onoff* – flag to enable (SUNTRUE) or disable (SUNFALSE) scaling

**Return value:**

- `ARKLS_SUCCESS` if successful

- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL
- *ARKLS\_ILL\_INPUT* if the attached linear solver is not matrix-based

**Notes:** Linear solution scaling is enabled by default when a matrix-based linear solver is attached.

### Optional inputs for matrix-free SUNLinearSolver modules

Optional input	Function name	Default
<i>Jv</i> functions ( <i>jtimes</i> and <i>jtsetup</i> )	<code>ARKStepSetJacTimes()</code>	DQ, none
<i>Jv</i> DQ rhs function ( <i>jtimesRhsFn</i> )	<code>ARKStepSetJacTimesRhsFn()</code>	fi
<i>Mv</i> functions ( <i>mtimes</i> and <i>mtsetup</i> )	<code>ARKStepSetMassTimes()</code>	none, none

As described in §2.10.2, when solving the Newton linear systems with matrix-free methods, the ARKLS interface requires a *jtimes* function to compute an approximation to the product between the Jacobian matrix  $J(t, y)$  and a vector  $v$ . The user can supply a custom Jacobian-times-vector approximation function, or use the default internal difference quotient function that comes with the ARKLS interface.

A user-defined Jacobian-vector function must be of type *ARKLsJacTimesVecFn* and can be specified through a call to `ARKStepSetJacTimes()` (see §5.5 for specification details). As with the user-supplied preconditioner functions, the evaluation and processing of any Jacobian-related data needed by the user's Jacobian-times-vector function is done in the optional user-supplied function of type *ARKLsJacTimesSetupFn* (see §5.5 for specification details). As with the preconditioner functions, a pointer to the user-defined data structure, *user\_data*, specified through `ARKStepSetUserData()` (or a NULL pointer otherwise) is passed to the Jacobian-times-vector setup and product functions each time they are called.

`int ARKStepSetJacTimes(void *arkode_mem, ARKLsJacTimesSetupFn jtsetup, ARKLsJacTimesVecFn jtimes)`  
Specifies the Jacobian-times-vector setup and product functions.

#### Arguments:

- *arkode\_mem* – pointer to the ARKStep memory block.
- *jtsetup* – user-defined Jacobian-vector setup function. Pass NULL if no setup is necessary.
- *jtimes* – user-defined Jacobian-vector product function.

#### Return value:

- *ARKLS\_SUCCESS* if successful.
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL.
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL.
- *ARKLS\_ILL\_INPUT* if an input has an illegal value.
- *ARKLS\_SUNLS\_FAIL* if an error occurred when setting up the Jacobian-vector product in the SUNLinearSolver object used by the ARKLS interface.

**Notes:** The default is to use an internal finite difference quotient for *jtimes* and to leave out *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 ARKLS system solver interface has been initialized through a call to `ARKStepSetLinearSolver()`.

The function types *ARKLsJacTimesSetupFn* and *ARKLsJacTimesVecFn* are described in §5.5.

When using the internal difference quotient the user may optionally supply an alternative implicit right-hand side function for use in the Jacobian-vector product approximation by calling [ARKStepSetJacTimesRhsFn\(\)](#). The alternative implicit right-hand side function should compute a suitable (and differentiable) approximation to the  $f^I$  function provided to [ARKStepCreate\(\)](#). For example, as done in [23], the alternative function may use lagged values when evaluating a nonlinearity in  $f^I$  to avoid differencing a potentially non-differentiable factor. We note that in many instances this same  $f^I$  routine would also have been desirable for the nonlinear solver, in which case the user should specify this through calls to both [ARKStepSetJacTimesRhsFn\(\)](#) and [ARKStepSetNlsRhsFn\(\)](#).

int **ARKStepSetJacTimesRhsFn**(void \*arkode\_mem, [ARKRhsFn](#) jtimesRhsFn)

Specifies an alternative implicit right-hand side function for use in the internal Jacobian-vector product difference quotient approximation.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *jtimesRhsFn* – the name of the C function (of type [ARKRhsFn\(\)](#)) defining the alternative right-hand side function.

**Return value:**

- *ARKLS\_SUCCESS* if successful.
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL.
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL.
- *ARKLS\_ILL\_INPUT* if an input has an illegal value.

**Notes:** The default is to use the implicit right-hand side function provided to [ARKStepCreate\(\)](#) in the internal difference quotient. If the input implicit right-hand side function is NULL, the default is used.

This function must be called *after* the ARKLS system solver interface has been initialized through a call to [ARKStepSetLinearSolver\(\)](#).

Similarly, if a problem involves a non-identity mass matrix,  $M \neq I$ , then matrix-free solvers require a *mtimes* function to compute an approximation to the product between the mass matrix  $M(t)$  and a vector  $v$ . This function must be user-supplied since there is no default value, it must be of type [ARKLsMassTimesVecFn\(\)](#), and can be specified through a call to the [ARKStepSetMassTimes\(\)](#) routine. Similarly to the user-supplied preconditioner functions, any evaluation and processing of any mass matrix-related data needed by the user's mass-matrix-times-vector function may be done in an optional user-supplied function of type [ARKLsMassTimesSetupFn](#) (see §5.5 for specification details).

int **ARKStepSetMassTimes**(void \*arkode\_mem, [ARKLsMassTimesSetupFn](#) mtsetup, [ARKLsMassTimesVecFn](#) mtimes, void \*mtimes\_data)

Specifies the mass matrix-times-vector setup and product functions.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *mtsetup* – user-defined mass matrix-vector setup function. Pass NULL if no setup is necessary.
- *mtimes* – user-defined mass matrix-vector product function.
- *mtimes\_data* – a pointer to user data, that will be supplied to both the *mtsetup* and *mtimes* functions.

**Return value:**

- *ARKLS\_SUCCESS* if successful.
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL.
- *ARKLS\_MASSMEM\_NULL* if the mass matrix solver memory was NULL.
- *ARKLS\_ILL\_INPUT* if an input has an illegal value.

- `ARKLS_SUNLS_FAIL` if an error occurred when setting up the mass-matrix-vector product in the `SUNLinearSolver` object used by the ARKLS interface.

**Notes:** There is no default finite difference quotient for `mtimes`, so if using the ARKLS mass matrix solver interface with NULL-valued `SUNMATRIX` input `M`, and this routine is called with NULL-valued `mtimes`, an error will occur. A user may specify NULL for `mtsetup`.

This function must be called *after* the ARKLS mass matrix solver interface has been initialized through a call to `ARKStepSetMassLinearSolver()`.

The function types `ARKLsMassTimesSetupFn` and `ARKLsMassTimesVecFn` are described in §5.5.

### Optional inputs for iterative `SUNLinearSolver` modules

Optional input	Function name	Default
Newton preconditioning functions	<code>ARKStepSetPreconditioner()</code>	NULL, NULL
Mass matrix preconditioning functions	<code>ARKStepSetMassPreconditioner()</code>	NULL, NULL
Newton linear and nonlinear tolerance ratio	<code>ARKStepSetEpsLin()</code>	0.05
Mass matrix linear and nonlinear tolerance ratio	<code>ARKStepSetMassEpsLin()</code>	0.05
Newton linear solve tolerance conversion factor	<code>ARKStepSetLSNormFactor()</code>	vector length
Mass matrix linear solve tolerance conversion factor	<code>ARKStepSetMassLSNormFactor()</code>	vector length

As described in §2.10.2, 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 ARKStep using either the function `ARKStepSetPreconditioner()` (for preconditioning the Newton system), or the function `ARKStepSetMassPreconditioner()` (for preconditioning the mass matrix system). The `psetup` function supplied to these routines should handle evaluation and preprocessing of any Jacobian or mass-matrix data needed by the user's preconditioner solve function, `psolve`. The user data pointer received through `ARKStepSetUserData()` (or a pointer to NULL if user data was not specified) is passed to the `psetup` and `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. If preconditioning is supplied for both the Newton and mass matrix linear systems, it is expected that the user will supply different `psetup` and `psolve` function for each.

Also, as described in §2.10.3.2, the ARKLS interface requires that iterative linear solvers stop when the norm of the preconditioned residual satisfies

$$\|r\| \leq \frac{\epsilon_L \epsilon}{10}$$

where the default  $\epsilon_L = 0.05$  may be modified by the user through the `ARKStepSetEpsLin()` function.

```
int ARKStepSetPreconditioner(void *arkode_mem, ARKLsPrecSetupFn psetup, ARKLsPrecSolveFn psolve)
    Specifies the user-supplied preconditioner setup and solve functions.
```

#### Arguments:

- `arkode_mem` – pointer to the ARKStep memory block.
- `psetup` – user defined preconditioner setup function. Pass NULL if no setup is needed.
- `psolve` – user-defined preconditioner solve function.

#### Return value:

- `ARKLS_SUCCESS` if successful.
- `ARKLS_MEM_NULL` if the ARKStep memory was NULL.
- `ARKLS_LMEM_NULL` if the linear solver memory was NULL.

- *ARKLS\_ILL\_INPUT* if an input has an illegal value.
- *ARKLS\_SUNLS\_FAIL* if an error occurred when setting up preconditioning in the SUNLinearSolver object used by the ARKLS interface.

**Notes:** The default is NULL for both arguments (i.e., no preconditioning).

This function must be called *after* the ARKLS system solver interface has been initialized through a call to [ARKStepSetLinearSolver\(\)](#).

Both of the function types [ARKLsPrecSetupFn\(\)](#) and [ARKLsPrecSolveFn\(\)](#) are described in §5.5.

```
int ARKStepSetMassPreconditioner(void *arkode_mem, ARKLsMassPrecSetupFn psetup,  
                                 ARKLsMassPrecSolveFn psolve)
```

Specifies the mass matrix preconditioner setup and solve functions.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *psetup* – user defined preconditioner setup function. Pass NULL if no setup is to be done.
- *psolve* – user-defined preconditioner solve function.

**Return value:**

- *ARKLS\_SUCCESS* if successful.
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL.
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL.
- *ARKLS\_ILL\_INPUT* if an input has an illegal value.
- *ARKLS\_SUNLS\_FAIL* if an error occurred when setting up preconditioning in the SUNLinearSolver object used by the ARKLS interface.

**Notes:** This function must be called *after* the ARKLS mass matrix solver interface has been initialized through a call to [ARKStepSetMassLinearSolver\(\)](#).

The default is NULL for both arguments (i.e. no preconditioning).

Both of the function types [ARKLsMassPrecSetupFn\(\)](#) and [ARKLsMassPrecSolveFn\(\)](#) are described in §5.5.

```
int ARKStepSetEpsLin(void *arkode_mem, realtype eplifac)
```

Specifies the factor  $\epsilon_L$  by which the tolerance on the nonlinear iteration is multiplied to get a tolerance on the linear iteration.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *eplifac* – linear convergence safety factor.

**Return value:**

- *ARKLS\_SUCCESS* if successful.
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL.
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL.
- *ARKLS\_ILL\_INPUT* if an input has an illegal value.

**Notes:** Passing a value  $eplifac \leq 0$  indicates to use the default value of 0.05.

This function must be called *after* the ARKLS system solver interface has been initialized through a call to [ARKStepSetLinearSolver\(\)](#).

int **ARKStepSetMassEpsLin**(void \*arkode\_mem, *realtype* eplifac)

Specifies the factor by which the tolerance on the nonlinear iteration is multiplied to get a tolerance on the mass matrix linear iteration.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *eplifac* – linear convergence safety factor.

**Return value:**

- *ARKLS\_SUCCESS* if successful.
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL.
- *ARKLS\_MASSMEM\_NULL* if the mass matrix solver memory was NULL.
- *ARKLS\_ILL\_INPUT* if an input has an illegal value.

**Notes:** This function must be called *after* the ARKLS mass matrix solver interface has been initialized through a call to [ARKStepSetMassLinearSolver\(\)](#).

Passing a value  $eplifac \leq 0$  indicates to use the default value of 0.05.

Since iterative linear solver libraries typically consider linear residual tolerances using the  $L_2$  norm, whereas ARKODE focuses on errors measured in the WRMS norm (2.14), the ARKLS interface internally converts between these quantities when interfacing with linear solvers,

$$\text{tol}_{L2} = \text{nrmfac} \text{ tol}_{WRMS}. \quad (5.1)$$

Prior to the introduction of [N\\_VGetLength\(\)](#) in SUNDIALS v5.0.0 the value of *nrmfac* was computed using the vector dot product. Now, the functions [ARKStepSetLSNormFactor\(\)](#) and [ARKStepSetMassLSNormFactor\(\)](#) allow for additional user control over these conversion factors.

int **ARKStepSetLSNormFactor**(void \*arkode\_mem, *realtype* nrmfac)

Specifies the factor to use when converting from the integrator tolerance (WRMS norm) to the linear solver tolerance ( $L_2$  norm) for Newton linear system solves.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nrmfac* – the norm conversion factor. If *nrmfac* is:
  - $> 0$  then the provided value is used.
  - $= 0$  then the conversion factor is computed using the vector length i.e., *nrmfac* = `sqrt(N_- VGetLength(y))` (*default*).
  - $< 0$  then the conversion factor is computed using the vector dot product i.e., *nrmfac* = `sqrt(N_- VDotProd(v, v))` where all the entries of *v* are one.

**Return value:**

- *ARK\_SUCCESS* if successful.
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL.

**Notes:** This function must be called *after* the ARKLS system solver interface has been initialized through a call to [ARKStepSetLinearSolver\(\)](#).

int **ARKStepSetMassLSNormFactor**(void \*arkode\_mem, *realtype* nrmfac)

Specifies the factor to use when converting from the integrator tolerance (WRMS norm) to the linear solver tolerance (L2 norm) for mass matrix linear system solves.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nrmfac* – the norm conversion factor. If *nrmfac* is:
  - > 0 then the provided value is used.
  - = 0 then the conversion factor is computed using the vector length i.e., *nrmfac* =  $\sqrt{N - VGetLength(y)}$  (*default*).
  - < 0 then the conversion factor is computed using the vector dot product i.e., *nrmfac* =  $\sqrt{N - VDotProd(v, v)}$  where all the entries of *v* are one.

**Return value:**

- *ARK\_SUCCESS* if successful.
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL.

**Notes:** This function must be called *after* the ARKLS mass matrix solver interface has been initialized through a call to [\*ARKStepSetMassLinearSolver\(\)\*](#).

## Rootfinding optional input functions

The following functions can be called to set optional inputs to control the rootfinding algorithm, the mathematics of which are described in §2.11.

Optional input	Function name	Default
Direction of zero-crossings to monitor	<a href="#"><i>ARKStepSetRootDirection()</i></a>	both
Disable inactive root warnings	<a href="#"><i>ARKStepSetNoInactiveRootWarn()</i></a>	enabled

int **ARKStepSetRootDirection**(void \*arkode\_mem, int \*rootdir)

Specifies the direction of zero-crossings to be located and returned.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *rootdir* – state array of length *nrtfn*, the number of root functions  $g_i$  (the value of *nrtfn* was supplied in the call to [\*ARKStepRootInit\(\)\*](#)). If *rootdir*[*i*] == 0 then crossing in either direction for  $g_i$  should be reported. 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:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The default behavior is to monitor for both zero-crossing directions.

int **ARKStepSetNoInactiveRootWarn**(void \*arkode\_mem)

Disables issuing a warning if some root function appears to be identically zero at the beginning of the integration.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL

**Notes:** ARKStep 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), ARKStep will issue a warning which can be disabled with this optional input function.

### 5.2.2.9 Interpolated output function

An optional function [\*ARKStepGetDky\(\)\*](#) is available to obtain additional values of solution-related quantities. This function should only be called after a successful return from [\*ARKStepEvolve\(\)\*](#), as it provides interpolated values either of  $y$  or of its derivatives (up to the 5th derivative) interpolated to any value of  $t$  in the last internal step taken by [\*ARKStepEvolve\(\)\*](#). Internally, this “dense output” or “continuous extension” algorithm is identical to the algorithm used for the maximum order implicit predictors, described in §2.10.5.2, except that derivatives of the polynomial model may be evaluated upon request.

```
int ARKStepGetDky(void *arkode_mem, realtyp t, int k, N_Vector dky)
```

Computes the  $k$ -th derivative of the function  $y$  at the time  $t$ , i.e.  $y^{(k)}(t)$ , for values of the independent variable satisfying  $t_n - h_n \leq t \leq t_n$ , with  $t_n$  as current internal time reached, and  $h_n$  is the last internal step size successfully used by the solver. This routine uses an interpolating polynomial of degree  $\min(\text{degree}, 5)$ , where *degree* is the argument provided to [\*ARKStepSetInterpolantDegree\(\)\*](#). The user may request *k* in the range  $\{0, \dots, \min(\text{degree}, \text{kmax})\}$  where *kmax* depends on the choice of interpolation module. For Hermite interpolants *kmax* = 5 and for Lagrange interpolants *kmax* = 3.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *t* – the value of the independent variable at which the derivative is to be evaluated.
- *k* – the derivative order requested.
- *dky* – output vector (must be allocated by the user).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_BAD\_K* if *k* is not in the range  $\{0, \dots, \min(\text{degree}, \text{kmax})\}$ .
- *ARK\_BAD\_T* if *t* is not in the interval  $[t_n - h_n, t_n]$
- *ARK\_BAD\_DKY* if the *dky* vector was NULL
- *ARK\_MEM\_NULL* if the ARKStep memory is NULL

**Notes:** It is only legal to call this function after a successful return from [\*ARKStepEvolve\(\)\*](#).

A user may access the values  $t_n$  and  $h_n$  via the functions [\*ARKStepGetCurrentTime\(\)\*](#) and [\*ARKStepGetLastStep\(\)\*](#), respectively.

### 5.2.2.10 Optional output functions

ARKStep provides an extensive set of functions that can be used to obtain solver performance information. We organize these into groups:

1. General ARKStep output routines are in §5.2.2.10,
2. ARKStep implicit solver output routines are in §5.2.2.10,
3. Output routines regarding root-finding results are in §5.2.2.10,
4. Linear solver output routines are in §5.2.2.10 and
5. General usability routines (e.g. to print the current ARKStep parameters, or output the current Butcher table(s)) are in §5.2.2.10.

Following each table, we elaborate on each function.

Some of the optional outputs, especially the various counters, can be very useful in determining the efficiency of various methods inside ARKStep. For example:

- The counters *nsteps*, *nfe\_evals* and *nfi\_evals* provide a rough measure of the overall cost of a given run, and can be compared between runs with different solver options to suggest which set of options is the most efficient.
- The ratio *nniters/nsteps* measures the performance of the nonlinear iteration in solving the nonlinear systems at each stage, providing a measure of the degree of nonlinearity in the problem. Typical values of this for a Newton solver on a general problem range from 1.1 to 1.8.
- When using a Newton nonlinear solver, the ratio *njevals/nniters* (when using a direct linear solver), and the ratio *nliters/nniters* (when using an iterative linear solver) can indicate the quality of the approximate Jacobian or preconditioner being used. For example, if this ratio is larger for a user-supplied Jacobian or Jacobian-vector product routine than for the difference-quotient routine, it can indicate that the user-supplied Jacobian is inaccurate.
- The ratio *expsteps/accsteps* can measure the quality of the ImEx splitting used, since a higher-quality splitting will be dominated by accuracy-limited steps, and hence a lower ratio.
- The ratio *nsteps/step\_attempts* can measure the quality of the time step adaptivity algorithm, since a poor algorithm will result in more failed steps, and hence a lower ratio.

It is therefore recommended that users retrieve and output these statistics following each run, and take some time to investigate alternate solver options that will be more optimal for their particular problem of interest.

## Main solver optional output functions

Optional output	Function name
Size of ARKStep real and integer workspaces	<a href="#">ARKStepGetWorkSpace()</a>
Cumulative number of internal steps	<a href="#">ARKStepGetNumSteps()</a>
Actual initial time step size used	<a href="#">ARKStepGetActualInitStep()</a>
Step size used for the last successful step	<a href="#">ARKStepGetLastStep()</a>
Step size to be attempted on the next step	<a href="#">ARKStepGetCurrentStep()</a>
Current internal time reached by the solver	<a href="#">ARKStepGetCurrentTime()</a>
Current internal solution reached by the solver	<a href="#">ARKStepGetCurrentState()</a>
Current $\gamma$ value used by the solver	<a href="#">ARKStepGetCurrentGamma()</a>
Suggested factor for tolerance scaling	<a href="#">ARKStepGetTolScaleFactor()</a>
Error weight vector for state variables	<a href="#">ARKStepGetErrWeights()</a>
Residual weight vector	<a href="#">ARKStepGetResWeights()</a>
Single accessor to many statistics at once	<a href="#">ARKStepGetStepStats()</a>
Name of constant associated with a return flag	<a href="#">ARKStepGetReturnFlagName()</a>
No. of explicit stability-limited steps	<a href="#">ARKStepGetNumExpSteps()</a>
No. of accuracy-limited steps	<a href="#">ARKStepGetNumAccSteps()</a>
No. of attempted steps	<a href="#">ARKStepGetNumStepAttempts()</a>
No. of calls to <i>fe</i> and <i>fi</i> functions	<a href="#">ARKStepGetNumRhsEvals()</a>
No. of local error test failures that have occurred	<a href="#">ARKStepGetNumErrTestFails()</a>
Current ERK and DIRK Butcher tables	<a href="#">ARKStepGetCurrentButcherTables()</a>
Estimated local truncation error vector	<a href="#">ARKStepGetEstLocalErrors()</a>
Single accessor to many statistics at once	<a href="#">ARKStepGetTimestepperStats()</a>
Number of constraint test failures	<a href="#">ARKStepGetNumConstrFails()</a>

int **ARKStepGetWorkSpace**(void \*arkode\_mem, long int \*lenrw, long int \*leniw)

Returns the ARKStep real and integer workspace sizes.

### Arguments:

- *arkode\_mem* – pointer to the ARKStep memory block.
- *lenrw* – the number of **realtype** values in the ARKStep workspace.
- *leniw* – the number of integer values in the ARKStep workspace.

### Return value:

- **ARK\_SUCCESS** if successful
- **ARK\_MEM\_NULL** if the ARKStep memory was NULL

int **ARKStepGetNumSteps**(void \*arkode\_mem, long int \*nsteps)

Returns the cumulative number of internal steps taken by the solver (so far).

### Arguments:

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nsteps* – number of steps taken in the solver.

### Return value:

- **ARK\_SUCCESS** if successful
- **ARK\_MEM\_NULL** if the ARKStep memory was NULL

int **ARKStepGetActualInitStep**(void \*arkode\_mem, *realtype* \*hinused)

Returns the value of the integration step size used on the first step.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *hinused* – actual value of initial step size.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

**Notes:** Even if the value of the initial integration step was specified by the user through a call to [\*ARKStepSetInitStep\*\(\*O\*\)](#), this value may have been changed by ARKStep to ensure that the step size fell within the prescribed bounds ( $h_{min} \leq h_0 \leq h_{max}$ ), or to satisfy the local error test condition, or to ensure convergence of the nonlinear solver.

int **ARKStepGetLastStep**(void \*arkode\_mem, *realtype* \*hlast)

Returns the integration step size taken on the last successful internal step.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *hlast* – step size taken on the last internal step.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

int **ARKStepGetCurrentStep**(void \*arkode\_mem, *realtype* \*hcur)

Returns the integration step size to be attempted on the next internal step.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *hcur* – step size to be attempted on the next internal step.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

int **ARKStepGetCurrentTime**(void \*arkode\_mem, *realtype* \*tcur)

Returns the current internal time reached by the solver.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *tcur* – current internal time reached.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

int **ARKStepGetCurrentState**(void \*arkode\_mem, *N\_Vector* \*ycur)

Returns the current internal solution reached by the solver.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *ycur* – current internal solution.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

**Notes:** Users should exercise extreme caution when using this function, as altering values of *ycur* may lead to undesirable behavior, depending on the particular use case and on when this routine is called.

int **ARKStepGetCurrentGamma**(void \*arkode\_mem, *realtype* \*gamma)

Returns the current internal value of  $\gamma$  used in the implicit solver Newton matrix (see equation (2.28)).

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *gamma* – current step size scaling factor in the Newton system.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

int **ARKStepGetTolScaleFactor**(void \*arkode\_mem, *realtype* \*tolsfac)

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:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *tolsfac* – suggested scaling factor for user-supplied tolerances.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

int **ARKStepGetErrWeights**(void \*arkode\_mem, *N\_Vector* eweight)

Returns the current error weight vector.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *eweight* – solution error weights at the current time.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

**Notes:** The user must allocate space for *eweight*, that will be filled in by this function.

int **ARKStepGetResWeights**(void \*arkode\_mem, *N\_Vector* rweight)

Returns the current residual weight vector.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *rweight* – residual error weights at the current time.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

**Notes:** The user must allocate space for *rweight*, that will be filled in by this function.

```
int ARKStepGetStepStats(void *arkode_mem, long int *nsteps, realtype *hinused, realtype *hlast, realtype *hcur,  
realtype *tcur)
```

Returns many of the most useful optional outputs in a single call.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nsteps* – number of steps taken in the solver.
- *hinused* – actual value of initial step size.
- *hlast* – step size taken on the last internal step.
- *hcur* – step size to be attempted on the next internal step.
- *tcur* – current internal time reached.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

```
char *ARKStepGetReturnFlagName(long int flag)
```

Returns the name of the ARKStep constant corresponding to *flag*.

**Arguments:**

- *flag* – a return flag from an ARKStep function.

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

```
int ARKStepGetNumExpSteps(void *arkode_mem, long int *expsteps)
```

Returns the cumulative number of stability-limited steps taken by the solver (so far).

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *expsteps* – number of stability-limited steps taken in the solver.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

```
int ARKStepGetNumAccSteps(void *arkode_mem, long int *accsteps)
```

Returns the cumulative number of accuracy-limited steps taken by the solver (so far).

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *accsteps* – number of accuracy-limited steps taken in the solver.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

---

**int ARKStepGetNumStepAttempts**(void \*arkode\_mem, long int \*step\_attempts)

Returns the cumulative number of steps attempted by the solver (so far).

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *step\_attempts* – number of steps attempted by solver.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

**int ARKStepGetNumRhsEvals**(void \*arkode\_mem, long int \*nfe\_evals, long int \*nfi\_evals)

Returns the number of calls to the user's right-hand side functions,  $f^E$  and  $f^I$  (so far).

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nfe\_evals* – number of calls to the user's  $f^E(t, y)$  function.
- *nfi\_evals* – number of calls to the user's  $f^I(t, y)$  function.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

**Notes:** The *nfi\_evals* value does not account for calls made to  $f^I$  by a linear solver or preconditioner module.

**int ARKStepGetNumErrTestFails**(void \*arkode\_mem, long int \*netfails)

Returns the number of local error test failures that have occurred (so far).

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *netfails* – number of error test failures.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

**int ARKStepGetCurrentButcherTables**(void \*arkode\_mem, *ARKodeButcherTable* \**Bi*, *ARKodeButcherTable* \**Be*)

Returns the explicit and implicit Butcher tables currently in use by the solver.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *Bi* – pointer to the implicit Butcher table structure.
- *Be* – pointer to the explicit Butcher table structure.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

**Note:** The *ARKodeButcherTable* data structure is defined as a pointer to the following C structure:

```
typedef struct ARKStepButcherTableMem {  
  
    int q;           /* method order of accuracy */  
    int p;           /* embedding order of accuracy */  
    int stages;     /* number of stages */  
    realtype **A;   /* Butcher table coefficients */  
    realtype *c;    /* canopy node coefficients */  
    realtype *b;    /* root node coefficients */  
    realtype *d;    /* embedding coefficients */  
  
} *ARKStepButcherTable;
```

For more details see §6.

int **ARKStepGetEstLocalErrors**(void \*arkode\_mem, *N\_Vector* ele)

Returns the vector of estimated local truncation errors for the current step.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *ele* – vector of estimated local truncation errors.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

**Notes:** The user must allocate space for *ele*, that will be filled in by this function.

The *ele* vector, together with the *eweight* vector from *ARKStepGetErrWeights()*, 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 WRMS 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]*.

```
int ARKStepGetTimestepperStats(void *arkode_mem, long int *expsteps, long int *accsteps, long int  
                                *step_attempts, long int *nfe_evals, long int *nfi_evals, long int *nlinsetups,  
                                long int *netfails)
```

Returns many of the most useful time-stepper statistics in a single call.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *expsteps* – number of stability-limited steps taken in the solver.
- *accsteps* – number of accuracy-limited steps taken in the solver.
- *step\_attempts* – number of steps attempted by the solver.
- *nfe\_evals* – number of calls to the user's  $f^E(t, y)$  function.
- *nfi\_evals* – number of calls to the user's  $f^I(t, y)$  function.
- *nlinsetups* – number of linear solver setup calls made.
- *netfails* – number of error test failures.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

**int *ARKStepGetNumConstrFails*(void \*arkode\_mem, long int \*nconstrfails)**  
Returns the cumulative number of constraint test failures (so far).

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nconstrfails* – number of constraint test failures.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

**Implicit solver optional output functions**

Optional output	Function name
No. of calls to linear solver setup function	<i>ARKStepGetNumLinSolvSetups()</i>
No. of nonlinear solver iterations	<i>ARKStepGetNumNonlinSolvIters()</i>
No. of nonlinear solver convergence failures	<i>ARKStepGetNumNonlinSolvConvFails()</i>
Single accessor to all nonlinear solver statistics	<i>ARKStepGetNonlinSolvStats()</i>

**int *ARKStepGetNumLinSolvSetups*(void \*arkode\_mem, long int \*nlinsetups)**  
Returns the number of calls made to the linear solver’s setup routine (so far).

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nlinsetups* – number of linear solver setup calls made.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

**Note:** This is only accumulated for the “life” of the nonlinear solver object; the counter is reset whenever a new nonlinear solver module is “attached” to ARKStep, or when ARKStep is resized.

**int *ARKStepGetNumNonlinSolvIters*(void \*arkode\_mem, long int \*nniters)**  
Returns the number of nonlinear solver iterations performed (so far).

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nniters* – number of nonlinear iterations performed.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL
- *ARK\_NLS\_OP\_ERR* if the SUNNONLINSOL object returned a failure flag

**Note:** This is only accumulated for the “life” of the nonlinear solver object; the counter is reset whenever a new nonlinear solver module is “attached” to ARKStep, or when ARKStep is resized.

int **ARKStepGetNumNonlinSolvConvFails**(void \*arkode\_mem, long int \*nncfails)

Returns the number of nonlinear solver convergence failures that have occurred (so far).

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nncfails* – number of nonlinear convergence failures.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

**Note:** This is only accumulated for the “life” of the nonlinear solver object; the counter is reset whenever a new nonlinear solver module is “attached” to ARKStep, or when ARKStep is resized.

int **ARKStepGetNonlinSolvStats**(void \*arkode\_mem, long int \*nniters, long int \*nncfails)

Returns all of the nonlinear solver statistics in a single call.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nniters* – number of nonlinear iterations performed.
- *nncfails* – number of nonlinear convergence failures.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL
- *ARK\_NLS\_OP\_ERR* if the SUNNONLINSOL object returned a failure flag

**Note:** This is only accumulated for the “life” of the nonlinear solver object; the counters are reset whenever a new nonlinear solver module is “attached” to ARKStep, or when ARKStep is resized.

## Rootfinding optional output functions

Optional output	Function name
Array showing roots found	<a href="#">ARKStepGetRootInfo()</a>
No. of calls to user root function	<a href="#">ARKStepGetNumGEvals()</a>

int **ARKStepGetRootInfo**(void \*arkode\_mem, int \*rootsfound)

Returns an array showing which functions were found to have a root.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *rootsfound* – array of length *nrtfn* with the indices of the user functions  $g_i$  found to have a root (the value of *nrtfn* was supplied in the call to [ARKStepRootInit\(\)](#)). For  $i = 0 \dots nrtfn-1$ , *rootsfound*[*i*] is nonzero if  $g_i$  has a root, and 0 if not.

**Return value:**

- *ARK\_SUCCESS* if successful

- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

**Notes:** The user must allocate space for *rootsfound* prior to calling this function.

For the components of  $g_i$  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  $g_i$ .

int **ARKStepGetNumGEvals**(void \*arkode\_mem, long int \*ngevals)

Returns the cumulative number of calls made to the user's root function  $g$ .

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *ngevals* – number of calls made to  $g$  so far.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

### Linear solver interface optional output functions

A variety of optional outputs are available from the ARKLS interface, as listed in the following table and elaborated below. We 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) or MLS (for Mass Linear Solver) has been added here (e.g. *lenrwLS*).

Optional output	Function name
Size of real and integer workspaces	<i>ARKStepGetLinWorkSpace()</i>
No. of Jacobian evaluations	<i>ARKStepGetNumJacEvals()</i>
No. of preconditioner evaluations	<i>ARKStepGetNumPrecEvals()</i>
No. of preconditioner solves	<i>ARKStepGetNumPrecSolves()</i>
No. of linear iterations	<i>ARKStepGetNumLinIters()</i>
No. of linear convergence failures	<i>ARKStepGetNumLinConvFails()</i>
No. of Jacobian-vector setup evaluations	<i>ARKStepGetNumJTEvals()</i>
No. of Jacobian-vector product evaluations	<i>ARKStepGetNumJtimesEvals()</i>
No. of $f_i$ calls for finite diff. $J$ or $Jv$ evals.	<i>ARKStepGetNumLinRhsEvals()</i>
Last return from a linear solver function	<i>ARKStepGetLastLinFlag()</i>
Name of constant associated with a return flag	<i>ARKStepGetLinReturnFlagName()</i>
Size of real and integer mass matrix solver workspaces	<i>ARKStepGetMassWorkSpace()</i>
No. of mass matrix solver setups (incl. $M$ evals.)	<i>ARKStepGetNumMassSetups()</i>
No. of mass matrix multiply setups	<i>ARKStepGetNumMassMultSetups()</i>
No. of mass matrix multiplies	<i>ARKStepGetNumMassMult()</i>
No. of mass matrix solves	<i>ARKStepGetNumMassSolves()</i>
No. of mass matrix preconditioner evaluations	<i>ARKStepGetNumMassPrecEvals()</i>
No. of mass matrix preconditioner solves	<i>ARKStepGetNumMassPrecSolves()</i>
No. of mass matrix linear iterations	<i>ARKStepGetNumMassIters()</i>
No. of mass matrix solver convergence failures	<i>ARKStepGetNumMassConvFails()</i>
No. of mass-matrix-vector setup evaluations	<i>ARKStepGetNumMTSetups()</i>
Last return from a mass matrix solver function	<i>ARKStepGetLastMassFlag()</i>

int **ARKStepGetLinWorkSpace**(void \*arkode\_mem, long int \*lenrwLS, long int \*leniwLS)

Returns the real and integer workspace used by the ARKLS linear solver interface.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *lenrwLS* – the number of `realtype` values in the ARKLS workspace.
- *leniwLS* – the number of integer values in the ARKLS workspace.

**Return value:**

- `ARKLS_SUCCESS` if successful
- `ARKLS_MEM_NULL` if the ARKStep memory was `NULL`
- `ARKLS_LMEM_NULL` if the linear solver memory was `NULL`

**Notes:** The workspace requirements reported by this routine correspond only to memory allocated within this interface and to memory allocated by the `SUNLinearSolver` object attached to it. The template Jacobian matrix allocated by the user outside of ARKLS is not included in this report.

In a parallel setting, the above values are global (i.e. summed over all processors).

int **ARKStepGetNumJacEvals**(void \*arkode\_mem, long int \*njevals)

Returns the number of Jacobian evaluations.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *njevals* – number of Jacobian evaluations.

**Return value:**

- `ARKLS_SUCCESS` if successful
- `ARKLS_MEM_NULL` if the ARKStep memory was `NULL`
- `ARKLS_LMEM_NULL` if the linear solver memory was `NULL`

**Note:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new linear solver module is “attached” to ARKStep, or when ARKStep is resized.

int **ARKStepGetNumPrecEvals**(void \*arkode\_mem, long int \*npevals)

Returns the total number of preconditioner evaluations, i.e. the number of calls made to `psetup` with `jok = SUNFALSE` and that returned `*jcurPtr = SUNTRUE`.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *npevals* – the current number of calls to `psetup`.

**Return value:**

- `ARKLS_SUCCESS` if successful
- `ARKLS_MEM_NULL` if the ARKStep memory was `NULL`
- `ARKLS_LMEM_NULL` if the linear solver memory was `NULL`

**Note:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new linear solver module is “attached” to ARKStep, or when ARKStep is resized.

int **ARKStepGetNumPrecSolves**(void \*arkode\_mem, long int \*npsolves)

Returns the number of calls made to the preconditioner solve function, `psolve`.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *npsolves* – the number of calls to `psolve`.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Note:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new linear solver module is “attached” to ARKStep, or when ARKStep is resized.

int **ARKStepGetNumLinIters**(void \*arkode\_mem, long int \*nliters)

Returns the cumulative number of linear iterations.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nliters* – the current number of linear iterations.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Note:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new linear solver module is “attached” to ARKStep, or when ARKStep is resized.

int **ARKStepGetNumLinConvFails**(void \*arkode\_mem, long int \*nlcfails)

Returns the cumulative number of linear convergence failures.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nlcfails* – the current number of linear convergence failures.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Note:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new linear solver module is “attached” to ARKStep, or when ARKStep is resized.

int **ARKStepGetNumJtSetupEvals**(void \*arkode\_mem, long int \*njtsetup)

Returns the cumulative number of calls made to the user-supplied Jacobian-vector setup function, *jtsetup*.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *njtsetup* – the current number of calls to *jtsetup*.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Note:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new linear solver module is “attached” to ARKStep, or when ARKStep is resized.

int **ARKStepGetNumJtimesEvals**(void \*arkode\_mem, long int \*njvevals)

Returns the cumulative number of calls made to the Jacobian-vector product function, *jtimes*.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *njvevals* – the current number of calls to *jtimes*.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Note:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new linear solver module is “attached” to ARKStep, or when ARKStep is resized.

int **ARKStepGetNumLinRhsEvals**(void \*arkode\_mem, long int \*nfevalsLS)

Returns the number of calls to the user-supplied implicit right-hand side function  $f^I$  for finite difference Jacobian or Jacobian-vector product approximation.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nfevalsLS* – the number of calls to the user implicit right-hand side function.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Notes:** The value *nfevalsLS* is incremented only if the default internal difference quotient function is used.

This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new linear solver module is “attached” to ARKStep, or when ARKStep is resized.

int **ARKStepGetLastLinFlag**(void \*arkode\_mem, long int \*lsflag)

Returns the last return value from an ARKLS routine.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *lsflag* – the value of the last return flag from an ARKLS function.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Notes:** If the ARKLS setup function failed 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. For all other failures, *lsflag* is negative.

Otherwise, if the ARKLS setup function failed ([ARKStepEvolve\(\)](#) returned *ARK\_LSETUP\_FAIL*), then *lsflag* will be *SUNLS\_PSET\_FAIL\_UNREC*, *SUNLS\_ASET\_FAIL\_UNREC* or *SUNLS\_PACKAGE\_FAIL\_UNREC*.

If the ARKLS solve function failed ([ARKStepEvolve\(\)](#) returned *ARK\_LSOLVE\_FAIL*), then *lsflag* contains the error return flag from the `SUNLinearSolver` object, which will be one of: *SUNLS\_MEM\_NULL*, indicating that the `SUNLinearSolver` memory is NULL; *SUNLS\_ATIMES\_NULL*, indicating that a matrix-free iterative solver was provided, but is missing a routine for the matrix-vector product approximation, *SUNLS\_ATIMES\_FAIL\_UNREC*, indicating an unrecoverable failure in the *Jv* function; *SUNLS\_PSOLVE\_NULL*, indicating that an iterative linear solver was configured to use preconditioning, but no preconditioner solve routine was provided, *SUNLS\_PSOLVE\_FAIL\_UNREC*, indicating that the preconditioner solve function failed unrecoverably; *SUNLS\_GS\_FAIL*, indicating a failure in the Gram-Schmidt procedure (SPGMR and SPFGMR only); *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.

`char *ARKStepGetLinReturnFlagName(long int lsflag)`  
Returns the name of the ARKLS constant corresponding to *lsflag*.

**Arguments:**

- *lsflag* – a return flag from an ARKLS function.

**Return value:** The return value is a string containing the name of the corresponding constant. If using the `SUNLINSOL_DENSE` or `SUNLINSOL_BAND` modules, then if  $1 \leq lsflag \leq n$  (LU factorization failed), this routine returns “NONE”.

`int ARKStepGetMassWorkSpace(void *arkode_mem, long int *lenrwMLS, long int *leniwMLS)`  
Returns the real and integer workspace used by the ARKLS mass matrix linear solver interface.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *lenrwMLS* – the number of `realtype` values in the ARKLS mass solver workspace.
- *leniwMLS* – the number of integer values in the ARKLS mass solver workspace.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Notes:** The workspace requirements reported by this routine correspond only to memory allocated within this interface and to memory allocated by the `SUNLinearSolver` object attached to it. The template mass matrix allocated by the user outside of ARKLS is not included in this report.

In a parallel setting, the above values are global (i.e. summed over all processors).

`int ARKStepGetNumMassSetups(void *arkode_mem, long int *nmsetups)`  
Returns the number of calls made to the ARKLS mass matrix solver ‘setup’ routine; these include all calls to the user-supplied mass-matrix constructor function.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nmsetups* – number of calls to the mass matrix solver setup routine.

**Return value:**

- *ARKLS\_SUCCESS* if successful

- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Note:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new mass-matrix linear solver module is “attached” to ARKStep, or when ARKStep is resized.

**int ARKStepGetNumMassMultSetups**(void \*arkode\_mem, long int \*nmvsetups)

Returns the number of calls made to the ARKLS mass matrix ‘matvec setup’ (matrix-based solvers) routine.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nmvsetups* – number of calls to the mass matrix matrix-times-vector setup routine.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Note:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new mass-matrix linear solver module is “attached” to ARKStep, or when ARKStep is resized.

**int ARKStepGetNumMassMult**(void \*arkode\_mem, long int \*nmmults)

Returns the number of calls made to the ARKLS mass matrix ‘matvec’ routine (matrix-based solvers) or the user-supplied *mtimes* routine (matrix-free solvers).

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nmmults* – number of calls to the mass matrix solver matrix-times-vector routine.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Note:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new mass-matrix linear solver module is “attached” to ARKStep, or when ARKStep is resized.

**int ARKStepGetNumMassSolves**(void \*arkode\_mem, long int \*nmsolves)

Returns the number of calls made to the ARKLS mass matrix solver ‘solve’ routine.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nmsolves* – number of calls to the mass matrix solver solve routine.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Note:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new mass-matrix linear solver module is “attached” to ARKStep, or when ARKStep is resized.

---

**int ARKStepGetNumMassPrecEvals**(void \*arkode\_mem, long int \*nmpevals)

Returns the total number of mass matrix preconditioner evaluations, i.e. the number of calls made to *psetup*.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nmpevals* – the current number of calls to *psetup*.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Note:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new mass-matrix linear solver module is “attached” to ARKStep, or when ARKStep is resized.

**int ARKStepGetNumMassPrecSolves**(void \*arkode\_mem, long int \*nmpsolves)

Returns the number of calls made to the mass matrix preconditioner solve function, *psolve*.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nmpsolves* – the number of calls to *psolve*.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Note:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new mass-matrix linear solver module is “attached” to ARKStep, or when ARKStep is resized.

**int ARKStepGetNumMassIters**(void \*arkode\_mem, long int \*nmiters)

Returns the cumulative number of mass matrix solver iterations.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nmiters* – the current number of mass matrix solver linear iterations.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Note:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new mass-matrix linear solver module is “attached” to ARKStep, or when ARKStep is resized.

**int ARKStepGetNumMassConvFails**(void \*arkode\_mem, long int \*nmcfails)

Returns the cumulative number of mass matrix solver convergence failures.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nmcfails* – the current number of mass matrix solver convergence failures.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Note:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new mass-matrix linear solver module is “attached” to ARKStep, or when ARKStep is resized.

int **ARKStepGetNumMTSetups**(void \*arkode\_mem, long int \*nmtsetup)

Returns the cumulative number of calls made to the user-supplied mass-matrix-vector product setup function, *mtsetup*.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nmtsetup* – the current number of calls to *mtsetup*.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Note:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new mass-matrix linear solver module is “attached” to ARKStep, or when ARKStep is resized.

int **ARKStepGetLastMassFlag**(void \*arkode\_mem, long int \*mlsflag)

Returns the last return value from an ARKLS mass matrix interface routine.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *mlsflag* – the value of the last return flag from an ARKLS mass matrix solver interface function.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the ARKStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Notes:** The values of *msflag* for each of the various solvers will match those described above for the function *ARKStepGetLastLSFlag()*.

## General usability functions

The following optional routines may be called by a user to inquire about existing solver parameters or write the current Butcher table(s). While neither of these would typically be called during the course of solving an initial value problem, they may be useful for users wishing to better understand ARKStep and/or specific Runge–Kutta methods.

Optional routine	Function name
Output all ARKStep solver parameters	<a href="#">ARKStepWriteParameters()</a>
Output the current Butcher table(s)	<a href="#">ARKStepWriteButcher()</a>

---

**int `ARKStepWriteParameters`(void \*arkode\_mem, FILE \*fp)**  
Outputs all ARKStep solver parameters to the provided file pointer.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *fp* – pointer to use for printing the solver parameters.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

**Notes:** The *fp* argument can be `stdout` or `stderr`, or it may point to a specific file created using `fopen`.

When run in parallel, only one process should set a non-NULL value for this pointer, since parameters for all processes would be identical.

**int `ARKStepWriteButcher`(void \*arkode\_mem, FILE \*fp)**  
Outputs the current Butcher table(s) to the provided file pointer.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *fp* – pointer to use for printing the Butcher table(s).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL

**Notes:** The *fp* argument can be `stdout` or `stderr`, or it may point to a specific file created using `fopen`.

If ARKStep is currently configured to run in purely explicit or purely implicit mode, this will output a single Butcher table; if configured to run an ImEx method then both tables will be output.

When run in parallel, only one process should set a non-NULL value for this pointer, since tables for all processes would be identical.

### 5.2.2.11 ARKStep re-initialization function

To reinitialize the ARKStep module for the solution of a new problem, where a prior call to `ARKStepCreate()` has been made, the user must call the function `ARKStepReInit()`. The new problem must have the same size as the previous one. This routine retains the current settings for all ARKstep module options and performs the same input checking and initializations that are done in `ARKStepCreate()`, but it performs no memory allocation as it assumes that the existing internal memory is sufficient for the new problem. A call to this re-initialization routine deletes the solution history that was stored internally during the previous integration. Following a successful call to `ARKStepReInit()`, call `ARKStepEvolve()` again for the solution of the new problem.

The use of `ARKStepReInit()` requires that the number of Runge–Kutta stages, denoted by *s*, be no larger for the new problem than for the previous problem. This condition is automatically fulfilled if the method order *q* and the problem type (explicit, implicit, ImEx) are left unchanged.

When using the ARKStep time-stepping module, if there are changes to the linear solver specifications, the user should make the appropriate calls to either the linear solver objects themselves, or to the ARKLS interface routines, as described in §5.2.2.3. Otherwise, all solver inputs set previously remain in effect.

One important use of the `ARKStepReInit()` function is in the treating of jump discontinuities in the RHS functions. 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 ODE model, using a call to `ARKStepReInit()`. 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 RHS functions *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 RHS functions (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.

```
int ARKStepReInit(void *arkode_mem, ARKRhsFn fe, ARKRhsFn fi, realtype t0, N_Vector y0)
```

Provides required problem specifications and re-initializes the ARKStep time-stepper module.

**Arguments:**

- `arkode_mem` – pointer to the ARKStep memory block.
- `fe` – the name of the C function (of type `ARKRhsFn()`) defining the explicit portion of the right-hand side function in  $M \dot{y} = f^E(t, y) + f^I(t, y)$ .
- `fi` – the name of the C function (of type `ARKRhsFn()`) defining the implicit portion of the right-hand side function in  $M \dot{y} = f^E(t, y) + f^I(t, y)$ .
- `t0` – the initial value of  $t$ .
- `y0` – the initial condition vector  $y(t_0)$ .

**Return value:**

- `ARK_SUCCESS` if successful
- `ARK_MEM_NULL` if the ARKStep memory was NULL
- `ARK_MEM_FAIL` if a memory allocation failed
- `ARK_ILL_INPUT` if an argument has an illegal value.

**Notes:** All previously set options are retained but may be updated by calling the appropriate “Set” functions.

If an error occurred, `ARKStepReInit()` also sends an error message to the error handler function.

### 5.2.2.12 ARKStep reset function

To reset the ARKStep module to a particular state  $(t_R, y(t_R))$  for the continued solution of a problem, where a prior call to `ARKStepCreate()` has been made, the user must call the function `ARKStepReset()`. Like `ARKStepReInit()` this routine retains the current settings for all ARKStep module options and performs no memory allocations but, unlike `ARKStepReInit()`, this routine performs only a *subset* of the input checking and initializations that are done in `ARKStepCreate()`. In particular this routine retains all internal counter values and the step size/error history and does not reinitialize the linear and/or nonlinear solver but it does indicate that a linear solver setup is necessary in the next step. Following a successful call to `ARKStepReset()`, call `ARKStepEvolve()` again to continue solving the problem. By default the next call to `ARKStepEvolve()` will use the step size computed by ARKStep prior to calling `ARKStepReset()`. To set a different step size or have ARKStep estimate a new step size use `ARKStepSetInitStep()`.

One important use of the `ARKStepReset()` function is in the treating of jump discontinuities in the RHS functions. 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 ODE model, using a call to `ARKStepReset()`. 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 RHS functions *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 RHS functions (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.

---

```
int ARKStepReset(void *arkode_mem, realtype tR, N_Vector yR)
```

Resets the current ARKStep time-stepper module state to the provided independent variable value and dependent variable vector.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *tR* – the value of the independent variable  $t$ .
- *yR* – the value of the dependent variable vector  $y(t_R)$ .

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ARKStep memory was NULL
- *ARK\_MEM\_FAIL* if a memory allocation failed
- *ARK\_ILL\_INPUT* if an argument has an illegal value.

**Notes:** By default the next call to [ARKStepEvolve\(\)](#) will use the step size computed by ARKStep prior to calling [ARKStepReset\(\)](#). To set a different step size or have ARKStep estimate a new step size use [ARKStepSetInitStep\(\)](#).

All previously set options are retained but may be updated by calling the appropriate “Set” functions.

If an error occurred, [ARKStepReset\(\)](#) also sends an error message to the error handler function.

### 5.2.2.13 ARKStep system resize function

For simulations involving changes to the number of equations and unknowns in the ODE system (e.g. when using spatially-adaptive PDE simulations under a method-of-lines approach), the ARKStep integrator may be “resized” between integration steps, through calls to the [ARKStepResize\(\)](#) function. This function modifies ARKStep’s internal memory structures to use the new problem size, without destruction of the temporal adaptivity heuristics. It is assumed that the dynamical time scales before and after the vector resize will be comparable, so that all time-stepping heuristics prior to calling [ARKStepResize\(\)](#) remain valid after the call. If instead the dynamics should be recomputed from scratch, the ARKStep memory structure should be deleted with a call to [ARKStepFree\(\)](#), and recreated with a call to [ARKStepCreate\(\)](#).

To aid in the vector resize operation, the user can supply a vector resize function that will take as input a vector with the previous size, and transform it in-place to return a corresponding vector of the new size. If this function (of type [ARKVecResizeFn\(\)](#)) is not supplied (i.e., is set to NULL), then all existing vectors internal to ARKStep will be destroyed and re-cloned from the new input vector.

In the case that the dynamical time scale should be modified slightly from the previous time scale, an input *hscale* is allowed, that will rescale the upcoming time step by the specified factor. If a value  $hscale \leq 0$  is specified, the default of 1.0 will be used.

```
int ARKStepResize(void *arkode_mem, N_Vector yR, realtype hscale, realtype tR, ARKVecResizeFn resize, void *resize_data)
```

Re-sizes ARKStep with a different state vector but with comparable dynamical time scale.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *yR* – the newly-sized state vector, holding the current dependent variable values  $y(t_R)$ .
- *hscale* – the desired time step scaling factor (i.e. the next step will be of size  $h*hscale$ ).
- *tR* – the current value of the independent variable  $t_R$  (this must be consistent with *yR*).

- *resize* – the user-supplied vector resize function (of type `ARKVecResizeFn()`).
- *resize\_data* – the user-supplied data structure to be passed to *resize* when modifying internal ARKStep vectors.

**Return value:**

- `ARK_SUCCESS` if successful
- `ARK_MEM_NULL` if the ARKStep memory was NULL
- `ARK_NO_MALLOC` if *arkode\_mem* was not allocated.
- `ARK_ILL_INPUT` if an argument has an illegal value.

**Notes:** If an error occurred, `ARKStepResize()` also sends an error message to the error handler function.

If inequality constraint checking is enabled a call to `ARKStepResize()` will disable constraint checking. A call to `ARKStepSetConstraints()` is required to re-enable constraint checking.

**Resizing the linear solver:** When using any of the SUNDIALS-provided linear solver modules, the linear solver memory structures must also be resized. At present, none of these include a solver-specific “resize” function, so the linear solver memory must be destroyed and re-allocated **following** each call to `ARKStepResize()`. Moreover, the existing ARKLS interface should then be deleted and recreated by attaching the updated SUNLinearSolver (and possibly SUNMatrix) object(s) through calls to `ARKStepSetLinearSolver()`, and `ARKStepSetMassLinearSolver()`.

If any user-supplied routines are provided to aid the linear solver (e.g. Jacobian construction, Jacobian-vector product, mass-matrix-vector product, preconditioning), then the corresponding “set” routines must be called again **following** the solver re-specification.

**Resizing the absolute tolerance array:** If using array-valued absolute tolerances, the absolute tolerance vector will be invalid after the call to `ARKStepResize()`, so the new absolute tolerance vector should be re-set **following** each call to `ARKStepResize()` through a new call to `ARKStepSVtolerances()` and possibly `ARKStepResVtolerance()` if applicable.

If scalar-valued tolerances or a tolerance function was specified through either `ARKStepSStolerances()` or `ARKStepWFtolerances()`, then these will remain valid and no further action is necessary.

**Example codes:**

- `examples/arkode/C_serial/ark_heat1D_adapt.c`

### 5.2.2.14 Interfacing with MRIStep

When using ARKStep as the inner (fast) integrator with MRIStep, the utility function `ARKStepCreateMRIStepInnerStepper()` should be used to wrap an ARKStep memory block as an `MRIStepInnerStepper`.

`int ARKStepCreateMRIStepInnerStepper(void *inner_arkode_mem, MRIStepInnerStepper *stepper)`  
Wraps an ARKStep memory block as an `MRIStepInnerStepper` for use with MRIStep.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *stepper* – the `MRIStepInnerStepper` object.

**Return value:**

- `ARK_SUCCESS` if successful
- `ARK_MEM_FAIL` if a memory allocation failed
- `ARK_ILL_INPUT` if an argument has an illegal value.

**Example usage:**

```

/* fast (inner) and slow (outer) ARKODE objects */
void *inner_arkode_mem = NULL;
void *outer_arkode_mem = NULL;

/* MRIStepInnerStepper to wrap the inner (fast) ARKStep object */
MRIStepInnerStepper stepper = NULL;

/* create an ARKStep object, setting fast (inner) right-hand side
   functions and the initial condition */
inner_arkode_mem = ARKStepCreate(ffe, ffi, t0, y0, sunctx);

/* setup ARKStep */
.

.

/* create MRIStepInnerStepper wrapper for the ARKStep memory block */
flag = ARKStepCreateMRIStepInnerStepper(inner_arkode_mem, &stepper);

/* create an MRIStep object, setting the slow (outer) right-hand side
   functions and the initial condition */
outer_arkode_mem = MRIStepCreate(fse, fsi, t0, y0, stepper, sunctx)

```

**Example codes:**

- examples/arkode/CXX\_parallel/ark\_diffusion\_reaction\_p.cpp

### 5.2.3 Preconditioner modules

The efficiency of Krylov iterative methods for the solution of linear systems can be greatly enhanced through preconditioning. For problems in which the user cannot define a more effective, problem-specific preconditioner, ARKODE provides two internal preconditioner modules that may be used by ARKStep: a banded preconditioner for serial and threaded problems (ARKBANDPRE) and a band-block-diagonal preconditioner for parallel problems (ARKBBDPRE).

#### 5.2.3.1 A serial banded preconditioner module

This preconditioner provides a band matrix preconditioner for use with iterative SUNLINSOL modules in a serial or threaded setting. It requires that the problem be set up using either the NVECTOR\_SERIAL, NVECTOR\_OPENMP or NVECTOR\_PTHREADS module, due to data access patterns. It also currently requires that the problem involve an identity mass matrix, i.e.,  $M = I$ .

This module uses difference quotients of the ODE right-hand side function  $f^I$  to generate a band matrix of bandwidth  $\text{ml} + \text{mu} + 1$ , where the number of super-diagonals ( $\text{mu}$ , the upper half-bandwidth) and sub-diagonals ( $\text{ml}$ , the lower half-bandwidth) are specified by the user. This band matrix is used to form a preconditioner for the Krylov linear solver. Although this matrix is intended to approximate the Jacobian  $J = \frac{\partial f^I}{\partial y}$ , it may be a very crude approximation, since the true Jacobian may not be banded, or its true bandwidth may be larger than  $\text{ml} + \text{mu} + 1$ . However, as long as the banded approximation generated for the preconditioner is sufficiently accurate, it may speed convergence of the Krylov iteration.

## ARKBANDPRE usage

In order to use the ARKBANDPRE module, the user need not define any additional functions. In addition to the header files required for the integration of the ODE problem (see §5.1), to use the ARKBANDPRE module, the user's program must include the header file `arkode_bandpre.h` which declares the needed function prototypes. The following is a summary of the usage of this module. Steps that are unchanged from the skeleton program presented in §5.2.1 are *italicized*.

1. *Initialize multi-threaded environment (if appropriate)*
2. *Set problem dimensions*
3. *Set vector of initial values*
4. *Create ARKStep object*
5. *Specify integration tolerances*
6. Create iterative linear solver object

When creating the iterative linear solver object, specify the type of preconditioning (SUN\_PREC\_LEFT or SUN\_PREC\_RIGHT) to use.

7. *Set linear solver optional inputs*
8. *Attach linear solver module*
9. Initialize the ARKBANDPRE preconditioner module

Specify the upper and lower half-bandwidths (`mu` and `ml`, respectively) and call

```
ier = ARKBandPrecInit(arkode_mem, N, mu, ml);
```

to allocate memory and initialize the internal preconditioner data.

10. *Set optional inputs*

Note that the user should not call `ARKStepSetPreconditioner()` as it will overwrite the preconditioner setup and solve functions.

11. *Create nonlinear solver object*
12. *Attach nonlinear solver module*
13. *Set nonlinear solver optional inputs*
14. *Specify rootfinding problem*
15. *Advance solution in time*
16. Get optional outputs

Additional optional outputs associated with ARKBANDPRE are available by way of the two routines described below, `ARKBandPrecGetWorkSpace()` and `ARKBandPrecGetNumRhsEvals()`.

17. *Deallocate memory for solution vector*
18. *Free solver memory*
19. *Free linear solver memory*

## ARKBANDPRE user-callable functions

The ARKBANDPRE preconditioner module is initialized and attached by calling the following function:

```
int ARKBandPrecInit(void *arkode_mem, sunindextype N, sunindextype mu, sunindextype ml)
```

Initializes the ARKBANDPRE preconditioner and allocates required (internal) memory for it.

### Arguments:

- *arkode\_mem* – pointer to the ARKStep memory block.
- *N* – problem dimension (size of ODE system).
- *mu* – upper half-bandwidth of the Jacobian approximation.
- *ml* – lower half-bandwidth of the Jacobian approximation.

### Return value:

- *ARKLS\_SUCCESS* if no errors occurred
- *ARKLS\_MEM\_NULL* if the ARKStep memory is **NULL**
- *ARKLS\_LMEM\_NULL* if the linear solver memory is **NULL**
- *ARKLS\_ILL\_INPUT* if an input has an illegal value
- *ARKLS\_MEM\_FAIL* if a memory allocation request failed

**Notes:** The banded approximate Jacobian will have nonzero elements only in locations  $(i, j)$  with  $ml \leq j - i \leq mu$ .

The following two optional output functions are available for use with the ARKBANDPRE module:

```
int ARKBandPrecGetWorkSpace(void *arkode_mem, long int *lenrwLS, long int *leniwLS)
```

Returns the sizes of the ARKBANDPRE real and integer workspaces.

### Arguments:

- *arkode\_mem* – pointer to the ARKStep memory block.
- *lenrwLS* – the number of **realtype** values in the ARKBANDPRE workspace.
- *leniwLS* – the number of integer values in the ARKBANDPRE workspace.

### Return value:

- *ARKLS\_SUCCESS* if no errors occurred
- *ARKLS\_MEM\_NULL* if the ARKStep memory is **NULL**
- *ARKLS\_LMEM\_NULL* if the linear solver memory is **NULL**
- *ARKLS\_PMEM\_NULL* if the preconditioner memory is **NULL**

**Notes:** The workspace requirements reported by this routine correspond only to memory allocated within the ARKBANDPRE module (the banded matrix approximation, banded SUNLinearSolver object, and temporary vectors).

The workspaces referred to here exist in addition to those given by the corresponding function **ARKStepGetLSWorkspace()**.

```
int ARKBandPrecGetNumRhsEvals(void *arkode_mem, long int *nfevalsBP)
```

Returns the number of calls made to the user-supplied right-hand side function  $f^I$  for constructing the finite-difference banded Jacobian approximation used within the preconditioner setup function.

### Arguments:

- *arkode\_mem* – pointer to the ARKStep memory block.
- *nfevalsBP* – number of calls to  $f^I$ .

**Return value:**

- *ARKLS\_SUCCESS* if no errors occurred
- *ARKLS\_MEM\_NULL* if the ARKStep memory is NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory is NULL
- *ARKLS\_PMEM\_NULL* if the preconditioner memory is NULL

**Notes:** The counter *nfevalsBP* is distinct from the counter *nfevalsLS* returned by the corresponding function `ARKStepGetNumLSRhsEvals()` and also from *nfi\_evals* returned by `ARKStepGetNumRhsEvals()`. The total number of right-hand side function evaluations is the sum of all three of these counters, plus the *nfe\_evals* counter for  $f^E$  calls returned by `ARKStepGetNumRhsEvals()`.

### 5.2.3.2 A parallel band-block-diagonal preconditioner module

A principal reason for using a parallel ODE solver (such as ARKODE) lies in the solution of partial differential equations (PDEs). Moreover, Krylov iterative methods are used on many such problems due to the nature of the underlying linear system of equations that needs to solved at each time step. For many PDEs, 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 is required. Otherwise, the rate of convergence of the Krylov iterative method is usually slow, and degrades as the PDE mesh is refined. Typically, an effective preconditioner must 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 with CVODE for several realistic, large-scale problems [37]. It is included in a software module within the ARKODE package, and is accessible within the ARKStep time stepping module. This preconditioning module works with the parallel vector module NVECTOR\_PARALLEL and is usable with any of the Krylov iterative linear solvers through the ARKLS interface. It 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 ARKBBDPRE.

One way to envision these preconditioners is to think of the computational PDE domain as being subdivided into  $Q$  non-overlapping subdomains, where each subdomain is assigned to one of the  $Q$  MPI tasks used to solve the ODE system. The basic idea is to isolate the preconditioning so that it is local to each process, and also to use a (possibly cheaper) approximate right-hand side function for construction of this preconditioning matrix. This requires the definition of a new function  $g(t, y) \approx f^I(t, y)$  that will be used to construct the BBD preconditioner matrix. At present, we assume that the ODE be written in explicit form as

$$\dot{y} = f^E(t, y) + f^I(t, y),$$

where  $f^I$  corresponds to the ODE components to be treated implicitly, i.e. this preconditioning module does not support problems with non-identity mass matrices. The user may set  $g = f^I$ , if no less expensive approximation is desired.

Corresponding to the domain decomposition, there is a decomposition of the solution vector  $y$  into  $Q$  disjoint blocks  $y_q$ , and a decomposition of  $g$  into blocks  $g_q$ . The block  $g_q$  depends both on  $y_p$  and on components of blocks  $y_{q'}$  associated with neighboring subdomains (so-called ghost-cell data). If we let  $\bar{y}_q$  denote  $y_q$  augmented with those other components on which  $g_q$  depends, then we have

$$g(t, y) = [g_1(t, \bar{y}_1), g_2(t, \bar{y}_2), \dots, g_Q(t, \bar{y}_Q)]^T,$$

and each of the blocks  $g_q(t, \bar{y}_q)$  is decoupled from one another.

The preconditioner associated with this decomposition has the form

$$P = \begin{bmatrix} P_1 & & & \\ & P_2 & & \\ & & \ddots & \\ & & & P_Q \end{bmatrix}$$

where

$$P_q \approx I - \gamma J_q$$

and where  $J_q$  is a difference quotient approximation to  $\frac{\partial g_q}{\partial \bar{y}_q}$ . This matrix is taken to be banded, with upper and lower half-bandwidths  $mudq$  and  $mldq$  defined as the number of non-zero diagonals above and below the main diagonal, respectively. The difference quotient approximation is computed using  $mudq + mldq + 2$  evaluations of  $g_m$ , but only a matrix of bandwidth  $mukeep + mlkeep + 1$  is retained. Neither pair of parameters need be the true half-bandwidths of the Jacobian of the local block of  $g$ , if smaller values provide a more efficient preconditioner. The solution of the complete linear system

$$Px = b$$

reduces to solving each of the distinct equations

$$P_q x_q = b_q, \quad q = 1, \dots, Q,$$

and this is done by banded LU factorization of  $P_q$  followed by a banded backsolve.

Similar block-diagonal preconditioners could be considered with different treatments of the blocks  $P_q$ . For example, incomplete LU factorization or an iterative method could be used instead of banded LU factorization.

### ARKBBDPRE user-supplied functions

The ARKBBDPRE module calls two user-provided functions to construct  $P$ : a required function *gloc* (of type [ARKLocalFn\(\)](#)) which approximates the right-hand side function  $g(t, y) \approx f^I(t, y)$  and which is computed locally, and an optional function *cfn* (of type [ARKCommFn\(\)](#)) which performs all inter-process communication necessary to evaluate the approximate right-hand side  $g$ . These are in addition to the user-supplied right-hand side function  $f^I$ . Both functions take as input the same pointer *user\_data* that is passed by the user to [ARKStepSetUserData\(\)](#) and that was passed to the user's function  $f^I$ . The user is responsible for providing space (presumably within *user\_data*) for components of  $y$  that are communicated between processes by *cfn*, and that are then used by *gloc*, which should not do any communication.

```
typedef int (*ARKLocalFn)(sunindextype Nlocal, realtype t, N_Vector y, N_Vector glocal, void *user_data)
This gloc function computes g(t,y). It fills the vector glocal as a function of t and y.
```

#### Arguments:

- *Nlocal* – the local vector length.
- *t* – the value of the independent variable.
- *y* – the value of the dependent variable vector on this process.
- *glocal* – the output vector of  $g(t, y)$  on this process.
- *user\_data* – a pointer to user data, the same as the *user\_data* parameter passed to [ARKStepSetUserData\(\)](#).

**Return value:** An *ARKLocalFn* should return 0 if successful, a positive value if a recoverable error occurred (in which case ARKStep will attempt to correct), or a negative value if it failed unrecoverably (in which case the integration is halted and *ARKStepEvolve()* will return *ARK\_LSETUP\_FAIL*).

**Notes:** This function should assume that all inter-process communication of data needed to calculate *glocal* has already been done, and that this data is accessible within user data.

The case where  $g$  is mathematically identical to  $f^I$  is allowed.

```
typedef int (*ARKCommFn)(sunindextype Nlocal, realtype t, N_Vector y, void *user_data)
```

This *cfn* function performs all inter-process communication necessary for the execution of the *gloc* function above, using the input vector *y*.

#### Arguments:

- *Nlocal* – the local vector length.
- *t* – the value of the independent variable.
- *y* – the value of the dependent variable vector on this process.
- *user\_data* – a pointer to user data, the same as the *user\_data* parameter passed to *ARKStepSetUserData()*.

**Return value:** An *ARKCommFn* should return 0 if successful, a positive value if a recoverable error occurred (in which case ARKStep will attempt to correct), or a negative value if it failed unrecoverably (in which case the integration is halted and *ARKStepEvolve()* will return *ARK\_LSETUP\_FAIL*).

**Notes:** The *cfn* function is expected to save communicated data in space defined within the data structure *user\_data*.

Each call to the *cfn* function is preceded by a call to the right-hand side function  $f^I$  with the same  $(t, y)$  arguments. Thus, *cfn* can omit any communication done by  $f^I$  if relevant to the evaluation of *glocal*. If all necessary communication was done in  $f^I$ , then *cfn* = NULL can be passed in the call to *ARKBBDPrecInit()* (see below).

## ARKBBDPRE usage

In addition to the header files required for the integration of the ODE problem (see §5.1), to use the ARKBBDPRE module, the user's program must include the header file `arkode_bbdpre.h` which declares the needed function prototypes.

The following is a summary of the proper usage of this module. Steps that are unchanged from the skeleton program presented in §5.2.1 are *italicized*.

1. *Initialize MPI*
2. *Set problem dimensions*
3. *Set vector of initial values*
4. *Create ARKStep object*
5. *Specify integration tolerances*
6. Create iterative linear solver object

When creating the iterative linear solver object, specify the type of preconditioning (SUN\_PREC\_LEFT or SUN\_PREC\_RIGHT) to use.

7. *Set linear solver optional inputs*
8. *Attach linear solver module*

9. Initialize the ARKBBDPRE preconditioner module

Specify the upper and lower half-bandwidths for computation `mudq` and `mldq`, the upper and lower half-bandwidths for storage `mukeep` and `mlkeep`, and call

```
ier = ARKBBDPrecInit(arkode_mem, Nlocal, mudq, mldq, mukeep, mlkeep, dqrely, gloc,
cfn);
```

to allocate memory and initialize the internal preconditioner data. The last two arguments of `ARKBBDPrecInit()` are the two user-supplied functions of type `ARKLocalFn()` and `ARKCommFn()` described above, respectively.

10. *Set optional inputs*

Note that the user should not call `ARKStepSetPreconditioner()` as it will overwrite the preconditioner setup and solve functions.

11. *Create nonlinear solver object*

12. *Attach nonlinear solver module*

13. *Set nonlinear solver optional inputs*

14. *Specify rootfinding problem*

15. *Advance solution in time*

16. *Get optional outputs*

Additional optional outputs associated with ARKBBDPRE are available through the routines `ARKBBDPrecGetWorkSpace()` and `ARKBBDPrecGetNumGfnEvals()`.

17. *Deallocate memory for solution vector*

18. *Free solver memory*

19. *Free linear solver memory*

20. *Finalize MPI*

## ARKBBDPRE user-callable functions

The ARKBBDPRE preconditioner module is initialized (or re-initialized) and attached to the integrator by calling the following functions:

```
int ARKBBDPrecInit(void *arkode_mem, sunindextype Nlocal, sunindextype mudq, sunindextype mldq,
                    sunindextype mukeep, sunindextype mlkeep, realtype dqrely, ARKLocalFn gloc, ARKCommFn
                    cfn)
```

Initializes and allocates (internal) memory for the ARKBBDPRE preconditioner.

**Arguments:**

- `arkode_mem` – pointer to the ARKStep memory block.
- `Nlocal` – local vector length.
- `mudq` – upper half-bandwidth to be used in the difference quotient Jacobian approximation.
- `mldq` – lower half-bandwidth to be used in the difference quotient Jacobian approximation.
- `mukeep` – upper half-bandwidth of the retained banded approximate Jacobian block.
- `mlkeep` – lower half-bandwidth of the retained banded approximate Jacobian block.

- $dqrely$  – the relative increment in components of  $y$  used in the difference quotient approximations. The default is  $dqrely = \sqrt{\text{unit roundoff}}$ , which can be specified by passing  $dqrely = 0.0$ .
- $gloc$  – the name of the C function (of type `ARKLocalFn()`) which computes the approximation  $g(t, y) \approx f^I(t, y)$ .
- $cfn$  – the name of the C function (of type `ARKCommFn()`) which performs all inter-process communication required for the computation of  $g(t, y)$ .

**Return value:**

- `ARKLS_SUCCESS` if no errors occurred
- `ARKLS_MEM_NULL` if the ARKStep memory is `NULL`
- `ARKLS_LMEM_NULL` if the linear solver memory is `NULL`
- `ARKLS_ILL_INPUT` if an input has an illegal value
- `ARKLS_MEM_FAIL` if a memory allocation request failed

**Notes:** If one of the half-bandwidths  $mudq$  or  $mldq$  to be used in the difference quotient calculation of the approximate Jacobian is negative or exceeds the value  $Nlocal-1$ , it is replaced by 0 or  $Nlocal-1$  accordingly.

The half-bandwidths  $mudq$  and  $mldq$  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  $mukeep$  and  $mlkeep$  of the retained banded approximate Jacobian block may be even smaller than  $mudq$  and  $mldq$ , to reduce storage and computational costs further.

For all four half-bandwidths, the values need not be the same on every processor.

The ARKBBDPRE module also provides a re-initialization function to allow solving a sequence of problems of the same size, with the same linear solver choice, provided there is no change in  $Nlocal$ ,  $mukeep$ , or  $mlkeep$ . After solving one problem, and after calling `ARKStepReInit()` to re-initialize ARKStep for a subsequent problem, a call to `ARKBBDPrecReInit()` can be made to change any of the following: the half-bandwidths  $mudq$  and  $mldq$  used in the difference-quotient Jacobian approximations, the relative increment  $dqrely$ , or one of the user-supplied functions  $gloc$  and  $cfn$ . 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 `ARKStepSet***` functions, must also be made (in the proper order).

```
int ARKBBDPrecReInit(void *arkode_mem, sunindextype mudq, sunindextype mldq, realtype dqrely)
    Re-initializes the ARKBBDPRE preconditioner module.
```

**Arguments:**

- $arkode\_mem$  – pointer to the ARKStep memory block.
- $mudq$  – upper half-bandwidth to be used in the difference quotient Jacobian approximation.
- $mldq$  – lower half-bandwidth to be used in the difference quotient Jacobian approximation.
- $dqrely$  – the relative increment in components of  $y$  used in the difference quotient approximations. The default is  $dqrely = \sqrt{\text{unit roundoff}}$ , which can be specified by passing  $dqrely = 0.0$ .

**Return value:**

- `ARKLS_SUCCESS` if no errors occurred
- `ARKLS_MEM_NULL` if the ARKStep memory is `NULL`
- `ARKLS_LMEM_NULL` if the linear solver memory is `NULL`
- `ARKLS_PMEM_NULL` if the preconditioner memory is `NULL`

**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 ARKBBDPRE module:

```
int ARKBBDPrecGetWorkSpace(void *arkode_mem, long int *lenrwBBDP, long int *leniwBBDP)
    Returns the processor-local ARKBBDPRE real and integer workspace sizes.
```

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *lenrwBBDP* – the number of **realtype** values in the ARKBBDPRE workspace.
- *leniwBBDP* – the number of integer values in the ARKBBDPRE workspace.

**Return value:**

- **ARKLS\_SUCCESS** if no errors occurred
- **ARKLS\_MEM\_NULL** if the ARKStep memory is **NULL**
- **ARKLS\_LMEM\_NULL** if the linear solver memory is **NULL**
- **ARKLS\_PMEM\_NULL** if the preconditioner memory is **NULL**

**Notes:** The workspace requirements reported by this routine correspond only to memory allocated within the ARKBBDPRE module (the banded matrix approximation, banded SUNLinearSolver 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 **ARKStepGetLSSpace()**.

```
int ARKBBDPrecGetNumGfnEvals(void *arkode_mem, long int *ngevalsBBDP)
```

Returns the number of calls made to the user-supplied *gloc* function (of type [ARKLocalFn\(\)](#)) due to the finite difference approximation of the Jacobian blocks used within the preconditioner setup function.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *ngevalsBBDP* – the number of calls made to the user-supplied *gloc* function.

**Return value:**

- **ARKLS\_SUCCESS** if no errors occurred
- **ARKLS\_MEM\_NULL** if the ARKStep memory is **NULL**
- **ARKLS\_LMEM\_NULL** if the linear solver memory is **NULL**
- **ARKLS\_PMEM\_NULL** if the preconditioner memory is **NULL**

In addition to the *ngevalsBBDP* *gloc* evaluations, the costs associated with ARKBBDPRE also include *nlinsetups* LU factorizations, *nlinsetups* calls to *cfn*, *npsolves* banded backsolve calls, and *nfevalsLS* right-hand side function evaluations, where *nlinsetups* is an optional ARKStep output and *npsolves* and *nfevalsLS* are linear solver optional outputs (see the table §5.2.2.10).

## 5.2.4 Multigrid Reduction in Time with XBraid

The prior sections discuss using ARKStep in a traditional sequential time integration setting i.e., the solution is advanced from one time to the next where all parallelism resides within the evaluation of a step e.g., the computation of the right-hand side, (non)linear solves, vector operations etc. For example, when discretizing a partial differential equation using a method of lines approach the spatially-discretized equations comprise a large set of ordinary differential equations that can be evolved with ARKStep. In this case the parallelization lies in decomposing the spatial domain unknowns across distributed computational nodes. Considering the strong scaling case at a given spatial resolution, as the problem is spread across greater numbers of computational nodes scalability in the spatial dimension is exhausted and sequential time integration becomes a bottleneck. This bottleneck is largely driven by the hardware shift from faster clock speeds to greater concurrency to achieve performance gains. In this case, at the spatial scaling limit and with stagnant clock speeds, more time steps will lead to an increased runtime.

An alternative approach to sequential time integration is to solve for all time values simultaneously. One such approach is multigrid reduction in time [24] (MGRIT) which uses a highly parallel iterative method to expose parallelism in the time domain in addition to the spatial parallelization. Starting with an initial temporal grid the multilevel algorithm constructs successively coarser time grids and uses each coarse grid solution to improve the solution at the next finer scale. In the two level case the MGRIT algorithm is as follows:

1. Relax the solution on the fine grid (parallel-in-time)
2. Restrict the solution to the fine grid (time re-discretization).
3. Solve the residual equation on the coarse grid (serial-in-time).
4. Correct the fine grid solution (parallel-in-time).

Applying this algorithm recursively for the solve step above leads to the multilevel algorithm.

The XBraid library [1] implements the MGRIT algorithm in a non-intrusive manner, enabling the reuse of existing software for sequential time integration. The following sections describe the ARKStep + XBraid interface and the steps necessary to modify an existing code that already uses ARKStep to also use XBraid.

### 5.2.4.1 SUNBraid Interface

Interfacing ARKStep with XBraid requires defining two data structures. The first is the XBraid application data structure that contains the data necessary for carrying out a time step and is passed to every interface function (much like the user data pointer in SUNDIALS packages). For this structure the SUNBraid interface defines the generic SUNBraidApp structure described below that serves as the basis for creating integrator-specific or user-defined interfaces to XBraid. The second structure holds the problem state data at a certain time value. This structure is defined by the SUNBraidVector structure and simply contains an N\_Vector. In addition to the two data structures several functions defined by the XBraid API are required. These functions include vector operations (e.g., computing vector sums or norms) as well as functions to initialize the problem state, access the current solution, and take a time step.

The ARKBraid interface, built on the SUNBraidApp and SUNBraidVector structures, provides all the functionality needed combine ARKStep and XBraid for parallel-in-time integration. As such, only a minimal number of changes are necessary to update an exsting code that uses ARKStep to also use XBraid.

## SUNBraidApp

As mentioned above the SUNBraid interface defines the SUNBraidApp structure to hold the data necessary to compute a time step. This structure, like other SUNDIALS generic objects, is defined as a structure consisting of an implementation specific *content* field and an operations structure comprised of a set of function pointers for implementation-defined operations on the object. Specifically the SUNBraidApp type is defined as

```
/* Define XBraid App structure */
struct _braid_App_struct
{
    void        *content;
    SUNBraidOps ops;
};

/* Pointer to the interface object (same as braid_App) */
typedef struct _braid_App_struct *SUNBraidApp;
```

Here, the SUNBraidOps structure is defined as

```
/* Structure containing function pointers to operations */
struct _SUNBraidOps
{
    int (*getvectmpl)(braid_App app, N_Vector *tmpl);
};

/* Pointer to operations structure */
typedef struct _SUNBraidOps *SUNBraidOps;
```

The generic SUNBraidApp defines and implements the generic operations acting on a SUNBraidApp obejct. These generic functions are nothing but wrappers to access the specific implementation through the object's operations structure. To illustrate this point we show below the implementation of the *SUNBraidApp\_GetVecTmp1()* function:

```
/* Get a template vector from the integrator */
int SUNBraidApp_GetVecTmp1(braid_App app, N_Vector *y)
{
    if (app->ops->getvectmpl == NULL) return SUNBRAID_OPNULL;
    return app->ops->getvectmpl(app, y);
}
```

The SUNBraidApp operations are define below in §5.2.4.1.

## SUNBraidOps

In this section we define the SUNBraidApp operations and, for each operation, we give the function signature, a description of the expected behavior, and an example usage of the function.

int **SUNBraidApp\_GetVecTmp1**(braid\_App app, *N\_Vector* \*y)

This function returns a vector to use as a template for creating new vectors with *N\_VClone()*.

### Arguments:

- *app* – input, a SUNBraidApp instance (XBraid app structure).
- *y* – output, the template vector.

**Return value:** If this function is not implemented by the SUNBraidApp implementation (i.e., the function pointer is NULL) then this function will return *SUNBRAID\_OPNULL*. Otherwise the return value depends on the particular SUNBraidApp implementation. Users are encouraged to utilize the return codes defined in `sundials/sundials_xbraid.h` and listed in [Table 5.2](#).

**Usage:**

```
/* Get template vector */
flag = SUNBraidApp_GetVecTmpl(app, y_ptr);
if (flag != SUNBRAID_SUCCESS) return flag;
```

## SUNBraidApp Utility Functions

In addition to the generic SUNBraidApp operations the following utility functions are provided to assist in creating and destroying a SUNBraidApp instance.

`int SUNBraidApp_NewEmpty(braid_App *app)`

This function creates a new SUNBraidApp instance with the content and operations initialized to NULL.

**Arguments:**

- *app* – output, an empty SUNBraidApp instance (XBraid app structure).

**Return value:**

- *SUNBRAID\_SUCCESS* if successful.
- *SUNBRAID\_ALLOCFAIL* if a memory allocation failed.

**Usage:**

```
/* Create empty XBraid interface object */
flag = SUNBraidApp_NewEmpty(app_ptr);
if (flag != SUNBRAID_SUCCESS) return flag;
```

`int SUNBraidApp_FreeEmpty(braid_App *app)`

This function destroys an empty SUNBraidApp instance.

**Arguments:**

- *app* – input, an empty SUNBraidApp instance (XBraid app structure).

**Return value:**

- *SUNBRAID\_SUCCESS* if successful.

**Usage:**

```
/* Free empty XBraid interface object */
flag = SUNBraidApp_FreeEmpty(app_ptr);
```

**Warning:** This function does not free the SUNBraidApp object's content structure. An implementation should free its content before calling `SUNBraidApp_FreeEmpty()` to deallocate the base SUNBraidApp structure.

## SUNBraidVector

As mentioned above the SUNBraid interface defines the SUNBraidVector structure to store a snapshot of solution data at a single point in time and this structure simply contains an N\_Vector. Specifically, the structure is defined as follows:

```
struct _braid_Vector_struct
{
    N_Vector y;
};

/* Poiner to vector wrapper (same as braid_Vector) */
typedef struct _braid_Vector_struct *SUNBraidVector;
```

To assist in creating creating and destroying this structure the following utility functions are provided.

**int SUNBraidVector\_New(N\_Vector y, SUNBraidVector \*u)**  
This function creates a new SUNBraidVector wrapping the N\_Vector y.

**Arguments:**

- *y* – input, the N\_Vector to wrap.
- *u* – output, the SUNBraidVector wrapping *y*.

**Return value:**

- *SUNBRAID\_SUCCESS* if successful.
- *SUNBRAID\_ILLINPUT* if *y* is NULL.
- *SUNBRAID\_ALLOCFAIL* if a memory allocation fails.

**Usage:**

```
/* Create new vector wrapper */
flag = SUNBraidVector_New(y, u_ptr);
if (flag != SUNBRAID_SUCCESS) return flag;
```

**Warning:** The SUNBraidVector takes ownership of the wrapped N\_Vector and as such the wrapped N\_Vector is destroyed when the SUNBraidVector is freed with *SUNBraidVector\_Free()*.

**int SUNBraidVector\_GetNVector(SUNBraidVector u, N\_Vector \*y)**  
This function retrieves the wrapped N\_Vector from the SUNBraidVector.

**Arguments:**

- *u* – input, the SUNBraidVector wrapping *y*.
- *y* – output, the wrapped N\_Vector.

**Return value:**

- *SUNBRAID\_SUCCESS* if successful.
- *SUNBRAID\_ILLINPUT* if *u* is NULL.
- *SUNBRAID\_MEMFAIL* if *y* is NULL.

**Usage:**

```
/* Create new vector wrapper */
flag = SUNBraidVector_GetNVector(u, y_ptr);
if (flag != SUNBRAID_SUCCESS) return flag;
```

Finally, the SUNBraid interface defines the following vector operations acting on SUNBraidVectors, that consist of thin wrappers to compatible SUNDIALS N\_Vector operations.

int **SUNBraidVector\_Clone**(braid\_App app, braid\_Vector u, braid\_Vector \*v\_ptr)

This function creates a clone of the input SUNBraidVector and copies the values of the input vector  $u$  into the output vector  $v\_ptr$  using [N\\_VClone\(\)](#) and [N\\_VScale\(\)](#).

**Arguments:**

- $app$  – input, a SUNBraidApp instance (XBraid app structure).
- $u$  – input, the SUNBraidVector to clone.
- $v\_ptr$  – output, the new SUNBraidVector.

**Return value:**

- *SUNBRAID\_SUCCESS* if successful.
- *SUNBRAID\_ILLINPUT* if  $u$  is NULL.
- *SUNBRAID\_MEMFAIL* if the N\_Vector  $y$  wrapped by  $u$  is NULL.
- *SUNBRAID\_ALLOCFAIL* if a memory allocation fails.

int **SUNBraidVector\_Free**(braid\_App app, braid\_Vector u)

This function destroys the SUNBraidVector and the wrapped N\_Vector using [N\\_VDestroy\(\)](#).

**Arguments:**

- $app$  – input, a SUNBraidApp instance (XBraid app structure).
- $u$  – input, the SUNBraidVector to destroy.

**Return value:**

- *SUNBRAID\_SUCCESS* if successful.

int **SUNBraidVector\_Sum**(braid\_App app, braid\_Real alpha, braid\_Vector x, braid\_Real beta, braid\_Vector y)

This function computes the vector sum  $\alpha x + \beta y \rightarrow y$  using [N\\_VLinearSum\(\)](#).

**Arguments:**

- $app$  – input, a SUNBraidApp instance (XBraid app structure).
- $alpha$  – input, the constant  $\alpha$ .
- $x$  – input, the vector  $x$ .
- $beta$  – input, the constant  $\beta$ .
- $y$  – input/output, the vector  $y$ .

**Return value:**

- *SUNBRAID\_SUCCESS* if successful.
- *SUNBRAID\_ILLINPUT* if  $x$  or  $y$  is NULL.
- *SUNBRAID\_MEMFAIL* if either of the wrapped N\_Vectors are NULL.

int **SUNBraidVector\_SpatialNorm**(braid\_App app, braid\_Vector u, braid\_Real \*norm\_ptr)

This function computes the 2-norm of the vector  $u$  using [N\\_VDotProd\(\)](#).

**Arguments:**

- *app* – input, a SUNBraidApp instance (XBraid app structure).
- *u* – input, the vector *u*.
- *norm\_ptr* – output, the L2 norm of *u*.

**Return value:**

- *SUNBRAID\_SUCCESS* if successful.
- *SUNBRAID\_ILLINPUT* if *u* is NULL.
- *SUNBRAID\_MEMFAIL* if the wrapped N\_Vector is NULL.

`int SUNBraidVector_BufSize(braid_App app, braid_Int *size_ptr, braid_BufferStatus bstatus)`

This function returns the buffer size for messages to exchange vector data using `SUNBraidApp_GetVecTmp()` and `N_VBufSize()`.

**Arguments:**

- *app* – input, a SUNBraidApp instance (XBraid app structure).
- *size\_ptr* – output, the buffer size.
- *bstatus* – input, a status object to query for information on the message type.

**Return value:**

- *SUNBRAID\_SUCCESS* if successful.
- An error flag from `SUNBraidApp_GetVecTmp()` or `N_VBufSize()`.

`int SUNBraidVector_BufPack(braid_App app, braid_Vector u, void *buffer, braid_BufferStatus bstatus)`

This function packs the message buffer for exchanging vector data using `N_VBufPack()`.

**Arguments:**

- *app* – input, a SUNBraidApp instance (XBraid app structure).
- *u* – input, the vector to pack into the exchange buffer.
- *buffer* – output, the packed exchange buffer to pack.
- *bstatus* – input, a status object to query for information on the message type.

**Return value:**

- *SUNBRAID\_SUCCESS* if successful.
- *SUNBRAID\_ILLINPUT* if *u* is NULL.
- An error flag from `N_VBufPack()`.

`int SUNBraidVector_BufUnpack(braid_App app, void *buffer, braid_Vector *u_ptr, braid_BufferStatus bstatus)`

This function unpacks the message buffer and creates a new N\_Vector and SUNBraidVector with the buffer data using `N_VBufUnpack()`, `SUNBraidApp_GetVecTmp()`, and `N_VClone()`.

**Arguments:**

- *app* – input, a SUNBraidApp instance (XBraid app structure).
- *buffer* – input, the exchange buffer to unpack.
- *u\_ptr* – output, a new SUNBraidVector containing the buffer data.
- *bstatus* – input, a status object to query for information on the message type.

**Return value:**

- *SUNBRAID\_SUCCESS* if successful.
- *SUNBRAID\_ILLINPUT* if *buffer* is NULL.
- *SUNBRAID\_ALLOCFAIL* if a memory allocation fails.
- An error flag from *SUNBraidApp\_GetVecTmp()* and *N\_VBufUnpack()*.

## SUNBraid Return Codes

The SUNBraid interface return values are given in [Table 5.2](#).

Table 5.2: SUNBraid Return Codes

Return value name	Value	Meaning
SUNBRAID_SUCCESS	0	The call/operation was successful.
SUNBRAID_ALLOCFAIL	-1	A memory allocation failed.
SUNBRAID_MEMFAIL	-2	A memory access fail.
SUNBRAID_OPNULL	-3	The SUNBraid operation is NULL.
SUNBRAID_ILLINPUT	-4	An invalid input was provided.
SUNBRAID_BRAIDFAIL	-5	An XBraid function failed.
SUNBRAID_SUNFAIL	-6	A SUNDIALS function failed.

### 5.2.4.2 ARKBraid Interface

This section describes the ARKBraid implementation of a SUNBraidApp for using the ARKStep integration module with XBraid. The following section [§5.2.4.2](#) describes routines for creating, initializing, and destroying the ARKStep + XBraid interface, routines for setting optional inputs, and routines for retrieving data from an ARKBraid instance. As noted above, interfacing with XBraid requires providing functions to initialize the problem state, access the current solution, and take a time step. The default ARKBraid functions for each of these actions are defined in [§5.2.4.2](#) and may be overridden by user-defined if desired. A skeleton of the user's main or calling program for using the ARKBraid interface is given in [§5.2.4.3](#). Finally, for advanced users that wish to create their own SUNBraidApp implementation using ARKStep, [§5.2.4.4](#) describes some helpful functions available to the user.

### ARKBraid Initialization and Deallocation Functions

This section describes the functions that are called by the user to create, initialize, and destroy an ARKBraid instance. Each user-callable function returns *SUNBRAID\_SUCCESS* (i.e., 0) on a successful call and a negative value if an error occurred. The possible return codes are given in [Table 5.2](#).

int **ARKBraid\_Create**(void \*arkode\_mem, braid\_App \*app)

This function creates a SUNBraidApp object, sets the content pointer to the private ARKBraid interface structure, and attaches the necessary SUNBraidOps implementations.

#### Arguments:

- *arkode\_mem* – input, a pointer to an ARKStep memory structure.
- *app* – output, an ARKBraid instance (XBraid app structure).

#### Return value:

- *SUNBRAID\_SUCCESS* if successful.
- *SUNBRAID\_ILLINPUT* *arkode\_mem* is NULL.
- *SUNBRAID\_ALLOCFAIL* if a memory allocation failed.

**Warning:** The ARKBraid interface is ARKStep-specific. Although one could eventually construct an XBraid interface to either ERKStep or MRIStep, those are not supported by this implementation.

```
int ARKBraid_BraidInit(MPI_Comm comm_w, MPI_Comm comm_t, realtype tstart, realtype tstop, sunindextype
                      ntime, braid_App app, braid_Core *core)
```

This function wraps the XBraid `braid_Init()` function to create the XBraid core memory structure and initializes XBraid with the ARKBraid and SUNBraidVector interface functions.

**Arguments:**

- *comm\_w* – input, the global MPI communicator for space and time.
- *comm\_t* – input, the MPI communicator for the time dimension.
- *tstart* – input, the initial time value.
- *tstop* – input, the final time value.
- *ntime* – input, the initial number of grid points in time.
- *app* – input, an ARKBraid instance.
- *core* – output, the XBraid core memory structure.

**Return value:**

- *SUNBRAID\_SUCCESS* if successful.
- *SUNBRAID\_ILLINPUT* if either MPI communicator is `MPI_COMM_NULL`, if *ntime* < 2, or if *app* or its content is `NULL`.
- *SUNBRAID\_BRAIDFAIL* if the `braid_Init()` call fails. The XBraid return value can be retrieved with `ARKBraid_GetLastBraidFlag()`.

---

**Note:** If desired, the default functions for vector initialization, accessing the solution, taking a time step, and computing the spatial norm should be overridden before calling this function. See §5.2.4.2 for more details.

---

**Warning:** The user is responsible for deallocating the XBraid core memory structure with the XBraid function `braid_Destroy()`.

```
int ARKBraid_Free(braid_App *app)
```

This function deallocates an ARKBraid instance.

**Arguments:**

- *app* – input, a pointer to an ARKBraid instance.

**Return value:**

- *SUNBRAID\_SUCCESS* if successful.

## ARKBraid Set Functions

This section describes the functions that are called by the user to set optional inputs to control the behavior of an ARKBraid instance or to provide alternative XBraid interface functions. Each user-callable function returns SUNBRAID\_SUCCESS (i.e., 0) on a successful call and a negative value if an error occurred. The possible return codes are given in [Table 5.2](#).

```
int ARKBraid_SetStepFn(braid_App app, braid_PtFcnStep step)
```

This function sets the step function provided to XBraid (default [ARKBraid\\_Step\(\)](#)).

### Arguments:

- *app* – input, an ARKBraid instance.
- *step* – input, an XBraid step function. If *step* is NULL, the default function will be used.

### Return value:

- SUNBRAID\_SUCCESS if successful.
- SUNBRAID\_ILLINPUT if *app* is NULL.
- SUNBRAID\_MEMFAIL if the *app* content is NULL.

---

**Note:** This function must be called prior to [ARKBraid\\_BraidInit\(\)](#).

---

```
int ARKBraid_SetInitFn(braid_App app, braid_PtFcnInit init)
```

This function sets the vector initialization function provided to XBraid (default [ARKBraid\\_Init\(\)](#)).

### Arguments:

- *app* – input, an ARKBraid instance.
- *init* – input, an XBraid vector initialization function. If *init* is NULL, the default function will be used.

### Return value:

- SUNBRAID\_SUCCESS if successful.
- SUNBRAID\_ILLINPUT if *app* is NULL.
- SUNBRAID\_MEMFAIL if the *app* content is NULL.

---

**Note:** This function must be called prior to [ARKBraid\\_BraidInit\(\)](#).

---

```
int ARKBraid_SetSpatialNormFn(braid_App app, braid_PtFcnSpatialNorm snorm)
```

This function sets the spatial norm function provided to XBraid (default SUNBraid\_SpatialNorm()).

### Arguments:

- *app* – input, an ARKBraid instance.
- *snorm* – input, an XBraid spatial norm function. If *snorm* is NULL, the default function will be used.

### Return value:

- SUNBRAID\_SUCCESS if successful.
- SUNBRAID\_ILLINPUT if *app* is NULL.
- SUNBRAID\_MEMFAIL if the *app* content is NULL.

---

**Note:** This function must be called prior to [ARKBraid\\_BraidInit\(\)](#).

---

**int ARKBraid\_SetAccessFn(braid\_App app, braid\_PtFcnAccess access)**

This function sets the user access function provided to XBraid (default [ARKBraid\\_Access\(\)](#)).

**Arguments:**

- *app* – input, an ARKBraid instance.
- *init* – input, an XBraid user access function. If *access* is NULL, the default function will be used.

**Return value:**

- SUNBRAID\_SUCCESS if successful.
- SUNBRAID\_ILLINPUT if *app* is NULL.
- SUNBRAID\_MEMFAIL if the *app* content is NULL.

---

**Note:** This function must be called prior to [ARKBraid\\_BraidInit\(\)](#).

---

## ARKBraid Get Functions

This section describes the functions that are called by the user to retrieve data from an ARKBraid instance. Each user-callable function returns SUNBRAID\_SUCCESS (i.e., 0) on a successful call and a negative value if an error occurred. The possible return codes are given in [Table 5.2](#).

**int ARKBraid\_GetVecTmp1(braid\_App app, *N\_Vector* \*tmpl)**

This function returns a vector from the ARKStep memory to use as a template for creating new vectors with [N\\_VClone\(\)](#) i.e., this is the ARKBraid implementation of [SUNBraidVector\\_GetVecTmp1\(\)](#).

**Arguments:**

- *app* – input, an ARKBraid instance.
- *tmpl* – output, a template vector.

**Return value:**

- SUNBRAID\_SUCCESS if successful.
- SUNBRAID\_ILLINPUT if *app* is NULL.
- SUNBRAID\_MEMFAIL if the *app* content or ARKStep memory is NULL.

**int ARKBraid\_GetARKStepMem(braid\_App app, void \*\*arkode\_mem)**

This function returns the ARKStep memory structure pointer attached with [ARKBraid\\_Create\(\)](#).

**Arguments:**

- *app* – input, an ARKBraid instance.
- *arkode\_mem* – output, a pointer to the ARKStep memory structure.

**Return value:**

- SUNBRAID\_SUCCESS if successful.
- SUNBRAID\_ILLINPUT if *app* is NULL.
- SUNBRAID\_MEMFAIL if the *app* content or ARKStep memory is NULL.

`int ARKBraid_GetUserData(braid_App app, void **user_data)`  
This function returns the user data pointer attached with `ARKStepSetUserData()`.

**Arguments:**

- *app* – input, an ARKBraid instance.
- *user\_data* – output, a pointer to the user data structure.

**Return value:**

- *SUNBRAID\_SUCCESS* if successful.
- *SUNBRAID\_ILLINPUT* if *app* is NULL.
- *SUNBRAID\_MEMFAIL* if the *app* content or ARKStep memory is NULL.

`int ARKBraid_GetLastBraidFlag(braid_App app, int *last_flag)`  
This function returns the return value from the most recent XBraid function call.

**Arguments:**

- *app* – input, an ARKBraid instance.
- *last\_flag* – output, the XBraid return value.

**Return value:**

- *SUNBRAID\_SUCCESS* if successful.
- *SUNBRAID\_ILLINPUT* if *app* is NULL.
- *SUNBRAID\_MEMFAIL* if the *app* content is NULL.

`int ARKBraid_GetLastARKStepFlag(braid_App app, int *last_flag)`  
This function returns the return value from the most recent ARKStep function call.

**Arguments:**

- *app* – input, an ARKBraid instance.
- *last\_flag* – output, the ARKStep return value.

**Return value:**

- *SUNBRAID\_SUCCESS* if successful.
- *SUNBRAID\_ILLINPUT* if *app* is NULL.
- *SUNBRAID\_MEMFAIL* if the *app* content is NULL.

`int ARKBraid_GetSolution(braid_App app, realtype *tout, N_Vector tout)`  
This function returns final time and state stored with the default access function `ARKBraid_Access()`.

**Arguments:**

- *app* – input, an ARKBraid instance.
- *last\_flag* – output, the ARKStep return value.

**Return value:**

- *SUNBRAID\_SUCCESS* if successful.
- *SUNBRAID\_ILLINPUT* if *app* is NULL.
- *SUNBRAID\_MEMFAIL* if the *app* content or the stored vector is NULL.

**Warning:** If providing a non-default access function the final time and state are not stored within the ARKBraid structure and this function will return an error. In this case the user should allocate space to store any desired output within the user data pointer attached to ARKStep with [ARKStepSetUserData\(\)](#). This user data pointer can be retrieved from the ARKBraid structure with [ARKBraid\\_GetUserData\(\)](#).

## ARKBraid Interface Functions

This section describes the default XBraid interface functions provided by ARKBraid and called by XBraid to perform certain actions. Any or all of these functions may be overridden by supplying a user-defined function through the set functions defined in §5.2.4.2. Each default interface function returns SUNBRAID\_SUCCESS (i.e., 0) on a successful call and a negative value if an error occurred. The possible return codes are given in [Table 5.2](#).

```
int ARKBraid_Step(braid_App app, braid_Vector ustop, braid_Vector fstop, braid_Vector u, braid_StepStatus status)
```

This is the default step function provided to XBraid. The step function is called by XBraid to advance the vector  $u$  from one time to the next using the ARKStep memory structure provided to [ARKBraid\\_Create\(\)](#). A user-defined step function may be set with [ARKBraid\\_SetStepFn\(\)](#).

### Arguments:

- $app$  – input, an ARKBraid instance.
- $ustop$  – input,  $u$  vector at the new time  $tstop$ .
- $fstop$  – input, the right-hand side vector at the new time  $tstop$ .
- $u$  - input/output, on input the vector at the start time and on return the vector at the new time.
- $status$  – input, a status object to query for information about  $u$  and to steer XBraid e.g., for temporal refinement.

### Return value:

- SUNBRAID\_SUCCESS if successful.
- SUNBRAID\_ILLINPUT if  $app$  is NULL.
- SUNBRAID\_MEMFAIL if the  $app$  content or ARKStep memory is NULL.
- SUNBRAID\_BRAIDFAIL if an XBraid function fails. The return value can be retrieved with [ARKBraid\\_GetLastBraidFlag\(\)](#).
- SUNBRAID\_SUNFAIL if a SUNDIALS function fails. The return value can be retrieved with [ARKBraid\\_GetLastARKStepFlag\(\)](#).

**Note:** If providing a non-default implementation of the step function the utility function [ARKBraid\\_TakeStep\(\)](#) should be used to advance the input vector  $u$  to the new time.

```
int ARKBraid_Init(braid_App app, realtype t, braid_Vector *u_ptr)
```

This is the default vector initialization function provided to XBraid. The initialization function is called by XBraid to create a new vector and set the initial guess for the solution at time  $t$ . When using this default function the initial guess at all time values is the initial condition provided to [ARKStepCreate\(\)](#). A user-defined init function may be set with [ARKBraid\\_SetInitFn\(\)](#).

### Arguments:

- $app$  – input, an ARKBraid instance.

- $t$  – input, the initialization time for the output vector.
- $u\_ptr$  – output, the new and initialized SUNBraidVector.

**Return value:**

- *SUNBRAID\_SUCCESS* if successful.
- *SUNBRAID\_ILLINPUT* if *app* is NULL.
- *SUNBRAID\_MEMFAIL* if the *app* content or ARKStep memory is NULL.
- *SUNBRAID\_ALLOCFAIL* if a memory allocation failed.

---

**Note:** If providing a non-default implementation of the vector initialization function the utility functions *SUNBraidApp\_GetVecTmp()* and *SUNBraidVector\_New()* can be helpful when creating the new vector returned by this function.

---

```
int ARKBraids_Access(braid_App app, braid_Vector u, braid_AccessStatus astatus)
```

This is the default access function provided to XBraid. The access function is called by XBraid to retrieve the current solution. When using this default function the final solution time and state are stored within the ARKBraids structure. This information can be retrieved with *ARKBraids\_GetSolution()*. A user-defined access function may be set with *ARKBraids\_SetAccessFn()*.

**Arguments:**

- *app* – input, an ARKBraids instance.
- *u* – input, the vector to be accessed.
- *status* – input, a status object to query for information about *u*.

**Return value:**

- *SUNBRAID\_SUCCESS* if successful.
- *SUNBRAID\_ILLINPUT* if any of the inputs are NULL.
- *SUNBRAID\_MEMFAIL* if the *app* content, the wrapped N\_Vector, or the ARKStep memory is NULL.
- *SUNBRAID\_ALLOCFAIL* if allocating storage for the final solution fails.
- *SUNBRAID\_BRAIDFAIL* if an XBraid function fails. The return value can be retrieved with *ARKBraids\_GetLastBraidsFlag()*.

### 5.2.4.3 A skeleton of the user's main program with XBraid

In addition to the header files required for the integration of the ODE problem (see the section §5.1), to use the ARKBraids interface, the user's program must include the header file `arkode/arkode_xbraid.h` which declares the needed function prototypes.

The following is a skeleton of the user's main program (or calling program) for the integration of an ODE IVP using ARKStep with XBraid for parallel-in-time integration. Most steps are unchanged from the skeleton program presented in §5.2.1. New or updated steps are **bold**.

1. **Initialize MPI**

If parallelizing in space and time split the global communicator into communicators for space and time with `braid_SplitCommworld()`.

2. *Set problem dimensions*

3. *Set vector of initial values*

4. *Create ARKStep object*
5. *Specify integration tolerances*
6. *Create matrix object*
7. *Create linear solver object*
8. *Set linear solver optional inputs*
9. *Attach linear solver module*
10. *Create nonlinear solver object*
11. *Attach nonlinear solver module*
12. *Set nonlinear solver optional inputs*
13. *Set optional inputs*

#### 14. **Create ARKBraids interface**

Call the constructor `ARKBraids_Create()` to create the XBraids app structure.

#### 15. **Set optional ARKBraids inputs**

See §5.2.4.2 for ARKBraids inputs.

#### 16. **Initialize the ARKBraids interface**

Call the initialization function `ARKBraids_BraidInit()` to create the XBraids core memory structure and attach the ARKBraids interface app and functions.

#### 17. **Set optional XBraids inputs**

See the XBraids documentation for available XBraids options.

#### 18. **Evolve the problem**

Call `braid_Drive()` to evolve the problem with MGRIT.

#### 19. **Get optional outputs**

See §5.2.4.2 for ARKBraids outputs.

#### 20. *Deallocate memory for solution vector*

#### 21. *Free solver memory*

#### 22. *Free linear solver memory*

#### 23. **Free ARKBraids and XBraids memory**

Call `ARKBraids_Free()` and `braid_Destroy` to deallocate the ARKBraids interface and XBraids core memory structures, respectively.

#### 24. *Finalize MPI*

### 5.2.4.4 Advanced ARKBraid Utility Functions

This section describes utility functions utilized in the ARKStep + XBraid interfacing. These functions are used internally by the above ARKBraid interface functions but are exposed to the user to assist in advanced usage of ARKODE and XBraid that requires defining a custom SUNBraidApp implementation.

```
int ARKBraid_TakeStep(void *arkode_mem, realtype tstart, realtype tstop, N_Vector y, int *ark_flag)
```

This function advances the vector *y* from *tstart* to *tstop* using a single ARKStep time step with step size  $h = tstop - start$ .

#### Arguments:

- *arkode\_mem* – input, the ARKStep memory structure pointer.
- *tstart* – input, the step start time.
- *tstop* – input, the step stop time.
- *y* – input/output, on input the solution at *tstop* and on return, the solution at time *tstop* if the step was successful (*ark\_flag*  $\geq 0$ ) or the solution at time *tstart* if the step failed (*ark\_flag*  $< 0$ ).
- *ark\_flag* – output, the step status flag. If *ark\_flag* is:
  - = 0 then the step succeeded and, if applicable, met the requested temporal accuracy.
  - > 0 then the step succeeded but failed to meet the requested temporal accuracy.
  - < 0 then the step failed e.g., a solver failure occurred.

**Return value:** If all ARKStep function calls are successful the return value is *ARK\_SUCCESS*, otherwise the return value is the error flag returned from the function that failed.

## 5.3 Using the ERKStep time-stepping module

This chapter is concerned with the use of the ERKStep time-stepping module for the solution of nonstiff initial value problems (IVPs) in a C or C++ language setting. The following sections discuss the header files and the layout of the user's main program, and provide descriptions of the ERKStep user-callable functions and user-supplied functions.

The example programs described in the companion document [48] may be helpful. Those codes may be used as templates for new codes and are included in the ARKODE package examples subdirectory.

ERKStep uses the input and output constants from the shared ARKODE infrastructure. These are defined as needed in this chapter, but for convenience the full list is provided separately in §13.

The relevant information on using ERKStep's C and C++ interfaces is detailed in the following sub-sections.

### 5.3.1 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 an ODE IVP using the ERKStep module. Most of the steps are independent of the NVECTOR implementation used. For the steps that are not, refer to §7 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. Create the SUNDIALS simulation context object.

Call `SUNContext_Create()` to allocate the `SUNContext` object.

3. Set problem dimensions, etc.

This generally includes the problem size,  $N$ , and may include the local vector length  $N_{local}$ .

**Note:** The variables  $N$  and  $N_{local}$  should be of type `sunindextype`.

4. Set vector of initial values

To set the vector  $y_0$  of initial values, 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

```
y0 = 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 = N_VNew_***(...);
```

and then set its elements by accessing the underlying data where it is located with a call of the form

```
ydata = N_VGetArrayPointer_***(y0);
```

For details on each of SUNDIALS' provided vector implementations, see the corresponding sections in §7 for details.

5. Create ERKStep object

Call `arkode_mem = ERKStepCreate(...)` to create the ERKStep memory block. `ERKStepCreate()` returns a `void*` pointer to this memory structure. See §5.3.2.1 for details.

6. Specify integration tolerances

Call `ERKStepSStolerances()` or `ERKStepSVtolerances()` to specify either a scalar relative tolerance and scalar absolute tolerance, or a scalar relative tolerance and a vector of absolute tolerances, respectively. Alternatively, call `ERKStepWFTolerances()` to specify a function which sets directly the weights used in evaluating WRMS vector norms. See §5.3.2.2 for details.

7. Set optional inputs

Call `ERKStepSet*` functions to change any optional inputs that control the behavior of ERKStep from their default values. See §5.3.2.5 for details.

8. Specify rootfinding problem

Optionally, call `ERKStepRootInit()` to initialize a rootfinding problem to be solved during the integration of the ODE system. See §5.3.2.3 for general details, and §5.3.2.5 for relevant optional input calls.

9. Advance solution in time

For each point at which output is desired, call

```
ier = ERKStepEvolve(arkode_mem, tout, yout, &tret, itask);
```

Here, `itask` specifies the return mode. The vector `yout` (which can be the same as the vector `y0` above) will contain  $y(t_{out})$ . See §5.3.2.4 for details.

10. Get optional outputs

Call `ERKStepGet*` functions to obtain optional output. See §5.3.2.7 for details.

## 11. Deallocate memory for solution vector

Upon completion of the integration, deallocate memory for the vector `y` (or `yout`) by calling the `NVECTOR` destructor function:

```
N_VDestroy(y);
```

## 12. Free solver memory

Call `ERKStepFree()` to free the memory allocated for the ERKStep module.

## 13. Finalize MPI, if used

Call `MPI_Finalize` to terminate MPI.

## 5.3.2 ERKStep User-callable functions

This section describes the functions that are called by the user to setup and then solve an IVP using the ERKStep time-stepping module. Some of these are required; however, starting with §5.3.2.5, the functions listed involve optional inputs/outputs or restarting, and those paragraphs may be skipped for a casual use of ARKODE's ERKStep module. In any case, refer to the preceding section, §5.3.1, for the correct order of these calls.

On an error, each user-callable function returns a negative value (or `NULL` if the function returns a pointer) and sends an error message to the error handler routine, which prints the message to `stderr` by default. However, the user can set a file as error output or can provide her own error handler function (see §5.3.2.5 for details).

### 5.3.2.1 ERKStep initialization and deallocation functions

`void *ERKStepCreate(ARKRhsFn f, realtype t0, N_Vector y0, SUNContext sunctx)`

This function allocates and initializes memory for a problem to be solved using the ERKStep time-stepping module in ARKODE.

#### Arguments:

- `f` – the name of the C function (of type `ARKRhsFn()`) defining the right-hand side function in  $\dot{y} = f(t, y)$ .
- `t0` – the initial value of  $t$ .
- `y0` – the initial condition vector  $y(t_0)$ .
- `sunctx` – the `SUNContext` object (see §4.1)

**Return value:** If successful, a pointer to initialized problem memory of type `void*`, to be passed to all user-facing ERKStep routines listed below. If unsuccessful, a `NULL` pointer will be returned, and an error message will be printed to `stderr`.

`void ERKStepFree(void **arkode_mem)`

This function frees the problem memory `arkode_mem` created by `ERKStepCreate()`.

#### Arguments:

- `arkode_mem` – pointer to the ERKStep memory block.

**Return value:** None

### 5.3.2.2 ERKStep tolerance specification functions

These functions specify the integration tolerances. One of them **should** be called before the first call to [ERKStepEvolve\(\)](#); otherwise default values of `reltol = 1e-4` and `abstol = 1e-9` will be used, which may be entirely incorrect for a specific problem.

The integration tolerances `reltol` and `abstol` define a vector of error weights, `ewt`. In the case of [ERKStepSStolerances\(\)](#), this vector has components

```
ewt[i] = 1.0/(reltol*abs(y[i]) + abstol);
```

whereas in the case of [ERKStepSVtolerances\(\)](#) the vector components are given by

```
ewt[i] = 1.0/(reltol*abs(y[i]) + abstol[i]);
```

This vector is used in all error tests, which use a weighted RMS norm on all error-like vectors `v`:

$$\|v\|_{WRMS} = \left( \frac{1}{N} \sum_{i=1}^N (v_i \text{ } ewt_i)^2 \right)^{1/2},$$

where  $N$  is the problem dimension.

Alternatively, the user may supply a custom function to supply the `ewt` vector, through a call to [ERKStepWFTolerances\(\)](#).

**int ERKStepSStolerances(void \*arkode\_mem, *realtype* reltol, *realtype* abstol)**  
This function specifies scalar relative and absolute tolerances.

#### Arguments:

- `arkode_mem` – pointer to the ERKStep memory block.
- `reltol` – scalar relative tolerance.
- `abstol` – scalar absolute tolerance.

#### Return value:

- `ARK_SUCCESS` if successful
- `ARK_MEM_NULL` if the ERKStep memory was NULL
- `ARK_NO_MALLOC` if the ERKStep memory was not allocated by the time-stepping module
- `ARK_ILL_INPUT` if an argument has an illegal value (e.g. a negative tolerance).

**int ERKStepSVtolerances(void \*arkode\_mem, *realtype* reltol, *N\_Vector* abstol)**

This function specifies a scalar relative tolerance and a vector absolute tolerance (a potentially different absolute tolerance for each vector component).

#### Arguments:

- `arkode_mem` – pointer to the ERKStep memory block.
- `reltol` – scalar relative tolerance.
- `abstol` – vector containing the absolute tolerances for each solution component.

#### Return value:

- `ARK_SUCCESS` if successful
- `ARK_MEM_NULL` if the ERKStep memory was NULL
- `ARK_NO_MALLOC` if the ERKStep memory was not allocated by the time-stepping module

- *ARK\_ILL\_INPUT* if an argument has an illegal value (e.g. a negative tolerance).

```
int ERKStepWFTolerances(void *arkode_mem, ARKEwtFn efun)
```

This function specifies a user-supplied function *efun* to compute the error weight vector *ewt*.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *efun* – the name of the function (of type *ARKEwtFn()*) that implements the error weight vector computation.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL
- *ARK\_NO\_MALLOC* if the ERKStep memory was not allocated by the time-stepping module

### General advice on the 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 a value of  $10^{-4}$  means that errors are controlled to .01%. We do not recommend using *reltol* larger than  $10^{-3}$ . On the other hand, *reltol* should not be so small that it is comparable to the unit roundoff of the machine arithmetic (generally around  $10^{-15}$  for double-precision).
- (2) The absolute tolerances *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 *abstol* (if scalar) or *abstol[i]* (if a vector) needs to be set to that noise level. If the different components have different noise levels, then *abstol* should be a vector. For example, see the example problem *ark\_robertson.c*, and the discussion of it in the ARKODE Examples Documentation [48]. In that problem, the three components vary between 0 and 1, and have different noise levels; hence the *atols* vector therein. It is impossible to give any general advice on *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 step. The final (global) errors are an accumulation of those per-step errors, where that accumulation factor is problem-dependent. A general rule of thumb is to reduce the tolerances by a factor of 10 from the actual desired limits on errors. So if you want .01% relative accuracy (globally), a good choice for *reltol* is  $10^{-5}$ . 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 nonphysical 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 (nonphysical) values can then occur. In most cases, these values are harmless, and simply need to be controlled, not eliminated, but in other cases any value that violates a constraint may cause a simulation to halt. For both of these scenarios the following pieces of advice are relevant.

- (1) The best 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  $y$  returned by ERKStep, with magnitude comparable to abstol or less, is equivalent to zero as far as the computation is concerned.
- (3) The user's right-hand side routine  $f$  should never change a negative value in the solution vector  $y$  to a non-negative value in attempt to "fix" this problem, since this can lead to numerical instability. If the  $f$  routine cannot tolerate a zero or negative value (e.g. because there is a square root or log), then the offending value should be changed to zero or a tiny positive number in a temporary variable (not in the input  $y$  vector) for the purposes of computing  $f(t, y)$ .
- (4) ERKStep supports component-wise constraints on solution components,  $y_i < 0$ ,  $y_i \leq 0$ ,  $y_i > 0$ , or  $y_i \geq 0$ , through the user-callable function `ERKStepSetConstraints()`. At each internal time step, if any constraint is violated then ERKStep will attempt a smaller time step that should not violate this constraint. This reduced step size is chosen such that the step size is the largest possible but where the solution component satisfies the constraint.
- (5) Positivity and non-negativity constraints on components can be enforced by use of the recoverable error return feature in the user-supplied right-hand side function,  $f$ . When a recoverable error is encountered, ERKStep will retry the step with a smaller step size, which typically alleviates the problem. However, because this option involves some additional overhead cost, it should only be exercised if the use of absolute tolerances to control the computed values is unsuccessful.

#### 5.3.2.3 Rootfinding initialization function

As described in §2.11, while solving the IVP, ARKODE's time-stepping modules have the capability to find the roots of a set of user-defined functions. To activate the root-finding algorithm, call the following function. This is normally called only once, prior to the first call to `ERKStepEvolve()`, but if the rootfinding problem is to be changed during the solution, `ERKStepRootInit()` can also be called prior to a continuation call to `ERKStepEvolve()`.

`int ERKStepRootInit(void *arkode_mem, int nrfn, ARKRootFn g)`

Initializes a rootfinding problem to be solved during the integration of the ODE system. It must be called after `ERKStepCreate()`, and before `ERKStepEvolve()`.

##### Arguments:

- *arkode\_mem* – pointer to the ERKStep memory block.
- *nrfn* – number of functions  $g_i$ , an integer  $\geq 0$ .
- *g* – name of user-supplied function, of type `ARKRootFn()`, defining the functions  $g_i$  whose roots are sought.

##### Return value:

- `ARK_SUCCESS` if successful

- *ARK\_MEM\_NULL* if the ERKStep memory was `NULL`
- *ARK\_MEM\_FAIL* if there was a memory allocation failure
- *ARK\_ILL\_INPUT* if *nrtfn* is greater than zero but *g* = `NULL`.

**Notes:** To disable the rootfinding feature after it has already been initialized, or to free memory associated with ERKStep's rootfinding module, call *ERKStepRootInit* with *nrtfn* = 0.

Similarly, if a new IVP is to be solved with a call to *ERKStepReInit()*, where the new IVP has no rootfinding problem but the prior one did, then call *ERKStepRootInit* with *nrtfn* = 0.

### 5.3.2.4 ERKStep solver function

This is the central step in the solution process – the call to perform the integration of the IVP. One of the input arguments (*itask*) specifies one of two modes as to where ERKStep is to return a solution. These modes are modified if the user has set a stop time (with a call to the optional input function *ERKStepSetStopTime()*) or has requested rootfinding.

```
int ERKStepEvolve(void *arkode_mem, realtype tout, N_Vector yout, realtype *tret, int itask)
    Integrates the ODE over an interval in t.
```

#### Arguments:

- *arkode\_mem* – pointer to the ERKStep memory block.
- *tout* – the next time at which a computed solution is desired.
- *yout* – the computed solution vector.
- *tret* – the time corresponding to *yout* (output).
- *itask* – a flag indicating the job of the solver for the next user step.

The *ARK\_NORMAL* option causes the solver to take internal steps until it has just overtaken a user-specified output time, *tout*, in the direction of integration, i.e.  $t_{n-1} < tout \leq t_n$  for forward integration, or  $t_n \leq tout < t_{n-1}$  for backward integration. It will then compute an approximation to the solution  $y(tout)$  by interpolation (using one of the dense output routines described in §2.2).

The *ARK\_ONE\_STEP* option tells the solver to only take a single internal step  $y_{n-1} \rightarrow y_n$  and then return control back to the calling program. If this step will overtake *tout* then the solver will again return an interpolated result; otherwise it will return a copy of the internal solution  $y_n$  in the vector *yout*.

#### Return value:

- *ARK\_SUCCESS* if successful.
- *ARK\_ROOT\_RETURN* if *ERKStepEvolve()* succeeded, and found one or more roots. If the number of root functions, *nrtfn*, is greater than 1, call *ERKStepGetRootInfo()* to see which  $g_i$  were found to have a root at (\**tret*).
- *ARK\_TSTOP\_RETURN* if *ERKStepEvolve()* succeeded and returned at *tstop*.
- *ARK\_MEM\_NULL* if the *arkode\_mem* argument was `NULL`.
- *ARK\_NO\_MALLOC* if *arkode\_mem* was not allocated.
- *ARK\_ILL\_INPUT* if one of the inputs to *ERKStepEvolve()* is illegal, or some other input to the solver was either illegal or missing. Details will be provided in the error message. Typical causes of this failure:
  - (a) A component of the error weight vector became zero during internal time-stepping.
  - (b) A root of one of the root functions was found both at a point *t* and also very near *t*.

- (c) The initial condition violates the inequality constraints.
- *ARK\_TOO MUCH\_WORK* if the solver took *mxstep* internal steps but could not reach *tout*. The default value for *mxstep* is *MXSTEP\_DEFAULT* = 500.
- *ARK\_TOO MUCH\_ACC* if the solver could not satisfy the accuracy demanded by the user for some internal step.
- *ARK\_ERR\_FAILURE* if error test failures occurred either too many times (*ark\_maxnef*) during one internal time step or occurred with  $|h| = h_{min}$ .
- *ARK\_VECTOROP\_ERR* a vector operation error occurred.

**Notes:** The input vector *yout* can use the same memory as the vector *y0* of initial conditions that was passed to [\*ERKStepCreate\(\)\*](#).

In *ARK\_ONE\_STEP* mode, *tout* is used only on the first call, and only to get the direction and a rough scale of the independent variable. All failure return values are negative and so testing the return argument for negative values will trap all [\*ERKStepEvolve\(\)\*](#) failures.

Since interpolation may reduce the accuracy in the reported solution, if full method accuracy is desired the user should issue a call to [\*ERKStepSetStopTime\(\)\*](#) before the call to [\*ERKStepEvolve\(\)\*](#) to specify a fixed stop time to end the time step and return to the user. Upon return from [\*ERKStepEvolve\(\)\*](#), a copy of the internal solution *yn* will be returned in the vector *yout*. Once the integrator returns at a *tstop* time, any future testing for *tstop* is disabled (and can be re-enabled only though a new call to [\*ERKStepSetStopTime\(\)\*](#)).

On any error return in which one or more internal steps were taken by [\*ERKStepEvolve\(\)\*](#), the returned values of *tret* and *yout* correspond to the farthest point reached in the integration. On all other error returns, *tret* and *yout* are left unchanged from those provided to the routine.

### 5.3.2.5 Optional input functions

There are numerous optional input parameters that control the behavior of ERKStep, each of which may be modified from its default value through calling an appropriate input function. The following tables list all optional input functions, grouped by which aspect of ERKStep they control. Detailed information on the calling syntax and arguments for each function are then provided following each table.

The optional inputs are grouped into the following categories:

- General ERKStep options ([Table 5.3](#)),
- IVP method solver options ([Table 5.4](#)),
- Step adaptivity solver options ([Table 5.5](#)), and
- Rootfinding options ([Table 5.6](#)).

For the most casual use of ERKStep, relying on the default set of solver parameters, the reader can skip to section on user-supplied functions, §5.5.

We note that, on an error return, all of the optional input functions send an error message to the error handler function. All error return values are negative, so a test on the return arguments for negative values will catch all errors. Finally, a call to an *ERKStepSet\*\*\** function can generally be made from the user's calling program at any time and, if successful, takes effect immediately. *ERKStepSet\*\*\** functions that cannot be called at any time note this in the “**Notes:**” section of the function documentation.

## Optional inputs for ERKStep

Table 5.3: Optional inputs for ERKStep

Optional input	Function name	Default
Return ERKStep solver parameters to their defaults	<a href="#"><code>ERKStepSetDefaults()</code></a>	internal
Set dense output interpolation type	<a href="#"><code>ERKStepSetInterpolantType()</code></a>	<code>ARK_INTERP_HERMITE</code>
Set dense output polynomial degree	<a href="#"><code>ERKStepSetInterpolantDegree()</code></a>	5
Supply a pointer to a diagnostics output file	<a href="#"><code>ERKStepSetDiagnostics()</code></a>	<code>NULL</code>
Supply a pointer to an error output file	<a href="#"><code>ERKStepSetErrFile()</code></a>	<code>stderr</code>
Supply a custom error handler function	<a href="#"><code>ERKStepSetErrorHandlerFn()</code></a>	internal fn
Disable time step adaptivity (fixed-step mode)	<a href="#"><code>ERKStepSetFixedStep()</code></a>	disabled
Supply an initial step size to attempt	<a href="#"><code>ERKStepSetInitStep()</code></a>	estimated
Maximum no. of warnings for $t_n + h = t_n$	<a href="#"><code>ERKStepSetMaxHnilWarns()</code></a>	10
Maximum no. of internal steps before $tout$	<a href="#"><code>ERKStepSetMaxNumSteps()</code></a>	500
Maximum absolute step size	<a href="#"><code>ERKStepSetMaxStep()</code></a>	$\infty$
Minimum absolute step size	<a href="#"><code>ERKStepSetMinStep()</code></a>	0.0
Set a value for $t_{stop}$	<a href="#"><code>ERKStepSetStopTime()</code></a>	$\infty$
Supply a pointer for user data	<a href="#"><code>ERKStepSetUserData()</code></a>	<code>NULL</code>
Maximum no. of ERKStep error test failures	<a href="#"><code>ERKStepSetMaxErrTestFails()</code></a>	7
Set inequality constraints on solution	<a href="#"><code>ERKStepSetConstraints()</code></a>	<code>NULL</code>
Set max number of constraint failures	<a href="#"><code>ERKStepSetMaxNumConstr-Fails()</code></a>	10

`int ERKStepSetDefaults(void *arkode_mem)`

Resets all optional input parameters to ERKStep's original default values.

#### Arguments:

- `arkode_mem` – pointer to the ERKStep memory block.

#### Return value:

- `ARK_SUCCESS` if successful
- `ARK_MEM_NULL` if the ERKStep memory is `NULL`
- `ARK_ILL_INPUT` if an argument has an illegal value

**Notes:** Does not change problem-defining function pointer `f` or the `user_data` pointer.

Also leaves alone any data structures or options related to root-finding (those can be reset using [`ERKStep-RootInit\(\)`](#)).

`int ERKStepSetInterpolantType(void *arkode_mem, int itype)`

Specifies use of the Lagrange or Hermite interpolation modules (used for dense output – interpolation of solution output values and implicit method predictors).

#### Arguments:

- `arkode_mem` – pointer to the ERKStep memory block.
- `itype` – requested interpolant type (`ARK_INTERP_HERMITE` or `ARK_INTERP_LAGRANGE`)

#### Return value:

- `ARK_SUCCESS` if successful

- *ARK\_MEM\_NULL* if the ERKStep memory is *NULL*
- *ARK\_MEM\_FAIL* if the interpolation module cannot be allocated
- *ARK\_ILL\_INPUT* if the *itype* argument is not recognized or the interpolation module has already been initialized

**Notes:** The Hermite interpolation module is described in §2.2.1, and the Lagrange interpolation module is described in §2.2.2.

This routine frees any previously-allocated interpolation module, and re-creates one according to the specified argument. Thus any previous calls to *ERKStepSetInterpolantDegree()* will be nullified.

This routine must be called *after* the call to *ERKStepCreate()*. After the first call to *ERKStepEvolve()* the interpolation type may not be changed without first calling *ERKStepReInit()*.

If this routine is not called, the Hermite interpolation module will be used.

int **ERKStepSetInterpolantDegree**(void \*arkode\_mem, int degree)

Specifies the degree of the polynomial interpolant used for dense output (i.e. interpolation of solution output values and implicit method predictors).

#### Arguments:

- *arkode\_mem* – pointer to the ERKStep memory block.
- *degree* – requested polynomial degree.

#### Return value:

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory or interpolation module are *NULL*
- *ARK\_INTERP\_FAIL* if this is called after *ERKStepEvolve()*
- *ARK\_ILL\_INPUT* if an argument has an illegal value or the interpolation module has already been initialized

**Notes:** Allowed values are between 0 and 5.

This routine should be called *after* *ERKStepCreate()* and *before* *ERKStepEvolve()*. After the first call to *ERKStepEvolve()* the interpolation degree may not be changed without first calling *ERKStepReInit()*.

If a user calls both this routine and *ERKStepSetInterpolantType()*, then *ERKStepSetInterpolantType()* must be called first.

Since the accuracy of any polynomial interpolant is limited by the accuracy of the time-step solutions on which it is based, the *actual* polynomial degree that is used by ERKStep will be the minimum of  $q - 1$  and the input *degree*, where  $q$  is the order of accuracy for the time integration method.

int **ERKStepSetDenseOrder**(void \*arkode\_mem, int dord)

*This function is deprecated, and will be removed in a future release. Users should transition to calling *ERKStepSetInterpolantDegree()* instead.*

int **ERKStepSetDiagnostics**(void \*arkode\_mem, FILE \*diagfp)

Specifies the file pointer for a diagnostics file where all ERKStep step adaptivity and solver information is written.

#### Arguments:

- *arkode\_mem* – pointer to the ERKStep memory block.
- *diagfp* – pointer to the diagnostics output file.

#### Return value:

- *ARK\_SUCCESS* if successful

- *ARK\_MEM\_NULL* if the ERKStep memory is **NULL**
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** This parameter can be `stdout` or `stderr`, although the suggested approach is to specify a pointer to a unique file opened by the user and returned by `fopen`. If not called, or if called with a **NULL** file pointer, all diagnostics output is disabled.

When run in parallel, only one process should set a non-**NULL** value for this pointer, since statistics from all processes would be identical.

int **ERKStepSetErrFile**(void \*arkode\_mem, FILE \*errfp)

Specifies a pointer to the file where all ERKStep warning and error messages will be written if the default internal error handling function is used.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *errfp* – pointer to the output file.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is **NULL**
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The default value for *errfp* is `stderr`.

Passing a **NULL** value disables all future error message output (except for the case wherein the ERKStep memory pointer is **NULL**). This use of the function is strongly discouraged.

If used, this routine should be called before any other optional input functions, in order to take effect for subsequent error messages.

int **ERKStepSetErrorHandlerFn**(void \*arkode\_mem, *ARKErrorHandlerFn* ehfun, void \*eh\_data)

Specifies the optional user-defined function to be used in handling error messages.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *ehfun* – name of user-supplied error handler function.
- *eh\_data* – pointer to user data passed to *ehfun* every time it is called.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is **NULL**
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Error messages indicating that the ERKStep solver memory is **NULL** will always be directed to `stderr`.

int **ERKStepSetFixedStep**(void \*arkode\_mem, *realtype* hfixed)

Disabled time step adaptivity within ERKStep, and specifies the fixed time step size to use for the following internal step(s).

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *hfixed* – value of the fixed step size to use.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Pass 0.0 to return ERKStep to the default (adaptive-step) mode.

Use of this function is not generally recommended, since we it gives no assurance of the validity of the computed solutions. It is primarily provided for code-to-code verification testing purposes.

When using *ERKStepSetFixedStep()*, any values provided to the functions *ERKStepSetInitStep()*, *ERKStepSetAdaptivityFn()*, *ERKStepSetMaxErrTestFails()*, *ERKStepSetAdaptivityMethod()*, *ERKStepSetCFLFraction()*, *ERKStepsetErrorBias()*, *ERKStepSetFixedStepBounds()*, *ERKStepSetMaxEfailGrowth()*, *ERKStepSetMaxFirstGrowth()*, *ERKStepSetMaxGrowth()*, *ERKStepSetMinReduction()*, *ERKStepSetSafetyFactor()*, *ERKStepSetSmallNumEFails()* and *ERKStepSetStabilityFn()* will be ignored, since temporal adaptivity is disabled.

If both *ERKStepSetFixedStep()* and *ERKStepSetStopTime()* are used, then the fixed step size will be used for all steps until the final step preceding the provided stop time (which may be shorter). To resume use of the previous fixed step size, another call to *ERKStepSetFixedStep()* must be made prior to calling *ERKStepEvolve()* to resume integration.

It is *not* recommended that *ERKStepSetFixedStep()* be used in concert with *ERKStepSetMaxStep()* or *ERKStepSetMinStep()*, since at best those latter two routines will provide no useful information to the solver, and at worst they may interfere with the desired fixed step size.

int **ERKStepSetInitStep**(void \*arkode\_mem, *realtyp* hin)

Specifies the initial time step size ERKStep should use after initialization, re-initialization, or resetting.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *hin* – value of the initial step to be attempted ( $\neq 0$ ).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Pass 0.0 to use the default value.

By default, ERKStep estimates the initial step size to be  $h = \sqrt{\frac{2}{\|\ddot{y}\|}}$ , where  $\ddot{y}$  is an estimate of the second derivative of the solution at  $t_0$ .

This routine will also reset the step size and error history.

int **ERKStepSetMaxHnilWarns**(void \*arkode\_mem, int mxhnil)

Specifies the maximum number of messages issued by the solver to warn that  $t + h = t$  on the next internal step, before ERKStep will instead return with an error.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *mxhnil* – maximum allowed number of warning messages ( $> 0$ ).

**Return value:**

- *ARK\_SUCCESS* if successful

- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The default value is 10; set *mxnil* to zero to specify this default.

A negative value indicates that no warning messages should be issued.

**int `ERKStepSetMaxNumSteps`(void \*arkode\_mem, long int mxsteps)**

Specifies the maximum number of steps to be taken by the solver in its attempt to reach the next output time, before ERKStep will return with an error.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *mxsteps* – maximum allowed number of internal steps.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Passing *mxsteps* = 0 results in ERKStep using the default value (500).

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

**int `ERKStepSetMaxStep`(void \*arkode\_mem, *realtype* hmax)**

Specifies the upper bound on the magnitude of the time step size.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *hmax* – maximum absolute value of the time step size ( $\geq 0$ ).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Pass *hmax*  $\leq 0.0$  to set the default value of  $\infty$ .

**int `ERKStepSetMinStep`(void \*arkode\_mem, *realtype* hmin)**

Specifies the lower bound on the magnitude of the time step size.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *hmin* – minimum absolute value of the time step size ( $\geq 0$ ).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Pass *hmin*  $\leq 0.0$  to set the default value of 0.

**int `ERKStepSetStopTime`(void \*arkode\_mem, *realtype* tstop)**

Specifies the value of the independent variable *t* past which the solution is not to proceed.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *tstop* – stopping time for the integrator.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The default is that no stop time is imposed.

int **ERKStepSetUserData**(void \*arkode\_mem, void \*user\_data)

Specifies the user data block *user\_data* and attaches it to the main ERKStep memory block.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *user\_data* – pointer to the user data.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** If specified, the pointer to *user\_data* is passed to all user-supplied functions for which it is an argument; otherwise NULL is passed.

int **ERKStepSetMaxErrTestFails**(void \*arkode\_mem, int maxnef)

Specifies the maximum number of error test failures permitted in attempting one step, before returning with an error.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *maxnef* – maximum allowed number of error test failures ( $> 0$ ).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The default value is 7; set *maxnef*  $\leq 0$  to specify this default.

int **ERKStepSetConstraints**(void \*arkode\_mem, *N\_Vector* constraints)

Specifies a vector defining inequality constraints for each component of the solution vector *y*.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.

- *constraints* – vector of constraint flags. Each component specifies the type of solution constraint:

$$\text{constraints}[i] = \begin{cases} 0.0 & \Rightarrow \text{no constraint is imposed on } y_i, \\ 1.0 & \Rightarrow y_i \geq 0, \\ -1.0 & \Rightarrow y_i \leq 0, \\ 2.0 & \Rightarrow y_i > 0, \\ -2.0 & \Rightarrow y_i < 0. \end{cases}$$

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is *NULL*
- *ARK\_ILL\_INPUT* if 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. A *NULL* constraints vector will disable constraint checking.

After a call to *ERKStepResize()* inequality constraint checking will be disabled and a call to *ERKStepSetConstraints()* is required to re-enable constraint checking.

Since constraint-handling is performed through cutting time steps that would violate the constraints, it is possible that this feature will cause some problems to fail due to an inability to enforce constraints even at the minimum time step size. Additionally, the features *ERKStepSetConstraints()* and *ERKStepSetFixedStep()* are incompatible, and should not be used simultaneously.

int **ERKStepSetMaxNumConstrFails**(void \*arkode\_mem, int maxfails)

Specifies the maximum number of constraint failures in a step before ERKStep will return with an error.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *maxfails* – maximum allowed number of constrain failures.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is *NULL*

**Notes:** Passing *maxfails*  $\leq 0$  results in ERKStep using the default value (10).

## Optional inputs for IVP method selection

Table 5.4: Optional inputs for IVP method selection

Optional input	Function name	Default
Set integrator method order	<i>ERKStepSetOrder()</i>	4
Set explicit RK table	<i>ERKStepSetTable()</i>	internal
Specify explicit RK table number	<i>ERKStepSetTableNum()</i>	internal

int **ERKStepSetOrder**(void \*arkode\_mem, int ord)

Specifies the order of accuracy for the ERK integration method.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.

- $ord$  – requested order of accuracy.

**Return value:**

- $ARK\_SUCCESS$  if successful
- $ARK\_MEM\_NULL$  if the ERKStep memory is NULL
- $ARK\_ILL\_INPUT$  if an argument has an illegal value

**Notes:** The allowed values are  $2 \leq ord \leq 8$ . Any illegal input will result in the default value of 4.

Since  $ord$  affects the memory requirements for the internal ERKStep memory block, it cannot be changed after the first call to `ERKStepEvolve()`, unless `ERKStepReInit()` is called.

int `ERKStepSetTable`(void \*arkode\_mem, `ARKodeButcherTable` B)

Specifies a customized Butcher table for the ERK method.

**Arguments:**

- $arkode\_mem$  – pointer to the ERKStep memory block.
- $B$  – the Butcher table for the explicit RK method.

**Return value:**

- $ARK\_SUCCESS$  if successful
- $ARK\_MEM\_NULL$  if the ERKStep memory is NULL
- $ARK\_ILL\_INPUT$  if an argument has an illegal value

**Notes:**

For a description of the `ARKodeButcherTable` type and related functions for creating Butcher tables, see §6.

No error checking is performed to ensure that either the method order  $p$  or the embedding order  $q$  specified in the Butcher table structure correctly describe the coefficients in the Butcher table.

Error checking is performed to ensure that the Butcher table is strictly lower-triangular (i.e. that it specifies an ERK method).

If the Butcher table does not contain an embedding, the user *must* call `ERKStepSetFixedStep()` to enable fixed-step mode and set the desired time step size.

int `ERKStepSetTableNum`(void \*arkode\_mem, `ARKODE_ERKTableID` etable)

Indicates to use a specific built-in Butcher table for the ERK method.

**Arguments:**

- $arkode\_mem$  – pointer to the ERKStep memory block.
- $etable$  – index of the Butcher table.

**Return value:**

- $ARK\_SUCCESS$  if successful
- $ARK\_MEM\_NULL$  if the ERKStep memory is NULL
- $ARK\_ILL\_INPUT$  if an argument has an illegal value

**Notes:**  $etable$  should match an existing explicit method from §14.1. Error-checking is performed to ensure that the table exists, and is not implicit.

## Optional inputs for time step adaptivity

The mathematical explanation of ARKODE's time step adaptivity algorithm, including how each of the parameters below is used within the code, is provided in §2.7.

Table 5.5: Optional inputs for time step adaptivity

Optional input	Function name	Default
Set a custom time step adaptivity function	<code>ERKStepSetAdaptivityFn()</code>	internal
Choose an existing time step adaptivity method	<code>ERKStepSetAdaptivityMethod()</code>	0
Explicit stability safety factor	<code>ERKStepSetCFLFraction()</code>	0.5
Time step error bias factor	<code>ERKStepsetErrorBias()</code>	1.5
Bounds determining no change in step size	<code>ERKStepSetFixedStepBounds()</code>	1.0 1.5
Maximum step growth factor on error test fail	<code>ERKStepSetMaxEFailGrowth()</code>	0.3
Maximum first step growth factor	<code>ERKStepSetMaxFirstGrowth()</code>	10000.0
Maximum allowed general step growth factor	<code>ERKStepSetMaxGrowth()</code>	20.0
Minimum allowed step reduction factor on error test fail	<code>ERKStepSetMinReduction()</code>	0.1
Time step safety factor	<code>ERKStepSetSafetyFactor()</code>	0.96
Error fails before MaxEFailGrowth takes effect	<code>ERKStepSetSmallNumEFails()</code>	2
Explicit stability function	<code>ERKStepSetStabilityFn()</code>	none

int `ERKStepSetAdaptivityFn`(void \*arkode\_mem, `ARKAdaptFn` hfun, void \*h\_data)

Sets a user-supplied time-step adaptivity function.

### Arguments:

- *arkode\_mem* – pointer to the ERKStep memory block.
- *hfun* – name of user-supplied adaptivity function.
- *h\_data* – pointer to user data passed to *hfun* every time it is called.

### Return value:

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** This function should focus on accuracy-based time step estimation; for stability based time steps the function `ERKStepSetStabilityFn()` should be used instead.

int `ERKStepSetAdaptivityMethod`(void \*arkode\_mem, int imethod, int idefault, int pq, `realtype` \*adapt\_params)

Specifies the method (and associated parameters) used for time step adaptivity.

### Arguments:

- *arkode\_mem* – pointer to the ERKStep memory block.
- *imethod* – accuracy-based adaptivity method choice ( $0 \leq imethod \leq 5$ ): 0 is PID, 1 is PI, 2 is I, 3 is explicit Gustafsson, 4 is implicit Gustafsson, and 5 is the ImEx Gustafsson.
- *idefault* – flag denoting whether to use default adaptivity parameters (1), or that they will be supplied in the *adapt\_params* argument (0).
- *pq* – flag denoting whether to use the embedding order of accuracy *p* (0) or the method order of accuracy *q* (1) within the adaptivity algorithm. *p* is the default.
- *adapt\_params[0]* –  $k_1$  parameter within accuracy-based adaptivity algorithms.
- *adapt\_params[1]* –  $k_2$  parameter within accuracy-based adaptivity algorithms.

- *adapt\_params[2]* –  $k_3$  parameter within accuracy-based adaptivity algorithms.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** If custom parameters are supplied, they will be checked for validity against published stability intervals.

If other parameter values are desired, it is recommended to instead provide a custom function through a call to *ERKStepSetAdaptivityFn()*.

int **ERKStepSetCFLFraction**(void \*arkode\_mem, *realtype* cfl\_frac)

Specifies the fraction of the estimated explicitly stable step to use.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *cfl\_frac* – maximum allowed fraction of explicitly stable step (default is 0.5).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any non-positive parameter will imply a reset to the default value.

int **ERKStepsetErrorBias**(void \*arkode\_mem, *realtype* bias)

Specifies the bias to be applied to the error estimates within accuracy-based adaptivity strategies.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *bias* – bias applied to error in accuracy-based time step estimation (default is 1.5).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any value below 1.0 will imply a reset to the default value.

int **ERKStepSetFixedStepBounds**(void \*arkode\_mem, *realtype* lb, *realtype* ub)

Specifies the step growth interval in which the step size will remain unchanged.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *lb* – lower bound on window to leave step size fixed (default is 1.0).
- *ub* – upper bound on window to leave step size fixed (default is 1.5).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any interval *not* containing 1.0 will imply a reset to the default values.

**int ERKStepSetMaxEfailGrowth(void \*arkode\_mem, *realtype* etamxf)**

Specifies the maximum step size growth factor upon multiple successive accuracy-based error failures in the solver.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *etamxf* – time step reduction factor on multiple error fails (default is 0.3).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any value outside the interval (0, 1] will imply a reset to the default value.

**int ERKStepSetMaxFirstGrowth(void \*arkode\_mem, *realtype* etamx1)**

Specifies the maximum allowed growth factor in step size following the very first integration step.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *etamx1* – maximum allowed growth factor after the first time step (default is 10000.0).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any value  $\leq$  1.0 will imply a reset to the default value.

**int ERKStepSetMaxGrowth(void \*arkode\_mem, *realtype* mx\_growth)**

Specifies the maximum allowed growth factor in step size between consecutive steps in the integration process.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *mx\_growth* – maximum allowed growth factor between consecutive time steps (default is 20.0).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any value  $\leq$  1.0 will imply a reset to the default value.

**int ERKStepSetMinReduction(void \*arkode\_mem, *realtype* eta\_min)**

Specifies the minimum allowed reduction factor in step size between step attempts, resulting from a temporal error failure in the integration process.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *eta\_min* – minimum allowed reduction factor time step after an error test failure (default is 0.1).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any value  $\geq 1.0$  or  $\leq 0.0$  will imply a reset to the default value.

int **ERKStepSetSafetyFactor**(void \*arkode\_mem, *realtyp* safety)

Specifies the safety factor to be applied to the accuracy-based estimated step.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *safety* – safety factor applied to accuracy-based time step (default is 0.96).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any non-positive parameter will imply a reset to the default value.

int **ERKStepSetSmallNumEFails**(void \*arkode\_mem, int small\_nef)

Specifies the threshold for “multiple” successive error failures before the *etamxf* parameter from *ERKStepSet-MaxFailGrowth()* is applied.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *small\_nef* – bound to determine “multiple” for *etamxf* (default is 2).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any non-positive parameter will imply a reset to the default value.

int **ERKStepSetStabilityFn**(void \*arkode\_mem, *ARKExpStabFn* EStab, void \*estab\_data)

Sets the problem-dependent function to estimate a stable time step size for the explicit portion of the ODE system.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *EStab* – name of user-supplied stability function.
- *estab\_data* – pointer to user data passed to *EStab* every time it is called.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** This function should return an estimate of the absolute value of the maximum stable time step for the ODE system. It is not required, since accuracy-based adaptivity may be sufficient for retaining stability, but this can be quite useful for problems where the right-hand side function  $f(t, y)$  contains stiff terms.

## Rootfinding optional input functions

The following functions can be called to set optional inputs to control the rootfinding algorithm, the mathematics of which are described in §2.11.

Table 5.6: Rootfinding optional input functions

Optional input	Function name	Default
Direction of zero-crossings to monitor	<code>ERKStepSetRootDirection()</code>	both
Disable inactive root warnings	<code>ERKStepSetNoInactiveRootWarn()</code>	enabled

int **ERKStepSetRootDirection**(void \*arkode\_mem, int \*rootdir)  
Specifies the direction of zero-crossings to be located and returned.

### Arguments:

- *arkode\_mem* – pointer to the ERKStep memory block.
- *rootdir* – state array of length *nrtfn*, the number of root functions  $g_i$  (the value of *nrtfn* was supplied in the call to `ERKStepRootInit()`). If *rootdir[i] == 0* then crossing in either direction for  $g_i$  should be reported. 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:

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The default behavior is to monitor for both zero-crossing directions.

int **ERKStepSetNoInactiveRootWarn**(void \*arkode\_mem)  
Disables issuing a warning if some root function appears to be identically zero at the beginning of the integration.

### Arguments:

- *arkode\_mem* – pointer to the ERKStep memory block.

### Return value:

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL

**Notes:** ERKStep 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), ERKStep will issue a warning which can be disabled with this optional input function.

### 5.3.2.6 Interpolated output function

An optional function `ERKStepGetDky()` is available to obtain additional values of solution-related quantities. This function should only be called after a successful return from `ERKStepEvolve()`, as it provides interpolated values either of  $y$  or of its derivatives (up to the 5th derivative) interpolated to any value of  $t$  in the last internal step taken by `ERKStepEvolve()`. Internally, this “dense output” or “continuous extension” algorithm is identical to the algorithm used for the maximum order implicit predictors, described in §2.10.5.2, except that derivatives of the polynomial model may be evaluated upon request.

```
int ERKStepGetDky(void *arkode_mem, realtype t, int k, N_Vector dky)
```

Computes the  $k$ -th derivative of the function  $y$  at the time  $t$ , i.e.,  $y^{(k)}(t)$ , for values of the independent variable satisfying  $t_n - h_n \leq t \leq t_n$ , with  $t_n$  as current internal time reached, and  $h_n$  is the last internal step size successfully used by the solver. This routine uses an interpolating polynomial of degree  $\min(\text{degree}, 5)$ , where  $\text{degree}$  is the argument provided to `ERKStepSetInterpolantDegree()`. The user may request  $k$  in the range  $\{0, \dots, \min(\text{degree}, k_{\max})\}$  where  $k_{\max}$  depends on the choice of interpolation module. For Hermite interpolants  $k_{\max} = 5$  and for Lagrange interpolants  $k_{\max} = 3$ .

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *t* – the value of the independent variable at which the derivative is to be evaluated.
- *k* – the derivative order requested.
- *dky* – output vector (must be allocated by the user).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_BAD\_K* if *k* is not in the range  $\{0, \dots, \min(\text{degree}, k_{\max})\}$ .
- *ARK\_BAD\_T* if *t* is not in the interval  $[t_n - h_n, t_n]$
- *ARK\_BAD\_DKY* if the *dky* vector was NULL
- *ARK\_MEM\_NULL* if the ERKStep memory is NULL

**Notes:** It is only legal to call this function after a successful return from `ERKStepEvolve()`.

A user may access the values  $t_n$  and  $h_n$  via the functions `ERKStepGetCurrentTime()` and `ERKStepGetLastStep()`, respectively.

### 5.3.2.7 Optional output functions

ERKStep provides an extensive set of functions that can be used to obtain solver performance information. We organize these into groups:

1. General ERKStep output routines are in §5.3.2.7,
2. Output routines regarding root-finding results are in §5.3.2.7,
3. General usability routines (e.g. to print the current ERKStep parameters, or output the current Butcher table) are in §5.3.2.7.

Following each table, we elaborate on each function.

Some of the optional outputs, especially the various counters, can be very useful in determining the efficiency of various methods inside ERKStep. For example:

- The counters *nsteps* and *nf\_evals* provide a rough measure of the overall cost of a given run, and can be compared between runs with different solver options to suggest which set of options is the most efficient.

- The ratio  $nsteps/step\_attempts$  can measure the quality of the time step adaptivity algorithm, since a poor algorithm will result in more failed steps, and hence a lower ratio.

It is therefore recommended that users retrieve and output these statistics following each run, and take some time to investigate alternate solver options that will be more optimal for their particular problem of interest.

### Main solver optional output functions

Table 5.7: Main solver optional output functions

Optional output	Function name
Size of ERKStep real and integer workspaces	<code>ERKStepGetWorkSpace()</code>
Cumulative number of internal steps	<code>ERKStepGetNumSteps()</code>
Actual initial time step size used	<code>ERKStepGetActualInitStep()</code>
Step size used for the last successful step	<code>ERKStepGetLastStep()</code>
Step size to be attempted on the next step	<code>ERKStepGetCurrentStep()</code>
Current internal time reached by the solver	<code>ERKStepGetCurrentTime()</code>
Suggested factor for tolerance scaling	<code>ERKStepGetTolScaleFactor()</code>
Error weight vector for state variables	<code>ERKStepGetErrWeights()</code>
Single accessor to many statistics at once	<code>ERKStepGetStepStats()</code>
Name of constant associated with a return flag	<code>ERKStepGetReturnFlagName()</code>
No. of explicit stability-limited steps	<code>ERKStepGetNumExpSteps()</code>
No. of accuracy-limited steps	<code>ERKStepGetNumAccSteps()</code>
No. of attempted steps	<code>ERKStepGetNumStepAttempts()</code>
No. of calls to $f$ function	<code>ERKStepGetNumRhsEvals()</code>
No. of local error test failures that have occurred	<code>ERKStepGetNumErrTestFails()</code>
Current ERK Butcher table	<code>ERKStepGetCurrentButcherTable()</code>
Estimated local truncation error vector	<code>ERKStepGetEstLocalErrors()</code>
Single accessor to many statistics at once	<code>ERKStepGetTimestepperStats()</code>
Number of constraint test failures	<code>ERKStepGetNumConstrFails()</code>

int `ERKStepGetWorkSpace`(void \*arkode\_mem, long int \*lenrw, long int \*leniw)

Returns the ERKStep real and integer workspace sizes.

#### Arguments:

- `arkode_mem` – pointer to the ERKStep memory block.
- `lenrw` – the number of `realtype` values in the ERKStep workspace.
- `leniw` – the number of integer values in the ERKStep workspace.

#### Return value:

- `ARK_SUCCESS` if successful
- `ARK_MEM_NULL` if the ERKStep memory was NULL

int `ERKStepGetNumSteps`(void \*arkode\_mem, long int \*nsteps)

Returns the cumulative number of internal steps taken by the solver (so far).

#### Arguments:

- `arkode_mem` – pointer to the ERKStep memory block.
- `nsteps` – number of steps taken in the solver.

#### Return value:

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

**int `ERKStepGetActualInitStep`(void \*arkode\_mem, *realtype* \*hinused)**

Returns the value of the integration step size used on the first step.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *hinused* – actual value of initial step size.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

**Notes:** Even if the value of the initial integration step was specified by the user through a call to [\*ERKStepSetInitStep\*\(\*O\*\)](#), this value may have been changed by ERKStep to ensure that the step size fell within the prescribed bounds ( $h_{min} \leq h_0 \leq h_{max}$ ), or to satisfy the local error test condition.

**int `ERKStepGetLastStep`(void \*arkode\_mem, *realtype* \*hlast)**

Returns the integration step size taken on the last successful internal step.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *hlast* – step size taken on the last internal step.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

**int `ERKStepGetCurrentStep`(void \*arkode\_mem, *realtype* \*hcur)**

Returns the integration step size to be attempted on the next internal step.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *hcur* – step size to be attempted on the next internal step.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

**int `ERKStepGetCurrentTime`(void \*arkode\_mem, *realtype* \*tcur)**

Returns the current internal time reached by the solver.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *tcur* – current internal time reached.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

`int ERKStepGetTolScaleFactor(void *arkode_mem, realtype *tolsfac)`

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:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *tolsfac* – suggested scaling factor for user-supplied tolerances.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

`int ERKStepGetErrWeights(void *arkode_mem, N_Vector eweight)`

Returns the current error weight vector.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *eweight* – solution error weights at the current time.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

**Notes:** The user must allocate space for *eweight*, that will be filled in by this function.

`int ERKStepGetStepStats(void *arkode_mem, long int *nsteps, realtype *hinused, realtype *hlast, realtype *hcur, realtype *tcur)`

Returns many of the most useful optional outputs in a single call.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *nsteps* – number of steps taken in the solver.
- *hinused* – actual value of initial step size.
- *hlast* – step size taken on the last internal step.
- *hcur* – step size to be attempted on the next internal step.
- *tcur* – current internal time reached.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

`char *ERKStepGetReturnFlagName(long int flag)`

Returns the name of the ERKStep constant corresponding to *flag*.

**Arguments:**

- *flag* – a return flag from an ERKStep function.

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

`int ERKStepGetNumExpSteps(void *arkode_mem, long int *expsteps)`

Returns the cumulative number of stability-limited steps taken by the solver (so far).

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *expsteps* – number of stability-limited steps taken in the solver.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

int **ERKStepGetNumAccSteps**(void \*arkode\_mem, long int \*accsteps)

Returns the cumulative number of accuracy-limited steps taken by the solver (so far).

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *accsteps* – number of accuracy-limited steps taken in the solver.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

int **ERKStepGetNumStepAttempts**(void \*arkode\_mem, long int \*step\_attempts)

Returns the cumulative number of steps attempted by the solver (so far).

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *step\_attempts* – number of steps attempted by solver.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

int **ERKStepGetNumRhsEvals**(void \*arkode\_mem, long int \*nf\_evals)

Returns the number of calls to the user's right-hand side function,  $f$  (so far).

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *nf\_evals* – number of calls to the user's  $f(t, y)$  function.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

int **ERKStepGetNumErrTestFails**(void \*arkode\_mem, long int \*netfails)

Returns the number of local error test failures that have occurred (so far).

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *netfails* – number of error test failures.

**Return value:**

- *ARK\_SUCCESS* if successful

- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

```
int ERKStepGetCurrentButcherTable(void *arkode_mem, ARKodeButcherTable *B)
```

Returns the Butcher table currently in use by the solver.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *B* – pointer to the Butcher table structure.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

**Notes:** The *ARKodeButcherTable* data structure is defined as a pointer to the following C structure:

```
typedef struct ARKodeButcherTableMem {  
  
    int q;          /* method order of accuracy */  
    int p;          /* embedding order of accuracy */  
    int stages;    /* number of stages */  
    realtype **A;  /* Butcher table coefficients */  
    realtype *c;   /* canopy node coefficients */  
    realtype *b;   /* root node coefficients */  
    realtype *d;   /* embedding coefficients */  
  
} *ARKodeButcherTable;
```

For more details see §6.

```
int ERKStepGetEstLocalErrors(void *arkode_mem, N_Vector ele)
```

Returns the vector of estimated local truncation errors for the current step.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *ele* – vector of estimated local truncation errors.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

**Notes:** The user must allocate space for *ele*, that will be filled in by this function.

The values returned in *ele* are valid only after a successful call to *ERKStepEvolve()* (i.e., it returned a non-negative value).

The *ele* vector, together with the *eweight* vector from *ERKStepGetErrWeights()*, 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 WRMS 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]*.

```
int ERKStepGetTimestepperStats(void *arkode_mem, long int *expsteps, long int *accsteps, long int  
                               *step_attempts, long int *nf_evals, long int *netfails)
```

Returns many of the most useful time-stepper statistics in a single call.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *expsteps* – number of stability-limited steps taken in the solver.
- *accsteps* – number of accuracy-limited steps taken in the solver.
- *step\_attempts* – number of steps attempted by the solver.
- *nf\_evals* – number of calls to the user’s  $f(t, y)$  function.
- *netfails* – number of error test failures.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

**int *ERKStepGetNumConstrFails*(void \*arkode\_mem, long int \*nconstrfails)**

Returns the cumulative number of constraint test failures (so far).

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *nconstrfails* – number of constraint test failures.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

**Rootfinding optional output functions**

Table 5.8: Rootfinding optional output functions

Optional output	Function name
Array showing roots found	<i>ERKStepGetRootInfo()</i>
No. of calls to user root function	<i>ERKStepGetNumGEvals()</i>

**int *ERKStepGetRootInfo*(void \*arkode\_mem, int \*rootsfound)**

Returns an array showing which functions were found to have a root.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *rootsfound* – array of length *nrtfn* with the indices of the user functions  $g_i$  found to have a root (the value of *nrtfn* was supplied in the call to *ERKStepRootInit()*). For  $i = 0 \dots nrtfn-1$ , *rootsfound*[*i*] is nonzero if  $g_i$  has a root, and 0 if not.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

**Notes:** The user must allocate space for *rootsfound* prior to calling this function.

For the components of  $g_i$  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  $g_i$ .

**int *ERKStepGetNumGEvals*(void \*arkode\_mem, long int \*ngevals)**

Returns the cumulative number of calls made to the user’s root function  $g$ .

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *ngevals* – number of calls made to *g* so far.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

**General usability functions**

The following optional routines may be called by a user to inquire about existing solver parameters, to retrieve stored Butcher tables, write the current Butcher table, or even to test a provided Butcher table to determine its analytical order of accuracy. While none of these would typically be called during the course of solving an initial value problem, these may be useful for users wishing to better understand ERKStep and/or specific Runge–Kutta methods.

Table 5.9: General usability functions

Optional routine	Function name
Output all ERKStep solver parameters	<i>ERKStepWriteParameters()</i>
Output the current Butcher table	<i>ERKStepWriteButcher()</i>

int **ERKStepWriteParameters**(void \*arkode\_mem, FILE \*fp)  
Outputs all ERKStep solver parameters to the provided file pointer.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *fp* – pointer to use for printing the solver parameters.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

**Notes:** The *fp* argument can be `stdout` or `stderr`, or it may point to a specific file created using `fopen`.

When run in parallel, only one process should set a non-NULL value for this pointer, since parameters for all processes would be identical.

int **ERKStepWriteButcher**(void \*arkode\_mem, FILE \*fp)  
Outputs the current Butcher table to the provided file pointer.

**Arguments:**

- *arkode\_mem* – pointer to the ERKStep memory block.
- *fp* – pointer to use for printing the Butcher table.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL

**Notes:** The *fp* argument can be `stdout` or `stderr`, or it may point to a specific file created using `fopen`.

When run in parallel, only one process should set a non-NULL value for this pointer, since tables for all processes would be identical.

### 5.3.2.8 ERKStep re-initialization function

To reinitialize the ERKStep module for the solution of a new problem, where a prior call to `ERKStepCreate()` has been made, the user must call the function `ERKStepReInit()`. The new problem must have the same size as the previous one. This routine retains the current settings for all ERKstep module options and performs the same input checking and initializations that are done in `ERKStepCreate()`, but it performs no memory allocation as it assumes that the existing internal memory is sufficient for the new problem. A call to this re-initialization routine deletes the solution history that was stored internally during the previous integration. Following a successful call to `ERKStepReInit()`, call `ERKStepEvolve()` again for the solution of the new problem.

The use of `ERKStepReInit()` requires that the number of Runge–Kutta stages, denoted by  $s$ , be no larger for the new problem than for the previous problem. This condition is automatically fulfilled if the method order  $q$  is left unchanged.

One important use of the `ERKStepReInit()` function is in the treating of jump discontinuities in the RHS 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 ODE model, using a call to this routine. 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 RHS 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 RHS 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.

`int ERKStepReInit(void *arkode_mem, ARKRhsFn f, realtype t0, N_Vector y0)`

Provides required problem specifications and re-initializes the ERKStep time-stepper module.

#### Arguments:

- `arkode_mem` – pointer to the ERKStep memory block.
- `f` – the name of the C function (of type `ARKRhsFn()`) defining the right-hand side function in  $\dot{y} = f(t, y)$ .
- `t0` – the initial value of  $t$ .
- `y0` – the initial condition vector  $y(t_0)$ .

#### Return value:

- `ARK_SUCCESS` if successful
- `ARK_MEM_NULL` if the ERKStep memory was `NULL`
- `ARK_MEM_FAIL` if a memory allocation failed
- `ARK_ILL_INPUT` if an argument has an illegal value.

**Notes:** All previously set options are retained but may be updated by calling the appropriate “Set” functions.

If an error occurred, `ERKStepReInit()` also sends an error message to the error handler function.

### 5.3.2.9 ERKStep reset function

To reset the ERKStep module to a particular state  $(t_R, y(t_R))$  for the continued solution of a problem, where a prior call to [ERKStepCreate\(\)](#) has been made, the user must call the function [ERKStepReset\(\)](#). Like [ERKStepReInit\(\)](#) this routine retains the current settings for all ERKStep module options and performs no memory allocations but, unlike [ERKStepReInit\(\)](#), this routine performs only a *subset* of the input checking and initializations that are done in [ERKStepCreate\(\)](#). In particular this routine retains all internal counter values and the step size/error history. Following a successful call to [ERKStepReset\(\)](#), call [ERKStepEvolve\(\)](#) again to continue solving the problem. By default the next call to [ERKStepEvolve\(\)](#) will use the step size computed by ERKStep prior to calling [ERKStepReset\(\)](#). To set a different step size or have ERKStep estimate a new step size use [ERKStepSetInitStep\(\)](#).

One important use of the [ERKStepReset\(\)](#) function is in the treating of jump discontinuities in the RHS functions. 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 ODE model, using a call to [ERKStepReset\(\)](#). 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 RHS functions *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 RHS functions (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.

```
int ERKStepReset(void *arkode_mem, realtype tR, N_Vector yR)
```

Resets the current ERKStep time-stepper module state to the provided independent variable value and dependent variable vector.

#### Arguments:

- *arkode\_mem* – pointer to the ERKStep memory block.
- *tR* – the value of the independent variable *t*.
- *yR* – the value of the dependent variable vector  $y(t_R)$ .

#### Return value:

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the ERKStep memory was NULL
- *ARK\_MEM\_FAIL* if a memory allocation failed
- *ARK\_ILL\_INPUT* if an argument has an illegal value.

**Notes:** By default the next call to [ERKStepEvolve\(\)](#) will use the step size computed by ERKStep prior to calling [ERKStepReset\(\)](#). To set a different step size or have ERKStep estimate a new step size use [ERKStepSetInitStep\(\)](#).

All previously set options are retained but may be updated by calling the appropriate “Set” functions.

If an error occurred, [ERKStepReset\(\)](#) also sends an error message to the error handler function.

### 5.3.2.10 ERKStep system resize function

For simulations involving changes to the number of equations and unknowns in the ODE system (e.g. when using spatially-adaptive PDE simulations under a method-of-lines approach), the ERKStep integrator may be “resized” between integration steps, through calls to the `ERKStepResize()` function. This function modifies ERKStep’s internal memory structures to use the new problem size, without destruction of the temporal adaptivity heuristics. It is assumed that the dynamical time scales before and after the vector resize will be comparable, so that all time-stepping heuristics prior to calling `ERKStepResize()` remain valid after the call. If instead the dynamics should be recomputed from scratch, the ERKStep memory structure should be deleted with a call to `ERKStepFree()`, and recreated with a call to `ERKStepCreate()`.

To aid in the vector resize operation, the user can supply a vector resize function that will take as input a vector with the previous size, and transform it in-place to return a corresponding vector of the new size. If this function (of type `ARKVecResizeFn()`) is not supplied (i.e., is set to `NULL`), then all existing vectors internal to ERKStep will be destroyed and re-cloned from the new input vector.

In the case that the dynamical time scale should be modified slightly from the previous time scale, an input `hscale` is allowed, that will rescale the upcoming time step by the specified factor. If a value  $hscale \leq 0$  is specified, the default of 1.0 will be used.

```
int ERKStepResize(void *arkode_mem, N_Vector yR, realtype hscale, realtype tR, ARKVecResizeFn resize, void *resize_data)
```

Re-sizes ERKStep with a different state vector but with comparable dynamical time scale.

#### Arguments:

- `arkode_mem` – pointer to the ERKStep memory block.
- `yR` – the newly-sized solution vector, holding the current dependent variable values  $y(t_R)$ .
- `hscale` – the desired time step scaling factor (i.e. the next step will be of size  $h*hscale$ ).
- `tR` – the current value of the independent variable  $t_R$  (this must be consistent with `yR`).
- `resize` – the user-supplied vector resize function (of type `ARKVecResizeFn()`).
- `resize_data` – the user-supplied data structure to be passed to `resize` when modifying internal ERKStep vectors.

#### Return value:

- `ARK_SUCCESS` if successful
- `ARK_MEM_NULL` if the ERKStep memory was `NULL`
- `ARK_NO_MALLOC` if `arkode_mem` was not allocated.
- `ARK_ILL_INPUT` if an argument has an illegal value.

**Notes:** If an error occurred, `ERKStepResize()` also sends an error message to the error handler function.

If inequality constraint checking is enabled a call to `ERKStepResize()` will disable constraint checking. A call to `ERKStepSetConstraints()` is required to re-enable constraint checking.

### Resizing the absolute tolerance array

If using array-valued absolute tolerances, the absolute tolerance vector will be invalid after the call to `ERKStepResize()`, so the new absolute tolerance vector should be re-set **following** each call to `ERKStepResize()` through a new call to `ERKStepSVtolerances()`.

If scalar-valued tolerances or a tolerance function was specified through either `ERKStepSStolerances()` or `ERKStepWFtolerances()`, then these will remain valid and no further action is necessary.

---

**Note:** For an example showing usage of the similar `ARKStepResize()` routine, see the supplied serial C example problem, `ark_heat1D_adapt.c`.

---

## 5.4 Using the MRIStep time-stepping module

This chapter is concerned with the use of the MRIStep time-stepping module for the solution of multirate initial value problems (IVPs) of the form (2.9) in a C or C++ language setting. The following sections discuss the header files and the layout of the user's main program, and provide descriptions of the MRIStep user-callable functions and user-supplied functions.

The example programs located in the source code `examples/arkode` folder, including those described in the companion document [48], may be helpful as templates for new codes.

MRIStep uses the input and output constants from the shared ARKODE infrastructure. These are defined as needed in this chapter, but for convenience the full list is provided separately in §13.

The relevant information on using MRIStep's C and C++ interfaces is detailed in the following subsections.

### 5.4.1 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 an ODE IVP using the MRIStep module. Most of the steps are independent of the NVECTOR, SUNMATRIX, SUNLINSOL and SUNNONLINSOL implementations used. For the steps that are not, refer to §7, §8, §9, and §10 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. Create the SUNDIALS context object

Call `SUNContext_Create()` to allocate the `SUNContext` object.

3. 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`.

---

4. Set vector of initial values

To set the vector `y0` of initial values, 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

```
y0 = 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 = N_VNew_***(...);
```

and then set its elements by accessing the underlying data where it is located with a call of the form

```
ydata = N_VGetArrayPointer_***(y0);
```

For details on each of SUNDIALS' provided vector implementations, see the corresponding sections in §7 for details.

#### 5. Create an inner stepper object to solve the fast (inner) IVP

- If using ARKStep as the fast (inner) integrator, create the ARKStep object with `ARKStepCreate()` and configure the integrator as desired for evolving the fast time scale. See sections §5.2.1 and §5.2.2.8 for details on configuring ARKStep.

Once the ARKStep object is setup, create an `MRISetInnerStepper` object with `ARKStepCreateMRIS-  
tepInnerStepper()`.

- If supplying a user-defined fast (inner) integrator, create the `MRISetInnerStepper` object as described in section §5.4.8.

---

**Note:** When using ARKStep as a fast (inner) integrator it is the user's responsibility to create, configure, and attach the integrator to the MRISet module. User-specified options regarding how this fast integration should be performed (e.g., adaptive vs. fixed time step, explicit/implicit/ImEx partitioning, algebraic solvers, etc.) will be respected during evolution of the fast time scale during MRISet integration.

Due to the algorithms supported in MRISet, the ARKStep module used for the fast time scale must be configured with an identity mass matrix.

If a `user_data` pointer needs to be passed to user functions called by the fast (inner) integrator then it should be attached here by calling `ARKStepSetUserData()`. This `user_data` pointer will only be passed to user-supplied functions that are attached to the fast (inner) integrator. To supply a `user_data` pointer to user-supplied functions called by the slow (outer) integrator the desired pointer should be attached by calling `MRISetSetUserData()` after creating the MRISet memory below. The `user_data` pointers attached to the inner and outer integrators may be the same or different depending on what is required by the user code.

Specifying a rootfinding problem for the fast integration is not supported. Rootfinding problems should be created and initialized with the slow integrator. See the steps below and `MRISetRootInit()` for more details.

---

#### 6. Create an MRISet object for the slow (outer) integration

Create the MRISet object by calling `MRISetCreate()`. One of the inputs to `MRISetCreate()` is the `MRIS-  
tepInnerStepper` object for solving the fast (inner) IVP created in the previous step.

#### 7. Set the slow step size

Call `MRISetSetFixedStep()` to specify the slow time step size.

#### 8. Create and configure implicit solvers (*as appropriate*)

Specifically, if MRISet is configured with an implicit slow right-hand side function in the prior step, then the following steps are recommended:

1. Specify integration tolerances

Call `MRISetSStolerances()` or `MRISetSVtolerances()` to specify either a scalar relative tolerance and scalar absolute tolerance, or a scalar relative tolerance and a vector of absolute tolerances, respectively. Alternatively, call `MRISetWFtolerances()` to specify a function which sets directly the weights used in evaluating WRMS vector norms. See §5.4.2.2 for details.

2. Create nonlinear solver object

If a non-default nonlinear solver object is desired for implicit MRI stage solves (see §5.4.2.4), then that nonlinear solver object must be created by using the appropriate functions defined by the particular SUNNONLINSOL implementation (e.g., `NLS = SUNNonlinSol_***(...)`; where `***` is the name of the nonlinear solver (see §10 for details).

For the SUNDIALS-supplied SUNNONLINSOL implementations, the nonlinear solver object may be created using a call of the form

```
SUNNonlinearSolver NLS = SUNNonlinSol_*(...);
```

where `*` can be replaced with “Newton”, “FixedPoint”, or other options, as discussed in the sections §5.2.2.5 and §10.

Note: by default, MRISet will use the Newton nonlinear solver (see section §10.3), so a custom nonlinear solver object is only needed when using a *different* solver, or for the user to exercise additional controls over the Newton solver.

3. Attach nonlinear solver module

If a nonlinear solver object was created above, then it must be attached to MRISet using the call (for details see §5.4.2.4):

```
ier = MRISetNonlinearSolver(...);
```

4. Set nonlinear solver optional inputs

Call the appropriate set functions for the selected nonlinear solver module to change optional inputs specific to that nonlinear solver. These *must* be called after attaching the nonlinear solver to MRISet, otherwise the optional inputs will be overridden by MRISet defaults. See §10 for more information on optional inputs.

5. Create matrix object

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

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

```
SUNMatrix A = SUNBandMatrix(...);
```

or similar for other matrix modules (see §8 for further information).

6. Create linear solver object

If a nonlinear solver requiring a linear solver will be used (e.g., a Newton iteration), then the desired linear solver object(s) must be created by using the appropriate functions 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

```
SUNLinearSolver LS = SUNLinSol_*(...);
```

where \* can be replaced with “Dense”, “SPGMR”, or other options, as discussed in §9.

#### 7. 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 §9 for details.

#### 8. Attach linear solver module

If a linear solver was created above for implicit MRI stage solves, initialize the ARKLS linear solver interface by attaching the linear solver object (and Jacobian matrix object, if applicable) with the call (for details see §5.4.2.3):

```
ier = MRIStepSetLinearSolver(...);
```

#### 9. Set optional inputs

Call `MRIStepSet*` functions to change any optional inputs that control the behavior of MRIStep from their default values. See §5.4.2.7 for details.

#### 10. Specify rootfinding problem

Optionally, call `MRIStepRootInit()` to initialize a rootfinding problem to be solved during the integration of the ODE system. See §5.4.2.5 for general details, and §5.4.2.7 for relevant optional input calls.

#### 11. Advance solution in time

For each point at which output is desired, call

```
ier = MRIStepEvolve(arkode_mem, tout, yout, &tret, itask);
```

Here, `itask` specifies the return mode. The vector `yout` (which can be the same as the vector `y0` above) will contain  $y(t_{\text{out}})$ . See §5.4.2.6 for details.

#### 12. Get optional outputs

Call `MRIStepGet*` and/or `ARKStepGet*` functions to obtain optional output from the slow or fast integrators respectively. See §5.4.6.3 and §5.2.2.10 for details.

#### 13. Deallocate memory for solution vector

Upon completion of the integration, deallocate memory for the vector `y` (or `yout`) by calling the NVECTOR destructor function:

```
N_VDestroy(y);
```

#### 14. Free solver memory

- If ARKStep was used as the fast (inner) IVP integrator, call `MRIStepInnerStepper_Free()` and `ARKStepFree()` to free the memory allocated for the fast (inner) integrator.
- If a user-defined fast (inner) integrator was supplied, free the integrator content and call `MRIStepInnerStepper_Free()` to free the `MRIStepInnerStepper` object.
- Call `MRIStepFree()` to free the memory allocated for the slow integration object.

#### 15. Free linear solver and matrix memory (*as appropriate*)

Call `SUNLinSolFree()` and (possibly) `SUNMatDestroy()` to free any memory allocated for any linear solver and/or matrix objects created above for either the fast or slow integrators.

16. Free nonlinear solver memory (*as appropriate*)

If a user-supplied `SUNNonlinearSolver` was provided to `MRIStep`, then call `SUNNonlinSolFree()` to free any memory allocated for the nonlinear solver object created above.

17. **Free the `SUNContext` object** Call `SUNContext_Free()` to free the memory allocated for the `SUNContext` object.

1. Finalize MPI, if used

Call `MPI_Finalize` to terminate MPI.

## 5.4.2 MRIStep User-callable functions

This section describes the functions that are called by the user to setup and then solve an IVP using the MRIStep time-stepping module. Some of these are required; however, starting with §5.4.2.7, the functions listed involve optional inputs/outputs or restarting, and those paragraphs may be skipped for a casual use of ARKODE’s MRIStep module. In any case, refer to the preceding section, §5.4.1, for the correct order of these calls.

On an error, each user-callable function returns a negative value (or `NULL` if the function returns a pointer) and sends an error message to the error handler routine, which prints the message to `stderr` by default. However, the user can set a file as error output or can provide her own error handler function (see §5.4.2.7 for details).

### 5.4.2.1 MRIStep initialization and deallocation functions

```
void *MRIStepCreate(ARKRhsFn fse, ARKRhsFn fsi, realtype t0, N_Vec tor y0, MRIStepInnerStepper stepper,  
SUNContext sunctx)
```

This function allocates and initializes memory for a problem to be solved using the MRIStep time-stepping module in ARKODE.

**Arguments:**

- *fse* – the name of the function (of type `ARKRhsFn()`) defining the explicit slow portion of the right-hand side function in  $\dot{y} = f^E(t, y) + f^I(t, y) + f^F(t, y)$ .
- *fsi* – the name of the function (of type `ARKRhsFn()`) defining the implicit slow portion of the right-hand side function in  $\dot{y} = f^E(t, y) + f^I(t, y) + f^F(t, y)$ .
- *t0* – the initial value of *t*.
- *y0* – the initial condition vector  $y(t_0)$ .
- *stepper* – an `MRIStepInnerStepper` for integrating the fast time scale.
- *sunctx* – the `SUNContext` object (see §4.1)

**Return value:** If successful, a pointer to initialized problem memory of type `void*`, to be passed to all user-facing MRIStep routines listed below. If unsuccessful, a `NULL` pointer will be returned, and an error message will be printed to `stderr`.

**Example usage:**

```
/* fast (inner) and slow (outer) ARKODE objects */  
void *inner_arkode_mem = NULL;  
void *outer_arkode_mem = NULL;  
  
/* MRIStepInnerStepper to wrap the inner (fast) ARKStep object */  
MRIStepInnerStepper stepper = NULL;
```

(continues on next page)

(continued from previous page)

```

/* create an ARKStep object, setting fast (inner) right-hand side
   functions and the initial condition */
inner_arkode_mem = ARKStepCreate(ffe, ffi, t0, y0, sunctx);

/* setup ARKStep */
.

.

/* create MRIStepInnerStepper wrapper for the ARKStep memory block */
flag = ARKStepCreateMRIStepInnerStepper(inner_arkode_mem, &stepper);

/* create an MRIStep object, setting the slow (outer) right-hand side
   functions and the initial condition */
outer_arkode_mem = MRIStepCreate(fse, fsi, t0, y0, stepper, sunctx)

```

**Example codes:**

- examples/arkode/C\_serial/ark\_brusselator\_mri.c
- examples/arkode/C\_serial/ark\_twowaycouple\_mri.c
- examples/arkode/C\_serial/ark\_brusselator\_1D\_mri.c
- examples/arkode/C\_serial/ark\_onewaycouple\_mri.c
- examples/arkode/C\_serial/ark\_reaction\_diffusion\_mri.c
- examples/arkode/C\_serial/ark\_kpr\_mri.c
- examples/arkode/CXX\_parallel/ark\_diffusion\_reaction\_p.cpp

void **MRIStepFree**(void \*\*arkode\_mem)

This function frees the problem memory *arkode\_mem* created by [MRIStepCreate\(\)](#).

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.

**Return value:** None

**5.4.2.2 MRIStep tolerance specification functions**

These functions specify the integration tolerances. One of them **should** be called before the first call to [MRIStepEvolve\(\)](#); otherwise default values of *reltol* = 1e-4 and *abstol* = 1e-9 will be used, which may be entirely incorrect for a specific problem.

The integration tolerances *reltol* and *abstol* define a vector of error weights, *ewt*. In the case of [MRIStepSStolerances\(\)](#), this vector has components

```
ewt[i] = 1.0/(reltol*abs(y[i]) + abstol);
```

whereas in the case of [MRIStepSVtolerances\(\)](#) the vector components are given by

```
ewt[i] = 1.0/(reltol*abs(y[i]) + abstol[i]);
```

This vector is used in all error tests, which use a weighted RMS norm on all error-like vectors *v*:

$$\|v\|_{WRMS} = \left( \frac{1}{N} \sum_{i=1}^N (v_i \text{ } ewt_i)^2 \right)^{1/2},$$

where  $N$  is the problem dimension.

Alternatively, the user may supply a custom function to supply the `ewt` vector, through a call to [`MRISetWFTolerances\(\)`](#).

```
int MRISetSStolerances(void *arkode_mem, realtype reltol, realtype abstol)
```

This function specifies scalar relative and absolute tolerances.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *reltol* – scalar relative tolerance.
- *abstol* – scalar absolute tolerance.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL
- *ARK\_NO\_MALLOC* if the MRIStep memory was not allocated by the time-stepping module
- *ARK\_ILL\_INPUT* if an argument has an illegal value (e.g. a negative tolerance).

```
int MRISetSVtolerances(void *arkode_mem, realtype reltol, N_Vec abstol)
```

This function specifies a scalar relative tolerance and a vector absolute tolerance (a potentially different absolute tolerance for each vector component).

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *reltol* – scalar relative tolerance.
- *abstol* – vector containing the absolute tolerances for each solution component.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL
- *ARK\_NO\_MALLOC* if the MRIStep memory was not allocated by the time-stepping module
- *ARK\_ILL\_INPUT* if an argument has an illegal value (e.g. a negative tolerance).

```
int MRISetWFTolerances(void *arkode_mem, ARKWtFn efun)
```

This function specifies a user-supplied function *efun* to compute the error weight vector `ewt`.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *efun* – the name of the function (of type [`ARKWtFn\(\)`](#)) that implements the error weight vector computation.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL
- *ARK\_NO\_MALLOC* if the MRIStep memory was not allocated by the time-stepping module

## General advice on the 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 a value of  $10^{-4}$  means that errors are controlled to .01%. We do not recommend using `reltol` larger than  $10^{-3}$ . On the other hand, `reltol` should not be so small that it is comparable to the unit roundoff of the machine arithmetic (generally around  $10^{-15}$  for double-precision).
- (2) The absolute tolerances `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 `abstol` (if scalar) or `abstol[i]` (if a vector) needs to be set to that noise level. If the different components have different noise levels, then `abstol` should be a vector. For example, see the example problem `ark_robertson.c`, and the discussion of it in the ARKODE Examples Documentation [48]. In that problem, the three components vary between 0 and 1, and have different noise levels; hence the `atols` vector therein. It is impossible to give any general advice on `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 step. The final (global) errors are an accumulation of those per-step errors, where that accumulation factor is problem-dependent. A general rule of thumb is to reduce the tolerances by a factor of 10 from the actual desired limits on errors. So if you want .01% relative accuracy (globally), a good choice for `reltol` is  $10^{-5}$ . 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 nonphysical 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 (nonphysical) values can then occur. In most cases, these values are harmless, and simply need to be controlled, not eliminated, but in other cases any value that violates a constraint may cause a simulation to halt. For both of these scenarios the following pieces of advice are relevant.

- (1) The best 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  $y$  returned by MRIStep, with magnitude comparable to `abstol` or less, is equivalent to zero as far as the computation is concerned.
- (3) The user's right-hand side routine  $f^I$  should never change a negative value in the solution vector  $y$  to a non-negative value in attempt to "fix" this problem, since this can lead to numerical instability. If the  $f^I$  routine cannot tolerate a zero or negative value (e.g. because there is a square root or log), then the offending value should be changed to zero or a tiny positive number in a temporary variable (not in the input  $y$  vector) for the purposes of computing  $f^I(t, y)$ .

### 5.4.2.3 Linear solver interface functions

As previously explained, the Newton iterations used in solving implicit systems within MRIStep require the solution of linear systems of the form

$$\mathcal{A} \left( z_i^{(m)} \right) \delta^{(m+1)} = -G \left( z_i^{(m)} \right)$$

where

$$\mathcal{A} \approx I - \gamma J, \quad J = \frac{\partial f^I}{\partial y}.$$

ARKODE's ARKLS linear solver interface supports all valid `SUNLinearSolver` modules for this task.

Matrix-based `SUNLinearSolver` modules utilize `SUNMatrix` objects to store the approximate Jacobian matrix  $J$ , the Newton matrix  $\mathcal{A}$ , and, when using direct solvers, the factorizations used throughout the solution process.

Matrix-free `SUNLinearSolver` modules instead use iterative methods to solve the Newton systems of equations, and only require the *action* of the matrix on a vector,  $\mathcal{A}v$ . With most of these methods, 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. For the specification of a preconditioner, see the iterative linear solver portions of §5.4.2.7 and §5.5.

If preconditioning is done, user-supplied functions should be used to define left and right preconditioner matrices  $P_1$  and  $P_2$  (either of which could be the identity matrix), such that the product  $P_1P_2$  approximates the Newton matrix  $\mathcal{A} = I - \gamma J$ .

To specify a generic linear solver for MRIStep to use for the Newton systems, after the call to `MRISetCreate()` but before any calls to `MRISetEvolve()`, the user's program must create the appropriate `SUNLinearSolver` object and call the function `MRISetLinearSolver()`, 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

```
SUNLinearSolver LS = SUNLinSol_*(...);
```

The current list of SUNDIALS-packaged `SUNLinSol` modules, and their constructor routines, may be found in chapter §9. Alternately, a user-supplied `SUNLinearSolver` module may be created and used. Specific information on how to create such user-provided modules may be found in §9.1.8.

Once this solver object has been constructed, the user should attach it to MRIStep via a call to `MRISetLinearSolver()`. The first argument passed to this function is the MRIStep memory pointer returned by `MRISetCreate()`; the second argument is the `SUNLinearSolver` object created above. The third argument is an optional `SUNMatrix` object to accompany matrix-based `SUNLinearSolver` inputs (for matrix-free linear solvers, the third argument should be `NULL`). A call to this function initializes the ARKLS linear solver interface, linking it to the MRIStep integrator, and allows the user to specify additional parameters and routines pertinent to their choice of linear solver.

```
int MRISetLinearSolver(void *arkode_mem, SUNLinearSolver LS, SUNMatrix J)
```

This function specifies the `SUNLinearSolver` object that MRIStep should use, as well as a template Jacobian `SUNMatrix` object (if applicable).

#### Arguments:

- `arkode_mem` – pointer to the MRIStep memory block.
- `LS` – the `SUNLinearSolver` object to use.
- `J` – the template Jacobian `SUNMatrix` object to use (or `NULL` if not applicable).

#### Return value:

- `ARKLS_SUCCESS` if successful
- `ARKLS_MEM_NULL` if the MRIStep memory was `NULL`

- *ARKLS\_MEM\_FAIL* if there was a memory allocation failure
- *ARKLS\_ILL\_INPUT* if ARKLS is incompatible with the provided *LS* or *J* input objects, or the current *N\_Vector* module.

**Notes:** If *LS* is a matrix-free linear solver, then the *J* argument should be *NULL*.

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 §8 for further information).

When using sparse linear solvers, it is typically much more efficient to supply *J* so that it includes the full sparsity pattern of the Newton system matrices  $\mathcal{A} = I - \gamma J$ , even if *J* itself has zeros in nonzero locations of *I*. The reasoning for this is that  $\mathcal{A}$  is constructed in-place, on top of the user-specified values of *J*, so if the sparsity pattern in *J* is insufficient to store  $\mathcal{A}$  then it will need to be resized internally by MRIStep.

#### 5.4.2.4 Nonlinear solver interface functions

When changing the nonlinear solver in MRIStep, after the call to *MRISetCreate()* but before any calls to *MRISetEvolve()*, the user's program must create the appropriate *SUNNonlinSol* object and call *MRISetNonlinearSolver()*, as documented below. If any calls to *MRISetEvolve()* have been made, then MRIStep will need to be reinitialized by calling *MRISetReInit()* to ensure that the nonlinear solver is initialized correctly before any subsequent calls to *MRISetEvolve()*.

The first argument passed to the routine *MRISetNonlinearSolver()* is the MRIStep memory pointer returned by *MRISetCreate()*; the second argument passed to this function is the desired *SUNNonlinearSolver* object to use for solving the nonlinear system for each implicit stage. A call to this function attaches the nonlinear solver to the main MRIStep integrator.

```
int MRISetNonlinearSolver(void *arkode_mem, SUNNonlinearSolver NLS)
```

This function specifies the *SUNNonlinearSolver* object that MRIStep should use for implicit stage solves.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *NLS* – the *SUNNonlinearSolver* object to use.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was *NULL*
- *ARK\_MEM\_FAIL* if there was a memory allocation failure
- *ARK\_ILL\_INPUT* if MRIStep is incompatible with the provided *NLS* input object.

**Notes:** MRIStep will use the Newton *SUNNonlinearSolver* module by default; a call to this routine replaces that module with the supplied *NLS* object.

### 5.4.2.5 Rootfinding initialization function

As described in the section §2.11, while solving the IVP, ARKODE's time-stepping modules have the capability to find the roots of a set of user-defined functions. In the MRIStep module root finding is performed between slow solution time steps only (i.e., it is not performed within the sub-stepping a fast time scales). To activate the root-finding algorithm, call the following function. This is normally called only once, prior to the first call to `MRIStepEvolve()`, but if the rootfinding problem is to be changed during the solution, `MRIStepRootInit()` can also be called prior to a continuation call to `MRIStepEvolve()`.

```
int MRIStepRootInit(void *arkode_mem, int nrtfn, ARKRootFn g)
```

Initializes a rootfinding problem to be solved during the integration of the ODE system. It must be called after `MRIStepCreate()`, and before `MRIStepEvolve()`.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *nrtfn* – number of functions  $g_i$ , an integer  $\geq 0$ .
- *g* – name of user-supplied function, of type `ARKRootFn()`, defining the functions  $g_i$  whose roots are sought.

**Return value:**

- `ARK_SUCCESS` if successful
- `ARK_MEM_NULL` if the MRIStep memory was `NULL`
- `ARK_MEM_FAIL` if there was a memory allocation failure
- `ARK_ILL_INPUT` if *nrtfn* is greater than zero but *g* = `NULL`.

**Notes:** To disable the rootfinding feature after it has already been initialized, or to free memory associated with MRIStep's rootfinding module, call `MRIStepRootInit` with *nrtfn* = 0.

Similarly, if a new IVP is to be solved with a call to `MRIStepReInit()`, where the new IVP has no rootfinding problem but the prior one did, then call `MRIStepRootInit` with *nrtfn* = 0.

Rootfinding is only supported for the slow (outer) integrator and should not be activated for the fast (inner) integrator.

### 5.4.2.6 MRIStep solver function

This is the central step in the solution process – the call to perform the integration of the IVP. The input argument *itask* specifies one of two modes as to where MRIStep is to return a solution. These modes are modified if the user has set a stop time (with a call to the optional input function `MRIStepSetStopTime()`) or has requested rootfinding.

```
int MRIStepEvolve(void *arkode_mem, realtype tout, N_Vector yout, realtype *tret, int itask)
```

Integrates the ODE over an interval in *t*.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *tout* – the next time at which a computed solution is desired.
- *yout* – the computed solution vector.
- *tret* – the time corresponding to *yout* (output).
- *itask* – a flag indicating the job of the solver for the next user step.

The `ARK_NORMAL` option causes the solver to take internal steps until it has just overtaken a user-specified output time, *tout*, in the direction of integration, i.e.  $t_{n-1} < tout \leq t_n$  for forward integration,

or  $t_n \leq tout < t_{n-1}$  for backward integration. It will then compute an approximation to the solution  $y(tout)$  by interpolation (as described in §2.2).

The `ARK_ONE_STEP` option tells the solver to only take a single internal step  $y_{n-1} \rightarrow y_n$  and then return control back to the calling program. If this step will overtake  $tout$  then the solver will again return an interpolated result; otherwise it will return a copy of the internal solution  $y_n$  in the vector  $yout$ .

**Return value:**

- `ARK_SUCCESS` if successful.
- `ARK_ROOT_RETURN` if `MRIStepEvolve()` succeeded, and found one or more roots. If the number of root functions,  $nrfni$ , is greater than 1, call `MRIStepGetRootInfo()` to see which  $g_i$  were found to have a root at (\**tret*).
- `ARK_TSTOP_RETURN` if `MRIStepEvolve()` succeeded and returned at *tstop*.
- `ARK_MEM_NULL` if the `arkode_mem` argument was NULL.
- `ARK_NO_MALLOC` if `arkode_mem` was not allocated.
- `ARK_ILL_INPUT` if one of the inputs to `MRIStepEvolve()` is illegal, or some other input to the solver was either illegal or missing. Details will be provided in the error message. Typical causes of this failure:
  - (a) A component of the error weight vector became zero during internal time-stepping.
  - (b) The linear solver initialization function (called by the user after calling `ARKStepCreate()`) failed to set the linear solver-specific *lsolve* field in `arkode_mem`.
  - (c) A root of one of the root functions was found both at a point *t* and also very near *t*.
- `ARK_TOO MUCH_WORK` if the solver took *mxstep* internal steps but could not reach *tout*. The default value for *mxstep* is `MXSTEP_DEFAULT = 500`.
- `ARK_CONV_FAILURE` if convergence test failures occurred too many times (*ark\_maxncf*) during one internal time step.
- `ARK_LINIT_FAIL` if the linear solver's initialization function failed.
- `ARK_LSETUP_FAIL` if the linear solver's setup routine failed in an unrecoverable manner.
- `ARK_LSOLVE_FAIL` if the linear solver's solve routine failed in an unrecoverable manner.
- `ARK_VECTOROP_ERR` a vector operation error occurred.
- `ARK_INNERSTEP_FAILED` if the inner stepper returned with an unrecoverable error. The value returned from the inner stepper can be obtained with `MRIStepGetLastInnerStepFlag()`.
- `ARK_INVALID_TABLE` if an invalid coupling table was provided.

**Notes:** The input vector *yout* can use the same memory as the vector *y0* of initial conditions that was passed to `MRIStepCreate()`.

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

All failure return values are negative and so testing the return argument for negative values will trap all `MRIStepEvolve()` failures.

Since interpolation may reduce the accuracy in the reported solution, if full method accuracy is desired the user should issue a call to `MRIStepSetStopTime()` before the call to `MRIStepEvolve()` to specify a fixed stop time to end the time step and return to the user. Upon return from `MRIStepEvolve()`, a copy of the

internal solution  $y_n$  will be returned in the vector  $yout$ . Once the integrator returns at a  $tstop$  time, any future testing for  $tstop$  is disabled (and can be re-enabled only though a new call to [`MRISetStepSetStopTime\(\)`](#)).

On any error return in which one or more internal steps were taken by [`MRISetEvolve\(\)`](#), the returned values of  $tret$  and  $yout$  correspond to the farthest point reached in the integration. On all other error returns,  $tret$  and  $yout$  are left unchanged from those provided to the routine.

#### 5.4.2.7 Optional input functions

There are numerous optional input parameters that control the behavior of MRISet, each of which may be modified from its default value through calling an appropriate input function. The following tables list all optional input functions, grouped by which aspect of MRISet they control. Detailed information on the calling syntax and arguments for each function are then provided following each table.

The optional inputs are grouped into the following categories:

- General MRISet options ([§5.4.2.7](#)),
- IVP method solver options ([§5.4.2.7](#)),
- Implicit stage solver options ([§5.4.2.7](#)),
- Linear solver interface options ([§5.4.2.7](#)), and
- Rootfinding options ([§5.4.6.1](#)).

For the most casual use of MRISet, relying on the default set of solver parameters, the reader can skip to the section on user-supplied functions, [§5.5](#).

We note that, on an error return, all of the optional input functions send an error message to the error handler function. All error return values are negative, so a test on the return arguments for negative values will catch all errors. Finally, a call to an `MRISetSet***` function can generally be made from the user's calling program at any time and, if successful, takes effect immediately. `MRISetSet***` functions that cannot be called at any time note this in the "Notes:" section of the function documentation.

#### Optional inputs for MRISet

Table 5.10: Optional inputs for MRISet

Optional input	Function name	Default
Return MRISet solver parameters to their defaults	<a href="#"><code>MRISetSetDefaults()</code></a>	internal
Set dense output interpolation type	<a href="#"><code>MRISetSetInterpolantType()</code></a>	ARK_INTERP_HERMITE
Set dense output polynomial degree	<a href="#"><code>MRISetSetInterpolantDegree()</code></a>	5
Supply a pointer to a diagnostics output file	<a href="#"><code>MRISetSetDiagnostics()</code></a>	NULL
Supply a pointer to an error output file	<a href="#"><code>MRISetSetErrFile()</code></a>	stderr
Supply a custom error handler function	<a href="#"><code>MRISetSetErrorHandlerFn()</code></a>	internal fn
Run with fixed-step sizes	<a href="#"><code>MRISetSetFixedStep()</code></a>	required
Maximum no. of warnings for $t_n + h = t_n$	<a href="#"><code>MRISetSetMaxHnilWarns()</code></a>	10
Maximum no. of internal steps before $tout$	<a href="#"><code>MRISetSetMaxNumSteps()</code></a>	500
Set a value for $t_{stop}$	<a href="#"><code>MRISetSetStopTime()</code></a>	$\infty$
Supply a pointer for user data	<a href="#"><code>MRISetSetUserData()</code></a>	NULL
Supply a function to be called prior to the inner integration	<a href="#"><code>MRISetSetPreInnerFn()</code></a>	NULL
Supply a function to be called after the inner integration	<a href="#"><code>MRISetSetPostInnerFn()</code></a>	NULL

---

```
int MRIStepSetDefaults(void *arkode_mem)
```

Resets all optional input parameters to MRIStep's original default values.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** This function does not change problem-defining function pointers *fs* and *ff* or the *user\_data* pointer. It also does not affect any data structures or options related to root-finding (those can be reset using [MRIStepRootInit\(\)](#)).

```
int MRIStepSetInterpolantType(void *arkode_mem, int itype)
```

Specifies use of the Lagrange or Hermite interpolation modules (used for dense output – interpolation of solution output values and implicit method predictors).

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *itype* – requested interpolant type (*ARK\_INTERP\_HERMITE* or *ARK\_INTERP\_LAGRANGE*)

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory is NULL
- *ARK\_MEM\_FAIL* if the interpolation module cannot be allocated
- *ARK\_ILL\_INPUT* if the *itype* argument is not recognized or the interpolation module has already been initialized

**Notes:** The Hermite interpolation module is described in §2.2.1, and the Lagrange interpolation module is described in §2.2.2.

This routine frees any previously-allocated interpolation module, and re-creates one according to the specified argument. Thus any previous calls to [MRIStepSetInterpolantDegree\(\)](#) will be nullified.

This routine must be called *after* the call to [MRIStepCreate\(\)](#). After the first call to [MRIStepEvolve\(\)](#) the interpolation type may not be changed without first calling [MRIStepReInit\(\)](#).

If this routine is not called, the Hermite interpolation module will be used.

```
int MRIStepSetInterpolantDegree(void *arkode_mem, int degree)
```

Specifies the degree of the polynomial interpolant used for dense output (i.e. interpolation of solution output values and implicit method predictors).

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *degree* – requested polynomial degree.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory or interpolation module are NULL

- *ARK\_INTERP\_FAIL* if this is called after [MRIStepEvolve\(\)](#)
- *ARK\_ILL\_INPUT* if an argument has an illegal value or the interpolation module has already been initialized

**Notes:** Allowed values are between 0 and 5.

This routine should be called *after* [MRIStepCreate\(\)](#) and *before* [MRIStepEvolve\(\)](#). After the first call to [MRIStepEvolve\(\)](#) the interpolation degree may not be changed without first calling [MRIStepReInit\(\)](#).

If a user calls both this routine and [MRIStepSetInterpolantType\(\)](#), then [MRIStepSetInterpolantType\(\)](#) must be called first.

Since the accuracy of any polynomial interpolant is limited by the accuracy of the time-step solutions on which it is based, the *actual* polynomial degree that is used by MRIStep will be the minimum of  $q - 1$  and the input *degree*, where  $q$  is the order of accuracy for the time integration method.

int **MRIStepSetDenseOrder**(void \*arkode\_mem, int dord)

*This function is deprecated, and will be removed in a future release. Users should transition to calling [MRIStepSetInterpolantDegree\(\)](#) instead.*

int **MRIStepSetDiagnostics**(void \*arkode\_mem, FILE \*diagfp)

Specifies the file pointer for a diagnostics file where all MRIStep step adaptivity and solver information is written.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *diagfp* – pointer to the diagnostics output file.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** This parameter can be `stdout` or `stderr`, although the suggested approach is to specify a pointer to a unique file opened by the user and returned by `fopen`. If not called, or if called with a NULL file pointer, all diagnostics output is disabled.

When run in parallel, only one process should set a non-NUL value for this pointer, since statistics from all processes would be identical.

int **MRIStepSetErrFile**(void \*arkode\_mem, FILE \*errfp)

Specifies a pointer to the file where all MRIStep warning and error messages will be written if the default internal error handling function is used.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *errfp* – pointer to the output file.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The default value for *errfp* is `stderr`.

Passing a NULL value disables all future error message output (except for the case wherein the MRIStep memory pointer is NULL). This use of the function is strongly discouraged.

If used, this routine should be called before any other optional input functions, in order to take effect for subsequent error messages.

**int MRIStepSetErrorHandlerFn(void \*arkode\_mem, *ARKErrHandlerFn* ehfun, void \*eh\_data)**

Specifies the optional user-defined function to be used in handling error messages.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *ehfun* – name of user-supplied error handler function.
- *eh\_data* – pointer to user data passed to *ehfun* every time it is called.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Error messages indicating that the MRIStep solver memory is NULL will always be directed to `stderr`.

**int MRIStepSetFixedStep(void \*arkode\_mem, *realtype* hs)**

Set the slow step size used within MRIStep for the following internal step(s).

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *hs* – value of the outer (slow) step size.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:**

The step sizes used by the inner (fast) stepper may be controlled through calling the appropriate “Set” routines on the inner integrator.

**int MRIStepSetMaxHnilWarns(void \*arkode\_mem, int mxhnil)**

Specifies the maximum number of messages issued by the solver to warn that  $t + h = t$  on the next internal step, before MRIStep will instead return with an error.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *mxhnil* – maximum allowed number of warning messages ( $> 0$ ).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The default value is 10; set *mxhnil* to zero to specify this default.

A negative value indicates that no warning messages should be issued.

int **MRISetSetMaxNumSteps**(void \*arkode\_mem, long int mxsteps)

Specifies the maximum number of steps to be taken by the solver in its attempt to reach the next output time, before MRISet will return with an error.

**Arguments:**

- *arkode\_mem* – pointer to the MRISet memory block.
- *mxsteps* – maximum allowed number of internal steps.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRISet memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Passing *mxsteps* = 0 results in MRISet using the default value (500).

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

int **MRISetSetStopTime**(void \*arkode\_mem, *realtype* tstop)

Specifies the value of the independent variable *t* past which the solution is not to proceed.

**Arguments:**

- *arkode\_mem* – pointer to the MRISet memory block.
- *tstop* – stopping time for the integrator.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRISet memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The default is that no stop time is imposed.

int **MRISetSetUserData**(void \*arkode\_mem, void \*user\_data)

Specifies the user data block *user\_data* for the outer integrator and attaches it to the main MRISet memory block.

**Arguments:**

- *arkode\_mem* – pointer to the MRISet memory block.
- *user\_data* – pointer to the user data.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRISet memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** If specified, the pointer to *user\_data* is passed to all user-supplied functions called by the outer integrator for which it is an argument; otherwise NULL is passed.

To attach a user data block to the inner integrator call the appropriate *SetUserData* function for the inner integrator memory structure (e.g., [ARKStepSetUserData\(\)](#) if the inner stepper is ARKStep). This pointer may be the same as or different from the pointer attached to the outer integrator depending on what is required by the user code.

`int MRIStepSetPreInnerFn(void *arkode_mem, MRIStepPreInnerFn prefn)`

Specifies the function called *before* each inner integration.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *prefn* – the name of the C function (of type `MRIStepPreInnerFn()`) defining pre inner integration function.

**Return value:**

- `ARK_SUCCESS` if successful
- `ARK_MEM_NULL` if the MRIStep memory is NULL

`int MRIStepSetPostInnerFn(void *arkode_mem, MRIStepPostInnerFn postfn)`

Specifies the function called *after* each inner integration.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *postfn* – the name of the C function (of type `MRIStepPostInnerFn()`) defining post inner integration function.

**Return value:**

- `ARK_SUCCESS` if successful
- `ARK_MEM_NULL` if the MRIStep memory is NULL

## Optional inputs for IVP method selection

Table 5.11: Optional inputs for IVP method selection

Optional input	Function name	Default
Set MRI coupling coefficients	<code>MRIStepSetCoupling()</code>	internal

`int MRIStepSetCoupling(void *arkode_mem, MRIStepCoupling C)`

Specifies a customized set of slow-to-fast coupling coefficients for the MRI method.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *C* – the table of coupling coefficients for the MRI method.

**Return value:**

- `ARK_SUCCESS` if successful
- `ARK_MEM_NULL` if the MRIStep memory is NULL
- `ARK_ILL_INPUT` if an argument has an illegal value

**Notes:**

For a description of the `MRIStepCoupling` type and related functions for creating Butcher tables see §5.4.7.

## Optional inputs for implicit stage solves

The mathematical explanation for the nonlinear solver strategies used by MRIStep, including how each of the parameters below is used within the code, is provided in §2.10.1.

Optional input	Function name	Default
Specify linearly implicit $f^I$	<a href="#">MRIStepSetLinear()</a>	SUNFALSE
Specify nonlinearly implicit $f^I$	<a href="#">MRIStepSetNonlinear()</a>	SUNTRUE
Implicit predictor method	<a href="#">MRIStepSetPredictorMethod()</a>	0
Maximum number of nonlinear iterations	<a href="#">MRIStepSetMaxNonlinIters()</a>	3
Coefficient in the nonlinear convergence test	<a href="#">MRIStepSetNonlinConvCoef()</a>	0.1
Nonlinear convergence rate constant	<a href="#">MRIStepSetNonlinCRDown()</a>	0.3
Nonlinear residual divergence ratio	<a href="#">MRIStepSetNonlinRDiv()</a>	2.3
User-provided implicit stage predictor	<a href="#">MRIStepSetStagePredictFn()</a>	NULL
RHS function for nonlinear system evaluations	<a href="#">MRIStepSetNlsRhsFn()</a>	NULL

int [MRIStepSetLinear](#)(void \*arkode\_mem, int timedepend)

Specifies that the implicit slow right-hand side function,  $f^I(t, y)$  is linear in  $y$ .

### Arguments:

- *arkode\_mem* – pointer to the MRIStep memory block.
- *timedepend* – flag denoting whether the Jacobian of  $f^I(t, y)$  is time-dependent (1) or not (0). Alternately, when using a matrix-free iterative linear solver this flag denotes time dependence of the preconditioner.

### Return value:

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Tightens the linear solver tolerances and takes only a single Newton iteration. Calls [MRIStepSetDeltaGammaMax\(\)](#) to enforce Jacobian recomputation when the step size ratio changes by more than 100 times the unit roundoff (since nonlinear convergence is not tested). Only applicable when used in combination with the modified or inexact Newton iteration (not the fixed-point solver).

The only SUNDIALS-provided SUNNonlinearSolver module that is compatible with the [MRIStepSetLinear\(\)](#) option is the Newton solver.

int [MRIStepSetNonlinear](#)(void \*arkode\_mem)

Specifies that the implicit slow right-hand side function,  $f^I(t, y)$  is nonlinear in  $y$ .

### Arguments:

- *arkode\_mem* – pointer to the MRIStep memory block.

### Return value:

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** This is the default behavior of MRIStep, so the function is primarily useful to undo a previous call to [MRIStepSetLinear\(\)](#). Calls [MRIStepSetDeltaGammaMax\(\)](#) to reset the step size ratio threshold to the default value.

---

**int MRIStepSetPredictorMethod**(void \*arkode\_mem, int method)

Specifies the method to use for predicting implicit solutions.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *method* – method choice ( $0 \leq \text{method} \leq 4$ ):
  - 0 is the trivial predictor,
  - 1 is the maximum order (dense output) predictor,
  - 2 is the variable order predictor, that decreases the polynomial degree for more distant RK stages,
  - 3 is the cutoff order predictor, that uses the maximum order for early RK stages, and a first-order predictor for distant RK stages,
  - 4 is the bootstrap predictor, that uses a second-order predictor based on only information within the current step. **deprecated**

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The default value is 0. If *method* is set to an undefined value, this default predictor will be used.

**The “bootstrap” predictor (option 4 above) has been deprecated, and will be removed from a future release.**

**int MRIStepSetMaxNonlinIters**(void \*arkode\_mem, int maxcor)

Specifies the maximum number of nonlinear solver iterations permitted per slow MRI stage within each time step.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *maxcor* – maximum allowed solver iterations per stage ( $> 0$ ).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value or if the SUNNONLINSOL module is NULL
- *ARK\_NLS\_OP\_ERR* if the SUNNONLINSOL object returned a failure flag

**Notes:** The default value is 3; set *maxcor*  $\leq 0$  to specify this default.

**int MRIStepSetNonlinConvCoef**(void \*arkode\_mem, *realtype* nlscoef)

Specifies the safety factor used within the nonlinear solver convergence test.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *nlscoef* – coefficient in nonlinear solver convergence test ( $> 0.0$ ).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory is NULL

- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The default value is 0.1; set  $nlscoef \leq 0$  to specify this default.

int **MRISetStepNonlinCRDown**(void \*arkode\_mem, *realtype* crdown)

Specifies the constant used in estimating the nonlinear solver convergence rate.

**Arguments:**

- *arkode\_mem* – pointer to the MRISet memory block.
- *crdown* – nonlinear convergence rate estimation constant (default is 0.3).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRISet memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any non-positive parameter will imply a reset to the default value.

int **MRISetStepNonlinRDiv**(void \*arkode\_mem, *realtype* rdiv)

Specifies the nonlinear correction threshold beyond which the iteration will be declared divergent.

**Arguments:**

- *arkode\_mem* – pointer to the MRISet memory block.
- *rdiv* – tolerance on nonlinear correction size ratio to declare divergence (default is 2.3).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRISet memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any non-positive parameter will imply a reset to the default value.

int **MRISetStepStagePredictFn**(void \*arkode\_mem, *ARKStagePredictFn* PredictStage)

Sets the user-supplied function to update the implicit stage predictor prior to execution of the nonlinear or linear solver algorithms that compute the implicit stage solution.

**Arguments:**

- *arkode\_mem* – pointer to the MRISet memory block.
- *PredictStage* – name of user-supplied predictor function. If NULL, then any previously-provided stage prediction function will be disabled.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRISet memory is NULL

**Notes:** See §5.5.7 for more information on this user-supplied routine.

int **MRISetNlsRhsFn**(void \*arkode\_mem, *ARKRhsFn* nls\_fs)

Specifies an alternative implicit slow right-hand side function for evaluating  $f^I(t, y)$  within nonlinear system function evaluations.

**Arguments:**

- *arkode\_mem* – pointer to the MRISet memory block.

- *nls\_fs* – the alternative C function for computing the right-hand side function  $f^I(t, y)$  in the ODE.

**Return value:**

- *ARK\_SUCCESS* if successful.
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL.

**Notes:** The default is to use the implicit slow right-hand side function provided to [MRIStepCreate\(\)](#) in non-linear system functions. If the input implicit slow right-hand side function is NULL, the default is used.

When using a non-default nonlinear solver, this function must be called *after* [MRIStepSetNonlinearSolver\(\)](#).

### Linear solver interface optional input functions

The mathematical explanation of the linear solver methods available to MRIStep is provided in §2.10.2. We group the user-callable routines into four categories: general routines concerning the update frequency for matrices and/or preconditioners, 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.

#### 5.4.3 Optional inputs for the ARKLS linear solver interface

As discussed in §2.10.2.3, ARKODE strives to reuse matrix and preconditioner data for as many solves as possible to amortize the high costs of matrix construction and factorization. To that end, MRIStep provides user-callable routines to modify this behavior. Recall that the Newton system matrices that arise within an implicit stage solve are  $\mathcal{A}(t, z) \approx I - \gamma J(t, z)$ , where the implicit right-hand side function has Jacobian matrix  $J(t, z) = \frac{\partial f^I(t, z)}{\partial z}$ .

The matrix or preconditioner for  $\mathcal{A}$  can only be updated within a call to the linear solver ‘setup’ routine. In general, the frequency with which the linear solver setup routine is called may be controlled with the *msbp* argument to [MRIStepSetLSetupFrequency\(\)](#). When this occurs, the validity of  $\mathcal{A}$  for successive time steps intimately depends on whether the corresponding  $\gamma$  and  $J$  inputs remain valid.

At each call to the linear solver setup routine the decision to update  $\mathcal{A}$  with a new value of  $\gamma$ , and to reuse or reevaluate Jacobian information, depends on several factors including:

- the success or failure of previous solve attempts,
- the success or failure of the previous time step attempts,
- the change in  $\gamma$  from the value used when constructing  $\mathcal{A}$ , and
- the number of steps since Jacobian information was last evaluated.

The frequency with which to update Jacobian information can be controlled with the *msbj* argument to [MRIStepSetJacEvalFrequency\(\)](#). We note that this is only checked *within* calls to the linear solver setup routine, so values *msbj* < *msbp* do not make sense. For linear-solvers with user-supplied preconditioning the above factors are used to determine whether to recommend updating the Jacobian information in the preconditioner (i.e., whether to set *jok* to SUNFALSE in calling the user-supplied [ARKLsPrecSetupFn\(\)](#)). For matrix-based linear solvers these factors determine whether the matrix  $J(t, y) = \frac{\partial f^I(t, y)}{\partial y}$  should be updated (either with an internal finite difference approximation or a call to the user-supplied [ARKLsJacFn](#)); if not then the previous value is reused and the system matrix  $\mathcal{A}(t, y) \approx I - \gamma J(t, y)$  is recomputed using the current  $\gamma$  value.

Optional input	Function name	Default
Max change in step signaling new $J$	<a href="#">MRIStepSetDeltaGammaMax()</a>	0.2
Linear solver setup frequency	<a href="#">MRIStepSetLSetupFrequency()</a>	20
Jacobian / preconditioner update frequency	<a href="#">MRIStepSetJacEvalFrequency()</a>	51

int **MRISetStepDeltaGammaMax**(void \*arkode\_mem, *realtype* dgmax)

Specifies a scaled step size ratio tolerance, beyond which the linear solver setup routine will be signaled.

**Arguments:**

- *arkode\_mem* – pointer to the MRISet memory block.
- *dgmax* – tolerance on step size ratio change before calling linear solver setup routine (default is 0.2).

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRISet memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** Any non-positive parameter will imply a reset to the default value.

int **MRISetStepLSetupFrequency**(void \*arkode\_mem, int msbp)

Specifies the frequency of calls to the linear solver setup routine.

**Arguments:**

- *arkode\_mem* – pointer to the MRISet memory block.
- *msbp* – the linear solver setup frequency.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRISet memory is NULL

**Notes:** Positive values of **msbp** specify the linear solver setup frequency. For example, an input of 1 means the setup function will be called every time step while an input of 2 means it will be called every other time step. If **msbp** is 0, the default value of 20 will be used. A negative value forces a linear solver step at each implicit stage.

int **MRISetStepJacEvalFrequency**(void \*arkode\_mem, long int msbj)

Specifies the frequency for recomputing the Jacobian or recommending a preconditioner update.

**Arguments:**

- *arkode\_mem* – pointer to the MRISet memory block.
- *msbj* – the Jacobian re-computation or preconditioner update frequency.

**Return value:**

- *ARKLS\_SUCCESS* if successful.
- *ARKLS\_MEM\_NULL* if the MRISet memory was NULL.
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL.

**Notes:** The Jacobian update frequency is only checked *within* calls to the linear solver setup routine, as such values of  $msbj < msbp$  will result in recomputing the Jacobian every  $msbp$  steps. See [MRISetStepLSetupFrequency\(\)](#) for setting the linear solver setup frequency  $msbp$ .

Passing a value  $msbj \leq 0$  indicates to use the default value of 50.

This function must be called *after* the ARKLS system solver interface has been initialized through a call to [MRISetStepLinearSolver\(\)](#).

#### 5.4.4 Optional inputs for matrix-based SUNLinearSolver modules

Optional input	Function name	Default
Jacobian function	<code>MRISetJacFn()</code>	DQ
Linear system function	<code>MRISetLinSysFn()</code>	internal
Enable or disable linear solution scaling	<code>MRISetLinearSolutionScaling()</code>	on

When using matrix-based linear solver modules, the ARKLS solver interface needs a function to compute an approximation to the Jacobian matrix  $J(t, y)$  or the linear system  $I - \gamma J$ . The function to evaluate the Jacobian must be of type `ARKLsJacFn()`. The user can supply a custom Jacobian function, or if using a dense or banded  $J$  can use the default internal difference quotient approximation that comes with the ARKLS interface. At present, we do not supply a corresponding routine to approximate Jacobian entries in sparse matrices  $J$ . To specify a user-supplied Jacobian function *jac*, MRIStep provides the function `MRISetJacFn()`. Alternatively, a function of type `ARKLsLinSysFn()` can be provided to evaluate the matrix  $I - \gamma J$ . By default, ARKLS uses an internal linear system function leveraging the SUNMATRIX API to form the matrix  $I - \gamma J$ . To specify a user-supplied linear system function *linsys*, MRIStep provides the function `MRISetLinSysFn()`. In either case the matrix information will be updated infrequently to reduce matrix construction and, with direct solvers, factorization costs. As a result the value of  $\gamma$  may not be current and a scaling factor is applied to the solution of the linear system to account for lagged value of  $\gamma$ . See §9.2.1 for more details. The function `MRISetLinearSolutionScaling()` can be used to disable this scaling when necessary, e.g., when providing a custom linear solver that updates the matrix using the current  $\gamma$  as part of the solve.

The ARKLS interface passes the user data pointer to the Jacobian and linear system functions. This allows the user to create an arbitrary structure with relevant problem data and access it during the execution of the user-supplied Jacobian or linear system functions, without using global data in the program. The user data pointer may be specified through `MRISetUserData()`.

`int MRISetJacFn(void *arkode_mem, ARKLsJacFn jac)`

Specifies the Jacobian approximation routine to be used for the matrix-based solver with the ARKLS interface.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *jac* – name of user-supplied Jacobian approximation function.

**Return value:**

- `ARKLS_SUCCESS` if successful
- `ARKLS_MEM_NULL` if the MRIStep memory was `NULL`
- `ARKLS_LMEM_NULL` if the linear solver memory was `NULL`

**Notes:** This routine must be called after the ARKLS linear solver interface has been initialized through a call to `MRISetLinearSolver()`.

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

The function type `ARKLsJacFn()` is described in §5.5.

`int MRISetLinSysFn(void *arkode_mem, ARKLsLinSysFn linsys)`

Specifies the linear system approximation routine to be used for the matrix-based solver with the ARKLS interface.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *linsys* – name of user-supplied linear system approximation function.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the MRIStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Notes:** This routine must be called after the ARKLS linear solver interface has been initialized through a call to *MRISetLinearSolver()*.

By default, ARKLS uses an internal linear system function that leverages the SUNMATRIX API to form the system  $I - \gamma J$ . If NULL is passed in for *linsys*, this default is used.

The function type *ARKLsLinSysFn()* is described in §5.5.

```
int MRISetLinearSolutionScaling(void *arkode_mem, boolean type onoff)
```

Enables or disables scaling the linear system solution to account for a change in  $\gamma$  in the linear system. For more details see §9.2.1.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *onoff* – flag to enable (SUNTRUE) or disable (SUNFALSE) scaling

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the MRIStep memory was NULL
- *ARKLS\_ILL\_INPUT* if the attached linear solver is not matrix-based

**Notes:** Linear solution scaling is enabled by default when a matrix-based linear solver is attached.

## 5.4.5 Optional inputs for matrix-free SUNLinearSolver modules

Optional input	Function name	Default
<i>Jv</i> functions ( <i>jtimes</i> and <i>jtsetup</i> )	<i>MRISetJacTimes()</i>	DQ, none
<i>Jv</i> DQ rhs function ( <i>jtimesRhsFn</i> )	<i>MRISetJacTimesRhsFn()</i>	fs

As described in §2.10.2, when solving the Newton linear systems with matrix-free methods, the ARKLS interface requires a *jtimes* function to compute an approximation to the product between the Jacobian matrix  $J(t, y)$  and a vector  $v$ . The user can supply a custom Jacobian-times-vector approximation function, or use the default internal difference quotient function that comes with the ARKLS interface.

A user-defined Jacobian-vector function must be of type *ARKLsJacTimesVecFn* and can be specified through a call to *MRISetJacTimes()* (see §5.5 for specification details). As with the user-supplied preconditioner functions, the evaluation and processing of any Jacobian-related data needed by the user's Jacobian-times-vector function is done in the optional user-supplied function of type *ARKLsJacTimesSetupFn* (see §5.5 for specification details). As with the preconditioner functions, a pointer to the user-defined data structure, *user\_data*, specified through *MRISetUserData()* (or a NULL pointer otherwise) is passed to the Jacobian-times-vector setup and product functions each time they are called.

```
int MRISetJacTimes(void *arkode_mem, ARKLsJacTimesSetupFn jtsetup, ARKLsJacTimesVecFn jtimes)
```

Specifies the Jacobian-times-vector setup and product functions.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.

- *jtsetup* – user-defined Jacobian-vector setup function. Pass NULL if no setup is necessary.
- *jtimes* – user-defined Jacobian-vector product function.

**Return value:**

- *ARKLS\_SUCCESS* if successful.
- *ARKLS\_MEM\_NULL* if the MRIStep memory was NULL.
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL.
- *ARKLS\_ILL\_INPUT* if an input has an illegal value.
- *ARKLS\_SUNLS\_FAIL* if an error occurred when setting up the Jacobian-vector product in the SUNLinearSolver object used by the ARKLS interface.

**Notes:** The default is to use an internal finite difference quotient for *jtimes* and to leave out *jtsetup*. If NULL is passed to *jtimes*, these defaults are used. A user may specify non-NUL *jtimes* and NULL *jtsetup* inputs.

This function must be called *after* the ARKLS system solver interface has been initialized through a call to [\*MRISetStepLinearSolver\(\)\*](#).

The function types [\*ARKLsJacTimesSetupFn\*](#) and [\*ARKLsJacTimesVecFn\*](#) are described in §5.5.

When using the internal difference quotient the user may optionally supply an alternative implicit right-hand side function for use in the Jacobian-vector product approximation by calling [\*MRISetStepJacTimesRhsFn\(\)\*](#). The alternative implicit right-hand side function should compute a suitable (and differentiable) approximation to the  $f^I$  function provided to [\*MRISetCreate\(\)\*](#). For example, as done in [23], the alternative function may use lagged values when evaluating a nonlinearity in  $f^I$  to avoid differencing a potentially non-differentiable factor.

```
int MRISetStepJacTimesRhsFn(void *arkode_mem, ARKRhsFn jtimesRhsFn)
```

Specifies an alternative implicit right-hand side function for use in the internal Jacobian-vector product difference quotient approximation.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *jtimesRhsFn* – the name of the C function (of type [\*ARKRhsFn\(\)\*](#)) defining the alternative right-hand side function.

**Return value:**

- *ARKLS\_SUCCESS* if successful.
- *ARKLS\_MEM\_NULL* if the MRIStep memory was NULL.
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL.
- *ARKLS\_ILL\_INPUT* if an input has an illegal value.

**Notes:** The default is to use the implicit right-hand side function provided to [\*MRISetCreate\(\)\*](#) in the internal difference quotient. If the input implicit right-hand side function is NULL, the default is used.

This function must be called *after* the ARKLS system solver interface has been initialized through a call to [\*MRISetStepLinearSolver\(\)\*](#).

### 5.4.6 Optional inputs for iterative SUNLinearSolver modules

Optional input	Function name	Default
Newton preconditioning functions	<a href="#">MRIStepSetPreconditioner()</a>	NULL, NULL
Newton linear and nonlinear tolerance ratio	<a href="#">MRIStepSetEpsLin()</a>	0.05
Newton linear solve tolerance conversion factor	<a href="#">MRIStepSetLSNormFactor()</a>	vector length

As described in §2.10.2, 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 MRIStep using the function [MRIStepSetPreconditioner\(\)](#). The *psetup* function supplied to these routines should handle evaluation and preprocessing of any Jacobian data needed by the user's preconditioner solve function, *psolve*. The user data pointer received through [MRIStepSetUserData\(\)](#) (or a pointer to NULL if user data was not specified) is passed to the *psetup* and *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 §2.10.3.2, the ARKLS interface requires that iterative linear solvers stop when the norm of the preconditioned residual satisfies

$$\|r\| \leq \frac{\epsilon_L \epsilon}{10}$$

where the default  $\epsilon_L = 0.05$ , which may be modified by the user through the [MRIStepSetEpsLin\(\)](#) function.

**int MRIStepSetPreconditioner(void \*arkode\_mem, ARKLSPrecSetupFn psetup, ARKLSPrecSolveFn psolve)**

Specifies the user-supplied preconditioner setup and solve functions.

#### Arguments:

- *arkode\_mem* – pointer to the MRIStep memory block.
- *psetup* – user defined preconditioner setup function. Pass NULL if no setup is needed.
- *psolve* – user-defined preconditioner solve function.

#### Return value:

- *ARKLS\_SUCCESS* if successful.
- *ARKLS\_MEM\_NULL* if the MRIStep memory was NULL.
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL.
- *ARKLS\_ILL\_INPUT* if an input has an illegal value.
- *ARKLS\_SUNLS\_FAIL* if an error occurred when setting up preconditioning in the SUNLinearSolver object used by the ARKLS interface.

**Notes:** The default is NULL for both arguments (i.e., no preconditioning).

This function must be called *after* the ARKLS system solver interface has been initialized through a call to [MRIStepSetLinearSolver\(\)](#).

Both of the function types *ARKLSPrecSetupFn()* and *ARKLSPrecSolveFn()* are described in §5.5.

**int MRIStepSetEpsLin(void \*arkode\_mem, realtype eplifac)**

Specifies the factor by which the tolerance on the nonlinear iteration is multiplied to get a tolerance on the linear iteration.

#### Arguments:

- *arkode\_mem* – pointer to the MRIStep memory block.

- *eplifac* – linear convergence safety factor.

**Return value:**

- *ARKLS\_SUCCESS* if successful.
- *ARKLS\_MEM\_NULL* if the MRIStep memory was NULL.
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL.
- *ARKLS\_ILL\_INPUT* if an input has an illegal value.

**Notes:** Passing a value *eplifac*  $\leq 0$  indicates to use the default value of 0.05.

This function must be called *after* the ARKLS system solver interface has been initialized through a call to [\*MRISetStepLinearSolver\(\)\*](#).

int **MRISetLSNormFactor**(void \*arkode\_mem, *realtyp* nrmfac)

Specifies the factor to use when converting from the integrator tolerance (WRMS norm) to the linear solver tolerance (L2 norm) for Newton linear system solves e.g., `tol_L2 = fac * tol_WRMS`.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *nrmfac* – the norm conversion factor. If *nrmfac* is:
  - $> 0$  then the provided value is used.
  - $= 0$  then the conversion factor is computed using the vector length i.e., `nrmfac = sqrt(N_VGetLength(y)) (default)`.
  - $< 0$  then the conversion factor is computed using the vector dot product i.e., `nrmfac = sqrt(N_VDotProd(v, v))` where all the entries of *v* are one.

**Return value:**

- *ARK\_SUCCESS* if successful.
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL.

**Notes:** This function must be called *after* the ARKLS system solver interface has been initialized through a call to [\*MRISetStepLinearSolver\(\)\*](#).

#### 5.4.6.1 Rootfinding optional input functions

The following functions can be called to set optional inputs to control the rootfinding algorithm, the mathematics of which are described in the section §2.11.

Optional input	Function name	Default
Direction of zero-crossings to monitor	<a href="#"><i>MRISetRootDirection()</i></a>	both
Disable inactive root warnings	<a href="#"><i>MRISetNoInactiveRootWarn()</i></a>	enabled

int **MRISetRootDirection**(void \*arkode\_mem, int \*rootdir)

Specifies the direction of zero-crossings to be located and returned.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.

- *rootdir* – state array of length *nrtfn*, the number of root functions  $g_i$  (the value of *nrtfn* was supplied in the call to [MRIStepRootInit\(\)](#)). If *rootdir*[*i*] == 0 then crossing in either direction for  $g_i$  should be reported. 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:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory is NULL
- *ARK\_ILL\_INPUT* if an argument has an illegal value

**Notes:** The default behavior is to monitor for both zero-crossing directions.

```
int MRIStepSetNoInactiveRootWarn(void *arkode_mem)
```

Disables issuing a warning if some root function appears to be identically zero at the beginning of the integration.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory is NULL

**Notes:** MRIStep 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), MRIStep will issue a warning which can be disabled with this optional input function.

#### 5.4.6.2 Interpolated output function

An optional function [MRIStepGetDky\(\)](#) is available to obtain additional values of solution-related quantities. This function should only be called after a successful return from [MRIStepEvolve\(\)](#), as it provides interpolated values either of  $y$  or of its derivatives (up to the 3rd derivative) interpolated to any value of  $t$  in the last internal step taken by [MRIStepEvolve\(\)](#). Internally, this “dense output” or “continuous extension” algorithm is identical to the algorithm used for the maximum order implicit predictors, described in §2.10.5.2, except that derivatives of the polynomial model may be evaluated upon request.

```
int MRIStepGetDky(void *arkode_mem, realtype t, int k, N_Vector dky)
```

Computes the  $k$ -th derivative of the function  $y$  at the time  $t$ , i.e.  $y^{(k)}(t)$ , for values of the independent variable satisfying  $t_n - h_n \leq t \leq t_n$ , with  $t_n$  as current internal time reached, and  $h_n$  is the last internal step size successfully used by the solver. This routine uses an interpolating polynomial of degree  $\min(\text{degree}, 5)$ , where *degree* is the argument provided to [MRIStepSetInterpolantDegree\(\)](#). The user may request  $k$  in the range  $\{0, \dots, \min(\text{degree}, \text{kmax})\}$  where *kmax* depends on the choice of interpolation module. For Hermite interpolants *kmax* = 5 and for Lagrange interpolants *kmax* = 3.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *t* – the value of the independent variable at which the derivative is to be evaluated.
- *k* – the derivative order requested.
- *dky* – output vector (must be allocated by the user).

**Return value:**

- *ARK\_SUCCESS* if successful

- *ARK\_BAD\_K* if  $k$  is not in the range  $\{0, \dots, \min(\text{degree}, k_{\max})\}$ .
- *ARK\_BAD\_T* if  $t$  is not in the interval  $[t_n - h_n, t_n]$
- *ARK\_BAD\_DKY* if the *dky* vector was `NULL`
- *ARK\_MEM\_NULL* if the *MRIStep* memory is `NULL`

**Notes:** It is only legal to call this function after a successful return from `MRISetEvolve()`.

A user may access the values  $t_n$  and  $h_n$  via the functions `MRISetGetCurrentTime()` and `MRISetGetLastStep()`, respectively.

#### 5.4.6.3 Optional output functions

*MRIStep* provides an extensive set of functions that can be used to obtain solver performance information. We organize these into groups:

1. General *MRIStep* output routines are in §5.4.6.3,
2. *MRIStep* implicit solver output routines are in §5.4.6.3,
3. Linear solver output routines are in §5.4.6.3 and
4. General usability routines (e.g. to print the current *MRIStep* parameters, or output the current coupling table) are in §5.4.6.3.
5. Output routines regarding root-finding results are in §5.4.6.3,

Following each table, we elaborate on each function.

Some of the optional outputs, especially the various counters, can be very useful in determining the efficiency of various methods inside *MRIStep*. For example:

- The number of steps and right-hand side evaluations at both the slow and fast time scales provide a rough measure of the overall cost of a given run, and can be compared between runs with different solver options to suggest which set of options is the most efficient.
- The ratio *niterations/nsteps* measures the performance of the nonlinear iteration in solving the nonlinear systems at each implicit stage, providing a measure of the degree of nonlinearity in the problem. Typical values of this for a Newton solver on a general problem range from 1.1 to 1.8.
- When using a Newton nonlinear solver, the ratio *njevals/niterations* (when using a direct linear solver), and the ratio *niterations/niterations* (when using an iterative linear solver) can indicate the quality of the approximate Jacobian or preconditioner being used. For example, if this ratio is larger for a user-supplied Jacobian or Jacobian-vector product routine than for the difference-quotient routine, it can indicate that the user-supplied Jacobian is inaccurate.

It is therefore recommended that users retrieve and output these statistics following each run, and take some time to investigate alternate solver options that will be more optimal for their particular problem of interest.

**Main solver optional output functions**

Table 5.12: Main solver optional output functions

Optional output	Function name
Size of MRIStep real and integer workspaces	<a href="#">MRIStepGetWorkSpace()</a>
Cumulative number of internal steps	<a href="#">MRIStepGetNumSteps()</a>
Step size used for the last successful step	<a href="#">MRIStepGetLastStep()</a>
Current internal time reached by the solver	<a href="#">MRIStepGetCurrentTime()</a>
Current internal solution reached by the solver	<a href="#">MRIStepGetCurrentState()</a>
Current $\gamma$ value used by the solver	<a href="#">MRIStepGetCurrentGamma()</a>
Error weight vector for state variables	<a href="#">MRIStepGetErrWeights()</a>
Suggested factor for tolerance scaling	<a href="#">MRIStepGetTolScaleFactor()</a>
Name of constant associated with a return flag	<a href="#">MRIStepGetReturnFlagName()</a>
No. of calls to the $f^E$ and $f^I$	<a href="#">MRIStepGetNumRhsEvals()</a>
Current MRI coupling tables	<a href="#">MRIStepGetCurrentCoupling()</a>
Last inner stepper return value	<a href="#">MRIStepGetLastInnerStepFlag()</a>

int **MRIStepGetWorkSpace**(void \*arkode\_mem, long int \*lenrw, long int \*leniw)

Returns the MRIStep real and integer workspace sizes.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *lenrw* – the number of *realtype* values in the MRIStep workspace.
- *leniw* – the number of integer values in the MRIStep workspace.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL

int **MRIStepGetNumSteps**(void \*arkode\_mem, long int \*nssteps, long int \*nfsteps)

Returns the cumulative number of slow and fast internal steps taken by the solver (so far).

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *nssteps* – number of slow steps taken in the solver.
- *nfsteps* – number of fast steps taken in the solver.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL

int **MRIStepGetLastStep**(void \*arkode\_mem, *realtype* \*hlast)

Returns the integration step size taken on the last successful internal step.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *hlast* – step size taken on the last internal step.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL

**int MRIStepGetCurrentTime**(void \*arkode\_mem, *realtype* \*tcur)  
 Returns the current internal time reached by the solver.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *tcur* – current internal time reached.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL

**int MRIStepGetCurrentState**(void \*arkode\_mem, *N\_Vector* \*ycur)  
 Returns the current internal solution reached by the solver.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *ycur* – current internal solution.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL

**Notes:** Users should exercise extreme caution when using this function, as altering values of *ycur* may lead to undesirable behavior, depending on the particular use case and on when this routine is called.

**int MRIStepGetCurrentGamma**(void \*arkode\_mem, *realtype* \*gamma)  
 Returns the current internal value of  $\gamma$  used in the implicit solver Newton matrix (see equation (2.28)).

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *gamma* – current step size scaling factor in the Newton system.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL

**int MRIStepGetTolScaleFactor**(void \*arkode\_mem, *realtype* \*tolfac)  
 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:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *tolfac* – suggested scaling factor for user-supplied tolerances.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL

int **MRISetGetErrWeights**(void \*arkode\_mem, *N\_Vector* eweight)

Returns the current error weight vector.

**Arguments:**

- *arkode\_mem* – pointer to the MRISet memory block.
- *eweight* – solution error weights at the current time.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRISet memory was NULL

**Notes:** The user must allocate space for *eweight*, that will be filled in by this function.

char \***MRISetGetReturnFlagName**(long int flag)

Returns the name of the MRISet constant corresponding to *flag*.

**Arguments:**

- *flag* – a return flag from an MRISet function.

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

int **MRISetGetNumRhsEvals**(void \*arkode\_mem, long int \*nfse\_evals, long int \*nfsi\_evals)

Returns the number of calls to the user's outer (slow) right-hand side functions,  $f^E$  and  $f^I$ , so far.

**Arguments:**

- *arkode\_mem* – pointer to the MRISet memory block.
- *nfse\_evals* – number of calls to the user's  $f^E(t, y)$  function.
- *nfsi\_evals* – number of calls to the user's  $f^I(t, y)$  function.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRISet memory was NULL

int **MRISetGetCurrentCoupling**(void \*arkode\_mem, *MRISetCoupling* \*C)

Returns the MRI coupling table currently in use by the solver.

**Arguments:**

- *arkode\_mem* – pointer to the MRISet memory block.
- *C* – pointer to slow-to-fast MRI coupling structure.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRISet memory was NULL

**Notes:** The *MRISetCoupling* data structure is defined in the header file `arkode/arkode_mrisetp.h`. It is defined as a pointer to the following C structure:

```
struct MRISetCouplingMem {  
    int nmat;           /* number of MRI coupling matrices */  
    int stages;         /* size of coupling matrices (stages * stages) */  
    int q;              /* method order of accuracy */  
    int p;              /* embedding order of accuracy */  
};
```

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```

realtype ***G; /* coupling matrices [nmat][stages][stages] */
realtype *c; /* abscissae */

};

typedef MRIStepCouplingMem *MRIStepCoupling;

```

For more details see §5.4.7.

**int MRIStepGetLastInnerStepFlag(void \*arkode\_mem, int \*flag)**

Returns the last return value from the inner stepper.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *flag* – inner stepper return value.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL

### Implicit solver optional output functions

Table 5.13: Implicit solver optional output functions

Optional output	Function name
No. of calls to linear solver setup function	<i>MRIStepGetNumLinSolvSetups()</i>
No. of nonlinear solver iterations	<i>MRIStepGetNumNonlinSolvIters()</i>
No. of nonlinear solver convergence failures	<i>MRIStepGetNumNonlinSolvConvFails()</i>
Single accessor to all nonlinear solver statistics	<i>MRIStepGetNonlinSolvStats()</i>

**int MRIStepGetNumLinSolvSetups(void \*arkode\_mem, long int \*nlinsolvsetups)**

Returns the number of calls made to the linear solver’s setup routine (so far).

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *nlinsolvsetups* – number of linear solver setup calls made.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL

**Notes:** This is only accumulated for the “life” of the nonlinear solver object; the counter is reset whenever a new nonlinear solver module is “attached” to MRIStep, or when MRIStep is resized.

**int MRIStepGetNumNonlinSolvIters(void \*arkode\_mem, long int \*nniters)**

Returns the number of nonlinear solver iterations performed (so far).

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *nniters* – number of nonlinear iterations performed.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL
- *ARK\_NLS\_OP\_ERR* if the SUNNONLINSOL object returned a failure flag

**Notes:** This is only accumulated for the “life” of the nonlinear solver object; the counter is reset whenever a new nonlinear solver module is “attached” to MRIStep, or when MRIStep is resized.

int **MRISetGetNumNonlinSolvConvFails**(void \*arkode\_mem, long int \*nncfails)

Returns the number of nonlinear solver convergence failures that have occurred (so far).

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *nncfails* – number of nonlinear convergence failures.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL

**Notes:** This is only accumulated for the “life” of the nonlinear solver object; the counter is reset whenever a new nonlinear solver module is “attached” to MRIStep, or when MRIStep is resized.

int **MRISetGetNonlinSolvStats**(void \*arkode\_mem, long int \*nniters, long int \*nncfails)

Returns all of the nonlinear solver statistics in a single call.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *nniters* – number of nonlinear iterations performed.
- *nncfails* – number of nonlinear convergence failures.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL
- *ARK\_NLS\_OP\_ERR* if the SUNNONLINSOL object returned a failure flag

**Notes:** These are only accumulated for the “life” of the nonlinear solver object; the counters are reset whenever a new nonlinear solver module is “attached” to MRIStep, or when MRIStep is resized.

### Linear solver interface optional output functions

A variety of optional outputs are available from the ARKLS interface, as listed in the following table and elaborated below. We 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 here (e.g. *lenrwLS*).

Table 5.14: Linear solver interface optional output functions

Optional output	Function name
Size of real and integer workspaces	<a href="#">MRIStepGetLinWorkSpace()</a>
No. of Jacobian evaluations	<a href="#">MRIStepGetNumJacEvals()</a>
No. of preconditioner evaluations	<a href="#">MRIStepGetNumPrecEvals()</a>
No. of preconditioner solves	<a href="#">MRIStepGetNumPrecSolves()</a>
No. of linear iterations	<a href="#">MRIStepGetNumLinIters()</a>
No. of linear convergence failures	<a href="#">MRIStepGetNumLinConvFails()</a>
No. of Jacobian-vector setup evaluations	<a href="#">MRIStepGetNumJtSetupEvals()</a>
No. of Jacobian-vector product evaluations	<a href="#">MRIStepGetNumJtimesEvals()</a>
No. of <i>fs</i> calls for finite diff. <i>J</i> or <i>Jv</i> evals.	<a href="#">MRIStepGetNumLinRhsEvals()</a>
Last return from a linear solver function	<a href="#">MRIStepGetLastLinFlag()</a>
Name of constant associated with a return flag	<a href="#">MRIStepGetLinReturnFlagName()</a>

int **MRIStepGetLinWorkSpace**(void \*arkode\_mem, long int \*lenrwLS, long int \*leniwLS)

Returns the real and integer workspace used by the ARKLS linear solver interface.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *lenrwLS* – the number of **realtype** values in the ARKLS workspace.
- *leniwLS* – the number of integer values in the ARKLS workspace.

**Return value:**

- **ARKLS\_SUCCESS** if successful
- **ARKLS\_MEM\_NULL** if the MRIStep memory was NULL
- **ARKLS\_LMEM\_NULL** if the linear solver memory was NULL

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

In a parallel setting, the above values are global (i.e., summed over all processors).

int **MRIStepGetNumJacEvals**(void \*arkode\_mem, long int \*njevals)

Returns the number of Jacobian evaluations.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *njevals* – number of Jacobian evaluations.

**Return value:**

- **ARKLS\_SUCCESS** if successful
- **ARKLS\_MEM\_NULL** if the MRIStep memory was NULL
- **ARKLS\_LMEM\_NULL** if the linear solver memory was NULL

**Notes:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new linear solver module is “attached” to MRIStep, or when MRIStep is resized.

int **MRIStepGetNumPrecEvals**(void \*arkode\_mem, long int \*npevals)

Returns the total number of preconditioner evaluations, i.e., the number of calls made to *psetup* with *jok* = **SUNFALSE** and that returned *\*jcurPtr* = **SUNTRUE**.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *npevals* – the current number of calls to *psetup*.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the MRIStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Notes:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new linear solver module is “attached” to MRIStep, or when MRIStep is resized.

int **MRIStepGetNumPrecSolves**(void \*arkode\_mem, long int \*npsolves)

Returns the number of calls made to the preconditioner solve function, *psolve*.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *npsolves* – the number of calls to *psolve*.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the MRIStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Notes:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new linear solver module is “attached” to MRIStep, or when MRIStep is resized.

int **MRIStepGetNumLinIters**(void \*arkode\_mem, long int \*nliters)

Returns the cumulative number of linear iterations.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *nliters* – the current number of linear iterations.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the MRIStep memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Notes:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new linear solver module is “attached” to MRIStep, or when MRIStep is resized.

int **MRIStepGetNumLinConvFails**(void \*arkode\_mem, long int \*nlcfails)

Returns the cumulative number of linear convergence failures.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *nlcfails* – the current number of linear convergence failures.

**Return value:**

- *ARKLS\_SUCCESS* if successful

- *ARKLS\_MEM\_NULL* if the MRIStep memory was **NULL**
- *ARKLS\_LMEM\_NULL* if the linear solver memory was **NULL**

**Notes:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new linear solver module is “attached” to MRIStep, or when MRIStep is resized.

**int MRIStepGetNumJTEvals**(void \*arkode\_mem, long int \*njtsetup)

Returns the cumulative number of calls made to the user-supplied Jacobian-vector setup function, *jtsetup*.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *njtsetup* – the current number of calls to *jtsetup*.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the MRIStep memory was **NULL**
- *ARKLS\_LMEM\_NULL* if the linear solver memory was **NULL**

**Notes:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new linear solver module is “attached” to MRIStep, or when MRIStep is resized.

**int MRIStepGetNumJtimesEvals**(void \*arkode\_mem, long int \*njvevals)

Returns the cumulative number of calls made to the Jacobian-vector product function, *jtimes*.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *njvevals* – the current number of calls to *jtimes*.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the MRIStep memory was **NULL**
- *ARKLS\_LMEM\_NULL* if the linear solver memory was **NULL**

**Notes:** This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new linear solver module is “attached” to MRIStep, or when MRIStep is resized.

**int MRIStepGetNumLinRhsEvals**(void \*arkode\_mem, long int \*nfevalsLS)

Returns the number of calls to the user-supplied implicit right-hand side function  $f^I$  for finite difference Jacobian or Jacobian-vector product approximation.

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *nfevalsLS* – the number of calls to the user implicit right-hand side function.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the MRIStep memory was **NULL**
- *ARKLS\_LMEM\_NULL* if the linear solver memory was **NULL**

**Notes:** The value *nfevalsLS* is incremented only if the default internal difference quotient function is used.

This is only accumulated for the “life” of the linear solver object; the counter is reset whenever a new linear solver module is “attached” to MRIStep, or when MRIStep is resized.

int **MRISetGetLastLinFlag**(void \*arkode\_mem, long int \*lsflag)

Returns the last return value from an ARKLS routine.

**Arguments:**

- *arkode\_mem* – pointer to the MRISet memory block.
- *lsflag* – the value of the last return flag from an ARKLS function.

**Return value:**

- *ARKLS\_SUCCESS* if successful
- *ARKLS\_MEM\_NULL* if the MRISet memory was NULL
- *ARKLS\_LMEM\_NULL* if the linear solver memory was NULL

**Notes:** If the ARKLS setup function failed 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. For all other failures, *lsflag* is negative.

Otherwise, if the ARKLS setup function failed ([MRISetEvolve\(\)](#) returned *ARK\_LSETUP\_FAIL*), then *lsflag* will be *SUNLS\_PSET\_FAIL\_UNREC*, *SUNLS\_ASET\_FAIL\_UNREC* or *SUNLS\_PACKAGE\_FAIL\_UNREC*.

If the ARKLS solve function failed ([MRISetEvolve\(\)](#) returned *ARK\_LSOLVE\_FAIL*), then *lsflag* contains the error return flag from the SUNLinearSolver object, which will be one of: *SUNLS\_MEM\_NULL*, indicating that the SUNLinearSolver memory is NULL; *SUNLS\_ATIMES\_NULL*, indicating that a matrix-free iterative solver was provided, but is missing a routine for the matrix-vector product approximation, *SUNLS\_ATIMES\_FAIL\_UNREC*, indicating an unrecoverable failure in the *Jv* function; *SUNLS\_PSOLVE\_NULL*, indicating that an iterative linear solver was configured to use preconditioning, but no preconditioner solve routine was provided, *SUNLS\_PSOLVE\_FAIL\_UNREC*, indicating that the preconditioner solve function failed unrecoverably; *SUNLS\_GS\_FAIL*, indicating a failure in the Gram-Schmidt procedure (SPGMR and SPFGMR only); *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.

char \***MRISetGetLinReturnFlagName**(long int lsflag)

Returns the name of the ARKLS constant corresponding to *lsflag*.

**Arguments:**

- *lsflag* – a return flag from an ARKLS function.

**Return value:** The return value is a string containing the name of the corresponding constant. If using the SUNLINSOL\_DENSE or SUNLINSOL\_BAND modules, then if  $1 \leq lsflag \leq n$  (LU factorization failed), this routine returns “NONE”.

## General usability functions

The following optional routines may be called by a user to inquire about existing solver parameters or write the current MRI coupling table. While neither of these would typically be called during the course of solving an initial value problem, these may be useful for users wishing to better understand MRISet.

Table 5.15: General usability functions

Optional routine	Function name
Output all MRISet solver parameters	<a href="#">MRISetWriteParameters()</a>
Output the current MRI coupling table	<a href="#">MRISetWriteCoupling()</a>

---

```
int MRIStepWriteParameters(void *arkode_mem, FILE *fp)
    Outputs all MRIStep solver parameters to the provided file pointer.
```

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *fp* – pointer to use for printing the solver parameters.

**Return value:**

- *ARKS\_SUCCESS* if successful
- *ARKS\_MEM\_NULL* if the MRIStep memory was NULL

**Notes:** The *fp* argument can be `stdout` or `stderr`, or it may point to a specific file created using `fopen`.

When run in parallel, only one process should set a non-NULL value for this pointer, since parameters for all processes would be identical.

```
int MRIStepWriteCoupling(void *arkode_mem, FILE *fp)
    Outputs the current MRI coupling table to the provided file pointer.
```

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *fp* – pointer to use for printing the Butcher tables.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL

**Notes:** The *fp* argument can be `stdout` or `stderr`, or it may point to a specific file created using `fopen`.

When run in parallel, only one process should set a non-NULL value for this pointer, since tables for all processes would be identical.

## Rootfinding optional output functions

Optional output	Function name
Array showing roots found	<a href="#">MRIStepGetRootInfo()</a>
No. of calls to user root function	<a href="#">MRIStepGetNumGEvals()</a>

```
int MRIStepGetRootInfo(void *arkode_mem, int *rootsfound)
    Returns an array showing which functions were found to have a root.
```

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *rootsfound* – array of length *nrtfn* with the indices of the user functions  $g_i$  found to have a root (the value of *nrtfn* was supplied in the call to [MRIStepRootInit\(\)](#)). For  $i = 0 \dots nrtfn-1$ , *rootsfound[i]* is nonzero if  $g_i$  has a root, and 0 if not.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL

**Notes:** The user must allocate space for *rootsfound* prior to calling this function.

For the components of  $g_i$  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  $g_i$ .

```
int MRIStepGetNumGEvals(void *arkode_mem, long int *ngevals)
    Returns the cumulative number of calls made to the user's root function g.
```

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *ngevals* – number of calls made to *g* so far.

**Return value:**

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL

#### 5.4.6.4 MRIStep re-initialization function

To reinitialize the MRIStep module for the solution of a new problem, where a prior call to *MRIStepCreate()* has been made, the user must call the function *MRIStepReInit()*. The new problem must have the same size as the previous one. This routine retains the current settings for all ARKstep module options and performs the same input checking and initializations that are done in *MRIStepCreate()*, but it performs no memory allocation as it assumes that the existing internal memory is sufficient for the new problem. A call to this re-initialization routine deletes the solution history that was stored internally during the previous integration. Following a successful call to *MRIStepReInit()*, call *MRIStepEvolve()* again for the solution of the new problem.

The use of *MRIStepReInit()* requires that the number of Runge–Kutta stages for both the slow and fast methods be no larger for the new problem than for the previous problem.

One important use of the *MRIStepReInit()* function is in the treating of jump discontinuities in the RHS functions. 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 ODE model, using a call to this routine. 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 RHS functions *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 RHS functions (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.

```
int MRIStepReInit(void *arkode_mem, ARKRhsFn fse, ARKRhsFn fsi, realtype t0, N_Vecor y0)
    Provides required problem specifications and re-initializes the MRIStep outer (slow) stepper.
```

**Arguments:**

- *arkode\_mem* – pointer to the MRIStep memory block.
- *fse* – the name of the function (of type *ARKRhsFn()*) defining the explicit slow portion of the right-hand side function in  $\dot{y} = f^E(t, y) + f^I(t, y) + f^F(t, y)$ .
- *fsi* – the name of the function (of type *ARKRhsFn()*) defining the implicit slow portion of the right-hand side function in  $\dot{y} = f^E(t, y) + f^I(t, y) + f^F(t, y)$ .
- *t0* – the initial value of *t*.
- *y0* – the initial condition vector  $y(t_0)$ .

**Return value:**

- *ARK\_SUCCESS* if successful

- *ARK\_MEM\_NULL* if the MRIStep memory was NULL
- *ARK\_MEM\_FAIL* if a memory allocation failed
- *ARK\_ILL\_INPUT* if an argument has an illegal value.

**Notes:** If the inner (fast) stepper also needs to be reinitialized, its reinitialization function should be called before calling `MRIStepReInit()` to reinitialize the outer stepper.

All previously set options are retained but may be updated by calling the appropriate “Set” functions.

If an error occurred, `MRIStepReInit()` also sends an error message to the error handler function.

#### 5.4.6.5 MRIStep reset function

To reset the MRIStep module to a particular state ( $t_R, y(t_R)$ ) for the continued solution of a problem, where a prior call to `MRIStepCreate()` has been made, the user must call the function `MRIStepReset()`. Like `MRIStepReInit()` this routine retains the current settings for all MRIStep module options and performs no memory allocations but, unlike `MRIStepReInit()`, this routine performs only a *subset* of the input checking and initializations that are done in `MRIStepCreate()`. In particular this routine retains all internal counter values and the step size/error history and does not reinitialize the linear and/or nonlinear solver but it does indicate that a linear solver setup is necessary in the next step. Following a successful call to `MRIStepReset()`, call `MRIStepEvolve()` again to continue solving the problem. By default the next call to `MRIStepEvolve()` will use the step size computed by MRIStep prior to calling `MRIStepReset()`. To set a different step size or have MRIStep estimate a new step size use `MRIStepSetInitStep()`.

One important use of the `MRIStepReset()` function is in the treating of jump discontinuities in the RHS functions. 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 ODE model, using a call to `MRIStepReset()`. 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 RHS functions *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 RHS functions (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.

int `MRIStepReset`(void \*arkode\_mem, *realtype* tR, *N\_Vector* yR)

Resets the current MRIStep outer (slow) time-stepper module state to the provided independent variable value and dependent variable vector.

##### Arguments:

- *arkode\_mem* – pointer to the MRIStep memory block.
- *tR* – the value of the independent variable  $t$ .
- *yR* – the value of the dependent variable vector  $y(t_R)$ .

##### Return value:

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL
- *ARK\_MEM\_FAIL* if a memory allocation failed
- *ARK\_ILL\_INPUT* if an argument has an illegal value.

**Notes:** If the inner (fast) stepper also needs to be reset, its reset function should be called before calling `MRIStepReset()` to reset the outer stepper.

All previously set options are retained but may be updated by calling the appropriate “Set” functions.

If an error occurred, [MRIStepReset\(\)](#) also sends an error message to the error handler function.

#### 5.4.6.6 MRIStep system resize function

For simulations involving changes to the number of equations and unknowns in the ODE system (e.g. when using spatially-adaptive PDE simulations under a method-of-lines approach), the MRIStep integrator may be “resized” between *slow* integration steps, through calls to the [MRIStepResize\(\)](#) function. This function modifies MRIStep’s internal memory structures to use the new problem size.

To aid in the vector resize operation, the user can supply a vector resize function that will take as input a vector with the previous size, and transform it in-place to return a corresponding vector of the new size. If this function (of type [ARKVecResizeFn\(\)](#)) is not supplied (i.e., is set to NULL), then all existing vectors internal to MRIStep will be destroyed and re-cloned from the new input vector.

```
int MRIStepResize(void *arkode_mem, N_Vector yR, realtype tR, ARKVecResizeFn resize, void *resize_data)
```

Re-initializes MRIStep with a different state vector.

##### Arguments:

- *arkode\_mem* – pointer to the MRIStep memory block.
- *yR* – the newly-sized solution vector, holding the current dependent variable values  $y(t_R)$ .
- *tR* – the current value of the independent variable  $t_R$  (this must be consistent with *yR*).
- *resize* – the user-supplied vector resize function (of type [ARKVecResizeFn\(\)](#)).
- *resize\_data* – the user-supplied data structure to be passed to *resize* when modifying internal MRIStep vectors.

##### Return value:

- *ARK\_SUCCESS* if successful
- *ARK\_MEM\_NULL* if the MRIStep memory was NULL
- *ARK\_NO\_MALLOC* if *arkode\_mem* was not allocated.
- *ARK\_ILL\_INPUT* if an argument has an illegal value.

**Notes:** If an error occurred, [MRIStepResize\(\)](#) also sends an error message to the error handler function.

#### Resizing the absolute tolerance array

If using array-valued absolute tolerances, the absolute tolerance vector will be invalid after the call to [MRIStepResize\(\)](#), so the new absolute tolerance vector should be re-set **following** each call to [MRIStepResize\(\)](#) through a new call to [MRIStepSVtolerances\(\)](#).

If scalar-valued tolerances or a tolerance function was specified through either [MRIStepSStolerances\(\)](#) or [MRIStepWFtolerances\(\)](#), then these will remain valid and no further action is necessary.

---

**Note:** For an example showing usage of the similar [ARKStepResize\(\)](#) routine, see the supplied serial C example problem, `ark_heat1D_adapt.c`.

---

### 5.4.7 MRI Coupling Coefficients Data Structure

MRIStep supplies several built-in MIS, MRI-GARK, and IMEX-MRI-GARK methods, see §5.4.7.2 for the current set of coupling tables and their corresponding identifiers. Additionally, a user may supply a custom set of slow-to-fast time scale coupling coefficients by constructing a coupling table and attaching it with `MRISTepSetCoupling()`.

As described in §2.5, the coupling from the slow time scale to the fast time scale is encoded by a vector of slow ‘stage time’ abscissae,  $c^S \in \mathbb{R}^{s+1}$  and a set of coupling matrices  $\Gamma^{\{k\}} \in \mathbb{R}^{(s+1) \times (s+1)}$  and  $\Omega^{\{k\}} \in \mathbb{R}^{(s+1) \times (s+1)}$ . An `MRISTepCoupling` object stores this information and provides several related utility functions for creating a coupling table. The `MRISTepCoupling` type is defined as:

```
typedef MRISTepCouplingMem *MRISTepCoupling
```

where `MRISTepCouplingMem` is the structure

```
struct MRISTepCouplingMem
{
    int nmat;
    int stages;
    int q;
    int p;
    realtype ***G;
    realtype ***W;
    realtype *c;
};
```

and the members of the strucutre are:

- `nmat` corresponds to the number of coupling matrices  $\Omega^{\{k\}}$  for the slow-nonstiff terms and/or  $\Gamma^{\{k\}}$  for the slow-stiff terms in (2.9),
- `stages` is the number of abscissae i.e.,  $s + 1$  above,
- `q` and `p` indicate the orders of accuracy for both the method and the embedding, respectively,
- `W` is a three-dimensional array with dimensions `[nmat][stages][stages]` containing the method’s  $\Omega^{\{k\}}$  coupling matrices for the slow-nonstiff (explicit) terms in (2.9),
- `G` is a three-dimensional array with dimensions `[nmat][stages][stages]` containing the method’s  $\Gamma^{\{k\}}$  coupling matrices for the slow-stiff (implicit) terms in (2.9), and
- `c` is an array of length `stages` containing the slow abscissae  $c^S$  for the method.

#### 5.4.7.1 MRISTepCoupling functions

This section describes the functions for creating and interacting with coupling tables. The function prototypes and as well as the relevant integer constants are defined `arkode/arkode_mrimestep.h`.

Table 5.16: MRIStepCoupling functions

Function name	Description
<code>MRIStepCoupling_LoadTable()</code>	Loads a pre-defined MRIStepCoupling table
<code>MRIStepCoupling_Alloc()</code>	Allocate an empty MRIStepCoupling table
<code>MRIStepCoupling_Create()</code>	Create a new MRIStepCoupling table from coefficients
<code>MRIStepCoupling_MISoMRI()</code>	Create a new MRIStepCoupling table from a slow Butcher table
<code>MRIStepCoupling_Copy()</code>	Create a copy of a MRIStepCoupling table
<code>MRIStepCoupling_Space()</code>	Get the MRIStepCoupling table real and integer workspace sizes
<code>MRIStepCoupling_Free()</code>	Deallocate a MRIStepCoupling table
<code>MRIStepCoupling_Write()</code>	Write the MRIStepCoupling table to an output file

*MRIStepCoupling* `MRIStepCoupling_LoadTable(ARKODE_MRITableID imethod)`

Retrieves a specified coupling table. For further information on the current set of coupling tables and their corresponding identifiers, see §5.4.7.2.

**Arguments:**

- `itable` – the coupling table identifier.

**Return value:**

- An *MRIStepCoupling* structure if successful.
- A NULL pointer if `itable` was invalid or an allocation error occurred.

*MRIStepCoupling* `MRIStepCoupling_Alloc(int nmat, int stages, int type)`

Allocates an empty MRIStepCoupling table.

**Arguments:**

- `nmat` – number of  $\Omega^{\{k\}}$  and/or  $\Gamma^{\{k\}}$  matrices in the coupling table.
- `stages` – number of stages in the coupling table.
- `type` – the method type: explicit (0), implicit (1), or ImEx (2).

**Return value:**

- An *MRIStepCoupling* structure if successful.
- A NULL pointer if `stages` or `type` was invalid or an allocation error occurred.

---

**Note:** For explicit methods only the W array is allocated, with implicit methods only the G array is allocated, and for ImEx methods both W and G are allocated.

---

*MRIStepCoupling* `MRIStepCoupling_Create(int nmat, int stages, int q, int p, realtype *W, realtype *G, realtype *c)`

Allocates a coupling table and fills it with the given values.

**Arguments:**

- `nmat` – number of  $\Omega^{\{k\}}$  and/or  $\Gamma^{\{k\}}$  matrices in the coupling table.
- `stages` – number of stages in the method.
- `q` – global order of accuracy for the method.
- `p` – global order of accuracy for the embedded method.

- $\bar{W}$  – array of coefficients defining the explicit coupling matrices  $\Omega^{\{k\}}$ . The entries should be stored as a 1D array of size `nmat * stages * stages`, in row-major order. If the slow method is implicit pass `NULL`.
- $G$  – array of coefficients defining the implicit coupling matrices  $\Gamma^{\{k\}}$ . The entries should be stored as a 1D array of size `nmat * stages * stages`, in row-major order. If the slow method is explicit pass `NULL`.
- $c$  – array of slow abscissae for the MRI method. The entries should be stored as a 1D array of length `stages`.

**Return value:**

- An `MRIStepCoupling` structure if successful.
- A `NULL` pointer if `stages` was invalid, an allocation error occurred, or the input data arrays are inconsistent with the method type.

**Note:** As embeddings are not currently supported in MRIStep, `p` should be equal to zero.

**`MRIStepCoupling MRIStepCoupling_MISToMRI(ARKodeButcherTable B, int q, int p)`**

Creates an MRI coupling table for a traditional MIS method based on the slow Butcher table  $B$ , following the formula shown in (2.11)

**Arguments:**

- $B$  – the `ARKodeButcherTable` for the ‘slow’ MIS method.
- $q$  – the overall order of the MIS/MRI method.
- $p$  – the overall order of the MIS/MRI embedding.

**Return value:**

- An `MRIStepCoupling` structure if successful.
- A `NULL` pointer if an allocation error occurred.

**Note:** The  $s$ -stage slow Butcher table must have an explicit first stage (i.e.,  $c_1 = 0$  and  $A_{1,j} = 0$  for  $1 \leq j \leq s$ ) and sorted abscissae (i.e.,  $c_i \geq c_{i-1}$  for  $2 \leq i \leq s$ ).

Since an MIS method is at most third order accurate, and even then only if it meets certain compatibility criteria (see (2.12)), the values of  $q$  and  $p$  may differ from the method and embedding orders of accuracy for the Runge–Kutta method encoded in  $B$ , which is why these arguments should be supplied separately.

As embeddings are not currently supported in MRIStep, then  $p$  should be equal to zero.

**`MRIStepCoupling MRIStepCoupling_Copy(MRIStepCoupling C)`**

Creates copy of the given coupling table.

**Arguments:**

- $C$  – the coupling table to copy.

**Return value:**

- An `MRIStepCoupling` structure if successful.
- A `NULL` pointer if an allocation error occurred.

**`void MRIStepCoupling_Space(MRIStepCoupling C, sunindextype *liw, sunindextype *lrw)`**

Get the real and integer workspace size for a coupling table.

**Arguments:**

- C – the coupling table.
- lenrw – the number of `realtypes` values in the coupling table workspace.
- leniw – the number of integer values in the coupling table workspace.

**Return value:**

- `ARK_SUCCESS` if successful.
- `ARK_MEM_NULL` if the Butcher table memory was `NULL`.

void **MRIStepCoupling\_Free**(*MRIStepCoupling* C)

Deallocate the coupling table memory.

**Arguments:**

- C – the coupling table.

void **MRIStepCoupling\_Write**(*MRIStepCoupling* C, FILE \*outfile)

Write the coupling table to the provided file pointer.

**Arguments:**

- C – the coupling table.
- outfile – pointer to use for printing the table.

---

**Note:** The *outfile* argument can be `stdout` or `stderr`, or it may point to a specific file created using `fopen`.

---

#### 5.4.7.2 MRI Coupling Tables

MRIStep currently includes three classes of coupling tables: those that encode methods that are explicit at the slow time scale, those that are diagonally-implicit and solve-decoupled at the slow time scale, and those that encode methods with an implicit-explicit method at the slow time scale. We list the current identifiers, multirate order of accuracy, and relevant references for each in the tables below. For methods with an implicit component, we also list the number of implicit solves per step that are required at the slow time scale.

Each of the coupling tables that are packaged with MRIStep are specified by a unique ID having type:

typedef int **ARKODE\_MRITableID**

with values specified for each method below (e.g., `ARKODE_MIS_KW3`).

Table 5.17: Explicit MRI-GARK coupling tables. The default method for each order is marked with an asterisk (\*).

Table name	Order	Reference
<code>ARKODE_MIS_KW3</code>	$3^*$	[53]
<code>ARKODE_MRI_GARK_ERK33a</code>	3	[51]
<code>ARKODE_MRI_GARK_ERK45a</code>	$4^*$	[51]

Table 5.18: Diagonally-implicit, solve-decoupled MRI-GARK coupling tables. The default method for each order is marked with an asterisk (\*).

Table name	Order	Implicit Solves	Reference
ARKODE_MRI_GARK_IRK21a	2*	1	[51]
ARKODE_MRI_GARK_ESDIRK34a	3*	3	[51]
ARKODE_MRI_GARK_ESDIRK46a	4*	5	[51]

Table 5.19: Diagonally-implicit, solve-decoupled IMEX-MRI-GARK coupling tables. The default method for each order is marked with an asterisk (\*).

Table name	Order	Implicit Solves	Reference
ARKODE_IMEX_MRI_GARK3a	3*	2	[17]
ARKODE_IMEX_MRI_GARK3b	3	2	[17]
ARKODE_IMEX_MRI_GARK4	4*	5	[17]

## 5.4.8 MRIStep Custom Inner Steppers

Recall, MIS and MRI-GARK methods require solving the auxiliary IVP

$$\dot{v}(t) = f^F(t, v) + r_i(t), \quad v(t_{n,i-1}^S) = z_{i-1} \quad (5.2)$$

for  $i \geq 2$  on the interval  $t \in [t_{n,i-1}^S, t_{n,i}^S]$  where  $t_{n,i-1}^S = t_{n-1} + c_{i-1}^S h^S$ . The forcing term  $r_i(t)$  presented in §2.5 can be equivalently written as

$$r_i(t) = \sum_{k \geq 0} \hat{\omega}_i^{\{k\}} \tau^k + \sum_{k \geq 0} \hat{\gamma}_i^{\{k\}} \tau^k \quad (5.3)$$

where  $\tau = (t - t_{n,i-1}^S)/(h^S \Delta c_i^S)$  is the normalized time with  $\Delta c_i^S = (c_i^S - c_{i-1}^S)$  and the polynomial coefficient vectors are

$$\hat{\omega}_i^{\{k\}} = \frac{1}{\Delta c_i^S} \sum_{j=1}^{i-1} \omega_{i,j}^{\{k\}} f^E(t_{n,j}^S, z_j) \quad \text{and} \quad \hat{\gamma}_i^{\{k\}} = \frac{1}{\Delta c_i^S} \sum_{j=1}^i \gamma_{i,j}^{\{k\}} f^I(t_{n,j}^S, z_j). \quad (5.4)$$

To evolve the IVP (5.2) MRIStep utilizes a generic time integrator interface defined by the `MRISStepInnerStepper` base class. This section presents the `MRISStepInnerStepper` base class and methods that define the integrator interface as well as detailing the steps for creating an `MRISStepInnerStepper`.

### 5.4.8.1 The `MRISStepInnerStepper` Class

As with other SUNDIALS classes, the `MRISStepInnerStepper` abstract base class is implemented using a C structure containing a content pointer to the derived class member data and a structure of function pointers the derived class implementations of the virtual methods. The `MRISStepInnerStepper` type is defined in `include/arkode/arkode.h` as

```
typedef struct _MRISStepInnerStepper *MRISStepInnerStepper
```

The actual definitions of the `_MRISStepInnerStepper` structure and the corresponding operations structure are kept private to allow for the object internals to change without impacting user code. The following sections describe the §5.4.8.1 and the virtual §5.4.8.1 that a must be provided by a derived class.

## Base Class Methods

This section describes methods provided by the `MRIStepInnerStepper` abstract base class that aid the user in implementing derived classes. This includes functions for creating and destroying a generic base class object, attaching and retrieving the derived class content pointer, setting function pointers to derived class method implementations, and accessing base class data e.g., for computing the forcing term (5.3).

### Creating and Destroying an Object

```
int MRIStepInnerStepper_Create(SUNContext sunctx, MRIStepInnerStepper *stepper)
```

This function creates an `MRIStepInnerStepper` object to which a user should attach the member data (content) pointer and method function pointers.

#### Arguments:

- `sunctx` – the SUNDIALS simulation context.
- `stepper` – a pointer to an inner stepper object.

#### Return value:

- `ARK_SUCCESS` if successful
- `ARK_MEM_FAIL` if a memory allocation error occurs

#### Example usage:

```
/* create an instance of the base class */
MRIStepInnerStepper inner_stepper = NULL;
flag = MRIStepInnerStepper_Create(&inner_stepper);
```

#### Example codes:

- `examples/arkode/CXX_parallel/ark_diffusion_reaction_p.cpp`

---

**Note:** See §5.4.8.1 and §5.4.8.1 for details on how to attach member data and method function pointers.

---

```
int MRIStepInnerStepper_Free(MRIStepInnerStepper *stepper)
```

This function destroys an `MRIStepInnerStepper` object.

#### Arguments:

- `stepper` – a pointer to an inner stepper object.

#### Return value:

- `ARK_SUCCESS` if successful

#### Example usage:

```
/* destroy an instance of the base class */
flag = MRIStepInnerStepper_Free(&inner_stepper);
```

#### Example codes:

- `examples/arkode/CXX_parallel/ark_diffusion_reaction_p.cpp`

---

**Note:** This function only frees memory allocated within the base class and the base class structure itself. The user is responsible for freeing any memory allocated for the member data (content).

---

### Attaching and Accessing the Content Pointer

```
int MRIStepInnerStepper_SetContent(MRIStepInnerStepper stepper, void *content)
This function attaches a member data (content) pointer to an MRIStepInnerStepper object.
```

#### Arguments:

- *stepper* – an inner stepper object.
- *content* – a pointer to the stepper member data.

#### Return value:

- ARK\_SUCCESS if successful
- ARK\_ILL\_INPUT if the stepper is NULL

#### Example usage:

```
/* set the inner stepper content pointer */
MyStepperContent my_object_data;
flag = MRIStepInnerStepper_SetContent(inner_stepper, &my_object_data);
```

#### Example codes:

- examples/arkode/CXX\_parallel/ark\_diffusion\_reaction\_p.cpp

```
int MRIStepInnerStepper_GetContent(MRIStepInnerStepper stepper, void **content)
This function retrieves the member data (content) pointer from an MRIStepInnerStepper object.
```

#### Arguments:

- *stepper* – an inner stepper object.
- *content* – a pointer to set to the stepper member data pointer.

#### Return value:

- ARK\_SUCCESS if successful
- ARK\_ILL\_INPUT if the stepper is NULL

#### Example usage:

```
/* get the inner stepper content pointer */
void          *content;
MyStepperContent *my_object_data;

flag = MRIStepInnerStepper_GetContent(inner_stepper, &content);
my_object_data = (MyStepperContent*) content;
```

#### Example codes:

- examples/arkode/CXX\_parallel/ark\_diffusion\_reaction\_p.cpp

## Setting Member Functions

```
int MRIStepInnerStepper_SetEvolveFn(MRIStepInnerStepper stepper, MRIStepInnerEvolveFn fn)
```

This function attaches an *MRIStepInnerEvolveFn* function to an *MRIStepInnerStepper* object.

### Arguments:

- *stepper* – an inner stepper object.
- *fn* – the *MRIStepInnerStepper* function to attach.

### Return value:

- ARK\_SUCCESS if successful
- ARK\_ILL\_INPUT if the stepper is NULL

### Example usage:

```
/* set the inner stepper evolve function */
flag = MRIStepInnerStepper_SetEvolveFn(inner_stepper, MyEvolve);
```

### Example codes:

- examples/arkode/CXX\_parallel/ark\_diffusion\_reaction\_p.cpp

```
int MRIStepInnerStepper_SetFullRhsFn(MRIStepInnerStepper stepper, MRIStepInnerFullRhsFn fn)
```

This function attaches an *MRIStepInnerFullRhsFn* function to an *MRIStepInnerStepper* object.

### Arguments:

- *stepper* – an inner stepper object.
- *fn* – the *MRIStepInnerFullRhsFn* function to attach.

### Return value:

- ARK\_SUCCESS if successful
- ARK\_ILL\_INPUT if the stepper is NULL

### Example usage:

```
/* set the inner stepper full right-hand side function */
flag = MRIStepInnerStepper_SetFullRhsFn(inner_stepper, MyFullRHS);
```

### Example codes:

- examples/arkode/CXX\_parallel/ark\_diffusion\_reaction\_p.cpp

```
int MRIStepInnerStepper_SetResetFn(MRIStepInnerStepper stepper, MRIStepInnerResetFn fn)
```

This function attaches an *MRIStepInnerResetFn* function to an *MRIStepInnerStepper* object.

### Arguments:

- *stepper* – an inner stepper object.
- *fn* – the *MRIStepInnerResetFn* function to attach.

### Return value:

- ARK\_SUCCESS if successful
- ARK\_ILL\_INPUT if the stepper is NULL

**Example usage:**

```
/* set the inner stepper reset function */
flag = MRIStepInnerStepper_SetResetFn(inner_stepper, MyReset);
```

**Example codes:**

- examples/arkode/CXX\_parallel/ark\_diffusion\_reaction\_p.cpp

**Applying and Accessing Forcing Data**

When integrating the ODE (5.2) the `MRIStepInnerStepper` is responsible for evaluating ODE right-hand side function  $f^F(t, v)$  as well as computing and applying the forcing term (5.3) to obtain the full right-hand side of the inner (fast) ODE (5.2). The functions in this section can be used to either apply the inner (fast) forcing or access the data necessary to construct the inner (fast) forcing polynomial.

`int MRIStepInnerStepper_AddForcing(MRIStepInnerStepper stepper, realtypes t, N_Vector ff)`

This function computes the forcing term (5.3) at the input time  $t$  and adds it to input vector  $ff$ , i.e., the inner (fast) right-hand side vector.

**Arguments:**

- *stepper* – an inner stepper object.
- *t* – the time at which the forcing should be evaluated.
- *f* – the vector to which the forcing should be applied.

**Return value:**

- ARK\_SUCCESS if successful
- ARK\_ILL\_INPUT if the stepper is NULL

**Example usage:**

```
/* compute the forcing term and add it to the fast RHS vector */
flag = MRIStepInnerStepper_AddForcing(inner_stepper, t, f_fast);
```

**Example codes:**

- examples/arkode/CXX\_parallel/ark\_diffusion\_reaction\_p.cpp

`int MRIStepInnerStepper_GetForcingData(MRIStepInnerStepper stepper, realtypes *tshift, realtypes *tscale,`  
`N_Vector **forcing, int *nforcing)`

This function provides access to data necessary to compute the forcing term (5.3). This includes the shift and scaling factors for the normalized time  $\tau = (t - t_{n,i-1}^S)/(h^S \Delta c_i^S)$  and the array of polynomial coefficient vectors  $\hat{\gamma}_i^{\{k\}}$ .

**Arguments:**

- *stepper* – an inner stepper object.
- *tshift* – the time shift to apply to the current time when computing the forcing,  $t_{n,i-1}^S$ .
- *tscale* – the time scaling to apply to the current time when computing the forcing,  $h^S \Delta c_i^S$ .
- *forcing* – a pointer to an array of forcing vectors,  $\hat{\gamma}_i^{\{k\}}$ .
- *nforcing* – the number of forcing vectors.

**Return value:**

- ARK\_SUCCESS if successful
- ARK\_ILL\_INPUT if the stepper is NULL

**Example usage:**

```
int      k, flag;
int      nforcing_vecs; /* number of forcing vectors */
double   tshift, tscale; /* time normalization values */
double   tau;           /* normalized time */
double   tau_k;         /* tau raised to the power k */
N_Vector *forcing_vecs; /* array of forcing vectors */

/* get the forcing data from the inner (fast) stepper */
flag = MRIStepInnerStepper_GetForcingData(inner_stepper, &tshift, &tscale,
                                           &forcing_vecs, &nforcing_vecs);

/* compute the normalized time, initialize tau^k */
tau    = (t - tshift) / tscale;
tau_k = 1.0;

/* compute the polynomial forcing terms and add them to fast RHS vector */
for (k = 0; k < nforcing_vecs; k++)
{
    N_VLinearSum(1.0, f_fast, tau_k, forcing_vecs[k], f_fast);
    tau_k *= tau;
}
```

**Example codes:**

- examples/arkode/CXX\_parallel/ark\_diffusion\_reaction\_p.cpp

## Implementation Specific Methods

This section describes the required and optional virtual methods defined by the `MRIStepInnerStepper` abstract base class.

### Required Member Functions

An `MRIStepInnerStepper` must provide implementations of the following member functions:

```
typedef int (*MRIStepInnerEvolveFn)(MRIStepInnerStepper stepper, realltype t0, realltype tout, N_Vector v)
```

This function advances the state vector  $v$  for the inner (fast) ODE system from time  $t0$  to time  $tout$ .

**Arguments:**

- $stepper$  – the inner stepper object.
- $t0$  – the initial time for the inner (fast) integration.
- $tout$  – the final time for the inner (fast) integration.
- $v$  – on input the state at time  $t0$  and, on output, the state at time  $tout$ .

**Return value:** An `MRIStepInnerEvolveFn` should return 0 if successful, a positive value if a recoverable error occurred, or a negative value if it failed unrecoverably.

**Example codes:**

- `examples/arkode/CXX_parallel/ark_diffusion_reaction_p.cpp`

```
typedef int (*MRIStepInnerFullRhsFn)(MRIStepInnerStepper stepper, realtype t, N_Vector v, N_Vector f, int mode)
```

This function computes the full right-hand side function of the inner (fast) ODE,  $f^F(t, v)$  in (5.2) for a given value of the independent variable  $t$  and state vector  $y$ .

**Arguments:**

- *stepper* – the inner stepper object.
- *t* – the current value of the independent variable.
- *y* – the current value of the dependent variable vector.
- *f* – the output vector that forms a portion the ODE right-hand side,  $f^F(t, y)$  in (2.9).
- *mode* – a flag indicating the purpose for which the right-hand side function evaluation is called.
  - `ARK_FULLRHS_START` – called at the beginning of the simulation
  - `ARK_FULLRHS_END` – called at the end of a successful step
  - `ARK_FULLRHS_OTHER` – called elsewhere e.g., for dense output

**Return value:** An `MRIStepInnerFullRhsFn` should return 0 if successful, a positive value if a recoverable error occurred, or a negative value if it failed unrecoverably.

**Example codes:**

- `examples/arkode/CXX_parallel/ark_diffusion_reaction_p.cpp`

## Optional Member Functions

An `MRIStepInnerStepper` may provide implementations of any of the following member functions:

```
typedef int (*MRIStepInnerResetFn)(MRIStepInnerStepper stepper, realtype tR, N_Vector vR)
```

This function resets the inner (fast) stepper state to the provided independent variable value and dependent variable vector.

**Arguments:**

- *stepper* – the inner stepper object.
- *tR* – the value of the independent variable  $t_R$ .
- *vR* – the value of the dependent variable vector  $v(t_R)$ .

**Return value:** An `MRIStepInnerResetFn` should return 0 if successful, a positive value if a recoverable error occurred, or a negative value if it failed unrecoverably.

**Example codes:**

- `examples/arkode/CXX_parallel/ark_diffusion_reaction_p.cpp`

### 5.4.8.2 Implementing an MRIStepInnerStepper

To create an `MRIStepInnerStepper` implementation:

1. Define the stepper-specific content.

This is typically a user-defined structure in C codes, a user-defined class or structure in C++ codes, or a user-defined module in Fortran codes. This content should hold any data necessary to perform the operations defined by the `MRIStepInnerStepper` member functions.

2. Define implementations of the required member functions (see §5.4.8.1).

These are typically user-defined functions in C, member functions of the user-defined structure or class in C++, or functions contained in the user-defined module in Fortran.

Note that all member functions are passed the `MRIStepInnerStepper` object and the stepper-specific content can, if necessary, be retrieved using `MRIStepInnerStepper_GetContent()`.

3. In the user code, before creating the `MRIStep` memory structure with `MRIStepCreate()`, do the following:

1. Create an `MRIStepInnerStepper` object with `MRIStepInnerStepper_Create()`.
2. Attach a pointer to the stepper content to the `MRIStepInnerStepper` object with `MRIStepInnerStepper_SetContent()` if necessary, e.g., when the content is a C structure.
3. Attach the member function implementations using the functions described in §5.4.8.1.
4. Attach the `MRIStepInnerStepper` object to the `MRIStep` memory structure with `MRIStepCreate()`.

For an example of creating and attaching a user-defined inner stepper see the example code `examples/arkode/CXX_parallel/ark_diffusion_reaction_p.cpp` where CVODE is wrapped as an `MRIStepInnerStepper`.

## 5.5 User-supplied functions

The user-supplied functions for ARKODE consist of:

- at least one function defining the ODE (required),
- a function that handles error and warning messages (optional),
- a function that provides the error weight vector (optional),
- a function that provides the residual weight vector (optional, ARKStep only),
- a function that handles adaptive time step error control (optional, ARKStep/ERKStep only),
- a function that handles explicit time step stability (optional, ARKStep/ERKStep only),
- a function that updates the implicit stage prediction (optional, ARKStep/MRIStep only),
- a function that defines the root-finding problem(s) to solve (optional),
- one or two functions that provide Jacobian-related information for the linear solver, if a component is treated implicitly and a Newton-based nonlinear iteration is chosen (optional, ARKStep/MRIStep only),
- one or two functions that define the preconditioner for use in any of the Krylov iterative algorithms, if linear systems of equations are to be solved using an iterative method (optional, ARKStep/MRIStep only),
- if the problem involves a non-identity mass matrix  $M \neq I$  with ARKStep:
  - one or two functions that provide mass-matrix-related information for the linear and mass matrix solvers (required),

- one or two functions that define the mass matrix preconditioner for use if an iterative mass matrix solver is chosen (optional), and
- a function that handles vector resizing operations, if the underlying vector structure supports resizing (as opposed to deletion/recreation), and if the user plans to call `ARKStepResize()`, `ERKStepResize()`, or `MRIStepResize()` (optional).
- MRIStep only: functions to be called before and after each inner integration to perform any communication or memory transfers of forcing data supplied by the outer integrator to the inner integrator, or state data supplied by the inner integrator to the outer integrator.

### 5.5.1 ODE right-hand side

The user must supply at least one function of type `ARKRhsFn` to specify the explicit and/or implicit portions of the ODE system to ARKStep, the ODE system function to ERKStep, or the “slow” right-hand side of the ODE system to MRIStep:

```
typedef int (*ARKRhsFn)(realtype t, N_Vector y, N_Vector ydot, void *user_data)
```

These functions compute the ODE right-hand side for a given value of the independent variable  $t$  and state vector  $y$ .

#### Arguments:

- $t$  – the current value of the independent variable.
- $y$  – the current value of the dependent variable vector.
- $ydot$  – the output vector that forms [a portion of] the ODE RHS  $f(t, y)$ .
- $user\_data$  – the  $user\_data$  pointer that was passed to `ARKStepSetUserData()`, `ERKStepSetUserData()`, or `MRIStepSetUserData()`.

#### Return value:

An `ARKRhsFn` should return 0 if successful, a positive value if a recoverable error occurred (in which case ARKODE will attempt to correct), or a negative value if it failed unrecoverably (in which case the integration is halted and `ARK_RHSFUNC_FAIL` is returned).

#### Notes:

Allocation of memory for  $ydot$  is handled within ARKODE.

The vector  $ydot$  may be uninitialized on input; it is the user’s responsibility to fill this entire vector with meaningful values.

A recoverable failure error return from the `ARKRhsFn` 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, ARKODE will attempt to recover (possibly repeating the nonlinear iteration, or reducing the step size in ARKStep or ERKStep) in order to avoid this recoverable error return. There are some situations in which recovery is not possible even if the right-hand side function returns a recoverable error flag. One is when this occurs at the very first call to the `ARKRhsFn` (in which case ARKODE returns `ARK_FIRST_RHSFUNC_ERR`). Another is when a recoverable error is reported by `ARKRhsFn` after the ARKStep integrator completes a successful stage, in which case ARKStep returns `ARK_UNREC_RHSFUNC_ERR`). Similarly, since MRIStep does not currently support adaptive time stepping at the slow time scale, it may halt on a recoverable error flag that would normally have resulted in a stepsize reduction.

## 5.5.2 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 `ARKStepSetErrFile()`, `ERKStepSetErrFile()`, and `MRIStepSetErrFile()`), the user may provide a function of type `ARKErrorHandlerFn` to process any such messages.

```
typedef void (*ARKErrorHandlerFn)(int error_code, const char *module, const char *function, char *msg, void *user_data)
```

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

### Arguments:

- *error\_code* – the error code.
- *module* – the name of the ARKODE module reporting the error.
- *function* – the name of the function in which the error occurred.
- *msg* – the error message.
- *user\_data* – a pointer to user data, the same as the *eh\_data* parameter that was passed to `ARKStepSetErrorHandlerFn()`, `ERKStepSetErrorHandlerFn()`, or `MRIStepSetErrorHandlerFn()`.

**Return value:** An `ARKErrorHandlerFn` function has no return value.

**Notes:** *error\_code* is negative for errors and positive (`ARK_WARNING`) for warnings. If a function that returns a pointer to memory encounters an error, it sets *error\_code* to 0.

## 5.5.3 Error weight function

As an alternative to providing the relative and absolute tolerances, the user may provide a function of type `ARKEwtFn` to compute a vector *ewt* containing the weights in the WRMS norm  $\|v\|_{WRMS} = \left( \frac{1}{n} \sum_{i=1}^n (ewt_i v_i)^2 \right)^{1/2}$ . These weights will be used in place of those defined in §2.6.

```
typedef int (*ARKEwtFn)(N_Vector y, N_Vector ewt, void *user_data)
```

This function computes the WRMS error weights for the vector *y*.

### Arguments:

- *y* – the dependent variable vector at which the weight vector is to be computed.
- *ewt* – the output vector containing the error weights.
- *user\_data* – a pointer to user data, the same as the *user\_data* parameter that was passed to `ARKStepSetUserData()`, `ERKStepSetUserData()`, or `MRIStepSetUserData()`.

**Return value:** An `ARKEwtFn` function must return 0 if it successfully set the error weights, and -1 otherwise.

**Notes:** Allocation of memory for *ewt* is handled within ARKODE.

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.

### 5.5.4 Residual weight function (ARKStep only)

As an alternative to providing the scalar or vector absolute residual tolerances (when the IVP units differ from the solution units), the user may provide a function of type `ARKRwtFn` to compute a vector `rwt` containing the weights in the WRMS norm  $\|v\|_{WRMS} = \left( \frac{1}{n} \sum_{i=1}^n (rwt_i v_i)^2 \right)^{1/2}$ . These weights will be used in place of those defined in §2.6.

```
typedef int (*ARKRwtFn)(N_Vector y, N_Vector rwt, void *user_data)
```

This function computes the WRMS residual weights for the vector `y`.

**Arguments:**

- `y` – the dependent variable vector at which the weight vector is to be computed.
- `rwt` – the output vector containing the residual weights.
- `user_data` – a pointer to user data, the same as the `user_data` parameter that was passed to `ARKStepSetUserData()`.

**Return value:** An `ARKRwtFn` function must return 0 if it successfully set the residual weights, and -1 otherwise.

**Notes:** Allocation of memory for `rwt` is handled within ARKStep.

The residual 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.

### 5.5.5 Time step adaptivity function (ARKStep and ERKStep only)

As an alternative to using one of the built-in time step adaptivity methods for controlling solution error, the user may provide a function of type `ARKAdaptFn` to compute a target step size `h` for the next integration step. These steps should be chosen such that the error estimate for the next time step remains below 1.

```
typedef int (*ARKAdaptFn)(N_Vector y, realtype t, realtype h1, realtype h2, realtype h3, realtype e1, realtype e2,
realtype e3, int q, int p, realtype *hnew, void *user_data)
```

This function implements a time step adaptivity algorithm that chooses `h` to satisfy the error tolerances.

**Arguments:**

- `y` – the current value of the dependent variable vector.
- `t` – the current value of the independent variable.
- `h1` – the current step size,  $t_n - t_{n-1}$ .
- `h2` – the previous step size,  $t_{n-1} - t_{n-2}$ .
- `h3` – the step size  $t_{n-2} - t_{n-3}$ .
- `e1` – the error estimate from the current step,  $n$ .
- `e2` – the error estimate from the previous step,  $n - 1$ .
- `e3` – the error estimate from the step  $n - 2$ .
- `q` – the global order of accuracy for the method.
- `p` – the global order of accuracy for the embedded method.
- `hnew` – the output value of the next step size.
- `user_data` – a pointer to user data, the same as the `h_data` parameter that was passed to `ARKStepSetAdaptivityFn()` or `ERKStepSetAdaptivityFn()`.

**Return value:** An *ARKAdaptFn* function should return 0 if it successfully set the next step size, and a non-zero value otherwise.

### 5.5.6 Explicit stability function (ARKStep and ERKStep only)

A user may supply a function to predict the maximum stable step size for the explicit portion of the problem,  $f^E(t, y)$  in ARKStep or the full  $f(t, y)$  in ERKStep. While the accuracy-based time step adaptivity algorithms may be sufficient for retaining a stable solution to the ODE system, these may be inefficient if the explicit right-hand side function contains moderately stiff terms. In this scenario, a user may provide a function of type *ARKExpStabFn* to provide this stability information to ARKODE. This function must set the scalar step size satisfying the stability restriction for the upcoming time step. This value will subsequently be bounded by the user-supplied values for the minimum and maximum allowed time step, and the accuracy-based time step.

```
typedef int (*ARKExpStabFn)(N_Vector y, realtype t, realtype *hstab, void *user_data)
```

This function predicts the maximum stable step size for the explicit portion of the ODE system.

**Arguments:**

- $y$  – the current value of the dependent variable vector.
- $t$  – the current value of the independent variable.
- $hstab$  – the output value with the absolute value of the maximum stable step size.
- $user\_data$  – a pointer to user data, the same as the *estab\_data* parameter that was passed to *ARKStepSetStabilityFn()* or *ERKStepSetStabilityFn()*.

**Return value:** An *ARKExpStabFn* function should return 0 if it successfully set the upcoming stable step size, and a non-zero value otherwise.

**Notes:** If this function is not supplied, or if it returns  $hstab \leq 0.0$ , then ARKODE will assume that there is no explicit stability restriction on the time step size.

### 5.5.7 Implicit stage prediction function (ARKStep and MRIStep only)

A user may supply a function to update the prediction for each implicit stage solution. If supplied, this routine will be called *after* any existing ARKStep or MRIStep predictor algorithm completes, so that the predictor may be modified by the user as desired. In this scenario, a user may provide a function of type *ARKStagePredictFn* to provide this implicit predictor to ARKODE. This function takes as input the already-predicted implicit stage solution and the corresponding “time” for that prediction; it then updates the prediction vector as desired. If the user-supplied routine will construct a full prediction (and thus the ARKODE prediction is irrelevant), it is recommended that the user *not* call *ARKStepSetPredictorMethod()* or *MRIStepSetPredictorMethod()*, thereby leaving the default trivial predictor in place.

```
typedef int (*ARKStagePredictFn)(realtype t, N_Vector zpred, void *user_data)
```

This function updates the prediction for the implicit stage solution.

**Arguments:**

- $t$  – the current value of the independent variable containing the “time” corresponding to the predicted solution.
- $zpred$  – the ARKStep-predicted stage solution on input, and the user-modified predicted stage solution on output.
- $user\_data$  – a pointer to user data, the same as the *user\_data* parameter that was passed to *ARKStepSetUserData()* or *MRIStepSetUserData()*.

**Return value:** An *ARKStagePredictFn* function should return 0 if it successfully set the upcoming stable step size, and a non-zero value otherwise.

**Notes:** This may be useful if there are bound constraints on the solution, and these should be enforced prior to beginning the nonlinear or linear implicit solver algorithm.

This routine is incompatible with the “minimum correction predictor” – option 5 to the routine [ARKStepSetPredictorMethod\(\)](#). If both are selected, then ARKStep will override its built-in implicit predictor routine to instead use option 0 (trivial predictor).

## 5.5.8 Rootfinding function

If a rootfinding problem is to be solved during integration of the ODE system, the user must supply a function of type [ARKRootFn](#).

`typedef int (*ARKRootFn)(realtype t, N_Vector y, realtype *gout, void *user_data)`

This function implements a vector-valued function  $g(t, y)$  such that roots are sought for the components  $g_i(t, y)$ ,  $i = 0, \dots, nrtfn-1$ .

**Arguments:**

- $t$  – the current value of the independent variable.
- $y$  – the current value of the dependent variable vector.
- $gout$  – the output array, of length  $nrtfn$ , with components  $g_i(t, y)$ .
- $user\_data$  – a pointer to user data, the same as the *user\_data* parameter that was passed to [ARKStepSetUserData\(\)](#), [ERKStepSetUserData\(\)](#), or [MRIStepSetUserData\(\)](#).

**Return value:** An *ARKRootFn* function should return 0 if successful or a non-zero value if an error occurred (in which case the integration is halted and ARKODE returns *ARK\_RTFUNC\_FAIL*).

**Notes:** Allocation of memory for *gout* is handled within ARKODE.

## 5.5.9 Jacobian construction (matrix-based linear solvers, ARKStep and MRIStep only)

If a matrix-based linear solver module is used (i.e., a non-NULL *SUNMatrix* object was supplied to [ARKStepSetLinearSolver\(\)](#) or [MRIStepSetLinearSolver\(\)](#)), the user may provide a function of type [ARKLsJacFn](#) to provide the Jacobian approximation or [ARKLsLinSysFn](#) to provide an approximation of the linear system  $\mathcal{A}(t, y) = M(t) - \gamma J(t, y)$ .

`typedef int (*ARKLsJacFn)(realtype t, N_Vector y, N_Vector fy, SUNMatrix Jac, void *user_data, N_Vector tmp1, N_Vector tmp2, N_Vector tmp3)`

This function computes the Jacobian matrix  $J(t, y) = \frac{\partial f^I}{\partial y}(t, y)$  (or an approximation to it).

**Arguments:**

- $t$  – the current value of the independent variable.
- $y$  – the current value of the dependent variable vector, namely the predicted value of  $y(t)$ .
- $fy$  – the current value of the vector  $f^I(t, y)$ .
- $Jac$  – the output Jacobian matrix.
- $user\_data$  – a pointer to user data, the same as the *user\_data* parameter that was passed to [ARKStepSetUserData\(\)](#) or [MRIStepSetUserData\(\)](#).

- *tmp1*, *tmp2*, *tmp3* – pointers to memory allocated to variables of type *N\_Vector* which can be used by an *ARKLsJacFn* as temporary storage or work space.

**Return value:** An *ARKLsJacFn* function should return 0 if successful, a positive value if a recoverable error occurred (in which case ARKODE will attempt to correct, while ARKLS sets *last\_flag* to *ARKLS\_JACFUNC\_RECVR*), or a negative value if it failed unrecoverably (in which case the integration is halted, *ARKStepEvolve()* or *MRISetStepEvolve()* returns *ARK\_LSETUP\_FAIL* and ARKLS sets *last\_flag* to *ARKLS\_JACFUNC\_UNRECVR*).

**Notes:** Information regarding 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 §8 for details).

When using a linear solver of type *SUNLINEARSOLVER\_DIRECT*, prior to calling the user-supplied Jacobian function, the Jacobian matrix  $J(t, y)$  is zeroed out, so only nonzero elements need to be loaded into *Jac*.

With the default Newton nonlinear solver, each call to the user's *ARKLsJacFn()* function is preceded by a call to the implicit *ARKRhsFn()* user function with the same  $(t, y)$  arguments. Thus, the Jacobian function can use any auxiliary data that is computed and saved during the evaluation of  $f^I(t, y)$ . In the case of a user-supplied or external nonlinear solver, this is also true if the nonlinear system function is evaluated prior to calling the linear solver setup function (see §10.1.4 for more information).

If the user's *ARKLsJacFn* function uses difference quotient approximations, then it may need to access quantities not in the argument list, including the current step size, the error weights, etc. To obtain these, the user will need to add a pointer to the *ark\_mem* structure to their *user\_data*, and then use the *ARKStepGet\** or *MRISetStepGet\** functions listed in §5.2.2.10 or §5.4.6.3. The unit roundoff can be accessed as *UNIT\_ROUNDOFF*, which is defined in the header file *sundials\_types.h*.

**dense**  $J(t, y)$ : A user-supplied dense Jacobian function must load the  $N$  by  $N$  dense matrix *Jac* with an approximation to the Jacobian matrix  $J(t, y)$  at the point  $(t, y)$ . Utility routines and accessor macros for the *SUNMATRIX\_DENSE* module are documented in §8.3.

**banded**  $J(t, y)$ : A user-supplied banded Jacobian function must load the band matrix *Jac* with the elements of the Jacobian  $J(t, y)$  at the point  $(t, y)$ . Utility routines and accessor macros for the *SUNMATRIX\_BAND* module are documented in §8.6.

**sparse**  $J(t, y)$ : A user-supplied sparse Jacobian function must load the compressed-sparse-column (CSC) or compressed-sparse-row (CSR) matrix *Jac* with an approximation to the Jacobian matrix  $J(t, y)$  at the point  $(t, y)$ . 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. Utility routines and accessor macros for the *SUNMATRIX\_SPARSE* type are documented in §8.8.

```
typedef int (*ARKLsLinSysFn)(realtype t, N_Vector y, N_Vector fy, SUNMatrix A, SUNMatrix M, booleantype jok,  
booleantype *jcur, realtype gamma, void *user_data, N_Vector tmp1, N_Vector tmp2, N_Vector tmp3)
```

This function computes the linear system matrix  $\mathcal{A}(t, y) = M(t) - \gamma J(t, y)$  (or an approximation to it).

#### Arguments:

- *t* – the current value of the independent variable.
- *y* – the current value of the dependent variable vector, namely the predicted value of  $y(t)$ .
- *fy* – the current value of the vector  $f^I(t, y)$ .
- *A* – the output linear system matrix.
- *M* – the current mass matrix (this input is NULL if  $M = I$ ).
- *jok* – is an input flag indicating whether the Jacobian-related data needs to be updated. The *jok* argument provides for the reuse of Jacobian data. When *jok* = *SUNFALSE*, the Jacobian-related data should be recomputed from scratch. When *jok* = *SUNTRUE* the Jacobian data, if saved from the previous call

to this function, can be reused (with the current value of *gamma*). A call with *jok* = SUNTRUE can only occur after a call with *jok* = SUNFALSE.

- *jcur* – is a pointer to a flag which should be set to SUNTRUE if Jacobian data was recomputed, or set to SUNFALSE if Jacobian data was not recomputed, but saved data was still reused.
- *gamma* – the scalar  $\gamma$  appearing in the Newton system matrix  $\mathcal{A} = M(t) - \gamma J(t, y)$ .
- *user\_data* – a pointer to user data, the same as the *user\_data* parameter that was passed to [ARKStepSetUserData\(\)](#) or [MRIStepSetUserData\(\)](#).
- *tmp1*, *tmp2*, *tmp3* – pointers to memory allocated to variables of type *N\_Vector* which can be used by an ARKLSLinSysFn as temporary storage or work space.

**Return value:** An ARKLSLinSysFn function should return 0 if successful, a positive value if a recoverable error occurred (in which case ARKODE will attempt to correct, while ARKLS sets *last\_flag* to *ARKLS\_JACFUNC\_RECVR*), or a negative value if it failed unrecoverably (in which case the integration is halted, [ARKStepEvolve\(\)](#) or [MRIStepEvolve\(\)](#) returns *ARK\_LSETUP\_FAIL* and ARKLS sets *last\_flag* to *ARKLS\_JACFUNC\_UNRECVR*).

### 5.5.10 Jacobian-vector product (matrix-free linear solvers, ARKStep and MRIStep only)

When using a matrix-free linear solver module for the implicit stage solves (i.e., a NULL-valued SUNMATRIX argument was supplied to [ARKStepSetLinearSolver\(\)](#) or [MRIStepSetLinearSolver\(\)](#)), the user may provide a function of type *ARKLsJacTimesVecFn* 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.

```
typedef int (*ARKLsJacTimesVecFn)(N_Vector v, N_Vector Jv, realtype t, N_Vector y, N_Vector fy, void *user_data,
N_Vector tmp)
```

This function computes the product  $Jv$  where  $J(t, y) \approx \frac{\partial f^I}{\partial y}(t, y)$  (or an approximation to it).

#### Arguments:

- *v* – the vector to multiply.
- *Jv* – the output vector computed.
- *t* – the current value of the independent variable.
- *y* – the current value of the dependent variable vector.
- *fy* – the current value of the vector  $f^I(t, y)$ .
- *user\_data* – a pointer to user data, the same as the *user\_data* parameter that was passed to [ARKStepSetUserData\(\)](#) or [MRIStepSetUserData\(\)](#).
- *tmp* – pointer to memory allocated to a variable of type *N\_Vector* which can be used as temporary storage or work space.

**Return value:** The value to be returned by the Jacobian-vector product function should be 0 if successful. Any other return value will result in an unrecoverable error of the generic Krylov solver, in which case the integration is halted.

**Notes:** If the user's *ARKLsJacTimesVecFn* function uses difference quotient approximations, it may need to access quantities not in the argument list. These include the current step size, the error weights, etc. To obtain these, the user will need to add a pointer to the *ark\_mem* structure to their *user\_data*, and then use the *ARKStepGet\** or *MRIStepGet\** functions listed in §5.2.2.10 or §5.4.6.3. The unit roundoff can be accessed as *UNIT\_ROUNDOFF*, which is defined in the header file *sundials\_types.h*.

### 5.5.11 Jacobian-vector product setup (matrix-free linear solvers, ARKStep and MRIStep only)

If the user's Jacobian-times-vector routine requires that any Jacobian-related data be preprocessed or evaluated, then this needs to be done in a user-supplied function of type `ARKLsJacTimesSetupFn`, defined as follows:

```
typedef int (*ARKLsJacTimesSetupFn)(realtype t, N_Vector y, N_Vector fy, void *user_data)
```

This function preprocesses and/or evaluates any Jacobian-related data needed by the Jacobian-times-vector routine.

#### Arguments:

- $t$  – the current value of the independent variable.
- $y$  – the current value of the dependent variable vector.
- $fy$  – the current value of the vector  $f^I(t, y)$ .
- $user\_data$  – a pointer to user data, the same as the  $user\_data$  parameter that was passed to `ARKStepSetUserData()` or `MRIStepSetUserData()`.

**Return value:** The value to be 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 implicit `ARKRhsFn` user function with the same  $(t, y)$  arguments. Thus, the setup function can use any auxiliary data that is computed and saved during the evaluation of the implicit ODE right-hand side.

If the user's `ARKLsJacTimesSetupFn` function uses difference quotient approximations, it may need to access quantities not in the argument list. These include the current step size, the error weights, etc. To obtain these, the user will need to add a pointer to the `ark_mem` structure to their  $user\_data$ , and then use the `ARKStepGet*` or `MRIStepGet*` functions listed in §5.2.2.10 or §5.4.6.3. The unit roundoff can be accessed as `UNIT_ROUNDOFF`, which is defined in the header file `sundials_types.h`.

### 5.5.12 Preconditioner solve (iterative linear solvers, ARKStep and MRIStep only)

If a user-supplied preconditioner is to be used with a SUNLinSol solver module, then the user must provide a function of type `ARKLsPrecSolveFn` to solve the linear system  $Pz = r$ , where  $P$  corresponds to either a left or right preconditioning matrix. Here  $P$  should approximate (at least crudely) the Newton matrix  $\mathcal{A}(t, y) = M(t) - \gamma J(t, y)$ , where  $M(t)$  is the mass matrix and  $J(t, y) = \frac{\partial f^I}{\partial y}(t, y)$ . If preconditioning is done on both sides, the product of the two preconditioner matrices should approximate  $\mathcal{A}$ .

```
typedef int (*ARKLsPrecSolveFn)(realtype t, N_Vector y, N_Vector fy, N_Vector r, N_Vector z, realtype gamma,  
realtype delta, int lr, void *user_data)
```

This function solves the preconditioner system  $Pz = r$ .

#### Arguments:

- $t$  – the current value of the independent variable.
- $y$  – the current value of the dependent variable vector.
- $fy$  – the current value of the vector  $f^I(t, y)$ .
- $r$  – the right-hand side vector of the linear system.
- $z$  – the computed output solution vector.
- $gamma$  – the scalar  $\gamma$  appearing in the Newton matrix given by  $\mathcal{A} = M(t) - \gamma J(t, y)$ .

- $\delta$  – 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 to be less than  $\delta$  in the weighted  $l_2$  norm, i.e.  $\left( \sum_{i=1}^n (Res_i * ewt_i)^2 \right)^{1/2} < \delta$ , where  $\delta = \text{delta}$ . To obtain the `N_Vector ewt`, call `ARKStepGetErrWeights()` or `MRIStepGetErrWeights()`.
- $lr$  – an input flag indicating whether the preconditioner solve is to use the left preconditioner ( $lr = 1$ ) or the right preconditioner ( $lr = 2$ ).
- $user\_data$  – a pointer to user data, the same as the  $user\_data$  parameter that was passed to `ARKStepSetUserData()` or `MRIStepSetUserData()`.

**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), or negative for an unrecoverable error (in which case the integration is halted).

### 5.5.13 Preconditioner setup (iterative linear solvers, ARKStep and MRIStep only)

If the user's preconditioner routine requires that any data be preprocessed or evaluated, then these actions need to occur within a user-supplied function of type `ARKLsPrecSetupFn`.

```
typedef int (*ARKLsPrecSetupFn)(realtype t, N_Vector y, N_Vector fy, booleantype jok, booleantype *jcurPtr,
                               realtype gamma, void *user_data)
```

This function preprocesses and/or evaluates Jacobian-related data needed by the preconditioner.

**Arguments:**

- $t$  – the current value of the independent variable.
- $y$  – the current value of the dependent variable vector.
- $fy$  – the current value of the vector  $f^I(t, y)$ .
- $jok$  – is an input flag indicating whether the Jacobian-related data needs to be updated. The  $jok$  argument provides for the reuse of Jacobian data in the preconditioner solve function. When  $jok = \text{SUNFALSE}$ , the Jacobian-related data should be recomputed from scratch. When  $jok = \text{SUNTRUE}$  the Jacobian data, if saved from the previous call to this function, can be reused (with the current value of  $gamma$ ). A call with  $jok = \text{SUNTRUE}$  can only occur after a call with  $jok = \text{SUNFALSE}$ .
- $jcurPtr$  – is a pointer to a flag which should be set to `SUNTRUE` if Jacobian data was recomputed, or set to `SUNFALSE` if Jacobian data was not recomputed, but saved data was still reused.
- $gamma$  – the scalar  $\gamma$  appearing in the Newton matrix given by  $\mathcal{A} = M(t) - \gamma J(t, y)$ .
- $user\_data$  – a pointer to user data, the same as the  $user\_data$  parameter that was passed to `ARKStepSetUserData()` or `MRIStepSetUserData()`.

**Return value:** The value to be 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), or 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 of the resulting approximation to  $\mathcal{A} = M(t) - \gamma J(t, y)$ .

With the default nonlinear solver (the native SUNDIALS Newton method), each call to the preconditioner setup function is preceded by a call to the implicit `ARKRhsFn` user function with the same  $(t, y)$  arguments. Thus, the preconditioner setup function can use any auxiliary data that is computed and saved during the evaluation of the implicit ODE right-hand side. In the case of a user-supplied or external nonlinear solver, this is also true if the nonlinear system function is evaluated prior to calling the linear solver setup function (see §10.1.4 for more information).

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 Newton iteration.

If the user's `ARKLsPrecSetupFn` function uses difference quotient approximations, it may need to access quantities not in the call list. These include the current step size, the error weights, etc. To obtain these, the user will need to add a pointer to the `ark_mem` structure to their `user_data`, and then use the `ARKStepGet*` or `MRIStepGet*` functions listed in §5.2.2.10 or §5.4.6.3. The unit roundoff can be accessed as `UNIT_ROUNDOFF`, which is defined in the header file `sundials_types.h`.

## 5.5.14 Mass matrix construction (matrix-based linear solvers, ARKStep only)

If a matrix-based mass-matrix linear solver is used (i.e., a non-NULL `SUNMATRIX` was supplied to `ARKStepSet-MassLinearSolver()`, the user must provide a function of type `ARKLsMassFn` to provide the mass matrix approximation.

```
typedef int (*ARKLsMassFn)(realtype t, SUNMatrix M, void *user_data, N_Vector tmp1, N_Vector tmp2, N_Vector tmp3)
```

This function computes the mass matrix  $M(t)$  (or an approximation to it).

### Arguments:

- $t$  – the current value of the independent variable.
- $M$  – the output mass matrix.
- `user_data` – a pointer to user data, the same as the `user_data` parameter that was passed to `ARKStepSe-tUserData()`.
- `tmp1, tmp2, tmp3` – pointers to memory allocated to variables of type `N_Vector` which can be used by an `ARKLsMassFn` as temporary storage or work space.

**Return value:** An `ARKLsMassFn` function should return 0 if successful, or a negative value if it failed unrecoverably (in which case the integration is halted, `ARKStepEvolve()` returns `ARK_MASSSETUP_FAIL` and ARKLS sets `last_flag` to `ARKLS_MASSFUNC_UNRECVR`).

**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 §8 for details).

Prior to calling the user-supplied mass matrix function, the mass matrix  $M(t)$  is zeroed out, so only nonzero elements need to be loaded into  $M$ .

**dense**  $M(t)$ : A user-supplied dense mass matrix function must load the  $N$  by  $N$  dense matrix  $M$  with an approximation to the mass matrix  $M(t)$ . Utility routines and accessor macros for the `SUNMATRIX_DENSE` module are documented in §8.3.

**banded**  $M(t)$ : A user-supplied banded mass matrix function must load the band matrix  $M$  with the elements of the mass matrix  $M(t)$ . Utility routines and accessor macros for the `SUNMATRIX_BAND` module are documented in §8.6.

**sparse**  $M(t)$ : A user-supplied sparse mass matrix function must load the compressed-sparse-column (CSR) or compressed-sparse-row (CSR) matrix  $M$  with an approximation to the mass matrix  $M(t)$ . Storage for  $M$  already exists on entry to this function, although the user should ensure that sufficient space is allocated in  $M$  to hold the nonzero values to be set; if the existing space is insufficient the user may reallocate the data and row index arrays as needed. Utility routines and accessor macros for the `SUNMATRIX_SPARSE` type are documented in §8.8.

### 5.5.15 Mass matrix-vector product (matrix-free linear solvers, ARKStep only)

If a matrix-free linear solver is to be used for mass-matrix linear systems (i.e., a NULL-valued SUNMATRIX argument was supplied to [ARKStepSetMassLinearSolver\(\)](#) in §5.2.1), the user *must* provide a function of type [ARKLs-MassTimesVecFn](#) in the following form, to compute matrix-vector products  $M(t)v$ .

```
typedef int (*ARKLsMassTimesVecFn)(N_Vector v, N_Vector Mv, realtype t, void *mtimes_data)
```

This function computes the product  $M(t)v$  (or an approximation to it).

#### Arguments:

- $v$  – the vector to multiply.
- $Mv$  – the output vector computed.
- $t$  – the current value of the independent variable.
- $mtimes\_data$  – a pointer to user data, the same as the  $mtimes\_data$  parameter that was passed to [ARK-StepSetMassTimes\(\)](#).

**Return value:** The value to be returned by the mass-matrix-vector product function should be 0 if successful.

Any other return value will result in an unrecoverable error of the generic Krylov solver, in which case the integration is halted.

### 5.5.16 Mass matrix-vector product setup (matrix-free linear solvers, ARKStep only)

If the user's mass-matrix-times-vector routine requires that any mass matrix-related data be preprocessed or evaluated, then this needs to be done in a user-supplied function of type [ARKLsMassTimesSetupFn](#), defined as follows:

```
typedef int (*ARKLsMassTimesSetupFn)(realtype t, void *mtimes_data)
```

This function preprocesses and/or evaluates any mass-matrix-related data needed by the mass-matrix-times-vector routine.

#### Arguments:

- $t$  – the current value of the independent variable.
- $mtimes\_data$  – a pointer to user data, the same as the  $mtimes\_data$  parameter that was passed to [ARK-StepSetMassTimes\(\)](#).

**Return value:** The value to be returned by the mass-matrix-vector setup function should be 0 if successful. Any other return value will result in an unrecoverable error of the ARKLS mass matrix solver interface, in which case the integration is halted.

### 5.5.17 Mass matrix preconditioner solve (iterative linear solvers, ARKStep only)

If a user-supplied preconditioner is to be used with a SUNLINEAR solver module for mass matrix linear systems, then the user must provide a function of type [ARKLsMassPrecSolveFn](#) to solve the linear system  $Pz = r$ , where  $P$  may be either a left or right preconditioning matrix. Here  $P$  should approximate (at least crudely) the mass matrix  $M(t)$ . If preconditioning is done on both sides, the product of the two preconditioner matrices should approximate  $M(t)$ .

```
typedef int (*ARKLsMassPrecSolveFn)(realtype t, N_Vector r, N_Vector z, realtype delta, int lr, void *user_data)
```

This function solves the preconditioner system  $Pz = r$ .

#### Arguments:

- $t$  – the current value of the independent variable.
- $r$  – the right-hand side vector of the linear system.
- $z$  – the computed output solution vector.

- $\delta$  – 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 to be less than  $\delta$  in the weighted  $l_2$  norm, i.e.  $\left( \sum_{i=1}^n (Res_i * ewt_i)^2 \right)^{1/2} < \delta$ , where  $\delta = \text{delta}$ . To obtain the `N_Vector ewt`, call `ARKStepGetErrWeights()`.
- $lr$  – an input flag indicating whether the preconditioner solve is to use the left preconditioner ( $lr = 1$ ) or the right preconditioner ( $lr = 2$ ).
- $user\_data$  – a pointer to user data, the same as the  $user\_data$  parameter that was passed to `ARKStepSetUserData()`.

**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), or negative for an unrecoverable error (in which case the integration is halted).

## 5.5.18 Mass matrix preconditioner setup (iterative linear solvers, ARKStep only)

If the user's mass matrix preconditioner above requires that any problem data be preprocessed or evaluated, then these actions need to occur within a user-supplied function of type `ARKLsMassPrecSetupFn`.

`typedef int (*ARKLsMassPrecSetupFn)(realtype t, void *user_data)`

This function preprocesses and/or evaluates mass-matrix-related data needed by the preconditioner.

**Arguments:**

- $t$  – the current value of the independent variable.
- $user\_data$  – a pointer to user data, the same as the  $user\_data$  parameter that was passed to `ARKStepSetUserData()`.

**Return value:** The value to be returned by the mass matrix 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), or negative for an unrecoverable error (in which case the integration is halted).

**Notes:** The operations performed by this function might include forming a mass matrix and performing an incomplete factorization of the result. Although such operations would typically be performed only once at the beginning of a simulation, these may be required if the mass matrix can change as a function of time.

If both this function and a `ARKLsMassTimesSetupFn` are supplied, all calls to this function will be preceded by a call to the `ARKLsMassTimesSetupFn`, so any setup performed there may be reused.

## 5.5.19 Vector resize function

For simulations involving changes to the number of equations and unknowns in the ODE system (e.g. when using spatial adaptivity in a PDE simulation), the ARKODE integrator may be “resized” between integration steps, through calls to the `ARKStepResize()`, `ERKStepResize()`, or `MRISetStepResize()` function. Typically, when performing adaptive simulations the solution is stored in a customized user-supplied data structure, to enable adaptivity without repeated allocation/deallocation of memory. In these scenarios, it is recommended that the user supply a customized vector kernel to interface between SUNDIALS and their problem-specific data structure. If this vector kernel includes a function of type `ARKVecResizeFn` to resize a given vector implementation, then this function may be supplied to `ARKStepResize()`, `ERKStepResize()`, or `MRISetStepResize()`, so that all internal ARKODE vectors may be resized, instead of deleting and re-creating them at each call. This resize function should have the following form:

`typedef int (*ARKVecResizeFn)(N_Vector y, N_Vector ytemplate, void *user_data)`

This function resizes the vector  $y$  to match the dimensions of the supplied vector,  $ytemplate$ .

**Arguments:**

- $y$  – the vector to resize.
- $y_{template}$  – a vector of the desired size.
- $user\_data$  – a pointer to user data, the same as the  $resize\_data$  parameter that was passed to [ARKStepResize\(\)](#), [ERKStepResize\(\)](#), or [MRIStepResize\(\)](#).

**Return value:** An `ARKVecResizeFn` function should return 0 if it successfully resizes the vector  $y$ , and a non-zero value otherwise.

**Notes:** If this function is not supplied, then ARKODE will instead destroy the vector  $y$  and clone a new vector  $y$  off of  $y_{template}$ .

## 5.5.20 Pre inner integrator communication function (MRIStep only)

The user may supply a function of type `MRIStepPreInnerFn` that will be called *before* each inner integration to perform any communication or memory transfers of forcing data supplied by the outer integrator to the inner integrator for the inner integration.

```
typedef int (*MRIStepPreInnerFn)(realtype t, N_Vector *f, int num_vecs, void *user_data)
```

**Arguments:**

- $t$  – the current value of the independent variable.
- $f$  – an `N_Vector` array of outer forcing vectors.
- $num\_vecs$  – the number of vectors in the `N_Vector` array.
- $user\_data$  – the `user_data` pointer that was passed to [MRIStepSetUserData\(\)](#).

**Return value:** An `MRIStepPreInnerFn` function should return 0 if successful, a positive value if a recoverable error occurred, or a negative value if an unrecoverable error occurred. As the MRIStep module only supports fixed step sizes at this time any non-zero return value will halt the integration.

**Notes:** In a heterogeneous computing environment if any data copies between the host and device vector data are necessary, this is where that should occur.

## 5.5.21 Post inner integrator communication function (MRIStep only)

The user may supply a function of type `MRIStepPostInnerFn` that will be called *after* each inner integration to perform any communication or memory transfers of state data supplied by the inner integrator to the outer integrator for the outer integration.

```
typedef int (*MRIStepPostInnerFn)(realtype t, N_Vector y, void *user_data)
```

**Arguments:**

- $t$  – the current value of the independent variable.
- $y$  – the current value of the dependent variable vector.
- $user\_data$  – the `user_data` pointer that was passed to [MRIStepSetUserData\(\)](#).

**Return value:** An `MRIStepPostInnerFn` function should return 0 if successful, a positive value if a recoverable error occurred, or a negative value if an unrecoverable error occurred. As the MRIStep module only supports fixed step sizes at this time any non-zero return value will halt the integration.

**Notes:** In a heterogeneous computing environment if any data copies between the host and device vector data are necessary, this is where that should occur.



# Chapter 6

## Butcher Table Data Structure

To store the Butcher table defining a Runge–Kutta method ARKODE provides the `ARKodeButcherTable` type and several related utility routines. We use the following Butcher table notation (shown for a 3-stage method):

$$\begin{array}{c|c} c & A \\ \hline q & b \\ p & \tilde{b} \end{array} = \begin{array}{c|ccc} c_1 & a_{1,1} & a_{1,2} & a_{1,3} \\ c_2 & a_{2,1} & a_{2,2} & a_{2,3} \\ c_3 & a_{3,1} & a_{3,2} & a_{3,3} \\ \hline q & b_1 & b_2 & b_3 \\ p & \tilde{b}_1 & \tilde{b}_2 & \tilde{b}_3 \end{array}$$

where the method and embedding share stage  $A$  and abscissa  $c$  values, but use their stages  $z_i$  differently through the coefficients  $b$  and  $\tilde{b}$  to generate methods of orders  $q$  (the main method) and  $p$  (the embedding, typically  $q = p + 1$ , though sometimes this is reversed). `ARKodeButcherTable` is defined as

```
typedef ARKodeButcherTableMem *ARKodeButcherTable
```

where `ARKodeButcherTableMem` is the structure

```
typedef struct ARKodeButcherTableMem {  
  
    int q;  
    int p;  
    int stages;  
    realtype **A;  
    realtype *c;  
    realtype *b;  
    realtype *d;  
  
};
```

where `stages` is the number of stages in the RK method, the variables `q`, `p`, `A`, `c`, and `b` have the same meaning as in the Butcher table above, and `d` is used to store  $\tilde{b}$ .

## 6.1 ARKodeButcherTable functions

Table 6.1: ARKodeButcherTable functions

Function name	Description
<code>ARKodeButcherTable_LoadERK()</code>	Retrieve a given explicit Butcher table by its unique name
<code>ARKodeButcherTable_LoadDIRK()</code>	Retrieve a given implicitly-implicit Butcher table by its unique name
<code>ARKodeButcherTable_Alloc()</code>	Allocate an empty Butcher table
<code>ARKodeButcherTable_Create()</code>	Create a new Butcher table
<code>ARKodeButcherTable_Copy()</code>	Create a copy of a Butcher table
<code>ARKodeButcherTable_Space()</code>	Get the Butcher table real and integer workspace size
<code>ARKodeButcherTable_Free()</code>	Deallocate a Butcher table
<code>ARKodeButcherTable_Write()</code>	Write the Butcher table to an output file
<code>ARKodeButcherTable_CheckOrder()</code>	Check the order of a Butcher table
<code>ARKodeButcherTable_CheckARKOrder()</code>	Check the order of an ARK pair of Butcher tables

`ARKodeButcherTable ARKodeButcherTable_LoadERK(ARKODE_ERKTableID emethod)`

Retrieves a specified explicit Butcher table. The prototype for this function, as well as the integer names for each provided method, are defined in the header file `arkode/arkode_butcher_erk.h`. For further information on these tables and their corresponding identifiers, see §14.

**Arguments:**

- *emethod* – integer input specifying the given Butcher table.

**Return value:**

- `ARKodeButcherTable` structure if successful.
- NULL pointer if *emethod* was invalid.

`ARKodeButcherTable ARKodeButcherTable_LoadDIRK(ARKODE_DIRKTableID imethod)`

Retrieves a specified diagonally-implicit Butcher table. The prototype for this function, as well as the integer names for each provided method, are defined in the header file `arkode/arkode_butcher_dirk.h`. For further information on these tables and their corresponding identifiers, see §14.

**Arguments:**

- *imethod* – integer input specifying the given Butcher table.

**Return value:**

- `ARKodeButcherTable` structure if successful.
- NULL pointer if *imethod* was invalid.

`ARKodeButcherTable ARKodeButcherTable_Alloc(int stages, boolean type embedded)`

Allocates an empty Butcher table.

**Arguments:**

- *stages* – the number of stages in the Butcher table.
- *embedded* – flag denoting whether the Butcher table has an embedding (SUNTRUE) or not (SUNFALSE).

**Return value:**

- `ARKodeButcherTable` structure if successful.
- NULL pointer if *stages* was invalid or an allocation error occurred.

---

*ARKodeButcherTable* **ARKodeButcherTable\_Create**(int s, int q, int p, *realtype* \*c, *realtype* \*A, *realtype* \*b, *realtype* \*d)

Allocates a Butcher table and fills it with the given values.

**Arguments:**

- *s* – number of stages in the RK method.
- *q* – global order of accuracy for the RK method.
- *p* – global order of accuracy for the embedded RK method.
- *c* – array (of length *s*) of stage times for the RK method.
- *A* – array of coefficients defining the RK stages. This should be stored as a 1D array of size *s\*s*, in row-major order.
- *b* – array of coefficients (of length *s*) defining the time step solution.
- *d* – array of coefficients (of length *s*) defining the embedded solution.

**Return value:**

- *ARKodeButcherTable* structure if successful.
- NULL pointer if *stages* was invalid or an allocation error occurred.

**Notes:** If the method does not have an embedding then *d* should be NULL and *p* should be equal to zero.

*ARKodeButcherTable* **ARKodeButcherTable\_Copy**(*ARKodeButcherTable* B)

Creates copy of the given Butcher table.

**Arguments:**

- *B* – the Butcher table to copy.

**Return value:**

- *ARKodeButcherTable* structure if successful.
- NULL pointer an allocation error occurred.

**void ARKodeButcherTable\_Space(*ARKodeButcherTable* B, *sunindextype* \*liw, *sunindextype* \*lrw)**

Get the real and integer workspace size for a Butcher table.

**Arguments:**

- *B* – the Butcher table.
- *lenrw* – the number of *realtype* values in the Butcher table workspace.
- *leniw* – the number of integer values in the Butcher table workspace.

**Return value:**

- *ARK\_SUCCESS* if successful.
- *ARK\_MEM\_NULL* if the Butcher table memory was NULL.

**void ARKodeButcherTable\_Free(*ARKodeButcherTable* B)**

Deallocate the Butcher table memory.

**Arguments:**

- *B* – the Butcher table.

**void ARKodeButcherTable\_Write(*ARKodeButcherTable* B, FILE \*outfile)**

Write the Butcher table to the provided file pointer.

**Arguments:**

- $B$  – the Butcher table.
- $outfile$  – pointer to use for printing the Butcher table.

**Notes:** The  $outfile$  argument can be `stdout` or `stderr`, or it may point to a specific file created using `fopen`.

`int ARKodeButcherTable_CheckOrder(ARKodeButcherTable B, int *q, int *p, FILE *outfile)`

Determine the analytic order of accuracy for the specified Butcher table. The analytic (necessary) conditions are checked up to order 6. For orders greater than 6 the Butcher simplifying (sufficient) assumptions are used.

**Arguments:**

- $B$  – the Butcher table.
- $q$  – the measured order of accuracy for the method.
- $p$  – the measured order of accuracy for the embedding; 0 if the method does not have an embedding.
- $outfile$  – file pointer for printing results; `NULL` to suppress output.

**Return value:**

- $0$  – success, the measured values of  $q$  and  $p$  match the values of  $q$  and  $p$  in the provided Butcher tables.
- $1$  – warning, the values of  $q$  and  $p$  in the provided Butcher tables are *lower* than the measured values, or the measured values achieve the *maximum order* possible with this function and the values of  $q$  and  $p$  in the provided Butcher tables table are higher.
- $-1$  – failure, the values of  $q$  and  $p$  in the provided Butcher tables are *higher* than the measured values.
- $-2$  – failure, the input Butcher table or critical table contents are `NULL`.

**Notes:** For embedded methods, if the return flags for  $q$  and  $p$  would differ, failure takes precedence over warning, which takes precedence over success.

`int ARKodeButcherTable_CheckARKOrder(ARKodeButcherTable B1, ARKodeButcherTable B2, int *q, int *p, FILE *outfile)`

Determine the analytic order of accuracy (up to order 6) for a specified ARK pair of Butcher tables.

**Arguments:**

- $B1$  – a Butcher table in the ARK pair.
- $B2$  – a Butcher table in the ARK pair.
- $q$  – the measured order of accuracy for the method.
- $p$  – the measured order of accuracy for the embedding; 0 if the method does not have an embedding.
- $outfile$  – file pointer for printing results; `NULL` to suppress output.

**Return value:**

- $0$  – success, the measured values of  $q$  and  $p$  match the values of  $q$  and  $p$  in the provided Butcher tables.
- $1$  – warning, the values of  $q$  and  $p$  in the provided Butcher tables are *lower* than the measured values, or the measured values achieve the *maximum order* possible with this function and the values of  $q$  and  $p$  in the provided Butcher tables table are higher.
- $-1$  – failure, the input Butcher tables or critical table contents are `NULL`.

**Notes:** For embedded methods, if the return flags for  $q$  and  $p$  would differ, warning takes precedence over success.

# Chapter 7

## Vector Data Structures

The SUNDIALS library comes packaged with a variety of NVECTOR implementations, designed for simulations in serial, shared-memory parallel, and distributed-memory parallel environments, as well as interfaces to vector data structures used within external linear solver libraries. All native implementations assume that the process-local data is stored contiguously, and they in turn provide a variety of standard vector algebra operations that may be performed on the data.

In addition, SUNDIALS provides a simple interface for generic vectors (akin to a C++ *abstract base class*). All of the major SUNDIALS solvers (CVODE(s), IDA(s), KINSOL, ARKODE) in turn are constructed to only depend on these generic vector operations, making them immediately extensible to new user-defined vector objects. The only exceptions to this rule relate to the dense, banded and sparse-direct linear system solvers, since they rely on particular data storage and access patterns in the NVECTORS used.

### 7.1 Description of the NVECTOR Modules

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, and specific to, the particular NVECTOR implementation. Users can provide a custom implementation of the NVECTOR module or use one provided within SUNDIALS. The generic operations are described below. In the sections following, the implementations provided with SUNDIALS are described.

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
```

and the generic structure is defined as

```
struct _generic_N_Vector {
    void *content;
    struct _generic_N_Vector_Ops *ops;
};
```

Here, the `_generic_N_Vector_Ops` structure is essentially a list of function 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);
```

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```

N_Vector (*nvcloneempty)(N_Vector);
void (*nvdestroy)(N_Vector);
void (*nvspace)(N_Vector, sunindextype *, sunindextype *);
realtype* (*nvgetarraypointer)(N_Vector);
realtype* (*nvgetdevicearraypointer)(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 (*nvscale)(realtype, N_Vector, N_Vector);
void (*nvabs)(N_Vector, N_Vector);
void (*nvinv)(N_Vector, N_Vector);
void (*nvaddconst)(N_Vector, realtype, N_Vector);
realtype (*nvdotprod)(N_Vector, N_Vector);
(*nvmaxnorm)(N_Vector);
realtype (*nvrmsnorm)(N_Vector, N_Vector);
realtype (*nvrmsnormmask)(N_Vector, N_Vector, N_Vector);
realtype (*nvmin)(N_Vector);
realtype (*nvwl2norm)(N_Vector, N_Vector);
realtype (*nvl1norm)(N_Vector);
void (*nvcompare)(realtype, N_Vector, N_Vector);
(*nvintest)(N_Vector, N_Vector);
booleantype (*nvconstrmask)(N_Vector, 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 *, realtype,
                                N_Vector *, N_Vector *);
int (*nvscalevectorarray)(int, realtype *, N_Vector *, N_Vector *);
int (*nvconstvectorarray)(int, realtype, N_Vector *);
int (*nvrmsnomrvectorarray)(int, N_Vector *, N_Vector *, realtype *);
int (*nvrmsnomrmaskvectorarray)(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);
realtype (*nvminlocal)(N_Vector);
realtype (*nvl1normlocal)(N_Vector);
booleantype (*nvintestlocal)(N_Vector, N_Vector);
booleantype (*nvconstrmasklocal)(N_Vector, N_Vector, N_Vector);
realtype (*nvminquotientlocal)(N_Vector, N_Vector);
realtype (*nvwsqrsumlocal)(N_Vector, N_Vector);
realtype (*nvwsqrsummasklocal)(N_Vector, N_Vector, N_Vector);
int (*nvdotprodmultilocal)(int, N_Vector, N_Vector *, realtype *);
int (*nvdotprodmultiallreduce)(int, N_Vector, realtype *);

```

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```

int (*nvbufsize)(N_Vector, sunindextype *);
int (*nvbufpack)(N_Vector, void*);
int (*nvbufunpack)(N_Vector, void*);
};

```

The generic NVECTOR module defines and implements the vector operations acting on a `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 operation  $z \leftarrow cx$  for vectors  $x$  and  $z$  and a scalar  $c$ :

```

void N_VScale(realtype c, N_Vector x, N_Vector z) {
    z->ops->nyscale(c, x, z);
}

```

[§7.2](#) contains a complete list of all standard vector operations defined by the generic NVECTOR module. [§7.2.2](#), [§7.2.3](#), [§7.2.4](#), [§7.2.5](#), and [§7.2.6](#) list *optional* fused, vector array, local reduction, single buffer reduction, and exchange operations, respectively.

Fused and vector array operations (see [§7.2.2](#) and [§7.2.3](#)) 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.

Local reduction operations (see [§7.2.4](#)) are similarly intended to reduce parallel communication on distributed memory systems, particularly when NVECTOR objects are combined together within an NVECTOR\_MANYVECTOR object (see [§7.16](#)). If a particular NVECTOR implementation defines a local reduction operation as `NULL`, the NVECTOR\_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 implementations.

The single buffer reduction operations ([§7.2.5](#)) are used in low-synchronization methods to combine separate reductions into one `MPI_Allreduce` call.

The exchange operations (see [§7.2.6](#)) are intended only for use with the XBraid library for parallel-in-time integration (accessible from ARKODE) and are otherwise unused by SUNDIALS packages.

### 7.1.1 NVECTOR Utility Functions

The generic NVECTOR module also defines several utility functions to aid in creation and management of arrays of `N_Vector` objects – these functions are particularly useful for Fortran users to utilize the NVECTOR\_MANYVECTOR or SUNDIALS' sensitivity-enabled packages CVODES and IDAS.

The functions `N_VCloneVectorArray()` and `N_VCloneVectorArrayEmpty()` create (by cloning) an array of `count` variables of type `N_Vector`, each of the same type as an existing `N_Vector` input:

`N_Vector *N_VCloneVectorArray(int count, N_Vector w)`

Clones an array of `count` `N_Vector` objects, allocating their data arrays (similar to `N_VClone()`).

#### Arguments:

- `count` – number of `N_Vector` objects to create.
- `w` – template `N_Vector` to clone.

**Return value:**

- pointer to a new N\_Vector array on success.
- NULL pointer on failure.

`N_Vector *N_VCloneVectorArrayEmpty(int count, N_Vector w)`

Clones an array of count N\_Vector objects, leaving their data arrays unallocated (similar to `N_VCloneEmpty()`).

**Arguments:**

- count – number of N\_Vector objects to create.
- w – template `N_Vector` to clone.

**Return value:**

- pointer to a new N\_Vector array on success.
- NULL pointer on failure.

An array of variables of type `N_Vector` can be destroyed by calling `N_VDestroyVectorArray()`:

`void N_VDestroyVectorArray(N_Vector *vs, int count)`

Destroys an array of count N\_Vector objects.

**Arguments:**

- vs – N\_Vector array to destroy.
- count – number of N\_Vector objects in vs array.

**Notes:** This routine will internally call the N\_Vector implementation-specific `N_VDestroy()` operation.

If vs was allocated using `N_VCloneVectorArray()` then the data arrays for each N\_Vector object will be freed; if vs was allocated using `N_VCloneVectorArrayEmpty()` then it is the user's responsibility to free the data for each N\_Vector object.

Finally, we note that users of the Fortran 2003 interface may be interested in the additional utility functions `N_VNewVectorArray()`, `N_VGetVecAtIndexVectorArray()`, and `N_VSetVecAtIndexVectorArray()`, that are wrapped as `FN_NewVectorArray`, `FN_VGetVecAtIndexVectorArray`, and `FN_VSetVecAtIndexVectorArray`, respectively. These functions allow a Fortran 2003 user to create an empty vector array, access a vector from this array, and set a vector within this array:

`N_Vector *N_VNewVectorArray(int count)`

Creates an array of count N\_Vector objects, the pointers to each are initialized as NULL.

**Arguments:**

- count – length of desired N\_Vector array.

**Return value:**

- pointer to a new N\_Vector array on success.
- NULL pointer on failure.

`N_Vector *N_VGetVecAtIndexVectorArray(N_Vector *vs, int index)`

Accesses the N\_Vector at the location index within the N\_Vector array vs.

**Arguments:**

- vs – N\_Vector array.
- index – desired N\_Vector to access from within vs.

**Return value:**

- pointer to the indexed N\_Vector on success.
- NULL pointer on failure (`index < 0` or `vs == NULL`).

**Notes:** This routine does not verify that `index` is within the extent of `vs`, since `vs` is a simple N\_Vector array that does not internally store its allocated length.

**void N\_VSetVecAtIndexVectorArray(N\_Vector \*vs, int index, N\_Vector w)**

Sets a pointer to `w` at the location `index` within the vector array `vs`.

#### Arguments:

- `vs` – N\_Vector array.
- `index` – desired location to place the pointer to `w` within `vs`.
- `w` – N\_Vector to set within `vs`.

**Notes:** This routine does not verify that `index` is within the extent of `vs`, since `vs` is a simple N\_Vector array that does not internally store its allocated length.

### 7.1.2 Implementing a custom NVECTOR

A particular implementation of the NVECTOR module must:

- Specify the `content` field of the N\_Vector structure.
- 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.

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 that only required operations need to be set, and that all operations are copied when cloning a vector.

**N\_Vector N\_VNewEmpty()**

This allocates a new generic N\_Vector object and initializes its content pointer and the function pointers in the operations structure to NULL.

**Return value:** If successful, this function returns an N\_Vector object. If an error occurs when allocating the object, then this routine will return NULL.

**void N\_VFreeEmpty(N\_Vector v)**

This routine frees the generic 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:

- `v` – an N\_Vector object

**int N\_VCopyOps(N\_Vector w, N\_Vector v)**

This function copies the function pointers in the `ops` structure of `w` into the `ops` structure of `v`.

**Arguments:**

- $w$  – the vector to copy operations from
- $v$  – the vector to copy operations to

**Return value:** If successful, this function returns `0`. If either of the inputs are `NULL` or the ops structure of either input is `NULL`, then this function returns a non-zero value.

Each NVECTOR implementation included in SUNDIALS has a unique identifier specified in enumeration and shown in Table 7.1. It is recommended that a user supplied NVECTOR implementation use the `SUNDIALS_NVEC_CUSTOM` identifier.

Table 7.1: Vector Identifications associated with vector kernels supplied with SUNDIALS

Vector ID	Vector type	ID Value
<code>SUNDIALS_NVEC_SERIAL</code>	Serial	0
<code>SUNDIALS_NVEC_PARALLEL</code>	Distributed memory parallel (MPI)	1
<code>SUNDIALS_NVEC_OPENMP</code>	OpenMP shared memory parallel	2
<code>SUNDIALS_NVEC_PTHREADS</code>	PThreads shared memory parallel	3
<code>SUNDIALS_NVEC_PARHYP</code>	<i>hypre</i> ParHyp parallel vector	4
<code>SUNDIALS_NVEC_PETSC</code>	PETSc parallel vector	5
<code>SUNDIALS_NVEC_CUDA</code>	CUDA vector	6
<code>SUNDIALS_NVEC_HIP</code>	HIP vector	7
<code>SUNDIALS_NVEC_SYCL</code>	SYCL vector	8
<code>SUNDIALS_NVEC_RAJA</code>	RAJA vector	9
<code>SUNDIALS_NVEC_OPENMPDEV</code>	OpenMP vector with device offloading	10
<code>SUNDIALS_NVEC_TRILINOS</code>	Trilinos Tpetra vector	11
<code>SUNDIALS_NVEC_MANYVECTOR</code>	“ManyVector” vector	12
<code>SUNDIALS_NVEC_MPIMANYVECTOR</code>	MPI-enabled “ManyVector” vector	13
<code>SUNDIALS_NVEC_MPIPLUSX</code>	MPI+X vector	14
<code>SUNDIALS_NVEC_CUSTOM</code>	User-provided custom vector	15

### 7.1.3 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 the subsection §7.2 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.,  $m = \min_{0 \leq i < n} \text{real}(x_i)$ .
- `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.,  $z_i = c + 0j$  for  $0 \leq i < n$ .
- `N_VAddConst()` should only update the real components of the vector with the input constant, leaving all imaginary components unchanged.
- `N_VWrmsNorm()`, `N_VWrmsNormMask()`, `N_VWSqrSumLocal()` and `N_VWSqrSumMaskLocal()` 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 `realtypes`, 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 each package's linear solver interface (e.g., ARKLS or CVLS) may be used on complex-valued problems, none of the built-in SUNMatrix or SUNLinearSolver modules will work (all of the direct linear solvers must store complex-valued data, and all of the iterative linear solvers require `N_VDotProd()`). Hence a complex-valued user must provide custom linear solver modules for their problem. At a minimum this will consist of a custom SUNLinearSolver implementation (see §9.1.8), and optionally a custom SUNMatrix as well. The user should then attach these modules as normal to the package's linear solver interface.

Similarly, although both the `SUNNonlinearSolver_Newton` and `SUNNonlinearSolver_FixedPoint` modules may be used with any of the IVP solvers (CVODE(S), IDA(S) and ARKODE) for complex-valued problems, the Anderson-acceleration option with `SUNNonlinearSolver_FixedPoint` cannot be used due to its reliance on `N_VDotProd()`. By this same logic, the Anderson acceleration feature within KINSOL will also not work with complex-valued vectors.

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`.

## 7.2 Description of the NVECTOR operations

### 7.2.1 Standard vector operations

The standard vector operations defined by the generic `N_Vector` module are defined as follows. For each of these operations, we give the name, usage of the function, and a description of its mathematical operations below.

#### `N_Vector_ID N_VGetVectorID(N_Vector w)`

Returns the vector type identifier for the vector `w`. It is used to determine the vector implementation type (e.g. serial, parallel, ...) from the abstract `N_Vector` interface. Returned values are given in [Table 7.1](#).

Usage:

```
id = N_VGetVectorID(w);
```

#### `N_Vector N_VClone(N_Vector w)`

Creates a new `N_Vector` of the same type as an existing vector `w` and sets the `ops` field. It does not copy the vector, but rather allocates storage for the new vector.

Usage:

```
v = N_VClone(w);
```

#### `N_Vector N_VCloneEmpty(N_Vector w)`

Creates a new `N_Vector` of the same type as an existing vector `w` and sets the `ops` field. It does not allocate storage for the new vector's data.

Usage:

```
v = N_VCloneEmpty(w);
```

void **N\_VDestroy**(*N\_Vector* v)

Destroys the *N\_Vector* v and frees memory allocated for its internal data.

Usage:

```
N_VDestroy(v);
```

void **N\_VSpace**(*N\_Vector* v, *sunindextype* \*lrw, *sunindextype* \*liw)

Returns storage requirements for the *N\_Vector* v:

- lrw contains the number of *realtypes* words
- 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.

Usage:

```
N_VSpace(nvSpec, &lrw, &liw);
```

*realtypes* \***N\_VGetArrayPointer**(*N\_Vector* v)

Returns a pointer to a *realtypes* array from the *N\_Vector* v. Note that this assumes that the internal data in the *N\_Vector* is a contiguous array of *realtypes* and is accessible from the CPU.

This routine is only used in the solver-specific interfaces to the dense and banded (serial) linear solvers, and in the interfaces to the banded (serial) and band-block-diagonal (parallel) preconditioner modules provided with SUNDIALS.

Usage:

```
vdata = N_VGetArrayPointer(v);
```

*realtypes* \***N\_VGetDeviceArrayPointer**(*N\_Vector* v)

Returns a device pointer to a *realtypes* array from the *N\_Vector* v. Note that this assumes that the internal data in *N\_Vector* is a contiguous array of *realtypes* and is accessible from the device (e.g., GPU).

This operation is *optional* except when using the GPU-enabled direct linear solvers.

Usage:

```
vdata = N_VGetArrayPointer(v);
```

void **N\_VSetArrayPointer**(*realtypes* \*vdata, *N\_Vector* v)

Replaces the data array pointer in an *N\_Vector* with a given array of *realtypes*. Note that this assumes that the internal data in the *N\_Vector* is a contiguous array of *realtypes*. This routine is only used in the interfaces to the dense (serial) linear solver, hence need not exist in a user-supplied NVECTOR module.

Usage:

```
N_VSetArrayPointer(vdata,v);
```

void \***N\_VGetCommunicator**(*N\_Vector* v)

Returns a pointer to the MPI\_Comm object associated with the vector (if applicable). For MPI-unaware vector implementations, this should return NULL.

Usage:

```
commprtr = N_VGetCommunicator(v);
```

***sunindextype N\_VGetLength(N\_Vector v)***

Returns the global length (number of “active” entries) in the 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.

Usage:

```
global_length = N_VGetLength(v);
```

***void N\_VLinearSum(realtype a, N\_Vector x, realtype b, N\_Vector y, N\_Vector z)***

Performs the operation  $z = ax + by$ , where  $a$  and  $b$  are **realtype** scalars and  $x$  and  $y$  are of type **N\_Vector**:

$$z_i = ax_i + by_i, \quad i = 0, \dots, n - 1.$$

The output vector  $z$  can be the same as either of the input vectors ( $x$  or  $y$ ).

Usage:

```
N_VLinearSum(a, x, b, y, z);
```

***void N\_VConst(realtype c, N\_Vector z)***

Sets all components of the **N\_Vector**  $z$  to **realtype**  $c$ :

$$z_i = c, \quad i = 0, \dots, n - 1.$$

Usage:

```
N_VConst(c, z);
```

***void N\_VProd(N\_Vector x, N\_Vector y, N\_Vector z)***

Sets the **N\_Vector**  $z$  to be the component-wise product of the **N\_Vector** inputs  $x$  and  $y$ :

$$z_i = x_i y_i, \quad i = 0, \dots, n - 1.$$

Usage:

```
N_VProd(x, y, z);
```

***void N\_VDiv(N\_Vector x, N\_Vector y, N\_Vector z)***

Sets the **N\_Vector**  $z$  to be the component-wise ratio of the **N\_Vector** inputs  $x$  and  $y$ :

$$z_i = \frac{x_i}{y_i}, \quad i = 0, \dots, n - 1.$$

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.

Usage:

```
N_VDiv(x, y, z);
```

***void N\_VScale(realtype c, N\_Vector x, N\_Vector z)***

Scales the **N\_Vector**  $x$  by the **realtype** scalar  $c$  and returns the result in  $z$ :

$$z_i = cx_i, \quad i = 0, \dots, n - 1.$$

Usage:

```
N_VScale(c, x, z);
```

void **N\_VAbs**(*N\_Vector* x, *N\_Vector* z)

Sets the components of the *N\_Vector*  $z$  to be the absolute values of the components of the *N\_Vector*  $x$ :

$$z_i = |x_i|, \quad i = 0, \dots, n - 1.$$

Usage:

```
N_VAbs(x, z);
```

void **N\_VInv**(*N\_Vector* x, *N\_Vector* z)

Sets the components of the *N\_Vector*  $z$  to be the inverses of the components of the *N\_Vector*  $x$ :

$$z_i = \frac{1}{x_i}, \quad i = 0, \dots, n - 1.$$

This routine may not check for division by 0. It should be called only with an  $x$  which is guaranteed to have all nonzero components.

Usage:

```
N_VInv(x, z);
```

void **N\_VAddConst**(*N\_Vector* x, *realtype* b, *N\_Vector* z)

Adds the *realtype* scalar  $b$  to all components of  $x$  and returns the result in the *N\_Vector*  $z$ :

$$z_i = x_i + b, \quad i = 0, \dots, n - 1.$$

Usage:

```
N_VAddConst(x, b, z);
```

*realtype* **N\_VDotProd**(*N\_Vector* x, *N\_Vector* z)

Returns the value of the dot-product of the *N\_Vectors*  $x$  and  $y$ :

$$d = \sum_{i=0}^{n-1} x_i y_i.$$

Usage:

```
d = N_VDotProd(x, y);
```

*realtype* **N\_VMaxNorm**(*N\_Vector* x)

Returns the value of the  $l_\infty$  norm of the *N\_Vector*  $x$ :

$$m = \max_{0 \leq i < n} |x_i|.$$

Usage:

```
m = N_VMaxNorm(x);
```

*realtype* **N\_VRmsNorm**(*N\_Vector* x, *N\_Vector* w)

Returns the weighted root-mean-square norm of the *N\_Vector*  $x$  with (positive) *realtype* weight vector  $w$ :

$$m = \sqrt{\left( \sum_{i=0}^{n-1} (x_i w_i)^2 \right) / n}$$

Usage:

```
m = N_VWrmsNorm(x, w);
```

*realtype* **N\_VWrmsNormMask**(*N\_Vector* x, *N\_Vector* w, *N\_Vector* id)

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  $H(\alpha) = \begin{cases} 1 & \alpha > 0 \\ 0 & \alpha \leq 0 \end{cases}$ .

Usage:

```
m = N_VWrmsNormMask(x, w, id);
```

*realtype* **N\_VMin**(*N\_Vector* x)

Returns the smallest element of the *N\_Vector* x:

$$m = \min_{0 \leq i < n} x_i.$$

Usage:

```
m = N_VMin(x);
```

*realtype* **N\_VWL2Norm**(*N\_Vector* x, *N\_Vector* w)

Returns the weighted Euclidean  $l_2$  norm of the *N\_Vector* x with *realtype* weight vector w:

$$m = \sqrt{\sum_{i=0}^{n-1} (x_i w_i)^2}.$$

Usage:

```
m = N_VWL2Norm(x, w);
```

*realtype* **N\_VL1Norm**(*N\_Vector* x)

Returns the  $l_1$  norm of the *N\_Vector* x:

$$m = \sum_{i=0}^{n-1} |x_i|.$$

Usage:

```
m = N_VL1Norm(x);
```

**void N\_VCompare**(*realtype* c, *N\_Vector* x, *N\_Vector* z)

Compares the components of the *N\_Vector* x to the *realtype* scalar c and returns an *N\_Vector* z such that for all  $0 \leq i < n$ ,

$$z_i = \begin{cases} 1.0 & \text{if } |x_i| \geq c, \\ 0.0 & \text{otherwise} \end{cases}.$$

Usage:

```
N_VCompare(c, x, z);
```

*booleantype* **N\_VInvTest**(*N\_Vector* x, *N\_Vector* z)

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:

$$z_i = \frac{1}{x_i}, \quad i = 0, \dots, n - 1.$$

This routine returns a boolean assigned to SUNTRUE if all components of x are nonzero (successful inversion) and returns SUNFALSE otherwise.

Usage:

```
t = N_VInvTest(x, z);
```

*booleantype* **N\_VConstrMask**(*N\_Vector* c, *N\_Vector* x, *N\_Vector* m)

Performs the following constraint tests based on the values in  $c_i$ :

$$\begin{aligned} x_i &> 0 & \text{if } c_i = 2, \\ x_i &\geq 0 & \text{if } c_i = 1, \\ x_i &< 0 & \text{if } c_i = -2, \\ x_i &\leq 0 & \text{if } c_i = -1. \end{aligned}$$

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.

Usage:

```
t = N_VConstrMask(c, x, m);
```

*realtype* **N\_VMinQuotient**(*N\_Vector* num, *N\_Vector* denom)

This routine returns the minimum of the quotients obtained by termwise dividing the elements of *n* by the elements in *d*:

$$\min_{0 \leq i < n} \frac{\text{num}_i}{\text{denom}_i}.$$

A zero element in *denom* will be skipped. If no such quotients are found, then the large value BIG\_REAL (defined in the header file sundials\_types.h) is returned.

Usage:

```
minq = N_VMinQuotient(num, denom);
```

## 7.2.2 Fused operations

The following fused vector operations are *optional*. These 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 one of the fused vector operations as NULL, the NVECTOR interface will call one of the above standard vector operations as necessary. As above, for each operation, we give the name, usage of the function, and a description of its mathematical operations below.

*int* **N\_VLinearCombination**(*int* nv, *realtype* \*c, *N\_Vector* \*X, *N\_Vector* z)

This routine computes the linear combination of *nv* vectors with *n* elements:

$$z_i = \sum_{j=0}^{nv-1} c_j x_{j,i}, \quad i = 0, \dots, n - 1,$$

where  $c$  is an array of  $nv$  scalars,  $x_j$  is a vector in the vector array  $X$ , and  $z$  is the output vector. If the output vector  $z$  is one of the vectors in  $X$ , then it *must* be the first vector in the vector array. The operation returns 0 for success and a non-zero value otherwise.

Usage:

```
retval = N_VLinearCombination(nv, c, X, z);
```

**int N\_VScaleAddMulti**(int nv, *realtype* \*c, *N\_Vector* x, *N\_Vector* \*Y, *N\_Vector* \*Z)

This routine scales and adds one vector to  $nv$  vectors with  $n$  elements:

$$z_{j,i} = c_j x_i + y_{j,i}, \quad j = 0, \dots, nv - 1 \quad i = 0, \dots, n - 1,$$

where  $c$  is an array of scalars,  $x$  is a vector,  $y_j$  is a vector in the vector array  $Y$ , and  $z_j$  is an output vector in the vector array  $Z$ . The operation returns 0 for success and a non-zero value otherwise.

Usage:

```
retval = N_VScaleAddMulti(nv, c, x, Y, Z);
```

**int N\_VDotProdMulti**(int nv, *N\_Vector* x, *N\_Vector* \*Y, *realtype* \*d)

This routine computes the dot product of a vector with  $nv$  vectors having  $n$  elements:

$$d_j = \sum_{i=0}^{n-1} x_i y_{j,i}, \quad j = 0, \dots, nv - 1,$$

where  $d$  is an array of scalars containing the computed dot products,  $x$  is a vector, and  $y_j$  is a vector in the vector array  $Y$ . The operation returns 0 for success and a non-zero value otherwise.

Usage:

```
retval = N_VDotProdMulti(nv, x, Y, d);
```

### 7.2.3 Vector array operations

The following vector array operations are also *optional*. As with the fused vector operations, these 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 one of the fused or vector array operations as NULL, the NVECTOR interface will call one of the above standard vector operations as necessary. As above, for each operation, we give the name, usage of the function, and a description of its mathematical operations below.

**int N\_VLinearSumVectorArray**(int nv, *realtype* a, *N\_Vector* X, *realtype* b, *N\_Vector* \*Y, *N\_Vector* \*Z)

This routine computes the linear sum of two vector arrays of  $nv$  vectors with  $n$  elements:

$$z_{j,i} = ax_{j,i} + by_{j,i}, \quad i = 0, \dots, n - 1 \quad j = 0, \dots, nv - 1,$$

where  $a$  and  $b$  are scalars,  $x_j$  and  $y_j$  are vectors in the vector arrays  $X$  and  $Y$  respectively, and  $z_j$  is a vector in the output vector array  $Z$ . The operation returns 0 for success and a non-zero value otherwise.

Usage:

```
retval = N_VLinearSumVectorArray(nv, a, X, b, Y, Z);
```

**int N\_VScaleVectorArray**(int nv, *realtype* \*c, *N\_Vector* \*X, *N\_Vector* \*Z)

This routine scales each element in a vector of  $n$  elements in a vector array of  $nv$  vectors by a potentially different constant:

$$z_{j,i} = c_j x_{j,i}, \quad i = 0, \dots, n-1 \quad j = 0, \dots, nv-1,$$

where  $c$  is an array of scalars,  $x_j$  is a vector in the vector array  $X$ , and  $z_j$  is a vector in the output vector array  $Z$ . The operation returns 0 for success and a non-zero value otherwise.

Usage:

```
retval = N_VScaleVectorArray(nv, c, X, Z);
```

**int N\_VConstVectorArray**(int nv, *realtype* c, *N\_Vector* \*Z)

This routine sets each element in a vector of  $n$  elements in a vector array of  $nv$  vectors to the same value:

$$z_{j,i} = c, \quad i = 0, \dots, n-1 \quad j = 0, \dots, nv-1,$$

where  $c$  is a scalar and  $z_j$  is a vector in the vector array  $Z$ . The operation returns 0 for success and a non-zero value otherwise.

Usage:

```
retval = N_VConstVectorArray(nv, c, Z);
```

**int N\_VWrmsNormVectorArray**(int nv, *N\_Vector* \*X, *N\_Vector* \*W, *realtype* \*m)

This routine computes the weighted root mean square norm of each vector in a vector array:

$$m_j = \left( \frac{1}{n} \sum_{i=0}^{n-1} (x_{j,i} w_{j,i})^2 \right)^{1/2}, \quad j = 0, \dots, nv-1,$$

where  $x_j$  is a vector in the vector array  $X$ ,  $w_j$  is a weight vector in the vector array  $W$ , and  $m$  is the output array of scalars containing the computed norms. The operation returns 0 for success and a non-zero value otherwise.

Usage:

```
retval = N_VWrmsNormVectorArray(nv, X, W, m);
```

**int N\_VWrmsNormMaskVectorArray**(int nv, *N\_Vector* \*X, *N\_Vector* \*W, *N\_Vector* id, *realtype* \*m)

This routine computes the masked weighted root mean square norm of each vector in a vector array:

$$m_j = \left( \frac{1}{n} \sum_{i=0}^{n-1} (x_{j,i} w_{j,i} H(id_i))^2 \right)^{1/2}, \quad j = 0, \dots, nv-1,$$

where  $H(id_i) = 1$  if  $id_i > 0$  and is zero otherwise,  $x_j$  is a vector in the vector array  $X$ ,  $w_j$  is a weight vector in the vector array  $W$ ,  $id$  is the mask vector, and  $m$  is the output array of scalars containing the computed norms. The operation returns 0 for success and a non-zero value otherwise.

Usage:

```
retval = N_VWrmsNormMaskVectorArray(nv, X, W, id, m);
```

**int N\_VScaleAddMultiVectorArray**(int nv, int nsum, *realtype* \*c, *N\_Vector* \*X, *N\_Vector* \*\*YY, *N\_Vector* \*\*ZZ)

This routine scales and adds a vector array of  $nv$  vectors to  $nsum$  other vector arrays:

$$z_{k,j,i} = c_k x_{j,i} + y_{k,j,i}, \quad i = 0, \dots, n-1 \quad j = 0, \dots, nv-1, \quad k = 0, \dots, nsum-1$$

where  $c$  is an array of scalars,  $x_j$  is a vector in the vector array  $X$ ,  $y_{k,j}$  is a vector in the array of vector arrays  $YY$ , and  $z_{k,j}$  is an output vector in the array of vector arrays  $ZZ$ . The operation returns 0 for success and a non-zero value otherwise.

Usage:

```
retval = N_VScaleAddMultiVectorArray(nv, nsum, c, x, YY, ZZ);
```

**int N\_VLinearCombinationVectorArray**(int nv, int nsum, *realtype* \*c, *N\_Vector* \*\*XX, *N\_Vector* \*Z)

This routine computes the linear combination of  $nsum$  vector arrays containing  $nv$  vectors:

$$z_{j,i} = \sum_{k=0}^{nsum-1} c_k x_{k,j,i}, \quad i = 0, \dots, n-1 \quad j = 0, \dots, nv-1,$$

where  $c$  is an array of scalars,  $x_{k,j}$  is a vector in array of vector arrays  $XX$ , and  $z_{j,i}$  is an output vector in the vector array  $Z$ . If the output vector array is one of the vector arrays in  $XX$ , it *must* be the first vector array in  $XX$ . The operation returns 0 for success and a non-zero value otherwise.

Usage:

```
retval = N_VLinearCombinationVectorArray(nv, nsum, c, XX, Z);
```

## 7.2.4 Local reduction operations

The following local reduction operations are also *optional*. As with the fused and vector array operations, these are intended to reduce parallel communication on distributed memory systems. If a particular NVECTOR implementation defines one of the local reduction operations as NULL, the NVECTOR interface will call one of the above standard vector operations as necessary. As above, for each operation, we give the name, usage of the function, and a description of its mathematical operations below.

*realtype* **N\_VDotProdLocal**(*N\_Vector* x, *N\_Vector* y)

This routine computes the MPI task-local portion of the ordinary dot product of  $x$  and  $y$ :

$$d = \sum_{i=0}^{nlocal-1} x_i y_i,$$

where  $nlocal$  corresponds to the number of components in the vector on this MPI task (or  $nlocal = n$  for MPI-unaware applications).

Usage:

```
d = N_VDotProdLocal(x, y);
```

*realtype* **N\_VMaxNormLocal**(*N\_Vector* x)

This routine computes the MPI task-local portion of the maximum norm of the NVECTOR  $x$ :

$$m = \max_{0 \leq i < nlocal} |x_i|,$$

where  $nlocal$  corresponds to the number of components in the vector on this MPI task (or  $nlocal = n$  for MPI-unaware applications).

Usage:

```
m = N_VMaxNormLocal(x);
```

*realtype* **N\_VMinLocal**(*N\_Vector* *x*)

This routine computes the smallest element of the MPI task-local portion of the NVECTOR *x*:

$$m = \min_{0 \leq i < n_{local}} x_i,$$

where  $n_{local}$  corresponds to the number of components in the vector on this MPI task (or  $n_{local} = n$  for MPI-unaware applications).

Usage:

```
m = N_VMinLocal(x);
```

*realtype* **N\_VL1NormLocal**(*N\_Vector* *x*)

This routine computes the MPI task-local portion of the  $l_1$  norm of the *N\_Vector* *x*:

$$n = \sum_{i=0}^{n_{local}-1} |x_i|,$$

where  $n_{local}$  corresponds to the number of components in the vector on this MPI task (or  $n_{local} = n$  for MPI-unaware applications).

Usage:

```
n = N_VL1NormLocal(x);
```

*realtype* **N\_VWSqrSumLocal**(*N\_Vector* *x*, *N\_Vector* *w*)

This routine computes the MPI task-local portion of the weighted squared sum of the NVECTOR *x* with weight vector *w*:

$$s = \sum_{i=0}^{n_{local}-1} (x_i w_i)^2,$$

where  $n_{local}$  corresponds to the number of components in the vector on this MPI task (or  $n_{local} = n$  for MPI-unaware applications).

Usage:

```
s = N_VWSqrSumLocal(x, w);
```

*realtype* **N\_VWSqrSumMaskLocal**(*N\_Vector* *x*, *N\_Vector* *w*, *N\_Vector* *id*)

This routine computes the MPI task-local portion of the weighted squared sum of the NVECTOR *x* with weight vector *w* built using only the elements of *x* corresponding to positive elements of the NVECTOR *id*:

$$m = \sum_{i=0}^{n_{local}-1} (x_i w_i H(id_i))^2,$$

where

$$H(\alpha) = \begin{cases} 1 & \alpha > 0 \\ 0 & \alpha \leq 0 \end{cases}$$

and  $n_{local}$  corresponds to the number of components in the vector on this MPI task (or  $n_{local} = n$  for MPI-unaware applications).

Usage:

```
s = N_VWSqrSumMaskLocal(x, w, id);
```

*booleantype* **N\_VInvTestLocal**(*N\_Vector* x)

This routine sets the MPI task-local components of the NVECTOR  $z$  to be the inverses of the components of the NVECTOR  $x$ , with prior testing for zero values:

$$z_i = \frac{1}{x_i}, \quad i = 0, \dots, n_{local} - 1$$

where  $n_{local}$  corresponds to the number of components in the vector on this MPI task (or  $n_{local} = n$  for MPI-unaware applications). This routine returns a boolean assigned to SUNTRUE if all task-local components of  $x$  are nonzero (successful inversion) and returns SUNFALSE otherwise.

Usage:

```
t = N_VInvTestLocal(x);
```

*booleantype* **N\_VConstrMaskLocal**(*N\_Vector* c, *N\_Vector* x, *N\_Vector* m)

Performs the following constraint tests based on the values in  $c_i$ :

$$\begin{aligned} x_i &> 0 & \text{if } c_i = 2, \\ x_i &\geq 0 & \text{if } c_i = 1, \\ x_i &< 0 & \text{if } c_i = -2, \\ x_i &\leq 0 & \text{if } c_i = -1. \end{aligned}$$

for all MPI task-local components of the vectors. This routine returns a boolean assigned to SUNFALSE if any task-local 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.

Usage:

```
t = N_VConstrMaskLocal(c, x, m);
```

*realtype* **N\_VMinQuotientLocal**(*N\_Vector* num, *N\_Vector* denom)

This routine returns the minimum of the quotients obtained by term-wise dividing  $num_i$  by  $denom_i$ , for all MPI task-local components of the vectors. A zero element in  $denom$  will be skipped. If no such quotients are found, then the large value BIG\_REAL (defined in the header file sundials\_types.h) is returned.

Usage:

```
minq = N_VMinQuotientLocal(num, denom);
```

## 7.2.5 Single Buffer Reduction Operations

The following *optional* operations are used to combine separate reductions into a single MPI call by splitting the local computation and communication into separate functions. These operations are used in low-synchronization orthogonalization methods to reduce the number of MPI Allreduce calls. If a particular NVECTOR implementation does not define these operations additional communication will be required.

*int* **N\_VDotProdMultiLocal**(*int* nv, *N\_Vector* x, *N\_Vector* \*Y, *realtype* \*d)

This routine computes the MPI task-local portion of the dot product of a vector  $x$  with  $nv$  vectors  $y_j$ :

$$d_j = \sum_{i=0}^{n_{local}-1} x_i y_{j,i}, \quad j = 0, \dots, nv - 1,$$

where  $d$  is an array of scalars containing the computed dot products,  $x$  is a vector,  $y_j$  is a vector in the vector array  $Y$ , and  $n_{local}$  corresponds to the number of components in the vector on this MPI task. The operation returns 0 for success and a non-zero value otherwise.

Usage:

```
retval = N_VDotProdMultiLocal(nv, x, Y, d);
```

int **N\_VDotProdMultiAllReduce**(int nv, *N\_Vector* x, *realtype* \*d)

This routine combines the MPI task-local portions of the dot product of a vector  $x$  with  $nv$  vectors:

```
retval = MPI_Allreduce(MPI_IN_PLACE, d, nv, MPI_SUNREALTYPE, MPI_SUM, comm)
```

where  $d$  is an array of  $nv$  scalars containing the local contributions to the dot product and  $comm$  is the MPI communicator associated with the vector  $x$ . The operation returns 0 for success and a non-zero value otherwise.

Usage:

```
retval = N_VDotProdMultiAllReduce(nv, x, d);
```

## 7.2.6 Exchange operations

The following vector exchange operations are also *optional* and are intended only for use when interfacing with the XBraid library for parallel-in-time integration. In that setting these operations are required but are otherwise unused by SUNDIALS packages and may be set to NULL. For each operation, we give the function signature, a description of the expected behavior, and an example of the function usage.

int **N\_VBufSize**(*N\_Vector* x, *sunindextype* \*size)

This routine returns the buffer size need to exchange in the data in the vector  $x$  between computational nodes.

Usage:

```
flag = N_VBufSize(x, &buf_size)
```

int **N\_VBufPack**(*N\_Vector* x, void \*buf)

This routine fills the exchange buffer  $buf$  with the vector data in  $x$ .

Usage:

```
flag = N_VBufPack(x, &buf)
```

int **N\_VBufUnpack**(*N\_Vector* x, void \*buf)

This routine unpacks the data in the exchange buffer  $buf$  into the vector  $x$ .

Usage:

```
flag = N_VBufUnpack(x, buf)
```

## 7.3 NVECTOR functions required by ARKODE

In Table 7.2 below, we list the vector functions in the `N_Vector` module that are called within the ARKODE package. The table also shows, for each function, which ARKODE module uses the function. The ARKSTEP and ERKSTEP columns show function usage within the main time-stepping modules and the shared ARKODE infrastructure, while the remaining columns show function usage within the ARKLS linear solver interface, the ARKBANDPRE and ARKBBD-PRE preconditioner modules.

Note that for ARKLS we only list the `N_Vector` routines used directly by ARKLS, each `SUNLinearSolver` module may have additional requirements that are not listed here. In addition, specific `SUNNonlinearSolver` modules attached to ARKODE may have additional `N_Vector` requirements. For additional requirements by specific `SUNLinearSolver` and `SUNNonlinearSolver` modules, please see the accompanying sections §9 and §10.

At this point, we should emphasize that the user does not need to know anything about ARKODE's usage of vector functions in order to use ARKODE. Instead, this information is provided primarily for users interested in constructing a custom `N_Vector` module. We note that a number of `N_Vector` functions from the section §7.1 are not listed in the above table. Therefore a user-supplied `N_Vector` module for ARKODE could safely omit these functions from their implementation (although some may be needed by `SUNNonlinearSolver` or `SUNLinearSolver` modules).

Table 7.2: List of vector functions usage by ARKODE code modules

Routine	ARK- STEP	ERK- STEP	MRIS- TEP	ARKLS	ARKBAND- PRE	ARKBBD- PRE
<code>N_VGetLength()</code>				4		
<code>N_VAbs()</code>	X	X				
<code>N_VAddConst()</code>	X	X				
<code>N_VClone()</code>	X	X	X	X		
<code>N_VCloneEmpty()</code>						
<code>N_VConst()</code>	X	X	X	X		
<code>N_VDestroy()</code>	X	X	X	X		
<code>N_VDiv()</code>	X	X				
<code>N_VGetArrayPointer()</code>				1	X	X
<code>N_VInv()</code>	X	X				
<code>N_VLinearSum()</code>	X	X	X	X		
<code>N_VMaxNorm()</code>	X	X				
<code>N_VMin()</code>	X	X				
<code>N_VScale()</code>	X	X	X	X	X	X
<code>N_VSetArrayPointer()</code>				1		
<code>N_VSpace()</code> <sup>2</sup>	X	X	X	X	X	X
<code>N_VWrmsNorm()</code>	X	X	X	X	X	X
<code>N_VLinearCombina- tion()</code> <sup>3</sup>	X	X	X			
<code>N_VMinQuotient()</code> <sup>5</sup>	X	X				
<code>N_VConstrMask()</code> <sup>5</sup>	X	X				
<code>N_VCompare()</code> <sup>5</sup>	X	X				

Special cases (numbers match markings in table):

1. This is only required with the `SUNMATRIX_DENSE` or `SUNMATRIX_BAND` modules, where the default difference-quotient Jacobian approximation is used.
2. The `N_VSpace()` function is only informational, and will only be called if provided by the `N_Vector` implementation.

3. The `N_VLinearCombination()` function is in fact optional; if it is not supplied then `N_VLinearSum()` will be used instead.
4. The `N_VGetLength()` function is only required when an iterative or matrix iterative SUNLinearSolver module is used.
5. The functions `N_VMinQuotient()`, `N_VConstrMask()`, and `N_VCompare()` are only used when inequality constraints are enabled and may be omitted if this feature is not used.

## 7.4 The NVECTOR\_SERIAL Module

The serial implementation of the NVECTOR module provided with SUNDIALS, NVECTOR\_SERIAL, defines the *content* field of an `N_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.

```
struct _N_VectorContent_Serial {
    sunindextype length;
    booleantype own_data;
    realtype *data;
};
```

The header file to be included 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.

### 7.4.1 NVECTOR\_SERIAL accessor macros

The following five macros are provided to access the content of an NVECTOR\_SERIAL vector. The suffix `_S` in the names denotes the serial version.

#### `NV_CONTENT_S(v)`

This macro gives access to the contents of the serial vector `N_Vector v`.

The assignment `v_cont = NV_CONTENT_S(v)` sets `v_cont` to be a pointer to the serial `N_Vector content` structure.

Implementation:

```
#define NV_CONTENT_S(v) ( (N_VectorContent_Serial)(v->content) )
```

#### `NV_OWN_DATA_S(v)`

Access the *own\_data* component of the serial `N_Vector v`.

Implementation:

```
#define NV_OWN_DATA_S(v) ( NV_CONTENT_S(v)->own_data )
```

#### `NV_DATA_S(v)`

The assignment `v_data = NV_DATA_S(v)` sets `v_data` to be a pointer to the first component of the *data* for the `N_Vector v`.

Similarly, the assignment `NV_DATA_S(v) = v_data` sets the component array of `v` to be `v_data` by storing the pointer `v_data`.

Implementation:

```
#define NV_DATA_S(v) ( NV_CONTENT_S(v)->data )
```

**NV\_LENGTH\_S(v)**

Access the *length* component of the serial **N\_Vector** *v*.

The assignment *v\_len* = **NV\_LENGTH\_S(v)** sets *v\_len* to be the *length* of *v*. On the other hand, the call **NV\_LENGTH\_S(v) = len\_v** sets the *length* of *v* to be *len\_v*.

Implementation:

```
#define NV_LENGTH_S(v) ( NV_CONTENT_S(v)->length )
```

**NV\_Ith\_S(v, i)**

This macro gives access to the individual components of the *data* array of an **N\_Vector**, using standard 0-based C indexing.

The assignment *r* = **NV\_Ith\_S(v, i)** sets *r* to be the value of the *i*-th component of *v*.

The assignment **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:

```
#define NV_Ith_S(v, i) ( NV_DATA_S(v)[i] )
```

## 7.4.2 NVECTOR\_SERIAL functions

The **NVECTOR\_SERIAL** module defines serial implementations of all vector operations listed in §7.2.1, §7.2.2, §7.2.3, and §7.2.4. Their names are obtained from those in those sections by appending the suffix **\_Serial** (e.g. **N\_VDestroy\_Serial**). All the standard vector operations listed in §7.2.1 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\_Vector N\_VNew\_Serial(sunindextype vec\_length, SUNContext sunctx)**

This function creates and allocates memory for a serial **N\_Vector**. Its only argument is the vector length.

**N\_Vector N\_VNewEmpty\_Serial(sunindextype vec\_length, SUNContext sunctx)**

This function creates a new serial **N\_Vector** with an empty (NULL) data array.

**N\_Vector N\_VMake\_Serial(sunindextype vec\_length, realtype \*v\_data, SUNContext sunctx)**

This function creates and allocates memory for a serial vector with user-provided data array, *v\_data*.

(This function does *not* allocate memory for *v\_data* itself.)

**void N\_VPrint\_Serial(N\_Vector v)**

This function prints the content of a serial vector to **stdout**.

**void N\_VPrintFile\_Serial(N\_Vector v, FILE \*outfile)**

This function prints the content of a serial vector to *outfile*.

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 that 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.

int **N\_VEnableFusedOps\_Serial**(*N\_Vector* v, *booleantype* tf)

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.

int **N\_VEnableLinearCombination\_Serial**(*N\_Vector* v, *booleantype* tf)

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.

int **N\_VEnableScaleAddMulti\_Serial**(*N\_Vector* v, *booleantype* tf)

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.

int **N\_VEnableDotProdMulti\_Serial**(*N\_Vector* v, *booleantype* tf)

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.

int **N\_VEnableLinearSumVectorArray\_Serial**(*N\_Vector* v, *booleantype* tf)

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.

int **N\_VEnableScaleVectorArray\_Serial**(*N\_Vector* v, *booleantype* tf)

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.

int **N\_VEnableConstVectorArray\_Serial**(*N\_Vector* v, *booleantype* tf)

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.

int **N\_VEnableWrmsNormVectorArray\_Serial**(*N\_Vector* v, *booleantype* tf)

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.

int **N\_VEnableWrmsNormMaskVectorArray\_Serial**(*N\_Vector* v, *booleantype* tf)

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.

int **N\_VEnableScaleAddMultiVectorArray\_Serial**(*N\_Vector* v, *booleantype* tf)

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.

int **N\_VEnableLinearCombinationVectorArray\_Serial**(*N\_Vector* v, *booleantype* tf)

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), or equivalently *v\_data* = *N\_VGetArrayPointer*(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* to SUNFALSE. The functions *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 length.

### 7.4.3 NVECTOR\_SERIAL Fortran Interface

The NVECTOR\_SERIAL module provides a Fortran 2003 module for use from Fortran applications.

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_fnvectorserial_mod.lib` in addition to the C library. For details on where the library and module file `fnvector_serial_mod.mod` are installed see §12. We note that the module is accessible from the Fortran 2003 SUNDIALS integrators *without* separately linking to the `libsundials_fnvectorserial_mod` library.

## 7.5 The NVECTOR\_PARALLEL Module

The NVECTOR\_PARALLEL implementation of the NVECTOR module provided with SUNDIALS is based on MPI. It defines the *content* field of an `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*.

```
struct _N_VectorContent_Parallel {
    sunindextype local_length;
    sunindextype global_length;
    booleantype own_data;
    realtype *data;
    MPI_Comm comm;
};
```

The header file to be included 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.

### 7.5.1 NVECTOR\_PARALLEL accessor macros

The following seven 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(v)`

This macro gives access to the contents of the parallel `N_Vector` *v*.

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:

```
#define NV_CONTENT_P(v) ( (N_VectorContent_Parallel)(v->content) )
```

#### `NV_OWN_DATA_P(v)`

Access the *own\_data* component of the parallel `N_Vector` *v*.

Implementation:

```
#define NV_OWN_DATA_P(v) ( NV_CONTENT_P(v)->own_data )
```

### **NV\_DATA\_P(v)**

The assignment `v_data = NV_DATA_P(v)` sets `v_data` to be a pointer to the first component of the *local\_data* for the `N_Vector` `v`.

The assignment `NV_DATA_P(v) = v_data` sets the component array of `v` to be `v_data` by storing the pointer `v_data` into `data`.

Implementation:

```
#define NV_DATA_P(v)      ( NV_CONTENT_P(v)->data )
```

### **NV\_LOCLENGTH\_P(v)**

The assignment `v_llen = NV_LOCLENGTH_P(v)` sets `v_llen` to be the length of the local part of `v`.

The call `NV_LOCLENGTH_P(v) = llen_v` sets the *local\_length* of `v` to be `llen_v`.

Implementation:

```
#define NV_LOCLENGTH_P(v)  ( NV_CONTENT_P(v)->local_length )
```

### **NV\_GLOBLENGTH\_P(v)**

The assignment `v_glen = NV_GLOBLENGTH_P(v)` sets `v_glen` to be the *global\_length* of the vector `v`.

The call `NV_GLOBLENGTH_P(v) = glen_v` sets the *global\_length* of `v` to be `glen_v`.

Implementation:

```
#define NV_GLOBLENGTH_P(v) ( NV_CONTENT_P(v)->global_length )
```

### **NV\_COMM\_P(v)**

This macro provides access to the MPI communicator used by the parallel `N_Vector` `v`.

Implementation:

```
#define NV_COMM_P(v) ( NV_CONTENT_P(v)->comm )
```

### **NV\_Ith\_P(v, i)**

This macro gives access to the individual components of the *local\_data* array of an `N_Vector`.

The assignment `r = NV_Ith_P(v, i)` sets `r` to be the value of the `i`-th component of the local part of `v`.

The assignment `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:

```
#define NV_Ith_P(v, i) ( NV_DATA_P(v)[i] )
```

## 7.5.2 NVECTOR\_PARALLEL functions

The NVECTOR\_PARALLEL module defines parallel implementations of all vector operations listed in §7.2. Their names are obtained from the generic names by appending the suffix `_Parallel` (e.g. `N_VDestroy_Parallel`). The module NVECTOR\_PARALLEL provides the following additional user-callable routines:

*N\_Vector* **N\_VNew\_Parallel**(*MPI\_Comm* `comm`, *sunindextype* `local_length`, *sunindextype* `global_length`,  
*SUNContext* `sunctx`)

This function creates and allocates memory for a parallel vector having global length `global_length`, having processor-local length `local_length`, and using the MPI communicator `comm`.

---

`N_Vector N_VNewEmpty_Parallel(MPI_Comm comm, sunindextype local_length, sunindextype global_length, SUNContext sunctx)`

This function creates a new parallel `N_Vector` with an empty (NULL) data array.

`N_Vector N_VMake_Parallel(MPI_Comm comm, sunindextype local_length, sunindextype global_length, realtype *v_data, SUNContext sunctx)`

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.)

`sunindextype N_VGetLocalLength_Parallel(N_Vector v)`

This function returns the local vector length.

`void N_VPrint_Parallel(N_Vector v)`

This function prints the local content of a parallel vector to `stdout`.

`void N_VPrintFile_Parallel(N_Vector v, FILE *outfile)`

This function prints the local content of a parallel vector to `outfile`.

By default all fused and vector array operations are disabled in the `NVECTOR_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()`. This guarantees that 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 `NVECTOR_PARALLEL` module.

`int N_VEnableFusedOps_Parallel(N_Vector v, boolean type tf)`

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.

`int N_VEnableLinearCombination_Parallel(N_Vector v, boolean type tf)`

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.

`int N_VEnableScaleAddMulti_Parallel(N_Vector v, boolean type tf)`

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.

`int N_VEnableDotProdMulti_Parallel(N_Vector v, boolean type tf)`

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.

`int N_VEnableLinearSumVectorArray_Parallel(N_Vector v, boolean type tf)`

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.

`int N_VEnableScaleVectorArray_Parallel(N_Vector v, boolean type tf)`

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.

`int N_VEnableConstVectorArray_Parallel(N_Vector v, boolean type tf)`

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.

`int N_VEnableWrmsNormVectorArray_Parallel(N_Vector v, boolean type tf)`

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.

```
int N_VEnableWrmsNormMaskVectorArray_Parallel(N_Vector v, booleantype tf)
```

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.

```
int N_VEnableScaleAddMultiVectorArray_Parallel(N_Vector v, booleantype tf)
```

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.

```
int N_VEnableLinearCombinationVectorArray_Parallel(N_Vector v, booleantype tf)
```

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* = *N\_VGetArrayPointer*(v), or equivalently *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* to SUNFALSE. The routines *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 NVECTOR\_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.

### 7.5.3 NVECTOR\_PARALLEL Fortran Interface

The NVECTOR\_PARALLEL module provides a Fortran 2003 module for use from Fortran applications.

The *fnvector\_parallel\_mod* Fortran module defines interfaces to all NVECTOR\_PARALLEL 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\_Parallel* is interfaced as *FN\_VNew\_Parallel*.

The Fortran 2003 NVECTOR\_PARALLEL interface module can be accessed with the use statement, i.e. `use fnvector_parallel_mod`, and linking to the library *libsundials\_fnvectorparallel\_mod.lib* in addition to the C library. For details on where the library and module file *fnvector\_parallel\_mod.mod* are installed see §12. We note that the module is accessible from the Fortran 2003 SUNDIALS integrators *without* separately linking to the *libsundials\_fnvectorparallel\_mod* library.

## 7.6 The NVECTOR\_OPENMP Module

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 OpenMP NVECTOR implementation provided with SUNDIALS, NVECTOR\_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, the number of threads used is based on the supplied argument in the vector constructor.

```
struct _N_VectorContent_OpenMP {
    sunindextype length;
    booleantype own_data;
    realtype *data;
    int num_threads;
};
```

The header file to be included when using this module is `nvector_openmp.h`. The installed module library to link to is `libsundials_nvecopenmp.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 `fnnvector_openmp_mod.mod`.

### 7.6.1 NVECTOR\_OPENMP accessor macros

The following six 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(v)`

This macro gives access to the contents of the OpenMP vector `N_Vector v`.

The assignment `v_cont = NV_CONTENT_OMP(v)` sets `v_cont` to be a pointer to the OpenMP `N_Vector` content structure.

Implementation:

```
#define NV_CONTENT_OMP(v) ( (N_VectorContent_OpenMP)(v->content) )
```

#### `NV_OWN_DATA_OMP(v)`

Access the `own_data` component of the OpenMP `N_Vector v`.

Implementation:

```
#define NV_OWN_DATA_OMP(v) ( NV_CONTENT_OMP(v)->own_data )
```

#### `NV_DATA_OMP(v)`

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`.

Similarly, the assignment `NV_DATA_OMP(v) = v_data` sets the component array of `v` to be `v_data` by storing the pointer `v_data`.

Implementation:

```
#define NV_DATA_OMP(v) ( NV_CONTENT_OMP(v)->data )
```

#### `NV_LENGTH_OMP(v)`

Access the `length` component of the OpenMP `N_Vector v`.

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`.

Implementation:

```
#define NV_LENGTH_OMP(v) ( NV_CONTENT_OMP(v)->length )
```

#### `NV_NUM_THREADS_OMP(v)`

Access the `num_threads` component of the OpenMP `N_Vector v`.

The assignment `v_threads = NV_NUM_THREADS_OMP(v)` sets `v_threads` to be the `num_threads` of `v`. On the other hand, the call `NV_NUM_THREADS_OMP(v) = num_threads_v` sets the `num_threads` of `v` to be `num_threads_v`.

Implementation:

```
#define NV_NUM_THREADS_OMP(v) ( NV_CONTENT_OMP(v)->num_threads )
```

#### `NV_Ith_OMP(v, i)`

This macro gives access to the individual components of the `data` array of an `N_Vector`, using standard 0-based C indexing.

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:

```
#define NV_Ith_OMP(v, i) ( NV_DATA_OMP(v)[i] )
```

## 7.6.2 NVECTOR\_OPENMP functions

The NVECTOR\_OPENMP module defines OpenMP implementations of all vector operations listed in §7.2, §7.2.2, §7.2.3, and §7.2.4. Their names are obtained from those in those sections by appending the suffix \_OpenMP (e.g. `N_VDestroy_OpenMP`). All the standard vector operations listed in §7.2 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:

`N_Vector N_VNew_OpenMP(sunindextype vec_length, int num_threads, SUNContext sunctx)`

This function creates and allocates memory for a OpenMP `N_Vector`. Arguments are the vector length and number of threads.

`N_Vector N_VNewEmpty_OpenMP(sunindextype vec_length, int num_threads, SUNContext sunctx)`

This function creates a new OpenMP `N_Vector` with an empty (NULL) data array.

`N_Vector N_VMake_OpenMP(sunindextype vec_length, realtype *v_data, int num_threads, SUNContext sunctx)`

This function creates and allocates memory for a OpenMP vector with user-provided data array, `v_data`.

(This function does *not* allocate memory for `v_data` itself.)

`void N_VPrint_OpenMP(N_Vector v)`

This function prints the content of an OpenMP vector to `stdout`.

`void N_VPrintFile_OpenMP(N_Vector v, FILE *outfile)`

This function prints the content of an OpenMP vector to `outfile`.

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.

`int N_VEnableFusedOps_OpenMP(N_Vector v, booleantype tf)`

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.

---

`int N_VEnableLinearCombination_OpenMP(N_Vector v, boolean type tf)`

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.

`int N_VEnableScaleAddMulti_OpenMP(N_Vector v, boolean type tf)`

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.

`int N_VEnableDotProdMulti_OpenMP(N_Vector v, boolean type tf)`

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.

`int N_VEnableLinearSumVectorArray_OpenMP(N_Vector v, boolean type tf)`

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.

`int N_VEnableScaleVectorArray_OpenMP(N_Vector v, boolean type tf)`

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.

`int N_VEnableConstVectorArray_OpenMP(N_Vector v, boolean type tf)`

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.

`int N_VEnableWrmsNormVectorArray_OpenMP(N_Vector v, boolean type tf)`

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.

`int N_VEnableWrmsNormMaskVectorArray_OpenMP(N_Vector v, boolean type tf)`

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.

`int N_VEnableScaleAddMultiVectorArray_OpenMP(N_Vector v, boolean type tf)`

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.

`int N_VEnableLinearCombinationVectorArray_OpenMP(N_Vector v, boolean type tf)`

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 = N_VGetArrayPointer(v)`, or equivalently `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` to SUNFALSE. The functions `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.

### 7.6.3 NVECTOR\_OPENMP Fortran Interface

The NVECTOR\_OPENMP module provides a Fortran 2003 module for use from Fortran applications.

The `fnvector_openmp_mod` Fortran module defines interfaces to all 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 §12.

## 7.7 The NVECTOR\_PTHREADS Module

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 be included when using this module is `nvector_pthreads.h`. The installed module library to link to is `libsundials_nvecptreads.lib` where `.lib` is typically `.so` for shared libraries and `.a` for static libraries.

### 7.7.1 NVECTOR\_PTHREADS accessor macros

The following six 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(v)`

This macro gives access to the contents of the Pthreads vector `N_Vector v`.

The assignment `v_cont = NV_CONTENT_PT(v)` sets `v_cont` to be a pointer to the Pthreads `N_Vector` content structure.

Implementation:

```
#define NV_CONTENT_PT(v) ( (N_VectorContent_Pthreads)(v->content) )
```

#### `NV_OWN_DATA_PT(v)`

Access the `own_data` component of the Pthreads `N_Vector v`.

Implementation:

```
#define NV_OWN_DATA_PT(v) ( NV_CONTENT_PT(v)->own_data )
```

**NV\_DATA\_PT(v)**

The assignment `v_data = NV_DATA_PT(v)` sets `v_data` to be a pointer to the first component of the `data` for the N\_Vector `v`.

Similarly, the assignment `NV_DATA_PT(v) = v_data` sets the component array of `v` to be `v_data` by storing the pointer `v_data`.

Implementation:

```
#define NV_DATA_PT(v) ( NV_CONTENT_PT(v)->data )
```

**NV\_LENGTH\_PT(v)**

Access the `length` component of the Pthreads N\_Vector `v`.

The assignment `v_len = NV_LENGTH_PT(v)` sets `v_len` to be the `length` of `v`. On the other hand, the call `NV_LENGTH_PT(v) = len_v` sets the `length` of `v` to be `len_v`.

Implementation:

```
#define NV_LENGTH_PT(v) ( NV_CONTENT_PT(v)->length )
```

**NV\_NUM\_THREADS\_PT(v)**

Access the `num_threads` component of the Pthreads N\_Vector `v`.

The assignment `v_threads = NV_NUM_THREADS_PT(v)` sets `v_threads` to be the `num_threads` of `v`. On the other hand, the call `NV_NUM_THREADS_PT(v) = num_threads_v` sets the `num_threads` of `v` to be `num_threads_v`.

Implementation:

```
#define NV_NUM_THREADS_PT(v) ( NV_CONTENT_PT(v)->num_threads )
```

**NV\_Ith\_PT(v, i)**

This macro gives access to the individual components of the `data` array of an N\_Vector, using standard 0-based C indexing.

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] )
```

## 7.7.2 NVECTOR\_PTHREADS functions

The NVECTOR\_PTHREADS module defines Pthreads implementations of all vector operations listed in §7.2, §7.2.2, §7.2.3, and §7.2.4. Their names are obtained from those in those sections by appending the suffix \_Pthreads (e.g. `N_VDestroy_Pthreads`). All the standard vector operations listed in §7.2 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\_Vector* **N\_VNew\_Pthreads**(*sunindextype* vec\_length, int num\_threads, *SUNContext* sunctx)

This function creates and allocates memory for a Pthreads N\_Vector. Arguments are the vector length and number of threads.

`N_Vector N_VNewEmpty_Pthreads(sunindextype vec_length, int num_threads, SUNContext sunctx)`

This function creates a new Pthreads `N_Vector` with an empty (NULL) data array.

`N_Vector N_VMake_Pthreads(sunindextype vec_length, realtype *v_data, int num_threads, SUNContext sunctx)`

This function creates and allocates memory for a Pthreads vector with user-provided data array, `v_data`.

(This function does *not* allocate memory for `v_data` itself.)

`void N_VPrint_Pthreads(N_Vector v)`

This function prints the content of a Pthreads vector to `stdout`.

`void N_VPrintFile_Pthreads(N_Vector v, FILE *outfile)`

This function prints the content of a Pthreads vector to `outfile`.

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.

`int N_VEnableFusedOps_Pthreads(N_Vector v, booleantype tf)`

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.

`int N_VEnableLinearCombination_Pthreads(N_Vector v, booleantype tf)`

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.

`int N_VEnableScaleAddMulti_Pthreads(N_Vector v, booleantype tf)`

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.

`int N_VEnableDotProdMulti_Pthreads(N_Vector v, booleantype tf)`

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.

`int N_VEnableLinearSumVectorArray_Pthreads(N_Vector v, booleantype tf)`

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.

`int N_VEnableScaleVectorArray_Pthreads(N_Vector v, booleantype tf)`

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.

`int N_VEnableConstVectorArray_Pthreads(N_Vector v, booleantype tf)`

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.

`int N_VEnableWrmsNormVectorArray_Pthreads(N_Vector v, booleantype tf)`

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.

`int N_VEnableWrmsNormMaskVectorArray_Pthreads(N_Vector v, booleantype tf)`

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.

`int N_VEnableScaleAddMultiVectorArray_Pthreads(N_Vector v, booleantype tf)`

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`.

```
int N_VEnableLinearCombinationVectorArray_Pthreads(N_Vector v, booleantype tf)
```

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 = N_VGetArrayPointer(v)`, or equivalently `v_data = NV_DATA_PT(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_Pthreads()`, `N_VMake_Pthreads()`, and `N_VCloneVectorArrayEmpty_Pthreads()` set the field `own_data` to `SUNFALSE`. The functions `N_VDestroy_Pthreads()` and `N_VDestroyVectorArray_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 `NVECTOR_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.

### 7.7.3 NVECTOR\_PTHREADS Fortran Interface

The `NVECTOR_PTHREADS` module provides a Fortran 2003 module for use from Fortran applications.

The `fnvector_pthreads_mod` Fortran module defines interfaces to all `NVECTOR_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 `NVECTOR_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 §12.

## 7.8 The NVECTOR\_PARHYP Module

The `NVECTOR_PARHYP` implementation of the `NVECTOR` 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_data;
    booleantype own_parvector;
    realtype *data;
    MPI_Comm comm;
    hypre_ParVector *x;
};
```

The header file to be included when using this module is `nvector_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, NVECTOR\_PARHYP does not provide macros to access its member variables. Note that NVECTOR\_PARHYP requires SUNDIALS to be built with MPI support.

### 7.8.1 NVECTOR\_PARHYP functions

The NVECTOR\_PARHYP module defines implementations of all vector operations listed in §7.2 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 programs for CVODE and the `ark_diurnal_kry_ph.c` example program for ARKODE.

The names of parhyp methods are obtained from those in §7.2, §7.2.2, §7.2.3, and §7.2.4 by appending the suffix `_ParHyp` (e.g. `N_VDestroy_ParHyp`). The module NVECTOR\_PARHYP provides the following additional user-callable routines:

`N_Vector N_VNewEmpty_ParHyp(MPI_Comm comm, sunindextype local_length, sunindextype global_length, SUNContext sunctx)`

This function creates a new parhyp `N_Vector` with the pointer to the HYPRE vector set to `NULL`.

`N_Vector N_VMake_ParHyp(hypre_ParVector *x, SUNContext sunctx)`

This function creates an `N_Vector` wrapper around an existing HYPRE parallel vector. It does *not* allocate memory for `x` itself.

`hypre_ParVector *N_VGetVector_ParHyp(N_Vector v)`

This function returns a pointer to the underlying HYPRE vector.

`void N_VPrint_ParHyp(N_Vector v)`

This function prints the local content of a parhyp vector to `stdout`.

`void N_VPrintFile_ParHyp(N_Vector v, FILE *outfile)`

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.

`int N_VEnableFusedOps_ParHyp(N_Vector v, boolean type tf)`

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`.

`int N_VEnableLinearCombination_ParHyp(N_Vector v, boolean type tf)`

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`.

`int N_VEnableScaleAddMulti_ParHyp(N_Vector v, boolean type tf)`

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`.

---

`int N_VEnableDotProdMulti_ParHyp(N_Vector v, booleantype tf)`

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.

`int N_VEnableLinearSumVectorArray_ParHyp(N_Vector v, booleantype tf)`

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.

`int N_VEnableScaleVectorArray_ParHyp(N_Vector v, booleantype tf)`

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.

`int N_VEnableConstVectorArray_ParHyp(N_Vector v, booleantype tf)`

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.

`int N_VEnableWrmsNormVectorArray_ParHyp(N_Vector v, booleantype tf)`

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.

`int N_VEnableWrmsNormMaskVectorArray_ParHyp(N_Vector v, booleantype tf)`

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.

`int N_VEnableScaleAddMultiVectorArray_ParHyp(N_Vector v, booleantype tf)`

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.

`int N_VEnableLinearCombinationVectorArray_ParHyp(N_Vector v, booleantype tf)`

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. The functions `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\_PARHYP 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.

## 7.9 The NVECTOR\_PETSC Module

The NVECTOR\_PETSC module is an NVECTOR wrapper around the PETSc vector. It defines the *content* field of a N\_Vector 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 *own\_data* indicating ownership of the wrapped PETSc vector.

```
struct _N_VectorContent_Petsc {
    sunindextype local_length;
    sunindextype global_length;
    booleantype own_data;
    Vec *pvec;
    MPI_Comm comm;
};
```

The header file to be included when using this module is `nvector_petsc.h`. The installed module library to link to is `libsundials_nvecpetsc.lib` where .lib is typically .so for shared libraries and .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.

### 7.9.1 NVECTOR\_PETSC functions

The NVECTOR\_PETSC module defines implementations of all vector operations listed in §7.2 except for `N_VGetArrayPointer()` and `N_VSetArrayPointer()`. 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 is provided in example programs for IDA.

The names of vector operations are obtained from those in §7.2, §7.2.2, §7.2.3, and §7.2.4 by appending the suffix `_Petsc` (e.g. `N_VDestroy_Petsc`). The module NVECTOR\_PETSC provides the following additional user-callable routines:

`N_Vector N_VNewEmpty_Petsc(MPI_Comm comm, sunindextype local_length, sunindextype global_length, SUNContext sunctx)`

This function creates a new PETSc N\_Vector with the pointer to the wrapped PETSc vector set to NULL. It is used by the `N_VMake_Petsc` and `N_VClone_Petsc` implementations. It should be used only with great caution.

`N_Vector N_VMake_Petsc(Vec *pvec, SUNContext sunctx)`

This function creates and allocates memory for an NVECTOR\_PETSC wrapper with a user-provided PETSc vector. It does *not* allocate memory for the vector `pvec` itself.

`Vec *N_VGetVector_Petsc(N_Vector v)`

This function returns a pointer to the underlying PETSc vector.

`void N_VPrint_Petsc(N_Vector v)`

This function prints the global content of a wrapped PETSc vector to `stdout`.

`void N_VPrintFile_Petsc(N_Vector v, const char fname[])`

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.

---

```
int N_VEnableFusedOps_Petsc(N_Vector v, boolean type tf)
```

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.

```
int N_VEnableLinearCombination_Petsc(N_Vector v, boolean type tf)
```

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.

```
int N_VEnableScaleAddMulti_Petsc(N_Vector v, boolean type tf)
```

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.

```
int N_VEnableDotProdMulti_Petsc(N_Vector v, boolean type tf)
```

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.

```
int N_VEnableLinearSumVectorArray_Petsc(N_Vector v, boolean type tf)
```

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.

```
int N_VEnableScaleVectorArray_Petsc(N_Vector v, boolean type tf)
```

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.

```
int N_VEnableConstVectorArray_Petsc(N_Vector v, boolean type tf)
```

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.

```
int N_VEnableWrmsNormVectorArray_Petsc(N_Vector v, boolean type tf)
```

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.

```
int N_VEnableWrmsNormMaskVectorArray_Petsc(N_Vector v, boolean type tf)
```

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.

```
int N_VEnableScaleAddMultiVectorArray_Petsc(N_Vector v, boolean type tf)
```

This function enables (SUNTRUE) or disables (SUNFALSE) 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.

```
int N_VEnableLinearCombinationVectorArray_Petsc(N_Vector v, boolean type tf)
```

This function enables (SUNTRUE) or disables (SUNFALSE) 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. The routines `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.

## 7.10 The NVECTOR\_CUDA Module

The NVECTOR\_CUDA module is an NVECTOR implementation in the CUDA language. The module allows for SUNDIALS vector kernels to run on NVIDIA 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 vector content layout is as follows:

```
struct _N_VectorContent_Cuda
{
    sunindextype      length;
    booleantype       own_helper;
    SUNMemory         host_data;
    SUNMemory         device_data;
    SUNCudaExecPolicy* stream_exec_policy;
    SUNCudaExecPolicy* reduce_exec_policy;
    SUNMemoryHelper   mem_helper;
    void*            priv; /* 'private' data */
};

typedef struct _N_VectorContent_Cuda *N_VectorContent_Cuda;
```

The content members are the vector length (size), boolean flags that indicate if the vector owns the execution policies and memory helper objects (i.e., it is in charge of freeing the objects), *SUNMemory* objects for the vector data on the host and device, pointers to execution policies that control how streaming and reduction kernels are launched, a *SUNMemoryHelper* for performing memory operations, and a private data structure which holds additional members that should not be accessed directly.

When instantiated with *N\_VNew\_Cuda()*, the underlying data will be allocated 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. Additionally, a user-defined *SUNMemoryHelper* for allocating/freeing data can be provided with the constructor *N\_VNewWith-MemHelp\_Cuda()*. Details on each of these constructors are provided below.

To use the NVECTOR\_CUDA module, include *nvector\_cuda.h* and link to the library *libsundials\_nveccuda.lib*. The extension, *.lib*, is typically *.so* for shared libraries and *.a* for static libraries.

### 7.10.1 NVECTOR\_CUDA functions

Unlike other native SUNDIALS vector types, the NVECTOR\_CUDA module does not provide macros to access its member variables. Instead, user should use the accessor functions:

*realtype* \**N\_VGetHostArrayPointer\_Cuda*(*N\_Vector* v)

This function returns pointer to the vector data on the host.

*realtype* \**N\_VGetDeviceArrayPointer\_Cuda*(*N\_Vector* v)

This function returns pointer to the vector data on the device.

*booleantype* *N\_VIsManagedMemory\_Cuda*(*N\_Vector* v)

This function returns a boolean flag indicating if the vector data array is in managed memory or not.

The NVECTOR\_CUDA module defines implementations of all standard vector operations defined in §7.2, §7.2.2, §7.2.3, and §7.2.4, except for *N\_VSetArrayPointer()*, and, if using unmanaged memory, *N\_VGetArrayPointer()*. As such, this vector can only be used with SUNDIALS direct solvers and preconditioners when using managed memory. The NVECTOR\_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 NVECTOR\_CUDA are provided in example programs for CVODE [36].

The names of vector operations are obtained from those in §7.2, §7.2.2, §7.2.3, and §7.2.4 by appending the suffix \_Cuda (e.g. N\_VDestroy\_Cuda). The module NVECTOR\_CUDA provides the following additional user-callable routines:

`N_Vector N_VNew_Cuda(sunindextype length, SUNContext sunctx)`

This function creates and allocates memory for a CUDA N\_Vector. The vector data array is allocated on both the host and device.

`N_Vector N_VNewManaged_Cuda(sunindextype vec_length, SUNContext sunctx)`

This function creates and allocates memory for a CUDA N\_Vector. The vector data array is allocated in managed memory.

`N_Vector N_VNewWithMemHelp_Cuda(sunindextype length, booleantype use_managed_mem, SUNMemoryHelper helper, SUNContext sunctx)`

This function creates a new CUDA N\_Vector with a user-supplied SUNMemoryHelper for allocating/freeing memory.

`N_Vector N_VNewEmpty_Cuda(sunindextype vec_length, SUNContext sunctx)`

This function creates a new CUDA N\_Vector where the members of the content structure have not been allocated.

This utility function is used by the other constructors to create a new vector.

`N_Vector N_VMake_Cuda(sunindextype vec_length, realtype *h_vdata, realtype *d_vdata, SUNContext sunctx)`

This function creates a CUDA N\_Vector with user-supplied vector data arrays for the host and the device.

`N_Vector N_VMakeManaged_Cuda(sunindextype vec_length, realtype *vdata, SUNContext sunctx)`

This function creates a CUDA N\_Vector with a user-supplied managed memory data array.

`N_Vector N_VMakeWithManagedAllocator_Cuda(sunindextype length, void *(*allocfn)(size_t size), void (*freefn)(void *ptr))`

This function creates a CUDA N\_Vector 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:

```
void N_VSetKernelExecPolicy_Cuda(N_Vector v, SUNCudaExecPolicy *stream_exec_policy,
                                  SUNCudaExecPolicy *reduce_exec_policy)
```

This function sets the execution policies which control the kernel parameters utilized when launching the streaming and reduction CUDA kernels. By default the vector is setup to use the `SUNCudaThreadDirectExecPolicy()` and `SUNCudaBlockReduceAtomicExecPolicy()`. Any custom execution policy for reductions must ensure that the grid dimensions (number of thread blocks) is a multiple of the CUDA warp size (32). See §7.10.2 below for more information about the `SUNCudaExecPolicy` class. Providing NULL for an argument will result in the default policy being restored.

**Note:** Note: All vectors used in a single instance of a SUNDIALS package must use the same execution policy. It is **strongly recommended** that this function is called immediately after constructing the vector, and any subsequent vector be created by cloning to ensure consistent execution policies across vectors

`realtype *N_VCopyToDevice_Cuda(N_Vector v)`

This function copies host vector data to the device.

`realtype *N_VCopyFromDevice_Cuda(N_Vector v)`

This function copies vector data from the device to the host.

`void N_VPrint_Cuda(N_Vector v)`

This function prints the content of a CUDA vector to `stdout`.

`void N_VPrintFile_Cuda(N_Vector v, FILE *outfile)`

This function prints the content of a CUDA vector to `outfile`.

By default all fused and vector array operations are disabled in the NVECTOR\_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 NVECTOR\_CUDA module.

**int N\_VEnableFusedOps\_Cuda([N\\_Vector](#) v, [booleantype](#) tf)**

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.

**int N\_VEnableLinearCombination\_Cuda([N\\_Vector](#) v, [booleantype](#) tf)**

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.

**int N\_VEnableScaleAddMulti\_Cuda([N\\_Vector](#) v, [booleantype](#) tf)**

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.

**int N\_VEnableDotProdMulti\_Cuda([N\\_Vector](#) v, [booleantype](#) tf)**

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.

**int N\_VEnableLinearSumVectorArray\_Cuda([N\\_Vector](#) v, [booleantype](#) tf)**

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.

**int N\_VEnableScaleVectorArray\_Cuda([N\\_Vector](#) v, [booleantype](#) tf)**

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.

**int N\_VEnableConstVectorArray\_Cuda([N\\_Vector](#) v, [booleantype](#) tf)**

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.

**int N\_VEnableWrmsNormVectorArray\_Cuda([N\\_Vector](#) v, [booleantype](#) tf)**

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.

**int N\_VEnableWrmsNormMaskVectorArray\_Cuda([N\\_Vector](#) v, [booleantype](#) tf)**

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.

**int N\_VEnableScaleAddMultiVectorArray\_Cuda([N\\_Vector](#) v, [booleantype](#) tf)**

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.

**int N\_VEnableLinearCombinationVectorArray\_Cuda([N\\_Vector](#) v, [booleantype](#) tf)**

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 [N\\_Vector\\_Cuda](#), v, 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 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.

### 7.10.2 The SUNCudaExecPolicy Class

In order to provide maximum flexibility to users, the CUDA kernel execution parameters used by kernels within SUNDIALS are defined by objects of the `sundials::cuda::ExecPolicy` abstract class type (this class can be accessed in the global namespace as `SUNCudaExecPolicy`). Thus, users may provide custom execution policies that fit the needs of their problem. The `SUNCudaExecPolicy` class is defined as

```
typedef sundials::cuda::ExecPolicy SUNCudaExecPolicy
```

where the `sundials::cuda::ExecPolicy` class is defined in the header file `sundials_cuda_policies.hpp`, as follows:

```
class ExecPolicy
{
public:
    ExecPolicy(cudaStream_t stream = 0) : stream_(stream) { }
    virtual size_t gridSize(size_t numWorkUnits = 0, size_t blockDim = 0) const = 0;
    virtual size_t blockSize(size_t numWorkUnits = 0, size_t gridDim = 0) const = 0;
    virtual const cudaStream_t* stream() const { return (&stream_); }
    virtual ExecPolicy* clone() const = 0;
    ExecPolicy* clone_new_stream(cudaStream_t stream) const {
        ExecPolicy* ex = clone();
        ex->stream_ = stream;
        return ex;
    }
    virtual bool atomic() const { return false; }
    virtual ~ExecPolicy() {}
protected:
    cudaStream_t stream_;
};
```

To define a custom execution policy, a user simply needs to create a class that inherits from the abstract class and implements the methods. The SUNDIALS provided `sundials::cuda::ThreadDirectExecPolicy` (aka in the global namespace as `SUNCudaThreadDirectExecPolicy`) class is a good example of what a custom execution policy may look like:

```
class ThreadDirectExecPolicy : public ExecPolicy
{
public:
    ThreadDirectExecPolicy(const size_t blockDim, cudaStream_t stream = 0)
        : blockDim_(blockDim), ExecPolicy(stream)
    {}

    ThreadDirectExecPolicy(const ThreadDirectExecPolicy& ex)
        : blockDim_(ex.blockDim_), ExecPolicy(ex.stream_)
    {}

    virtual size_t gridSize(size_t numWorkUnits = 0, size_t /*blockDim*/ = 0) const
    {
```

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```

/* ceil(n/m) = floor((n + m - 1) / m) */
return (numWorkUnits + blockSize() - 1) / blockSize();
}

virtual size_t blockSize(size_t /*numWorkUnits*/ = 0, size_t /*gridDim*/ = 0) const
{
    return blockDim_;
}

virtual ExecPolicy* clone() const
{
    return static_cast<ExecPolicy*>(new ThreadDirectExecPolicy(*this));
}

private:
    const size_t blockDim_;
};

```

In total, SUNDIALS provides 3 execution policies:

**SUN\_cudaThreadDirectExecPolicy**(const size\_t blockDim, const cudaStream\_t stream = 0)

Maps each CUDA thread to a work unit. The number of threads per block (blockDim) can be set to anything. The grid size will be calculated so that there are enough threads for one thread per element. If a CUDA stream is provided, it will be used to execute the kernel.

**SUN\_cudaGridStrideExecPolicy**(const size\_t blockDim, const size\_t gridDim, const cudaStream\_t stream = 0)

Is for kernels that use grid stride loops. The number of threads per block (blockDim) can be set to anything. The number of blocks (gridDim) can be set to anything. If a CUDA stream is provided, it will be used to execute the kernel.

**SUN\_cudaBlockReduceExecPolicy**(const size\_t blockDim, const cudaStream\_t stream = 0)

Is for kernels performing a reduction across individual thread blocks. The number of threads per block (blockDim) can be set to any valid multiple of the CUDA warp size. The grid size (gridDim) can be set to any value greater than 0. If it is set to 0, then the grid size will be chosen so that there is enough threads for one thread per work unit. If a CUDA stream is provided, it will be used to execute the kernel.

**SUN\_cudaBlockReduceAtomicExecPolicy**(const size\_t blockDim, const cudaStream\_t stream = 0)

Is for kernels performing a reduction across individual thread blocks using atomic operations. The number of threads per block (blockDim) can be set to any valid multiple of the CUDA warp size. The grid size (gridDim) can be set to any value greater than 0. If it is set to 0, then the grid size will be chosen so that there is enough threads for one thread per work unit. If a CUDA stream is provided, it will be used to execute the kernel.

For example, a policy that uses 128 threads per block and a user provided stream can be created like so:

```

cudaStream_t stream;
cudaStreamCreate(&stream);
SUN_cudaThreadDirectExecPolicy thread_direct(128, stream);

```

These default policy objects can be reused for multiple SUNDIALS data structures (e.g. a [SUNMatrix](#) and an [N\\_Vector](#)) since they do not hold any modifiable state information.

## 7.11 The NVECTOR\_HIP Module

The NVECTOR\_HIP module is an NVECTOR implementation using the AMD ROCm HIP library [64]. The module allows for SUNDIALS vector kernels to run on AMD or NVIDIA GPU devices. It is intended for users who are already familiar with HIP and GPU programming. Building this vector module requires the HIP-clang compiler. The vector content layout is as follows:

```
struct _N_VectorContent_Hip
{
    sunindextype      length;
    booleantype       own_helper;
    SUNMemory         host_data;
    SUNMemory         device_data;
    SUNHipExecPolicy* stream_exec_policy;
    SUNHipExecPolicy* reduce_exec_policy;
    SUNMemoryHelper   mem_helper;
    void*            priv; /* 'private' data */
};

typedef struct _N_VectorContent_Hip *N_VectorContent_Hip;
```

The content members are the vector length (size), a boolean flag that signals if the vector owns the data (i.e. it is in charge of freeing the data), pointers to vector data on the host and the device, pointers to *SUNHipExecPolicy* implementations that control how the HIP kernels are launched for streaming and reduction vector kernels, and a private data structure which holds additional members that should not be accessed directly.

When instantiated with *N\_VNew\_Hip()*, the underlying data will be allocated on both the host and the device. Alternatively, a user can provide host and device data arrays by using the *N\_VMake\_Hip()* constructor. To use managed memory, the constructors *N\_VNewManaged\_Hip()* and *N\_VMakeManaged\_Hip()* are provided. Additionally, a user-defined *SUNMemoryHelper* for allocating/freeing data can be provided with the constructor *N\_VNewWithMemHelp\_Hip()*. Details on each of these constructors are provided below.

To use the NVECTOR\_HIP module, include *nvector\_hip.h* and link to the library *libsundials\_nvechip.lib*. The extension, .lib, is typically .so for shared libraries and .a for static libraries.

### 7.11.1 NVECTOR\_HIP functions

Unlike other native SUNDIALS vector types, the NVECTOR\_HIP module does not provide macros to access its member variables. Instead, user should use the accessor functions:

*realtype* \**N\_VGetHostArrayPointer\_Hip*(*N\_Vector* v)

This function returns pointer to the vector data on the host.

*realtype* \**N\_VGetDeviceArrayPointer\_Hip*(*N\_Vector* v)

This function returns pointer to the vector data on the device.

*booleantype* *N\_VIsManagedMemory\_Hip*(*N\_Vector* v)

This function returns a boolean flag indicating if the vector data array is in managed memory or not.

The NVECTOR\_HIP module defines implementations of all standard vector operations defined in §7.2, §7.2.2, §7.2.3, and §7.2.4, except for *N\_VSetArrayPointer()*. The names of vector operations are obtained from those in §7.2, §7.2.2, §7.2.3, and §7.2.4 by appending the suffix \_Hip (e.g. *N\_VDestroy\_Hip()*). The module NVECTOR\_HIP provides the following additional user-callable routines:

*N\_Vector* **N\_VNew\_Hip**(*sunindextype* length, *SUNContext* sunctx)

This function creates and allocates memory for a HIP *N\_Vector*. The vector data array is allocated on both the host and device.

*N\_Vector* **N\_VNewManaged\_Hip**(*sunindextype* vec\_length, *SUNContext* sunctx)

This function creates and allocates memory for a HIP *N\_Vector*. The vector data array is allocated in managed memory.

*N\_Vector* **N\_VNewWithMemHelp\_Hip**(*sunindextype* length, *booleantype* use\_managed\_mem, *SUNMemoryHelper* helper, *SUNContext* sunctx)

This function creates a new HIP *N\_Vector* with a user-supplied *SUNMemoryHelper* for allocating/freeing memory.

*N\_Vector* **N\_VNewEmpty\_Hip**(*sunindextype* vec\_length, *SUNContext* sunctx)

This function creates a new HIP *N\_Vector* where the members of the content structure have not been allocated.

This utility function is used by the other constructors to create a new vector.

*N\_Vector* **N\_VMake\_Hip**(*sunindextype* vec\_length, *realtype* \*h\_vdata, *realtype* \*d\_vdata, *SUNContext* sunctx)

This function creates a HIP *N\_Vector* with user-supplied vector data arrays for the host and the device.

*N\_Vector* **N\_VMakeManaged\_Hip**(*sunindextype* vec\_length, *realtype* \*vdata, *SUNContext* sunctx)

This function creates a HIP *N\_Vector* with a user-supplied managed memory data array.

The module NVECTOR\_HIP also provides the following user-callable routines:

**void N\_VSetKernelExecPolicy\_Hip(*N\_Vector* v, *SUNHipExecPolicy* \*stream\_exec\_policy, *SUNHipExecPolicy* \*reduce\_exec\_policy)**

This function sets the execution policies which control the kernel parameters utilized when launching the streaming and reduction HIP kernels. By default the vector is setup to use the *SUNHipThreadDirectExecPolicy()* and *SUNHipBlockReduceExecPolicy()*. Any custom execution policy for reductions must ensure that the grid dimensions (number of thread blocks) is a multiple of the HIP warp size (32 for NVIDIA GPUs, 64 for AMD GPUs). See §7.11.2 below for more information about the *SUNHipExecPolicy* class. Providing NULL for an argument will result in the default policy being restored.

---

**Note:** Note: All vectors used in a single instance of a SUNDIALS package must use the same execution policy. It is **strongly recommended** that this function is called immediately after constructing the vector, and any subsequent vector be created by cloning to ensure consistent execution policies across vectors\*

---

*realtype* \***N\_VCopyToDevice\_Hip(*N\_Vector* v)**

This function copies host vector data to the device.

*realtype* \***N\_VCopyFromDevice\_Hip(*N\_Vector* v)**

This function copies vector data from the device to the host.

**void N\_VPrint\_Hip(*N\_Vector* v)**

This function prints the content of a HIP vector to *stdout*.

**void N\_VPrintFile\_Hip(*N\_Vector* v, *FILE* \*outfile)**

This function prints the content of a HIP vector to *outfile*.

By default all fused and vector array operations are disabled in the NVECTOR\_HIP 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\_Hip()*, 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\_Hip()* will have the default settings for the NVECTOR\_HIP module.

`int N_VEnableFusedOps_Hip(N_Vector v, boolean type tf)`

This function enables (SUNTRUE) or disables (SUNFALSE) all fused and vector array operations in the HIP vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

`int N_VEnableLinearCombination_Hip(N_Vector v, boolean type tf)`

This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination fused operation in the HIP vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

`int N_VEnableScaleAddMulti_Hip(N_Vector v, boolean type tf)`

This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector to multiple vectors fused operation in the HIP vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

`int N_VEnableDotProdMulti_Hip(N_Vector v, boolean type tf)`

This function enables (SUNTRUE) or disables (SUNFALSE) the multiple dot products fused operation in the HIP vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

`int N_VEnableLinearSumVectorArray_Hip(N_Vector v, boolean type tf)`

This function enables (SUNTRUE) or disables (SUNFALSE) the linear sum operation for vector arrays in the HIP vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

`int N_VEnableScaleVectorArray_Hip(N_Vector v, boolean type tf)`

This function enables (SUNTRUE) or disables (SUNFALSE) the scale operation for vector arrays in the HIP vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

`int N_VEnableConstVectorArray_Hip(N_Vector v, boolean type tf)`

This function enables (SUNTRUE) or disables (SUNFALSE) the const operation for vector arrays in the HIP vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

`int N_VEnableWrmsNormVectorArray_Hip(N_Vector v, boolean type tf)`

This function enables (SUNTRUE) or disables (SUNFALSE) the WRMS norm operation for vector arrays in the HIP vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

`int N_VEnableWrmsNormMaskVectorArray_Hip(N_Vector v, boolean type tf)`

This function enables (SUNTRUE) or disables (SUNFALSE) the masked WRMS norm operation for vector arrays in the HIP vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

`int N_VEnableScaleAddMultiVectorArray_Hip(N_Vector v, boolean type tf)`

This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector array to multiple vector arrays operation in the HIP vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

`int N_VEnableLinearCombinationVectorArray_Hip(N_Vector v, boolean type tf)`

This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination operation for vector arrays in the HIP 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_Hip`, `v`, it is recommended to use functions `N_VGetDeviceArrayPointer_Hip()` or `N_VGetHostArrayPointer_Hip()`. However, when using managed memory, the function `N_VGetArrayPointer()` may also be used.
- To maximize efficiency, vector operations in the NVECTOR\_HIP 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.

## 7.11.2 The SUNHipExecPolicy Class

In order to provide maximum flexibility to users, the HIP kernel execution parameters used by kernels within SUNDIALS are defined by objects of the `sundials::hip::ExecPolicy` abstract class type (this class can be accessed in the global namespace as `SUNHipExecPolicy`). Thus, users may provide custom execution policies that fit the needs of their problem. The `SUNHipExecPolicy` class is defined as

```
typedef sundials::hip::ExecPolicy SUNHipExecPolicy
```

where the `sundials::hip::ExecPolicy` class is defined in the header file `sundials_hip_policies.hpp`, as follows:

```
class ExecPolicy
{
public:
    ExecPolicy(hipStream_t stream = 0) : stream_(stream) { }
    virtual size_t gridSize(size_t numWorkUnits = 0, size_t blockDim = 0) const = 0;
    virtual size_t blockSize(size_t numWorkUnits = 0, size_t gridDim = 0) const = 0;
    virtual const hipStream_t* stream() const { return (&stream_); }
    virtual ExecPolicy* clone() const = 0;
    ExecPolicy* clone_new_stream(hipStream_t stream) const {
        ExecPolicy* ex = clone();
        ex->stream_ = stream;
        return ex;
    }
    virtual bool atomic() const { return false; }
    virtual ~ExecPolicy() {}
protected:
    hipStream_t stream_;
};
```

To define a custom execution policy, a user simply needs to create a class that inherits from the abstract class and implements the methods. The SUNDIALS provided `sundials::hip::ThreadDirectExecPolicy` (aka in the global namespace as `SUNHipThreadDirectExecPolicy`) class is a good example of what a custom execution policy may look like:

```
class ThreadDirectExecPolicy : public ExecPolicy
{
public:
    ThreadDirectExecPolicy(const size_t blockDim, hipStream_t stream = 0)
        : blockDim_(blockDim), ExecPolicy(stream)
    {}

    ThreadDirectExecPolicy(const ThreadDirectExecPolicy& ex)
        : blockDim_(ex.blockDim_), ExecPolicy(ex.stream_)
    {}

    virtual size_t gridSize(size_t numWorkUnits = 0, size_t /*blockDim*/ = 0) const
    {
        /* ceil(n/m) = floor((n + m - 1) / m) */
        return (numWorkUnits + blockSize() - 1) / blockSize();
    }

    virtual size_t blockSize(size_t /*numWorkUnits*/ = 0, size_t /*gridDim*/ = 0) const
    {
```

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```

    return blockDim_;
}

virtual ExecPolicy* clone() const
{
    return static_cast<ExecPolicy*>(new ThreadDirectExecPolicy(*this));
}

private:
    const size_t blockDim_;
};

```

In total, SUNDIALS provides 4 execution policies:

**SUNHipThreadDirectExecPolicy**(const size\_t blockDim, const hipStream\_t stream = 0)

Maps each HIP thread to a work unit. The number of threads per block (blockDim) can be set to anything. The grid size will be calculated so that there are enough threads for one thread per element. If a HIP stream is provided, it will be used to execute the kernel.

**SUNHipGridStrideExecPolicy**(const size\_t blockDim, const size\_t gridDim, const hipStream\_t stream = 0)

Is for kernels that use grid stride loops. The number of threads per block (blockDim) can be set to anything. The number of blocks (gridDim) can be set to anything. If a HIP stream is provided, it will be used to execute the kernel.

**SUNHipBlockReduceExecPolicy**(const size\_t blockDim, const hipStream\_t stream = 0)

Is for kernels performing a reduction across individual thread blocks. The number of threads per block (blockDim) can be set to any valid multiple of the HIP warp size. The grid size (gridDim) can be set to any value greater than 0. If it is set to 0, then the grid size will be chosen so that there is enough threads for one thread per work unit. If a HIP stream is provided, it will be used to execute the kernel.

**SUNHipBlockReduceAtomicExecPolicy**(const size\_t blockDim, const hipStream\_t stream = 0)

Is for kernels performing a reduction across individual thread blocks using atomic operations. The number of threads per block (blockDim) can be set to any valid multiple of the HIP warp size. The grid size (gridDim) can be set to any value greater than 0. If it is set to 0, then the grid size will be chosen so that there is enough threads for one thread per work unit. If a HIP stream is provided, it will be used to execute the kernel.

For example, a policy that uses 128 threads per block and a user provided stream can be created like so:

```

hipStream_t stream;
hipStreamCreate(&stream);
SUNHipThreadDirectExecPolicy thread_direct(128, stream);

```

These default policy objects can be reused for multiple SUNDIALS data structures (e.g. a *SUNMatrix* and an *N\_-Vector*) since they do not hold any modifiable state information.

## 7.12 The NVECTOR\_RAJA Module

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 AMD, NVIDIA, or Intel 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 either the NVIDIA CUDA programming environment, the AMD ROCm HIP programming environment, or a compiler that supports the SYCL abstraction layer. When using the AMD ROCm HIP environment, the HIP-clang compiler must be utilized. Users can select which backend to compile with by setting the `SUNDIALS_RAJA_BACKENDS` CMake variable to either CUDA, HIP, or SYCL. Besides the CUDA, HIP, and SYCL backends, RAJA has other backends such as serial, OpenMP, and OpenACC. These backends are not used in this SUNDIALS release.

The vector content layout is as follows:

```
struct _N_VectorContent_Raja
{
    sunindextype length;
    booleantype own_data;
    realtype* host_data;
    realtype* device_data;
    void*     priv; /* 'private' data */
};
```

The content members are the vector length (size), a boolean flag that signals if the vector owns the data (i.e., it is in charge of freeing the data), pointers to vector data on the host and the device, and a private data structure which holds the memory management type, which should not be accessed directly.

When instantiated with `N_VNew_Raja()`, the underlying data will be allocated on both the host and the device. Alternatively, a user can provide host and device data arrays by using the `N_VMake_Raja()` constructor. To use managed memory, the constructors `N_VNewManaged_Raja()` and `N_VMakeManaged_Raja()` are provided. Details on each of these constructors are provided below.

The header file to include when using this is `nvector_raja.h`. The installed module library to link to is `libsundials_nveccudaraja.lib` when using the CUDA backend, `libsundials_nvecchipraja.lib` when using the HIP backend, and `libsundials_nvecsyclraja.lib` when using the SYCL backend. The extension `.lib` is typically `.so` for shared libraries `.a` for static libraries.

### 7.12.1 NVECTOR\_RAJA functions

Unlike other native SUNDIALS vector types, the NVECTOR\_RAJA module does not provide macros to access its member variables. Instead, user should use the accessor functions:

`realtype *N_VGetHostArrayPointer_Raja(N_Vector v)`

This function returns pointer to the vector data on the host.

`realtype *N_VGetDeviceArrayPointer_Raja(N_Vector v)`

This function returns pointer to the vector data on the device.

`booleantype N_VIsManagedMemory_Raja(N_Vector v)`

This function returns a boolean flag indicating if the vector data is allocated in managed memory or not.

The NVECTOR\_RAJA module defines the implementations of all vector operations listed in §7.2, §7.2.2, §7.2.3, and §7.2.4, 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 NVECTOR\_RAJA implementation in the future. Additionally, the operations `N_VGetArrayPointer()` and `N_VSetArrayPointer()` are not implemented by the RAJA vector. As such, this vector cannot be used with SUNDIALS direct

solvers and preconditioners. The NVECTOR\_RAJA module provides separate functions to access data on the host and on the device. It also provides methods for copying from the host to the device and vice versa. Usage examples of NVECTOR\_RAJA are provided in some example programs for CVODE [36].

The names of vector operations are obtained from those in §7.2, §7.2.2, §7.2.3, and §7.2.4 by appending the suffix `_Raja` (e.g. `N_VDestroy_Raja`). The module NVECTOR\_RAJA provides the following additional user-callable routines:

**`N_Vector N_VNew_Raja(sunindextype vec_length, SUNContext sunctx)`**

This function creates and allocates memory for a RAJA `N_Vector`. The memory is allocated on both the host and the device. Its only argument is the vector length.

**`N_Vector N_VNewManaged_Raja(sunindextype vec_length, SUNContext sunctx)`**

This function creates and allocates memory for a RAJA `N_Vector`. The vector data array is allocated in managed memory.

**`N_Vector N_VMake_Raja(sunindextype length, realtype *h_data, realtype *v_data, SUNContext sunctx)`**

This function creates an NVECTOR\_RAJA with user-supplied host and device data arrays. This function does not allocate memory for data itself.

**`N_Vector N_VMakeManaged_Raja(sunindextype length, realtype *vdata, SUNContext sunctx)`**

This function creates an NVECTOR\_RAJA with a user-supplied managed memory data array. This function does not allocate memory for data itself.

**`N_Vector N_VNewWithMemHelp_Raja(sunindextype length, booleantype use_managed_mem, SUNMemoryHelper helper, SUNContext sunctx)`**

This function creates an NVECTOR\_RAJA with a user-supplied SUNMemoryHelper for allocating/freeing memory.

**`N_Vector N_VNewEmpty_Raja()`**

This function creates a new `N_Vector` where the members of the content structure have not been allocated. This utility function is used by the other constructors to create a new vector.

**`void N_VCopyToDevice_Raja(N_Vector v)`**

This function copies host vector data to the device.

**`void N_VCopyFromDevice_Raja(N_Vector v)`**

This function copies vector data from the device to the host.

**`void N_VPrint_Raja(N_Vector v)`**

This function prints the content of a RAJA vector to `stdout`.

**`void N_VPrintFile_Raja(N_Vector v, FILE *outfile)`**

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.

**`int N_VEnableFusedOps_Raja(N_Vector v, booleantype tf)`**

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.

**`int N_VEnableLinearCombination_Raja(N_Vector v, booleantype tf)`**

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.

```
int N_VEnableScaleAddMulti_Raja(N_Vector v, booleantype tf)
```

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.

```
int N_VEnableLinearSumVectorArray_Raja(N_Vector v, booleantype tf)
```

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.

```
int N_VEnableScaleVectorArray_Raja(N_Vector v, booleantype tf)
```

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.

```
int N_VEnableConstVectorArray_Raja(N_Vector v, booleantype tf)
```

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.

```
int N_VEnableScaleAddMultiVectorArray_Raja(N_Vector v, booleantype tf)
```

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.

```
int N_VEnableLinearCombinationVectorArray_Raja(N_Vector v, booleantype tf)
```

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 NVECTOR\_RAJA vector, it is recommended to use functions *N\_VGetDeviceArrayPointer\_Raja()* or *N\_VGetHostArrayPointer\_Raja()*. However, when using managed memory, the function *N\_VGetArrayPointer()* may also be used.
- 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.

## 7.13 The NVECTOR\_SYCL Module

The NVECTOR\_SYCL module is an experimental NVECTOR implementation using the **SYCL** abstraction layer. At present the only supported SYCL compiler is the DPC++ (Intel oneAPI) compiler. This module allows for SUNDIALS vector kernels to run on Intel GPU devices. The module is intended for users who are already familiar with SYCL and GPU programming.

The vector content layout is as follows:

```
struct _N_VectorContent_Sycl
{
    sunindextype      length;
    booleantype       own_exec;
    booleantype       own_helper;
    SUNMemory         host_data;
    SUNMemory         device_data;
    SUNSyclExecPolicy* stream_exec_policy;
    SUNSyclExecPolicy* reduce_exec_policy;
    SUNMemoryHelper   mem_helper;
```

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```

    sycl::queue*      queue;
    void*           priv; /* 'private' data */
};

typedef struct _N_VectorContent_Sycl *N_VectorContent_Sycl;

```

The content members are the vector length (size), boolean flags that indicate if the vector owns the execution policies and memory helper objects (i.e., it is in charge of freeing the objects), *SUNMemory* objects for the vector data on the host and device, pointers to execution policies that control how streaming and reduction kernels are launched, a *SUNMemoryHelper* for performing memory operations, the SYCL queue, and a private data structure which holds additional members that should not be accessed directly.

When instantiated with *N\_VNew\_Sycl()*, the underlying data will be allocated on both the host and the device. Alternatively, a user can provide host and device data arrays by using the *N\_VMake\_Sycl()* constructor. To use managed (shared) memory, the constructors *N\_VNewManaged\_Sycl()* and *N\_VMakeManaged\_Sycl()* are provided. Additionally, a user-defined *SUNMemoryHelper* for allocating/freeing data can be provided with the constructor *N\_VNewWithMemHelp\_Sycl()*. Details on each of these constructors are provided below.

The header file to include when using this is `nvector_sycl.h`. The installed module library to link to is `libsundials_nvecsycl.lib`. The extension `.lib` is typically `.so` for shared libraries `.a` for static libraries.

### 7.13.1 NVECTOR\_SYCL functions

The NVECTOR\_SYCL module implementations of all vector operations listed in §7.2, §7.2.2, §7.2.3, and §7.2.4, except for *N\_VDotProdMulti()*, *N\_VWrmsNormVectorArray()*, *N\_VWrmsNormMaskVectorArray()* as support for arrays of reduction vectors is not yet supported. These functions will be added to the NVECTOR\_SYCL implementation in the future. The names of vector operations are obtained from those in the aforementioned sections by appending the suffix `_Sycl` (e.g., `N_VDestroy_Sycl`).

Additionally, the NVECTOR\_SYCL module provides the following user-callable constructors for creating a new NVECTOR\_SYCL:

`N_Vector N_VNew_Sycl(sunindextype vec_length, sycl::queue *Q, SUNContext sunctx)`

This function creates and allocates memory for an NVECTOR\_SYCL. Vector data arrays are allocated on both the host and the device associated with the input queue. All operation are launched in the provided queue.

`N_Vector N_VNewManaged_Sycl(sunindextype vec_length, sycl::queue *Q, SUNContext sunctx)`

This function creates and allocates memory for a NVECTOR\_SYCL. The vector data array is allocated in managed (shared) memory using the input queue. All operation are launched in the provided queue.

`N_Vector N_VMake_Sycl(sunindextype length, realtype *h_vdata, realtype *d_vdata, sycl::queue *Q, SUNContext sunctx)`

This function creates an NVECTOR\_SYCL with user-supplied host and device data arrays. This function does not allocate memory for data itself. All operation are launched in the provided queue.

`N_Vector N_VMakeManaged_Sycl(sunindextype length, realtype *vdata, sycl::queue *Q, SUNContext sunctx)`

This function creates an NVECTOR\_SYCL with a user-supplied managed (shared) data array. This function does not allocate memory for data itself. All operation are launched in the provided queue.

`N_Vector N_VNewWithMemHelp_Sycl(sunindextype length, booleantype use_managed_mem, SUNMemoryHelper helper, sycl::queue *Q, SUNContext sunctx)`

This function creates an NVECTOR\_SYCL with a user-supplied SUNMemoryHelper for allocating/freeing memory. All operation are launched in the provided queue.

**N\_Vector N\_VNewEmpty\_Sycl()**

This function creates a new N\_Vector where the members of the content structure have not been allocated. This utility function is used by the other constructors to create a new vector.

The following user-callable functions are provided for accessing the vector data arrays on the host and device and copying data between the two memory spaces. Note the generic NVECTOR operations [N\\_VGetArrayPointer\(\)](#) and [N\\_VSetArrayPointer\(\)](#) are mapped to the corresponding HostArray functions given below. To ensure memory coherency, a user will need to call the CopyTo or CopyFrom functions as necessary to transfer data between the host and device, unless managed (shared) memory is used.

**realtype \*N\_VGetHostArrayPointer\_Sycl(N\_Vector v)**

This function returns a pointer to the vector host data array.

**realtype \*N\_VGetDeviceArrayPointer\_Sycl(N\_Vector v)**

This function returns a pointer to the vector device data array.

**void N\_VSetHostArrayPointer\_Sycl(realtype \*h\_vdata, N\_Vector v)**

This function sets the host array pointer in the vector v.

**void N\_VSetDeviceArrayPointer\_Sycl(realtype \*d\_vdata, N\_Vector v)**

This function sets the device array pointer in the vector v.

**void N\_VCopyToDevice\_Sycl(N\_Vector v)**

This function copies host vector data to the device.

**void N\_VCopyFromDevice\_Sycl(N\_Vector v)**

This function copies vector data from the device to the host.

**booleantype N\_VIsManagedMemory\_Sycl(N\_Vector v)**

This function returns SUNTRUE if the vector data is allocated as managed (shared) memory otherwise it returns SUNFALSE.

The following user-callable function is provided to set the execution policies for how SYCL kernels are launched on a device.

**int N\_VSetKernelExecPolicy\_Sycl(N\_Vector v, [SUNSyclExecPolicy](#) \*stream\_exec\_policy, [SUNSyclExecPolicy](#) \*reduce\_exec\_policy)**

This function sets the execution policies which control the kernel parameters utilized when launching the streaming and reduction kernels. By default the vector is setup to use the [SUNSyclThreadDirectExecPolicy\(\)](#) and [SUNSyclBlockReduceExecPolicy\(\)](#). See §7.13.2 below for more information about the [SUNSyclExecPolicy](#) class.

---

**Note:** All vectors used in a single instance of a SUNDIALS package must use the same execution policy. It is **strongly recommended** that this function is called immediately after constructing the vector, and any subsequent vector be created by cloning to ensure consistent execution policies across vectors.

---

The following user-callable functions are provided to print the host vector data array. Unless managed memory is used, a user may need to call [N\\_VCopyFromDevice\\_Sycl\(\)](#) to ensure consistency between the host and device array.

**void N\_VPrint\_Sycl(N\_Vector v)**

This function prints the host data array to `stdout`.

**void N\_VPrintFile\_Sycl(N\_Vector v, FILE \*outfile)**

This function prints the host data array to `outfile`.

By default all fused and vector array operations are disabled in the NVECTOR\_SYCL 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 one of the above constructors, enable/disable the desired operations on that vector with the functions below, and then use this vector in conjunction with [N\\_VClone\(\)](#)

to create any additional vectors. 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 by any of the constructors above will have the default settings for the NVECTOR\_SYCL module.

**int N\_VEnableFusedOps\_Sycl(N\_Vector v, boolean type tf)**

This function enables (SUNTRUE) or disables (SUNFALSE) all fused and vector array operations in the SYCL vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**int N\_VEnableLinearCombination\_Sycl(N\_Vector v, boolean type tf)**

This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination fused operation in the SYCL vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**int N\_VEnableScaleAddMulti\_Sycl(N\_Vector v, boolean type tf)**

This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector to multiple vectors fused operation in the SYCL vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**int N\_VEnableLinearSumVectorArray\_Sycl(N\_Vector v, boolean type tf)**

This function enables (SUNTRUE) or disables (SUNFALSE) the linear sum operation for vector arrays in the SYCL vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**int N\_VEnableScaleVectorArray\_Sycl(N\_Vector v, boolean type tf)**

This function enables (SUNTRUE) or disables (SUNFALSE) the scale operation for vector arrays in the SYCL vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**int N\_VEnableConstVectorArray\_Sycl(N\_Vector v, boolean type tf)**

This function enables (SUNTRUE) or disables (SUNFALSE) the const operation for vector arrays in the SYCL vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**int N\_VEnableScaleAddMultiVectorArray\_Sycl(N\_Vector v, boolean type tf)**

This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector array to multiple vector arrays operation in the SYCL vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**int N\_VEnableLinearCombinationVectorArray\_Sycl(N\_Vector v, boolean type tf)**

This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination operation for vector arrays in the SYCL 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\_SYCL, v, it is recommended to use [N\\_VGetDeviceArrayPointer\(\)](#) to access the device array or [N\\_VGetArrayPointer\(\)](#) for the host array. When using managed (shared) memory, either function may be used. To ensure memory coherency, a user may need to call the CopyTo or CopyFrom functions as necessary to transfer data between the host and device, unless managed (shared) memory is used.
- To maximize efficiency, vector operations in the NVECTOR\_SYCL 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.

### 7.13.2 The SUNSyclExecPolicy Class

In order to provide maximum flexibility to users, the SYCL kernel execution parameters used by kernels within SUNDIALS are defined by objects of the `sundials::sycl::ExecPolicy` abstract class type (this class can be accessed in the global namespace as `SUNsyclExecPolicy`). Thus, users may provide custom execution policies that fit the needs of their problem. The `SUNsyclExecPolicy` class is defined as

```
typedef sundials::sycl::ExecPolicy SUNsyclExecPolicy
```

where the `sundials::sycl::ExecPolicy` class is defined in the header file `sundials_sycl_policies.hpp`, as follows:

```
class ExecPolicy
{
public:
    virtual size_t gridSize(size_t numWorkUnits = 0, size_t blockDim = 0) const = 0;
    virtual size_t blockSize(size_t numWorkUnits = 0, size_t gridDim = 0) const = 0;
    virtual ExecPolicy* clone() const = 0;
    virtual ~ExecPolicy() {};
};
```

For consistency the function names and behavior mirror the execution policies for the CUDA and HIP vectors. In the SYCL case the `blockSize` is the local work-group range in a one-dimensional `nd_range` (threads per group). The `gridSize` is the number of local work groups so the global work-group range in a one-dimensional `nd_range` is `blockSize * gridSize` (total number of threads). All vector kernels are written with a many-to-one mapping where work units (vector elements) are mapped in a round-robin manner across the global range. As such, the `blockSize` and `gridSize` can be set to any positive value.

To define a custom execution policy, a user simply needs to create a class that inherits from the abstract class and implements the methods. The SUNDIALS provided `sundials::sycl::ThreadDirectExecPolicy` (aka in the global namespace as `SUNsyclThreadDirectExecPolicy`) class is a good example of what a custom execution policy may look like:

```
class ThreadDirectExecPolicy : public ExecPolicy
{
public:
    ThreadDirectExecPolicy(const size_t blockDim)
        : blockDim_(blockDim)
    {}

    ThreadDirectExecPolicy(const ThreadDirectExecPolicy& ex)
        : blockDim_(ex.blockDim_)
    {}

    virtual size_t gridSize(size_t numWorkUnits = 0, size_t blockDim = 0) const
    {
        return (numWorkUnits + blockSize() - 1) / blockSize();
    }

    virtual size_t blockSize(size_t numWorkUnits = 0, size_t gridDim = 0) const
    {
        return blockDim_;
    }

    virtual ExecPolicy* clone() const
```

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```

{
    return static_cast<ExecPolicy*>(new ThreadDirectExecPolicy(*this));
}

private:
    const size_t blockDim_;
};

```

SUNDIALS provides the following execution policies:

**SUNSyclThreadDirectExecPolicy**(const size\_t blockDim)

Is for kernels performing streaming operations and maps each work unit (vector element) to a work-item (thread). Based on the local work-group range (number of threads per group, `blockSize`) the number of local work-groups (`gridSize`) is computed so there are enough work-items in the global work-group range ( total number of threads, `blockSize * gridSize`) for one work unit per work-item (thread).

**SUNSyclGridStrideExecPolicy**(const size\_t blockDim, const size\_t gridDim)

Is for kernels performing streaming operations and maps each work unit (vector element) to a work-item (thread) in a round-robin manner so the local work-group range (number of threads per group, `blockSize`) and the number of local work-groups (`gridSize`) can be set to any positive value. In this case the global work-group range (total number of threads, `blockSize * gridSize`) may be less than the number of work units (vector elements).

**SUNSyclBlockReduceExecPolicy**(const size\_t blockDim)

Is for kernels performing a reduction, the local work-group range (number of threads per group, `blockSize`) and the number of local work-groups (`gridSize`) can be set to any positive value or the `gridSize` may be set to `0` in which case the global range is chosen so that there are enough threads for at most two work units per work-item.

By default the NVECTOR\_SYCL module uses the `SUNSyclThreadDirectExecPolicy` and `SUNSyclBlockReduceExecPolicy` where the default `blockDim` is determined by querying the device for the `max_work_group_size`. User may specify different policies by constructing a new `SyclExecPolicy` and attaching it with `N_VSetKernelExecPolicy_Sycl()`. For example, a policy that uses 128 work-items (threads) per group can be created and attached like so:

```

N_Vector v = N_VNew_Sycl(length, SUNContext sunctx);
SUNSyclThreadDirectExecPolicy thread_direct(128);
SUNSyclBlockReduceExecPolicy block_reduce(128);
flag = N_VSetKernelExecPolicy_Sycl(v, &thread_direct, &block_reduce);

```

These default policy objects can be reused for multiple SUNDIALS data structures (e.g. a `SUNMatrix` and an `N_Vector`) since they do not hold any modifiable state information.

## 7.14 The NVECTOR\_OPENMPDEV Module

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.

### 7.14.1 NVECTOR\_OPENMPDEV accessor macros

The following macros are provided to access the content of an NVECTOR\_OPENMPDEV vector.

#### NV\_CONTENT\_OMPDEV(v)

This macro gives access to the contents of the NVECTOR\_OPENMPDEV `N_Vector v`.

The assignment `v_cont = NV_CONTENT_S(v)` sets `v_cont` to be a pointer to the NVECTOR\_OPENMPDEV content structure.

Implementation:

```
#define NV_CONTENT_OMPDEV(v) ( (N_VectorContent_OpenMPDEV)(v->content) )
```

#### NV\_OWN\_DATA\_OMPDEV(v)

Access the `own_data` component of the OpenMPDEV `N_Vector v`.

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`.

Implementation:

```
#define NV_OWN_DATA_OMPDEV(v) ( NV_CONTENT_OMPDEV(v)->own_data )
```

#### NV\_DATA\_HOST\_OMPDEV(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`.

Implementation:

```
#define NV_DATA_HOST_OMPDEV(v) ( NV_CONTENT_OMPDEV(v)->host_data )
```

#### NV\_DATA\_DEV\_OMPDEV(v)

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`.

Implementation:

```
#define NV_DATA_DEV_OMPDEV(v) ( NV_CONTENT_OMPDEV(v)->dev_data )
```

#### NV\_LENGTH\_OMPDEV(V)

Access the `length` component of the OpenMPDEV `N_Vector v`.

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`.

```
#define NV_LENGTH_OMPDEV(v) ( NV_CONTENT_OMPDEV(v)->length )
```

### 7.14.2 NVECTOR\_OPENMPDEV functions

The NVECTOR\_OPENMPDEV module defines OpenMP device offloading implementations of all vector operations listed in §7.2, §7.2.2, §7.2.3, and §7.2.4, except for `N_VSetArrayPointer()`. As such, this vector cannot be used 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 the vector operations are obtained from those in §7.2, §7.2.2, §7.2.3, and §7.2.4 by appending the suffix `_OpenMPDEV` (e.g. `N_VDestroy_OpenMPDEV`). The module NVECTOR\_OPENMPDEV provides the following additional user-callable routines:

`N_Vector N_VNew_OpenMPDEV(sunindextype vec_length, SUNContext sunctx)`

This function creates and allocates memory for an NVECTOR\_OPENMPDEV `N_Vector`.

`N_Vector N_VNewEmpty_OpenMPDEV(sunindextype vec_length, SUNContext sunctx)`

This function creates a new NVECTOR\_OPENMPDEV `N_Vector` with an empty (NULL) data array.

`N_Vector N_VMake_OpenMPDEV(sunindextype vec_length, realtype *h_vdata, realtype *d_vdata, SUNContext sunctx)`

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.

`realtype *N_VGetHostArrayPointer_OpenMPDEV(N_Vector v)`

This function returns a pointer to the host data array.

`realtype *N_VGetDeviceArrayPointer_OpenMPDEV(N_Vector v)`

This function returns a pointer to the device data array.

`void N_VPrint_OpenMPDEV(N_Vector v)`

This function prints the content of an NVECTOR\_OPENMPDEV vector to `stdout`.

`void N_VPrintFile_OpenMPDEV(N_Vector v, FILE *outfile)`

This function prints the content of an NVECTOR\_OPENMPDEV vector to `outfile`.

`void N_VCopyToDevice_OpenMPDEV(N_Vector v)`

This function copies the content of an NVECTOR\_OPENMPDEV vector's host data array to the device data array.

`void N_VCopyFromDevice_OpenMPDEV(N_Vector v)`

This function copies the content of an NVECTOR\_OPENMPDEV vector's device data array to the host data array.

By default all fused and vector array operations are disabled in the NVECTOR\_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 NVECTOR\_OPENMPDEV module.

`int N_VEnableFusedOps_OpenMPDEV(N_Vector v, boolean type tf)`

This function enables (SUNTRUE) or disables (SUNFALSE) all fused and vector array operations in the NVECTOR\_OPENMPDEV vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

```
int N_VEnableLinearCombination_OpenMPDEV(N_Vector v, booleantype tf)
```

This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination fused 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.

```
int N_VEnableScaleAddMulti_OpenMPDEV(N_Vector v, booleantype tf)
```

This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector to multiple vectors fused 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.

```
int N_VEnableDotProdMulti_OpenMPDEV(N_Vector v, booleantype tf)
```

This function enables (SUNTRUE) or disables (SUNFALSE) the multiple dot products fused 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.

```
int N_VEnableLinearSumVectorArray_OpenMPDEV(N_Vector v, booleantype tf)
```

This function enables (SUNTRUE) or disables (SUNFALSE) the linear sum 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.

```
int N_VEnableScaleVectorArray_OpenMPDEV(N_Vector v, booleantype tf)
```

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.

```
int N_VEnableConstVectorArray_OpenMPDEV(N_Vector v, booleantype tf)
```

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.

```
int N_VEnableWrmsNormVectorArray_OpenMPDEV(N_Vector v, booleantype tf)
```

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.

```
int N_VEnableWrmsNormMaskVectorArray_OpenMPDEV(N_Vector v, booleantype tf)
```

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.

```
int N_VEnableScaleAddMultiVectorArray_OpenMPDEV(N_Vector v, booleantype tf)
```

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.

```
int N_VEnableLinearCombinationVectorArray_OpenMPDEV(N_Vector v, booleantype tf)
```

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* = *N\_VGetArrayPointer*(v) for the host array or *v\_data* = *N\_VGetDeviceArrayPointer*(v) for the device array, or equivalently to use the macros *h\_data* = *NV\_DATA\_HOST\_OMPDEV*(v) for the host array or *v\_data* = *NV\_DATA\_DEV\_OMPDEV*(v) for the device array, and then access *h\_data*[i] or *v\_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` to `SUNFALSE`. The functions `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 pointers.
- 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 length.

## 7.15 The NVECTOR\_TRILINOS Module

The `NVECTOR_TRILINOS` module is an `NVECTOR` wrapper around the `Trilinos` Tpetra vector. The interface to Tpetra is implemented in the `sundials::trilinos::nvector_tpetra::TpetraVectorInterface` class. This class simply stores a reference counting pointer to a Tpetra vector and inherits from an empty structure

```
struct _N_VectorContent_Trlilinos {};
```

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::trilinos::nvector_tpetra::TpetraVectorInterface` class is defined as:

```
typedef Tpetra::Vector<realtype, int, sunindextype> vector_type;
```

The Tpetra vector will use the SUNDIALS-specified `realtype` as its scalar type, `int` as the local ordinal type, and `sunindextype` as the global ordinal type. This type definition will use Tpetra's default node type. Available Kokkos node types as of the 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_nvectriliнос.lib` where `.lib` is typically `.so` for shared libraries and `.a` for static libraries.

### 7.15.1 NVECTOR\_TRILINOS functions

The `NVECTOR_TRILINOS` module defines implementations of all vector operations listed in §7.2, §7.2.2, §7.2.3, and §7.2.4, except for `N_VGetArrayPointer()` and `N_VSetArrayPointer()`. As such, this vector cannot be used 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.

The names of vector operations are obtained from those in §7.2 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::trilinos::nvector_tpetra::TpetraVector`, located in the file `SundialsTpetraVectorKernels.hpp`. The module `NVECTOR_TRILINOS` provides the following additional user-callable routines:

`Teuchos::RCP<vector_type> N_VGetVector_Trilinos(N_Vector v)`

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.

`N_Vector N_VMake_Trilinos(Teuchos::RCP<vector_type> v)`

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.

## Notes

- The template parameter `vector_type` should be set as:

```
typedef sundials::trilinos::nvector_tpetra::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.

## 7.16 The NVECTOR\_MANYVECTOR Module

The NVECTOR\_MANYVECTOR module is designed to facilitate problems with an inherent data partitioning within a computational node for the solution vector. 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. Two potential use cases for this flexibility include:

- Heterogenous computational architectures:* for data partitioning between different computing resources on a node, architecture-specific subvectors may be created for each partition. For example, a user could create one GPU-accelerated component based on [NVECTOR\\_CUDA](#), and another CPU threaded component based on [NVECTOR\\_OPENMP](#).
- Structure of arrays (SOA) data layouts:* for problems that require separate subvectors for each solution component. For example, in an incompressible Navier-Stokes simulation, separate subvectors may be used for velocities and pressure, which are combined together into a single NVECTOR\_MANYVECTOR for the overall “solution”.

The above use cases are neither exhaustive nor 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 “standard” set of operations in §7.2.1. 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 function, DAE or nonlinear solver residual function, preconditioners, or custom [SUNLinearSolver](#) or [SUNNonlinearSolver](#) modules.

## 7.16.1 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`.

```
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 `libsundials_nvecmanyvector.lib` where `.lib` is typically `.so` for shared libraries and `.a` for static libraries.

## 7.16.2 NVECTOR\_MANYVECTOR functions

The NVECTOR\_MANYVECTOR module implements all vector operations listed in §7.2 except for `N_VGetArrayPointer()`, `N_VSetArrayPointer()`, `N_VScaleAddMultiVectorArray()`, and `N_VLinearCombinationVectorArray()`. As such, this vector cannot be used 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 §7.2 by appending the suffix `_ManyVector` (e.g. `N_VDestroy_ManyVector`). The module NVECTOR\_MANYVECTOR provides the following additional user-callable routines:

`N_Vector N_VNew_ManyVector(sunindextype num_subvectors, N_Vector *vec_array, SUNContext sunctx)`

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 §4.4.2.5, and the functions are documented in §7.1.1.

`N_Vector N_VGetSubvector_ManyVector(N_Vector v, sunindextype vec_num)`

This function returns the `vec_num` subvector from the NVECTOR array.

`realtype *N_VGetSubvectorArrayPointer_ManyVector(N_Vector v, sunindextype vec_num)`

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.

`int N_VSetSubvectorArrayPointer_ManyVector(realtype *v_data, N_Vector v, sunindextype vec_num)`

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 -1 is returned; otherwise it returns 0.

*sunindextype N\_VGetNumSubvectors\_ManyVector(N\_Vector v)*

This function returns the overall number of subvectors in the ManyVector object.

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()*.

**int N\_VEnableFusedOps\_ManyVector(N\_Vector v, boolean type tf)**

This function enables (SUNTRUE) or disables (SUNFALSE) all fused and vector array operations in the manyvector vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**int N\_VEnableLinearCombination\_ManyVector(N\_Vector v, boolean type tf)**

This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination fused operation in the manyvector vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**int N\_VEnableScaleAddMulti\_ManyVector(N\_Vector v, boolean type tf)**

This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector to multiple vectors fused operation in the manyvector vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**int N\_VEnableDotProdMulti\_ManyVector(N\_Vector v, boolean type tf)**

This function enables (SUNTRUE) or disables (SUNFALSE) the multiple dot products fused operation in the manyvector vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**int N\_VEnableLinearSumVectorArray\_ManyVector(N\_Vector v, boolean type tf)**

This function enables (SUNTRUE) or disables (SUNFALSE) the linear sum operation for vector arrays in the manyvector vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**int N\_VEnableScaleVectorArray\_ManyVector(N\_Vector v, boolean type tf)**

This function enables (SUNTRUE) or disables (SUNFALSE) the scale operation for vector arrays in the manyvector vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**int N\_VEnableConstVectorArray\_ManyVector(N\_Vector v, boolean type tf)**

This function enables (SUNTRUE) or disables (SUNFALSE) the const operation for vector arrays in the manyvector vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**int N\_VEnableWrmsNormVectorArray\_ManyVector(N\_Vector v, boolean type tf)**

This function enables (SUNTRUE) or disables (SUNFALSE) the WRMS norm operation for vector arrays in the manyvector vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

**int N\_VEnableWrmsNormMaskVectorArray\_ManyVector(N\_Vector v, boolean type tf)**

This function enables (SUNTRUE) or disables (SUNFALSE) the masked WRMS norm operation for vector arrays in the manyvector vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

## Notes

- *N\_VNew\_ManyVector()* sets the field `own_data` = SUNFALSE. *N\_VDestroy\_ManyVector()* will not attempt to call *N\_VDestroy()* on any subvectors contained in the subvector array for any *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 NVECTOR\_MANYVECTOR 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 subvector representations.

## 7.17 The NVECTOR\_MPIMANYVECTOR Module

The NVECTOR\_MPIMANYVECTOR module is designed to facilitate problems with an inherent data partitioning for the solution vector, and when using distributed-memory parallel architectures. As such, this implementation supports all use cases allowed by the MPI-unaware NVECTOR\_MANYVECTOR implementation, as well as partitioning data between nodes in a parallel environment. 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\_MPIMANYVECTOR. Three potential use cases for this module include:

- A. *Heterogenous computational architectures (single-node or multi-node)*: for data partitioning between different computing resources on a node, architecture-specific subvectors may be created for each partition. For example, a user could create one MPI-parallel component based on *NVECTOR\_PARALLEL*, another GPU-accelerated component based on *NVECTOR\_CUDA*.
- B. *Process-based multiphysics decompositions (multi-node)*: for computations that combine separate MPI-based simulations together, each subvector may reside on a different MPI communicator, and the MPIManyVector combines these via an MPI *intercommunicator* that connects these distinct simulations together.
- C. *Structure of arrays (SOA) data layouts (single-node or multi-node)*: for problems that require separate subvectors for each solution component. For example, in an incompressible Navier-Stokes simulation, separate subvectors may be used for velocities and pressure, which are combined together into a single MPIManyVector for the overall “solution”.

The above use cases are neither exhaustive nor 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 “standard” set of operations in §7.2.1, however significant performance benefits may be obtained when subvectors additionally implement the optional local reduction operations listed in §7.2.4.

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 function, DAE or nonlinear solver residual function, preconditioners, or custom *SUNLinearSolver* or *SUNNonlinearSolver* modules.

## 7.17.1 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 ranks), 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`.

```
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 `libsundials_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\_MANYVECTOR implementation is designed for ManyVector use cases in an MPI-unaware environment.

---

## 7.17.2 NVECTOR\_MPIMANYVECTOR functions

The NVECTOR\_MPIMANYVECTOR module implements all vector operations listed in §7.2, except for `N_VGetArrayPointer()`, `N_VSetArrayPointer()`, `N_VScaleAddMultiVectorArray()`, and `N_VLinearCombinationVectorArray()`. As such, this vector cannot be used 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 §7.2 by appending the suffix `_MPIManyVector` (e.g. `N_VDestroy_MPIManyVector`). The module NVECTOR\_MPIMANYVECTOR provides the following additional user-callable routines:

`N_Vector N_VNew_MPIManyVector(sunindextype num_subvectors, N_Vector *vec_array, SUNContext sunctx)`

This function creates a 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 `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 MPIManyVector that contains them.

Upon successful completion, the new MPIManyVector is returned; otherwise this routine returns 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 `N_Vector` utility functions `N_VNewVectorArray()`, and `N_VSetVecAtIndexVectorArray()` to create the `N_Vector*` argument. This is further explained in §4.4.2.5, and the functions are documented in §7.1.1.

---

`N_Vector N_VMake_MPIManyVector(MPI_Comm comm, sunindextype num_subvectors, N_Vector *vec_array, SUNContext suncxt)`

This function creates a 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 `comm`. We note that this routine is designed to support any combination of the use cases above.

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_MPIManyVector()`.

If all subvectors are MPI-unaware, then the input `comm` argument should be `MPI_COMM_NULL`, although in this case, it would be simpler to call `N_VNew_MPIManyVector()` instead, or to just use the NVECTOR\_MANYVECTOR module.

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 MPIManyVector that contains them.

Upon successful completion, the new MPIManyVector is returned; otherwise this routine returns `NULL` (e.g., if the input `vec_array` is `NULL`).

`N_Vector N_VGetSubvector_MPIManyVector(N_Vector v, sunindextype vec_num)`

This function returns the `vec_num` subvector from the NVECTOR array.

`realtype *N_VGetSubvectorArrayPointer_MPIManyVector(N_Vector v, sunindextype vec_num)`

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.

`int N_VSetSubvectorArrayPointer_MPIManyVector(realtype *v_data, N_Vector v, sunindextype vec_num)`

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 `-1` is returned; otherwise it returns `0`.

`sunindextype N_VGetNumSubvectors_MPIManyVector(N_Vector v)`

This function returns the overall number of subvectors in the MPIManyVector object.

By default all fused and vector array operations are disabled in the NVECTOR\_MPIMANYVECTOR 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_VMake_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_VMake_MPIManyVector()` will have the default settings for the NVECTOR\_MPIMANYVECTOR 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_VMake_MPIManyVector()`.

`int N_VEnableFusedOps_MPIManyVector(N_Vector v, booleantype tf)`

This function enables (SUNTRUE) or disables (SUNFALSE) all fused and vector array operations in the MPI-ManyVector vector. The return value is `0` for success and `-1` if the input vector or its ops structure are `NULL`.

`int N_VEnableLinearCombination_MPIManyVector(N_Vector v, booleantype tf)`

This function enables (SUNTRUE) or disables (SUNFALSE) the linear combination fused operation in the MPI-ManyVector vector. The return value is `0` for success and `-1` if the input vector or its ops structure are `NULL`.

```
int N_VEnableScaleAddMulti_MPIManyVector(N_Vector v, booleantype tf)
```

This function enables (SUNTRUE) or disables (SUNFALSE) the scale and add a vector to multiple vectors fused operation in the MPIManyVector vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

```
int N_VEnableDotProdMulti_MPIManyVector(N_Vector v, booleantype tf)
```

This function enables (SUNTRUE) or disables (SUNFALSE) the multiple dot products fused operation in the MPI-ManyVector vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

```
int N_VEnableLinearSumVectorArray_MPIManyVector(N_Vector v, booleantype tf)
```

This function enables (SUNTRUE) or disables (SUNFALSE) the linear sum operation for vector arrays in the MPI-ManyVector vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

```
int N_VEnableScaleVectorArray_MPIManyVector(N_Vector v, booleantype tf)
```

This function enables (SUNTRUE) or disables (SUNFALSE) the scale operation for vector arrays in the MPI-ManyVector vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

```
int N_VEnableConstVectorArray_MPIManyVector(N_Vector v, booleantype tf)
```

This function enables (SUNTRUE) or disables (SUNFALSE) the const operation for vector arrays in the MPI-ManyVector vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

```
int N_VEnableWrmsNormVectorArray_MPIManyVector(N_Vector v, booleantype tf)
```

This function enables (SUNTRUE) or disables (SUNFALSE) the WRMS norm operation for vector arrays in the MPIManyVector vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

```
int N_VEnableWrmsNormMaskVectorArray_MPIManyVector(N_Vector v, booleantype tf)
```

This function enables (SUNTRUE) or disables (SUNFALSE) the masked WRMS norm operation for vector arrays in the MPIManyVector vector. The return value is 0 for success and -1 if the input vector or its ops structure are NULL.

## Notes

- *N\_VNew\_MPIManyVector()* and *N\_VMake\_MPIManyVector()* set the field `own_data = SUNFALSE`. *N\_VDestroy\_MPIManyVector()* will not attempt to call *N\_VDestroy()* on any subvectors contained in the subvector array for any *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 NVECTOR\_MPIANYVECTOR 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 subvector representations.

## 7.18 The NVECTOR\_MPIPLUSX Module

The NVECTOR\_MPIPLUSX module 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 NVECTOR\_MPIPLUSX implementation is designed to work with any NVECTOR that implements the minimum “standard” set of operations in §7.2.1. However, it is not recommended to use the NVECTOR\_PARALLEL, NVECTOR\_PARHYP, NVECTOR\_PETSC, or NVECTOR\_TRILINOS implementations underneath the NVECTOR\_MPIPLUSX module since they already provide MPI capabilities.

## 7.18.1 NVECTOR\_MPIPLUSX structure

The NVECTOR\_MPIPLUSX implementation is a thin wrapper around the NVECTOR\_MPIMANYVECTOR. Accordingly, it adopts the same content structure as defined in §7.17.1.

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.

---

## 7.18.2 NVECTOR\_MPIPLUSX functions

The NVECTOR\_MPIPLUSX module adopts all vector operations listed in §7.2, from the NVECTOR\_MPIMANYVECTOR (see §7.17) 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, its compatibility 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_Vector N_VMake_MPIPlusX(MPI_Comm comm, N_Vector *local_vector, SUNContext sunctx)`

This function creates a 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 NVECTOR 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).

`N_Vector N_VGetLocal_MPIPlusX(N_Vector v)`

This function returns the local vector underneath the MPIPlusX NVECTOR.

`realtype *N_VGetArrayPointer_MPIPlusX(N_Vector v)`

This function returns the data array pointer for the local vector.

If the local vector does not support the `N_VGetArrayPointer()` operation, then NULL is returned.

`void N_VSetArrayPointer_MPIPlusX(realtype *v_data, N_Vector v)`

This function sets the data array pointer for the local vector if the local vector implements the `N_VSetArrayPointer()` operation.

The NVECTOR\_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 NVECTOR\_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 subvector representations.

## 7.19 NVECTOR Examples

There are NVECTOR examples that may be installed for each implementation. Each implementation makes use of the functions in `test_nvvector.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_nvvector.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_N_VLinearSum Case 3`: Test  $z = x + y$
- `Test_N_VLinearSum Case 4a`: Test  $z = x - y$
- `Test_N_VLinearSum Case 4b`: Test  $z = -x + y$
- `Test_N_VLinearSum Case 5a`: Test  $z = x + by$
- `Test_N_VLinearSum Case 5b`: Test  $z = ax + y$
- `Test_N_VLinearSum Case 6a`: Test  $z = -x + by$
- `Test_N_VLinearSum Case 6b`: Test  $z = ax - y$
- `Test_N_VLinearSum Case 7`: Test  $z = a(x + y)$
- `Test_N_VLinearSum Case 8`: Test  $z = a(x - y)$
- `Test_N_VLinearSum Case 9`: Test  $z = ax + by$
- `Test_N_VConst`: Fill vector with constant and check result.
- `Test_N_VProd`: Test vector multiply:  $z = x * y$

- `Test_N_VDiv`: Test vector division:  $z = x / y$
  - `Test_N_VScale`: Case 1: scale:  $x = cx$
  - `Test_N_VScale`: Case 2: copy:  $z = x$
  - `Test_N_VScale`: Case 3: negate:  $z = -x$
  - `Test_N_VScale`: Case 4: combination:  $z = cx$
  - `Test_N_VAbs`: Create absolute value of vector.
  - `Test_N_VInv`: Compute  $z[i] = 1 / x[i]$
- \*\* `Test_N_VAddConst`: add constant vector:  $z = c + x$
- `Test_N_VDotProd`: Calculate dot product of two vectors.
  - `Test_N_VMaxNorm`: Create vector with known values, find and validate the max norm.
  - `Test_N_VWrmsNorm`: Create vector of known values, find and validate the weighted root mean square.
  - `Test_N_VWrmsNormMask`: Create vector of known values, find and validate the weighted root mean square using all elements except one.
  - `Test_N_VMin`: Create vector, find and validate the min.
  - `Test_N_VWL2Norm`: Create vector, find and validate the weighted Euclidean L2 norm.
  - `Test_N_VL1Norm`: Create vector, find and validate the L1 norm.
  - `Test_N_VCompare`: Compare vector with constant returning and validating comparison vector.
  - `Test_N_VInvTest`: Test  $z[i] = 1 / x[i]$
  - `Test_N_VConstrMask`: Test mask of vector  $x$  with vector  $c$ .
  - `Test_N_VMinQuotient`: Fill two vectors with known values. Calculate and validate minimum quotient.
  - `Test_N_VLinearCombination`: Case 1a: Test  $x = a x$
  - `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_VConstVectorArray`: Case 1a:  $z = c$
- `Test_N_VConstVectorArray`: Case 1b:  $Z[i] = c$
- `Test_N_VWrmsNormVectorArray`: Case 1a: Create a vector of known values, find and validate the weighted root mean square norm.
- `Test_N_VWrmsNormVectorArray`: Case 1b: Create a vector array of three vectors of known values, find and validate the weighted root mean square norm of each.
- `Test_N_VWrmsNormMaskVectorArray`: Case 1a: Create a vector of known 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 known 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:  $Z[j][0] = a[j] X[0] + Y[j][0]$
- `Test_N_VScaleAddMultiVectorArray`: Case 3a:  $Y[0][i] = a[0] X[i] + Y[0][i]$
- `Test_N_VScaleAddMultiVectorArray`: Case 3b:  $Z[0][i] = a[0] X[i] + Y[0][i]$
- `Test_N_VScaleAddMultiVectorArray`: Case 4a:  $Y[j][i] = a[j] X[i] + Y[j][i]$
- `Test_N_VScaleAddMultiVectorArray`: Case 4b:  $Z[j][i] = a[j] X[i] + Y[j][i]$
- `Test_N_VLinearCombinationVectorArray`: Case 1a:  $x = a x$
- `Test_N_VLinearCombinationVectorArray`: Case 1b:  $z = a x$
- `Test_N_VLinearCombinationVectorArray`: Case 2a:  $x = a x + b y$
- `Test_N_VLinearCombinationVectorArray`: Case 2b:  $z = a x + b y$
- `Test_N_VLinearCombinationVectorArray`: Case 3a:  $x = a x + b y + c z$
- `Test_N_VLinearCombinationVectorArray`: Case 3b:  $w = a x + b y + c z$
- `Test_N_VLinearCombinationVectorArray`: Case 4a:  $X[0][i] = c[0] X[0][i]$
- `Test_N_VLinearCombinationVectorArray`: Case 4b:  $Z[i] = c[0] X[0][i]$
- `Test_N_VLinearCombinationVectorArray`: Case 5a:  $X[0][i] = c[0] X[0][i] + c[1] X[1][i]$
- `Test_N_VLinearCombinationVectorArray`: Case 5b:  $Z[i] = c[0] X[0][i] + c[1] X[1][i]$
- `Test_N_VLinearCombinationVectorArray`: Case 6a:  $X[0][i] = X[0][i] + c[1] X[1][i] + c[2] X[2][i]$
- `Test_N_VLinearCombinationVectorArray`: Case 6b:  $X[0][i] = c[0] X[0][i] + c[1] X[1][i] + c[2] X[2][i]$
- `Test_N_VLinearCombinationVectorArray`: Case 6c:  $Z[i] = c[0] X[0][i] + c[1] X[1][i] + c[2] X[2][i]$
- `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.
- `Test_N_VMBufSize`: Tests for accuracy in the reported buffer size.
- `Test_N_VMBufPack`: Tests for accuracy in the buffer packing routine.
- `Test_N_VMBufUnpack`: Tests for accuracy in the buffer unpacking routine.



# Chapter 8

# Matrix Data Structures

The SUNDIALS library comes packaged with a variety of `SUNMatrix` implementations, designed for simulations requiring direct linear solvers for problems in serial or shared-memory parallel environments. SUNDIALS additionally provides a simple interface for generic matrices (akin to a C++ *abstract base class*). All of the major SUNDIALS packages (CVODE(s), IDA(s), KINSOL, ARKODE), are constructed to only depend on these generic matrix operations, making them immediately extensible to new user-defined matrix objects. For each of the SUNDIALS-provided matrix types, SUNDIALS also provides `SUNLinearSolver` implementations that factor these matrix objects and use them in the solution of linear systems.

## 8.1 Description of the SUNMATRIX Modules

For problems that involve direct methods for solving linear systems, the SUNDIALS packages 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 `N_Vector` and/or linear solver modules, and require matrices that are compatible with those implementations. The generic `SUNMatrix` operations are described below, and descriptions of the SUNMATRIX implementations provided with SUNDIALS follow.

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
```

and the generic structure is defined as

```
struct _generic_SUNMatrix {
    void *content;
    struct _generic_SUNMatrix_Ops *ops;
};
```

Here, the `_generic_SUNMatrix_Ops` structure is essentially a list of function pointers to the various actual matrix operations, and is defined as

```
struct _generic_SUNMatrix_Ops {
    SUNMatrix_ID (*getid)(SUNMatrix);
    SUNMatrix     (*clone)(SUNMatrix);
```

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```

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 a **SUNMatrix**. 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:

```

int SUNMatZero(SUNMatrix A)
{
    return((int) A->ops->zero(A));
}

```

§8.2 contains a complete list of all matrix operations defined by the generic **SUNMATRIX** module. 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 package and/or linear 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 as needed for that particular implementation to be used to access different parts in the *content* field of the newly defined **SUNMatrix**.

To aid in the creation of custom **SUNMATRIX** modules the generic **SUNMATRIX** module provides three utility functions ***SUNMatNewEmpty()***, ***SUNMatCopyOps()***, and ***SUNMatFreeEmpty()***. 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.

#### ***SUNMatrix SUNMatNewEmpty()***

This function allocates a new generic **SUNMatrix** object and initializes its content pointer and the function pointers in the operations structure to NULL.

**Return value:** If successful, this function returns a **SUNMatrix** object. If an error occurs when allocating the object, then this routine will return NULL.

#### ***int SUNMatCopyOps(**SUNMatrix** A, **SUNMatrix** B)***

This function copies the function pointers in the *ops* structure of A into the *ops* structure of B.

#### **Arguments:**

- $A$  – the matrix to copy operations from.
- $B$  – the matrix to copy operations to.

**Return value:** If successful, this function returns `0`. If either of the inputs are `NULL` or the `ops` structure of either input is `NULL`, then this function returns a non-zero value.

void **SUNMatFreeEmpty**(*SUNMatrix* A)

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:

- $A$  – the `SUNMatrix` object to free

Each `SUNMATRIX` implementation included in SUNDIALS has a unique identifier specified in enumeration and shown in [Table 8.1](#). It is recommended that a user-supplied `SUNMATRIX` implementation use the `SUNMATRIX_CUSTOM` identifier.

Table 8.1: Identifiers associated with matrix kernels supplied with SUNDIALS

Matrix ID	Matrix type	ID Value
<code>SUNMATRIX_DENSE</code>	Dense $M \times N$ matrix	0
<code>SUNMATRIX_MAGMADENSE</code>	Magma dense $M \times N$ matrix	1
<code>SUNMATRIX_BAND</code>	Band $M \times M$ matrix	2
<code>SUNMATRIX_SPARSE</code>	Sparse (CSR or CSC) $M \times N$ matrix	3
<code>SUNMATRIX_SLUNRLOC</code>	<code>SUNMatrix</code> wrapper for SuperLU_DIST SuperMatrix	4
<code>SUNMATRIX_CUSPARSE</code>	CUDA sparse CSR matrix	5
<code>SUNMATRIX_CUSTOM</code>	User-provided custom matrix	6

## 8.2 Description of the `SUNMATRIX` operations

For each of the `SUNMatrix` operations, we give the name, usage of the function, and a description of its mathematical operations below.

`SUNMatrix_ID` **SUNMatGetID**(*SUNMatrix* A)

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. Returned values are given in [Table 8.1](#).

Usage:

```
id = SUNMatGetID(A);
```

*SUNMatrix* **SUNMatClone**(*SUNMatrix* A)

Creates a new `SUNMatrix` of the same type as an existing matrix  $A$  and sets the `ops` field. It does not copy the matrix values, but rather allocates storage for the new matrix.

Usage:

```
B = SUNMatClone(A);
```

void **SUNMatDestroy**(*SUNMatrix* A)

Destroys the `SUNMatrix`  $A$  and frees memory allocated for its internal data.

Usage:

```
SUNMatDestroy(A);
```

int **SUNMatSpace**(*SUNMatrix* A, long int \*lrw, long int \*liw)

Returns the storage requirements for the matrix *A*. *lrw* contains the number of realtype words and *liw* contains the number of integer words. The return value denotes success/failure of the operation.

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.

Usage:

```
retval = SUNMatSpace(A, &lrw, &liw);
```

int **SUNMatZero**(*SUNMatrix* A)

Zeros all entries of the **SUNMatrix** *A*. The return value is an integer flag denoting success/failure of the operation:

$$A_{i,j} = 0, \quad i = 1, \dots, m, \quad j = 1, \dots, n.$$

Usage:

```
retval = SUNMatZero(A);
```

int **SUNMatCopy**(*SUNMatrix* A, *SUNMatrix* B)

Performs the operation *B* gets *A* for all entries of the matrices *A* and *B*. The return value is an integer flag denoting success/failure of the operation:

$$B_{i,j} = A_{i,j}, \quad i = 1, \dots, m, \quad j = 1, \dots, n.$$

Usage:

```
retval = SUNMatCopy(A,B);
```

int **SUNMatScaleAdd**(*realtype* c, *SUNMatrix* A, *SUNMatrix* B)

Performs the operation *A* gets *cA + B*. The return value is an integer flag denoting success/failure of the operation:

$$A_{i,j} = cA_{i,j} + B_{i,j}, \quad i = 1, \dots, m, \quad j = 1, \dots, n.$$

Usage:

```
retval = SUNMatScaleAdd(c, A, B);
```

int **SUNMatScaleAddI**(*realtype* c, *SUNMatrix* A)

Performs the operation *A* gets *cA + I*. The return value is an integer flag denoting success/failure of the operation:

$$A_{i,j} = cA_{i,j} + \delta_{i,j}, \quad i, j = 1, \dots, n.$$

Usage:

```
retval = SUNMatScaleAddI(c, A);
```

int **SUNMatMatvecSetup**(*SUNMatrix* A)

Performs any setup necessary to perform a matrix-vector product. The return value is an integer flag denoting success/failure of the operation. It is useful for **SUNMatrix** implementations which need to prepare the matrix itself, or communication structures before performing the matrix-vector product.

Usage:

```
retval = SUNMatMatvecSetup(A);
```

int **SUNMatMatvec**(*SUNMatrix A*, *N\_Vecor x*, *N\_Vecor y*)

Performs the matrix-vector product  $y \leftarrow Ax$ . It should only be called with vectors  $x$  and  $y$  that are compatible with the matrix  $A$  – both in storage type and dimensions. The return value is an integer flag denoting success/failure of the operation:

$$y_i = \sum_{j=1}^n A_{i,j}x_j, \quad i = 1, \dots, m.$$

Usage:

```
retval = SUNMatMatvec(A, x, y);
```

### 8.2.1 SUNMatrix return codes

The functions provided to SUNMatrix modules within the SUNDIALS-provided SUNMatrix implementations utilize a common set of return codes, listed below. These adhere to a common pattern: 0 indicates success, a negative value indicates a 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 SUNMatrix failure.

- **SUNMAT\_SUCCESS** (0) – successful call
- **SUNMAT\_ILL\_INPUT** (-1) – an illegal input has been provided to the function
- **SUNMAT\_MEM\_FAIL** (-2) – failed memory access or allocation
- **SUNMAT\_OPERATION\_FAIL** (-3) – a SUNMatrix operation returned nonzero
- **SUNMAT\_MATVEC\_SETUP\_REQUIRED** (-4) – the *SUNMatMatvecSetup()* routine needs to be called prior to calling *SUNMatMatvec()*

## 8.3 The SUNMATRIX\_DENSE Module

The dense implementation of the SUNMatrix module, SUNMATRIX\_DENSE, defines the *content* field of SUNMatrix to be the following structure:

```
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
- $\text{data}$  - pointer to a contiguous block of **realtype** variables. The elements of the dense matrix are stored columnwise, i.e. the  $(i, j)$  element of a dense SUNMatrix object (with  $0 \leq i < M$  and  $0 \leq j < N$ ) may be accessed via  $\text{data}[j*M+i]$ .
- $\text{ldata}$  - length of the data array ( $= M \cdot N$ ).

- `cols` - array of pointers. `cols[j]` points to the first element of the  $j$ -th column of the matrix in the array `data`. The  $(i, j)$  element of a dense `SUNMatrix` (with  $0 \leq i < M$  and  $0 \leq j < N$ ) may be accessed via `cols[j][i]`.

The header file to be included when using this module is `sunmatrix/sunmatrix_dense.h`.

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(A)`

This macro gives access to the contents of the dense `SUNMatrix` `A`.

The assignment `A_cont = SM_CONTENT_D(A)` sets `A_cont` to be a pointer to the dense `SUNMatrix` content structure.

Implementation:

```
#define SM_CONTENT_D(A) ( (SUNMatrixContent_Dense)(A->content) )
```

#### `SM_ROWS_D(A)`

Access the number of rows in the dense `SUNMatrix` `A`.

This may be used either to retrieve or to set the value. 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_ROWS_D(A) = A_rows` sets the number of columns in `A` to equal `A_rows`.

Implementation:

```
#define SM_ROWS_D(A) ( SM_CONTENT_D(A)->M )
```

#### `SM_COLUMNS_D(A)`

Access the number of columns in the dense `SUNMatrix` `A`.

This may be used either to retrieve or to set the value. For example, the assignment `A_columns = SM_COLUMNS_D(A)` sets `A_columns` to be the number of columns in the matrix `A`. Similarly, the assignment `SM_COLUMNS_D(A) = A_columns` sets the number of columns in `A` to equal `A_columns`.

Implementation:

```
#define SM_COLUMNS_D(A) ( SM_CONTENT_D(A)->N )
```

#### `SM_LDATA_D(A)`

Access the total data length in the dense `SUNMatrix` `A`.

This may be used either to retrieve or to set the value. For example, the assignment `A_ldata = SM_LDATA_D(A)` sets `A_ldata` to be the length of the data array in the matrix `A`. Similarly, the assignment `SM_LDATA_D(A) = A_ldata` sets the parameter for the length of the data array in `A` to equal `A_ldata`.

Implementation:

```
#define SM_LDATA_D(A) ( SM_CONTENT_D(A)->lodata )
```

#### `SM_DATA_D(A)`

This macro gives access to the `data` pointer 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`.

Implementation:

```
#define SM_DATA_D(A) (SM_CONTENT_D(A)->data)
```

**SM\_COLS\_D(A)**

This macro gives access to the `cols` pointer for the matrix entries.

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_COLS_D(A) (SM_CONTENT_D(A)->cols)
```

**SM\_COLUMN\_D(A)**

This macros gives access to the individual columns 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  $M \times N$  dense matrix `A` (with  $0 \leq j < N$ ). 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  $M-1$ .

Implementation:

```
#define SM_COLUMN_D(A, j) ((SM_CONTENT_D(A)->cols)[j])
```

**SM\_ELEMENT\_D(A)**

This macro gives access to the individual entries of the data array of a dense `SUNMatrix`.

The assignments `SM_ELEMENT_D(A, i, j) = a_ij` and `a_ij = SM_ELEMENT_D(A, i, j)` reference the  $A_{i,j}$  element of the  $M \times N$  dense matrix `A` (with  $0 \leq i < M$  and  $0 \leq j < N$ ).

Implementation:

```
#define SM_ELEMENT_D(A, i, j) ((SM_CONTENT_D(A)->cols)[j][i])
```

The `SUNMATRIX_DENSE` module defines dense implementations of all matrix operations listed in §8.2. Their names are obtained from those in that section by appending the suffix `_Dense` (e.g. `SUNMatCopy_Dense`). The module `SUNMATRIX_DENSE` provides the following additional user-callable routines:

`SUNMatrix SUNDenseMatrix(sunindextype M, sunindextype N, SUNContext sunctx)`

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.

`void SUNDenseMatrix_Print(SUNMatrix A, FILE *outfile)`

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.

`sunindextype SUNDenseMatrix_Rows(SUNMatrix A)`

This function returns the number of rows in the dense `SUNMatrix`.

`sunindextype SUNDenseMatrix_Columns(SUNMatrix A)`

This function returns the number of columns in the dense `SUNMatrix`.

`sunindextype SUNDenseMatrix_LData(SUNMatrix A)`

This function returns the length of the data array for the dense `SUNMatrix`.

`realtype *SUNDenseMatrix_Data(SUNMatrix A)`

This function returns a pointer to the data array for the dense `SUNMatrix`.

*realtype* \*\***SUNDenseMatrix\_Cols**(*SUNMatrix* A)

This function returns a pointer to the cols array for the dense *SUNMatrix*.

*realtype* \***SUNDenseMatrix\_Column**(*SUNMatrix* A, *sunindextype* j)

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.

#### Notes

- When looping over the components of a dense *SUNMatrix* A, the most efficient approaches are to:
  - First obtain the component array via *A\_data* = **SUNDenseMatrix\_Data**(A), or equivalently *A\_data* = **SM\_DATA\_D**(A), and then access *A\_data[i]* within the loop.
  - First obtain the array of column pointers via *A\_cols* = **SUNDenseMatrix\_Cols**(A), or equivalently *A\_cols* = **SM\_COLS\_D**(A), and then access *A\_cols[j][i]* within the loop.
  - Within a loop over the columns, access the column pointer via *A\_colj* = **SUNDenseMatrix\_Column**(A, j) and then to access the entries within that column using *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 *N\_Vector* 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.

## 8.4 The SUNMATRIX\_MAGMA DENSE Module

The SUNMATRIX\_MAGMA DENSE module interfaces to the **MAGMA** linear algebra library and can target NVIDIA's CUDA programming model or AMD's HIP programming model [59]. All data stored by this matrix implementation resides on the GPU at all times. The implementation currently supports a standard LAPACK column-major storage format as well as a low-storage format for block-diagonal matrices

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_0 & 0 & \cdots & 0 \\ 0 & \mathbf{A}_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{A}_{n-1} \end{bmatrix}$$

This matrix implementation is best paired with the **SUNLinearSolver\_MagmaDense** *SUNLinearSolver*.

The header file to include when using this module is `sunmatrix/sunmatrix_magmadense.h`. The installed library to link to is `libsundials_sunmatrixmagmadense.lib` where `lib` is typically `.so` for shared libraries and `.a` for static libraries.

**Warning:** The SUNMATRIX\_MAGMA DENSE module is experimental and subject to change.

### 8.4.1 SUNMATRIX\_MAGMA DENSE Functions

The SUNMATRIX\_MAGMA DENSE module defines GPU-enabled implementations of all matrix operations listed in §8.2.

- SUNMatGetID\_MagmaDense – returns SUNMATRIX\_MAGMA DENSE
- SUNMatClone\_MagmaDense
- SUNMatDestroy\_MagmaDense
- SUNMatZero\_MagmaDense
- SUNMatCopy\_MagmaDense
- SUNMatScaleAdd\_MagmaDense
- SUNMatScaleAddI\_MagmaDense
- SUNMatMatvecSetup\_MagmaDense
- SUNMatMatvec\_MagmaDense
- SUNMatSpace\_MagmaDense

In addition, the SUNMATRIX\_MAGMA DENSE module defines the following implementation specific functions:

*SUNMatrix* **SUNMatrix\_MagmaDense**(*sunindextype* M, *sunindextype* N, *SUNMemoryType* memtype,  
*SUNMemoryHelper* memhelper, void \*queue, *SUNContext* sunctx)

This constructor function creates and allocates memory for an  $M \times N$  SUNMATRIX\_MAGMA DENSE SUNMatrix.

#### Arguments:

- *M* – the number of matrix rows.
- *N* – the number of matrix columns.
- *memtype* – the type of memory to use for the matrix data; can be SUNMEMTYPE\_UVM or SUNMEMTYPE\_DEVICE.
- *memhelper* – the memory helper used for allocating data.
- *queue* – a *cudaStream\_t* when using CUDA or a *hipStream\_t* when using HIP.
- *sunctx* – the *SUNContext* object (see §4.1)

**Return value:** If successful, a SUNMatrix object otherwise NULL.

*SUNMatrix* **SUNMatrix\_MagmaDenseBlock**(*sunindextype* nblocks, *sunindextype* M\_block, *sunindextype* N\_block,  
*SUNMemoryType* memtype, *SUNMemoryHelper* memhelper, void  
\*queue, *SUNContext* sunctx)

This constructor function creates and allocates memory for a block diagonal SUNMATRIX\_MAGMA DENSE SUNMatrix with *nblocks* of size  $M \times N$ .

#### Arguments:

- *nblocks* – the number of matrix rows.
- *M\_block* – the number of matrix rows in each block.
- *N\_block* – the number of matrix columns in each block.
- *memtype* – the type of memory to use for the matrix data; can be SUNMEMTYPE\_UVM or SUNMEMTYPE\_DEVICE.
- *memhelper* – the memory helper used for allocating data.

- *queue* – a `cudaStream_t` when using CUDA or a `hipStream_t` when using HIP.
- *sunctx* – the `SUNContext` object (see §4.1)

**Return value:** If successful, a `SUNMatrix` object otherwise `NULL`.

*sunindextype* `SUNMatrix_MagmaDense_Rows`(*SUNMatrix A*)

This function returns the number of rows in the `SUNMatrix` object. For block diagonal matrices, the number of rows is computed as  $M_{\text{block}} \times \text{nblocks}$ .

**Arguments:**

- *A* – a `SUNMatrix` object.

**Return value:** If successful, the number of rows in the `SUNMatrix` object otherwise `SUNMATRIX_ILL_INPUT`.

*sunindextype* `SUNMatrix_MagmaDense_Columns`(*SUNMatrix A*)

This function returns the number of columns in the `SUNMatrix` object. For block diagonal matrices, the number of columns is computed as  $N_{\text{block}} \times \text{nblocks}$ .

**Arguments:**

- *A* – a `SUNMatrix` object.

**Return value:** If successful, the number of columns in the `SUNMatrix` object otherwise `SUNMATRIX_ILL_INPUT`.

*sunindextype* `SUNMatrix_MagmaDense_BlockRows`(*SUNMatrix A*)

This function returns the number of rows in a block of the `SUNMatrix` object.

**Arguments:**

- *A* – a `SUNMatrix` object.

**Return value:** If successful, the number of rows in a block of the `SUNMatrix` object otherwise `SUNMATRIX_ILL_INPUT`.

*sunindextype* `SUNMatrix_MagmaDense_BlockColumns`(*SUNMatrix A*)

This function returns the number of columns in a block of the `SUNMatrix` object.

**Arguments:**

- *A* – a `SUNMatrix` object.

**Return value:** If successful, the number of columns in a block of the `SUNMatrix` object otherwise `SUNMATRIX_ILL_INPUT`.

*sunindextype* `SUNMatrix_MagmaDense_LData`(*SUNMatrix A*)

This function returns the length of the `SUNMatrix` data array.

**Arguments:**

- *A* – a `SUNMatrix` object.

**Return value:** If successful, the length of the `SUNMatrix` data array otherwise `SUNMATRIX_ILL_INPUT`.

*sunindextype* `SUNMatrix_MagmaDense_NumBlocks`(*SUNMatrix A*)

This function returns the number of blocks in the `SUNMatrix` object.

**Arguments:**

- *A* – a `SUNMatrix` object.

**Return value:** If successful, the number of blocks in the `SUNMatrix` object otherwise `SUNMATRIX_ILL_INPUT`.

*realtype* \*`SUNMatrix_MagmaDense_Data`(*SUNMatrix A*)

This function returns the `SUNMatrix` data array.

**Arguments:**

- $A$  – a SUNMatrix object.

**Return value:** If successful, the SUNMatrix data array otherwise NULL.

*realtype* **\*\*SUNMatrix\_MagmaDense\_BlockData**(*SUNMatrix* A)

This function returns an array of pointers that point to the start of the data array for each block in the SUNMatrix.

**Arguments:**

- $A$  – a SUNMatrix object.

**Return value:** If successful, an array of data pointers to each of the SUNMatrix blocks otherwise NULL.

*realtype* **\*SUNMatrix\_MagmaDense\_Block**(*SUNMatrix* A, *sunindextype* k)

This function returns a pointer to the data array for block  $k$  in the SUNMatrix.

**Arguments:**

- $A$  – a SUNMatrix object.
- $k$  – the block index.

**Return value:** If successful, a pointer to the data array for the SUNMatrix block otherwise NULL.

**Note:** No bounds-checking is performed by this function,  $j$  should be strictly less than  $nblocks$ .

*realtype* **\*SUNMatrix\_MagmaDense\_Column**(*SUNMatrix* A, *sunindextype* j)

This function returns a pointer to the data array for column  $j$  in the SUNMatrix.

**Arguments:**

- $A$  – a SUNMatrix object.
- $j$  – the column index.

**Return value:** If successful, a pointer to the data array for the SUNMatrix column otherwise NULL.

**Note:** No bounds-checking is performed by this function,  $j$  should be strictly less than  $nblocks * N_{block}$ .

*realtype* **\*SUNMatrix\_MagmaDense\_BlockColumn**(*SUNMatrix* A, *sunindextype* k, *sunindextype* j)

This function returns a pointer to the data array for column  $j$  of block  $k$  in the SUNMatrix.

**Arguments:**

- $A$  – a SUNMatrix object.
- $k$  – the block index.
- $j$  – the column index.

**Return value:** If successful, a pointer to the data array for the SUNMatrix column otherwise NULL.

**Note:** No bounds-checking is performed by this function,  $k$  should be strictly less than  $nblocks$  and  $j$  should be strictly less than  $N_{block}$ .

int **SUNMatrix\_MagmaDense\_CopyToDevice**(*SUNMatrix* A, *realtype* \*h\_data)

This function copies the matrix data to the GPU device from the provided host array.

**Arguments:**

- $A$  – a `SUNMatrix` object
- $h\_data$  – a host array pointer to copy data from.

**Return value:**

- `SUNMAT_SUCCESS` – if the copy is successful.
- `SUNMAT_ILL_INPUT` – if either the `SUNMatrix` is not a `SUNMATRIX_MAGMADENSE` matrix.
- `SUNMAT_MEM_FAIL` – if the copy fails.

```
int SUNMatrix_MagmaDense_CopyFromDevice(SUNMatrix A, realtype *h_data)
```

This function copies the matrix data from the GPU device to the provided host array.

**Arguments:**

- $A$  – a `SUNMatrix` object
- $h\_data$  – a host array pointer to copy data to.

**Return value:**

- `SUNMAT_SUCCESS` – if the copy is successful.
- `SUNMAT_ILL_INPUT` – if either the `SUNMatrix` is not a `SUNMATRIX_MAGMADENSE` matrix.
- `SUNMAT_MEM_FAIL` – if the copy fails.

## 8.4.2 SUNMATRIX\_MAGMADENSE Usage Notes

**Warning:** When using the `SUNMATRIX_MAGMADENSE` module with a SUNDIALS package (e.g. CVODE), the stream given to matrix should be the same stream used for the NVECTOR object that is provided to the package, and the NVECTOR object given to the SUNMatvec operation. If different streams are utilized, synchronization issues may occur.

## 8.5 The SUNMATRIX\_ONEMKLdense Module

The `SUNMATRIX_ONEMKLdense` module is intended for interfacing with direct linear solvers from the [Intel oneAPI Math Kernel Library \(oneMKL\)](#) using the SYCL (DPC++) programming model. The implementation currently supports a standard LAPACK column-major storage format as well as a low-storage format for block-diagonal matrices,

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_0 & 0 & \cdots & 0 \\ 0 & \mathbf{A}_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{A}_{n-1} \end{bmatrix}$$

This matrix implementation is best paired with the `SUNLinearSolver_OneMklDense` linear solver.

The header file to include when using this class is `sunmatrix/sunmatrix_onemkldense.h`. The installed library to link to is `libsundials_sunmatrixonemkldense.lib` where `lib` is typically `.so` for shared libraries and `.a` for static libraries.

**Warning:** The `SUNMATRIX_ONEMKLdense` class is experimental and subject to change.

## 8.5.1 SUNMATRIX\_ONEMKLDENSE Functions

The SUNMATRIX\_ONEMKLDENSE class defines implementations of the following matrix operations listed in §8.2.

- `SUNMatGetID_OneMklDense` – returns `SUNMATRIX_ONEMKLDENSE`
- `SUNMatClone_OneMklDense`
- `SUNMatDestroy_OneMklDense`
- `SUNMatZero_OneMklDense`
- `SUNMatCopy_OneMklDense`
- `SUNMatScaleAdd_OneMklDense`
- `SUNMatScaleAddI_OneMklDense`
- `SUNMatMatvec_OneMklDense`
- `SUNMatSpace_OneMklDense`

In addition, the `SUNMATRIX_ONEMKLDENSE` class defines the following implementation specific functions.

### 8.5.1.1 Constructors

`SUNMatrix SUNMatrix_OneMklDense(sunindextype M, sunindextype N, SUNMemoryType memtype, SUNMemoryHelper memhelper, sycl::queue *queue, SUNContext sunctx)`

This constructor function creates and allocates memory for an  $M \times N$  `SUNMATRIX_ONEMKLDENSE` `SUNMatrix`.

#### Arguments:

- $M$  – the number of matrix rows.
- $N$  – the number of matrix columns.
- $memtype$  – the type of memory to use for the matrix data; can be `SUNMEMTYPE_UVM` or `SUNMEMTYPE_DEVICE`.
- $memhelper$  – the memory helper used for allocating data.
- $queue$  – the SYCL queue to which operations will be submitted.
- $sunctx$  – the `SUNContext` object (see §4.1)

**Return value:** If successful, a `SUNMatrix` object otherwise `NULL`.

`SUNMatrix SUNMatrix_OneMklDenseBlock(sunindextype nblocks, sunindextype M_block, sunindextype N_block, SUNMemoryType memtype, SUNMemoryHelper memhelper, sycl::queue *queue, SUNContext sunctx)`

This constructor function creates and allocates memory for a block diagonal `SUNMATRIX_ONEMKLDENSE` `SUNMatrix` with  $nblocks$  of size  $M_{block} \times N_{block}$ .

#### Arguments:

- $nblocks$  – the number of matrix rows.
- $M_{block}$  – the number of matrix rows in each block.
- $N_{block}$  – the number of matrix columns in each block.
- $memtype$  – the type of memory to use for the matrix data; can be `SUNMEMTYPE_UVM` or `SUNMEMTYPE_DEVICE`.
- $memhelper$  – the memory helper used for allocating data.

- *queue* – the SYCL queue to which operations will be submitted.
- *sunctx* – the *SUNContext* object (see §4.1)

**Return value:** If successful, a *SUNMatrix* object otherwise NULL.

### 8.5.1.2 Access Matrix Dimensions

*sunindextype SUNMatrix\_OneMklDense\_Rows(SUNMatrix A)*

This function returns the number of rows in the *SUNMatrix* object. For block diagonal matrices, the number of rows is computed as  $M_{\text{block}} \times \text{nblocks}$ .

**Arguments:**

- *A* – a *SUNMatrix* object.

**Return value:** If successful, the number of rows in the *SUNMatrix* object otherwise *SUNMATRIX\_ILL\_INPUT*.

*sunindextype SUNMatrix\_OneMklDense\_Columns(SUNMatrix A)*

This function returns the number of columns in the *SUNMatrix* object. For block diagonal matrices, the number of columns is computed as  $N_{\text{block}} \times \text{nblocks}$ .

**Arguments:**

- *A* – a *SUNMatrix* object.

**Return value:** If successful, the number of columns in the *SUNMatrix* object otherwise *SUNMATRIX\_ILL\_INPUT*.

### 8.5.1.3 Access Matrix Block Dimensions

*sunindextype SUNMatrix\_OneMklDense\_NumBlocks(SUNMatrix A)*

This function returns the number of blocks in the *SUNMatrix* object.

**Arguments:**

- *A* – a *SUNMatrix* object.

**Return value:** If successful, the number of blocks in the *SUNMatrix* object otherwise *SUNMATRIX\_ILL\_INPUT*.

*sunindextype SUNMatrix\_OneMklDense\_BlockRows(SUNMatrix A)*

This function returns the number of rows in a block of the *SUNMatrix* object.

**Arguments:**

- *A* – a *SUNMatrix* object.

**Return value:** If successful, the number of rows in a block of the *SUNMatrix* object otherwise *SUNMATRIX\_ILL\_INPUT*.

*sunindextype SUNMatrix\_OneMklDense\_BlockColumns(SUNMatrix A)*

This function returns the number of columns in a block of the *SUNMatrix* object.

**Arguments:**

- *A* – a *SUNMatrix* object.

**Return value:** If successful, the number of columns in a block of the *SUNMatrix* object otherwise *SUNMATRIX\_ILL\_INPUT*.

#### 8.5.1.4 Access Matrix Data

*sunindextype SUNMatrix\_OneMklDense\_LData(SUNMatrix A)*

This function returns the length of the SUNMatrix data array.

**Arguments:**

- *A* – a SUNMatrix object.

**Return value:** If successful, the length of the SUNMatrix data array otherwise SUNMATRIX\_ILL\_INPUT.

*realtype \*SUNMatrix\_OneMklDense\_Data(SUNMatrix A)*

This function returns the SUNMatrix data array.

**Arguments:**

- *A* – a SUNMatrix object.

**Return value:** If successful, the SUNMatrix data array otherwise NULL.

*realtype \*SUNMatrix\_OneMklDense\_Column(SUNMatrix A, sunindextype j)*

This function returns a pointer to the data array for column *j* in the SUNMatrix.

**Arguments:**

- *A* – a SUNMatrix object.
- *j* – the column index.

**Return value:** If successful, a pointer to the data array for the SUNMatrix column otherwise NULL.

**Note:** No bounds-checking is performed by this function, *j* should be strictly less than *nblocks \* Nblock*.

#### 8.5.1.5 Access Matrix Block Data

*sunindextype SUNMatrix\_OneMklDense\_BlockLData(SUNMatrix A)*

This function returns the length of the SUNMatrix data array for each block of the SUNMatrix object.

**Arguments:**

- *A* – a SUNMatrix object.

**Return value:** If successful, the length of the SUNMatrix data array for each block otherwise SUNMATRIX\_ILL\_INPUT.

*realtype \*\*SUNMatrix\_OneMklDense\_BlockData(SUNMatrix A)*

This function returns an array of pointers that point to the start of the data array for each block in the SUNMatrix.

**Arguments:**

- *A* – a SUNMatrix object.

**Return value:** If successful, an array of data pointers to each of the SUNMatrix blocks otherwise NULL.

*realtype \*SUNMatrix\_OneMklDense\_Block(SUNMatrix A, sunindextype k)*

This function returns a pointer to the data array for block *k* in the SUNMatrix.

**Arguments:**

- *A* – a SUNMatrix object.
- *k* – the block index.

**Return value:** If successful, a pointer to the data array for the SUNMatrix block otherwise NULL.

---

**Note:** No bounds-checking is performed by this function,  $j$  should be strictly less than  $nblocks$ .

---

`realtype *SUNMatrix_OneMklDense_BlockColumn(SUNMatrix A, sunindextype k, sunindextype j)`

This function returns a pointer to the data array for column  $j$  of block  $k$  in the SUNMatrix.

**Arguments:**

- $A$  – a SUNMatrix object.
- $k$  – the block index.
- $j$  – the column index.

**Return value:** If successful, a pointer to the data array for the SUNMatrix column otherwise NULL.

---

**Note:** No bounds-checking is performed by this function,  $k$  should be strictly less than  $nblocks$  and  $j$  should be strictly less than  $N_{block}$ .

---

### 8.5.1.6 Copy Data

`int SUNMatrix_OneMklDense_CopyToDevice(SUNMatrix A, realtype *h_data)`

This function copies the matrix data to the GPU device from the provided host array.

**Arguments:**

- $A$  – a SUNMatrix object
- $h\_data$  – a host array pointer to copy data from.

**Return value:**

- SUNMAT\_SUCCESS – if the copy is successful.
- SUNMAT\_ILL\_INPUT – if either the SUNMatrix is not a SUNMATRIX\_ONEMKLDENSE matrix.
- SUNMAT\_MEM\_FAIL – if the copy fails.

`int SUNMatrix_OneMklDense_CopyFromDevice(SUNMatrix A, realtype *h_data)`

This function copies the matrix data from the GPU device to the provided host array.

**Arguments:**

- $A$  – a SUNMatrix object
- $h\_data$  – a host array pointer to copy data to.

**Return value:**

- SUNMAT\_SUCCESS – if the copy is successful.
- SUNMAT\_ILL\_INPUT – if either the SUNMatrix is not a SUNMATRIX\_ONEMKLDENSE matrix.
- SUNMAT\_MEM\_FAIL – if the copy fails.

## 8.5.2 SUNMATRIX\_ONEMKLDENSE Usage Notes

**Warning:** The SUNMATRIX\_ONEMKLDENSE class only supports 64-bit indexing, thus SUNDIALS must be built for 64-bit indexing to use this class.

When using the SUNMATRIX\_ONEMKLDENSE class with a SUNDIALS package (e.g. CVODE), the queue given to matrix should be the same stream used for the NVECTOR object that is provided to the package, and the NVECTOR object given to the `SUNMatMatvec()` operation. If different streams are utilized, synchronization issues may occur.

## 8.6 The SUNMATRIX\_BAND Module

The banded implementation of the SUNMatrix module, SUNMATRIX\_BAND, defines the *content* field of SUNMatrix to be the following structure:

```
struct _SUNMatrixContent_Band {
    sunindextype M;
    sunindextype N;
    sunindextype mu;
    sunindextype ml;
    sunindextype smu;
    sunindextype ldim;
    realtype *data;
    sunindextype ldata;
    realtype **cols;
};
```

A diagram of the underlying data representation in a banded matrix is shown in Fig. 8.1. A more complete description of the parts of this *content* field is given below:

- $M$  - number of rows
- $N$  - number of columns ( $N = M$ )
- $\mu$  - upper half-bandwidth,  $0 \leq \mu < N$
- $\mu_l$  - lower half-bandwidth,  $0 \leq \mu_l < N$
- $smu$  - storage upper bandwidth,  $\mu \leq smu < N$ . The LU decomposition routines in the associated `SUNLINSOL_BAND` and `SUNLINSOL_LAPACKBAND` modules write the LU factors into the existing storage for the band matrix. The upper triangular factor  $U$ , however, may have an upper bandwidth as big as  $\min(N-1, \mu+\mu_l)$  because of partial pivoting. The `smu` field holds the upper half-bandwidth allocated for the band matrix.
- $ldim$  - leading dimension ( $ldim \geq smu + ml + 1$ )
- `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 banded matrix.
- $ldata$  - length of the data array ( $= ldim N$ )
- `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 `smu-mu` (to access the uppermost element within the band in the  $j$ -th column) to `smu+ml` (to access the lowest element within the band in the  $j$ -th column). Indices from 0 to `smu-`

$\text{mu}-1$  give access to extra storage elements required by the LU decomposition function. Finally,  $\text{cols}[j][i-\text{j}+\text{smu}]$  is the  $(i, j)$ -th element with  $j - \text{mu} \leq i \leq j + \text{ml}$ .

The header file to be included when using this module is `sunmatrix/sunmatrix_band.h`.

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(A)`

This macro gives access to the contents of the banded `SUNMatrix A`.

The assignment `A_cont = SM_CONTENT_B(A)` sets `A_cont` to be a pointer to the banded `SUNMatrix` content structure.

Implementation:

```
#define SM_CONTENT_B(A) ( (SUNMatrixContent_Band)(A->content) )
```

### `SM_ROWS_B(A)`

Access the number of rows in the banded `SUNMatrix A`.

This may be used either to retrieve or to set the value. For example, the assignment `A_rows = SM_ROWS_B(A)` sets `A_rows` to be the number of rows in the matrix `A`. Similarly, the assignment `SM_ROWS_B(A) = A_rows` sets the number of columns in `A` to equal `A_rows`.

Implementation:

```
#define SM_ROWS_B(A) ( SM_CONTENT_B(A)->M )
```

### `SM_COLUMNS_B(A)`

Access the number of columns in the banded `SUNMatrix A`. As with `SM_ROWS_B`, this may be used either to retrieve or to set the value.

Implementation:

```
#define SM_COLUMNS_B(A) ( SM_CONTENT_B(A)->N )
```

### `SM_UBAND_B(A)`

Access the `mu` parameter in the banded `SUNMatrix A`. As with `SM_ROWS_B`, this may be used either to retrieve or to set the value.

Implementation:

```
#define SM_UBAND_B(A) ( SM_CONTENT_B(A)->mu )
```

### `SM_LBAND_B(A)`

Access the `ml` parameter in the banded `SUNMatrix A`. As with `SM_ROWS_B`, this may be used either to retrieve or to set the value.

Implementation:

```
#define SM_LBAND_B(A) ( SM_CONTENT_B(A)->ml )
```

### `SM_SUBAND_B(A)`

Access the `smu` parameter in the banded `SUNMatrix A`. As with `SM_ROWS_B`, this may be used either to retrieve or to set the value.

Implementation:

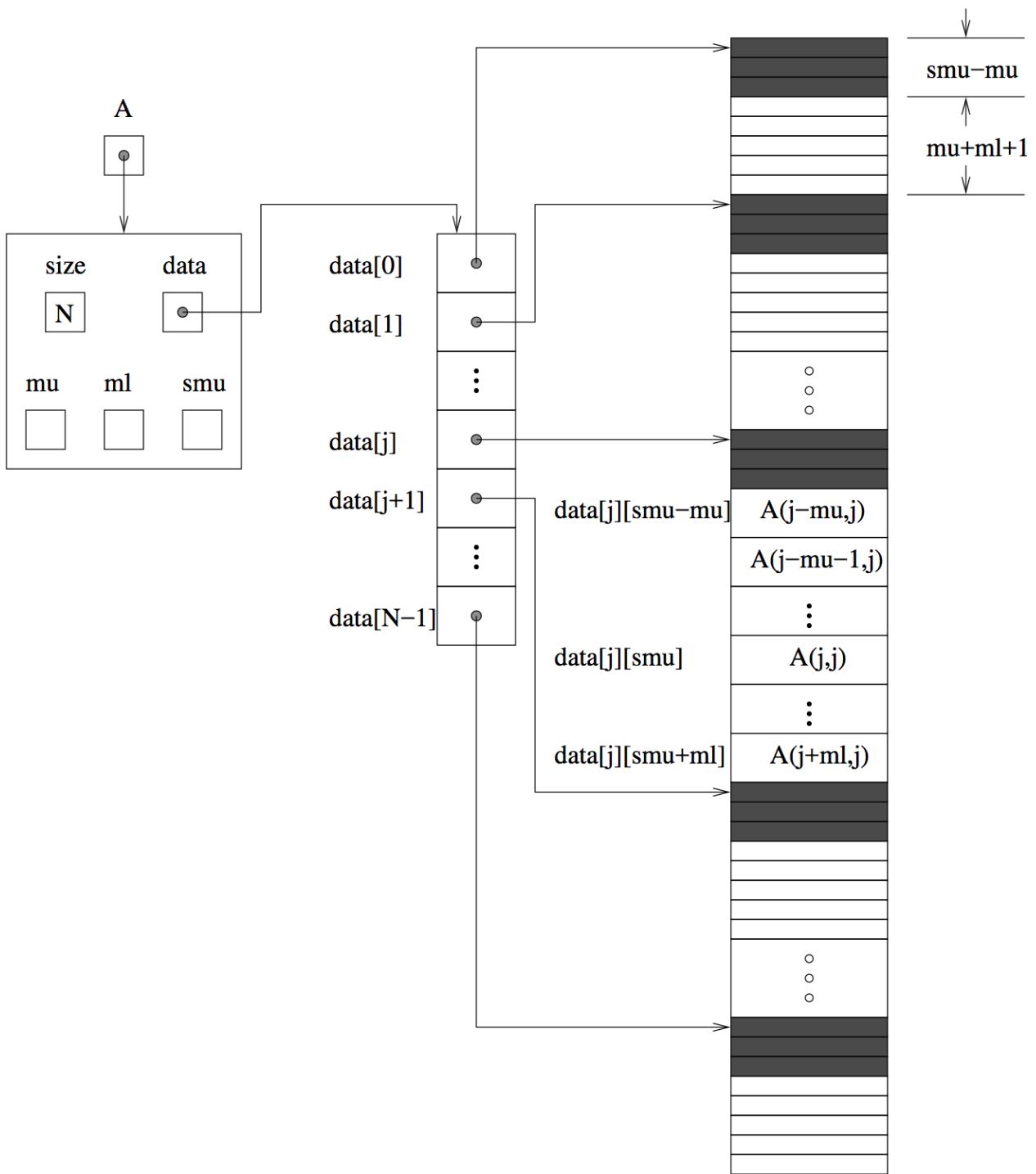


Fig. 8.1: Diagram of the storage for the SUNMATRIX\_BAND module. Here  $A$  is an  $N \times N$  band matrix with upper and lower half-bandwidths  $\text{mu}$  and  $\text{ml}$ , respectively. The rows and columns of  $A$  are numbered from 0 to  $N-1$  and the  $(i,j)$ -th element of  $A$  is denoted  $A(i,j)$ . The greyed out areas of the underlying component storage are used by the associated SUNLINSOL\_BAND or SUNLINSOL\_LAPACKBAND linear solver.

```
#define SM_SUBAND_B(A) (SM_CONTENT_B(A)->smu)
```

**SM\_LDIM\_B(A)**

Access the `ldim` parameter in the banded `SUNMatrix A`. As with `SM_ROWS_B`, this may be used either to retrieve or to set the value.

Implementation:

```
#define SM_LDIM_B(A) (SM_CONTENT_B(A)->ldim)
```

**SM\_LDATA\_B(A)**

Access the `ldata` parameter in the banded `SUNMatrix A`. As with `SM_ROWS_B`, this may be used either to retrieve or to set the value.

Implementation:

```
#define SM_LDATA_B(A) (SM_CONTENT_B(A)->ldata)
```

**SM\_DATA\_B(A)**

This macro gives access to the `data` pointer for the matrix entries.

The assignment `A_data = SM_DATA_B(A)` sets `A_data` to be a pointer to the first component of the data array for the banded `SUNMatrix A`. The assignment `SM_DATA_B(A) = A_data` sets the data array of `A` to be `A_data` by storing the pointer `A_data`.

Implementation:

```
#define SM_DATA_B(A) (SM_CONTENT_B(A)->data)
```

**SM\_COLS\_B(A)**

This macro gives access to the `cols` pointer for the matrix entries.

The assignment `A_cols = SM_COLS_B(A)` sets `A_cols` to be a pointer to the array of column pointers for the banded `SUNMatrix A`. The assignment `SM_COLS_B(A) = A_cols` sets the column pointer array of `A` to be `A_cols` by storing the pointer `A_cols`.

Implementation:

```
#define SM_COLS_B(A) (SM_CONTENT_B(A)->cols)
```

**SM\_COLUMN\_B(A)**

This macros gives access to the individual columns of the data array of a banded `SUNMatrix`.

The assignment `col_j = SM_COLUMN_B(A, j)` sets `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 `SM_COLUMN_B(A, j)` is `realtype *`. The pointer returned by the call `SM_COLUMN_B(A, j)` can be treated as an array which is indexed from `-mu` to `ml`.

Implementation:

```
#define SM_COLUMN_B(A, j) ((SM_CONTENT_B(A)->cols)[j])+SM_SUBAND_B(A)
```

**SM\_ELEMENT\_B(A)**

This macro gives access to the individual entries of the data array of a banded `SUNMatrix`.

The assignments `SM_ELEMENT_B(A, i, j) = a_ij` and `a_ij = 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  $j - mu \leq i \leq j + ml$ .

Implementation:

```
#define SM_ELEMENT_B(A,i,j) ((SM_CONTENT_B(A)->cols)[j][(i)-(j)+SM_SUBAND_B(A)])
```

**SM\_COLUMN\_ELEMENT\_B(A)**

This macro gives access to the individual entries of the data array of a banded SUNMatrix.

The assignments  $\text{SM\_COLUMN\_ELEMENT\_B}(\text{col\_j}, i, j) = \text{a}_{ij}$  and  $\text{a}_{ij} = \text{SM\_COLUMN\_ELEMENT\_B}(\text{col\_j}, i, j)$  reference the  $(i, j)$ -th entry of the band matrix A when used in conjunction with **SM\_COLUMN\_B** to reference the j-th column through **col\_j**. The index  $(i, j)$  should satisfy  $j - \mu \leq i \leq j + m_l$ .

Implementation:

```
#define SM_COLUMN_ELEMENT_B(col_j,i,j) (col_j[(i)-(j)])
```

The SUNMATRIX\_BAND module defines banded implementations of all matrix operations listed in §8.2. Their names are obtained from those in that section by appending the suffix \_Band (e.g. **SUNMatCopy\_Band**). The module **SUNMATRIX\_BAND** provides the following additional user-callable routines:

**SUNMatrix SUNBandMatrix**(*sunindextype* N, *sunindextype* mu, *sunindextype* ml, *SUNContext* sunctx)

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.

**SUNMatrix SUNBandMatrixStorage**(*sunindextype* N, *sunindextype* mu, *sunindextype* ml, *sunindextype* smu, *SUNContext* sunctx)

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  $\min(N-1, \mu+m_l)$  if the matrix will be used by the SUNLinSol\_Band module;
- exactly equal to  $\mu+m_l$  if the matrix will be used by the SUNLinSol\_LapackBand 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.

void **SUNBandMatrix\_Print**(*SUNMatrix* A, FILE \*outfile)

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.

*sunindextype* **SUNBandMatrix\_Rows**(*SUNMatrix* A)

This function returns the number of rows in the banded SUNMatrix.

*sunindextype* **SUNBandMatrix\_Columns**(*SUNMatrix* A)

This function returns the number of columns in the banded SUNMatrix.

*sunindextype* **SUNBandMatrix\_LowerBandwidth**(*SUNMatrix* A)

This function returns the lower half-bandwidth for the banded SUNMatrix.

*sunindextype* **SUNBandMatrix\_UpperBandwidth**(*SUNMatrix* A)

This function returns the upper half-bandwidth of the banded SUNMatrix.

*sunindextype* **SUNBandMatrix\_StoredUpperBandwidth**(*SUNMatrix* A)

This function returns the stored upper half-bandwidth of the banded SUNMatrix.

*sunindextype* **SUNBandMatrix\_LDim**(*SUNMatrix* A)

This function returns the length of the leading dimension of the banded *SUNMatrix*.

*realtype* \***SUNBandMatrix\_Data**(*SUNMatrix* A)

This function returns a pointer to the data array for the banded *SUNMatrix*.

*realtype* \*\***SUNBandMatrix\_Cols**(*SUNMatrix* A)

This function returns a pointer to the *cols* array for the band *SUNMatrix*.

*realtype* \***SUNBandMatrix\_Column**(*SUNMatrix* A, *sunindextype* j)

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 -*mu* to *m1*.

## Notes

- When looping over the components of a banded *SUNMatrix* A, the most efficient approaches are to:
  - First obtain the component array via *A\_data* = **SUNBandMatrix\_Data**(A), or equivalently *A\_data* = **SM\_DATA\_B**(A), and then access *A\_data*[*i*] within the loop.
  - First obtain the array of column pointers via *A\_cols* = **SUNBandMatrix\_Cols**(A), or equivalently *A\_cols* = **SM\_COLS\_B**(A), and then access *A\_cols*[*j*][*i*] within the loop.
  - Within a loop over the columns, access the column pointer via *A\_colj* = **SUNBandMatrix\_Column**(A, *j*) and then to access the entries within that column using **SM\_COLUMN\_ELEMENT\_B**(*A\_colj*, *i*, *j*).

All three of these are more efficient than using **SM\_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 *N\_Vector* 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.

## 8.7 The SUNMATRIX\_CUSPARSE Module

The SUNMATRIX\_CUSPARSE module is an interface to the NVIDIA cuSPARSE matrix for use on NVIDIA GPUs [69]. All data stored by this matrix implementation resides on the GPU at all times.

The header file to be included when using this module is *sunmatrix/sunmatrix\_cusparse.h*. The installed library to link to is *libsundials\_sunmatrixcusparse.lib* where .lib is typically .so for shared libraries and .a for static libraries.

### 8.7.1 SUNMATRIX\_CUSPARSE Description

The implementation currently supports the cuSPARSE CSR matrix format described in the cuSPARSE documentation, as well as a unique low-storage format for block-diagonal matrices of the form

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_0 & 0 & \cdots & 0 \\ 0 & \mathbf{A}_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{A}_{n-1} \end{bmatrix},$$

where all the block matrices  $\mathbf{A}_j$  share the same sparsity pattern. We will refer to this format as BCSR (not to be confused with the canonical BSR format where each block is stored as dense). In this format, the CSR column indices and row pointers are only stored for the first block and are computed only as necessary for other blocks. This can drastically reduce the amount of storage required compared to the regular CSR format when the number of blocks is

large. This format is well-suited for, and intended to be used with, the `SUNLinearSolver_cuSolverSp_batchQR` linear solver (see §9.17).

**The `SUNMATRIX_CUSPARSE` module is experimental and subject to change.**

## 8.7.2 SUNMATRIX\_CUSPARSE Functions

The `SUNMATRIX_CUSPARSE` module defines GPU-enabled sparse implementations of all matrix operations listed in §8.2 except for the `SUNMatSpace()` and `SUNMatMatvecSetup()` operations:

- `SUNMatGetID_cuSparse` – returns `SUNMATRIX_CUSPARSE`
- `SUNMatClone_cuSparse`
- `SUNMatDestroy_cuSparse`
- `SUNMatZero_cuSparse`
- `SUNMatCopy_cuSparse`
- `SUNMatScaleAdd_cuSparse` – performs  $A = cA + B$ , where  $A$  and  $B$  must have the same sparsity pattern
- `SUNMatScaleAddI_cuSparse` – performs  $A = cA + I$ , where the diagonal of  $A$  must be present
- `SUNMatMatvec_cuSparse`

In addition, the `SUNMATRIX_CUSPARSE` module defines the following implementation specific functions:

`SUNMatrix SUNMatrix_cuSparse_NewCSR(int M, int N, int NNZ, cusparseHandle_t cusp, SUNContext sunctx)`

This constructor function creates and allocates memory for a `SUNMATRIX_CUSPARSE` `SUNMatrix` that uses the CSR storage format. Its arguments are the number of rows and columns of the matrix, `M` and `N`, the number of nonzeros to be stored in the matrix, `NNZ`, and a valid `cusparseHandle_t`.

`SUNMatrix SUNMatrix_cuSparse_NewBlockCSR(int nbblocks, int blockrows, int blockcols, int blocknnz, cusparseHandle_t cusp, SUNContext sunctx)`

This constructor function creates and allocates memory for a `SUNMATRIX_CUSPARSE` `SUNMatrix` object that leverages the `SUNMAT_CUSPARSE_BCSR` storage format to store a block diagonal matrix where each block shares the same sparsity pattern. The blocks must be square. The function arguments are the number of blocks, `nbblocks`, the number of rows, `blockrows`, the number of columns, `blockcols`, the number of nonzeros in each each block, `blocknnz`, and a valid `cusparseHandle_t`.

**Warning:** The `SUNMAT_CUSPARSE_BCSR` format currently only supports square matrices, i.e., `blockrows == blockcols`.

`SUNMatrix SUNMatrix_cuSparse_MakeCSR(cusparseMatDescr_t mat_descr, int M, int N, int NNZ, int *rowptrs, int *colind, realtype *data, cusparseHandle_t cusp, SUNContext sunctx)`

This constructor function creates a `SUNMATRIX_CUSPARSE` `SUNMatrix` object from user provided pointers. Its arguments are a `cusparseMatDescr_t` that must have index base `CUSPARSE_INDEX_BASE_ZERO`, the number of rows and columns of the matrix, `M` and `N`, the number of nonzeros to be stored in the matrix, `NNZ`, and a valid `cusparseHandle_t`.

`int SUNMatrix_cuSparse_Rows(SUNMatrix A)`

This function returns the number of rows in the sparse `SUNMatrix`.

`int SUNMatrix_cuSparse_Columns(SUNMatrix A)`

This function returns the number of columns in the sparse `SUNMatrix`.

`int SUNMatrix_cuSparse_NNZ(SUNMatrix A)`

This function returns the number of entries allocated for nonzero storage for the sparse SUNMatrix.

`int SUNMatrix_cuSparse_SparseType(SUNMatrix A)`

This function returns the storage type (SUNMAT\_CUSPARSE\_CSR or SUNMAT\_CUSPARSE\_BCSR) for the sparse SUNMatrix.

`realtype *SUNMatrix_cuSparse_Data(SUNMatrix A)`

This function returns a pointer to the data array for the sparse SUNMatrix.

`int *SUNMatrix_cuSparse_IndexValues(SUNMatrix A)`

This function returns a pointer to the index value array for the sparse SUNMatrix – for the CSR format this is an array of column indices for each nonzero entry. For the BCSR format this is an array of the column indices for each nonzero entry in the first block only.

`int *SUNMatrix_cuSparse_IndexPointers(SUNMatrix A)`

This function returns a pointer to the index pointer array for the sparse SUNMatrix – for the CSR format this is an array of the locations of the first entry of each row in the data and `indexvalues` arrays, for the BCSR format this is an array of the locations of each row in the `data` and `indexvalues` arrays in the first block only.

`int SUNMatrix_cuSparse_NumBlocks(SUNMatrix A)`

This function returns the number of matrix blocks.

`int SUNMatrix_cuSparse_BlockRows(SUNMatrix A)`

This function returns the number of rows in a matrix block.

`int SUNMatrix_cuSparse_BlockColumns(SUNMatrix A)`

This function returns the number of columns in a matrix block.

`int SUNMatrix_cuSparse_BlockNNZ(SUNMatrix A)`

This function returns the number of nonzeros in each matrix block.

`realtype *SUNMatrix_cuSparse_BlockData(SUNMatrix A, int blockidx)`

This function returns a pointer to the location in the `data` array where the data for the block, `blockidx`, begins. Thus, `blockidx` must be less than `SUNMatrix_cuSparse_NumBlocks(A)`. The first block in the SUNMatrix is index 0, the second block is index 1, and so on.

`cusparseMatDescr_t SUNMatrix_cuSparse_MatDescr(SUNMatrix A)`

This function returns the `cusparseMatDescr_t` object associated with the matrix.

`int SUNMatrix_cuSparse_CopyToDevice(SUNMatrix A, realtype *h_data, int *h_idxptrs, int *h_idxvals)`

This functions copies the matrix information to the GPU device from the provided host arrays. A user may provide NULL for any of `h_data`, `h_idxptrs`, or `h_idxvals` to avoid copying that information.

The function returns `SUNMAT_SUCCESS` if the copy operation(s) were successful, or a nonzero error code otherwise.

`int SUNMatrix_cuSparse_CopyFromDevice(SUNMatrix A, realtype *h_data, int *h_idxptrs, int *h_idxvals)`

This functions copies the matrix information from the GPU device to the provided host arrays. A user may provide NULL for any of `h_data`, `h_idxptrs`, or `h_idxvals` to avoid copying that information. Otherwise:

- The `h_data` array must be at least `SUNMatrix_cuSparse_NNZ(A)*sizeof(realtype)` bytes.
- The `h_idxptrs` array must be at least `(SUNMatrix_cuSparse_BlockDim(A)+1)*sizeof(int)` bytes.
- The `h_idxvals` array must be at least `(SUNMatrix_cuSparse_BlockNNZ(A))*sizeof(int)` bytes.

The function returns `SUNMAT_SUCCESS` if the copy operation(s) were successful, or a nonzero error code otherwise.

`int SUNMatrix_cuSparse_SetFixedPattern(SUNMatrix A, booleantype yesno)`

This function changes the behavior of the the `SUNMatZero` operation on the object `A`. By default the matrix sparsity pattern is not considered to be fixed, thus, the `SUNMatZero` operation zeros out all data array as well

as the `indexvalues` and `indexpointers` arrays. Providing a value of 1 or `SUNTRUE` for the `yesno` argument changes the behavior of `SUNMatZero` on `A` so that only the data is zeroed out, but not the `indexvalues` or `indexpointers` arrays. Providing a value of 0 or `SUNFALSE` for the `yesno` argument is equivalent to the default behavior.

```
int SUNMatrix_cuSparse_SetKernelExecPolicy(SUNMatrix A, SUNCudaExecPolicy *exec_policy)
```

This function sets the execution policies which control the kernel parameters utilized when launching the CUDA kernels. By default the matrix is setup to use a policy which tries to leverage the structure of the matrix. See §7.10.2 for more information about the `SUNCudaExecPolicy` class.

### 8.7.3 SUNMATRIX\_CUSPARSE Usage Notes

The `SUNMATRIX_CUSPARSE` module only supports 32-bit indexing, thus SUNDIALS must be built for 32-bit indexing to use this module.

The `SUNMATRIX_CUSPARSE` module can be used with CUDA streams by calling the `cuSPARSE` function `cusparseSetStream` on the `cusparseHandle_t` that is provided to the `SUNMATRIX_CUSPARSE` constructor.

**Warning:** When using the `SUNMATRIX_CUSPARSE` module with a SUNDIALS package (e.g. ARKODE), the stream given to `cuSPARSE` should be the same stream used for the `NVECTOR` object that is provided to the package, and the `NVECTOR` object given to the `SUNMatvec` operation. If different streams are utilized, synchronization issues may occur.

## 8.8 The SUNMATRIX\_SPARSE Module

The sparse implementation of the `SUNMatrix` module, `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:

```
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 in a sparse matrix is shown in Fig. 8.2. 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 at construction based the input choice 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 **SUNMATRIX\_SPARSE** content structure 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  $5 \times 4$  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 as a CSC matrix in this structure as either

```
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 = CSC_MAT;
indexvals = {1, 3, 0, 2, 0, 1, 3, 4};
indexptrs = {0, 2, 4, 5, 8};
```

or

```
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};
```

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

```
M = 5;
N = 4;
NNZ = 8;
NP = M;
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};
```

The header file to be included when using this module is `sunmatrix/sunmatrix_sparse.h`.

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(A)`

This macro gives access to the contents of the sparse `SUNMatrix`  $A$ .

The assignment `A_cont = SM_CONTENT_S(A)` sets `A_cont` to be a pointer to the sparse `SUNMatrix` content structure.

Implementation:

```
#define SM_CONTENT_S(A) ( (SUNMatrixContent_Sparse)(A->content) )
```

#### `SM_ROWS_S(A)`

Access the number of rows in the sparse `SUNMatrix`  $A$ .

This may be used either to retrieve or to set the value. For example, the assignment `A_rows = SM_ROWS_S(A)` sets `A_rows` to be the number of rows in the matrix  $A$ . Similarly, the assignment `SM_ROWS_S(A) = A_rows` sets the number of columns in  $A$  to equal `A_rows`.

Implementation:

```
#define SM_ROWS_S(A) ( SM_CONTENT_S(A)->M )
```

#### `SM_COLUMNS_S(A)`

Access the number of columns in the sparse `SUNMatrix`  $A$ . As with `SM_ROWS_S`, this may be used either to retrieve or to set the value.

Implementation:

```
#define SM_COLUMNS_S(A) ( SM_CONTENT_S(A)->N )
```

#### `SM_NNZ_S(A)`

Access the allocated number of nonzeros in the sparse `SUNMatrix`  $A$ . As with `SM_ROWS_S`, this may be used either to retrieve or to set the value.

Implementation:

```
#define SM_NNZ_S(A) ( SM_CONTENT_S(A)->NNZ )
```

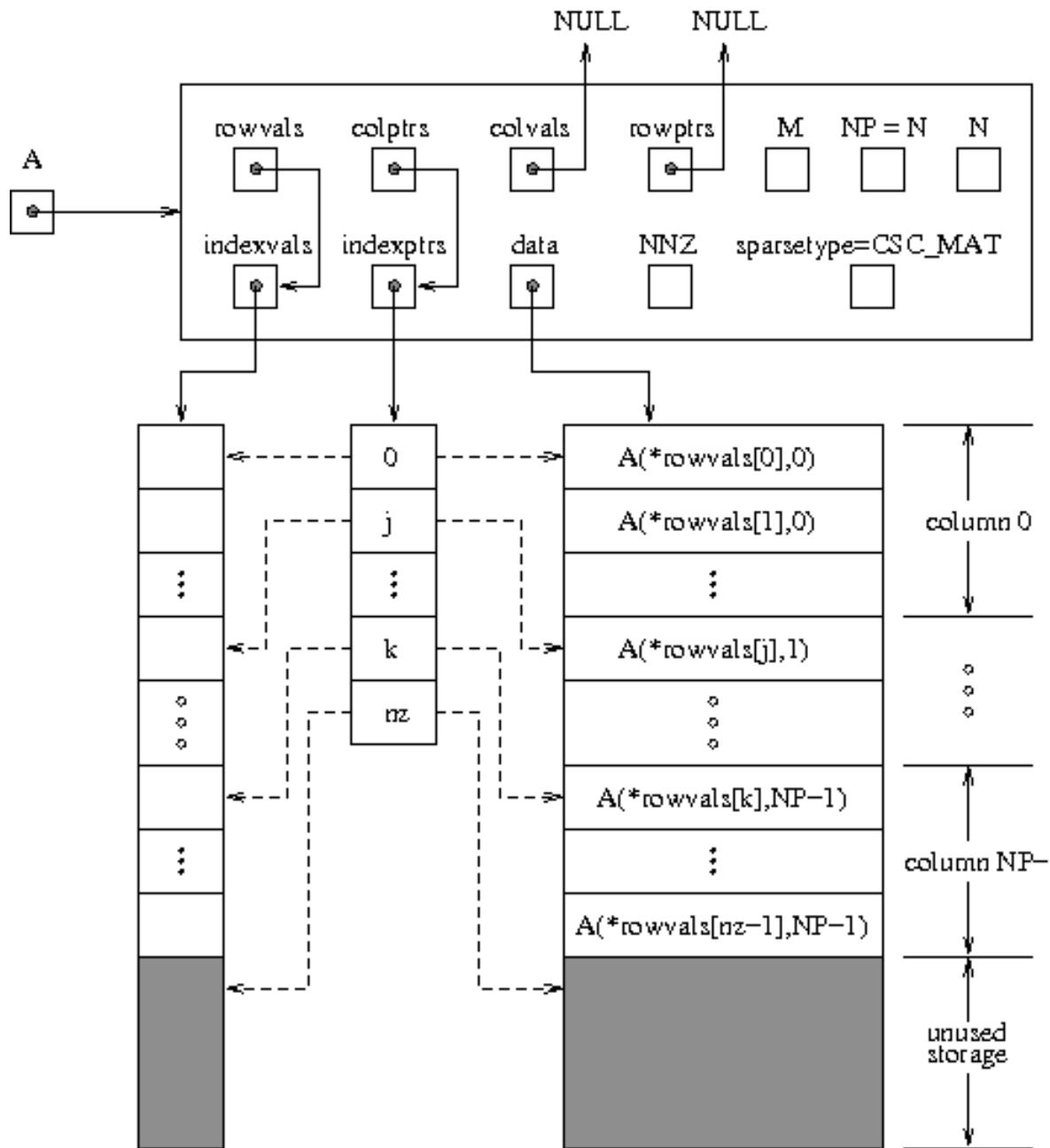


Fig. 8.2: Diagram of the storage for a compressed-sparse-column matrix of type SUNMATRIX\_SPARSE: Here A is an  $M \times N$  sparse CSC matrix with storage for up to NNZ nonzero entries (the allocated length of both data and indexvals). The entries in indexvals may assume values from 0 to  $M-1$ , corresponding to the row index (zero-based) of each nonzero value. The entries in 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 indexptrs array contains  $N+1$  entries; the first  $N$  denote the starting index of each column within the indexvals and data arrays, while the final entry points one past the final nonzero entry. Here, although NNZ values are allocated, only nz are actually filled in; the greyed-out portions of data and indexvals indicate extra allocated space.

**SM\_NP\_S(A)**

Access the number of index pointers NP in the sparse SUNMatrix A. As with SM\_ROWS\_S, this may be used either to retrieve or to set the value.

Implementation:

```
#define SM_NP_S(A) ( SM_CONTENT_S(A)->NP )
```

**SM\_SPARSETYPE\_S(A)**

Access the sparsity type parameter in the sparse SUNMatrix A. As with SM\_ROWS\_S, this may be used either to retrieve or to set the value.

Implementation:

```
#define SM_SPARSETYPE_S(A) ( SM_CONTENT_S(A)->sparsetype )
```

**SM\_DATA\_S(A)**

This macro gives access to the data pointer for the matrix entries.

The assignment `A_data = SM_DATA_S(A)` sets `A_data` to be a pointer to the first component of the data array for the sparse SUNMatrix A. The assignment `SM_DATA_S(A) = A_data` sets the data array of A to be `A_data` by storing the pointer `A_data`.

Implementation:

```
#define SM_DATA_S(A) ( SM_CONTENT_S(A)->data )
```

**SM\_INDEXVALS\_S(A)**

This macro gives access to the `indexvals` pointer for the matrix entries.

The assignment `A_indexvals = SM_INDEXVALS_S(A)` sets `A_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.

Implementation:

```
#define SM_INDEXVALS_S(A) ( SM_CONTENT_S(A)->indexvals )
```

**SM\_INDEXPTRS\_S(A)**

This macro gives access to the `indexptrs` pointer for the matrix entries.

The assignment `A_indexptrs = SM_INDEXPTRS_S(A)` sets `A_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:

```
#define SM_INDEXPTRS_S(A) ( SM_CONTENT_S(A)->indexptrs )
```

The SUNMATRIX\_SPARSE module defines sparse implementations of all matrix operations listed in §8.2. Their names are obtained from those in that section by appending the suffix `_Sparse` (e.g. `SUNMatCopy_Sparse`). The module SUNMATRIX\_SPARSE provides the following additional user-callable routines:

*SUNMatrix SUNSparseMatrix*(*sunindextype* M, *sunindextype* N, *sunindextype* NNZ, int sparsetype, *SUNContext* sunctx)

This constructor 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 choices are `CSR_MAT` or `CSC_MAT`).

**SUNMatrix SUNSparseFromDenseMatrix**(*SUNMatrix A*, *realtype droptol*, *int sparsetype*)

This constructor function creates a new sparse matrix from an existing SUNMATRIX\_DENSE object by copying all values with magnitude larger than *droptol* into the sparse matrix structure.

Requirements:

- *A* must have type SUNMATRIX\_DENSE
- *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.

**SUNMatrix SUNSparseFromBandMatrix**(*SUNMatrix A*, *realtype droptol*, *int sparsetype*)

This constructor function creates a new sparse matrix from an existing SUNMATRIX\_BAND object 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.

**int SUNSparseMatrix\_Realloc**(*SUNMatrix A*)

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).

**void SUNSparseMatrix\_Print**(*SUNMatrix A*, *FILE \*outfile*)

This function prints the content of a sparse SUNMatrix to the output stream specified by *outfile*. Note: std-out or stderr may be used as arguments for *outfile* to print directly to standard output or standard error, respectively.

*sunindextype SUNSparseMatrix\_Rows*(*SUNMatrix A*)

This function returns the number of rows in the sparse SUNMatrix.

*sunindextype SUNSparseMatrix\_Columns*(*SUNMatrix A*)

This function returns the number of columns in the sparse SUNMatrix.

*sunindextype SUNSparseMatrix\_NNZ*(*SUNMatrix A*)

This function returns the number of entries allocated for nonzero storage for the sparse SUNMatrix.

*sunindextype SUNSparseMatrix\_NP*(*SUNMatrix A*)

This function returns the number of index pointers for the sparse SUNMatrix (the *indexptrs* array has NP+1 entries).

**int SUNSparseMatrix\_SparseType**(*SUNMatrix A*)

This function returns the storage type (CSR\_MAT or CSC\_MAT) for the sparse SUNMatrix.

*realtype \*SUNSparseMatrix\_Data*(*SUNMatrix A*)

This function returns a pointer to the data array for the sparse SUNMatrix.

*sunindextype \*SUNSparseMatrix\_IndexValues*(*SUNMatrix A*)

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.

`sunindextype *SUNSparseMatrix_IndexPointers(SUNMatrix A)`

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.

---

**Note:** Within the `SUNMatMatvec_Sparse` routine, internal consistency checks are performed to ensure that the matrix is called with consistent `N_Vector` 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.

---

## 8.9 The SUNMATRIX\_SLUNRLOC Module

The SUNMATRIX\_SLUNRLOC module is an interface to the `SuperMatrix` structure provided by the SuperLU\_DIST sparse matrix factorization and solver library written by X. Sherry Li and collaborators [28, 45, 46, 70]. It is designed to be used with the SuperLU\_DIST SUNLinearSolver module discussed in §9.15. To this end, it defines the `content` field of `SUNMatrix` to be the following structure:

```
struct _SUNMatrixContent_SLUNRloc {
    booleantype 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.

## 8.9.1 SUNMATRIX\_SLUNRLOC Functions

The SUNMATRIX\_SLUNRLOC module provides the following user-callable routines:

*SUNMatrix* **SUNMatrix\_SLUNRloc**(*SuperMatrix* \*Asuper, *gridinfo\_t* \*grid, *SUNContext* sunctx)

This constructor function creates and allocates memory for a SUNMATRIX\_SLUNRLOC object. Its arguments are a fully-allocated SuperLU\_DIST *SuperMatrix* with *Stype* = *SLU\_NR\_loc*, *Dtype* = *SLU\_D*, *Mtype* = *SLU\_GE* and an initialized SuperLU\_DIST 2D process grid structure. It returns a *SUNMatrix* object if *Asuper* is compatible else it returns NULL.

void **SUNMatrix\_SLUNRloc\_Print**(*SUNMatrix* A, FILE \*fp)

This function prints the underlying *SuperMatrix* content. It is useful for debugging. Its arguments are the *SUNMatrix* object and a FILE pointer to print to. It returns void.

*SuperMatrix* \***SUNMatrix\_SLUNRloc\_SuperMatrix**(*SUNMatrix* A)

This function returns the underlying *SuperMatrix* of A. Its only argument is the *SUNMatrix* object to access.

*gridinfo\_t* \***SUNMatrix\_SLUNRloc\_ProcessGrid**(*SUNMatrix* A)

This function returns the SuperLU\_DIST 2D process grid associated with A. Its only argument is the *SUNMatrix* object to access.

*booleantype* **SUNMatrix\_SLUNRloc\_OwnData**(*SUNMatrix* A)

This function returns true if the *SUNMatrix* object is responsible for freeing the underlying *SuperMatrix*, otherwise it returns false. Its only argument is the *SUNMatrix* object to access.

The SUNMATRIX\_SLUNRLOC module also defines implementations of all generic *SUNMatrix* operations listed in §8.2:

- *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  $A = cA + B$ , where  $A$  and  $B$  must have the same sparsity pattern
- *SUNMatScaleAddI\_SLUNRloc* – performs  $A = cA + I$ , where 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*

## 8.10 SUNMATRIX Examples

There are *SUNMatrix* examples that may be installed for each implementation, that make use of the functions in *test\_sunmatrix.c*. These example functions show simple usage of the *SUNMatrix* family of functions. The inputs to the examples depend on the matrix 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\_sunmatrix.c*:

- *Test\_SUNMatGetID*: Verifies the returned matrix ID against the value that should be returned.

- `Test_SUNMatClone`: Creates clone of an existing matrix, copies the data, and checks that their values match.
- `Test_SUNMatZero`: Zeros out an existing matrix and checks that each entry equals 0.0.
- `Test_SUNMatCopy`: Clones an input matrix, copies its data to a clone, and verifies that all values match.
- `Test_SUNMatScaleAdd`: Given an input matrix  $A$  and an input identity matrix  $I$ , this test clones and copies  $A$  to a new matrix  $B$ , computes  $B = -B + B$ , and verifies that the resulting matrix entries equal 0. Additionally, if the matrix is square, this test clones and copies  $A$  to a new matrix  $D$ , clones and copies  $I$  to a new matrix  $C$ , computes  $D = D + I$  and  $C = C + A$  using `SUNMatScaleAdd()`, and then verifies that  $C = D$ .
- `Test_SUNMatScaleAddI`: Given an input matrix  $A$  and an input identity matrix  $I$ , this clones and copies  $I$  to a new matrix  $B$ , computes  $B = -B + I$  using `SUNMatScaleAddI()`, and verifies that the resulting matrix entries equal 0.
- `Test_SUNMatMatvecSetup`: verifies that `SUNMatMatvecSetup()` can be called.
- `Test_SUNMatMatvec` Given an input matrix  $A$  and input vectors  $x$  and  $y$  such that  $y = Ax$ , this test has different behavior depending on whether  $A$  is square. If it is square, it clones and copies  $A$  to a new matrix  $B$ , computes  $B = 3B + I$  using `SUNMatScaleAddI()`, clones  $y$  to new vectors  $w$  and  $z$ , computes  $z = Bx$  using `SUNMatMatvec()`, computes  $w = 3y + x$  using `N_VLinearSum`, and verifies that  $w == z$ . If  $A$  is not square, it just clones  $y$  to a new vector  $z$ , computes  $z = Ax$  using `SUNMatMatvec()`, and verifies that  $y = z$ .
- `Test_SUNMatSpace`: verifies that `SUNMatSpace()` can be called, and outputs the results to `stdout`.

## 8.11 SUNMATRIX functions used by ARKODE

In Table Table 8.2, we list the matrix functions in the `SUNMatrix` module used within the ARKODE package. The table also shows, for each function, which of the code modules uses the function. The main ARKODE time step modules, `ARKStep`, `ERKStep`, and `MRIStep`, do not call any `SUNMatrix` functions directly, so the table columns are specific to the `ARKLS` interface and the `ARKBANDPRE` and `ARKBBDPRE` preconditioner modules. We further note that the `ARKLS` interface only utilizes these routines when supplied with a *matrix-based* linear solver, i.e. the `SUNMatrix` object ( $J$  or  $M$ ) passed to `ARKStepSetLinearSolver()` or `ARKStepSetMassLinearSolver()` was not `NULL`.

At this point, we should emphasize that the ARKODE user does not need to know anything about the usage of matrix functions by the ARKODE code modules in order to use ARKODE. The information is presented as an implementation detail for the interested reader.

Table 8.2: List of matrix functions usage by ARKODE code modules

	<b>ARKLS</b>	<b>ARKBANDPRE</b>	<b>ARKBBDPRE</b>
<code>SUNMatGetID()</code>	X		
<code>SUNMatClone()</code>	X		
<code>SUNMatDestroy()</code>	X	X	X
<code>SUNMatZero()</code>	X	X	X
<code>SUNMatCopy()</code>	X	X	X
<code>SUNMatScaleAddI()</code>	X	X	X
<code>SUNMatScaleAdd()</code>	1		
<code>SUNMatMatvec()</code>	1		
<code>SUNMatMatvecSetup()</code>	1,2		
<code>SUNMatSpace()</code>	2	2	2

1. These matrix functions are only used for problems involving a non-identity mass matrix.
2. These matrix functions 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`). If not supplied, these modules will assume that the matrix requires no storage.

We note that both the ARKBANDPRE and ARKBBDPRE preconditioner modules are hard-coded to use the SUNDIALS-supplied band `SUNMatrix` type, so the most useful information above for user-supplied `SUNMatrix` implementations is the column relating to ARKLS requirements.

## Chapter 9

# Linear Algebraic Solvers

For problems that require the solution of linear systems of equations, the SUNDIALS packages operate using generic linear solver modules defined through the [SUNLinearSolver](#), or “`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 [N\\_Vector](#), and optionally [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 `N_Vector` 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

$$\tilde{A}\tilde{x} = \tilde{b} \tag{9.1}$$

where

$$\begin{aligned} \tilde{A} &= S_1 P_1^{-1} A P_2^{-1} S_2^{-1}, \\ \tilde{b} &= S_1 P_1^{-1} b, \\ \tilde{x} &= S_2 P_2 x, \end{aligned} \tag{9.2}$$

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  $P_2x$ .

SUNDIALS solvers request that iterative linear solvers stop based on the 2-norm of the scaled preconditioned residual meeting a prescribed tolerance, i.e.,

$$\left\| \tilde{b} - \tilde{A}\tilde{x} \right\|_2 < \text{tol.}$$

When provided an iterative SUNLinSol implementation that does not support the scaling matrices  $S_1$  and  $S_2$ , the SUNDIALS packages will adjust the value of tol accordingly (see the iterative linear tolerance section that follows for more details). In this case, they instead request that iterative linear solvers stop based on the criterion

$$\left\| P_1^{-1}b - P_1^{-1}Ax \right\|_2 < \text{tol.}$$

We note that the corresponding adjustments to tol in this case may not be 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 `SUNLinearSolver` 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 §9.1.1 – §9.1.3. This is followed by the definition of functions supplied to a linear solver implementation in §9.1.4. The linear solver return codes are described in Table 9.1. The `SUNLinearSolver` type and the generic SUNLinSol module are defined in §9.1.6. §9.1.8 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 section that then follows describes the SUNLinSol functions required by this SUNDIALS package, and provides additional package specific details. Then the remaining sections of this chapter present the SUNLinSol modules provided with SUNDIALS.

## 9.1 The `SUNLinearSolver` API

The SUNLinSol API defines several linear solver operations that enable SUNDIALS packages to utilize this API. These functions can be divided into three categories. The first are the core linear solver functions. The second consist of “set” routines to supply the linear solver with functions provided by the SUNDIALS packages 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_linearsolver.h`.

### 9.1.1 `SUNLinearSolver` core functions

The core linear solver functions consist of two **required** functions: `SUNLinSolGetType()` returns the linear solver type, and `SUNLinSolSolve()` solves the linear system  $Ax = b$ .

The remaining **optional** functions return the solver ID (`SUNLinSolGetID()`), initialize the linear solver object once all solver-specific options have been set (`SUNLinSolInitialize()`), set up the linear solver object to utilize an updated matrix  $A$  (`SUNLinSolSetup()`), and destroy a linear solver object (`SUNLinSolFree()`).

`SUNLinearSolver_Type SUNLinSolGetType(SUNLinearSolver LS)`

Returns the type identifier for the linear solver  $LS$ .

**Return value:**

- `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 [SUNLinSolSetupATimes\(\)](#) 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 by the package-supplied `ATimes` routine. As the solver computes the solution only inexactly (or may diverge), the linear solver should check for solution convergence/accuracy as appropriate.
- SUNLINEARSOLVER\_MATRIX\_EMBEDDED (3) – the SUNLinSol module sets up and solves the specified linear system at each linear solve call. Any matrix-related data structures are held internally to the linear solver itself, and are not provided by the SUNDIALS package.

**Usage:**

```
type = SUNLinSolGetType(LS);
```

---

**Note:** See §9.1.8.1 for more information on intended use cases corresponding to the linear solver type.

---

`SUNLinearSolver_ID SUNLinSolGetID(SUNLinearSolver LS)`

Returns a non-negative linear solver identifier (of type `int`) for the linear solver *LS*.

**Return value:**

Non-negative linear solver identifier (of type `int`), defined by the enumeration `SUNLinearSolver_ID`, with values shown in [Table 9.2](#) and defined in the `sundials_linear solver.h` header file.

**Usage:**

```
id = SUNLinSolGetID(LS);
```

---

**Note:** It is recommended that a user-supplied `SUNLinearSolver` return the `SUNLINEARSOLVER_CUSTOM` identifier.

---

`int SUNLinSolInitialize(SUNLinearSolver LS)`

Performs linear solver initialization (assuming that all solver-specific options have been set).

**Return value:**

Zero for a successful call, and a negative value for a failure. Ideally, this should return one of the generic error codes listed in [Table 9.1](#).

**Usage:**

```
retval = SUNLinSolInitialize(LS);
```

`int SUNLinSolSetup(SUNLinearSolver LS, SUNMatrix A)`

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.

**Return value:**

Zero for a successful call, a positive value for a recoverable failure, and a negative value for an unrecoverable failure. Ideally this should return one of the generic error codes listed in [Table 9.1](#).

**Usage:**

```
retval = SUNLinSolSetup(LS, A);
```

int **SUNLinSolSolve**(*SUNLinearSolver* LS, *SUNMatrix* A, *N\_Vector* x, *N\_Vector* b, *realtype* tol)

This required function solves a linear system  $Ax = b$ .

**Arguments:**

- *LS* – a *SUNLinSol* object.
- *A* – a *SUNMatrix* object.
- *x* – an *N\_Vector* object containing the initial guess for the solution of the linear system on input, and the solution to the linear system upon return.
- *b* – an *N\_Vector* object containing the linear system right-hand side.
- *tol* – the desired linear solver tolerance.

**Return value:**

Zero for a successful call, a positive value for a recoverable failure, and a negative value for an unrecoverable failure. Ideally this should return one of the generic error codes listed in [Table 9.1](#).

**Notes:**

**Direct solvers:** can ignore the *tol* argument.

**Matrix-free solvers:** (those that identify as *SUNLINEARSOLVER\_ITERATIVE*) can ignore the *SUNMatrix* input *A*, and should 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 *tol* in a weighted 2-norm. If the solver does not support scaling then it should just use a 2-norm.

**Matrix-embedded solvers:** should ignore the *SUNMatrix* input *A* as this will be NULL. It is assumed that within this function, the solver will call interface routines from the relevant SUNDIALS package to directly form the linear system matrix *A*, and then solve  $Ax = b$  before returning with the solution *x*.

**Usage:**

```
retval = SUNLinSolSolve(LS, A, x, b, tol);
```

int **SUNLinSolFree**(*SUNLinearSolver* LS)

Frees memory allocated by the linear solver.

**Return value:**

Zero for a successful call, and a negative value for a failure. Ideally, this should return one of the generic error codes listed in [Table 9.1](#).

**Usage:**

```
retval = SUNLinSolFree(LS);
```

### 9.1.2 SUNLinearSolver “set” functions

The following functions supply linear solver modules with functions defined by the SUNDIALS packages and modify solver parameters. Only the routine for setting the matrix-vector product routine is required, and even then is only required 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.

```
int SUNLinSolSetATimes(SUNLinearSolver LS, void *A_data, SUNATimesFn ATimes)
```

*Required for matrix-free linear solvers (otherwise optional).*

Provides a *SUNATimesFn* function pointer, as well as a *void\** pointer to a data structure used by this routine, to the linear solver object *LS*. SUNDIALS packages 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.

**Return value:**

Zero for a successful call, and a negative value for a failure. Ideally, this should return one of the generic error codes listed in [Table 9.1](#).

**Usage:**

```
retval = SUNLinSolSetATimes(LS, A_data, ATimes);
```

```
int SUNLinSolSetPreconditioner(SUNLinearSolver LS, void *P_data, SUNPSetupFn Pset, SUNPSolveFn Psol)
```

This *optional* routine provides *SUNPSetupFn* and *SUNPSolveFn* function pointers that implement the preconditioner solves  $P_1^{-1}$  and  $P_2^{-1}$  from (9.2). This routine is called by a SUNDIALS package, which provides translation between the generic *Pset* and *Psol* calls and the package- or user-supplied routines.

**Return value:**

Zero for a successful call, and a negative value for a failure. Ideally, this should return one of the generic error codes listed in [Table 9.1](#).

**Usage:**

```
retval = SUNLinSolSetPreconditioner(LS, Pdata, Pset, Psol);
```

```
int SUNLinSolSetScalingVectors(SUNLinearSolver LS, N_Vector s1, N_Vector s2)
```

This *optional* routine provides left/right scaling vectors for the linear system solve. Here, *s1* and *s2* are *N\_Vectors* of positive scale factors containing the diagonal of the matrices  $S_1$  and  $S_2$  from (9.2), respectively. Neither vector needs to be tested for positivity, and a NULL argument for either indicates that the corresponding scaling matrix is the identity.

**Return value:**

Zero for a successful call, and a negative value for a failure. Ideally, this should return one of the generic error codes listed in [Table 9.1](#).

**Usage:**

```
retval = SUNLinSolSetScalingVectors(LS, s1, s2);
```

```
int SUNLinSolSetZeroGuess(SUNLinearSolver LS, booleantype onoff)
```

This *optional* routine indicates if the upcoming *SUNlinSolSolve()* call will be made with a zero initial guess (SUNTRUE) or a non-zero initial guess (SUNFALSE).

**Return value:**

Zero for a successful call, and a negative value for a failure. Ideally, this should return one of the generic error codes listed in [Table 9.1](#).

**Usage:**

```
retval = SUNLinSolSetZeroGuess(LS, onoff);
```

**Notes:**

It is assumed that the initial guess status is not retained across calls to `SUNLinSolSolve()`. As such, the linear solver interfaces in each of the SUNDIALS packages call `SUNLinSolSetZeroGuess()` prior to each call to `SUNLinSolSolve()`.

### 9.1.3 SUNLinearSolver “get” functions

The following functions allow SUNDIALS packages to retrieve results from a linear solve. *All routines are optional.*

`int SUNLinSolNumIters(SUNLinearSolver LS)`

This *optional* routine should return the number of linear iterations performed in the most-recent “solve” call.

**Usage:**

```
its = SUNLinSolNumIters(LS);
```

`realtype SUNLinSolResNorm(SUNLinearSolver LS)`

This *optional* routine should return the final residual norm from the most-recent “solve” call.

**Usage:**

```
rnorm = SUNLinSolResNorm(LS);
```

`N_Vector SUNLinSolResid(SUNLinearSolver LS)`

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 `N_Vector` containing the preconditioned initial residual vector.

**Usage:**

```
rvec = SUNLinSolResid(LS);
```

**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.

`sunindextype SUNLinSolLastFlag(SUNLinearSolver LS)`

This *optional* routine should return the last error flag encountered within the linear solver. Although not called by the SUNDIALS packages directly, this may be called by the user to investigate linear solver issues after a failed solve.

**Usage:**

```
lflag = SUNLinLastFlag(LS);
```

`int SUNLinSolSpace(SUNLinearSolver LS, long int *lenrwLS, long int *leniwLS)`

This *optional* routine should return the storage requirements for the linear solver `LS`:

- `lrw` is a `long int` containing the number of `realtype` words
- `liw` is a `long int` containing the number of integer words.

The return value is an integer flag denoting success/failure of the operation.

This function is advisory only, for use by users to help determine their total space requirements.

**Usage:**

```
retval = SUNLinSolSpace(LS, &lrw, &liw);
```

### 9.1.4 Functions provided by SUNDIALS packages

To interface with 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 linear solver API. The function types for these routines are defined in the header file `sundials/sundials_iterative.h`, and are described below.

`typedef int (*SUNATimesFn)(void *A_data, N_Vector v, N_Vector z)`

Computes the action of a matrix on a vector, performing the operation  $z \leftarrow Av$ . Memory for  $z$  will already be allocated prior to calling this function. The parameter `A_data` is a pointer to any information about  $A$  which the function needs in order to do its job. The vector  $v$  should be left unchanged.

**Return value:**

Zero for a successful call, and non-zero upon failure.

`typedef int (*SUNPSetupFn)(void *P_data)`

Sets up any requisite problem data in preparation for calls to the corresponding `SUNPSolveFn`.

**Return value:**

Zero for a successful call, and non-zero upon failure.

`typedef int (*SUNPSolveFn)(void *P_data, N_Vector r, N_Vector z, realtype tol, int lr)`

Solves the preconditioner equation  $Pz = r$  for the vector  $z$ . Memory for  $z$  will 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 `SUNPSetupFn`). The parameter `lr` is input, and indicates whether  $P$  is to be taken as the left or 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 error weight vector for the WRMS norm may be accessed from the main package memory structure. The vector  $r$  should not be modified by the `SUNPSolveFn`.

**Return value:**

Zero for a successful call, a negative value for an unrecoverable failure condition, or a positive value for a recoverable failure condition (thus the calling routine may reattempt the solution after updating preconditioner data).

### 9.1.5 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, listed in [Table 9.1](#). 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 provide additional information to the user in case of a linear solver failure.

Table 9.1: SUNLinSol error codes

Error code	Value	Meaning
SUNLS_SUCCESS	0	successful call or converged solve
SUNLS_MEM_NULL	-801	the memory argument to the function is NULL
SUNLS_ILL_INPUT	-802	an illegal input has been provided to the function
SUNLS_MEM_FAIL	-803	failed memory access or allocation
SUNLS_ATIMES_NULL	-804	the <code>ATimes</code> function is NULL
SUNLS_ATIMES_FAIL_UNREC	-805	an unrecoverable failure occurred in the <code>ATimes</code> routine
SUNLS_PSET_FAIL_UNREC	-806	an unrecoverable failure occurred in the <code>Pset</code> routine
SUNLS_PSOLVE_NULL	-807	the preconditioner solve function is NULL
SUNLS_PSOLVE_FAIL_UNREC	-808	an unrecoverable failure occurred in the <code>Psolve</code> routine
SUNLS_PACKAGE_FAIL_UNREC	-809	an unrecoverable failure occurred in an external linear solver package
SUNLS_GS_FAIL	-810	a failure occurred during Gram-Schmidt orthogonalization (SPGMR/SPFGMR)
SUNLS_QRSOL_FAIL	-811	a singular \$R\$ matrix was encountered in a QR factorization (SPGMR/SPFGMR)
SUNLS_VECTOROP_ERR	-812	a vector operation error occurred
SUNLS_RES_REDUCED	801	an iterative solver reduced the residual, but did not converge to the desired tolerance
SUNLS_CONV_FAIL	802	an iterative solver did not converge (and the residual was not reduced)
SUNLS_ATIMES_FAIL_REC	803	a recoverable failure occurred in the <code>ATimes</code> routine
SUNLS_PSET_FAIL_REC	804	a recoverable failure occurred in the <code>Pset</code> routine
SUNLS_PSOLVE_FAIL_REC	805	a recoverable failure occurred in the <code>Psolve</code> routine
SUNLS_PACKAGE_FAIL_REC	806	a recoverable failure occurred in an external linear solver package
SUNLS_QRFACT_FAIL	807	a singular matrix was encountered during a QR factorization (SPGMR/SPFGMR)
SUNLS_LUFACT_FAIL	808	a singular matrix was encountered during a LU factorization

### 9.1.6 The generic SUNLinearSolver module

SUNDIALS packages interact with specific SUNLinSol implementations through the generic SUNLinearSolver abstract base class. The SUNLinearSolver type is a pointer to a structure containing an implementation-dependent *content* field, and an *ops* field, and is defined as

```
typedef struct _generic_SUNLinearSolver *SUNLinearSolver
```

and the generic structure is defined as

```
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

```
struct _generic_SUNLinearSolver_Ops {
    SUNLinearSolver_Type (*gettype)(SUNLinearSolver);
    SUNLinearSolver_ID (*getid)(SUNLinearSolver);
    int (*setatimes)(SUNLinearSolver, void*, SUNATimesFn);
    int (*setpreconditioner)(SUNLinearSolver, void*,
                           SUNPSetupFn, SUNPSolveFn);
    int (*setscalingvectors)(SUNLinearSolver,
                           N_Vector, N_Vector);
    int (*setzeroguess)(SUNLinearSolver, booleantype);
    int (*initialize)(SUNLinearSolver);
    int (*setup)(SUNLinearSolver, SUNMatrix);
    int (*solve)(SUNLinearSolver, SUNMatrix, N_Vector,
                N_Vector, realtype);
    int (*numiters)(SUNLinearSolver);
    realtype (*resnorm)(SUNLinearSolver);
    sunindextype (*lastflag)(SUNLinearSolver);
    int (*space)(SUNLinearSolver, long int*, long int*);
    N_Vector (*resid)(SUNLinearSolver);
    int (*free)(SUNLinearSolver);
};
```

The generic SUNLinSol class defines and implements the linear solver operations defined in §9.1.1 – §9.1.3. 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 SUNLinearSolver base class, namely *SUNLinSolInitialize()*, that initializes a SUNLinearSolver object for use after it has been created and configured, and returns a flag denoting a successful or failed operation:

```
int SUNLinSolInitialize(SUNLinearSolver S)
{
    return ((int) S->ops->initialize(S));
}
```

### 9.1.7 Compatibility of SUNLinearSolver modules

Not all SUNLinearSolver implementations are compatible with all SUNMatrix and N\_Vector implementations provided in SUNDIALS. More specifically, all of the SUNDIALS iterative linear solvers (*SPGMR*, *SPFGMR*, *SPBCGS*, *SPTFQMR*, and *PCG*) are compatible with all of the SUNDIALS N\_Vector modules, but the matrix-based direct SUNLinSol modules are specifically designed to work with distinct SUNMatrix and N\_Vector modules. In the list below, we summarize the compatibility of each matrix-based SUNLinearSolver module with the various SUNMatrix and N\_Vector modules. For a more thorough discussion of these compatibilities, we defer to the documentation for each individual SUNLinSol module in the sections that follow.

- *Dense*
  - SUNMatrix: *Dense* or user-supplied
  - N\_Vector: *Serial*, *OpenMP*, *Pthreads*, or user-supplied
- *LapackDense*
  - SUNMatrix: *Dense* or user-supplied
  - N\_Vector: *Serial*, *OpenMP*, *Pthreads*, or user-supplied
- *Band*
  - SUNMatrix: *Band* or user-supplied
  - N\_Vector: *Serial*, *OpenMP*, *Pthreads*, or user-supplied
- *LapackBand*
  - SUNMatrix: *Band* or user-supplied
  - N\_Vector: *Serial*, *OpenMP*, *Pthreads*, or user-supplied
- *KLU*
  - SUNMatrix: *Sparse* or user-supplied
  - N\_Vector: *Serial*, *OpenMP*, *Pthreads*, or user-supplied
- *SuperLU\_MT*
  - SUNMatrix: *Sparse* or user-supplied
  - N\_Vector: *Serial*, *OpenMP*, *Pthreads*, or user-supplied
- *SuperLU\_Dist*
  - SUNMatrix: *SLUNRLOC* or user-supplied
  - N\_Vector: *Serial*, *OpenMP*, *Pthreads*, *Parallel*, *\*hypre\**, *PETSc*, or user-supplied
- *Magma Dense*
  - SUNMatrix: *Magma Dense* or user-supplied
  - N\_Vector: *HIP*, *RAJA*, or user-supplied
- *OneMKL Dense*
  - SUNMatrix: *One MKL Dense* or user-supplied
  - N\_Vector: *SYCL*, *RAJA*, or user-supplied
- *cuSolverSp batchQR*
  - SUNMatrix: *cuSparse* or user-supplied
  - N\_Vector: *CUDA*, *RAJA*, or user-supplied

### 9.1.8 Implementing a custom SUNLinearSolver module

A particular implementation of the SUNLinearSolver module must:

- Specify the *content* field of the SUNLinSol module.
- Define and implement the required linear solver operations.

---

**Note:** 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 whether the associated functionality is supported.

To aid in the creation of custom SUNLinearSolver modules the generic SUNLinearSolver module provides the utility function `SUNLinSolNewEmpty()`. When used in custom SUNLinearSolver constructors this function will ease the introduction of any new optional linear solver operations to the SUNLinearSolver API by ensuring that only required operations need to be set.

#### *SUNLinearSolver* `SUNLinSolNewEmpty()`

This function allocates a new generic SUNLinearSolver object and initializes its content pointer and the function pointers in the operations structure to NULL.

##### **Return value:**

If successful, this function returns a SUNLinearSolver object. If an error occurs when allocating the object, then this routine will return NULL.

#### `void SUNLinSolFreeEmpty(SUNLinearSolver LS)`

This routine frees the generic SUNLinearSolver 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* – a SUNLinearSolver object

Additionally, a SUNLinearSolver 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 for a particular problem.
- Provide additional user-callable “get” routines acting on the SUNLinearSolver object, e.g., for returning various solve statistics.

Each SUNLinSol implementation included in SUNDIALS has a unique identifier specified in enumeration and shown in [Table 9.2](#). It is recommended that a user-supplied SUNLinSol implementation use the `SUNLINEARSOLVER_CUSTOM` identifier.

Table 9.2: Identifiers associated with SUNLinearSolver modules supplied with SUNDIALS

SUNLinSol ID	Linear solver type	ID Value
SUNLINEARSOLVER_BAND	Banded direct linear solver (internal)	0
SUNLINEARSOLVER_DENSE	Dense direct linear solver (internal)	1
SUNLINEARSOLVER_KLU	Sparse direct linear solver (KLU)	2
SUNLINEARSOLVER_LAPACKBAND	Banded direct linear solver (LAPACK)	3
SUNLINEARSOLVER_LAPACKDENSE	Dense direct linear solver (LAPACK)	4
SUNLINEARSOLVER_PCG	Preconditioned conjugate gradient iterative solver	5
SUNLINEARSOLVER_SPBCGS	Scaled-preconditioned BiCGStab iterative solver	6
SUNLINEARSOLVER_SPFGMR	Scaled-preconditioned FGMRES iterative solver	7
SUNLINEARSOLVER_SPGMR	Scaled-preconditioned GMRES iterative solver	8
SUNLINEARSOLVER_SPTFQMR	Scaled-preconditioned TFQMR iterative solver	9
SUNLINEARSOLVER_SUPERLUDIST	Parallel sparse direct linear solver (SuperLU-Dist)	10
SUNLINEARSOLVER_SUPERLUMT	Threaded sparse direct linear solver (SuperLU-MT)	11
SUNLINEARSOLVER_CUSOLVERSP-BATCHQR	Sparse direct linear solver (CUDA)	12
SUNLINEARSOLVER_MAGMA DENSE	Dense or block-dense direct linear solver (MAGMA)	13
SUNLINEARSOLVER_ONEMKL DENSE	Dense or block-dense direct linear solver (OneMKL)	14
SUNLINEARSOLVER_CUSTOM	User-provided custom linear solver	15

### 9.1.8.1 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. Many external solvers provide routines with similar functionality and thus may require minimal effort to wrap within custom SUNMATRIX and SUNLinSol implementations. As SUNDIALS packages utilize generic SUNLinSol modules they may naturally leverage user-supplied SUNLinearSolver implementations, thus there exist 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 sections below.

#### Direct linear solvers

Direct linear solver modules require a matrix and compute an “exact” solution to the linear system *defined by the matrix*. SUNDIALS packages strive to amortize the high cost of matrix construction by reusing matrix information for multiple nonlinear iterations or time steps. As a result, each package’s linear solver interface recomputes matrix 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 §8 and §9. *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 instead compute an inexact solution to the linear system *defined by the package-supplied ATimes routine*. SUNDIALS supplies multiple scaled, preconditioned iterative SUNLinSol modules that support scaling, allowing packages to handle non-dimensionalization, and users to define variables and equations as natural in their applications. However, for linear solvers that do not support left/right scaling, SUNDIALS packages must instead adjust the tolerance supplied to the linear solver to compensate (see the iterative linear tolerance section that follows for more details) – this strategy may be non-optimal since it cannot handle situations where the magnitudes of different solution components or equations vary dramatically within a single application.

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 §9. *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 resued across multiple solves to amortize the cost of matrix construction. As in the direct linear solver case, only thin SUNMATRIX and SUNLinSol wrappers for the underlying matrix and linear solver structures need to be created to utilize such a 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; this 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 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 scaled, preconditioned iterative linear solver implementations ([SUNLinSol\\_SPGMR\(\)](#), [SUNLinSol\\_SPFGMR\(\)](#), [SUNLinSol\\_SPBCGS\(\)](#), [SUNLinSol\\_SPTFQMR\(\)](#), or [SUNLinSol\\_PCG\(\)](#)) as the outer solver. The creation and storage of the preconditioner matrix, and interfacing with the corresponding matrix-based linear solver, can be handled through a package’s preconditioner “setup” and “solve” functionality without creating SUNMATRIX and SUNLinSol implementations. This usage mode is recommended primarily because the SUNDIALS-provided modules support variable and equation 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 SUNATimesFn routine.

### Application-specific linear solvers with embedded matrix structure

Many applications can exploit additional linear system structure arising from implicit couplings in their model equations. In certain circumstances, the linear solve  $Ax = b$  may be performed without the need for a global system matrix  $A$ , as the unformed  $A$  may be block diagonal or block triangular, and thus the overall linear solve may be performed through a sequence of smaller linear solves. In other circumstances, a linear system solve may be accomplished via specialized fast solvers, such as the fast Fourier transform, fast multipole method, or treecode, in which case no matrix structure may be explicitly necessary. In many of the above situations, construction and preprocessing of the linear system matrix  $A$  may be inexpensive, and thus increased performance may be possible if the current linear system information is used within every solve (instead of being lagged, as occurs with matrix-based solvers that reuse  $A$ ).

To support such application-specific situations, SUNDIALS supports user-provided linear solvers with the `SUNLINEAR-SOLVER_MATRIX_EMBEDDED` type. For an application to leverage this support, it should define a custom `SUNLinSol` implementation having this type, that only needs to implement the required `SUNLinSolGetType()` and `SUNLinSolSolve()` operations. Within `SUNLinSolSolve()`, the linear solver implementation should call package-specific interface routines (e.g., `ARKStepGetNonlinearSystemData`, `CVodeGetNonlinearSystemData`, `IDAGetNonlinearSystemData`, `ARKStepGetCurrentGamma`, `CVodeGetCurrentGamma`, `IDAGetCurrentCj`, or `MRIStepGetCurrentGamma`) to construct the relevant system matrix  $A$  (or portions thereof), solve the linear system  $Ax = b$ , and return the solution vector  $x$ .

We note that when attaching this custom `SUNLinearSolver` object with the relevant SUNDIALS package `SetLinearSolver` routine, the input `SUNMatrix A` should be set to `NULL`.

For templates of such user-provided “matrix-embedded” `SUNLinSol` implementations, see the SUNDIALS examples `ark_analytic_mels.c`, `cvAnalytic_mels.c`, `cvsAnalytic_mels.c`, `idaAnalytic_mels.c`, and `idasAnalytic_mels.c`.

## 9.2 ARKODE SUNLinearSolver interface

In Table 9.3, we list the `SUNLinSol` module functions used within the ARKLS interface. As with the `SUNMATRIX` module, we emphasize that the ARKODE user does not need to know detailed usage of linear solver functions by the ARKODE code modules in order to use ARKODE. The information is presented as an implementation detail for the interested reader.

Table 9.3: List of SUNLinSol functions called by the ARKODE linear solver interface, depending on the self-identified “type” reported from `SUNLinSolGetType()`. Functions marked with “X” are required; functions marked with “O” are only called if they are non-NULL in the SUNLinearSolver implementation that is being used.

Routine	DI-RECT	ITERA-TIVE	MATRIX	ITERA-TIVE	MATRIX	EMBEDDED
<code>SUNLinSolGetType()</code>	X	X	X		X	
<code>SUNLinSolSetATimes()</code>	O	X	O			
<code>SUNLinSolSetPreconditioner()</code>	O	O	O			
<code>SUNLinSolSetScalingVectors()</code>	O	O	O			
<code>SUNLinSolInitialize()</code>	X	X	X			
<code>SUNLinSolSetup()</code>	X	X	X			
<code>SUNLinSolSolve()</code>	X	X	X		X	
<code>SUNLinSolNumIters()</code> <sup>1</sup>		O	O			
<code>SUNLinSolResNorm()</code> <sup>2</sup>		O	O			
<code>SUNLinSolLastFlag()</code> <sup>3</sup>						
<code>SUNLinSolFree()</code> <sup>4</sup>						
<code>SUNLinSolSpace()</code>	O	O	O		O	

Notes:

1. `SUNLinSolNumIters()` is only used to accumulate overall iterative linear solver statistics. If it is not implemented by the SUNLinearSolver module, then ARKLS will consider all solves as requiring zero iterations.
2. Although `SUNLinSolResNorm()` is optional, if it is not implemented by the SUNLinearSolver then ARKLS will consider all solves a being *exact*.
3. Although ARKLS does not call `SUNLinSolLastFlag()` directly, this routine is available for users to query linear solver failure modes.
4. Although ARKLS 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 ARKLS interface, in the case that interested users wish to develop custom SUNLinSol modules.

### 9.2.1 Lagged matrix information

If the SUNLinSol module identifies as having type `SUNLINEARSOLVER_DIRECT` or `SUNLINEARSOLVER_MATRIX_ITERATIVE`, then it solves a linear system *defined* by a SUNMATRIX object. ARKLS will update the matrix information infrequently according to the strategies outlined in §2.10.2.3. To this end, we differentiate between the *desired* linear system  $\mathcal{A}x = b$  with  $\mathcal{A} = (M - \gamma J)$  and the *actual* linear system

$$\tilde{\mathcal{A}}\tilde{x} = b \Leftrightarrow (M - \tilde{\gamma}J)\tilde{x} = b.$$

Since ARKLS updates the SUNMATRIX object infrequently, it is likely that  $\gamma \neq \tilde{\gamma}$ , and in turn  $\mathcal{A} \neq \tilde{\mathcal{A}}$ . Therefore, after calling the SUNLinSol-provided `SUNLinSolSolve()` routine, we test whether  $\gamma/\tilde{\gamma} \neq 1$ , and if this is the case we scale the solution  $\tilde{x}$  to obtain the desired linear system solution  $x$  via

$$x = \frac{2}{1 + \gamma/\tilde{\gamma}}\tilde{x}. \quad (9.3)$$

The motivation for this selection of the scaling factor  $c = 2/(1 + \gamma/\tilde{\gamma})$  follows the derivation in [10, 35]. In short, if we consider a stationary iteration for the linear system as consisting of a solve with  $\tilde{A}$  followed with a 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  $E = I - c\tilde{A}^{-1}\mathcal{A}$ , 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  $E$ .

### 9.2.2 Iterative linear solver tolerance

If the SUNLinSol object self-identifies as having type SUNLINEARSOLVER\_ITERATIVE or SUNLINEARSOLVER\_MATRIX\_ITERATIVE, then ARKLS will set the input tolerance `delta` as described in §2.10.3.2. However, if the iterative linear solver does not support scaling matrices (i.e., the `SUNLinSolSetScalingVectors()` routine is `NULL`), then ARKLS will attempt to adjust the linear solver tolerance to account for this lack of functionality. To this end, the following assumptions are made:

- All solution components have similar magnitude; hence the residual weight vector  $w$  used in the WRMS norm (see §2.6), corresponding to the left scaling matrix  $S_1$ , should satisfy the assumption

$$w_i \approx w_{mean}, \quad \text{for } i = 0, \dots, n - 1.$$

- The SUNLinSol object uses a standard 2-norm to measure convergence.

Under these assumptions, ARKLS adjusts the linear solver convergence requirement as follows (using the notation from (9.2)):

$$\begin{aligned} & \|\tilde{b} - \tilde{A}\tilde{x}\|_2 < \text{tol} \\ \Leftrightarrow & \|S_1 P_1^{-1} b - S_1 P_1^{-1} A x\|_2 < \text{tol} \\ \Leftrightarrow & \sum_{i=0}^{n-1} [w_i (P_1^{-1}(b - Ax))_i]^2 < \text{tol}^2 \\ \Leftrightarrow & w_{mean}^2 \sum_{i=0}^{n-1} [(P_1^{-1}(b - Ax))_i]^2 < \text{tol}^2 \\ \Leftrightarrow & \sum_{i=0}^{n-1} [(P_1^{-1}(b - Ax))_i]^2 < \left(\frac{\text{tol}}{w_{mean}}\right)^2 \\ \Leftrightarrow & \|P_1^{-1}(b - Ax)\|_2 < \frac{\text{tol}}{w_{mean}} \end{aligned}$$

Therefore we compute the tolerance scaling factor

$$w_{mean} = \|w\|_2 / \sqrt{n}$$

and supply the scaled tolerance `delta = tol/w_mean` to the SUNLinSol object.

### 9.2.3 Providing a custom SUNLinearSolver

In certain instances, users may wish to provide a custom SUNLinSol implementation to ARKODE in order to leverage the structure of a problem. While the “standard” API for these routines is typically sufficient for most users, others may need additional ARKODE-specific information on top of what is provided. For these purposes, we note the following advanced output functions available in ARKStep and MRIStep:

**ARKStep advanced outputs:** when solving the Newton nonlinear system of equations in predictor-corrector form,

$$\begin{aligned} G(z_{cor}) &\equiv z_{cor} - \gamma f^I(t_{n,i}^I, z_i) - \tilde{a}_i = 0 & [M = I], \\ G(z_{cor}) &\equiv Mz_{cor} - \gamma f^I(t_{n,i}^I, z_i) - \tilde{a}_i = 0 & [M \text{ static}], \\ G(z_{cor}) &\equiv M(t_{n,i}^I)(z_{cor} - \tilde{a}_i) - \gamma f^I(t_{n,i}^I, z_i) = 0 & [M \text{ time-dependent}]. \end{aligned}$$

- `ARKStepGetCurrentTime()` – when called within the computation of a step (i.e., within a solve) this returns  $t_{n,i}^I$ . Otherwise the current internal solution time is returned.
- `ARKStepGetCurrentState()` – when called within the computation of a step (i.e., within a solve) this returns the current stage vector  $z_i = z_{cor} + z_{pred}$ . Otherwise the current internal solution is returned.
- `ARKStepGetCurrentGamma()` – returns  $\gamma$ .
- `ARKStepGetCurrentMassMatrix()` – returns  $M(t)$ .
- `ARKStepGetNonlinearSystemData()` – returns  $z_i$ ,  $z_{pred}$ ,  $f^I(t_{n,i}^I, y_{cur})$ ,  $\tilde{a}_i$ , and  $\gamma$ .

**MRISet advanced outputs:** when solving the Newton nonlinear system of equations in predictor-corrector form,

$$G(z_{cor}) \equiv z_{cor} - \gamma f^I(t_{n,i}^S, z_i) - \tilde{a}_i = 0$$

- `MRISetGetCurrentTime()` – when called within the computation of a step (i.e., within a solve) this returns  $t_{n,i}^S$ . Otherwise the current internal solution time is returned.
- `MRISetGetCurrentState()` – when called within the computation of a step (i.e., within a solve) this returns the current stage vector  $z_i = z_{cor} + z_{pred}$ . Otherwise the current internal solution is returned.
- `MRISetGetCurrentGamma()` – returns  $\gamma$ .
- `MRISetGetNonlinearSystemData()` – returns  $z_i$ ,  $z_{pred}$ ,  $f^I(t_{n,i}^I, y_{cur})$ ,  $\tilde{a}_i$ , and  $\gamma$ .

## 9.3 The SUNLinSol\_Band Module

The SUNLinSol\_Band implementation of the SUNLinearSolver class is designed to be used with the corresponding `SUNMATRIX_BAND` matrix type, and one of the serial or shared-memory `N_Vector` implementations (NVECTOR\_SERIAL, NVECTOR\_OPENMP or NVECTOR\_PTHREADS).

### 9.3.1 SUNLinSol\_Band Usage

The header file to be included when using this module is `sunlinsol/sunlinsol_band.h`. The SUNLinSol\_Band module is accessible from all SUNDIALS packages *without* linking to the `libsundials_sunlinsolband` module library.

The SUNLinSol\_Band module provides the following user-callable constructor routine:

`SUNLinearSolver SUNLinSol_Band(N_Vector y, SUNMatrix A, SUNContext sunctx)`

This function creates and allocates memory for a band SUNLinearSolver.

#### Arguments:

- `y` – vector used to determine the linear system size
- `A` – matrix used to assess compatibility
- `sunctx` – the `SUNContext` object (see §4.1)

**Return value:** New SUNLinSol\_Band object, or NULL if either `A` or `y` are incompatible.

**Notes:** This routine will perform consistency checks to ensure that it is called with consistent `N_Vector` 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.

For backwards compatibility, we also provide the following wrapper function:

`SUNLinearSolver SUNBandLinearSolver(N_Vector y, SUNMatrix A)`  
Wrapper function for `SUNLinSol_Band()`, with identical input and output arguments.

### 9.3.2 SUNLinSol\_Band Description

The SUNLinSol\_Band module defines the *content* field of a *SUNLinearSolver* to be the following structure:

```
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.

This solver is constructed to perform the following operations:

- The “setup” call performs an *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  $\text{smu} = \text{MIN}(N-1, \mu + \text{ml})$ . The lower triangular factor *L* has lower bandwidth *ml*.

The SUNLinSol\_Band module defines band implementations of all “direct” linear solver operations listed in §9.1:

- `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`

## 9.4 The SUNLinSol\_Dense Module

The SUNLinSol\_Dense implementation of the `SUNLinearSolver` class is designed to be used with the corresponding `SUNMATRIX_DENSE` matrix type, and one of the serial or shared-memory `N_Vector` implementations (`NVECTOR_SERIAL`, `NVECTOR_OPENMP` or `NVECTOR_PTHREADS`).

### 9.4.1 SUNLinSol\_Dense Usage

The header file to be included when using this module is `sunlinsol/sunlinsol_dense.h`. The SUNLinSol\_Dense module is accessible from all SUNDIALS solvers *without* linking to the `libsundials_sunlinsoldense` module library.

The module SUNLinSol\_Dense provides the following user-callable constructor routine:

`SUNLinearSolver SUNLinSol_Dense(N_Vector y, SUNMatrix A, SUNContext sunctx)`

This function creates and allocates memory for a dense `SUNLinearSolver`.

#### Arguments:

- `y` – vector used to determine the linear system size.
- `A` – matrix used to assess compatibility.
- `sunctx` – the `SUNContext` object (see §4.1)

**Return value:** New `SUNLinSol_Dense` object, or `NULL` if either `A` or `y` are incompatible.

**Notes:** This routine will perform consistency checks to ensure that it is called with consistent `N_Vector` 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.

For backwards compatibility, we also provide the following wrapper function:

`SUNLinearSolver SUNDenseLinearSolver(N_Vector y, SUNMatrix A)`

Wrapper function for `SUNLinSol_Dense()`, with identical input and output arguments

### 9.4.2 SUNLinSol\_Dense Description

The `SUNLinSol_Dense` module defines the `content` field of a `SUNLinearSolver` to be the following structure:

```
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.

This solver is constructed to perform the following operations:

- The “setup” call performs an  $LU$  factorization with partial (row) pivoting ( $\mathcal{O}(N^3)$  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 ( $\mathcal{O}(N^2)$  cost).

The `SUNLinSol_Dense` module defines dense implementations of all “direct” linear solver operations listed in §9.1:

- `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 `N`, `last_flag`, and `pivots`.
- `SUNLinSolFree_Dense`

## 9.5 The `SUNLinSol_KLU` Module

The `SUNLinSol_KLU` implementation of the `SUNLinearSolver` class is designed to be used with the corresponding `SUNMATRIX_SPARSE` matrix type, and one of the serial or shared-memory `N_Vector` implementations (NVECTOR\_SERIAL, NVECTOR\_OPENMP, or NVECTOR\_PTHREADS).

### 9.5.1 `SUNLinSol_KLU` Usage

The header file to be included 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 module `SUNLinSol_KLU` provides the following additional user-callable routines:

`SUNLinearSolver SUNLinSol_KLU(N_Vector y, SUNMatrix A, SUNContext sunctx)`

This constructor function creates and allocates memory for a `SUNLinSol_KLU` object.

#### Arguments:

- `y` – vector used to determine the linear system size.
- `A` – matrix used to assess compatibility.
- `sunctx` – the `SUNContext` object (see §4.1)

**Return value:** New `SUNLinSol_KLU` object, or `NULL` if either `A` or `y` are incompatible.

**Notes:** This routine will perform consistency checks to ensure that it is called with consistent `N_Vector` 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.

---

int **SUNLinSol\_KLUReInit**(*SUNLinearSolver* S, *SUNMatrix* A, *sunindextype* nnz, int reinit\_type)

This function 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 nonzeros has changed or if the structure of the linear system has changed which would require a new symbolic (and numeric factorization).

**Arguments:**

- *S* – existing *SUNLinSol\_KLU* object to reinitialize.
- *A* – sparse *SUNMatrix* matrix (with updated structure) to use for reinitialization.
- *nnz* – maximum number of nonzeros expected for Jacobian matrix.
- *reinit\_type* – governs 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 *SUNKLUReInit* call).

**Return value:**

- **SUNLS\_SUCCESS** – reinitialization successful.
- **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.

**Notes:** This routine assumes no other changes to solver use are necessary.

int **SUNLinSol\_KLUSetOrdering**(*SUNLinearSolver* S, int ordering\_choice)

This function sets the ordering used by KLU for reducing fill in the linear solve.

**Arguments:**

- *S* – existing *SUNLinSol\_KLU* object to update.
- *ordering\_choice* – type of ordering to use, options are:
  0. AMD,
  1. COLAMD, and
  2. the natural ordering.

The default is 1 for COLAMD.

**Return value:**

- **SUNLS\_SUCCESS** – ordering choice successfully updated.
- **SUNLS\_MEM\_NULL** – *S* is NULL.
- **SUNLS\_ILL\_INPUT** – *ordering\_choice*.

*sun\_klu\_symbolic* \***SUNLinSol\_KLUGetSymbolic**(*SUNLinearSolver* S)

This function returns a pointer to the KLU symbolic factorization stored in the *SUNLinSol\_KLU* content structure.

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 compiled with 64-bit indices (*SUNDIALS\_INDEX\_SIZE*=64) this is mapped to the KLU type *klu\_l\_symbolic*.

`sun_klu_numeric *SUNLinSol_KLUGetNumeric(SUNLinearSolver S)`

This function returns a pointer to the KLU numeric factorization stored in the SUNLinSol\_KLU content structure.

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`.

`sun_klu_common *SUNLinSol_KLUGetCommon(SUNLinearSolver S)`

This function returns a pointer to the KLU common structure stored in the SUNLinSol\_KLU content structure.

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`.

For backwards compatibility, we also provide the following wrapper functions, each with identical input and output arguments to the routines that they wrap:

`SUNLinearSolver SUNKLU(N_Vector y, SUNMatrix A)`

Wrapper function for `SUNLinSol_KLU()`

`int SUNKLUReInit(SUNLinearSolver S, SUNMatrix A, sunindextype nnz, int reinit_type)`

Wrapper function for `SUNLinSol_KLUReInit()`

`int SUNKLUSetOrdering(SUNLinearSolver S, int ordering_choice)`

Wrapper function for `SUNLinSol_KLUSetOrdering()`

## 9.5.2 SUNLinSol\_KLU Description

The SUNLinSol\_KLU module defines the *content* field of a SUNLinearSolver to be the following structure:

```
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).

The SUNLinSol\_KLU module is a `SUNLinearSolver` wrapper for the KLU sparse matrix factorization and solver library written by Tim Davis and collaborators ([18, 66]). 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 §12.1.4 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 *Data Types* for details). Since the KLU library supports both 32-bit and 64-bit integers, this interface will be compiled for either of the available `sunindextype` options.

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 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.

The SUNLinSol\_KLU module defines implementations of all “direct” linear solver operations listed in §9.1:

- `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.
- `SUNLinSolFree_KLU`

## 9.6 The SUNLinSol\_LapackBand Module

The SUNLinSol\_LapackBand implementation of the SUNLinearSolver class is designed to be used with the corresponding SUNMATRIX\_BAND matrix type, and one of the serial or shared-memory N\_Vector implementations (NVECTOR\_SERIAL, NVECTOR\_OPENMP, or NVECTOR\_PTHREADS). The

### 9.6.1 SUNLinSol\_LapackBand Usage

The header file to be included when using this module is `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 module SUNLinSol\_LapackBand provides the following user-callable routine:

`SUNLinearSolver SUNLinSol_LapackBand(N_Vector y, SUNMatrix A, SUNContext sunctx)`

This function creates and allocates memory for a LAPACK band SUNLinearSolver.

#### Arguments:

- `y` – vector used to determine the linear system size.
- `A` – matrix used to assess compatibility.
- `sunctx` – the `SUNContext` object (see §4.1)

**Return value:** New SUNLinSol\_LapackBand object, or `NULL` if either `A` or `y` are incompatible.

**Notes:** This routine will perform consistency checks to ensure that it is called with consistent N\_Vector 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.

For backwards compatibility, we also provide the following wrapper function:

`SUNLinearSolver SUNLapackBand(N_Vector y, SUNMatrix A)`

Wrapper function for `SUNLinSol_LapackBand()`, with identical input and output arguments.

### 9.6.2 SUNLinSol\_LapackBand Description

SUNLinSol\_LapackBand module defines the *content* field of a SUNLinearSolver to be the following structure:

```
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.

The SUNLinSol\_LapackBand module is a `SUNLinearSolver` 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 `realtyp`e set to double or single, respectively (see §5.1.1 for details). 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 §12.1.4 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 `realtyp`e. Similarly, since there do not exist 64-bit integer LAPACK routines, the SUNLinSol\_LapackBand module also cannot be compiled when using `int64_t` for the `sunindextyp`e.

This solver is constructed to perform the following operations:

- The “setup” call performs an  $LU$  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 `samu = MIN(N-1, mu+ml)`. The lower triangular factor  $L$  has lower bandwidth `ml`.

The SUNLinSol\_LapackBand module defines band implementations of all “direct” linear solver operations listed in §9.1:

- `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`

## 9.7 The SUNLinSol\_LapackDense Module

The SUNLinSol\_LapackDense implementation of the `SUNLinearSolver` class is designed to be used with the corresponding `SUNMATRIX_DENSE` matrix type, and one of the serial or shared-memory `N_Vector` implementations (`NVECTOR_SERIAL`, `NVECTOR_OPENMP`, or `NVECTOR_PTHREADS`).

### 9.7.1 SUNLinSol\_LapackDense Usage

The header file to be included when using this module is `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 module `SUNLinSol_LapackDense` provides the following additional user-callable constructor routine:

`SUNLinearSolver SUNLinSol_LapackDense(N_Vector y, SUNMatrix A, SUNContext sunctx)`

This function creates and allocates memory for a LAPACK dense `SUNLinearSolver`.

#### Arguments:

- `y` – vector used to determine the linear system size.
- `A` – matrix used to assess compatibility.
- `sunctx` – the `SUNContext` object (see §4.1)

**Return value:** New `SUNLinSol_LapackDense` object, or `NULL` if either `A` or `y` are incompatible.

**Notes:** This routine will perform consistency checks to ensure that it is called with consistent `N_Vector` 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.

For backwards compatibility, we also provide the following wrapper function:

`SUNLinearSolver SUNLapackDense(N_Vector y, SUNMatrix A)`

Wrapper function for `SUNLinSol_LapackDense()`, with identical input and output arguments.

### 9.7.2 SUNLinSol\_LapackDense Description

The `SUNLinSol_LapackDense` module defines the `content` field of a `SUNLinearSolver` to be the following structure:

```
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.

The `SUNLinSol_LapackDense` module is a `SUNLinearSolver` 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 §5.1.1 for details). 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 §12.1.4 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 `int64_t` for the `sunindextype`.

This solver is constructed to perform the following operations:

- The “setup” call performs an  $LU$  factorization with partial (row) pivoting ( $\mathcal{O}(N^3)$  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 ( $\mathcal{O}(N^2)$  cost).

The SUNLinSol\_LapackDense module defines dense implementations of all “direct” linear solver operations listed in §9.1:

- `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`

## 9.8 The SUNLinSol\_MagmaDense Module

The SUNLinearSolver\_MagmaDense implementation of the SUNLinearSolver class is designed to be used with the SUNMATRIX\_MAGMADENSE matrix, and a GPU-enabled vector. The header file to include when using this module is `sunlinsol/sunlinsol_magmadense.h`. The installed library to link to is `libsundials_sunlinsolmagmadense.lib` where `lib` is typically `.so` for shared libraries and `.a` for static libraries.

**Warning:** The SUNLinearSolver\_MagmaDense module is experimental and subject to change.

### 9.8.1 SUNLinearSolver\_MagmaDense Description

The SUNLinearSolver\_MagmaDense implementation provides an interface to the dense LU and dense batched LU methods in the **MAGMA** linear algebra library [59]. The batched LU methods are leveraged when solving block diagonal linear systems of the form

$$\begin{bmatrix} \mathbf{A}_0 & 0 & \cdots & 0 \\ 0 & \mathbf{A}_1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{A}_{n-1} \end{bmatrix} \mathbf{x}_j = \mathbf{b}_j.$$

## 9.8.2 SUNLinearSolver\_MagmaDense Functions

The SUNLinearSolver\_MagmaDense module defines implementations of all “direct” linear solver operations listed in §9.1:

- SUNLinSolGetType\_MagmaDense
- SUNLinSolInitialize\_MagmaDense
- SUNLinSolSetup\_MagmaDense
- SUNLinSolSolve\_MagmaDense
- SUNLinSolLastFlag\_MagmaDense
- SUNLinSolFree\_MagmaDense

In addition, the module provides the following user-callable routines:

*SUNLinearSolver* **SUNLinSol\_MagmaDense**(*N\_Vecotr* *y*, *SUNMatrix* *A*, *SUNContext* *sunctx*)

This constructor function creates and allocates memory for a SUNLinearSolver object.

**Arguments:**

- *y* – a vector for checking compatibility with the solver.
- *A* – a SUNMATRIX\_MAGMADENSE matrix for checking compatibility with the solver.
- *sunctx* – the *SUNContext* object (see §4.1)

**Return value:** If successful, a SUNLinearSolver object. If either *A* or *y* are incompatible then this routine will return NULL. This routine analyzes the input matrix and vector to determine the linear system size and to assess compatibility with the solver.

int **SUNLinSol\_MagmaDense\_SetAsync**(*SUNLinearSolver* *LS*, *booleantype* *onoff*)

This function can be used to toggle the linear solver between asynchronous and synchronous modes. In asynchronous mode (default), SUNLinearSolver operations are asynchronous with respect to the host. In synchronous mode, the host and GPU device are synchronized prior to the operation returning.

**Arguments:**

- *LS* – a SUNLinSol\_MagmaDense object
- *onoff* – 0 for synchronous mode or 1 for asynchronous mode (default 1)

**Return value:**

- SUNLS\_SUCCESS if successful
- SUNLS\_MEM\_NULL if *LS* is NULL

## 9.8.3 SUNLinearSolver\_MagmaDense Content

The SUNLinearSolver\_MagmaDense module defines the object *content* field of a SUNLinearSolver to be the following structure:

```
struct _SUNLinearSolverContent_MagmaDense {  
    int last_flag;  
    booleantype async;  
    sunindextype N;  
    SUNMemory pivots;  
    SUNMemory pivotsarr;
```

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```

SUNMemory      dpivotsarr;
SUNMemory      infoarr;
SUNMemory      rhsarr;
SUNMemoryHelper memhelp;
magma_queue_t   q;
} ;

```

## 9.9 The SUNLinSol\_OneMklDense Module

The SUNLinearSolver\_OneMklDense implementation of the SUNLinearSolver class interfaces to the direct linear solvers from the Intel oneAPI Math Kernel Library (oneMKL) for solving dense systems or block-diagonal systems with dense blocks. This linear solver is best paired with the SUNMatrix\_OneMklDense matrix.

The header file to include when using this class is `sunlinsol/sunlinsol_onemkldense.h`. The installed library to link to is `libsundials_sunlinsolonemkldense.lib` where `lib` is typically `.so` for shared libraries and `.a` for static libraries.

**Warning:** The SUNLinearSolver\_OneMklDense class is experimental and subject to change.

### 9.9.1 SUNLinearSolver\_OneMklDense Functions

The SUNLinearSolver\_OneMklDense class defines implementations of all “direct” linear solver operations listed in §9.1:

- `SUNLinSolGetType_OneMklDense` – returns `SUNLINEARSOLVER_ONEMKLDENSE`
- `SUNLinSolInitialize_OneMklDense`
- `SUNLinSolSetup_OneMklDense`
- `SUNLinSolSolve_OneMklDense`
- `SUNLinSolLastFlag_OneMklDense`
- `SUNLinSolFree_OneMklDense`

In addition, the class provides the following user-callable routines:

`SUNLinearSolver SUNLinSol_OneMklDense(N_Vector y, SUNMatrix A, SUNContext sunctx)`  
 This constructor function creates and allocates memory for a SUNLinearSolver object.

#### Arguments:

- `y` – a vector for checking compatibility with the solver.
- `A` – a SUNMatrix\_OneMklDense matrix for checking compatibility with the solver.
- `sunctx` – the `SUNContext` object (see §4.1)

**Return value:** If successful, a SUNLinearSolver object. If either `A` or `y` are incompatible then this routine will return `NULL`. This routine analyzes the input matrix and vector to determine the linear system size and to assess compatibility with the solver.

## 9.9.2 SUNLinearSolver\_OneMklDense Usage Notes

**Warning:** The SUNLinearSolver\_OneMklDense class only supports 64-bit indexing, thus SUNDIALS must be built for 64-bit indexing to use this class.

When using the SUNLinearSolver\_OneMklDense class with a SUNDIALS package (e.g. CVODE), the queue given to the matrix is also used for the linear solver.

## 9.10 The SUNLinSol\_PCG Module

The SUNLinSol\_PCG implementation of the SUNLinearSolver class performs the PCG (Preconditioned Conjugate Gradient [33]) method; this is an iterative linear solver that is designed to be compatible with any N\_Vector 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.

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 N\_Vector, supplied by the user.

In this notation, PCG applies the underlying CG algorithm to the equivalent transformed system

$$\tilde{A}\tilde{x} = \tilde{b} \tag{9.4}$$

where

$$\begin{aligned} \tilde{A} &= SP^{-1}AP^{-1}S, \\ \tilde{b} &= SP^{-1}b, \\ \tilde{x} &= S^{-1}Px. \end{aligned} \tag{9.5}$$

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:

$$\begin{aligned} \|\tilde{b} - \tilde{A}\tilde{x}\|_2 &< \delta \\ \Leftrightarrow \quad \|SP^{-1}b - SP^{-1}Ax\|_2 &< \delta \\ \Leftrightarrow \quad \|P^{-1}b - P^{-1}Ax\|_S &< \delta \end{aligned}$$

where  $\|v\|_S = \sqrt{v^T S^T S v}$ , with an input tolerance  $\delta$ .

### 9.10.1 SUNLinSol\_PCG Usage

The header file to be included when using this module is `sunlinsol/sunlinsol_pcg.h`. The SUNLinSol\_PCG module is accessible from all SUNDIALS solvers *without* linking to the `libsundials_sunlinsolpcg` module library.

The module SUNLinSol\_PCG provides the following user-callable routines:

*SUNLinearSolver* **SUNLinSol\_PCG**(*N\_Vector* y, int pretype, int maxl, *SUNContext* sunctx)

This constructor function creates and allocates memory for a PCG *SUNLinearSolver*.

**Arguments:**

- *y* – a template vector.
- *pretype* – a flag indicating the type of preconditioning to use:
  - SUN\_PREC\_NONE
  - SUN\_PREC\_LEFT
  - SUN\_PREC\_RIGHT
  - SUN\_PREC\_BOTH
- *maxl* – the maximum number of linear iterations to allow.
- *sunctx* – the *SUNContext* object (see §4.1)

**Return value:** If successful, 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 *N\_Vector* implementation (i.e. that it supplies the requisite vector operations).

A *maxl* argument that is  $\leq 0$  will result in the default value (5).

Since the PCG algorithm is designed to only support symmetric preconditioning, then any of the *pretype* inputs SUN\_PREC\_LEFT, SUN\_PREC\_RIGHT, or SUN\_PREC\_BOTH will result in use of the symmetric preconditioner; any other integer input will result in the default (no preconditioning). 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.

**int SUNLinSol\_PCGSetPreType(*SUNLinearSolver* S, int pretype)**

This function updates the flag indicating use of preconditioning.

**Arguments:**

- *S* – SUNLinSol\_PCG object to update.
- *pretype* – a flag indicating the type of preconditioning to use:
  - SUN\_PREC\_NONE
  - SUN\_PREC\_LEFT
  - SUN\_PREC\_RIGHT
  - SUN\_PREC\_BOTH

**Return value:**

- SUNLS\_SUCCESS – successful update.
- SUNLS\_ILL\_INPUT – illegal *pretype*

- SUNLS\_MEM\_NULL – S is NULL

**Notes:** As above, any one of the input values, SUN\_PREC\_LEFT, SUN\_PREC\_RIGHT, or SUN\_PREC\_BOTH will enable preconditioning; SUN\_PREC\_NONE disables preconditioning.

int **SUNLinSol\_PCGSetMaxl**(*SUNLinearSolver* S, int maxl)

This function updates the number of linear solver iterations to allow.

**Arguments:**

- *S* – SUNLinSol\_PCG object to update.
- *maxl* – maximum number of linear iterations to allow. Any non-positive input will result in the default value (5).

**Return value:**

- SUNLS\_SUCCESS – successful update.
- SUNLS\_MEM\_NULL – S is NULL

int **SUNLinSolSetInfoFile\_PCG**(*SUNLinearSolver* LS, FILE \*info\_file)

The function *SUNLinSolSetInfoFile\_PCG()* sets the output file where all informative (non-error) messages should be directed.

**Arguments:**

- *LS* – a SUNLinSol object
- *info\_file* – pointer to output file (`stdout` by default); a NULL input will disable output

**Return value:**

- *SUNLS\_SUCCESS* if successful
- *SUNLS\_MEM\_NULL* if the *SUNLinearSolver* memory was NULL
- *SUNLS\_ILL\_INPUT* if SUNDIALS was not built with monitoring enabled

**Notes:** This function is intended for users that wish to monitor the linear solver progress. By default, the file pointer is set to `stdout`.

**SUNDIALS must be built with the CMake option `SUNDIALS_BUILD_WITH_MONITORING` to utilize this function.** See [§12.1.2](#) for more information.

int **SUNLinSolSetPrintLevel\_PCG**(*SUNLinearSolver* LS, int print\_level)

The function *SUNLinSolSetPrintLevel\_PCG()* specifies the level of verbosity of the output.

**Arguments:**

- *LS* – a SUNLinSol object
- *print\_level* – flag indicating level of verbosity; must be one of:
  - 0, no information is printed (default)
  - 1, for each linear iteration the residual norm is printed

**Return value:**

- *SUNLS\_SUCCESS* if successful
- *SUNLS\_MEM\_NULL* if the *SUNLinearSolver* memory was NULL
- *SUNLS\_ILL\_INPUT* if SUNDIALS was not built with monitoring enabled, or if the print level value was invalid

**Notes:** This function is intended for users that wish to monitor the linear solver progress. By default, the print level is 0.

**SUNDIALS must be built with the CMake option SUNDIALS\_BUILD\_WITH\_MONITORING to utilize this function.** See §12.1.2 for more information.

For backwards compatibility, we also provide the following wrapper functions, each with identical input and output arguments to the routines that they wrap:

*SUNLinearSolver* **SUNPCG**(*N\_Vector* y, int pretype, int maxl)

Wrapper function for *SUNLinSol\_PCG()*

int **SUNPCGSetPrecType**(*SUNLinearSolver* S, int pretype)

Wrapper function for *SUNLinSol\_PCGSetPrecType()*

int **SUNPCGSetMaxl**(*SUNLinearSolver* S, int maxl)

Wrapper function for *SUNLinSol\_PCGSetMaxl()*

## 9.10.2 SUNLinSol\_PCG Description

The SUNLinSol\_PCG module defines the *content* field of a *SUNLinearSolver* to be the following structure:

```
struct _SUNLinearSolverContent_PCG {
    int maxl;
    int pretype;
    booleantype zeroguess;
    int numiters;
    realtype resnorm;
    int last_flag;
    SUNATimesFn ATimes;
    void* ATData;
    SUNPSetupFn Psetup;
    SUNPSolveFn Psolve;
    void* PData;
    N_Vector s;
    N_Vector r;
    N_Vector p;
    N_Vector z;
    N_Vector Ap;
    int      print_level;
    FILE*   info_file;
};
```

These entries of the *content* field contain the following information:

- **maxl** - number of PCG iterations to allow (default is 5),
- **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` - a `N_Vector` which holds the preconditioned linear system residual,
- `p`, `z`, `Ap` - `N_Vector` used for workspace by the PCG algorithm.
- `print_level` - controls the amount of information to be printed to the info file
- `info_file` - the file where all informative (non-error) messages will be directed

This solver is constructed to perform the following operations:

- During construction all `N_Vector` solver data is allocated, with vectors cloned from a template `N_Vector` 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.

The `SUNLinSol_PCG` module defines implementations of all “iterative” linear solver operations listed in §9.1:

- `SUNLinSolGetType_PCG`
- `SUNLinSolInitialize_PCG`
- `SUNLinSolSetATimes_PCG`
- `SUNLinSolSetPreconditioner_PCG`
- `SUNLinSolSetScalingVectors_PCG` – since PCG only supports symmetric scaling, the second `N_Vector` argument to this function is ignored.
- `SUNLinSolSetZeroGuess_PCG` – note the solver assumes a non-zero guess by default and the zero guess flag is reset to `SUNFALSE` after each call to `SUNLinSolSolve_PCG()`.
- `SUNLinSolSetup_PCG`
- `SUNLinSolSolve_PCG`
- `SUNLinSolNumIters_PCG`
- `SUNLinSolResNorm_PCG`
- `SUNLinSolResid_PCG`
- `SUNLinSolLastFlag_PCG`
- `SUNLinSolSpace_PCG`
- `SUNLinSolFree_PCG`

## 9.11 The SUNLinSol\_SPBCGS Module

The SUNLinSol\_SPBCGS implementation of the `SUNLinearSolver` class performs a Scaled, Preconditioned, Bi-Conjugate Gradient, Stabilized [61] method; this is an iterative linear solver that is designed to be compatible with any `N_Vector` implementation that supports a minimal subset of operations (`N_VClone()`, `N_VDotProd()`, `N_VScale()`, `N_VLinearSum()`, `N_VProd()`, `N_VDiv()`, and `N_VDestroy()`). Unlike the SPGMR and SPFGMR algorithms, SPBCGS requires a fixed amount of memory that does not increase with the number of allowed iterations.

### 9.11.1 SUNLinSol\_SPBCGS Usage

The header file to be included when using this module is `sunlinsol/sunlinsol_spbcgs.h`. The SUNLinSol\_SPBCGS module is accessible from all SUNDIALS solvers *without* linking to the `libsundials_sunlinsolspbcgs` module library.

The module SUNLinSol\_SPBCGS provides the following user-callable routines:

`SUNLinearSolver SUNLinSol_SPBCGS(N_Vector y, int pretype, int maxl, SUNContext sunctx)`  
This constructor function creates and allocates memory for a SPBCGS `SUNLinearSolver`.

#### Arguments:

- `y` – a template vector.
- `pretype` – a flag indicating the type of preconditioning to use:
  - `SUN_PREC_NONE`
  - `SUN_PREC_LEFT`
  - `SUN_PREC_RIGHT`
  - `SUN_PREC_BOTH`
- `maxl` – the maximum number of linear iterations to allow.
- `sunctx` – the `SUNContext` object (see §4.1)

**Return value:** If successful, 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 `N_Vector` implementation (i.e. that it supplies the requisite vector operations).

A `maxl` argument that is  $\leq 0$  will result in the default value (5).

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.

---

**Note:** With `SUN_PREC_RIGHT` or `SUN_PREC_BOTH` the initial guess must be zero (use `SUNLinSolSetZeroGuess()` to indicate the initial guess is zero).

---

`int SUNLinSol_SPBCGSSetPreType(SUNLinearSolver S, int pretype)`

This function updates the flag indicating use of preconditioning.

#### Arguments:

- `S` – SUNLinSol\_SPBCGS object to update.

- *pretype* – a flag indicating the type of preconditioning to use:
  - SUN\_PREC\_NONE
  - SUN\_PREC\_LEFT
  - SUN\_PREC\_RIGHT
  - SUN\_PREC\_BOTH

**Return value:**

- SUNLS\_SUCCESS – successful update.
- SUNLS\_ILL\_INPUT – illegal pretype
- SUNLS\_MEM\_NULL – S is NULL

```
int SUNLinSol_SPBCGSSetMaxl(SUNLinearSolver S, int maxl)
```

This function updates the number of linear solver iterations to allow.

**Arguments:**

- *S* – SUNLinSol\_SPBCGS object to update.
- *maxl* – maximum number of linear iterations to allow. Any non-positive input will result in the default value (5).

**Return value:**

- SUNLS\_SUCCESS – successful update.
- SUNLS\_MEM\_NULL – S is NULL

```
int SUNLinSolSetInfoFile_SPBCGS(SUNLinearSolver LS, FILE *info_file)
```

The function [SUNLinSolSetInfoFile\\_SPBCGS\(\)](#) sets the output file where all informative (non-error) messages should be directed.

**Arguments:**

- *LS* – a SUNLinSol object
- *info\_file* – pointer to output file (**stdout by default**); a NULL input will disable output

**Return value:**

- *SUNLS\_SUCCESS* if successful
- *SUNLS\_MEM\_NULL* if the SUNLinearSolver memory was NULL
- *SUNLS\_ILL\_INPUT* if SUNDIALS was not built with monitoring enabled

**Notes:** This function is intended for users that wish to monitor the linear solver progress. By default, the file pointer is set to `stdout`.

**SUNDIALS must be built with the CMake option `SUNDIALS_BUILD_WITH_MONITORING` to utilize this function.** See §12.1.2 for more information.

```
int SUNLinSolSetPrintLevel_SPBCGS(SUNLinearSolver LS, int print_level)
```

The function [SUNLinSolSetPrintLevel\\_SPBCGS\(\)](#) specifies the level of verbosity of the output.

**Arguments:**

- *LS* – a SUNLinSol object
- *print\_level* – flag indicating level of verbosity; must be one of:
  - 0, no information is printed (default)

- 1, for each linear iteration the residual norm is printed

**Return value:**

- *SUNLS\_SUCCESS* if successful
- *SUNLS\_MEM\_NULL* if the SUNLinearSolver memory was NULL
- *SUNLS\_ILL\_INPUT* if SUNDIALS was not built with monitoring enabled, or if the print level value was invalid

**Notes:** This function is intended for users that wish to monitor the linear solver progress. By default, the print level is 0.

**SUNDIALS must be built with the CMake option *SUNDIALS\_BUILD\_WITH\_MONITORING* to utilize this function.** See §12.1.2 for more information.

For backwards compatibility, we also provide the following wrapper functions, each with identical input and output arguments to the routines that they wrap:

*SUNLinearSolver* **SUNSPBCGS**(*N\_Vector* y, int pretype, int maxl)  
Wrapper function for *SUNLinSol\_SPBCGS()*

int **SUNSPBCGSSetPrecType**(*SUNLinearSolver* S, int pretype)  
Wrapper function for *SUNLinSol\_SPBCGSSetPrecType()*

int **SUNSPBCGSSetMaxl**(*SUNLinearSolver* S, int maxl)  
Wrapper function for *SUNLinSol\_SPBCGSSetMaxl()*

## 9.11.2 SUNLinSol\_SPBCGS Description

The SUNLinSol\_SPBCGS module defines the *content* field of a *SUNLinearSolver* to be the following structure:

```
struct _SUNLinearSolverContent_SPBCGS {
    int maxl;
    int pretype;
    booleantype zeroguess;
    int numiters;
    realtype resnorm;
    int last_flag;
    SUNATimesFn ATimes;
    void* ATData;
    SUNPSetupFn Psetup;
    SUNPSolveFn 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;
    int      print_level;
    FILE*   info_file;
};
```

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),
- `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` - a `N_Vector` which holds the current scaled, preconditioned linear system residual,
- `r_star` - a `N_Vector` which holds the initial scaled, preconditioned linear system residual,
- `p, q, u, Ap, vtemp` - `N_Vector` used for workspace by the SPBCGS algorithm.
- `print_level` - controls the amount of information to be printed to the info file
- `info_file` - the file where all informative (non-error) messages will be directed

This solver is constructed to perform the following operations:

- During construction all `N_Vector` solver data is allocated, with vectors cloned from a template `N_Vector` 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_SPBCGS` to supply the `ATimes`, `PSetup`, 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` `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 SPBCGS iteration is performed. This will include scaling and preconditioning if those options have been supplied.

The `SUNLinSol_SPBCGS` module defines implementations of all “iterative” linear solver operations listed in §9.1:

- `SUNLinSolGetType_SPBCGS`
- `SUNLinSolInitialize_SPBCGS`
- `SUNLinSolSetATimes_SPBCGS`
- `SUNLinSolSetPreconditioner_SPBCGS`
- `SUNLinSolSetScalingVectors_SPBCGS`
- `SUNLinSolSetZeroGuess_SPBCGS` – note the solver assumes a non-zero guess by default and the zero guess flag is reset to `SUNFALSE` after each call to `SUNLinSolSolve_SPBCGS()`.
- `SUNLinSolSetup_SPBCGS`

- SUNLinSolSolve\_SPBCGS
- SUNLinSolNumIters\_SPBCGS
- SUNLinSolResNorm\_SPBCGS
- SUNLinSolResid\_SPBCGS
- SUNLinSolLastFlag\_SPBCGS
- SUNLinSolSpace\_SPBCGS
- SUNLinSolFree\_SPBCGS

## 9.12 The SUNLinSol\_SPFGMR Module

The SUNLinSol\_SPFGMR implementation of the `SUNLinearSolver` class performs a Scaled, Preconditioned, Flexible, Generalized Minimum Residual [49] method; this is an iterative linear solver that is designed to be compatible with any `N_Vector` 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 other Krylov iterative linear solvers supplied with SUNDIALS, FGMRES is specifically designed to work with a changing preconditioner (e.g. from an iterative method).

### 9.12.1 SUNLinSol\_SPFGMR Usage

The header file to be included when using this module is `sunlinsol/sunlinsol_spfgmr.h`. The `SUNLinSol_SPFGMR` module is accessible from all SUNDIALS solvers *without* linking to the `libsundials_sunlinsolspfgmr` module library.

The module `SUNLinSol_SPFGMR` provides the following user-callable routines:

`SUNLinearSolver SUNLinSol_SPFGMR(N_Vector y, int pretype, int maxl, SUNContext sunctx)`  
This constructor function creates and allocates memory for a SPFGMR `SUNLinearSolver`.

#### Arguments:

- *y* – a template vector.
- *pretype* – a flag indicating the type of preconditioning to use:
  - `SUN_PREC_NONE`
  - `SUN_PREC_LEFT`
  - `SUN_PREC_RIGHT`
  - `SUN_PREC_BOTH`
- *maxl* – the number of Krylov basis vectors to use.
- *sunctx* – the `SUNContext` object (see §4.1)

**Return value:** If successful, 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 `N_Vector` implementation (i.e. that it supplies the requisite vector operations).

A *maxl* argument that is  $\leq 0$  will result in the default value (5).

Since the FGMRES algorithm is designed to only support right preconditioning, then any of the *pretype* inputs `SUN_PREC_LEFT`, `SUN_PREC_RIGHT`, or `SUN_PREC_BOTH` will result in use of `SUN_PREC_RIGHT`;

any other integer input will result in the default (no preconditioning). We note that some SUNDIALS solvers are designed to only work with left preconditioning (IDA and IDAS). While it is possible to use a right-preconditioned SUNLinSol\_SPFGMR object for these packages, this use mode is not supported and may result in inferior performance.

int **SUNLinSol\_SPFGMRS**et**PrecType**(*SUNLinearSolver* S, int pretype)

This function updates the flag indicating use of preconditioning.

**Arguments:**

- *S* – SUNLinSol\_SPFGMR object to update.
- *pretype* – a flag indicating the type of preconditioning to use:
  - SUN\_PREC\_NONE
  - SUN\_PREC\_LEFT
  - SUN\_PREC\_RIGHT
  - SUN\_PREC\_BOTH

**Return value:**

- SUNLS\_SUCCESS – successful update.
- SUNLS\_ILL\_INPUT – illegal pretype
- SUNLS\_MEM\_NULL – S is NULL

**Notes:** Since the FGMRES algorithm is designed to only support right preconditioning, then any of the *pretype* inputs SUN\_PREC\_LEFT, SUN\_PREC\_RIGHT, or SUN\_PREC\_BOTH will result in use of SUN\_PREC\_RIGHT; any other integer input will result in the default (no preconditioning).

int **SUNLinSol\_SPFGMRS**et**GSType**(*SUNLinearSolver* S, int gstype)

This function sets the type of Gram-Schmidt orthogonalization to use.

**Arguments:**

- *S* – SUNLinSol\_SPFGMR object to update.
- *gstype* – a flag indicating the type of orthogonalization to use:
  - SUN\_MODIFIED\_GS
  - SUN\_CLASSICAL\_GS

**Return value:**

- SUNLS\_SUCCESS – successful update.
- SUNLS\_ILL\_INPUT – illegal gstype
- SUNLS\_MEM\_NULL – S is NULL

int **SUNLinSol\_SPFGMRS**et**MaxRestarts**(*SUNLinearSolver* S, int maxrs)

This function sets the number of FGMRES restarts to allow.

**Arguments:**

- *S* – SUNLinSol\_SPFGMR object to update.
- *maxrs* – maximum number of restarts to allow. A negative input will result in the default of 0.

**Return value:**

- SUNLS\_SUCCESS – successful update.
- SUNLS\_MEM\_NULL – S is NULL

---

```
int SUNLinSolSetInfoFile_SPFGMR(SUNLinearSolver LS, FILE *info_file)
```

The function `SUNLinSolSetInfoFile_SPFGMR()` sets the output file where all informative (non-error) messages should be directed.

**Arguments:**

- *LS* – a `SUNLinSol` object
- *info\_file* – pointer to output file (`stdout` by default); a NULL input will disable output

**Return value:**

- `SUNLS_SUCCESS` if successful
- `SUNLS_MEM_NULL` if the `SUNLinearSolver` memory was NULL
- `SUNLS_ILL_INPUT` if SUNDIALS was not built with monitoring enabled

**Notes:** This function is intended for users that wish to monitor the linear solver progress. By default, the file pointer is set to `stdout`.

**SUNDIALS must be built with the CMake option `SUNDIALS_BUILD_WITH_MONITORING` to utilize this function.** See §12.1.2 for more information.

```
int SUNLinSolSetPrintLevel_SPFGMR(SUNLinearSolver LS, int print_level)
```

The function `SUNLinSolSetPrintLevel_SPFGMR()` specifies the level of verbosity of the output.

**Arguments:**

- *LS* – a `SUNLinSol` object
- *print\_level* – flag indicating level of verbosity; must be one of:
  - 0, no information is printed (default)
  - 1, for each linear iteration the residual norm is printed

**Return value:**

- `SUNLS_SUCCESS` if successful
- `SUNLS_MEM_NULL` if the `SUNLinearSolver` memory was NULL
- `SUNLS_ILL_INPUT` if SUNDIALS was not built with monitoring enabled, or if the print level value was invalid

**Notes:** This function is intended for users that wish to monitor the linear solver progress. By default, the print level is 0.

**SUNDIALS must be built with the CMake option `SUNDIALS_BUILD_WITH_MONITORING` to utilize this function.** See §12.1.2 for more information.

For backwards compatibility, we also provide the following wrapper functions, each with identical input and output arguments to the routines that they wrap:

`SUNLinearSolver` `SUNSPFGMR(N_Vector y, int pretype, int maxl)`

Wrapper function for `SUNLinSol_SPFGMR()`

`int SUNSPFGMRSetPrecType(SUNLinearSolver S, int pretype)`

Wrapper function for `SUNLinSol_SPFGMRSetPrecType()`

`int SUNSPFGMRSetGType(SUNLinearSolver S, int gstype)`

Wrapper function for `SUNLinSol_SPFGMRSetGType()`

`int SUNSPFGMRSetMaxRestarts(SUNLinearSolver S, int maxrs)`

Wrapper function for `SUNLinSol_SPFGMRSetMaxRestarts()`

## 9.12.2 SUNLinSol\_SPFGMR Description

The SUNLinSol\_SPFGMR module defines the *content* field of a SUNLinearSolver to be the following structure:

```
struct _SUNLinearSolverContent_SPFGMR {
    int maxl;
    int pretype;
    int gstype;
    int max_restarts;
    booleantype zeroguess;
    int numiters;
    realtype resnorm;
    int last_flag;
    SUNATimesFn ATimes;
    void* ATData;
    SUNPSetupFn Psetup;
    SUNPSolveFn Psolve;
    void* PData;
    N_Vecor s1;
    N_Vecor s2;
    N_Vecor *V;
    N_Vecor *Z;
    realtype **Hes;
    realtype *givens;
    N_Vecor xcor;
    realtype *yg;
    N_Vecor vtemp;
    int print_level;
    FILE* info_file;
};
```

These entries of the *content* field contain the following information:

- **maxl** - number of FGMRES basis vectors to use (default is 5),
- **pretype** - flag for use of preconditioning (default is none),
- **gstype** - flag for type of Gram-Schmidt orthogonalization (default is modified Gram-Schmidt),
- **max\_restarts** - number of FGMRES 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,
- **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  $v_1, \dots, v_{\text{maxl}+1}$ , stored in  $\text{V}[0], \dots, \text{V}[\text{maxl}]$ . Each  $v_i$  is a vector of type **N\_Vecor**,

- **Z** - the array of preconditioned Krylov basis vectors  $z_1, \dots, z_{\text{maxl}+1}$ , stored in **Z[0]**, ..., **Z[maxl]**. Each  $z_i$  is a vector of type **N\_Vector**,
- **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 **Hes[i][j]**,
- **givens** - a length 2 **maxl** array which represents the Givens rotation matrices that arise in the FGMRES algorithm. These matrices are  $F_0, F_1, \dots, F_j$ , where

$$F_i = \begin{bmatrix} 1 & & & & \\ & \ddots & & & \\ & & 1 & & \\ & & & c_i & -s_i \\ & & & s_i & c_i \\ & & & & 1 \\ & & & & & \ddots \\ & & & & & & 1 \end{bmatrix},$$

are represented in the **givens** vector as **givens[0] = c<sub>0</sub>**, **givens[1] = s<sub>0</sub>**, **givens[2] = c<sub>1</sub>**, **givens[3] = s<sub>1</sub>**, ..., **givens[2j] = c<sub>j</sub>**, **givens[2j+1] = s<sub>j</sub>**,

- **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.
- **print\_level** - controls the amount of information to be printed to the info file
- **info\_file** - the file where all informative (non-error) messages will be directed

This solver is constructed to perform the following operations:

- During construction, the **xcor** and **vtemp** arrays are cloned from a template **N\_Vector** 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**, 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 FGMRES iteration is performed. This will include scaling, preconditioning, and restarts if those options have been supplied.

The **SUNLinSol\_SPFGMR** module defines implementations of all “iterative” linear solver operations listed in §9.1:

- **SUNLinSolGetType\_SPFGMR**
- **SUNLinSolInitialize\_SPFGMR**
- **SUNLinSolSetATimes\_SPFGMR**
- **SUNLinSolSetPreconditioner\_SPFGMR**
- **SUNLinSolSetScalingVectors\_SPFGMR**
- **SUNLinSolSetZeroGuess\_SPFGMR** – note the solver assumes a non-zero guess by default and the zero guess flag is reset to **SUNFALSE** after each call to **SUNLinSolSolve\_SPFGMR()**.

- SUNLinSolSetup\_SPFGMR
- SUNLinSolSolve\_SPFGMR
- SUNLinSolNumIters\_SPFGMR
- SUNLinSolResNorm\_SPFGMR
- SUNLinSolResid\_SPFGMR
- SUNLinSolLastFlag\_SPFGMR
- SUNLinSolSpace\_SPFGMR
- SUNLinSolFree\_SPFGMR

## 9.13 The SUNLinSol\_SPGMR Module

The SUNLinSol\_SPGMR implementation of the `SUNLinearSolver` class performs a Scaled, Preconditioned, Generalized Minimum Residual [50] method; this is an iterative linear solver that is designed to be compatible with any `N_Vector` 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()`).

### 9.13.1 SUNLinSol\_SPGMR Usage

The header file to be included when using this module is `sunlinsol/sunlinsol_spgmr.h`. The SUNLinSol\_SPGMR module is accessible from all SUNDIALS solvers *without* linking to the `libsundials_sunlinsolspgmr` module library.

The module SUNLinSol\_SPGMR provides the following user-callable routines:

`SUNLinearSolver SUNLinSol_SPGMR(N_Vector y, int pretype, int maxl, SUNContext sunctx)`

This constructor function creates and allocates memory for a SPGMR `SUNLinearSolver`.

#### Arguments:

- *y* – a template vector.
- *pretype* – a flag indicating the type of preconditioning to use:
  - `SUN_PREC_NONE`
  - `SUN_PREC_LEFT`
  - `SUN_PREC_RIGHT`
  - `SUN_PREC_BOTH`
- *maxl* – the number of Krylov basis vectors to use.

**Return value:** If successful, 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 `N_Vector` implementation (i.e. that it supplies the requisite vector operations).

A *maxl* argument that is  $\leq 0$  will result in the default value (5).

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\_SPGMR object to use any of the preconditioning options with these solvers, this use mode is not supported and may result in inferior performance.

---

int **SUNLinSol\_SPGMRSetPrecType**(*SUNLinearSolver* S, int pretype)

This function updates the flag indicating use of preconditioning.

**Arguments:**

- *S* – *SUNLinSol\_SPGMR* object to update.
- *pretype* – a flag indicating the type of preconditioning to use:
  - SUN\_PREC\_NONE
  - SUN\_PREC\_LEFT
  - SUN\_PREC\_RIGHT
  - SUN\_PREC\_BOTH

**Return value:**

- SUNLS\_SUCCESS – successful update.
- SUNLS\_ILL\_INPUT – illegal pretype
- SUNLS\_MEM\_NULL – *S* is NULL

int **SUNLinSol\_SPGMRSetGstype**(*SUNLinearSolver* S, int gstype)

This function sets the type of Gram-Schmidt orthogonalization to use.

**Arguments:**

- *S* – *SUNLinSol\_SPGMR* object to update.
- *gstype* – a flag indicating the type of orthogonalization to use:
  - SUN\_MODIFIED\_GS
  - SUN\_CLASSICAL\_GS

**Return value:**

- SUNLS\_SUCCESS – successful update.
- SUNLS\_ILL\_INPUT – illegal gstype
- SUNLS\_MEM\_NULL – *S* is NULL

int **SUNLinSol\_SPGMRSetMaxRestarts**(*SUNLinearSolver* S, int maxrs)

This function sets the number of GMRES restarts to allow.

**Arguments:**

- *S* – *SUNLinSol\_SPGMR* object to update.
- *maxrs* – maximum number of restarts to allow. A negative input will result in the default of 0.

**Return value:**

- SUNLS\_SUCCESS – successful update.
- SUNLS\_MEM\_NULL – *S* is NULL

int **SUNLinSolSetInfoFile\_SPGMR**(*SUNLinearSolver* LS, FILE \*info\_file)

The function *SUNLinSolSetInfoFile\_SPGMR()* sets the output file where all informative (non-error) messages should be directed.

**Arguments:**

- *LS* – a *SUNLinSol* object
- *info\_file* – pointer to output file (*stdout* by default); a NULL input will disable output

**Return value:**

- *SUNLS\_SUCCESS* if successful
- *SUNLS\_MEM\_NULL* if the SUNLinearSolver memory was NULL
- *SUNLS\_ILL\_INPUT* if SUNDIALS was not built with monitoring enabled

**Notes:** This function is intended for users that wish to monitor the linear solver progress. By default, the file pointer is set to `stdout`.

**SUNDIALS must be built with the CMake option `SUNDIALS_BUILD_WITH_MONITORING` to utilize this function.** See §12.1.2 for more information.

```
int SUNLinSolSetPrintLevel_SPGMR(SUNLinearSolver LS, int print_level)
```

The function `SUNLinSolSetPrintLevel_SPGMR()` specifies the level of verbosity of the output.

**Arguments:**

- *LS* – a SUNLinSol object
- *print\_level* – flag indicating level of verbosity; must be one of:
  - 0, no information is printed (default)
  - 1, for each linear iteration the residual norm is printed

**Return value:**

- *SUNLS\_SUCCESS* if successful
- *SUNLS\_MEM\_NULL* if the SUNLinearSolver memory was NULL
- *SUNLS\_ILL\_INPUT* if SUNDIALS was not built with monitoring enabled, or if the print level value was invalid

**Notes:** This function is intended for users that wish to monitor the linear solver progress. By default, the print level is 0.

**SUNDIALS must be built with the CMake option `SUNDIALS_BUILD_WITH_MONITORING` to utilize this function.** See §12.1.2 for more information.

For backwards compatibility, we also provide the wrapper functions, each with identical input and output arguments to the routines that they wrap:

```
SUNLinearSolver SUNSPGMR(N_Vector y, int pretype, int maxl)
```

Wrapper function for `SUNLinSol_SPGMR()`

```
int SUNSPGMRSetPrecType(SUNLinearSolver S, int pretype)
```

Wrapper function for `SUNLinSol_SPGMRSetPrecType()`

```
int SUNSPGMRSetGSType(SUNLinearSolver S, int gstype)
```

Wrapper function for `SUNLinSol_SPGMRSetGSType()`

```
int SUNSPGMRSetMaxRestarts(SUNLinearSolver S, int maxrs)
```

Wrapper function for `SUNLinSol_SPGMRSetMaxRestarts()`

### 9.13.2 SUNLinSol\_SPGMR Description

The SUNLinSol\_SPGMR module defines the *content* field of a SUNLinearSolver to be the following structure:

```
struct _SUNLinearSolverContent_SPGMR {
    int maxl;
    int pretype;
    int gstype;
    int max_restarts;
    booleantype zeroguess;
    int numiters;
    realtype resnorm;
    int last_flag;
    SUNATimesFn ATimes;
    void* ATData;
    SUNPSetupFn Psetup;
    SUNPSolveFn Psolve;
    void* PData;
    N_Vecor s1;
    N_Vecor s2;
    N_Vecor *V;
    realtype **Hes;
    realtype *givens;
    N_Vecor xcor;
    realtype *yg;
    N_Vecor vtemp;
    int print_level;
    FILE* info_file;
};
```

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,
- **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  $v_1, \dots, v_{\text{maxl}+1}$ , stored in  $V[0], \dots, V[\text{maxl}]$ . Each  $v_i$  is a vector of type **N\_Vecor**,

- **Hes** - the  $(\maxl + 1) \times \maxl$  Hessenberg matrix. It is stored row-wise so that the  $(i,j)$ th element is given by `Hes[i][j]`,
- **givens** - a length 2  $\maxl$  array which represents the Givens rotation matrices that arise in the GMRES algorithm. These matrices are  $F_0, F_1, \dots, F_j$ , where

$$F_i = \begin{bmatrix} 1 & & & & \\ & \ddots & & & \\ & & 1 & & \\ & & & c_i & -s_i \\ & & & s_i & c_i \\ & & & & 1 \\ & & & & & \ddots \\ & & & & & & 1 \end{bmatrix},$$

are represented in the **givens** vector as `givens[0] = c0`, `givens[1] = s0`, `givens[2] = c1`, `givens[3] = s1`, ..., `givens[2j] = cj`, `givens[2j+1] = sj`,

- **xcor** - a vector which holds the scaled, preconditioned correction to the initial guess,
- **yg** - a length  $(\maxl + 1)$  array of **realtype** values used to hold “short” vectors (e.g.  $y$  and  $g$ ),
- **vtemp** - temporary vector storage.
- **print\_level** - controls the amount of information to be printed to the info file
- **info\_file** - the file where all informative (non-error) messages will be directed

This solver is constructed to perform the following operations:

- During construction, the **xcor** and **vtemp** arrays are cloned from a template **N\_Vector** 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.

The **SUNLinSol\_SPGMR** module defines implementations of all “iterative” linear solver operations listed in §9.1:

- **SUNLinSolGetType\_SPGMR**
- **SUNLinSolInitialize\_SPGMR**
- **SUNLinSolSetATimes\_SPGMR**
- **SUNLinSolSetPreconditioner\_SPGMR**
- **SUNLinSolSetScalingVectors\_SPGMR**
- **SUNLinSolSetZeroGuess\_SPGMR** – note the solver assumes a non-zero guess by default and the zero guess flag is reset to **SUNFALSE** after each call to **SUNLinSolSolve\_SPGMR()**.
- **SUNLinSolSetup\_SPGMR**

- SUNLinSolSolve\_SPGMR
- SUNLinSolNumIters\_SPGMR
- SUNLinSolResNorm\_SPGMR
- SUNLinSolResid\_SPGMR
- SUNLinSolLastFlag\_SPGMR
- SUNLinSolSpace\_SPGMR
- SUNLinSolFree\_SPGMR

## 9.14 The SUNLinSol\_SPTFQMR Module

The SUNLinSol\_SPTFQMR implementation of the SUNLinearSolver class performs a Scaled, Preconditioned, Transpose-Free Quasi-Minimum Residual [27] method; this is an iterative linear solver that is designed to be compatible with any `N_Vecotr` 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.

### 9.14.1 SUNLinSol\_SPTFQMR Usage

The header file to be included when using this module is `sunlinsol/sunlinsol_sptfqmr.h`. The SUNLinSol\_SPTFQMR module is accessible from all SUNDIALS solvers *without* linking to the `libsundials_sunlinsolsptfqmr` module library.

The module SUNLinSol\_SPTFQMR provides the following user-callable routines:

`SUNLinearSolver SUNLinSol_SPTFQMR(N_Vecotr y, int pretype, int maxl, SUNContext sunctx)`

This constructor function creates and allocates memory for a SPTFQMR `SUNLinearSolver`.

#### Arguments:

- *y* – a template vector.
- *pretype* – a flag indicating the type of preconditioning to use:
  - `SUN_PREC_NONE`
  - `SUN_PREC_LEFT`
  - `SUN_PREC_RIGHT`
  - `SUN_PREC_BOTH`
- *maxl* – the number of Krylov basis vectors to use.
- *sunctx* – the `SUNContext` object (see §4.1)

**Return value:** If successful, 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 `N_Vecotr` implementation (i.e. that it supplies the requisite vector operations).

A *maxl* argument that is  $\leq 0$  will result in the default value (5).

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.

---

**Note:** With SUN\_PREC\_RIGHT or SUN\_PREC\_BOTH the initial guess must be zero (use [SUNLinSolSetZeroGuess\(\)](#) to indicate the initial guess is zero).

---

int **SUNLinSol\_SPTFQMRSetPrecType**(*SUNLinearSolver* S, int pretype)

This function updates the flag indicating use of preconditioning.

**Arguments:**

- *S* – *SUNLinSol\_SPGMR* object to update.
- *pretype* – a flag indicating the type of preconditioning to use:
  - SUN\_PREC\_NONE
  - SUN\_PREC\_LEFT
  - SUN\_PREC\_RIGHT
  - SUN\_PREC\_BOTH

**Return value:**

- SUNLS\_SUCCESS – successful update.
- SUNLS\_ILL\_INPUT – illegal *pretype*
- SUNLS\_MEM\_NULL – *S* is NULL

int **SUNLinSol\_SPTFQMRSetMaxI**(*SUNLinearSolver* S, int maxI)

This function updates the number of linear solver iterations to allow.

**Arguments:**

- *S* – *SUNLinSol\_SPTFQMR* object to update.
- *maxI* – maximum number of linear iterations to allow. Any non-positive input will result in the default value (5).

**Return value:**

- SUNLS\_SUCCESS – successful update.
- SUNLS\_MEM\_NULL – *S* is NULL

int **SUNLinSolSetInfoFile\_SPTFQMR**(*SUNLinearSolver* LS, FILE \*info\_file)

The function [SUNLinSolSetInfoFile\\_SPTFQMR\(\)](#) sets the output file where all informative (non-error) messages should be directed.

**Arguments:**

- *LS* – a *SUNLinSol* object
- *info\_file* – pointer to output file (**stdout by default**); a NULL input will disable output

**Return value:**

- *SUNLS\_SUCCESS* if successful
- *SUNLS\_MEM\_NULL* if the *SUNLinearSolver* memory was NULL
- *SUNLS\_ILL\_INPUT* if SUNDIALS was not built with monitoring enabled

**Notes:** This function is intended for users that wish to monitor the linear solver progress. By default, the file pointer is set to `stdout`.

**SUNDIALS must be built with the CMake option SUNDIALS\_BUILD\_WITH\_MONITORING to utilize this function.** See §12.1.2 for more information.

int **SUNLinSolSetPrintLevel\_SPTFQMR**(*SUNLinearSolver* LS, int print\_level)

The function `SUNLinSolSetPrintLevel_SPTFQMR()` specifies the level of verbosity of the output.

#### Arguments:

- *LS* – a `SUNLinSol` object
- *print\_level* – flag indicating level of verbosity; must be one of:
  - 0, no information is printed (default)
  - 1, for each linear iteration the residual norm is printed

#### Return value:

- `SUNLS_SUCCESS` if successful
- `SUNLS_MEM_NULL` if the `SUNLinearSolver` memory was `NULL`
- `SUNLS_ILL_INPUT` if SUNDIALS was not built with monitoring enabled, or if the print level value was invalid

**Notes:** This function is intended for users that wish to monitor the linear solver progress. By default, the print level is 0.

**SUNDIALS must be built with the CMake option SUNDIALS\_BUILD\_WITH\_MONITORING to utilize this function.** See §12.1.2 for more information.

For backwards compatibility, we also provide the following wrapper functions, each with identical input and output arguments to the routines that they wrap:

*SUNLinearSolver* **SUNSPTFQMR**(*N\_Vector* y, int pretype, int maxl)

Wrapper function for `SUNLinSol_SPTFQMR()`

int **SUNSPTFQMRSetPrecType**(*SUNLinearSolver* S, int pretype)

Wrapper function for `SUNLinSol_SPTFQMRSetPrecType()`

int **SUNSPTFQMRSetMaxl**(*SUNLinearSolver* S, int maxl)

Wrapper function for `SUNLinSol_SPTFQMRSetMaxl()`

## 9.14.2 SUNLinSol\_SPTFQMR Description

The `SUNLinSol_SPTFQMR` module defines the *content* field of a `SUNLinearSolver` to be the following structure:

```
struct _SUNLinearSolverContent_SPTFQMR {
    int maxl;
    int pretype;
    booleantype zeroguess;
    int numiters;
    realtype resnorm;
    int last_flag;
    SUNATimesFn ATimes;
    void* ATData;
    SUNPSetupFn Psetup;
    SUNPSolveFn Psolve;
```

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```

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;
int print_level;
FILE* info_file;
};

```

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 **N\_Vector** which holds the initial scaled, preconditioned linear system residual,
- **q**, **d**, **v**, **p**, **u** - **N\_Vector** used for workspace by the SPTFQMR algorithm,
- **r** - array of two **N\_Vector** used for workspace within the SPTFQMR algorithm,
- **vtemp1**, **vtemp2**, **vtemp3** - temporary vector storage.
- **print\_level** - controls the amount of information to be printed to the info file
- **info\_file** - the file where all informative (non-error) messages will be directed

This solver is constructed to perform the following operations:

- During construction all **N\_Vector** solver data is allocated, with vectors cloned from a template **N\_Vector** 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**, **PSetup**, 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 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 TFQMR iteration is performed. This will include scaling and preconditioning if those options have been supplied.

The SUNLinSol\_SPTFQMR module defines implementations of all “iterative” linear solver operations listed in §9.1:

- SUNLinSolGetType\_SPTFQMR
- SUNLinSolInitialize\_SPTFQMR
- SUNLinSolSetATimes\_SPTFQMR
- SUNLinSolSetPreconditioner\_SPTFQMR
- SUNLinSolSetScalingVectors\_SPTFQMR
- SUNLinSolSetZeroGuess\_SPTFQMR – note the solver assumes a non-zero guess by default and the zero guess flag is reset to SUNFALSE after each call to SUNLinSolSolve\_SPTFQMR().
- SUNLinSolSetup\_SPTFQMR
- SUNLinSolSolve\_SPTFQMR
- SUNLinSolNumIters\_SPTFQMR
- SUNLinSolResNorm\_SPTFQMR
- SUNLinSolResid\_SPTFQMR
- SUNLinSolLastFlag\_SPTFQMR
- SUNLinSolSpace\_SPTFQMR
- SUNLinSolFree\_SPTFQMR

## 9.15 The SUNLinSol\_SuperLUDIST Module

The SUNLinsol\_SuperLUDIST implementation of the `SUNLinearSolver` class interfaces with the SuperLU\_DIST library. This is designed to be used with the `SUNMatrix_SLUNRloc` `SUNMatrix`, and one of the serial, threaded or parallel `N_Vector` implementations (`NVECTOR_SERIAL`, `NVECTOR_OPENMP`, `NVECTOR_PTHREADS`, `NVECTOR_PARALLEL`, `NVECTOR_PARHYP`).

### 9.15.1 SUNLinSol\_SuperLUDIST Usage

The header file to be included 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.

The module SUNLinSol\_SuperLUDIST provides the following user-callable routines:

**Warning:** Starting with SuperLU\_DIST version 6.3.0, some structures were renamed to have a prefix for the floating point type. The double precision API functions have the prefix ‘d’. To maintain backwards compatibility with the unprefixed types, SUNDIALS provides macros to these SuperLU\_DIST types with an ‘x’ prefix that expand to the correct prefix. E.g., the SUNDIALS macro `xLUstruct_t` expands to `dLUstruct_t` or `LUstruct_t` based on the SuperLU\_DIST version.

*SUNLinearSolver* **SUNLinSol\_SuperLUDIST**(*N\_Vector* *y*, SuperMatrix \**A*, gridinfo\_t \**grid*, xLUstruct\_t \**lu*,  
xScalePermstruct\_t \**scaleperm*, xSOLVEstruct\_t \**solve*,  
SuperLUStat\_t \**stat*, superlu\_dist\_options\_t \**options*, *SUNContext*  
*sunctx*)

This constructor function creates and allocates memory for a SUNLinSol\_SuperLUDIST object.

**Arguments:**

- *y* – a template vector.
- *A* – a template matrix
- *grid, lu, scaleperm, solve, stat, options* – SuperLU\_DIST object pointers.
- *sunctx* – the *SUNContext* object (see §4.1)

**Return value:** If successful, a *SUNLinearSolver* object; otherwise this routine will return NULL.

**Notes:** This routine analyzes the input matrix and vector to determine the linear system size and to assess the compatibility with the SuperLU\_DIST library.

This routine will perform consistency checks to ensure that it is called with consistent *N\_Vector* and *SUNMatrix* implementations. These are currently limited to the *SUNMatrix\_SLUNRloc* matrix type and the *NVECTOR\_SERIAL*, *NVECTOR\_OPENMP*, *NVECTOR\_PTHREADS*, *NVECTOR\_PARALLEL*, and *NVECTOR\_PARHYP* vector types. As additional compatible matrix and vector implementations are added to SUNDIALS, these will be included within this compatibility check.

The *grid*, *lu*, *scaleperm*, *solve*, and *options* arguments are not checked and are passed directly to SuperLU\_DIST routines.

Some struct members of the *options* argument are modified internally by the SUNLinSol\_SuperLUDIST solver. Specifically, the member *Fact* is modified in the setup and solve routines.

*realtype* **SUNLinSol\_SuperLUDIST\_GetBerr**(*SUNLinearSolver* *LS*)

This function returns the componentwise relative backward error of the computed solution. It takes one argument, the *SUNLinearSolver* object. The return type is *realtype*.

gridinfo\_t \***SUNLinSol\_SuperLUDIST\_GetGridinfo**(*SUNLinearSolver* *LS*)

This function returns a pointer to the SuperLU\_DIST structure that contains the 2D process grid. It takes one argument, the *SUNLinearSolver* object.

xLUstruct\_t \***SUNLinSol\_SuperLUDIST\_GetLUstruct**(*SUNLinearSolver* *LS*)

This function returns a pointer to the SuperLU\_DIST structure that contains the distributed L and U structures. It takes one argument, the *SUNLinearSolver* object.

superlu\_dist\_options\_t \***SUNLinSol\_SuperLUDIST\_GetSuperLUOptions**(*SUNLinearSolver* *LS*)

This function returns a pointer to the SuperLU\_DIST structure that contains the options which control how the linear system is factorized and solved. It takes one argument, the *SUNLinearSolver* object.

xScalePermstruct\_t \***SUNLinSol\_SuperLUDIST\_GetScalePermstruct**(*SUNLinearSolver* *LS*)

This function returns a pointer to the SuperLU\_DIST structure that contains the vectors that describe the transformations done to the matrix *A*. It takes one argument, the *SUNLinearSolver* object.

xSOLVEstruct\_t \***SUNLinSol\_SuperLUDIST\_GetSOLVEstruct**(*SUNLinearSolver* *LS*)

This function returns a pointer to the SuperLU\_DIST structure that contains information for communication during the solution phase. It takes one argument the *SUNLinearSolver* object.

SuperLUStat\_t \***SUNLinSol\_SuperLUDIST\_GetSuperLUStat**(*SUNLinearSolver* *LS*)

This function returns a pointer to the SuperLU\_DIST structure that stores information about runtime and flop count. It takes one argument, the *SUNLinearSolver* object.

## 9.15.2 SUNLinSol\_SuperLUDIST Description

The SUNLinSol\_SuperLUDIST module defines the *content* field of a SUNLinearSolver to be the following structure:

```
struct _SUNLinearSolverContent_SuperLUDIST {
    booleantype           first_factorize;
    int                  last_flag;
    realtype              berr;
    gridinfo_t            *grid;
    xLUstruct_t           *lu;
    superlu_dist_options_t *options;
    xScalePermstruct_t    *scaleperm;
    xSOLVEstruct_t        *solve;
    SuperLUStat_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 internal function evaluations,
- **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,
- **scaleperm** – pointer to the SuperLU\_DIST structure that stores vectors describing the transformations done to the matrix A,
- **options** – pointer to the SuperLU\_DIST stucture which contains options that control how the linear system is factorized and solved,
- **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.

The SUNLinSol\_SuperLUDIST module is a SUNLinearSolver adapter for the SuperLU\_DIST sparse matrix factorization and solver library written by X. Sherry Li and collaborators [28, 45, 46, 70]. 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 §12.1.4 for details). Additionally, the wrapper 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 factorized and 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 `DFACT` 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.

The `SUNLinSol_SuperLUDIST` module defines implementations of all “direct” linear solver operations listed in §9.1:

- `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`

## 9.16 The `SUNLinSol_SuperLUMT` Module

The `SUNLinSol_SuperLUMT` implementation of the `SUNLinearSolver` class interfaces with the SuperLU\_MT library. This is designed to be used with the corresponding `SUNMATRIX_SPARSE` matrix type, and one of the serial or shared-memory `N_Vector` 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 SuperLU\_MT library has also been compiled with OpenMP.

### 9.16.1 `SUNLinSol_SuperLUMT` Usage

The header file to be included 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 module `SUNLinSol_SuperLUMT` provides the following user-callable routines:

`SUNLinearSolver SUNLinSol_SuperLUMT(N_Vector y, SUNMatrix A, int num_threads, SUNContext sunctx)`  
This constructor function creates and allocates memory for a `SUNLinSol_SuperLUMT` object.

#### Arguments:

- `y` – a template vector.

- $A$  – a template matrix
- $num\_threads$  – desired number of threads (OpenMP or Pthreads, depending on how SuperLU\_MT was installed) to use during the factorization steps.
- $sunctx$  – the `SUNContext` object (see §4.1)

**Return value:** If successful, a `SUNLinearSolver` object; otherwise 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\_MT library.

This routine will perform consistency checks to ensure that it is called with consistent `N_Vector` 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 SuperLU\_MT routines.

`int SUNLinSol_SuperLUMTSetOrdering(SUNLinearSolver S, int ordering_choice)`

This function sets the ordering used by SuperLU\_MT for reducing fill in the linear solve.

#### Arguments:

- $S$  – the `SUNLinSol_SuperLUMT` object to update.
- $ordering\_choice$ :
  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:

- `SUNLS_SUCCESS` – option successfully set
- `SUNLS_MEM_NULL` –  $S$  is `NULL`
- `SUNLS_ILL_INPUT` – invalid `ordering_choice`

For backwards compatibility, we also provide the following wrapper functions, each with identical input and output arguments to the routines that they wrap:

`SUNLinearSolver SUNSuperLUMT(N_Vector y, SUNMatrix A, int num_threads)`

Wrapper for `SUNLinSol_SuperLUMT()`.

and

`int SUNSuperLUMTSetOrdering(SUNLinearSolver S, int ordering_choice)`

Wrapper for `SUNLinSol_SuperLUMTSetOrdering()`.

## 9.16.2 SUNLinSol\_SuperLUMT Description

The SUNLinSol\_SuperLUMT module defines the *content* field of a SUNLinearSolver to be the following structure:

```
struct _SUNLinearSolverContent_SuperLUMT {
    int          last_flag;
    int          first_factorize;
    SuperMatrix *A, *AC, *L, *U, *B;
    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 SuperLU\_MT options structure.

The SUNLinSol\_SuperLUMT module is a SUNLinearSolver wrapper for the SuperLU\_MT sparse matrix factorization and solver library written by X. Sherry Li and collaborators [20, 44, 71]. 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 SuperLU\_MT, it is assumed that SuperLU\_MT has been installed on the system prior to installation of SUNDIALS, and that SUNDIALS has been configured appropriately to link with SuperLU\_MT (see §12.1.4 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 §5.1.1 for details). Moreover, since the SuperLU\_MT library may be installed to support either 32-bit or 64-bit integers, it is assumed that the SuperLU\_MT library is installed using the same integer precision as the SUNDIALS *sunindextype* option.

The SuperLU\_MT 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  $A^T * A$ , 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 SuperLU\_MT data structures. We note that in this solve SuperLU\_MT operates on the native data arrays for the right-hand side and solution vectors, without requiring costly data copies.

The SUNLinSol\_SuperLUMT module defines implementations of all “direct” linear solver operations listed in §9.1:

- SUNLinSolGetType\_SuperLUMT
- SUNLinSolInitialize\_SuperLUMT – this sets the `first_factorize` flag to 1 and resets the internal SuperLU\_MT statistics variables.
- SUNLinSolSetup\_SuperLUMT – this performs either a *LU* factorization or refactorization of the input matrix.
- SUNLinSolSolve\_SuperLUMT – this calls the appropriate SuperLU\_MT 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 SuperLU\_MT documentation.
- SUNLinSolFree\_SuperLUMT

## 9.17 The SUNLinSol\_cuSolverSp\_batchQR Module

The SUNLinSol\_cuSolverSp\_batchQR implementation of the `SUNLinearSolver` class is designed to be used with the `SUNMATRIX_CUSPARSE` matrix, and the `NVECTOR_CUDA` vector. The header file to include when using this module is `sunlinsol/sunlinsol_cusolversp_batchqr.h`. The installed library to link to is `libsundials_sunlinsolcusolversp.lib` where `.lib` is typically `.so` for shared libraries and `.a` for static libraries.

**Warning:** The `SUNLinearSolver_cuSolverSp_batchQR` module is experimental and subject to change.

### 9.17.1 SUNLinSol\_cuSolverSp\_batchQR description

The `SUNLinearSolver_cuSolverSp_batchQR` implementation provides an interface to the batched sparse QR factorization method provided by the NVIDIA cuSOLVER library [68]. The module is designed for solving block diagonal linear systems of the form

$$\begin{bmatrix} \mathbf{A}_1 & 0 & \cdots & 0 \\ 0 & \mathbf{A}_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{A}_n \end{bmatrix} x_j = b_j$$

where all block matrices  $\mathbf{A}_j$  share the same sparsity pattern. The matrix must be the `SUNMatrix.cuSparse`.

## 9.17.2 SUNLinSol\_cuSolverSp\_batchQR functions

The SUNLinearSolver\_cuSolverSp\_batchQR module defines implementations of all “direct” linear solver operations listed in §9.1:

- 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:

*SUNLinearSolver* **SUNLinSol\_cuSolverSp\_batchQR**(*N\_Vecotr* *y*, *SUNMatrix* *A*, *cusolverHandle\_t* *cusol*,  
*SUNContext* *sunctx*)

The function `SUNLinSol_cuSolverSp_batchQR` creates and allocates memory for a `SUNLinearSolver` object.

### Arguments:

- *y* – a vector for checking compatibility with the solver.
- *A* – a `SUNMATRIX_cuSparse` matrix for checking compatibility with the solver.
- *cusol* – `cuSolverSp` object to use.
- *sunctx* – the `SUNContext` object (see §4.1)

**Return value:** If successful, 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 `N_Vecotr` and `SUNMatrix` implementations. These are currently limited to the `SUNMATRIX_CUSPARSE` matrix type and the `NVECTOR_CUDA` vector type. Since the `SUNMATRIX_CUSPARSE` matrix type is only compatible with the `NVECTOR_CUDA` 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.

void **SUNLinSol\_cuSolverSp\_batchQR\_GetDescription**(*SUNLinearSolver* *LS*, char \*\**desc*)

The function `SUNLinSol_cuSolverSp_batchQR_GetDescription` accesses the string description of the object (empty by default).

void **SUNLinSol\_cuSolverSp\_batchQR\_SetDescription**(*SUNLinearSolver* *LS*, const char \**desc*)

The function `SUNLinSol_cuSolverSp_batchQR_SetDescription` sets the string description of the object (empty by default).

void **SUNLinSol\_cuSolverSp\_batchQR\_GetDeviceSpace**(*SUNLinearSolver* *S*, size\_t \**cuSolverInternal*, size\_t \**cuSolverWorkspace*)

The function `SUNLinSol_cuSolverSp_batchQR_GetDeviceSpace` returns the cuSOLVER batch QR method internal buffer size, in bytes, in the argument `cuSolverInternal` and the cuSOLVER batch QR workspace buffer size, in bytes, in the argument `cuSolverWorkspace`. The size of the internal buffer is proportional to the number of matrix blocks while the size of the workspace is almost independent of the number of blocks.

### 9.17.3 SUNLinSol\_cuSolverSp\_batchQR content

The SUNLinSol\_cuSolverSp\_batchQR module defines the *content* field of a SUNLinearSolver to be the following structure:

```
struct _SUNLinearSolverContent_cuSolverSp_batchQR {
    int           last_flag;          /* last return flag */ */
    booleantype   first_factorize;    /* is this the first factorization? */ */
    size_t        internal_size;      /* size of cusolver buffer for Q and R */ */
    size_t        workspace_size;     /* size of cusolver memory for factorization */ */
    cusolverSpHandle_t cusolver_handle; /* cuSolverSp context */ */
    csrqrInfo_t   info;              /* opaque cusolver data structure */ */
    void*         workspace;         /* memory block used by cusolver */ */
    const char*   desc;              /* description of this linear solver */ */
};
```

## 9.18 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 modules. 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_SUNLinSolGetID`: Verifies the returned solver identifier 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  $A$ , `N_Vecor` 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  $10*tol$ , 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_SUNLinSolSetZeroGuess` (iterative solvers only): Verifies that `SUNLinSolSetZeroGuess` 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 10

## Nonlinear Algebraic Solvers

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 systems 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) in ARKODE, see §10.2.

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 §10.1 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 the sections §10.1.1, §10.1.2 and §10.1.3. This is followed by the definition of functions supplied to a nonlinear solver implementation in the section §10.1.4. The nonlinear solver return codes are given in the section §10.1.5. The `SUNNonlinearSolver` type and the generic SUNNonlinSol module are defined in the section §10.1.6. Finally, the section §10.1.7 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 templates for supplying custom nonlinear solver modules.

### 10.1 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 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_nonlinearsolver.h`.

### 10.1.1 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 functions for nonlinear solver initialization (`SUNNonlinSolInitialization()`), setup (`SUNNonlinSolSetup()`), and destruction (`SUNNonlinSolFree()`) are optional.

`SUNNonlinearSolver_Type SUNNonlinSolGetType(SUNNonlinearSolver NLS)`

This *required* function returns the nonlinear solver type.

#### Arguments:

- *NLS* – a SUNNonlinSol object.

**Return value:** The SUNNonlinSol type identifier (of type `int`) will be one of the following:

- `SUNNONLINEARSOLVER_ROOTFIND` – 0, the SUNNonlinSol module solves  $F(y) = 0$ .
- `SUNNONLINEARSOLVER_FIXEDPOINT` – 1, the SUNNonlinSol module solves  $G(y) = y$ .

`int SUNNonlinSolInitialize(SUNNonlinearSolver NLS)`

This *optional* function handles nonlinear solver initialization and may perform any necessary memory allocations.

#### Arguments:

- *NLS* – a SUNNonlinSol object.

**Return value:** The return value 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`.

`int SUNNonlinSolSetup(SUNNonlinearSolver NLS, N_Vector y, void *mem)`

This *optional* function performs any solver setup needed for a nonlinear solve.

#### Arguments:

- *NLS* – a SUNNonlinSol object.
- *y* – the initial guess passed to the nonlinear solver.
- *mem* – the SUNDIALS integrator memory structure.

**Return value:** The return value 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`.

`int SUNNonlinSolSolve(SUNNonlinearSolver NLS, N_Vector y0, N_Vector ycor, N_Vector w, realtype tol, booleantype callILSetup, void *mem)`

This *required* function solves the nonlinear system  $F(y) = 0$  or  $G(y) = y$ .

#### Arguments:

- *NLS* – a SUNNonlinSol object.
- *y0* – the predicted value for the new solution state. This *must* remain unchanged throughout the solution process.
- *ycor* – on input the initial guess for the correction to the predicted state (zero) and on output the final correction to the predicted state.
- *w* – the solution error weight vector used for computing weighted error norms.
- *tol* – the requested solution tolerance in the weighted root-mean-squared norm.

- *callLSetup* – a flag indicating that the integrator recommends for the linear solver setup function to be called.
- *mem* – the SUNDIALS integrator memory structure.

**Return value:** The return value 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).

int **SUNNonlinSolFree**(*SUNNonlinearSolver* NLS)

This *optional* function frees any memory allocated by the nonlinear solver.

**Arguments:**

- *NLS* – a SUNNonlinSol object.

**Return value:** The return value 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.

### 10.1.2 SUNNonlinearSolver “set” functions

The following 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 (*SUNNonlinSolSetSysFn()*) is required. All other set functions are optional.

int **SUNNonlinSolSetSysFn**(*SUNNonlinearSolver* NLS, *SUNNonlinSolSysFn* SysFn)

This *required* function 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.

**Arguments:**

- *NLS* – a SUNNonlinSol object.
- *SysFn* – the function defining the nonlinear system. See §10.1.4 for the definition of *SUNNonlinSol-SysFn*.

**Return value:** The return value should be zero for a successful call, and a negative value for a failure.

int **SUNNonlinSolSetLSetupFn**(*SUNNonlinearSolver* NLS, *SUNNonlinSolLSetupFn* SetupFn)

This *optional* function is called by SUNDIALS integrators to provide the nonlinear solver with access to its linear solver setup function.

**Arguments:**

- *NLS* – a SUNNonlinSol object.
- *SetupFn* – a wrapper function to the SUNDIALS integrator’s linear solver setup function. See §10.1.4 for the definition of *SUNNonlinSolLSetupFn*.

**Return value:** The return value should be zero for a successful call, and a negative value for a failure.

**Notes:** The *SUNNonlinSolLSetupFn* 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.

int **SUNNonlinSolSetLSolveFn**(*SUNNonlinearSolver* NLS, *SUNNonlinSolLSolveFn* SolveFn)

This *optional* function is called by SUNDIALS integrators to provide the nonlinear solver with access to its linear solver solve function.

**Arguments:**

- *NLS* – a SUNNonlinSol object.
- *SolveFn* – a wrapper function to the SUNDIALS integrator’s linear solver solve function. See §10.1.4 for the definition of [SUNNonlinSolLSolveFn](#).

**Return value:** The return value should be zero for a successful call, and a negative value for a failure.

**Notes:** The [SUNNonlinSolLSolveFn](#) 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.

```
int SUNNonlinSolSetConvTestFn(SUNNonlinearSolver NLS, SUNNonlinSolConvTestFn CTestFn, void  
                               *ctest_data)
```

This *optional* function 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* – a SUNNonlinSol object.
- *CTestFn* – a SUNDIALS integrator’s nonlinear solver convergence test function. See §10.1.4 for the definition of [SUNNonlinSolConvTestFn](#).
- *ctest\_data* – is a data pointer passed to *CTestFn* every time it is called.

**Return value:** The return value 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.

```
int SUNNonlinSolSetMaxIters(SUNNonlinearSolver NLS, int maxiters)
```

This *optional* function 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:**

- *NLS* – a SUNNonlinSol object.
- *maxiters* – the maximum number of nonlinear iterations.

**Return value:** The return value should be zero for a successful call, and a negative value for a failure (e.g.,  $maxiters < 1$ ).

### 10.1.3 SUNNonlinearSolver “get” functions

The following functions allow SUNDIALS integrators to retrieve nonlinear solver statistics. The routines to get the number of iterations in the most recent solve ([SUNNonlinSolGetNumIters\(\)](#)) and number of convergence failures 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 when using an iterative SUNLinSol linear solver module; otherwise [SUNNonlinSolGetCurIter\(\)](#) is optional.

```
int SUNNonlinSolGetNumIters(SUNNonlinearSolver NLS, long int *niter)
```

This *optional* function returns the number of nonlinear solver iterations in the most recent solve. This is typically called by the SUNDIALS integrator to store the nonlinear solver statistics, but may also be called by the user.

**Arguments:**

- *NLS* – a SUNNonlinSol object.
- *niter* – the total number of nonlinear solver iterations.

**Return value:** The return value should be zero for a successful call, and a negative value for a failure.

```
int SUNNonlinSolGetCurIter(SUNNonlinearSolver NLS, int *iter)
```

This function returns the iteration index of the current nonlinear solve. This function is *required* when using SUNDIALS integrator-provided convergence tests or when using an iterative SUNLinSol linear solver module; otherwise it is *optional*.

**Arguments:**

- *NLS* – a SUNNonlinSol object.
- *iter* – the nonlinear solver iteration in the current solve starting from zero.

**Return value:** The return value should be zero for a successful call, and a negative value for a failure.

```
int SUNNonlinSolGetNumConvFails(SUNNonlinearSolver NLS, long int *nconvfails)
```

This *optional* function returns the number of nonlinear solver convergence failures in the most recent solve. This is typically called by the SUNDIALS integrator to store the nonlinear solver statistics, but may also be called by the user.

**Arguments:**

- *NLS* – a SUNNonlinSol object.
- *nconvfails* – the total number of nonlinear solver convergence failures.

**Return value:** The return value should be zero for a successful call, and a negative value for a failure.

#### 10.1.4 Functions provided by SUNDIALS integrators

To interface with SUNNonlinSol 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 functions provided to a SUNNonlinSol module have types defined in the header file `sundials/sundials_nonlinearsolver.h`; these are also described below.

```
typedef int (*SUNNonlinSolSysFn)(N_Vector ycor, N_Vector F, void *mem)
```

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 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.
- *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 is zero for a successful solve, a positive value for a recoverable error, and a negative value for an unrecoverable error.

**Notes:** 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. These stored values are then directly used in the integrator-supplied linear solver setup and solve functions as applicable.

```
typedef int (*SUNNonlinSolLSetupFn)(booleantype jbad, booleantype *jcur, void *mem)
```

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).
- *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 is zero for a successful solve, a positive value for a recoverable error, and a negative value for an unrecoverable error.

**Notes:** The *SUNNonlinSolLSetupFn* 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).

```
typedef int (*SUNNonlinSolLSolveFn)(N_Vector b, void *mem)
```

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 is zero for a successful solve, a positive value for a recoverable error, and a negative value for an unrecoverable error.

**Notes:** The *SUNNonlinSolLSolveFn* 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 setup may utilize saved values from the nonlinear system evaluation (e.g., the updated solution).

```
typedef int (*SUNNonlinSolConvTestFn)(SUNNonlinearSolver NLS, N_Vector ycor, N_Vector del, realtype tol,  
N_Vector ewt, void *ctest_data)
```

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.

### 10.1.5 `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 in [Table 10.1](#). Here, negative values correspond to non-recoverable failures, positive values to recoverable failures, and zero to a successful call.

Table 10.1: Description of the `SUNNonlinearSolver` return codes.

Name	Value	Description
<code>SUN_NLS_SUCCESS</code>	0	successful call or converged solve
<code>SUN_NLS_CONTINUE</code>	901	the nonlinear solver is not converged, keep iterating
<code>SUN_NLS_CONV_RECVR</code>	902	the nonlinear solver appears to be diverging, try to recover
<code>SUN_NLS_MEM_NULL</code>	-901	a memory argument is <code>NULL</code>
<code>SUN_NLS_MEM_FAIL</code>	-902	a memory access or allocation failed
<code>SUN_NLS_ILL_INPUT</code>	-903	an illegal input option was provided
<code>SUN_NLS_VECTOROP_ERR</code>	-904	a NVECTOR operation failed
<code>SUN_NLS_EXT_FAIL</code>	-905	an external library call returned an error

### 10.1.6 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
```

and the generic structure is defined as

```
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);
```

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```

int          (*setup)(SUNNonlinearSolver, N_Vector, void* );
int          (*solve)(SUNNonlinearSolver, N_Vector, N_Vector,
                     N_Vector, realtype, booleantype, void* );
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 §10.1.1–§10.1.3. 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:

```

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));
}

```

### 10.1.7 Implementing a Custom SUNNonlinearSolver Module

A SUNNonlinSol implementation *must* do the following:

- Specify the content of the SUNNonlinSol module.
- Define and implement the required nonlinear solver operations defined in §10.1.1–§10.1.3. Note that the names of the module routines should be unique to that implementation in order to permit using more than one SUNNonlinSol module (each with different `SUNNonlinearSolver` internal data representations) in the same code.
- Define and implement a user-callable constructor to create a `SUNNonlinearSolver` object.

To aid in the creation of custom `SUNNonlinearSolver` modules, the generic `SUNNonlinearSolver` module provides the utility functions `SUNNonlinSolNewEmpty()` and `SUNNonlinSolFreeEmpty()`. When used in custom `SUNNonlinearSolver` constructors these functions will ease the introduction of any new optional nonlinear solver operations to the `SUNNonlinearSolver` API by ensuring that only required operations need to be set.

#### `SUNNonlinearSolver SUNNonlinSolNewEmpty()`

This function allocates a new generic `SUNNonlinearSolver` object and initializes its content pointer and the function pointers in the operations structure to NULL.

**Return value:** If successful, this function returns a `SUNNonlinearSolver` object. If an error occurs when allocating the object, then this routine will return NULL.

---

```
void SUNNonlinSolFreeEmpty(SUNNonlinearSolver NLS)
```

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* – a `SUNNonlinearSolver` object

Additionally, a `SUNNonlinearSolver` implementation *may* do the following:

- Define and implement additional user-callable “set” routines acting on the `SUNNonlinearSolver` object, e.g., for setting various configuration options to tune the performance of the nonlinear solve algorithm.
- Provide additional user-callable “get” routines acting on the `SUNNonlinearSolver` object, e.g., for returning various solve statistics.

## 10.2 ARKODE SUNNonlinearSolver interface

As discussed in §2 integration steps often require the (approximate) solution of nonlinear systems. These systems can be formulated as the rootfinding problem

$$\begin{aligned} G(z_i) &\equiv z_i - \gamma f^I(t_{n,i}^I, z_i) - a_i = 0 & [M = I], \\ G(z_i) &\equiv Mz_i - \gamma f^I(t_{n,i}^I, z_i) - a_i = 0 & [M \text{ static}], \\ G(z_i) &\equiv M(t_{n,i}^I)(z_i - a_i) - \gamma f^I(t_{n,i}^I, z_i) = 0 & [M \text{ time-dependent}], \end{aligned}$$

where  $z_i$  is the i-th stage at time  $t_i$  and  $a_i$  is known data that depends on the integration method.

Alternately, the nonlinear system above may be formulated as the fixed-point problem

$$z_i = z_i - M(t_{n,i}^I)^{-1}G(z_i),$$

where  $G(z_i)$  is the variant of the rootfinding problem listed above, and  $M(t_{n,i}^I)$  may equal either  $M$  or  $I$ , as applicable.

Rather than solving the above nonlinear systems for the stage value  $z_i$  directly, ARKODE modules solve for the correction  $z_{cor}$  to the predicted stage value  $z_{pred}$  so that  $z_i = z_{pred} + z_{cor}$ . Thus these nonlinear systems rewritten in terms of  $z_{cor}$  are

$$\begin{aligned} G(z_{cor}) &\equiv z_{cor} - \gamma f^I(t_{n,i}^I, z_i) - \tilde{a}_i = 0 & [M = I], \\ G(z_{cor}) &\equiv Mz_{cor} - \gamma f^I(t_{n,i}^I, z_i) - \tilde{a}_i = 0 & [M \text{ static}], \\ G(z_{cor}) &\equiv M(t_{n,i}^I)(z_{cor} - \tilde{a}_i) - \gamma f^I(t_{n,i}^I, z_i) = 0 & [M \text{ time-dependent}], \end{aligned} \tag{10.1}$$

for the rootfinding problem and

$$z_{cor} = z_{cor} - M(t_{n,i}^I)^{-1}G(z_i), \tag{10.2}$$

for the fixed-point problem.

The nonlinear system functions provided by ARKODE modules to the nonlinear solver module internally update the current value of the stage based on the input correction vector i.e.,  $z_i = z_{pred} + z_{cor}$ . The updated vector  $z_i$  is used when calling the ODE right-hand side function and when setting up linear solves (e.g., updating the Jacobian or preconditioner).

ARKODE modules also provide several advanced functions that will not be needed by most users, but might be useful for users who choose to provide their own `SUNNonlinSol` implementation for use by ARKODE. These routines provide access to the internal integrator data required to evaluate (10.1) or (10.2).

### 10.2.1 ARKStep advanced output functions

Two notable functions were already listed in §5.2.2.10:

- `ARKStepGetCurrentState()` – returns the current state vector. When called within the computation of a step (i.e., during a nonlinear solve) this is the current stage state vector  $z_i = z_{pred} + z_{cor}$ . Otherwise this is the current internal solution state vector  $y(t)$ . In either case the corresponding stage or solution time can be obtained from `ARKStepGetCurrentTime()`.
- `ARKStepGetCurrentGamma()` – returns the current value of the scalar  $\gamma$ .

Additional advanced output functions that are provided to aid in the construction of user-supplied SUNNonlinSol modules are as follows.

`int ARKStepGetCurrentMassMatrix(void *arkode_mem, SUNMatrix *M)`

Returns the current mass matrix. For a time dependent mass matrix the corresponding time can be obtained from `ARKStepGetCurrentTime()`.

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *M* – *SUNMatrix* pointer that will get set to the current mass matrix  $M(t)$ . If a matrix-free method is used the output is NULL.

**Return value:**

- `ARK_SUCCESS` if successful.
- `ARK_MEM_NULL` if the ARKStep memory was NULL.

`int ARKStepGetNonlinearSystemData(void *arkode_mem, realtype *tcur, N_Vector *zpred, N_Vector *z, N_Vector *Fi, realtype *gamma, N_Vector *sdata, void **user_data)`

Returns all internal data required to construct the current nonlinear implicit system (10.1) or (10.2):

**Arguments:**

- *arkode\_mem* – pointer to the ARKStep memory block.
- *tcur* – value of the independent variable corresponding to implicit stage,  $t_{n,i}^I$ .
- *zpred* – the predicted stage vector  $z_{pred}$  at  $t_{n,i}^I$ . This vector must not be changed.
- *z* – the stage vector  $z_i$  above. This vector may be not current and may need to be filled (see the note below).
- *Fi* – the implicit function evaluated at the current time and state,  $f^I(t_{n,i}^I, z_i)$ . This vector may be not current and may need to be filled (see the note below).
- *gamma* – current  $\gamma$  for implicit stage calculation.
- *sdata* – accumulated data from previous solution and stages,  $\tilde{a}_i$ . This vector must not be changed.
- *user\_data* – pointer to the user-defined data structure (as specified through `ARKStepSetUserData()`, or NULL otherwise)

**Return value:**

- `ARK_SUCCESS` if successful.
- `ARK_MEM_NULL` if the ARKStep memory was NULL.

---

**Note:** This routine is intended for users who wish to attach a custom `SUNNonlinSolSysFn` to an existing `SUNNonlinearSolver` object (through a call to `SUNNonlinSolSetSysFn()`) or who need access to nonlinear system data to compute the nonlinear system function as part of a custom `SUNNonlinearSolver` object.

When supplying a custom `SUNNonlinSolSysFn` to an existing `SUNNonlinearSolver` object, the user should call `ARKStepGetNonlinearSystemData()` **inside** the nonlinear system function to access the requisite data for evaluating the nonlinear system function of their choosing. Additionally, if the `SUNNonlinearSolver` object (existing or custom) leverages the `SUNNonlinSolLSetupFn` and/or `SUNNonlinSolLSolveFn` functions supplied by ARKStep (through calls to `SUNNonlinSolSetLSetupFn()` and `SUNNonlinSolSetLSolveFn()` respectively) the vectors  $z$  and  $F_i$  **must be filled** in by the user's `SUNNonlinSolSysFn` with the current state and corresponding evaluation of the right-hand side function respectively i.e.,

$$\begin{aligned} z &= z_{\text{pred}} + z_{\text{cor}}, \\ F_i &= f^I(t_{n,i}^I, z_i), \end{aligned}$$

where  $z_{\text{cor}}$  was the first argument supplied to the `SUNNonlinSolSysFn`.

If this function is called as part of a custom linear solver (i.e., the default `SUNNonlinSolSysFn` is used) then the vectors  $z$  and  $F_i$  are only current when `ARKStepGetNonlinearSystemData()` is called after an evaluation of the nonlinear system function.

---

`int ARKStepComputeState(void *arkode_mem, N_Vector zcor, N_Vector z)`

Computes the current stage state vector using the stored prediction and the supplied correction from the nonlinear solver i.e.,  $z_i(t) = z_{\text{pred}} + z_{\text{cor}}$ .

#### Arguments:

- `arkode_mem` – pointer to the ARKStep memory block.
- `zcor` – the correction from the nonlinear solver.
- `z` – on output, the current stage state vector  $z_i$ .

#### Return value:

- `ARK_SUCCESS` if successful.
- `ARK_MEM_NULL` if the ARKStep memory was NULL.

### 10.2.2 MRIStep advanced output functions

Two notable functions were already listed in §5.4.6.3:

- `MRIStepGetCurrentState()` – returns the current state vector. When called within the computation of a step (i.e., during a nonlinear solve) this is the current stage state vector  $z_i = z_{\text{pred}} + z_{\text{cor}}$ . Otherwise this is the current internal solution state vector  $y(t)$ . In either case the corresponding stage or solution time can be obtained from `MRIStepGetCurrentTime()`.
- `MRIStepGetCurrentGamma()` – returns the current value of the scalar  $\gamma$ .

Additional advanced output functions that are provided to aid in the construction of user-supplied `SUNNonlinSol` modules are as follows.

`int MRIStepGetNonlinearSystemData(void *arkode_mem, realtype *tcur, N_Vector *zpred, N_Vector *z, N_Vector *Fi, realtype *gamma, N_Vector *sdata, void **user_data)`

Returns all internal data required to construct the current nonlinear implicit system (10.1) or (10.2):

#### Arguments:

- `arkode_mem` – pointer to the MRIStep memory block.
- `tcur` – value of independent variable corresponding to slow stage ( $t_{n,i}^S$  above).
- `zpred` – predicted nonlinear solution ( $z_{\text{pred}}$  above). This vector must not be changed.

- $z$  – stage vector ( $z_i$  above). This vector may be not current and may need to be filled (see the note below).
- $F_i$  – memory available for evaluating the slow implicit RHS ( $f^I(t_{n,i}^S, z_i)$  above). This vector may be not current and may need to be filled (see the note below).
- $\gamma$  – current  $\gamma$  for slow stage calculation.
- $sdata$  – accumulated data from previous solution and stages ( $\tilde{a}_i$  above). This vector must not be changed.
- $user\_data$  – pointer to the user-defined data structure (as specified through `MRISetUserData()`, or `NULL` otherwise).

**Return value:**

- `ARK_SUCCESS` if successful.
- `ARK_MEM_NULL` if the `MRISet` memory was `NULL`.

---

**Note:** This routine is intended for users who wish to attach a custom `SUNNonlinSolSysFn` to an existing `SUNNonlinearSolver` object (through a call to `SUNNonlinSolSetSysFn()`) or who need access to nonlinear system data to compute the nonlinear system function as part of a custom `SUNNonlinearSolver` object.

When supplying a custom `SUNNonlinSolSysFn` to an existing `SUNNonlinearSolver` object, the user should call `MRISetGetNonlinearSystemData()` **inside** the nonlinear system function to access the requisite data for evaluating the nonlinear system function of their choosing. Additionally, if the `SUNNonlinearSolver` object (existing or custom) leverages the `SUNNonlinSolLSetupFn` and/or `SUNNonlinSolLSolveFn` functions supplied by `MRISet` (through calls to `SUNNonlinSolSetLSetupFn()` and `SUNNonlinSolSetLSolveFn()` respectively) the vectors  $z$  and  $F$  **must be filled** in by the user's `SUNNonlinSolSysFn` with the current state and corresponding evaluation of the right-hand side function respectively i.e.,

$$\begin{aligned} z &= z_{pred} + z_{cor}, \\ F_i &= f^I(t_{n,i}^S, z_i), \end{aligned}$$

where  $z_{cor}$  was the first argument supplied to the `SUNNonlinSolSysFn`.

If this function is called as part of a custom linear solver (i.e., the default `SUNNonlinSolSysFn` is used) then the vectors  $z$  and  $F_i$  are only current when `MRISetGetNonlinearSystemData()` is called after an evaluation of the nonlinear system function.

---

```
int MRISetComputeState(void *arkode_mem, N_Vector zcor, N_Vector z)
```

Computes the current stage state vector using the stored prediction and the supplied correction from the nonlinear solver i.e.,  $z_i = z_{pred} + z_{cor}$ .

**Arguments:**

- `arkode_mem` – pointer to the `MRISet` memory block.
- `zcor` – the correction from the nonlinear solver.
- `z` – on output, the current stage state vector  $z_i$ .

**Return value:**

- `ARK_SUCCESS` if successful.
- `ARK_MEM_NULL` if the `MRISet` memory was `NULL`.

## 10.3 The SUNNonlinSol\_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_sunnonlinsol-newton` module library.

### 10.3.1 SUNNonlinSol\_Newton description

To find the solution to

$$F(y) = 0 \quad (10.3)$$

given an initial guess  $y^{(0)}$ , Newton's method computes a series of approximate solutions

$$y^{(m+1)} = y^{(m)} + \delta^{(m+1)}$$

where  $m$  is the Newton iteration index, and the Newton update  $\delta^{(m+1)}$  is the solution of the linear system

$$A(y^{(m)})\delta^{(m+1)} = -F(y^{(m)}), \quad (10.4)$$

in which  $A$  is the Jacobian matrix

$$A \equiv \partial F / \partial y. \quad (10.5)$$

Depending on the linear solver used, the SUNNonlinSol\_Newton module will employ either a Modified Newton method or an Inexact Newton method [9, 12, 19, 21, 39]. 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 `SUNNonlinSolSetupFn` 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 `SUNNonlinSolSetupFn` 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 `SUNNonlinSolSetupFn()` function.

Whether the Jacobian matrix  $A$  is fully or partially updated depends on logic unique to each integrator-supplied `SUNNonlinSolSetupFn` routine. We refer to the discussion of nonlinear solver strategies provided in the package-specific Mathematics section of the documentation for details.

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.

### 10.3.2 SUNNonlinSol\_Newton functions

The SUNNonlinSol\_Newton module provides the following constructor for creating the SUNNonlinearSolver object.

*SUNNonlinearSolver* **SUNNonlinSol\_Newton**(*N\_Vector* *y*, *SUNContext* *sunctx*)

This 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* – a template for cloning vectors needed within the solver.
- *sunctx* – the *SUNContext* object (see §4.1)

**Return value:** A SUNNonlinSol object if the constructor exits successfully, otherwise it will be NULL.

The SUNNonlinSol\_Newton module implements all of the functions defined in §10.1.1–§10.1.3 except for *SUNNonlinSolSetup*(). 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 §10.1.1–§10.1.3 should be called in favor of the SUNNonlinSol\_Newton-specific implementations.

The SUNNonlinSol\_Newton module also defines the following user-callable function.

**int** **SUNNonlinSolGetSysFn\_Newton**(*SUNNonlinearSolver* *NLS*, *SUNNonlinSolSysFn* \**SysFn*)

This returns the residual function that defines the nonlinear system.

**Arguments:**

- *NLS* – a SUNNonlinSol object.
- *SysFn* – the function defining the nonlinear system.

**Return value:** The return value 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*.

**int** **SUNNonlinSolSetInfoFile\_Newton**(*SUNNonlinearSolver* *NLS*, *FILE* \**info\_file*)

This sets the output file where all informative (non-error) messages should be directed.

**Arguments:**

- *NLS* – a SUNNonlinSol object.
- *info\_file* – pointer to output file (**stdout** by default); a NULL input will disable output.

**Return value:**

- **SUN\_NLS\_SUCCESS** if successful.
- **SUN\_NLS\_MEM\_NULL** if the SUNNonlinSol memory was NULL.
- **SUN\_NLS\_ILL\_INPUT** if SUNDIALS was not built with monitoring enabled.

**Notes:** This function is intended for users that wish to monitor the nonlinear solver progress. By default, the file pointer is set to **stdout**.

**Warning:** SUNDIALS must be built with the CMake option **SUNDIALS\_BUILD\_WITH\_MONITORING** to utilize this function. See §12.1.2 for more information.

int **SUNNonlinSolSetPrintLevel\_Newton**(*SUNNonlinearSolver* NLS, int print\_level)

This specifies the level of verbosity of the output.

**Arguments:**

- *NLS* – a SUNNonlinSol object.
- *print\_level* – flag indicating level of verbosity; must be one of:
  - 0, no information is printed (default).
  - 1, for each nonlinear iteration the residual norm is printed.

**Return value:**

- SUN\_NLS\_SUCCESS if successful.
- SUN\_NLS\_MEM\_NULL if the SUNNonlinearSolver memory was NULL.
- SUN\_NLS\_ILL\_INPUT if SUNDIALS was not built with monitoring enabled, or the print level value was invalid.

**Notes:** This function is intended for users that wish to monitor the nonlinear solver progress. By default, the print level is 0.

**Warning:** SUNDIALS must be built with the CMake option SUNDIALS\_BUILD\_WITH\_MONITORING to utilize this function. See §12.1.2 for more information.

### 10.3.3 SUNNonlinSol\_Newton content

The *content* field of the SUNNonlinSol\_Newton module is the following structure.

```
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;

    int         print_level;
    FILE*      info_file;
};
```

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,

- `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,
- `ctest_data` – the data pointer passed to the convergence test function,
- `print_level` - controls the amount of information to be printed to the info file,
- `info_file` - the file where all informative (non-error) messages will be directed.

## 10.4 The SUNNonlinSol\_FixedPoint implementation

This section describes the SUNNonlinSol implementation of a fixed point (functional) iteration with optional Anderson acceleration. To access the SUNNonlinSol\_FixedPoint module, include the header file `sunnonlinsol/sunnonlinsol_fixedpoint.h`. We note that the SUNNonlinSol\_FixedPoint module is accessible from SUNDIALS integrators *without* separately linking to the `libsundials_sunnonlinsolfixedpoint` module library.

### 10.4.1 SUNNonlinSol\_FixedPoint description

To find the solution to

$$G(y) = y \quad (10.6)$$

given an initial guess  $y^{(0)}$ , the fixed point iteration computes a series of approximate solutions

$$y^{(n+1)} = G(y^{(n)}) \quad (10.7)$$

where  $n$  is the iteration index. The convergence of this iteration may be accelerated using Anderson's method [2, 25, 47, 62]. With Anderson acceleration using subspace size  $m$ , the series of approximate solutions can be formulated as the linear combination

$$y^{(n+1)} = \beta \sum_{i=0}^{m_n} \alpha_i^{(n)} G(y^{(n-m_n+i)}) + (1 - \beta) \sum_{i=0}^{m_n} \alpha_i^{(n)} y_{n-m_n+i} \quad (10.8)$$

where  $m_n = \min \{m, n\}$  and the factors

$$\alpha^{(n)} = (\alpha_0^{(n)}, \dots, \alpha_{m_n}^{(n)})$$

solve the minimization problem  $\min_{\alpha} \|F_n \alpha^T\|_2$  under the constraint that  $\sum_{i=0}^{m_n} \alpha_i = 1$  where

$$F_n = (f_{n-m_n}, \dots, f_n)$$

with  $f_i = G(y^{(i)}) - y^{(i)}$ . Due to this constraint, in the limit of  $m = 0$  the accelerated fixed point iteration formula (10.8) simplifies to the standard fixed point iteration (10.7).

Following the recommendations made in [62], the SUNNonlinSol\_FixedPoint implementation computes the series of approximate solutions as

$$y^{(n+1)} = G(y^{(n)}) - \sum_{i=0}^{m_n-1} \gamma_i^{(n)} \Delta g_{n-m_n+i} - (1-\beta)(f(y^{(n)}) - \sum_{i=0}^{m_n-1} \gamma_i^{(n)} \Delta f_{n-m_n+i}) \quad (10.9)$$

with  $\Delta g_i = G(y^{(i+1)}) - G(y^{(i)})$  and where the factors

$$\gamma^{(n)} = (\gamma_0^{(n)}, \dots, \gamma_{m_n-1}^{(n)})$$

solve the unconstrained minimization problem  $\min_{\gamma} \|f_n - \Delta F_n \gamma^T\|_2$  where

$$\Delta F_n = (\Delta f_{n-m_n}, \dots, \Delta f_{n-1}),$$

with  $\Delta f_i = f_{i+1} - f_i$ . The least-squares problem is solved by applying a QR factorization to  $\Delta F_n = Q_n R_n$  and solving  $R_n \gamma = Q_n^T f_n$ .

The acceleration subspace size  $m$  is required when constructing the SUNNonlinSol\_FixedPoint object. The default maximum number of iterations and the stopping criteria for the fixed point iteration are supplied by the SUNDIALS integrator when SUNNonlinSol\_FixedPoint is attached to it. Both the maximum number of iterations and the convergence test function may be modified by the user by calling `SUNNonlinSolSetMaxIters()` and `SUNNonlinSolSetConvTestFn()` after attaching the SUNNonlinSol\_FixedPoint object to the integrator.

#### 10.4.2 SUNNonlinSol\_FixedPoint functions

The SUNNonlinSol\_FixedPoint module provides the following constructor for creating the SUNNonlinearSolver object.

`SUNNonlinearSolver SUNNonlinSol_FixedPoint(N_Vector y, int m, SUNContext sunctx)`

This creates a SUNNonlinearSolver object for use with SUNDIALS integrators to solve nonlinear systems of the form  $G(y) = y$ .

**Arguments:**

- $y$  – a template for cloning vectors needed within the solver.
- $m$  – the number of acceleration vectors to use.
- $sunctx$  – the `SUNContext` object (see §4.1)

**Return value:** A SUNNonlinSol object if the constructor exits successfully, otherwise it will be NULL.

Since the accelerated fixed point iteration (10.7) does not require the setup or solution of any linear systems, the SUNNonlinSol\_FixedPoint module implements all of the functions defined in §10.1.1–§10.1.3 except for the `SUNNonlinSolSetup()`, `SUNNonlinSolSetLSetupFn()`, and `SUNNonlinSolSetLSolveFn()` functions, that are set to NULL. The SUNNonlinSol\_FixedPoint functions have the same names as those defined by the generic SUNNonlinSol API with `_FixedPoint` appended to the function name. Unless using the SUNNonlinSol\_FixedPoint module as a standalone nonlinear solver the generic functions defined in §10.1.1–§10.1.3 should be called in favor of the SUNNonlinSol\_FixedPoint-specific implementations.

The SUNNonlinSol\_FixedPoint module also defines the following user-callable functions.

`int SUNNonlinSolGetSysFn_FixedPoint(SUNNonlinearSolver NLS, SUNNonlinSolSysFn *SysFn)`

This returns the fixed-point function that defines the nonlinear system.

**Arguments:**

- $NLS$  – a SUNNonlinSol object.
- $SysFn$  – the function defining the nonlinear system.

**Return value:** The return value is zero for a successful call, and a negative value for a failure.

**Notes:** This function is intended for users that wish to evaluate the fixed-point function in a custom convergence test function for the SUNNonlinSol\_FixedPoint module. We note that SUNNonlinSol\_FixedPoint will not leverage the results from any user calls to *SysFn*.

```
int SUNNonlinSolSetDamping_FixedPoint(SUNNonlinearSolver NLS, realtype beta)
```

This sets the damping parameter  $\beta$  to use with Anderson acceleration. By default damping is disabled i.e.,  $\beta = 1.0$ .

**Arguments:**

- *NLS* – a SUNNonlinSol object.
- *beta* – the damping parameter  $0 < \beta \leq 1$ .

**Return value:**

- SUN\_NLS\_SUCCESS if successful.
- SUN\_NLS\_MEM\_NULL if NLS was NULL.
- SUN\_NLS\_ILL\_INPUT if beta was negative.

**Notes:** A beta value should satisfy  $0 < \beta < 1$  if damping is to be used. A value of one or more will disable damping.

```
int SUNNonlinSolSetInfoFile_FixedPoint(SUNNonlinearSolver NLS, FILE *info_file)
```

This sets the output file where all informative (non-error) messages should be directed.

**Arguments:**

- *NLS* – a SUNNonlinSol object.
- *info\_file* – pointer to output file (**stdout by default**); a NULL input will disable output.

**Return value:**

- SUN\_NLS\_SUCCESS if successful.
- SUN\_NLS\_MEM\_NULL if NLS was NULL.
- SUN\_NLS\_ILL\_INPUT if SUNDIALS was not built with monitoring enabled.

**Notes:** This function is intended for users that wish to monitor the nonlinear solver progress. By default, the file pointer is set to *stdout*.

**Warning:** SUNDIALS must be built with the CMake option `SUNDIALS_BUILD_WITH_MONITORING` to utilize this function. See §12.1.2 for more information.

```
int SUNNonlinSolSetPrintLevel_FixedPoint(SUNNonlinearSolver NLS, int print_level)
```

This specifies the level of verbosity of the output.

**Arguments:**

- *NLS* – a SUNNonlinSol object.
- *print\_level* – flag indicating level of verbosity; must be one of:
  - 0, no information is printed (default).
  - 1, for each nonlinear iteration the residual norm is printed.

**Return value:**

- SUN\_NLS\_SUCCESS if successful.
- SUN\_NLS\_MEM\_NULL if NLS was NULL.
- SUN\_NLS\_ILL\_INPUT if SUNDIALS was not built with monitoring enabled, or the print level value was invalid.

**Notes:** This function is intended for users that wish to monitor the nonlinear solver progress. By default, the print level is 0.

**Warning:** SUNDIALS must be built with the CMake option SUNDIALS\_BUILD\_WITH\_MONITORING to utilize this function. See §12.1.2 for more information.

### 10.4.3 SUNNonlinSol\_FixedPoint content

The *content* field of the SUNNonlinSol\_FixedPoint module is the following structure.

```
struct _SUNNonlinearSolverContent_FixedPoint {
    SUNNonlinSolSysFn      Sys;
    SUNNonlinSolConvTestFn CTest;

    int                  m;
    int                  *imap;
    realtype   *R;
    booleantype damping
    realtype   beta
    realtype   *gamma;
    realtype   *cvals;
    N_Vector   *df;
    N_Vector   *dg;
    N_Vector   *q;
    N_Vector   *Xvecs;
    N_Vector   yprev;
    N_Vector   gy;
    N_Vector   fold;
    N_Vector   gold;
    N_Vector   delta;
    int        curiter;
    int        maxiters;
    long int   niters;
    long int   nconvfails;
    void       *ctest_data;
    int        print_level;
    FILE*     info_file;
};
```

The following entries of the *content* field are always allocated:

- **Sys** – function for evaluating the nonlinear system,
- **CTest** – function for checking convergence of the fixed point iteration,
- **yprev** – **N\_Vector** used to store previous fixed-point iterate,

- `gy` – `N_Vector` used to store  $G(y)$  in fixed-point algorithm,
- `delta` – `N_Vector` used to store difference between successive fixed-point iterates,
- `curiter` – the current number of iterations in the solve attempt,
- `maxiters` – the maximum number of fixed-point 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,
- `ctest_data` – the data pointer passed to the convergence test function,
- `m` – number of acceleration vectors,
- `print_level` - controls the amount of information to be printed to the info file, and
- `info_file` - the file where all informative (non-error) messages will be directed.

If Anderson acceleration is requested (i.e.,  $m > 0$  in the call to `SUNNonlinSol_FixedPoint()`), then the following items are also allocated within the `content` field:

- `imap` – index array used in acceleration algorithm (length  $m$ ),
- `damping` – a flag indicating if damping is enabled,
- `beta` – the damping parameter,
- `R` – small matrix used in acceleration algorithm (length  $m*m$ ),
- `gamma` – small vector used in acceleration algorithm (length  $m$ ),
- `cvals` – small vector used in acceleration algorithm (length  $m+1$ ),
- `df` – array of `N_Vectors` used in acceleration algorithm (length  $m$ ),
- `dg` – array of `N_Vectors` used in acceleration algorithm (length  $m$ ),
- `q` – array of `N_Vectors` used in acceleration algorithm (length  $m$ ),
- `Xvecs` – `N_Vector` pointer array used in acceleration algorithm (length  $m+1$ ),
- `fold` – `N_Vector` used in acceleration algorithm, and
- `gold` – `N_Vector` used in acceleration algorithm.

## 10.5 The SUNNonlinSol\_PetscSNES implementation

This section describes the SUNNonlinSol interface to the PETSc SNES nonlinear solver(s). To enable the SUNNonlinSol\_PetscSNES module, SUNDIALS must be configured to use PETSc. Instructions on how to do this are given in §12.1.4.5. To access the SUNNonlinSol\_PetscSNES module, include the header file `sunnonlinsol/sunnonlinsol_petscsnes.h`. The library to link to is `libsundials_sunnonlinsolpetsc.lib` where `.lib` is typically `.so` for shared libraries and `.a` for static libraries. Users of the SUNNonlinSol\_PetscSNES module should also see §7.9 which discusses the NVECTOR interface to the PETSc Vec API.

### 10.5.1 SUNNonlinSol\_PetscSNES description

The SUNNonlinSol\_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 SUNNonlinSol\_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.

*Important usage notes for the SUNNonlinSol\_PetscSNES implementation:*

- The SUNNonlinSol\_PetscSNES implementation handles calling `SNESSetFunction` at construction. The actual residual function  $F(y)$  is set by the SUNDIALS integrator when the SUNNonlinSol\_PetscSNES object is attached to it. Therefore, a user should not call `SNESSetFunction` on a SNES object that is being used with SUNNonlinSol\_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 `SNESCreate`.
- 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 SUNNonlinSol\_PetscSNES module is not currently compatible with the CVODES or IDAS staggered or simultaneous sensitivity strategies.

### 10.5.2 SUNNonlinearSolver\_PetscSNES functions

The SUNNonlinSol\_PetscSNES module provides the following constructor for creating a `SUNNonlinearSolver` object.

`SUNNonlinearSolver SUNNonlinSol_PetscSNES(N_Vecor y, SNES snes, SUNContext sunctx)`

This creates a SUNNonlinSol object that wraps a PETSc SNES object for use with SUNDIALS. This will call `SNESSetFunction` on the provided SNES object.

**Arguments:**

- `snes` – a PETSc SNES object.
- `y` – a `N_Vecor` object of type `NVECTOR_PETSC` that is used as a template for the residual vector.
- `sunctx` – the `SUNContext` object (see §4.1)

**Return value:** A SUNNonlinSol object if the constructor exits successfully, otherwise it will be `NULL`.

**Warning:** 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 §10.1.1–§10.1.3 except for `SUNNonlinSolSetup()`, `SUNNonlinSolSetLSetupFn()`, `SUNNonlinSolSetLSolveFn()`, `SUNNonlinSolSetConvTestFn()`, and `SUNNonlinSolSetMaxIters()`.

The SUNNonlinSol\_PetscSNES functions have the same names as those defined by the generic SUNNonlinSol API with `_PetscSNES` appended to the function name. Unless using the SUNNonlinSol\_PetscSNES module as a standalone nonlinear solver the generic functions defined in §10.1.1–§10.1.3 should be called in favor of the SUNNonlinSol\_PetscSNES specific implementations.

The SUNNonlinSol\_PetscSNES module also defines the following user-callable functions.

**int SUNNonlinSolGetSNES\_PetscSNES(*SUNNonlinearSolver* NLS, SNES \*snes)**

This gets the SNES object that was wrapped.

**Arguments:**

- *NLS* – a SUNNonlinSol object.
- *snes* – a pointer to a PETSc SNES object that will be set upon return.

**Return value:** The return value (of type int) should be zero for a successful call, and a negative value for a failure.

**int SUNNonlinSolGetPetcError\_PetscSNES(*SUNNonlinearSolver* NLS, PesticErrorCode \*error)**

This gets the last error code returned by the last internal call to a PETSc API function.

**Arguments:**

- *NLS* – a SUNNonlinSol object.
- *error* – a pointer to a PETSc error integer that will be set upon return.

**Return value:** The return value (of type int) should be zero for a successful call, and a negative value for a failure.

**int SUNNonlinSolGetSysFn\_PetscSNES(*SUNNonlinearSolver* NLS, *SUNNonlinSolSysFn* \*SysFn)**

This returns the residual function that defines the nonlinear system.

**Arguments:**

- *NLS* – a SUNNonlinSol object.
- *SysFn* – the function defining the nonlinear system.

**Return value:** The return value (of type int) should be zero for a successful call, and a negative value for a failure.

### 10.5.3 SUNNonlinearSolver\_PetscSNES content

The *content* field of the SUNNonlinSol\_PetscSNES module is the following structure.

```
struct _SUNNonlinearSolverContent_PetscSNES {
    int sysfn_last_err;
    PetscErrorCode petsc_last_err;
    long int nconvfails;
    long int nni;
    void *imem;
    SNES snes;
    Vec r;
    N_Vecor 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 object,
- `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.



# Chapter 11

## Tools for Memory Management

To support applications which leverage memory pools, or utilize a memory abstraction layer, SUNDIALS provides a set of utilities that we collectively refer to as the `SUNMemoryHelper` API. The goal of this API is to allow users to leverage operations defined by native SUNDIALS data structures while allowing the user to have finer-grained control of the memory management.

### 11.1 The `SUNMemoryHelper` API

This API consists of three new SUNDIALS types: `SUNMemoryType`, `SUNMemory`, and `SUNMemoryHelper`:

```
typedef struct _SUNMemory *SUNMemory
```

The `SUNMemory` type is a pointer to a structure containing a pointer to actual data (`ptr`), the data memory type, and a flag indicating ownership of that data pointer. This structure is defined as

```
struct _SUNMemory
{
    void*          ptr;
    SUNMemoryType type;
    booleantype   own;
};
```

```
enum SUNMemoryType
```

The `SUNMemoryType` type is an enumeration that defines the supported memory types:

```
typedef enum
{
    SUNMEMTYPE_HOST,      /* pageable memory accessible on the host */
    SUNMEMTYPE_PINNED,    /* page-locked memory accessible on the host */
    SUNMEMTYPE_DEVICE,    /* memory accessible from the device */
    SUNMEMTYPE_UVM        /* memory accessible from the host or device */
} SUNMemoryType;
```

```
typedef struct _SUNMemoryHelper *SUNMemoryHelper
```

The `SUNMemoryHelper` type is a pointer to a structure containing a pointer to the implementation-specific member data (`content`) and a virtual method table of member functions (`ops`). This structure is defined as

```
struct _SUNMemoryHelper
{
```

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```
void* content;
SUNMemoryHelper_Ops ops;
};
```

typedef struct \_SUNMemoryHelper\_Ops \***SUNMemoryHelper\_Ops**

The **SUNMemoryHelper\_Ops** type is defined as a pointer to the structure containing the function pointers to the member function implementations. This structure is define as

```
struct _SUNMemoryHelper_Ops
{
    /* operations that implementations are required to provide */
    int (*alloc)(SUNMemoryHelper, SUNMemory* memptr size_t mem_size,
                 SUNMemoryType mem_type, void* queue);
    int (*dealloc)(SUNMemoryHelper, SUNMemory mem, void* queue);
    int (*copy)(SUNMemoryHelper, SUNMemory dst, SUNMemory src,
                size_t mem_size, void* queue);

    /* operations that provide default implementations */
    int (*copyasync)(SUNMemoryHelper, SUNMemory dst,
                     SUNMemory src, size_t mem_size,
                     void* queue);
    SUNMemoryHelper (*clone)(SUNMemoryHelper);
    int (*destroy)(SUNMemoryHelper);
};
```

### 11.1.1 Implementation defined operations

The SUNMemory API defines the following operations that an implementation to must define:

**SUNMemory SUNMemoryHelper\_Alloc(SUNMemoryHelper helper, SUNMemory \*memptr, size\_t mem\_size, SUNMemoryType mem\_type, void \*queue)**

Allocates a SUNMemory object whose ptr field is allocated for mem\_size bytes and is of type mem\_type. The new object will have ownership of ptr and will be deallocated when **SUNMemoryHelper\_Dealloc()** is called.

**Arguments:**

- helper – the SUNMemoryHelper object.
- memptr – pointer to the allocated SUNMemory.
- mem\_size – the size in bytes of the ptr.
- mem\_type – the SUNMemoryType of the ptr.
- queue – typically a handle for an object representing an alternate execution stream (e.g., a CUDA/HIP stream or SYCL queue), but it can also be any implementation specific data.

**Returns:**

- An int flag indicating success (zero) or failure (non-zero).

**int SUNMemoryHelper\_Dealloc(SUNMemoryHelper helper, SUNMemory mem, void \*queue)**  
Deallocates the mem->ptr field if it is owned by mem, and then deallocates the mem object.

**Arguments:**

- helper – the SUNMemoryHelper object.

- `mem` – the `SUNMemory` object.
- `queue` – typically a handle for an object representing an alternate execution stream (e.g., a CUDA/HIP stream or SYCL queue), but it can also be any implementation specific data.

**Returns:**

- An `int` flag indicating success (zero) or failure (non-zero).

`int SUNMemoryHelper_Copy(SUNMemoryHelper helper, SUNMemory dst, SUNMemory src, size_t mem_size, void *queue)`

Synchronously copies `mem_size` bytes from the source memory to the destination memory. The copy can be across memory spaces, e.g. host to device, or within a memory space, e.g. host to host. The `helper` object should use the memory types of `dst` and `src` to determine the appropriate transfer type necessary.

**Arguments:**

- `helper` – the `SUNMemoryHelper` object.
- `dst` – the destination memory to copy to.
- `src` – the source memory to copy from.
- `mem_size` – the number of bytes to copy.
- `queue` – typically a handle for an object representing an alternate execution stream (e.g., a CUDA/HIP stream or SYCL queue), but it can also be any implementation specific data.

**Returns:**

- An `int` flag indicating success (zero) or failure (non-zero).

### 11.1.2 Utility Functions

The `SUNMemoryHelper` API defines the following functions which do not require a `SUNMemoryHelper` instance:

`SUNMemory SUNMemoryHelper_Alias(SUNMemory mem1)`

Returns a `SUNMemory` object whose `ptr` field points to the same address as `mem1`. The new object *will not* have ownership of `ptr`, therefore, it will not free `ptr` when `SUNMemoryHelper_Dealloc()` is called.

**Arguments:**

- `mem1` – a `SUNMemory` object.

**Returns:**

- A `SUNMemory` object or `NULL` if an error occurs.

`SUNMemory SUNMemoryHelper_Wrap(void *ptr, SUNMemoryType mem_type)`

Returns a `SUNMemory` object whose `ptr` field points to the `ptr` argument passed to the function. The new object *will not* have ownership of `ptr`, therefore, it will not free `ptr` when `SUNMemoryHelper_Dealloc()` is called.

**Arguments:**

- `ptr` – the data pointer to wrap in a `SUNMemory` object.
- `mem_type` – the `SUNMemoryType` of the `ptr`.

**Returns:**

- A `SUNMemory` object or `NULL` if an error occurs.

`SUNMemoryHelper SUNMemoryHelper_NewEmpty()`

Returns an empty `SUNMemoryHelper`. This is useful for building custom `SUNMemoryHelper` implementations.

**Returns:**

- A `SUNMemoryHelper` object or `NULL` if an error occurs.

`int SUNMemoryHelper_CopyOps(SUNMemoryHelper src, SUNMemoryHelper dst)`

Copies the `ops` field of `src` to the `ops` field of `dst`. This is useful for building custom `SUNMemoryHelper` implementations.

**Arguments:**

- `src` – the object to copy from.
- `dst` – the object to copy to.

**Returns:**

- An `int` flag indicating success (zero) or failure (non-zero).

### 11.1.3 Implementation overridable operations with defaults

In addition, the `SUNMemoryHelper` API defines the following *optionally overridable* operations which an implementation may define:

`int SUNMemoryHelper_CopyAsync(SUNMemoryHelper helper, SUNMemory dst, SUNMemory src, size_t mem_size, void *queue)`

Asynchronously copies `mem_size` bytes from the source memory to the destination memory. The copy can be across memory spaces, e.g. host to device, or within a memory space, e.g. host to host. The `helper` object should use the memory types of `dst` and `src` to determine the appropriate transfer type necessary. The `ctx` argument is used when a different execution stream needs to be provided to perform the copy in, e.g. with CUDA this would be a `cudaStream_t`.

**Arguments:**

- `helper` – the `SUNMemoryHelper` object.
- `dst` – the destination memory to copy to.
- `src` – the source memory to copy from.
- `mem_size` – the number of bytes to copy.
- `queue` – typically a handle for an object representing an alternate execution stream (e.g., a CUDA/HIP stream or SYCL queue), but it can also be any implementation specific data.

**Returns:**

An `int` flag indicating success (zero) or failure (non-zero).

---

**Note:** If this operation is not defined by the implementation, then `SUNMemoryHelper_Copy()` will be used.

---

`SUNMemoryHelper SUNMemoryHelper_Clone(SUNMemoryHelper helper)`

Clones the `SUNMemoryHelper` object itself.

**Arguments:**

- `helper` – the `SUNMemoryHelper` object to clone.

**Returns:**

- A `SUNMemoryHelper` object.

---

**Note:** If this operation is not defined by the implementation, then the default clone will only copy the SUNMemoryHelper\_Ops structure stored in helper->ops, and not the helper->content field.

---

int **SUNMemoryHelper\_Destroy**(*SUNMemoryHelper* helper)  
Destroys (frees) the SUNMemoryHelper object itself.

**Arguments:**

- helper – the SUNMemoryHelper object to destroy.

**Returns:**

- An int flag indicating success (zero) or failure (non-zero).

---

**Note:** If this operation is not defined by the implementation, then the default destroy will only free the helper->ops field and the helper itself. The helper->content field will not be freed.

---

### 11.1.4 Implementing a custom SUNMemoryHelper

A particular implementation of the SUNMemoryHelper API must:

- Define and implement the required operations. Note that the names of these routines should be unique to that implementation in order to permit using more than one SUNMemoryHelper module in the same code.
- Optionally, specify the *content* field of SUNMemoryHelper.
- Optionally, define and implement additional user-callable routines acting on the newly defined SUNMemoryHelper.

An example of a custom SUNMemoryHelper is given in `examples/utilities/custom_memory_helper.h`.

## 11.2 The SUNMemoryHelper\_Cuda Implementation

The SUNMemoryHelper\_Cuda module is an implementation of the SUNMemoryHelper API that interfaces to the NVIDIA [67] library. The implementation defines the constructor

*SUNMemoryHelper* **SUNMemoryHelper\_Cuda**(*SUNContext* sunctx)

Allocates and returns a SUNMemoryHelper object for handling CUDA memory if successful. Otherwise it returns NULL.

### 11.2.1 SUNMemoryHelper\_Cuda API Functions

The implementation provides the following operations defined by the SUNMemoryHelper API:

*SUNMemory* **SUNMemoryHelper\_Alloc\_Cuda**(*SUNMemoryHelper* helper, *SUNMemory* memptr, *size\_t* mem\_size, *SUNMemoryType* mem\_type, void \*queue)

Allocates a SUNMemory object whose ptr field is allocated for mem\_size bytes and is of type mem\_type. The new object will have ownership of ptr and will be deallocated when *SUNMemoryHelper\_Dealloc()* is called.

**Arguments:**

- helper – the SUNMemoryHelper object.
- memptr – pointer to the allocated SUNMemory.

- `mem_size` – the size in bytes of the `ptr`.
- `mem_type` – the `SUNMemoryType` of the `ptr`. Supported values are:
  - `SUNMEMTYPE_HOST` – memory is allocated with a call to `malloc`.
  - `SUNMEMTYPE_PINNED` – memory is allocated with a call to `cudaMallocHost`.
  - `SUNMEMTYPE_DEVICE` – memory is allocated with a call to `cudaMalloc`.
  - `SUNMEMTYPE_UVM` – memory is allocated with a call to `cudaMallocManaged`.
- `queue` – currently unused.

**Returns:**

- An `int` flag indicating success (zero) or failure (non-zero).

```
int SUNMemoryHelper_Dealloc_Cuda(SUNMemoryHelper helper, SUNMemory mem, void *queue)
```

Deallocates the `mem->ptr` field if it is owned by `mem`, and then deallocates the `mem` object.

**Arguments:**

- `helper` – the `SUNMemoryHelper` object.
- `mem` – the `SUNMemory` object.
- `queue` – currently unused.

**Returns:**

- An `int` flag indicating success (zero) or failure (non-zero).

```
int SUNMemoryHelper_Copy_Cuda(SUNMemoryHelper helper, SUNMemory dst, SUNMemory src, size_t  
                           mem_size, void *queue)
```

Synchronously copies `mem_size` bytes from the source memory to the destination memory. The copy can be across memory spaces, e.g. host to device, or within a memory space, e.g. host to host. The `helper` object will use the memory types of `dst` and `src` to determine the appropriate transfer type necessary.

**Arguments:**

- `helper` – the `SUNMemoryHelper` object.
- `dst` – the destination memory to copy to.
- `src` – the source memory to copy from.
- `mem_size` – the number of bytes to copy.
- `queue` – currently unused.

**Returns:**

- An `int` flag indicating success (zero) or failure (non-zero).

```
int SUNMemoryHelper_CopyAsync_Cuda(SUNMemoryHelper helper, SUNMemory dst, SUNMemory src, size_t  
                                 mem_size, void *queue)
```

Asynchronously copies `mem_size` bytes from the source memory to the destination memory. The copy can be across memory spaces, e.g. host to device, or within a memory space, e.g. host to host. The `helper` object will use the memory types of `dst` and `src` to determine the appropriate transfer type necessary.

**Arguments:**

- `helper` – the `SUNMemoryHelper` object.
- `dst` – the destination memory to copy to.
- `src` – the source memory to copy from.

- `mem_size` – the number of bytes to copy.
- `queue` – the `cudaStream_t` handle for the stream that the copy will be performed on.

**Returns:**

- An `int` flag indicating success (zero) or failure (non-zero).

## 11.3 The SUNMemoryHelper\_Hip Implementation

The `SUNMemoryHelper_Hip` module is an implementation of the `SUNMemoryHelper` API that interfaces to the AMD ROCm HIP library [64]. The implementation defines the constructor

`SUNMemoryHelper SUNMemoryHelper_Hip(SUNContext sunctx)`

Allocates and returns a `SUNMemoryHelper` object for handling HIP memory if successful. Otherwise it returns `NULL`.

### 11.3.1 SUNMemoryHelper\_Hip API Functions

The implementation provides the following operations defined by the `SUNMemoryHelper` API:

`SUNMemory SUNMemoryHelper_Alloc_Hip(SUNMemoryHelper helper, SUNMemory memptr, size_t mem_size, SUNMemoryType mem_type, void *queue)`

Allocates a `SUNMemory` object whose `ptr` field is allocated for `mem_size` bytes and is of type `mem_type`. The new object will have ownership of `ptr` and will be deallocated when `SUNMemoryHelper_Dealloc()` is called.

**Arguments:**

- `helper` – the `SUNMemoryHelper` object.
- `memptr` – pointer to the allocated `SUNMemory`.
- `mem_size` – the size in bytes of the `ptr`.
- `mem_type` – the `SUNMemoryType` of the `ptr`. Supported values are:
  - `SUNMEMORYTYPE_HOST` – memory is allocated with a call to `malloc`.
  - `SUNMEMORYTYPE_PINNED` – memory is allocated with a call to `hipMallocHost`.
  - `SUNMEMORYTYPE_DEVICE` – memory is allocated with a call to `hipMalloc`.
  - `SUNMEMORYTYPE_UVM` – memory is allocated with a call to `hipMallocManaged`.
- `queue` – currently unused.

**Returns:**

- An `int` flag indicating success (zero) or failure (non-zero).

`int SUNMemoryHelper_Dealloc_Hip(SUNMemoryHelper helper, SUNMemory mem, void *queue)`

Deallocates the `mem->ptr` field if it is owned by `mem`, and then deallocates the `mem` object.

**Arguments:**

- `helper` – the `SUNMemoryHelper` object.
- `mem` – the `SUNMemory` object.

**Returns:**

- An `int` flag indicating success (zero) or failure (non-zero).

```
int SUNMemoryHelper_Copy_Hip(SUNMemoryHelper helper, SUNMemory dst, SUNMemory src, size_t mem_size,
                             void *queue)
```

Synchronously copies `mem_size` bytes from the source memory to the destination memory. The copy can be across memory spaces, e.g. host to device, or within a memory space, e.g. host to host. The `helper` object will use the memory types of `dst` and `src` to determine the appropriate transfer type necessary.

**Arguments:**

- `helper` – the `SUNMemoryHelper` object.
- `dst` – the destination memory to copy to.
- `src` – the source memory to copy from.
- `mem_size` – the number of bytes to copy.

**Returns:**

- An `int` flag indicating success (zero) or failure (non-zero).

```
int SUNMemoryHelper_CopyAsync_Hip(SUNMemoryHelper helper, SUNMemory dst, SUNMemory src, size_t
                                   mem_size, void *queue)
```

Asynchronously copies `mem_size` bytes from the source memory to the destination memory. The copy can be across memory spaces, e.g. host to device, or within a memory space, e.g. host to host. The `helper` object will use the memory types of `dst` and `src` to determine the appropriate transfer type necessary.

**Arguments:**

- `helper` – the `SUNMemoryHelper` object.
- `dst` – the destination memory to copy to.
- `src` – the source memory to copy from.
- `mem_size` – the number of bytes to copy.
- `queue` – the `hipStream_t` handle for the stream that the copy will be performed on.

**Returns:**

- An `int` flag indicating success (zero) or failure (non-zero).

## 11.4 The `SUNMemoryHelper_Sycl` Implementation

The `SUNMemoryHelper_Sycl` module is an implementation of the `SUNMemoryHelper` API that interfaces to the `SYCL` abstraction layer. The implementation defines the constructor

`SUNMemoryHelper SUNMemoryHelper_Sycl(SUNContext sunctx)`

Allocates and returns a `SUNMemoryHelper` object for handling SYCL memory using the provided queue. Otherwise it returns NULL.

### 11.4.1 SUNMemoryHelper\_Sycl API Functions

The implementation provides the following operations defined by the SUNMemoryHelper API:

`SUNMemory SUNMemoryHelper_Alloc_Sycl(SUNMemoryHelper helper, SUNMemory memptr, size_t mem_size, SUNMemoryType mem_type, void *queue)`

Allocates a SUNMemory object whose ptr field is allocated for mem\_size bytes and is of type mem\_type. The new object will have ownership of ptr and will be deallocated when `SUNMemoryHelper_Dealloc()` is called.

**Arguments:**

- helper – the SUNMemoryHelper object.
- memptr – pointer to the allocated SUNMemory.
- mem\_size – the size in bytes of the ptr.
- mem\_type – the SUNMemoryType of the ptr. Supported values are:
  - SUNMEMTYPE\_HOST – memory is allocated with a call to `malloc`.
  - SUNMEMTYPE\_PINNED – memory is allocated with a call to `sycl::malloc_host`.
  - SUNMEMTYPE\_DEVICE – memory is allocated with a call to `sycl::malloc_device`.
  - SUNMEMTYPE\_UVM – memory is allocated with a call to `sycl::malloc_shared`.
- queue – the `sycl::queue` handle for the stream that the allocation will be performed on.

**Returns:**

- An int flag indicating success (zero) or failure (non-zero).

`int SUNMemoryHelper_Dealloc_Sycl(SUNMemoryHelper helper, SUNMemory mem, void *queue)`  
Deallocates the mem->ptr field if it is owned by mem, and then deallocates the mem object.

**Arguments:**

- helper – the SUNMemoryHelper object.
- mem – the SUNMemory object.
- queue – the `sycl::queue` handle for the queue that the deallocation will be performed on.

**Returns:**

- An int flag indicating success (zero) or failure (non-zero).

`int SUNMemoryHelper_Copy_Sycl(SUNMemoryHelper helper, SUNMemory dst, SUNMemory src, size_t mem_size, void *queue)`

Synchronously copies mem\_size bytes from the source memory to the destination memory. The copy can be across memory spaces, e.g. host to device, or within a memory space, e.g. host to host. The helper object will use the memory types of dst and src to determine the appropriate transfer type necessary.

**Arguments:**

- helper – the SUNMemoryHelper object.
- dst – the destination memory to copy to.
- src – the source memory to copy from.
- mem\_size – the number of bytes to copy.
- queue – the `sycl::queue` handle for the queue that the copy will be performed on.

**Returns:**

- An int flag indicating success (zero) or failure (non-zero).

```
int SUNMemoryHelper_CopyAsync_Sycl(SUNMemoryHelper helper, SUNMemory dst, SUNMemory src, size_t  
mem_size, void *queue)
```

Asynchronously copies `mem_size` bytes from the source memory to the destination memory. The copy can be across memory spaces, e.g. host to device, or within a memory space, e.g. host to host. The `helper` object will use the memory types of `dst` and `src` to determine the appropriate transfer type necessary.

**Arguments:**

- `helper` – the `SUNMemoryHelper` object.
- `dst` – the destination memory to copy to.
- `src` – the source memory to copy from.
- `mem_size` – the number of bytes to copy.
- `queue` – the `sycl::queue` handle for the queue that the copy will be performed on.

**Returns:**

- An int flag indicating success (zero) or failure (non-zero).

## Chapter 12

# SUNDIALS 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`, `cicode`, `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 -zxf 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 begin with a few common observations:

1. 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/lib`, with `INSTDIR` specified at configuration time.

2. 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.
3. The installation directory `INSTDIR` can not be the same as the source directory `SOLVERDIR`.
4. 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.)

Further details on the CMake-based installation procedures, instructions for manual compilation, and a roadmap of the resulting installed libraries and exported header files, are provided in §12.1 and §12.2.

## 12.1 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 3.12.0 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` or `cmake-gui`), while on Windows it requires Visual Studio. While many Linux distributions offer CMake, the version included may be out of date. CMake adds new features regularly, and you should download the latest version 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` or `cmake-gui` (depending on the version of CMake), 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.

### 12.1.1 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, or from a `wxWidgets` or `QT` based GUI by using the `cmake-gui` command. Examples for using both text and graphical 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:

```
$ mkdir (...)/INSTDIR  
$ mkdir (...)/BUILDDIR  
$ cd (...)/BUILDDIR
```

#### 12.1.1.1 Building with the GUI

Using CMake with the `ccmake` GUI follows the general process:

1. Select and modify values, run configure (`c` key)
2. New values are denoted with an asterisk
3. 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

4. Repeat until all values are set as desired and the generate option is available (g key)
5. Some variables (advanced variables) are not visible right away; to see advanced variables, toggle to advanced mode (t key)
6. To search for a variable press the / key, and to repeat the search, press the n key

Using CMake with the `cmake-gui` GUI follows a similar process:

1. Select and modify values, click **Configure**
2. The first time you click **Configure**, make sure to pick the appropriate generator (the following will assume generation of Unix Makfiles).
3. New values are highlighted in red
4. To set a variable, click on or move the cursor to the variable and press enter
  - If it is a boolean (ON/OFF) it will check/uncheck the box
  - If it is string or file, it will allow editing of the string. Additionally, an ellipsis button will appear ... on the far right of the entry. Clicking this button will bring up the file or directory selection dialog.
  - For files and directories, the <tab> key can be used to complete
5. Repeat until all values are set as desired and click the **Generate** button
6. Some variables (advanced variables) are not visible right away; to see advanced variables, click the **advanced** button

To build the default configuration using the curses GUI, from the BUILDDIR enter the `ccmake` command and point to the SOLVERDIR:

```
$ ccmake (...)/SOLVERDIR
```

Similarly, to build the default configuration using the wxWidgets GUI, from the BUILDDIR enter the `cmake-gui` command and point to the SOLVERDIR:

```
$ cmake-gui (...)/SOLVERDIR
```

The default curses configuration screen is shown in the following figure.

The default INSTDIR for both SUNDIALS and the corresponding examples can be changed by setting the `CMAKE_INSTALL_PREFIX` and the `EXAMPLES_INSTALL_PATH` as shown in the following figure.

Pressing the g key or clicking generate will generate Makefiles including all dependencies and all rules to build SUNDIALS on this system. Back at the command prompt, you can now run:

```
$ make
```

or for a faster parallel build (e.g. using 4 threads), you can run

```
$ make -j 4
```

To install SUNDIALS in the installation directory specified in the configuration, simply run:

```
$ make install
```

```

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BUILD_ARKODE           *ON
BUILD_CVODE             *ON
BUILD_CVODES            *ON
BUILD_EXAMPLES          *ON
BUILD_IDA               *ON
BUILD_IDAS              *ON
BUILD_KINSOL             *ON
BUILD_SHARED_LIBS        *ON
BUILD_STATIC_LIBS        *ON
BUILD_TESTING            *ON
CMAKE_BUILD_TYPE         *
CMAKE_CXX_COMPILER       */usr/bin/c++
CMAKE_CXX_FLAGS          *
CMAKE_C_COMPILER          */usr/bin/cc
CMAKE_C_FLAGS             *
CMAKE_INSTALL_LIBDIR      *lib64
CMAKE_INSTALL_PREFIX      */usr/local
ENABLE_CUDA               *OFF
ENABLE_FORTRAN            *OFF
ENABLE_HYPRE              *OFF
ENABLE_KLU                *OFF
ENABLE_LAPACK              *OFF
ENABLE_MPI                *OFF
ENABLE_OPENMP              *OFF
ENABLE_OPENMP_DEVICE       *OFF
ENABLE_PETSC              *OFF
ENABLE_PTHREAD             *OFF
ENABLE_RAJA                *OFF
ENABLE_SUPERLUDIST         *OFF
ENABLE_SUPERLUMT            *OFF
ENABLE_TRILINOS            *OFF
EXAMPLES_ENABLE_C          *ON
EXAMPLES_ENABLE_CXX        *ON
EXAMPLES_INSTALL            *ON
EXAMPLES_INSTALL_PATH      */usr/local/examples
SUNDIALS_BUILD_WITH_MONITORING *OFF
SUNDIALS_INDEX_SIZE        *64
SUNDIALS_PRECISION          *DOUBLE
USE_GENERIC_MATH            *ON
USE_XSDK_DEFAULTS          *OFF

BUILD_ARKODE: Build the ARKODE library
Press [enter] to edit option Press [d] to delete an entry
Press [c] to configure
Press [h] for help      Press [q] to quit without generating
Press [t] to toggle advanced mode (Currently Off)
CMake Version 3.12.1

```

Fig. 12.1: Default configuration screen. Note: Initial screen is empty. To get this default configuration, press ‘c’ repeatedly (accepting default values denoted with asterisk) until the ‘g’ option is available.

```

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BUILD_ARKODE           *ON
BUILD_CVODE             *ON
BUILD_CVODES            *ON
BUILD_EXAMPLES          *ON
BUILD_IDA               *ON
BUILD_IDAS              *ON
BUILD_KINSOL             *ON
BUILD_SHARED_LIBS        *ON
BUILD_STATIC_LIBS        *ON
BUILD_TESTING            *ON
CMAKE_BUILD_TYPE         *
CMAKE_CXX_COMPILER       */usr/bin/c++
CMAKE_CXX_FLAGS          *
CMAKE_C_COMPILER          */usr/bin/cc
CMAKE_C_FLAGS             *
CMAKE_INSTALL_LIBDIR      *lib64
CMAKE_INSTALL_PREFIX      */usr/casc/sundials/instdir
ENABLE_CUDA               *OFF
ENABLE_FORTRAN            *OFF
ENABLE_HYPRE              *OFF
ENABLE_KLU                *OFF
ENABLE_LAPACK              *OFF
ENABLE_MPI                *OFF
ENABLE_OPENMP              *OFF
ENABLE_OPENMP_DEVICE       *OFF
ENABLE_PETSC              *OFF
ENABLE_PTHREAD             *OFF
ENABLE_RAJA                *OFF
ENABLE_SUPERLUDIST         *OFF
ENABLE_SUPERLUMT            *OFF
ENABLE_TRILINOS            *OFF
EXAMPLES_ENABLE_C          *ON
EXAMPLES_ENABLE_CXX        *ON
EXAMPLES_INSTALL            *ON
EXAMPLES_INSTALL_PATH      */usr/casc/sundials/instdir/examples
SUNDIALS_BUILD_WITH_MONITORING *OFF
SUNDIALS_INDEX_SIZE        *64
SUNDIALS_PRECISION          *DOUBLE
USE_GENERIC_MATH            *ON
USE_XSDK_DEFAULTS          *OFF

EXAMPLES_INSTALL_PATH: Output directory for installing example files
Press [enter] to edit option Press [d] to delete an entry
Press [c] to configure
Press [h] for help           Press [q] to quit without generating
Press [t] to toggle advanced mode (Currently Off)
                                         CMake Version 3.12.1

```

Fig. 12.2: Changing the INSTDIR for SUNDIALS and corresponding EXAMPLES.

### 12.1.1.2 Building from the command line

Using CMake from the command line is simply a matter of specifying CMake variable settings with the `cmake` command. The following will build the default configuration:

```
$ cmake -DCMAKE_INSTALL_PREFIX=/home/myname/sundials/instdir \
> -DEXAMPLES_INSTALL_PATH=/home/myname/sundials/instdir/examples \
> ./srcdir
$ make
$ make install
```

### 12.1.2 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, 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\_C\_STANDARD**

The C standard to build C parts of SUNDIALS with.

Default: 99

Options: 90, 99, 11, 17.

**CMAKE\_C\_EXTENSIONS**

Enable compiler specific C extensions.

Default: OFF

**CMAKE\_CXX\_COMPILER**

C++ compiler

Default: `/usr/bin/c++`

---

**Note:** A C++ compiler is only required when a feature requiring C++ is enabled (e.g., CUDA, HIP, SYCL, RAJA, etc.) or the C++ examples are enabled.

All SUNDIALS solvers can be used from C++ applications 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\_CXX\_STANDARD**

The C++ standard to build C++ parts of SUNDIALS with.

Default: 11

Options: 98, 11, 14, 17, 20.

**CMAKE\_CXX\_EXTENSIONS**

Enable compiler specific C++ extensions.

Default: OFF

**CMAKE\_Fortran\_COMPILER**

Fortran compiler

Default: /usr/bin/gfortran

---

**Note:** Fortran support (and all related options) are triggered only if either Fortran-C support (BUILD\_FORTRAN\_MODULE\_INTERFACE) or LAPACK (ENABLE\_LAPACK) support is enabled.

---

**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\_LIBDIR**

The directory under which libraries will be installed.

Default: Set based on the system: lib, lib64, or lib/<multiarch-tuple>

**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 lib of CMAKE\_INSTALL\_PREFIX,

respectively.

---

**ENABLE\_CUDA**

Build the SUNDIALS CUDA modules.

Default: OFF

**CMAKE\_CUDA\_ARCHITECTURES**

Specifies the CUDA architecture to compile for.

Default: sm\_30

**ENABLE\_XBRAID**

Enable or disable the ARKStep + XBraid interface.

Default: OFF

---

**Note:** See additional information on building with *XBraid* enabled in §12.1.4.

---

**EXAMPLES\_ENABLE\_C**

Build the SUNDIALS C examples

Default: ON

**EXAMPLES\_ENABLE\_CXX**

Build the SUNDIALS C++ examples

Default: OFF

**EXAMPLES\_ENABLE\_CUDA**

Build the SUNDIALS CUDA examples

Default: OFF

---

**Note:** You need to enable CUDA support to build these examples.

---

**EXAMPLES\_ENABLE\_F2003**

Build the SUNDIALS Fortran2003 examples

Default: ON (if BUILD\_FORTRAN\_MODULE\_INTERFACE 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.

---

**BUILD\_FORTRAN\_MODULE\_INTERFACE**

Enable Fortran2003 interface

Default: OFF

**ENABLE\_HYPRE**

Flag to enable *hypre* support

Default: OFF

---

**Note:** See additional information on building with *hypre* enabled in §12.1.4.

---

**HYPRE\_INCLUDE\_DIR**

Path to *hypre* header files

Default: none

**HYPRE\_LIBRARY**

Path to *hypre* installed library files

Default: none

**ENABLE\_KLU**

Enable KLU support

Default: OFF

---

**Note:** See additional information on building with KLU enabled in §12.1.4.

---

**KLU\_INCLUDE\_DIR**

Path to SuiteSparse header files

Default: none

**KLU\_LIBRARY\_DIR**

Path to SuiteSparse installed library files

Default: none

**ENABLE\_LAPACK**

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 §12.1.4.

---

**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.

---

**ENABLE\_MAGMA**

Enable MAGMA support.

Default: OFF

---

**Note:** Setting this option to ON will trigger additional options related to MAGMA.

---

**MAGMA\_DIR**

Path to the root of a MAGMA installation.

Default: none

**SUNDIALS\_MAGMA\_BACKENDS**

Which MAGMA backend to use under the SUNDIALS MAGMA interface.

Default: CUDA

**ENABLE\_MPI**

Enable MPI support. This will build the parallel nvector 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:

---

**Note:** This option is triggered only if MPI is enabled (ENABLE\_MPI 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 ENABLE\_MPI.

---

**MPI\_Fortran\_COMPILER**

mpif90 program

Default:

---

**Note:** This option is triggered only if MPI is enabled (ENABLE\_MPI is ON) and Fortran-C support is enabled (EXAMPLES\_ENABLE\_F2003 is ON).

---

**MPIEXEC\_EXECUTABLE**

Specify the executable for running MPI programs

Default: mpirun

---

**Note:** This option is triggered only if MPI is enabled (ENABLE\_MPI is ON).

---

**ENABLE\_ONEMKL**

Enable oneMKL support.

Default: OFF

**ONEMKL\_DIR**

Path to oneMKL installation.

Default: none

**ENABLE\_OPENMP**

Enable OpenMP support (build the OpenMP NVector)

Default: OFF

**ENABLE\_PETSC**

Enable PETSc support

Default: OFF

---

**Note:** See additional information on building with PETSc enabled in §12.1.4.

---

**PETSC\_DIR**

Path to PETSc installation

Default: none

**PETSC\_LIBRARIES**

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: none

**PETSC\_INCLUDES**

Semi-colon separated list of PETSc include directroies. Unless provided by the user, this is autopopulated based on the PETSc installation found in PETSC\_DIR.

Default: none

**ENABLE\_PTHREAD**

Enable Pthreads support (build the Pthreads NVector)

Default: OFF

**ENABLE\_RAJA**

Enable RAJA support.

Default: OFF

---

**Note:** You need to enable CUDA or HIP in order to build the RAJA vector module.

---

**SUNDIALS\_RAJA\_BACKENDS**

If building SUNDIALS with RAJA support, this sets the RAJA backend to target. Values supported are CUDA, HIP, or SYCL.

Default: CUDA

**ENABLE\_SUPERLUDIST**

Enable SuperLU\_DIST support

Default: OFF

---

**Note:** See additional information on building with SuperLU\_DIST enabled in §12.1.4.

---

**SUPERLUDIST\_INCLUDE\_DIR**

Path to SuperLU\_DIST header files (under a typical SuperLU\_DIST install, this is typically the SuperLU\_DIST SRC directory)

Default: none

**SUPERLUDIST\_LIBRARY\_DIR**

Path to SuperLU\_DIST installed library files

Default: none

**SUPERLUDIST\_LIBRARIES**

Semi-colon separated list of libraries needed for SuperLU\_DIST

Default: none

**SUPERLUDIST\_OpenMP**

Enable SUNDIALS support for SuperLU\_DIST built with OpenMP

Default: none

Note: SuperLU\_DIST must be built with OpenMP support for this option to function. Additionally the environment variable OMP\_NUM\_THREADS must be set to the desired number of threads.

**ENABLE\_SUPERLUMT**

Enable SuperLU\_MT support

Default: OFF

---

**Note:** See additional information on building with SuperLU\_MT enabled in §12.1.4.

---

**SUPERLUMT\_INCLUDE\_DIR**

Path to SuperLU\_MT header files (under a typical SuperLU\_MT install, this is typically the SuperLU\_MT SRC directory)

Default: none

**SUPERLUMT\_LIBRARY\_DIR**

Path to SuperLU\_MT installed library files

Default: none

**SUPERLUMT\_THREAD\_TYPE**

Must be set to Pthread or OpenMP, depending on how SuperLU\_MT was compiled.

Default: Pthread

**ENABLE\_SYCL**

Enable SYCL support.

Default: OFF

---

**Note:** At present the only supported SYCL compiler is the DPC++ (Intel oneAPI) compiler. CMake does not currently support autodetection of SYCL compilers and `CMAKE_CXX_COMPILER` must be set to a valid SYCL compiler i.e., `dpcpp` in order to build with SYCL support.

---

#### **SUNDIALS\_BUILD\_WITH\_MONITORING**

Build SUNDIALS with capabilities for fine-grained monitoring of solver progress and statistics. This is primarily useful for debugging.

Default: OFF

**Warning:** Building with monitoring may result in minor performance degradation even if monitoring is not utilized.

#### **SUNDIALS\_BUILD\_WITH\_PROFILING**

Build SUNDIALS with capabilities for fine-grained profiling.

Default: OFF

**Warning:** Profiling will impact performance, and should be enabled judiciously.

#### **ENABLE\_CALIPER**

Enable CALIPER support

Default: OFF

---

**Note:** Using Caliper requires setting `SUNDIALS_BUILD_WITH_PROFILING` to ON.

---

#### **CALIPER\_DIR**

Path to the root of a Caliper installation

Default: None

#### **SUNDIALS\_F77\_FUNC\_CASE**

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**

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**

Integer type used for SUNDIALS indices. The size must match the size provided for the SUNDIALS\_INDEX\_SIZE option.

Default: Automatically determined based on *SUNDIALS\_INDEX\_SIZE*

---

**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 deprecated. 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**

The floating-point precision used in SUNDIALS packages and class implementations, options are: double, single, or extended

Default: double

**SUNDIALS\_INSTALL\_CMAKEDIR**

Installation directory for the SUNDIALS cmake files (relative to *CMAKE\_INSTALL\_PREFIX*).

Default: *CMAKE\_INSTALL\_PREFIX*/cmake/sundials

**USE\_GENERIC\_MATH**

Use generic (stdc) math libraries

Default: ON

**XBRAID\_DIR**

The root directory of the XBraid installation.

Default: OFF

**XBRAID\_INCLUDES**

Semi-colon separated list of XBraid include directories. Unless provided by the user, this is autopopulated based on the XBraid installation found in *XBRAID\_DIR*.

Default: none

**XBRAID\_LIBRARIES**

Semi-colon separated list of XBraid link libraries. Unless provided by the user, this is autopopulated based on the XBraid installation found in *XBRAID\_DIR*.

Default: none

**USE\_XSDK\_DEFAULTS**

Enable xSDK (see <https://xSDK.info> for more information) default configuration settings. This sets *CMAKE\_BUILD\_TYPE* to Debug, *SUNDIALS\_INDEX\_SIZE* to 32 and *SUNDIALS\_PRECISION* to double.

Default: OFF

### 12.1.3 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 `mpif90` 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 \
> -DENABLE_MPI=ON \
> /home/myname/sundials/srcdir

% 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 \
> -DENABLE_MPI=ON \
> -DEXAMPLES_INSTALL=OFF \
> /home/myname/sundials/srcdir

% make install
```

### 12.1.4 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.

#### 12.1.4.1 Building with LAPACK

To enable LAPACK, set the `ENABLE_LAPACK` 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 \
> -DENABLE_LAPACK=ON \
> -DLAPACK_LIBRARIES=/mylapackpath/lib/libblas.so;/mylapackpath/lib/liblapack.so \
> /home/myname/sundials/srcdir

% make install
```

---

**Note:** 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.

---

SUNDIALS has been tested with OpenBLAS 0.3.18.

#### 12.1.4.2 Building with KLU

KLU is a software package for the direct solution of sparse nonsymmetric linear systems of equations that arise in circuit simulation and is part of SuiteSparse, a suite of sparse matrix software. The library is developed by Texas A&M University and is available from the [SuiteSparse GitHub repository](#).

To enable KLU, set `ENABLE_KLU` 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`.

SUNDIALS has been tested with SuiteSparse version 5.10.1.

#### 12.1.4.3 Building with SuperLU\_DIST

SuperLU\_DIST is a general purpose library for the direct solution of large, sparse, nonsymmetric systems of linear equations in a distributed memory setting. The library is developed by Lawrence Berkeley National Laboratory and is available from the [SuperLU\\_DIST GitHub repository](#).

To enable SuperLU\_DIST, set `ENABLE_SUPERLUDIST` to ON, set `SUPERLUDIST_INCLUDE_DIR` to the `SRC` path of the SuperLU\_DIST installation, and set the variable `SUPERLUMT_LIBRARY_DIR` to the `lib` path of the SuperLU\_DIST installation. 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 utilize the OpenMP functionality of SuperLU\_DIST.

SUNDIALS has been tested with SuperLU\_DIST 7.1.1.

#### 12.1.4.4 Building with SuperLU\_MT

SuperLU\_MT is a general purpose library for the direct solution of large, sparse, nonsymmetric systems of linear equations on shared memory parallel machines. The library is developed by Lawrence Berkeley National Laboratory and is available from the [SuperLU\\_MT GitHub repository](#).

To enable SuperLU\_MT, set `ENABLE_SUPERLUMT` 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 `ENABLE_OPENMP` or `ENABLE_PTHREAD` set to ON then SuperLU\_MT should be set to use the same threading type.

SUNDIALS has been tested with SuperLU\_MT version 3.1.

#### **12.1.4.5 Building with PETSc**

The Portable, Extensible Toolkit for Scientific Computation (PETSc) is a suite of data structures and routines for simulating applications modeled by partial differential equations. The library is developed by Argonne National Laboratory and is available from the [PETSc GitLab repository](#).

To enable PETSc, set `ENABLE_PETSC` to ON, and 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 PETSc libraries in `PETSC_LIBRARIES`.

SUNDIALS has been tested with PETSc version 3.16.1.

#### **12.1.4.6 Building with *hypre***

*hypre* is a library of high performance preconditioners and solvers featuring multigrid methods for the solution of large, sparse linear systems of equations on massively parallel computers. The library is developed by Lawrence Livermore National Laboratory and is available from the [hypre GitHub repository](#).

To enable *hypre*, set `ENABLE_HYPRE` 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` is compatible with `HYPRE_BigInt` in the *hypre* installation.

---

SUNDIALS has been tested with *hypre* version 2.23.0

#### **12.1.4.7 Building with MAGMA**

The Matrix Algebra on GPU and Multicore Architectures (MAGMA) project provides a dense linear algebra library similar to LAPACK but targeting heterogeneous architectures. The library is developed by the University of Tennessee and is available from the [UTK webpage](#).

To enable the SUNDIALS MAGMA interface set `ENABLE_MAGMA` to ON, `MAGMA_DIR` to the MAGMA installation path, and `SUNDIALS_MAGMA_BACKENDS` to the desired MAGMA backend to use with SUNDIALS e.g., CUDA or HIP.

SUNDIALS has been tested with MAGMA version 2.6.1.

#### **12.1.4.8 Building with oneMKL**

The Intel [oneAPI Math Kernel Library \(oneMKL\)](#) includes CPU and DPC++ interfaces for LAPACK dense linear algebra routines. The SUNDIALS oneMKL interface targets the DPC++ routines, to utilize the CPU routine see §12.1.4.1.

To enable the SUNDIALS oneMKL interface set `ENABLE_ONEMKL` to ON and `ONEMKL_DIR` to the oneMKL installation path.

SUNDIALS has been tested with oneMKL version 2021.4.

#### 12.1.4.9 Building with CUDA

The NVIDIA CUDA Toolkit provides a development environment for GPU-accelerated computing with NVIDIA GPUs. The CUDA Toolkit and compatible NVIDIA drivers are available from the [NVIDIA developer website](#).

To enable CUDA, set `ENABLE_CUDA` 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.

SUNDIALS has been tested with the CUDA toolkit versions 10 and 11.

#### 12.1.4.10 Building with RAJA

RAJA is a performance portability layer developed by Lawrence Livermore National Laboratory and can be obtained from the [RAJA GitHub repository](#).

Building SUNDIALS RAJA modules requires a CUDA, HIP, or SYCL enabled RAJA installation. To enable RAJA, set `ENABLE_RAJA` to ON, set `SUNDIALS_RAJA_BACKENDS` to the desired backend (CUDA, HIP, or SYCL), and set `ENABLE_CUDA`, `ENABLE_HIP`, or `ENABLE_SYCL` to ON depending on the selected backend. 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_CXX` to ON.

SUNDIALS has been tested with RAJA version 0.14.0.

#### 12.1.4.11 Building with XBraid

XBraid is parallel-in-time library implementing an optimal-scaling multigrid reduction in time (MGRIT) solver. The library is developed by Lawrence Livermore National Laboratory and is available from the [XBraid GitHub repository](#).

To enable XBraid support, set `ENABLE_XBRAID` to ON, set `XBRAID_DIR` to the root install location of XBraid or the location of the clone of the XBraid repository.

---

**Note:** At this time the XBraid types `braid_Int` and `braid_Real` are hard-coded to `int` and `double` respectively. As such SUNDIALS must be configured with `SUNDIALS_INDEX_SIZE` set to 32 and `SUNDIALS_PRECISION` set to `double`. Additionally, SUNDIALS must be configured with `ENABLE_MPI` set to ON.

---

SUNDIALS has been tested with XBraid version 3.0.0.

### 12.1.5 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
```

### 12.1.6 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` or `cmake-gui` 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.

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**Note:** There will potentially be differences in the output due to machine architecture, compiler versions, use of third party libraries etc.

---

### 12.1.7 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.

## 12.2 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/lib and INSTDIR/include, respectively. The location can be changed by setting the CMake variable CMAKE\_INSTALL\_PREFIX. Although all installed libraries reside under LIBDIR/lib, the public header files are further organized into subdirectories under INCLUDEDIR/include.

The installed libraries and exported header files are listed for reference in the table below. The file extension .LIB is typically .so for shared libraries and .a for static libraries. Note that, in this table 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., sunlinsol\_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.

### 12.2.1 Using SUNDIALS as a Third Party Library in other CMake Projects

The `make install` command will also install a CMake package configuration file that other CMake projects can load to get all the information needed to build against SUNDIALS. In the consuming project's CMake code, the `find_package` command may be used to search for the configuration file, which will be installed to `installdir/SUNDIALS-INSTALL_CMAKEDIR/SUNDIALSConfig.cmake` alongside a package version file `installdir/SUNDIALS_INSTALL_CMAKEDIR/SUNDIALSConfigVersion.cmake`. Together these files contain all the information the consuming project needs to use SUNDIALS, including exported CMake targets. The SUNDIALS exported CMake targets follow the same naming convention as the generated library binaries, e.g. the exported target for CVODE is `SUNDIALS::cvode`. The CMake code snipped below shows how a consuming project might leverage the SUNDIALS package configuration file to build against SUNDIALS in their own CMake project.

```
project(MyProject)

# Set the variable SUNDIALS_DIR to the SUNDIALS installdir.
# When using the cmake CLI command, this can be done like so:
#   cmake -D SUNDIALS_DIR=/path/to/sundials/installation

find_package(SUNDIALS REQUIRED)

add_executable(myexec main.c)

# Link to SUNDIALS libraries through the exported targets.
# This is just an example, users should link to the targets appropriate
# for their use case.
target_link_libraries(myexec PUBLIC SUNDIALS::cvode SUNDIALS::nvecpetsc)
```

Table 12.1: SUNDIALS shared libraries and header files

Shared	Headers	sundials/sundials_band.h sundials/sundials_config.h sundials/sundials_context.h sundials/sundials_cuda_policies.hpp
--------	---------	--

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		sundials/sundials_dense.h sundials/sundials_direct.h sundials/sundials_hip_policies.hpp sundials/sundials_iterative.h sundials/sundials_linearsolver.h sundials/sundials_math.h sundials/sundials_matrix.h sundials/sundials_memory.h sundials/sundials_mpi_types.h sundials/sundials_nonlinearsolver.h sundials/sundials_nvector.h sundials/sundials_types.h sundials/sundials_version.h sundials/sundials_xbraid.h
<b>NVECTOR Modules</b>		
SERIAL	Libraries	libsundials_nvecserial.LIB
	Headers	nvector/nvector_serial.h
PARALLEL	Libraries	libsundials_nvecparallel.LIB
	Headers	nvector/nvector_parallel.h
OPENMP	Libraries	libsundials_nvecopenmp.LIB
	Headers	nvector/nvector_openmp.h
PTHREADS	Libraries	libsundials_nvecpthreads.LIB
	Headers	nvector/nvector_pthreads.h
PARHYP	Libraries	libsundials_nvecparhyp.LIB
	Headers	nvector/nvector_parhyp.h
PETSC	Libraries	libsundials_nvecpetsc.LIB
	Headers	nvector/nvector_petsc.h
CUDA	Libraries	libsundials_nveccuda.LIB
	Headers	nvector/nvector_cuda.h
HIP	Libraries	libsundials_nvechip.LIB
	Headers	nvector/nvector_hip.h
RAJA	Libraries	libsundials_nveccudaraja.LIB
	Headers	libsundials_nvechipraja.LIB
SYCL	Libraries	libsundials_nvecsycl.LIB
	Headers	nvector/nvector_sycl.h
MANYVECTOR	Libraries	libsundials_nvecmanyvector.LIB
	Headers	nvector/nvector_manyvector.h
MPI MANYVECTOR	Libraries	libsundials_nvecmpimanyvector.LIB
	Headers	nvector/nvector_mpimanyvector.h
MPIPLUSX	Libraries	libsundials_nvecmpiplusx.LIB
	Headers	nvector/nvector_mpiplusx.h
<b>SUNMATRIX Modules</b>		
BAND	Libraries	libsundials_sunmatrixband.LIB
	Headers	sunmatrix/sunmatrix_band.h
CUSPARSE	Libraries	libsundials_sunmatrixcusparse.LIB
	Headers	sunmatrix/sunmatrix_cusparse.h
DENSE	Libraries	libsundials_sunmatrixdense.LIB
	Headers	sunmatrix/sunmatrix_dense.h
MAGMA DENSE	Libraries	libsundials_sunmatrixmagmadense.LIB
	Headers	sunmatrix/sunmatrix_magmadense.h
ONE MKL DENSE	Libraries	libsundials_sunmatrixonemkldense.LIB

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	Headers	<code>sunmatrix/summatrix_onemkldense.h</code>
SPARSE	Libraries	<code>libsundials_sunmatrixsparse.LIB</code>
	Headers	<code>sunmatrix/summatrix_sparse.h</code>
SLUNRLOC	Libraries	<code>libsundials_sunmatrixslunrloc.LIB</code>
	Headers	<code>sunmatrix/summatrix_slunrloc.h</code>
<b>SUNLINSOL Modules</b>		
BAND	Libraries	<code>libsundials_sunlinsolband.LIB</code>
	Headers	<code>sunlinsol/sunlinsol_band.h</code>
CUSOLVERSP_BATCHQR	Libraries	<code>libsundials_sunlinsolcusolversp.LIB</code>
	Headers	<code>sunlinsol/sunlinsol_cusolversp_batchqr.h</code>
DENSE	Libraries	<code>libsundials_sunlinsoldense.LIB</code>
	Headers	<code>sunlinsol/sunlinsol_dense.h</code>
KLU	Libraries	<code>libsundials_sunlinsolklu.LIB</code>
	Headers	<code>sunlinsol/sunlinsol_klu.h</code>
LAPACKBAND	Libraries	<code>libsundials_sunlinsolapackband.LIB</code>
	Headers	<code>sunlinsol/sunlinsol_lapackband.h</code>
LAPACKDENSE	Libraries	<code>libsundials_sunlinsolapackdense.LIB</code>
	Headers	<code>sunlinsol/sunlinsol_lapackdense.h</code>
MAGMADENSE	Libraries	<code>libsundials_sunlinsolmagmadense.LIB</code>
	Headers	<code>sunlinsol/sunlinsol_magmadense.h</code>
ONEMKLDENSE	Libraries	<code>libsundials_sunlinsolonemkldense.LIB</code>
	Headers	<code>sunlinsol/sunlinsol_onemkldense.h</code>
PCG	Libraries	<code>libsundials_sunlinsolpcg.LIB</code>
	Headers	<code>sunlinsol/sunlinsol_pcg.h</code>
SPBCGS	Libraries	<code>libsundials_sunlinsolspbcgs.LIB</code>
	Headers	<code>sunlinsol/sunlinsol_spbcgs.h</code>
SPFGMR	Libraries	<code>libsundials_sunlinsolspfgmr.LIB</code>
	Headers	<code>sunlinsol/sunlinsol_spfgmr.h</code>
SPGMR	Libraries	<code>libsundials_sunlinsolspgmr.LIB</code>
	Headers	<code>sunlinsol/sunlinsol_spgmr.h</code>
SPTFQMR	Libraries	<code>libsundials_sunlinsolsptfqmr.LIB</code>
	Headers	<code>sunlinsol/sunlinsol_sptfqmr.h</code>
SUPERLUDIST	Libraries	<code>libsundials_sunlinsolsuperludist.LIB</code>
	Headers	<code>sunlinsol/sunlinsol_superludist.h</code>
SUPERLUMT	Libraries	<code>libsundials_sunlinsolsuperlumt.LIB</code>
	Headers	<code>sunlinsol/sunlinsol_superlumt.h</code>
<b>SUNNONLINSOL Modules</b>		
NEWTON	Libraries	<code>libsundials_sunnonlinsolnewton.LIB</code>
	Headers	<code>sunnonlinsol/sunnonlinsol_newton.h</code>
FIXEDPOINT	Libraries	<code>libsundials_sunnonlinsolfixedpoint.LIB</code>
	Headers	<code>sunnonlinsol/sunnonlinsol_fixedpoint.h</code>
PETSCSNES	Libraries	<code>libsundials_sunnonlinsolpetscsnes.LIB</code>
	Headers	<code>sunnonlinsol/sunnonlinsol_petscsnes.h</code>
<b>SUNMEMORY Modules</b>		
SYSTEM	Libraries	<code>libsundials_sunmemsys.LIB</code>
	Headers	<code>sunmemory/sunmemory_system.h</code>
CUDA	Libraries	<code>libsundials_sunmemcuda.LIB</code>
	Headers	<code>sunmemory/sunmemory_cuda.h</code>
HIP	Libraries	<code>libsundials_sunmemhip.LIB</code>
	Headers	<code>sunmemory/sunmemory_hip.h</code>
SYCL	Libraries	<code>libsundials_sunmemsycl.LIB</code>

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	Headers	<code>sunmemory/sunmemory_sycl.h</code>
<b>SUNDIALS Packages</b>		
CVODE	Libraries Headers	<code>libsundials_cvode.LIB</code>
		<code>cvode/cvode.h</code>
		<code>cvode/cvode_bandpre.h</code>
		<code>cvode/cvode_bbdpre.h</code>
		<code>cvode/cvode_diag.h</code>
		<code>cvode/cvode_direct.h</code>
		<code>cvode/cvode_impl.h</code>
		<code>cvode/cvode_ls.h</code>
		<code>cvode/cvode_proj.h</code>
		<code>cvode/cvode_spils.h</code>
CVODES	Libraries Headers	<code>libsundials_cvodes.LIB</code>
		<code>cvodes/cvodes.h</code>
		<code>cvodes/cvodes_bandpre.h</code>
		<code>cvodes/cvodes_bbdpre.h</code>
		<code>cvodes/cvodes_diag.h</code>
		<code>cvodes/cvodes_direct.h</code>
		<code>cvodes/cvodes_impl.h</code>
		<code>cvodes/cvodes_ls.h</code>
		<code>cvodes/cvodes_spils.h</code>
ARKODE	Libraries	<code>libsundials_arkode.LIB</code>
		<code>libsundials_xbraid.LIB</code>
	Headers	<code>arkode/arkode.h</code>
		<code>arkode/arkode_arkstep.h</code>
		<code>arkode/arkode_bandpre.h</code>
		<code>arkode/arkode_bbdpre.h</code>
		<code>arkode/arkode_butcher.h</code>
		<code>arkode/arkode_butcher_dirk.h</code>
		<code>arkode/arkode_butcher_erk.h</code>
		<code>arkode/arkode_erkstep.h</code>
IDA	Libraries	<code>libsundials_ida.LIB</code>
	Headers	<code>ida/ida.h</code>
		<code>ida/ida_bbdpre.h</code>
		<code>ida/ida_direct.h</code>
		<code>ida/ida_impl.h</code>
IDAS	Libraries	<code>libsundials_idas.LIB</code>
	Headers	<code>idas/idas.h</code>
		<code>idas/idas_bbdpre.h</code>
		<code>idas/idas_direct.h</code>
		<code>idas/idas_impl.h</code>
KINSOL	Libraries	<code>libsundials_kinsol.LIB</code>
	Headers	<code>kinsol/kinsol.h</code>
		<code>kinsol/kinsol_bbdpre.h</code>
		<code>kinsol/kinsol_direct.h</code>

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		kinsol/kinsol_impl.h
		kinsol/kinsol_ls.h
		kinsol/kinsol_spils.h



# Chapter 13

## Appendix: ARKODE Constants

Below we list all input and output constants used by the main solver, timestepper, and linear solver modules, together with a short description of their meaning. Table 13.1 contains the ARKODE input constants, and Table 13.2 contains the ARKODE output constants.

Table 13.1: ARKODE input constants

<b>Shared input constants</b>	
ARK_NORMAL	Solver should return at a specified output time.
ARK_ONE_STEP	Solver should return after each successful step.
<b>Full right-hand side evaluation constants</b>	
ARK_FULLRHS_START	Calling the full right-hand side function at the start of the integration.
ARK_FULLRHS_END	Calling the full right-hand side function at the end of a step.
ARK_FULLRHS_OTHER	Calling the full right-hand side function at the some other point e.g., for dense output.
<b>Interpolation module input constants</b>	
ARK_INTERP_HERMITE	Specifies use of the Hermite polynomial interpolation module (for non-stiff problems).
ARK_INTERP_LAGRANGE	Specifies use of the Lagrange polynomial interpolation module (for stiff problems).
ARK_INTERP_MAX_DEGREE	Maximum possible interpolating polynomial degree.
<b>Explicit Butcher table specification</b>	
ARKODE_HEUN_EULER_2_1_2	Use the Heun-Euler-2-1-2 ERK method.
ARKODE_BOGACKI_SHAMPINE_4_2_3	Use the Bogacki-Shampine-4-2-3 ERK method.
ARKODE_ARK324L2SA_ERK_4_2_3	Use the ARK-4-2-3 ERK method.
ARKODE_ZONNEVELD_5_3_4	Use the Zonneveld-5-3-4 ERK method.
ARKODE_ARK436L2SA_ERK_6_3_4	Use the ARK-6-3-4 ERK method.
ARKODE_SAYFY_ABURUB_6_3_4	Use the Sayfy-Aburub-6-3-4 ERK method.
ARKODE_CASH_KARP_6_4_5	Use the Cash-Karp-6-4-5 ERK method.
ARKODE_FEHLBERG_6_4_5	Use the Fehlberg-6-4-5 ERK method.
ARKODE_DORMAND_PRINCE_7_4_5	Use the Dormand-Prince-7-4-5 ERK method.
ARKODE_ARK548L2SA_ERK_8_4_5	Use the ARK-8-4-5 ERK method.
ARKODE_VERNER_8_5_6	Use the Verner-8-5-6 ERK method.

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Table 13.1 – continued from previous page

ARKODE_FEHLBERG_13_7_8	Use the Fehlberg-13-7-8 ERK method.
ARKODE_KNOTH_WOLKE_3_3	Use the Knoth-Wolke-3-3 ERK method.
ARKODE_ARK437L2SA_ERK_7_3_4	Use the ARK-7-3-4 ERK method.
ARKODE_ARK548L2SAb_ERK_8_4_5	Use the ARK-8-4-5b ERK method.
ARKSTEP_DEFAULT_ERK_2	Use ARKStep's default second-order ERK method (ARKODE_-HEUN_EULER_2_1_2).
ARKSTEP_DEFAULT_ERK_3	Use ARKStep's default third-order ERK method (ARKODE_BO-GACKI_SHAMPINE_4_2_3).
ARKSTEP_DEFAULT_ERK_4	Use ARKStep's default fourth-order ERK method (ARKODE_-ZONNEVELD_5_3_4).
ARKSTEP_DEFAULT_ERK_5	Use ARKStep's default fifth-order ERK method (ARKODE_-CASH_KARP_6_4_5).
ARKSTEP_DEFAULT_ERK_6	Use ARKStep's default sixth-order ERK method (ARKODE_-VERNER_8_5_6).
ARKSTEP_DEFAULT_ERK_8	Use ARKStep's default eighth-order ERK method (ARKODE_-FEHLBERG_13_7_8).
ERKSTEP_DEFAULT_2	Use ERKStep's default second-order ERK method (ARKODE_-HEUN_EULER_2_1_2).
ERKSTEP_DEFAULT_3	Use ERKStep's default third-order ERK method (ARKODE_BO-GACKI_SHAMPINE_4_2_3).
ERKSTEP_DEFAULT_4	Use ERKStep's default fourth-order ERK method (ARKODE_-ZONNEVELD_5_3_4).
ERKSTEP_DEFAULT_5	Use ERKStep's default fifth-order ERK method (ARKODE_-CASH_KARP_6_4_5).
ERKSTEP_DEFAULT_6	Use ERKStep's default sixth-order ERK method (ARKODE_-VERNER_8_5_6).
ERKSTEP_DEFAULT_8	Use ERKStep's default eighth-order ERK method (ARKODE_-FEHLBERG_13_7_8).

**Implicit Butcher table specification**

ARKODE_SDIRK_2_1_2	Use the SDIRK-2-1-2 SDIRK method.
ARKODE_BILLINGTON_3_3_2	Use the Billington-3-3-2 SDIRK method.
ARKODE_TRBDF2_3_3_2	Use the TRBDF2-3-3-2 ESDIRK method.
ARKODE_KVAERNO_4_2_3	Use the Kvaerno-4-2-3 ESDIRK method.
ARKODE_ARK324L2SA_DIRK_4_2_3	Use the ARK-4-2-3 ESDIRK method.
ARKODE_CASH_5_2_4	Use the Cash-5-2-4 SDIRK method.
ARKODE_CASH_5_3_4	Use the Cash-5-3-4 SDIRK method.
ARKODE_SDIRK_5_3_4	Use the SDIRK-5-3-4 SDIRK method.
ARKODE_KVAERNO_5_3_4	Use the Kvaerno-5-3-4 ESDIRK method.
ARKODE_ARK436L2SA_DIRK_6_3_4	Use the ARK-6-3-4 ESDIRK method.
ARKODE_KVAERNO_7_4_5	Use the Kvaerno-7-4-5 ESDIRK method.
ARKODE_ARK548L2SA_DIRK_8_4_5	Use the ARK-8-4-5 ESDIRK method.
ARKODE_ARK437L2SA_DIRK_7_3_4	Use the ARK-7-3-4 ESDIRK method.
ARKODE_ARK548L2SAb_DIRK_8_4_5	Use the ARK-8-4-5b ESDIRK method.
ARKSTEP_DEFAULT_DIRK_2	Use ARKStep's default second-order DIRK method (ARKODE_-SDIRK_2_1_2).
ARKSTEP_DEFAULT_DIRK_3	Use ARKStep's default third-order DIRK method (ARKODE_-ARK324L2SA_DIRK_4_2_3).
ARKSTEP_DEFAULT_DIRK_4	Use ARKStep's default fourth-order DIRK method (ARKODE_-SDIRK_5_3_4).

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ARKSTEP_DEFAULT_DIRK_5	Use ARKStep's default fifth-order DIRK method (ARKODE-ARK548L2SA_DIRK_8_4_5).
<b>ImEx Butcher table specification</b>	
ARKODE_ARK324L2SA_ERK_4_2_3 & ARKODE_ARK324L2SA_DIRK_4_2_3	Use the ARK-4-2-3 ARK method.
ARKODE_ARK436L2SA_ERK_6_3_4 & ARKODE_ARK436L2SA_DIRK_6_3_4	Use the ARK-6-3-4 ARK method.
ARKODE_ARK437L2SA_ERK_7_3_4 & ARKODE_ARK437L2SA_DIRK_7_3_4	Use the ARK-7-3-4 ARK method.
ARKODE_ARK548L2SA_ERK_8_4_5 & ARKODE_ARK548L2SA_DIRK_8_4_5	Use the ARK-8-4-5 ARK method.
ARKODE_ARK548L2SAb_ERK_8_4_5 & ARKODE_ARK548L2SAb_DIRK_8_4_5	Use the ARK-8-4-5b ARK method.
ARKSTEP_DEFAULT_ARK_ETABLE_3 & ARKSTEP_DEFAULT_ARK_ITABLE_3	Use ARKStep's default third-order ARK method (ARKODE-ARK324L2SA_ERK_4_2_3 and ARKODE_ARK324L2SA_DIRK_4_2_3).
ARKSTEP_DEFAULT_ARK_ETABLE_4 & ARKSTEP_DEFAULT_ARK_ITABLE_4	Use ARKStep's default fourth-order ARK method (ARKODE-ARK436L2SA_ERK_6_3_4 and ARKODE_ARK436L2SA_DIRK_6_3_4).
ARKSTEP_DEFAULT_ARK_ETABLE_5 & ARKSTEP_DEFAULT_ARK_ITABLE_5	Use ARKStep's default fifth-order ARK method (ARKODE-ARK548L2SA_ERK_8_4_5 and ARKODE_ARK548L2SA_DIRK_8_4_5).
<b>MRI method types</b>	
MRISTEP_EXPLICIT	Use an explicit (at the slow time scale) MRI method.
MRISTEP_IMPLICIT	Use an implicit (at the slow time scale) MRI method.
MRISTEP_IMEX	Use an ImEx (at the slow time scale) MRI method.
<b>MRI coupling table specification</b>	
ARKODE_MIS_MW3	Use the Knoth-Wolke-3 MIS method.
ARKODE_MRI_GARK_ERK33a	Use the ERK33a MRI-GARK method.
ARKODE_MRI_GARK_ERK45a	Use the ERK45a MRI-GARK method.
ARKODE_MRI_GARK_IRK21a	Use the IRK21a MRI-GARK method.
ARKODE_MRI_GARK_ESDIRK34a	Use the ESDIRK34a MRI-GARK method.
ARKODE_MRI_GARK_ESDIRK46a	Use the ESDIRK46a MRI-GARK method.
ARKODE_IMEX_MRI_GARK3a	Use the IMEX-MRI-GARK3a method.
ARKODE_IMEX_MRI_GARK3b	Use the IMEX-MRI-GARK3b method.
ARKODE_IMEX_MRI_GARK4	Use the IMEX-MRI-GARK4 method.
MRISTEP_DEFAULT_EXPL_TABLE_3	Use MRISTep's default 3rd-order explicit method (MIS_MW3).
MRISTEP_DEFAULT_EXPL_TABLE_4	Use MRISTep's default 4th-order explicit method (MRI_GARK_ERK45a).
MRISTEP_DEFAULT_IMPL_SD_TABLE_2	Use MRISTep's default 2nd-order solve-decoupled implicit method (MRI_GARK_IRK21a).
MRISTEP_DEFAULT_IMPL_SD_TABLE_3	Use MRISTep's default 3rd-order solve-decoupled implicit method (MRI_GARK_ESDIRK34a).
MRISTEP_DEFAULT_IMPL_SD_TABLE_4	Use MRISTep's default 4th-order solve-decoupled implicit method (MRI_GARK_ESDIRK46a).
MRISTEP_DEFAULT_IMEX_SD_TABLE_3	Use MRISTep's default 3rd-order solve-decoupled ImEx method (IMEX_MRI_GARK3b).

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Table 13.1 – continued from previous page

MRISTEP_DEFAULT_IMEX_SD_TABLE_4	Use MRIStep's default 4th-order solve-decoupled ImEx method (IMEX_MRI_GARK4).
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Table 13.2: ARKODE output constants

Shared output constants		
ARK_SUCCESS	0	Successful function return.
ARK_TSTOP_RETURN	1	ARKODE succeeded by reaching the specified stopping point.
ARK_ROOT_RETURN	2	ARKODE succeeded and found one or more roots.
ARK_WARNING	99	ARKODE succeeded but an unusual situation occurred.
ARK_TOO MUCH_WORK	-1	The solver took mxstep internal steps but could not reach tout.
ARK_TOO MUCH_ACC	-2	The solver could not satisfy the accuracy demanded by the user for some internal step.
ARK_ERR_FAILURE	-3	Error test failures occurred too many times during one internal time step, or the minimum step size was reached.
ARK_CONV_FAILURE	-4	Convergence test failures occurred too many times during one internal time step, or the minimum step size was reached.
ARK_INIT_FAIL	-5	The linear solver's initialization function failed.
ARK_LSETUP_FAIL	-6	The linear solver's setup function failed in an unrecoverable manner.
ARK_LSOLVE_FAIL	-7	The linear solver's solve function failed in an unrecoverable manner.
ARK_RHSFUNC_FAIL	-8	The right-hand side function failed in an unrecoverable manner.
ARK_FIRST_RHSFUNC_ERR	-9	The right-hand side function failed at the first call.
ARK_REPTD_RHSFUNC_ERR	-10	The right-hand side function had repeated recoverable errors.
ARK_UNREC_RHS FUNC_ERR	-11	The right-hand side function had a recoverable error, but no recovery is possible.
ARK_RT FUNC_FAIL	-12	The rootfinding function failed in an unrecoverable manner.
ARK_LFREE_FAIL	-13	The linear solver's memory deallocation function failed.
ARK_MASSINIT_FAIL	-14	The mass matrix linear solver's initialization function failed.
ARK_MASSETUP_FAIL	-15	The mass matrix linear solver's setup function failed in an unrecoverable manner.
ARK_MASSSOLVE_FAIL	-16	The mass matrix linear solver's solve function failed in an unrecoverable manner.
ARK_MASSFREE_FAIL	-17	The mass matrix linear solver's memory deallocation function failed.
ARK_MASSMULT_FAIL	-18	The mass matrix-vector product function failed.
ARK_CONSTR_FAIL	-19	The inequality constraint test failed repeatedly or failed with the minimum step size.
ARK_MEM_FAIL	-20	A memory allocation failed.
ARK_MEM_NULL	-21	The arkode_mem argument was NULL.
ARK_ILL_INPUT	-22	One of the function inputs is illegal.
ARK_NO_MALLOC	-23	The ARKODE memory block was not allocated by a call to <a href="#">ARKStepCreate()</a> , <a href="#">ERKStepCreate()</a> , or <a href="#">MRISStepCreate()</a> .
ARK_BAD_K	-24	The derivative order k is larger than allowed.
ARK_BAD_T	-25	The time t is outside the last step taken.
ARK_BAD_DKY	-26	The output derivative vector is NULL.
ARK_TOO CLOSE	-27	The output and initial times are too close to each other.
ARK_VECTOROP_ERR	-28	An error occurred when calling an <a href="#">N_Vector</a> routine.
ARK_NLS_INIT_FAIL	-29	An error occurred when initializing a SUNNonlinSol module.
ARK_NLS_SETUP_FAIL	-30	A non-recoverable error occurred when setting up a SUNNonlinSol module.

continues on next page

Table 13.2 – continued from previous page

ARK_NLS_SETUP_- RECVR	-31	A recoverable error occurred when setting up a SUNNonlinSol module.
ARK_NLS_OP_ERR	-32	An error occurred when calling a set/get routine in a SUNNonlinSol module.
ARK_INNERSTEP_AT- TACH_ERR	-33	An error occurred when attaching the inner stepper module.
ARK_INNERSTEP_FAIL	-34	An error occurred in the inner stepper module.
ARK_PREINNERFN_FAIL	-35	An error occurred in the MRIStep pre inner integrator function.
ARK_POSTINNERFN_- FAIL	-36	An error occurred in the MRIStep post inner integrator function.
ARK_INTERP_FAIL	-40	An error occurred in the ARKODE polynomial interpolation module.
ARK_INVALID_TABLE	-41	An invalid Butcher or MRI table was encountered.
ARK_UNRECOGNIZED_- ERROR	-99	An unknown error was encountered.

**ARKLS linear solver module output constants**

ARKLS_SUCCESS	0	Successful function return.
ARKLS_MEM_NULL	-1	The <code>arkode_mem</code> argument was NULL.
ARKLS_LMEM_NULL	-2	The ARKLS linear solver interface has not been initialized.
ARKLS_ILL_INPUT	-3	The ARKLS solver interface is not compatible with the current <code>N_Vector</code> module, or an input value was illegal.
ARKLS_MEM_FAIL	-4	A memory allocation request failed.
ARKLS_PMEM_NULL	-5	The preconditioner module has not been initialized.
ARKLS_MASSMEM_- NULL	-6	The ARKLS mass-matrix linear solver interface has not been initialized.
ARKLS_JACFUNC_UN- RECVR	-7	The Jacobian function failed in an unrecoverable manner.
ARKLS_JACFUNC_- RECVR	-8	The Jacobian function had a recoverable error.
ARKLS_MASSFUNC_UN- RECVR	-9	The mass matrix function failed in an unrecoverable manner.
ARKLS_MASSFUNC_- RECVR	-10	The mass matrix function had a recoverable error.
ARKLS_SUNMAT_FAIL	-11	An error occurred with the current <code>SUNMatrix</code> module.
ARKLS_SUNLS_FAIL	-12	An error occurred with the current <code>SUNLinearSolver</code> module.



# Chapter 14

## Appendix: Butcher tables

Here we catalog the full set of Butcher tables included in ARKODE. We group these into three categories: *explicit*, *implicit* and *additive*. However, since the methods that comprise an additive Runge–Kutta method are themselves explicit and implicit, their component Butcher tables are listed within their separate sections, but are referenced together in the additive section.

In each of the following tables, we use the following notation (shown for a 3-stage method):

$c_1$	$a_{1,1}$	$a_{1,2}$	$a_{1,3}$
$c_2$	$a_{2,1}$	$a_{2,2}$	$a_{2,3}$
$c_3$	$a_{3,1}$	$a_{3,2}$	$a_{3,3}$
<hr/>	<hr/>	<hr/>	<hr/>
$q$	$b_1$	$b_2$	$b_3$
$p$	$\tilde{b}_1$	$\tilde{b}_2$	$\tilde{b}_3$

where here the method and embedding share stage  $A$  and  $c$  values, but use their stages  $z_i$  differently through the coefficients  $b$  and  $\tilde{b}$  to generate methods of orders  $q$  (the main method) and  $p$  (the embedding, typically  $q = p + 1$ , though sometimes this is reversed).

Method authors often use different naming conventions to categorize their methods. For each of the methods below with an embedding, we follow the uniform naming convention:

NAME-S-P-Q

where here

- NAME is the author or the name provided by the author (if applicable),
- S is the number of stages in the method,
- P is the global order of accuracy for the embedding,
- Q is the global order of accuracy for the method.

For methods without an embedding (e.g., fixed-step methods) P is omitted so that methods follow the naming convention NAME-S-Q.

In the code, unique integer IDs are defined inside `arkode_butcher_erk.h` and `arkode_butcher_dirk.h` for each method, which may be used by calling routines to specify the desired method. These names are specified in `fixed width` font at the start of each method’s section below.

Additionally, for each method we provide a plot of the linear stability region in the complex plane. These have been computed via the following approach. For any Runge–Kutta method as defined above, we may define the stability function

$$R(\eta) = 1 + \eta b[I - \eta A]^{-1} e,$$

where  $e \in \mathbb{R}^s$  is a column vector of all ones,  $\eta = h\lambda$  and  $h$  is the time step size. If the stability function satisfies  $|R(\eta)| \leq 1$  for all eigenvalues,  $\lambda$ , of  $\frac{\partial}{\partial y} f(t, y)$  for a given IVP, then the method will be linearly stable for that problem and step size. The stability region

$$S = \{\eta \in \mathbb{C} : |R(\eta)| \leq 1\}$$

is typically given by an enclosed region of the complex plane, so it is standard to search for the border of that region in order to understand the method. Since all complex numbers with unit magnitude may be written as  $e^{i\theta}$  for some value of  $\theta$ , we perform the following algorithm to trace out this boundary.

1. Define an array of values `Theta`. Since we wish for a smooth curve, and since we wish to trace out the entire boundary, we choose 10,000 linearly-spaced points from 0 to  $16\pi$ . Since some angles will correspond to multiple locations on the stability boundary, by going beyond  $2\pi$  we ensure that all boundary locations are plotted, and by using such a fine discretization the Newton method (next step) is more likely to converge to the root closest to the previous boundary point, ensuring a smooth plot.
2. For each value  $\theta \in \text{Theta}$ , we solve the nonlinear equation

$$0 = f(\eta) = R(\eta) - e^{i\theta}$$

using a finite-difference Newton iteration, using tolerance  $10^{-7}$ , and differencing parameter  $\sqrt{\varepsilon}$  ( $\approx 10^{-8}$ ).

In this iteration, we use as initial guess the solution from the previous value of  $\theta$ , starting with an initial-initial guess of  $\eta = 0$  for  $\theta = 0$ .

3. We then plot the resulting  $\eta$  values that trace the stability region boundary.

We note that for any stable IVP method, the value  $\eta_0 = -\varepsilon + 0i$  is always within the stability region. So in each of the following pictures, the interior of the stability region is the connected region that includes  $\eta_0$ . Resultingly, methods whose linear stability boundary is located entirely in the right half-plane indicate an *A-stable* method.

## 14.1 Explicit Butcher tables

In the category of explicit Runge–Kutta methods, ARKODE includes methods that have orders 2 through 6, with embeddings that are of orders 1 through 5. Each of ARKODE’s explicit Butcher tables are specified via a unique ID:

enum `ARKODE_ERKTableID`

with values specified for each method below (e.g., `ARKODE_HEUN_EULER_2_1_2`).

### 14.1.1 Heun-Euler-2-1-2

Accessible via the constant `ARKODE_HEUN_EULER_2_1_2` to `ARKStepSetTableNum()`, `ERKStepSetTableNum()` or `ARKodeButcherTable_LoadERK()`. This is the default 2nd order explicit method.

0	0	0
1	1	0
2	$\frac{1}{2}$	$\frac{1}{2}$
1	1	0

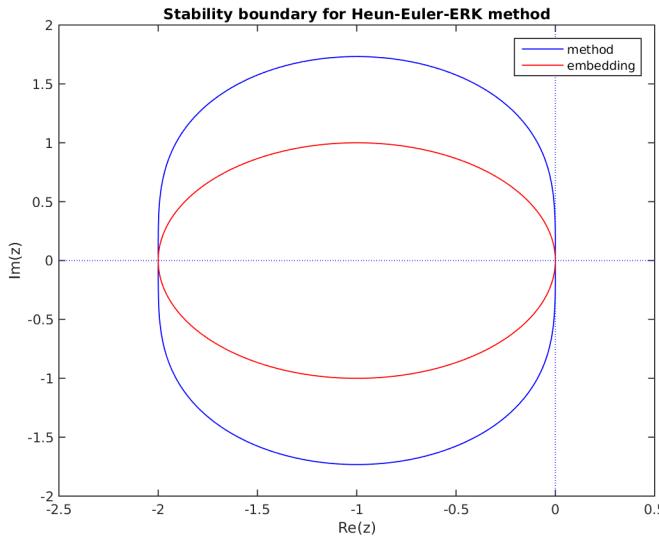


Fig. 14.1: Linear stability region for the Heun-Euler method. The method’s region is outlined in blue; the embedding’s region is in red.

### 14.1.2 Bogacki-Shampine-4-2-3

Accessible via the constant `ARKODE_BOGACKI_SHAMPINE_4_2_3` to `ARKStepSetTableNum()`, `ERKStepSetTableNum()` or `ARKodeButcherTable_LoadERK()`. This is the default 3rd order explicit method (from [8]).

0	0	0	0	0
$\frac{1}{2}$	$\frac{1}{2}$	0	0	0
$\frac{3}{4}$	0	$\frac{3}{4}$	0	0
1	$\frac{2}{9}$	$\frac{1}{3}$	$\frac{4}{9}$	0
3	$\frac{2}{9}$	$\frac{1}{3}$	$\frac{4}{9}$	
2	$\frac{7}{24}$	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{1}{8}$

### 14.1.3 ARK-4-2-3 (explicit)

Accessible via the constant `ARKODE_ARK324L2SA_ERK_4_2_3` to `ARKStepSetTableNum()`, `ERKStepSetTableNum()` or `ARKodeButcherTable_LoadERK()`. This is the explicit portion of the default 3rd order additive method (from [40]).

0	0	0	0	0
$\frac{1767732205903}{2027836641118}$	$\frac{1767732205903}{2027836641118}$	0	0	0
$\frac{3}{5}$	$\frac{5535828885825}{10492691773637}$	$\frac{788022342437}{10882634858940}$	0	0
1	$\frac{6485989280629}{16251701735622}$	$-\frac{4246266847089}{9704473918619}$	$\frac{10755448449292}{10357097424841}$	0
3	$\frac{1471266399579}{7840856788654}$	$-\frac{4482444167858}{7529755066697}$	$\frac{11266239266428}{11593286722821}$	$\frac{1767732205903}{4055673282236}$
2	$\frac{2756255671327}{12835298489170}$	$-\frac{10771552573575}{22201958757719}$	$\frac{9247589265047}{10645013368117}$	$\frac{2193209047091}{5459859503100}$

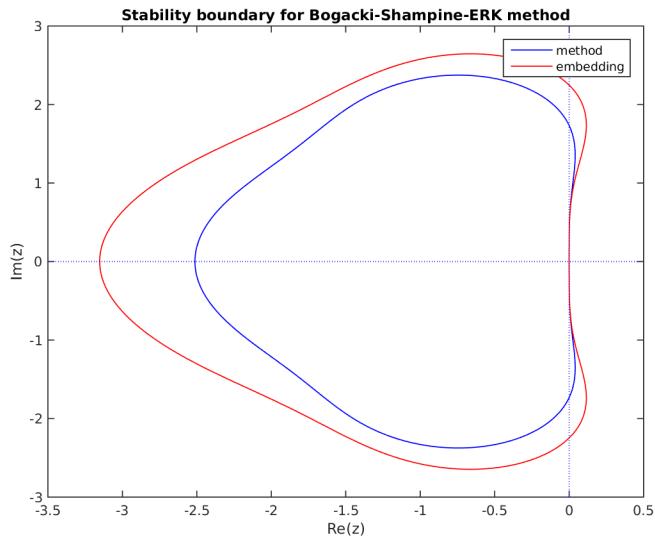


Fig. 14.2: Linear stability region for the Bogacki-Shampine method. The method's region is outlined in blue; the embedding's region is in red.

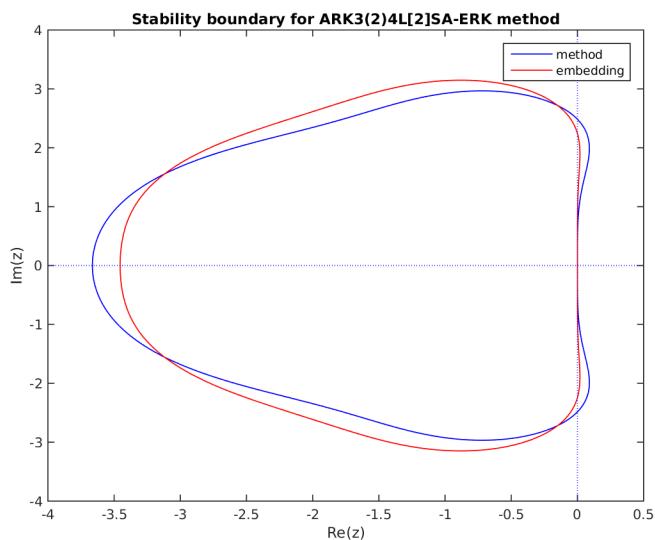


Fig. 14.3: Linear stability region for the explicit ARK-4-2-3 method. The method's region is outlined in blue; the embedding's region is in red.

#### 14.1.4 Knoth-Wolke-3-3

Accessible via the constant `ARKODE_KNOTH_WOLKE_3_3` to `MRISetStepSetMRITableNum()` and `ARKodeButcherTable_LoadERK()`. This is the default 3th order slow and fast MRIStep method (from [42]).

0	0	0	0
$\frac{1}{3}$	$\frac{1}{3}$	0	0
$\frac{3}{4}$	$-\frac{3}{16}$	$\frac{15}{16}$	0
3	$\frac{1}{6}$	$\frac{3}{10}$	$\frac{8}{15}$

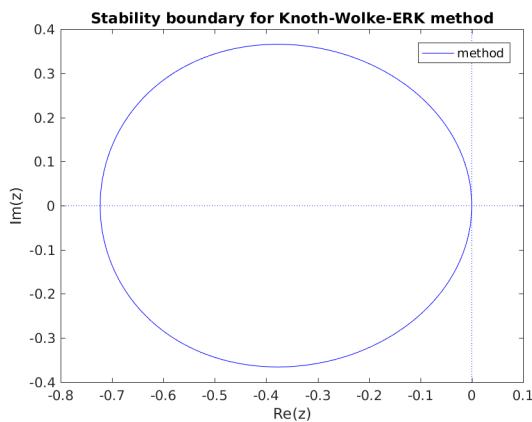


Fig. 14.4: Linear stability region for the Knoth-Wolke method

#### 14.1.5 Zonneveld-5-3-4

Accessible via the constant `ARKODE_ZONNEVELD_5_3_4` to `ARKStepSetTableNum()`, `ERKStepSetTableNum()` or `ARKodeButcherTable_LoadERK()`. This is the default 4th order explicit method (from [63]).

0	0	0	0	0	0
$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
$\frac{1}{2}$	0	$\frac{1}{2}$	0	0	0
1	0	0	1	0	0
$\frac{3}{4}$	$\frac{5}{32}$	$\frac{7}{32}$	$\frac{13}{32}$	$-\frac{1}{32}$	0
4	$\frac{1}{6}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{6}$	0
3	$-\frac{1}{2}$	$\frac{7}{3}$	$\frac{7}{3}$	$\frac{13}{6}$	$-\frac{16}{3}$

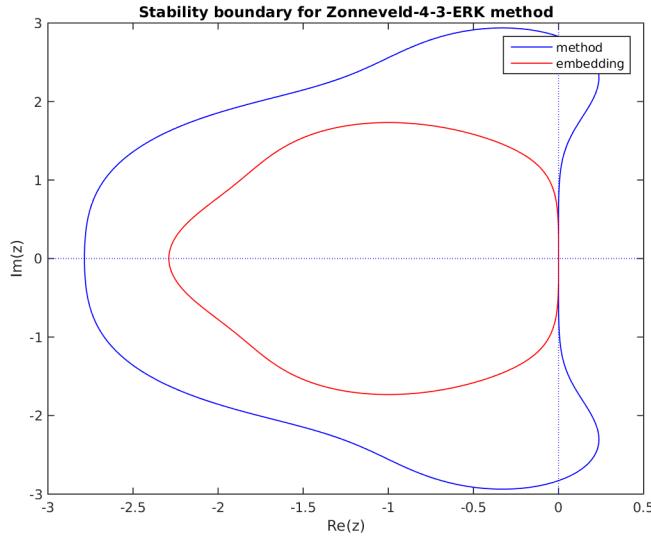


Fig. 14.5: Linear stability region for the Zonneveld method. The method's region is outlined in blue; the embedding's region is in red.

#### 14.1.6 ARK-6-3-4 (explicit)

Accessible via the constant `ARKODE_ARK436L2SA_ERK_6_3_4` to `ARKStepSetTableNum()`, `ERKStepSetTableNum()` or `ARKodeButcherTable_LoadERK()`. This is the explicit portion of the default 4th order additive method (from [40]).

0	0	0	0	0	0	0
$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0	0
$\frac{83}{250}$	$\frac{13861}{62500}$	$\frac{6889}{62500}$	0	0	0	0
$\frac{31}{50}$	$-\frac{116923316275}{2393684061468}$	$-\frac{2731218467317}{15368042101831}$	$\frac{9408046702089}{11113171139209}$	0	0	0
$\frac{17}{20}$	$-\frac{451086348788}{2902428689909}$	$-\frac{2682348792572}{7519795681897}$	$\frac{12662868775082}{11960479115383}$	$\frac{3355817975965}{11060851509271}$	0	0
1	$\frac{647845179188}{3216320057751}$	$\frac{73281519250}{8382639484533}$	$\frac{552539513391}{3454668386233}$	$\frac{3354512671639}{8306763924573}$	$\frac{4040}{17871}$	0
4	$\frac{82889}{524892}$	0	$\frac{15625}{83664}$	$\frac{69875}{102672}$	$-\frac{2260}{8211}$	$\frac{1}{4}$
3	$\frac{4586570599}{29645900160}$	0	$\frac{178811875}{945068544}$	$\frac{814220225}{1159782912}$	$-\frac{3700637}{11593932}$	$\frac{61727}{225920}$

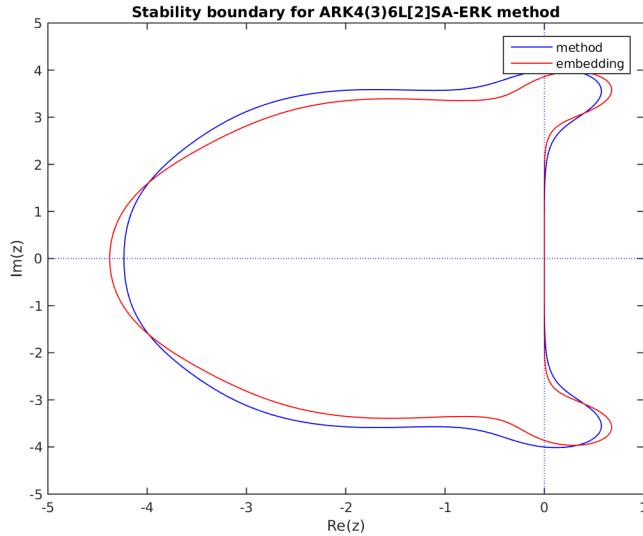


Fig. 14.6: Linear stability region for the explicit ARK-6-3-4 method. The method's region is outlined in blue; the embedding's region is in red.

### 14.1.7 ARK-7-3-4 (explicit)

Accessible via the constant `ARKODE_ARK437L2SA_ERK_7_3_4` to `ARKStepSetTableNum()`, `ERKStepSetTableNum()` or `ARKodeButcherTable_LoadERK()`. This is the explicit portion of the 4th order additive method (from [41]).

0	0	0	0	0	0	0	0
$\frac{247}{1000}$	$\frac{247}{1000}$	0	0	0	0	0	0
$\frac{4276536705230}{10142255878289}$	$\frac{247}{4000}$	$\frac{2694949928731}{7487940209513}$	0	0	0	0	0
$\frac{67}{200}$	$\frac{464650059369}{8764239774964}$	$\frac{878889893998}{2444806327765}$	$-\frac{952945855348}{12294611323341}$	0	0	0	0
$\frac{3}{40}$	$\frac{476636172619}{8159180917465}$	$-\frac{1271469283451}{7793814740893}$	$-\frac{859560642026}{4356155882851}$	$\frac{1723805262919}{4571918432560}$	0	0	0
$\frac{7}{10}$	$\frac{6338158500785}{11769362343261}$	$-\frac{4970555480458}{10924838743837}$	$\frac{3326578051521}{2647936831840}$	$-\frac{880713585975}{1841400956686}$	$-\frac{1428733748635}{8843423958496}$	0	0
1	$\frac{760814592956}{3276306540349}$	$\frac{760814592956}{3276306540349}$	$-\frac{47223648122716}{6934462133451}$	$\frac{71187472546993}{9669769126921}$	$-\frac{13330509492149}{9695768672337}$	$\frac{11565764226357}{8513123442827}$	0
4	0	0	$\frac{9164257142617}{17756377923965}$	$-\frac{10812980402763}{74029279521829}$	$\frac{1335994250573}{5691609445217}$	$\frac{2273837961795}{8368240463276}$	$\frac{247}{2000}$
3	0	0	$\frac{4469248916618}{8635866897933}$	$-\frac{621260224600}{4094290005349}$	$\frac{696572312987}{2942599194819}$	$\frac{1532940081127}{5565293938103}$	$\frac{2441}{20000}$

### 14.1.8 Sayfy-Aburub-6-3-4

Accessible via the constant ARKODE\_SAYFY\_ABURUB\_6\_3\_4 to `ARKStepSetTableNum()`, `ERKStepSetTableNum()` or `ARKodeButcherTable_LoadERK()` (from [52]).

0	0	0	0	0	0	0
$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0	0
1	-1	2	0	0	0	0
1	$\frac{1}{6}$	$\frac{2}{3}$	$\frac{1}{6}$	0	0	0
$\frac{1}{2}$	0.137	0.226	0.137	0	0	0
1	0.452	-0.904	-0.548	0	2	0
4	$\frac{1}{6}$	$\frac{1}{3}$	$\frac{1}{12}$	0	$\frac{1}{3}$	$\frac{1}{12}$
3	$\frac{1}{6}$	$\frac{2}{3}$	$\frac{1}{6}$	0	0	0

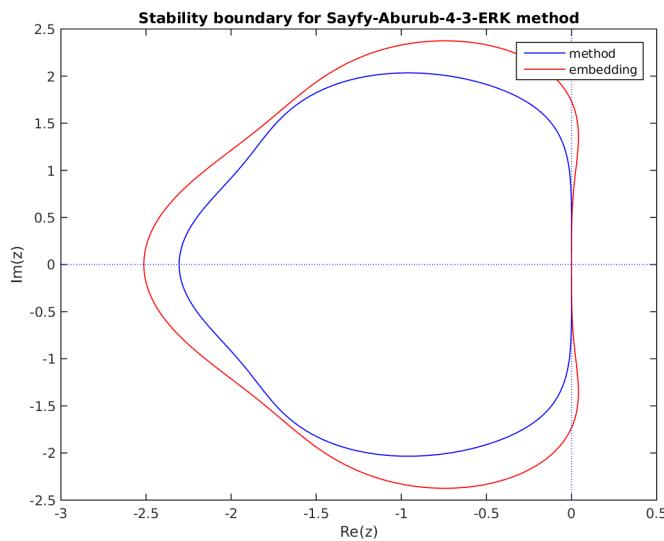


Fig. 14.7: Linear stability region for the Sayfy-Aburub-6-3-4 method. The method's region is outlined in blue; the embedding's region is in red.

### 14.1.9 Cash-Karp-6-4-5

Accessible via the constant `ARKODE_CASH_KARP_6_4_5` to `ARKStepSetTableNum()`, `ERKStepSetTableNum()` or `ARKodeButcherTable_LoadERK()`. This is the default 5th order explicit method (from [16]).

0	0	0	0	0	0	0
$\frac{1}{5}$	$\frac{1}{5}$	0	0	0	0	0
$\frac{3}{10}$	$\frac{3}{40}$	$\frac{9}{40}$	0	0	0	0
$\frac{3}{5}$	$\frac{3}{10}$	$-\frac{9}{10}$	$\frac{6}{5}$	0	0	0
1	$-\frac{11}{54}$	$\frac{5}{2}$	$-\frac{70}{27}$	$\frac{35}{27}$	0	0
$\frac{7}{8}$	$\frac{1631}{55296}$	$\frac{175}{512}$	$\frac{575}{13824}$	$\frac{44275}{110592}$	$\frac{253}{4096}$	0
5	$\frac{37}{378}$	0	$\frac{250}{621}$	$\frac{125}{594}$	0	$\frac{512}{1771}$
4	$\frac{2825}{27648}$	0	$\frac{18575}{48384}$	$\frac{13525}{55296}$	$\frac{277}{14336}$	$\frac{1}{4}$

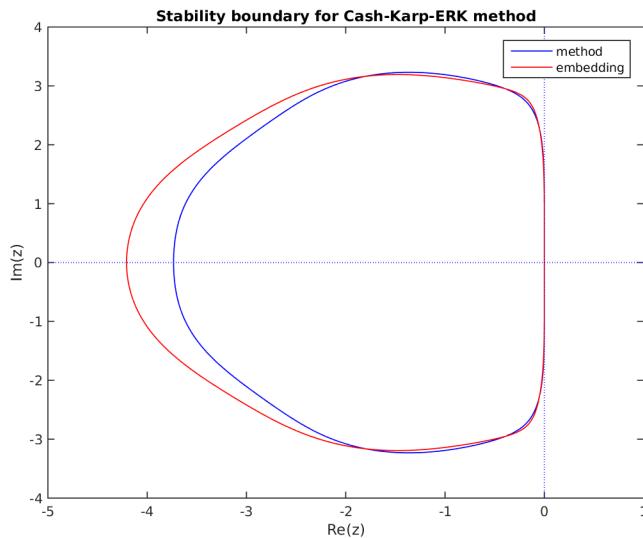


Fig. 14.8: Linear stability region for the Cash-Karp method. The method's region is outlined in blue; the embedding's region is in red.

### 14.1.10 Fehlberg-6-4-5

Accessible via the constant `ARKODE_FEHLBERG_6_4_5` to `ARKStepSetTableNum()`, `ERKStepSetTableNum()` or `ARKodeButcherTable_LoadERK()` (from [26]).

0	0	0	0	0	0	0
$\frac{1}{4}$	$\frac{1}{4}$	0	0	0	0	0
$\frac{3}{8}$	$\frac{3}{32}$	$\frac{9}{32}$	0	0	0	0
$\frac{12}{13}$	$\frac{1932}{2197}$	$-\frac{7200}{2197}$	$\frac{7296}{2197}$	0	0	0
1	$\frac{439}{216}$	-8	$\frac{3680}{513}$	$-\frac{845}{4104}$	0	0
$\frac{1}{2}$	$-\frac{8}{27}$	2	$-\frac{3544}{2565}$	$\frac{1859}{4104}$	$-\frac{11}{40}$	0
5	$\frac{16}{135}$	0	$\frac{6656}{12825}$	$\frac{28561}{56430}$	$-\frac{9}{50}$	$\frac{2}{55}$
4	$\frac{25}{216}$	0	$\frac{1408}{2565}$	$\frac{2197}{4104}$	$-\frac{1}{5}$	0

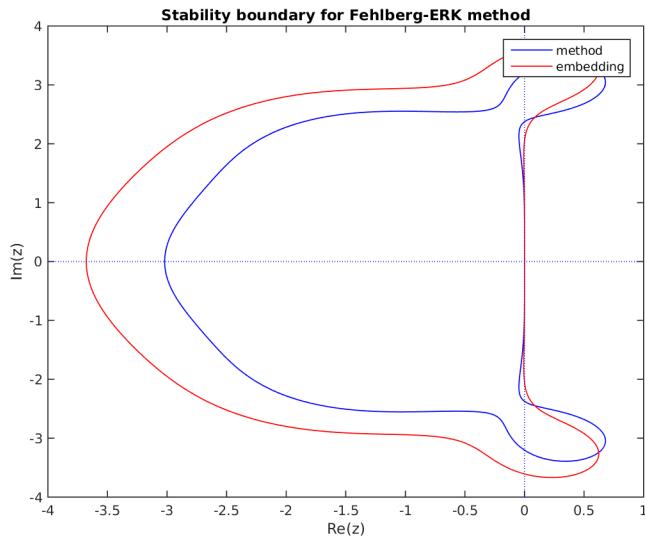


Fig. 14.9: Linear stability region for the Fehlberg method. The method's region is outlined in blue; the embedding's region is in red.

### 14.1.11 Dormand-Prince-7-4-5

Accessible via the constant `ARKODE_DORMAND_PRINCE_7_4_5` to `ARKStepSetTableNum()`, `ERKStepSetTableNum()` or `ARKodeButcherTable_LoadERK()` (from [22]).

0	0	0	0	0	0	0	0
$\frac{1}{5}$	$\frac{1}{5}$	0	0	0	0	0	0
$\frac{3}{10}$	$\frac{3}{40}$	$\frac{9}{40}$	0	0	0	0	0
$\frac{4}{5}$	$\frac{44}{45}$	$-\frac{56}{15}$	$\frac{32}{9}$	0	0	0	0
$\frac{8}{9}$	$\frac{19372}{6561}$	$-\frac{25360}{2187}$	$\frac{64448}{6561}$	$-\frac{212}{729}$	0	0	0
1	$\frac{9017}{3168}$	$-\frac{355}{33}$	$\frac{46732}{5247}$	$\frac{49}{176}$	$-\frac{5103}{18656}$	0	0
1	$\frac{35}{384}$	0	$\frac{500}{1113}$	$\frac{125}{192}$	$-\frac{2187}{6784}$	$\frac{11}{84}$	0
5	$\frac{35}{384}$	0	$\frac{500}{1113}$	$\frac{125}{192}$	$-\frac{2187}{6784}$	$\frac{11}{84}$	0
4	$\frac{5179}{57600}$	0	$\frac{7571}{16695}$	$\frac{393}{640}$	$-\frac{92097}{339200}$	$\frac{187}{2100}$	$\frac{1}{40}$

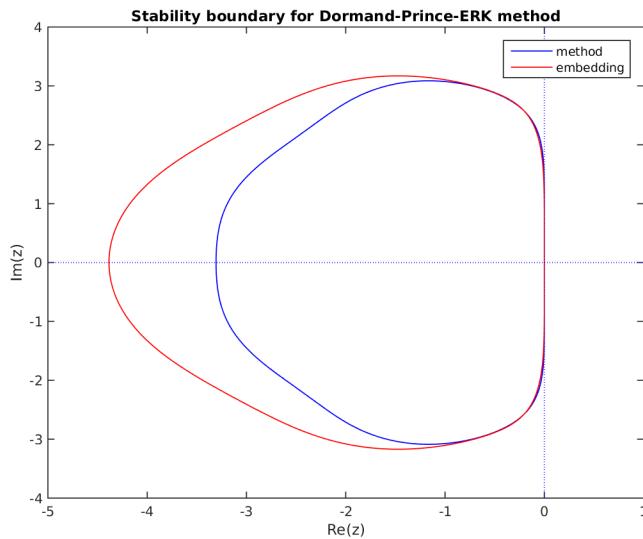


Fig. 14.10: Linear stability region for the Dormand-Prince method. The method's region is outlined in blue; the embedding's region is in red.

### 14.1.12 ARK-8-4-5 (explicit)

Accessible via the constant `ARKODE_ARK548L2SA_ERK_8_4_5` to `ARKStepSetTableNum()`, `ERKStepSetTableNum()` or `ARKodeButcherTable_LoadERK()`. This is the explicit portion of the default 5th order additive

method (from [40]).

0	0	0	0	0	0	0	0
$\frac{41}{100}$	$\frac{41}{100}$	0	0	0	0	0	0
$\frac{2935347310677}{11292855782101}$	$\frac{367902744464}{2072280473677}$	$\frac{677623207551}{8224143866563}$	0	0	0	0	0
$\frac{1426016391358}{7196633302097}$	$\frac{1268023523408}{10340822734521}$	0	$\frac{1029933939417}{13636558850479}$	0	0	0	0
$\frac{92}{100}$	$\frac{14463281900351}{6315353703477}$	0	$\frac{66114435211212}{5879490589093}$	$-\frac{54053170152839}{4284798021562}$	0	0	0
$\frac{24}{100}$	$\frac{14090043504691}{34967701212078}$	0	$\frac{15191511035443}{11219624916014}$	$-\frac{18461159152457}{12425892160975}$	$-\frac{281667163811}{9011619295870}$	0	0
$\frac{3}{5}$	$\frac{19230459214898}{13134317526959}$	0	$\frac{21275331358303}{2942455364971}$	$-\frac{38145345988419}{4862620318723}$	$-\frac{1}{8}$	$-\frac{1}{8}$	0
1	$-\frac{19977161125411}{11928030595625}$	0	$-\frac{40795976796054}{6384907823539}$	$\frac{177454434618887}{12078138498510}$	$\frac{782672205425}{8267701900261}$	$-\frac{69563011059811}{9646580694205}$	$735662$
5	$-\frac{872700587467}{9133579230613}$	0	0	$\frac{22348218063261}{9555858737531}$	$-\frac{1143369518992}{8141816002931}$	$-\frac{39379526789629}{19018526304540}$	$3272738$
4	$-\frac{975461918565}{9796059967033}$	0	0	$\frac{78070527104295}{32432590147079}$	$-\frac{548382580838}{3424219808633}$	$-\frac{33438840321285}{15594753105479}$	$3629800$

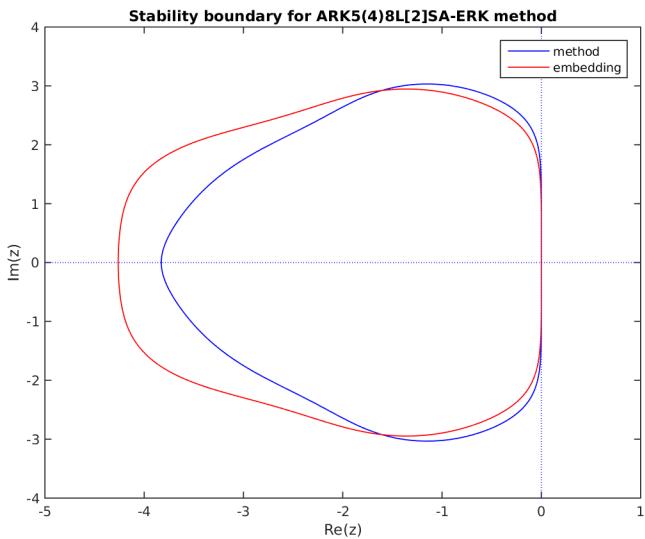


Fig. 14.11: Linear stability region for the explicit ARK-8-4-5 method. The method's region is outlined in blue; the embedding's region is in red.

### 14.1.13 ARK-8-4-5b (explicit)

Accessible via the constant `ARKODE_ARK548L2SAb_ERK_8_4_5` to `ARKStepSetTableNum()`, `ERKStepSetTableNum()` or `ARKodeButcherTable_LoadERK()`. This is the explicit portion of the 5th order additive method from [41].

0	0	0	0	0	0	0	0	0
$\frac{4}{9}$	$\frac{4}{9}$	0	0	0	0	0	0	0
$\frac{6456083330201}{8509243623797}$	$\frac{1}{9}$	$\frac{1183333538310}{1827251437969}$	0	0	0	0	0	0
$\frac{1632083962415}{14158861528103}$	$\frac{895379019517}{9750411845327}$	$\frac{477606656805}{13473228687314}$	$\frac{-112564739183}{9373365219272}$	0	0	0	0	0
$\frac{6365430648612}{1784276412687}$	$\frac{-4458043123994}{13015289567637}$	$\frac{-2500665203865}{9342069639922}$	$\frac{983347055801}{889351964487}$	$\frac{2185051477207}{2551468980502}$	0	0	0	0
$\frac{18}{25}$	$\frac{-167316361917}{17121522574472}$	$\frac{1605541814917}{7619724128744}$	$\frac{991021770328}{13052792161721}$	$\frac{2342280609577}{11279663441611}$	$\frac{3012424348531}{12792462456678}$	0	0	0
$\frac{191}{200}$	$\frac{6680998715867}{14310383562358}$	$\frac{5029118570809}{3897454228471}$	$\frac{2415062538259}{6382199904604}$	$\frac{-3924368632305}{6964820224454}$	$\frac{-4331110370267}{15021686902756}$	$\frac{-3944303808049}{11994238218192}$	0	0
1	$\frac{2193717860234}{3570523412979}$	$\frac{2193717860234}{3570523412979}$	$\frac{5952760925747}{18750164281544}$	$\frac{-4412967128996}{6196664114337}$	$\frac{4151782504231}{36106512998704}$	$\frac{572599549169}{6265429158920}$	$\frac{-4578743561}{113064980363}$	0
5	0	0	$\frac{3517720773327}{20256071687669}$	$\frac{4569610470461}{17934693873752}$	$\frac{2819471173109}{11655438449929}$	$\frac{3296210113763}{10722700128969}$	$\frac{-1142099968}{57109839269}$	0
4	0	0	$\frac{520639020421}{8300446712847}$	$\frac{4550235134915}{17827758688493}$	$\frac{1482366381361}{6201654941325}$	$\frac{5551607622171}{13911031047899}$	$\frac{-5266607656}{367889688436}$	0

### 14.1.14 Verner-8-5-6

Accessible via the constant `ARKODE_VERNER_8_5_6` to `ARKStepSetTableNum()`, `ERKStepSetTableNum()` or `ARKodeButcherTable_LoadERK()`. This is the default 6th order explicit method (from [60]).

0	0	0	0	0	0	0	0	0
$\frac{1}{6}$	$\frac{1}{6}$	0	0	0	0	0	0	0
$\frac{4}{15}$	$\frac{4}{75}$	$\frac{16}{75}$	0	0	0	0	0	0
$\frac{2}{3}$	$\frac{5}{6}$	$-\frac{8}{3}$	$\frac{5}{2}$	0	0	0	0	0
$\frac{5}{6}$	$-\frac{165}{64}$	$\frac{55}{6}$	$-\frac{425}{64}$	$\frac{85}{96}$	0	0	0	0
1	$\frac{12}{5}$	-8	$\frac{4015}{612}$	$-\frac{11}{36}$	$\frac{88}{255}$	0	0	0
$\frac{1}{15}$	$-\frac{8263}{15000}$	$\frac{124}{75}$	$-\frac{643}{680}$	$-\frac{81}{250}$	$\frac{2484}{10625}$	0	0	0
1	$\frac{3501}{1720}$	$-\frac{300}{43}$	$\frac{297275}{52632}$	$-\frac{319}{2322}$	$\frac{24068}{84065}$	0	$\frac{3850}{26703}$	0
6	$\frac{3}{40}$	0	$\frac{875}{2244}$	$\frac{23}{72}$	$\frac{264}{1955}$	0	$\frac{125}{11592}$	$\frac{43}{616}$
5	$\frac{13}{160}$	0	$\frac{2375}{5984}$	$\frac{5}{16}$	$\frac{12}{85}$	$\frac{3}{44}$	0	0

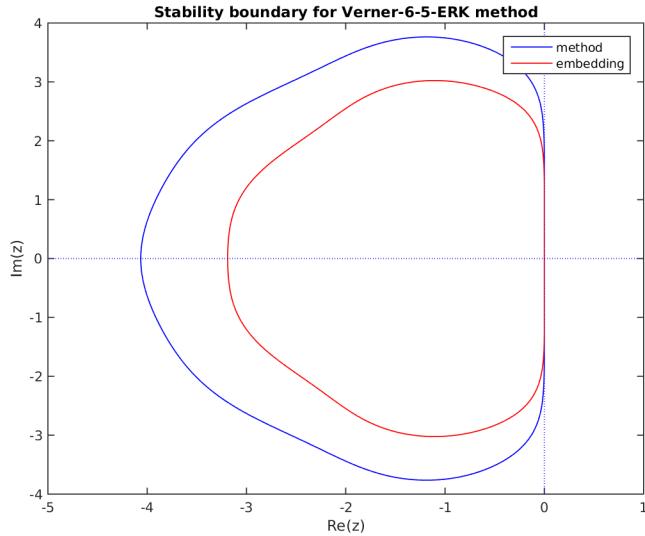


Fig. 14.12: Linear stability region for the Verner-8-5-6 method. The method's region is outlined in blue; the embedding's region is in red.

### 14.1.15 Fehlberg-13-7-8

Accessible via the constant `ARKODE_FEHLBERG_13_7_8` to `ARKStepSetTableNum()`, `ERKStepSetTableNum()` or `ARKodeButcherTable_LoadERK()`. This is the default 8th order explicit method (from [13]).

0	0	0	0	0	0	0	0	0	0	0	0	0	0
$\frac{2}{27}$	$\frac{2}{27}$	0	0	0	0	0	0	0	0	0	0	0	0
$\frac{1}{9}$	$\frac{1}{36}$	$\frac{1}{12}$	0	0	0	0	0	0	0	0	0	0	0
$\frac{1}{6}$	$\frac{1}{24}$	0	$\frac{1}{8}$	0	0	0	0	0	0	0	0	0	0
$\frac{5}{12}$	$\frac{5}{12}$	0	$-\frac{25}{16}$	$\frac{25}{16}$	0	0	0	0	0	0	0	0	0
$\frac{1}{2}$	$\frac{1}{20}$	0	0	$\frac{1}{4}$	$\frac{1}{5}$	0	0	0	0	0	0	0	0
$\frac{5}{6}$	$-\frac{25}{108}$	0	0	$\frac{125}{108}$	$-\frac{65}{27}$	$\frac{125}{54}$	0	0	0	0	0	0	0
$\frac{1}{6}$	$\frac{31}{300}$	0	0	0	$\frac{61}{225}$	$-\frac{2}{9}$	$\frac{13}{900}$	0	0	0	0	0	0
$\frac{2}{3}$	2	0	0	$-\frac{53}{6}$	$\frac{704}{45}$	$-\frac{107}{9}$	$\frac{67}{90}$	3	0	0	0	0	0
$\frac{1}{3}$	$-\frac{91}{108}$	0	0	$\frac{23}{108}$	$-\frac{976}{135}$	$\frac{311}{54}$	$-\frac{19}{60}$	$\frac{17}{6}$	$-\frac{1}{12}$	0	0	0	0
1	$\frac{2383}{4100}$	0	0	$-\frac{341}{164}$	$\frac{4496}{1025}$	$-\frac{301}{82}$	$\frac{2133}{4100}$	$\frac{45}{82}$	$\frac{45}{164}$	$\frac{18}{41}$	0	0	0
0	$\frac{3}{205}$	0	0	0	0	$-\frac{6}{41}$	$-\frac{3}{205}$	$-\frac{3}{41}$	$\frac{3}{41}$	$\frac{6}{41}$	0	0	0
1	$-\frac{1777}{4100}$	0	0	$-\frac{341}{164}$	$\frac{4496}{1025}$	$-\frac{289}{82}$	$\frac{2193}{4100}$	$\frac{51}{82}$	$\frac{33}{164}$	$\frac{12}{41}$	0	1	0
8	0	0	0	0	0	$\frac{34}{105}$	$\frac{9}{35}$	$\frac{9}{35}$	$\frac{9}{280}$	$\frac{9}{280}$	0	$\frac{41}{840}$	$\frac{41}{840}$
7	$\frac{41}{840}$	0	0	0	0	$\frac{34}{105}$	$\frac{9}{35}$	$\frac{9}{35}$	$\frac{9}{280}$	$\frac{9}{280}$	$\frac{41}{840}$	0	0

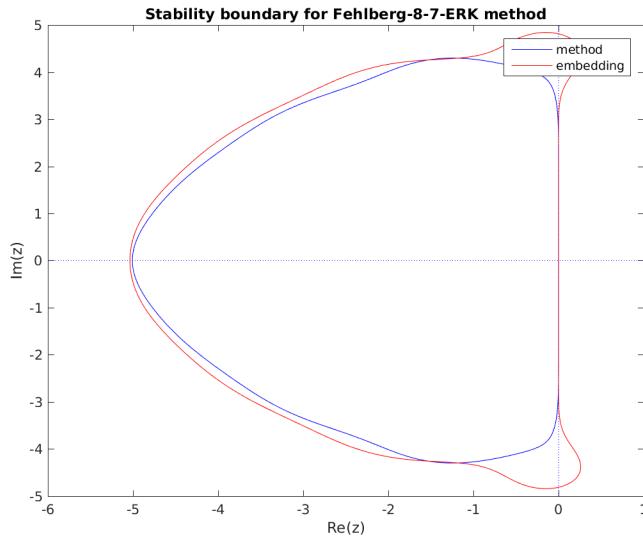


Fig. 14.13: Linear stability region for the Fehlberg-13-7-8 method. The method's region is outlined in blue; the embedding's region is in red.

## 14.2 Implicit Butcher tables

In the category of diagonally implicit Runge–Kutta methods, ARKODE includes methods that have orders 2 through 5, with embeddings that are of orders 1 through 4.

Each of ARKODE’s diagonally-implicit Butcher tables are specified via a unique ID:

```
enum ARKODE_DIRKTableID
```

with values specified for each method below (e.g., `ARKODE_SDIRK_2_1_2`).

### 14.2.1 SDIRK-2-1-2

Accessible via the constant `ARKODE_SDIRK_2_1_2` to `ARKStepSetTableNum()` or `ARKodeButcherTable_LoadDIRK()`. This is the default 2nd order implicit method. Both the method and embedding are A- and B-stable.

1	1	0
0	−1	1
2	$\frac{1}{2}$	$\frac{1}{2}$
1	1	0

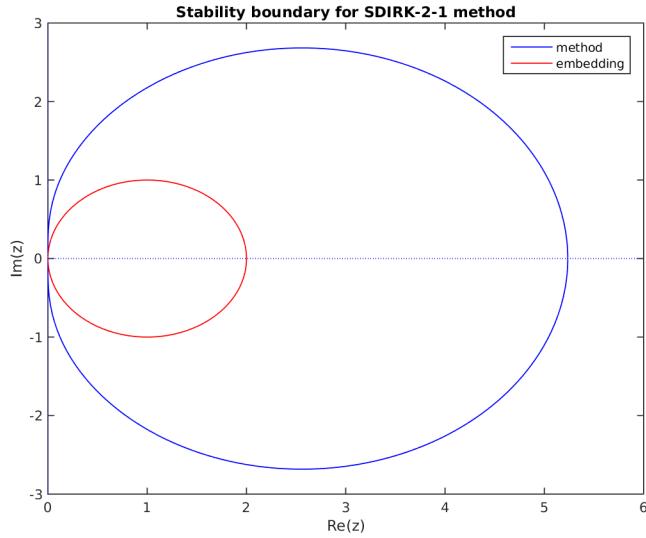


Fig. 14.14: Linear stability region for the SDIRK-2-1-2 method. The method’s region is outlined in blue; the embedding’s region is in red.

### 14.2.2 Billington-3-3-2

Accessible via the constant `ARKODE_BILLINGTON_3_3_2` to `ARKStepSetTableNum()` or `ARKodeButcherTable_LoadDIRK()`. Here, the higher-order embedding is less stable than the lower-order method (from [6]).

0.292893218813	0.292893218813	0	0
1.091883092037	0.798989873223	0.292893218813	0
1.292893218813	0.740789228841	0.259210771159	0.292893218813
2	0.740789228840	0.259210771159	0
3	0.691665115992	0.503597029883	-0.195262145876

### 14.2.3 TRBDF2-3-3-2

Accessible via the constant `ARKODE_TRBDF2_3_3_2` to `ARKStepSetTableNum()` or `ARKodeButcherTable_LoadDIRK()`. As with Billington, here the higher-order embedding is less stable than the lower-order method (from [5]).

0	0	0	0
$2 - \sqrt{2}$	$\frac{2-\sqrt{2}}{2}$	$\frac{2-\sqrt{2}}{2}$	0
1	$\frac{\sqrt{2}}{4}$	$\frac{\sqrt{2}}{4}$	$\frac{2-\sqrt{2}}{2}$
2	$\frac{\sqrt{2}}{4}$	$\frac{\sqrt{2}}{4}$	$\frac{2-\sqrt{2}}{2}$
3	$\frac{1-\frac{\sqrt{2}}{4}}{3}$	$\frac{\frac{3\sqrt{2}}{4}+1}{3}$	$\frac{2-\sqrt{2}}{6}$

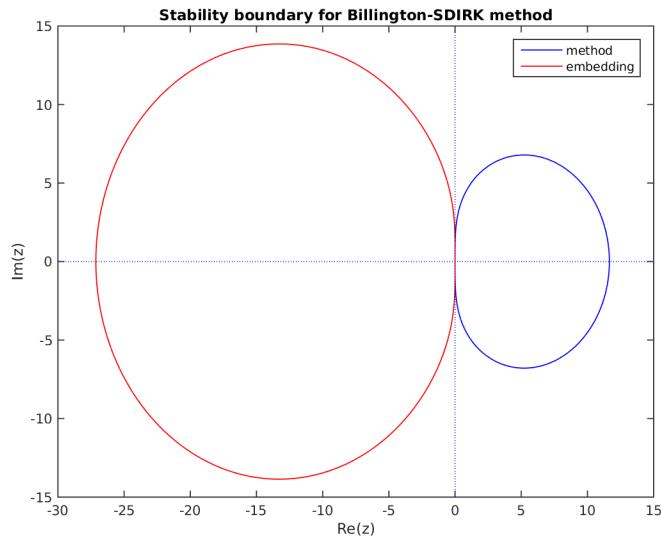


Fig. 14.15: Linear stability region for the Billington method. The method’s region is outlined in blue; the embedding’s region is in red.

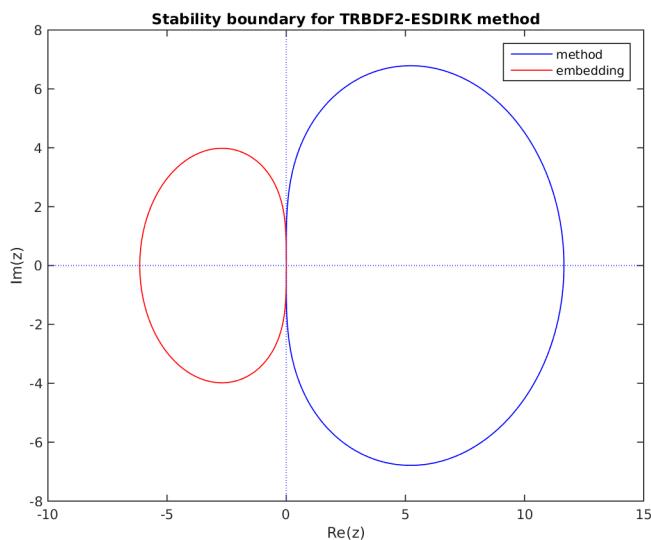


Fig. 14.16: Linear stability region for the TRBDF2 method. The method’s region is outlined in blue; the embedding’s region is in red.

### 14.2.4 Kvaerno-4-2-3

Accessible via the constant `ARKODE_KVAERNO_4_2_3` to `ARKStepSetTableNum()` or `ARKodeButcherTable_LoadDIRK()`. Both the method and embedding are A-stable; additionally the method is L-stable (from [43]).

0	0	0	0	0
0.871733043	0.4358665215	0.4358665215	0	0
1	0.490563388419108	0.073570090080892	0.4358665215	0
1	0.308809969973036	1.490563388254106	-1.235239879727145	0.4358665215
3	0.308809969973036	1.490563388254106	-1.235239879727145	0.4358665215
2	0.490563388419108	0.073570090080892	0.4358665215	0

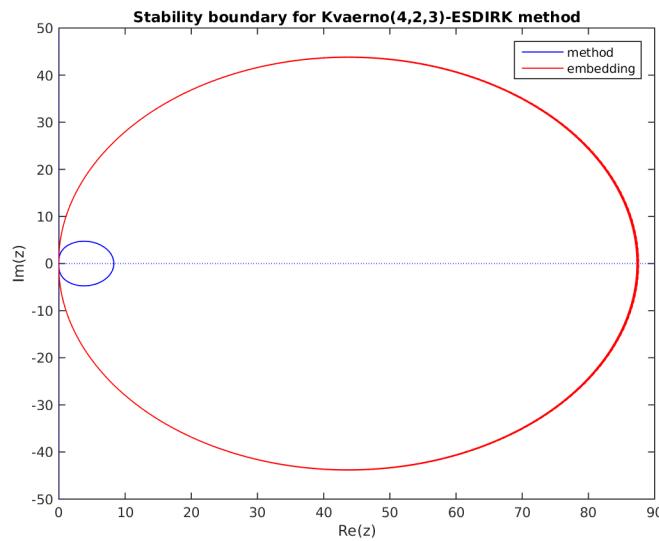


Fig. 14.17: Linear stability region for the Kvaerno-4-2-3 method. The method's region is outlined in blue; the embedding's region is in red.

### 14.2.5 ARK-4-2-3 (implicit)

Accessible via the constant `ARKODE_ARK324L2SA_DIRK_4_2_3` to `ARKStepSetTableNum()` or `ARKodeButcherTable_LoadDIRK()`. This is the default 3rd order implicit method, and the implicit portion of the default 3rd order additive method. Both the method and embedding are A-stable; additionally the method is L-stable (from [40]).

0	0	0	0	0
$\frac{1767732205903}{2027836641118}$	$\frac{1767732205903}{4055673282236}$	$\frac{1767732205903}{4055673282236}$	0	0
$\frac{3}{5}$	$\frac{2746238789719}{10658868560708}$	$-\frac{640167445237}{6845629431997}$	$\frac{1767732205903}{4055673282236}$	0
1	$\frac{1471266399579}{7840856788654}$	$-\frac{4482444167858}{7529755066697}$	$\frac{11266239266428}{11593286722821}$	$\frac{1767732205903}{4055673282236}$
3	$\frac{1471266399579}{7840856788654}$	$-\frac{4482444167858}{7529755066697}$	$\frac{11266239266428}{11593286722821}$	$\frac{1767732205903}{4055673282236}$
2	$\frac{2756255671327}{12835298489170}$	$-\frac{10771552573575}{22201958757719}$	$\frac{9247589265047}{10645013368117}$	$\frac{2193209047091}{5459859503100}$

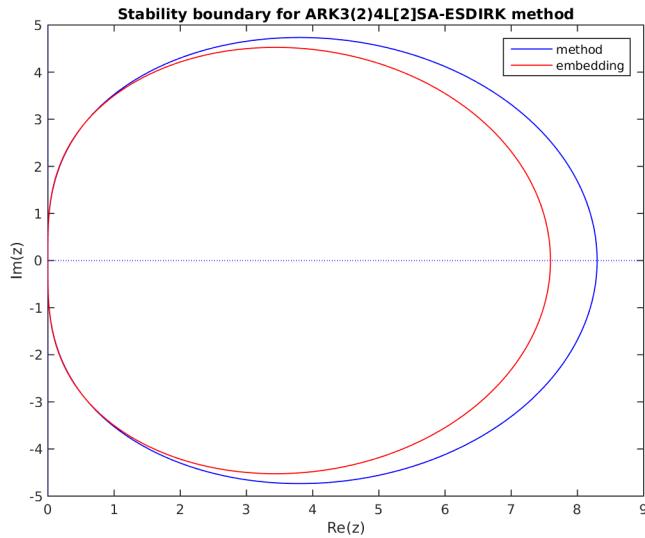


Fig. 14.18: Linear stability region for the implicit ARK-4-2-3 method. The method's region is outlined in blue; the embedding's region is in red.

#### 14.2.6 Cash-5-2-4

Accessible via the constant `ARKODE_CASH_5_2_4` to `ARKStepSetTableNum()` or `ARKodeButcherTable_LoadDIRK()`. Both the method and embedding are A-stable; additionally the method is L-stable (from [15]).

0.435866521508	0.435866521508	0	0	0	0
-0.7	-1.13586652150	0.435866521508	0	0	0
0.8	1.08543330679	-0.721299828287	0.435866521508	0	0
0.924556761814	0.416349501547	0.190984004184	-0.118643265417	0.435866521508	0
1	0.896869652944	0.0182725272734	-0.0845900310706	-0.266418670647	0.435866521508
4	0.896869652944	0.0182725272734	-0.0845900310706	-0.266418670647	0.435866521508
2	1.05646216107052	-0.0564621610705236	0	0	0

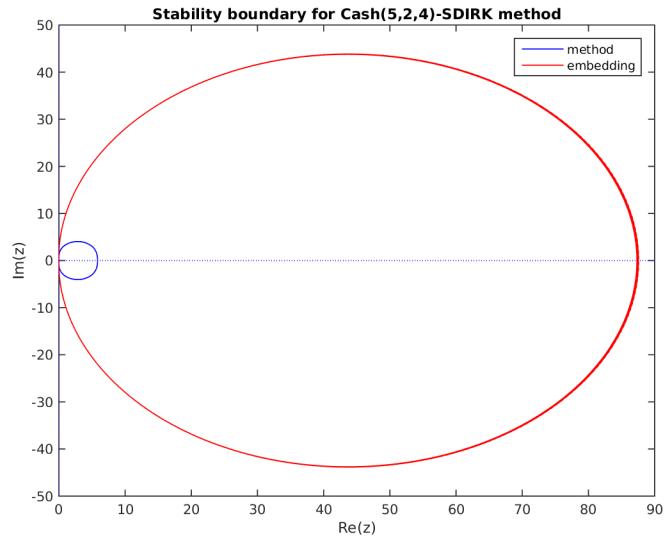


Fig. 14.19: Linear stability region for the Cash-5-2-4 method. The method's region is outlined in blue; the embedding's region is in red.

### 14.2.7 Cash-5-3-4

Accessible via the constant `ARKODE_CASH_5_3_4` to `ARKStepSetTableNum()` or `ARKodeButcherTable_LoadDIRK()`. Both the method and embedding are A-stable; additionally the method is L-stable (from [15]).

0.435866521508	0.435866521508	0	0	0	0
-0.7	-1.13586652150	0.435866521508	0	0	0
0.8	1.08543330679	-0.721299828287	0.435866521508	0	0
0.924556761814	0.416349501547	0.190984004184	-0.118643265417	0.435866521508	0
1	0.896869652944	0.0182725272734	-0.0845900310706	-0.266418670647	0.435866521508
4	0.896869652944	0.0182725272734	-0.0845900310706	-0.266418670647	0.435866521508
3	0.776691932910	0.0297472791484	-0.0267440239074	0.220304811849	0

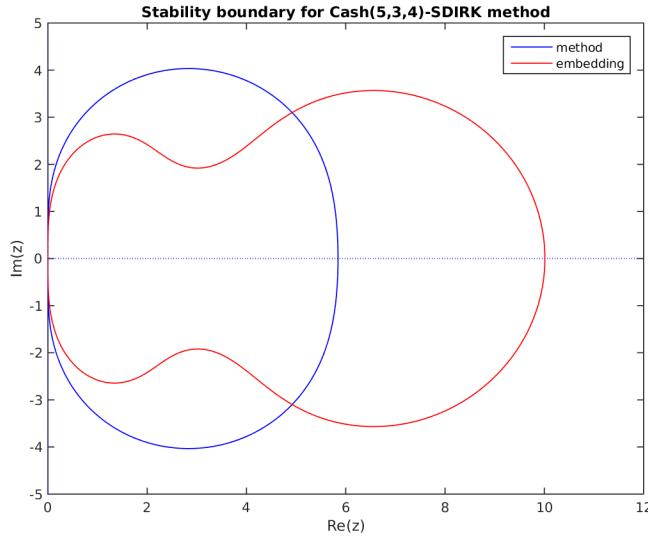


Fig. 14.20: Linear stability region for the Cash-5-3-4 method. The method’s region is outlined in blue; the embedding’s region is in red.

### 14.2.8 SDIRK-5-3-4

Accessible via the constant `ARKODE_SDIRK_5_3_4` to `ARKStepSetTableNum()` or `ARKodeButcherTable_LoadDIRK()`. This is the default 4th order implicit method. Here, the method is both A- and L-stable, although the embedding has reduced stability (from [32]).

$\frac{1}{4}$	$\frac{1}{4}$	0	0	0	0
$\frac{3}{4}$	$\frac{1}{2}$	$\frac{1}{4}$	0	0	0
$\frac{11}{20}$	$\frac{17}{50}$	$-\frac{1}{25}$	$\frac{1}{4}$	0	0
$\frac{1}{2}$	$\frac{371}{1360}$	$-\frac{137}{2720}$	$\frac{15}{544}$	$\frac{1}{4}$	0
1	$\frac{25}{24}$	$-\frac{49}{48}$	$\frac{125}{16}$	$-\frac{85}{12}$	$\frac{1}{4}$
4	$\frac{25}{24}$	$-\frac{49}{48}$	$\frac{125}{16}$	$-\frac{85}{12}$	$\frac{1}{4}$
3	$\frac{59}{48}$	$-\frac{17}{96}$	$\frac{225}{32}$	$-\frac{85}{12}$	0

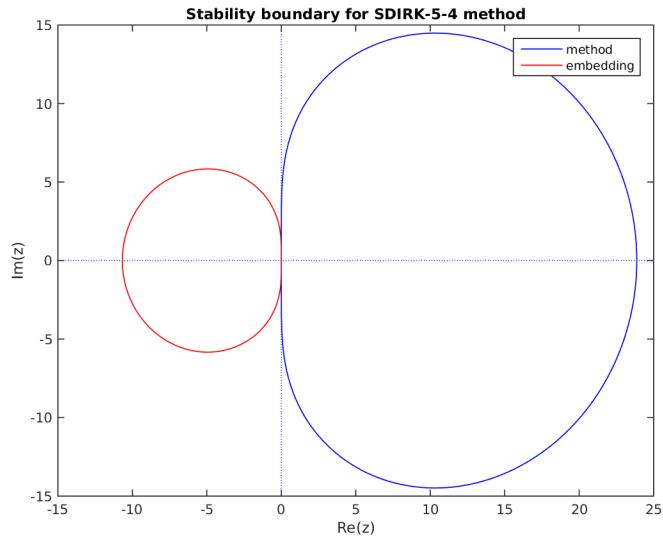


Fig. 14.21: Linear stability region for the SDIRK-5-3-4 method. The method's region is outlined in blue; the embedding's region is in red.

### 14.2.9 Kvaerno-5-3-4

Accessible via the constant `ARKODE_KVAERNO_5_3_4` to `ARKStepSetTableNum()` or `ARKodeButcherTable_LoadDIRK()`. Both the method and embedding are A-stable (from [43]).

	0	0	0	0	0	0
0.871733043		0.4358665215	0.4358665215	0	0	0
0.468238744853136		0.140737774731968	-0.108365551378832	0.4358665215	0	0
1	0.102399400616089	-0.376878452267324	0.838612530151233	0.4358665215	0	
1	0.157024897860995	0.117330441357768	0.61667803039168	-0.326899891110444	0.4358665215	
4	0.157024897860995	0.117330441357768	0.61667803039168	-0.326899891110444	0.4358665215	
3	0.102399400616089	-0.376878452267324	0.838612530151233	0.4358665215		0

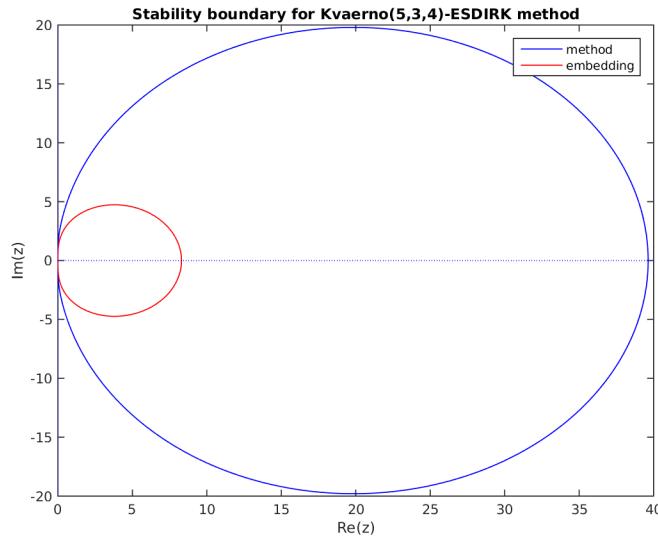


Fig. 14.22: Linear stability region for the Kvaerno-5-3-4 method. The method's region is outlined in blue; the embedding's region is in red.

### 14.2.10 ARK-6-3-4 (implicit)

Accessible via the constant `ARKODE_ARK436L2SA_DIRK_6_3_4` to `ARKStepSetTableNum()` or `ARKodeButcherTable_LoadDIRK()`. This is the implicit portion of the default 4th order additive method. Both the method and embedding are A-stable; additionally the method is L-stable (from [40]).

0	0	0	0	0	0	0
$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{4}$	0	0	0	0
$\frac{83}{250}$	$\frac{8611}{62500}$	$-\frac{1743}{31250}$	$\frac{1}{4}$	0	0	0
$\frac{31}{50}$	$\frac{5012029}{34652500}$	$-\frac{654441}{2922500}$	$\frac{174375}{388108}$	$\frac{1}{4}$	0	0
$\frac{17}{20}$	$\frac{15267082809}{155376265600}$	$-\frac{71443401}{120774400}$	$\frac{730878875}{902184768}$	$\frac{2285395}{8070912}$	$\frac{1}{4}$	0
1	$\frac{82889}{524892}$	0	$\frac{15625}{83664}$	$\frac{69875}{102672}$	$-\frac{2260}{8211}$	$\frac{1}{4}$
4	$\frac{82889}{524892}$	0	$\frac{15625}{83664}$	$\frac{69875}{102672}$	$-\frac{2260}{8211}$	$\frac{1}{4}$
3	$\frac{4586570599}{29645900160}$	0	$\frac{178811875}{945068544}$	$\frac{814220225}{1159782912}$	$-\frac{3700637}{11593932}$	$\frac{61727}{225920}$

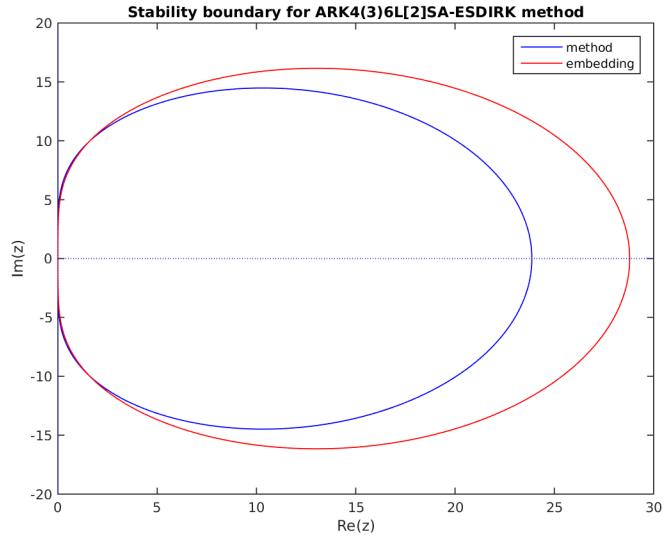


Fig. 14.23: Linear stability region for the implicit ARK-6-3-4 method. The method's region is outlined in blue; the embedding's region is in red.

### 14.2.11 ARK-7-3-4 (implicit)

Accessible via the constant `ARKODE_ARK437L2SA_DIRK_7_3_4` to `ARKStepSetTableNum()` or `ARKode-ButcherTable_LoadDIRK()`. This is the implicit portion of the 4th order additive method from [41].

0	0	0	0	0	0	0	0
$\frac{247}{1000}$	$\frac{1235}{10000}$	$\frac{1235}{10000}$	0	0	0	0	0
$\frac{4276536705230}{10142255878289}$	$\frac{624185399699}{4186980696204}$	$\frac{624185399699}{4186980696204}$	$\frac{1235}{10000}$	0	0	0	0
$\frac{67}{200}$	$\frac{1258591069120}{10082082980243}$	$\frac{1258591069120}{10082082980243}$	$-\frac{322722984531}{8455138723562}$	$\frac{1235}{10000}$	0	0	0
$\frac{3}{40}$	$-\frac{436103496990}{5971407786587}$	$-\frac{436103496990}{5971407786587}$	$-\frac{2689175662187}{11046760208243}$	$\frac{4431412449334}{12995360898505}$	$\frac{1235}{10000}$	0	0
$\frac{7}{10}$	$-\frac{2207373168298}{14430576638973}$	$-\frac{2207373168298}{14430576638973}$	$\frac{242511121179}{3358618340039}$	$\frac{3145666661981}{7780404714551}$	$\frac{5882073923981}{14490790706663}$	$\frac{1235}{10000}$	0
1	0	0	$\frac{9164257142617}{17756377923965}$	$-\frac{10812980402763}{74029279521829}$	$\frac{1335994250573}{5691609445217}$	$\frac{2273837961795}{8368240463276}$	$\frac{1235}{10000}$
4	0	0	$\frac{9164257142617}{17756377923965}$	$-\frac{10812980402763}{74029279521829}$	$\frac{1335994250573}{5691609445217}$	$\frac{2273837961795}{8368240463276}$	$\frac{1235}{10000}$
3	0	0	$\frac{4469248916618}{8635866897933}$	$-\frac{621260224600}{4094290005349}$	$\frac{696572312987}{2942599194819}$	$\frac{1532940081127}{5565293938103}$	$\frac{2441}{20000}$

### 14.2.12 Kvaerno-7-4-5

Accessible via the constant `ARKODE_KVAERNO_7_4_5` to `ARKStepSetTableNum()` or `ARKodeButcherTable_LoadDIRK()`. Both the method and embedding are A-stable; additionally the method is L-stable (from [43]).

0	0	0	0	0
0.52	0.26	0.26	0	0
1.230333209967908	0.13	0.84033320996790809	0.26	0
0.895765984350076	0.22371961478320505	0.47675532319799699	-0.06470895363112615	0.26
0.436393609858648	0.16648564323248321	0.10450018841591720	0.03631482272098715	-0.13090704451073998
1	0.13855640231268224	0	-0.04245337201752043	0.02446657898003141
1	0.13659751177640291	0	-0.05496908796538376	-0.04118626728321046
5	0.13659751177640291	0	-0.05496908796538376	-0.04118626728321046
4	0.13855640231268224	0	-0.04245337201752043	0.02446657898003141
				0.61
				0.62

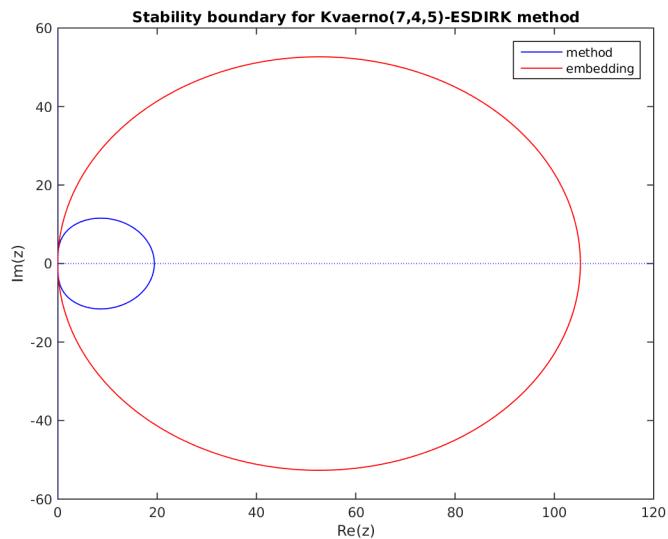


Fig. 14.24: Linear stability region for the Kvaerno-7-4-5 method. The method’s region is outlined in blue; the embedding’s region is in red.

### 14.2.13 ARK-8-4-5 (implicit)

Accessible via the constant `ARKODE_ARK548L2SA_DIRK_8_4_5` for `ARKStepSetTableNum()` or `ARKodeButcherTable_LoadDIRK()`. This is the default 5th order implicit method, and the implicit portion of the default 5th order additive method. Both the method and embedding are A-stable; additionally the method is L-stable (from

[40]).

0	0	0	0	0	0	0
$\frac{41}{100}$	$\frac{41}{200}$	$\frac{41}{200}$	0	0	0	0
$\frac{2935347310677}{11292855782101}$	$\frac{41}{400}$	$-\frac{567603406766}{11931857230679}$	$\frac{41}{200}$	0	0	0
$\frac{1426016391358}{7196633302097}$	$\frac{683785636431}{9252920307686}$	0	$-\frac{110385047103}{1367015193373}$	$\frac{41}{200}$	0	0
$\frac{92}{100}$	$\frac{3016520224154}{10081342136671}$	0	$\frac{30586259806659}{12414158314087}$	$-\frac{22760509404356}{11113319521817}$	$\frac{41}{200}$	0
$\frac{24}{100}$	$\frac{218866479029}{1489978393911}$	0	$\frac{638256894668}{5436446318841}$	$-\frac{1179710474555}{5321154724896}$	$-\frac{60928119172}{8023461067671}$	$\frac{41}{200}$
$\frac{3}{5}$	$\frac{1020004230633}{5715676835656}$	0	$\frac{25762820946817}{25263940353407}$	$-\frac{2161375909145}{9755907335909}$	$-\frac{211217309593}{5846859502534}$	$-\frac{4269925059573}{7827059040749}$
1	$-\frac{872700587467}{9133579230613}$	0	0	$\frac{22348218063261}{9555858737531}$	$-\frac{1143369518992}{8141816002931}$	$-\frac{39379526789629}{19018526304540}$
5	$-\frac{872700587467}{9133579230613}$	0	0	$\frac{22348218063261}{9555858737531}$	$-\frac{1143369518992}{8141816002931}$	$-\frac{39379526789629}{19018526304540}$
4	$-\frac{975461918565}{9796059967033}$	0	0	$\frac{78070527104295}{32432590147079}$	$-\frac{548382580838}{3424219808633}$	$-\frac{33438840321285}{15594753105479}$
						$-\frac{327273}{429000}$

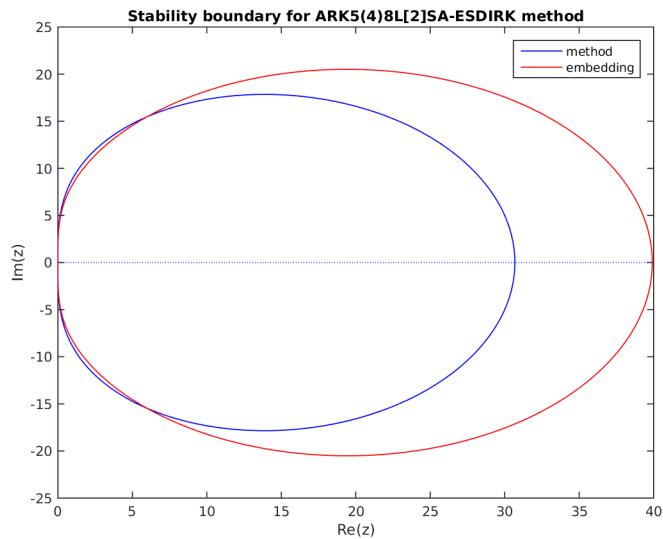


Fig. 14.25: Linear stability region for the implicit ARK-8-4-5 method. The method's region is outlined in blue; the embedding's region is in red.

### 14.2.14 ARK-8-4-5b (implicit)

Accessible via the constant `ARKODE_ARK548L2SAb_DIRK_8_4_5` for `ARKStepSetTableNum()` or `ARKode-ButcherTable_LoadDIRK()`. This is the 5th order implicit method from [41].

0	0	0	0	0	0	0	0
$\frac{4}{9}$	$\frac{2}{9}$	$\frac{2}{9}$	0	0	0	0	0
$\frac{6456083330201}{8509243623797}$	$\frac{2366667076620}{8822750406821}$	$\frac{2366667076620}{8822750406821}$	$\frac{2}{9}$	0	0	0	0
$\frac{1632083962415}{14158861528103}$	$-\frac{257962897183}{4451812247028}$	$-\frac{257962897183}{4451812247028}$	$\frac{128530224461}{14379561246022}$	$\frac{2}{9}$	0	0	0
$\frac{6365430648612}{17842476412687}$	$-\frac{486229321650}{11227943450093}$	$-\frac{486229321650}{11227943450093}$	$-\frac{225633144460}{6633558740617}$	$\frac{1741320951451}{6824444397158}$	$\frac{2}{9}$	0	0
$\frac{18}{25}$	$\frac{621307788657}{4714163060173}$	$\frac{621307788657}{4714163060173}$	$-\frac{125196015625}{3866852212004}$	$\frac{940440206406}{7593089888465}$	$\frac{961109811699}{6734810228204}$	$\frac{2}{9}$	
$\frac{191}{200}$	$\frac{2036305566805}{6583108094622}$	$\frac{2036305566805}{6583108094622}$	$-\frac{3039402635899}{4450598839912}$	$-\frac{1829510709469}{31102090912115}$	$-\frac{286320471013}{6931253422520}$	$\frac{8651533662697}{9642993110008}$	
1	0	0	$\frac{3517720773327}{20256071687669}$	$\frac{4569610470461}{17934693873752}$	$\frac{2819471173109}{11655438449929}$	$\frac{3296210113763}{10722700128969}$	$-\frac{11420}{57108}$
5	0	0	$\frac{3517720773327}{20256071687669}$	$\frac{4569610470461}{17934693873752}$	$\frac{2819471173109}{11655438449929}$	$\frac{3296210113763}{10722700128969}$	$-\frac{11420}{57108}$
4	0	0	$\frac{520639020421}{8300446712847}$	$\frac{4550235134915}{17827758688493}$	$\frac{1482366381361}{6201654941325}$	$\frac{5551607622171}{13911031047899}$	$-\frac{52666}{36788}$

## 14.3 Additive Butcher tables

In the category of additive Runge–Kutta methods for split implicit and explicit calculations, ARKODE includes methods that have orders 3 through 5, with embeddings that are of orders 2 through 4. These Butcher table pairs are as follows:

- 3rd-order pair: §14.1.3 with §14.2.5, corresponding to Butcher tables `ARKODE_ARK324L2SA_ERK_4_2_3` and `ARKODE_ARK324L2SA_DIRK_4_2_3` for `ARKStepSetTableNum()`.
- 4th-order pair: §14.1.6 with §14.2.10, corresponding to Butcher tables `ARKODE_ARK436L2SA_ERK_6_3_4` and `ARKODE_ARK436L2SA_DIRK_6_3_4` for `ARKStepSetTableNum()`.
- 4th-order pair: §14.1.7 with §14.2.11, corresponding to Butcher tables `ARKODE_ARK437L2SA_ERK_7_3_4` and `ARKODE_ARK437L2SA_DIRK_7_3_4` for `ARKStepSetTableNum()`.
- 5th-order pair: §14.1.12 with §14.2.13, corresponding to Butcher tables `ARKODE_ARK548L2SA_ERK_8_4_5` and `ARKODE_ARK548L2SA_ERK_8_4_5` for `ARKStepSetTableNum()`.
- 5th-order pair: §14.1.13 with §14.2.14, corresponding to Butcher tables `ARKODE_ARK548L2SAb_ERK_8_4_5` and `ARKODE_ARK548L2SAb_ERK_8_4_5` for `ARKStepSetTableNum()`.



## Chapter 15

# Appendix: SUNDIALS Release History

Date	SUNDIALS	ARKODE	CVODE	CVODES	IDA	IDAS	KINSOL
Dec 2021	6.0.0	5.0.0	6.0.0	6.0.0	6.0.0	5.0.0	6.0.0
Sep 2021	5.8.0	4.8.0	5.8.0	5.8.0	5.8.0	4.8.0	5.8.0
Jan 2021	5.7.0	4.7.0	5.7.0	5.7.0	5.7.0	4.7.0	5.7.0
Dec 2020	5.6.1	4.6.1	5.6.1	5.6.1	5.6.1	4.6.1	5.6.1
Dec 2020	5.6.0	4.6.0	5.6.0	5.6.0	5.6.0	4.6.0	5.6.0
Oct 2020	5.5.0	4.5.0	5.5.0	5.5.0	5.5.0	4.5.0	5.5.0
Sep 2020	5.4.0	4.4.0	5.4.0	5.4.0	5.4.0	4.4.0	5.4.0
May 2020	5.3.0	4.3.0	5.3.0	5.3.0	5.3.0	4.3.0	5.3.0
Mar 2020	5.2.0	4.2.0	5.2.0	5.2.0	5.2.0	4.2.0	5.2.0
Jan 2020	5.1.0	4.1.0	5.1.0	5.1.0	5.1.0	4.1.0	5.1.0
Oct 2019	5.0.0	4.0.0	5.0.0	5.0.0	5.0.0	4.0.0	5.0.0
Feb 2019	4.1.0	3.1.0	4.1.0	4.1.0	4.1.0	3.1.0	4.1.0
Jan 2019	4.0.2	3.0.2	4.0.2	4.0.2	4.0.2	3.0.2	4.0.2
Dec 2018	4.0.1	3.0.1	4.0.1	4.0.1	4.0.1	3.0.1	4.0.1
Dec 2018	4.0.0	3.0.0	4.0.0	4.0.0	4.0.0	3.0.0	4.0.0
Oct 2018	3.2.1	2.2.1	3.2.1	3.2.1	3.2.1	2.2.1	3.2.1
Sep 2018	3.2.0	2.2.0	3.2.0	3.2.0	3.2.0	2.2.0	3.2.0
Jul 2018	3.1.2	2.1.2	3.1.2	3.1.2	3.1.2	2.1.2	3.1.2
May 2018	3.1.1	2.1.1	3.1.1	3.1.1	3.1.1	2.1.1	3.1.1
Nov 2017	3.1.0	2.1.0	3.1.0	3.1.0	3.1.0	2.1.0	3.1.0
Sep 2017	3.0.0	2.0.0	3.0.0	3.0.0	3.0.0	2.0.0	3.0.0
Sep 2016	2.7.0	1.1.0	2.9.0	2.9.0	2.9.0	1.3.0	2.9.0
Aug 2015	2.6.2	1.0.2	2.8.2	2.8.2	2.8.2	1.2.2	2.8.2
Mar 2015	2.6.1	1.0.1	2.8.1	2.8.1	2.8.1	1.2.1	2.8.1
Mar 2015	2.6.0	1.0.0	2.8.0	2.8.0	2.8.0	1.2.0	2.8.0
Mar 2012	2.5.0	–	2.7.0	2.7.0	2.7.0	1.1.0	2.7.0
May 2009	2.4.0	–	2.6.0	2.6.0	2.6.0	1.0.0	2.6.0
Nov 2006	2.3.0	–	2.5.0	2.5.0	2.5.0	–	2.5.0
Mar 2006	2.2.0	–	2.4.0	2.4.0	2.4.0	–	2.4.0
May 2005	2.1.1	–	2.3.0	2.3.0	2.3.0	–	2.3.0
Apr 2005	2.1.0	–	2.3.0	2.2.0	2.3.0	–	2.3.0
Mar 2005	2.0.2	–	2.2.2	2.1.2	2.2.2	–	2.2.2
Jan 2005	2.0.1	–	2.2.1	2.1.1	2.2.1	–	2.2.1
Dec 2004	2.0.0	–	2.2.0	2.1.0	2.2.0	–	2.2.0

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Table 15.1 – continued from previous page

Date	SUNDIALS	ARKODE	CVODE	CVODES	IDA	IDAS	KINSOL
Jul 2002	1.0.0	–	2.0.0	1.0.0	2.0.0	–	2.0.0
Mar 2002	–	–	1.0.0 <sup>3</sup>	–	–	–	–
Feb 1999	–	–	–	–	1.0.0 <sup>4</sup>	–	–
Aug 1998	–	–	–	–	–	–	1.0.0 <sup>5</sup>
Jul 1997	–	–	1.0.0 <sup>2</sup>	–	–	–	–
Sep 1994	–	–	1.0.0 <sup>1</sup>	–	–	–	–

1. CVODE written
2. PVODE written
3. CVODE and PVODE combined
4. IDA written
5. KINSOL written

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