Axom Documentation

LLNL

Jul 06, 2020

Quickstart Guide

1 Axom Quickstart Guide 3

2 Axom Software Documentation 13

3 Other Tools Application Developers May Find Useful 185

4 Communicating with the Axom Team 263

5 Axom Copyright and License Information 265

Note: This page is under heavy construction.

Axom is a project in WCI/WSC that is funded by ECP/ATDM. Its principal goal is to provide a collection of robust and flexible software components that serve as building blocks for LLNL simulation tools. The emphasis is on sharing core infrastructure software amongst applications rather than having different codes develop and maintain similar capabilities.

A key objective of Axom is to facilitate integration of novel, forward-looking computer science capabilities into LLNL simulation codes. Thus, a central function of Axom is to enable and simplify data exchange between applications and tools that Axom provides. To meet these objectives, developers of Axom components emphasize the following features in software design and implementation:

- Flexibility to meet the needs of a diverse set of applications
- High-quality, with well designed APIs, good documentation, tested well, high performance, etc.
- Consistency in software engineering practices
- Integrability so that components work well together and are easily adopted by applications

The main drivers of the Axom project are to:

- Provide the CS infrastructure foundation of the ECP/ATDM multi-physics application at LLNL
- Support current ASC and other production applications and as they continue to evolve
- Provide capabilities for LLNL research codes, proxy apps, etc. that simplify technology transfer from research efforts into production applications

CHAPTER 1

Axom Quickstart Guide

This guide provides information to help Axom users and developers get up and running quickly.

It provides instructions for:

- Obtaining, building and installing third-party libraries on which Axom depends
- Configuring, building and installing the Axom component libraries you want to use
- Compiling and linking an application with Axom

Additional information about Axom can be found on the main Axom Web Page:

- Build system
- User guides and source code documentation for individual Axom components
- Developer guide, coding guidelines, etc.
- Communicating with the Axom development team (email lists, chat room, etc.)

Contents:

1.1 Zero to Axom: Quick install of Axom and Third Party Dependencies

The quickest path to install Axom and its dependencies is via uberenv, a script included in Axom's repo:

```
$ git clone --recursive ssh://git@cz-bitbucket.llnl.gov:7999/atk/axom.git
$ cd axom
$ python scripts/uberenv/uberenv.py --install --prefix="build"
```

After this completes, `build/axom-install` will contain an Axom install.

1.1.1 Using Axom in Your Project

The install includes examples that demonstrate how to use Axom in a CMake-based and Makefile-based build systems.

CMake-based build system example

```
project(using_with_cmake)

include("FindAxom.cmake")

# create our example
add_executable(example example.cpp)

# setup the axom include path
target_include_directories(example PRIVATE ${AXOM_INCLUDE_DIRS})

# link to axom targets
target_link_libraries(example axom)
```

See: `examples/axom/using-with-cmake`

Makefile-based build system example

```
LINK_FLAGS=-L$(AXOM_DIR)/lib/ -laxom

main:
	$(CXX) $(INC_FLAGS) example.cpp $(LINK_FLAGS) -o example
```

See: `examples/axom/using-with-make`

1.2 The Code

Our Git repository contains the Axom source code, documentation, test suites and all files and scripts used for configuring and building the code. The repository lives in our CZ Bitbucket project.

We use our JIRA project space for issue tracking. Please report issues, feature requests, etc. there or send email to the Axom development team.

1.2.1 Getting the Code

Access to our repository and Atlassian tools requires membership in the LC group `axom`. If you're not in the group, please send email to 'axom-dev@llnl.gov' and request to be added.

SSH keys

If you have not used Bitbucket before, you will need to create an SSH key and add the key to your Bitbucket profile.

Cloning the repo

To clone the repo into your local working space, type the following:

```
$ git clone --recursive ssh://git@cz-bitbucket.llnl.gov:7999/atk/axom.git
```

Important notes:

- You don't need to remember the URL for the Axom repo above. It can be found by going to the Axom repo on our Bitbucket project and clicking on the 'Clone' button that appears when you hover your mouse cursor over the ellipses at top of the web page on the left.
- The `--recursive` argument above is needed to pull in Axom's submodules. This includes our data directory, which is used for testing, as well as our build system called *BLT*, a standalone product that lives in its own repository. Documentation for BLT can be found here.
- If you forget to pass the `--recursive` argument to the git clone command, the following commands can be typed after cloning:

```
$ cd axom
$ git submodule init
$ git submodule update
```

1.2.2 Repository Layout

If you need to look through the repository, this section explains how it is organized. If you do not need this information and just want to build the code, please continue on to the next section.

The top-level Axom directory contains the following directories:

data The optional *axom_data* submodule is cloned here.

host-configs Detailed configuration information for platforms and compilers we support.

See *Host-config files* for more information.

scripts Scripts that we maintain to simplify development and usage tasks

src The bulk of the repo contents.

Within the **src** directory, you will find the following directories:

axom Directories for individual Axom components (see below)

cmake Axom's build system lives here.

The BLT submodule is cloned into the **blt** subdirectory.

docs General Axom documentation files

examples Example programs that utilize Axom in their build systems

thirdparty Built-in third party libraries with tests to ensure they are built properly.

In the **axom** directory, you will find a directory for each of the Axom components. Although there are dependencies among them, each is developed and maintained in a largely self-contained fashion. Axom component dependencies are essentially treated as library dependencies. Each component directory contains subdirectories for the component header and implementation files, as well as user documentation, examples and tests.

Axom has the following built-in third party libraries:

fmt BSD-licensed string formatting library

CLI11 BSD-licenced C++ options parser

sparsehash BSD-licenced associative containers for C++

1.3 Configuration and Building

This section provides information about configuring and building the Axom software after you have cloned the repository. The main steps for using Axom are:

1. Configure, build, and install third-party libraries (TPLs) on which Axom depends.
2. Build and install Axom component libraries that you wish to use.
3. Build and link your application with the Axom installation.

Depending on how your team uses Axom, some of these steps, such as installing the Axom TPLs and Axom itself, may need to be done only once. These installations can be shared across the team.

1.3.1 Requirements, Dependencies, and Supported Compilers

Basic requirements:

- C++ Compiler
- CMake
- Fortran Compiler (optional)

Compilers we support (listed with minimum supported version):

- Clang 3.9.1
- GCC 4.9.3
- IBM XL 13
- Intel 15
- Microsoft Visual Studio 2015
- Microsoft Visual Studio 2015 with the Intel toolchain

Please see the `<axom_src>/scripts/uberenv/spack_configs/*/compilers.yaml` for an up to date list of the supported compilers for each platform.

External Dependencies:

Axom's dependencies come in two flavors: *Library dependencies* contain code that axom must link against, while *tool dependencies* are executables that we use as part of our development process, e.g. to generate documentation and format our code. Unless otherwise marked, the dependencies are optional.

Library dependencies

Library	Dependent Components	Build system variable
Conduit	Sidre (required)	CONDUIT_DIR
HDF5	Sidre (optional)	HDF5_DIR
MFEM	Quest (optional)	MFEM_DIR
RAJA	Mint (optional)	RAJA_DIR
SCR	Sidre (optional)	SCR_DIR
Umpire	Core (optional)	UMPIRE_DIR

Each library dependency has a corresponding build system variable (with the suffix `_DIR`) to supply the path to the library's installation directory. For example, `hdf5` has a corresponding variable `HDF5_DIR`.

Tool dependencies

Tool	Purpose	Build system variable
CppCheck	Static C/C++ code analysis	CPPCHECK_EXECUTABLE
Doxygen	Source Code Docs	DOXYGEN_EXECUTABLE
Lcov	Code Coverage Reports	LCOV_EXECUTABLE
Shroud	Multi-language binding generation	SHROUD_EXECUTABLE
Sphinx	User Docs	SPHINX_EXECUTABLE
Uncrustify	Code Style Checks	UNCRUSTIFY_EXECUTABLE

Each tool has a corresponding build system variable (with the suffix `_EXECUTABLE`) to supply the tool's executable path. For example, `sphinx` has a corresponding build system variable `SPHINX_EXECUTABLE`.

Note: To get a full list of all dependencies of Axom's dependencies in an `uberenv` build of our TPLs, please go to the TPL root directory and run the following spack command `./spack/bin/spack spec uberenv-axom`.

1.3.2 Building and Installing Third-party Libraries

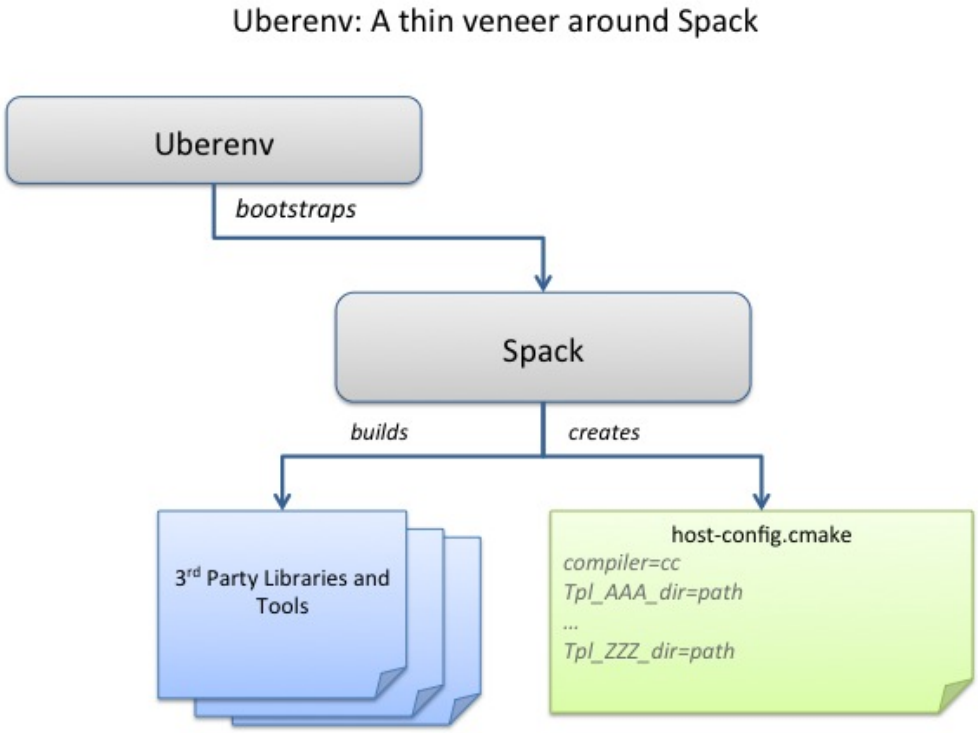
We use the Spack Package Manager to manage and build TPL dependencies for Axom. The Spack process works on Linux and macOS systems. Axom does not currently have a tool to automatically build dependencies for Windows systems.

To make the TPL process easier (you don't really need to learn much about Spack) and automatic, we drive it with a python script called `uberenv.py`, which is located in the `scripts/uberenv` directory. Running this script does several things:

- Clones the Spack repo from GitHub and checks out a specific version that we have tested.
- Configures Spack compiler sets, adds custom package build rules and sets any options specific to Axom.
- Invokes Spack to build a complete set of TPLs for each configuration and generates a *host-config* file that captures all details of the configuration and build dependencies.

The figure illustrates what the script does.

The uberenv script is run from Axom's top-level directory like this:


Uberenv: A thin veneer around Spack
Uberenv
bootstraps
Spack
builds
creates
3rd Party Libraries and Tools
host-config.cmake
compiler=cc
Tpl_AAA_dir=path
...
Tpl_ZZZ_dir=path

```
$ python ./scripts/uberenv/uberenv.py --prefix {install path}  \
                                      --spec spec              \
                                    [ --mirror {mirror path} ]
```

For more details about `uberenv.py` and the options it supports, see the uberenv docs

You can also see examples of how Spack spec names are passed to `uberenv.py` in the python scripts we use to build TPLs for the Axom development team on LC platforms at LLNL. These scripts are located in the directory `scripts/uberenv/llnl_install_scripts`.

1.3.3 Building and Installing Axom

This section provides essential instructions for building the code.

Axom uses BLT, a CMake-based system, to configure and build the code. There are two ways to configure Axom:

- Using a helper script `config-build.py`
- Directly invoke CMake from the command line.

Either way, we typically pass in many of the configuration options and variables using platform-specific *host-config* files.

Host-config files

Host-config files help make Axom's configuration process more automatic and reproducible. A host-config file captures all build configuration information used for the build such as compiler version and options, paths to all TPLs, etc. When passed to CMake, a host-config file initializes the CMake cache with the configuration specified in the file.

We noted in the previous section that the uberenv script generates a 'host-config' file for each item in the Spack spec list given to it. These files are generated by spack in the directory where the TPLs were installed. The name of each file contains information about the platform and spec.

Python helper script

The easiest way to configure the code for compilation is to use the `config-build.py` python script located in Axom's base directory; e.g.,:

```
$ ./config-build.py -hc {host-config file name}
```

This script requires that you pass it a *host-config* file. The script runs CMake and passes it the host-config. See *Host-config files* for more information.

Running the script, as in the example above, will create two directories to hold the build and install contents for the platform and compiler specified in the name of the host-config file.

To build the code and install the header files, libraries, and documentation in the install directory, go into the build directory and run `make`; e.g.,:

```
$ cd {build directory}
$ make
$ make install
```

Caution: When building on LC systems, please don't compile on login nodes.

Tip: Most make targets can be run in parallel by supplying the '-j' flag along with the number of threads to use. E.g. `$ make -j8` runs make using 8 threads.

The python helper script accepts other arguments that allow you to specify explicitly the build and install paths and build type. Following CMake conventions, we support three build types: 'Release', 'RelWithDebInfo', and 'Debug'. To see the script options, run the script without any arguments; i.e.,:

```
$ ./config-build.py
```

You can also pass extra CMake configuration variables through the script; e.g.,:

```
$ ./config-build.py -hc {host-config file name}          \
                    -DBUILD_SHARED_LIBS=ON               \
                    -DENABLE_FORTRAN=OFF
```

This will configure cmake to build shared libraries and disable fortran for the generated configuration.

Run CMake directly

You can also configure the code by running CMake directly and passing it the appropriate arguments. For example, to configure, build and install a release build with the gcc compiler, you could pass a host-config file to CMake:

```
$ mkdir build-gcc-release
$ cd build-gcc-release
$ cmake -C {host config file for gcc compiler}           \
        -DCMAKE_BUILD_TYPE=Release                       \
        -DCMAKE_INSTALL_PREFIX=../install-gcc-release    \
        ../src/
$ make
$ make install
```

Alternatively, you could forego the host-config file entirely and pass all the arguments you need, including paths to third-party libraries, directly to CMake; for example:

```
$ mkdir build-gcc-release
$ cd build-gcc-release
$ cmake -DCMAKE_C_COMPILER={path to gcc compiler}        \
        -DCMAKE_CXX_COMPILER={path to g++ compiler}      \
        -DCMAKE_BUILD_TYPE=Release                       \
        -DCMAKE_INSTALL_PREFIX=../install-gcc-release    \
        -DCONDUIT_DIR={path/to/conduit/install}          \
        {many other args}                                \
        ../src/
$ make
$ make install
```

CMake configuration options

Here are the key build system options in Axom.

OPTION	Default	Description
AXOM_ENABLE_ALL_COMPONENTS	ON	Enable all components by default
AXOM_ENABLE_<FOO>	ON	Enables the axom component named 'foo' (e.g. AXOM_ENABLE_SIDRE) for the sidre component
AXOM_ENABLE_DOCS	ON	Builds documentation
AXOM_ENABLE_EXAMPLES	ON	Builds examples
AXOM_ENABLE_TESTS	ON	Builds unit tests
BUILD_SHARED_LIBS	OFF	Build shared libraries. Default is Static libraries
ENABLE_ALL_WARNINGS	ON	Enable extra compiler warnings in all build targets
ENABLE_BENCHMARKS	OFF	Enable google benchmark
ENABLE_CODECOV	ON	Enable code coverage via gcov
ENABLE_FORTRAN	ON	Enable Fortran compiler support
ENABLE_MPI	OFF	Enable MPI
ENABLE_OPENMP	OFF	Enable OpenMP
ENABLE_WARNINGS_AS_ERRORS	OFF	Compiler warnings treated as errors.

If `AXOM_ENABLE_ALL_COMPONENTS` is OFF, you must explicitly enable the desired components (other than 'common', which is always enabled).

See Axom software documentation for a list of Axom's components and their dependencies.

Note: To configure the version of the C++ standard, you can supply one of the following values for **BLT_CXX_STD**: 'c++11' or 'c++14'. Axom requires at least 'c++11', the default value.

See *External Dependencies:* for configuration variables to specify paths to Axom's dependencies.

1.3.4 Make targets

Our system provides a variety of make targets to build individual Axom components, documentation, run tests, examples, etc. After running CMake (using either the python helper script or directly), you can see a listing of all available targets by passing 'help' to make; i.e.,:

```
$ make help
```

The name of each target should be sufficiently descriptive to indicate what the target does. For example, to run all tests and make sure the Axom components are built properly, execute the following command:

```
$ make test
```

1.3.5 Compiling and Linking with an Application

Please see *Using Axom in Your Project* for examples of how to use Axom in your project.

The Axom Quickstart Guide contains information about accessing the code, configuring and building, linking with an application, etc.

CHAPTER 2

Axom Software Documentation

The following lists contain links to user guides and source code documentation for Axom software components:

2.1 Slic User Guide

Slic provides a *light-weight*, *modular* and *extensible* logging infrastructure that simplifies logging application messages.

Key Features

- Interoperability across the constituent libraries of an application. Messages logged by an application and any of its libraries using Slic have a unified format and routed to a centralized output destination.
- Customizable *Log Message Format* to suit application requirements.
- Customizable handling and filtering of log messages by extending the *Log Stream* base class.
- *Built-In Log Streams* to support common logging use cases, e.g., log to a file or console.
- Native integration with Lumberjack for logging and filtering of messages at scale.
- Fortran bindings that provide an idiomatic API for Fortran applications.

Requirements

Slic is designed to be *light-weight* and *self-contained*. The only requirement for using Slic is a C++11 compliant compiler. However, to use Slic in the context of a distributed parallel application and in conjunction with Lumberjack, support for building with MPI is provided.

For further information on how to build the Axom Toolkit, consult the Axom Quick Start Guide.

About this Guide

This guide presents core concepts, key capabilities, and guiding design principles of Slic's *Component Architecture*. To get started with using Slic quickly within an application, see the *Getting Started with Slic* section. For more detailed information on the interfaces of the various classes and functions in Slic, developers are advised to consult the Slic Doxygen API.

Additional questions, feature requests or bug reports on Slic can be submitted by creating a new issue on Github or by sending e-mail to the Axom Developers mailing list at axom-dev@llnl.gov.

2.1.1 Getting Started with Slic

This section illustrates some of the key concepts and capabilities of Slic by presenting a short walk-through of a C++ application. The complete *Slic Application Code Example* is included in the *Appendix* section and is also available within the Slic source code, under `src/axom/slic/examples/basic/logging.cpp`.

This example illustrates the following concepts:

- Initializing the Slic Logging Environment,
- Prescribing the *Log Message Format*,
- Basic logging to the console using the *Generic Output Stream*, and,
- Using some of the various *Slic Macros Used in Axom* to log messages.

Step 1: Add Header Includes

First, the Slic header must be included to make all the Slic functions and classes accessible to an application:

```
1 // Slic includes
2 #include "axom/slic.hpp"
```

Note: All the classes and functions in Slic are encapsulated within the `axom::slic` namespace.

Step 2: Initialize Slic

Prior to logging any messages, the Slic Logging Environment is initialized by the following:

```
1   slic::initialize();
```

This creates the root logger instance. However, in order to log messages, an application must first specify an output destination and optionally, prescribe the format of the log messages. These steps are demonstrated in the following sections.

Step 3: Set the Message Format

The *Log Message Format* is specified as a string consisting of keywords, enclosed in `< ... >`, that Slic knows how to interpret when assembling the log message.

```
1   std::string format = std::string( "<TIMESTAMP>\n" ) +
2                        std::string( "[<LEVEL>]: <MESSAGE> \n" ) +
3                        std::string( "FILE=<FILE>\n" ) +
4                        std::string( "LINE=<LINE>\n\n" );
```

For example, the `format` string in the code snippet above indicates that the resulting log messages will have the following format:

- A line with the message time stamp
- A line consisting of the *Log Message Level*, enclosed in brackets `[ ]`, followed by the user-supplied message,

- A third line with the name of the file where the message was emitted and
- The corresponding line number location within the file, in the fourth line.

The format string is used in *Step 5: Register a Log Stream*. Specifically, it is passed as an argument to the *Generic Output Stream* object constructor to prescribe the format of the messages.

See the *Log Message Format* section for the complete list of keyword options available that may be used to customize the format of the messsages.

Note: This step is optional. If the format is not specified, a *Default Message Format* will be used to assemble the message.

Step 4: Set Severity Level

The severity of log messages to be captured may also be adjusted at runtime to the desired *Log Message Level* by calling `slic::setLoggingMsgLevel()`. This provides another knob that the application can use to filter the type and level of messages to be captured.

All log messages with the specified severity level or higher are captured. For example, the following code snippet sets the severity level to *debug*.

```
1  slic::setLoggingMsgLevel( slic::message::Debug );
```

This indicates that all log messages that are *debug* or higher are captured otherwise, the messages are ignored. Since *debug* is the lowest severity level, all messages will be captured in this case.

Step 5: Register a Log Stream

Log messages can have one or more output destination. The output destination is specified by registering a corresponding *Log Stream* object to each *Log Message Level*.

The following code snippet uses the *Generic Output Stream* object, one of the *Built-In Log Streams* provided by Slic, to specify `std::cout` as the output destination for messages at each *Log Message Level*.

```
1  slic::addStreamToAllMsgLevels(
2    new slic::GenericOutputStream( &std::cout,format) );
```

Note: Instead of calling `slic::addStreamToAllMsgLevels()` an application may use `slic::addStreamToMsgLevel()` that allows more fine grain control of how to bind *Log Stream* objects to each *Log Message Level*. Consult the Slic Doxygen API Documentation for more information.

The *Generic Output Stream*, takes two arguments in its constructor:

- A C++ `std::ostream` object that specifies the destination of messages. Consequently, output of messages can be directed to the console, by passing `std::cout` or `std::cerr`, or to a file by passing a C++ `std::ofstream` object. In this case, `std::cout` is specified as the output destination.
- A string corresponding to the *Log Message Format*, discussed in *Step 3: Set the Message Format*.

Note: Slic maintains ownership of all registered *Log Stream* instances and will deallocate them when `slic::finalize()` is called.

Step 5: Log Messages

Once the output destination of messages is specified, messages can be logged using the *Slic Macros Used in Axom*, as demonstrated in the code snippet below.

```
1   SLIC_DEBUG( "Here is a debug message!" );
2   SLIC_INFO( "Here is an info mesage!" );
3   SLIC_WARNING( "Here is a warning!" );
4   SLIC_ERROR( "Here is an error message!" );
```

Note: By default, `SLIC_ERROR()` will print the specified message and a stacktrace to the corresponding output destination and call *axom::utilities::processAbort()* to gracefully abort the application. This behavior can be toggled by calling `slic::disableAbortOnError()`. See the Slic Doxygen API Documentation for more details.

Step 6: Finalize Slic

Before the application terminates, the Slic Logging Environment must be finalized, as follows:

```
1   slic::finalize();
```

Calling `slic::finalize()` will properly deallocate the registered *Log Stream* objects and terminate the Slic Logging Environment.

Step 7: Run the Example

After building the Axom Toolkit the *Slic Application Code Example* may be run from within the build space directory as follows:

```
> ./example/slic_logging_ex
```

The resulting output should look similar to the following:

```
Fri Apr 26 14:29:53 2019
[DEBUG]: Here is a debug message!
FILE=/Users/zagaris2/dev/AXOM/source/axom/src/axom/slic/examples/basic/logging.cpp
LINE=44

Fri Apr 26 14:29:53 2019
[INFO]: Here is an info mesage!
FILE=/Users/zagaris2/dev/AXOM/source/axom/src/axom/slic/examples/basic/logging.cpp
LINE=45

Fri Apr 26 14:29:53 2019
[WARNING]: Here is a warning!
FILE=/Users/zagaris2/dev/AXOM/source/axom/src/axom/slic/examples/basic/logging.cpp
LINE=46

Fri Apr 26 14:29:53 2019
[ERROR]: Here is an error message!
** StackTrace of 3 frames **
Frame 1: axom::slic::logErrorMessage(std::__1::basic_string<char, std::__1::char_
↪traits<char>,
std::__1::allocator<char> > const&, std::__1::basic_string<char, std::__1::char_traits
↪<char>,
```

(continues on next page)

(continued from previous page)

```
std::__1::allocator<char> > const&, int)
Frame 2: main
Frame 3: start
=====


FILE=/Users/zagaris2/dev/AXOM/source/axom/src/axom/slic/examples/basic/logging.cpp
LINE=47

Abort trap: 6
```

2.1.2 Component Architecture

Slic provides a simple and easy to use logging interface for applications.

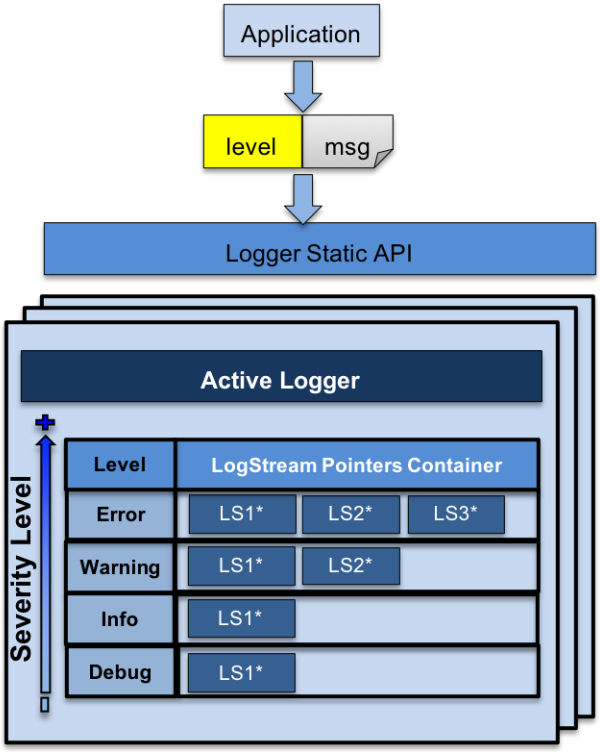


Fig. 2.1: Basic Component Architecture of Slic.

The basic component architecture of Slic, depicted in Fig. 2.1, consists of three main components:

1. A static logger API. This serves as the primary interface to the application.
2. One or more Logger object instances. In addition to the root logger, which is created when Slic is initialized, an application may create additional loggers. However, at any given instance, there is only a single *active* logger to which all messages are logged.
    - A Logger consists of *four* log message levels: `ERROR`, `WARNING`, `INFO` and `DEBUG`.
    - Each *Log Message Level* can have one or more *Log Stream* instances, which, specify the output destination, format and filtering of messages.

3. One or more *Log Stream* instances, bound to a particular logger, that can be shared between log message levels.

The application logs messages at an appropriate *Log Message Level*, i.e., `ERROR`, `WARNING`, `INFO`, or, `DEBUG` using the static API. Internally, the Logger routes the message to the corresponding *Log Stream* instances that are bound to the associated *Log Message Level*.

The following sections discuss some of these concepts in more detail.

Log Message Level

The *Log Message Level* indicates the severity of a message. Slic provides four levels of messages ranked from highest to lowest as follows:

Message Level	Usage Description
`ERROR`	Indicates that the application encountered a critical error or a faulty state. Includes also stack-trace.
`WARNING`	Indicates that the application encountered an error, but, the application should proceed.
`INFO`	General information reported by an application.
`DEBUG`	Information useful to application developers.

Note: `ERROR` messages by default will cause the application to abort. This behavior may be toggled by calling `slic::enableAbortOnError()` and `slic::disableAbortOnError()`. See the Slic Doxygen API Documentation for more details.

An application may adjust at runtime the severity level of messages to capture by calling `slic::setLoggingMsgLevel()`. For example, the following code snippet, sets the severity level to `WARNING`

```
slic::setLoggingMsgLevel( slic::message::Warning );
```

This indicates that all messages with a level of severity of `WARNING` and higher will be captured, namely `WARNING` and `ERROR` messages. Thereby, enable the application to filter out messages with lower severity.

Log Stream

The *Log Stream* class, is an abstract base class that facilitates the following:

- Specifying the *Log Message Format* and output destination of log messages.
- Implementing logic for handling and filtering messages.
- Defines a pure abstract interface for all *Log Stream* instances.

Since *Log Stream* is an abstract base class, it cannot be instantiated and used directly. Slic provides a set of *Built-In Log Streams*, which provide concrete implementations of the *Log Stream* base class that support common use cases for logging, e.g., logging to a file or output to the console.

Applications requiring custom functionality, may extend the *Log Stream* class and provide a concrete *Log Stream* instance implementation that implements the abstract interface defined by the *Log Stream* base class. See the *Add a Custom Log Stream* section for details.

A concrete *Log Stream* instance can be attached to one or more *Log Message Level* by calling `slic::addStreamToMsgLevel()` and `slic::addStreamToAllMsgLevels()`. See the Slic Doxygen API Documentation for more details.

Log Message Format

The *Log Message Format* is specified as a string consisting of keywords that are encapsulated in <...>, which, Slic knows to interpret when assembling the log message.

The list of keywords is summarized in the table below.

key-word	Replaced With
<TIMES-TAMP>	A textual representation of the time a message is logged, as returned by `std::asctime()`.
<LEVEL>	The *Log Message Level*, i.e., `ERROR`, `WARNING`, `INFO`, or `DEBUG`.
<MES-SAGE>	The supplied message that is being logged.
<FILE>	The file from where the message was emmitted.
<LINE>	The line location where the message was emmitted.
<TAG>	A string tag associated with a given message, e.g., for filtering during post-processing, etc.
<RANK>	The MPI rank that emmitted the message. Only applicable when the Axom Toolkit is compiled with MPI enabled and with MPI-aware *Log Stream* instances, such as, the *Synchronized Output Stream* and *Lumberjack Stream*.

These keywords can be combined in a string to specify a template for a log message.

For example, the following code snippet, specifies that all reported log messages consist of the level, enclosed in brackets followed by the user-supplied log message.

```
std::string format = "[<LEVEL>]: <MESSAGE>";
```

To get the file and line location within the file where the message was emitted, the format string above could be amended with the following:

```
std::string format = "[<LEVEL>]: <MESSAGE> \n\t<FILE>:<LINE>";
```

This indicates that the in addition to the level and user-supplied, the resulting log messages will have an additional line consisting of the file and line where the message was emitted.

Default Message Format

If the *Log Message Format* is not specified, the *Log Stream* base class defines a default format that is set to the following:

```
std::string DEFAULT_FORMAT = "*****\n[<LEVEL>]\n\n <MESSAGE> \n\n <FILE>\n<LINE>
↪\n****\n"
```

Built-In Log Streams

The *Built-In Log Streams* provided by Slic are summarized in the following table, followed by a brief description for each.

Log Stream	Use & Availability
Generic Output Stream	Always available. Used in serial applications, or, for logging on rank zero.
Synchronized Output Stream	Requires MPI. Used with MPI applications.
Lumberjack Stream	Requires MPI. Used with MPI applications.

Generic Output Stream

The *Generic Output Stream*, is a concrete implementation of the *Log Stream* base class, that can be constructed by specifying:

1. A C++ `std::ostream` object instance, e.g., `std::cout`, ``std::cerr` for console output, or to a file by passing a C++ `std::ofstream` object, and,
2. Optionally, a string that specifies the *Log Message Format*.

For example, the following code snippet registers a *Generic Output Stream* object that is bound to the the `std::cout`.

```
slic::addStreamToAllMsgLevels(
  new slic::GenericOutputStream( &std::cout, format ) );
```

Similarly, the following code snippet, registers a *Generic Output Stream* object that is bound to a file.

```
std::ofstream log_file;
log_file.open( "logfile.dat" );

slic::addStreamToAllMsgLevels(
  new slic::GenericOutputStream( &log_file, format ) );
```

Synchronized Output Stream

The *Synchronized Output Stream* is intended to be used with parallel MPI applications, primarily for debugging. The *Synchronized Output Stream* provides similar functionality to the *Generic Output Stream*, however, the log messages are synchronized across the MPI ranks of the specified communicator.

Similar to the *Generic Output Stream* the *Synchronized Output Stream* is constructed by specifying:

1. A C++ `std::ostream` object instance, e.g., `std::cout`, ``std::cerr` for console output, or to a file by passing a C++ `std::ofstream` object.
2. The MPI communicator, and,
3. Optionally, a string that specifies the *Log Message Format*.

The following code snippet illustrates how to register a *Synchronized Output Stream* object with Slic to log messages to `std::cout`.

```
slic::addStreamToAllMsgLevels(
   new slic::SynchronizedOutputStream( &std::cout, mpi_comm, format ) );
```

Note: Since, the *Synchronized Output Stream* works across MPI ranks, logging messages using the *Slic Macros Used in Axom* or the static API directly only logs the messages locally. To send the messages to the output destination the application must call `slic::flushStreams()` explicitly, which, in this context is a collective call.

Lumberjack Stream

The *Lumberjack Stream*, is intended to be used with parallel MPI applications. In contrast to the *Synchronized Output Stream*, which logs messages from all ranks, the *Lumberjack Stream* uses Lumberjack internally to filter out duplicate messages that are emitted from multiple ranks.

The *Lumberjack Stream* is constructed by specifying:

1. A C++ `std::ostream` object instance, e.g., `std::cout`, ``std::cerr` for console output, or to a file by passing a C++ `std::ofstream` object.
2. The MPI communicator,
3. An integer that sets a limit on the number of duplicate messsages reported per rank, and,
4. Optionally, a string that specifies the *Log Message Format*.

The following code snippet illustrates how to register a *Lumberjack Stream* object with Slic to log messages to `std::cout`.

```
slic::addStreamToAllMsgLevels(
   new slic::LumberjackStream( &std::cout, mpi_comm, 5, format ) );
```

Note: Since, the *Lumberjack Stream* works across MPI ranks, logging messages using the *Slic Macros Used in Axom* or the static API directly only logs the messages locally. To send the messages to the output destination the application must call `slic::flushStreams()` explicitly, which, in this context is a collective call.

Add a Custom Log Stream

Slic can be customized by implementing a new subclass of the *Log Stream*. This section demonstrates the basic steps required to *Add a Custom Log Stream* by walking through the implementation of a new *Log Stream* instance, which we will call `MyStream`.

Note: `MyStream` provides the same functionality as the *Generic Output Stream*. The implementation presented herein is primarily intended for demonstrating the basic process for extending Slic by providing a custom *Log Stream*.

Create a LogStream Subclass

First, we create a new class, `MyStream`, that is a subclass of the *Log Stream* class, as illustrated in the code snippet below.

```
1  class MyStream : public LogStream
2  {
3   public:
4
5     MyStream( ) = delete;
6     MyStream( std::ostream* os, const std::string& format );
7
8     virtual ~MyStream();
9
10    /// \see LogStream::append
11    virtual void append( message::Level msgLevel,
12                         const std::string& message,
13                         const std::string& tagName,
14                         const std::string& fileName,
15                         int line,
16                         bool filter_duplicates );
17  private:
18    std::ostream* m_stream;
19
```

(continues on next page)

(continued from previous page)

```
   // disable copy & assignment
   MyStream( const MyStream & ) = delete;
   MyStream& operator=(const MyStream&) = delete;

   // disable move & assignment
   MyStream( const MyStream&& ) = delete;
   MyStream& operator=(const MyStream&&) = delete;
};
```

The class has a pointer to a C++ `std::ostream` object as a private class member. The `std::ostream` object holds a reference to the output destination for log messages, which can be any `std::ostream` instance, e.g., `std::cout`, `std::cerr`, or a file `std::ofstream`, etc.

The reference to the `std::ostream` is specified in the class constructor and is supplied by the application when a `MyStream` object is instantiated.

Since `MyStream` is a concrete instance of the *Log Stream* base class, it must implement the `append()` method, which is a pure *virtual* method.

Implement LogStream::append()

The `MyStream` class implements the `LogStream::append()` method of the *Log Stream* base class, as demonstrated in the code snippet below.

```
 void MyStream::append( message::Level msgLevel,
                        const std::string& message,
                        const std::string& tagName,
                        const std::string& fileName,
                        int line,
                        bool AXOM_NOT_USED(filtered_duplicates) )
{
   assert( m_stream != nillptr );

   (*m_stream) << this->getFormatedMessage( message::getLevelAsString(msgLevel),
                                            message,
                                            tagName,
                                            "",
                                            fileName,
                                            line );
}
```

The `append()` method takes all the metadata associated with a message through its argument list:

- The *Log Message Level*
- The user-specified message
- A tag associated with the message, may be set `MSG_IGNORE_TAG`
- The file where the message was emitted
- The line location within the file where the message was emitted

The `append()` method calls `LogStream::getFormatedMessage()`, a method implemented in the *Log Stream* base class, which, applies the *Log Message Format* according to the specified format string supplied to the `MyStream` class constructor, when the class is instantiated.

Register the new class with Slic

The new *Log Stream* class may be used with Slic in a similar manner to any of the *Built-In Log Streams*, as demonstrated in the code snippet below:

```
slic::addStreamToAllMsgLevels( new MyStream( &std::cout, format ) );
```

2.1.3 Wrapping Slic in Macros

The recommended way of integrating Slic into an application is to wrap the Slic API for logging messages into a set of convenience application macros that are used throughout the application code.

This allows the application code to:

- Centralize all use of Slic behind a thin macro layer,
- Insulate the application from API changes in Slic,
- Customize and augment the behavior of logging messages if needed, e.g., provide macros that are only active when the code is compiled with debug symbols etc.

The primary function used to log messages is `slic::logMessage()`, which in its most basic form takes the following arguments:

1. The *Log Message Level* associated with the message
2. A string corresponding to the user-supplied message
3. The name of the file where the message was emitted
4. The corresponding line number within the file where the message was emitted

There are additional variants of the `slic::logMessage()` function that allow an application to specify a `TAG` for different types of messages, etc. Consult the Slic Doxygen API Documentation for more details.

For example, an application, `MYAPP`, may want to define macros to log `DEBUG`, `INFO`, `WARNING` and `ERROR` messages as illustrated below

```
#define MYAPP_LOGMSG( LEVEL, msg )                                          \
{                                                                           \
  std::ostringstream oss;                                                   \
  oss << msg;                                                               \
  slic::logMessage( LEVEL, oss.str(), __FILE__, __LINE__ );                 \
}

#define MYAPP_ERROR( msg ) MYAPP_LOGMSG( slic::message::Error, msg )
#define MYAPP_WARNING( msg ) MYAPP_LOGMSG( slic::message::Warning, msg )
#define MYAPP_INFO( msg ) MYAPP_LOGMSG( slic::message::Info, msg )
#define MYAPP_DEBUG( msg ) MYAPP_LOGMSG( slic::message::Debug, msg )
```

These macros can then be used in the application code as follows:

```
MYAPP_INFO( "this is an info message")
MYAPP_ERROR( "this is an error message" );
...
```

Note: Another advantage of encapsulating the Slic API calls in macros is that this approach alleviates the burden from application developers to have to pass the `__FILE__` and `__LINE__` to the `logMessage()` function each

time.

The *Slic Macros Used in Axom* provide a good resource for the type of macros that an application may want to adopt and extend. Although these macros are tailored for use within the Axom Toolkit, these are also callable by application code.

2.1.4 Appendix

Slic Application Code Example

Below is the complete *Slic Application Code Example* presented in the *Getting Started with Slic* section. The code can be found in the Axom source code under `src/axom/slic/examples/basic/logging.cpp`.

```
// SPHINX_SLIC_INCLUDES_BEGIN
// Slic includes
#include "axom/slic.hpp"
// SPHINX_SLIC_INCLUDES_END

using namespace axom;

//------------------------------------------------------------------------------
int main( int AXOM_NOT_USED(argc), char** AXOM_NOT_USED(argv) )
{
  // SPHINX_SLIC_INIT_BEGIN

  slic::initialize();

  // SPHINX_SLIC_INIT_END

  slic::disableAbortOnError();

  // SPHINX_SLIC_FORMAT_MSG_BEGIN

  std::string format = std::string( "<TIMESTAMP>\n" ) +
                       std::string( "[<LEVEL>]: <MESSAGE> \n" ) +
                       std::string( "FILE=<FILE>\n" ) +
                       std::string( "LINE=<LINE>\n\n" );

  // SPHINX_SLIC_FORMAT_MSG_END

  // SPHINX_SLIC_SET_SEVERITY_BEGIN

  slic::setLoggingMsgLevel( slic::message::Debug );

  // SPHINX_SLIC_SET_SEVERITY_END

  // SPHINX_SLIC_SET_STREAM_BEGIN
  slic::addStreamToAllMsgLevels(
    new slic::GenericOutputStream( &std::cout,format) );

  // SPHINX_SLIC_SET_STREAM_END

```

(continues on next page)

(continued from previous page)

```
40    // SPHINX_SLIC_LOG_MESSAGES_BEGIN
41
42    SLIC_DEBUG( "Here is a debug message!" );
43    SLIC_INFO( "Here is an info mesage!" );
44    SLIC_WARNING( "Here is a warning!" );
45    SLIC_ERROR( "Here is an error message!" );
46
47    // SPHINX_SLIC_LOG_MESSAGES_END
48
49    // SPHINX_SLIC_FINALIZE_BEGIN
50
51    slic::finalize();
52
53    // SPHINX_SLIC_FINALIZE_END
54
55    return 0;
56  }
```

axom::utilities::processAbort()

The *axom::utilities::processAbort()* function gracefully aborts the application by:

1. Calling `abort()` if it is a serial application.
2. Calls `MPI_Abort()` if the Axom Toolkit is compiled with MPI and the application has initialized MPI, i.e., it's a distributed MPI application.

Slic Macros Used in Axom

Slic provides a set of convenience macros that can be used to streamline logging within an application.

Note: The *Slic Macros Used in Axom* are not the only interface to log messages with Slic. They are used within the Axom Toolkit for convenience. Applications or libraries that adopt Slic, typically, use the C++ API directly, e.g., call `slic::logMessage()` and wrap the functionality in application specific macros to better suit the requirements of the application.

SLIC_INFO

The `SLIC_INFO` macro logs `INFO` messages that consist general information reported by an application.

The following code snippet illustrates the usage of the `SLIC_INFO` macro:

```
SLIC_INFO( "Total number of mesh cells:" <<  N );
```

SLIC_INFO_IF

The `SLIC_INFO_IF` macro provides the same functionality with the *SLIC_INFO* macro, however, it takes one additional argument, a boolean expression, that allows the application to conditionally log an `INFO` message depending on the value of the boolean expression.

For example, the following code snippet illustrates the usage of the `SLIC_INFO_IF` macro.

```
SLIC_INFO_IF( (myval >= 0), "[" << myval << "] is positive!" );
```

In this case, the `INFO` message is only logged when the boolean expression, `(myval >=0)` evaluates to `true`.

Note: The primary intent is to provide a convenience layer and facilitate in a cleaner and more compact code style by encapsulating the conditional branching logic within a macro.

SLIC_ERROR

The `SLIC_ERROR` macro logs `ERROR` messages that indicate that the application has encountered a critical error.

The following code snippet illustrates the basic usage of the `SLIC_ERROR` macro:

```
SLIC_ERROR( "jacobian is negative!" );
```

A stacktrace of the application is appended to all `ERROR` messages to facilitate debugging.

Note: By default, an `ERROR` message triggers a call to `abort()` the application. However, this behavior can be toggled by calling `slic::enableAbortOnError()` and `slic::disableAbortOnError()` accordingly. See the Slic Doxygen API Documentation for more information.

SLIC_ERROR_IF

The `SLIC_ERROR_IF` provides the same functionality with the *SLIC_ERROR* macro, however, it takes one additional argument, a boolean expression, that allows the application to conditionally log an `ERROR` message depending on the value of the boolean expression.

The following code snippet illustrates the usage of the `SLIC_ERROR_IF` macro.

```
SLIC_ERROR_IF( (jacobian < 0.0 + TOL), "jacobian is negative!" );
```

In this case, the `ERROR` message in only logged when the boolean expression, `(jacobian < 0.0 + TOL)` evaluates to `true`.

Note: The primary intent is to provide a convenience layer and facilitate in a cleaner and more compact code style by encapsulating the conditional branching logic within a macro.

SLIC_WARNING

The `SLIC_WARNING` macro logs `WARNING` messages that indicate that the application has encountered an error, however, the error is not critical and the application can proceed.

The following code snippet illustrates the basic usage of the `SLIC_WARNING` macro.

```
SLIC_WARNING( "Region [" << ir << "] defined but not used in the problem!" );
```

SLIC_WARNING_IF

Similarly, the `SLIC_WARNING_IF` macro provides the same functionality with the *SLIC_WARNING* macro, however, it takes one additional argument, a boolean expression, that allows the application to conditionally log a `WARNING` message depending on the value of the boolean expression.

The following code snippet illustrates the basic usage of the `SLIC_WARNING_IF` macro.

```
SLIC_WARNING_IF( (val < 1), "val cannot be less than 1. Forcing value to 1." );
val = 1;
```

In this case, the `WARNING` message is only logged when the boolean expression, `(val < 1)`, evaluates to ‘‘ true‘‘.

Note: The primary intent is to provide a convenience layer and facilitate in a cleaner and more compact code style by encapsulating the conditional branching logic within a macro.

SLIC_DEBUG

The `SLIC_DEBUG` macro logs `DEBUG` messages that are intended for debugging information intended for developers.

The following code snippet illustrates the basic usage of the `SLIC_DEBUG` macro

```
SLIC_DEBUG( "Application is running with " << N << " threads!" );
```

Warning: This macro will log messages only when the Axom Toolkit is configured and built with debug symbols. Consult the Axom Quick Start Guide for more information.

SLIC_DEBUG_IF

Similarly, the `SLIC_DEBUG_IF` macro provides the same functionality with the *SLIC_DEBUG* macro, however, it take one additional argument, a boolean expression, that allows the application to conditionally log a `DEBUG` message depending on the value of the supplied boolean expression.

The following code snippet illustrates the basic usage of the `SLIC_DEBUG_IF` macro.

```
SLIC_DEBUG_IF( (value < 0), "value is negative!" );
```

In this case, the `DEBUG` message is only logged when the boolean expression, `(value <0)`, evaluates to `true`.

Note: The primary intent is to provide a convenience layer and facilitate in a cleaner and more compact code style by encapsulating the conditional branching logic within a macro.

Warning: This macro will log messages only when the Axom Toolkit is configured and built with debug symbols. Consult the Axom Quick Start Guide for more information.

SLIC_ASSERT

The SLIC_ASSERT macro is used in a similar manner to the C++ assert() function call. It evaluates the given expression and logs an ERROR message if the assertion is not true. The contents of the error message consist of the supplied expression.

The SLIC_ASSERT macro is typically used to capture programming errors and to ensure pre-conditions and post-conditions are satisfied.

The following code snippet illustrates the basic usage of the SLIC_ASSERT macro.

```
SLIC_ASSERT( data != nullptr );
```

Warning: This macro will log messages only when the Axom Toolkit is configured and built with debug symbols. Consult the Axom Quick Start Guide for more information.

SLIC_ASSERT_MSG

The SLIC_ASSERT_MSG macro provides the same functionality with the *SLIC_ASSERT* macro, however, it allows the application to supply a custom message in addition to the boolean expression that is evaluated.

The following code snippet illustrates the basic usage of the SLIC_ASSERT_MSG macro.

```
SLIC_ASSERT_MSG( data != nullptr, "supplied pointer is null!" );
```

Warning: This macro will log messages only when the Axom Toolkit is configured and built with debug symbols. Consult the Axom Quick Start Guide for more information.

SLIC_CHECK

The SLIC_CHECK macro evaluates a given boolean expression, similar to the *SLIC_ASSERT* macro. However, in contrast to the *SLIC_ASSERT* macro, when the boolean expression evaluates to false, the macro logs a WARNING instead of an ERROR.

The following code snippet illustrates the basic usage of the SLIC_CHECK macro.

```
SLIC_CHECK( data != nullptr );
```

Warning: This macro will log messages only when the Axom Toolkit is configured and built with debug symbols. Consult the Axom Quick Start Guide for more information.

SLIC_CHECK_MSG

The SLIC_CHECK_MSG macro provides the same functionality with the *SLIC_CHECK* macro, however, it allows for the application to supply a custom message in addition to the boolean expression that is evaluated.

The following code snippet illustrates the basic usage of the SLIC_CHECK_MSG macro.

```
SLIC_CHECK_MSG( data != nullptr, "supplied pointer is null!" );
```

Warning: This macro will log messages only when the Axom Toolkit is configured and built with debug symbols. Consult the Axom Quick Start Guide for more information.

2.2 Lumberjack User Documentation

Lumberjack, named because it cuts down logs, is a C++ library that provides scalable logging while reducing the amount of messages written out the screen or file system.

2.2.1 Introduction

Lumberjack was created to provide scalable logging with a simple programming model while allowing developers to customize its behavior. It is named Lumberjack because it cuts down logs. It uses MPI and a scalable binary tree reduction scheme to combine duplicate messages and limit output to only the root node.

2.2.2 Requirements

- MPI - MPI is fundamental to Lumberjack and without MPI, Lumberjack is not useful.
- C++11 - Required for compiling Lumberjack

2.2.3 Code Guarding

You tell if Axom was built with Lumberjack enabled by using the following include and compiler define:

```
#include "axom/config.hpp"
#ifdef AXOM_USE_LUMBERJACK
    // Lumberjack code
#endif
```

2.2.4 Classes

Basic

- *Lumberjack* - Performs all high level functionality for the Lumberjack library.
- *Message* - Holds all information pertaining to a Message.

Communicators

Handles all node-to-node Message passing.

- *Communicator* - Abstract base class that all Communicators must inherit from.
- *BinaryTreeCommunicator* - Main Communicator that is implemented with a scalable Binary Tree scheme

- *RootCommunicator* - non-scalable communication scheme that all nodes connect to the root node. This is given for diagnostic purposes only.

Combiners

Handles Message combination and tests whether Message classes should be combined.

- *Combiner* - Abstract base class that all Combiners must inherit from.
- *TextEqualityCombiner* - Combines Message classes that have equal Text member variables.

Contents:

Core Concepts

The following are core concepts required to understand how Lumberjack works.

Combining

Combining Messages is how Lumberjack cuts down on the number of Messages output from your program. It does so by giving the currently held Messages at the current node, two at a time, to the Combiner classes that are currently registered to Lumberjack when a Push happens.

Lumberjack only provides one Combiner, the TextEqualityCombiner. You can write your own Combiners and register them with Lumberjack. The idea is that each Combiner would have its own criteria for whether a Message should be combined and how to combine that specific Message with another of the same type.

Combiner's have two main functions, shouldMessagesBeCombined and combine.

The function shouldMessagesBeCombined, returns True if the pair of messages satisfy the associated criteria. For example in the TextEqualityCombiner, if the Text strings are exactly equal, it signals they should be combined.

The function combine, takes two Messages and combines them in the way that is specific to that Combiner class. For example in the TextEqualityCombiner, the only thing that happens is the second Message's ranks gets added to the first and the message count is increased. This is because the text strings were equal. This may not be the case for all Combiners that you write yourself.

Communication

Communicating Messages between nodes in an intelligent way is how Lumberjack scales logging Messages. The *Communicator* class instance handles the specifics on how the communication is implemented. For example, it handles where a specific node passes its Messages and which nodes are allowed to output messages. As of now, there are two implemented Communicators: *BinaryTreeCommunicator* and *RootCommunicator*.

BinaryTreeCommunicator, as the name implies, utilizes a standard Binary Tree algorithm to define how the nodes are connected. Children pass their Messages to their parent and the root node is the only node allowed to output Messages.

RootCommunicator has a very simple communication scheme that does not scale well but is useful in some cases for its simplicity. All nodes connect directly to the root node which is also the only node allowed to output Messages.

Pushing

A push has three steps: combining, sending, and receiving Messages. When you queue a Message into Lumberjack, it is held at the node that generated the Message until you indicate the Lumberjack to push, either once or fully. If you do not push, then only the Messages generated at the root node will be outputed.

In a single push, nodes send their currently held Messages to the nodes their are connected to based on the Communicator's communcation scheme. For example in the BinaryTreeCommunicator, children nodes send their Messages to their parent. While the root node only receives Messages. After a single push, it is not guaranteed that all Messages will be ready to be outputted.

A full push is a number of single pushes until all currently held Messages. The Communicator tells the Lumberjack class how many single pushes it takes to fully flush the system of Messages. For example in the BinaryTreeCommunicator, it is the log of the number of nodes.

Quick Start

This quick start guide goes over the bare minimum you need to do to get up and running with Lumberjack. You can find this example in the repository under Lumberjack's examples directory.

This example uses the Binary Tree Communicator and queues one unique message and three similar messages per rank. They are combined and then *pushed* fully through the tree.

The following files need to be included for Lumberjack:

```
# Lumberjack specific header
#include "axom/lumberjack.hpp"

# MPI and C++
#include <mpi.h>
#include <iostream>
```

Basic MPI setup and information:

```
// Initialize MPI and get rank and comm size
MPI_Init(&argc, &argv);

int commRank = -1;
MPI_Comm_rank(MPI_COMM_WORLD, &commRank);
int commSize = -1;
MPI_Comm_size(MPI_COMM_WORLD, &commSize);
```

Initialize Lumberjack:

```
// Determine how many ranks we want to individually track per message
int ranksLimit = commSize/2;

// Initialize which lumberjack communicator we want
axom::lumberjack::BinaryTreeCommunicator communicator;
communicator.initialize(MPI_COMM_WORLD, ranksLimit);

// Initialize lumberjack
axom::lumberjack::Lumberjack lj;
lj.initialize(&communicator, ranksLimit);
```

This queues the individual messages into Lumberjack:

```
// Queue messages into lumberjack
if (commRank == 0){
    lj.queueMessage("This message will not be combined");
}
else {
    lj.queueMessage("This message will be combined");
    lj.queueMessage("This message will be combined");
    lj.queueMessage("This message will be combined");
}
```

This is how you fully *push* all Messages through the Communicator, which also *combines* Messages before and after pushing :

```
// Push messages fully through lumberjack's communicator
lj.pushMessagesFully();
```

Optionally, you could spread the *pushing* over the course of your work by doing the following:

```
int cycleCount = 0;
int cycleLimit = 10;
for (int i = 0; i < someLoopLength; ++i){
    //
    // Do some work
    //
    lj.queueMessage("This message will combine")
    ++cycleCount;
    if (cycleCount > cycleLimit) {
        // Incrementally push messages through system
        lj.pushMessagesOnce();
        cycleCount = 0;
    }
}
```

Once you are ready to retrieve your messages, do so by the following:

```
// Determine if this is an output node
if (lj.isOutputNode()){
    // Get Messages from Lumberjack
    std::vector<axom::lumberjack::Message*> messages = lj.getMessages();
    for(int i=0; i<(int)(messages.size()); ++i){
        // Output a single Message at a time to screen
        std::cout << "(" << messages[i]->stringOfRanks() << ") " << messages[i]->
↪count() <<
                     " '" << messages[i]->text() << "'" << std::endl;
    }
    // Clear already outputted Messages from Lumberjack
    lj.clearMessages();
}
```

Finalize Lumberjack, the Lumberjack Communicator and MPI in the following order to guarantee nothing goes wrong:

```
// Finalize lumberjack
lj.finalize();
// Finalize the lumberjack communicator
communicator.finalize();
// Finalize MPI
MPI_Finalize();
```

Lumberjack Class

The Lumberjack class is where all high-level functionality of the library is done, such as adding, retrieving, and combining messages and telling the given Communicator to push Messages through the communication scheme. You can also add and remove Combiner classes, as well as tell if the current node is supposed to output any messages.

Functions

General

Name	Description
initialize	Starts up Lumberjack. Must be called before anything else.
finalize	Cleans up Lumberjack. Must be called when done with Lumberjack.
isOutputNode	Returns whether this node should output messages.
ranksLimit	Sets the limit on individually tracked ranks
ranksLimit	Gets the limit on individually tracked ranks

Combiners

Name	Description
addCombiner	Adds a combiner to Lumberjack
removeCombiner	Removes a specific combiner from Lumberjack
clearCombiners	Removes all currently registered Combiners from Lumberjack

Messages

Name	Description
clearMessages	Delete all Messages currently held by this node.
getMessages	Get all Messages currently held by this node.
queueMessage	Adds a Message to Lumberjack
pushMessagesOnce	Moves Messages up the communication scheme once
pushMessagesFully	Moves all Messages through the communication scheme to the output node.

Message Class

The Message class holds the information about a single message or multiple messages that were combined via a Combiner instance.

Information

The Message class contains the following information. All fields have their respective getters and setters.

Name	Description
text	Contents of the message
ranks	Truncated list of where the message originated
count	Total count of how many individual messages occurred
fileName	File name that generated the message
lineNumber	Line number that generated the message
level	Message severity (error, warning, debug, etc.)
tag	Tag for showing what part of the code generated the message

Functions

The Message class also contains the following helper functions to ease use of the class.

Name	Description
stringOfRanks	Returns a string of the ranks
pack	Returns a packed version of all the message's information
unpack	Takes a packed message and overwrites all the message's information
addRank	Add a rank to the message to the given limit
addRanks	Add ranks to the message to the given limit

Communicator Class

The Communicator class is an abstract base class that defines the interface for all Communicator classes. Concrete instances need to inherit from this class and implement these functions to be used when the Lumberjack class does any communication work.

Functions

Name	Description
initialize	Starts up the Communicator. Must be called before anything else.
finalize	Cleans up the Communicator. Must be called when finished.
rank	Returns the rank of the current node.
ranksLimit	Getter/Setter for the limit on individually stored ranks.
numPushesToFlush	Returns the number of individual pushes to completely flush all Messages.
push	Pushes all currently held Messages once up structure.
isOutputNode	Returns whether this node should output messages.

Concrete Instances

BinaryTreeCommunicator

Note: This is the recommended Communicator.

This Communicator uses a standard Binary Tree design to scalably pass Messages between nodes. Rank 0 is the root of the Binary Tree and the only node allowed to output messages. For each single push, the child nodes send

their currently held messages to their parents without waiting to receive messages themselves. For a full push, this communicator takes the log of nodes to completely flush all currently held messages to the root node.

RootCommunicator

Note: This Communicator is useful for debugging purposes, but will not scale as well as the recommended BinaryTreeCommunicator.

This Communicator has all nodes directly connecting to the root node which is rank 0. The root node is the only node allowed to output messages. Each single push, the child nodes send their currently held messages to the root. After each push the tree is completely flushed.

Combiner Class

The Combiner class is an abstract base class that defines the interface for all Combiner classes. Concrete instances need to inherit from this class and implement these functions to be used when Message classes are combined by the Lumberjack class.

Functions

Name	Description
id	Returns the unique differentiating identifier for the class instance.
shouldMessagesBeCombined	Indicates if two messages should be combined.
combine	Combines the second message into the first.

Concrete Instances

TextEqualityCombiner

Note: This is the only Combiner automatically added to Lumberjack for you. You can remove it by calling Lumberjack::removeCombiner("TextEqualityCombiner").

This Combiner combines the two given Messages if the Message text strings are equal. It does so by adding the second Message's ranks to the first Message (if not past the ranksLimit) and incrementing the Message's count as well. This is handled by Message.addRanks().

2.3 Sidre User Documentation

The Sidre (Simulation data repository) component of Axom provides tools to centralize data management in HPC applications: data description, allocation, access, and so forth. The goal of Sidre is efficient coordination and sharing of data: across physics packages in integrated applications, and between applications and tools that provide capabilities such as file I/O, *in situ* visualization, and analysis.

The design of Sidre is based on substantial experience with current LLNL applications and requirements identified for new codes to run on future architectures. All of these codes must carefully manage data allocation and placement to run efficiently. Related capabilities in existing codes were typically developed independently for each code with little regard to sharing. In contrast, Sidre is designed from inception to be shared by different applications.

2.3.1 Introduction

Sidre provides simple application-level semantics to describe, allocate/deallocate, and provide access to data. Currently supported capabilities include:

- Separate data description and allocation operations. This allows applications to describe their data and then decide how best to place the data in memory.
- Multiple different "views" into a chunk of (shared) data. A Sidre view includes description semantics to define data type, number of elements, offset, stride, etc. Thus, a chunk of data in memory can be interpreted conceptually in different ways using different views into it.
- Externally-owned "opaque" or described data. Sidre can accept a pointer to externally-allocated data and provide access to it by name. When external data is described to Sidre, it can be processed in the same ways as data that Sidre owns. When data is not described (i.e., it is "opaque"), Sidre can provide access to the data via a pointer, but the consumer of the pointer must know type information to do anything substantial with the data.
- Attributes, or metadata associated with a Sidre view. This metadata is available to user code to facilitate program logic and is also used in Axom to enable selective writing data sets to files.
- Tree-structured data hierarchies. Many mesh-based application codes organize data into hierarchies of contexts (e.g., domains, regions, blocks, mesh centerings, subsets of elements containing different materials, etc.). Sidre supports hierarchical, tree-based organizations in a simple, flexible way that aligns with the data organization in many applications.
- APIs for C++, C, and Fortran along with mechanisms to ensure inter-language data consistency.

So far, Sidre development has focused on designing and building flexible and powerful concepts to build on. The Sidre API includes five main concepts:

- **Datastore.** The main access point to data managed by Sidre; it contains a collection of Buffers, a collection of default Attributes, and a tree structure of Groups.
- **Buffer.** Describes and holds a chunk of data in memory owned by Sidre.
- **Group.** Defines a tree structure like a filesystem, where Groups are like folders and Views are like files.
- **View.** Describes a conceptual layout of data in memory. Each View has a collection of its explicitly-set Attributes.
- **Attribute.** Provides an item of metadata describing a View.

These concepts will be described in more detail in later sections.

At this point, Sidre supports simple data types such as scalars, strings, and (multidimensional) arrays of scalars. Fundamentally, Sidre does not preclude the use of more complex data structures, but does not currently support them directly. Future Sidre development will expand core functionality to support additional features such as:

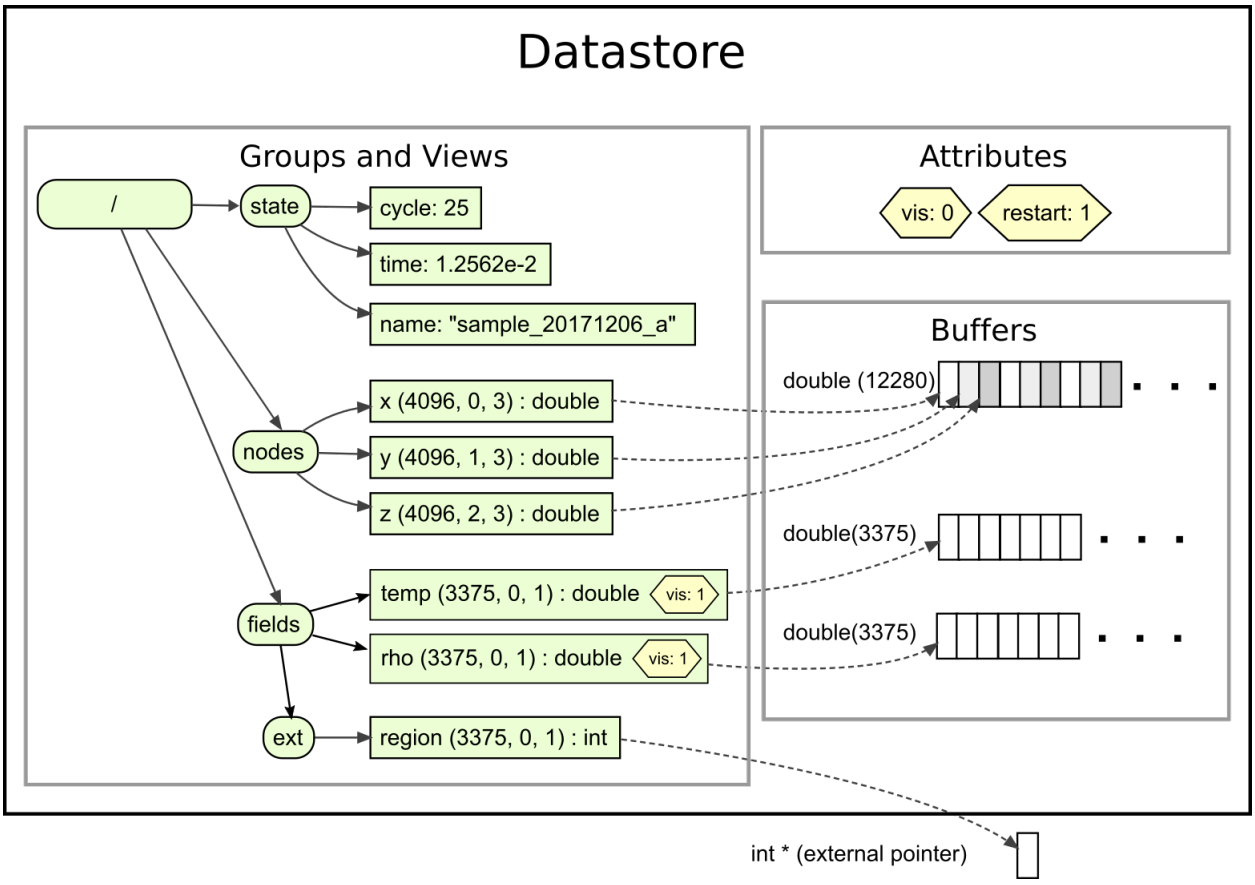
- Mechanisms to associate data with memory spaces and transfer data between spaces.
- Support for more complex data types.
- Complex queries and actions involving Attributes.

Support for these enhancements and others will be added based on application needs and use cases.

Contents:

An introductory example

As an introduction to the core concepts in Sidre and how they work, here is an example where we construct the Sidre Datastore shown in the following figure:



Symbol	Sidre class
rounded rectangle	Group
rectangle	View
hexagon	Attribute

The diagram represents a Datastore, which contains all Sidre objects and provides the main interface to access those objects. Rounded rectangles represent Sidre Group objects. Each Group has a name and one parent Group, except for the root Group (i.e. "/") which has no parent. A Group may have and zero or more child Groups (indicated by an arrow from the parent to each child). The Datastore provides exactly one root Group (i.e. "/") which is created when a Datastore object is constructed; thus, an application does not create the root. Each Group also owns zero or more View objects, which are shown as rectangles. An arrow points from a Group to each View it owns.

A Sidre View object has a name and, typically, some data associated with it. This example shows various types of data that can be described by a View, including scalars, strings, and data in arrays (both externally allocated and owned by Sidre Buffer objects). Each array View has a data pointer and describes data in terms of data type, number of elements, offset, and stride. Data pointers held by array Views are shown as dashed arrows.

A Datastore contains a collection of Buffer objects, shown as segmented rectangles.

A Datastore contains a list of Attributes. Each Attribute is outlined with a hexagon and defines a metadata label and a default value associated with that label. In this example, the Datastore has Attributes "vis" (with default value 0) and "restart" (with default value 1). Default Attributes apply to all Views unless explicitly set for individual Views. In this example, the Views "temp" and "rho" have the Attribute "vis" set to 1.

Various aspects of Sidre usage are illustrated in the C++ code shown next. Sidre provides full C and Fortran APIs that can also be used to generate the same result.

First, we create a Datastore object, define some Attributes along with their default values, and add some child Groups to the root Group.

```
// Create Sidre datastore object and get root group
DataStore* ds = new DataStore();
Group* root = ds->getRoot();

// Create two attributes
ds->createAttributeScalar("vis", 0);
ds->createAttributeScalar("restart", 1);

// Create group children of root group
Group* state = root->createGroup("state");
Group* nodes = root->createGroup("nodes");
Group* fields = root->createGroup("fields");
```

The `Group::createViewScalar()` method lets an application store scalar values in Views owned by a Group.

```
// Populate "state" group
state->createViewScalar("cycle", 25);
state->createViewScalar("time", 1.2562e-2);
state->createViewString("name", "sample_20171206_a");
```

This example stores (x, y, z) node position data in one array. The array is managed through a Buffer object and three Views point into it. C++ Sidre operations that create Buffers, Groups, and Views, as shown in the following code, return a pointer to the object that is created. This allows chaining operations. (Chaining is supported in the C++ API but not in C or Fortran.)

```
int N = 16;
int nodecount = N * N * N;
int eltcount = (N-1) * (N-1) * (N-1);

// Populate "nodes" group
//
// "x", "y", and "z" are three views into a shared Sidre buffer object that
// holds 3 * nodecount doubles.  These views might describe the location of
// each node in a 16 x 16 x 16 hexahedron mesh.  Each view is described by
// number of elements, offset, and stride into that data.
Buffer* buff = ds->createBuffer(sidre::DOUBLE_ID, 3*nodecount)->allocate();
nodes->createView("x", buff)->apply(sidre::DOUBLE_ID, nodecount, 0, 3);
nodes->createView("y", buff)->apply(sidre::DOUBLE_ID, nodecount, 1, 3);
nodes->createView("z", buff)->apply(sidre::DOUBLE_ID, nodecount, 2, 3);
```

The last two integral arguments to the 'createView()' method specify the offset from the beginning of the array and the stride of the data. Thus, the x, y, z values for each position are stored contiguously with the x values, y values, and z values each offset from each other by a stride of three in the array.

The next snippet creates two views ("temp" and "rho") and allocates each of their data as an array of type double with length 'eltcount'. Then, it sets an Attribute ("vis") on each of those Views with a value of 1. Lastly, it creates a Group ("ext") that has a View that holds an external pointer ("region"). The 'apply()' method describes the View data as an

array of integer type and length 'eltcount'. Note that it is the responsibility of the caller to ensure that the allocation to which the "region" pointer references is adequate to contain that data description.

```
// Populate "fields" group
//
// "temp" is a view into a buffer that is not shared with another View.
// In this case, the data Buffer is allocated directly through the View
// object.  Likewise with "rho."  Both Views have the default offset (0)
// and stride (1).  These Views could point to data associated with
// each of the 15 x 15 x 15 hexahedron elements defined by the nodes above.
View* temp =
  fields->createViewAndAllocate("temp", sidre::DOUBLE_ID, eltcount);
View* rho =
  fields->createViewAndAllocate("rho", sidre::DOUBLE_ID, eltcount);

// Explicitly set values for the "vis" Attribute on the "temp" and "rho"
// buffers.
temp->setAttributeScalar("vis", 1);
rho->setAttributeScalar("vis", 1);

// The "fields" Group also contains a child Group "ext" which holds a pointer
// to an externally owned integer array.  Although Sidre does not own the
// data, the data can still be described to Sidre.
Group* ext = fields->createGroup("ext");
// int * region has been passed in as a function argument.  As with "temp"
// and "rho", view "region" has default offset and stride.
ext->createView("region", region)->apply(sidre::INT_ID, eltcount);
```

The next code example shows various methods to retrieve Groups and data out of Views in the Group hierarchy.

```
// Retrieve Group pointers
Group* root = ds->getRoot();
Group* state = root->getGroup("state");
Group* nodes = root->getGroup("nodes");
Group* fields = root->getGroup("fields");

// Accessing a Group that is not there gives a null pointer
// Requesting a nonexistent View also gives a null pointer
Group* goofy = root->getGroup("goofy");
if (goofy == nullptr)
{
  std::cout << "no such group: goofy" << std::endl;
}
else
{
  std::cout << "Something is very wrong!" << std::endl;
}

// Access items in "state" group
int cycle = state->getView("cycle")->getScalar();
double time = state->getView("time")->getScalar();
const char* name = state->getView("name")->getString();

// Access some items in "nodes" and "fields" groups
double* y = nodes->getView("y")->getArray();
int ystride = nodes->getView("y")->getStride();
double* temp = fields->getView("temp")->getArray();
int* region = fields->getView("ext/region")->getArray();
```

(continues on next page)

(continued from previous page)

```
// Nudge the 3rd node, adjust temp and region of the 3rd element
y[2 * ystride] += 0.0032;
temp[2] *= 1.0021;
region[2] = 6;
```

In the last section, the code accesses the arrays associated with the views "y", "temp", and "region". While "temp" and "region" have the default offset (0) and stride (1), "y" has offset 1 and stride 3 (as described earlier). The pointer returned by `View::getPointer()` always points to the first data element described by the View (the View takes care of the offset), but use of a stride other than 1 must be done by the code itself.

Unix-style path syntax using the slash ("/") delimiter is supported for traversing Sidre Group and View hierarchies and accessing their contents. However, '..' and '.' syntax (up-directory and current directory) is not supported. This usage is shown in the last call to `getView()` in the code example above. The method call retrieves the View named "region" in the Group "ext" that is a child of the "fields" Group. Character sequences before the first slash and between two consecutive slashes are assumed to be Group names (describing parent-child relationships). For this method, and others dealing with Views, the sequence following the last slash is assumed to be the name of a View. Similar path syntax can be used to retrieve Groups, create Groups and Views, and so forth.

Core concepts

Sidre provides five main classes: Datastore, Buffer, Group, View, and Attribute. In combination, these classes implement a data store with a tree structure to organize data in a hierarchy:

- DataStore is the main interface to access a data hierarchy.
- Buffer describes and holds data in memory.
- Group defines parent-child relationships in a hierarchical tree data structure and provides access to file I/O operations.
- View provides a virtual description of data and access to it.
- Attribute allows a program to attach metadata to View objects for processing data selectively.

The following sections summarize the main interface features and functionality of these Sidre classes.

Note: Interfaces for each of these classes are provided natively in C++, C, and Fortran.

DataStore

A Sidre DataStore object provides the main access point for Sidre contents, including the data managed by Sidre. In particular, a DataStore maintains the group at the root of the Sidre group hierarchy, a collection of Buffer objects, and a collection of Attribute objects. Generally, the first thing a Sidre user does is create a DataStore; this operation also creates the root group. Apart from providing access to the root group, a DataStore object provides methods to interact with Buffer and Attribute objects.

Note: Buffer and Attribute objects can only be created and destroyed using DataStore methods noted below. Their constructors and destructors are private.

DataStore methods for Buffers support the following operations:

- Create, destroy, and allocate data in Buffer objects

- Query the number of Buffers that exist
- Query whether a Buffer exists with given id
- Retrieve Buffer with given id
- Iterate over the set of Buffers in a DataStore

Please see *Buffer* for more information about using Buffer objects.

DataStore methods for Attributes support the following operations:

- Create and destroy Attributes
- Query the number of Attributes that exist
- Query whether an Attribute exists with given name or id
- Retrieve Attribute with given name or id
- Iterate over the set of Attributes in a DataStore

Please see *Attribute* for more information about using Attribute objects.

Buffer

A Sidre Buffer object holds an array of data *described* by a data type and length. The data owned by a Buffer is unique to that Buffer object; i.e., Buffer objects do not share data.

A Buffer can be created without a data description and then described later in a separate operation, or it can be described when it is created. In either case, data description and allocation are distinct operations. This allows an application to create buffers it needs, then assess the types and amount of data they will hold before deciding how and when to allocate data.

Note:

- Buffer objects can only be created and destroyed using DataStore methods. The Buffer constructor and destructor are private (see *DataStore*).
- Each Buffer object has a unique integer identifier generated when it is created. If you want to interact with a Buffer object directly, you must keep a pointer to it or note its id so that you can retrieve it from the DataStore when needed.

Buffer objects are used to hold data for Sidre View objects in most cases. Each Buffer object maintains references to the Views that refer to its data. These references are created when a Buffer object is attached to a View, or data is allocated through a View. Data stored in a Buffer may be accessed through a View object or through the Buffer directly. See *View* for more information about Views.

The Buffer interface includes the following operations:

- Retrieve the unique id of the Buffer object.
- Query whether a Buffer is *described* or *allocated*.
- Describe Buffer data (type and number of elements).
- Allocate, reallocate, deallocate Buffer data.
- Copy a given number of bytes of data from a given pointer to a Buffer allocation.
- Get data held by a Buffer as a pointer or conduit::Node::Value type.

- Get information about data held by a Buffer: type, number of elements, total number of bytes, number of bytes per element, etc.
- Retrieve the number of Views the Buffer is attached to.
- Copy Buffer description and its data to/from a conduit::Node.

Group

Sidre Group objects are used to define a tree-like hierarchical organization for application data, such as meshes and fields used in a simulation. Each Group has a name and one parent Group (except for the root Group) and contains zero or more child Groups and zero or more Views. A Sidre DataStore has exactly one root Group which is created when the DataStore object is created. The root Group's name is initially the empty string. See *DataStore* for more information.

A Group hierarchy is constructed by creating Groups that are children of the root Group, children of those Groups, and so on. All Groups in a subtree rooted at a particular Group are considered descendants of that Group. View objects can be created in Groups to hold or provide access to data.

Note: Group and View objects can only be created and destroyed using Group methods provided for this. The Group and View constructors and destructors are private.

A Group or View object is owned by the Group that created it; i.e., its parent Group or *owning* Group, respectively. Groups and Views maintain pointers to their parent/owning Group. Thus, one may *walk* up or down a Group hierarchy to access different Groups and Views in it.

Note:

- The name (string) of a Group or View **must be unique** within its parent/owning Group.
- A Group or View has a unique integer identifier within its parent/owning group, which is generated when it is created.
- Views and child Groups in a Group can be accessed by name or integer id.

A Group object can be moved or copied to another Group. When a Group is moved to another Group, it is removed from its original parent and the Group to which it is moved becomes its parent. This implies that the entire subtree of Groups and Views within the moved Group is moved as well and can no longer be accessed via the original parent Group. When a Group is copied to another Group, a copy of the entire Group subtree rooted at the copied Group is added to the Group to which it is copied. A **shallow** copy is performed for the data in each View; i.e., a new View object is created in the destination, but the data is shared by the original and new View.

Note: View copy operations perform **shallow** copies of the View data.

Some methods for creating, destroying, querying, and retrieving Groups and Views take a string with *path syntax*, where parent and child Group names are joined with the path separator character, '/'. Other methods take the name of an immediate child of a Group. Methods that require the name of a direct child are marked with 'Child' in their name, such as `hasChildView()` and `hasChildGroup()`. When a path string is passed to a method that accepts path syntax, the last item in the path indicates the item to be created, destroyed, accessed, etc. For example,:

```
View* view = group->createView("foo/bar/baz");
```

is equivalent to:

```
View* view = group->createGroup("foo")->createGroup("bar")->createView("baz");
```

In particular, intermediate Groups "foo" and "bar" will be created in this case if they don't already exist. The path syntax is similar to a Unix filesystem, but the path string **may not** contain the parent entry (such as "../foo").

Methods to Operate on Groups

The following lists summarize Group methods that support operations related to Group objects.

Note:

- Methods that access Groups by index only work with the direct children of the current Group because an id has no meaning outside of the indexing of the current group. None of these methods is marked with 'Child' in its name.
- When Groups are created, destroyed, copied, or moved, ids of other Views and Groups in parent Group objects may become invalid. This is analogous to iterator invalidation for containers when the container contents change.

Create, Modify, and Destroy Groups

- Create a child Group given a name (child) or path (other descendant). If a path is given, intermediate Groups in path are created, if needed.
- Rename a Group. A Group cannot be renamed to the empty string, to a string containing the path separator character, or to the name of another Group or View owned by the same parent.
- Destroy a descendant Group with given id (child), or name/path (child or other descendant).
- Destroy all child groups in a Group.

Note: When a Group is destroyed, all Groups and Views in the subtree rooted at the destroyed Group are also destroyed. However, the data associated with those Views will remain intact.

Group Properties

- Retrieve the name or id of a Group object.
- Retrieve the full path name from the root of the tree to a Group object.
- Get a pointer to the parent Group of a Group.
- Query the number of child Groups of a Group.
- Query whether a Group has a descendant Group with a given name or path.
- Query whether a Group has a child Group with a given integer id.
- Query the name of a child Group with a given id, or the id of a child Group with a given name.
- Get a pointer to the DataStore that owns the hierarchy in which a Group resides.

Group Access

- Retrieve an immediate child Group with a given name or id, or a descendant Group with a given path.
- Iterate over the set of child Groups in a Group.

Move and Copy Groups

- Move a Group, and its associated subtree, from its parent Group and make it a child of another Group.
- Create a copy of Group subtree rooted at some Group and make it a child of another Group.
- Query whether Group subtree is equivalent to another; i.e., identical subtree structures with same names for all Groups and Views, and Views are also equivalent (see *View Property Operations*).

Methods to Operate on Views

The Group methods that support operations related to View objects are summarized below. For more details on View concepts and operations, please see *View*.

Note: Methods that access Views by index work only with the Views owned by the current Group because an id has no meaning outside of the indexing of the current group. None of these methods is marked with 'Child' in its name.

Create Views

- Create a View in the Group with a name only.
- Create a View in the Group with a name and data description.
- Create a View in the Group with a name and with a Buffer attached. The View may or may not have a data description.
- Create a View in the Group with a name and an external data pointer. The data may or may not be described.
- Create a View in the Group with a name and data description, and allocate the data. Implicitly the data is held in a Buffer that is attached to the View.
- Create a View in the Group with a name holding a given scalar or string.

Destroy Views

- Destroy View with given id (child), or name/path (View in the Group or some descendant Group), and leave View data intact.
- Destroy all Views in the Group, and leave their data intact.
- Destroy View with given id, or name/path, and destroy their data.
- Destroy all Views in the Group and destroy their data.

View Queries

- Query the number of Views in a Group.
- Query whether a Group subtree has a View with a given name or path.
- Query whether a Group has a View with a given integer id.
- Query the name of a View with a given id, or the id of a View with a given name.

View Access

- Retrieve a View with a given name or id, or a descendant View (somewhere in the subtree) with a given path.
- Iterate over the set of Views in a Group.

Move and Copy Views

- Move a View from its owning Group to another Group (removed from original owning Group).
- Copy a View to another Group. Note that this is **shallow** copy of the View data; i.e., it is shared by the original and new View.

Group I/O Operations

The Group interface provides methods to perform data I/O operations on Views in the Group subtree rooted at any Group.

- Copy a description of a Group subtree to a conduit::Node.
- Create native and external data layouts in conduit::Node hierarchies (used mainly for I/O operations)
- Save and load Group subtrees, including data in associated Views, to and from files. A variety of methods are provided to support different I/O operations, different I/O protocols, etc.

I/O methods on the Group class use Conduit to *write the data (sub)tree* rooted in a Group to a file, HDF5 handle, or other Conduit protocol, or to an in-memory Conduit data structure. An application may provide an Attribute to the method call, so only Views with that Attribute explicitly set will be written. See *Parallel File I/O* for more information.

View

A Sidre View describes data and provides access to it. A View can describe a (portion) of a data allocation in **any way that is compatible** with the allocation. Specifically, the allocation must contain enough bytes to support the description. In particular, the data type of a View description need not match the types associated with the allocation employed by other Views into that data.

Note: View objects can only be created and destroyed using Group methods provided for this. The View constructor and destructor are private.

Each View object has a name and is owned by one Group in a Sidre Group hierarchy; its *owning* Group. A View maintains a pointer to the Group that owns it.

Note:

- The name (string) of a View **must be unique** within its owning Group.
- A View has a unique integer identifier within its owning group, which is generated when the View is created.
- Views in a Group can be accessed by name or integer id.

A View object can describe and provide access to data referenced by a pointer in one of four ways described below. In that case, a View data description includes: a data type, a length (number of elements), an offset and a stride (based on the pointer address and data type).

- A View can describe (a subset of) data owned by a pre-existing Buffer. In this case, the Buffer is manually *attached* to the View and the View's data description is applied to the Buffer data. Buffer data can be (re)allocated or deallocated by the View if and only if it is the only View attached to the Buffer. **In general, a Buffer can be attached to more than one View.**
- A View description can be used to allocate data for View using a View `allocate()` method similar to Buffer data description and allocation (see *Buffer*). In this case, the View is usually exclusively associated with a Buffer and no other View is allowed to (re)allocate or deallocate the data held by the Buffer.
- A View can **describe** data associated with a pointer to an *external* data allocation. In this case, the View cannot (re)allocate or deallocate the data. However, all other View operations can be applied to the data in essentially the same ways as the previous two cases.
- A View can hold a pointer to an undescribed (*opaque*) data pointer. In this case, the View knows nothing about the type or structure of the data; it can only provide access to it. A user is entirely responsible for casting the pointer to a proper type, knowing the size of the data, etc.

A View may also refer to a scalar quantity or a string. Such Views hold their data differently than the pointer cases described above.

Before we describe the Sidre View interface, we present some View concepts that describe various *states* a View can be in at any given time. Hopefully, this will provide some useful context for the method descriptions that follow.

The key View concepts that users should be aware of are:

- View data description (data type, number of elements, stride, offset, etc.)
- View data association (data lives in an attached Sidre Buffer object, accessed via external pointer, or is a scalar or string owned by the View)
- Whether the View data description is applied to the data

The table below summarizes View data associations (rows) and View states with respect to that data (columns).

The three View data state methods at the tops of columns and their return values are:

- **isDescribed()** returns true if a View has a data description, and false otherwise.
- **isAllocated()** returns true if a View is associated with data, such as a non-null pointer, and false otherwise.
- **isApplied()** returns true if the View has a data description and is associated with data that is compatible with that description, and the description has been applied to the data; otherwise false is returned.

The rows indicate data associations; the View interface has methods to query these as well; e.g., isEmpty(), hasBuffer(), etc. The associations are:

- **EMPTY.** A View with no associated data; the View may or may not have a data description.
- **BUFFER.** A View with an attached buffer; the View may or may not have a data description and the Buffer may or may not be allocated and the description (if View has one) may or may not be applied to the Buffer data (if allocated).
- **EXTERNAL.** A View has a non-null pointer to external data; the View may or may not have a data description and the description (if View has one) may or may not be applied to the external data.

	isDescribed()	isAllocated()	isApplied()
EMPTY	**True:** view has data description **False:** view has no data description	**False**	**False**
BUFFER	**True:** view has buffer and data description **False:** view has buffer and no data description	**True:** view's buffer is allocated **False:** view's buffer is not allocated	**True:** view's description is applied to buffer data **False:** if view has a description, it is not applied to buffer data
EXTERNAL	**True:** view has non-null external data ptr and data description **False:** view has non-null external data ptr and no data description	**True:** view has non-null external data ptr	**True:** view's description is applied to non-null external data ptr **False:** if view has a description, it is not applied to buffer data
SCALAR	**True**	**True**	**True**
STRING	**True**	**True**	**True**

Fig. 2.2: This table summarizes Sidre View *data associations* and *data states*. Each row is a data association and each column refers to a data state. The True/False entries in the cells indicate return values of the View methods at the tops of the columns. The circumstances under which those values are returned are noted as well.

- **SCALAR.** View was created to hold a scalar value; such a View always has a valid data description, is allocated, and description is applied.
- **STRING.** View was created to hold a string; such a View always has a valid data description, is allocated, and description is applied.

Note that there are specific consequences that follow from each particular association/state that a View is in. For example, an EMPTY View cannot have an attached Buffer. Neither can an EXTERNAL, SCALAR or STRING View. A View that is EMPTY, BUFFER, SCALAR, or STRING cannot be EXTERNAL. Etc.

The following lists summarize the parts of the View interface:

Note: Most View methods return a pointer to the View object on which the method is called. This allows operations to be chained; e.g.,

```
View* view = ...;
view->describe(...)->allocate(...)->apply();
```

View Property Operations

- Retrieve the name or id of the View object.
- Retrieve the View path name from the root of the tree or the path to the Group that owns it.
- Get a pointer to the Group that owns the View.

- Is View equivalent to another View; i.e., are names and data descriptions the same?
- Rename a View.

Data Association Queries

- Is View empty?
- Does View have a Buffer attached?
- Is View associated with external data?
- Is it a scalar View?
- Is it a string View?

Data State Queries

- Does View have a data description?
- Is View data allocated?
- Is View data description applied to data?
- Is View opaque; i.e., it has an external pointer and no description?

Data Description Queries

- Get type of data.
- Get total number of bytes.
- Get number of elements (total bytes / size of type).
- Get number of bytes per data element (for type).
- Get data offet.
- Get data stride.
- Get number of dimensions and shape of multi-dimensional data.
- Get a conduit::Schema object that contains the View data description.

Data Management Operations

- Allocate, reallocate, and deallocate View data.
- Attach Buffer to View (with or without data description), and detach Buffer from View.
- Apply current View description to data or apply a new description.
- Set View scalar value.
- Set View string.
- Set external data pointer, with or without a data description.

Data Access Methods

- Get a pointer to View data, actual type or void*.
- Get scalar value for a scalar View.
- Retrieve pointer to Buffer attached to View.
- Get a conduit::Node object that holds the View data.

Attribute Methods

- Query whether View has an Attribute with given id or name.
- Get Attribute associated with a View by id or name.
- Query whether Attribute has been set explicitly for View.
- Reset Attribute with given id or name to its default value.
- Set Attribute with given id or name to a given scalar value or string.
- Retrieve scalar value or string of an Attribute.
- Iterate over Attributes of a View.

I/O Operations

- Copy View data description to a conduit::Node.

Attribute

Sidre Attributes enable attaching metadata (strings and values) to Sidre Views to support queries (e.g., search for Views with a given attribute name), outputting data for a subset of Views to files, and other ways an application may need to selectively process Views in a Sidre DataStore hierarchy.

An Attribute is created with a string name and a default scalar or string value. A default value can be changed later as needed.

Note:

- Attribute objects can only be created and destroyed using DataStore methods. The Attribute constructor and destructor are private (see *DataStore*).
- Each Attribute has a unique name and integer identifier. Either can be used to retrieve it from the DataStore.

Each Sidre View inherits all Attributes contained in the DataStore at their default strings or values. Then, an application may explicitly set any Attribute on a View. The application may also query the value of a View Attribute, query whether the Attribute was explicitly set, or set the Attribute back to its default value. See *View* for more information about Views.

The Attribute interface includes the following operations:

- Retrieve the name and unique id of the Attribute object.
- Set the scalar or string value of an Attribute.
- Get the type of an Attribute's scalar value.

Serial File I/O

Sidre provides for file I/O to HDF5 files and file handles and to JSON files. Serial I/O is accomplished using methods of the Group class; parallel I/O is done using the IOManager class.

HDF5 is an optional dependency for Sidre. Sidre APIs that rely on HDF5 will be available only if Sidre was compiled with HDF5 support. The symbol that controls dependency on HDF5 is `AXOM_USE_HDF5`, defined in the source file axom/config.hpp.

File I/O using Group class

The Group class contains the `save()`, `load()`, and `loadExternalData()` methods. Each method can be called with a file name or an HDF5 handle. The `save()` and `load()` methods allow the code to specify a protocol, specifying how the operation should be performed and what file format should be used. The `loadExternalData()` method takes no protocol argument since it is only used with the sidre_hdf5 protocol. The `save()` method can also take a pointer to an Attribute object. If that Attribute pointer is null, all Views are saved, but if an Attribute pointer is provided, only Views with that Attribute explicitly set will be saved.

Insert a link to Doxygen for Group, and mention that protocols are listed here.

The `load()` method retrieves the hierarchical data structure stored in the file or pointer, and instantiates Groups, Views and Attributes to represent the structure rooted in this Group. By default, the contents of this Group are destroyed prior to reading the file's contents. This can be suppressed by passing true as the preserve_contents argument to `load()`, resulting in the current Group's subtree being merged with the file's contents.

Usage of `save()` and `load()` is shown in the following example.

```
// Save the data store to a file, using the default sidre_hdf5 protocol,
// saving all Views
ds->getRoot()->save("example.hdf5");
// Delete the data hierarchy under the root, then load it from the file
ds->getRoot()->load("example.hdf5");
Group* additional = ds->getRoot()->createGroup("additional");
additional->createGroup("yetanother");
// Load another copy of the data store into the "additional" group
// without first clearing all its contents
std::string groupname;
additional->load("example.hdf5", "sidre_hdf5", true, groupname);
```

The `loadExternalData()` method is used to read "external" data from an HDF5 file created with the sidre_hdf5 protocol. This is data referred to by Views that is not stored in Sidre Buffers but in a raw pointer.

The overloads of `save()` and `load()` that take HDF5 handles and the `loadExternalData()` method are public APIs that are used to implement parallel I/O through the IOManager class.

Parallel File I/O

The Sidre IOManager class provides an interface to manage parallel I/O of the data managed by Sidre. It enables the writing of data from parallel runs and can be used for the purposes of restart or visualization.

Introduction

The IOManager class provides parallel I/O services to Sidre. IOManager relies on the fact that Sidre's Group and View objects are capable of saving and loading themselves. These I/O operations in Sidre are inherently serial, so IOManager coordinates the I/O operations of multiple Sidre objects that exist across the MPI ranks of a parallel run.

- The internal details of the I/O of individual Sidre objects are opaque to IOManager, which needs only to make calls to the I/O methods in Sidre's public API.
- Sidre data is written from M ranks to N files (M >= N), and the files can be read to restart a run on M ranks.
- When saving output, a root file is created that contains some bookkeeping data that is used to coordinate a subsequent restart read.
- The calling code can also add extra data to the root file to provide metadata that gives necessary instructions to visualization tools.

Parallel I/O using IOManager class

To accomplish parallel I/O, Sidre provides the IOManager class. This class is instantiated with an MPI communicator and provides several overloads of the `write()` and `read()` methods. These methods save a Group in parallel to a set of files and read a Group from existing files. IOManager optionally uses the SCR library for scalable I/O management (such as using burst buffers if available).

In typical usage, a run that calls `read()` on a certain set of files should be executed on the same number of MPI ranks as the run that created those files with a `write()` call. However, if using the "sidre_hdf5" protocol, there are some usage patterns that do not have this limitation.

A `read()` call using "sidre_hdf5" will work when called from a greater number of processors. If `write()` was executed on N ranks and `read()` is called while running on M ranks (M > N), then data will be read into ranks 0 to N-1, and all ranks higher than N-1 will receive no data.

If `read()` is called using "sidre_hdf5" to read data that was created on a larger number of processors, this will work only in the case that the data was written in a file-per-processor mode (M ranks to M files). In this case the data in the Group being filled with file input will look a bit different than in other usage patterns, since a Group on one rank will end up with data from multiple ranks. An integer scalar View named `reduced_input_ranks` will be added to the Group with the value being the number of ranks that wrote the files. The data from each output rank will be read into subgroups located at `rank_{%07d}/sidre_input` in the input Group's data hierarchy.

> **Warning:** If `read()` is called to read data that was created on a larger number of processors than the current run with files produced in M-to-N mode (M > N), an error will occur. Support for this type of usage is intended to be added in future releases.

In the following example, an IOManager is created and used to write the contents of the Group "root" in parallel.

First include needed headers.

```
#include "axom/config.hpp"   // for AXOM_USE_HDF5

#include "conduit_relay.hpp"

#ifdef AXOM_USE_HDF5
#include "conduit_relay_io_hdf5.hpp"
#endif

#include "axom/sidre/core/sidre.hpp"
#include "axom/sidre/spio/IOManager.hpp"
#include "fmt/fmt.hpp"

#include "mpi.h"
```

Then use IOManager to save in parallel.

```
  /*
   * Contents of the DataStore written to files with IOManager.
   */
  int num_files = num_output;
  axom::sidre::IOManager writer(MPI_COMM_WORLD);

  const std::string file_name = "out_spio_parallel_write_read";

  writer.write(root, num_files, file_name, PROTOCOL);

  std::string root_name = file_name + ROOT_EXT;
```

Loading data in parallel is easy:

```
  /*
   * Create another DataStore that holds nothing but the root group.
   */
  DataStore* ds2 = new DataStore();

  /*
   * Read from the files that were written above.
   */
  IOManager reader(MPI_COMM_WORLD);


  reader.read(ds2->getRoot(), root_name);
```

IOManager class use

An IOManager is constructed with an MPI communicator and does I/O operations on all ranks associated with that communicator

The core functionality of IOManager is contained in the `write()` and `read()` methods.

```
void write(sidre::DataGroup * group,
           int num_files,
           const std::string& file_string,
           const std::string& protocol);
```

`write()` is called in parallel with each rank passing in a Group pointer for its local data. The calling code specifies the number of output files, and IOManager organizes the output so that each file receives data from a roughly equal number of ranks. The files containing the data from the group will have names of the format "file_string/file_string_*******.suffix", with a 7-digit integer value identifying the files from 0 to num_files-1, and the suffix indicating the file format according to the protocol argument. Additionally `write()` will produce a root file with the name file_string.root that holds some bookkeeping data about the other files and can also receive extra user-specified data.

```
void read(sidre::DataGroup * group,
          const std::string& root_file);
```

`read()` is called in parallel with the root file as an argument. It must be called on a run with the same processor count as the run that called `write()`. The first argument is a pointer to a group that contains no child groups or views, and the information in the root file is used to identify the files that each processor will read to load data into the argument group.

The `write()` and `read()` methods above are sufficient to do a restart save/load when the data is the group is completely owned by the Sidre data structures. If Sidre is used to manage data that is externally allocated, the loading procedure requires some additional steps to restore data in the same externally-allocated state.

First the `read()` method is called, and the full hierarchy structure of the group is loaded into the Sidre Group, but no data is allocated for Views identified as external. Then the calling code can examine the group and allocate data for the external Views. `View::setExternalDataPtr()` is used to associate the pointer with the view. Once this is done, IOManager's `loadExternalData()` can be used to load the data from the file into the user-allocated arrays.

Below is a code example for loading external data. We assume that this code somehow has knowledge that the root group contains a single external view at the location "fields/external_array" describing an array of doubles. See the Group and View documentation for information about how to query the Sidre data structures for this type of information when the code does not have a priori knowledge.

```
// Construct a DataStore with an empty root group.
DataStore * ds = new DataStore();
DataGroup * root = ds->getRoot();

// Read from file into the root group.  The full Sidre hierarchy is built,
// but the external view is created without allocating a data buffer.
IOManager reader(MPI_COMM_WORLD);
reader.read(root, "checkpoint.root");

// Get a pointer to the external view.
DataView * external_view = root->getView("fields/external_array");

// Allocate storage for the array and associate it with the view.
double * external_array = new double[external_view->getNumElements()];
external_view->setExternalDataPtr(external_array);

// Load the data values from file into the external view.
reader.loadExternalData(root, "checkpoint.root");
```

User-specified data in the root file

The root file is automatically created to provide the IOManager with bookkeeping information that is used when reading data, but it can also be used to store additional data that may be useful to the calling code or is needed to allow other tools to interact with the data in the output files, such as for visualization. For example, Conduit's blueprint index can be *stored in a DataGroup* written to the root file to provide metadata about the mesh layout and data fields that can be visualized from the output files.

```
void writeGroupToRootFile(sidre::DataGroup * group,
                          const std::string& file_name);

void writeGroupToRootFileAtPath(sidre::DataGroup * group,
                                const std::string& file_name,
                                const std::string& group_path);

void writeViewToRootFileAtPath(sidre::DataView * view,
                               const std::string& file_name,
                               const std::string& group_path);
```

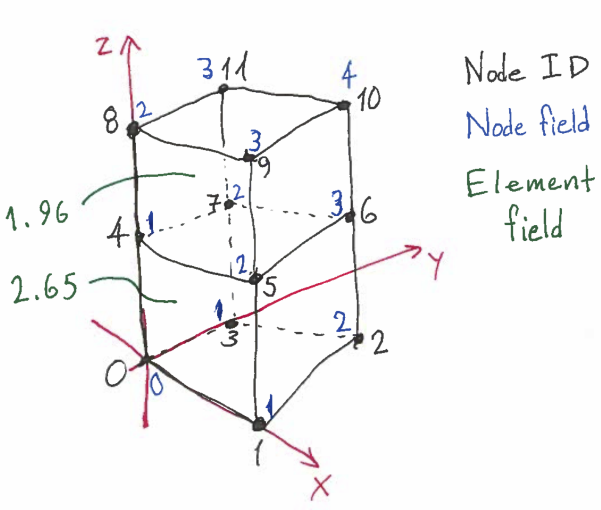
The above methods are used to write this extra data to the root file. The first simply writes data from the given group to the top of the root file, while the latter two methods write their Sidre objects to a path that must already exist in the root file.

Sidre Interaction with Conduit

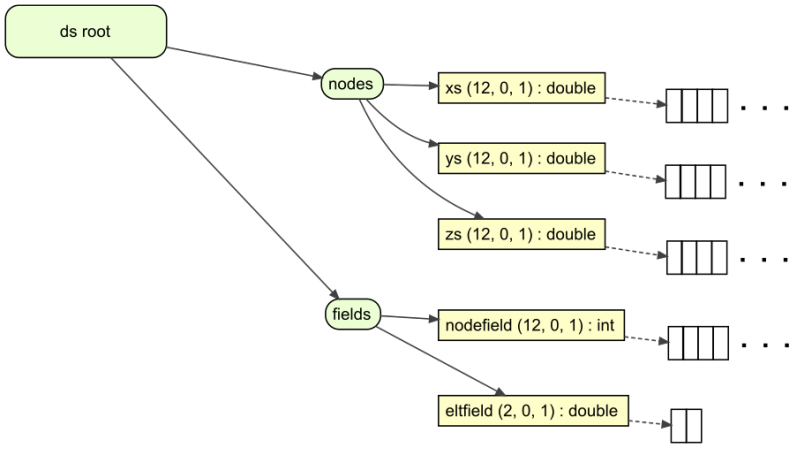
Internally, Sidre uses the in-memory data description capabilities of Conduit. Sidre also leverages Conduit to facilitate data exchange, demonstrated here as applied to visualization. The following discussion gives a basic overview of Sidre's capabilities when combined with Conduit. Please see the reference documentation for more details.

Mesh Blueprint

The Mesh Blueprint is a data exchange protocol supported by Conduit, consisting of a properly-structured Datastore saved as an HDF5 or JSON file and a Conduit index file. The Blueprint can accomodate structured or unstructured meshes, with node- or element-centered fields. The following example shows how to create a Blueprint-conforming Datastore containing two unstructured adjacent hexahedrons with one node-centered field and one element-centered field. In the diagram, nodes are labeled in black, the node-centered field values are in blue, and the element-centered field values are in green.



A simulation organizes its Sidre data as the code design dictates. Here is a simple example.



Here is the code to create that Dataset `ds`.

```
DataStore* ds = new DataStore();

int nodecount = 12;
int elementcount = 2;

// Create views and buffers to hold node positions and field values
Group* nodes = ds->getRoot()->createGroup("nodes");
View* xs = nodes->createViewAndAllocate("xs", sidre::DOUBLE_ID, nodecount);
View* ys = nodes->createViewAndAllocate("ys", sidre::DOUBLE_ID, nodecount);
View* zs = nodes->createViewAndAllocate("zs", sidre::DOUBLE_ID, nodecount);

Group* fields = ds->getRoot()->createGroup("fields");
View* nodefield =
  fields->createViewAndAllocate("nodefield", sidre::INT_ID, nodecount);
View* eltfield =
  fields->createViewAndAllocate("eltfield", sidre::DOUBLE_ID, elementcount);

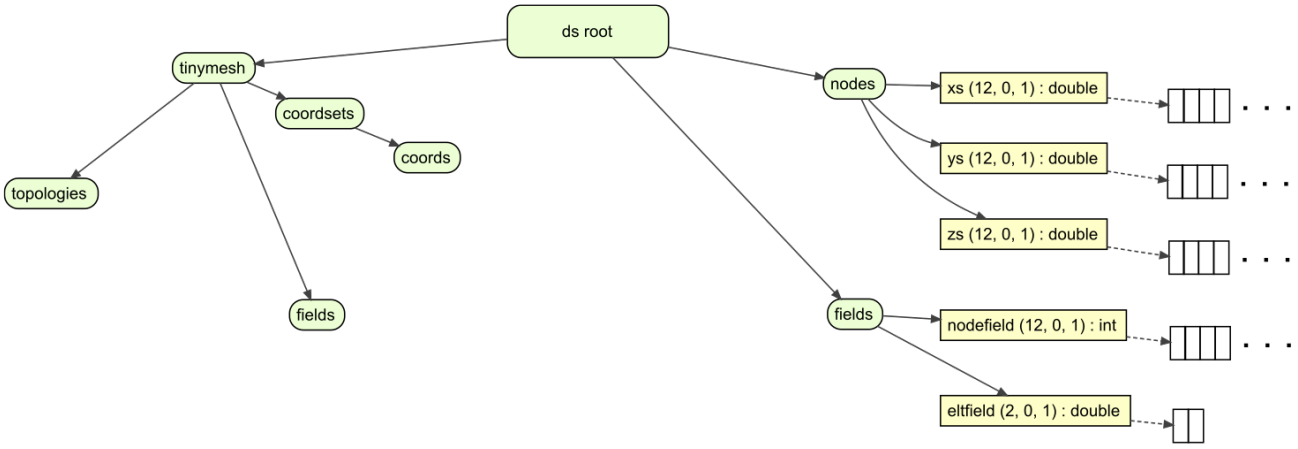
// Set node position for two adjacent hexahedrons
double* xptr = xs->getArray();
double* yptr = ys->getArray();
double* zptr = zs->getArray();
for (int pos = 0 ; pos < nodecount ; ++pos)
{
  xptr[pos] = ((pos + 1) / 2) % 2;
  yptr[pos] = (pos / 2) % 2;
  zptr[pos] = pos / 4;
}

// Assign a value to the node field
int* nf = nodefield->getArray();
for (int pos = 0 ; pos < nodecount ; ++pos)
{
  nf[pos] = static_cast<int>(xptr[pos] + yptr[pos] + zptr[pos]);
}
// and to the element field.
double* ef = eltfield->getArray();
// There are only two elements.
ef[0] = 2.65;
ef[1] = 1.96;

return ds;
```

To use the Mesh Blueprint, make a new Group `tinymesh` conforming to the protocol. The structure of the conforming Group is shown below (summarizing the Mesh Blueprint documentation).

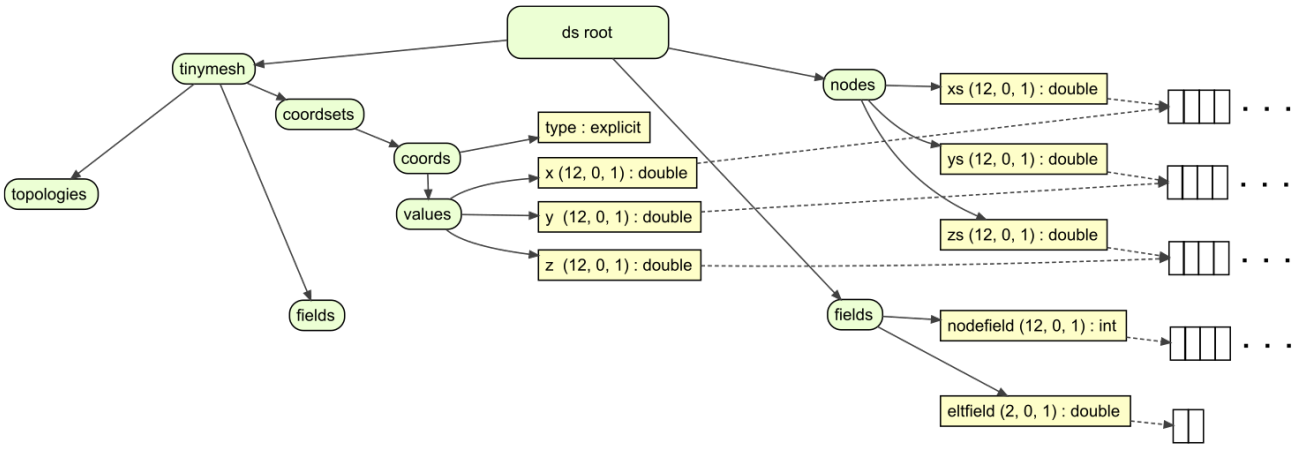
First build top-level groups required by the Blueprint.




```
// Conduit needs a specific hierarchy.
// We'll make a new DataStore with that hierarchy, pointing at the
// application's data.
std::string mesh_name = "tinymesh";

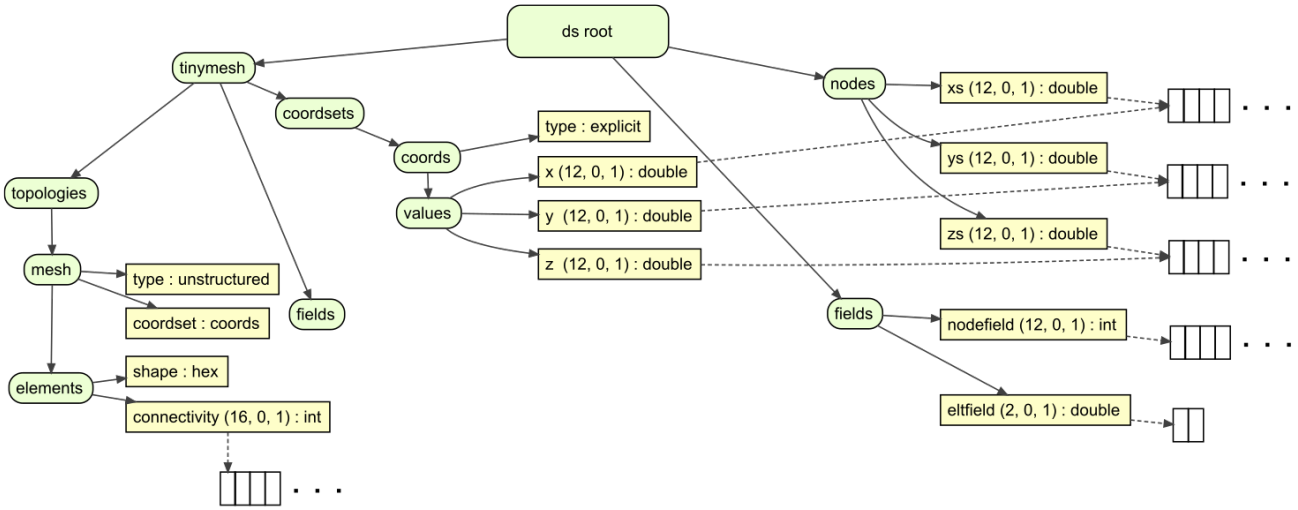
// The Conduit specifies top-level groups:
Group* mroot = ds->getRoot()->createGroup(mesh_name);
Group* coords = mroot->createGroup("coordsets/coords");
Group* topos = mroot->createGroup("topologies");
// no material sets in this example
Group* fields = mroot->createGroup("fields");
// no adjacency sets in this (single-domain) example
```

Add the node coordinates. The Views under `tinymesh` will point to the same Buffers that were created for the Views under `nodes` so that `tinymesh` can use the data without any new allocation or copying.



```
// Set up the coordinates as Mesh Blueprint requires
coords->createViewString("type", "explicit");
// We use prior knowledge of the layout of the original datastore
View* origv = ds->getRoot()->getView("nodes/xs");
Group* conduitval = coords->createGroup("values");
conduitval->createView("x", sidre::DOUBLE_ID,
                       origv->getNumElements(),
                       origv->getBuffer());
origv = ds->getRoot()->getView("nodes/ys");
conduitval->createView("y", sidre::DOUBLE_ID,
                       origv->getNumElements(),
                       origv->getBuffer());
origv = ds->getRoot()->getView("nodes/zs");
conduitval->createView("z", sidre::DOUBLE_ID,
                       origv->getNumElements(),
                       origv->getBuffer());
```

Arrange the nodes into elements. Each simulation has its own knowledge of topology. This tiny example didn't previously encode topology, so we must explicitly specify it.




```
// Sew the nodes together into the two hexahedra, using prior knowledge.
Group* connmesh = topos->createGroup("mesh");
connmesh->createViewString("type", "unstructured");
connmesh->createViewString("coordset", "coords");
Group* elts = connmesh->createGroup("elements");
elts->createViewString("shape", "hex");

// We have two eight-node hex elements, so we need 2 * 8 = 16 ints.
View* connectivity =
  elts->createViewAndAllocate("connectivity", sidre::INT_ID, 16);

// The Mesh Blueprint connectivity array for a hexahedron lists four nodes on
// one face arranged by right-hand rule to indicate a normal pointing into
// the element, then the four nodes of the opposite face arranged to point
// the normal the same way (out of the element).  This is the same as for
// a VTK_HEXAHEDRON.  See
```

(continues on next page)

(continued from previous page)

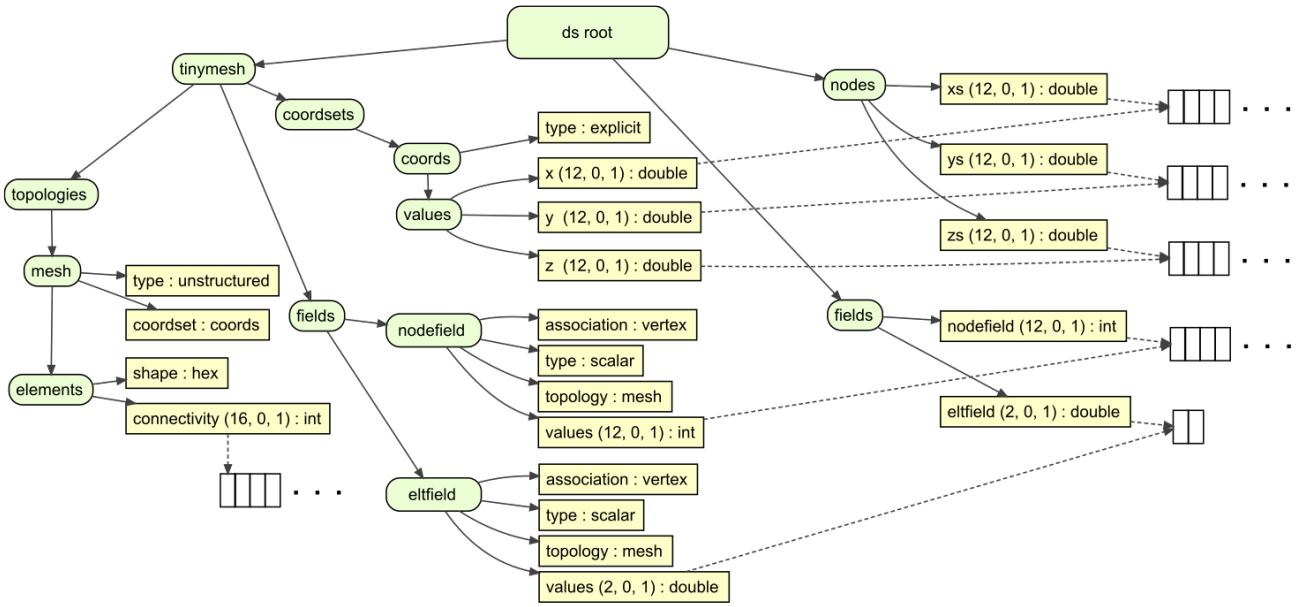
```
// https://www.vtk.org/wp-content/uploads/2015/04/file-formats.pdf.

int* c = connectivity->getArray();

// First hex.  In this example, the Blueprint node ordering matches the
// dataset layout.  This is fortuitous but not required.
c[0] = 0; c[1] = 1; c[2] = 2; c[3] = 3;
c[4] = 4; c[5] = 5; c[6] = 6; c[7] = 7;

// Second and last hex
c[8] = 4; c[9] = 5; c[10] = 6; c[11] = 7;
c[12] = 8; c[13] = 9; c[14] = 10; c[15] = 11;
```

Link the fields into `tinymesh`. As with the node positions, the Views point to the existing Buffers containing the field data.




```
// Set up the node-centered field
// Get the original data
View* origv = ds->getRoot()->getView("fields/nodefield");
Group* nodefield = fields->createGroup("nodefield");
nodefield->createViewString("association", "vertex");
nodefield->createViewString("type", "scalar");
nodefield->createViewString("topology", "mesh");
nodefield->createView("values", sidre::INT_ID,
                      origv->getNumElements(),
                      origv->getBuffer());

// Set up the element-centered field
// Get the original data
origv = ds->getRoot()->getView("fields/eltfield");
Group* eltfield = fields->createGroup("eltfield");
eltfield->createViewString("association", "element");
eltfield->createViewString("type", "scalar");
eltfield->createViewString("topology", "mesh");
eltfield->createView("values", sidre::DOUBLE_ID,
```

(continues on next page)

(continued from previous page)

```
                        origv->getNumElements(),
                        origv->getBuffer());
```

Conduit includes a `verify` method to test if the structure of the `tinymesh` conforms to the Mesh Blueprint. This is valuable for writing and debugging data adapters. Once the Datastore is properly structured, save it, then use Conduit to save the index file (ending with *.root*). This toy data set is small enough that we can choose to save it as JSON.

```
conduit::Node info, mesh_node, root_node;
ds->getRoot()->createNativeLayout(mesh_node);
std::string bp_protocol = "mesh";
if (conduit::blueprint::verify(bp_protocol, mesh_node[mesh_name], info))
{
  // Generate the Conduit index
  conduit::Node & index = root_node["blueprint_index"];
  conduit::blueprint::mesh::generate_index(mesh_node[mesh_name],
                                           mesh_name,
                                           1,
                                           index[mesh_name]);

  std::string root_output_path = mesh_name + ".root";
  std::string output_path = mesh_name + ".json";

  root_node["protocol/name"] = "json";
  root_node["protocol/version"] = "0.1";
  root_node["number_of_files"] = 1;
  root_node["number_of_trees"] = 1;
  root_node["file_pattern"] = output_path;
  root_node["tree_pattern"] = "/";

  // Now save both the index and the data set
  conduit::relay::io::save(root_node, root_output_path, "json");
  conduit::relay::io::save(mesh_node, output_path, "json");
}
else
{
  std::cout << "does not conform to Mesh Blueprint: ";
  info.print();
  std::cout << std::endl;
}
```

The code listed above produces the files *tinymesh.json* and *tinymesh.root*. Any code that uses Mesh Blueprint can open and use this pair of files.

The DataStore also contains a method that can automatically generate the Blueprint index within a Sidre Group rather than calling directly into Conduit. Set up a mesh similarly to the example above.

```
// Conduit needs a specific hierarchy.
// We'll make a new Group with that hierarchy, pointing at the
// application's data.
std::string domain_name = "domain";
std::string domain_location = "domain_data/" + domain_name;
std::string mesh_name = "mesh";
std::string domain_mesh = domain_location + "/" + mesh_name;

Group* mroot = ds->getRoot()->createGroup(domain_location);
Group* coords = mroot->createGroup(mesh_name + "/coordsets/coords");
Group* topos = mroot->createGroup(mesh_name + "/topologies");
```

(continues on next page)

(continued from previous page)

```
  // no material sets in this example
  Group* fields = mroot->createGroup(mesh_name + "/fields");
  // no adjacency sets in this (single-domain) example
```

Then use `DataStore::generateBlueprintIndex` to generate the index within a Group held by the DataStore. Then additional data needed in the root file can be added and saved using Sidre I/O calls.

```
  conduit::Node info, mesh_node, root_node;
  ds->getRoot()->createNativeLayout(mesh_node);
  std::string bp_protocol = "mesh";
  if (conduit::blueprint::verify(bp_protocol, mesh_node[domain_mesh], info))
  {
    std::string bp("rootfile_data/blueprint_index/automesh");

    ds->generateBlueprintIndex(domain_mesh, mesh_name, bp, 1);

    Group* rootfile_grp = ds->getRoot()->getGroup("rootfile_data");
    rootfile_grp->createViewString("protocol/name", "json");
    rootfile_grp->createViewString("protocol/version", "0.1");
    rootfile_grp->createViewScalar("number_of_files", 1);
    rootfile_grp->createViewScalar("number_of_trees", 1);
    rootfile_grp->createViewScalar("file_pattern", "bpgen.json");
    rootfile_grp->createViewScalar("tree_pattern", "/domain");
    rootfile_grp->save("bpgen.root", "json");

    ds->getRoot()->getGroup("domain_data")->save("bpgen.json", "json");
  }
  else
  {
    std::cout << "does not conform to Mesh Blueprint: ";
    info.print();
    std::cout << std::endl;
  }
```

Additionally, the Sidre Parallel I/O (SPIO) class `IOManager` provides a method that both generates a Blueprint index and adds it to a root file. Using the same mesh data from the last example, first write out all of the parallel data using `IOManager::write`. This will output to files all of the data for all domains, and will also create a basic root file. Then `IOManager::writeBlueprintIndexToRootFile` can be used to generate the Blueprint index and add it to the root file. This is currently only implemented to work with the `sidre_hdf5` I/O protocol.

```
  IOManager writer(MPI_COMM_WORLD);

  conduit::Node info, mesh_node, root_node;
  ds->getRoot()->createNativeLayout(mesh_node);
  std::string bp_protocol = "mesh";
  if (conduit::blueprint::verify(bp_protocol, mesh_node[domain_mesh], info))
  {

    std::string bp_rootfile("bpspio.root");

    writer.write(ds->getRoot()->getGroup(
                   domain_location), 1, "bpspio", "sidre_hdf5");

    writer.writeBlueprintIndexToRootFile(ds, domain_mesh, bp_rootfile,
                                         mesh_name);
```

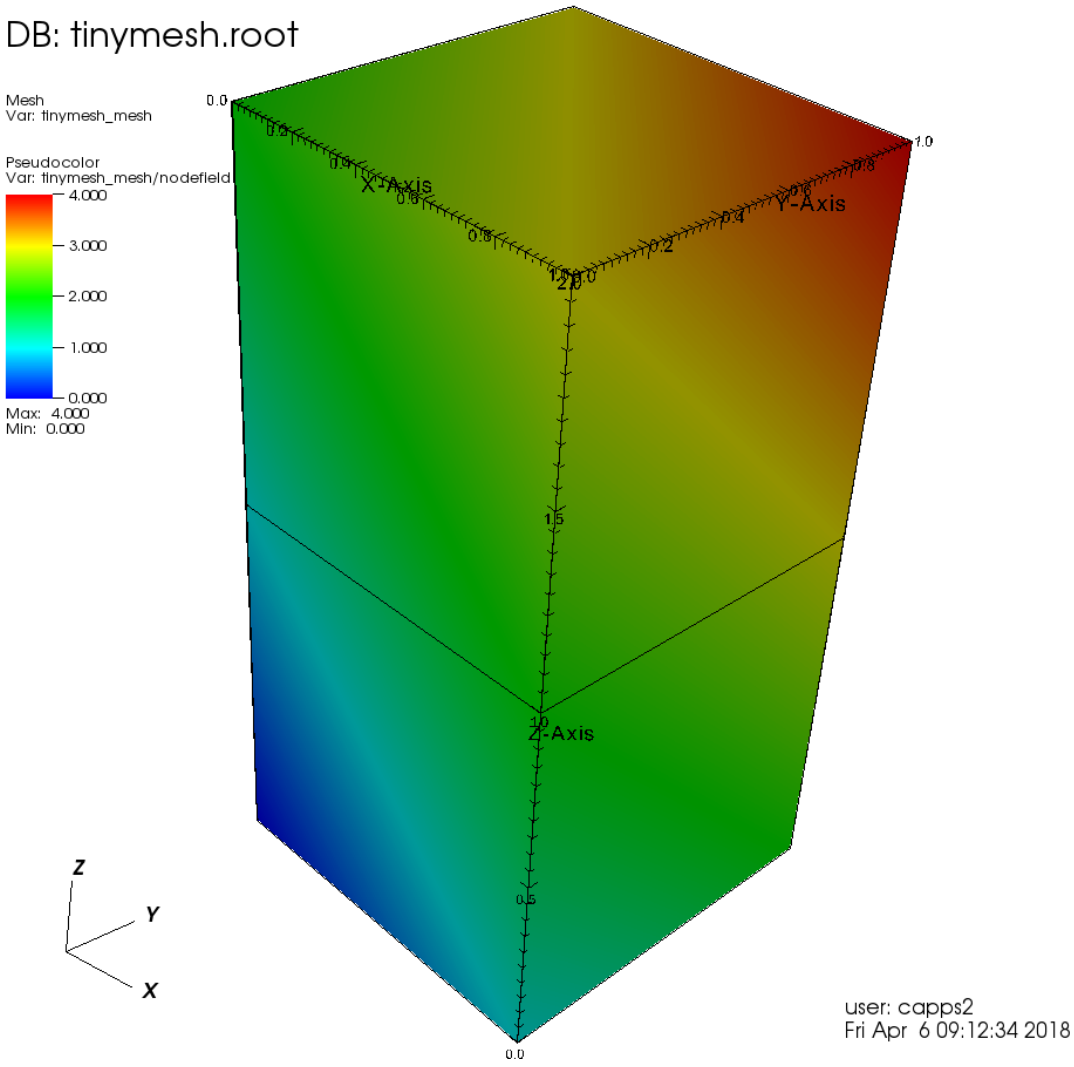
(continues on next page)

(continued from previous page)

```
}
```

Data Visualization

The VisIt tool can read in a Blueprint, interpret the index file, and sensibly display the data contained in the data file. Starting from version 2.13.1, VisIt can open a *.root* file just like any other data file. VisIt produced the following image from the Mesh Blueprint file saved above.



Conduit is also a foundational building block for the Ascent project, which provides a powerful data analytics and visualization facility (without copying memory) to distributed-memory simulation codes.

2.4 Slam User Documentation

Axom's Set-theoretic Lightweight API for Meshes (SLAM) component provides high performance building blocks for distributed-memory mesh data structures in HPC simulation codes.

Simulation codes have a broad range of requirements for their mesh data structures, spanning the complexity gamut from structured Cartesian grids to fully unstructured polyhedral meshes. Codes also need to support features like dynamic topology changes, adaptive mesh refinement (AMR), submesh elements and ghost/halo layers, in addition to other custom features.

Slam targets the low level implementation of these distributed mesh data structures and is aimed at developers who implement mesh data structures within HPC applications.

Slam's design is motivated by the observation that despite vast differences in the high level features of such mesh data structures, many of the core concepts are shared at a lower level, where we need to define and process mesh entities and their associated data and relationships.

Slam provides a simple, intuitive, API centered around a set-theoretic abstraction for meshes and associated data. Specifically, it models three core set-theoretic concepts:

- **Sets** of entities (e.g. vertices, cells, domains)
- **Relations** among a pair of sets (e.g. incidence, adjacency and containment relations)
- **Maps** defining fields and attributes on the elements of a given set.

The goal is for users to program against Slam's interface without having to be aware of different design choices, such as the memory layout and underlying data containers. The exposed API is intended to feel natural to end users (e.g. application developers and domain scientists) who operate on the meshes that are built up from Slam's abstractions.

See *Core concepts* for more details.

There is considerable variability in how these abstractions can be implemented and user codes make many different design choices. For example, we often need different data structures to support dynamic meshes than we do for static meshes. Similarly, codes might choose different container types for their arrays (e.g. STL vectors vs. raw C-arrays vs. custom array types).

Performance considerations can also come in to play. For example, in some cases, a code has knowledge of some fixed parameters (e.g. the stride between elements in a relation). Specifying this information at compile-time allows the compiler to better optimize the generated code than specifying it at runtime.

Slam uses a Policy-based design to orthogonally decompose the feature space without sacrificing performance. This makes it easier to customize the behavior of Slam's sets, relations and maps and to extend support for custom features extend the basic interface.

See *Policy-based design* for more details.

- Slam is under active development with many features planned.
- Support for GPUs in Slam is under development.
- Slam's policy-based design enable highly configurable classes which are explicitly defined via type aliases. We are investigating ways to simplify this set up using *Generator* classes where enumerated strings can define related types within a mesh configuration.

2.4.1 An introductory example

This file contains an introductory example to define and traverse a simple quadrilateral mesh. The code for this example can be found in `axom/src/axom/slam/examples/UserDocs.cpp`.

We first import the unified Slam header, which includes all necessary files for working with slam:

```
#include "axom/slam.hpp"
```

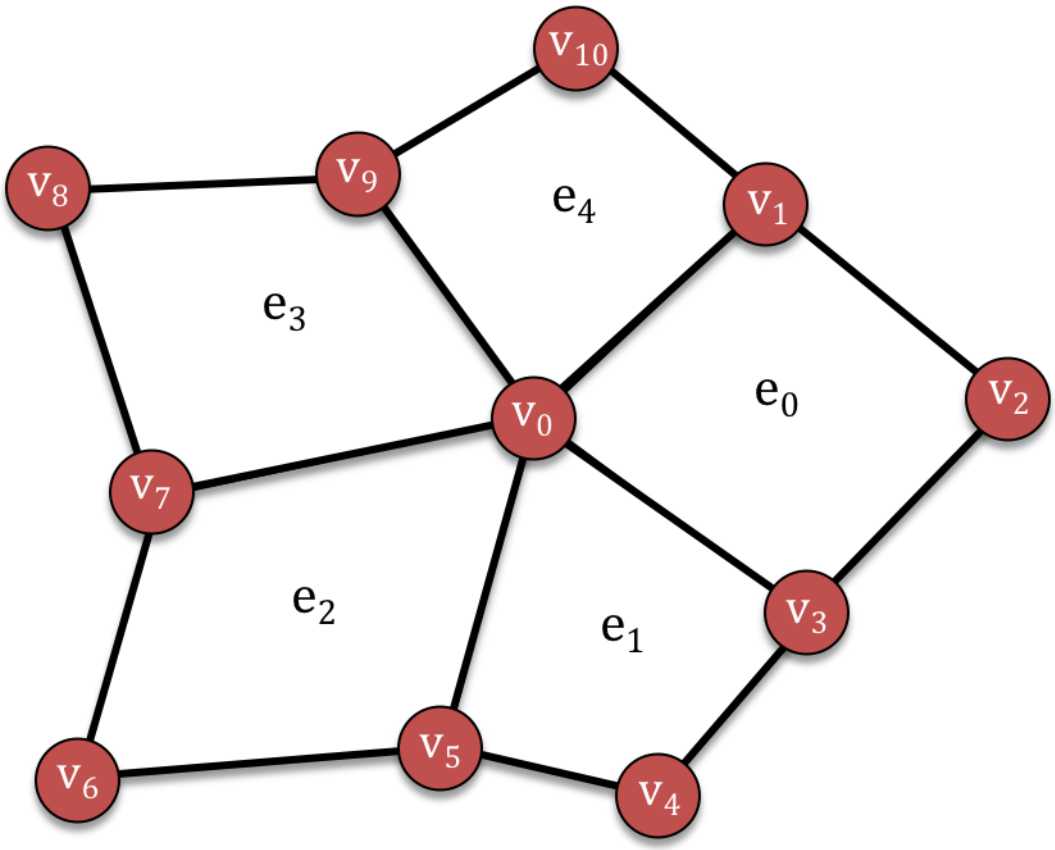


Fig. 2.3: An unstructured mesh with eleven vertices (red circles) and five elements (quadrilaterals bounded by black lines)

Note: All code in slam is in the `axom::slam` namespace. For convenience, we add the following namespace declaration to our example to allow us to directly use the `slam` namespace:

```
namespace slam = axom::slam;
```

Type aliases and variables

We begin by defining some type aliases for the Sets, Relations and Maps in our mesh. These type aliases would typically be found in a configuration file or in class header files.

We use the following types throughout this example:

```
  using ArrayIndir = slam::policies::ArrayIndirection<PosType,ElemType>;
```

Sets

Our mesh is defined in terms of two sets: Vertices and Elements, whose entities are referenced by integer-valued indices. Since both sets use a contiguous range of indices starting from 0, we use `slam::PositionSet` to represent them.

We define the following type aliases:

```
  using PosType = slam::DefaultPositionType;
  using ElemType = slam::DefaultElementType;
  using VertSet = slam::PositionSet<PosType, ElemType>;
  using ElemSet = slam::PositionSet<PosType, ElemType>;
```

and declare them as:

```
  VertSet verts; // The set of vertices in the mesh
  ElemSet elems; // The set of elements in the mesh
```

For other available set types, see *Set*.

Relations

We also have relations describing the incidences between the mesh vertices and elements.

The element-to-vertex *boundary* relation encodes the indices of the vertices in the boundary of each element. Since this is a quad mesh and there are always four vertices in the boundary of a quadrilateral, we use a `ConstantCardinality` policy with a `CompileTimeStride` set to 4 for this `StaticRelation`.

```
  // Type aliases for element-to-vertex boundary relation
  enum { VertsPerElem = 4};
  using CTStride = slam::policies::CompileTimeStride<PosType,VertsPerElem>;
  using ConstCard = slam::policies::ConstantCardinality<PosType, CTStride>;
  using ElemToVertRelation = slam::StaticRelation<PosType,ElemType,
                                                  ConstCard,ArrayIndir,
                                                  ElemSet,VertSet>;
```

The vertex-to-element *coboundary* relation encodes the indices of all elements incident in each of the vertices. Since the cardinality of this relation changes for different vertices, we use a `VariableCardinality` policy for this `StaticRelation`.

```
// Type aliases for vertex-to-element coboundary relation
using VarCard = slam::policies::VariableCardinality<PosType, ArrayIndir>;
using VertToElemRelation = slam::StaticRelation<PosType,ElemType,
                                                VarCard,ArrayIndir,
                                                VertSet,ElemSet>;
```

We declare them as:

```
ElemToVertRelation bdry;   // Boundary relation from elements to vertices
VertToElemRelation cobdry; // Coboundary relation from vertices to elements
```

For other available set types, see *Relation*.

Maps

Finally, we have some maps that attach data to our sets.

The following defines a type alias for the positions of the mesh vertices. It is templated on a point type (`Point2`) that handles simple operations on 2D points.

```
using BaseSet = slam::Set<PosType,ElemType>;
using ScalarMap = slam::Map<BaseSet, Point2>;
using PointMap = slam::Map<BaseSet, Point2>;
using VertPositions = PointMap;
```

It is declared as:

```
VertPositions position; // vertex position
```

Constructing the mesh

This example uses a very simple fixed mesh, which is assumed to not change after it has been initialized.

Sets

The sets are created using a constructor that takes the number of elements.

```
  verts = VertSet(11); // Construct vertex set with 11 vertices
  elems = ElemSet(5);  // Construct the element set with 5 elements
```

The values of the vertex indices range from `0` to `verts.size()-1` (and similarly for `elems`).

Note: All sets, relations and maps in Slam have internal validity checks using the `isValid()` function:

```
  SLIC_ASSERT_MSG( verts.isValid(), "Vertex set is not valid." );
  SLIC_ASSERT_MSG( elems.isValid(), "Elment set is not valid." );
```

Relations

The relations are constructed by binding their associated sets and arrays of data to the relation instance. In this example, we use an internal helper class `RelationBuilder`.

We construct the boundary relation by attaching its two sets (`elems` for its `fromSet` and `verts` for its `toSet`) and an array of indices for the relation's data.

```
// construct boundary relation from elements to vertices
using RelationBuilder = ElemToVertRelation::RelationBuilder;
bdry = RelationBuilder()
       .fromSet( &elems )
       .toSet( &verts )
       .indices(RelationBuilder::IndicesSetBuilder()
                .size( evInds.size() )
                .data( evInds.data() ) );
```

The Coboundary relation requires an additional array of offsets (`begins`) to indicate the starting index in the relation for each vertex:

```
// construct coboundary relation from vertices to elements
using RelationBuilder = VertToElemRelation::RelationBuilder;
cobdry = RelationBuilder()
         .fromSet( &verts )
         .toSet( &elems )
         .begins( RelationBuilder::BeginsSetBuilder()
                  .size( verts.size() )
                  .data( veBegins.data() ) )
         .indices( RelationBuilder::IndicesSetBuilder()
                   .size( veInds.size() )
                   .data( veInds.data() ) );
```

Since these are static relations, we used data that was constructed elsewhere. Note that these relations are lightweight wrappers over the underlying data – no data is copied. To iteratively build the relations, we would use the `DynamicConstantRelation` and `DynamicVariableRelation` classes.

See *Simplifying mesh setup* for more details about Slam's `Builder` classes for sets, relations and maps.

Maps

We define the positions of the mesh vertices as a `Map` on the `verts` set. For this example, we set the first vertex to lie at the origin, and the remaining vertices line within an annulus around the unit circle.

```
// construct the position map on the vertices
position = VertPositions( &verts );

// first vertex is at origin
position[0] = Point2( 0.,0. );

// remaining vertices lie within annulus around unit disk
// in cw order, starting at angleOffset
constexpr double rInner = 0.8;
constexpr double rOuter = 1.2;
constexpr double angleOffset = 0.75;
const double N = verts.size()-1;
```

(continues on next page)

(continued from previous page)

```
  for(int i=1 ; i< verts.size() ; ++i)
  {
    const double angle = -(i-1)/ N * 2 * M_PI + angleOffset;
    const double mag = axom::utilities::random_real(rInner, rOuter);

    position[i] = Point2(mag * std::cos(angle), mag * std::sin(angle));
  }
```

Traversing the mesh

Now that we've constructed the mesh, we can start traversing the mesh connectivity and attaching more fields.

Computing a derived field

Our first traversal loops through the vertices and computes a derived field on the position map. For each vertex, we compute its distance to the origin.

```
  // Create a Map of scalars over the vertices
  ScalarMap distances( &verts );

  for(int i=0 ; i< distances.size() ; ++i)     // <-- Map::size()
  {
    auto vID = verts[i];                       // <-- Set::operator[]
    const Point2& pt = position[vID];          // <-- Map::operator[]

    distances[i] = std::sqrt( pt[0]*pt[0]      // <-- Map::operator[]
                              + pt[1]*pt[1]);
  }
```

Computing element centroids

Our next example uses element-to-vertex boundary relation to compute the *centroids* of each element as the average of its vertex positions.

```
  // Create a Map of Point2 over the mesh elements
  using ElemCentroidMap = PointMap;
  ElemCentroidMap centroid = ElemCentroidMap( &elems );

  // for each element...
  for(int eID=0 ; eID < elems.size() ; ++eID) // <-- Set::size()
  {
    Point2 ctr;

    auto elVerts = bdry[eID];                  // <-- Relation::operator[]

    // find average position of incident vertices
    for(int i=0 ; i < elVerts.size() ; ++i)    // <-- Set::size()
    {
      auto vID = elVerts[i];                   // <-- Set::operator[]
      ctr += position[vID];                    // <-- Map::operator[]
    }
    ctr /= elVerts.size();                     // <-- Set::size())
```

(continues on next page)

(continued from previous page)

```
    centroid[eID] = ctr;                        // <-- Map::operator[]
  }
```

Perhaps the most interesting line here is when we call the relation's subscript operator (`bdry[eID]`). This function takes an element index (`eID`) and returns the *set* of vertices that are incident in this element. As such, we can use all functions in the Set API on this return type, e.g. `size()` and the subscript operator.

Outputting mesh to disk

As a final example, we highlight several different ways to iterate through the mesh's Sets, Relations and Maps as we output the mesh to disk (in the `vtk` format).

This is a longer example, but the callouts (left-aligned comments of the form `// <-- message`) point to different iteration patterns.

```
  std::ofstream meshfile;
  meshfile.open("quadMesh.vtk");
  std::ostream_iterator<PosType> out_it (meshfile," ");

  // write header
  meshfile << "# vtk DataFile Version 3.0\n"
           << "vtk output\n"
           << "ASCII\n"
           << "DATASET UNSTRUCTURED_GRID\n\n"
           << "POINTS " << verts.size() << " double\n";

  // write positions
  for(auto pos: position)          // <-- Uses range-based for on position map
  {
    meshfile << pos[0] << " " << pos[1] << " 0\n";
  }

  // write elem-to-vert boundary relation
  meshfile << "\nCELLS " << elems.size() << " " << 5 * elems.size();
  for(auto e: elems)               // <-- uses range-based for on element set
  {
    meshfile<<"\n4 ";
    std::copy ( bdry.begin(e),     // <-- uses relation's iterators
                bdry.end(e), out_it );
  }

  // write element types ( 9 == VKT_QUAD )
  meshfile << "\n\nCELL_TYPES " << elems.size() << "\n";
  for(int i=0 ; i< elems.size() ; ++i)
  {
    meshfile << "9 ";
  }

  // write element ids
  meshfile << "\n\nCELL_DATA " << elems.size()
           << "\nSCALARS cellIds int 1"
           << "\nLOOKUP_TABLE default \n";
  for(int i=0 ; i< elems.size() ; ++i)
  {
    meshfile << elems[i] <<" ";    // <-- uses size() and operator[] on set
```

(continues on next page)

(continued from previous page)

```
  }

  // write vertex ids
  meshfile << "\n\nPOINT_DATA " << verts.size()
           << "\nSCALARS vertIds int 1"
           << "\nLOOKUP_TABLE default \n";
  for(int i=0 ; i< verts.size() ; ++i)
  {
    meshfile << verts[i] <<" ";
  }
  meshfile <<"\n";
```

2.4.2 Core concepts

Describe Slam concepts, what they mean, how they are used, etc.

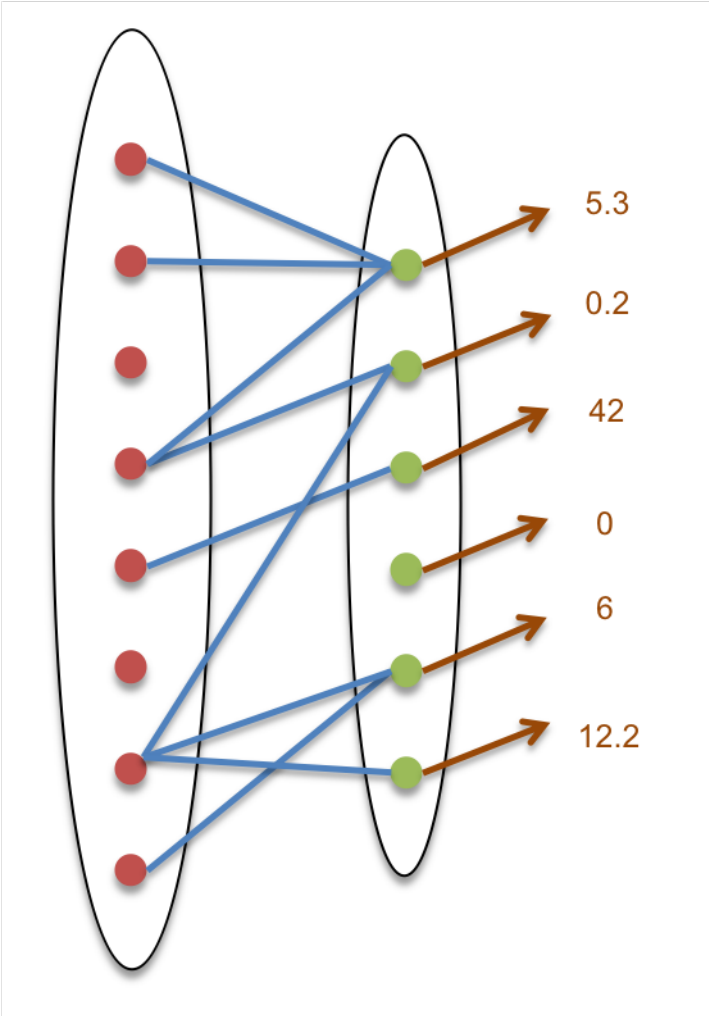


Fig. 2.4: A **relation** (blue lines) between two **sets** (ovals with red and green dots, as elements) and a **map** of scalar values (brown) on the second set.

Set

- Taxonomy of set types (OrderedSet, IndirectionSet, Subset, static vs. dynamic)
- Simple API (including semantics of operator[] and iterators)
- Example to show how we iterate through a set

Relation

- Relational operator (from element of Set A to set of elements in Set B)
- **Taxonomy:**
  - Cardinality: Fixed vs Variable number of elements per relation
  - Mutability: Static vs. Dynamic relation
  - Storage: Implicit vs. Explicit (e.g. product set)
- Simple API (including semantics of operator[])
- **Three ways to iterate through a relations**
  - Double subscript
  - Separate subscripts
  - Iterators

Map

- Data associated with all members of a set
- Simple API (including semantics of operator[])

2.4.3 Implementation details

Policy-based design

Handling the combinatorial explosion of features; avoid paying for what we don't need

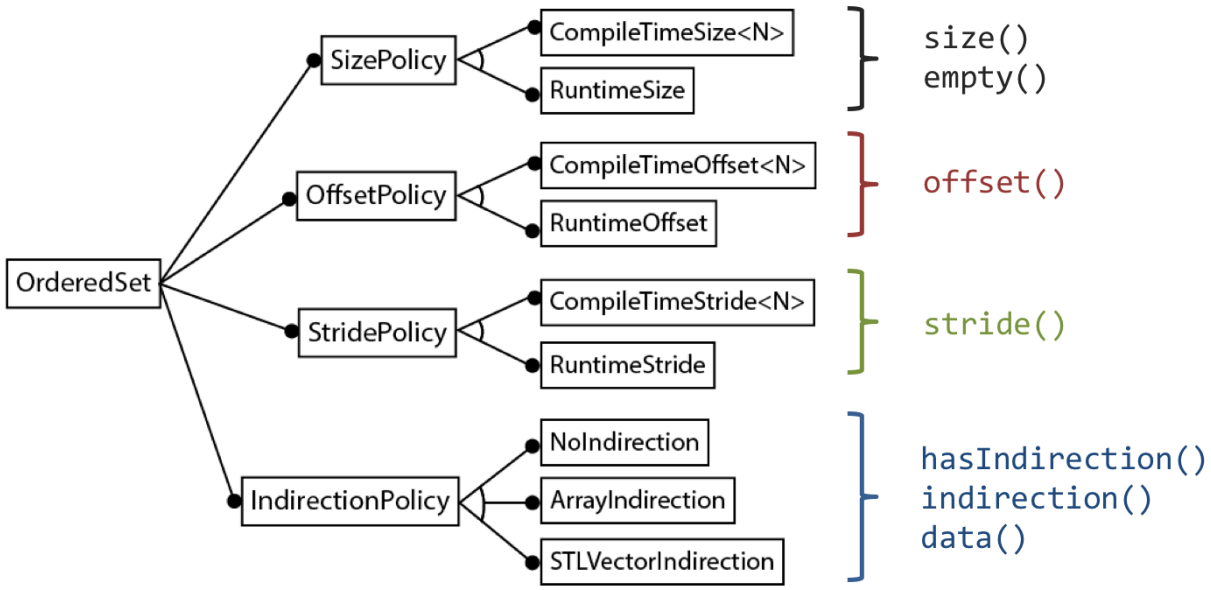
- SizePolicy, StridePolicy, OffsetPolicy (compile time vs. runtime)
- IndirectionPolicy (none, C-array, std::vector, custom, e.g. mfem::Array)
- SubsettingPolicy (none, virtual parent, concrete parent)
- OwnershipPolicy (local, sidre, other repository)

Feature diagram of OrderedSet policies (subset).

The figure shows how certain these policies interact with the subscript operator.

Simplifying mesh setup

- **Builder classes**
  - Chained initialization using named-parameter idiom
- Generator classes to simplify types




```
aSet[eltId] := indirection(eltID*stride() + offset() )
```

- API documentation
- Axom main docs

2.5 Spin User Documentation

The Spin component of Axom provides several index data structures to accelerate spatial queries. The Morton code classes relate each point in a region of interest to a point on a one-dimensional space filling curve, and the RectangularLattice helps in the computation of bin coordinates. The UniformGrid and ImplicitGrid classes build one-level indexes of non-intersecting bins, while the BVHTree and SpatialOctree classes build nesting hierarchies of bounding boxes indexing a region of interest.

2.5.1 RectangularLattice

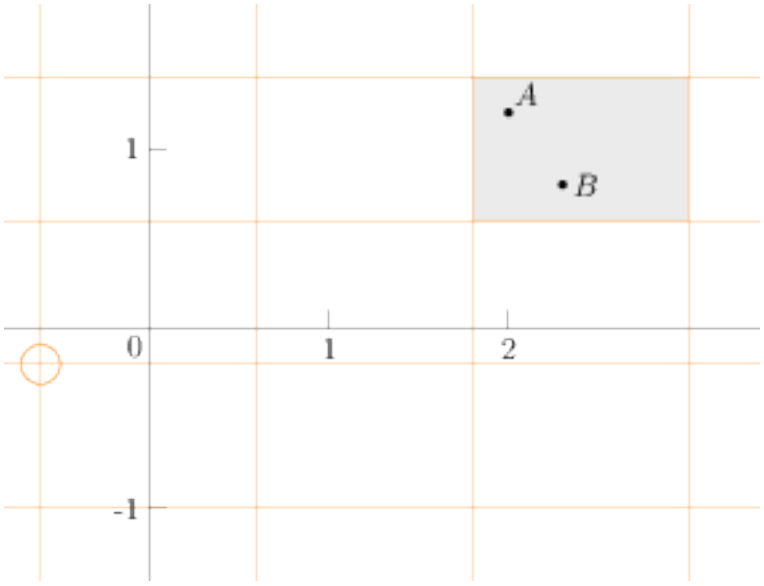
The `RectangularLattice` is a helper class that maps all of N-D space into a regular, rectangular grid of cells identified by integer coordinates. The grid is defined by an origin point and a vector indicating spacing in each dimension.

The figure shows an example `RectangularLattice` in 2D, with its origin (circled) at (-0.6, -0.2) and spacing (1.2, 0.8). Given a query point, the `RectangularLattice` will return the coordinates of the cell that contains the point. It will also return the bounding box of a cell, or the coordinates of a cell's lower-left corner.

The following example shows the use of the `RectangularLattice`. First, include the header and (if desired) declare type aliases. Using `const int in2d = 2` makes a 2D lattice.

```
#include "axom/spin/RectangularLattice.hpp"
// We'll be using a 2D lattice with space coordinates of type double
// and cell coordinates of type int.
using RectLatticeType = axom::spin::RectangularLattice<in2D, double, int>;
```

(continues on next page)



(continued from previous page)

```
// Get the types of coordinates and bounding box from the RectangularLattice
using RLGridCell = RectLatticeType::GridCell;
using RLSpacePt = RectLatticeType::SpacePoint;
using RLSpaceVec = RectLatticeType::SpaceVector;
using RLBBox = RectLatticeType::SpatialBoundingBox;
```

Use the `RectangularLattice` to find grid cells.

```
  // Origin and spacing
  double origin[] = {-0.6, -0.2};
  double spacing[] = {1.2, 0.8};

  // Instantiate a RectangularLattice.
  // Other constructors allow the use of Point and Vector objects.
  RectLatticeType lat(origin, spacing);

  // Query point (2.0, 1.2) should be in grid cell (2, 1)
  RLSpacePt pA = RLSpacePt::make_point(2.0, 1.2);
  RLGridCell cA = lat.gridCell(pA);
  std::cout << "Point " << pA << " is in grid cell " << cA <<
    " (should be (2, 1))" << std::endl;

  // Query point (2.3, 0.8) should also be in grid cell (2, 1)
  RLSpacePt pB = RLSpacePt::make_point(2.3, 0.8);
  RLGridCell cB = lat.gridCell(pB);
  std::cout << "Point " << pB << " is in grid cell " << cB <<
    " (should be (2, 1))" << std::endl;

  // What is the lowest corner and bounding box of the shared cell?
  RLSpacePt cellcorner = lat.spacePoint(cB);
  RLBBox cellbbox = lat.cellBounds(cB);
  std::cout << "The lower corner of the grid cell is " << cellcorner <<
    " and its bounding box is " << cellbbox << std::endl;
```

2.5.2 Mortonizer

The `Mortonizer` (along with its associated class `MortonBase`) implements the Morton index, an operation that associates each point in N-D space with a point on a space-filling curve[1]. The `PointHash` class adapts the `Mortonizer` to provide a hashing functionality for use with `std::unordered_map` or similar container classes.

The math of the Morton index works with integers. Thus the `Mortonizer` and its dependent class `PointHash` will not work with floating point coordinates. The following code example shows how the cells of a `RectangularLattice`, which have integer coordinates, can be used with a hash table.

The `Mortonizer` works by interleaving bits from each coordinate of the input point and finite computer hardware limits its resolution. If the `MortonIndexType` is 64-bits, then in 2D it can uniquely index the least significant 32 bits of the x- and y-coordinates. In 3D, it can uniquely index the least significant 21 bits of the x-, y-, and z-coordinates.

To use the `PointHash`, include the header and (as desired) declare type aliases.

```
#include "axom/spin/MortonIndex.hpp"
#include <unordered_map>
// The PointHash will allow us to use integral N-D coordinates as a hash key.
// This example will use RectangularLattice grid cell coordinates as keys to
// a std::unordered_map.
using PointHashType = axom::spin::PointHash<RLGridCell::CoordType>;
// Here's a class defined elsewhere that will do some work on a point.
class DataContainer;
using MapType = std::unordered_map<RLGridCell, DataContainer, PointHashType>;
```

The `RectangularLattice` grid cell associated with a query point can be stored, using a `PointHash`, in a `std::unordered_map`.

```
  // Make a RectangularLattice to bin query points.
  double origin[] = {-0.6, -0.2};
  double spacing[] = {1.2, 0.8};
  RectLatticeType lat(origin, spacing);

  // Make the map from grid point to DataContainer
  MapType map;

  // For several query points, create a DataContainer if necessary and register
  // the point.
  std::vector<RLSpacePt> pts = generatePoints();
  for (RLSpacePt p : pts)
  {
    RLGridCell g = lat.gridCell(p);
    DataContainer dat;
    if (map.count(g) > 0)
    {
      dat = map[g];
    }
    dat.registerPoint(p);
    map[g] = dat;
  }

  // Report on what was registered.
  for (auto iter : map)
  {
    RLGridCell g = iter.first;
    DataContainer dat = iter.second;
```

(continues on next page)

[1] The Morton index is also known, among other things, as the Z-order curve: see its Wikipedia page.

(continued from previous page)

```
    std::cout << "Grid cell " << g << " holds "
              << dat.count << " points." << std::endl;
  }
```

2.5.3 UniformGrid

The `UniformGrid` is inspired by and can be used to implement the Cell list. This data structure tiles a rectilinear region of interest into non-intersecting subregions (or "bins") of uniform size. Each bin gets a reference to every object in the region of interest that intersects that bin. `UniformGrid` can be used when a code compares each primitive in a collection to every other spatially-close primitive, such as when checking if a triangle mesh intersects itself. The following naive implementation is straightforward but runs in $O(n^2)$ time, where n is the number of triangles.

```
void findTriIntersectionsNaively(
  std::vector<TriangleType> & tris,
  std::vector< std::pair<int, int> > & clashes
  )
{
  int tcount = tris.size();

  for (int i = 0 ; i < tcount ; ++i)
  {
    TriangleType & t1 = tris[i];
    for (int j = i + 1 ; j < tcount ; ++j)
    {
      TriangleType & t2 = tris[j];
      if (intersect(t1, t2))
      {
        clashes.push_back(std::make_pair(i, j));
      }
    }
  }
}
```

We want to call `intersect()` only for triangles that can intersect, ignoring widely-separated triangles. The `UniformGrid` enables this optimization. In the following figure, the `UniformGrid` divides the region of interest into three by three bins outlined in grey. A triangle t (shown in orange) will be compared with neighbor triangles (shown in black) that fall into the bins occupied by t. Other triangles (shown in blue) are too far away to intersect and are not compared with t.

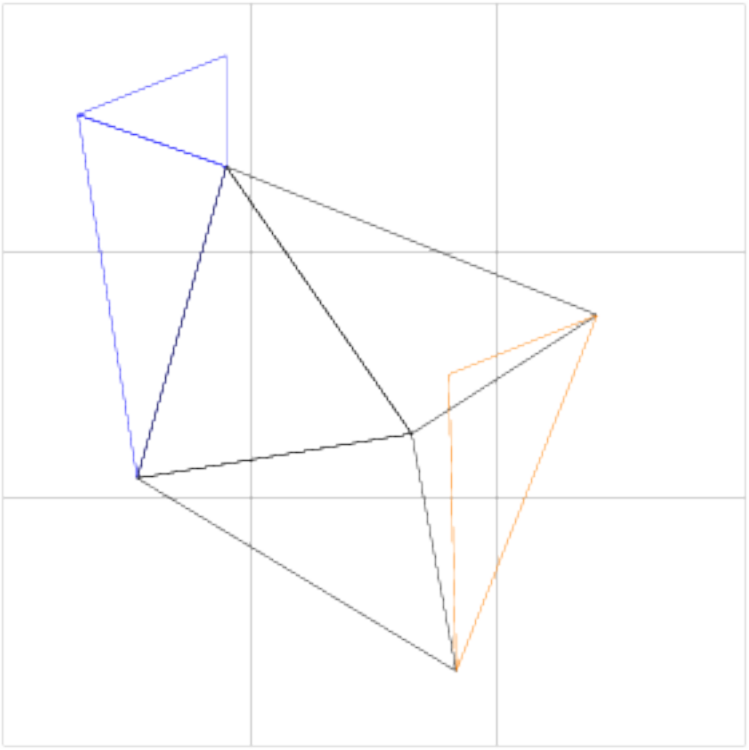
First, construct the `UniformGrid` and load it with triangles.

```
#include "axom/spin/UniformGrid.hpp"
// the UniformGrid will store ints ("thing" indexes) in 3D
using UniformGridType = axom::spin::UniformGrid<int, in3D>;
```

```
BoundingBoxType findBbox(std::vector<TriangleType> & tris);
BoundingBoxType findBbox(TriangleType & tri);

UniformGridType* buildUniformGrid(std::vector<TriangleType> & tris)
{
  // Prepare to construct the UniformGrid.
  BoundingBoxType allbbox = findBbox(tris);
  const PointType & minBBPt = allbbox.getMin();
  const PointType & maxBBPt = allbbox.getMax();
```

(continues on next page)



(continued from previous page)

```
  int tcount = tris.size();

  // The number of bins along one side of the UniformGrid.
  // This is a heuristic.
  int res = (int)(1 + std::pow(tcount, 1/3.));
  int ress[3] = {res, res, res};

  // Construct the UniformGrid with minimum point, maximum point,
  // and number of bins along each side.  Then insert the triangles.
  UniformGridType* ugrid =
    new UniformGridType(minBBPt.data(), maxBBPt.data(), ress);
  for (int i = 0 ; i < tcount ; ++i)
  {
    TriangleType & t1 = tris[i];
    BoundingBoxType bbox = findBbox(t1);
    ugrid->insert(bbox, i);
  }

  return ugrid;
}
```

Then, for every triangle, look up its possible neighbors

```
void findNeighborCandidates(TriangleType & t1,
                            int i,
                            UniformGridType* ugrid,
                            std::vector<int> & neighbors)
{
```

(continues on next page)

(continued from previous page)

```
  BoundingBoxType bbox = findBbox(t1);

  // Get all the bins t1 occupies
  const std::vector<int> bToCheck = ugrid->getBinsForBbox(bbox);
  size_t checkcount = bToCheck.size();

  // Load all the triangles in these bins whose indices are
  // greater than i into a vector.
  for (size_t curb = 0 ; curb < checkcount ; ++curb)
  {
    std::vector<int> ntlist = ugrid->getBinContents(bToCheck[curb]);
    for (size_t j = 0 ; j < ntlist.size() ; ++j)
    {
      if (ntlist[j] > i)
      {
        neighbors.push_back(ntlist[j]);
      }
    }
  }

  // Sort the neighboring triangles, and throw out duplicates.
  // This is not strictly necessary but saves some calls to intersect().
  std::sort(neighbors.begin(), neighbors.end());
  std::vector<int>::iterator jend =
    std::unique(neighbors.begin(), neighbors.end());
  neighbors.erase(jend, neighbors.end());
}
```

and test the triangle against those neighbors.

```
void findTriIntersectionsAccel(
  std::vector<TriangleType> & tris,
  UniformGridType* ugrid,
  std::vector< std::pair<int, int> > & clashes)
{
  int tcount = tris.size();

  // For each triangle t1,
  for (int i = 0 ; i < tcount ; ++i)
  {
    TriangleType & t1 = tris[i];
    std::vector<int> neighbors;
    findNeighborCandidates(t1, i, ugrid, neighbors);

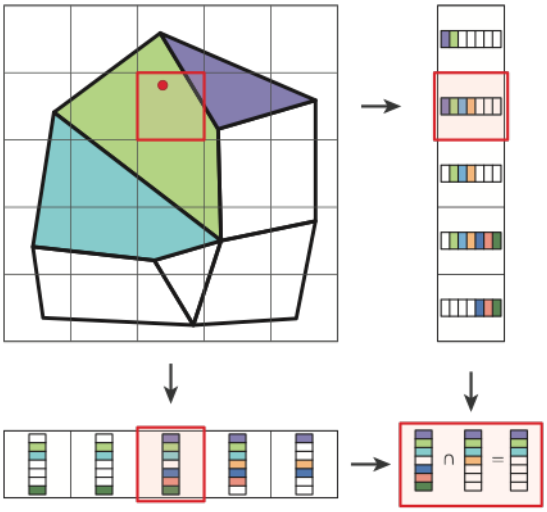
    // Test for intersection between t1 and each of its neighbors.
    int ncount = neighbors.size();
    for (int n = 0 ; n < ncount ; ++n)
    {
      int j = neighbors[n];
      TriangleType & t2 = tris[j];
      if (axom::primal::intersect(t1, t2))
      {
        clashes.push_back(std::make_pair(i, j));
      }
    }
  }
}
```

The `UniformGrid` has its best effect when objects are roughly the same size and evenly distributed over the region of interest, and when bins are close to the characteristic size of objects in the region of interest.

2.5.4 ImplicitGrid

Where the `UniformGrid` divides a rectangular region of interest into bins, the `ImplicitGrid` divides each axis of the region of interest into bins. Each `UniformGrid` bin holds indexes of items that intersect that bin; each `ImplicitGrid` bin is a bitset that indicates the items intersecting that bin.

The following figure shows a 2D `ImplicitGrid` indexing a collection of polygons. A query point determines the bin to search for intersecting polygons. The application retrieves that bin's bitset from each axis and computes bitwise AND operator. The code takes that result and tests for query point intersection (possibly an expensive operation) with each of the polygons indicated by bits set "on."



The `ImplicitGrid` is designed for quick indexing and searching over a static index space in a relatively coarse grid, making it suitable for repeated construction as well as lookup. The following example shows the use of the `ImplicitGrid`. It is similar to the figure but tests a point against 2D triangles instead of polygons.

```
#include "axom/spin/ImplicitGrid.hpp"

// the ImplicitGrid will be in 2D
using IGridT = axom::spin::ImplicitGrid<in2D>;

// useful derived types
using IGridCell = typename IGridT::GridCell;
using ISpacePt = typename IGridT::SpacePoint;
using IBBox = typename IGridT::SpatialBoundingBox;
using IBitsetType = typename IGridT::BitsetType;
using IBitsetIndexType = typename IBitsetType::Index;

// some functions we'll use
bool expensiveTest(ISpacePt & query, Triangle2DType & tri);
void makeTriangles(std::vector<Triangle2DType> & tris);
```

After including the header and setting up types, set up the index.

```
// here are the triangles.
std::vector<Triangle2DType> tris;
makeTriangles(tris);

// Set up the ImplicitGrid: ten bins on an axis
IGridCell res(10);
// establish the domain of the ImplicitGrid.
IBBox bbox(ISpacePt::zero(), ISpacePt::ones());
// room for one hundred elements in the index
const int numElts = tris.size();
IGridT grid(bbox, &res, numElts);

// load the bounding box of each triangle, along with its index,
// into the ImplicitGrid.
for (int i = 0 ; i < numElts ; ++i)
{
  grid.insert(findBbox(tris[i]), i);
}
```

Inexpensive queries to the index reduce the number of calls to a (possibly) expensive test routine.

```
// Here is our query point
ISpacePt qpt = ISpacePt::make_point(0.63, 0.42);

// Which triangles might it intersect?
IBitsetType candidates = grid.getCandidates(qpt);
int totalTrue = 0;

// Iterate over the bitset and test the candidates expensively.
IBitsetIndexType index = candidates.find_first();
while (index != IBitsetType::npos)
{
  if (expensiveTest(qpt, tris[index]))
  {
    totalTrue += 1;
  }
  index = candidates.find_next(index);
}
```

2.5.5 BVHTree

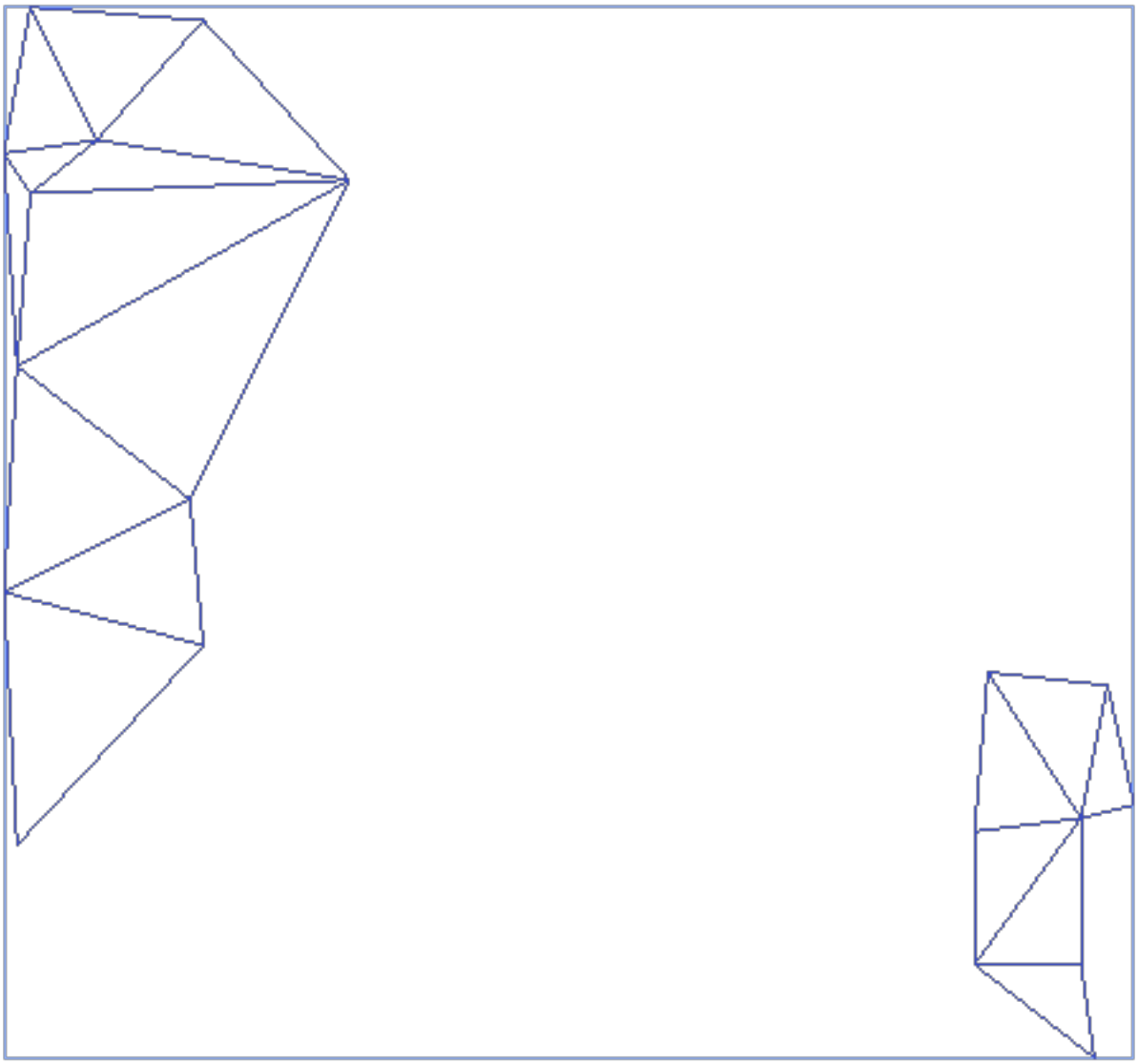
The `BVHTree` implements a bounding volume hierarchy tree. This data structure recursively subdivides a rectilinear region of interest into a "tree" of subregions, stopping when a subregion contains less than some number of objects or when the tree reaches a specified height. Similar to `UniformGrid`, subregions are also called bins.

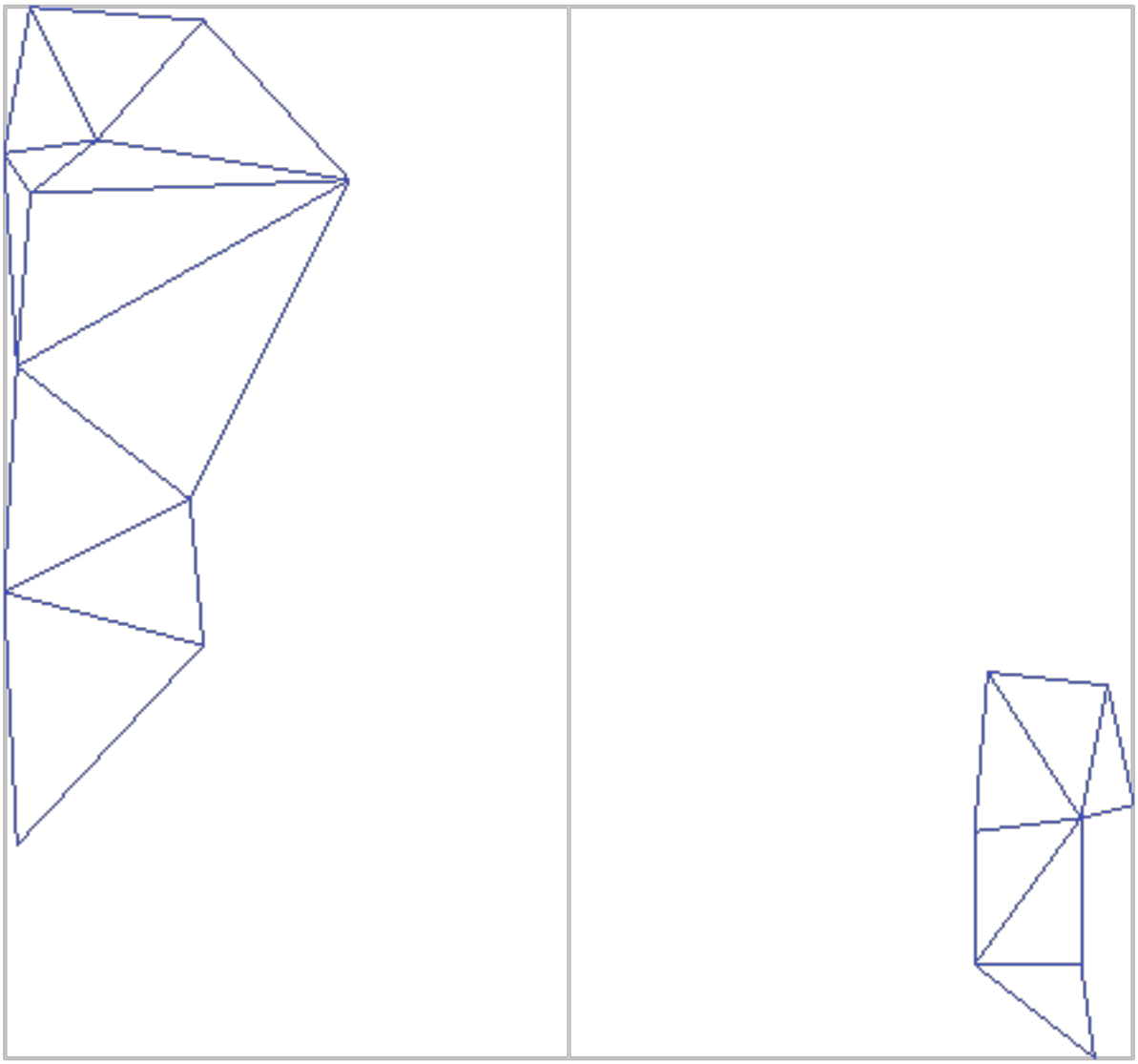
The `BVHTree` is well-suited for particle-mesh or ray-mesh intersection tests. It is also well-suited to data sets where the contents are unevenly distributed, since the bins are subdivided based on their contents. The figure below shows several 2D triangles and their bounding box, which serves as the root bin in the tree.

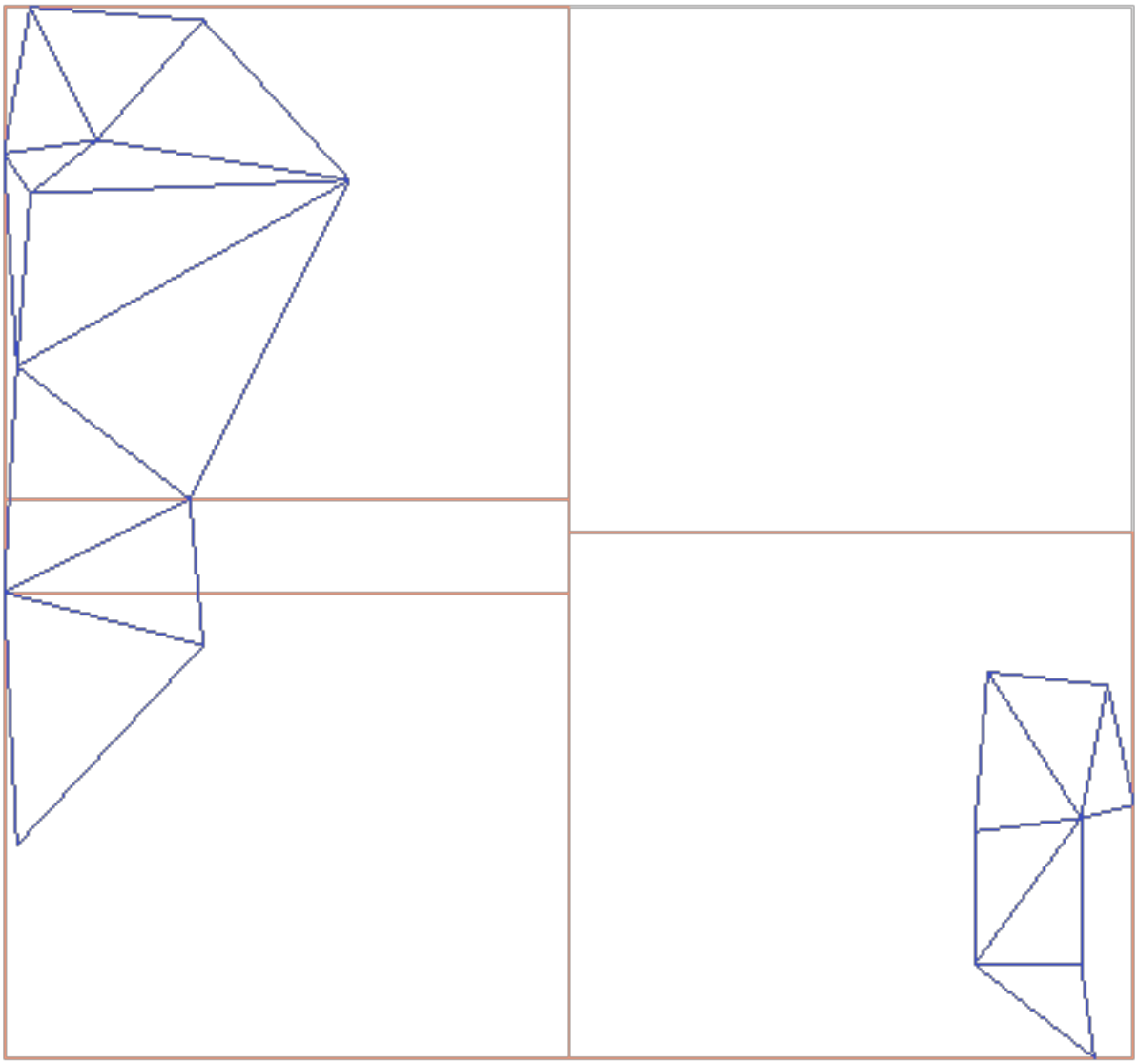
The `BVHTree::build()` method recurses into each bin, creating up to two child bins depending on how many objects are located there and how they are distributed.

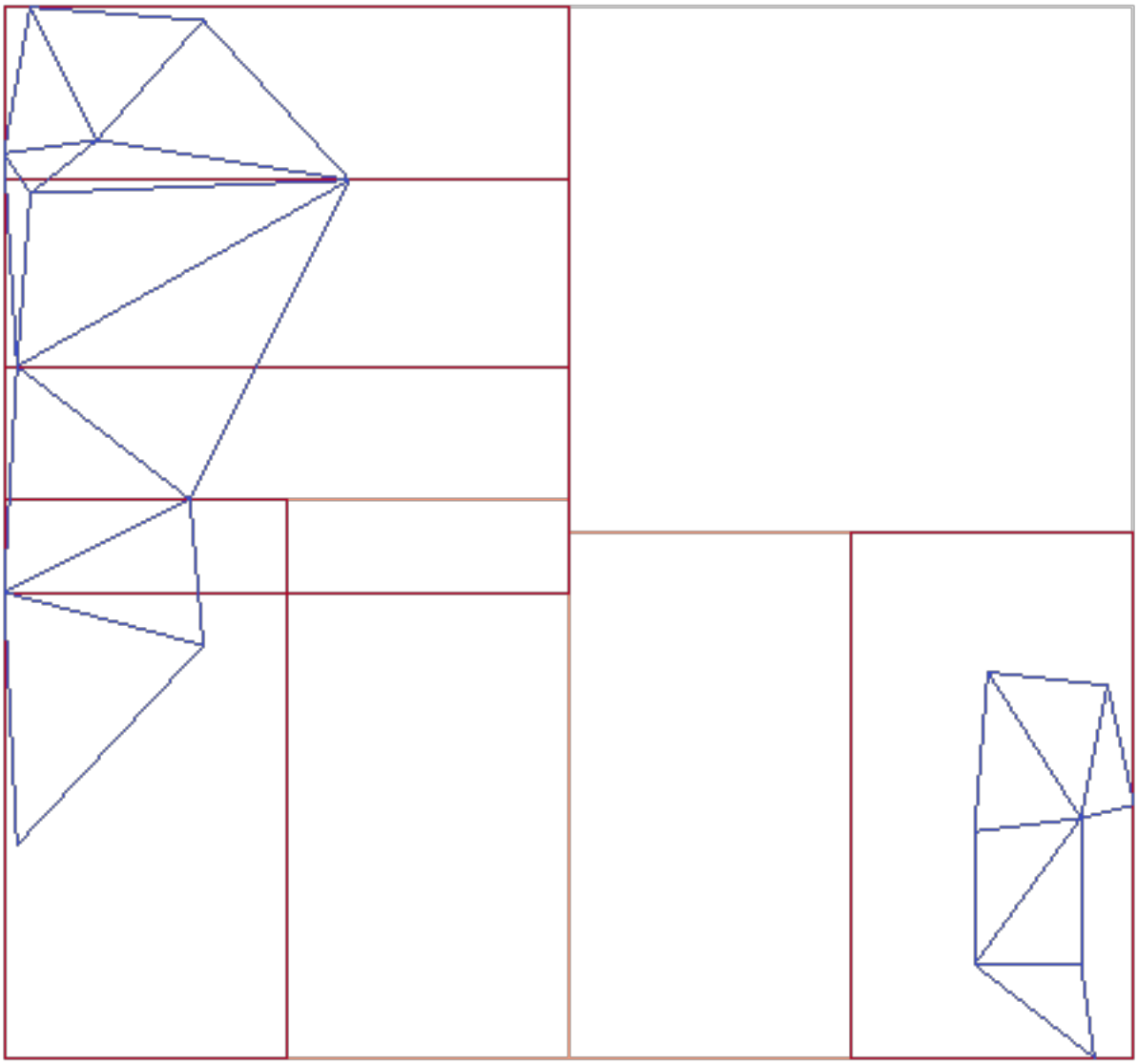
Unlike the `UniformGrid`, `BVHTree` bins can overlap.

The following code example shows how a `BVHTree` can be used to accelerate a point-mesh intersection algorithm. First, we insert all triangles into the index and call `BVHTree::build()`.









```
#include "axom/spin/BVHTree.hpp"
// the BVHTree is in 2D, storing an index to 2D triangles
using BVHTree2DType = axom::spin::BVHTree<int, in2D>;
// supporting classes
using BoundingBox2DType = axom::primal::BoundingBox<double, in2D>;
using Point2DType = axom::primal::Point<double, in2D>;
using Triangle2DType = axom::primal::Triangle<double, in2D>;
```

```
BoundingBox2DType findBbox(Triangle2DType & tri);

BVHTree2DType* buildBVHTree(std::vector<Triangle2DType> & tris)
{
  // Initialize BVHTree with the triangles
  const int MaxBinFill = 1;
  const int MaxLevels = 4;
  int tricount = tris.size();
  BVHTree2DType* tree  = new BVHTree2DType( tricount, MaxLevels );

  for ( int i=0 ; i < tricount ; ++i )
  {
    tree->insert( findBbox( tris[i] ), i );
  }

  // Build bounding volume hierarchy
  tree->build( MaxBinFill );

  return tree;
}
```

After the structure is built, make a list of triangles that are candidate neighbors to the query point. Call `BVHTree::find()` to get the list of bins that the query point intersects. The key idea of `find()` is that testing for probe intersection with a bin (bounding box) is cheap. If a bin intersection test fails (misses), the contents of the bin are cheaply pruned out of the search. If the probe does intersect a bin, the next level of bins is tested for probe intersection. Without the acceleration data structure, each probe point must be tested against each triangle.

```
void findCandidateBVHTreeBins(BVHTree2DType* tree,
                              Point2DType ppoint,
                              std::vector<int> & candidates)
{
  // Which triangles does the probe point intersect?
  // Get the candidate bins
  std::vector<int> bins;
  tree->find(ppoint, bins);
  size_t nbins = bins.size();

  // for each candidate bin,
  for (size_t curb = 0 ; curb < nbins ; ++curb)
  {
    // get its size and object array
    int bcount = tree->getBucketNumObjects(bins[curb]);
    const int* ary = tree->getBucketObjectArray(bins[curb]);

    // For each object in the current bin,
    for (int j = 0 ; j < bcount ; ++j)
    {
      // find the tree's internal object ID
      int treeObjID = ary[j];
```

(continues on next page)

(continued from previous page)

```
      // and use it to retrieve the triangle's ID.
      int triID = tree->getObjectData(treeObjID);

      // Then store the ID in the candidates list.
      candidates.push_back(triID);
    }
  }

  // Sort the candidate triangles, and throw out duplicates.
  // This is not strictly necessary but saves some calls to checkInTriangle().
  std::sort(candidates.begin(), candidates.end());
  std::vector<int>::iterator jend =
    std::unique(candidates.begin(), candidates.end());
  candidates.erase(jend, candidates.end());
}
```

Finally, test the point against all candidate neighbor triangles.

```
void findIntersectionsWithCandidates(std::vector<Triangle2DType> & tris,
                                     std::vector<int> & candidates,
                                     Point2DType ppoint,
                                     std::vector<int> & intersections)
{
  // Test if ppoint lands in any of its neighbor triangles.
  int csize = candidates.size();
  for (int i = 0 ; i < csize ; ++i)
  {
    Triangle2DType & t = tris[candidates[i]];
    if (t.checkInTriangle(ppoint))
    {
      intersections.push_back(candidates[i]);
    }
  }
}
```

2.5.6 SpatialOctree

Axom provides an implementation of the octree spatial index. The `SpatialOctree` recursively divides a bounding box into a hierarchy of non-intersecting bounding boxes. Each level of subdivision divides the bounding box of interest along each of its dimensions, so 2D `SpatialOctree` objects contain four child bounding boxes at each level, while 3D objects contain eight children at each level.

The `Octree` class hierarchy is useful for building custom spatial acceleration data structures, such as `quest::InOutOctree`.

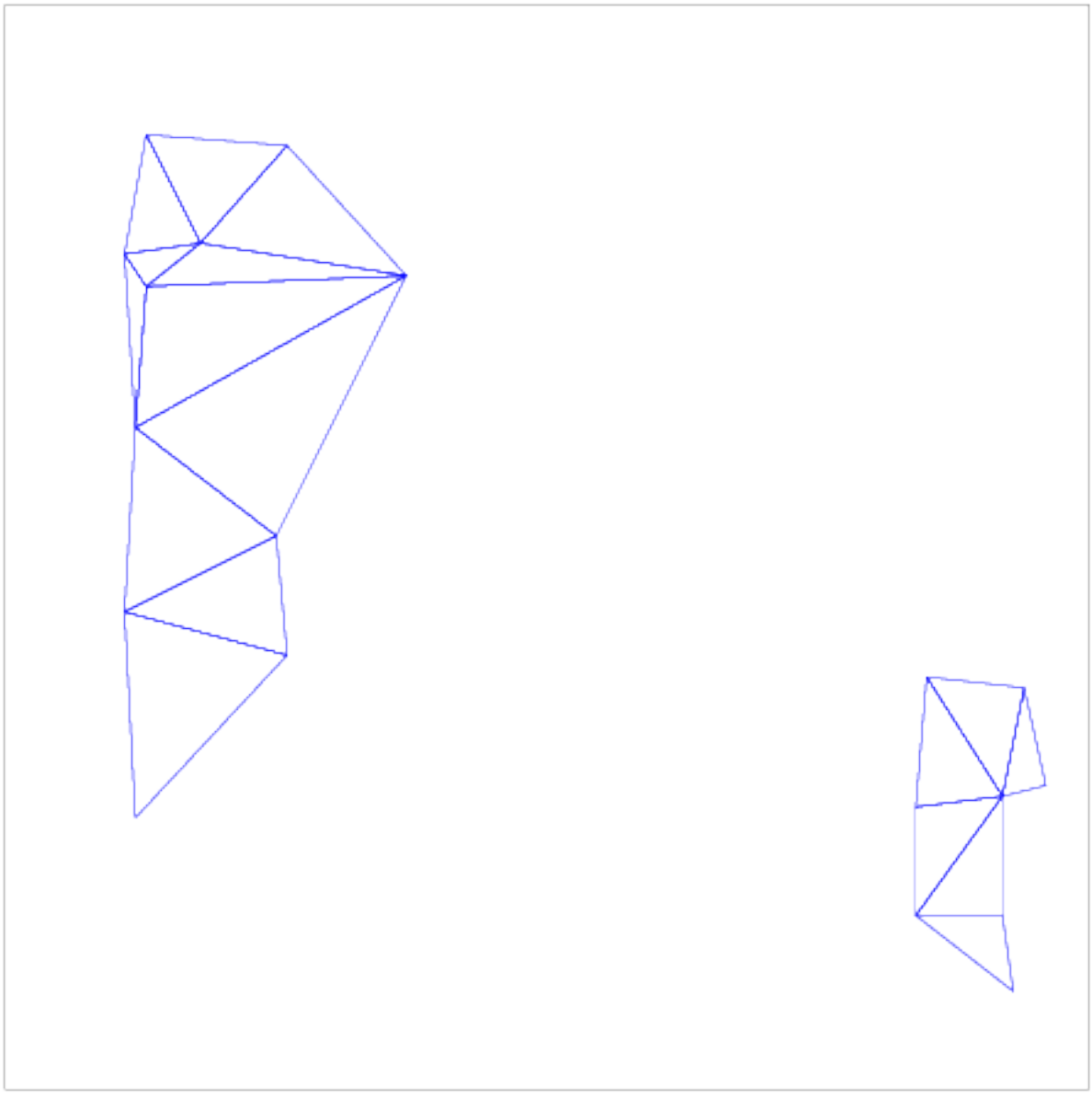
The figure below shows the construction of several levels of a 2D octree.

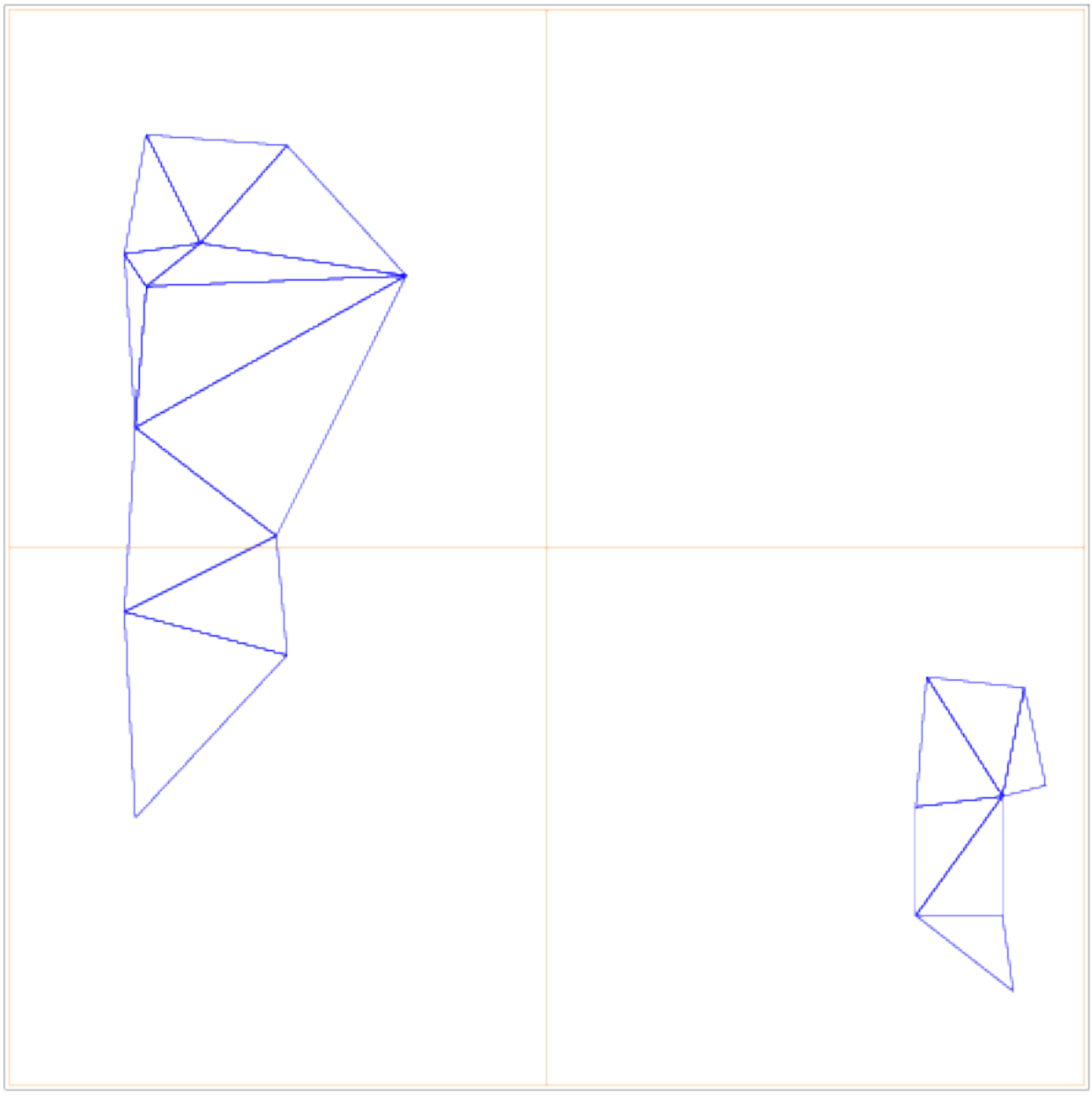
In contrast to a BVHTree, which computes a bounding box at each step, the octree structure begins with a user-specified bounding box.

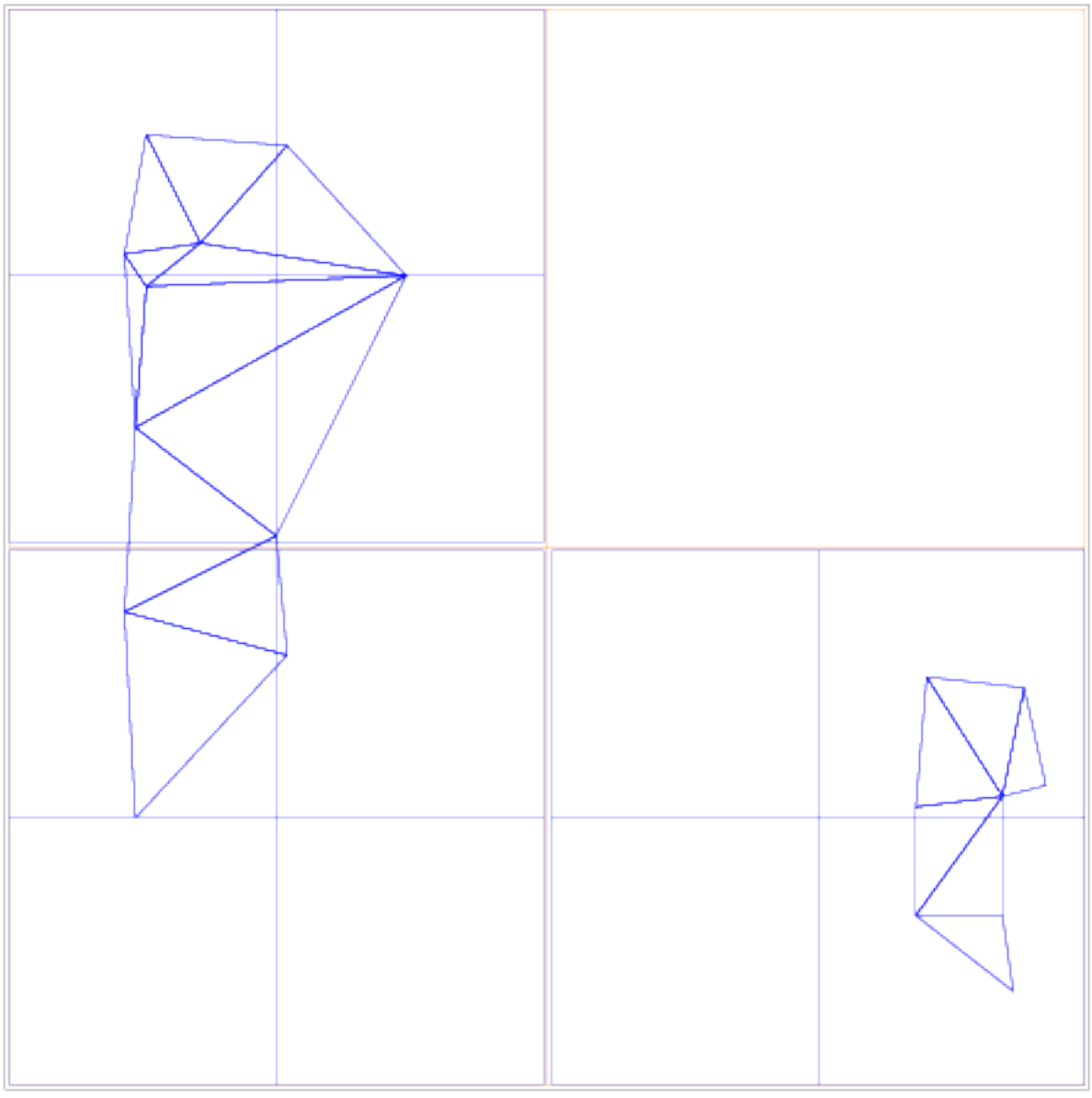
The octree divides all dimensions in half at each step.

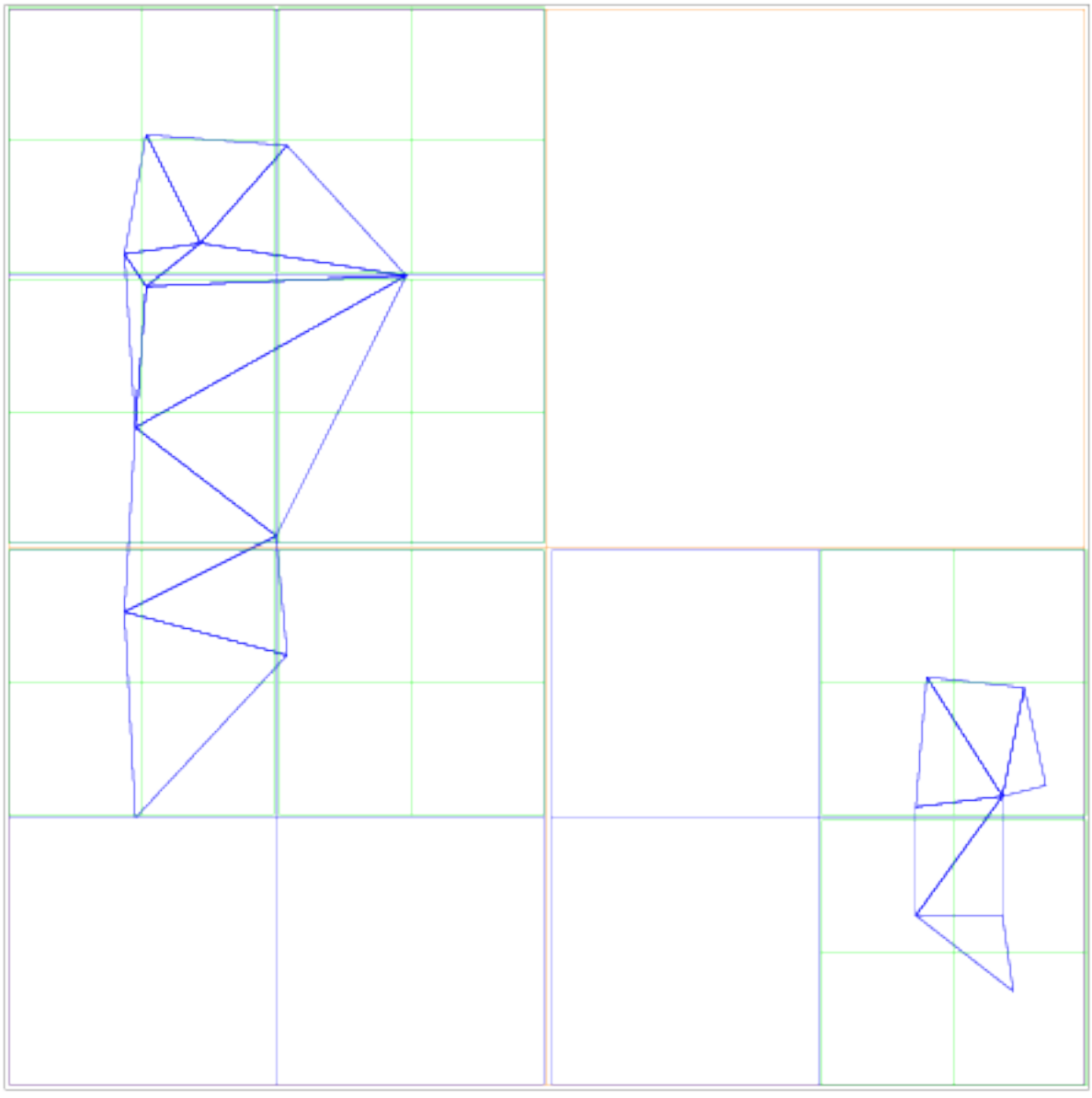
Similar to the BVHTree, the Octree divides a bounding box only if an object intersects that bounding box. In contrast to the BVHTree, the bounding box bins are non-intersecting, and division does not depend on the data in the bounding box. An N-dimensional octree divides into 2^N bounding boxes at each step.

The following code example shows use of the `SpatialOctree`. Include headers and define types:









```
#include "axom/spin/SpatialOctree.hpp"

using LeafNodeType = axom::spin::BlockData;

using OctreeType = axom::spin::SpatialOctree<in3D, LeafNodeType>;
using OctBlockIndex = OctreeType::BlockIndex;
using OctSpacePt = OctreeType::SpacePt;
using OctBBox = OctreeType::GeometricBoundingBox;
```

Then, instantiate the `SpatialOctree` and locate or refine blocks that contain query points.

```
  OctBBox bb(OctSpacePt(10), OctSpacePt(20));

  // Generate a point within the bounding box
  double alpha = 2./3.;
  OctSpacePt queryPt = OctSpacePt::lerp(bb.getMin(), bb.getMax(), alpha);

  // Instantiate the Octree
  OctreeType octree(bb);

  // Find the block containing the query point
  OctBlockIndex leafBlock = octree.findLeafBlock(queryPt);
  // and the bounding box of the block.
  OctBBox leafBB = octree.blockBoundingBox(leafBlock);

  for(int i=0 ; i< octree.maxInternalLevel() ; ++i)
  {
    // SpatialOctree allows a code to refine (subdivide) a block
    octree.refineLeaf( leafBlock );
    // and locate the (new) child block containing the query point.
    leafBlock = octree.findLeafBlock(queryPt);
  }
```

Unlike the `BVHTree` class, the `SpatialOctree` is intended as a building block for further specialization. Please see the `quest::InOutOctree` as an example of this.

Some ancillary classes used in the implementation of `SpatialOctree` include `BlockData`, which ties data to a block; `Brood`, used to construct and organize sibling blocks; `OctreeBase`, implementing non-geometric operations such as refinement and identification of parent or child nodes; and `SparseOctreeLevel` and `DenseOctreeLevel`, which hold the blocks at any one level of the `SpatialOctree`. Of these, library users will probably be most interested in providing a custom implementation of `BlockData` to hold algorithm data associated with a box within an octree. See the `quest::InOutOctree` class for an example of this.

2.6 Quest User Documentation

The Quest component of Axom provides several spatial operations and queries on a `mint::Mesh`.

- Operations
  - *Read a surface mesh* from an STL file
  - *Check for some common mesh errors; deduplicate vertices*
    - vertex welding: merge vertices closer than a specified distance “epsilon”
    - find self-intersections and degenerate triangles in a surface mesh
    - watertightness test: is a surface mesh a watertight manifold?

- Point queries
  - Surface mesh point queries *in C* or *in C++*
    - in/out query: is a point inside or outside a surface mesh?
    - signed distance query: find the minimum distance from a query point to a surface mesh
  - *Point in cell query*: for a query point, find the cell of the mesh that holds the point and the point's isoparametric coordinates within that cell
  - *All nearest neighbors*: given a list of point locations and regions, find all neighbors of each point in a different region

2.6.1 Reading in a mesh

Applications commonly need to read a mesh file from disk. Quest provides the `STLReader` class, which can read binary or ASCII STL files, as well as the `PSTLReader` class for use in parallel codes. STL (stereolithography) is a common file format for triangle surface meshes. The STL reader classes will read the file from disk and build a `mint::Mesh` object.

The code examples are excerpts from the file `<axom>/src/tools/mesh_tester.cpp`.

We include the STL reader header

```
#include "axom/quest/stl/STLReader.hpp"
```

and also the mint Mesh and UnstructuredMesh headers.

```
#include "axom/mint/mesh/Mesh.hpp"
#include "axom/mint/mesh/UnstructuredMesh.hpp"
```

For convenience, we use typedefs in the axom namespace.

```
using namespace axom;

using UMesh = mint::UnstructuredMesh< mint::SINGLE_SHAPE >;
```

The following example shows usage of the STLReader class:

```
  // Read file
  SLIC_INFO("Reading file: '" <<  params.stlInput << "'...\n");
  quest::STLReader* reader = new quest::STLReader();
  reader->setFileName( params.stlInput );
  reader->read();

  // Get surface mesh
  UMesh* surface_mesh = new UMesh( 3, mint::TRIANGLE );
  reader->getMesh( surface_mesh );

  // Delete the reader
  delete reader;
  reader = nullptr;

  SLIC_INFO(
    "Mesh has " << surface_mesh->getNumberOfNodes() << " vertices and "
                <<  surface_mesh->getNumberOfCells() << " triangles.");
```

After reading the STL file, the `STLReader::getMesh` method gives access to the underlying mesh data. The reader may then be deleted.

2.6.2 Check and repair a mesh

The STL file format specifies triangles without de-duplicating their vertices. Vertex welding is needed for several mesh algorithms that require a watertight manifold. Additionally, mesh files often contain errors and require some kind of cleanup. The following code examples are excerpts from the file `<axom>/src/tools/mesh_tester.cpp`.

Quest provides a function to weld vertices within a distance of some specified epsilon. This function takes arguments `mint::UnstructuredMesh< mint::SINGLE_SHAPE > **surface_mesh` and `double epsilon`, and modifies `surface_mesh`. In addition to the mint Mesh and UnstructuredMesh headers (see previous page), we include the headers declaring the functions for checking and repairing surface meshes.

```
#include "axom/quest/MeshTester.hpp"
```

The function call itself:

```
    quest::weldTriMeshVertices(&surface_mesh, params.weldThreshold);
```

One problem that can occur in a surface mesh is self-intersection. A well-formed mesh will have each triangle touching the edge of each of its neighbors. Intersecting or degenerate triangles can cause problems for some spatial algorithms. To detect such problems using Quest, we first make containers to record defects that might be found.

```
    std::vector< std::pair<int, int> > collisions;
    std::vector<int> degenerate;
```

Then, we call the function to detect self-intersections and degenerate triangles.

```
      // Use a spatial index
      quest::findTriMeshIntersections(surface_mesh,
                                      collisions,
                                      degenerate,
                                      params.resolution);
```

After calling `findTriMeshIntersections`, `collisions` will hold the indexes of each pair of intersecting triangles and `degenerate` will contain the index of each degenerate triangle. The user code can then address or report any triangles found. Mesh repair beyond welding close vertices is beyond the scope of the Quest component.

Check for watertightness

Before using Quest's surface point queries, a mesh must be watertight, with no cracks or holes. Quest provides a function to test for watertightness, declared in the same header file as the tests self-intersection and an enum indicating watertightness of a mesh. If the code is working with a mesh read in from an STL file, *weld the vertices* (see above) before checking for watertightness!

```
    quest::WatertightStatus wtstat =
      quest::isSurfaceMeshWatertight(surface_mesh);
```

This routine builds the face relation of the supplied triangle surface mesh. The face of a triangle is a one-dimensional edge. If the mesh is big, building the face relation may take some time. Once built, the routine queries face relation: each edge of every triangle must be incident in two triangles. If the mesh has a defect where more than two triangles share an edge, the routine returns `CHECK_FAILED`. If the mesh has a hole, at least one triangle edge is incident in only one triangle and the routine returns `NOT_WATERTIGHT`. Otherwise, each edge is incident in two triangles, and the routine returns `WATERTIGHT`.

After testing for watertightness, report the result.

```
  switch (wtstat)
  {
  case quest::WatertightStatus::WATERTIGHT:
    std::cout << "The mesh is watertight." << std::endl;
    break;
  case quest::WatertightStatus::NOT_WATERTIGHT:
    std::cout << "The mesh is not watertight: at least one " <<
      "boundary edge was detected." << std::endl;
    break;
  default:
    std::cout << "An error was encountered while checking." << std::endl <<
      "This may be due to a non-manifold mesh." << std::endl;
    break;
  }
```

After an STL mesh has

- been read in with `STLReader`,
- had vertices welded using `weldTriMeshVertices()`,
- contains no self-intersections as reported by `findTriMeshIntersections()`,
- and is watertight as reported by `isSurfaceMeshWatertight()`,

the in-out and distance field queries will work as designed.

2.6.3 Surface mesh point queries: C API

Quest provides the in/out and distance field queries to test a point against a surface mesh. These queries take a mesh composed of triangles in 3D and a query point. The in/out query tests whether the point is contained within the surface mesh. The distance query calculates the signed distance from the query point to the mesh.

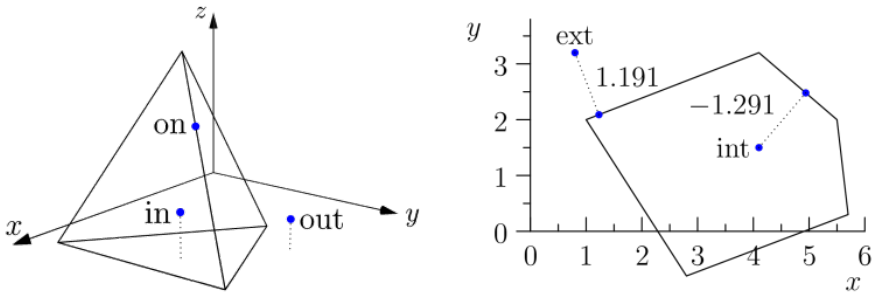


Fig. 2.5: Types of point-vs-surface-mesh queries provided by Quest. **Left:** In/out query, characterizing points as inside or outside the mesh. Points that lie on the boundary might or might not be categorized as inside the mesh. **Right:** Distance query, calculating the signed distance from each query point to its closest point on the mesh. A negative result indicates an interior query point.

The following examples show Quest's C interface to these queries. The general pattern is to set some query parameters, then pass a `mint::Mesh *` or file name string to an initialization function, call an `evaluate` function for each query point, then clean up with a `finalize` function.

In/out C API

The in/out query operates on a 3D surface mesh, that is, triangles forming a watertight surface enclosing a 3D volume. The in/out API utilizes integer-valued return codes with values `quest::QUEST_INOUT_SUCCESS` and `quest::QUEST_INOUT_FAILED` to indicate the success of each operation. These examples are excerpted from `<axom>/src/axom/quest/examples/quest_inout_interface.cpp`.

To get started, we first include some header files.

```
#include "axom/quest/interface/inout.hpp"

#ifdef AXOM_USE_MPI
  #include <mpi.h>
#endif
```

Before initializing the query, we can set some parameters, for example, to control the logging verbosity and to set a threshold for welding vertices of the triangle mesh while generating the spatial index.

```
  // -- Set quest_inout parameters
  rc = quest::inout_set_verbose(isVerbose);
  if(rc != quest::QUEST_INOUT_SUCCESS)
  {
    cleanAbort();
  }

  rc = quest::inout_set_vertex_weld_threshold( weldThresh );
  if(rc != quest::QUEST_INOUT_SUCCESS)
  {
    cleanAbort();
  }
```

By default, the verbosity is set to `false` and the welding threshold is set to `1E-9`.

We are now ready to initialize the query.

```
    #ifdef AXOM_USE_MPI
    rc = quest::inout_init( fileName, MPI_COMM_WORLD);
    #else
    rc = quest::inout_init( fileName);
    #endif
```

The variable `fileName` is a `std::string` that indicates a triangle mesh file. Another overload of `quest::inout_init()` lets a user code pass a reference to a `mint::Mesh*` to query meshes that were previously read in or built up. If initialization succeeded (returned `quest::QUEST_INOUT_SUCCESS`), the code can

- Query the mesh bounds with `quest::inout_mesh_min_bounds(double[3])` and `quest::inout_mesh_max_bounds(double[3])`.
- Find mesh center of mass with `quest::inout_mesh_center_of_mass(double[3])`.
- Test if a query point is inside the mesh surface. In this example `pt` is a `double[3]` and `numInside` is a running total.

```
    const double x = pt[0];
    const double y = pt[1];
    const double z = pt[2];

    const bool ins = quest::inout_evaluate(x,y,z);
    numInside += ins ? 1 : 0;
```

Once we are done, we clean up with the following command:

```
quest::inout_finalize();
```

Signed Distance query C API

Excerpted from `<axom>/src/axom/quest/examples/quest_signed_distance_interface.cpp`.

Quest header:

```
#include "axom/quest.hpp"
```

Before initialization, a code can set some parameters for the distance query.

- Passing `true` to `quest::signed_distance_set_closed_surface(bool)` lets the user read in a non-closed "terrain mesh" that divides its bounding box into "above" (positive distance to the surface mesh) and "below" (negative distance).
- `quest::signed_distance_set_max_levels()` and `quest::signed_distance_set_max_occupancy()` control options for the BVH tree spatial index used to accelerate signed distance queries.
- If the SLIC logging environment is in use, passing `true` to `quest::signed_distance_set_verbose()` will turn on verbose logging.
- Use of MPI-3 shared memory can be enabled by passing `true` to `quest::signed_distance_use_shared_memory()`.

The distance query must be initialized before use. In this example, `Arguments` is a POD struct containing parameters to the executable. As with the in/out query, a user code may pass either a file name or a reference to a `mint::Mesh *` to `quest::signed_distance_init()`.

```
int rc = quest::signed_distance_init( Arguments.fileName, global_comm );
```

Once the query is initialized, the user code may retrieve mesh bounds with `quest::signed_distance_get_mesh_bounds(double* lo, double* hi)`. Test query points against the mesh with `quest::signed_distance_evaluate()`. Here, `pt` is a `double[3]`, `phi` is a `double` array, and `inode` is an integer.

```
   phi[ inode ] = quest::signed_distance_evaluate( pt[0], pt[1], pt[2] );
```

Finally, clean up.

```
quest::signed_distance_finalize( );
```

2.6.4 Surface mesh point queries: C++ API

Codes written in C++ may use the object-oriented C++ APIs to perform in/out and signed distance queries. In addition to language choice, the C++ API lets a code work with more than one mesh at the same time. Unlike the C API, the C++ API for in/out and signed distance queries has no initializer taking a file name: readying the mesh is a separate, prior step.

In/out Octree

The C++ in/out query is provided by the `quest::InOutOctree` class, from the following header. See `<axom>/src/axom/quest/tests/quest_inout_octree.cpp`.

```
#include "axom/quest/InOutOctree.hpp"
```

Some type aliases are useful for the sake of brevity. The class is templated on the dimensionality of the mesh. Currently, only meshes in 3D are supported; here `DIM` equals 3.

```
using Octree3D = axom::quest::InOutOctree<DIM>;

using GeometricBoundingBox = Octree3D::GeometricBoundingBox;
using SpacePt = Octree3D::SpacePt;
```

Instantiate the object using `GeometricBoundingBox bbox` and a mesh, and generate the index.

```
  Octree3D octree(bbox, mesh);
  octree.generateIndex();
```

Test a query point.

```
SpacePt pt = SpacePt::make_point(2., 3., 1.);
bool inside = octree.within(pt);
```

All cleanup happens when the index object's destructor is called (in this case, when the variable `octree` goes out of scope).

Signed Distance

The C++ signed distance query is provided by the `quest::SignedDistance` class, which wraps an instance of `primal::BVHTree`. Examples from `<axom>/src/axom/quest/tests/quest_signed_distance.cpp`.

Class header:

```
#include "axom/primal/geometry/Point.hpp"

#include "axom/quest/SignedDistance.hpp"  // quest::SignedDistance
```

The constructor takes several arguments. Here, `surface_mesh` is a pointer to a triangle surface mesh. The second argument indicates the mesh is a watertight mesh, a manifold. The signed distance from a point to a manifold is mathematically well-defined. When the input is not a closed surface mesh, the mesh must span the entire computational mesh domain, dividing it into two regions. The third and fourth arguments are used to build the underlying BVH tree spatial index. They indicate that BVH tree buckets will be split after 25 objects and that the BVH tree will contain at most 10 levels. These are safe default values and can be adjusted if application benchmarking shows a need. Note that the second and subsequent arguments to the constructor correspond to `quest::signed_distance_set` functions in the C API.

As with the `InOutOctree`, the class is templated on the dimensionality of the mesh, with only 3D meshes being supported.

```
  axom::quest::SignedDistance< 3 > signed_distance( surface_mesh,true, 25, 10 );
```

Test a query point.

```
axom::primal::Point< double,3 > pt =
  axom::primal::Point< double,3 >::make_point(2., 3., 1.);
double signedDistance = signed_distance.computeDistance(pt);
```

The object destructor takes care of all cleanup.

2.6.5 Point-in-cell query

The point-in-cell query is particularly useful with high-order meshes. It takes a 2D quad or 3D hex mesh and locates a query point in that mesh, reporting both the cell containing the point and the isoparametric coordinates of the query point within the cell.

Note: If a query point lies on the boundary in more than one cell, the point-in-cell query will return the cell with the lowest index.

If the point lies outside of any cell, the query returns the special value `quest::PointInCellTraits<mesh_tag>::NO_CELL` or using the MeshTraits typedef, `MeshTraits::NO_CELL`.

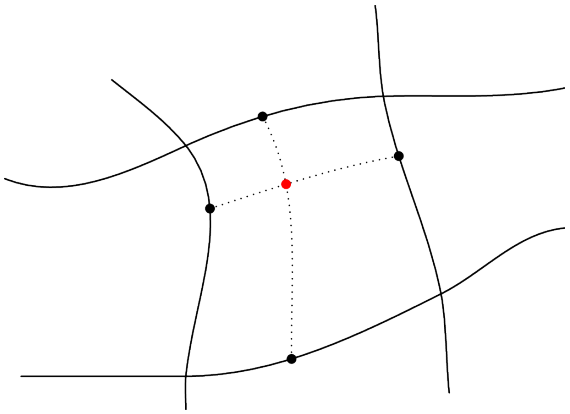


Fig. 2.6: Point-in-cell query, identifying the cell that contains a physical point and finding the point's isoparametric coordinates within the cell.

The point-in-cell query is currently implemented using MFEM, so to use this query Axom must be compiled with MFEM as a dependency. The following example (from `<axom>/src/tests/quest_point_in_cell_mfem.cpp`) shows the use of the query, beginning with inclusion of required header files.

```
#include "axom/quest/PointInCell.hpp"

#ifdef AXOM_USE_MFEM
# include "axom/quest/detail/PointInCellMeshWrapper_mfem.hpp"
#else
# error "Quest's PointInCell tests on mfem meshes requires mfem library."
#endif
```

We use typedefs for the sake of brevity. The class is templated on a struct (provided by Quest, referred to as `mesh_tag`) that is used to select MFEM as the backend implementation for point location. To implement a new backend, a developer must declare a new (empty) struct and provide a specialization of the `PointInCellTraits` and `PointInCellMeshWrapper` templated on the new struct that fulfill the interface documented for those classes.

```
  typedef axom::primal::Point<int,DIM> GridCell;

  typedef axom::quest::quest_point_in_cell_mfem_tag mesh_tag;
  typedef axom::quest::PointInCellTraits<mesh_tag> MeshTraits;

  typedef axom::quest::PointInCell<mesh_tag> PointInCellType;
```

Instantiate the object using an MFEM mesh and a spatial index 25 bins on a side.

```
    PointInCellType spatialIndex(m_mesh, GridCell(25).data() );
```

Test a query point. Here `idx` receives the ID of the cell that contains `queryPoint` and `isoPar` is a `primal::Point` that receives the isoparametric coordinates of `queryPoint` within cell `idx`.

```
      int idx = spatialIndex.locatePoint( queryPoint.data(), isoPar.data() );
```

From cell ID and isoparametric coordinates, reconstruct the input physical coordinates.

```
        SpacePt untransformPt;
        spatialIndex.reconstructPoint(idx, isoPar.data(),
                                      untransformPt.data() );
```

The destructor of the index object cleans up resources used (in this case, when the variable `spatialIndex` goes out of scope).

2.6.6 All nearest neighbors query

Some applications need to work with the interaction of points that are close to each other. For example, in one technique used for additive manufacturing, the particles in a powder bed are melted using a laser. Particle behavior against nearby particles determines droplet formation. The all-nearest-neighbors query takes as input a list of point positions and regions and a maximum radius. For each point, using the L2 norm as the distance measure, the query calculates the nearest neighbor point not in the same region, as shown in the figure.

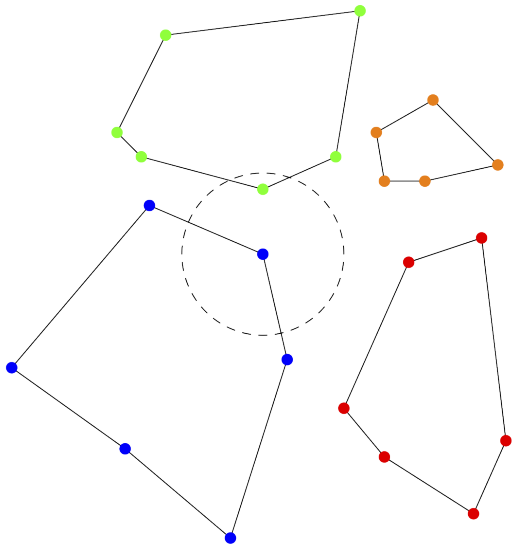


Fig. 2.7: All nearest neighbors query. Here, points belong to one of four regions. Given a maximum search radius, the query finds the closest neighbor to each point in another region.

Here is an example of query usage, from `<axom>/src/axom/quest/tests/quest_all_nearest_neighbors.cpp`.

First, include the header.

```
#include "axom/quest/AllNearestNeighbors.hpp"
```

Query input consists of the points' x, y, and z positions and region IDs, the point count, and the search radius.

```
  double x[] = {-1.2, -1.0, -0.8, -1.0, 0.8,  1.0, 1.2, 1.0};
  double y[] = { 0.0, -0.2,  0.0,  0.2, 0.0, -0.2, 0.0, 0.2};
  double z[] = { 0.0,  0.0,  0.0,  0.0, 0.0,  0.0, 0.0, 0.0};
  int region[] = {0, 0, 0, 0, 1, 1, 1, 1};
  int n = 8;
  double limit = 1.9;
```

For each input point, the output arrays give the point's neighbor index and squared distance from the point to that neighbor.

```
    axom::quest::all_nearest_neighbors(x, y, z, region, n, limit,
                                       neighbor, dsq);
```

2.7 Mint User Guide

Mint provides a *comprehensive mesh data model* and a mesh-aware, fine-grain, parallel execution model that underpins the development of computational tools and numerical discretization methods. Thereby, enable implementations that are born *parallel* and *portable* to new and emerging architectures.

Key Features

- Support for 1D/2D/3D mesh geometry.
- Efficient data structures to represent *Particle Mesh*, *Structured Mesh* and *Unstructured Mesh* types, including unstructured meshes with *Mixed Cell Type Topology*.
- Native support for a variety of commonly employed *Cell Types*.
- A flexible *Mesh Storage Management* system, which can optionally inter-operate with Sidre as the underlying, in-memory, hierarchical datastore, facilitating the integration across packages.
- Basic support for *Finite Elements*, consisting of commonly employed *shape functions* and *quadratures*.
- A Mesh-Aware *Execution Model*, based on the RAJA programming model abstraction layer that supports on-node parallelism for mesh-traversals, enabling the implementation of computational kernels that are born parallel and portable across different processor architectures.

Requirements

Mint is designed to be *light-weight* and *self-contained*. The only requirement for using Mint is a C++11 compliant compiler. However, to realize the full spectrum of capabilities, support for the following third-party libraries is provided:

- RAJA, used for the parallel execution and portability layer.
- Conduit , for using Sidre as the *Mesh Storage Management* system.
- Umpire, for memory management on next-generation architectures.

For further information on how to build the Axom Toolkit using these third-party libraries, consult the Axom Quick Start Guide.

About this Guide

This guide discusses the basic concepts and architecture of Mint.

- The *Getting Started with Mint* section provides a quick introduction to Mint, designed to illustrate high-level concepts and key capabilities, in the context of a small working example.
- The *Tutorial* section provides code snippets that demonstrate specific topics in a structured and simple format.
- For complete documentation of the interfaces of the various classes and functions in Mint consult the Mint Doxygen API Documentation.
- Complete examples and code walk-throughs of mini-apps using Mint are provided in the *Examples* section.

Additional questions, feature requests or bug reports on Mint can be submitted by creating a new issue on Github or by sending e-mail to the Axom Developers mailing list at axom-dev@llnl.gov.

2.7.1 Getting Started with Mint

This section presents a complete code walk-through of an example Mint application, designed to illustrate some of the key concepts and capabilities of Mint. The complete *Mint Application Code Example*, is included in the *Appendix* section and is also available in the Axom source code under `src/axom/mint/examples/user_guide/mint_getting_started.cpp`.

The example Mint application demonstrates how Mint is used to develop kernels that are both *mesh-agnostic* and *device-agnostic*.

Tip: Mint's RAJA-based *Execution Model* helps facilitate the implementation of various computational kernels that are both *mesh-agnostic* and *device-agnostic*. Both kernels discussed in this example do not make any assumptions about the underlying mesh type or the target execution device, e.g. CPU or GPU. Consequently, the same implementation can operate on both *Structured Mesh* and *Unstructured Mesh* types and run sequentially or in parallel on all execution devices supported through RAJA.

Prerequisites

Understanding the discussion and material presented in this section requires:

- Working knowledge of C++ templates and Lambda Expression functions.
- High-level understanding of nested memory hierarchies on heterogeneous architectures and CUDA Unified Memory.
- Basics of the *Execution Model* (recommended)

Note: Mint does not provide a memory manager. The application must explicitly specify the desired allocation strategy and memory space to use. This is facilitated by using Umpire for memory management. Specifically, this example uses CUDA Unified Memory when compiled with RAJA and CUDA enabled by setting the default Umpire allocator in the beginning of the program as follows:

```
  // NOTE: use unified memory if we are using CUDA
#if defined(AXOM_USE_RAJA) && defined(AXOM_USE_CUDA)
  const int allocID = axom::getResourceAllocatorID( umpire::resource::Unified );
  axom::setDefaultAllocator( axom::getAllocator( allocID) );
#endif
```

When Umpire , RAJA and CUDA are not enabled, the code will use the `malloc()` internally to allocate memory on the host and all kernels will be executed on the CPU.

Goals

Completion of the walk-though of this simple code example should only require a few minutes. Upon completion, the user will be familiar with using Mint to:

- Create and evaluate fields on a mesh
- Use the *Node Traversal Functions* and *Cell Traversal Functions* of the *Execution Model* to implement kernels that operate on the mesh and associated fields.
- Plot the mesh and associated fields in VTK for visualization.

Step 1: Add Header Includes

First, the Mint header must be included for the definition of the various Mint classes and functions. Note, this example also makes use of Axom's Matrix class, which is also included by the following:

```
#include "axom/config.hpp"                          // compile time definitions
#include "axom/core/execution/execution_space.hpp" // for execution_space traits

#include "axom/mint.hpp"                   // for mint classes and functions
#include "axom/core/numerics/Matrix.hpp"  // for numerics::Matrix
```

Step 2: Get a Mesh

The example application is designed to operate on either a *Structured Mesh* or an *Unstructured Mesh*. The type of mesh to use is specified by a runtime option that can be set by the user at the command line. See *Step 7: Run the Example* for more details.

To make the code work with both *Structured Mesh* and *Unstructured Mesh* instances the kernels are developed in terms of the *The Mesh Base Class*, `mint::Mesh`.

The pointer to a `mint::Mesh` object is acquired as follows:

```
  mint::Mesh* mesh =
    ( Arguments.useUnstructured ) ? getUnstructuredMesh( ) : getUniformMesh( );
```

When using a *Uniform Mesh*, the mesh is constructed by the following:

```
mint::Mesh* getUniformMesh( )
{
  // construct a N x N grid within a domain defined in [-5.0, 5.0]
  const double lo[]   = { -5.0, -5.0 };
  const double hi[]   = {  5.0,  5.0 };
  mint::Mesh* m = new mint::UniformMesh( lo, hi, Arguments.res, Arguments.res );
  return( m );
}
```

This creates an $N \times N$ *Uniform Mesh*, defined on a domain given by the interval $\mathcal{I} : [-5.0, 5.0] \times [-5.0, 5.0]$, where $N = 25$, unless specified otherwise by the user at the command line.

When an *Unstructured Mesh* is used, the code will generate the *Uniform Mesh* internally and triangulate it by subdividing each quadrilateral element into four triangles. See the complete *Mint Application Code Example* for details.

See the *Tutorial* for more details on how to *Create a Uniform Mesh* or *Create an Unstructured Mesh*.

Step 3: Add Fields

Fields are added to the mesh by calling the `createField()` method on the mesh object:

```
  // add a cell-centered and a node-centered field
  double* phi = mesh->createField< double >( "phi", mint::NODE_CENTERED );
  double* hc  = mesh->createField< double >( "hc", mint::CELL_CENTERED );

  constexpr int NUM_COMPONENTS = 2;
  double* xc  = mesh->createField< double >( "xc", mint::CELL_CENTERED, NUM_
↪COMPONENTS );
```

- The *node-centered* field, `phi`, stores the result, computed in *Step 4: Evaluate a Scalar Field*
- The *cell-centered* field, `hc`, stores the nodal average of `phi`, computed in *Step 5: Average to Cell Centers*
- The *cell-centered* field, `xc`, stores the cell-centers, computed in *Step 5: Average to Cell Centers*

Note, the template argument to the `createField()` method indicates the underlying field type, e.g. `double`, `int`, etc. In this case, all three fields have a `double` field type.

The first required argument to the `createField()` method is a *string* corresponding to the *name* of the field. The second argument, which is also required, indicates the centering of the field, i.e. *node-centered*, *cell-centered* or *face-centered*.

A third, *optional*, argument *may* be specified to indicate the number of components of the corresponding field. In this case, the node-centered field, `phi`, is a scalar field. However, the cell-centered field, `xc`, is a 2D vector quantity, which is specified explicitly by supplying the third argument in the `createField()` method invocation.

Note: Absence of the third argument when calling `createField()` indicates that the number of components of the field defaults to 1 and thereby the field is assumed to be a scalar quantity.

See the *Tutorial* for more details on *Working with Fields* on a mesh.

Step 4: Evaluate a Scalar Field

The first kernel employs the `for_all_nodes()` traversal function of the *Execution Model* to iterate over the constituent mesh *Nodes* and evaluate Himmelblau's Function at each node:

```
  // loop over the nodes and evaluate Himmelblaus Function
  mint::for_all_nodes< ExecPolicy, xargs::xy >(
      mesh, AXOM_LAMBDA( IndexType nodeIdx, double x, double y )
  {
    const double x_2 = x * x;
    const double y_2 = y * y;
    const double A   = x_2 + y   - 11.0;
    const double B   = x   + y_2 - 7.0;

    phi[ nodeIdx ] = A * A + B * B;
  } );
```

- The arguments to the `for_all_nodes()` function consists of:
  1. A pointer to the mesh object, and
  2. The *kernel* that defines the *per-node* operations, encapsulated within a Lambda Expression, using the convenience *AXOM_LAMBDA Macro*.
- In addition, the `for_all_nodes()` function has two template arguments:
  1. `ExecPolicy`: The execution policy specifies, *where* and *how* the kernel is executed. It is a required template argument that corresponds to an *Execution Policy* defined by the *Execution Model*.
  2. `xargs::xy`: Indicates that in addition to the index of the node, `nodeIdx`, the kernel takes the `x` and `y` node coordinates as additional arguments.

Within the body of the kernel, Himmelblau's Function is evaluated using the supplied `x` and `y` node coordinates. The result is stored in the corresponding field array, `phi`, which is captured by the Lambda Expression, at the corresponding node location, `phi[ nodeIdx ]`.

See the *Tutorial* for more details on using the *Node Traversal Functions* of the *Execution Model*.

Step 5: Average to Cell Centers

The second kernel employs the `for_all_cells()` traversal function of the *Execution Model* to iterate over the constituent mesh *Cells* and performs the following:

1. computes the corresponding cell centroid, a 2D *vector* quantity,
2. averages the node-centered field, `phi`, computed in *Step 4: Evaluate a Scalar Field*, the cell center.

```
// loop over cells and compute cell centers
mint::for_all_cells< ExecPolicy, xargs::coords >(
    mesh, AXOM_LAMBDA( IndexType cellIdx,
                       const numerics::Matrix< double >& coords,
                       const IndexType* nodeIds )
{
  // NOTE: A column vector of the coords matrix corresponds to a nodes coords

  // Sum the cell's nodal coordinates
  double xsum = 0.0;
  double ysum = 0.0;
  double hsum = 0.0;

  const IndexType numNodes = coords.getNumColumns();
  for ( IndexType inode=0; inode < numNodes; ++inode )
  {
    const double* node = coords.getColumn( inode );
    xsum += node[ mint::X_COORDINATE ];
    ysum += node[ mint::Y_COORDINATE ];

    hsum += phi[ nodeIds[ inode] ];
  } // END for all cell nodes

  // compute cell centroid by averaging the nodal coordinate sums
  const IndexType offset = cellIdx * NUM_COMPONENTS;
  const double invnnodes = 1.f / static_cast< double >( numNodes );
  xc[ offset   ] = xsum * invnnodes;
  xc[ offset+1 ] = ysum * invnnodes;

```

(continues on next page)

(continued from previous page)

```
30     hc[ cellIdx ] = hsum * invnnodes;
31   } );
```

- Similarly, the arguments to the `for_all_cells()` function consists of:
  1. A pointer to the mesh object, and
  2. The *kernel* that defines the *per-cell* operations, encapsulated within a Lambda Expression, using the convenience *AXOM_LAMBDA Macro*.
- In addition, the `for_all_cells()` function has two template arguments:
  1. `ExecPolicy`: As with the `for_all_nodes()` function, the execution policy specifies, *where* and *how* the kernel is executed.
  2. `xargs::coords`: Indicates that in addition to the index of the cell, `cellIdx`, the supplied kernel takes two additional arguments:
     a. `coords`, a matrix that stores the node coordinates of the cell, and
     b. `nodeIds`, an array that stores the IDs of the constituent cell nodes.

The cell node coordinates matrix, defined by `axom::numerics::Matrix` is organized such that:

- The number of rows of the matrix corresponds to the cell dimension, and,
- The number of columns of the matrix corresponds to the number of cell nodes.
- The ith column vector of the matrix stores the coordinates of the ith cell node.

In this example, the 2D *Uniform Mesh*, consists of 2D rectangular cells, which are defined by 4 nodes. Consequently, the supplied node coordinates matrix to the kernel, `coords`, will be a 2×4 matrix of the following form:

$$\begin{pmatrix} x_0 & x_1 & x_2 & x_3 \\ y_0 & y_1 & y_2 & y_3 \end{pmatrix}$$

Within the body of the kernel, the centroid of the cell is calculated by averaging the node coordinates. The code loops over the columns of the `coords` matrix (i.e., the cell nodes) and computes the sum of each node coordinate in `xsum` and `ysum` respectively. Then, the average is evaluated by multiplying each coordinate sum with $1/N$, where N is the number of nodes of a cell. The result is stored in the corresponding field array, `xc`, which is captured by the Lambda Expression.

Since, the cell centroid is a 2D vector quantity, each cell entry has an x-component and y-component. Multi-component fields in Mint are stored using a 2D row-major contiguous memory layout, where, the number of rows corresponds to the number of cells, and the number of columns correspond to the number of components of the field. Consequently, the x-component of the centroid of a cell with ID, `cellIdx` is stored at `xc[ cellIIdx * NUM_COMPONENTS ]` and the y-component is stored at `xc[ cellIdx * NUM_COMPONENTS + 1 ]`, where `NUM_COMPONENTS=2`.

In addition, the node-centered quantity, `phi`, computed in *Step 4: Evaluate a Scalar Field* is averaged and stored at the cell centers. The kernel first sums all the nodal contributions in `hsum` and then multiplies by $1/N$, where N is the number of nodes of a cell.

See the *Tutorial* for more details on using the *Cell Traversal Functions* of the *Execution Model*.

Step 6: Output the Mesh in VTK

Last, the resulting mesh and data can be output in the Legacy VTK File Format, which can be visualized by a variety of visualization tools, such as VisIt and ParaView as follows:

```
1  // write the mesh in a VTK file for visualization
2  std::string vtkfile =
3    (Arguments.useUnstructured) ? "unstructured_mesh.vtk" : "uniform_mesh.vtk";
4  mint::write_vtk( mesh, vtkfile );
```

A VTK file corresponding to the VTK File Format specification for the mesh type used will be generated.

Step 7: Run the Example

After building the Axom Toolkit, the basic Mint example may be run from within the build space directory as follows:

```
> ./examples/mint_getting_started_ex
```

By default the example will use a 25×25 *Uniform Mesh* domain defined on the interval $\mathcal{I} : [-5.0, 5.0] \times [-5.0, 5.0]$. The resulting VTK file is stored in the specified file, `uniform_mesh.vtk`. A depiction of the mesh showing a plot of Himmelblau's Function computed over the constituent *Nodes* of the mesh is illustrated in Fig. 2.8.

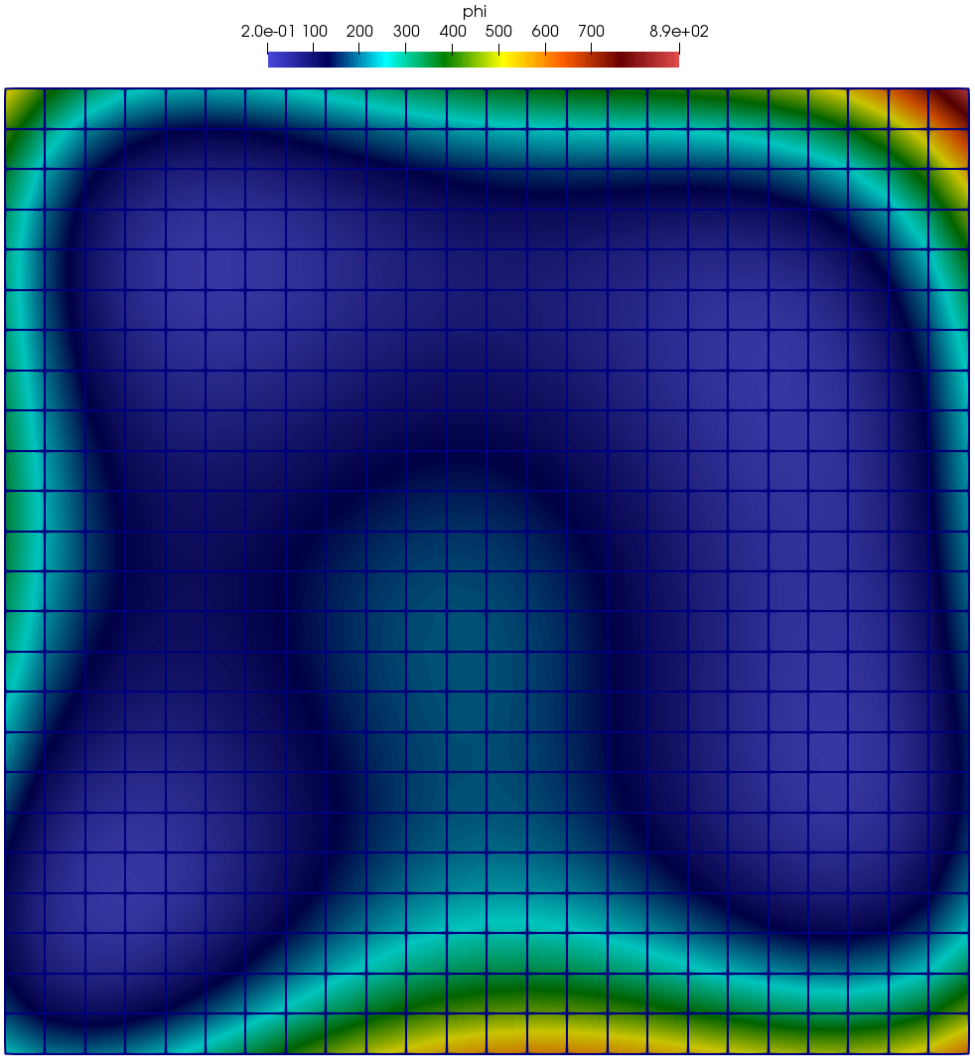


Fig. 2.8: Plot of Himmelblau's Function computed over the constituent *Nodes* of the *Uniform Mesh*.

The user may choose to use an *Unstructured Mesh* instead by specifying the `--unstructured` option at the command line as follows:

```
> ./examples/mint_getting_started_ex --unstructured
```

The code will generate an *Unstructured Mesh* by triangulating the *Uniform Mesh* such that each quadrilateral is subdivided into four triangles. The resulting unstructured mesh is stored in a VTK file, `unstructured_mesh.vtk`, depicted in Fig. 2.9.

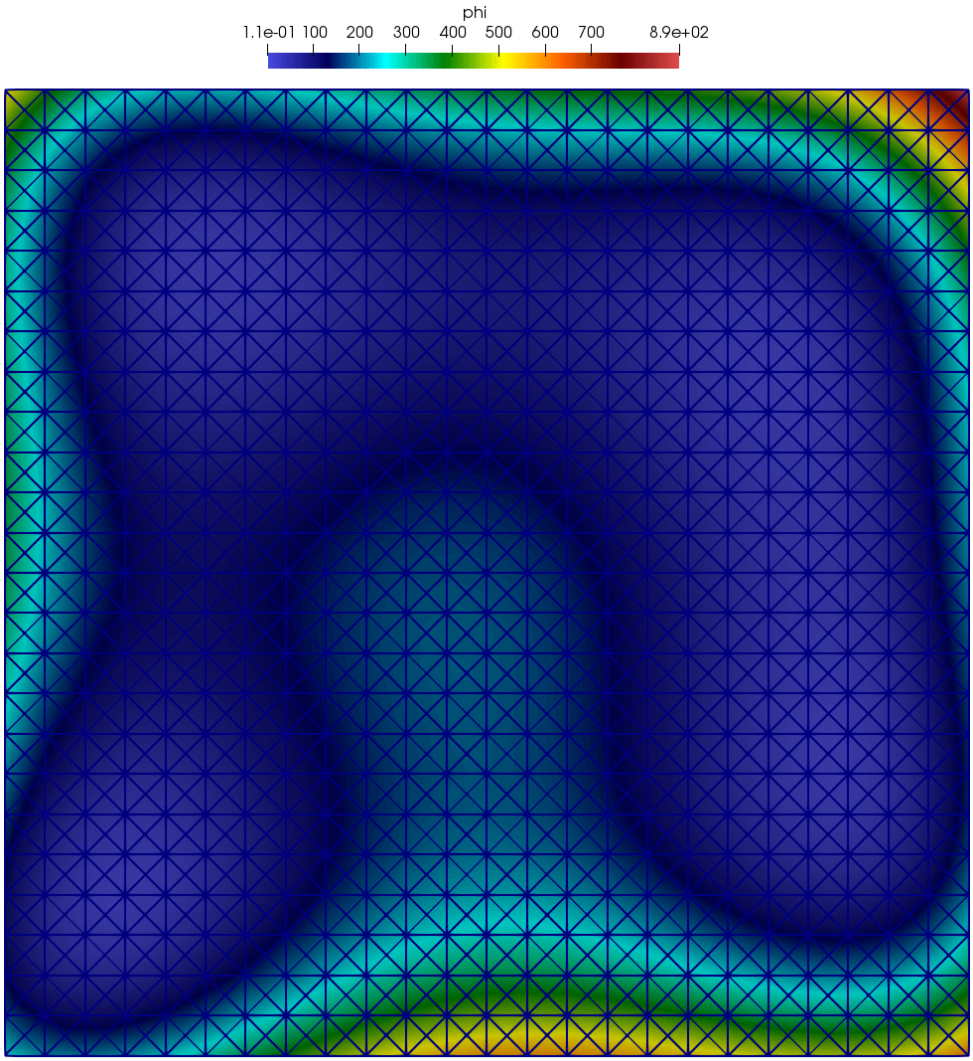


Fig. 2.9: Plot of Himmelblau's Function computed over the constituent *Nodes* of the *Unstructured Mesh*.

By default the resolution of the mesh is set to 25×25. A user may set the desired resolution to use at the command line, using the `--resolution [N]` command line option.

For example, the following indicates that a mesh of resolution 100×100 will be used instead when running the example.

```
> ./examples/mint_getting_started_ex --resolution 100
```

Note: This example is designed to run:

- In parallel on the GPU when the Axom Toolkit is compiled with RAJA and CUDA enabled.
- In parallel on the CPU when the Axom Toolkit is compiled with RAJA and OpenMP enabled.
- Sequentially on the CPU, otherwise.

2.7.2 Preliminary Concepts

A mesh (sometimes also called a *grid*), denoted by $\mathcal{M}(\Omega)$, provides a discrete represenation of a geometric domain of interest, Ω, on which, the underlying *mathematical model* is evaluated. The mathematical model is typically defined by a system of governing *Partial Differential Equations (PDEs)* and associated boundary and initial conditions. The solution to the governing PDE predicts a physical process that occurs and evolves on Ω over time. For example, consider the flow around an aircraft, turbulence modeling, blast wave propagation over complex terrains, or, heat transfer in contacting objects, to name a few. Evolving the mathematical model to predict such a physical process is typically done numerically, which requires discretizing the governing PDE by a numerical scheme, such as a Finite Difference (FD), Finite Volume (FV), or, the Finite Element Method (FEM), chief among them.

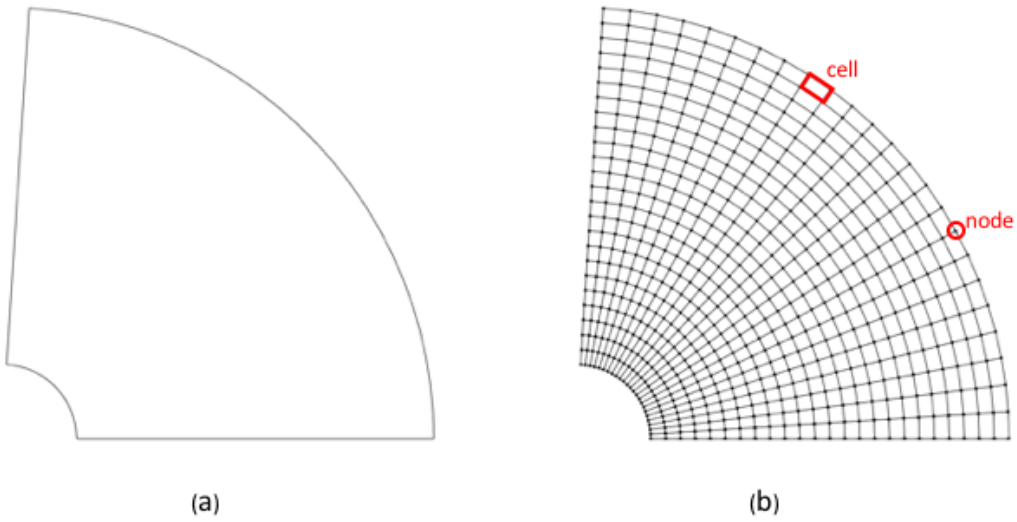


Fig. 2.10: Mesh discretization of a geometric domain: (a) Sample geometric domain, Ω. (b) Corresponding mesh of the domain, $\mathcal{M}(\Omega)$. The *nodes* and *cells* of the mesh, depicted in red, correspond to the discrete locations where the unknown variables of the governing PDE are stored and evaluated.

Discretization of the governing PDE requires the domain to be approximated with a mesh. For example, Fig. 2.10 (a) depicts a geometric domain, Ω. The corresponding mesh, $\mathcal{M}(\Omega)$, is illustrated in Fig. 2.10 (b). The mesh approximates the geometric domain, Ω, by a finite number of simple geometric entities, such as *nodes* and *cells*, depicted in red in Fig. 2.10 (b). These geometric entities comprising the mesh define the discrete locations, in space and time, at which the unknown variables, i.e., the *degrees of freedom* of the governing PDE, are evaluated, by the numerical scheme being employed.

There are a variety of different *Mesh Types* one can choose from. The type of mesh employed depends on the choice of the underlying numerical discretization scheme. For example, a finite difference scheme typically requires a *Structured Mesh*. However, the finite volume and finite element methods may be implemented for both *Structured Mesh* and

Unstructured Mesh types. In contrast, *meshless* or *mesh-free* methods, such as *Smoothed Particle Hydrodynamics (SPH)*, discretize the governing PDE over a set of *particles* or *nodes*, using a *Particle Mesh* representation.

2.7.3 Mesh Representation

Irrespective of the mesh type, a mesh essentially provides a data structure that enables efficient *storage*, *management* and *access* of:

1. Mesh *Geometry* information (i.e., nodal coordinates),
2. Mesh *Topology* information (i.e., cell-to-node connectivity, etc.), and
3. *Field Data* stored on a mesh

The underlying, concrete representation of the *Geometry* and *Topology* of a mesh is the key distinguishing characteristic used to classify a mesh into the different *Mesh Types*. As a prerequisite to the proceeding discussion on the taxonomy of the various *Mesh Types*, this section provides a high level description of the key constituents of the *Mesh Representation*. Namely, the *Topology*, *Geometry* and *Field Data* comprising a mesh.

Topology

The topology of a mesh, $\mathcal{M}(\Omega) \in \mathbb{R}^d$, is defined by the collection of topological entities, e.g. the *Cells*, *Faces* and *Nodes*, comprising the mesh and the associated *adjacency* information that encodes the topological connections between them, broadly referred to as *Connectivity* information. Each topological entity in the mesh is identified by a unique index, as depicted in the sample *Unstructured Mesh* shown in Fig. 2.11. This provides a convenient way to traverse and refer to individual entities in the mesh.

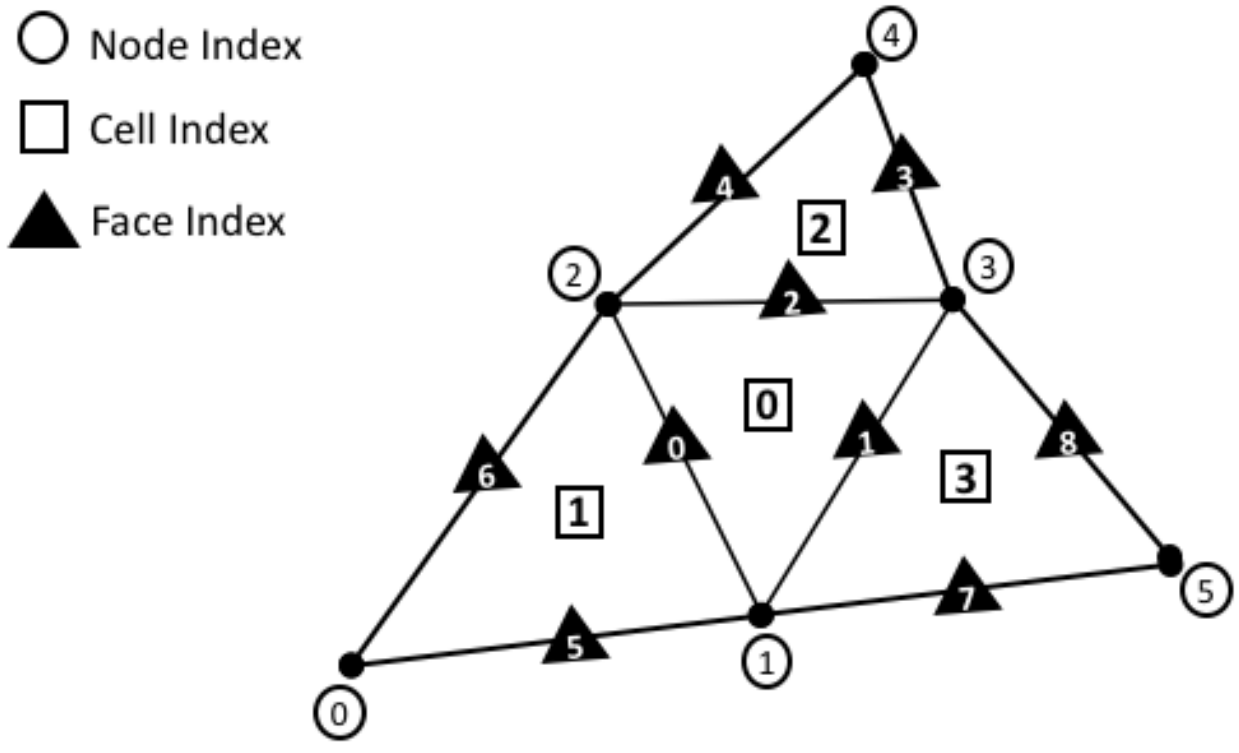


Fig. 2.11: Sample unstructured mesh. Each node, cell and face on the mesh has a unique index.

In Mint, the three fundamental topological entities comprising a mesh are (1) *Cells*, (2) *Faces*, and (3) *Nodes*.

Note: The current implementation does not provide first class support for edges and associated edge data in 3D. However, this is a feature we are planning to support in future versions of Mint.

Cells

A cell, $\mathcal{C}_i$, is given by an ordered list of *Nodes*, $\mathcal{C}_i = \{n_0, n_1, ...n_k\}$, where each entry, $n_j \in \mathcal{C}_i$, corresponds to a unique node index in the mesh. The order of *Nodes* defining a cell is determined according to a prescribed local numbering convention for a particular cell type. See Fig. 2.22 and Fig. 2.23. All Mint *Cell Types* follow the CGNS Numbering Conventions.

Faces

Similarly, a face, $\mathcal{F}_i$, is defined by an ordered list of *Nodes*, $\mathcal{F}_i = \{n_0, n_1, ..., n_k\}$. Faces are essentially *Cells* whose topological dimension is one less than the dimension of the *Cells* they are bound to. See Fig. 2.12. Consequently, the constituent faces of a 3D cell are 2D topological entities, such as *triangles* or *quads*, depending on the cell type. The faces of a 2D cell are 1D topological entities, i.e. *segments*. Last, the faces of a 1D cell are 0D topological entities, i.e. *Nodes*.

Note: In 1D the *Faces* of a cell are equivalent to the constituent mesh *Nodes*, hence, Mint does not explicitly support *Faces* in 1D.

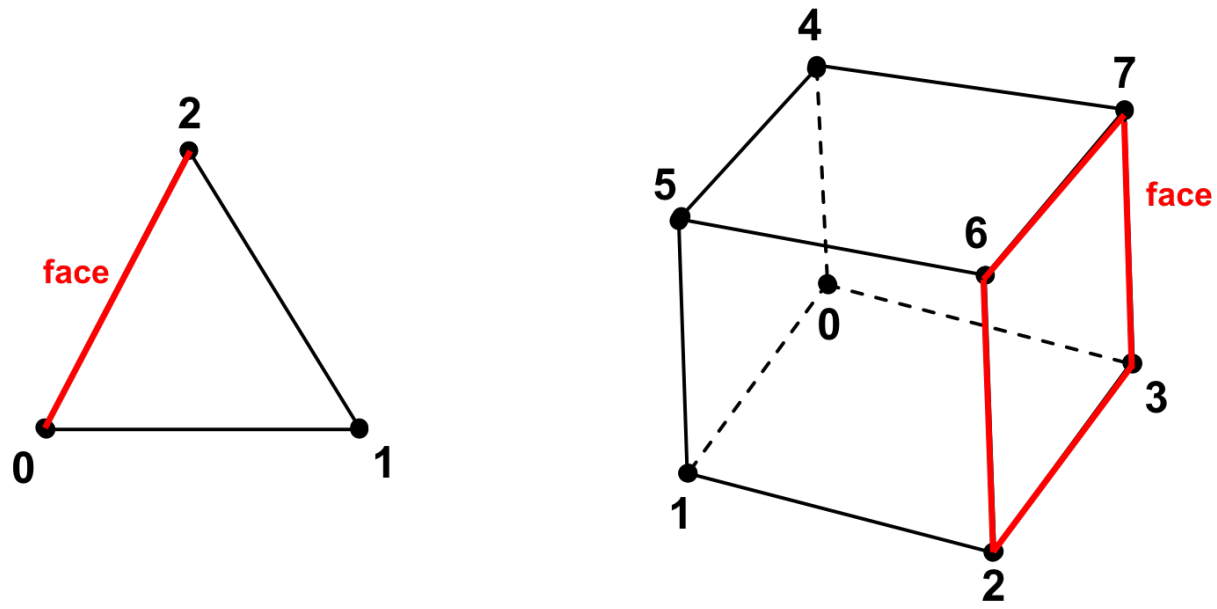


Fig. 2.12: Constituent faces of a cell in 2D and 3D respectively. the constituent faces of a 3D cell are 2D topological entities, such as *triangles* or *quads*, depending on the cell type. The faces of a 2D cell are 1D topological entities, i.e. *segments*.

Face Types

A mesh face can be bound to either *one* or *two* *Cells*:

- *Faces* bound to two *Cells*, within the same domain, are called **internal faces**.
- *Faces* bound to two *Cells*, across different domains (or partitions), are called **internal boundary faces**. Internal boundary faces define the communication boundaries where ghost data is exchanged between domains.
- *Faces* bound to a single cell are called **external boundary faces**. External boundary faces (and/or their consistuent nodes) are typically associated with a boundary condition.

Face Orientation

As with *Cells*, the ordering of the constituent nodes of a face is determined by the cell type. However, by convention, the orientation of a face is according to an outward pointing face normal, as illustrated in Fig. 2.13.

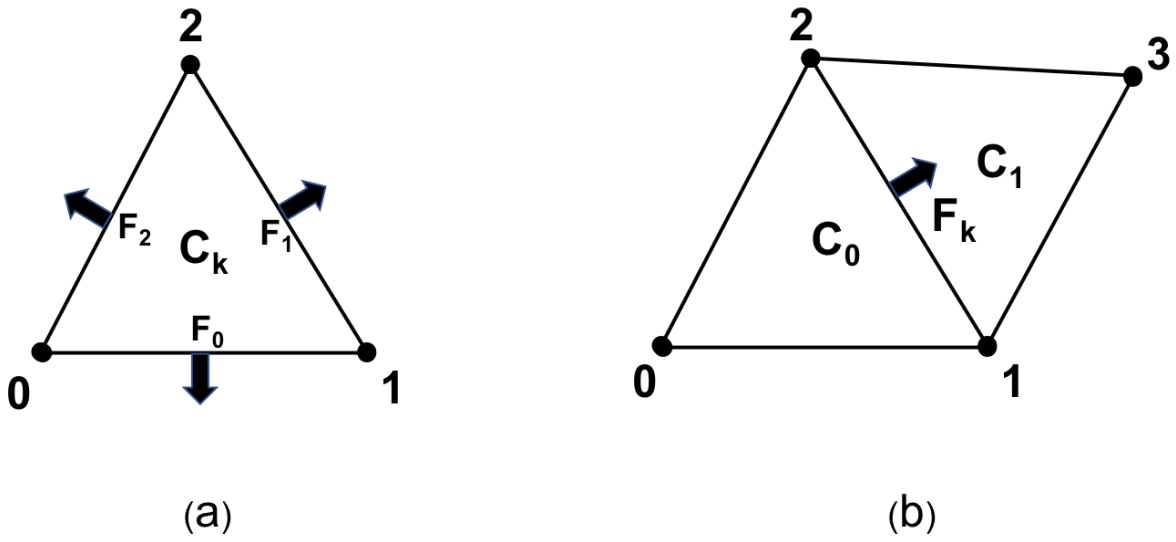


Fig. 2.13: Face Orientation. (a) From the viewpoint of a cell, its constituent faces are oriented according to an outward facing normal. (b) From the viewpoint of a face, a face is oriented according to an outward facing normal with respect to the first cell abutting to the face, denoted by, $\mathcal{C}_0$.

From the viewpoint of a cell, $\mathcal{C}_k$, its constituent faces, defined in the local node numbering of the cell, are oriented according to an outward facing normal with respect to the cell, $\mathcal{C}_k$. For example, in Fig. 2.13 (a), the triangle, $\mathcal{C}_k$, has three faces that are oriented according to an outward facing normal and defined using local node numbers with respect to their cell as follows, $\mathcal{F}_0 = \{0, 1\}$, $\mathcal{F}_1 = \{1, 2\}$ and $\mathcal{F}_2 = \{2, 0\}$

As noted earlier, a face can have at most two adjacent *Cells*, denoted by $\mathcal{C}_0$ and $\mathcal{C}_1$. By convention, from the viewpoint of a face, $\mathcal{F}_k$, defined using global node numbers, the face is oriented according to an outward facing normal with respect to the cell corresponding to $\mathcal{C}_0$. As depicted in Fig. 2.13 (b), the face denoted by $\mathcal{F}_k$ has an outward facing normal with respect to $\mathcal{C}_0$, consequently it is defined as follows, $\mathcal{F}_k = \{1, 2\}$.

Note: By convention, $\mathcal{C}_1$ is set to -1 for *external boundary faces*, which are bound to a single cell.

Nodes

The *Nodes* are *zero* dimensional topological entities and hence, are the lowest dimensional constituent entities of a mesh. The *Nodes* are associated with the spatial coordinates of the mesh and are used in defining the topology of the higher dimensional topological entities comprising the mesh, such as the *Cells*, *Faces*, etc., as discussed earlier. In a sense, the *Nodes* provide the means to link the *Topology* of the mesh to its constituent *Geometry* and thereby instantiate the mesh in physical space.

Definition

A mesh node, $\backslash\rangle$, is associated with a point, $p_i \in \mathbb{R}^d$ and provides the means to:

1. Link the *Topology* of the mesh to its constituent *Geometry*
2. Support one or more *degrees of freedom*, evaluated at the given node location.

Notably, the nodes of a mesh may be more than just the *vertices* of the mesh. As discussed in the *Preliminary Concepts* section, a mesh is a discretization of a PDE. Recall, the primary purpose of the mesh is to define the discrete locations, in both *space* and *time*, at which the *unknown variables* or *degrees of freedom* of the governing PDE are evaluated. Depending on the numerical scheme employed and the *Cell Types* used, additional mesh *Nodes* may be located on the constituent cell faces, edges and in the cell interior. For example, in the Finite Element Method (FEM), the nodes for the linear Lagrange Finite Elements, see Fig. 2.22, are located at the cell *vertices*. However, for quadratic *Cell Types*, see Fig. 2.23, the *Lagrange* P^2 finite element, for the quadrilateral and hexahedron (in 3D) cells, includes as *Nodes*, the cell, face and edge (in 3D) centroids in addition to the cell *vertices*. Other higher order finite elements may involve additional nodes for each edge and face as well as in the interior of the cell.

Connectivity

The topological connections or *adjecencies* between the *Cells*, *Faces* and *Nodes* comprising the mesh, give rise to a hierarchical topological structure, depicted in Fig. 2.14, that is broadly referred to as *Connectivity* information. At the top level, a mesh consists of one or more *Cells*, which constitute the highest dimensional entity comprising the mesh. Each cell is bounded by zero or more *Faces*, each of which is bounded by one or more *Nodes*.

The topological connections between the constituent entities of the mesh can be distinguished in (a) *downward* and (b) *upward* topological connections, as illustrated in Fig. 2.14.

- The downward topological connections encode the connections from higher dimensional mesh entities to lower dimensional entities, such as *cell-to-node*, *face-to-node* or *cell-to-face*.
- The upward topological connections, also called *reverse connectivities*, encode the connections from lower dimensional mesh entities to higher dimensional entities, such as *face-to-cell*.

Two key guiding considerations in the design and implementation of mesh data structures are *storage* and *computational efficiency*. In that respect, the various *Mesh Types* offer different advantages and tradeoffs. For example, the inherent regular topology of a *Structured Mesh* implicitly defines the *Connectivity* information. Consequently, the topological connections between mesh entities can be efficiently computed on-the-fly. However, for an *Unstructured Mesh*, the *Connectivity* information has to be extracted and stored explicitly so that it is readily available for computation.

An *Unstructured Mesh* representation that explicitly stores all 0 to d topological entities and associated *downward* and *upward* *Connectivity* information is said to be a *full mesh representation*. Otherwise, it is called a *reduced mesh representation*. In practice, it can be prohibitively expensive to store a *full mesh representation*. Consequently, most applications keep a *reduced mesh representation*.

The question that needs to be addressed at this point is what *Connectivity* information is generally required. The answer can vary depending on the application. The type of operations performed on the mesh impose the requirements for the

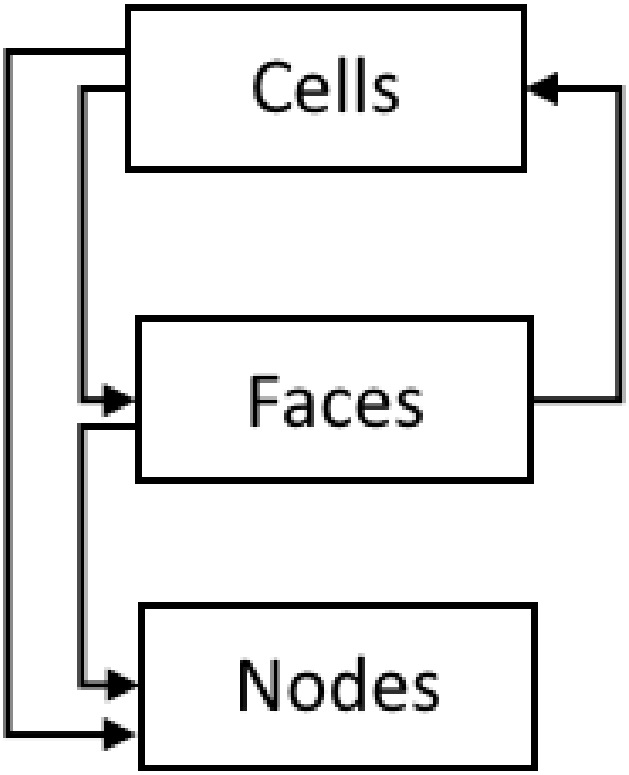


Fig. 2.14: Hierarchical topological structure illustrating the *downward* and *upward* topological connections of the constituent mesh entities supported in Mint.

Connectivity information needed. The *minimum sufficient* representation for an *Unstructured Mesh* is the *cell-to-node Connectivity*, since, all additional *Connectivity* information can be subsequently computed based on this information.

In an effort to balance both flexibility and simplicity, Mint, in its simplest form, employs the *minumum sufficient Unstructured Mesh* representation, consisting of the *cell-to-node Connectivity*. This allows applications to employ a fairly *light-weight* mesh representation when possible. However, for applications that demand additional *Connectivity* information, Mint provides methods to compute the needed additional information.

Warning: The present implementation of Mint provides first class support for *cell-to-node*, *cell-to-face*, *face-to-cell* and *face-to-node Connectivity* information for all the *Mesh Types*. Support for additional *Connectivity* information will be added in future versions based on demand by applications.

Geometry

The *Geometry* of a mesh is given by a set of *Nodes*. Let $\mathcal{N} = \{n_0, n_1, n_2, ..., n_k\}$ be the finite set of nodes comprising a mesh, $\mathcal{M}(\Omega) \in \mathbb{R}^d$, where d is the spatial dimension, $d \in \{1, 2, 3\}$. Each node, $n_i \in \mathcal{N}$, corresponds to a point, $p_i \in \mathbb{R}^d$, whose spatial coordinates, i.e. an ordered tuple, define the physical location of the node in space, $n_i \in \mathbb{R}^d$. The *Nodes* link the *Geometry* of the mesh to its *Topology*. The *Geometry* and *Topology* of the mesh collectively define the physical *shape*, *size* and *location* of the mesh in space.

Field Data

The *Field Data* are used to define various physical quantities over the constituent mesh entities, i.e. the *Cells*, *Faces* and *Nodes* of the mesh. Each constituent mesh entity can be associated with zero or more *fields*, each of which may correspond to a *scalar*, *vector* or *tensor* quantity, such as temperature, velocity, pressure, etc. Essentially, the *Field Data* are used to define the solution to the unknown variables of the governing PDE that are evaluated on a given mesh, as well as, any other auxiliary variables or derived quantities that an application may need.

Warning: The present implementation of Mint supports *Field Data* defined on *Cells*, *Faces* and *Nodes*. Support for storing *Field Data* on edges will be added in future versions based on application demand.

2.7.4 Mesh Types

The underlying, concrete, representation of the constituent *Geometry* and *Topology* of a mesh is the key defining charachteristic used in classifying a mesh into the different *Mesh Types*. The *Geometry* and *Topology* of a mesh is specified in one of the following three representations:

1. **Implicit Representation**: based on mesh metadata
2. **Explicit Representation**: employs explicitly stored information.
3. **Semi-Implicit Representation**: combines mesh metadata and explicitly stored information.

The possible representation combinations of the constituent *Geometry* and *Topology* comprising a mesh define a taxonomy of *Mesh Types* summarized in the table below.

Mesh Type	Geometry	Topology
Curvilinear Mesh	*explicit*	*implicit*
Rectilinear Mesh	*semi-implicit*	*implicit*
Uniform Mesh	*implicit*	*implicit*
Unstructured Mesh	*explicit*	*explicit*
Particle Mesh	*explicit*	*implicit*

A brief overview of the distinct characteristics of each of the *Mesh Types* is provided in the following sections.

Structured Mesh

A *Structured Mesh* discretization is characterized by its *ordered*, *regular*, *Topology*. A *Structured Mesh* divides the computational domain into *Cells* that are logically arranged on a *regular grid*. The regular grid topology allows for the constituent *Nodes*, *Cells* and *Faces* of the mesh to be identified using an *IJK* ordering scheme.

Numbering and Ordering Conventions in a Structured Mesh

The *IJK* ordering scheme employs indices along each dimension, typically using the letters *i,j,k* for the 1st, 2nd and 3rd dimension respectively. The IJK indices can be thought of as counters. Each index counts the number of *Nodes* or *Cells* along a given dimension. As noted in the general *Mesh Representation* section, the constituent entities of the mesh *Topology* are associated with a unique index. Therefore, a convention needs to be established for mapping the IJK indices to the corresponding unique index and *vice-versa*.

The general convention and what Mint employs is the following:

- All *Nodes* and *Cells* of a *Structured Mesh* are indexed first along the *I*-direction, then along the *J*-direction and last along the *K*-direction.
- Likewise, the *Faces* of a *Structured Mesh* are indexed by first counting the *Faces* of each of the *Cells* along the *I*-direction (*I-Faces*), then the *J*-direction (*J-Faces*) and last the *K*-direction (*K-Faces*).

One of the important advantages of a *Structured Mesh* representation is that the constituent *Topology* of the mesh is *implicit*. This enables a convenient way for computing the *Connectivity* information automatically without the need to store this information explicitly. For example, an interior 2D cell (i.e., not at a boundary) located at $C = (i, j)$, will always have four face neighbors given by the following indices:

- $N_0 = (i - 1, j)$,
- $N_1 = (i + 1, j)$,
- $N_2 = (i, j - 1)$ and
- $N_3 = (i, j + 1)$

Notably, the neighboring information follows directly from the *IJK* ordering scheme and therefore does not need to be stored explicitly.

In addition to the convenience of having automatic *Connectivity*, the *IJK* ordering of a *Structured Mesh* offers one other important advantage over an *Unstructured Mesh* discretization. The *IJK* ordering results in coefficient matrices that are *banded*. This enables the use of specialized algebraic solvers that rely on the *banded* structure of the matrix that are generally more efficient.

While a *Structured Mesh* discretization offers several advantages, there are some notable tradeoffs and considerations. Chief among them, is the implied restriction imposed by the regular topology of the *Structured Mesh*. Namely, the number of *Nodes* and *Cells* on opposite sides must be matching. This requirement makes *local refinement* less effective, since grid lines need to span across the entire range along a given dimension. Moreover, meshing of complex geometries, consisting of sharp features, is complicated and can lead to degenerate *Cells* that can be problematic in

the computation. These shortcomings are alleviated to an extent using a *block-structured meshing strategy* and/or *patch-based AMR*, however the fundamental limitations still persist.

All *Structured Mesh* types have implicit *Topology*. However, depending on the underlying, concrete representation of the consituent mesh *Geometry*, a *Structured Mesh* is distinguished into three subtypes:

1. *Curvilinear Mesh*,
2. *Rectilinear Mesh*, and,
3. *Uniform Mesh*

The key characteristics of each of theses types is discussed in more detail in the following sections.

Curvilinear Mesh

The *Curvilinear Mesh*, shown in Fig. 2.15, is logically a *regular* mesh, however in contrast to the *Rectilinear Mesh* and *Uniform Mesh*, the *Nodes* of a *Curvilinear Mesh* are not placed along the *Cartesian* grid lines. Instead, the equations of the governing PDE are transformed from the *Cartesian* coordinates to a new coordinate system, called a *curvilinear coordinate system*. Consequently, the *Topology* of a *Curvilinear Mesh* is *implicit*, however its *Geometry*, given by the constituent *Nodes* of the mesh, is *explicit*.

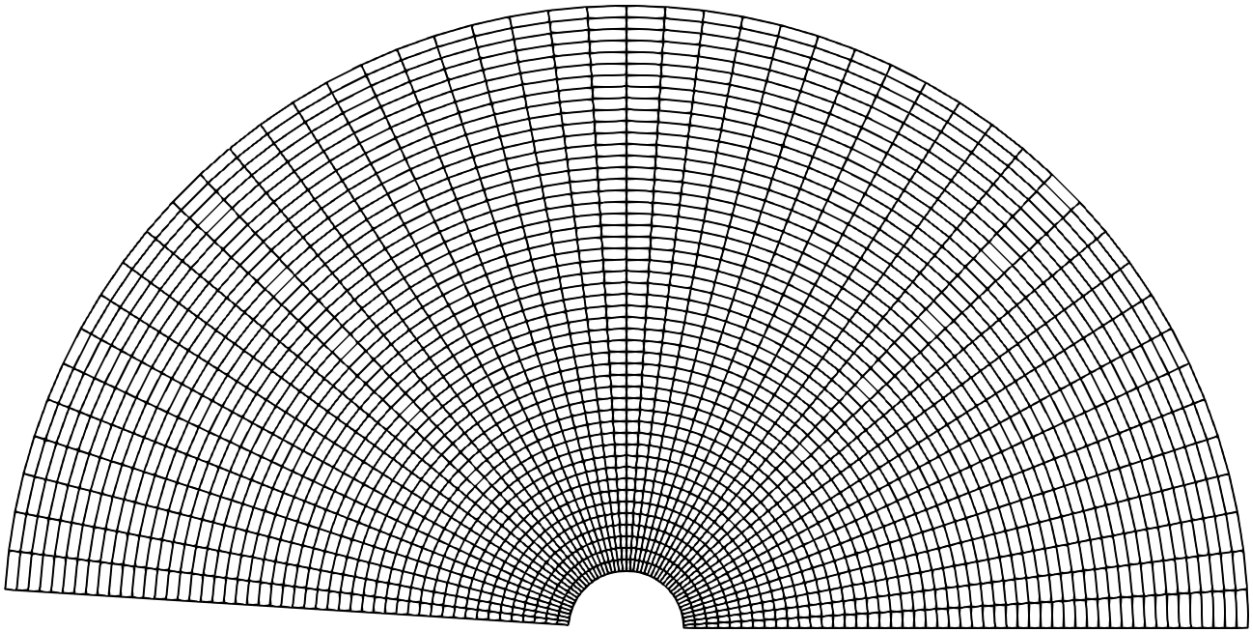


Fig. 2.15: Sample Curvilinear Mesh example.

The mapping of coordinates to the *curvilinear coordinate system* facilitates the use of structured meshes for bodies of arbitrary shape. Note, the axes defining the *curvilinear coordinate system* do not need to be straight lines. They can be curves and align with the contours of a solid body. For this reason, the resulting *Curvilinear Mesh* is often called a *mapped mesh* or *body-fitted mesh*.

See the *Tutorial* for an example that demonstrates how to *Create a Curvilinear Mesh*.

Rectilinear Mesh

A *Rectilinear Mesh*, depicted in Fig. 2.16, divides the computational domain into a set of rectangular *Cells*, arranged on a *regular lattice*. However, in contrast to the *Curvilinear Mesh*, the *Geometry* of the mesh is not mapped to a

different coordinate system. Instead, the rows and columns of *Nodes* comprising a *Rectilinear Mesh* are parallel to the axis of the *Cartesian* coordinate system. Due to this restriction, the geometric domain and resulting mesh are always rectangular.

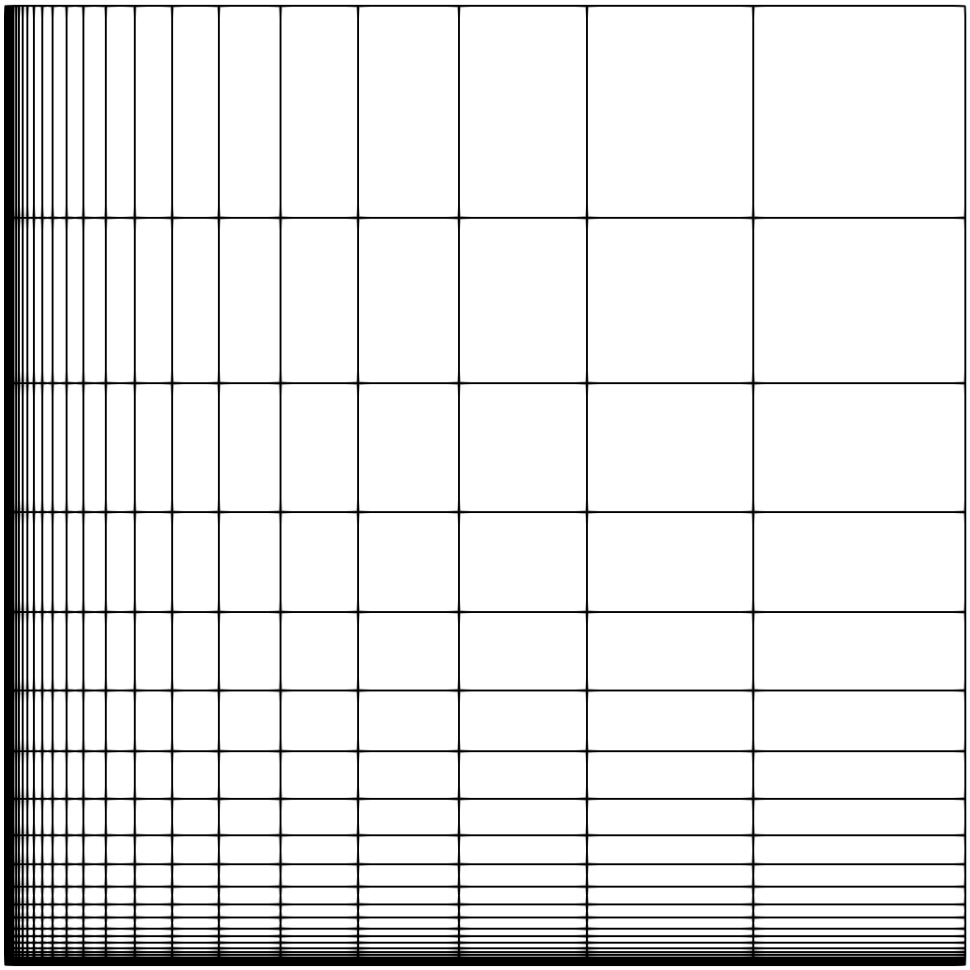


Fig. 2.16: Sample Rectilinear Mesh example.

The *Topology* of a *Rectilinear Mesh* is *implicit*, however its constituent *Geometry* is *semi-implicit*. Although, the *Nodes* are aligned with the *Cartesian* coordinate axis, the spacing between adjacent *Nodes* can vary. This allows a *Rectilinear Mesh* to have tighter spacing over regions of interest and be sufficiently coarse in other parts of the domain. Consequently, the spatial coordinates of the *Nodes* along each axis are specified explicitly in a seperate array for each coordinate axis, i.e. x, y and z arrays for each dimension respectively. Given the *IJK* index of a node, its corresponding physical coordinates can be obtained by taking the *Cartesian* product of the corresponding coordinate along each coordinate axis. For this reason, the *Rectilinear Mesh* is sometimes called a *product* mesh.

See the *Tutorial* for an example that demonstrates how to *Create a Rectilinear Mesh*.

Uniform Mesh

A *Uniform Mesh*, depicted in Fig. 2.17, is the simplest of all three *Structured Mesh* types, but also, relatively the most restrictive of all *Mesh Types*. As with the *Rectilinear Mesh*, a *Uniform Mesh* divides the computational domain into a set of rectangular *Cells* arranged on a *regular lattice*. However, a *Uniform Mesh* imposes the additional restriction that *Nodes* are uniformly distributed parallel to each axis. Therefore, in contrast to the *Rectilinear Mesh*, the spacing between adjacent *Nodes* in a *Uniform Mesh* is constant.

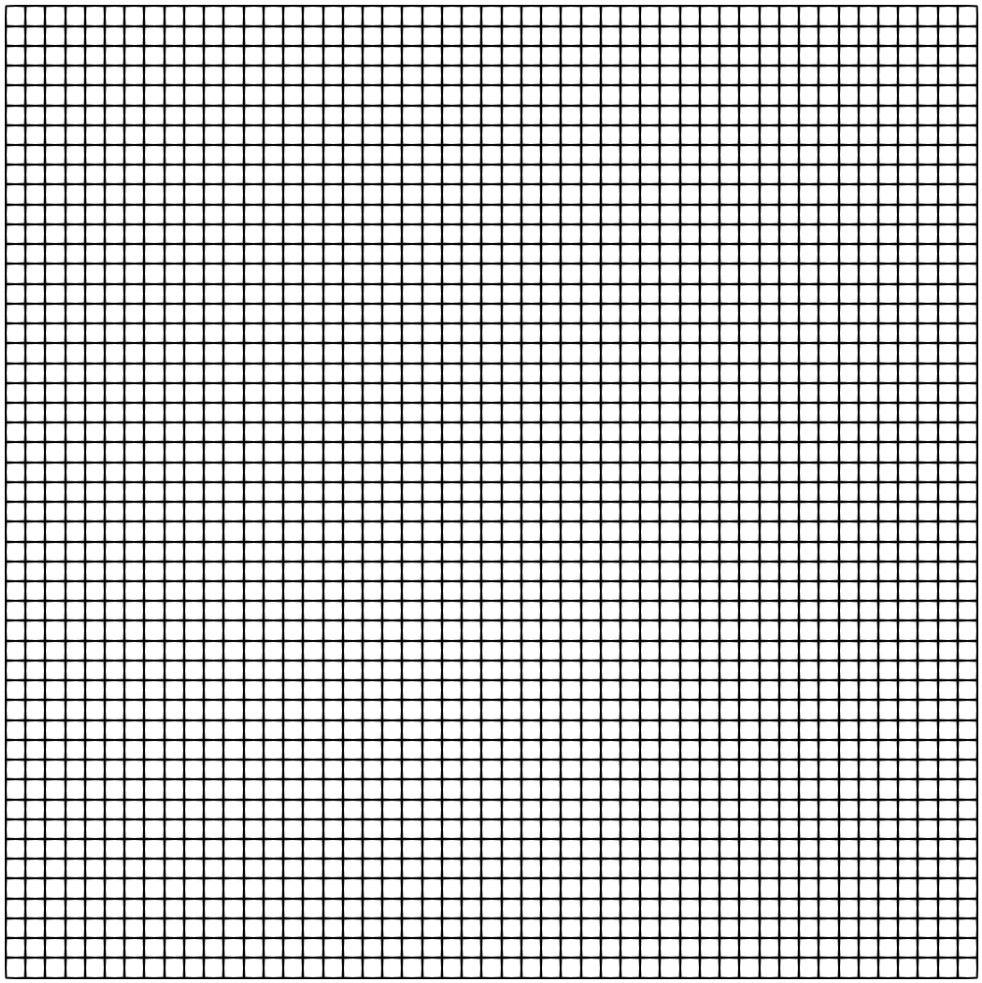


Fig. 2.17: Sample Uniform Mesh example.

The inherent constraints of a *Uniform Mesh* allow for a more compact representation. Notably, both the *Topology* and *Geometry* of a *Uniform Mesh* are *implicit*. Given the origin of the mesh, $X_0 = (x_0, y_0, z_0)^T$, i.e. the coordinates of the lowest corner of the rectangular domain, and spacing along each direction, $H = (h_x, h_y, h_z)^T$, the spatial coordinates of any point, $\hat{p} = (p_x, p_y, p_z)^T$, corresponding to a node with lattice coordinates, (i, j, k), are computed as follows:

$$\begin{aligned} p_x &= x_0 \\ i &\times h_x \end{aligned} + \tag{2.1}$$

$$\begin{aligned} p_y &= y_0 \\ j &\times h_y \end{aligned} + \tag{2.2}$$

$$\begin{aligned} p_z &= z_0 \\ k &\times h_z \end{aligned} + \tag{2.3}$$

$$\tag{2.4}$$

See the *Tutorial* for an example that demonstrates how to *Create a Uniform Mesh*.

Unstructured Mesh

The impetus for an *Unstructured Mesh* discretization is largely prompted by the need to model physical phenomena on complex geometries. In relation to the various *Mesh Types*, an *Unstructured Mesh* discretization provides the most flexibility. Notably, an *Unstructured Mesh* can accomodate different *Cell Types* and does not enforce any constraints or particular ordering on the constituent *Nodes* and *Cells*. This makes an *Unstructured Mesh* discretization particularly attractive, especially for applications that require *local adaptive mesh refinement* (i.e., local h-refinement) and deal with complex geometries.

Generally, the advantages of using an *Unstructured Mesh* come at the cost of an increase in memory requirements and computational intensity. This is due to the inherently *explicit*, *Mesh Representation* required for an *Unstructured Mesh*. Notably, both *Topology* and *Geometry* are represented explicitly thereby increasing the storage requirements and computational time needed per operation. For example, consider a stencil operation. For a *Structured Mesh*, the neighbor indices needed by the stencil can be automatically computed directly from the *IJK* ordering, a relatively fast and local operation. However, to obtain the neighbor indices in an *Unstructured Mesh*, the arrays that store the associated *Connectivity* information need to be accessed, resulting in additional load/store operations that are generaly slower.

Depending on the application, the constituent *Topology* of an *Unstructured Mesh* may employ a:

1. *Single Cell Type Topology*, i.e. consisting of *Cells* of the *same type*, or,
2. *Mixed Cell Type Topology*, i.e. consisting of *Cells* of different type, i.e. *mixed cell type*.

There are subtle differrences in the underlying *Mesh Representation* that can result in a more compact and efficient representation when the *Unstructured Mesh* employs a *Single Cell Type Topology*. The following sections discuss briefly these differences and other key aspects of the *Single Cell Type Topology* and *Mixed Cell Type Topology* representations. Moreover, the list of natively supported *Cell Types* that can be used with an *Unstructured Mesh* is presented, as well as, the steps necessary to *Add a New Cell Type* in Mint.

Note: In an effort to balance both flexibility and simplicity, Mint, in its simplest form, employs the *minumum sufficient Unstructured Mesh Mesh Representation*, consisting of the *cell-to-node Connectivity*. This allows applications to employ a fairly *light-weight* mesh representation when possible. However, for applications that demand additional *Connectivity* information, Mint provides methods to compute the needed additional information.

Single Cell Type Topology

An *Unstructured Mesh* with *Single Cell Type Topology* consists of a collection of *Cells* of the same cell type. Any *Structured Mesh* can be treated as an *Unstructured Mesh* with *Single Cell Type Topology*, in which case, the resulting

Cells would either be *segments* (in 1D), *quadrilaterals* (in 2D) or *hexahedrons* (in 3D). However, an *Unstructured Mesh* can have arbitrary *Connectivity* and does not impose any ordering constraints. Moreover, the *Cells* can also be *triangular* (in 2D) or *tetrahedral* (in 3D). The choice of cell type generally depends on the application, the physics being modeled, and the numerical scheme employed. An example tetrahedral *Unstructured Mesh* of the F-17 blended wing fuselage configuration is shown in Fig. 2.18. For this type of complex geometries it is nearly impossible to obtain a *Structured Mesh* that is adequate for computation.

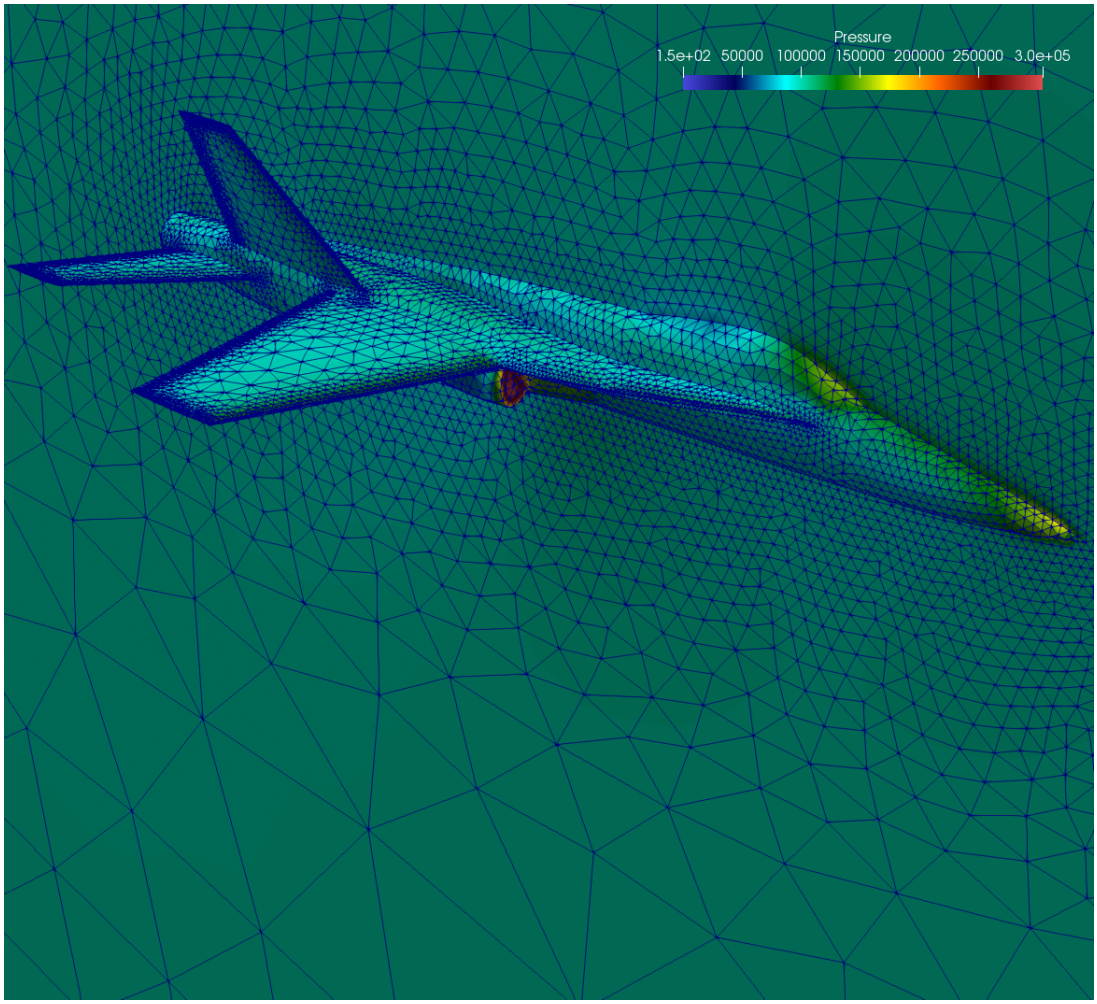


Fig. 2.18: Sample unstructured tetrahedral mesh of the F-17 blended wing fuselage configuration.

Mint's *Mesh Representation* of an *Unstructured Mesh* with *Single Cell Type Topology* consists of a the cell type specification and the cell-to-node *Connectivity* information. The *Connectivity* information is specified with a flat array consisting of the node indices that comprise each cell. Since the constituent mesh *Cells* are of the same type, cell-to-node information for a particular cell can be obtained by accessing the *Connectivity* array with a constant stride, where the stride corresponds to the number of *Nodes* of the cell type being used. This is equivalent to a 2D row-major array layout where the number of rows corresponds to the number of *Cells* in the mesh and the number of columns corresponds to the *stride*, i.e. the number of *Nodes* per cell.

This simple concept is best illustrated with an example. Fig. 2.19 depicts a sample *Unstructured Mesh* with *Single Cell Type Topology* consisting of $N_c = 4$ triangular *Cells*. Each triangular cell, C_i, is defined by $||C_i||$ *Nodes*. In this case, $||C_i|| = 3$.

Note: The number of *Nodes* of the cell type used to define an *Unstructured Mesh* with *Single Cell Type Topology*,

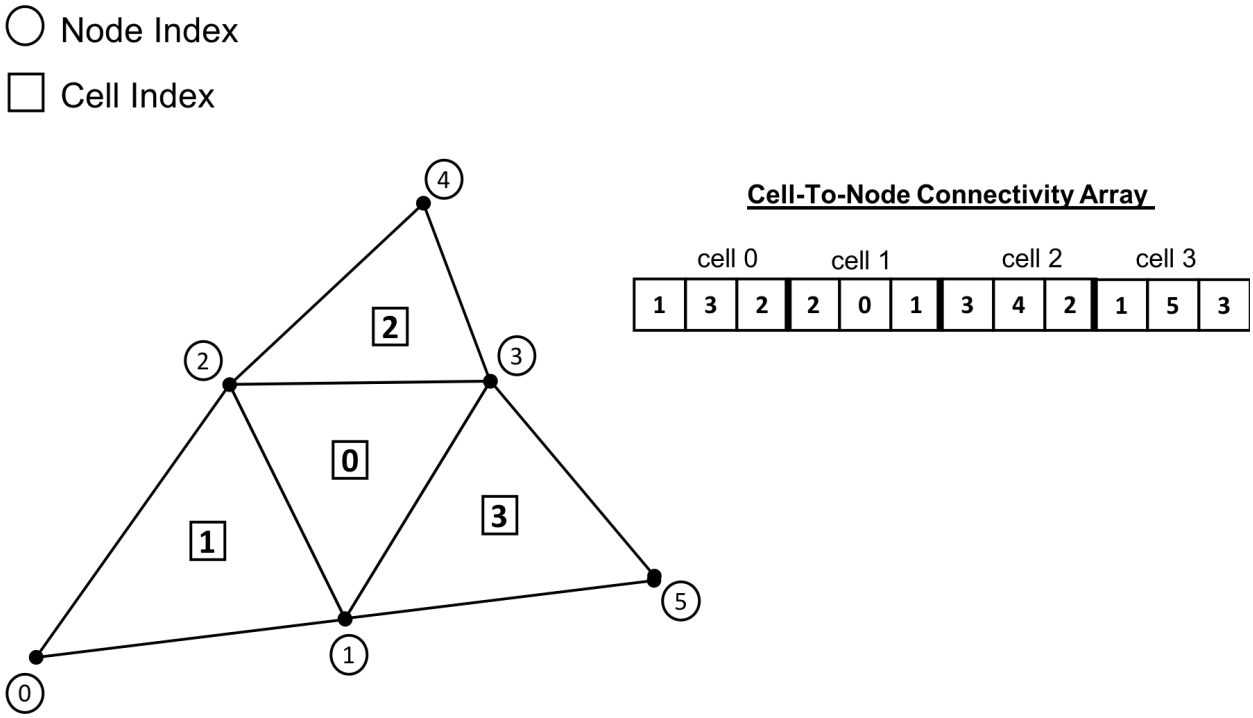


Fig. 2.19: *Mesh Representation* of an *Unstructured Mesh* with *Single Cell Type Topology* consiting of *triangular Cells*. Knowing the cell type enables traversing the cell-to-node *Connectivity* array with a constant stride of 3, which corresponds to the number of constituent *Nodes* of each triangle.

denoted by $||C_i||$, corresponds to the constant stride used to access the flat cell-to-node *Connectivity* array.

Consequently, the length of the cell-to-node *Connectivity* array is then given by $N_c \times ||C_i||$. The node indices for each of the cells are stored from left to right. The base offset for a given cell is given as a multiple of the cell index and the *stride*. As illustrated in Fig. 2.19, the base offset for cell C_0 is $0 \times 3 = 0$, the offest for cell C_1 is $1 \times 3 = 3$, the offset for cell C_2 is $2 \times 3 = 6$ and so on.

Direct Stride Cell Access in a Single Cell Type Topology UnstructuredMesh

In general, the *Nodes* of a cell, C_i, of an *Unstructured Mesh* with *Single Cell Type Topology* and cell stride $||C_i|| = k$, can be obtained from a given cell-to-node *Connectivity* array as follows:

$$n_0 = cell_to_node[i \times k] \tag{2.5}$$
$$n_1 = cell_to_node[i \times k + 1] \tag{2.6}$$
$$... \tag{2.7}$$
$$n_k = cell_to_node[i \times k + (k - 1)] \tag{2.8}$$

Cell Type	Stride	Topological Dimension	Spatial Dimension
Quadrilateral	4	2	2,3
Triangle	3	2	2,3
Hexahdron	8	3	3
Tetrahedron	4	3	3

The same procedure follows for any cell type. Thereby, the stride for a mesh consisting of *quadrilaterals* is 4, the stride for a mesh consisting of *tetrahedrons* is 4 and the stride for a mesh consisting of *hexahedrons* is 8. The table above summarizes the possible *Cell Types* that can be employed for an *Unstructured Mesh* with *Single Cell Type Topology*, corresponding *stride* and applicalble topological and spatial dimension.

See the *Tutorial* for an example that demonstrates how to *Create an Unstructured Mesh*.

Mixed Cell Type Topology

An *Unstructured Mesh* with *Mixed Cell Type Topology* provides the most flexibility relative to the other *Mesh Types*. Similar to the *Single Cell Type Topology Unstructured Mesh*, the constituent *Nodes* and *Cells* of a *Mixed Cell Type Topology Unstructured Mesh* can have arbitrary ordering. Both *Topology* and *Geometry* are *explicit*. However, a *Mixed Cell Type Topology Unstructured Mesh* may consist *Cells* of different cell type. Hence, the cell topology and cell type is said to be *mixed*.

Note: The constituent *Cells* of an *Unstructured Mesh* with *Mixed Cell Type Topology* have a *mixed cell type*. For this reason, an *Unstructured Mesh* with *Mixed Cell Type Topology* is sometimes also called a *mixed cell mesh* or *hybrid mesh*.

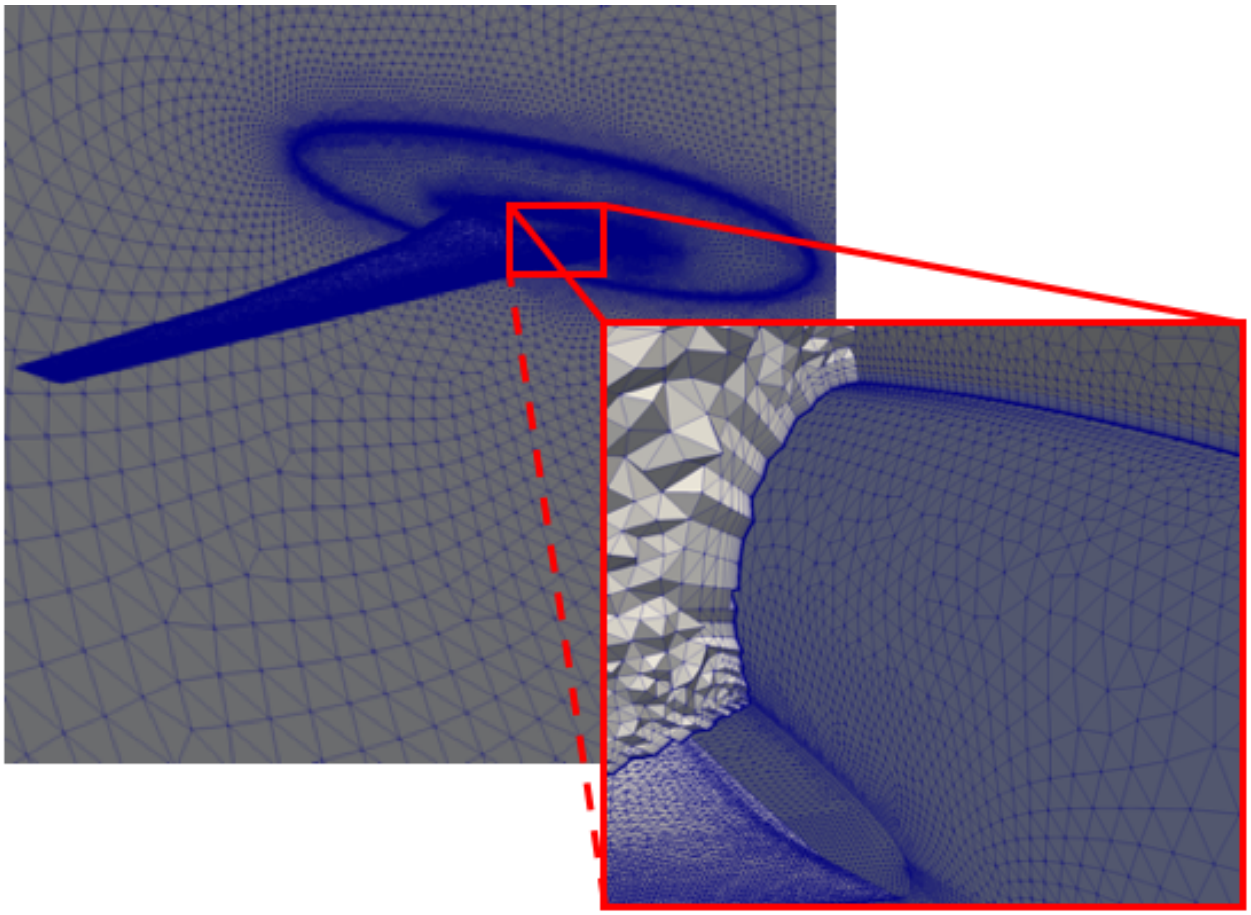


Fig. 2.20: Sample *Unstructured Mesh* with *Mixed Cell Type Topology* of a Generic wing/fuselage configuration. The mesh consists of high-aspect ratio prism cells in the viscous region of the computational domain to accurately capture the high gradients across the boundary layer and tetrahedra cells for the inviscid/Euler portion of the mesh.

Several factors need to be taken in to account when selecting the cell topology of the mesh. The physics being modeled, the PDE discretization employed and the required simulation fidelity are chief among them. Different *Cell Types* can have superior properties for certain calculations. The continuous demand for increasing fidelity in physics-based predictive modeling applications has prompted practitioners to employ a *Mixed Cell Type Topology Unstructured Mesh* discretization in order to accurately capture the underlying physical phenomena.

For example, for Navier-Stokes *viscous* fluid-flow computations, at high Reynolds numbers, it is imperative to capture the high gradients across the boundary layer normal to the wall. Typically, high-aspect ratio, anisotropic *triangular prisms* or *hexahedron Cells* are used for discretizing the viscous region of the computational domain, while isotropic *tetrahedron* or *hexahedron Cells* are used in the *inviscid* region to solve the Euler equations. The sample *Mixed Cell Type Topology Unstructured Mesh*, of a Generic Wing/Fuselage configuration, depicted in Fig. 2.20, consists of *triangular prism Cells* for the *viscous* boundary layer portion of the domain that are stitched to *tetrahedra Cells* for the inviscid/Euler portion of the mesh.

The added flexibility enabled by employing a *Mixed Cell Type Topology Unstructured Mesh* imposes additional requirements to the underlying *Mesh Representation*. Most notably, compared to the *Single Cell Type Topology Mesh Representation*, the cell-to-node *Connectivity* array can consist *Cells* of different cell type, where each cell can have a different number of *Nodes*. Consequently, the simple stride array access indexing scheme, used for the *Single Cell Type Topology Mesh Representation*, cannot be employed to obtain cell-to-node information. For a *Mixed Cell Type Topology* an *indirect addressing* access scheme must be used instead.

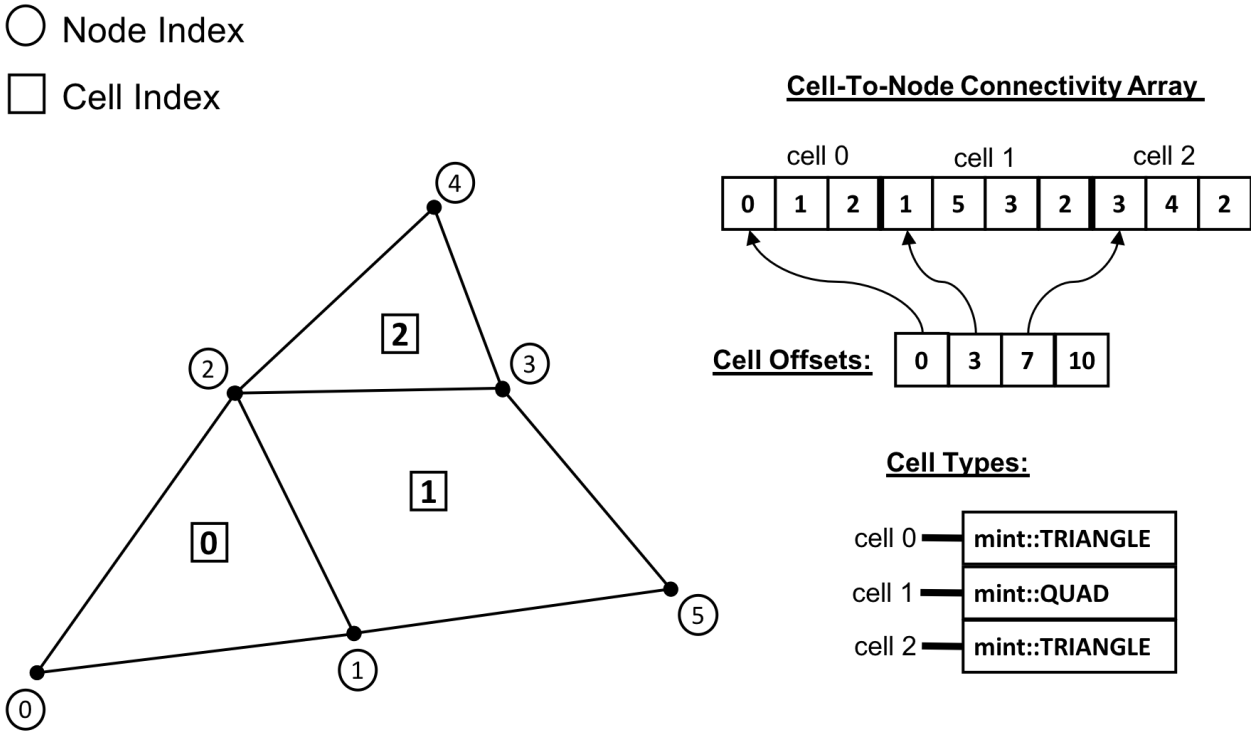


Fig. 2.21: *Mesh Representation* of a *Mixed Cell Type Topology Unstructured Mesh* with a total of $N = 3$ *Cells*, 2 *triangles* and 1 *quadrilateral*. The *Mixed Cell Type Topology* representation consists of two additional arrays. First, the *Cell Offsets* array, an array of size $N+1$, where the first N entries store the starting position to the flat cell-to-node *Connectivity* array for each cell. The last entry of the *Cell Offsets* array stores the total length of the *Connectivity* array. Second, the *Cell Types* array , an array of size N, which stores the cell type of each constituent cell of the mesh.

There are a number of ways to represent a *Mixed Cell Type Topology* mesh. In addition to the cell-to-node *Connectivity* array, Mint's *Mesh Representation* for a *Mixed Cell Type Topology Unstructured Mesh* employs two additional arrays. See sample mesh and corresponding *Mesh Representation* in Fig. 2.21. First, the *Cell Offsets* array is used to provide indirect addressing to the cell-to-node information of each constituent mesh cell. Second, the *Cell Types* array is used

to store the cell type of each cell in the mesh.

The *Cell Offsets* is an array of size $N + 1$, where the first N entries, corresponding to each cell in the mesh, store the start index position to the cell-to-node *Connectivity* array for the given cell. The last entry of the *Cell Offsets* array stores the total length of the *Connectivity* array. Moreover, the number of constituent cell *Nodes* for a given cell can be directly computed by subtracting a Cell's start index from the next adjacent entry in the *Cell Offsets* array.

However, knowing the start index position to the cell-to-node *Connectivity* array and number of constituent *Nodes* for a given cell is not sufficient to disambiguate and deduce the cell type. For example, both *tetrahedron* and *quadrilateral Cells* are defined by 4 *Nodes*. The cell type is needed in order to correctly interpret the *Topology* of the cell according to the cell's local numbering. Consequently, the *Cell Types* array, whose length is N, corresponding to the number of cells in the mesh, is used to store the cell type for each constituent mesh cell.

Indirect Address Cell Access in a Mixed Cell Type Topology UnstructuredMesh

In general, for a given cell, C_i, of a *Mixed Cell Type Topology Unstructured Mesh*, the number of *Nodes* that define the cell, $||C_i||$, is given by:

$$k = ||C_i|| \quad = \quad cells_offset[i+1] - cells_offset[i] \tag{2.9}$$
$$\tag{2.10}$$

The corresponding cell type is directly obtained from the *Cell Types* array:

$$ctype \quad = \quad cell_types[i] \tag{2.11}$$
$$\tag{2.12}$$

The list of constituent cell *Nodes* can then obtained from the cell-to-node *Connectivity* array as follows:

offset = cells_offset[i+1] (2.13)

k = cells_offset[i + 1] - cell_offset[i] (2.14)
(2.15)

$n_0 = cell_to_node[offset]$(2.16)

$n_1 = cell_to_node[offset + 1]$(2.17)

... (2.18)

$n_k = cell_to_node[offset + (k - 1)]$(2.19)

See the *Tutorial* for an example that demonstrates how to *Create a Mixed Unstructured Mesh*.

Cell Types

Mint currently supports the common Linear *Cell Types*, depicted in Fig. 2.22, as well as, support for quadratic, quadrilateral and hexahedron *Cells*, see Fig. 2.23.

Note: All Mint *Cell Types* follow the CGNS Numbering Conventions.

Moreover, Mint is designed to be extensible. It is relatively straightforward to *Add a New Cell Type* in Mint. Each of the *Cell Types* in Mint simply encode the following attributes:

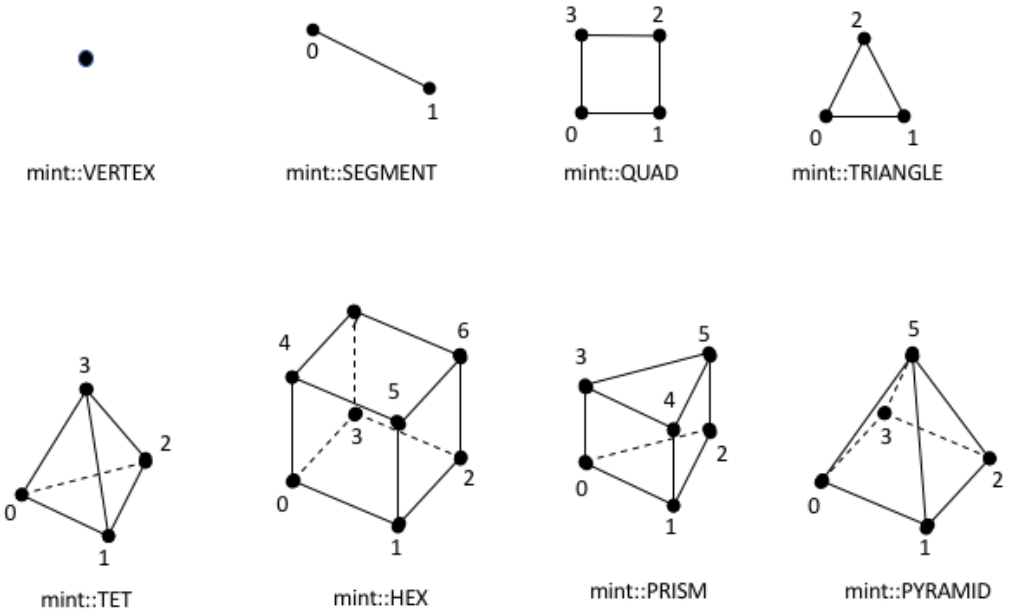


Fig. 2.22: List of supported linear cell types and their respective local node numbering.

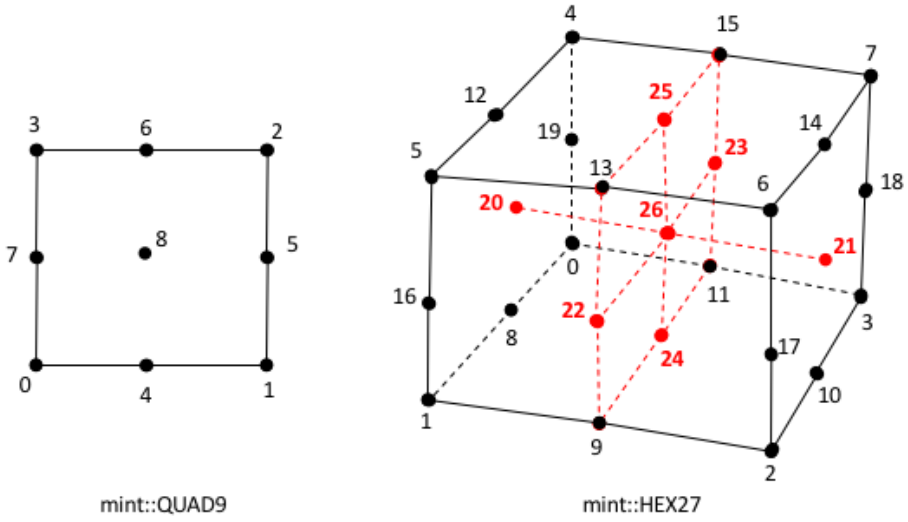


Fig. 2.23: List of supported quadratic cell types and their respective local node numbering.

- the cell's topology, e.g. number of nodes, faces, local node numbering etc.,
- the corresponding VTK type, used for VTK dumps, and,
- the associated blueprint name, conforming to the Blueprint conventions, used for storing the mesh in Sidre

Warning: The Blueprint specification does not currently support the following cell types:

1. Transitional cell types, Pyramid(`mint::PYRAMID`) and Prism(`mint::PRISM`)
2. Quadratic cells, the 9-node, quadratic Quadrilateral(`mint::QUAD9`) and the 27-node, quadratic Hexahedron(`mint::HEX27`)

Add a New Cell Type

Warning: This section is under construction.

Particle Mesh

A *Particle Mesh*, depicted in Fig. 2.24, discretizes the computational domain by a set of *particles* which correspond to the *Nodes* at which the solution is evaluated. A *Particle Mesh* is commonly employed in the so called *particle* methods, such as *Smoothed Particle Hydrodynamics* (SPH) and *Particle-In-Cell* (PIC) methods, which are used in a variety of applications ranging from astrophysics and cosmology simulations to plasma physics.

There is no special ordering imposed on the particles. Therefore, the particle coordinates are explicitly specified by nodal coordinates, similar to an *Unstructured Mesh*. However, the particles are not connected to form a *control volume*, i.e. a filled region of space. Consequently, a *Particle Mesh* does not have *Faces* and any associated *Connectivity* information. For this reason, methods that employ a *Particle Mesh* discretization are often referred to as *meshless* or *mesh-free* methods.

A *Particle Mesh* can be thought of as having *explicit Geometry*, but, *implicit Topology*. Mint's *Mesh Representation* for a *Particle Mesh*, associates the constituent particles with the *Nodes* of the mesh. The *Nodes* of the *Particle Mesh* can also be thought of as *Cells* that are defined by a single node index. However, since this information can be trivially obtained there is no need to be stored explicitly.

Note: A *Particle Mesh* can only store variables at its constituent particles, i.e. the *Nodes* of the mesh. Consequently, a *Particle Mesh* in Mint can only be associated with node-centered *Field Data*.

2.7.5 Component Architecture

This section links the core concepts, presented in the *Mesh Representation* and *Mesh Types* sections, to the underlying implementation of the Mint *mesh data model*. The *Component Architecture* of Mint's *mesh data model* consists of a class hierarchy that follows directly the taxonomy of *Mesh Types* discussed earlier. The constituent classes of the *mesh data model* are combined using a mix of class *inheritance* and *composition*, as illustrated in the class diagram depicted in Fig. 2.25.

At the top level, *The Mesh Base Class*, implemented in `mint::Mesh`, stores common mesh attributes and fields. Moreover, it defines a unified Application Programming Interface (API) for the various *Mesh Types*. See the Mint Doxygen API Documentation for a complete specification of the API. The *Concrete Mesh Classes* extend *The Mesh Base Class* and implement the *Mesh Representation* for each of the *Mesh Types* respectively. The `mint::ConnectivityArray` and `mint::MeshCoordinates` classes, are the two main internal support

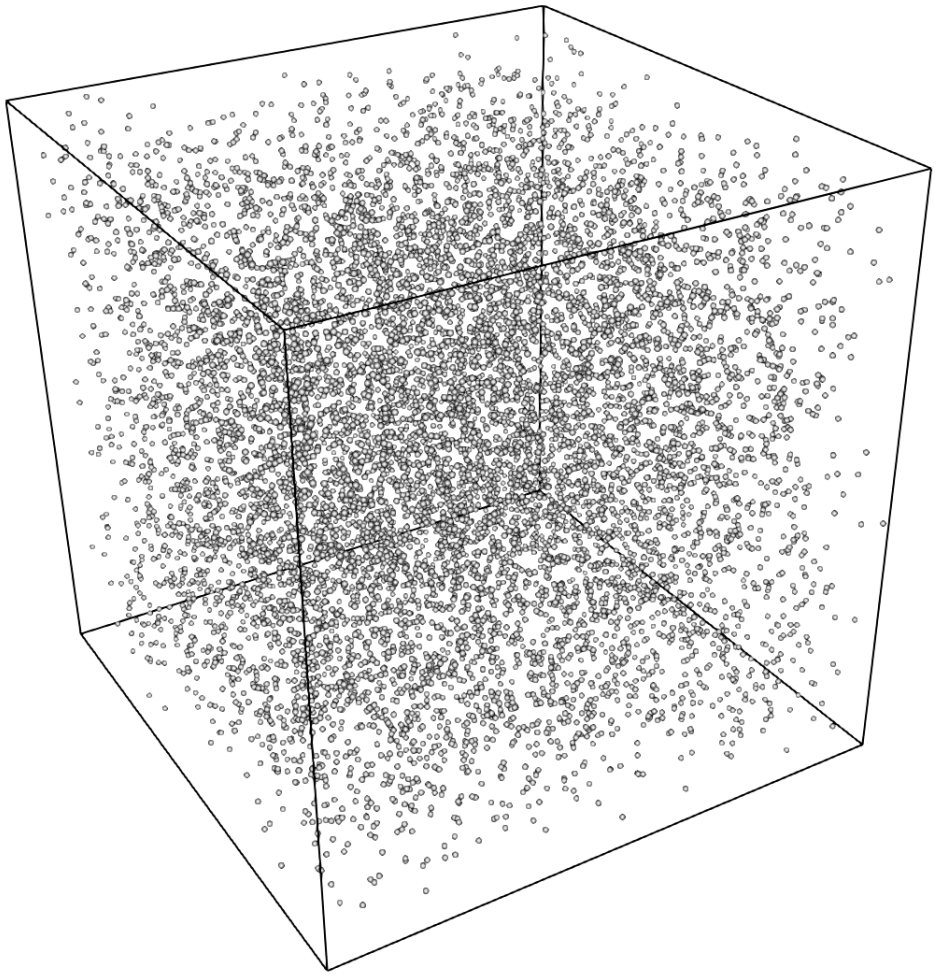


Fig. 2.24: Sample *Particle Mesh* within a box domain.

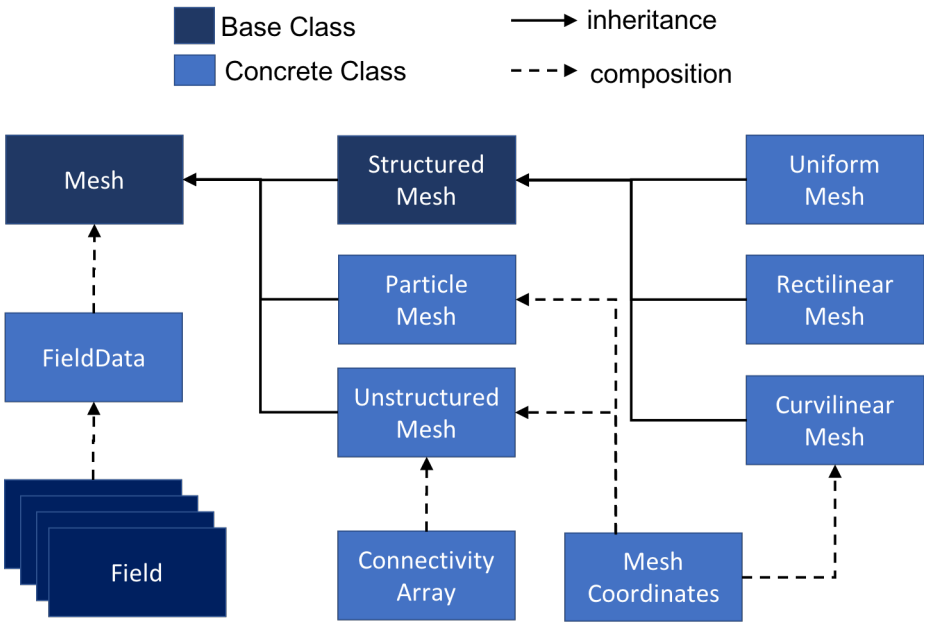


Fig. 2.25: *Component Architecture* of the Mint *mesh data model*, depicting the core mesh classes and the inter-relationship between them. The solid arrows indicate an *inheritance* relationship, while the dashed arrows indicate an *ownership* relationship between two classes.

classes that underpin the implementation of the *Concrete Mesh Classes* and facilitate the representation of the constituent *Geometry* and *Topology* of the mesh.

Note: All Mint classes and functions are encapsulated in the `axom::mint` namespace.

The Mesh Base Class

The Mesh Base Class stores common attributes associated with a mesh. Irrespective of the mesh type, a Mint mesh has two identifiers. The mesh *BlockID* and mesh *DomainID*, which are assigned by domain decomposition. Notably, the computational domain can consist of one or more blocks, which are usually defined by the user or application. Each block is then subsequently partitioned to multiple domains that are distributed across processing units for parallel computation. For example, a sample block and domain decomposition is depicted in Fig. 2.26. Each of the constituent domains is represented by a corresponding `mint::Mesh` instance, which in aggregate define the entire problem domain.

Note: A `mint::Mesh` instance provides the means to store the mesh *BlockID* and *DomainID* respectively. However, Mint does not impose a numbering or partitioning scheme. Assignment of the *BlockID* and *DomainID* is handled at the application level and by the underlying mesh partitioner that is being employed.

Moreover, each `mint::Mesh` instance has associated *Mesh Field Data*, represented by the `mint::FieldData` class. Each of the constituent topological mesh entities, i.e. the *Cells*, *Faces* and *Nodes* comprising the mesh, has a handle to a corresponding `mint::FieldData` instance. The `mint::FieldData` object essentialy provides a container to store and manage a collection of fields, defined over the corresponding mesh entity.

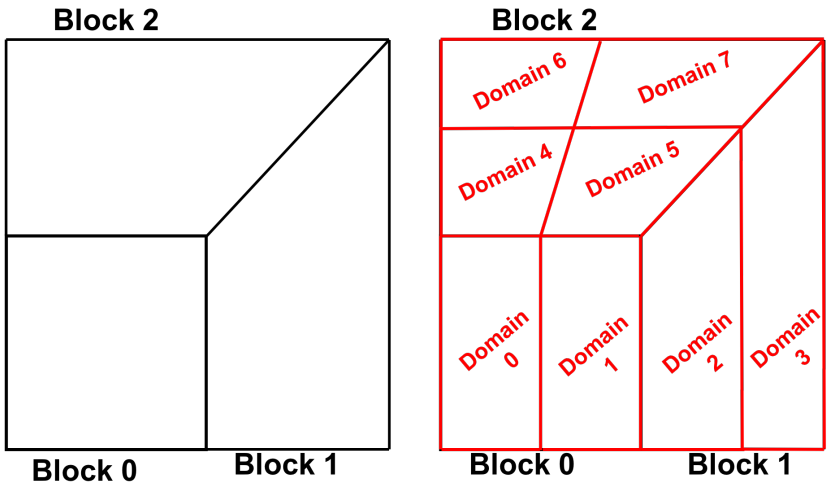


Fig. 2.26: Sample block & domain decomposition of the computational domain. The computational domain is defined using 3 blocks (left). Each block is further partitioned into two or more domains(right). A `mint::Mesh` instance represents one of the constituent domains used to define the overall problem domain.

Warning: Since a *Particle Mesh* is defined by a set of *Nodes*, it can only store *Field Data* at its constituent *Nodes*. All other supported *Mesh Types* can have *Field Data* associated with their constituent *Cells*, *Faces* and *Nodes*.

Mesh Field Data

A `mint::FieldData` instance typically stores multiple fields. Each field is represented by an instance of a `mint::Field` object and defines a named numerical quantity, such as *mass*, *velocity*, *temperature*, etc., defined on a given mesh. Moreover, a field can be either *single-component*, i.e. a *scalar* quantity, or, *multi-component*, e.g. a *vector* or *tensor* quantity. Typically, a field represents some physical quantity that is being modeled, or, an auxiliary quantity that is needed to perform a particular calculation.

In addition, each `mint::Field` instance can be of different data type. The `mint::FieldData` object can store different types of fields. For example, *floating point* quantities i.e., `float` or `double`, as well as, *integral* quantities, i.e. `int32_t`, `int64_t`, etc. This is accomplished using a combination of C++ templates and *inheritance*. The `mint::Field` object is an abstract base class that defines a type-agnostic interface to encapsulate a field. Since `mint::Field` is an abstract base class, it is not instantiated directly. Instead, all fields are created by instantiating a `mint::FieldVariable` object, a class templated on data type, that derives from the `mint::Field` base class. For example, the code snippet below illustrates how fields of different type can be instantiated.

```
...

// create a scalar field to store mass as a single precision quantity
mint::Field* mass = new mint::FieldVariable< float >( "mass", size );

// create a velocity vector field as a double precision floating point quantity
constexpr int NUM_COMPONENTS = 3;
mint::Field* vel = new mint::FieldVariable< double >( "vel", size, NUM_COMPONENTS );

...
```

Generally, in application code, it is not necessary to create fields using the `mint::FieldVariable` class directly.

The `mint::Mesh` object provides convenience methods for adding, removing and accessing fields on a mesh. Consult the *Tutorial* for more details on *Working with Fields* on a Mesh.

Concrete Mesh Classes

The *Concrete Mesh Classes*, extend *The Mesh Base Class* and implement the underlying *Mesh Representation* of the various *Mesh Types*, depicted in Fig. 2.27.

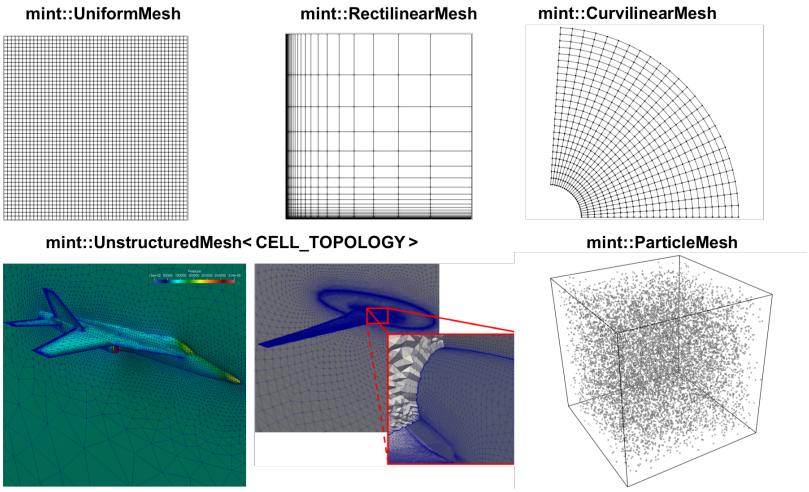


Fig. 2.27: Depiction of the supported *Mesh Types* with labels of the corresponding Mint class used for the underlying *Mesh Representation*.

Structured Mesh

All *Structured Mesh* types in Mint can be represented by an instance of the `mint::StructuredMesh` class, which derives directly from *The Mesh Base Class*, `mint::Mesh`. The `mint::StructuredMesh` class is also an abstract base class that encapsulates the implementation of the *implicit*, *ordered* and *regular* *Topology* that is common to all *Structured Mesh* types. The distinguishing characteristic of the different *Structured Mesh* types is the representation of the constituent *Geometry*. Mint implements each of the different *Structured Mesh* types by a corresponding class, which derives directly from `mint::StructuredMesh` and thereby inherit its implicit *Topology* representation.

Consequently, support for the *Uniform Mesh* is implemented in `mint::UniformMesh`. The *Geometry* of a *Uniform Mesh* is *implicit*, given by two attributes, the mesh *origin* and *spacing*. Consequently, the `mint::UniformMesh` consists of two data members to store the *origin* and *spacing* of the *Uniform Mesh* and provides functionality for evaluating the spatial coordinates of a node given its corresponding IJK lattice coordinates.

Similarly, support for the *Rectilinear Mesh* is implemented in `mint::RectilinearMesh`. The constituent *Geometry* representation of the *Rectilinear Mesh* is *semi-implicit*. The spatial coordinates of the *Nodes* along each axis are specified explicitly while the coordinates of the interior *Nodes* are evaluated by taking the *Cartesian* product of the corresponding coordinate along each coordinate axis. The `mint::RectilinearMesh` consists of seperate arrays to store the coordinates along each axis for the *semi-implicit* *Geometry* representation of the *Rectilinear Mesh*.

Support for the *Curvilinear Mesh* is implemented by the `mint::CurvilinearMesh` class. The *Curvilinear Mesh* requires *explicit* representation of its constituent *Geometry*. The `mint::CurvilinearMesh` makes use of the `mint::MeshCoordinates` class to explicitly represent the spatial coordinates associated with the constituent *Nodes* of the mesh.

Unstructured Mesh

Mint's *Unstructured Mesh* representation is provided by the `mint::UnstructuredMesh` class, which derives directly from the *The Mesh Base Class*, `mint::Mesh`. An *Unstructured Mesh* has both *explicit Geometry* and *Topology*. As with the `mint::CurvilinearMesh` class, the *explicit Geometry* representation of the *Unstructured Mesh* employs the `mint::MeshCoordinates`. The constituent *Topology* is handled by the `mint::ConnectivityArray`, which is employed for the representation of all the topological *Connectivity* information, i.e. *cell-to-node*, *face-to-node*, *face-to-cell*, etc.

Note: Upon construction, a `mint::UnstructuredMesh` instance consists of the *minimum sufficient* representation for an *Unstructured Mesh* comprised of the *cell-to-node Connectivity* information. Applications that require face *Connectivity* information must explicitly call the `initializeFaceConnectivity()` method on the corresponding *Unstructured Mesh* object.

Depending on the cell *Topology* being employed, an *Unstructured Mesh* can be classified as either a *Single Cell Type Topology Unstructured Mesh* or a *Mixed Cell Type Topology Unstructured Mesh*. To accomodate these two different representations, the `mint::UnstructuredMesh` class, is templated on `CELL_TOPOLOGY`. Internally, the template argument is used to indicate the type of `mint::ConnectivityArray` to use, i.e. whether, *stride access addressing* or *indirect addressing* is used, for *Single Cell Type Topology* and *Mixed Cell Type Topology* respectively.

Particle Mesh

Support for the *Particle Mesh* representation is implemented in `mint::ParticleMesh`, which derives directly from *The Mesh Base Class*, `mint::Mesh`. A *Particle Mesh* discretizes the domain by a set of particles, which correspond to the constituent *Nodes* of the mesh. The *Nodes* of a *Particle Mesh* can also be thought of as *Cells*, however, since this information is trivially obtrained, there is not need to be stored explicitly, e.g. using a *Single Cell Type Topology Unstructured Mesh* representation. Consequently, the *Particle Mesh* representation consists of *explicit Geometry* and *implicit Topology*. As with the `mint::CurvilinearMesh` and `mint::UnstructuredMesh`, the explicit *Geometry* of the *Particle Mesh* is represented by employing the `mint::MeshCoordinates` as an internal class member.

The following code snippet provides a simple examples illustrating how to construct and operate on a *Particle Mesh*.

```
1  // Copyright (c) 2017-2020, Lawrence Livermore National Security, LLC and
2  // other Axom Project Developers. See the top-level COPYRIGHT file for details.
3  //
4  // SPDX-License-Identifier: (BSD-3-Clause)
5
6  /*!
7   * \file
8   *
9   * \brief Illustrates how to construct and use a ParticleMesh to perform
10  *  operations on a set of particles.
11  */
12
13 // Axom utilities
14 #include "axom/core.hpp"
15 #include "axom/mint.hpp"
16
17 // namespace aliases
18 namespace mint      = axom::mint;
19 namespace utilities = axom::utilities;
20
```

(continues on next page)

(continued from previous page)

```
21
22 //------------------------------------------------------------------------------
23 int main( int AXOM_NOT_USED(argc), char** AXOM_NOT_USED(argv) )
24 {
25   using int64 = axom::IndexType;
26   const axom::IndexType NUM_PARTICLES = 100;
27   const int DIMENSION = 3;
28
29   const double HI  = 10.0;
30   const double LO  = -10.0;
31   const double VLO = 0.0;
32   const double VHI = 1.0;
33
34   // STEP 0: create the ParticleMesh
35   mint::ParticleMesh particles( DIMENSION, NUM_PARTICLES );
36
37   // STEP 1: Add fields to the Particles
38   double* vx = particles.createField< double >( "vx", mint::NODE_CENTERED );
39   double* vy = particles.createField< double >( "vy", mint::NODE_CENTERED );
40   double* vz = particles.createField< double >( "vz", mint::NODE_CENTERED );
41   int64* id  = particles.createField< int64 >( "id", mint::NODE_CENTERED );
42
43   // STEP 2: grab handle to the particle position arrays
44   double* px = particles.getCoordinateArray( mint::X_COORDINATE );
45   double* py = particles.getCoordinateArray( mint::Y_COORDINATE );
46   double* pz = particles.getCoordinateArray( mint::Z_COORDINATE );
47
48   // STEP 3: loop over the particle data
49   const int64 numParticles = particles.getNumberOfNodes();
50   for ( int64 i=0 ; i < numParticles ; ++i )
51   {
52
53     px[ i ] = utilities::random_real( LO, HI );
54     py[ i ] = utilities::random_real( LO, HI );
55     pz[ i ] = utilities::random_real( LO, HI );
56
57     vx[ i ] = utilities::random_real( VLO, VHI );
58     vy[ i ] = utilities::random_real( VLO, VHI );
59     vz[ i ] = utilities::random_real( VLO, VHI );
60
61     id[ i ] = i;
62
63   } // END
64
65   // STEP 4: write the particle mesh in VTK format for visualization
66   mint::write_vtk( &particles, "particles.vtk" );
67
68   return 0;
69 }
```

Mesh Storage Management

Mint provides a flexible *Mesh Storage Management* system that can optionally interoperate with Sidre as the underlying, in-memory, hierarchichal datastore. This enables Mint to natively conform to Conduit's Blueprint protocol for representing a computational mesh in memory and thereby, facilitate with the integration across different physics packages.

Mint's *Mesh Storage Management* substrate supports three storage options. The applicable operations and ownership state of each storage option are summarized in the table below, followed by a brief description of each option.

	Modify	Reallocate	Ownership
Native Storage	✓	✓	Mint
External Storage	✓		Application
Sidre Storage	✓	✓	Sidre

Native Storage

A Mint object using *Native Storage* owns all memory and associated data. The data can be modified and the associated memory space can be reallocated to grow and shrink as needed. However, once the Mint object goes out-of-scope, all data is deleted and the memory is returned to the system.

See the *Tutorial* for more information and a set of concrete examples on how to create a mesh using *Native Storage*.

External Storage

A Mint object using *External Storage* has a pointer to a supplied application buffer. In this case, the data can be modified, but the application maintains ownership of the underlying memory. Consequently, the memory space cannot be reallocated and once the Mint object goes out-of-scope, the data is not deleted. The data remains persistent in the application buffers until it is deleted by the application.

See the *Tutorial* for more information on *Using External Storage*.

Sidre Storage

A Mint object using *Sidre Storage* is associated with a Sidre Group object which has owneship of the mesh data. In this case the data can be modified and the associated memory can be reallocated to grow and shrink as needed. However, when the Mint object goes out-of-scope, the data remains persistent in Sidre.

See the *Tutorial* for more information and a set of concrete examples on *Using Sidre*.

2.7.6 Execution Model

Mint provides a mesh-aware *Execution Model*, based on the RAJA programming model abstraction layer. The execution model supports on-node fine-grain parallelism for mesh traversals. Thereby, enable the implementation of computational kernels that are born parallel and portable across different processor architectures.

Note: To utilize NVIDIA GPUs, using the RAJA CUDA backend, Axom needs to be compiled with CUDA support and linked to a CUDA-enabled RAJA library. Consult the Axom Quick Start Guide for more information.

The execution model consists of a set of templated functions that accept two arguments:

1. A pointer to a mesh object corresponding to one of the supported *Mesh Types*.
2. The *kernel* that defines the operations on the supplied mesh, which is usually specified by a C++11 *Lambda Expression*.

Note: Instead of a C++11 Lambda Expression a C++ functor may also be used to encapsulate a kernel. However, in our experience, using C++11 functors, usually requires more boiler plate code, which reduces readability and may potentially have a negative impact on performance.

The *Execution Model* provides *Node Traversal Functions*, *Cell Traversal Functions* and *Face Traversal Functions* to iterate and operate on the constituent *Nodes*, *Cells* and *Faces* of the mesh respectively. The general form of these functions is shown in Fig. 2.28.

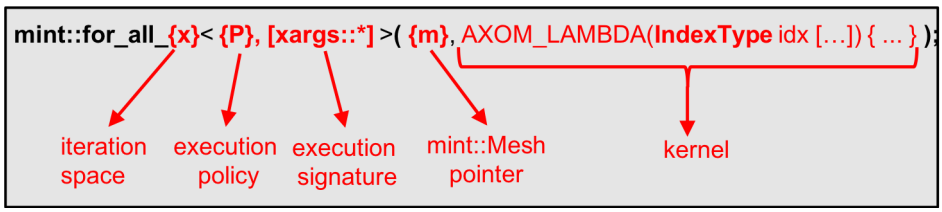


Fig. 2.28: General form of the constituent templated functions of the *Execution Model*

As shown in Fig. 2.28, the key elements of the functions that comprise the *Execution Model* are:

- **The Iteration Space:** Indicated by the function suffix, used to specify the mesh entities to traverse and operate upon, e.g. the *Nodes*, *Cells* or *Faces* of the mesh.
- The *Execution Policy*: Specified as as the first, *required*, template argument to the constituent functions of the *Execution Model*. The *Execution Policy* specifies *where* and *how* the kernel is executed.
- The *Execution Signature*: Specified by a second, *optional*, template argument to the constituent functions of the *Execution Model*. The *Execution Signature* specifies the type of arguments supplied to a given *kernel*.
- **The Kernel:** Supplied as an argument to the constituent functions of the *Execution Model*. It defines the body of operations performed on the supplied mesh.

See the *Tutorial* for code snippets that illustrate how to use the *Node Traversal Functions*, *Cell Traversal Functions* and *Face Traversal Functions* of the *Execution Model*.

Execution Policy

The *Execution Policy* is specifed as the first template argument and is required by all of the constituent functions of the *Execution Model*. Axom defines a set of high-level execution spaces, summarized in the table below.

Execution Policy	Requirements	Description
SEQ_EXEC	None.	Sequential execution on the CPU.
OMP_EXEC	RAJA + OpenMP	Parallel execution on the CPU using OpenMP.
CUDA_EXEC< BLOCK-SIZE >	RAJA + CUDA + Umpire (memory management)	Parallel execution on CUDA-enabled GPUs.
CUDA_EXEC< BLOCK-SIZE, ASYNC >	RAJA + CUDA + Umpire (memory management)	Asynchronous parallel execution on CUDA-enabled GPUs.

Internally, the implementation uses the `axom::execution_space` traits object to map each execution space to corresponding RAJA execution policies and bind the default memory space for a given execution space. For example, the default memory space for the `axom::CUDA_EXEC` execution space is unified memory, which can be accessed from both the host (CPU) and device (GPU).

Execution Signature

The *Execution Signature* is specified as the second, *optional* template argument to the constituent functions of the *Execution Model*. The *Execution Signature* indicates the list of arguments that are supplied to the user-specified kernel.

Note: If not specified, the default *Execution Signature* is set to `mint::xargs::index`, which indicates that the supplied kernel takes a single argument that corresponds to the index of the corresponding iteration space, i.e, the loop index.

The list of currently available *Execution Signature* options is based on commonly employed access patterns found in various mesh processing and numerical kernels. However, the *Execution Model* is designed such that it can be extended to accomodate additional access patterns.

- **`mint::xargs::index`**
  - Default *Execution Signature* to all functions of the *Execution Model*
  - Indicates that the supplied kernel takes a single argument that corresponds to the index of the iteration space, i.e. the loop index.
- **`mint::xargs::ij`/`mint::xargs::ijk`**
  - Applicable only with a *Structured Mesh*.
  - Used with *Node Traversal Functions* (`mint::for_all_nodes()`) and *Cell Traversal Functions* (`mint::for_all_cells()`).
  - Indicates that the supplied kernel takes the corresonding (i, j) or (i, j, k) indices, in 2D or 3D respectively, as additional arguments.
- **`mint::xargs::x`/`mint::xargs::xy`/`mint::xargs::xyz`**
  - Used with *Node Traversal Functions* (`mint::for_all_nodes()`).
  - Indicates that the supplied kernel takes the corresponding nodal coordinates, x in 1D, (x, y) in 2D and (x, y, z) in 3D, in addition to the corresponding node index, `nodeIdx`.
- **`mint::xargs::nodeids`**
  - Used with *Cell Traversal Functions* (`mint::for_all_cells()`) and *Face Traversal Functions* (`mint::for_all_faces()`).
  - Indicates that the specified kernel is supplied the constituent node IDs as an array argument to the kernel.
- **`mint::xargs::coords`**
  - Used with *Cell Traversal Functions* (`mint::for_all_cells()`). and *Face Traversal Functions* (`mint::for_all_faces()`)
  - Indicates that the specified kernel is supplied the constituent node IDs and corresponding coordinates as arguments to the kernel.
- **`mint::xargs::faceids`**
  - Used with the *Cell Traversal Functions* (`mint::for_all_cells()`).
  - Indicates that the specified kernel is supplied an array consisting of the constituent cell face IDs as an additional argument.
- **`mint::xargs::cellids`**

- Used with the *Face Traversal Functions* (`mint::for_all_faces()`).
- Indicates that the specified kernel is supplied the ID of the two abutting *Cells* to the given. By conventions, tor *external boundary Faces*, that are bound to a single cell, the second cell is set to -1.

Warning: Calling a traversal function with an unsupported *Execution Signature* will result in a compile time error.

2.7.7 Finite Elements

The Finite Element Method (FEM) is a widely used numerical technique, employed for the solution of *partial differential equations* (PDEs), arising in *structural engineering analysis* and more broadly in the field of *continuum mechanics*.

However, due to their generality and mathematically sound foundation, *Finite Elements*, are often employed in the implementation of other numerical schemes and for various computational operators, e.g. interpolation, integration, etc.

Mint provides basic support for *Finite Elements* that consists:

1. *Lagrange Basis shape functions* for commonly employed *Cell Types*
2. Corresponding *Quadratures* (under development)
3. Routines for forward/inverse *Isoparametric Mapping*, and
4. Infrastructure to facilitate adding *shape functions* for new *Cell Types*, as well as, to *Add a New Finite Element Basis*.

This functionality is collectively exposed to the application through the `mint::FiniteElement` class. Concrete examples illustrating the usage of the `mint::FiniteElement` class within an application code are provided in the *Finite Elements* tutorial section.

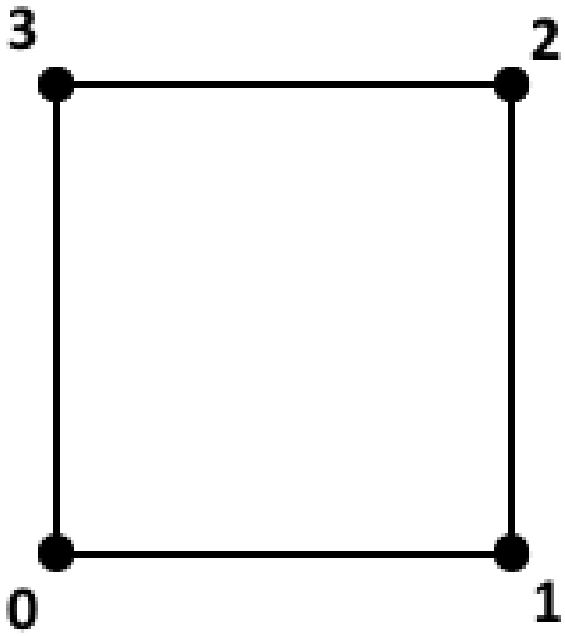
A *Finite Element Basis* consists of a family of *shape functions* corresponding to different *Cell Types*. Mint currently supports Lagrange isoparametric *Finite Elements*.

Lagrange Basis

The Lagrange basis consists of *Cell Types* whose *shape functions* are formed from products of the one-dimensional Lagrange polynomial. This section provides a summary of supported *Lagrange Basis Cell Types*, their associated *shape functions*, and summarize the process to *Add a New Lagrange Element*.

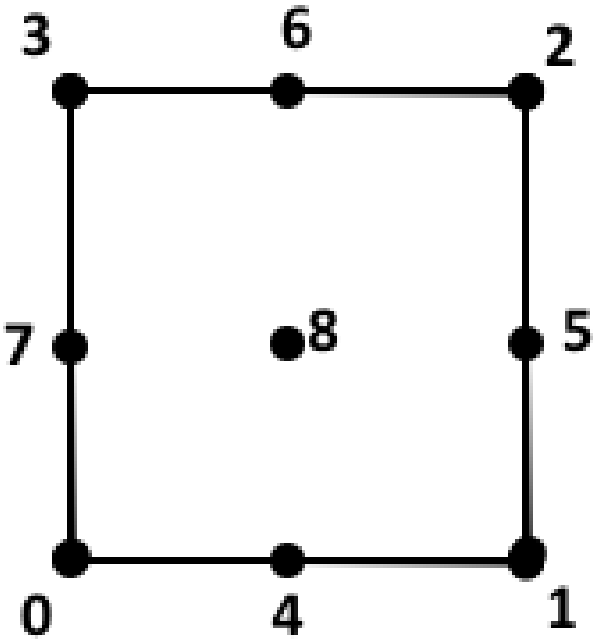
Note: The shape functions of **all** Lagrange *Cells* in Mint, follow the CGNS Numbering Conventions and are defined within a reference coordinate system, on the closed interval $\hat{\xi} \in [0, 1]$.

QUAD: *Linear Quadrilateral*



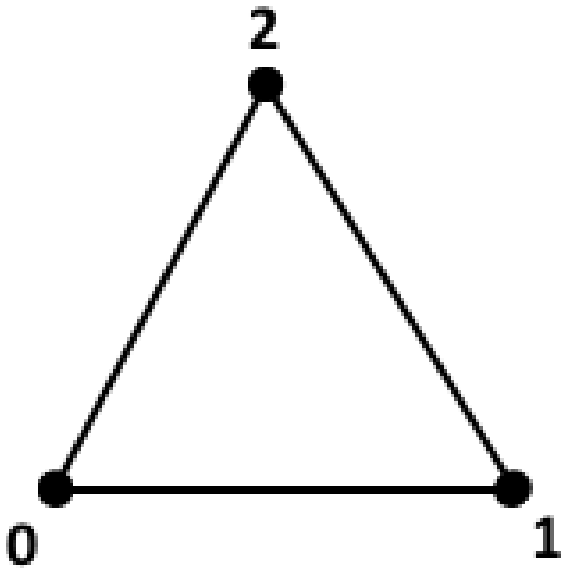
$$
\begin{aligned}
N_0 &= (1-\xi) \times (1-\eta) \\
N_1 &= \xi \times (1-\eta) \\
N_2 &= \xi \times \eta \\
N_3 &= (1-\xi) \times \eta
\end{aligned}
$$

QUAD9: *Quadratic Quadrilateral*



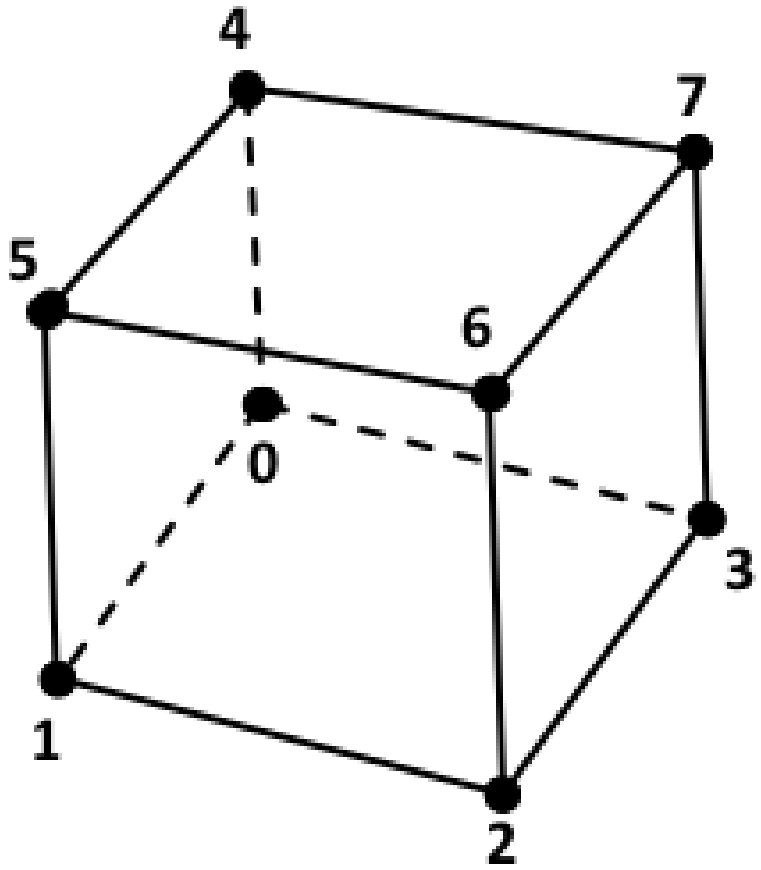
$$
\begin{aligned}
N_0 &= (\xi-1)(2\xi-1) \times (\eta-1)(2\eta-1) \\
N_1 &= \xi(2\xi-1) \times (\eta-1)(2\eta-1) \\
N_2 &= \xi(2\xi-1) \times \eta(2\eta-1) \\
N_3 &= (\xi-1)(2\xi-1) \times \eta(2\eta-1) \\
\\
N_4 &= 4\xi(1-\xi) \times (\eta-1)(2\eta-1) \\
N_5 &= \xi(2\xi-1) \times 4\eta(1-\eta) \\
N_6 &= 4\xi(1-\xi) \times \eta(2\eta-1) \\
N_7 &= (\xi-1)(2\xi-1) \times 4\eta(1-\eta) \\
\\
N_8 &= 4\xi(1-\xi) \times 4\eta(1-\eta)
\end{aligned}
$$

TRIANGLE: *Linear Triangle*



$$
\begin{aligned}
N_0 &= 1-\xi-\eta \\
N_1 &= \xi \\
N_2 &= \eta
\end{aligned}
$$

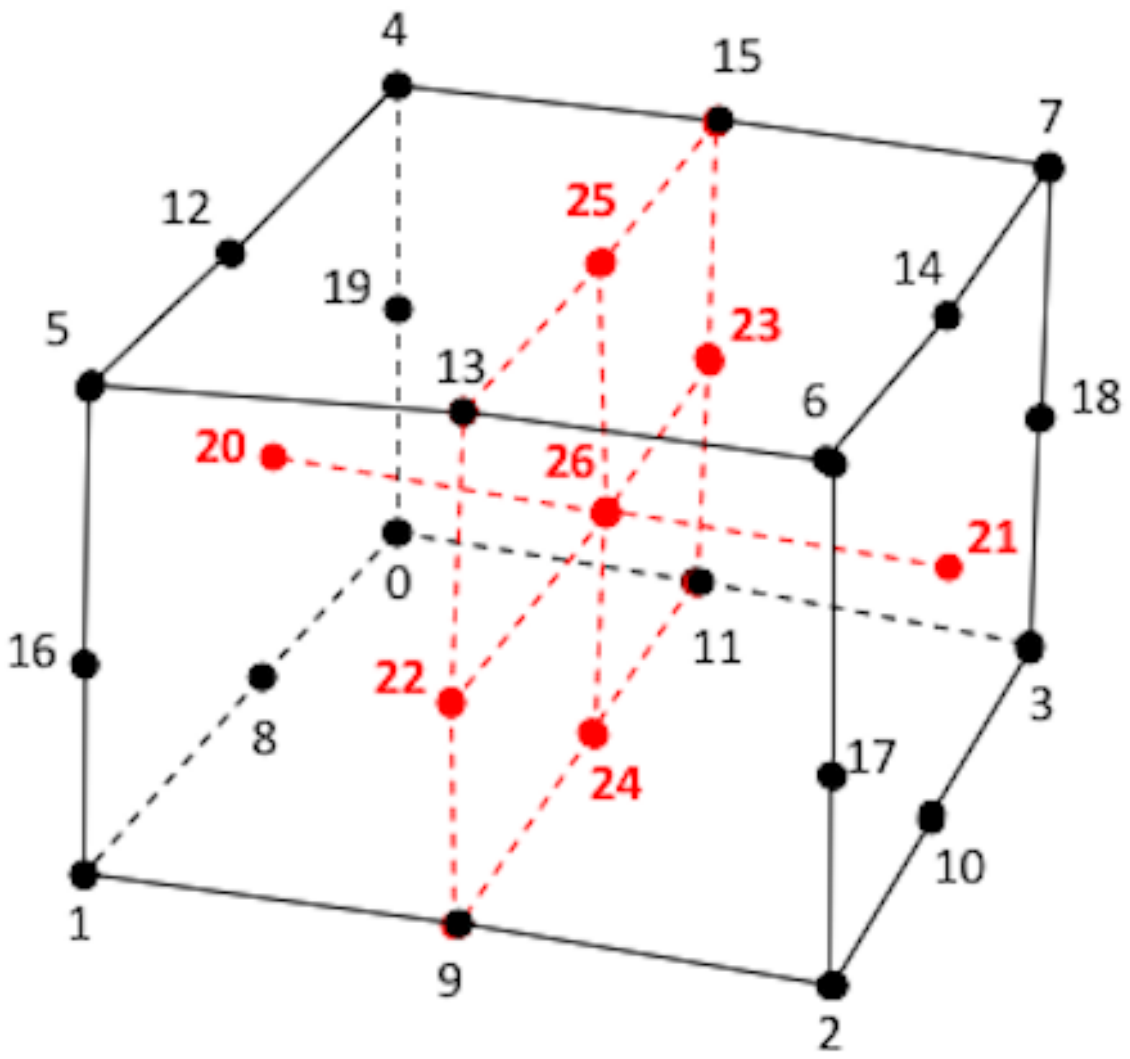
HEX: *Linear Hexahedron*



$$
\begin{aligned}
N_0 &= (1-\xi) \times (1-\eta) \times (1-\zeta) \\
N_1 &= \xi \times (1-\eta) \times (1-\zeta) \\
N_2 &= \xi \times \eta \times (1-\zeta) \\
N_3 &= (1-\xi) \times \eta \times (1-\zeta)
\end{aligned}
$$

$$
\begin{aligned}
N_4 &= (1-\xi) \times (1-\eta) \times \zeta \\
N_5 &= \xi \times (1-\eta) \times \zeta \\
N_6 &= \xi \times \eta \times \zeta \\
N_7 &= (1-\xi) \times \eta \times \zeta
\end{aligned}
$$

HEX27: *Quadratic Hexahedron*



$$
\begin{aligned}
N_0 &= (\xi-1)(2\xi-1) \times (\eta-1)(2\eta-1) \times (\zeta-1)(2\zeta-1) \\
N_1 &= \xi(2\xi-1) \times (\eta-1)(2\eta-1) \times (\zeta-1)(2\zeta-1) \\
N_2 &= \xi(2\xi-1) \times \eta(2\eta-1) \times (\zeta-1)(2\zeta-1) \\
N_3 &= (\xi-1)(2\xi-1) \times \eta(2\eta-1) \times (\zeta-1)(2\zeta-1)
\end{aligned}
$$

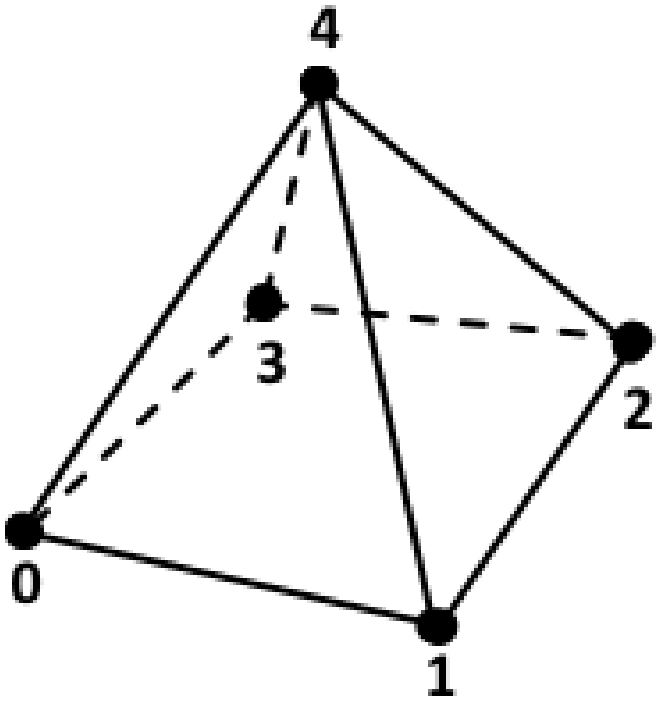
$$
\begin{aligned}
N_4 &= (\xi-1)(2\xi-1) \times (\eta-1)(2\eta-1) \times \zeta(2\zeta-1) \\
N_5 &= \xi(2\xi-1) \times (\eta-1)(2\eta-1) \times \zeta(2\zeta-1) \\
N_6 &= \xi(2\xi-1) \times \eta(2\eta-1) \times \zeta(2\zeta-1) \\
N_7 &= (\xi-1)(2\xi-1) \times \eta(2\eta-1) \times \zeta(2\zeta-1)
\end{aligned}
$$

$$
\begin{aligned}
N_8 &= 4\xi(1-\xi) \times (\eta-1)(2\eta-1) \times (\zeta-1)(2\zeta-1) \\
N_9 &= \xi(2\xi-1) \times 4\eta(1-\eta) \times (\zeta-1)(2\zeta-1) \\
N_{10} &= 4\xi(1-\xi) \times \eta(2\eta-1) \times (\zeta-1)(2\zeta-1) \\
N_{11} &= (\xi-1)(2\xi-1) \times 4\eta(1-\eta) \times (\zeta-1)(2\zeta-1)
\end{aligned}
$$

$$
\begin{aligned}
N_{12} &= 4\xi(1-\xi) \times (\eta-1)(2\eta-1) \times \zeta(2\zeta-1) \\
N_{13} &= \xi(2\xi-1) \times 4\eta(1-\eta) \times \zeta(2\zeta-1) \\
N_{14} &= 4\xi(1-\xi) \times \eta(2\eta-1) \times \zeta(2\zeta-1) \\
N_{15} &= (\xi-1)(2\xi-1) \times 4\eta(1-\eta) \times \zeta(2\zeta-1)
\end{aligned}
$$

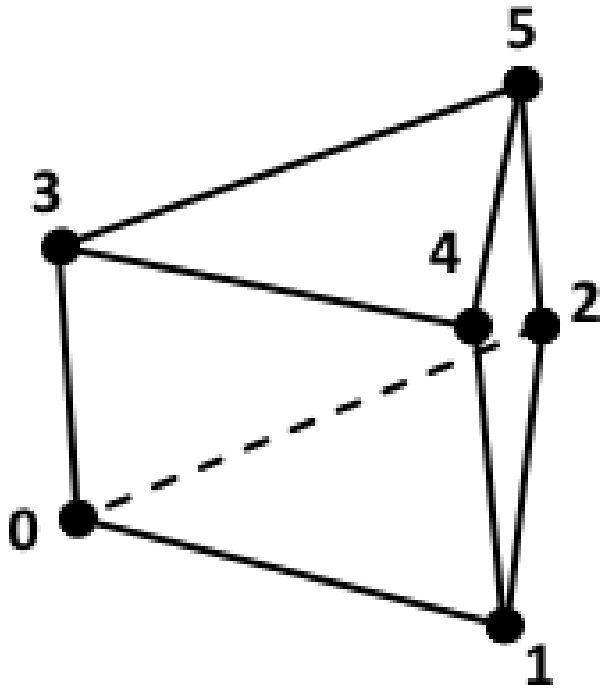
$$
\begin{aligned}
N_{16} &= (\xi-1)(2\xi-1) \times (\eta-1)(2\eta-1) \times 4\zeta(1-\zeta) \\
N_{17} &= \xi(2\xi-1) \times (\eta-1)(2\eta-1) \times 4\zeta(1-\zeta) \\
N_{18} &= \xi(2\xi-1) \times \eta(2\eta-1) \times 4\zeta(1-\zeta)
\end{aligned}
$$

PYRAMID: ***Linear Pyramid***



$$
\begin{array}{lcllcl}
N_0 & = & (1-\xi) & \times & (1-\eta) & \times & (1-\zeta) \\
N_1 & = & \xi & \times & (1-\eta) & \times & (1-\zeta) \\
N_2 & = & \xi & \times & \eta & \times & (1-\zeta) \\
N_3 & = & (1-\xi) & \times & \eta & \times & (1-\zeta) \\
N_4 & = & \zeta & & & &
\end{array}
$$

PRISM: *Linear Prism/Wedge*



$$
\begin{aligned}
N_0 &= (1-\xi)-\eta \times (1-\zeta) \\
N_1 &= \xi \times (1-\zeta) \\
N_2 &= \eta \times (1-\zeta) \\
N_3 &= (1-\xi)-\eta \times \zeta \\
N_4 &= \xi \times \zeta \\
N_5 &= \eta \times \zeta
\end{aligned}
$$

Add a New Lagrange Element

Warning: This section is under construction.

Isoparametric Mapping

Warning: This section is under construction.

Quadratures

Warning: Support for Quadratures in Mint is under development.

Add a New Finite Element Basis

Warning: This section is under construction.

2.7.8 Tutorial

The *Tutorial* section consists of simple examples and code snippets that illustrate how to use Mint's core classes and functions to construct and operate on the various supported *Mesh Types*. The examples presented herein aim to illustrate specific Mint concepts and capabilities in a structured and simple format. To quickly learn basic Mint concepts and capabilities through an illustrative walk-through of a complete working code example, see the *Getting Started with Mint* section. Additional code examples, based on Mint mini-apps, are provided in the *Examples* section. For thorough documentation of the interfaces of the various classes and functions in Mint, developers are advised to consult the Mint Doxygen API Documentation, in conjunction with this *Tutorial*.

Create a Uniform Mesh

A *Uniform Mesh* is relatively the simplest *Structured Mesh* type, but also, the most restrictive mesh out of all *Mesh Types*. The constituent *Nodes* of the *Uniform Mesh* are *uniformly* spaced along each axis on a regular lattice. Consequently, a *Uniform Mesh* can be easily constructed by simply specifying the spatial extents of the domain and desired dimensions, e.g. the number of *Nodes* along each dimension.

For example, a 50×50 *Uniform Mesh*, defined on a bounded domain given by the interval $\mathcal{I} : [-5.0, 5.0] \times [-5.0, 5.0]$, can be easily constructed as follows:

```
1  const double lo[]   = { -5.0, -5.0 };
2  const double hi[]   = {  5.0,  5.0 };
3  mint::UniformMesh mesh( lo, hi, 50, 50 );
```

The resulting mesh is depicted in Fig. 2.29.

Create a Rectilinear Mesh

A *Rectilinear Mesh*, also called a *product mesh*, is similar to a *Uniform Mesh*. However, the constituent *Nodes* of a *Rectilinear Mesh* are not uniformly spaced. The spacing between adjacent *Nodes* can vary arbitrarily along each axis, but the *Topology* of the mesh remains a regular *Structured Mesh Topology*. To allow for this flexibility, the coordinates of the *Nodes* along each axis are explicitly stored in separate arrays, i.e. x, y and z, for each coordinate axis respectively.

The following code snippet illustrates how to construct a 25×25 *Rectilinear Mesh* where the spacing of the *Nodes* grows according to an exponential *stretching function* along the x and y axis respectively. The resulting mesh is depicted in Fig. 2.30.

```
1  constexpr double beta = 0.1;
2  const double expbeta  = exp( beta );
3  const double invf     = 1 / ( expbeta - 1.0 );
4
5  // construct a N x N rectilinear mesh
6  constexpr axom::IndexType N = 25;
7  mint::RectilinearMesh mesh( N, N );
8  double* x = mesh.getCoordinateArray( mint::X_COORDINATE );
9  double* y = mesh.getCoordinateArray( mint::Y_COORDINATE );
10
11
12 // fill the coordinates along each axis
13 x[ 0 ] = y[ 0 ] = 0.0;
14 for ( int i=1; i < N; ++i )
15 {
16   const double delta = ( exp( i*beta ) - 1.0 ) * invf;
17   x[ i ] = x[ i-1 ] + delta;
```

(continues on next page)

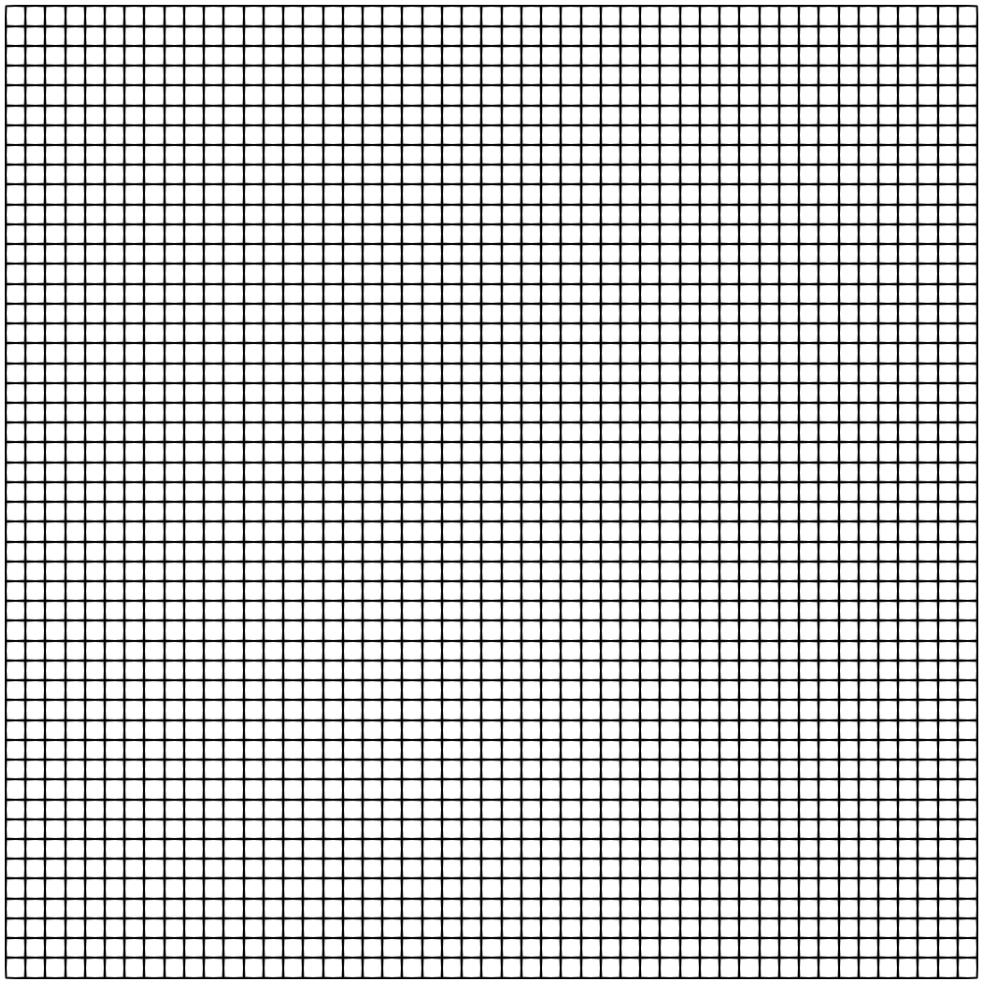


Fig. 2.29: Resulting Uniform Mesh.

(continued from previous page)

```
    y[ i ] = y[ i-1 ] + delta;
  }
```

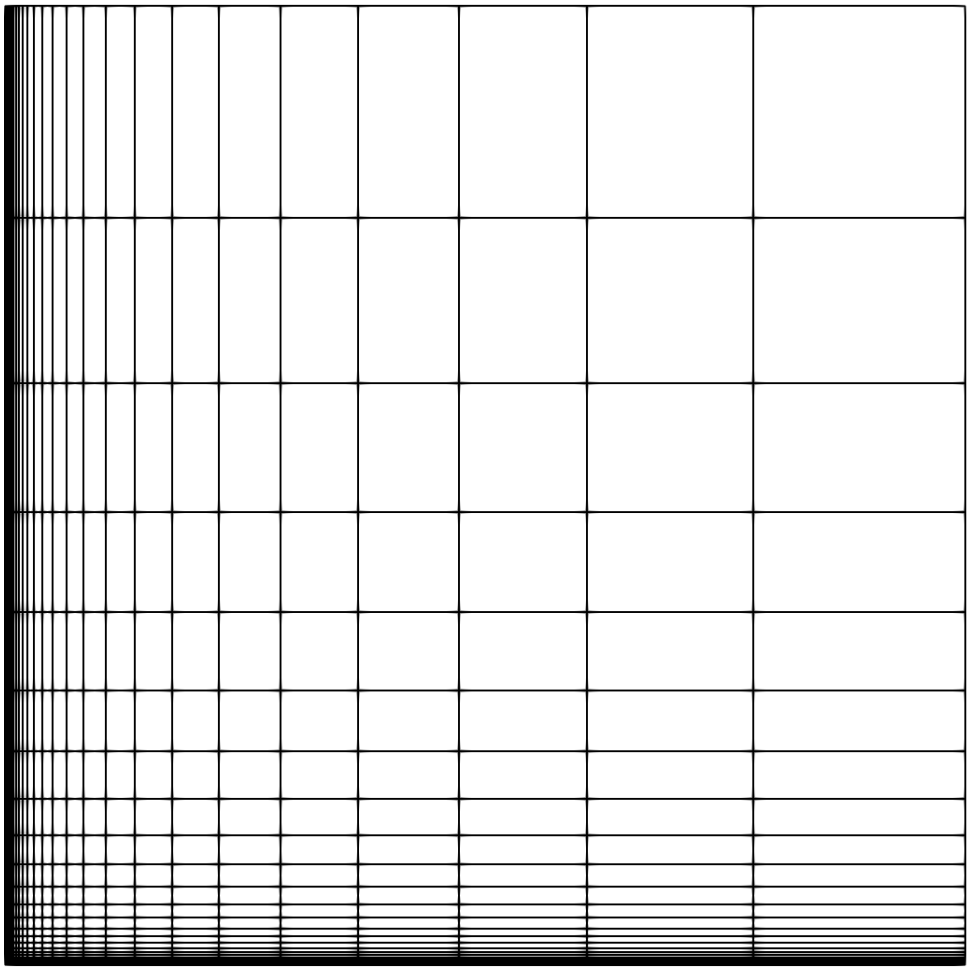


Fig. 2.30: Resulting *Rectilinear Mesh*.

Create a Curvilinear Mesh

A *Curvilinear Mesh*, also called a *body-fitted mesh*, is the most general of the *Structured Mesh* types. Similar to the *Uniform Mesh* and *Rectilinear Mesh* types, a *Curvilinear Mesh* also has regular *Structured Mesh Topology*. However, the coordinates of the *Nodes* comprising a *Curvilinear Mesh* are defined explicitly, enabling the use of a *Structured Mesh* discretization with more general geometric domains, i.e., the domain may not be necessarily Cartesian. Consequently, the coordinates of the *Nodes* are specified explicitly in separate arrays, x, y, and z.

The following code snippet illustrates how to construct a 25×25 *Curvilinear Mesh*. The coordinates of the *Nodes* follow from the equation of a cylinder with a radius of 2.5. The resulting mesh is depicted in Fig. 2.31.

```
constexpr double R           = 2.5;
constexpr double M           = (2 * M_PI) / 50.0;
constexpr double h           = 0.5;
constexpr axom::IndexType N = 25;
```

(continues on next page)

(continued from previous page)

```
5
6   // construct the curvilinear mesh object
7   mint::CurvilinearMesh mesh( N, N );
8
9   // get a handle on the coordinate arrays
10  double* x = mesh.getCoordinateArray( mint::X_COORDINATE );
11  double* y = mesh.getCoordinateArray( mint::Y_COORDINATE );
12
13  // fill the coordinates of the curvilinear mesh
14  const axom::IndexType jp = mesh.nodeJp();
15  for ( axom::IndexType j=0; j < N; ++j )
16  {
17    const axom::IndexType j_offset = j * jp;
18
19    for ( axom::IndexType i=0; i < N; ++i )
20    {
21      const axom::IndexType nodeIdx = i + j_offset;
22
23      const double xx    = h * i;
24      const double yy    = h * j;
25      const double alpha = yy + R;
26      const double beta  = xx * M;
27
28      x[ nodeIdx ] = alpha * cos( beta );
29      y[ nodeIdx ] = alpha * sin( beta );
30    } // END for all i
31
32  } // END for all j
```

Create an Unstructured Mesh

An *Unstructured Mesh* with *Single Cell Type Topology* has both explicit *Topology* and *Geometry*. However, the cell type that the mesh stores is known *a priori*, allowing for an optimized underlying *Mesh Representation*, compared to the more general *Mixed Cell Type Topology Mesh Representation*.

Since both *Geometry* and *Topology* are explicit, an *Unstructured Mesh* is created by specifying:

1. the coordinates of the constituent *Nodes*, and
2. the *Cells* comprising the mesh, defined by the *cell-to-node Connectivity*

The following code snippet illustrates how to create the simple *Unstructured Mesh* depicted in Fig. 2.32.

```
1   constexpr int DIMENSION           = 2;
2   constexpr mint::CellType CELL_TYPE = mint::TRIANGLE;
3
4   // Construct the mesh object
5   mint::UnstructuredMesh< mint::SINGLE_SHAPE > mesh( DIMENSION, CELL_TYPE );
6
7   // Append the mesh nodes
8   const axom::IndexType n0 = mesh.appendNode( 0.0, 0.0 );
9   const axom::IndexType n1 = mesh.appendNode( 2.0, 0.0 );
10  const axom::IndexType n2 = mesh.appendNode( 1.0, 1.0 );
11  const axom::IndexType n3 = mesh.appendNode( 3.5, 1.0 );
12  const axom::IndexType n4 = mesh.appendNode( 2.5, 2.0 );
13  const axom::IndexType n5 = mesh.appendNode( 5.0, 0.0 );
```

(continues on next page)

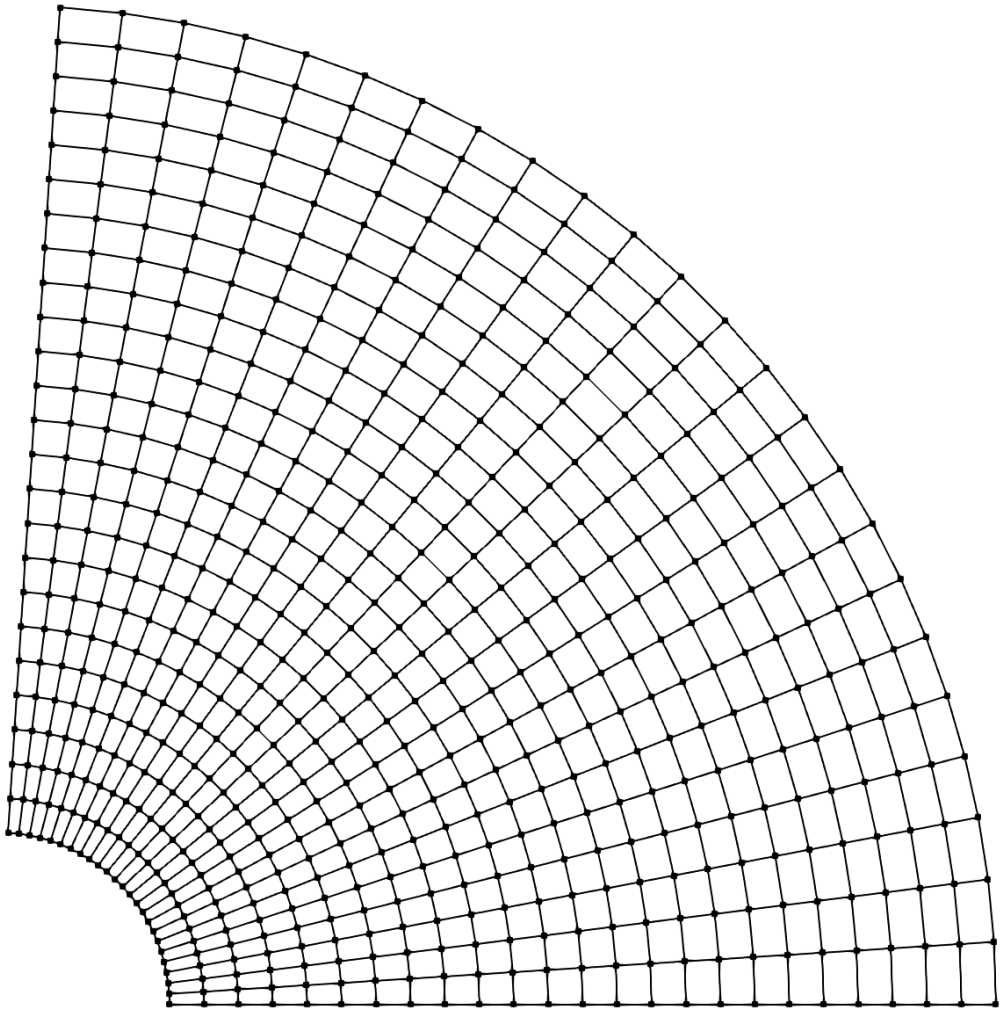


Fig. 2.31: Resulting *Curvilinear Mesh*.

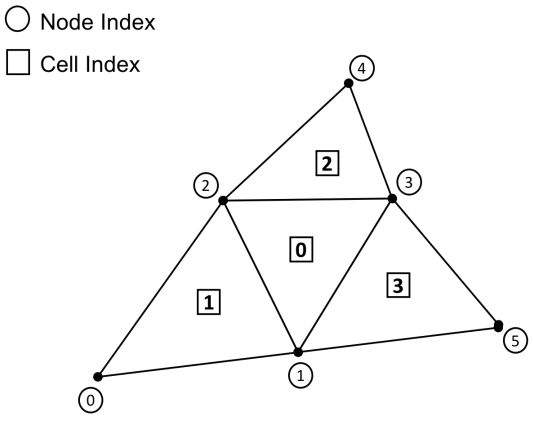


Fig. 2.32: Resulting *Single Cell Type Topology Unstructured Mesh*

(continued from previous page)

```
14
15  // Append mesh cells
16  const axom::IndexType c0[ ] = { n1, n3, n2 };
17  const axom::IndexType c1[ ] = { n2, n0, n1 };
18  const axom::IndexType c2[ ] = { n3, n4, n2 };
19  const axom::IndexType c3[ ] = { n1, n5, n3 };
20
21  mesh.appendCell( c0 );
22  mesh.appendCell( c1 );
23  mesh.appendCell( c2 );
24  mesh.appendCell( c3 );
```

An *Unstructured Mesh* is represented by the `mint::UnstructuredMesh` template class. The template argument of the class, `mint::SINGLE_SHAPE` indicates the mesh has *Single Cell Type Topology*. The two arguments to the class constructor correspond to the problem dimension and cell type, which in this case, is 2 and `mint::TRIANGLE` respectively. Once the mesh is constructed, the *Nodes* and *Cells* are appended to the mesh by calls to the `appendNode()` and `appendCell()` methods respectively. The resulting mesh is shown in Fig. 2.32.

Tip: The storage for the `mint::UstructuredMesh` will grow dynamically as new *Nodes* and *Cells* are appended on the mesh. However, reallocations tend to be costly operations. For best performance, it is advised the node capacity and cell capacity for the mesh are specified in the constructor if known *a priori*. Consult the Mint Doxygen API Documentation for more details.

Create a Mixed Unstructured Mesh

Compared to the *Single Cell Type Topology Unstructured Mesh*, a *Mixed Cell Type Topology Unstructured Mesh* has also explicit *Topology* and *Geometry*. However, the cell type is not fixed. Notably, the mesh can store different *Cell Types*, e.g. triangles and quads, as shown in the simple 2D mesh depicted in Fig. 2.33.

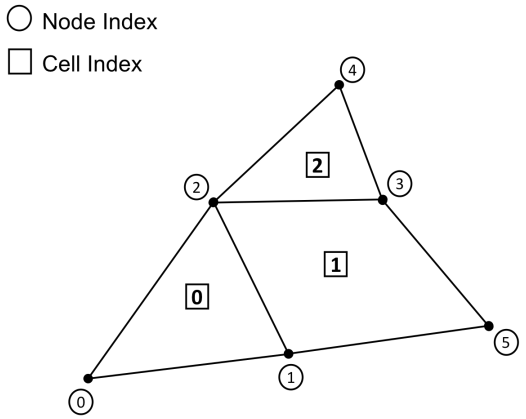


Fig. 2.33: Sample *Mixed Cell Type Topology Unstructured Mesh*

As with the *Single Cell Type Topology Unstructured Mesh*, a *Mixed Cell Type Topology Unstructured Mesh* is created by specifying:

1. the coordinates of the constituent *Nodes*, and
2. the *Cells* comprising the mesh, defined by the *cell-to-node Connectivity*

The following code snippet illustrates how to create the simple *Mixed Cell Type Topology Unstructured Mesh* depicted in Fig. 2.33, consisting of 2 *triangles* and 1 *quadrilateral Cells*.

```
constexpr int DIMENSION = 2;

// Construct the mesh object
mint::UnstructuredMesh< mint::MIXED_SHAPE > mesh( DIMENSION );

// Append the mesh nodes
const axom::IndexType n0 = mesh.appendNode( 0.0, 0.0 );
const axom::IndexType n1 = mesh.appendNode( 2.0, 0.0 );
const axom::IndexType n2 = mesh.appendNode( 1.0, 1.0 );
const axom::IndexType n3 = mesh.appendNode( 3.5, 1.0 );
const axom::IndexType n4 = mesh.appendNode( 2.5, 2.0 );
const axom::IndexType n5 = mesh.appendNode( 5.0, 0.0 );

// Append mesh cells
const axom::IndexType c0[ ] = { n0, n1, n2 };
const axom::IndexType c1[ ] = { n1, n5, n3, n2 };
const axom::IndexType c2[ ] = { n3, n4, n2 };

mesh.appendCell( c0, mint::TRIANGLE );
mesh.appendCell( c1, mint::QUAD );
mesh.appendCell( c2, mint::TRIANGLE );
```

Similarly, a *Mixed Cell Type Topology Unstructured Mesh* is represented by the `mint::UnstructuredMesh` template class. However, the template argument to the class is `mint::MIXED_SHAPE`, which indicates that the mesh has *Mixed Cell Type Topology*. In this case, the class constructor takes only a single argument that corresponds to the problem dimension, i.e. 2. Once the mesh is constructed, the constituent *Nodes* of the mesh are specified by calling the `appendNode()` method on the mesh. Similarly, the *Cells* are specified by calling the `appendCell()` method. However, in this case, `appendCell()` takes one additional argument that specifies the cell type, since that can vary.

Tip: The storage for the `mint::UstructuredMesh` will grow dynamically as new *Nodes* and *Cells* are appended on the mesh. However, reallocations tend to be costly operations. For best performance, it is advised the node capacity and cell capacity for the mesh are specified in the constructor if known *a priori*. Consult the Mint Doxygen API Documentation for more details.

Working with Fields

A mesh typically has associated *Field Data* that store various numerical quantities on the constituent *Nodes*, *Cells* and *Faces* of the mesh.

Warning: Since a *Particle Mesh* is defined by a set of *Nodes*, it can only store *Field Data* at its constituent *Nodes*. All other supported *Mesh Types* can have *Field Data* associated with their constituent *Cells*, *Faces* and *Nodes*.

Add Fields

Given a `mint::Mesh` instance, a field is created by specifying:

1. The name of the field,

2. The field association, i.e. centering, and
3. Optionally, the number of components of the field, required if the field is not a scalar quantity.

For example, the following code snippet creates the *scalar density* field, `den`, stored at the cell centers, and the *vector velocity* field, `vel`, stored at the *Nodes*:

```
double* den = mesh->createField< double >( "den", mint::CELL_CENTERED );
double* vel = mesh->createField< double >( "vel", mint::NODE_CENTERED, 3 );
```

Note: If Sidre is used as the backend *Mesh Storage Management* substrate, `createField()` will populate the Sidre tree hierarchy accordingly. See *Using Sidre* for more information.

- Note, the template argument to the `createField()` method indicates the underlying field type, e.g. `double`, `int` , etc. In this case, both fields are of `double` field type.
- The *name* of the field is specified by the first required argument to the `createField()` call.
- The field association, is specified by the second argument to the `createField()` call.
- A third, *optional*, argument *may* be specified to indicate the number of components of the corresponding field. In this case, since `vel` is a *vector quantity* the number of components must be explicitly specified.
- The `createField()` method returns a raw pointer to the data corresponding to the new field, which can be used by the application.

Note: Absence of the third argument when calling `createField()` indicates that the number of components of the field defaults to 1 and thereby the field is assumed to be a scalar quantity.

Request Fields by Name

Specific, existing fields can be requested by calling `getFieldPtr()` on the target mesh as follows:

```
double* den = mesh->getFieldPtr< double >( "den", mint::CELL_CENTERED );

axom::IndexType nc = -1; // number of components
double* vel = mesh->getFieldPtr< double >( "vel", mint::NODE_CENTERED, nc );
```

- As with the `createField()` method, the template argument indicates the underlying field type, e.g. `double`, `int` , etc.
- The first argument specifies the name of the requested field
- The second argument specifies the corresponding association of the requested field.
- The third argument is optional and it can be used to get back the number of components of the field, i.e. if the field is not a *scalar* quantity.

Note: Calls to `getFieldPtr()` assume that the caller knows *a priori* the:

- Field name,
- Field association, i.e. centering, and
- The underlying field type, e.g. `double`, `int`, etc.

Check Fields

An application can also check if a field exists by calling `hasField()` on the mesh, which takes as arguments the field name and corresponding field association as follows:

```
const bool hasDen = mesh->hasField( "den", mint::CELL_CENTERED );
const bool hasVel = mesh->hasField( "vel", mint::NODE_CENTERED );
```

The `hasField()` method returns `true` or `false` indicating whether a given field is defined on the mesh.

Remove Fields

A field can be removed from a mesh by calling `removeField()` on the target mesh, which takes as arguments the field name and corresponding field association as follows:

```
bool isRemoved = mesh->removeField( "den", mint::CELL_CENTERED );
```

The `removeField()` method returns `true` or `false` indicating whether the corresponding field was removed successfully from the mesh.

Query Fields

In some cases, an application may not always know *a priori* the name or type of the field, or, we may want to write a function to process all fields, regardless of their type.

The following code snippet illustrates how to do that:

```
const mint::FieldData* fieldData = mesh->getFieldData( FIELD_ASSOCIATION );

const int numFields = fieldData->getNumFields( );
for ( int ifield=0; ifield < numFields; ++ifield )
{
  const mint::Field* field = fieldData->getField( ifield );

  const std::string& fieldName  = field->getName();
  axom::IndexType numTuples     = field->getNumTuples();
  axom::IndexType numComponents = field->getNumComponents();

  std::cout << "field name: "    << fieldName << std::endl;
  std::cout << "numTuples: "     << numTuples << std::endl;
  std::cout << "numComponents: " << numComponents << std::endl;

  if ( field->getType() == mint::DOUBLE_FIELD_TYPE )
  {
    double* data = mesh->getFieldPtr< double >(fieldName, FIELD_ASSOCIATION);
    data[ 0 ] = 42.0;
    // process double precision floating point data
    // ...
  }
  else if ( field->getType() == mint::INT32_FIELD_TYPE )
  {
    int* data = mesh->getFieldPtr< int >( fieldName, FIELD_ASSOCIATION);
    data[ 0 ] = 42;
    // process integral data
```

(continues on next page)

(continued from previous page)

```
      // ...
    }
    // ...

  } // END for all fields
```

- The `mint::FieldData` instance obtained by calling `getFieldData()` on the target mesh holds all the fields with a field association given by `FIELD_ASSOCIATION`.
- The total number of fields can be obtained by calling `getNumFields()` on the `mint::FieldData` instance, which allows looping over the fields with a simple `for` loop.
- Within the loop, a pointer to a `mint::Field` instance, corresponding to a particular field, can be requested by calling `getField()` on the `mint::FieldData` instance, which takes the field index, `ifield`, as an argument.
- Given the pointer to a `mint::Field` instance, an application can query the following field metadata:
  - The field name, by calling `getName`,
  - The number of tuples of the field, by calling `getNumTuples()`
  - The number of components of the field, by calling `getNumComponents()`
  - The underlying field type by calling `getType()`
- Given the above metadata, the application can then obtain a pointer to the raw field data by calling `getFieldPtr()` on the target mesh, as shown in the code snippet above.

Using External Storage

A Mint mesh may also be constructed from *External Storage*. In this case, the application holds buffers that describe the constituent *Geometry*, *Topology* and *Field Data* of the mesh, which are wrapped in Mint for further processing.

The following code snippet illustrates how to use *External Storage* using the *Single Cell Type Topology Unstructured Mesh* used to demonstrate how to *Create an Unstructured Mesh* with *Native Storage*:

```
constexpr axom::IndexType NUM_NODES = 6;
constexpr axom::IndexType NUM_CELLS = 4;

// application buffers
double x[ ] = { 0.0, 2.0, 1.0, 3.5, 2.5, 5.0 };
double y[ ] = { 0.0, 0.0, 1.0, 1.0, 2.0, 0.0 };

axom::IndexType cell_connectivity[ ] = {
  1, 3, 2, // c0
  2, 0, 1, // c1
  3, 4, 2, // c2
  1, 5, 3  // c3
};

// cell-centered density field values
double den[ ] = { 0.5, 1.2, 2.5, 0.9 };

// construct mesh object with external buffers
using MeshType = mint::UnstructuredMesh< mint::SINGLE_SHAPE >;
MeshType* mesh = new MeshType( mint::TRIANGLE, NUM_CELLS, cell_connectivity,
                               NUM_NODES, x, y );
```

(continues on next page)

(continued from previous page)

```
22
23  // register external field
24  mesh->createField< double >( "den", mint::CELL_CENTERED, den );
25
26  // output external mesh to vtk
27  mint::write_vtk( mesh, "tutorial_external_mesh.vtk" );
28
29  // delete the mesh, doesn't touch application buffers
30  delete mesh;
31  mesh = nullptr;
```

- The application has the following buffers:
  - `x` and `y` buffers to hold the coordinates of the *Nodes*
  - `cell_connectivity`, which stores the *cell-to-node* connectivity
  - `den` which holds a *scalar density* field defined over the constituent *Cells* of the mesh.
- The mesh is created by calling the `mint::UnstructuredMesh` class constructor, with the following arguments:
  - The cell type, i.e, `mint::TRIANGLE`,
  - The total number of cells, `NUM_CELLS`,
  - The `cell_connectivity` which specifies the *Topology* of the *Unstructured Mesh*,
  - The total number of nodes, `NUM_NODES`, and
  - The `x`, `y` coordinate buffers that specify the *Geometry* of the *Unstructured Mesh*.
- The *scalar density* field is registered with Mint by calling the `createField()` method on the target mesh instance, as before, but also passing the raw pointer to the application buffer in a third argument.

Note: The other *Mesh Types* can be similarly constructed using *External Storage* by calling the appropriate constructor. Consult the Mint Doxygen API Documentation for more details.

The resulting mesh instance points to the application's buffers. Mint may be used to process the data e.g., *Output to VTK* etc. The values of the data may also be modified, however the mesh cannot dynamically grow or shrink when using *External Storage*.

Warning: A mesh using *External Storage* may modify the values of the application data. However, the data is owned by the application that supplied the external buffers. Mint cannot reallocate external buffers to grow or shrink the the mesh. Once the mesh is deleted, the data remains persistent in the application buffers until it is deleted by the application.

Using Sidre

Mint can also use Sidre as the underlying *Mesh Storage Management* substrate, thereby, facilitate the integration of packages or codes within the overarching WSC software ecosystem. Sidre is another component of the Axom Toolkit that provides a centralized data management system that enables efficient coordination of data across the constituent packages of a multi-physics application.

There are two primary operations a package/code may want to perform:

1. *Create a new Mesh in Sidre* so that it can be shared with other packages.
2. *Import a Mesh from Sidre*, presumably created by different package or code upstream, to operate on, e.g. evaluate a new field on the mesh, etc.

Code snippets illustrating these two operations are presented in the following sections using a simple *Unstructured Mesh* example. However, the basic concepts extend to all supported *Mesh Types*.

Note: To use Sidre with Mint, the Axom Toolkit must be compiled with Conduit support and Sidre must be enabled (default). Consult the Axom Quick Start Guide for the details on how to build the Axom Toolkit.

Create a new Mesh in Sidre

Creating a mesh using Sidre is very similar to creating a mesh that uses *Native Storage*. The key difference is that when calling the mesh constructor, the target `sidre::Group`, that will consist of the mesh, must be specified.

Warning: The target `sidre::Group` supplied to the mesh constructor is expected to be empty.

The following code snippet illustrates this capability using the *Single Cell Type Topology Unstructured Mesh* used to demonstrate how to *Create an Unstructured Mesh* with *Native Storage*. The key differences in the code are highlighted below:

```
1  // create a Sidre Datastore to store the mesh
2  sidre::DataStore ds;
3  sidre::Group* group = ds.getRoot();
4
5  // Construct the mesh object and populate the supplied Sidre Group
6  mint::UnstructuredMesh< mint::SINGLE_SHAPE > mesh( 2, mint::TRIANGLE, group );
7
8  // Append the mesh nodes
9  const axom::IndexType n0 = mesh.appendNode( 0.0, 0.0 );
10 const axom::IndexType n1 = mesh.appendNode( 2.0, 0.0 );
11 const axom::IndexType n2 = mesh.appendNode( 1.0, 1.0 );
12 const axom::IndexType n3 = mesh.appendNode( 3.5, 1.0 );
13 const axom::IndexType n4 = mesh.appendNode( 2.5, 2.0 );
14 const axom::IndexType n5 = mesh.appendNode( 5.0, 0.0 );
15
16 // Append mesh cells
17 const axom::IndexType c0[ ] = { n1, n3, n2 };
18 const axom::IndexType c1[ ] = { n2, n0, n1 };
19 const axom::IndexType c2[ ] = { n3, n4, n2 };
20 const axom::IndexType c3[ ] = { n1, n5, n3 };
21
22 mesh.appendCell( c0 );
23 mesh.appendCell( c1 );
24 mesh.appendCell( c2 );
25 mesh.appendCell( c3 );
26
27 // create a cell-centered field
28 double* den = mesh.createField< double >( "den", mint::CELL_CENTERED );
29
30 // set density values at each cell
31 den[ 0 ] = 0.5; // c0
```

(continues on next page)

(continued from previous page)

```
  den[ 1 ] = 1.2; // c1
  den[ 2 ] = 2.5; // c2
  den[ 3 ] = 0.9; // c3
```

Note: A similar construction follows for all supported *Mesh Types*. To *Create a new Mesh in Sidre* the target `sidre::Group` that will consist of the mesh is specified in the constructor in addition to any other arguments. Consult the Mint Doxygen API Documentation for more details.

When the constructor is called, the target `sidre::Group` is populated according to the Conduit Blueprint mesh description. Any subsequent changes to the mesh are reflected accordingly to the corresponding `sidre::Group`. The *Raw Sidre Data* generated after the above code snippet executes are included for reference in the *Appendix*.

However, once the mesh object goes out-of-scope the mesh description and any data remains persisted in Sidre. The mesh can be deleted from Sidre using the corresponding Sidre API calls.

Warning: A Mint mesh, bound to a Sidre Group, can only be deleted from Sidre when the Group consisting the mesh is deleted from Sidre, or, when the Sidre Datastore instance that holds the Group is deleted. When a mesh, bound to a Sidre Group is deleted, its mesh representation and any data remain persistent within the corresponding Sidre Group hierarchy.

Import a Mesh from Sidre

Support for importing an existing mesh from Sidre, that conforms to the Conduit Blueprint mesh description, is provided by the `mint::getMesh()` function. The `mint::getMesh()` function takes the `sidre::Group` instance consisting of the mesh as an argument and returns a corresponding `mint::Mesh` instance. Notably, the returned `mint:Mesh` instance can be any of the supported *Mesh Types*.

The following code snippet illustrates this capability:

```
mint::Mesh* imported_mesh = mint::getMesh( group );
std::cout << "Mesh Type: " << imported_mesh->getMeshType() << std::endl;
std::cout << "hasSidre: "  << imported_mesh->hasSidreGroup() << std::endl;

mint::write_vtk( imported_mesh, "tutorial_imported_mesh.vtk" );

delete imported_mesh;
imported_mesh = nullptr;
```

- The mesh is imported from Sidre by calling `mint::getMesh()`, passing the `sidre::Group` consisting of the mesh as an argument.
- The mesh type of the imported mesh can be queried by calling the `getMeshType()` on the imported mesh object.
- Moreover, an application can check if the mesh is bound to a Sidre group by calling `hasSidreGroup()` on the mesh.
- Once the mesh is imported, the application can operate on it, e.g. *Output to VTK*, etc., as illustrated in the above code snippet.
- Any subsequent changes to the mesh are reflected accordingly to the corresponding `sidre::Group`

However, once the mesh object goes out-of-scope the mesh description and any data remains persisted in Sidre. The mesh can be deleted from Sidre using the corresponding Sidre API calls.

Warning:

- When a Mint mesh bound to a Sidre Group is deleted, its mesh representation and any data remain persistent within the corresponding Sidre Group hierarchy.
- A Mint mesh, bound to a Sidre Group, is deleted from Sidre by deleting the corresponding Sidre Group, or, when the Sidre Datastore instance that holds the Group is deleted.

Node Traversal Functions

The *Node Traversal Functions* iterate over the constituent *Nodes* of the mesh and apply a user-supplied kernel operation, often specified with a Lambda Expression. The *Node Traversal Functions* are implemented by the `mint::for_all_nodes()` family of functions, which take an *Execution Policy* as the first template argument, and optionally, a second template argument to indicate the *Execution Signature* of the supplied kernel.

Note: If a second template argument is not specified, the default *Execution Signature* is set to `xargs::index`, which indicates that the supplied kernel takes a single argument corresponding to the index of the iteration space, in this case the node index, `nodeIdx`.

Simple Loop Over Nodes

The following code snippet illustrates a simple loop over the *Nodes* of a 2D mesh that computes the velocity magnitude, `vmag`, given the corresponding velocity components, `vx` and `vy`.

```
1  const double* vx = mesh.getFieldPtr< double >( "vx", mint::NODE_CENTERED );
2  const double* vy = mesh.getFieldPtr< double >( "vy", mint::NODE_CENTERED );
3
4  double* vmag = mesh.getFieldPtr< double >( "vmag", mint::NODE_CENTERED );
5
6  mint::for_all_nodes< exec_policy >( &mesh, AXOM_LAMBDA( IndexType nodeIdx )
7  {
8    const double vx2 = vx[ nodeIdx ] * vx[ nodeIdx ];
9    const double vy2 = vy[ nodeIdx ] * vy[ nodeIdx ];
10   vmag[ nodeIdx ]  = sqrt( vx2 + vy2 );
11 } );
```

Loop with Coordinates

The coordinates of a node are sometimes also required in addition to its index. This additional information may be requested by supplying `xargs::x` (in 1D), `xargs::xy` (in 2D) or `xargs::xyz` (in 3D), as the second template argument to the `for_all_nodes()` method to specify the *Execution Signature* for the kernel.

This capability is demonstrated by the following code snippet, consisting of a kernel that updates the nodal velocity components, based on old node positions, stored at the `xold` and `yold` node-centered fields, respectively.

```
1  double invdt = 0.5;
2
```

(continues on next page)

(continued from previous page)

```
    const double* xold = mesh.getFieldPtr< double >("xold",mint::NODE_CENTERED);
    const double* yold = mesh.getFieldPtr< double >("yold",mint::NODE_CENTERED);

    double* vx = mesh.getFieldPtr< double >( "vx", mint::NODE_CENTERED );
    double* vy = mesh.getFieldPtr< double >( "vy", mint::NODE_CENTERED );

    mint::for_all_nodes< exec_policy, mint::xargs::xy >(
        &mesh, AXOM_LAMBDA( IndexType nodeIdx, double x, double y )
    {
      vx[ nodeIdx ] = ( x - xold[ nodeIdx ] ) * invdt;
      vy[ nodeIdx ] = ( y - yold[ nodeIdx ] ) * invdt;
    } );
```

Note:

- The second template argument, `mint::xargs::xy`, indicates that the supplied kernel expects the `x` and `y` node coordinates as arguments in addition to its `nodeIdx`.

Loop with IJK Indices

When working with a *Structured Mesh*, it is sometimes required to expose the regular *Topology* of the *Structured Mesh* to obtain higher performance for a particular algorithm. This typically entails using the *logical IJK* ordering of the *Structured Mesh* to implement certain operations. The template argument, `xargs::ij` or `xargs::ijk`, for 2D or 3D respectively, may be used as the second template argument to the `for_all_nodes()` function to specify the *Execution Signature* of the supplied kernel.

For example, the following code snippet illustrates how to obtain a node's `i` and `j` indices within a sample kernel that computes the linear index of each node and stores the result in a node-centered field, `ID`.

```
    const IndexType jp = mesh.nodeJp();

    IndexType* ID = mesh.getFieldPtr< IndexType >( "ID", mint::NODE_CENTERED );
    mint::for_all_nodes< exec_policy, mint::xargs::ij >(
        &mesh, AXOM_LAMBDA( IndexType nodeIdx, IndexType i, IndexType j )
    {
      ID[ nodeIdx ] = i + j * jp;
    } );
```

Warning: In this case, the kernel makes use of the IJK indices and hence it is only applicable for a *Structured Mesh*.

Cell Traversal Functions

The *Cell Traversal Functions* iterate over the constituent *Cells* of the mesh and apply a user-supplied kernel operation, often specified with a Lambda Expression. The *Cell Traversal Functions* are implemented by the `mint::for_all_cells()` family of functions, which take an *Execution Policy* as the first template argument, and optionally, a second template argument to indicate the *Execution Signature* of the supplied kernel.

Note: If a second template argument is not specified, the default *Execution Signature* is set to `xargs::index`, which indicates that the supplied kernel takes a single argument corresponding to the index of the iteration space, in

this case the cell index, `cellIdx`.

Simple Loop Over Cells

The following code snippet illustrates a simple loop over the constituent *Cells* of the mesh that computes the cell density (`den`), given corresponding mass (`mass`) and volume (`vol`) quantities.

```
    const double* mass = mesh.getFieldPtr< double >("mass",mint::CELL_CENTERED);
    const double* vol  = mesh.getFieldPtr< double >("vol",mint::CELL_CENTERED);

    double* den = mesh.getFieldPtr< double >( "den", mint::CELL_CENTERED );

    mint::for_all_cells< exec_policy >( &mesh, AXOM_LAMBDA( IndexType cellIdx )
    {
      den[ cellIdx ] = mass[ cellIdx ] / vol[ cellIdx ];
    } );
```

Loop with Node IDs

Certain operations may require the IDs of the constituent cell *Nodes* for some calculation. The template argument, `xargs::nodeids`, may be used as the second template argument to the `for_all_cells()` function to specify the *Execution Signature* for the kernel. The `xargs::nodeids` indicates that the supplied kernel also takes the the IDs of the constituent cell *Nodes* as an argument.

This feature is demonstrated with the following code snippet, which averages the node-centered velocity components to corresponding cell-centered fields:

```
    const double* vx = mesh.getFieldPtr< double >( "vx", mint::NODE_CENTERED );
    const double* vy = mesh.getFieldPtr< double >( "vy", mint::NODE_CENTERED );

    double* cell_vx = mesh.getFieldPtr< double >("cell_vx",mint::CELL_CENTERED);
    double* cell_vy = mesh.getFieldPtr< double >("cell_vy",mint::CELL_CENTERED);

    mint::for_all_cells< exec_policy, mint::xargs::nodeids >(
        &mesh, AXOM_LAMBDA( IndexType cellIdx,
                            const IndexType* nodeIDs,
                            IndexType N )
    {

       // sum nodal contributions
       cell_vx[ cellIdx ] = 0.0;
       cell_vy[ cellIdx ] = 0.0;
       for ( IndexType inode=0; inode < N; ++inode )
       {
         cell_vx[ cellIdx ] += vx[ nodeIDs[ inode ] ];
         cell_vy[ cellIdx ] += vy[ nodeIDs[ inode ] ];
       } // END for all cell nodes

       // average at the cell center
       const double invf = 1.0 / static_cast< double >( N );
       cell_vx[ cellIdx ] *= invf;
       cell_vy[ cellIdx ] *= invf;

    } );
```

Note:

- `xargs::nodeids` indicates that the specified kernel takes three arguments:
  - `cellIdx`, the ID of the cell,
  - `nodeIDs`, an array of the constituent node IDs, and
  - `N`, the number of *Nodes* for the given cell.

Loop with Coordinates

The coordinates of the constituent cell *Nodes* are often required in some calculations. A cell's node coordinates may be supplied to the specified kernel as an argument using `xargs::coords` as the second template argument to the `for_all_cells()` function, to specify the *Execution Signature* of the supplied kernel.

This feature is demonstrated with the following code snippet, which computes the cell centroid by averaging the coordinates of the constituent cell *Nodes*:

Note: Since this kernel does not use the node IDs, the argument to the kernel is annotated using the `AXOM_NOT_USED` macro to silence compiler warnings.

```
1  double* xc = mesh.getFieldPtr< double >( "xc", mint::CELL_CENTERED );
2  double* yc = mesh.getFieldPtr< double >( "yc", mint::CELL_CENTERED );
3
4  mint::for_all_cells< exec_policy, mint::xargs::coords >(
5      &mesh, AXOM_LAMBDA( IndexType cellIdx,
6                          const numerics::Matrix< double >& coords,
7                          const IndexType* AXOM_NOT_USED(nodeIdx) )
8  {
9    // sum nodal coordinates
10   double xsum = 0.0;
11   double ysum = 0.0;
12   const int numNodes = coords.getNumColumns();
13   for ( int inode=0; inode < numNodes; ++inode )
14   {
15     const double* node = coords.getColumn( inode );
16     xsum += node[ mint::X_COORDINATE ];
17     ysum += node[ mint::Y_COORDINATE ];
18   } // end for all cell nodes
19
20   // compute centroid by averaging nodal coordinates
21   const double invf = 1.0 / static_cast< double >( numNodes );
22   xc[ cellIdx ] = xsum * invf;
23   yc[ cellIdx ] = ysum * invf;
24
25 } );
```

Note:

- `xargs::coords` indicates that the specified kernel takes the following arguments:
  - `cellIdx`, the ID of the cell,
  - `coords`, a matrix that stores the cell coordinates, such that:

    * The number of rows corresponds to the problem dimension, and,
    * The number of columns corresponds to the number of nodes.
    * The ith column vector of the matrix stores the coordinates of the ith node.
  - `nodeIdx` array of corresponding node IDs.

Loop with Face IDs

The IDs of the constituent cell *Faces* are sometimes needed to access the corresponding face-centered quantities for certain operations. The face IDs can be obtained using `xargs::faceids` as the second template argument to the `for_all_faces()` function, to specify the *Execution Signature* of the supplied kernel.

This feature is demonstrated with the following code snippet, which computes the perimeter of each cell by summing the pre-computed face areas:

```
    const double* area = mesh.getFieldPtr< double >("area",mint::FACE_CENTERED);
    double* perimeter  =
        mesh.getFieldPtr< double >( "perimeter", mint::CELL_CENTERED );

    mint::for_all_cells< exec_policy, mint::xargs::faceids >(
        &mesh, AXOM_LAMBDA( IndexType cellIdx,
                            const IndexType* faceIDs,
                            IndexType N )
    {
      perimeter[ cellIdx ] = 0.0;
      for ( IndexType iface=0; iface < N; ++iface )
      {
        perimeter[ cellIdx ] += area[ faceIDs[ iface ] ];
      }

    } );
```

Note:

- `xargs::faceids` indicates that the specified kernel takes the following arguments:
  - `cellIdx`, the ID of the cell,
  - `faceIDs`, an array of the constituent face IDs, and,
  - `N`, the number of *Faces* for the given cell.

Loop with IJK Indices

As with the *Node Traversal Functions*, when working with a *Structured Mesh*, it is sometimes required to expose the regular *Topology* of the *Structured Mesh* to obtain higher performance for a particular algorithm. This typically entails using the *logical IJK* ordering of the *Structured Mesh* to implement certain operations. The template argument, `xargs::ij` (in 2D) or `xargs::ijk` (in 3D) may be used as the second template argument to the `for_all_cells()` function, to specify the *Execution Signature* of the supplied kernel.

For example, the following code snippet illustrates to obtain a cell's `i` and `j` indices within a kernel that computes the linear index of each cell and stores the result in a cell-centered field, `ID`.

```
    const IndexType jp = mesh.cellJp();

    IndexType* ID = mesh.getFieldPtr< IndexType >( "ID", mint::CELL_CENTERED );
    mint::for_all_cells< exec_policy, mint::xargs::ij >(
        &mesh, AXOM_LAMBDA( IndexType cellIdx, IndexType i, IndexType j )
    {
      ID[ cellIdx ] = i + j * jp;
    } );
```

Warning: In this case, the kernel makes use of the IJK indices and hence it is only applicable for a *Structured Mesh*.

Face Traversal Functions

The *Face Traversal Functions* functions iterate over the constituent *Faces* of the mesh and apply a user-supplied kernel operation, often specified with a Lambda Expression. The *Face Traversal Functions* are implemented by the `mint::for_all_faces()` family of functions. which take an *Execution Policy* as the first template argument, and optionally, a second template argument to indicate the *Execution Signature* of the supplied kernel.

Note: If a second template argument is not specified, the default *Execution Signature* is set to `xargs::index`, which indicates that the supplied kernel takes a single argument corresponding to the index of the iteration space, in this case the face index, `faceIdx`.

Simple Loop Over Faces

The following code snippet illustrates a simple loop over the constituent *Faces* of a 2D mesh that computes an interpolated face-centered quantity (`temp`) based on pre-computed interpolation coefficients `t1` , `t2` and `w`.

```
    const double* t1 = mesh.getFieldPtr< double >( "t1", mint::FACE_CENTERED );
    const double* t2 = mesh.getFieldPtr< double >( "t2", mint::FACE_CENTERED );
    const double* w  = mesh.getFieldPtr< double >( "w", mint::FACE_CENTERED );

    double* temp = mesh.getFieldPtr< double >( "temp", mint::FACE_CENTERED );
    mint::for_all_faces< exec_policy >( &mesh, AXOM_LAMBDA( IndexType faceIdx )
    {
      const double wf = w[ faceIdx ];
      const double a  = t1[ faceIdx ];
      const double b  = t2[ faceIdx ];

      temp[ faceIdx ] = wf*a + (1.-wf)*b;
    } );
```

Loop with Node IDs

The IDs of the constituent face *Nodes* are sometimes needed to access associated node-centered data for certain calculations. The template argument, `xargs::nodeids`, may be used as the second template argument to the `for_all_faces()` function to specify the *Execution Signature* of the supplied kernel. The `xargs::nodeids` template argument indicates that the supplied kernel also takes the IDs of the constituent face Nodes as an argument.

This feature is demonstrated with the following code snippet which averages the node-centered velocity components to corresponding face-centered quantities:

```
    const double* vx = mesh.getFieldPtr< double >( "vx", mint::NODE_CENTERED );
    const double* vy = mesh.getFieldPtr< double >( "vy", mint::NODE_CENTERED );

    double* face_vx = mesh.getFieldPtr< double >("face_vx",mint::FACE_CENTERED);
    double* face_vy = mesh.getFieldPtr< double >("face_vy",mint::FACE_CENTERED);

    mint::for_all_faces< exec_policy, mint::xargs::nodeids >(
        &mesh, AXOM_LAMBDA( IndexType faceIdx,
                            const IndexType* nodeIDs,
                            IndexType N )
    {
      // sum constituent face node contributions
      face_vx[ faceIdx ] = 0.0;
      face_vy[ faceIdx ] = 0.0;
      for ( int inode=0; inode < N; ++inode )
      {
        face_vx[ faceIdx ] += vx[ nodeIDs[ inode ] ];
        face_vy[ faceIdx ] += vy[ nodeIDs[ inode ] ];
      } // END for all face nodes

      // average
      const double invf = 1.0 / static_cast< double >( N );
      face_vx[ faceIdx ] *= invf;
      face_vy[ faceIdx ] *= invf;
    } );
```

Note:

- `xargs::nodeids` indicates that the specified kernel takes three arguments:
  - `faceIdx`, the ID of the cell,
  - `nodeIDs`, an array of the constituent node IDs, and
  - `N`, the number of *Nodes* for the corresponding face.

Loop with Coordinates

The coordinates of the constituent face *Nodes* are often required in some calculations. The constituent face node coordinates may be supplied to the specified kernel as an argument using `xargs::coords` as the second template argument to the `for_all_faces()` function, to specify the *Execution Signature* of the supplied kernel.

This feature is demonstrated with the following code snippet, which computes the face centroid by averaging the coordinates of the constituent face *Nodes*:

Note: Since this kernel does not use the node IDs, the argument to the kernel is annotated using the `AXOM_NOT_USED` macro to silence compiler warnings.

```
    double* fx = mesh.getFieldPtr< double >( "fx", mint::FACE_CENTERED );
    double* fy = mesh.getFieldPtr< double >( "fy", mint::FACE_CENTERED );

```

(continues on next page)

(continued from previous page)

```
    mint::for_all_faces< exec_policy, mint::xargs::coords >(
        &mesh, AXOM_LAMBDA( IndexType faceIdx,
                            const numerics::Matrix< double >& coords,
                            const IndexType* AXOM_NOT_USED(nodeIdx) )
    {
      // sum nodal coordinates
      double xsum = 0.0;
      double ysum = 0.0;
      const int numNodes = coords.getNumColumns();
      for ( int inode=0; inode < numNodes; ++inode )
      {
        const double* node = coords.getColumn( inode );
        xsum += node[ mint::X_COORDINATE ];
        ysum += node[ mint::Y_COORDINATE ];
      } // end for all face nodes

      // compute centroid by averaging nodal coordinates
      const double invf = 1.0 / static_cast< double >( numNodes );
      fx[ faceIdx ] = xsum * invf;
      fy[ faceIdx ] = ysum * invf;
    } );
```

Note:

- `xargs::coords` indicates that the specified kernel takes the following arguments:
- `faceIdx`, the ID of the cell,
- `coords`, a matrix that stores the cell coordinates, such that:
  - The number of rows corresponds to the problem dimension, and,
  - The number of columns corresponds to the number of nodes.
  - The ith column vector of the matrix stores the coordinates of the ith node.
- `nodeIdx` array of corresponding node IDs.

Loop with Cell IDs

The constituent *Faces* of a mesh can be bound to either one or two *Cells*. The IDs of the *Cells* abutting a face are required in order to obtain the corresponding cell-centered quantities, needed by some calculations. The template argument, `xargs::cellids`, may be used as the second template argument to the `for_all_faces()` function to specify the *Execution Signature* of the supplied kernel. Thereby, indicate that the supplied kernel also takes the IDs of the two abutting cells as an argument.

Note: External boundary faces are only bound to one cell. By convention, the ID of the second cell for external boundary faces is set to -1.

This functionality is demonstrated with the following example that loops over the constituent *Faces* of a mesh and marks external boundary faces:

```
  constexpr IndexType ON_BOUNDARY = 1;
  constexpr IndexType INTERIOR    = 0;

  IndexType* boundary =
      mesh.getFieldPtr< IndexType >( "boundary", mint::FACE_CENTERED );

  mint::for_all_faces< exec_policy, mint::xargs::cellids >(
     &mesh, AXOM_LAMBDA( IndexType faceIdx,
                         IndexType AXOM_NOT_USED(c1),
                         IndexType c2 )
  {

    boundary[ faceIdx ] = ( c2 == -1 ) ? ON_BOUNDARY : INTERIOR;

  } );
```

Note:

- `xargs::coords` indicates that the specified kernel takes the following arguments:
- `faceIdx`, the ID of the cell,
- `c1`, the ID of the first cell,
- `c2`, the ID of the second cell, set to a -1 if the face is an external boundary face.

Finite Elements

Mint provides basic support for *Finite Elements* consisting of *Lagrange Basis shape functions* for commonly employed *Cell Types* and associated operations, such as functions to evaluate the Jacobian and compute the forward and inverse *Isoparametric Mapping*.

Warning: Porting and refactoring of Mint's *Finite Elements* for GPUs is under development. This feature will be available in future versions of Mint.

Create a Finite Element Object

All associated functionality with *Finite Elements* is exposed to the application through the `mint::FiniteElement` class. The following code snippet illustrates how to *Create a Finite Element Object* using a Linear Lagrangian Quadrilateral Finite Element as an example:

```
  constexpr bool ZERO_COPY = true;

  double coords[ ] = {
    0.0, 0.0, // x1, y1
    5.0, 0.0, // x2, y2
    5.0, 5.0, // x3, y3,
    0.0, 5.0  // x4, y4
  };

  numerics::Matrix< double > nodes_matrix( 2, 4, coords, ZERO_COPY );
  mint::FiniteElement fe( nodes_matrix, mint::QUAD );
```

(continues on next page)

(continued from previous page)

```
12
13   // bind to FE basis, wires the shape function pointers
14   mint::bind_basis< MINT_LAGRANGE_BASIS, mint::QUAD >( fe );
```

- The `mint::FiniteElement` constructor takes two arguments:
  - An $N \times M$ Matrix consisting of the cell coordinates, where, N corresponds to physical dimension of the cell and M corresponds to the number of constituent cell nodes. The cell coordinates are organized in the matrix such that, each column vector stores the coordinates of a corresponding node.
  - The cell type, e.g. `mint::QUAD`
- Then, `mint::bind_basis()` is called to bind the Finite Element object to the *Lagrange Basis*. Effectively, this step wires the pointers to the *Lagrange Basis shape functions* for the particular cell type.

A similar construction follows for different *Cell Types* and associated supported *shape functions*.

The Finite Element object, once constructed and bound to a basis, it may be used to perform the following operations:

1. Given a point in reference space, $\hat{\xi} \in \bar{\Omega}$:
   - *Evaluate Shape Functions*, $N_i(\xi)$, associated with each of the constituent cell nodes, which are often used as *interpolation weights*,
   - *Evaluate the Jacobian*, $J(\xi)$, and
   - Compute the *Forward Isoparametric Map* $\vec{x} : \bar{\Omega} \rightarrow \Omega^e$
2. Given a point in physical space, $\hat{x} \in \Omega$:
   - Compute the *Inverse Isoparametric Map*, which attempts to evaluate the corresponding reference coordinates of the point, $\hat{\xi} \in \bar{\Omega}$, with respect to the finite element, Ω^e. This operation is only defined for points that are *inside* the element (within some ϵ).

Evaluate Shape Functions

The *shape functions* can be readily computed from any `mint::FiniteElement` instance by calling the `evaluateShapeFunctions()` method on the finite element object. The following code snippet illustrates how to *Evaluate Shape Functions* at the isoparametric center of a quadrilateral element, given by $\xi = (0.5, 0.5)^T$:

```
1   // isoparametric center
2   double xi[ ] = { 0.5, 0.5 };
3   double N[ 4 ];
4   fe.evaluateShapeFunctions( xi, N );
```

- The `evaluateShapeFunctions()` method takes two arguments:
  - `xi`, an input argument corresponding to the reference coordinates of the point, $\hat{\xi}$, where the *shape functions* will be evaluated, and
  - `N`, an output argument which is an array of length equal to the number of constituent cell *Nodes*, storing the corresponding *shape functions*.

Evaluate the Jacobian

Similarly, for a reference point, $\hat{\xi} \in \bar{\Omega}$, the Jacobian matrix, consisting the sums of derivatives of *shape functions* and the corresponding determinant of the Jacobian, can be readily computed from the finite element object as follows:

```
numerics::Matrix< double > J( 2, 2 );
fe.jacobian( xi, J );

const double jdet = numerics::determinant( J );
std::cout << "jacobian determinant: " << jdet << std::endl;
```

- The Jacobian matrix is computed by calling the `jacobian()` method on the finite element object, which takes two arguments:
  - `xi`, an input argument corresponding to the reference coordinates of the point, $\hat{\xi}$, where the Jacobian will be evaluated, and
  - A matrix, represented by the `axom::numerics::Matrix` class, to store the resulting Jacobian.

Note: The Jacobian matrix is not necessarily a square matrix. It can have $N \times M$ dimensions, where, N corresponds to the dimension in the reference xi-space and M is the physical dimension. For example, a quadrilateral element is defined in a 2D reference space, but it may be instantiated within a 3D ambient space. Consequently, the dimensions of the corresponding Jacobian would be 2×3 in this case.

- The determinant of the Jacobian can then be computed by calling `axom::numerics::determinant()`, with the Jacobian as the input argument.

Forward Isoparametric Map

Given a point in reference space, $\hat{\xi} \in \bar{\Omega}$, the corresponding physical point, $\hat{x} \in \Omega^e$ is computed by calling the `computePhysicalCoords()` method on the finite element object as illustrated below:

```
double xc[ 2 ];
fe.computePhysicalCoords( xi, xc );
std::cout << "xc: ( ";
std::cout << xc[ 0 ] << ", "  << xc[ 1 ];
std::cout << " )\n";
```

The `computePhysicalCoords()` method takes two arguments:

- `xi`, an input argument corresponding to the reference coordinates of the point, $\hat{\xi}$, whose physical coordinates are computed, and
- `xc`, an output array argument that stores the computed physical coordinates, $\hat{x} \in \Omega^e$

Inverse Isoparametric Map

Similarly, given a point in physical space, $\hat{x} \in \Omega$, a corresponding point in the reference space of the element, $\hat{\xi} \in \bar{\Omega}$, can be obtained by calling the `computeReferenceCoords()` method on the finite element object as illustrated by the following:

```
double xr[ 2 ];
int status = fe.computeReferenceCoords( xc, xr );

switch( status )
{
case mint::INVERSE_MAP_FAILED:
  std::cout << "Newton-Raphson failed!";
```

(continues on next page)

(continued from previous page)

```
    break;
  case mint::OUTSIDE_ELEMENT:
    std::cout << "point is outside!\n";
    break;
  default:
    // found the reference coordinates!
    std::cout << "xr: ( ";
    std::cout << xr[ 0 ] << ", " << xr[ 1 ];
    std::cout << " )\n";
  }
```

The `computeReferenceCoords()` method takes two arguments:

- `xc` an input argument consisting of the physical point coordinates, whose reference coordinates are computed, and
- `xi` an output array to store the computed reference coordinates, if successful.

The *Inverse Isoparametric Map* typically requires an iterative, non-linear solve, which is typically implemented with a Newton-Raphson. Moreover, the *Inverse Isoparametric Map* is only defined for points within the element, Ω^e. Consequently, the `computeReferenceCoords()` method returns a status that indicates whether the operation was successful. Specifically, `computeReferenceCoords()` can return the following statuses:

- **`INVERSE_MAP_FAILED`** This typically indicates that the Newton-Raphson iteration did not converge, e.g., negative Jacobian, etc.
- **`OUTSIDE_ELEMENT`** This indicates that the Newton-Raphson converged, but the point is outside the element. Consequently, valid reference coordinates do not exist for the given point with respect to the element.
- **`INSIDE_ELEMENT`** This indicates the the Newton-Raphson converged and the point is inside the element

Output to VTK

Mint provides native support for writing meshes in the ASCII Legacy VTK File Format. Legacy VTK files are popular due to their simplicity and can be read by a variety of visualization tools, such as VisIt and ParaView. Thereby, enable quick visualization of the various *Mesh Types* and constituent *Field Data*, which can significantly aid in debugging.

Warning: The Legacy VTK File Format does not provide support for face-centered fields. Consequently, the output consists of only the node-centered and cell-centered fields of the mesh.

The functionality for outputting a mesh to VTK is provided by the `mint::write_vtk()` function. This is a free function in the `axom::mint` namespace, which takes two arguments: (1) a pointer to a `mint::Mesh` object, and, (2) the filename of the target VTK file, as illustrated in the code snippet below:

```
  mint::write_vtk( mesh, fileName );
```

This function can be invoked on a `mint::Mesh` object, which can correspond to any of the supported *Mesh Types*. The concrete mesh type will be reflected in the resulting VTK output file according to the VTK File Format specification.

Note: Support for VTK output is primarily intended for debugging and quick visualization of meshes. This functionality is not intended for routine output or restart dumps from a simulation. Production I/O capabilities in the Axom Toolkit are supported through Sidre. Consult the Sidre documentation for the details.

2.7.9 Examples

Warning: This section is under development

2.7.10 FAQ

Warning: This section is under development.

2.7.11 Appendix

Mint Application Code Example

Below is the complete *Mint Application Code Example* presented in the *Getting Started with Mint* section. The code can be found in the Axom source code under `src/axom/mint/examples/user_guide/mint_getting_started.cpp`.

```
// sphinx_tutorial_walkthrough_includes_start

#include "axom/config.hpp"                          // compile time definitions
#include "axom/core/execution/execution_space.hpp" // for execution_space traits

#include "axom/mint.hpp"                   // for mint classes and functions
#include "axom/core/numerics/Matrix.hpp"  // for numerics::Matrix

// sphinx_tutorial_walkthrough_includes_end

// namespace aliases
namespace mint     = axom::mint;
namespace numerics = axom::numerics;
namespace xargs    = mint::xargs;

using IndexType    = axom::IndexType;

// compile-time switch for execution policy
#if defined(AXOM_USE_RAJA) && defined(AXOM_USE_CUDA)
  constexpr int NUM_BLOCKS = 512;
  using ExecPolicy = axom::CUDA_EXEC< NUM_BLOCKS >;
#elif defined(AXOM_USE_RAJA) && defined(AXOM_USE_OPENMP)
  using ExecPolicy = axom::OMP_EXEC;
#else
  using ExecPolicy = axom::SEQ_EXEC;
#endif

constexpr IndexType NUM_NODES_PER_CELL = 4;
constexpr double ONE_OVER_4 = 1. / static_cast< double >( NUM_NODES_PER_CELL );

/*!
 * \brief Holds command-line arguments
 */
static struct
{
  int res;
```

(continues on next page)

(continued from previous page)

```
  bool useUnstructured;
} Arguments;

//------------------------------------------------------------------------------
// FUNCTION PROTOTYPES
//------------------------------------------------------------------------------
void parse_args(  int argc, char** argv );
mint::Mesh* getUniformMesh( );
mint::Mesh* getUnstructuredMesh( );

//------------------------------------------------------------------------------
// PROGRAM MAIN
//------------------------------------------------------------------------------
int main ( int argc, char** argv )
{

  parse_args( argc, argv );

// sphinx_tutorial_walkthrough_set_memory_start
  // NOTE: use unified memory if we are using CUDA
#if defined(AXOM_USE_RAJA) && defined(AXOM_USE_CUDA)
  const int allocID = axom::getResourceAllocatorID( umpire::resource::Unified );
  axom::setDefaultAllocator( axom::getAllocator( allocID) );
#endif
// sphinx_tutorial_walkthrough_set_memory_end

// sphinx_tutorial_walkthrough_construct_mesh_start

  mint::Mesh* mesh =
    ( Arguments.useUnstructured ) ? getUnstructuredMesh( ) : getUniformMesh( );

// sphinx_tutorial_walkthrough_construct_mesh_end

// sphinx_tutorial_walkthrough_add_fields_start

  // add a cell-centered and a node-centered field
  double* phi = mesh->createField< double >( "phi", mint::NODE_CENTERED );
  double* hc  = mesh->createField< double >( "hc", mint::CELL_CENTERED );

  constexpr int NUM_COMPONENTS = 2;
  double* xc  = mesh->createField< double >( "xc", mint::CELL_CENTERED, NUM_
↪COMPONENTS );

// sphinx_tutorial_walkthrough_add_fields_end

// sphinx_tutorial_walkthrough_compute_hf_start

  // loop over the nodes and evaluate Himmelblaus Function
  mint::for_all_nodes< ExecPolicy, xargs::xy >(
      mesh, AXOM_LAMBDA( IndexType nodeIdx, double x, double y )
  {
    const double x_2 = x * x;
    const double y_2 = y * y;
    const double A   = x_2 + y   - 11.0;
    const double B   = x   + y_2 - 7.0;

    phi[ nodeIdx ] = A * A + B * B;
```

(continues on next page)

(continued from previous page)

```
  } );

// sphinx_tutorial_walkthrough_compute_hf_end

// sphinx_tutorial_walkthrough_cell_centers_start

  // loop over cells and compute cell centers
  mint::for_all_cells< ExecPolicy, xargs::coords >(
      mesh, AXOM_LAMBDA( IndexType cellIdx,
                         const numerics::Matrix< double >& coords,
                         const IndexType* nodeIds )
  {
    // NOTE: A column vector of the coords matrix corresponds to a nodes coords

    // Sum the cell's nodal coordinates
    double xsum = 0.0;
    double ysum = 0.0;
    double hsum = 0.0;

    const IndexType numNodes = coords.getNumColumns();
    for ( IndexType inode=0; inode < numNodes; ++inode )
    {
      const double* node = coords.getColumn( inode );
      xsum += node[ mint::X_COORDINATE ];
      ysum += node[ mint::Y_COORDINATE ];

      hsum += phi[ nodeIds[ inode] ];
    } // END for all cell nodes

    // compute cell centroid by averaging the nodal coordinate sums
    const IndexType offset = cellIdx * NUM_COMPONENTS;
    const double invnnodes = 1.f / static_cast< double >( numNodes );
    xc[ offset   ] = xsum * invnnodes;
    xc[ offset+1 ] = ysum * invnnodes;

    hc[ cellIdx ] = hsum * invnnodes;
  } );

// sphinx_tutorial_walkthrough_cell_centers_end

// sphinx_tutorial_walkthrough_vtk_start

  // write the mesh in a VTK file for visualization
  std::string vtkfile =
    (Arguments.useUnstructured) ? "unstructured_mesh.vtk" : "uniform_mesh.vtk";
  mint::write_vtk( mesh, vtkfile );

// sphinx_tutorial_walkthrough_vtk_end

  delete mesh;
  mesh = nullptr;

  return 0;
}

//------------------------------------------------------------------------------
//  FUNCTION PROTOTYPE IMPLEMENTATION
```

(continues on next page)

(continued from previous page)

```
150 //------------------------------------------------------------------------------
151 void parse_args( int argc, char** argv )
152 {
153   Arguments.res = 25;
154   Arguments.useUnstructured = false;
155 
156   for ( int i=1; i < argc; ++i )
157   {
158 
159     if ( strcmp( argv[ i ], "--unstructured" )==0 )
160     {
161       Arguments.useUnstructured = true;
162     }
163 
164     else if ( strcmp( argv[ i ], "--resolution" )==0 )
165     {
166       Arguments.res = std::atoi( argv[ ++i ] );
167     }
168 
169   } // END for all arguments
170 
171   SLIC_ERROR_IF( Arguments.res < 2,
172       "invalid mesh resolution! Please, pick a value greater than 2." );
173 }
174 
175 //------------------------------------------------------------------------------
176 // sphinx_tutorial_walkthrough_construct_umesh_start
177 mint::Mesh* getUniformMesh( )
178 {
179   // construct a N x N grid within a domain defined in [-5.0, 5.0]
180   const double lo[]   = { -5.0, -5.0 };
181   const double hi[]   = {  5.0,  5.0 };
182   mint::Mesh* m = new mint::UniformMesh( lo, hi, Arguments.res, Arguments.res );
183   return( m );
184 }
185 // sphinx_tutorial_walkthrough_construct_umesh_end
186 
187 //------------------------------------------------------------------------------
188 mint::Mesh* getUnstructuredMesh( )
189 {
190   mint::Mesh* umesh = getUniformMesh();
191   const IndexType umesh_ncells = umesh->getNumberOfCells();
192   const IndexType umesh_nnodes = umesh->getNumberOfNodes();
193 
194   const IndexType ncells = umesh_ncells * 4; // split each quad into 4 triangles
195   const IndexType nnodes = umesh_nnodes + umesh_ncells;
196 
197   constexpr int DIMENSION = 2;
198   using MeshType = mint::UnstructuredMesh< mint::SINGLE_SHAPE >;
199   MeshType* m = new MeshType( DIMENSION, mint::TRIANGLE, nnodes, ncells );
200   m->resize( nnodes, ncells );
201 
202   double* x = m->getCoordinateArray( mint::X_COORDINATE );
203   double* y = m->getCoordinateArray( mint::Y_COORDINATE );
204   IndexType* cells = m->getCellNodesArray();
205 
206   // fill coordinates from uniform mesh
```

(continues on next page)

(continued from previous page)

```
  mint::for_all_nodes< ExecPolicy, xargs::xy >(
        umesh, AXOM_LAMBDA( IndexType nodeIdx, double nx, double ny )
  {
    x[ nodeIdx ] = nx;
    y[ nodeIdx ] = ny;
  } );


  // loop over cells, compute cell centers and fill connectivity
  mint::for_all_cells< ExecPolicy, xargs::coords >(
        umesh, AXOM_LAMBDA( IndexType cellIdx,
                            const numerics::Matrix< double >& coords,
                            const IndexType* nodeIds )
  {
    // NOTE: A column vector of the coords matrix corresponds to a nodes coords

    // Sum the cell's nodal coordinates
    double xsum = 0.0;
    double ysum = 0.0;
    for ( IndexType inode=0; inode < NUM_NODES_PER_CELL; ++inode )
    {
      const double* node = coords.getColumn( inode );
      xsum += node[ mint::X_COORDINATE ];
      ysum += node[ mint::Y_COORDINATE ];
    } // END for all cell nodes

    // compute cell centroid by averaging the nodal coordinate sums
    const IndexType nc = umesh_nnodes + cellIdx; /* centroid index */
    x[ nc ] = xsum * ONE_OVER_4;
    y[ nc ] = ysum * ONE_OVER_4;

    // triangulate
    const IndexType& n0 = nodeIds[ 0 ];
    const IndexType& n1 = nodeIds[ 1 ];
    const IndexType& n2 = nodeIds[ 2 ];
    const IndexType& n3 = nodeIds[ 3 ];

    const IndexType offset = cellIdx * 12;

    cells[ offset      ] = n0;
    cells[ offset + 1  ] = nc;
    cells[ offset + 2  ] = n3;

    cells[ offset + 3  ] = n0;
    cells[ offset + 4  ] = n1;
    cells[ offset + 5  ] = nc;

    cells[ offset + 6  ] = n1;
    cells[ offset + 7  ] = n2;
    cells[ offset + 8  ] = nc;

    cells[ offset + 9  ] = n2;
    cells[ offset + 10 ] = n3;
    cells[ offset + 11 ] = nc;
  } );

  // delete uniform mesh
```

(continues on next page)

(continued from previous page)

```
  delete umesh;
  umesh = nullptr;

  return ( m );
}
```

AXOM_LAMBDA Macro

The `AXOM_LAMBDA` convenience macro expands to:

- `[=]` capture by value when the Axom Toolkit is compiled without CUDA.
- `[=] __host__ __device__` when the Axom Toolkit is compiled with CUDA

Raw Sidre Data

```
{
  "name": "",
  "groups":
  {
    "state":
    {
      "name": "state",
      "groups":
      {
        "t1":
        {
          "name": "t1",
          "views":
          {
            "block_id":
            {
              "name": "block_id",
              "schema": "{\"dtype\":\"int32\", \"number_of_elements\": 1, \"offset\":
↪0, \"stride\": 4, \"element_bytes\": 4, \"endianness\": \"little\"}",
              "value": "-1",
              "state": "SCALAR",
              "is_applied": 1
            },
            "partition_id":
            {
              "name": "partition_id",
              "schema": "{\"dtype\":\"int32\", \"number_of_elements\": 1, \"offset\":
↪0, \"stride\": 4, \"element_bytes\": 4, \"endianness\": \"little\"}",
              "value": "-1",
              "state": "SCALAR",
              "is_applied": 1
            }
          }
        }
      }
    },
    "coordsets":
    {
```

(continues on next page)

(continued from previous page)

```
      "name": "coordsets",
      "groups":
      {
        "c1":
        {
          "name": "c1",
          "views":
          {
            "type":
            {
              "name": "type",
              "schema": "{\"dtype\":\"char8_str\", \"number_of_elements\": 9, \"offset\": 0, \"stride\": 1, \"element_bytes\": 1, \"endianness\": \"little\"}",
              "value": "\"explicit\"",
              "state": "STRING",
              "is_applied": 1
            }
          },
          "groups":
          {
            "values":
            {
              "name": "values",
              "views":
              {
                "x":
                {
                  "name": "x",
                  "schema": "{\"dtype\":\"float64\", \"number_of_elements\": 6, \"offset\": 0, \"stride\": 8, \"element_bytes\": 8, \"endianness\": \"little\"}",
                  "value": "[0.0, 2.0, 1.0, 3.5, 2.5, 5.0]",
                  "state": "BUFFER",
                  "is_applied": 1
                },
                "y":
                {
                  "name": "y",
                  "schema": "{\"dtype\":\"float64\", \"number_of_elements\": 6, \"offset\": 0, \"stride\": 8, \"element_bytes\": 8, \"endianness\": \"little\"}",
                  "value": "[0.0, 0.0, 1.0, 1.0, 2.0, 0.0]",
                  "state": "BUFFER",
                  "is_applied": 1
                }
              }
            }
          }
        }
      }
    },
    "topologies":
    {
      "name": "topologies",
      "groups":
      {
        "t1":
        {
          "name": "t1",
```

(continues on next page)

(continued from previous page)

```
          "views":
          {
            "coordset":
            {
              "name": "coordset",
              "schema": "{\"dtype\":\"char8_str\", \"number_of_elements\": 3, \"offset\": 0, \"stride\": 1, \"element_bytes\": 1, \"endianness\": \"little\"}",
              "value": "\"c1\"",
              "state": "STRING",
              "is_applied": 1
            },
            "type":
            {
              "name": "type",
              "schema": "{\"dtype\":\"char8_str\", \"number_of_elements\": 13, \"offset\": 0, \"stride\": 1, \"element_bytes\": 1, \"endianness\": \"little\"}",
              "value": "\"unstructured\"",
              "state": "STRING",
              "is_applied": 1
            }
          },
          "groups":
          {
            "elements":
            {
              "name": "elements",
              "views":
              {
                "shape":
                {
                  "name": "shape",
                  "schema": "{\"dtype\":\"char8_str\", \"number_of_elements\": 4, \"offset\": 0, \"stride\": 1, \"element_bytes\": 1, \"endianness\": \"little\"}",
                  "value": "\"tri\"",
                  "state": "STRING",
                  "is_applied": 1
                },
                "connectivity":
                {
                  "name": "connectivity",
                  "schema": "{\"dtype\":\"int32\", \"number_of_elements\": 12, \"offset\": 0, \"stride\": 4, \"element_bytes\": 4, \"endianness\": \"little\"}",
                  "value": "[1, 3, 2, 2, 0, 1, 3, 4, 2, 1, 5, 3]",
                  "state": "BUFFER",
                  "is_applied": 1
                },
                "stride":
                {
                  "name": "stride",
                  "schema": "{\"dtype\":\"int32\", \"number_of_elements\": 1, \"offset\": 0, \"stride\": 4, \"element_bytes\": 4, \"endianness\": \"little\"}",
                  "value": "3",
                  "state": "SCALAR",
                  "is_applied": 1
                }
              }
            }
```

(continues on next page)

(continued from previous page)


```
            }
          }
        }
    },
    "fields":
    {
      "name": "fields",
      "groups":
      {
        "den":
        {
          "name": "den",
          "views":
          {
            "association":
            {
              "name": "association",
              "schema": "{\"dtype\":\"char8_str\", \"number_of_elements\": 8, \
↪"offset\": 0, \"stride\": 1, \"element_bytes\": 1, \"endianness\": \"little\"}",
              "value": "\"element\"",
              "state": "STRING",
              "is_applied": 1
            },
            "volume_dependent":
            {
              "name": "volume_dependent",
              "schema": "{\"dtype\":\"char8_str\", \"number_of_elements\": 5, \
↪"offset\": 0, \"stride\": 1, \"element_bytes\": 1, \"endianness\": \"little\"}",
              "value": "\"true\"",
              "state": "STRING",
              "is_applied": 1
            },
            "topology":
            {
              "name": "topology",
              "schema": "{\"dtype\":\"char8_str\", \"number_of_elements\": 3, \
↪"offset\": 0, \"stride\": 1, \"element_bytes\": 1, \"endianness\": \"little\"}",
              "value": "\"t1\"",
              "state": "STRING",
              "is_applied": 1
            },
            "values":
            {
              "name": "values",
              "schema": "{\"dtype\":\"float64\", \"number_of_elements\": 4, \"offset\
↪": 0, \"stride\": 8, \"element_bytes\": 8, \"endianness\": \"little\"}",
              "value": "[0.5, 1.2, 2.5, 0.9]",
              "state": "BUFFER",
              "is_applied": 1
            }
          }
        }
      }
    }
  }
}
```

2.8 Primal User Documentation

Primal is a component of Axom that provides efficient and general purpose algorithms and data structures for computational geometry. Primal provides:

- Classes to represent geometric primitives such as Point and Ray
- Functions operating on Primal's classes to implement geometric operators, including distance and intersection

This tutorial contains a collection of brief examples demonstrating Primal primitives and operators. The examples instantiate geometric primitives as needed and demonstrate geometric operators. These examples also show representative overloads of each of the Primal operators (see the API documentation for more details).

2.8.1 Primitives

Primal includes the following primitives:

- Point
- Segment, Ray, Vector
- Plane, Triangle, Polygon
- Sphere
- Tetrahedron
- BoundingBox, OrientedBoundingBox

Primal also provides the NumericArray class, which implements arithmetic operations on numerical tuples and supports Primal's Point and Vector classes. Classes in Primal are templated on coordinate type (double, float, etc.) and dimension. The primitives do not inherit from a common base class. This was a design choice in favor of simplicity and performance. Geometric primitives can be tested for equality and can be printed to strings.

Primal also includes functions to merge a pair of BoundingBox or a pair of OrientedBoundingBox objects and to create new OrientedBoundingBox objects from a list of points.

The following includes header files for primal's primitives as well as some `using` directives and `typedef` statements that will be used in the examples. Header files for operations will be shown next to code examples. Although the examples `#include` separate class header files, it is easier and less error-prone to write `#include axom/primal.hpp`.

```
// Axom primitives
#include "axom/primal/geometry/BoundingBox.hpp"
#include "axom/primal/geometry/OrientedBoundingBox.hpp"
#include "axom/primal/geometry/Point.hpp"
#include "axom/primal/geometry/Polygon.hpp"
#include "axom/primal/geometry/Ray.hpp"
#include "axom/primal/geometry/Segment.hpp"
#include "axom/primal/geometry/Triangle.hpp"
#include "axom/primal/geometry/Vector.hpp"
```

```
// "using" directives to simplify code
using namespace axom;
using namespace primal;

// almost all our examples are in 3D
constexpr int in3D = 3;
```

(continues on next page)

(continued from previous page)

```
// primitives represented by doubles in 3D
typedef Point<double, in3D> PointType;
typedef Triangle<double, in3D> TriangleType;
typedef BoundingBox<double, in3D> BoundingBoxType;
typedef OrientedBoundingBox<double, in3D> OrientedBoundingBoxType;
typedef Polygon<double, in3D> PolygonType;
typedef Ray<double, in3D> RayType;
typedef Segment<double, in3D> SegmentType;
typedef Vector<double, in3D> VectorType;
```

2.8.2 Operators

Primal implements geometric operators with unbound functions. Currently, these include the following:

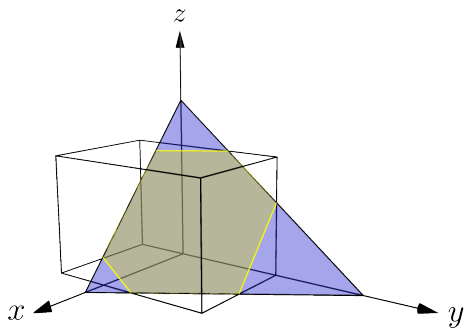
- `clip` finds the polygon resulting from a bounding box clipping a triangle.
- `closest_point` takes a primitive P and a query point Q and returns the point on P closest to Q.
- `compute_bounding_box` finds the bounding box for a given primitive.
- `squared_distance` computes the squared distance from a point to another primitive.
- `orientation` finds the side of a line segment or triangle where a query point lies.
- `intersect` predicate tests if two primitives intersect. Some of the combinations also indicate the point of intersection of a 1D primitive with another primitive.

Note: Most use cases have low dimension, usually 2 or 3. Dimensionality has been generalized to support other values where it does not interfere with the common case, but some operators such as triangle intersection do not support other dimensionality than 2 or 3.

Note: Many of the operations includes a tolerance parameter `eps` for improved geometric robustness. For example, `orientation()` considers a point to be on the boundary (`OrientationResult::ON_BOUNDARY`) when the point is within `eps` of the plane. This parameter is explicitly exposed in the primal API for some operations (e.g. some versions of `intersect()`), but not others (e.g. `orientation()`).

Clip triangle against bounding box

The clip operator clips a triangle against a bounding box, returning the resulting polygon. The figure shows the triangle in blue and the polygon resulting from `clip()` in grey.



```
#include "axom/primal/operators/clip.hpp"
```

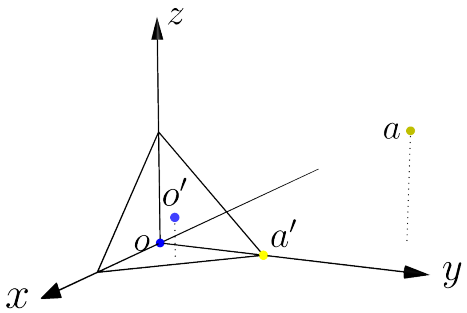
```
  TriangleType tri(PointType::make_point(1.2,   0,   0),
                   PointType::make_point(  0, 1.8,   0),
                   PointType::make_point(  0,   0, 1.4));

  BoundingBoxType bbox(PointType::make_point(0, -0.5, 0),
                       PointType::make_point(1,    1, 1));

  PolygonType poly = clip(tri, bbox);
```

Closest point query

The closest point operator finds the point on a triangle that is closest to a query point. Query point o (shown in dark blue), at the origin, is closest to point o' (light blue), which lies in the triangle's interior. Query point a (olive) is closest to point a' (yellow), which lies on the triangle's edge at a vertex.




```
#include "axom/primal/operators/closest_point.hpp"
```

```
  TriangleType tri(PointType::make_point(1, 0, 0),
                   PointType::make_point(0, 1, 0),
                   PointType::make_point(0, 0, 1));

  PointType pto = PointType::make_point( 0, 0, 0);
  PointType pta = PointType::make_point(-1, 2, 1);

  // Query point o lies at the origin.  Its closest point lies in the
  // interior of tri.
  PointType cpto = closest_point(pto, tri);

  // Query point a lies farther from the triangle.  Its closest point
  // is on tri's edge.
  int lcpta = 0;
  PointType cpta = closest_point(pta, tri, &lcpta);
```

As the code example shows, `closest_point()` can take a pointer to an `int` as an optional third parameter. If supplied, the function writes a value into the `int` that indicates which of the triangle's vertices or sides contains the closest point (or the interior).

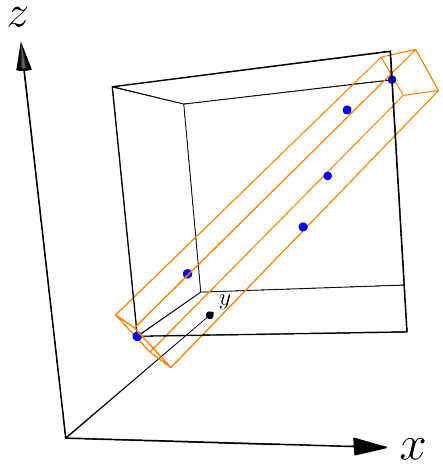
Compute bounding box

Primal's bounding boxes are rectangular right prisms. That is, they are boxes where neighboring walls are at right angles.

The BoundingBox class represents an axis-aligned bounding box, which has two walls perpendicular to the X-axis, two perpendicular to the Y-axis, and two perpendicular to the Z-axis. This is sufficient for many computations; range and intersection operations tend to be fast.

The OrientedBoundingBox class can be oriented in any way with respect to the coordinate axes. This can provide a tighter fit to the bounded data, but construction, intersection, and range calculation are more costly.

Here a group of points is used to create both an (axis-aligned) BoundingBox and an OrientedBoundingBox. The points are drawn in blue, the BoundingBox in black, and the OrientedBoundingBox in orange.




```
#include "axom/primal/operators/compute_bounding_box.hpp"
```

```
  // An array of Points to include in the bounding boxes
  const int nbr_points = 6;
  PointType data[nbr_points];
  data[0] = PointType::make_point(0.6, 1.2, 1.0);
  data[1] = PointType::make_point(1.3, 1.6, 1.8);
  data[2] = PointType::make_point(2.9, 2.4, 2.3);
  data[3] = PointType::make_point(3.2, 3.5, 3.0);
  data[4] = PointType::make_point(3.6, 3.2, 4.0);
  data[5] = PointType::make_point(4.3, 4.3, 4.5);

  // A BoundingBox constructor takes an array of Point objects
  BoundingBoxType bbox(data, nbr_points);
  // Make an OrientedBoundingBox
  OrientedBoundingBoxType obbox =
    compute_oriented_bounding_box(data, nbr_points);
```

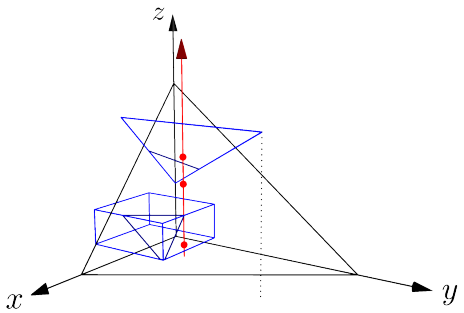
Primal also provides a `merge_boxes()` function to produce a bounding box that contains two input bounding boxes. This is available for client codes to use and also supports the operation of the BVHTree class.

Intersection

The intersection test is provided by `intersect()`. It takes two primitives and returns a boolean indicating if the primitives intersect. Some overloads return the point of intersection in an output argument. The overloads for `intersect()` are summarized in the table below.

Arg 1	Arg 2	Additional arguments and notes
Triangle	Triangle	include boundaries[1] (default false)
Ray	Segment	return intersection point. 2D only.
Segment	BoundingBox	return intersection point
Ray	BoundingBox	return intersection point
BoundingBox	BoundingBox	
Sphere	Sphere	specify tolerance
Triangle	BoundingBox	
Triangle	Ray	return parameterized intersection point (on Ray), return barycentric intersection point (on Triangle)
Triangle	Segment	return parameterized intersection point (on Segment), return barycentric intersection point (on Triangle)
OrientedBoundingBox	OrientedBoundingBox	specify tolerance

The example below tests for intersection between two triangles, a ray, and a BoundingBox.




```
#include "axom/primal/operators/intersect.hpp"
```

```
  // Two triangles
  TriangleType tri1(PointType::make_point(1.2,   0,   0),
                    PointType::make_point(  0, 1.8,   0),
                    PointType::make_point(  0,   0, 1.4));

  TriangleType tri2(PointType::make_point(  0,   0, 0.5),
                    PointType::make_point(0.8, 0.1, 1.2),
                    PointType::make_point(0.8, 1.4, 1.2));

  // tri1 and tri2 should intersect
  if (intersect(tri1, tri2))
  {
    std::cout << "Triangles intersect as expected." << std::endl;
  }
  else
  {
    std::cout << "There's an error somewhere..." << std::endl;
  }

  // A vertical ray constructed from origin and point
  RayType ray(SegmentType(PointType::make_point(0.4, 0.4, 0),
                          PointType::make_point(0.4, 0.4, 1)));
```

(continues on next page)

[1] By default, the triangle intersection algorithm considers only the triangles' interiors, so that non-coplanar triangles that share two vertices are not reported as intersecting. The caller to `intersect()` can specify an optional argument to include triangle boundaries in the intersection test.

(continued from previous page)

```
  // t will hold the intersection point between ray and tri1,
  // as parameterized along ray.
  double rt1t = 0;
  // rt1b will hold the intersection point barycentric coordinates,
  // and rt1p will hold the physical coordinates.
  PointType rt1b, rt1p;

  // The ray should intersect tri1 and tri2.
  if (intersect(tri1, ray, rt1t, rt1b) && intersect(tri2, ray))
  {
    // Retrieve the physical coordinates from barycentric coordinates
    rt1p = tri1.baryToPhysical(rt1b);
    // Retrieve the physical coordinates from ray parameter
    PointType rt1p2 = ray.at(rt1t);
    std::cout << "Ray intersects tri1 as expected.  Parameter t: " <<
      rt1t << std::endl << "  Intersection point along ray: " << rt1p2 <<
      std::endl << "  Intersect barycentric coordinates: " << rt1b <<
      std::endl << "  Intersect physical coordinates: " << rt1p << std::endl <<
      "Ray also intersects tri2 as expected." << std::endl;
  }
  else
  {
    std::cout << "There's an error somewhere..." << std::endl;
  }

  // A bounding box
  BoundingBoxType bbox(PointType::make_point(0.1, -0.23, 0.1),
                       PointType::make_point(0.8,  0.5,  0.4));

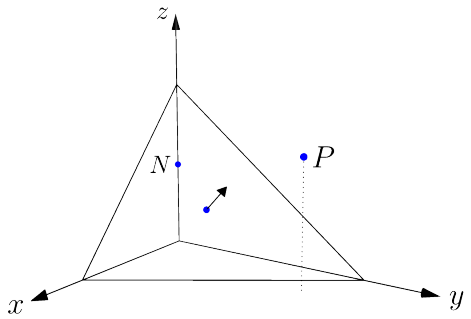
  // The bounding box should intersect tri1 and ray but not tr2.
  PointType bbtr1;
  if (intersect(ray, bbox, bbtr1) && intersect(tri1, bbox) &&
      !intersect(tri2, bbox))
  {
    std::cout << "As hoped, bounding box intersects tri1 at " << bbtr1 <<
      " and ray, but not tri2." << std::endl;
  }
  else
  {
    std::cout << "There is at least one error somewhere..." << std::endl;
  }
```

In the diagram, the point where the ray enters the bounding box is shown as the intersection point (not the exit point or some point inside the box). This is because if a ray intersects a bounding box at more than one point, the first intersection point along the ray (the intersection closest to the ray's origin) is reported as the intersection. If a ray originates inside a bounding box, the ray's origin will be reported as the point of intersection.

Orientation

Axom contains two overloads of `orientation()`. The 3D case tests a point against a triangle and reports which side it lies on; the 2D case tests a point against a line segment. Here is an example of the 3D point-triangle orientation test.

```
#include "axom/primal/operators/orientation.hpp"
```




```
// A triangle
TriangleType tri(PointType::make_point(1.2,   0,   0),
                 PointType::make_point(  0, 1.8,   0),
                 PointType::make_point(  0,   0, 1.4));

// Three points:
//    one on the triangle's positive side,
PointType pos = PointType::make_point(0.45, 1.5, 1);
//    one coplanar to the triangle, the centroid,
PointType cpl = PointType::lerp(PointType::lerp(tri[0], tri[1], 0.5),
                                tri[2], 1./3.);
//    and one on the negative side
PointType neg = PointType::make_point(0, 0, 0.7);

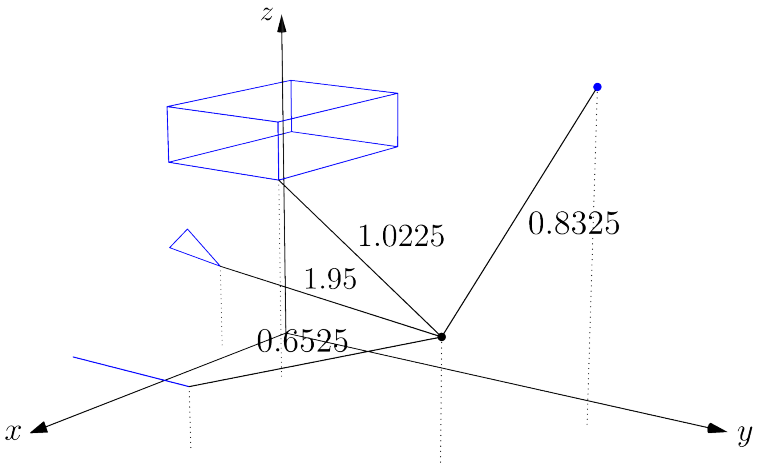
// Test orientation
if (orientation(pos, tri)  == ON_POSITIVE_SIDE &&
    orientation(cpl, tri) == ON_BOUNDARY &&
    orientation(neg, tri)  == ON_NEGATIVE_SIDE)
{
  std::cout << "As expected, point pos is on the positive side," <<
    std::endl << "    point cpl is on the boundary (on the triangle)," <<
    std::endl << "    and point neg is on the negative side." << std::endl;
}
else
{
  std::cout << "Someone wrote this wrong." << std::endl;
}
```

The triangle is shown with its normal vector pointing out of its centroid. The triangle's plane divides space into a positive half-space, pointed into by the triangle's normal vector, and the opposing negative half-space. The test point on the z axis, labelled N, is on the negative side of the triangle. The centroid lies in the triangle, on the boundary between the two half-spaces. The remaining test point, labelled P, is on the triangle's positive side.

Distance

The various overloads of `squared_distance()` calculate the squared distance between a query point and several different primitives:

- another point,
- a BoundingBox,
- a Segment,
- a Triangle.




```
#include "axom/primal/operators/squared_distance.hpp"
```

```
  // The point from which we'll query
  PointType q = PointType::make_point(0.75, 1.2, 0.4);

  // Find distance to:
  PointType p = PointType::make_point(0.2, 1.4, 1.1);
  SegmentType seg(PointType::make_point(1.1, 0.0, 0.2),
                  PointType::make_point(1.1, 0.5, 0.2));
  TriangleType tri(PointType::make_point(0.2,  -0.3, 0.4),
                   PointType::make_point(0.25, -0.1, 0.3),
                   PointType::make_point(0.3,  -0.3, 0.35));
  BoundingBoxType bbox(PointType::make_point(-0.3, -0.2, 0.7),
                       PointType::make_point( 0.4,  0.3, 0.9));

  double dp = squared_distance(q, p);
  double dseg = squared_distance(q, seg);
  double dtri = squared_distance(q, tri);
  double dbox = squared_distance(q, bbox);
```

The example shows the squared distance between the query point, shown in black in the figure, and four geometric primitives. For clarity, the diagram also shows the projection of the query point and its closest points to the XY plane.

2.9 Source Code Documentation

- Axom
- Core
- Lumberjack
- Mint
- Primal
- Quest
- Sidre
- Spin

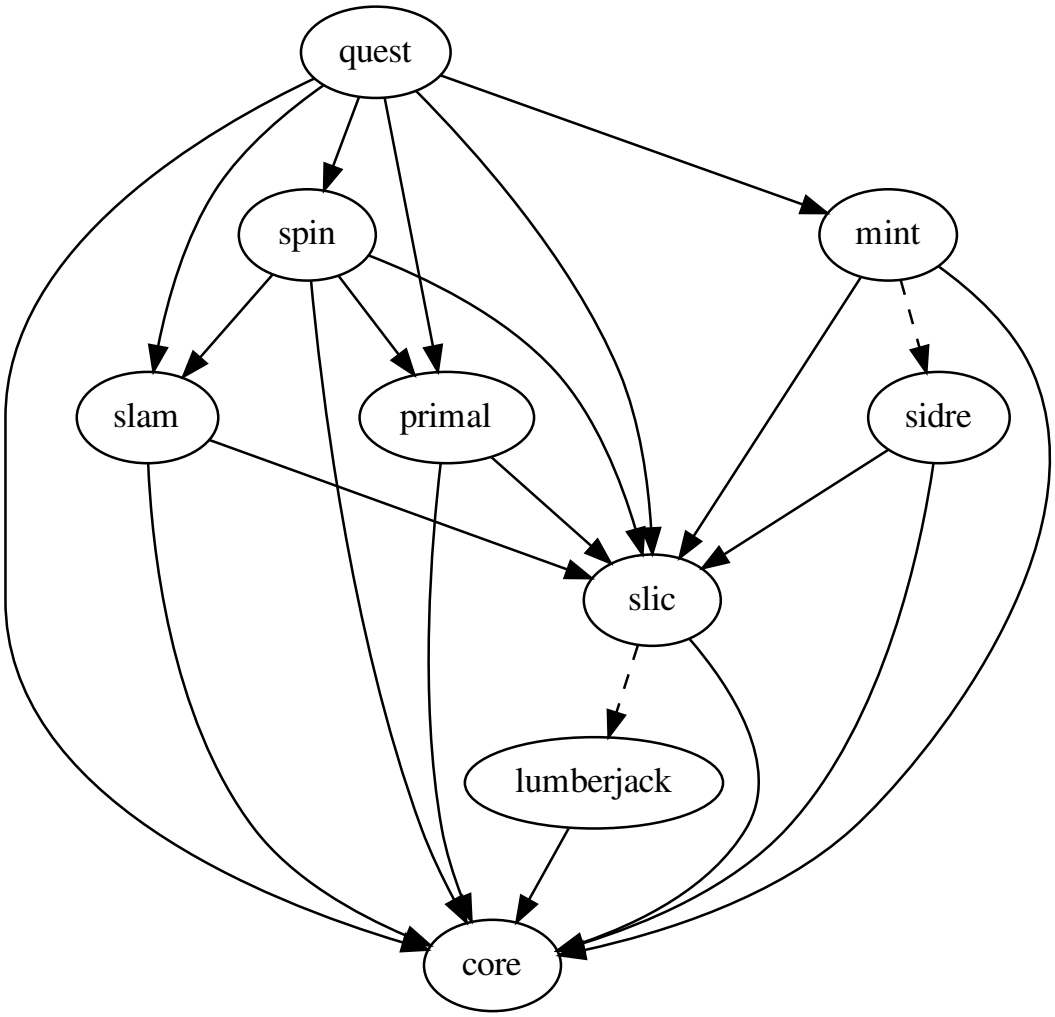
- Slic
- Slam

Look for documentation to appear for new components as they are developed.

Dependencies between modules are as follows:

- Core has no dependencies, and the other modules depend on Core
- Slic optionally depends on Lumberjack
- Slam, Spin, Primal, Mint, Quest, and Sidre depend on Slic
- Mint optionally depends on Sidre
- Quest depends on Slam, Spin, Primal, and Mint

The figure below summarizes the dependencies between the modules. Solid links indicate hard dependencies; dashed links indicate optional dependencies.



CHAPTER 3

Other Tools Application Developers May Find Useful

Axom developers support other tools that can be used by software projects independent of the Axom. These include:

- BLT (CMake-based build system developed by the Axom team to simplify CMake usage and development tool integration)
- Shroud (Generator for native C and Fortran APIs from C++ code)
- Conduit (Library for describing and managing in-memory data structures)

3.1 Axom Developer Guide

This guide describes important aspects of software development processes used by the Axom project. It does not contain information about building the code or coding guidelines. Please see the note below.

This development guide is intended for all team members and contributors. It is especially helpful for individuals who are less familiar with the project and wish to understand how the team works. We attempt to employ simple practices that are easy to understand and follow and which improve our software without being overly burdensome. We believe that when everyone on our team follows similar practices, the likelihood that our software will be high quality (i.e., robust, correct, easy to use, etc.) is improved. Everyone who contributes to Axom should be aware of and follow these guidelines.

We also believe that the benefits of uniformity and rigor are best balanced with allowances for individual preferences, which may work better in certain situations. Therefore, we do not view these processes as fixed for all time. They should evolve with project needs and be improved when it makes sense. Changes should be agreed to by team members after assessing their merits using our collective professional judgment. When changes are made, this guide should be updated accordingly.

Note: This document does not describe how to configure and build the Axom code, or discuss Axom coding guidelines. For information on those topics please refer to the following documents: Axom Quickstart Guide, Axom Coding Guide.

Contents:

3.1.1 Axom Development Process Summary

This section provides a high-level overview of key Axom software development topics and includes links to more detailed discussion.

Software Development Cycles

The Axom team uses a sprint-based development process. We collect and track issues (bugs, feature requests, tasks, etc.) using `JIRA` and define a set of development tasks (i.e., issues) to complete for each sprint. While the team meets to discuss issues and plan which ones will be worked in each sprint, developers of individual Axom components may plan and schedule work in any way that works for them as long as this is coordinated with other team efforts. Work performed in each sprint work period is tracked as a single unified sprint encompassing activities for the entire project.

See *JIRA: Issue Tracking and Release Cycles* for more information about how we do issue tracking and release planning.

Software Releases and Version Numbers

Typically, Axom releases are done when it makes sense to make new features or other changes available to users. A release may coincide with the completion of a sprint cycle or it may not.

See *Axom Release Process* for a description of the Axom release process.

The Axom team follows the **semantic versioning** scheme for assigning release numbers. Semantic versioning conveys specific meaning about the code and modifications from version to version by the way version numbers are constructed.

See *Semantic Versioning* for a description of semantic versioning.

Branch Development

The Axom project has a `CZ Bitbucket` project space and the team follows the **Gitflow** branching model for software development and reviews. Gitflow is a common workflow centered around software releases. It makes clear which branches correspond to which phases of development and those phases are represented explicitly in the structure of the source code repository. As in other branching models, developers develop code locally and push their work to a central repository.

See *Gitflow Branching Model* for a detailed description of how we use Gitflow.

Code Reviews and Acceptance

Before any code is merged into one of our main Gitflow branches (i.e., develop or master), it must be adequately tested, documented, and reviewed for acceptance by other team members. The review process is initiated via a *pull request* on the Axom Bitbucket project.

See *Pull Requests and Code Reviews* for a description of our review process and how we use pull requests.

Testing and Code Health

Comprehensive software testing processes and use of code health tools (e.g., static analysis, memory checkers, code coverage) are essential ingredients in the Axom development process.

See *Axom Tests and Examples* for a description of our software testing process, including *continuous integration*.

Software Development Tools

In addition to the tools listed above, we use a variety of other tools to help manage and automate our software development processes. The *tool philosophy* adopted by the Axom project focuses on three central tenets:

- Employ robust, commonly-used tools and don't re-invent something that already exists.
- Apply tools in ways that non-experts find easy to use.
- Strive for automation and reproducibility.

The main interaction hub for Axom developers is the **Atlassian tool suite** on the Livermore Computing Collaboration Zone (CZ). These tools can be accessed through the MyLC Portal. Developer-level access to Axom project spaces in these tools requires membership in the LC group 'axomdev'. If you are not in this group, and need to be, please send an email request to 'axom-dev@llnl.gov'.

The main Atlassian tools we use are listed below. Please navigate the links provided for details about how we use them and helpful information about getting started with them.

- **Confluence.** We use the Axom Confluence space for team discussion (e.g., hashing out design ideas), maintaining meeting notes, etc.
- **Bitbucket.** We use the Axom Bitbucket project to manage our Git repository which contains the Axom source code, build configurations, scripts, test suites, documentation, etc.
  - See *Git/Bitbucket: Version Control and Branch Development* for more information about how we use Git and Bitbucket.
- **JIRA.** We use the Axom JIRA project for issue tracking and release planning.
  - See *JIRA: Issue Tracking and Release Cycles* for more information about how we use JIRA.
- **Bamboo.** We use two Bamboo projects for continuous integration tasks.: Axom CZ Bamboo project and Axom RZ Bamboo project
  - See *Continuous Integration* for more information about how we use Bamboo.

3.1.2 JIRA: Issue Tracking and Release Cycles

We use our Axom JIRA project space for issue tracking and work planning. In JIRA, you can create, edit and comment on issues. You can also assign issues to individuals, check on their status, group them together for sprint development, and search for issues in various ways.

This section describes Axom software development cycles and basic issue work flow.

Sprint Cycles and Work Planning

The Axom project plans work regularly for sprint development cycles, which are typically 2 or 3 months long. Although this is long for typical sprint-based development, we find that it works well for our project where multiple software components are under development concurrently since it gives component developers flexibility to plan and coordinate work with other components in a way that works best for them.

Note: Our sprint development cycles often coincide with software releases, but not always. We may do multiple releases in a sprint or a single release may contain work from more than one sprint. Releases are determined mostly by when it makes sense to push a set of features out to our users.

In JIRA, the project maintains two `Sprints`, called `Current Sprint` and `Next Sprint`. The current sprint contains JIRA issues that are planned, in progress, or closed in the current sprint work period. The next sprint is used

to stage issues for future development in the next sprint. The `Scrum Board` maintained by the project is called `Axom Development`; it contains the two sprints and the project backlog, which contains issues issues that have been identified but have not been planned for work.

At the end of the current sprint cycle and before starting the next, the team meets to discuss any issues encountered in the current sprint. The goal is to prevent issues that arise during development from being repeated. Then, issues in the next sprint and the backlog are reviewed for working in the next sprint. Any issues in the next sprint that will not be worked on during the next sprint cycle are moved to the backlog. Any issues in the backlog that will be worked in the next sprint are moved to the next sprint. Next, the team decides which issues that were not completed in the current sprint should be moved to the next sprint cycle. Hopefully, there are not many and typically all unresolved issues will propagate to the next sprint. Any unresolved issues that will not be worked on the next sprint are moved to the backlog. While identifying issues for the next sprint, the team should attempt to make sure that each issue is assigned to a developer to work on.

Finally, the Current Sprint is 'Completed' by clicking `Complete Sprint` on the upper right of the sprint. JIRA will ask what to do with unresolved issues and, based on the discussion in the previous paragraph, we move them to the next sprint.

Before starting a new sprint cycle, the sprint boards are renamed by swapping their names; `Current Sprint` becomes `Next Sprint` and `Next Sprint` becomes `Current Sprint` (just like swapping pointers!). Then, the new sprint is started with the `Current Sprint` board. This involves setting the completion date for the sprint and configuring the sprint board so that issues are sorted into horizontal "swimlanes" one for each developer. There are three vertical columns on the sprint board that intersect the swimlanes to indicate issues that: have not been started, are in progress, are done.

Note that as development occurs during a sprint, work will be reviewed and merged from feature branches to the develop branch using pull requests. Reviewing work in smaller increments is much easier than reviewing everything at once.

Note: Developers must close issues in JIRA when they are complete.

Depending on the need to make changes available to users, we will merge the develop branch into the master branch and tag a new release on the master branch. This may happen at the end of a sprint or not. For a description of how the master and develop branches interact, see *Gitflow Branching Model*.

Issue Workflow

We have customized our JIRA issue workflow to make it simple and easy to understand. This section explains key elements of the workflow and how to use it.

Issue states

For the Axom project, each issue has three possible states:

- **Open.** Every issue starts out in an open state. An open issue can be assigned to someone or left unassigned. When an issue is assigned, this means that the assignee owns the issue and is responsible for working on it. An open issue that is left unassigned means that it has not been been discussed or reviewed, or we have not decided how to act on it. In general, an open issue is not being worked on.
- **In Progress.** An issue in progress is one that is actively being worked on.
- **Closed.** When an issue is closed, work on it has been completed, or a decision has been made that it will not be addressed.

An ‘open’ issue can transition to either ‘in progress’ or ‘closed’. An ‘in progress’ issue can transition to either ‘open’ (work on it has stopped, but it is not finished) or ‘closed’. Finally, a ‘closed’ issue can be re-opened, which changes its state to ‘open’. The complete issue workflow is shown in the figure below.

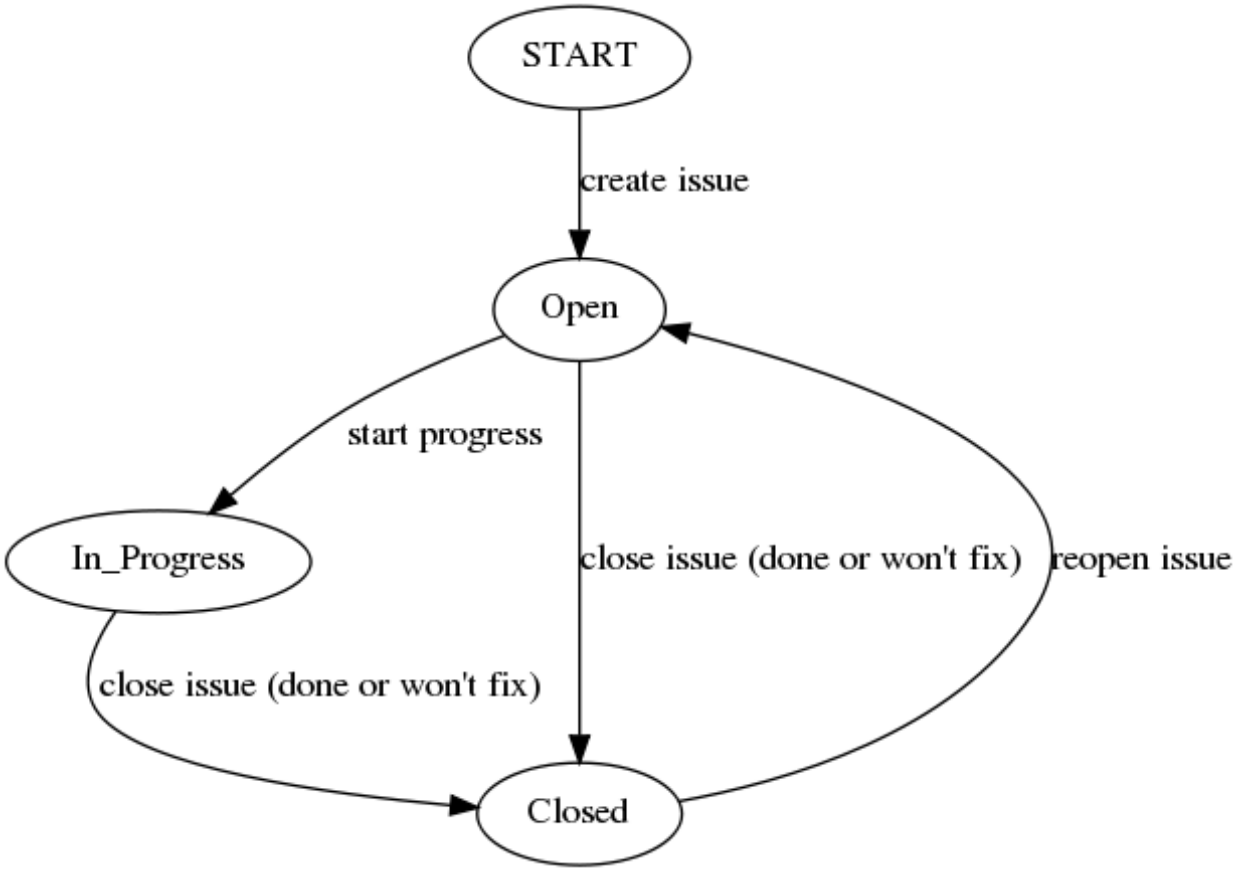


Fig. 3.1: This figure shows allowed state transitions in our JIRA issue workflow.

Creating a new issue

To create a new issue, click the ‘Create’ button at the top of the Axom JIRA project page and enter information in the issue fields. Filling in the fields properly helps team members search through project issues more easily. Note that issue fields marked with a red asterisk are required – they must be set to create a new issue. Other fields are not required, but may be used to include helpful information. The main issue fields we use are:

Project Axom will show up as the default. You shouldn’t need to change this.

Issue Type We use only three issue types: *Bug*, *New Feature*, and *Task*. A bug is something broken that needs to be fixed. A new feature is something that adds functionality, enhances an interface, etc. Task is a “catch-all” issue type for any other issue.

Summary Provide a short descriptive summary. A good (and brief) summary makes it easy to scan a list of issues to find one you are looking for.

Priority Select an appropriate issue priority to identify its level of importance or urgency. Clicking on the question mark to the right of the priority field provides a description of each option.

Components Each issue is labeled with the Axom component it applies to. Component labels also include things like: build system, documentation, testing, etc.

Assignee Unless you are certain which team member should be assigned an issue, leave the issue 'Unassigned', which is the default in our JIRA configuration. This indicates that the issue requires discussion and review before we decide how to treat it.

Reporter Unless you explicitly enter someone in this field, you, as the issue creator, will be the reporter. This is the correct choice in almost all cases.

Description The description field should be used to include important details about the issue that will help the developer who will work on it.

Environment The environment field can be useful when an issue affects a particular compiler or platform.

Epic-link An *epic* is a special issue type in the Agile methodology that is used to define a larger body of work that can be comprised of many issues. **However, that's not what we use epics for. See note below.**

You may also use the other fields that appear if you think they will help describe the issue. However, the team seldom uses fields apart from the list above.

Important: We use epics in JIRA and link our issues to them to get a convenient label on each each issue when we look at a sprint board or the issue backlog. We have an epic for each of our components for this purpose and the epic name matches the corresponding component name.

Starting and stopping work on an issue

When you begin work on an issue, you should note this by changing its state from 'open' to 'in progress'. There are two ways to perform this transition. The first is to open the issue and click the 'Start Progress' button at the top of the issue menu. Alternatively, if the issue is in the 'open' column on a sprint board, you can drag and drop it into the 'in progress' column. Either way changes the issue status to 'in progress'.

If there is still work to do on the issue, but you will stop working on it for a while, you can click the 'Stop Progress' button at the top of the issue. Alternatively, if the issue is in the 'in progress' column on a sprint board, you can drag and drop it into the 'open' column. Either way changes the issue status to *open*.

Closing an issue

When work on an issue is complete (including testing, documentation, etc.), or the issue will not be addressed, it should be closed. To close an issue, click the 'Close' button and select the appropriate issue resolution. There are two options: *Done* and *Won't Fix*. 'Done' means that the issue is resolved. 'Won't Fix' means that the issue will not be addressed for some reason.

When closing an issue, adding information to the 'Comment' field is helpful. For example, when an issue is closed as 'Won't Fix', it is helpful to enter a brief explanation as to why this is so.

Issue assignee

Note that an assigned issue can be assigned to someone else to work on it. An assigned issue can also be set back to 'Unassigned' if it needs further discussion by the team.

JIRA tips

Here are some links to short videos (a couple of minutes each) that demonstrate how to use JIRA features:

- JIRA Instant Search Bar Demo
- JIRA System Files Demo
- Creating and Editing JIRA Issues

3.1.3 Axom Release Process

The Axom team decides as a group when the code is ready for a release. Typically, a release is done when we want to make changes available to users; e.g., when some new functionality is sufficiently complete or we want users to try something out and give us feedback early in the development process. A release may also be done when some other development goal is reached. This section describes how an Axom releases is done. The process is fairly informal. However, we want to ensure that the software is in a reasonably robust and stable state when a release is done. We follow this process to avoid simple oversights and issues that we do not want to pass on to users.

In the *Gitflow Branching Model* section, we noted that the **master branch records the official release history of the project**. Specifically, whenever, the master branch is changed, it is tagged with a new version number. We use a git 'lightweight tag' for this purpose. Such a tag is essentially a pointer to a specific commit on the master branch.

We finalize preparations for a release on a release branch so that other work may continue on the develop branch without interruption.

Note: No significant code development is performed on a release branch. In addition to preparing release notes and other documentation, the only code changes that should be done are bug fixes identified during release preparations

---

Here are the steps to follow for an Axom release.

1: Start Release Candidate Branch

Create a release candidate branch off of the develop branch to initiate a release. The name of a release branch must contain the associated release version number. Typically, we use a name like v0.5.0-rc (i.e., version 0.5.0 release candidate). See *Semantic Versioning* for a description of how version numbers are chosen.

2: Issue a Pull Request

Create a pull request to merge the release candidate branch into master so that release changes can be reviewed. Such changes include:

1. Update the version information (major, minor, and patch version numbers) at the top of the `axom/src/cmake/AxomVersion.cmake` file and in the `axom/RELEASE` file.
2. Update the release notes in `axom/RELEASE-NOTES.md` by adding the release version number and release date in the heading, as well as, the corresponding link to the version on Github.
3. Test the code by running it through all continuous integration tests and builds. This will ensure that all build configurations are working properly and all tests pass.
4. Fix any issues discovered during final release testing if code changes are reasonably small and re-run appropriate tests to ensure issues are resolved. If a major bug is discovered, and it requires significant code modifications to fix, do not fix it on the release branch. Create a new Github issue for it and note it in the `known bugs` section of the release notes.

5. Make sure all documentation (source code, user guides, etc.) is updated and reviewed. This should not be a substantial undertaking as most of this should have been done during the regular development cycle.
6. Proofread the release notes for completeness and clarity and address any shortcomings. Again, this should not take much time as release notes should be updated during the regular development cycle. See *Release Notes* for information about release notes.

3: Merge Release Candidate

Merge the release candidate branch into master branch once it is ready and approved. At this point, the release candidate branch can be deleted.

4: Draft a Github Release

Draft a new Release on Github

1. Enter the desired tag version, e.g., v0.5.0
2. Select **master** as the target branch to tag a release.
3. Enter a Release title. We typically use titles of the following form *Axom-v0.3.1*
4. Copy and paste the information for the release from the `axom/RELEASE-NOTES.md` into the release description (omit any sections if empty).
5. Publish the release. This will create a tag at the tip of the master branch and add corresponding entry in the Releases section

---

Note: Github will add a corresponding tarbal and zip archives consisting of the source files for each release. However, these files do not include any submodules. Consequently, a tarball that includes all of the submodules is generated manually in a seperate step.

5: Make a Release Tarball

- Checkout the master branch locally and run `axom/scripts/make_release_tarball.sh --with-data` This will generate a two tarballs of the form `Axom-v0.3.1.tar.gz` and `AxomData-v0.3.1.tar.gz` each consistsing of the axom source and data respectively.
- Upload the tarballs for the corresponding release, by going to the Github Releases section and `Edit` the release created earlier.
- Attach the tarball to the release.
- Add a note at the top of the release description that indicates which tarball consists of all the submodules, e.g., *"Please download the Axom-v0.3.1.tar.gz tarball below, which includes all of the Axom submodules as well"*
- Update the release.

6: Merge Master to Develop

Create a pull request to merge master into develop. When approved, merge it.

3.1.4 Release Notes

Axom release notes are maintained in a single file `axom/RELEASE-NOTES.md`. The release notes for the latest version are at the top of the file. Notes for previous releases appear after that in descending version number order.

For each version, the release notes must contain the following information:

- Axom version number and date of release
- One or two sentence overview of release, including any major changes.
- Release note items should be broken out into the following sections:
  - Added: Descriptions of new features
  - Removed: Notable removed functionality
  - Deprecated: Deprecated features that will be removed in a future release
  - Changed: Enhancements or other changes to existing functionality
  - Fixed: Major bug fixes
  - Known bugs: Existing issues that are important for users to know about

---

Note: Release notes for each Axom version should explain what changed in that version of the software – and nothing else!!

Release notes are an important way to communicate software changes to users (functionality enhancements, new features, bug fixes, etc.). Arguably, they are the simplest and easiest way to do so. Each change listed in the release notes should contain a clear, concise statement of the change. Items should be ordered based on the impact to users (higher impact - first, lower impact last).

Note: When writing release notes, think about what users need to know and what is of value to them.

Release notes should summarize new developments and provide enough detail for users to get a clear sense of what's new. They should be brief – don't make them overly verbose or detailed. Provide enough description for users to understand a change, but no more than necessary. In other words, release notes summarize major closed issues in a human-readable narrative. Direct users to other documentation (user guides, software documentation, example codes) for details and additional information.

Note: Release notes should be updated as work is completed and reviewed along with other documentation in a pull request. This is much easier than attempting to compile release notes before a release by looking at commit logs, etc. Preparing release notes as part of the release process should take no more than one hour.

Lastly, release notes provide an easy-to-find retrospective record of progress for users and other stakeholders. They are useful for developers and for project reporting and reviews.

3.1.5 Semantic Versioning

The Axom team uses the *semantic* versioning scheme for assigning release numbers. Semantic versioning is a methodology for assigning version numbers to software releases in a way that conveys specific meaning about the code and modifications from version to version. See Semantic Versioning for a more detailed description.

Version Numbers and Meaning

Semantic versioning is based on a three part version number *MM.mm.pp*:

- *MM* is the *major* version number. It is incremented when an incompatible API change is made. That is, the API changes in a way that may break code using an earlier release of the software with a smaller major version number. Following Gitflow (above), the major version number may be changed when the develop branch is merged into the master branch.
- *mm* is the *minor* version number. It changes when functionality is added that is backward-compatible. The API may grow to support new functionality. However, the software will function the same as any earlier release of the software with a smaller minor version number when used through the intersection of two APIs. Following Gitflow (above), the minor version number is always changed when the develop branch is merged into the master branch, except possibly when the major version is changed.
- *pp* is the *patch* version number. It changes when a bug fix is made that is backward compatible. That is, such a bug fix is an internal implementation change that fixes incorrect behavior. Following Gitflow (above), the patch version number is always changed when a hotfix branch is merged into master, or when develop is merged into master and the changes only contain bug fixes.

What Does a Change in Version Number Mean?

A key consideration in meaning for these three version numbers is that the software has a public API. Changes to the API or code functionality are communicated by the way the version number is incremented. Some important conventions followed when using semantic versioning are:

- Once a version of the software is released, the contents of the release *must not* change. If the software is modified, it *must* be released as a new version.
- A major version number of zero (i.e., *0.mm.pp*) is considered initial development where anything may change. The API is not considered stable.
- Version *1.0.0* defines the first stable public API. Version number increments beyond this point depend on how the public API changes.
- When the software is changed so that any API functionality becomes deprecated, the minor version number *must* be incremented.
- A pre-release version may be denoted by appending a hyphen and a series of dot-separated identifiers after the patch version. For example, *1.0.1-alpha*, *1.0.1-alpha.1*, *1.0.2-0.2.5*.
- Versions are compared using precedence that is calculated by separating major, minor, patch, and pre-release identifiers in that order. Major, minor, and patch numbers are compared numerically from left to right. For example, 1.0.0 < 2.0.0 < 2.1.0 < 2.1.1. When major, minor, and patch numbers are equal, a pre-release version has lower precedence. For example, 1.0.0-alpha < 1.0.0.

By following these conventions, it is fairly easy to communicate intent of version changes to users and it should be straightforward for users to manage dependencies on Axom.

3.1.6 Gitflow Branching Model

The Axom team uses the 'Gitflow' branch development model, which is summarized in this section. See the Atlassian Gitflow Description for more details.

Gitflow is a branching model centered around software releases. It is a simple workflow that makes clear which branches correspond to which phases of development and those phases are represented explicitly in the structure of the repository. As in other branching models, developers develop code locally and push their work to a central repository.

Master and Develop Branches

The **master** and **develop** branches are the two main branches used in Gitflow. They always exist and the distinction between them is central to the Gitflow model. Other branches are temporary and used to perform specific development tasks.

The master branch records the official release history of the project. Each time the master branch is changed, it is tagged with a new version number. For a description of our versioning scheme, see *Semantic Versioning*.

The develop branch is used to integrate and test new features and most bug fixes before they are merged into master.

Important: Development never occurs directly on the master or develop branches.

Topic Branches

Topic branches are created off of other branches (usually develop) and are used to develop new features and resolve issues before they propagate to master. Topic branches are temporary, living only as long as they are needed to complete a development task.

Each new feature, or other well-defined portion of work, is developed on its own topic branch, with changes being pushed to the central repository regularly for backup. We typically include a label, such as "feature" or "bugfix", in the topic branch name to make it clear what type of work is being done on the branch. See *Topic Branch Development* for a description of common Git mechanics when doing topic branch development.

When a feature is complete, a pull request is submitted for review by other team members. When all issues arising in a review have been addressed and reviewers have approved the pull request, the feature branch is merged into develop. See *Pull Requests and Code Reviews* for more information about code reviews and pull request approval.

Important: Feature branches never interact directly with the master branch.

Release Branches

Release branches are another important temporary branch type in Gitflow: When the team has decided that enough features, bug fixes, etc. have been merged into develop (for example, all items identified for a release have been completed), a release branch is created off of develop to finalize the release. Creating a release branch starts the next release cycle on develop. At that point, new work can start on feature branches for the next release. Only changes required to complete the release are added to a release branch. When a release branch is ready, it is merged into master and master is tagged with a new version number. Finally, master is merged back into develop since it may have changed since the release was initiated.

The basic mechanics for generating a new release of the master branch for the Axom project are described in *Axom Release Process*.

Important: No new features are added to a release branch. Only bug fixes, documentation, and other release-oriented changes go into a release branch.

Hotfix Branches

The last important temporary branch type in Gitflow is a hotfix branch. Sometimes, there is a need to resolve an issue in a released version on the master branch. When the fix is complete, it is reviewed using a pull request and then

merged into both master and develop when approved. At this point, master is tagged with a new version number. A dedicated line of development for a bug fix, using a hotfix branch, allows the team to quickly address issues without disrupting other parts of the workflow.

Important: Hotfix branches are the only branches created off of master.

Gitflow Illustrated

The figure below shows how branches interact in Gitflow.

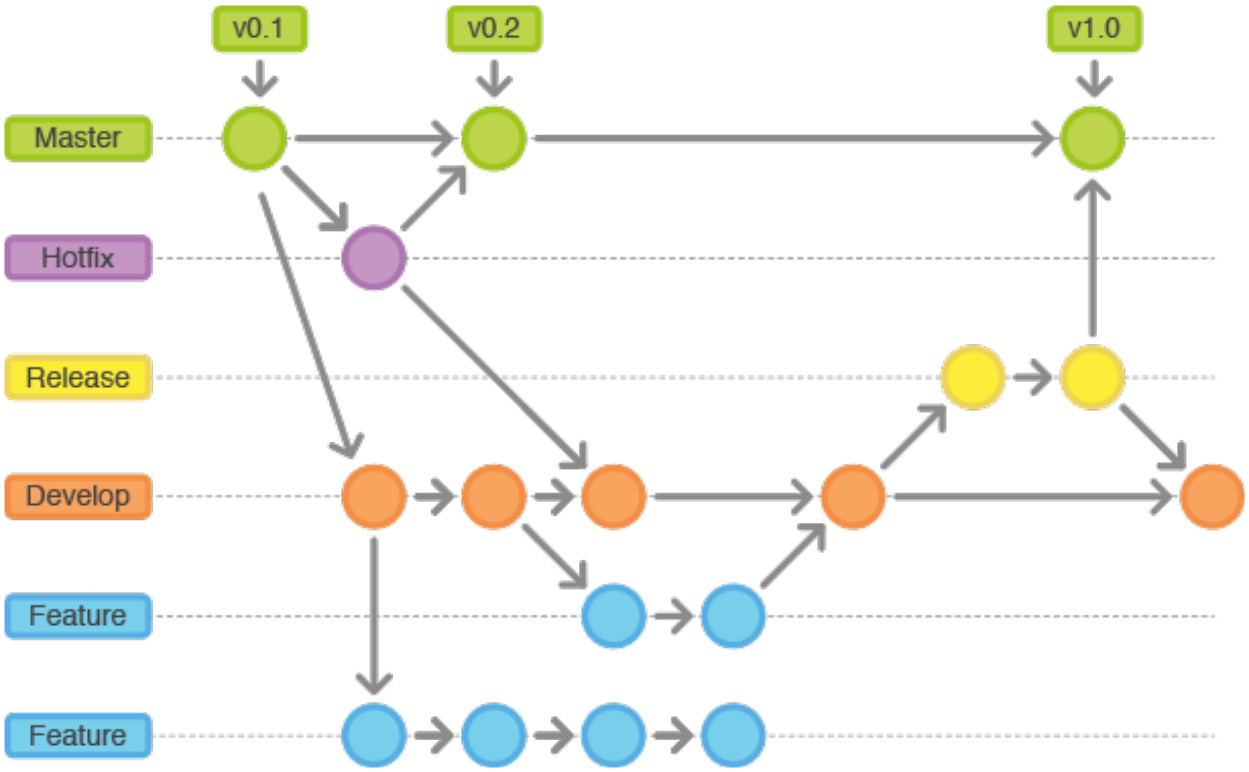


Fig. 3.2: This figure shows typical interactions between branches in the Gitflow workflow. Here, master was merged into develop after tagging version v0.1. A fix was needed and so a hotfix branch was created. When the fix was completed, it was merged into master and develop. Master was tagged with version v0.2. Also, work was performed on two feature branches. When one feature branch was done, it was merged into develop. Then, a release branch was created and it was merged into master when the release was finalized. Finally, master was tagged with version v1.0.

3.1.7 Git/Bitbucket: Version Control and Branch Development

This section provides information about getting started with Git and Bitbucket and describes some mechanics of topic branch development on the Axom project. For most project work, we interact with our Git repository via our Bitbucket project.

If you are new to the Git or want to brush up on its features, there are several good sources of information available on the web:

- Atlassian Git Tutorial has a lot of useful stuff.

- The Git Docs is a complete reference for Git commands and options. It also provides some *cheat sheets* you can download.
- Learn Git Branching is nice for visual, hands-on learners.
- The e-book Pro Git, by Scott Chacon is an excellent overview guide to using Git effectively.

SSH Keys

If you have not used Bitbucket before, you should start by doing two things:

- Create an SSH key
- Add the SSH key to your Bitbucket profile.

Performing these two simple steps will make it easier for you to interact with our Git repository without having to repeatedly enter login credentials.

Cloning the Repo

All development work on Axom is performed in a *local workspace copy* of the Git repository. To make a local workspace copy, you clone the repo into a directory that you will work in. This is done by typing:

```
$ git clone --recursive ssh://git@cz-bitbucket.llnl.gov:7999/atk/axom.git
```

Note: You don't need to remember the URL for the Axom repo above. It can be found by going to the Axom repo on our Bitbucket project and clicking on the 'Clone' action button that appears when you hover your mouse cursor over the ellipses on the top left of the web page.

The '–recursive' argument above is needed to pull in all Git *submodules* that we use in the project. In particular, you will need the BLT build system, which is a Git sub-module in Axom, in your local copy of the repo. In case you forget to pass the '–recursive' argument to the 'git clone' command, you can type the following commands after cloning:

```
$ cd axom
$ git submodule init
$ git submodule update
```

Either way, the end result is the same and you are good to go.

Git Environment Support

After cloning, we recommend that you run the development setup script we provide in the top-level Axom directory to ensure that your Git environment is configured properly; i.e.,:

```
$ cd axom
$ ./scripts/setup-for-development.sh
```

This script sets up several things we find useful, such as Git editor, aliases, client-side hooks, useful tips, etc.

You can also define your own aliases for common git commands to simplify your workflow. For example, the following sets up an alias for unstaging files:

```
$ git config alias.unstage 'reset HEAD--'
```

Then, the alias can be used as a regular Git command as illustrated below:

```
$ git unstage <file>
```

Moreover, you may want to tap in to some of your shell's features to enhance your Git experience. Chief among the most notable and widely used features are:

1. Git Completion, which allows tab-completion of Git commands and branch names.
2. Prompt Customization, which allows modifying your prompt to indicate the current branch name, whether there are local changes, etc.

Git ships with contributed plugins for popular shells. Examples illustrating how to use these plugins in bash and tcsh/csh are given below.

Setting up your Bash Environment

If you are in Bash, you can set your environment as follows:

1. Get the git-prompt.sh and auto-completion scripts from github

```
$ wget https://raw.githubusercontent.com/git/git/master/contrib/completion/git-
↪prompt.sh
$ wget https://raw.githubusercontent.com/git/git/master/contrib/completion/git-
↪completion.bash
```

2. Optionally, you may want to move the files to another location. Nominaly, folks put those as hidden files in their home directory

```
$ mv git-prompt.sh $HOME/.git-prompt.sh
$ mv git-completion.bash $HOME/.git-completion.bash
```

3. Add the following to your *.bashrc*

```
source ~/.git-prompt.sh
source ~/.git-completion.bash
export GIT_PS1_SHOWDIRTYSTATE=1
export GIT_PS1_SHOWSTASHSTATE=1
export GIT_PS1_SHOWUNTRACKEDFILES=1

## Set your PS1 variable
reset=$(tput sgr0)
bold=$(tput bold)
export PS1='[\w] \[$bold\]$(__git_ps1 " (%s)")\[$reset\]\n\[$bold\]\u@\h\[
↪$reset\] > '
```

Setting up your tcsh/csh Environment

Likewise, if you are using tcsh/csh, you can do the following:

1. Get the auto-completion scripts from github. Note, git-completion.tcsh makes calls to git-completion.bash, so you need to have both

```
$ wget https://raw.githubusercontent.com/git/git/master/contrib/completion/git-
↪completion.tcsh
$ wget https://raw.githubusercontent.com/git/git/master/contrib/completion/git-
↪completion.bash
```

2. Optionally, you may want to move the files to another location. Nominally, folks put those as hidden files in their home directory

```
$ mv git-completion.tcsh $HOME/.git-completion.tcsh
$ mv git-completion.bash $HOME/.git-completion.bash
```

3. Add the following to your *.tcshrc* or *.cshrc*

```
source ~/.git-completion.tcsh

## Add alias to get the branch
alias __git_current_branch 'git rev-parse --abbrev-ref HEAD >& /dev/null && echo "
↪{`git rev-parse --abbrev-ref HEAD`}"'

## Set your prompt variable for example:
alias precmd 'set prompt="%n@%m[%c2]`__git_current_branch` "'
```

Topic Branch Development

It is worth re-emphasizing a fundamental principle of the Gitflow development model that we described in *Gitflow Branching Model*.

Important: We never work directly on the develop or master branches. All development occurs on topic branches.

When we refer to a *topic branch*, it could be a *feature branch*, a *bugfix branch*, etc. The basic workflow for performing development on a topic branch is:

1. Create a topic branch off the develop branch and push the new branch to Bitbucket.
2. Make changes and commit them to your branch in your local copy of the repository. Remember to push changes to the main repo on Bitbucket regularly for backup and so you can easily recover earlier versions of your work if you need to do so.
3. If you are working on your topic branch for a while, it is a good idea to keep your topic branch current with the develop branch by merging develop into your topic branch regularly. This will simplify the process of merging your work into the develop branch when you are ready.
4. When your work is complete (including required testing, documentation, etc.), create a pull request so others on the team can review your work. See *Pull Requests and Code Reviews*.

Here are some details about each of these steps.

Step 1 – Create a topic branch

Most development occurs on a topic branch created off the develop branch. Occasions where a branch is created from another branch, such as a 'hotfix' branch created off master, are described in *Gitflow Branching Model*. To create a branch in Git, provide the `-b` option to the `git checkout` command, followed by the name of your topic branch. A topic branch name should include your username (i.e., login id) and a brief description indicating the purpose of the branch. Typically, we label such branches using "feature", "bugfix", etc. to make it clear what type of work is being performed on a branch. For example,:

```
$ git checkout -b feature/<userid>/my-cool-new-feature
$ git push -u
```

You can also attach a JIRA issue number to the branch name if the work you will do on the branch is related to a JIRA issue. Then, Bitbucket will associate the issue with the commit when you merge your branch to the develop branch. For example,:

```
$ git checkout -b bugfix/<userid>/jira-atk-<issue #>
$ git push -u
```

Alternatively, if your branch addresses multiple JIRA issues, you should add the appropriate JIRA issue numbers (e.g., ATK-374) to the messages in your commits that address them.

In each of these examples, the 'git push -u' command pushes the branch to the Bitbucket server and it will appear in the list of branches you and other developers can see there.

Step 2 – Do development work

After you've created a topic branch and pushed it to Bitbucket, perform your development work on it; i.e., edit files, add files, etc. Common commands you will use are:

```
$ git add <file>
$ git commit
$ git push
```

The 'add' command adds a file (or files) to be staged for a commit operation. The 'commit' command moves your staged changes to your local copy of the repository. The 'push' command pushes these changes to the topic branch in the main Git repo. To push your work, you could also do:

```
$ git push origin
```

This is equivalent to 'git push' if you specified the '-u' option when you originally pushed your topic branch when you created it.

Important: You may perform several local commits before you push your work to the main repo. Generally, it is a good idea to limit the amount of modifications contained in any one commit. By restricting individual commits to a reasonable size that contain closely related work, it is easier to refer back to specific changes you make when the need arises (as it inevitably will!). For example, if you regularly run your code through a formatting tool (we use *uncrustify* on the Axom project), it is preferable to commit other content changes first and then commit formatting changes in a separate commit. That way, you can distinguish substance from cosmetic changes easily in the Git history.

Recall the Git environment setup script we recommended that you run after cloning the repo in the *Cloning the Repo* section above. One of the Git pre-commit hooks that the script sets up applies formatting constraints on the commit message you provide when you execute the 'commit' command. The constraints are recommended Git practices that help make it easier to use various tools with the Git version control system. Specifically:

- Commit message subject line is at most 50 characters
- Subject line and main body of commit message are separated by a blank line
- Main body of commit message is wrapped to 78 characters

Step 3 – Keep current with develop

If you will be working on your topic branch for a while, it is a good idea to merge changes (made by other developers) from the develop branch to your topic branch regularly. This will help avoid getting too far out of sync with the branch into which your work will be merged eventually. Otherwise, you may have many conflicts to resolve when you are ready to merge your topic branch into develop and the merge could be difficult.

Before you begin the merge, make sure all outstanding changes to your topic branch are committed. Then, make sure your local repo is up-to-date with the main develop branch by checking it out and pulling in the latest changes; i.e.,:

```
$ git checkout develop
$ git pull
```

Next, checkout your topic branch and merge changes in from the develop branch, and check for conflicts:

```
$ git checkout <your topic branch>
$ git merge develop
```

The 'merge' command will tell you whether there are conflicts and which files have them. Hopefully, you will not see any conflicts and you can continue working on your topic branch. If there are conflicts, you must resolve them before you will be able to merge your topic branch to develop. So, you may as well resolve them right away. You can resolve them by editing the conflicting files and committing the changes. Merge conflicts appear in a file surrounded by lines with special characters on them. For example, if you open a conflicted file in an editor, you may see:

```
<<<<<<< HEAD
// lines of code, etc...
=======
// more lines of code, etc...
>>>>>>> develop
```

The section above the '=======' line are the file contents in the current branch head (your topic branch). The lines below are the contents of the develop branch that conflict with yours. To resolve the conflict, choose the correct version of contents you want and delete the other lines.

Alternatively, you can use a tool to help resolve your conflicts. The 'git mergetool' command helps you run a merge tool. One such tool is called "meld", which is very powerful and intuitive. Diff tools like "tkdiff" are also helpful for resolving merge conflicts.

Important: Git will not let you commit a file with merge conflicts. After you resolve merge conflicts in a file, you must stage the file for commit (i.e., *git add <filename>), commit it (i.e., 'git commit*), and push it to the main repo (i.e., *git push*) before you can merge.

Step 4 – Create a pull request

When your work is complete, and you are ready to merge your topic branch to the develop branch, you must initiate a pull request in Bitbucket. Go into the Axom Bitbucket project, select your branch, and click *Create pull request* in the left column. Make sure you select the correct destination branch. The default destination branch in our project is set up to be the develop branch. So, in most cases, you won't have to do anything special.

You must also select appropriate team members to review changes. Our Bitbucket project is set up to require at least one other developer to approve the pull request before a merge.

Important: You cannot approve your own pull request.

When your pull request is approved (see *Code Review Checklist* for more information), you merge your topic branch to the develop branch by clicking the "merge" button in Bitbucket. If there are no merge conflicts, the merge will proceed and you are done. If there are conflicts, Bitbucket will indicate this and will not let you merge until all conflicts are resolved.

Important: You must run the CZ Bamboo plan 'Build and Test Branch' and verify all tests pass before you merge. See *Continuous Integration* for more information.

The preferred way to resolve conflicts at this point is to go into your topic branch and do the following:

```
$ git fetch origin
$ git merge origin
```

The 'fetch' command pulls changes from the remote branch into your local branch. Running the 'merge' command will show which files have conflicts. Fix the conflicts as described in *Step 3 – Keep current with develop*. After all conflicts are resolved, run the 'commit' and 'push' commands as usual:

```
$ git commit
$ git push
```

Lastly, complete the merge in Bitbucket by clicking the merge button.

Important: To keep things tidy, please delete your topic branch in Bitbucket after it is merged if you no longer need it for further development. Bitbucket provides an option to automatically delete the source branch of a merge after the merge is complete. Alternatively, you can click on the Bitbucket branches tab and manually delete the branch.

Checking Out an Existing Branch

When working on multiple branches, or working on one with someone else on the team, you will need to checkout a specific branch. Any existing branch can be checked out from the Git repository. Here are some useful commands:

```
$ git fetch
$ git branch -a
$ git checkout <branch name>
```

The 'fetch' command retrieves new work committed by others on branches you may have checked out, but *without merging* those changes into your local copies of those branches. You will need to merge branches if you want changes from one branch to be moved into another. The 'branch' command lists all available remote branches. The 'checkout' command checks out the specified branch into your local working space.

Note: You do not give the '-b' option when checking out an existing branch. This option is only used when creating a new branch.

Here is a concrete example:

```
$ git branch -a | grep homer
  remotes/origin/feature/homer/pick-up-bart
$ git checkout feature/homer/pick-up-bart
  Branch feature/homer/pick-up-bart set up to track remote branch feature/homer/pick-
↪up-bart
  Switched to a new branch 'feature/homer/pick-up-bart'
```

3.1.8 Pull Requests and Code Reviews

Before any code is merged into the develop or master branches, it must be tested, documented, reviewed, and accepted. Creating a pull request on the Axom Bitbucket project to merge a branch into develop or master initiates the test and review processes. All required build configurations and tests must pass for a pull request to be approved. Also, new tests (unit, integration, etc.) must be created that exercise any new functionality that is introduced. This will be assessed by reviewers of each pull request. See *Step 4 – Create a pull request* for details about creating pull requests.

Code changes in a pull request must be accepted by at least one member of the Axom development team other than the originator of the pull request. It is recommended that several team members review pull requests, especially when changes affect APIs, dependencies (within Axom and external), etc. Pull request reviewers can be selected on Bitbucket when the pull request is created. Changes reviewed by the team are accepted, rejected, or commented on for improvement; e.g., issues to be addressed, suggested changes, etc. Pull requests can be updated with additional changes and commits as needed. When a pull request is approved, it can be merged. If the merged branch is no longer needed for development, it should be deleted.

In addition to successful compilation and test passing, changes to the develop and master branches should be scrutinized in other ways and using other code health tools we use. See *Continuous Integration* for more information about using our continuous integration tools.

Pull Request Summary

To recap, here is a summary of steps in a pull request:

1. When code is ready to be considered for acceptance, create a pull request on the Axom Bitbucket project. Identify the appropriate reviewers and add them to the pull request.
2. Code must build successfully and all relevant tests must pass, including new tests required for new functionality.
3. All issues (build failures, test failures, reviewer requests) must be addressed before a pull request is accepted.
4. Pull requests must be approved by at least one member of development team other than the pull request originator.
5. When a pull request is approved it may be merged. If the merged branch is no longer needed, it should be deleted. This can be done when merging with Bitbucket.

Code Review Checklist

Beyond build and test correctness, we also want to ensure that code follows common conventions before acceptance. The following list is a high-level summary of the types of concerns we want to identify during pull request reviews and resolve before a pull request is merged. Please see the Axom Coding Guide for details on items in this list.

1. A new file or directory must be placed in its proper location; e.g., in the same directory with existing files supporting related functionality.
2. File contents must be organized clearly and structure must be consistent with conventions.
3. Namespace and other scoping conventions must be followed.

4. Names (files, types, methods, variables, etc.) must be clear, easily understood by others, and consistent with usage in other parts of the code. Terminology must be constrained; i.e., don't introduce a new term for something that already exists and don't use the same term for different concepts.
5. Documentation must be clear and follow conventions. Minimal, but adequate, documentation is preferred.
6. Implementations must be correct, robust, portable, and understandable to other developers.
7. Adequate tests (unit and performance) tests must be added for new functionality.

3.1.9 Axom Component Structure

This section describes the structure of directories, files, and their contents for an Axom component. This section should be used as a guide to identify tasks to be done when adding a new software component to Axom. These include:

- Creating the appropriate directory structure
- Modifying and adding CMake files and variables
- Generating C and Fortran interfaces
- Writing documentation
- Writing tests

Note: The discussion here does not contain coding guidelines. Please see Axom Coding Guide for that information.

Component Directory Structure

In the *axom/src/components* directory, you will find a subdirectory for each Axom component. For example:

```
$ cd axom/src/components
$ ls -1
CMakeLists.txt
axom_utils
lumberjack
mint
...
```

All files for each component are contained in subdirectories in the component directory.

To illustrate, consider the *sidre* component directory:

```
$ cd axom/src/components/sidre
$ ls -1 -F
CMakeLists.txt
README.md
docs/
examples/
src/
tests/
uncrustify.cfg
```

Note that, besides directories, the top-level component directory contains a few files:

- **CMakeLists.txt** contains CMake information for the component in the Axom build system.

- **README.md** is the markdown overview file for the component. Its contents appear in the Axom Bitbucket project when you navigate through the source tree.

The **docs** directory contains the component documentation. Subdirectories in the docs directory are named for each type of documentation. The directories *doxygen* and *sphinx* are required. Each Axom component uses *Doxygen* for source code documentation and *Sphinx* for user documentation. Other documentation directories can be used as needed. For example, *sidre* also contains documentation directories *dot* for dot-generated figures, and *design* for design documents.

The **src** directory contains all header and source files for the component. These files, which are typically C++, can be organized in subdirectories within the *src* directory in whatever manner makes sense. For example, in *sidre*, these core header and source files are in a subdirectory called *core*. As is common practice for C++ libraries, associated header and source files are co-located in the same directories.

The **interface** directory contains interface files for use by languages other than C++. To make it easy for applications written in C and Fortran, for example, to use Axom directly in their native languages, Axom components provide APIs in these languages. For information about how we generate these APIs, see *C and Fortran Interfaces*.

A **test** directory is required for each component which contains a comprehensive set of unit tests. See *Axom Tests and Examples* for information about writing tests and inserting them into our testing framework.

An **examples** directory is optional, but recommended. It contains simple code examples illustrating component usage.

Important: For consistency, these subdirectory names within the top-level component directory should be the same for each Axom components.

CMake Files and Variables

To properly configure and compile code for a component, and generate consistent make targets, existing CMake files and variables need to be modified in addition to adding CMake files for the new component. In this section, we describe the sort of changes and additions that are required. For additional details about our CMake and BLT usage, please look in files in existing Axom components.

Add CMake macro definitions

The top-level CMake directory *axom/src/cmake* contains a file called *AxomConfig.cmake* that defines macro constants for enabling Axom components and setting third-party library (TPL) dependencies that are used to enforce consistency for conditionally-compiled code. When a new component or dependency is added, that file must be modified by:

1. Adding the name of the component to the *COMPS* variable
2. Adding new TPL dependency to the *TPL_DEPS* variable

The CMake variables are used to generate macro constants in the Axom configuration header file. For each new CMake variable added, an associated *#cmakedefine* definition must be added to the *config.hpp.in* file in the *axom/src/include* directory.

Modify top-level CMakeLists.txt file

When adding a new Axom component, the file *axom/src/components/CMakeLists.txt* must be modified to hook the component into the CMake build configuration system. Specifically:

1. Add option to enable component. For example,:

```
axom_add_component(COMPONENT_NAME sidre DEFAULT_STATE ${AXOM_ENABLE_ALL_
↪COMPONENTS})
```

2. Add component dependency target by adding component name to the *axom_components* variable.

Add component CMakeLists.txt files

There are several *CMakeLists.txt* files that must be added in various component directories. We try to maintain consistent organization and usage across all Axom components to avoid confusion. To illustrate, we describe the key contents of the CMakeLists.txt files in the *sidre* Axom component. See those files or those in other components for more details.

Top-level component directory

The top-level component directory contains a *CMakeLists.txt*, e.g., *axom/src/components/sidre/CmakeLists.txt*, which contains the following items:

1. Checks for necessary dependencies with useful error or warning messages; e.g.,:

```
if(NOT HDF5_FOUND)
  message(FATAL_ERROR "Sidre requires HDF5. Set HDF5_DIR to HDF5 installation.")
endif()
```

2. Subdirectories additions with guards as needed; e.g.,:

```
add_subdirectory(src)
```

and:

```
if (AXOM_ENABLE_TESTS)
  add_subdirectory(tests)
endif()
```

3. CMake exports of component targets; e.g.,:

```
install(EXPORT <component name>-targets DESTINATION lib/cmake)
```

4. Code formatting and static analysis targets; e.g.,:

```
axom_add_code_checks(BASE_NAME <component name>)
```

Note: Each Axom component should use the common uncrustify configuration file defined for the project at src/uncrustify.cfg. The file is used to define source code formatting options that are applied when the *uncrustify* tool is run on the code.

Component src directory

The *CMakeLists.txt* file in the component *src* directory defines:

1. A variable for component header files named <*component name*>*_headers*
2. A variable for component source files named <*component name*>*_sources*

3. A variable for component dependencies named <*component name*>*_depends*

For example, these variables for the *sidre* component are *sidre_headers*, *sidre_sources*, and *sidre_depends*.

Note: It is important to account for all conditional inclusion of items in these CMake variable names. For example, a C interface is generated to support a Fortran API, typically. So if Fortran is not enabled, it is usually not necessary to include the C header files in *sidre_headers*. Similarly, do not include items in the dependency variable if they are not found.

This file also adds source subdirectories as needed (using the CMake *add_subdirectory* command), adds the component as a Axom library, and adds target definitions for dependencies. For example, the command to add *sidre* as a library is:

```
blt_add_library( NAME
                     sidre
                 SOURCES
                     "${sidre_sources}"
                     "${sidre_fortran_sources}"
                 HEADERS
                     "${sidre_headers}"
                 HEADERS_OUTPUT_SUBDIR
                     sidre
                 DEPENDS_ON
                     ${sidre_depends}
                 )
```

All components should follow this format to describe the library information.

Component docs directory

A component *docs* directory contains a *CMakeLists.txt* file that uses the CMake *add_subdirectory* command to add *sphinx* and *doxygen* subdirectories to the build configuration. These should be guarded to prevent addition if either *Sphinx* or *Doxygen* are not found.

CMakeLists.txt files in the *sphinx* and *doxygen* subdirectories add targets and dependencies for each type of documentation build. For example, the *sidre* component generates *sidre_docs* and *sidre_doxygen* targets for these document types.

Component tests and examples

The content of component *tests* and *examples* directories, including as CMake files are discussed in *Axom Tests and Examples*.

Filename and CMake Target Conventions for Axom Documentation

The conventions in this section are intended to make it easy to generate a specific piece of documentation for a an Axom component manually. In Axom, we use 'make' targets to build documentation. Typing *make help* will list all available targets. When the following conventions are followed, all documentation targets for a component will be grouped together in this listing. Also, it should be clear from each target name what the target is for.

CMake targets for component user guides and source code docs (i.e., Doxygen) are:

```
<component name>_user_docs
```

and

```
<component name>_doxygen_docs
```

respectively. For example:

```
sidre_user_docs     (sidre component user guide)
sidre_doxygen_docs  (sidre Doxygen source code docs)
```

C and Fortran Interfaces

Typically, we use the Shroud tool to generate C and Fortran APIs from our C++ interface code. Shroud is a python script that generate code from a *yaml* file that describes C++ types and their interfaces. It was developed for the Axom project and has since been generalized and is supported as a standalone project. ***Add link to Shroud project**** To illustrate what is needed to generate multi-language API code via a make target in the Axom build system, we describe the contents of the *sidre* Axom component interface directory *axom/src/components/sidre/src/interface* that must be added:

1. A *yaml* file, named *sidre_shroud.yaml*, which contains an annotated description of C++ types and their interfaces in *sidre* C++ files. This file and its contents are generated manually.
2. Header files, such as *sidre.h*, that can be included in C files. Such a file includes files containing Shroud-generated 'extern C' prototypes.
3. Directories to hold the generated files for different languages; e.g., *c_fortran* for C and Fortran APIs, *python* for python API, etc.
4. 'Splicer' files containing code snippets that get inserted in the generated files.
5. A *CMakeLists.txt* files that contains information for generating CMake targets for Shroud to generate the desired interface code. For example:

   ```
   add_shroud( YAML_INPUT_FILE sidre_shroud.yaml
        YAML_OUTPUT_DIR yaml
        C_FORTRAN_OUTPUT_DIR c_fortran
        PYTHON_OUTPUT_DIR python
        DEPENDS_SOURCE
            c_fortran/csidresplicer.c c_fortran/fsidresplicer.f
            python/pysidresplicer.c
        DEPENDS_BINARY genfsidresplicer.f
   )
   ```

   This tells shroud which *yaml* file to generate code files from, which directories to put generated files in, which splicer files to use, etc.

The end result of properly setting up these pieces is a make target called *generate_sidre_shroud* that can be invoked to generate *sidre* API code in other languages Axom supports.

Documentation

Complete documentation for an Axom component consists of several parts described in the following sections. All user documentation is accessible on the Axom LC web space.

README File

Each Axom component should have a basic *README.md* markdown file in its top-level directory that briefly describes the role and capabilities of the component. The contents of this file will appear when the component source code is viewed on the Axom Bitbucket project.

User Documentation

Each Axom component uses *Sphinx* for user documentation. This documentation is generated by invoking appropriate make targets in our build system. For example, *make sidre_docs* builds *html files* from *Sphinx* user documentation for the *sidre* component.

The main goal of good user documentation is to introduce the software to users so that they can quickly understand what it does and how to use it. A user guide for an Axom component should enable a new user to get a reasonable sense of the capabilities the component provides and what the API looks like in under 30 minutes. Beyond introductory material, the user guide should also help users understand all major features and ways the software may be used. Here is a list of tips to help you write good documentation:

1. Try to limit documentation length and complexity. Using figures, diagrams, tables, bulleted lists, etc. can help impart useful information more quickly than text alone.
2. Use examples. Good examples can help users grasp concepts quickly and learn to tackle problems easily.
3. Place yourself in the shoes of targeted users. Detailed instructions may be best for some users, but may be onerous for others who can quickly figure things out on their own. Consider providing step-by-step instructions for completeness in an appendix, separate chapter, via hyperlink, etc. to avoid clutter in sections where you are trying to get the main ideas across.
4. Try to anticipate user difficulties. When possible, describe workarounds, caveats, and places where software is immature to help users set expectations and assumptions about the quality and state of your software.
5. *Test* your documentation. Follow your own instructions completely. If something is unclear or missing, fix your documentation. Working with a co-worker who is new to your work, or less informed about it, is also a good way to get feedback and improve your documentation.
6. Make documentation interesting to read. While you are not writing a scintillating novel, you want to engage users with your documentation enough so that they don't fall asleep reading it.
7. Quickly incorporate feedback. When a user provides some useful feedback on your documentation, it shows they care enough to help you improve it to benefit others. Incorporate their suggestions in a timely fashion and ask them if you've addressed their concerns. Hopefully, this will encourage them to continue to help.

Speaking of good user documentation, the reStructuredText Primer provides enough information to quickly learn enough to start using the markdown language for generating sphinx documentation.

Code Documentation

Each Axom component uses *Doxygen* for code documentation. This documentation is generated by invoking appropriate make targets in our build system. For example, *make sidre_doxygen* builds *html* files from *Doxygen* code documentation for the *sidre* component.

The main goal of code documentation is to provide an easily navigable reference document of your software interfaces and implementations for users who need to understand details of your code.

We have a useful discussion of our Doxygen usage conventions in the Documentation Section of the Axom Coding Guide. The Doxygen Manual contains a lot more details.

Fill in more details when we have a better handle on how we want to organize our doxygen stuff...

3.1.10 Axom Tests and Examples

This section describes how to build and organize tests and examples for Axom components. These live in *tests* and *examples* directories within each component top-level directory.

Comprehensive collections of well-designed unit tests and integration tests are important tools for developing quality software. Good tests help to ensure that software operates as expected as it is being developed and as it is used in different ways. To maintain a high level of usefulness, tests must be maintained and developed along with the rest of project software. Tests should be expanded and modified as software evolves so that they can always be used to verify that software functionality is correct.

Unit tests are most effective for designing and modifying **individual** software units to make sure they continue work properly. Integration tests help to make sure that various sets of software units work together. Typically, integration testing is more complex and subtle than the sum of the independent unit tests of the parts that comprise the integrated system. Proving that component X and component Y each work independently doesn't prove that X and Y are compatible or that they will work together. Also, defects in individual components may bear no relationship to issues an end user would see.

When developing software, it is important to keep these thoughts in mind and to use tests effectively to meet your goals. Exposing issues when designing and refactoring individual software components may be best accomplished with unit tests, often run manually as you are adding or modifying code. Detecting broken regressions (e.g., "this used to work, but something changed and now it doesn't") may be best done by frequently running automated integration tests.

This section describes how to write and manually run tests in Axom. In *Continuous Integration*, we describe our automated testing process using the Atlassian Bamboo tool.

A Few Guidelines for Writing Tests

Before we describe the mechanics of writing tests in the Axom framework, we describe some test guidelines. The aim of these guidelines is to help ensure that tests are complete, correct, easy to run, and easy to modify as needed when software changes.

- Decompose tests so that each test is independent of the others. For example, a unit test file should test features of a single class and not contain tests of other classes.
- Each specific behavior should be specified in one and only one test. For example, all unit tests for a container class may live in a single test file, but you should verify each container operation (e.g., container creation/destruction, item insertion, item removal, container traversal, etc.) in exactly one test. In particular, if a test covers some behavior, checking that same behavior in another test is unnecessary.
- Limit each test to as few logical assertions as possible. Ideally, each behavior should require one logical assertion. However, sometimes it makes sense to have more than one check. For example, a test for an empty container may assert that its 'empty' method returns *true* and also assert that its 'size' method returns *zero*.
- Tests should be independent on the order in which they are run.
- Tests should be independent of the platform (hardware architecture, compiler, etc.) on which they are run.
- Tests should be named clearly and consistently. See *Filename and CMake Target Conventions for Axom Tests and Examples* for a description of Axom conventions for test names.

Unit Tests

In Axom, we use the Google Test framework for C and C++ unit tests and we use the Fortran Unit Test Framework (FRUIT) for Fortran unit tests.

Organization of tests in either language/framework are similar should follow the principles summarized in the guidelines above. Each Google Test or FRUIT file is compiled into its own executable that can be run directly or as a 'make' target. Each executable may contain multiple tests. So that running individual tests as needed is not overly burdensome, such as unit tests for a C++ class, we put all tests for distinct software units in files separate from those for other units. Tests within each file should be sized so that too many different behaviors are not executed or verified in a single test.

See *Filename and CMake Target Conventions for Axom Tests and Examples* for test file naming and make target conventions.

Google Test (C++/C Tests)

The contents of a typical Google Test file look like this:

```
#include "gtest/gtest.h"

#include ...    // include Axom headers needed to compiler tests in file

// ...

TEST(<test_case_name>, <test_name_1>)
{
   // Test 1 code here...
   // EXPECT_EQ(...);
}

TEST(<test_case_name>, <test_name_2>)
{
   // Test 2 code here...
   // EXPECT_TRUE(...);
}

// Etc.
```

Each unit test is defined by the Google Test *TEST()* macro which accepts a *test case name* identifier, such as the name of the C++ class being tested, and a *test name*, which indicates the functionality being verified by the test. For each test, logical assertions are defined using Google Test *assertion macros*. Failure of expected values will cause the test to fail, but other tests will continue to run.

Note that the Google Test framework will generate a 'main()' routine for each test file if it is not explicitly provided. However, sometimes it is necessary to provide a 'main()' routine that contains operation to run before or after the unit tests in a file; e.g., initialization code or pre-/post-processing operations. A 'main()' routine provided in a test file should be placed at the end of the file in which it resides.

Here is an example 'main()' from an Axom test that sets up a slic logger object to be used in tests:

```
int main(int argc, char * argv[])
{
  int result = 0;

  ::testing::InitGoogleTest(&argc, argv);

  UnitTestLogger logger;  // create & initialize test logger,
                          // finalized when exiting main scope

  ::testing::FLAGS_gtest_death_test_style = "threadsafe";
  result = RUN_ALL_TESTS();
```

(continues on next page)

(continued from previous page)

```
  return result;
}
```

Note that Google Test is initialized first, followed by initialization of the slic UnitTestLogger object. The *RUN_ALL_TESTS()* Google Test macro will run all the tests in the file.

As another example, consider a set of tests that use MPI. The 'main()' routine will initialize and finalize MPI before and after tests are run, respectively:

```
int main(int argc, char * argv[])
{
  int result = 0;

  ::testing::InitGoogleTest(&argc, argv);

  UnitTestLogger logger;  // create & initialize test logger,
                          // finalized when exiting main scope

  MPI_Init(&argc, &argv);

  result = RUN_ALL_TESTS();

  MPI_Finalize();

  return result;
}
```

Note that Google test is initialized before 'MPI_Init()' is called.

Other Google Test features, such as *fixtures*, may be used as well.

See the Google Test Primer for discussion of Google Test concepts, how to use them, and a listing of available assertion macros, etc.

FRUIT (Fortran Tests)

Fortran unit tests using the FRUIT framework are similar in structure to the Google Test tests for C and C++ described above.

The contents of a typical FRUIT test file look like this:

```
module <test_case_name>
  use iso_c_binding
  use fruit
  use <axom_module_name>
  implicit none

contains

subroutine test_name_1
!  Test 1 code here...
!  call assert_equals(...)
end subroutine test_name_1

subroutine test_name_2
```

(continues on next page)

(continued from previous page)

```
!  Test 2 code here...
!  call assert_true(...)
end subroutine test_name_2

! Etc.
```

The tests in a FRUIT test file are placed in a Fortran *module* named for the *test case name*, such as the name of the C++ class whose Fortran interface is being tested. Each unit test is in its own Fortran subroutine named for the *test name*, which indicates the functionality being verified by the unit test. Within each unit test, logical assertions are defined using FRUIT methods. Failure of expected values will cause the test to fail, but other tests will continue to run.

Note that each FRUIT test file defines an executable Fortran program. The program is defined at the end of the test file and is organized as follows:

```
program fortran_test
  use fruit
  use <axom_component_unit_name>
  implicit none
  logical ok

  ! initialize fruit
  call init_fruit

  ! run tests
  call test_name_1
  call test_name_2

  ! compile summary and finalize fruit
  call fruit_summary
  call fruit_finalize

  call is_all_successful(ok)
  if (.not. ok) then
    call exit(1)
  endif
end program fortran_test
```

Please refer to the FRUIT documentation for more information.

Integration Tests

Important: Fill this in when we know what we want to do for this...

CMake Files and Variables for Tests

The *CMakeLists.txt* file in component test directory defines the following items:

1. Variables for test source files as needed. Separate variables should be used for Fortran, C++, etc. For example, *gtest_sidre_tests* for C++ tests, *gtest_sidre_C_tests* for C tests, and *fruit_sidre_tests* for Fortran tests. Note that we use the *Google Test* framework for C and C++ tests and *Fruit* for Fortran tests.
2. An executable and test variable for each test executable to be generated. These variables use the *blt_add_executable* and *blt_add_test* macros, respectively, as described above.

Note: Fortran executables and tests should be guarded to prevent generation when Fortran is not enabled.

See *Axom Tests and Examples* for details about writing tests in Axom.

Examples

Examples for Axom components serve to illustrate more realistic usage of those components. They can also be run as tests if that's appropriate.

The source code for each component test should be contained in the component *examples* directory if it is contained in one file. If it contains multiple files, these should be placed in a descriptively-named subdirectory of the *examples* directory.

In addition, each example should be given its own CMake-generated make target.

CMake Files and Variables for Examples

The *CMakeLists.txt* file in each component's 'examples' directory defines the following items:

1. Variables for example source files and header files as needed Separate variables should be used for Fortran, C++, etc. For example, *example_sources* for C++, *F_example_sources* for Fortran.
2. An executable and test variable for each example executable to be generated and each executable to be run as a test. These definitions use the *blt_add_executable* and *blt_add_test* macros, respectively. For example:

```
blt_add_executable(NAME  <example executable name>
                   SOURCES <example source>
                   OUTPUT_DIR ${EXAMPLE_OUTPUT_DIRECTORY}
                   DEPENDS_ON <example dependencies>)
```

and:

```
blt_add_test(NAME <example executable name>
             COMMAND <example executable name>)
```

Fortran executables and tests should be guarded to prevent generation if Fortran is not enabled.

Filename and CMake Target Conventions for Axom Tests and Examples

The conventions in this section are intended to make it easy to tell what is in a given component test or example file and to make it easy to run desired test or example. In Axom, we use 'make' targets to build and run tests and examples. Typing *make help* will list all available targets. When the following conventions are followed, all test and example targets for a component will be grouped together in this listing. Also, it will be clear from each target name what the target is for.

Test file names and make targets

The format of a test file name is:

```
<component name>_<test name>_<optional language specifier>
```

Examples:

```
sidre_buffer.cpp      ('Buffer' class C++ unit test)
sidre_buffer_C.cpp    ('Buffer' class C unit test)
sidre_buffer_F.f      ('Buffer' class Fortran unit test)
```

When test files are named like this, it is easy to see what they contain. Additionally, when added to the appropriate CMakeLists.txt file (see src/components/sidre/tests/CmakeLists.txt file for example), the extension '_test' will be added to the make target name so that the test will appear as follows in the make target listing when 'make help' is typed:

```
sidre_buffer_test
sidre_buffer_C_test
sidre_buffer_F_test
```

Note: We should also add a target for each component to run all its tests; e.g., 'make sidre_tests'

Example file names and make targets

The format of an example file name is:

```
<component name>_<example name>_<optional language specifier>_ex
```

Examples:: sidre_shocktube_ex.cpp ('shocktube' C++ example) sidre_shocktube_F_ex.f ('shocktube' Fortran example)

Running Tests and Examples

Axom examples and tests can be run in multiple different ways using make targets, Bamboo continuous integration (CI) tool, or manually. The best choice for running them depends on what you are trying to do.

For example, if you build Axom and want to make sure everything is working properly, you can type the following command in the build directory:

```
$ make test
```

This will run all tests and examples and report a summary of passes and failures. Detailed output on individual tests is suppressed.

If a test fails, you can invoke its executable directly to see the detailed output of which checks passed or failed. This is especially useful when you are modifying or adding code and need to understand how unit test details are working, for example.

Lastly, you can run suites of tests, such as all tests on a set of platforms and compilers, using Bamboo. See *Continuous Integration* for information about running tests using the *Bamboo* tool.

3.1.11 Continuous Integration

Bamboo is a continuous integration (CI) tool that is part of the Atlassian tool suite. The Axom project uses two Bamboo projects, one on the LC Collaboration Zone (CZ) and one on the LC Restricted Zone (RZ).

The basic mechanics for managing test plans described in *Bamboo Test Plans* is the same for both Bamboo instances.

CZ Bamboo Project

We use the Axom CZ Bamboo project primarily for manually running Bamboo plans on specific branches. For example, if you are working on a branch and you want to build the branch code and run tests on several LC platforms on the CZ with a variety of compilers, you can do this easily. The plans for such branch testing are configured so that when a new Axom git branch is created and pushed to our Bitbucket project, the branch will appear in the list of branches on which a plan can be run.

There are Bamboo plan options for this branch testing. One is a "smoke test" that will build and run tests on a single platform with our default GNU compiler. The other is a more comprehensive plan that will build and run tests on each of the platforms we need to support using the compilers and versions our users require.

To run a plan on a specific branch, do the following:

1. Log into the CZ Bamboo tool.
2. Click on the 'Axom' project.
3. Select the test plan you want to run.
4. Click on the branch you want to build and test.
5. Click 'Run plan' via the 'Run' pulldown menu on the upper right.

Depending on resource availability and what the plan does, the plan may take a while to run. When the plan completes, you will receive an email indicating this and whether everything passed or if there were any failures. If you need to look at the detailed results (e.g., if a test failed), you can do the following:

1. Click the branch name in the plan.
2. Click the run number in the summary.
3. Click the 'artifacts' tab.
4. Click the artifact that you want to see. The test plan artifacts contain the detailed output generated by Google Test and FRUIT.

We also have one plan that is scheduled to automatically build and run tests on the master branch on a select set of platforms and compilers once per week. This plan may be run manually at any time by selecting the plan and clicking on 'Run plan' as described above. Each member of the team receives an email notification indicating passes and failures of builds and tests run by this plan.

RZ Bamboo Project

We use the Axom RZ Bamboo project for the bulk of Axom automated build and test operations. This includes: nightly scheduled builds and tests of the develop branch on each of the platform types we support with a variety of compilers, nightly builds of user documentation installation of this documentation on our LC web pages, and weekly third-party library builds.

Similar to our CZ Bamboo plans, each of these plans may be run manually at any time by selecting the plan and clicking on 'Run plan'.

Bamboo Test Plans

A Bamboo plan consists of stages, each of which represents a step in a build and/or test process. Each stage may contain one or more jobs that can be run in parallel by Bamboo. For example, you may have a stage that compiles a code and multiple testing stages which follow that can run in parallel. Each stage contains specific tasks to run. Currently, Axom plans don't exercise parallel execution in Bamboo. A typical Axom test plan consists of a set of stages, one to build the code and run tests for each platform and compiler combination. The tasks comprising a stage

are shell commands that navigate workspace directories on LC systems, check out the axom code, and run scripts (that we archive in our source code repo) that encode all of the code compilation and test execution operations. A final stage parses CTest output.

Note: All of our scripts that are run in Bamboo can be found in the source directory *axom/scripts/bamboo*.

To see the specific contents of any particular plan, click on the Axom project in one of our Bamboo projects and click on a plan. Then, in the 'Actions' pull-down menu at the upper right, click on 'Configure plan'. Clicking on the 'Stages' tab will reveal the stages in the plan and clicking on a stage will show the tasks in the stage, including shell commands, scripts that are run, etc.

Creating and configuring a Bamboo plan

Here are the steps to create and set up a Bamboo plan once you are in the appropriate Axom Bamboo project (either CZ or RZ):

1. Click the 'Create' button at the top of the page and choose either 'Create a new plan' or 'Clone an existing plan'.
   - When you choose to create a new plan, you can define everything about what the plan does.
   - When you clone an existing plan, you make a copy of the plan and its entire configuration.
2. Enter information in all required fields (i.e., required fields are denoted with a red asterisk).
   - If you clone an existing plan, make sure you choose the correct **destination project** for the plan.
   - Make sure you link the correct repository and branch to the plan.

     Note: This only applies to the CZ Bamboo project since our repo lives on the CZ Bitbucket server. We could use the Bamboo plugin to clone the repo as a plan task; however, we typically do not do this and use the 'script' interface to clone via the git clone command. Nevertheless, linking a repo to a plan allows us to set up the plan to run on any branch in the repo.

     A CZ repo cannot be linked to a plan on the RZ Bamboo project due to LC security constraints. To set up an RZ Bamboo plan that is not associated with a repository choose 'Link new repository' and select 'None' from the pulldown menu.

     ---
3. Click 'Configure plan'. Bamboo will ask you to configure plan tasks.
4. Click 'Add task' for each task you wish to add to the plan. Note that a typical Axom plan includes **script** tasks (either inline or run from files).
   - Start typing 'script' in the search field and select the script icon when it appears.
5. Configure each task. For a 'script' task, this means:
   - Enter a short script description.
   - Choose 'inline' or 'file'. If inline, type in the script commands. If file, choose the file containing the script to run.
   - Fill in arguments, environment variables, etc. as needed.
6. Check the box under 'Enable this plan?'
7. Click the 'Create' button.

Important: After a plan is created, many of its configuration options can be set or modified using the appropriate option tabs that appear across the top of the web page when 'Configure plan' is selected from the 'Actions' pulldown menu.

Associating an agent to a Bamboo plan

Every Bamboo project has *agents* the run Bamboo jobs on LC platforms. When Bamboo executes a plan, it communicates with an agent associated with it for the desired platform that runs tasks on the machine. Here are the steps to associate an agent with a plan:

1. Log on to the *MyLC* portal for the appropriate network (CZ or RZ).
2. Switch to the Axom *shared user account* which is the account under which all Axom plans run. First, click the 'change user' link at the upper right. Enter 'atk' as the user in the field at the upper left, choose the account associated with the 'atk' LC username, and check the 'su to user' box.
3. Go into the 'bamboo agent management' portlet. You will see a list of agents and machines that we have. Select the machine you want to create the agent on and enter a descriptive name (e.g., axom-rzalastor), and click 'create'.
4. Finally, to attach the agent to a plan, you must send an email to the LC Atlassian email list *lc-atlassian-admin@llnl.gov* requesting that the named agent you created be attached to the plans you want.

Restarting agents

Occasionally, agents must be restarted. When an agent dies, Bamboo jobs will be queued and stalled until the agent that should run them is restarted.

We have 'cron' jobs running on the CZ and RZ to check our agents and restart those that need it. The crontab files are located in the directory *axom/scripts/bamboo* in our source code repo.

Disabling or deleting a Bamboo plan

Any Bamboo plan may be disabled by selecting the plan, clicking the 'Actions' pulldown menu and then clicking 'Disable plan'. When a plan is disabled, its configuration and history is preserved, but it will not run.

Deleting a plan removes its configuration, history, artifacts, labels, etc. If the plan is ever needed again after it is deleted, it must be completely reconstructed from scratch. Therefore, a plan should only be deleted if it is clear that it will not be needed in the future. A couple of other important points to note:

- A plan that is running cannot be deleted – the plan must be stopped first.
- A record of a plans results can be preserved, if necessary, before it is deleted. See Exporting data for backup for details.

To delete a Bamboo plan, select it, click the 'Actions' pulldown menu and click on 'Configure plan'. Then, click the 'Actions' pulldown menu and click on 'Delete plan'.

Other Bamboo Things...

- Run plan from command line. I believe this can be done using the *queue_build.py* script in *axom/scripts/bamboo* but am not sure how...

3.1.12 Miscellaneous Development Items

This section describes various development tasks that need to be performed that are not covered in earlier sections.

Web Documentation

Describe how to build and install web documentation...

Shared LC web content location axom/src/docs/sphinx/web

Third-party Library Installation

Describe how to run the scripts to install third-party libraries for testing different versions locally on a branch and for installing new libraries for the team to use...

Building and installing TPLs for all compilers on LC CHAOS platforms (CZ):

```
$ python ./scripts/uberenv/llnl_install_scripts/llnl_cz_uberenv_install_chaos_5_x86_
↪64_ib_all_compilers.py
```

Questions we need to answer include:

- How does one add a new compiler or platform to the mix?
- How does one build a new set of TPLs with for a single platform or compiler for testing?
- What is the procedure for changing versions of one or more TPLs?
- How do we keep things straight when using different TPL versions for different branches?
- How to use the scripts for team TPL support vs. local development experimentation?
- Others?

Note: Pull in content from ../web/build_system/thirdparty_deps.rst ... fill in gaps and make sure it it up-to-date...

Code Health Tools

This section describes how to run code health tools we use.

Code Coverage

Setting up and running code coverage analysis...

Static Analysis

Setting up and running static analysis tools....

Memory Checking

Setting up and running memory checking tools....

3.2 Axom Coding Guidelines

These guidelines define code style conventions for the Axom project. Most of the items were taken from the cited references, sometimes with modifications and simplifications; see *References and Useful Resources*.

The guidelines emphasize code readability, correctness, portability, and interoperability. Agreement on coding style and following common idioms and patterns provides many benefits to a project with multiple developers. A uniform "look and feel" makes it easier to read and understand source code, which increases team productivity and reduces confusion and coding errors when developers work with code they did not write. Also, guidelines facilitate code reviews by enforcing consistency and focusing developers on common concerns. Some of these guidelines are arbitrary, but all are based on practical experience and widely accepted sound practices. For brevity, most guidelines contain little detailed explanation or justification.

Each guideline is qualified by one of three auxiliary verbs: "must", "should", or "may" (or "must not", "should not", "may not").

- A "must" item is an absolute requirement.
- A "should" item is a strong recommendation.
- A "may" item is a potentially beneficial stylistic suggestion.

How to apply "should" and "may" items often depends on the particular code situation. It is best to use these in ways that enhance code readability and help reduce user and developer errors.

Important:

- Variations in coding style for different Axom components is permitted. However, coding style *within each* Axom component **must** be consistent.
- Deviations from these guidelines **must** be agreed upon by the Axom team.
- When the team agrees to change the guidelines, this guide **must** be updated.

Contents:

3.2.1 1 Changing Existing Code

Follow existing code style

1.1 When modifying existing code, the style conventions already in use in each file **must** be followed unless the scope of changes makes sense (see next item). This is not intended to stifle personal creativity - mixing style is disruptive and may cause confusion for users and fellow developers.

1.2 When making stylistic changes to existing code, those changes **should** extend to a point where the style is consistent across a reasonable scope. This may mean that an entire file is changed to prevent multiple conflicting styles.

Only change code from other sources when it makes sense

1.3 The Axom project may contain code pulled in from sources outside Axom. These guidelines apply to code developed within Axom primarily. The decision to modify externally-developed code that we pull into Axom will be evaluated on a case-by-case basis. Modifying such code to be compliant with these guidelines should typically be done only if a significant rewrite is undertaken for other reasons.

3.2.2 2 Names

Good names are essential to sound software design. This section contains guidelines for naming files, types, functions, class members, variables, etc. The main goal is to use clear and unambiguous names. Also, we want naming conventions for different entities so that, when applied, the role of each is obvious from the form of its name.

Good names are clear and meaningful

2.1 Every name **must** be meaningful. In particular, its meaning **must** be clear to other code developers and users, not just the author of the name.

> A substantial benefit of good name selection is that it can greatly reduce the amount of developer debate to define a concept. A good name also tends to reduce the amount of documentation required for others to understand it. For example, when the name of a function clearly indicates what it does and the meaning and purpose of each argument is clear from its name, then code comments may be unnecessary. Documentation can be a substantial part of software and requires maintenance. Minimizing the amount of required documentation reduces this burden.

Avoid cryptic names

2.2 Tersely abbreviated or cryptic names **should** be avoided. However, common acronyms and jargon that are well understood by team members and users **may** be used.

Use terminology consistently

2.3 Terminology **must** be used consistently; i.e., for names and concepts in the code and in documentation. Multiple terms **should not** be used to refer to the same concept and a concept **should not** be referred to by multiple terms.

> Using a clear, limited set of terminology in a software project helps maintain the consistency and integrity of the software, and it makes the code easier to understand for developers and users.

2.4 Each name **must** be consistent with other similar names in the code.

> For example, if getter/setter methods follow the convention "getFoo" and "setFoo" respectively, then adding a new setter method called "putBar" is clearly inconsistent.

Name directories so it's easy to know what's in them

2.5 Each directory **must** be named so that the collective purpose of the files it contains is clear. All directory names **should** follow the same style conventions.

> All directory names **should** use all lower case letters and consist of a single word in most cases. A directory name with more than one word **should** use an 'underscore' to separate words.
>
> For example, use:

```
cool_stuff
```

> not

```
cool-stuff
```

Follow file extension conventions

2.6 C++ header and source file extensions **must** be: *.hpp and *.cpp, respectively.

2.7 C header and source files (e.g., tests, examples, and generated API code) **must** have extensions *.h and *.c, respectively.

2.8 Fortran source files (e.g., tests and examples, and generated API code) **must** have the extension *.f or *.F . *.F **must** be used if the preprocessor is needed to compile the source file.

Associated source and header file names should match

2.9 The names of associated header and source files **should** match, apart from the file extension, to make their association clear.

> For example, the header and source files for a class "Foo" **should** be named "Foo.hpp" and "Foo.cpp", respectively.
>
> Also, files that are closely related in other ways, such as a header file containing prototypes for a set of methods that are not class members and a source file containing implementations of those methods, **should** be named the same or sufficiently similar so that their relationship is clear.

File contents should be clear from file name

2.10 The name of each file **must** clearly indicate its contents.

> For example, the header and source file containing the definition and implementation of a major type, such as a class **must** include the type name of the type in the file name. For example, the header and implementation file for a class called "MyClass" should be named "MyClass.hpp" and "MyClass.cpp", respectively.
>
> Files that are not associated with a single type, but which contain closely related functionality or concepts, **must** be named so that the functionality or concepts are clear from the name. For example, files that define and implement methods that handle file I/O **should** be named "FileIO.hpp" and "FileUtils.cpp", or similar.

File names should not differ only by case

2.11 File names that differ only in letter case **must not** be used.

> Since we must support Windows platforms, which have limited case sensitivity for file names, having files with names "MyClass.hpp" and "myclass.hpp", for example, is not acceptable.

Namespace name format

2.12 All namespaces defined **must** use all lowercase letters for consistency and to avoid user confusion.

Type name format

2.13 Type names (i.e., classes, structs, typedefs, enums, etc.) **must** be nouns and **should** be in mixed case with each word starting with an upper case letter and all other letters in lower cases.

> For example, these are preferred type names:

```
DataStore, MyCollection, TypeUtils
```

These type names should not be used:

```
dataStore, mycollection, TYPEUTILS
```

2.14 Separating characters, such as underscores, **should not** be used between words in a type name.

For example, these names are not preferred type names:

```
Data_store, My_Collection
```

Note: **Exceptions to the guidelines above** include cases where types play a similar role to those in common use elsewhere. For example, naming an iterator class "base_iterator" would be acceptable if it is conceptually similar with the C++ standard library class.

2.15 Suffixes that may be used by compilers for name mangling, or which are used in the C++ standard library, such as "_t", **must not** be used in type names.

Function name format

2.16 Function names **must** use "camelCase" or "pot_hole" style. camelCase is preferred.

camelCase style: The first word has all lower case letters. If multiple words are used, each word after the first starts with an upper case letter and all other letters in the word are lower case. Underscores must not be used in camelCase names, but numbers may be used.

For example, these are proper camelCase names:

```
getLength(), createView2()
```

pot_hole style: All letters are lower case. If multiple words are used, they are separated by a single underscore. Numbers may be used in pothole style names.

For example, these are acceptable pothole style variable names:

```
push_front(), push_back_2()
```

2.17 Names of related functions, such as methods for a class, **should** follow the same style.

Note: **Exception:** While consistency is important, name style may be mixed when it makes sense to do so. While camelCase style is preferred for class member functions, a class may also contain methods that follow pot_hole style if those methods perform operations that are similar to C++ standard library functions, for example.

For example, the following method names are acceptable for a class with camelCase style names:

```
push_back(), push_front()
```

if those methods are similar in behavior to C++ standard methods.

Function names should indicate behavior

2.18 Each function name **must** indicate clearly indicate what the function does.

For example:

```
calculateDensity(), getDensity()
```

are good function names because they distinguish the fact that the first performs a calculation and the second returns a value. If a function were named:

```
density()
```

what it actually does is murky; i.e., folks would have to read its documentation or look at its implementation to see what it actually does.

2.19 Function names **should** begin with a verb because they perform an action.

2.20 Verbs such as "is", "has", "can", etc. **should** be used for functions with a boolean return type.

For example, the following names are preferred:

```
isInitialized(), isAllocated()
```

Related functions should have similar names

2.21 Complementary verbs such as "get/set", "add/remove" and "create/destroy" **must** be used for routines that perform complementary operations.

Such symmetry prevents confusion and makes interfaces easier to use.

Data member and variable name format

2.22 All variables (class/struct members, function-scoped variables, function arguments, etc.) **must** use either "camelCase" style or "pot_hole" style. Pot_hole style is preferred since it distinguishes variable names from method names.

For example, these are acceptable variable names:

```
myAverage, person_name, pressure2
```

2.23 Non-static class and struct data member names **must** have the prefix "m_".

This convention makes it obvious which variables are class members/struct fields and which are other local variables. For example, the following are acceptable names for class data members using camelCase style:

```
m_myAverage, m_personName
```

and acceptable pothole style:

```
m_my_average, m_person_name
```

2.24 Static class/struct data member names and static file scope variables **must** have the prefix "s_".

Similar to the guideline above, this makes it obvious that the variable is static.

Variable names should indicate type

2.25 Verbs, such as "is", "has", "can", etc., **should** be used for boolean variables (i.e., either type bool or integer that indicates true/false).

For example, these names are preferred:

```
m_is_initialized, has_license
```

to these names:

```
m_initialized, license
```

2.26 A variable that refers to a non-fundamental type **should** give an indication of its type.

For example,:

```
Topic* my_topic;
```

is clearer than:

```
Topic* my_value;
```

Macro and enumeration name format

2.27 Preprocessor macro constants **must** be named using all uppercase letters and underscores **should** be used between words.

For example, these are acceptable macro names:

```
MAX_ITERATIONS, READ_MODE
```

These are not acceptable:

```
maxiterations, readMode
```

2.28 The name of each enumeration value **should** start with a capital letter and use an underscore between words when multiple words are used.

For example,:

```
enum Orange
{
   Navel,
   Valencia,
   Num_Orange_Types
};
```

3.2.3 3 Directory Organization

The goal of the guidelines in this section is to make it easy to locate a file easily and quickly. Make it easy for your fellow developers to find stuff they need.

Limit scope of directory contents

3.1 The contents of each directory and file **must** be well-defined and limited so that the directory can be named to clearly indicate its contents. The goal is to prevent directories and files from becoming bloated with too many divergent concepts.

Put files where it's easy to find them

3.2 Header files and associated implementation files **should** reside in the same directory unless there is a good reason to do otherwise. This is common practice for C++ libraries.

3.3 Each file **must** reside in the directory that corresponds to (and named for) the code functionality supported by the contents of the file.

3.2.4 4 Header File Organization

The goal of these guidelines is to make it easy to find essential information in header files easily and quickly. Header files define software interfaces so consistently-applied conventions for file organization can significantly improve user understanding and developer productivity.

All header file contents should be related

4.1 A header file **may** contain multiple type definitions (e.g., structs, classes, enums, etc.). However, type definitions and function declarations in a header file **must** be related closely and/or support the primary type for which the file is named.

4.2 A "typedef" statement, when used, **should** appear in the header file where the type is defined.

> This practice helps ensure that all names associated with a given type are available when the appropriate header file is used and eliminates potentially inconsistent type names.

Include in a header file only what's needed to compile it

4.3 A header file **must** be self-contained and self-sufficient.

> Specifically, each header file
>
> - **Must** have proper header file include guards (see *Header file layout details*) to prevent multiple inclusion. The macro symbol name for each guard must be chosen to guarantee uniqueness within *every* compilation unit in which it appears.
> - **Must** include all other headers and/or forward declarations it needs to be compiled standalone. In addition, a file **should not** rely on symbols defined in other header files it includes; the other files **should** be included explicitly.
> - **Must** contain implementations of all generic templates and inline methods defined in it. A compiler will require the full definitions of these constructs to be seen in every source file that uses them.

Note: Function templates or class template members whose implementations are fully specialized with all template arguments **must** be defined in an associated source file to avoid linker errors (e.g., multiply-defined symbols). Fully specialized templates *are not* templates and are treated just like regular functions.

4.4 Extraneous header files or forward declarations (i.e., those not required for standalone compilation) **must not** be included in header files.

> Spurious header file inclusions, in particular, introduce spurious file dependencies, which can increase compilation time unnecessarily.

Use forward declarations when you can

4.5 Header files **should** use forward declarations instead of header file inclusions when possible. This may speed up compilation, especially when recompiling after header file changes.

Note: Exceptions to this guideline:

- Header files that define external APIs for the Axom project **must** include all header files for all types that appear in the API. This makes use of the API much easier.
- When using a function, such as an inline method or template, that is implemented in a header file, the header file containing the implementation **must** be included.
- When using C++ standard library types in a header file, it **may** be preferable to include the actual headers rather than forward reference headers, such as 'iosfwd', to make the header file easier to use. This prevents users from having to explicitly include standard headers wherever your header file is used.

4.6 A forward type declaration **must** be used in a header file when an include statement would result in a circular dependency among header files.

Note: Forward references, or C++ standard 'fwd' headers, are preferred over header file inclusions when they are sufficient.

Organize header file contents for easy understanding

4.7 Header file include statements **should** use the same ordering pattern for all files.

This improves code readability, helps to avoid misunderstood dependencies, and insures successful compilation regardless of dependencies in other files. A common, recommended header file inclusion ordering scheme is (only some of these may be needed):

1. Headers in the same Axom component
2. Other headers within the project
3. TPL headers; e.g., MPI, OpenMP, HDF5, etc.
4. C++ and C standard library headers
5. System headers

Also, code is easier to understand when include files are ordered alphabetically within each of these sections and a blank line is inserted between sections. Adding comments that describe the header file categories can be helpful as well. For example,

```
// Headers from this component
#include "OtherClassInThisComponent.hpp"

// "other" component headers
#include "other/SomeOtherClass.hpp"

// C standard library
#include <stdio.h>

// C++ standard library
#include <unordered_map>
```

(continues on next page)

(continued from previous page)

```
#include <vector>

// Non-std system header
#include <unistd.h>
```

Note: Ideally, header file inclusion ordering should not matter. Inevitably, this will not always be the case. Following the ordering prescription above helps to avoid problems when others' header files are not constructed following best practices.

4.8 Routines **should** be ordered and grouped in a header file so that code readability and understanding are enhanced.

For example, all related methods should be grouped together. Also, public methods, which are part of an interface, should appear before private methods.

All function arguments should have names

4.9 The name of each function argument **must** be specified in a header file declaration. Also, names in function declarations and definitions **must** match.

For example, this is not an acceptable function declaration:

```
void doSomething(int, int, int);
```

Without argument names, the only way to tell what the arguments mean is to look at the implementation or hope that the method is documented well.

Header file layout details

Content **must** be organized consistently in all header files. This section summarizes the recommended header file layout using numbers and text to illustrate the basic structure. Details about individual items are contained in the guidelines after the summary.

```
// (1) Axom copyright and release statement

// (2) Doxygen file prologue

// (3a) Header file include guard, e.g.,
#ifndef MYCLASS_HPP
#define MYCLASS_HPP

// (4) Header file inclusions (when NEEDED in lieu of forward declarations)
#include "myHeader.hpp"

// (5) Forward declarations NEEDED in header file (outside of project namespace)
class ForwardDeclaredClass;

// (6a) Axom project namespace declaration
namespace axom {

// (7a) Internal namespace (if used); e.g.,
namespace awesome {

// (8) Forward declarations NEEDED in header file (in project namespace(s))
```

(continues on next page)

(continued from previous page)

```
class AnotherForwardDeclaredClass;

// (9) Type definitions (class, enum, etc.) with Doxygen comments e.g.,
/*!
 * \brief Brief ...summary comment text...
 *
 * ...detailed comment text...
 */
class MyClass {
   int m_classMember;
};

// (7b) Internal namespace closing brace (if needed)
} // awesome namespace closing brace

// (6b) Project namespace closing brace
} // axom namespace closing brace

// (3b) Header file include guard closing endif */
#endif // closing endif for header file include guard
```

4.10 **(Item 1)** Each header file **must** contain a comment section that includes the Axom copyright and release statement.

> See *7 Code Documentation* for details.

4.11 **(Item 2)** Each header file **must** begin with a Doxygen file prologue.

> See *7 Code Documentation* for details.

4.12 **(Items 3a,3b)** The contents of each header file **must** be guarded using a preprocessor directive that defines a unique "guard name" for the file.

> The guard must appear immediately after the file prologue and use the '#ifndef' directive (item 2a); this requires a closing '#endif' statement at the end of the file (item 2b).
>
> The preprocessor constant must use the file name followed by "_HPP" for C++ header files; e.g., "MYCLASS_HPP" as above.
>
> The preprocessor constant must use the file name followed by "_H" for C header files.

4.13 **(Item 4)** All necessary header file inclusion statements **must** appear immediately after copyright and release statement and before any forward declarations, type definitions, etc.

4.14 **(Item 5)** Any necessary forward declarations for types defined outside the project namespace **must** appear after the header include statements and before the Axom project namespace statement.

4.15 **(Items 6a, 6b, 7a, 7b)** All types defined and methods defined in a header file **must** be included in a namespace.

> Either the project "axom" namespace (item 6a) or a namespace nested within the project namespace (item 7a) may be used, or both may be used. A closing brace ("}") is required to close each namespace declaration (items 6b and 7b) before the closing '#endif' for the header file include guard.

4.16 **(Item 8)** Forward declarations needed **must** appear in the appropriate namespace before any other statements (item 8).

4.17 **(Item 9)** All class and other type definitions **must** appear after header file inclusions and forward declarations. A proper class prologue **must** appear before the class definition. See *7 Code Documentation* for details.

3.2.5 5 Source File Organization

The goal is to make it easy to find essential information in a file easily and quickly. Consistently-applied conventions for file organization can significantly improve user understanding and developer productivity.

Each source file should have an associated header file

5.1 Each source file **should** have an associated header file with a matching name, such as "Foo.hpp" for the source file "Foo.cpp".

Note: **Exceptions:** Test files may not require headers.

Header file include order should follow rules for header files

5.2 The first header file inclusion in a source file **must** be the header file associated with the source file (when there is one). After that the rules for including headers in other headers apply. For example,

```
#include "MyAssociatedHeaderFile.hpp"

// Other header file inclusions...
```

See *Organize header file contents for easy understanding* for header file inclusion rules.

Avoid extraneous header file inclusions

5.2 Unnecessary header files **should not** be included in source files (i.e., headers not needed to compile the file standalone).

> Such header file inclusions introduce spurious file dependencies, which may increases compilation time unnecessarily.

Function order in source and header files should match

5.3 The order of functions implemented in a source file **should** match the order in which they appear in the associated header file.

> This makes the methods easier to locate and compare with documentation in the header file.

Source file layout details

Content **must** be organized consistently in all source files. This section summarizes the recommended source file layout using numbers and text to illustrate the basic structure. Details about individual items are contained in the guidelines after the summary.

```
// (1) Axom copyright and release statement

// (2) Doxygen file prologue

// (3) Header file inclusions (only those that are NECESSARY)
#include "..."
```

(continues on next page)

(continued from previous page)

```
// (4a) Axom project namespace declaration
namespace axom {

// (5a) Internal namespace (if used); e.g.,
namespace awesome {

// (6) Initialization of static variables and data members, if any; e.g.,
Foo* MyClass::s_shared_foo = 0;

// (7) Implementation of static class member functions, if any

// (8) Implementation of non-static class members and other methods

// (5b) Internal namespace closing brace (if needed)
} // awesome namespace closing brace

// (4b) Project namespace closing brace
} // axom namespace closing brace
```

5.4 **(Item 1)** Each source file **must** contain a comment section that includes the Axom copyright and release statement.

See *7 Code Documentation* for details.

5.5 **(Item 2)** Each source file **must** begin with a Doxygen file prologue.

See *7 Code Documentation* for details.

5.6 **(Item 3)** All necessary header file include statements **must** appear immediately after the copyright and release statement and before any implementation statements in the file.

Note: If a header is included in a header file, it **should not** be included in the associated source file.

5.7 **(Items 4a, 4b, 5a, 5b)** All contents in a source file **must** follow the same namespace inclusion pattern as its corresponding header file (See *Header file layout details*).

Either the main project namespace (item 4a) or internal namespace (item 5a) may be used, or both may be used. A closing brace ("}") is required to close each namespace declaration (items 4b and 5b).

5.8 **(Item 6)** Any static variables and class data members that are defined in a header file **must** be initialized in the associated source file before any method implementations.

5.9 **(Items 7, 8)** Static method implementations **must** appear before non-static method implementations.

3.2.6 6 Scope

Use namespaces to avoid name collisions

6.1 All Axom code **must** be included in the project namespace 'axom'; e.g.,:

```
namespace axom {
     // . . .
}
```

6.2 Each Axom component **must** define its own unique namespace within the "axom" namespace. All contents of each component **must** reside within that namespace.

Use namespaces to hide non-API code in header files

6.3 Code that must be appear in header files (e.g., templates) that is not intended to be part of a public interface, such as helper classes/structs and methods, **should** be placed in an internal namespace.

> Common names for such namespaces include 'internal' (for implementations used only internally) and 'detailed' (for types, etc. used only internally). Any reasonable choice is acceptable; however, the choice **must** be the same within each Axom component.
>
> Note that declaring helper classes/structs private within a class definition is another good option. See *Hide nested classes when possible* for details.

Use 'unnamed' namespace for hiding code in source files

6.4 Classes/structs and methods that are meant to be used only internally to a single source file **should** be placed in the 'unnamed' namespace to make them invisible outside the file.

> This guarantees link-time name conflicts will not occur. For example:

```
namespace {
   void myInternalFunction();
}
```

Apply the 'using directive' carefully

6.5 The 'using directive' **must not** be used in any header file.

> Applying this directive in a header file leverages a bad decision to circumvent the namespace across every file that directly or indirectly includes that header file.

Note: This guideline implies that each type name appearing in a header file **must be fully-qualified** (i.e., using the namespace identifier and scope operator) if it resides in a different namespace than the contents of the file.

6.6 The 'using directive' **may** be used in a source file to avoid using a fully-qualified type name at each declaration. Using directives **must** appear after all "#include" directives in a source file.

6.7 When only parts of a namespace are used in an implementation file, only those parts **should** be included with a using directive instead of the entire namespace contents.

> For example, if you only need the standard library vector container form the "std" namespace, it is preferable to use:

```
using std::vector;
```

> rather than:

```
using namespace std;
```

Use access qualifiers to control class interfaces

6.8 Class members **must** be declared in the following order:

1. "public"
2. "protected"

3. "private"

That is, order members using these access qualifiers in terms of "decreasing scope of visibility".

Note: Declaring methods before data members is preferred because methods are more commonly considered part of a class interface. Also, separating methods and data into their own access qualified sections usually helps make a class definition clearer.

6.9 Class data members **should** be "private". The choice to use "public" or "protected" data members **must** be scrutinized by other team members.

Information hiding is an essential part of good software engineering and private data is the best means for a class to preserve its invariants. Specifically, a class should maintain control of how object state can be modified to minimize side effects. In addition, restricting direct access to class data enforces encapsulation and facilitates design changes through refactoring.

Use 'friend' and 'static' rarely

6.10 "Friend" declarations **should** be used rarely. When used, they **must** appear within the body of a class definition before any class member declarations. This helps make the friend relationship obvious.

Note that placing "friend" declarations before the "public:" keyword makes them private, which preserves encapsulation.

6.11 Static class members (methods or data) **must** be used rarely. In every case, their usage **should** be carefully reviewed by the team.

When it is determined that a static member is needed, it **must** appear first in the appropriate member section. Typically, static member functions **should** be "public" and static data members **should** be "private".

Hide nested classes when possible

6.12 Nested classes **should** be private unless they are part of the enclosing class interface.

For example:

```
class Outer
{
   // ...
private:
   class Inner
   {
      // ...
   };
};
```

When only the enclosing class uses a nested class, making it private does not pollute the enclosing scope needlessly. Furthermore, nested classes may be forward declared within the enclosing class definition and then defined in the implementation file of the enclosing class. For example:

```
class Outer
{
   class Inner; // forward declaration

   // use name 'Inner' in Outer class definition
```

(continues on next page)

(continued from previous page)

```
};

// In Outer.cpp implementation file...
class Outer::Inner
{
   // Inner class definition
}
```

This makes it clear that the nested class is only needed in the implementation and does not clutter the class definition.

Limit scope of local variables

6.13 Local variables **should** be declared in the narrowest scope possible and as close to first use as possible.

Minimizing variable scope makes source code easier to comprehend and may have performance and other benefits. For example, declaring a loop index inside a for-loop statement such as:

```
for (int ii = 0; ...) {
```

is preferable to:

```
int ii;
...
for (ii = 0; ...) {
```

Beyond readability, this rule has benefits for thread safety, etc.

Note:

Exception: When a local variable is an object, its constructor and destructor may be invoked every time a scope (such as a loop) is entered and exited, respectively.

Thus, instead of this:

```
for (int ii = 0; ii < 1000000; ++ii) {
   Foo f;
   f.doSomethingCool(ii);
}
```

it may be more efficient to do this:

```
Foo f;
for (int ii = 0; ii < 1000000; ++ii) {
   f.doSomethingCool(ii);
}
```

6.14 A local reference to any item in the global namespace (which should be rare if needed at all) **should** use the scope operator ("::") to make the fact that it resides in the global namespace clear.

For example:

```
int local_val = ::global_val;
```

3.2.7 7 Code Documentation

This section contains guidelines for content and formatting of code documentation mentioned in earlier sections. The aims of these guidelines are to:

- Document files, data types, functions, etc. consistently.
- Promote good documentation practices so that essential information is presented clearly and lucidly, and which do not over-burden developers.
- Generate source code documentation using the Doxygen system.

Document only what's needed

7.1 Documentation **should** only include what is essential for users and other developers to easily understand code. Comments **should** be limited to describing constraints, pre- and post-conditions, and other issues that are important, but not obvious. Extraneous comments (e.g., documenting "the obvious") **should** be avoided.

> Code that uses clear, descriptive names (functions, variables, etc.) and clear logical structure is preferable to code that relies on a lot of comments for understanding. To be useful, comments must be understood by others and kept current with the actual code. Generally, maintenance and understanding are better served by rewriting tricky, unclear code than by adding comments to it.

Documenting new code vs. existing code

7.2 New source code **must** be documented following the guidelines in this section. Documentation of existing code **should** be modified to conform to these guidelines when appropriate.

7.3 Existing code documentation **should** be improved when its inadequate, incorrect, or unclear.

Note: When code is modified, documentation **must** be changed to reflect the changes.

Write clear documentation

7.4 To make comment text clear and reduce confusion, code comments **should** be written in grammatically-correct complete sentences or easily understood sentence fragments.

Documentation should be easy to spot

7.5 End-of-line comments **should not** be used to document code logic, since they tend to be less visible than other comment forms and may be difficult to format cleanly.

> Short end-of-line comments **may** be useful for labeling closing braces associated with nested loops, conditionals, for scope in general, and for documenting local variable declarations.

7.6 All comments, except end-of-line comments, **should** be indented to match the indentation of the code they are documenting. Multiple line comment blocks **should** be aligned vertically on the left.

7.7 Comments **should** be clearly delimited from executable code with blank lines and "blocking characters" (see examples below) to make them stand out and, thus, improve the chances they will be read.

7.8 White space, such as blank lines, indentation, and vertical alignment **should** be used in comment blocks to enhance readability, emphasize important information, etc.

General Doxygen usage

The Doxygen code documentation system uses C or C++ style comment sections with special markings and Doxygen-specific commands to extract documentation from source and header files. Although Doxygen provides many sophisticated documentation capabilities and can generate a source code manual in a variety of formats such as LaTeX, PDF, and HTML, these guidelines address only a small subset of Doxygen syntax. The goal of adhering to a small, simple set of documentation commands is that developers will be encouraged to build useful documentation when they are writing code.

Brief vs. detailed comments

The Doxygen system interprets each documentation comment as either "brief" or "detailed".

- A brief comment is a concise statement of purpose for an item (usually no more than one line) and starts with the Doxygen command "\brief" (or "@brief"). Brief comments appear in summary sections of the generated documentation. They are typically seen before detailed comments when scanning the documentation; thus good brief comments make it easier to can or navigate a source code manual.
- A detailed comment is any comment that is not identified as 'brief'.

7.9 A "brief" description **should** be provided in the Doxygen comment section for each of the following items:

- A type definition (i.e., class, struct, typedef, enum, etc.)
- A macro definition
- A struct field or class data member
- A class member function declaration (in the header file class definition)
- An unbound function signature (in a header file)
- A function implementation (when there is no description in the associated header file)

7.10 Important information of a more lengthy nature (e.g., usage examples spanning multiple lines) **should** be provided for files, major data types and definitions, functions, etc. when needed. A detailed comment **must** be separated from a brief comment in the same comment block with a line containing no documentation text.

Doxygen comment blocks

7.11 Doxygen comment blocks **may** use either JavaDoc, Qt style, or one of the C++ comment forms described below.

JavaDoc style comments consist of a C-style comment block starting with two *'s, like this:

```
/**
 * ...comment text...
 */
```

Qt style comments add an exclamation mark (!) after the opening of a C-style comment block,like this:

```
/*!
 * ...comment text...
 */
```

For JavaDoc or Qt style comments, the asterisk characters ("*") on intermediate lines are optional, but encouraged.

C++ comment block forms start each line with an additional slash:

```
///
/// ...comment text...
///
```

or an exclamation mark:

```
//!
//! ...comment text...
//!
```

For these C++ style comment forms, the comment delimiter is required on each line.

7.12 A consistent Doxygen comment block style **must** be used within a component.

7.13 Doxygen comment blocks **must** appear immediately before the items they describe; i.e., no blank lines between comment and documented item. This insures that Doxygen will properly associate the comment with the item.

Doxygen inline comments

7.14 Inline Doxygen comments **may** be used for class/struct data members, enum values, function arguments, etc.

When inline comments are used, they **must** appear after the item **on the same line** and **must** use the following syntax:

```
/*!< ...comment text... */
```

Note that the "<" character must appear immediately after the opening of the Doxygen comment (with no space before). This tells Doxygen that the comment applies to the item immediately preceding the comment. See examples in later sections.

7.15 When an item is documented using the inline form, the comment **should not** span multiple lines.

Copyright and release statement

7.16 Each file **must** contain a comment section that includes the project software release information (using whichever comment characters are appropriate for the language the file is written in). In the interest of brevity, the complete release statement is summarized here to show the essential information. The full version can be found in any of the project files.

Note: Change this when we release the code.

```
/*
 * Copyright (c) 2017-2020, Lawrence Livermore National Security, LLC.
 * Produced at the Lawrence Livermore National Laboratory.
 *
 * All rights reserved.
 *
 * This source code cannot be distributed without permission and
 * further review from Lawrence Livermore National Laboratory.
 */
```

See *Header file layout details* and *Source file layout details* for guidelines on placement of copyright and release statement in header and source files, respectively.

File documentation

7.17 Each header file that declares a global type, method, etc. **must** have a Doxygen file prologue similar to the following:

```
/*!
 ******************************************************************************
 *
 * \file ...optional name of file...
 *
 * \brief A brief statement describing the file contents/purpose. (optional)
 *
 * Optional detailed explanatory notes about the file.
 *
 ******************************************************************************
 */

   The "\\file" command **must** appear first in the file prologue. It
   identifies the comment section as documentation for the file.

   The file name **may** include (part of) the path if the file name is not
   unique. If the file name is omitted on the line after the "\\file"
   command, then any documentation in the comment block will belong to
   the file in which it is located instead of the summary documentation
   in the listing of documented files.
```

Note: Doxygen requires that a file itself must be documented for documentation to be generated for any global item (global function, typedef, enum, etc.) defined in the file.

See *Header file layout details* and *Source file layout details* for guidelines on placement of file prologue in header and source files, respectively.

Brief and detailed comments

7.18 A brief statement of purpose for the file **should** appear as the first comment after the file command. If included, the brief statement, **must** be preceded by the "\brief" command.

7.19 Any detailed notes about the file **may** be included after the brief comment. If this is done, the detailed comments **must** be separated from the brief statement by a line containing no documentation text.

Type documentation

7.20 Each type and macro definition appearing in a header file **must** have a Doxygen type definition comment prologue immediately before it. For example

```
/*!
 ******************************************************************************
 *
 * \brief A brief statement of purpose of the type or macro.
 *
 * Optional detailed information that is helpful in understanding the
 * purpose, usage, etc. of the type/macro ...
 *
```

(continues on next page)

(continued from previous page)

```
 * \sa optional cross-reference to other types, functions, etc...
 * \sa etc...
 *
 * \warning This class is only partially functional.
 *
 ******************************************************************************
 */
```

Note: Doxygen requires that a compound entity, such as a class, struct, etc. be documented in order to document any of its members.

Brief and detailed comments

7.21 A brief statement describing the type **must** appear as the first text comment using the Doxygen command "\brief".

7.22 Important details about the item **should** be included after the brief comment and, if included, **must** be separated from the brief comment by a blank line.

Cross-references and caveats

7.23 Cross-references to other items, such as other related types **should** be included in the prologue to enhance the navigability of the documentation.

> The Doxygen command "\sa" (for "see also") **should** appear before each such cross-reference so that links are generated in the documentation.

7.24 Caveats or limitations about the documented type **should** be noted using the "\warning" Doxygen command as shown above.

Function documentation

7.25 Each unbound function **should** be be documented with a function prologue in the header file where its prototype appears or in a source file immediately preceding its implementation.

7.26 Since C++ class member functions define the class interface, they **should** be documented with a function prologue immediately preceding their declaration in the class definition.

Example function documentation

The following examples show two function prologue variations that may be used to document a method in a class definition. The first shows how to document the function arguments in the function prologue.

```
/*!
 ******************************************************************************
 *
 * \brief Initialize a Foo object with given operation mode.
 *
 * The "read" mode means one thing, while "write" mode means another.
 *
 * \return bool indicating success or failure of initialization.
```

(continues on next page)

(continued from previous page)

```
 *              Success returns true, failure returns false.
 *
 * \param[in] mode OpMode enum value specifying initialization mode.
 *                 ReadMode and WriteMode are valid options.
 *                 Any other value generates a warning message and the
 *                 failure value ("false") is returned.
 *
 ****************************************************************************
 */
bool initMode(OpMode mode);
```

The second example shows how to document the function argument inline.

```
/*!
 ****************************************************************************
 *
 * @brief Initialize a Foo object to given operation mode.
 *
 * The "read" mode means one thing, while "write" mode means another.
 *
 * @return bool value indicating success or failure of initialization.
 *             Success returns true, failure returns false.
 *
 ****************************************************************************
 */
bool initMode(OpMode mode /*!< [in] ReadMode, WriteMode are valid options */ );
```

Note that the first example uses the "\" character to identify Doxygen commands; the second uses "@".

Brief and detailed comments

7.27 A brief statement of purpose for a function must appear as the first text comment after the Doxygen command "\brief" (or "@brief").

7.28 Any detailed function description, when included, **must** appear after the brief comment and **must** be separated from the brief comment by a line containing no text.

Return values

7.29 If the function has a non-void return type, the return value **should** be documented in the prologue using the Doxygen command "\return" (or "@return") preceding a description of the return value.

> Functions with "void" return type and C++ class constructors and destructors **should not** have such documentation.

Arguments

7.30 Function arguments **should** be documented in the function prologue or inline (as shown above) when the intent or usage of the arguments is not obvious.

> The inline form of the comment may be preferable when the argument documentation is short. When a longer description is provided (such as when noting the range of valid values, error conditions, etc.) the description **should** be placed within the function prologue for readability. However, the two alternatives

for documenting function arguments **must not** be mixed within the documentation of a single function to reduce confusion.

In any case, superfluous documentation should be avoided. For example, when there are one or two arguments and their meaning is obvious from their names or the description of the function, providing no comments is better than cluttering the code by documenting the obvious. Comments that impart no useful information are distracting and less helpful than no comment at all.

7.31 When a function argument is documented in the prologue comment section, the Doxygen command "param" **should** appear before the comment as in the first example above.

7.32 The "in/out" status of each function argument **should** be documented.

The Doxygen "param" command supports this directly by allowing such an attribute to be specified as "param[in]", "param[out]", or "param[in,out]". Although the inline comment form does not support this, such a description **should** be included; e.g., by using "[in]", "[out]", or "[in,out]" in the comment.

Grouping small functions

7.33 Short, simple functions (e.g., inline methods) **may** be grouped together and documented with a single descriptive comment when this is sufficient.

An example of Doxygen syntax for such a grouping is:

```
//@{
//! @name Setters for data members

void setMember1(int arg1) { m_member1 = arg1; }
void setMember2(int arg2) { m_member2 = arg2; }

//@}
```

Header file vs. source file documentation

7.34 Important implementation details (vs. usage detailed) about a function **should** be documented in the source file where the function is implemented, rather than the header file where the function is declared.

Header file documentation **should** include only purpose and usage information germane to an interface. When a function has separate implementation documentation, the comments **must not** contain Doxygen syntax. Using Doxygen syntax to document an item in more than one location (e.g., header file and source file) can cause undesired Doxygen formatting issues and potentially confusing documentation.

A member of a class may be documented as follows in the source file for the class as follows (i.e., no Doxygen comments):

```
/*
 ******************************************************************************
 *
 * Set operation mode for a Foo object.
 *
 * Important detailed information about what the function does...
 *
 ******************************************************************************
 */
 bool Foo::initMode(OpMode mode)
 {
```

(continues on next page)

(continued from previous page)

```
    ...function body...
}
```

Data member documentation

7.35 Each struct field or class data member **should** have a descriptive comment indicating its purpose.

This comment may as appear as a prologue before the item, such as:

```
/*!
 * \brief Brief statement describing the input mode...
 *
 * Optional detailed information about the input mode...
 */
int m_input_mode;
```

or, it may appear after the item as an inline comment such as:

```
int m_input_mode; /*!< \brief Brief statement describing the input mode....␣
↪*/
```

Brief and detailed comments

7.36 Regardless of which documentation form is used, a brief description **must** be included using the Doxygen command "\brief" (or "@brief").

7.37 Any detailed description of an item, if included, **must** appear after the brief comment and be separated from the brief comment with a line containing no documentation text.

When a detailed comment is provided, or the brief statement requires more than one line, the prologue comment form **should** be used instead of the inline form to make the documentation easier to read.

Grouping data members

7.38 If the names of data members are sufficiently clear that their meaning and purpose are obvious to other developers (which should be determined in a code review), then the members **may** be grouped together and documented with a single descriptive comment.

An example of Doxygen syntax for such a grouping is:

```
//@{
//!  @name Data member description...

int m_member1;
int m_member2;
...
//@}
```

Summary of common Doxygen commands

This Section provides an overview of commonly used Doxygen commands. Please see the Doxygen guide for more details and information about other commands.

Note that to be processed properly, Doxygen commands **must** be preceded with either "\" or "@" character. For brevity, we use "\" for all commands described here.

\brief The "brief" command is used to begin a brief description of a documented item. The brief description ends at the next blank line.

\file The "file" command is used to document a file. Doxygen requires that to document any global item (function, typedef, enum, etc.), the file in which it is defined **must be** documented.

\name The "name" command, followed by a name containing no blank spaces, is used to define a name that can be referred to elsewhere in the documentation (via a link).

\param The "param" command documents a function parameter/argument. It is followed by the parameter name and description. The "\param" command can be given an optional attribute to indicate usage of the function argument; possible values are "[in]", "[out]", and "[in,out]".

\return The "return" command is used to describe the return value of a function.

\sa The "sa" command (i.e., "see also") is used to refer (and provide a link to) another documented item. It is followed by the target of the reference (e.g., class/struct name, function name, documentation page, etc.).

@{,@} These two-character sequences begin and end a grouping of documented items. Optionally, the group can be given a name using the "name" command. Groups are useful for providing additional organization in the documentation, and also when several items can be documented with a single description (e.g., a set of simple, related functions).

\verbatim, \endverbatim The "verbatim/endverbatim" commands are used to start/stop a block of text that is to appear exactly as it is typed, without additional formatting, in the generated documentation.

-, -# The "-" and "-#" symbols begin an item in a bulleted list or numbered list, respectively. In either case, the item ends at the next blank line or next item.

\b, \e These symbols are used to make the next word bold or emphasized/italicized, respectively, in the generated documentation.

3.2.8 8 Design and Implement for Correctness and Robustness

The guidelines in this section describe various software design and implementation practices that help enforce correctness and robustness and avoid mis-interpretation or confusion by others.

Keep it simple...

8.1 Simplicity, clarity, ease of modification and extension **should** always be a main goal when writing new code or changing existing code.

8.2 Each entity (class, struct, variable, function, etc.) **should** embody one clear, well-defined concept.

The responsibilities of an entity may increase as it is used in new and different ways. However, changes that divert it from its original intent **should** be avoided. Also, large, monolithic entities that provide too much functionality or which include too many concepts tend to increase code coupling and complexity and introduce undesirable side effects. Smaller, clearly constrained objects are easier to write, test, maintain, and use correctly. Also, small, simple objects tend to get used more often and reduce code redundancy.

Avoid global and static data

8.3 Global, complex, or opaque data sharing **should not** be used. Shared data increases coupling and contention between different parts of a code base, which makes maintenance and modification difficult.

8.4 Static or global variables of class type **must not** be used.

> Due to indeterminate order of construction, their use may cause bugs that are very hard to find. Static or global variables that are pointers to class types **may** be used and must be initialized properly in a single source file.

Avoid macros and magic numbers for constants

8.5 Preprocessor macros **should not** be used when there is a better alternative, such as an inline function or a constant variable definition.

> For example, this:

```
const double PI = 3.14159265358979323846264338327;
```

> is preferable to this:

```
#define PI (3.14159265358979323846264338327)
```

> Macros circumvent the ability of a compiler to enforce beneficial language concepts such as scope and type safety. Macros are also context-specific and can produce errors that cannot be understood easily in a debugger. Macros **should be used only** when there is no better choice for a particular situation.

8.6 Hard-coded numerical constants and other "magic numbers" **must not** be used directly in source code. When such values are needed, they **should** be declared as named constants to enhance code readability and consistency.

Avoid issues with compiler-generated class methods

The guidelines in this section apply to class methods that may be *automatically generated* by a compiler, including constructors, destructors, copy, and move methods. Developers should be aware of the conditions under which compilers will and will not generate these methods. Developers should also be aware of when compiler-generated methods suffice and when they do not. After providing some guidelines, we discuss standard C++ rules that compilers follow for generating class methods when they are not explicitly defined. See *Understand standard rules for compiler-generated methods*.

The most important cases to pay attention to involve the destructor, copy constructor, and copy-assignment operator. Classes that provide these methods, either explicitly or compiler-generated, are referred to as *copyable*. Failing to follow the rules for these methods can be damaging due to errors or unexpected behavior. Rules involving the move constructor and move-assignment operator are less important since they mostly affect efficiency and not correctness. Copy operations can be used to accomplish the same end result as move operations, just less efficiently. Move semantics are an important optimization feature of C++. The C++11 standard requires compilers to use move operations instead of copy operations when certain conditions are fulfilled. Classes that provide move operations, either explicitly or compiler-generated, are referred to as *movable*.

Rule of three

8.7 Each class **must** follow the *Rule of Three* which states: if the destructor, copy constructor, or copy-assignment operator is explicitly defined, then the others **must** be defined.

> Compiler-generated and explicit versions of these methods **must not** be mixed. If a class requires one of these methods to be implemented, it almost certainly requires all three to be implemented.
>
> This rule helps guarantee that class resources are managed properly. C++ copies and copy-assigns objects of user-defined types in various situations (e.g., passing/returning by value, container manipulations,

etc.). These special member functions will be called, if accessible. If they are not user-defined, they are implicitly-defined by the compiler.

Compiler-generated special member functions can be incorrect if a class manages a resource whose handle is an object of non-class type. Consider a class data member which is a bare pointer to an object. The compiler-generated class destructor will not free the object. Also, the compiler-generated copy constructor and copy-assignment operator will perform a "shallow copy"; i.e., they will copy the value of the pointer without duplicating the underlying resource.

Neglecting to free a pointer or perform a deep copy when those operations are expected can result in serious logic errors. Following the Rule of Three guards against such errors. On the rare occasion these actions are intentional, a programmer-written destructor, copy constructor, and copy-assignment operator are ideal places to document intent of design decisions.

Restrict copying of non-copyable resources

8.8 A class that manages non-copyable resources through non-copyable handles, such as pointers, **should** declare the copy methods private and and leave them unimplemented.

When the intent is that such methods should never be called, this is a good way to help a compiler to catch unintended usage. For example:

```
class MyClass
{
   // ...

private:
   DISABLE_DEFAULT_CTOR(MyClass);
   DISABLE_COPY_AND_ASSIGNMENT(MyClass);

   // ...
};
```

When code does not have access to the private members of a class tries to use such a method, a compile-time error will result. If a class does have private access and tries to use one of these methods an link-time error will result.

This is another application of the "Rule of Three".

Please see *10 Common Code Development Macros, Types, etc.* for more information about the macros used in this example to disable compiler-generated methods.

Note: **Exception:** If a class inherits from a base class that declares these methods private, the subclass need not declare the methods private. Including comments in the derived class header indicating that the the parent class enforces the non-copyable properties of the class is helpful.

Rely on compiler-generated methods when appropriate

8.9 When the compiler-generated methods are appropriate (i.e., correct and sufficiently fast), the default constructor, copy constructor, destructor, and copy assignment **may** be left undeclared. In this case, it is often helpful to add comments to the class header file indicating that the compiler-generated versions of these methods will be used.

8.10 If a class is default-constructable and has POD ("plain old data") or pointer data members, a default constructor **should** be provided explicitly and its data members **must** be initialized explicitly if a default constructor is provided.

A compiler-generated default constructor will not initialize such members, in general, and so will leave a constructed object in an undefined state.

For example, the following class should provide a default constructor and initialize its data members in it:

```
class MyClass
{
   MyClass();

   // ...

private:
   double* m_dvals;
   int[]   m_ivals;

};
```

Functors should always be copyable

8.11 By convention, a functor class **should** have a copy constructor and copy-assignment operator.

Typically, the compiler-generated versions are sufficient when the class has no state or non-POD data members. Since such classes are usually small and simple, the compiler-generated versions of these methods **may** be used without documenting the use of default value semantics in the functor definition.

For example:

```
class MyFunctor
{
   // Compiler-generated copy ctor and copy assignment sufficient

private:
   DIABLE_DEFAULT_CTOR(MyFunctor); // prevent default construction

   // ...
};
```

Note that in this example, the default constructor is disabled to prevent default construction. This can help prevent programming errors when object state must be fully initialized on construction. For more information about common Axom macros, see *10 Common Code Development Macros, Types, etc.*.

Understand standard rules for compiler-generated methods

This section provides some background information related to the guidelines in the previous section. There, we provide guidelines that help to decide when to define class methods that may be generated automatically by a compiler and when relying on compiler-generated versions suffices. Here, we describe the conditions under which compilers generate methods automatically.

Consider the following simple class:

```
class MyClass
{
public:
   int x;
};
```

How many methods does it have? None?

Actually, MyClass may have as many as **six** methods depending on how it is used: a default constructor, destructor, copy constructor, copy-assignment operator, move constructor, and move-assignment operator. Any of these may be generated by a compiler.

Note: See *11 Portability, Compilation, and Dependencies* for discussion about using C++11 features such as *move semantics*.

C++ compiler rules for generating class member functions are:

- The parameter-less default constructor is generated if a class does not define *any* constructor and all base classes and data members are default-constructable. This means that once you declare a copy constructor (perhaps to disable the automatically provided one), the compiler will not supply a default constructor.
- The destructor is automatically supplied if possible, based on the members and the base classes.
- A copy constructor is generated if all base classes and members are copy-constructable. Note that reference members are copy-constructable.
- The copy-assignment operator is generated if all base classes and members are copy-assignable. For this purpose, reference members are not considered copy-assignable.
- A move constructor is supplied unless the class has any of the following: a user-defined copy constructor, copy-assignment operator, move-assignment operator, or destructor. If the move constructor cannot be implemented because not all base classes or members are move-constructable, the supplied move constructor will be defined as deleted.
- A move-assignment operator is generated under the same conditions as the move constructor.

The importance of understanding these rules and applying the guidelines in the previous section is underscored by the fact that compiler-generated methods may have different behaviors depending on how they are used. Here we provide some examples based on MyClass defined above.

If MyClass has a user-defined constructor, then

```
MyClass item1;
```

and

```
MyClass item2 = MyClass();
```

will both call the user-defined default constructor "MyClass()" and there is only one behavior.

However, if MyClass relies on the compiler-generated constructor

```
MyClass item1;
```

performs *default initialization*, while

```
MyClass item2 = MyClass();
```

performs *value initialization*.

Default initialization calls the constructors of any base classes, and nothing else. Since constructors for intrinsic types do not do anything, that means all member variables will have garbage values; specifically, whatever values happen to reside in the corresponding addresses.

Value initialization also calls the constructors of any base classes. Then, one of two things happens:

- If MyClass is a POD class (all member variables are either intrinsic types or classes that only contain intrinsic types and have no user-defined constructor/destructor), all data is initialized to 0.
- If MyClass is not a POD class, the constructor does not touch any data, which is the same as default initialization (so member variables have garbage values unless explicitly constructed otherwise).

Other points worth noting:

- Intrinsic types, such as int, float, bool, pointers, etc. have constructors that do nothing (not even initialize to zero), destructors that do nothing, and copy constructors and copy assignment-ers that blindly copy bytes.
- Comparison operators, such as "==" or "!=" are never automatically generated by a compiler, even if all base classes and members are comparable.

Initializing and copying class members

Initialize all members at construction

8.12 Class type variables **should** be defined using direct initialization instead of copy initialization to avoid unwanted and spurious type conversions and constructor calls that may be generated by compilers.

For example, use:

```
std::string name("Bill");
```

instead of:

```
std::string name = "Bill";
```

or:

```
std::string name = std::string("Bill");
```

8.13 Each class data member **must** be initialized (using default values when appropriate) in every class constructor. That is, an initializer or initialization **must** be provided for each class data member so that every object is in a well-defined state upon construction.

Generally, this requires a user-defined default constructor when a class has POD members. Do not assume that a compiler-generated default constructor will leave any member variable in a well-defined state.

Note: **Exception:** A class that has no data members, including one that is derived from a base class with a default constructor that provides full member initialization, does not require a user-defined default constructor since the compiler-generated version will suffice.

Know when to use initialization vs. assignment

8.14 Data member initialization **should** be used instead of assignment in constructors, especially for small classes. Initialization prevents needless run-time work and is often faster.

8.15 When using initialization instead of assignment to set data member values in a constructor, data members **should** always be initialized in the order in which they appear in the class definition.

Compilers adhere to this order regardless of the order that members appear in the class initialization list. So you may as well agree with the compiler rules and avoid potential errors that could result when one member depends on the state of another.

8.16 For classes with complex data members, assignment within the body of the constructor **may** be preferable.

> If the initialization process is sufficiently complex, it **may** be better to initialize (i.e., assign) member objects in a method that is called after object creation, such as "init()".

Use the copy-and-swap idiom

8.17 A user-supplied implementation of a class copy-assignment operator **should** check for assignment to self, **must** copy all data members from the object passed to operator, and **must** return a reference to "*this".

> The *copy-and-swap* idiom **should** be used.

Initializing, copying, and inheritance

8.18 A constructor **must not** call a virtual function on any data member object since an overridden method defined in a subclass cannot be called until the object is fully constructed.

> There is no general guarantee that data members are fully-created before a constructor exits.

8.19 All constructors and copy operations for a derived class **must** call the necessary constructors and copy operations for each of its base classes to insure that each object is properly allocated and initialized.

Prefer composition to inheritance

8.20 Class composition **should** be used instead of inheritance to extend behavior.

> Looser coupling between objects is typically more flexible and easier to maintain and refactor.

Keep inheritance relationships simple

8.21 Class hierarchies **should** be designed so that subclasses inherit from abstract interfaces; i.e., pure virtual base classes.

> Inheritance is often done to reuse code that exists in a base class. However, there are usually better design choices to achieve reuse. Good object-oriented use of inheritance is to reuse existing *calling* code by exploiting base class interfaces using polymorphism. Put another way, "interface inheritance" should be used instead of "implementation inheritance".

8.22 Deep inheritance hierarchies; i.e., more than 2 or 3 levels, **should** be avoided.

8.23 Multiple inheritance **should** be restricted so that only one base class contains methods that are not "pure virtual".

8.24 "Private" and "protected" inheritance **must not** be used unless you absolutely understand the ramifications of such a choice and are sure that it will not create design and implementation problems.

> Such a choice **must** be reviewed with team members. There almost always exist better alternatives.

Design for/against inheritance

8.25 One **should not** inherit from a class that was not designed to be a base class; e.g., if it does not have a virtual destructor.

> Doing so is bad practice and can cause problems that may not be reported by a compiler; e.g., hiding base class members. To add functionality, one **should** employ class composition rather than by "tweaking" an existing class.

8.26 The destructor of a class that is designed to be a base class **must** be declared "virtual".

> However, sometimes a destructor should not be declared virtual, such as when deletion through a pointer to a base class object should be disallowed.

Use virtual functions responsibly

8.27 Virtual functions **should** be overridden responsibly. That is, the pre- and post-conditions, default arguments, etc. of the virtual functions should be preserved.

> Also, the behavior of an overridden virtual function **should not** deviate from the intent of the base class. Remember that derived classes are subsets, not supersets, of their base classes.

8.28 Inherited non-virtual methods **must not** be overloaded or hidden.

8.29 A virtual function in a base class **should only** be implemented in the base class if its behavior is always valid default behavior for *any* derived class.

8.30 If a method in a base class is not expected to be overridden in any derived class, then the method **should not** be declared virtual.

8.31 If each derived class has to provide specific behavior for a base class virtual function, then it **should** be declared *pure virtual*.

8.32 Virtual functions **must not** be called in a class constructor or destructor. Doing so is undefined behavior. Even if it seems to work correctly, it is fragile and potentially non-portable.

Inline functions

Function inlining is a compile time operation and the full definition of an inline function must be seen wherever it is called. Thus, the implementation of every function to be inlined must be provided in a header file.

Whether or not a function implemented in a header file is explicitly declared inline using the "inline" keyword, the compiler decides if the function will be inlined. A compiler will not inline a function that it considers too long or too complex (e.g., if it contains complicated conditional logic). When a compiler inlines a function, it replaces the function call with the body of the function. Most modern compilers do a good job of deciding when inlining is a good choice.

It is possible to specify function attributes and compiler flags that can force a compiler to inline a function. Such options should be applied with care to prevent excessive inlining that may cause executable code bloat and/or may make debugging difficult.

Note: When in doubt, don't use the "inline" keyword and let the compiler decide whether to inline a function.

Inline short, simple functions

8.33 Simple, short frequently called functions, such as accessors, that will almost certainly be inlined by most compilers **should** be implemented inline in header files.

Only inline a class constructor when it makes sense

8.34 Class constructors **should not** be inlined in most cases.

A class constructor implicitly calls the constructors for its base classes and initializes some or all of its data members, potentially calling more constructors. If a constructor is inlined, the construction and initialization needed for its members and bases will appear at every object declaration.

Note: **Exception:** A class/struct that has only POD members, is not a subclass, and does not explicitly declare a destructor, can have its constructor safely inlined in most cases.

Do not inline virtual methods

8.35 Virtual functions **must not** be inlined due to polymorphism.

For example, do not declare a virtual class member function as:

```
inline virtual void foo( ) { }
```

In most circumstances, a virtual method cannot be inlined because a compiler must do runtime dispatch on a virtual method when it doesn't know the complete type at compile time.

Note: **Exception:** It is safe to define an empty destructor inline in an abstract base class with no data members.

Important: Should we add something about C++11 'final' keyword???

Function and operator overloading

There's a fine line between clever and...

8.36 Operator overloading **must not** be used to be clever to the point of obfuscation and cause others to think too hard about an operation. Specifically, an overloaded operator must preserve "natural" semantics by appealing to common conventions and **must** have meaning similar to non-overloaded operators of the same name.

Overloading operators can be beneficial, but **should not** be overused or abused. Operator overloading is essentially "syntactic sugar" and an overloaded operator is just a function like any other function. An important benefit of overloading is that it often allows more appropriate syntax that more easily communicates the meaning of an operation. The resulting code can be easier to write, maintain, and understand, and it may be more efficient since it may allow the compiler to take advantage of longer expressions than it could otherwise.

Overload consistently

8.37 Function overloading **must not** be used to define functions that do conceptually different things.

Someone reading declarations of overloaded functions should be able to assume (and rightfully so!) that functions with the same name do something very similar.

8.38 If an overloaded virtual method in a base class is overridden in a derived class, all overloaded methods with the same name in the base class **must** be overridden in the derived class.

This prevents unexpected behavior when calling such member functions. Remember that when a virtual function is overridden, the overloads of that function in the base class **are not visible** to the derived class.

Common operators

8.39 Both boolean operators "==" and "!=" **should** be implemented if one of them is.

For consistency and correctness, the "!=" operator **should** be implemented using the "==" operator implementation. For example:

```
bool MyClass::operator!= (const MyClass& rhs)
{
   return !(this == rhs);
}
```

8.40 Standard operators, such as "&&", "||", and "," (i.e., comma), **must not** be overloaded.

Built-in versions of these operators are typically treated specially by a compiler. Thus, programmers cannot implement their full semantics. This can cause confusion. For example, the order of operand evaluation cannot be guaranteed when overloading operators "&&" or "||". This may cause problems as someone may write code that assumes that evaluation order is the same as the built-in versions.

Function arguments

Consistent argument order makes interfaces easier to use

8.41 Function arguments **must** be ordered similarly for all routines in an Axom component.

Common conventions are either to put all input arguments first, then outputs, or vice versa. Input and output arguments **must not** be mixed in a function signature. Parameters that are both input and output can make the best choice unclear. Conventions consistent with related functions **must** always be followed. When adding a new parameter to an existing method, the established ordering convention **must** be followed.

Note: When adding an argument to an existing method, do not just stick it at the end of the argument list.

Pointer and reference arguments and const

8.42 Each function argument that is not a built-in type (i.e., int, double, char, etc.) **should** be passed either by reference or as a pointer to avoid unnecessary copies.

8.43 Each function reference or pointer argument that is not changed by the function **must** be declared "const".

Always name function arguments

8.44 Each argument in a function declaration **must** be given a name that exactly matches the function implementation.

For example, use:

```
void computeSomething(int op_count, int mode);
```

not:

```
void computeSomething(int, int);
```

Function return points

8.45 Each function **should** have exactly one return point to make control logic clear.

Functions with multiple return points tend to be a source of errors when trying to understand or modify code, especially if there are multiple return points within a scope. Such code can always be refactored to have a single return point by using local scope boolean variables and/or different control logic.

A function **may** have two return points if the first return statement is associated with error condition check, for example. In this case, the error check **should** be performed at the start of the function body before other statements are reached. For example, the following is a reasonable use of two function return points because the error condition check and the return value for successful completion are clearly visible:

```
int computeSomething(int in_val)
{
   if (in_val < 0) { return -1; }

   // ...rest of function implementation...

   return 0;
}
```

Note: Exception. If multiple return points actually fit well into the logical structure of some code, they **may** be used. For example, a routine may contain extended if/else conditional logic with several "if-else" clauses. If needed, the code may be more clear if each clause contains a return point.

Proper type usage

8.46 The "bool" type **should** be used instead of "int" for boolean true/false values.

8.47 The "string" type **should** be used instead of "char*".

The string type supports and optimizes many character string manipulation operations which can be error-prone and less efficient if implemented explicitly using "char*" and standard C library functions. Note that "string" and "char*" types are easily interchangeable, which allows C++ string data to be used when interacting with C routines.

8.48 An enumeration type **should** be used instead of macro definitions or "int" data for sets of related constant values.

Since C++ enums are distinct types with a compile-time specified set of values, there values cannot be implicitly cast to integers or vice versa – a "static_cast" operator must be used to make the conversion explicit. Thus, enums provide type and value safety and scoping benefits.

In many cases, the C++11 *enum class* construct **should** be used since it provides stronger type safety and better scoping than regular enum types.

Templates

8.49 A class or function **should** only be made a template when its implementation is independent of the template type parameter.

Note that class member templates (e.g., member functions that are templates of a class that is not a template) are often useful to reduce code redundancy.

8.50 Generic templates that have external linkage **must** be defined in the header file where they are declared since template instantiation is a compile time operation. Implementations of class templates and member templates that are non-trivial **should** be placed in the class header file after the class definition.

Use const to enforce correct usage

8.51 The "const" qualifier **should** be used for variables and methods when appropriate to clearly indicate usage and to take advantage of compiler-based error-checking. For example, any class member function that does not change the state of the object on which it is called **should** be declared "const"

> Constant declarations can make code safer and less error-prone since they enforce intent at compile time. They also improve code understanding because a constant declaration clearly indicates that the state of a variable or object will not change in the scope in which the declaration appears.

8.52 Any class member function that does not change a data member of the associated class **must** be declared "const".

> This enables the compiler to detect unintended usage.

8.53 Any class member function that returns a class data member that should not be changed by the caller **must** be declared "const" and **must** return the data member as a "const" reference or pointer.

> Often, both "const" and non-"const" versions of member access functions are needed so that callers may declare the variable that holds the return value with the appropriate "const-ness".

Casts and type conversions

Avoid C-style casts, const_cast, and reinterpret_cast

8.54 C-style casts **must not** be used.

> All type conversions **must** be done explicitly using the named C++ casting operators; i.e., "static_cast", "const_cast", "dynamic_cast", "reinterpret_cast".

8.55 The "const_cast" operator **should** be avoided.

> Casting away "const-ness" is usually a poor programming decision and can introduce errors.

Note: **Exception:** It may be necessary in some circumstances to cast away const-ness, such as when calling const-incorrect APIs.

8.56 The "reinterpret_cast" **must not** be used unless absolutely necessary.

> This operator was designed to perform a low-level reinterpretation of the bit pattern of an operand. This is needed only in special circumstances and circumvents type safety.

Use the explicit qualifier to avoid unwanted conversions

8.57 A class constructor that takes a single *non-default* argument, or a single argument with a *default* value, **must** be declared "explicit".

> This prevents compilers from performing unexpected (and, in many cases, unwanted!) implicit type conversions. For example:

```
class MyClass
{
public:
   explicit MyClass(int i, double x = 0.0);
};
```

Note that, without the explicit declaration, an implicit conversion from an integer to an object of type MyClass could be allowed. For example:

```
MyClass mc = 2;
```

Clearly, this is confusing. The "explicit" keyword forces the following usage pattern:

```
MyClass mc(2);
```

to get the same result, which is much more clear.

Memory management

Allocate and deallocate memory in the same scope

8.58 Memory **should** be deallocated in the same scope in which it is allocated.

8.59 All memory allocated in a class constructor **should** be deallocated in the class destructor.

Note that the intent of constructors is to acquire resources and the intent of destructors is to free those resources.

8.60 Pointers **should** be set to null explicitly when memory is deallocated. This makes it easy to check pointers for "null-ness" when needed.

Use new/delete consistently

8.61 Data managed exclusively within C++ code **must** be allocated and deallocated using the "new" and "delete" operators.

The operator "new" is type-safe, simpler to use, and less error-prone than the "malloc" family of C functions. C++ new/delete operators **must not** be combined with C malloc/free functions.

8.62 Every C++ array deallocation statement **must** include "[ ]" (i.e., "delete[ ]") to avoid memory leaks.

The rule of thumb is: when "[ ]" appears in the allocation, then "[ ]" **must** appear in the corresponding deallocation statement.

3.2.9 9 Code Formatting

Conditional statements and loops

9.1 Curly braces **should** be used in all conditionals, loops, etc. even when the content inside the braces is a "one-liner".

This helps prevent coding errors and misinterpretation of intent. For example, this:

```
if (done) { ... }
```

is preferable to this:

```
if (done) ...
```

9.2 One-liners **may** be used for "if" conditionals with "else/else if" clauses when the resulting code is clear.

For example, either of the following styles **may** be used:

```
if (done) {
   id = 3;
} else {
   id = 0;
}
```

or:

```
if (done) { id = 3; } else { id = 0; }
```

9.3 Complex "if/else if" conditionals with many "else if" clauses **should** be avoided.

Such statements can always be refactored using local boolean variables or "switch" statements. Doing so often makes code easier to read and understand and may improve performance.

9.4 An explicit test for zero/nonzero **must** be used in a conditional unless the tested quantity is a boolean or pointer type.

For example, a conditional based on an integer value should use:

```
if (num_lines != 0) { ... }
```

not:

```
if (num_lines) { ... }
```

White space and code alignment

Most conventions for indentation, spacing and code alignment preferred by the team are enforced by using the *uncrustify* tool. It can be run from the top-level Axom directory...

Important: Insert section on our use of uncrustify for code formatting.

Not all preferred formatting conventions are supported by uncrustify. The following guidelines provide additional recommendations to make code easier to read and understand.

White space enhances code readability

9.5 Blank lines and indentation **should** be used throughout code to enhance readability.

Examples of helpful white space include:

- Between operands and operators in arithmetic expressions.
- After reserved words, such as "while", "for", "if", "switch", etc. and before the parenthesis or curly brace that follows.
- After commas separating arguments in functions.
- After semi-colons in for-loop expressions.

- Before and after curly braces in almost all cases.

9.6 White space **must not** appear between a function name and the opening parenthesis to the argument list. In particular, if a function call is broken across source lines, the break **must not** come between the function name and the opening parenthesis.

9.7 Tabs **must not** be used for indentation since this can be problematic for developers with different text editor settings.

Vertical alignment helps to show scope

9.8 When function arguments (in either a declaration or implementation) appear on multiple lines, the arguments **should** be vertically aligned for readability.

9.9 All statements within a function body **should** be indented within the surrounding curly braces.

9.10 All source lines in the same scope **should** be vertically aligned. Continuation of previous lines **may** be indented if it make the code easier to read.

Break lines where it makes sense

9.11 When a line is broken at a comma or semi-colon, it **should** be broken after the comma or semi-colon, not before. This helps make it clear that the statement continues on the next line.

9.12 When a source line is broken at an arithmetic operator (i.e., +, -, etc.), it **should** be broken after the operator, not before.

Use parentheses for clarity

9.13 Parentheses **should** be used in non-trivial mathematical and logical expressions to clearly indicate structure and intended order of operations. Do not assume everyone who reads the code knows all the rules for operator precedence.

3.2.10 10 Common Code Development Macros, Types, etc.

This section provides guidelines for consistent use of macros and types defined in Axom components, such as "axom_utils" and "slic", and in our build system that we use in day-to-day code development.

Important: Code that is guarded with macros described in this section **must not** change the *externally-observable* execution behavior of the code.

The macros are intended to help users and developers avoid unintended or potentially erroneous usage, etc. not confuse them.

Unused variables

10.2 To silence compiler warnings and express variable usage intent more clearly, macros in the *AxomMacros.hpp* header file in the source include directory **must** be used when appropriate. For example,:

```
void my_function(int x, int AXOM_DEBUG_PARAM(y))
{
  // use variable y only for debug compilation
}
```

Here, the *AXOM_DEBUG_PARAM* macro indicates that the variable 'y' is only used when the code is compiled in debug mode. It also removes the variable name in the argument list in non-debug compilation to prevent unwanted compiler warnings.

Please see the *AxomMacros.hpp* header file for other available macros and usage examples.

Disabling compiler-generated methods

10.3 To disable compiler-generated class/struct methods when this is desired and to clearly express this intent, the *AXOMMacros.hpp* header file in source include directory contains macros that **should** be used for this purpose. See *Avoid issues with compiler-generated class methods* for more information about compiler-generated methods.

Please see the *AXOMMacros.hpp* header file for other available macros and usage examples.

Conditionally compiled code

10.4 Macros defined by Axom build system **must** be used to control conditional code compilation.

For example, complex or multi-line code that is intended to be exposed only for a debug build **must** be guarded using the *AXOM_DEBUG* macro:

```
void MyMethod(...)
{
#if defined(AXOM_DEBUG)
  // Code that performs debugging checks on object state, method args,
  // reports diagnostic messages, etc. goes here
#endif

   // rest of method implementation
}
```

The Axom build system provides various other macros for controlling conditionally-compiled code. The macro constants will be defined based on CMake options given when the code is configured. Please see the *config.hpp* header file in the source include directory for a complete list.

Error handling

10.5 Macros provided in the "slic" component **should** be used to provide runtime checks for incorrect or questionable usage and informative messages for developers and users.

Runtime checks for incorrect or questionable usage and generation of informative warning, error, notice messages can be a tremendous help to users and developers. This is an excellent way to provide run-time debugging capabilities in code. Using the "slic" macros ensures that syntax and meaning are consistent and that output information is handled similarly throughout the code.

When certain conditions are encountered, the macros can emit failed boolean expressions and descriptive messages that help to understand potentially problematic usage. Here's an example of common *SLIC* macro usage in AXOM:

```
Bar* myCoolFunction(int in_val, Foo* in_foo)
{
  if ( in_val < 0 || in_foo == nullptr )
  {
    SLIC_CHECK_MSG( in_val >= 0, "in_val must be non-negative" );
    SLIC_CHECK( in_foo != nullptr );
    return nullptr;
  } else if ( !in_foo->isSet() ) {
    SLIC_CHECK_MSG( in_foo->isSet(),
                    "in_foo is not set, will use default settings");
    const int val = in_val >= 0 ? in_val : DEFAULT_VAL;
    in_foo->setDefaults( val );
  }

  Bar* bar = new Bar(in_foo);

  return bar;
}
```

This example uses slic macros that are only active when the code is compiled in debug mode. When compiled in release mode, for example, the macros are empty and so do nothing. Also, when a condition is encountered that is problematic, such as 'in_val < 0' or 'in_foo == nullptr', the code will emit the condition and an optional message and not halt. This allows calling code to catch the issue (in this case a null return value) and react. There are other macros (e.g., SLIC_ASSERT) that will halt the code if that is desired.

Slic macros operate in one of two compilation-defined modes. Some macros are active only in for a debug compile. Others are active for any build type. Macros provided for each of these modes can be used to halt the code or not after describing the condition that triggered them. The following table summarizes the SLIC macros.

Macro type	When active?	Halts code?
ERROR	Always	Yes
WARNING	Always	No
ASSERT	Debug only	Yes
CHECK	Debug only	No

Typically, we use macros ERROR/WARNING macros rarely. They are used primarily to catch cases that are obvious programming errors or would put an application in a state where continuing is seriously in doubt. CHECK macros are used most often, since they provide useful debugging information and do not halt the code – they allow users to catch cases from which they can recover. ASSERT macros are used in cases where halting the code is desired, but only in debug mode.

Please see the *slic.hpp* header file to see which macros are available and how to use them.

Important: It is important to apply these macros judiciously so that they benefit users and other developers. We want to help folks use our software correctly and not "spam" them with too much information.

3.2.11 11 Portability, Compilation, and Dependencies

C++ is a huge language with many advanced and powerful features. To avoid over-indulgence and obfuscation, we would like to avoid C++ feature bloat. By constraining or even banning the use of certain language features and libraries, we hope to keep our code simple and portable. We also hope to avoid errors and problems that may occur when language features are not completely understood or not used consistently. This section lists such restrictions and explains why use of certain features is constrained or restricted.

Portability

Nothing beyond C++11

11.1 C++ language features beyond standard C++11 **must not** be used unless reviewed by the team and verified that the features are supported by all compilers we need to support.

Changing this guideline requires full consensus of all team members.

No non-standard language constructs

11.2 Special non-standard language constructs, such as GNU extensions, **must not** be used if they hinder portability.

Note: Any deviation from these C++ usage requirements must be agreed on by all members of the team and vetted with our main application users.

Compilation

Avoid conditional compilation

11.3 Excessive use of the preprocessor for conditional compilation at a fine granularity (e.g., selectively including or removing individual source lines) **should** be avoided.

While it may seem convenient, this practice typically produces confusing and error-prone code. Often, it is better to refactor the code into separate routines or large code blocks subject to conditional compilation where it is more clear.

Code reviews by team members will dictate what is/is not acceptable.

The compiler is your friend

11.4 Developers **should** rely on compile-time and link-time errors to check for code correctness and invariants.

Errors that occur at run-time and which depend on specific control flow and program state are inconvenient for users and can be difficult to detect and fix.

Important: Add specific guidance on how this should be done...

Minimize dependencies on third-party libraries (TPLs)

11.5 While it is generally desirable to avoid recreating functionality that others have already implemented, we **should** limit third-party library dependencies for Axom to make it easier for users. We are a library, and everything we necessarily depend on will become a dependency for our user.

Before introducing any significant TPL dependency on Axom (e.g., hdf5), it must be agreed on by the development team and vetted with our main users.

11.6 Unless absolutely necessary, any TPL we depend on **must not** be exposed through any public interface in Axom.

3.2.12 References and Useful Resources

Most of the guidelines here were gathered from the following list sources. The list contains a variety of useful resources for programming in C++ beyond what is presented in these guidelines.

1. *The Chromium Projects: C++ Dos and Don'ts*. https://chromium.googlesource.com/chromium/src/+/HEAD/styleguide/c++/c++-dos-and-donts.md
2. Dewhurst, S., *C++ Gotchas: Avoiding Common Problems in Coding and Design*, Addison-Wesley, 2003.
3. Dewhurst S., *C++ Common Knowledge: Essential Intermediate Programming*, Addison-Wesley, 2005.
4. *Doxygen manual*, http://www.doxygen.nl/manual/
5. *Google C++ Style Guide*, https://google.github.io/styleguide/cppguide.html
6. *ISO/IEC 14882:2011 C++ Programming Language Standard*.
7. Josuttis, N., *The C++ Standard Library: A Tutorial and Reference, Second Edition*, Addison-Wesley, 2012.
8. *LLVM Coding Standards*, llvm.org/docs/CodingStandards.html
9. Meyers, S., *More Effective C++: 35 New Ways to Improve Your Programs and Designs*, Addison-Wesley, 1996.
10. Meyers, S., *Effective STL: 50 Specific Ways to Improve Your Use of the Standard Template Library*, Addison-Wesley, 2001.
11. Meyers, S., *Effective C++: 55 Specific Ways to Improve Your Programs and Designs (3rd Edition)*, Addison-Wesley, 2005.
12. Meyers, S., *Effective Modern C++: 42 Specific Ways to Improve Your Use of C++11 and C++14*, O'Reilly.
13. Programming Research Ltd., *High-integrity C++ Coding Standard, Version 4.0*, 2013.
14. Sutter, H. and A. Alexandrescu, *C++ Coding Standards: 101 Rules, Guidelines, and Best Practices*, Addison-Wesley, 2005.

3.3 Indices and tables

- genindex
- search

CHAPTER 4

Communicating with the Axom Team

4.1 Mailing Lists

The project maintains two email lists:

- 'axom-users@llnl.gov' is how Axom users can contact developers for questions, report issues, etc.
- 'axom-dev@llnl.gov' is for communication among team members.

4.2 Chat Room

We also have a chat room on LLNL's Cisco Jabber instance called 'Axom Dev'. It is open to anyone on the llnl network. Just log onto Jabber and join the room.

4.3 Atlassian Tools

The main interaction hub for the Axom software is the Atlassian tool suite on the Livermore Computing Collaboration Zone (CZ). These tools can be accessed through the MyLC Portal.

Direct links to the Axom Atlassian projects/spaces are:

- Bitbucket project/git repository
- Jira issue tracker
- Bamboo continuous integration
- Confluence (primarily for developers)

4.4 LC Groups

Access to Axom projects/spaces in these Atlassian tools requires membership in the *axom* group on LC systems. Please contact the team for group access by sending an email request to 'axom-dev@llnl.gov'.

CHAPTER 5

Axom Copyright and License Information

Please see the *Axom License*.

Copyright (c) 2017-2020, Lawrence Livermore National Security, LLC. Produced at the Lawrence Livermore National Laboratory.

LLNL-CODE-741217

5.1 License Info

5.1.1 Axom License

Copyright (c) 2017-2020, Lawrence Livermore National Security, LLC. All rights reserved.

Redistribution and use in source and binary forms, with or without modification, are permitted provided that the following conditions are met:

- Redistributions of source code must retain the above copyright notice, this list of conditions and the following disclaimer.
- Redistributions in binary form must reproduce the above copyright notice, this list of conditions and the following disclaimer in the documentation and/or other materials provided with the distribution.
- Neither the name of the copyright holder nor the names of its contributors may be used to endorse or promote products derived from this software without specific prior written permission.

THIS SOFTWARE IS PROVIDED BY THE COPYRIGHT HOLDERS AND CONTRIBUTORS “AS IS” AND ANY EXPRESS OR IMPLIED WARRANTIES, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE ARE DISCLAIMED. IN NO EVENT SHALL THE COPYRIGHT HOLDER OR CONTRIBUTORS BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO, PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY

WAY OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.