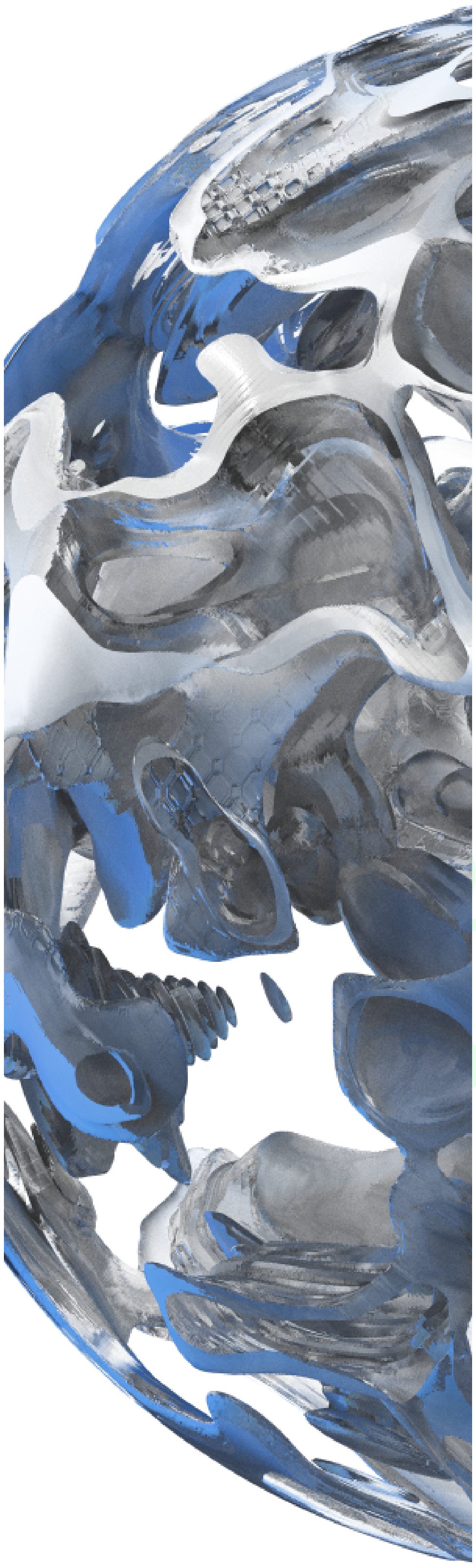


The VTK-m User's Guide

VTK-m version 1.0

Kenneth Moreland

December 16, 2016

http://m.vtk.org
http://kitware.com

Published by Kitware Inc. ©2016
All product names mentioned herein are the trademarks of their respective owners.
This document is available under a Creative Commons Attribution 4.0 International license available at [ADD URL]

This project has been funded in whole or in part with Federal funds from the Department of Energy, including from Sandia National Laboratories, Los Alamos National Laboratory, Advanced Simulation and Computing, and Oak Ridge National Laboratory.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Printed and produced in the United States of America.
ISBN number [FILL IN ISBN NUMBERS HERE]

CONTRIBUTORS

This book includes contributions from the VTK-m community including the VTK-m development team and the user community.

ABOUT THE COVER

Join the VTK-m Commuity at m.vtk.org

CONTENTS

LIST OF FIGURES

LIST OF EXAMPLES

Part I

Getting Started

CHAPTER

ONE

INTRODUCTION

High-performance computing relies on ever finer threading. Advances in processor technology include ever greater numbers of cores, hyperthreading, accelerators with integrated blocks of cores, and special vectorized instructions, all of which require more software parallelism to achieve peak performance. Traditional visualization solutions cannot support this extreme level of concurrency. Extreme scale systems require a new programming model and a fundamental change in how we design algorithms. To address these issues we created VTK-m: the visualization toolkit for multi-/many-core architectures.

VTK-m supports a number of algorithms and the ability to design further algorithms through a top-down design with an emphasis on extreme parallelism. VTK-m also provides support for finding and building links across topologies, making it possible to perform operations that determine manifold surfaces, interpolate generated values, and find adjacencies. Although VTK-m provides a simplified high-level interface for programming, its template-based code removes the overhead of abstraction.

VTK-m simplifies the development of parallel scientific visualization algorithms by providing a framework of supporting functionality that allows developers to focus on visualization operations. Consider the listings in Figure 1.1 that compares the size of the implementation for the Marching Cubes algorithm in VTK-m with the equivalent reference implementation in the CUDA software development kit. Because VTK-m internally manages the parallel distribution of work and data, the VTK-m implementation is shorter and easier to maintain. Additionally, VTK-m provides data abstractions not provided by other libraries that make code written in VTK-m more versatile.

Did you know?

VTK-m is written in C++ and makes extensive use of templates. The toolkit is implemented as a header library, meaning that all the code is implemented in header files (with extension .h*) and completely included in any code that uses it. This allows the compiler to inline and specialize code for better performance.*

1.1 How to Use This Guide

This user's guide is organized into three parts to help guide novice to advanced users and to provide a convenient reference. Part I, Getting Started, provides everything needed to get up and running with VTK-m. In this part we learn the basics of reading and writing data files, using filters to process data, and perform basic rendering to view the results.

Part II, Using VTK-m, dives deeper into the VTK-m library and provides all the information needed to customize VTK-m's data structures and support multiple devices.

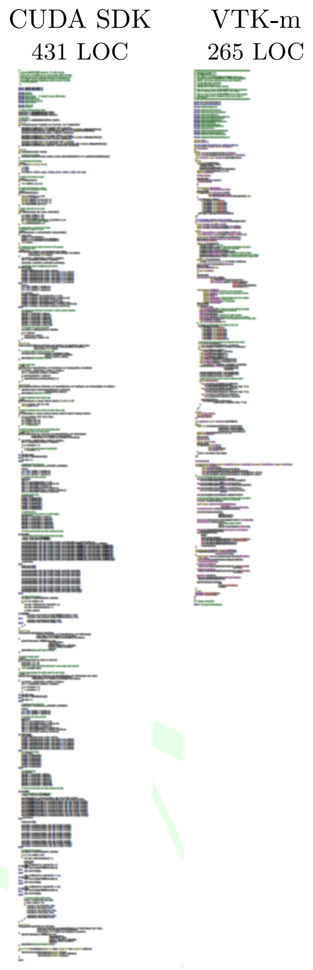


Figure 1.1: Comparison of the Marching Cubes algorithm in VTK-m and the reference implementation in the CUDA SDK. Implementations in VTK-m are simpler, shorter, more general, and easier to maintain. (Lines of code (LOC) measurements come from cloc.)

Part III, Developing with VTK-m, documents how to use VTK-m's framework to develop new or custom visualization algorithms. This part describes how worklets are used to implement and execute algorithms and how to use worklets to implement new filters. Part III also describes the facilities available in the execution environment that help write visualization algorithms.

Part IV, Advanced Development, exposes the inner workings of VTK-m and allows you to design new algorithmic structures not already available. [This might be removed in the first version of the book.]

1.2 Conventions Used in This Guide

When documenting the VTK-m API, the following conventions are used.

- Filenames are printed in a sans serif font.
- C++ code is printed in a `monospace font`.

- Macros and namespaces from VTK-m are printed in `red`.
- Identifiers from VTK-m are printed in `blue`.
- Signatures, described in Chapter 14, and the tags used in them are printed in `green`.

This guide provides actual code samples throughout its discussions to demonstrate their use. These examples are all valid code that can be compiled and used although it is often the case that code snippets are provided. In such cases, the code must be placed in a larger context.

Did you know?

In this guide we periodically use these ***Did you know?*** *boxes to provide additional information related to the topic at hand.*

Common Errors

Common Errors *blocks are used to highlight some of the common problems or complications you might encounter when dealing with the topic of discussion.*

CHAPTER

TWO

BUILD AND INSTALL VTK-M

Before we begin describing how to develop with VTK-m, we have a brief overview of how to build VTK-m, optionally install it on your system, and start your own programs that use VTK-m.

2.1 Getting VTK-m

VTK-m is an open source software product where the code is made freely available. To get the latest released version of VTK-m, go to the VTK-m releases page:

http://m.vtk.org/index.php/VTK-m_Releases

For access to the most recent work, the VTK-m development team provides public anonymous read access to their main source code repository. The main VTK-m repository on a gitlab instance hosted at Kitware, Inc. The repository can be browsed from its project web page:

https://gitlab.kitware.com/vtk/vtk-m

The source code in the VTK-m repository is access through the git version control tool. If you have not used git before, there are several resources available to help you get familiar with it. Github has a nice setup guide (https://help.github.com/articles/set-up-git) to help you get up and running quickly. For more complete documentation, we recommend the *Pro Git* book (https://git-scm.com/book).

To get a copy of the VTK-m repository, issue a git clone command.

Example 2.1: Cloning the main VTK-m git repository.

```
git clone https://gitlab.kitware.com/vtk/vtk-m.git
```

The git clone command will create a copy of all the source code to your local machine. As time passes and you want to get an update of changes in the repository, you can do that with the git pull command.

Example 2.2: Updating a git repository with the pull command.

```
git pull
```

Did you know?

The proceeding examples for using git are based on the git *command line tool, which is particularly prevalent on Unix-based and Mac systems. There also exist several GUI tools for accessing git repositories. These tools each have their own interface and they can be quite different. However, they all should have roughly equivalent commands named "clone" to download a repository given a url and "pull" to update an existing repository.*

2.2 Configure VTK-m

VTK-m uses a cross-platform configuration tool named CMake to simplify the configuration and building across many supported platforms. CMake is available from many package distribution systems and can also be downloaded for many platforms from http://cmake.org.

Most distributions of CMake come with a convenient GUI application (cmake-gui) that allows you to browse all of the available configuration variables and run the configuration. Many distributions also come with an alternative terminal-based version (ccmake), which is helpful when accessing remote systems where creating GUI windows is difficult.

One helpful feature of CMake is that it allows you to establish a build directory separate from the source directory, and the VTK-m project requires that separation. Thus, when you run CMake for the first time, you want to set the build directory to a new empty directory and the source to the downloaded or cloned files. The following example shows the steps for the case where the VTK-m source is cloned from the git repository. (If you extracted files from an archive downloaded from the VTK-m web page, the instructions are the same from the second line down.)

Example 2.3: Running CMake on a cloned VTK-m repository.

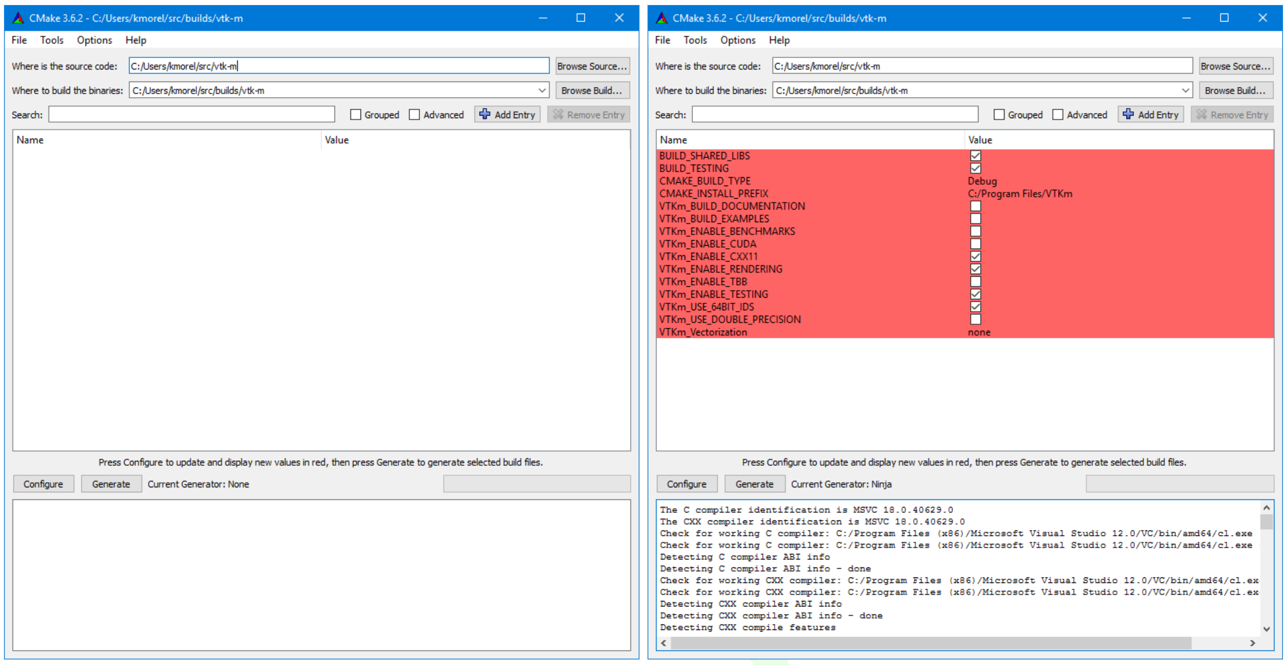
```
git clone https://gitlab.kitware.com/vtk/vtk-m.git
mkdir vtkm-build
cd vtkm-build
cmake-gui ../vtk-m
```

The first time the CMake GUI runs, it initially comes up blank as shown at left in Figure 2.1. Verify that the source and build directories are correct (located at the top of the GUI) and then click the "Configure" button near the bottom. The first time you run configure, CMake brings up a dialog box asking what generator you want for the project. This allows you to select what build system or IDE to use (e.g. make, ninja, Visual Studio). Once you click "Finish," CMake will perform its first configuration. Don't worry if CMake gives an error about an error in this first configuration process.

Common Errors

Most options in CMake can be reconfigured at any time, but not the compiler and build system used. These must be set the first time configure is run and cannot be subsequently changed. If you want to change the compiler or the project file types, you will need to delete everything in the build directory and start over.

After the first configuration, the CMake GUI will provide several configuration options as shown in Figure 2.1 on the right. You now have a chance to modify the configuration of VTK-m, which allows you to modify both



Where is the source code: C:/Users/kmorel/src/vtk-m

Where to build the binaries: C:/Users/kmorel/src/builds/vtk-m

Press Configure to update and display new values in red, then press Generate to generate selected build files.

Current Generator: None

Name	Value
BUILD_SHARED_LIBS	✓
BUILD_TESTING	✓
CMAKE_BUILD_TYPE	Debug
CMAKE_INSTALL_PREFIX	C:/Program Files/VTKm
VTKm_BUILD_DOCUMENTATION	☐
VTKm_BUILD_EXAMPLES	☐
VTKm_ENABLE_BENCHMARKS	☐
VTKm_ENABLE_CUDA	☐
VTKm_ENABLE_CXX11	✓
VTKm_ENABLE_RENDERING	✓
VTKm_ENABLE_TBB	☐
VTKm_ENABLE_TESTING	✓
VTKm_USE_64BIT_IDS	✓
VTKm_USE_DOUBLE_PRECISION	☐
VTKm_Vectorization	none

Current Generator: Ninja

```
The C compiler identification is MSVC 18.0.40629.0
The CXX compiler identification is MSVC 18.0.40629.0
Check for working C compiler: C:/Program Files (x86)/Microsoft Visual Studio 12.0/VC/bin/amd64/cl.exe
Check for working C compiler: C:/Program Files (x86)/Microsoft Visual Studio 12.0/VC/bin/amd64/cl.exe
Detecting C compiler ABI info
Detecting C compiler ABI info - done
Check for working CXX compiler: C:/Program Files (x86)/Microsoft Visual Studio 12.0/VC/bin/amd64/cl.ex
Check for working CXX compiler: C:/Program Files (x86)/Microsoft Visual Studio 12.0/VC/bin/amd64/cl.ex
Detecting CXX compiler ABI info
Detecting CXX compiler ABI info - done
Detecting CXX compile features
```

Figure 2.1: The CMake GUI configuring the VTK-m project. At left is the initial blank configuration. At right is the state after a configure pass.

the behavior of the compiled VTK-m code as well as find components on your system. Using the CMake GUI is usually an iterative process where you set configuration options and re-run "Configure." Each time you configure, CMake might find new options, which are shown in red in the GUI.

It is often the case during this iterative configuration process that configuration errors occur. This can occur after a new option is enabled but CMake does not automatically find the necessary libraries to make that feature possible. For example, to enable TBB support, you may have to first enable building TBB, configure for TBB support, and then tell CMake where the TBB include directories and libraries are.

Once you have set all desired configuration variables and resolved any CMake errors, click the "Generate" button. This will create the build files (such as makefiles or project files depending on the generator chosen at the beginning). You can then close the CMake GUI.

There are a great number of configuration parameters available when running CMake on VTK-m. The following list contains the most common configuration parameters.

BUILD_SHARED_LIBS Determines whether static or shared libraries are built.

CMAKE_BUILD_TYPE Selects groups of compiler options from categories like Debug and Release. Debug builds are, obviously, easier to debug, but they run *much* slower than Release builds. Use Release builds whenever releasing production software or doing performance tests.

CMAKE_INSTALL_PREFIX The root directory to place files when building the install target.

VTKm_BUILD_EXAMPLES The VTK-m repository comes with an examples directory. This macro determines whether they are built.

VTKm_ENABLE_BENCHMARKS If on, the VTK-m build includes several benchmark programs. The benchmarks are regression tests for performance.

VTKm_ENABLE_CUDA Determines whether VTK-m is built to run on CUDA GPU devices.

VTKm_ENABLE_RENDERING Determines whether to build the rendering library.

VTKm_ENABLE_TBB Determines whether VTK-m is built to run on multi-core x86 devices using the Intel Threading Building Blocks library.

VTKm_ENABLE_TESTING If on, the VTK-m build includes building many test programs. The VTK-m source includes hundreds of regression tests to ensure quality during development.

VTKm_USE_64BIT_IDS If on, then VTK-m will be compiled to use 64-bit integers to index arrays and other lists. If off, then VTK-m will use 32-bit integers. 32-bit integers take less memory but could cause failures on larger data.

VTKm_USE_DOUBLE_PRECISION If on, then VTK-m will use double precision (64-bit) floating point numbers for calculations where the precision type is not otherwise specified. If off, then single precision (32-bit) floating point numbers are used. Regardless of this setting, VTK-m's templates will accept either type.

2.3 Building VTK-m

Once CMake successfully configures VTK-m and generates the files for the build system, you are ready to build VTK-m. As stated earlier, CMake supports generating configuration files for several different types of build tools. Make and ninja are common build tools, but CMake also supports building project files for several different types of integrated development environments such as Microsoft Visual Studio and Apple XCode.

The VTK-m libraries and test files are compiled when the default build is invoked. For example, if Makefiles were generated, the build is invoked by calling make in the build directory. Expanding on Example 2.3

Example 2.4: Using make to build VTK-m.

```
git clone https://gitlab.kitware.com/vtk/vtk-m.git
mkdir vtkm-build
cd vtkm-build
cmake-gui ../vtk-m
make -j
make test
make install
```

Did you know?

The Makefiles and other project files generated by CMake support parallel builds, which run multiple compile steps simultaneously. On computers that have multiple processing cores (as do almost all modern computers), this can significantly speed up the overall compile. Some build systems require a special flag to engage parallel compiles. For example, make requires the -j flag to start parallel builds as demonstrated in Example 2.4.

Common Errors

CMake allows you to switch between several types of builds including default, Debug, and Release. Programs and libraries compiled as release builds can run much *faster than those from other types of builds. Thus, it is important to perform Release builds of all software released for production or where runtime is a concern. Some integrated development environments such as Microsoft Visual Studio allow you to specify the different build types within the build system. But for other build programs, like* make*, you have to specify the build type in the* CMAKE_BUILD_TYPE *CMake configuration variable, which is described in Section 2.2.*

CMake creates several build "targets" that specify the group of things to build. The default target builds all of VTK-m's libraries as well as tests, examples, and benchmarks if enabled. The test target executes each of the VTK-m regression tests and verifies they complete successfully on the system. The install target copies the subset of files required to use VTK-m to a common installation directory. The install target may need to be run as an administrator user if the installation directory is a system directory.

Did you know?

A good portion of VTK-m is a header-only library, which does not need to be built in a traditional sense. However, VTK-m contains a significant amount of tests to ensure that the header code does compile and run correctly on a given system. If you are not concerned with testing a build on a given system, you can turn off building the testing, benchmarks, and examples using the CMake configuration variables described in Section 2.2. This can shorten the VTK-m compile time.

2.4 Linking to VTK-m

Ultimately, the value of VTK-m is the ability to link it into external projects that you write. The header files and libraries installed with VTK-m are typical, and thus you can link VTK-m into a software project using any type of build system. However, VTK-m comes with several CMake configuration files that simplify linking VTK-m into another project that is also managed by CMake. Thus, the documentation in this section is specifically for finding and configuring VTK-m for CMake projects.

VTK-m can be configured from an external project using the `find_package` CMake function. The behavior and use of this function is well described in the CMake documentation. The first argument to `find_package` is the name of the package, which in this case is `VTKm`. CMake configures this package by looking for a file named VTKmConfig.cmake, which will be located in the lib directory of the install or build of VTK-m. The configurable CMake variable VTKm_DIR can be set to the directory that contains this file.

Did you know?

The CMake `find_package` *function also supports several features not discussed here including specifying a minimum or exact version of VTK-m and turning off some of the status messages. See the CMake documentation for more details.*

The CMake package for VTK-m is broken down into components that let you load particular features of VTK-m. Package components can be specified with the `COMPONENTS` and `OPTIONAL_COMPONENTS` arguments to the `find_package` function. The following example demonstrates using `find_package` to find the VTK-m package that requires the Serial backend as well as the Rendering and OpenGL features as well as optionally using the TBB and CUDA backends.

Example 2.5: Loading VTK-m configuration from an external CMake project.

```
find_package(VTKm REQUIRED
  COMPONENTS Serial OpenGL Rendering
  OPTIONAL_COMPONENTS TBB CUDA
  )
```

The following components are available. Many of the features for these components are described elsewhere within this book.

Base The "base" configuration required for using any part of VTK-m. This component is loaded automatically even if no components are specified in `find_package`.

Serial The serial backend for VTK-m, which is useful for debugging and when no other backend is available.

OpenGL Support for the integration of OpenGL features with VTK-m.

OSMesa Support for creating off screen canvases using the OSMesa library.

EGL Support for creating off screen canvases using the EGL library.

GLFW A convenience component that loads the necessary configuration to use the GLFW library, which provides a cross-platform interface for creating OpenGL windows.

GLUT A convenience component that loads the necessary configuration to use the GLUT library, which provides a cross-platform interface for creating OpenGL windows.

Interop Support for transferring VTK-m array data directly to OpenGL objects.

Rendering Use of the lightweight VTK-m rendering library, which provides basic rendering of VTK-m data objects.

TBB The Intel Threading Building Blocks (TBB) backend for VTK-m, which uses multiple cores and threads for parallel processing.

CUDA The CUDA backend for VTK-m, which uses GPU processors for parallel processing.

After the `find_package` function completes, C++ libraries and executables can be creating using the configuration variables defined. The following is a simple example of creating an executable.

Example 2.6: Loading VTK-m configuration from an external CMake project.

```
find_package(VTKm REQUIRED
  COMPONENTS Serial OpenGL Rendering
  OPTIONAL_COMPONENTS TBB CUDA
  )

add_executable(myprog myprog.cxx)
target_include_directories(myprog PRIVATE ${VTKm_INCLUDE_DIRS})
target_link_libraries(myprog ${VTKm_LIBRARIES})
target_compile_options(myprog PRIVATE ${VTKm_COMPILE_OPTIONS})
```

Common Errors

It is not sufficient to just call `find_package` *to compile code using VTK-m. You must also use the VTKm_-INCLUDE_DIRS and VTKm_LIBRARIES CMake variables to configure the compiler to load VTK-m's components. (Although technically not required, it is highly advisable to also use the VTKm_COMPILE_OPTIONS variable as well.)*

The following is a list of all the CMake variables defined when the `find_package` function completes.

VTKm_FOUND Set to true if the VTK-m CMake package, all its dependent packages, and all the specified components were successfully configured. If `find_package` was not called with the `REQUIRED` option, then this variable should be checked before attempting to use VTK-m.

VTKm_<*component_name*>_FOUND For each component specified in the `find_package` call, one of these variables will be defined as true or false depending on whether the component successfully loaded. For components specified as an `OPTIONAL_COMPONENTS` argument, the VTKm_FOUND might still be true (because all required components succeeded) while the associated VTKm_<*component_name*>_FOUND could be false if that specific component failed to load.

VTKm_INCLUDE_DIRS Contains a list of all directories that need to be specified to properly include VTK-m header files. These also include the directories needed for header files that VTK-m depends on and specified components. Targets should use the `target_include_directories` CMake function to add this list of directories to the compile commands.

VTKm_LIBRARIES Contains a list of all requested VTK-m libraries and component libraries. Targets should use the `target_link_libraries` CMake function to add this list of libraries to the link commands.

VTKm_COMPILE_OPTIONS Contains a string of options that VTK-m suggests to add to the compiler. Targets should use the `target_compile_options` CMake function to add this list of options to the compile commands.

CHAPTER

THREE

FILE I/O

Before VTK-m can be used to process data, data need to be loaded into the system. VTK-m comes with a basic file I/O package to get started developing very quickly. All the file I/O classes are declared under the `vtkm::io` namespace.

Did you know?

Files are just one of many ways to get data in and out of VTK-m. In Part II we explore efficient ways to define VTK-m data structures. In particular, Section 12.1 describes how to build VTK-m data set objects and Section 10.4 documents how to adapt data structures defined in other libraries to be used directly in VTK-m.

3.1 Readers

All reader classes provided by VTK-m are located in the `vtkm::io::reader` namespace. The general interface for each reader class is to accept a filename in the constructor and to provide a `ReadDataSet` method to load the data from disk.

The data in the file are returned in a `vtkm::cont::DataSet` object. Chapter 12 provides much more details about the contents of a data set object, but for now we treat `DataSet` as an opaque object that can be passed around readers, writers, filters, and rendering units.

3.1.1 Legacy VTK File Reader

Legacy VTK files are a simple open format for storing visualization data. These files typically have a .vtk extension. Legacy VTK files are popular because they are simple to create and read and are consequently supported by a large number of tools. The format of legacy VTK files is well documented in *The VTK User's Guide*[1]. Legacy VTK files can also be read and written with tools like ParaView and VisIt.

Legacy VTK files can be read using the `vtkm::io::reader::VTKDataSetReader` class. The constructor for this class takes a string containing the filename. The `ReadDataSet` method reads the data from the previously indicated file and returns a `vtkm::cont::DataSet` object, which can be used with filters and rendering.

[1] A free excerpt describing the file format is available at http://www.vtk.org/Wiki/File:VTK-File-Formats.pdf.

Example 3.1: Reading a legacy VTK file.

```
#include <vtkm/io/reader/VTKDataSetReader.h>

vtkm::cont::DataSet OpenDataFromVTKFile()
{
  vtkm::io::reader::VTKDataSetReader reader("data.vtk");

  return reader.ReadDataSet();
}
```

3.2 Writers

All writer classes provided by VTK-m are located in the `vtkm::io::writer` namespace. The general interface for each writer class is to accept a filename in the constructor and to provide a `WriteDataSet` method to save data to the disk. The `WriteDataSet` method takes a `vtkm::cont::DataSet` object as an argument, which contains the data to write to the file.

3.2.1 Legacy VTK File Writer

Legacy VTK files can be written using the `vtkm::io::writer::VTKDataSetWriter` class. The constructor for this class takes a string containing the filename. The `WriteDataSet` method takes a `vtkm::cont::DataSet` object and writes its data to the previously indicated file.

Example 3.2: Writing a legacy VTK file.

```
#include <vtkm/io/writer/VTKDataSetWriter.h>

void SaveDataAsVTKFile(vtkm::cont::DataSet data)
{
  vtkm::io::writer::VTKDataSetWriter writer("data.vtk");

  writer.WriteDataSet(data);
}
```

CHAPTER

FOUR

PROVIDED FILTERS

Filters are functional units that take data as input and write new data as output. Filters operate on vtkm::cont::DataSet objects, which are introduced with the file I/O operations in Chapter 3 and are described in more detail in Chapter 12. For now we treat DataSet mostly as an opaque object that can be passed around readers, writers, filters, and rendering units.

Did you know?

The structure of filters in VTK-m is significantly simpler than their counterparts in VTK. VTK filters are arranged in a dataflow network (a.k.a. a visualization pipeline) and execution management is handled automatically. In contrast, VTK-m filters are simple imperative units, which are simply called with input data and return output data.

VTK-m comes with several filters ready for use, and in this chapter we will give a brief overview of these filters. All VTK-m filters are currently defined in the vtkm::filter namespace. We group filters based on the type of operation that they do and the shared interfaces that they have. Later Part III describes the necessary steps in creating new filters in VTK-m.

4.1 Field Filters

Every vtkm::cont::DataSet object contains a list of *fields*. A field describes some numerical value associated with different parts of the data set in space. Fields often represent physical properties such as temperature, pressure, or velocity. *Field filters* are a class of filters that generate a new field. These new fields are typically derived from one or more existing fields or point coordinates on the data set. For example, mass, volume, and density are interrelated, and any one can be derived from the other two.

All field filters contain an Execute method that takes two arguments. The first argument is a vtkm::cont::DataSet object with the input data. The second argument specifies the field from which to derive a new field. The field can be specified as either a string naming a field in the input DataSet object, as a vtkm::cont::Field object, or as a coordinate system (typically retrived from a DataSet object with the GetCoordianteSystem method). See Sections 12.3 and 12.4 for more information on fields and coordinate systems, respectively.

Field filters often need more information than just a data set and a field. Any additional information is provided using methods in the filter class that changes the state. These methods are called before Execute. One such method that all field filters have is SetOutputFieldName, which specifies the name assigned to the generated field. If not specified, then the filter will use a default name.

The Execute method returns a vtkm::filter::ResultField object, which contains the state of the execution and the data generated. A ResultField object has the following methods.

IsValid Returns a bool value specifying whether the execution completed successfully. If true, then the execution was successful and the data stored in the ResultField is valid. If false, then the execution failed.

GetDataSet Returns a DataSet containing the results of the execution. The data set returned is a shallow copy of the input data with the generated field added.

GetField Returns the field information in a vtkm::cont::Field object. Field objects are described in Section 12.3.

FieldAs Given a vtkm::cont::ArrayHandle object, allocates the array and copies the generated field data into it.

The following example provides a simple demonstration of using a field filter. It specifically uses the point elevation filter, which is one of the field filters.

Example 4.1: Using PointElevation, which is a field filter.

```
VTKM_CONT
vtkm::cont::DataSet ComputeAirPressure(vtkm::cont::DataSet dataSet)
{
  vtkm::filter::PointElevation elevationFilter;

  // Use the elevation filter to estimate atmospheric pressure based on the
  // height of the point coordinates. Atmospheric pressure is 101325 Pa at
  // sea level and drops about 12 Pa per meter.
  elevationFilter.SetOutputFieldName("pressure");
  elevationFilter.SetLowPoint(0.0, 0.0, 0.0);
  elevationFilter.SetHighPoint(0.0, 0.0, 2000.0);
  elevationFilter.SetRange(101325.0, 77325.0);

  vtkm::filter::ResultField result =
      elevationFilter.Execute(dataSet, dataSet.GetCoordinateSystem());

  if (!result.IsValid())
  {
    throw vtkm::cont::ErrorControlBadValue("Failed to run elevation filter.");
  }

  return result.GetDataSet();
}
```

4.1.1 Cell Average

vtkm::filter::CellAverage is the cell average filter. It will take a data set with a collection of cells and a field defined on the points of the data set and create a new field defined on the cells. The values of this new derived field are computed by averaging the values of the input field at all the incident points. This is a simple way to convert a point field to a cell field. Both the input data set and the input field are specified as arguments to the Execute method.

The default name for the output cell field is the same name as the input point field. The name can be overridden using the SetOutputFieldName method.

In addition the standard SetOutputFieldName and Execute methods, CellAverage provides the following methods.

`SetActiveCellSet` Sets the index for the cell set to use from the `DataSet` provided to the `Execute` method. The default index is 0, which is the first cell set. If you want to set the active cell set by name, you can use the `GetCellSetIndex` method on the `DataSet` object that will be used with `Execute`.

`GetActiveCellSetIndex` Returns the index to be used when getting a cell set from the `DataSet` passed to `Execute`. Set with `SetActiveCellSet`.

4.1.2 Point Elevation

`vtkm::filter::PointElevation` computes the "elevation" of a field of point coordinates in space. The filter will take a data set and a field of 3 dimensional vectors and compute the distance along a line defined by a low point and a high point. Any point in the plane touching the low point and perpendicular to the line is set to the minimum range value in the elevation whereas any point in the plane touching the high point and perpendicular to the line is set to the maximum range value. All other values are interpolated linearly between these two planes. This filter is commonly used to compute the elevation of points in some direction, but can be repurposed for a variety of measures.

The input field (or coordinate system) is specified as the second argument to the `Execute` method. A `vtkm::cont::DataSet` that is expected to contain the field is also given but is otherwise unused. Example 4.1 gives a demonstration of the elevation filter.

The default name for the output field is "elevation", but that can be overridden using the `SetOutputFieldName` method.

In addition to the standard `SetOutputFieldName` and `Execute` methods, `PointElevation` provides the following methods.

`SetLowPoint/SetHighPoint` This pair of methods is used to set the low and high points, respectively, of the elevation. Each method takes three floating point numbers specifying the x, y, and z components of the low or high point.

`SetRange` Sets the range of values to use for the output field. This method takes two floating point numbers specifying the low and high values, respectively.

4.2 Data Set Filters

Data set filters are a class of filters that generate a new data set with a new topology. This new topology is typically derived from an existing data set. For example, a data set can be significantly altered by adding, removing, or replacing cells.

All data set filters contain an `Execute` method that takes one argument: a `vtkm::cont::DataSet` object with the input data.

Some data set filters need more information that just a data set when executing. Any additional information is provided using methods in the filter class that changes the state. These methods are called before `Execute`. One such method that all data set filters have is `SetActiveCellSet`, which selects which cell set in the input `DataSet` to operate on. Likewise, `SetActiveCoordinateSystem` selects which coordinate system to operate on. By default, the filter will operate on the first cell set and coordinate system. (See Sections 12.2 and 12.4 for more information about cell sets and coordinate systems, respectively.)

The `Execute` method returns a `vtkm::filter::ResultDataSet` object, which contains the state of the execution and the data generated. A `ResultDataSet` object has the following methods.

`IsValid` Returns a `bool` value specifying whether the execution completed successfully. If `true`, then the execution was successful and the data stored in the `ResultField` is valid. If `false`, then the execution failed.

`GetDataSet` Returns a `DataSet` containing the results of the execution.

Because the new data set is derived from existing data, it can often inherit field information from the original data. All data set filters also contain a `MapFieldOntoOutput` method to map fields from the output to the input. This method takes two arguments. The first argument is the `ResultDataSet` object returned from the last call to `Execute`. The second argument is a `vtkm::cont::Field` object that comes from the input. `MapFieldOntoOutput` returns a `bool` that is true if the field was successfully mapped and added to the output data set in the `ResultDataSet` object.

Common Errors

Not all data set filters support the mapping of all input fields to the output. If the mapping is not supported, `MapFieldOntoOutput` *will simply return false.*

The following example provides a simple demonstration of using a data set filter. It specifically uses the vertex clustering filter, which is one of the data set filters.

Example 4.2: Using `VertexClustering`, which is a data set filter.

```
vtkm::filter::VertexClustering vertexClustering;

vertexClustering.SetNumberOfDivisions(vtkm::Id3(128,128,128));

vtkm::filter::ResultDataSet result =
    vertexClustering.Execute(originalSurface);

if (!result.IsValid())
{
  throw vtkm::cont::ErrorControlBadValue("Failed to run vertex clustering.");
}

for (vtkm::IdComponent fieldIndex = 0;
     fieldIndex < originalSurface.GetNumberOfFields();
     fieldIndex++)
{
  vertexClustering.MapFieldOntoOutput(result,
                                      originalSurface.GetField(fieldIndex));
}

vtkm::cont::DataSet simplifiedSurface = result.GetDataSet();
```

4.2.1 External Faces

`vtkm::filter::ExternalFaces` is a filter that extracts all the external faces from a polyhedral data set. An external face is any face that is on the boundary of a mesh. Thus, if there is a hole in a volume, the boundary of that hole will be considered external. More formally, an external face is one that belongs to only one cell in a mesh.

Common Errors

The current implementation of the external faces filter only supports tetrahedron cell cells. Future versions will support general 3D cell shapes. [Remove this when the code is updated.]

The external faces filter has no extra methods beyond the base methods of data set filters (such as `Execute` and `MapFieldOntoOutput`) because it requires no further metadata for its operations.

4.2.2 Vertex Clustering

`vtkm::filter::VertexClustering` is a filter that simplifies a polygonal mesh. It does so by dividing space into a uniform grid of bin and then merges together all points located in the same bin. The smaller the dimensions of this binning grid, the fewer polygons will be in the output cells and the coarser the representation. This surface simplification is an important operation to support level of detail (LOD) rendering in visualization applications. Example 4.2 provides a demonstration of the vertex clustering filter.

In addition to the standard `Execute`, `MapFieldOntoOutput`, and other methods, `VertexClustering` provides the following methods.

`SetNumberOfDivisions` Set the dimensions of the uniform grid that establishes the bins used for clustering. Setting smaller numbers of dimensions produces a smaller output, but with a coarser representation of the surface. The dimensions are provided as a `vtkm::Id3`.

`GetNumberOfDimensions` Returns the number of dimensions used for binning. The dimensions are returned as a `vtkm::Id3`.

4.3 Data Set and Field Filters

Data set and field filters are a class of filters that generate a new data set with a new topology. This new topology is derived from an existing data set and at least one of the fields in the data set. For example, a field might determine how each cell is culled, clipped, or sliced.

All data set and field filters contain an `Execute` method that takes two arguments. The first argument is a `vtkm::cont::DataSet` object with the input data. The second argument specifies the field from which to derive a new field. The field can be specified as either a string naming a field in the input `DataSet` object, as a `vtkm::cont::Field` object, or as a coordinate system (typically retrieved from a `DataSet` object with the `GetCoordianteSystem` method). See Sections 12.3 and 12.4 for more information on fields and coordinate systems, respectively.

Some data set filters need more information that just a data set when executing. Any additional information is provided using methods in the filter class that changes the state. These methods are called before `Execute`. One such method that all data set filters have is `SetActiveCellSet`, which selects which cell set in the input `DataSet` to operate on. Likewise, `SetActiveCoordinateSystem` selects which coordinate system to operate on. By default, the filter will operate on the first cell set and coordinate system. (See Sections 12.2 and 12.4 for more information about cell sets and coordinate systems, respectively.)

The `Execute` method returns a `vtkm::filter::ResultDataSet` object, which contains the state of the execution and the data generated. A `ResultDataSet` object has the following methods.

`IsValid` Returns a `bool` value specifying whether the execution completed successfully. If `true`, then the execution was successful and the data stored in the `ResultField` is valid. If `false`, then the execution failed.

`GetDataSet` Returns a `DataSet` containing the results of the execution.

Because the new data set is derived from existing data, it can often inherit field information from the original data. All data set filters also contain a `MapFieldOntoOutput` method to map fields from the output to the input. This method takes two arguments. The first argument is the `ResultDataSet` object returned from the last call to `Execute`. The second argument is a `vtkm::cont::Field` object that comes from the input. `MapFieldOntoOutput` returns a `bool` that is true if the field was successfully mapped and added to the output data set in the `ResultDataSet` object.

Common Errors

Not all data set filters support the mapping of all input fields to the output. If the mapping is not supported, `MapFieldOntoOutput` *will simply return false.*

The following example provides a simple demonstration of using a data set and field filter. It specifically uses the Marching Cubes filter, which is one of the data set and field filters.

Example 4.3: Using `MarchingCubes`, which is a data set and field filter.

```
vtkm::filter::MarchingCubes marchingCubes;

marchingCubes.SetIsoValue(10.0);

vtkm::filter::ResultDataSet result =
    marchingCubes.Execute(inData, "pointvar");

if (!result.IsValid())
{
  throw vtkm::cont::ErrorControlBadValue("Failed to run Marching Cubes.");
}

for (vtkm::IdComponent fieldIndex = 0;
     fieldIndex < inData.GetNumberOfFields();
     fieldIndex++)
{
  marchingCubes.MapFieldOntoOutput(result, inData.GetField(fieldIndex));
}

vtkm::cont::DataSet isosurface = result.GetDataSet();
```

4.3.1 Marching Cubes

Contouring is one of the most fundamental filters in scientific visualization. A contour is the locus where a field is equal to a particular value. A topographic map showing curves of various elevations often used when hiking in hilly regions is an example of contours of an elevation field in 2 dimensions. Extended to 3 dimensions, a contour gives a surface. Thus, a contour is often called an *isosurface*. Marching Cubes is a well know algorithm for computing contours and is implemented by `vtkm::filter::MarchingCubes`. Example 4.3 provides a demonstration of the Marching Cubes filter.

In addition to the standard `Execute`, `MapFieldOntoOutput`, and other methods, `MarchingCubes` provides the following methods.

`SetIsoValue` Provide the value on which to extract the contour. The contour will be the surface where the field (provided to `Execute`) is equal to this value.

`GetIsoValue` Retrieve the currently set iso value.

`SetMergeDuplicatePoints` Sets a Boolean flag to determine whether coincident points in the data set should be merged. Because the Marching Cubes filter (like all filters in VTK-m) runs in parallel, parallel threads can (and often do) create duplicate versions of points. When this flag is set to true, a secondary operation will find all duplicated points and combine them together.

`GetMergeDuplicatePoints` Returns the merge duplicate points flag.

`SetGenerateNormals` Sets a Boolean flag to determine whether to generate normal vectors for the surface. Normals are used in shading calculations during rendering and can make the surface appear more smooth. Generated normals are based on the gradient of the field being contoured.

`GetGenerateNormals` Returns the generate normals flag.

4.3.2 Threshold

A threshold operation removes topology elements from a data set that do not meet a specified criterion. The `vtkm::filter::Threshold` filter removes all cells where the field (provided to `Execute`) is not between a range of values.

In addition to the standard `Execute`, `MapFieldOntoOutput`, and other methods, `Threshold` provides the following methods.

`SetLowerThreshold` Sets the lower scalar value. Any cells where the scalar field is less than this value are removed.

`SetUpperThreshold` Sets the upper scalar value. Any cells where the scalar field is more than this value are removed.

`GetLowerThreshold` Returns the lower threshold value.

`GetUpperThreshold` Returns the upper threshold value.

CHAPTER

FIVE

RENDERING

Rendering, the generation of images from data, is a key component to visualization. To assist with rendering, VTK-m provides a rendering package to produce imagery from data, which is located in the vtkm::rendering namespace.

The rendering package in VTK-m is not intended to be a fully featured rendering system or library. Rather, it is a lightweight rendering package with two primary use cases:

1. New users getting started with VTK-m need a "quick and dirty" render method to see their visualization results.
2. In situ visualization that integrates VTK-m with a simulation or other data-generation system might need a lightweight rendering method.

Both of these use cases require just a basic rendering platform. Because VTK-m is designed to be integrated into larger systems, it does not aspire to have a fully featured rendering system.

Did you know?

VTK-m's big sister toolkit VTK is already integrated with VTK-m and has its own fully featured rendering system. If you need more rendering capabilities than what VTK-m provides, you can leverage VTK instead.

5.1 Creating a Rendering Canvas

The first step in using VTK-m's rendering package is to create a *canvas*, which is managed by vtkm::rendering::Canvas and its subclasses. The Canvas object manages the frame buffers and the rendering context.

Subclasses of Canvas establish a context for different rendering systems. Currently, there are two main subclasses: one for using OpenGL rendering (vtkm::rendering::CanvasGL) and one for using built in ray tracing (vtkm::rendering::CanvasRayTracer).

5.1.1 Creating an OpenGL Context with GLUT

One feature that is notably (and intentionally) missing from the VTK-m rendering package is the ability to open a rendering window or build a graphical user interface. However, VTK-m can use an OpenGL context established elsewhere to perform rendering. OpenGL is a widely-accepted rendering library supported by all hardware vendors on pretty much all computing platforms. It is also extensively used by many applications performing rendering, particularly scientific visualization applications.

Once an OpenGL rendering context is established, it can be used by VTK-m by simply creating a `vtkm::rendering::CanvasGL`. When created, `CanvasGL` will find the current OpenGL context, query its size, and ready the VTK-m rendering system to use it.

Unfortunately, creating a window with an OpenGL context is platform dependent. There are numerous libraries available that provide the ability to create an OpenGL window that have been ported to many platforms (such as MS Windows, Unix, and Mac OSX). One such library is *GLUT*.

GLUT is a very simple utility toolkit that provides a basic mechanism for creating a window with an OpenGL context. It additionally provides simple user interface features to capture keystrokes and mouse movements. For the purposes of demonstration, we will provide examples that use GLUT to make a simple interactive rendering application.

Did you know?

We are demonstrating rendering with GLUT for illustrative purposes only. VTK-m is not directly associated with GLUT: It neither comes with GLUT nor depends on GLUT. You are welcome to follow these boilerplate examples, or you can integrate with another rendering system of your choosing.

This section provides a terse description of getting a GLUT application up and running. This is not meant to be a thorough description of the GLUT library. There are other resources that document using the GLUT API, the most complete of which is the book *OpenGL Programming for the X Window System* by Mark J. Kilgard. The information provided here is just enough to get you started.

Common Errors

Although distributed for free, the original GLUT library was not released as open source. Unfortunately, the GLUT copyright holders are not as actively developing GLUT as they once were, and consequently some systems are declaring GLUT as deprecated. However, there some newer projects like FreeGLUT and OpenGLUT that are open source, that are being more actively developed, and that are drop in replacements to the original GLUT library. There are also alternative libraries such as GLFW that have similar capabilities but a different API. These are not documented here, but are worth investigating if GLUT does not work for you.

The first call made to the GLUT library should be to the function `glutInit`, which takes as arguments the `argc` and `argv` arguments passed to the `main` C function. `glutInit` will find any window-system specific flags (such as `-display`), use them to initialize the windowing system, and strip them from the arguments.

Next, the parameters for the window to be created should be established. The function `glutInitWindowSize` takes the width and the height of the renderable space in the window. The function `glutInitDisplayMode` takes a mask of flags that are or-ed together to specify the capabilities of the window. We recommend the flags `GLUT_RGBA`, `GLUT_DOUBLE`, `GLUT_ALPHA`, and `GLUT_DEPTH`. Once these are specified a call to `glutCreateWindow` will create a window and initialize the OpenGL context. `glutCreateWindow` takes a string for an argument that is used in the title bar of the window.

Example 5.1: Initializing the GLUT library and creating a window to render into.

```
glutInit(&argc, argv);
glutInitWindowSize(960, 600);
glutInitDisplayMode(GLUT_RGBA | GLUT_DOUBLE | GLUT_ALPHA | GLUT_DEPTH);
glutCreateWindow("VTK-m Example");
```

Apart from the initial setup, most of the interaction with the GLUT library happens through callbacks. As part of its initialization, an application provides function pointers to GLUT. GLUT then calls these provided functions when certain events happen. GLUT supports many callbacks for different types of events. Here is the small set of callbacks we use in our small example.

`glutDisplayFunc` The display function is called when the window needs to be redrawn. The callback should issue the appropriate OpenGL rendering calls and then call `glutSwapBuffers` to show the result.

`glutReshapeFunc` The reshape function is called whenever the window is resized. The callback is given the width and height of the new rendering window.

`glutMouseFunc` The mouse button function is called whenever a mouse button is pressed or released. The GLUT system gives the index of the button, the state the button changed to (`GLUT_DOWN` or `GLUT_UP`) and the pixel location of the event.

`glutMotionFunc` The mouse motion function is called whenever the mouse is moved while any button is pressed. The callback is given the pixel location to where the mouse moved to, but not the state of any of the buttons. If the button state is important, it must be preserved in a global variable. If the mouse motion should result in a change in the rendered view, the function should call `glutPostRedisplay`, which will tell GLUT to call the display function when the windowing system is ready.

`glutKeygboardFunc` The keyboard function is called whenever a regular key is pressed. The callback is given the character of the key pressed as well as the pixel location of the mouse when the key was pressed. If the key press should result in a change in the rendered view, the function should call `glutPostRedisplay`, which will tell GLUT to call the display function when the windowing system is ready.

Did you know?

There are many other GLUT callbacks not documented here. Consult the GLUT documentation for more information.

Example 5.2: Registering callbacks with GLUT.

```
glutDisplayFunc(DisplayCallback);
glutReshapeFunc(WindowReshapeCallback);
glutMouseFunc(MouseButtonCallback);
glutMotionFunc(MouseMoveCallback);
glutKeyboardFunc(KeyPressCallback);
```

Once the GLUT library is initialized, the rendering window created, and all the necessary callbacks are registered, call `glutMainLoop`. This causes GLUT to enter its main event loop where it will manage the windowing system. `glutMainLoop` will never return. Rather, it will continue to respond to events and invoke the callbacks until the program is otherwise interrupted.

Example 5.3 puts this all together to give a full example of a simple GLUT program rendering with VTK-m. The output of the program is shown in Figure 5.1. The examples of the GLUT callbacks are straightforward. The VTK-m rendering classes used are documented in the following sections.

Example 5.3: A simple but full example of an application using GLUT and VTK-m together.

```
#include <vtkm/io/reader/VTKDataSetReader.h>

#include <vtkm/rendering/Actor.h>
#include <vtkm/rendering/Camera.h>
#include <vtkm/rendering/CanvasGL.h>
#include <vtkm/rendering/MapperGL.h>
#include <vtkm/rendering/View3D.h>

#ifdef __APPLE__
#include <GLUT/glut.h>
#else
#include <GL/glut.h>
#endif

namespace BasicGlutExample {

vtkm::rendering::View3D *gViewPointer = NULL;

int gButtonState[3] = { GLUT_UP, GLUT_UP, GLUT_UP };
int gMousePositionX;
int gMousePositionY;

void DisplayCallback()
{
  gViewPointer->Paint();
  glutSwapBuffers();
}

void WindowReshapeCallback(int width, int height)
{
  gViewPointer->GetCanvas().ResizeBuffers(width, height);
}

void MouseButtonCallback(int buttonIndex, int state, int x, int y)
{
  gButtonState[buttonIndex] = state;
  gMousePositionX = x;
  gMousePositionY = y;
}

void MouseMoveCallback(int x, int y)
{
  vtkm::Id width = gViewPointer->GetCanvas().GetWidth();
  vtkm::Id height = gViewPointer->GetCanvas().GetHeight();

  vtkm::Float32 lastX = (2.0f*gMousePositionX)/width - 1.0f;
  vtkm::Float32 lastY = 1.0f - (2.0f*gMousePositionY)/height;
  vtkm::Float32 nextX = (2.0f*x)/width - 1.0f;
  vtkm::Float32 nextY = 1.0f - (2.0f*y)/height;

  if (gButtonState[0] == GLUT_DOWN)
  {
    gViewPointer->GetCamera().TrackballRotate(lastX, lastY, nextX, nextY);
  }
  else if (gButtonState[1] == GLUT_DOWN)
  {
    gViewPointer->GetCamera().Pan(nextX-lastX, nextY-lastY);
  }
  else if (gButtonState[2] == GLUT_DOWN)
  {
    gViewPointer->GetCamera().Zoom(nextY-lastY);
  }

  gMousePositionX = x;
  gMousePositionY = y;

  glutPostRedisplay();
}

void KeyPressCallback(unsigned char key, int x, int y)
{
  switch (key)
  {
    case 'q':
    case 'Q':
      delete gViewPointer;
      gViewPointer = NULL;
      exit(0);
      break;
  }
}

int main(int argc, char *argv[])
{
  // Initialize GLUT window and callbacks
  glutInit(&argc, argv);
  glutInitWindowSize(960, 600);
  glutInitDisplayMode(GLUT_RGBA | GLUT_DOUBLE | GLUT_ALPHA | GLUT_DEPTH);
  glutCreateWindow("VTK-m Example");

  glutDisplayFunc(DisplayCallback);
  glutReshapeFunc(WindowReshapeCallback);
  glutMouseFunc(MouseButtonCallback);
  glutMotionFunc(MouseMoveCallback);
  glutKeyboardFunc(KeyPressCallback);

  // Initialize VTK-m rendering classes
  vtkm::cont::DataSet surfaceData;
  try
  {
    vtkm::io::reader::VTKDataSetReader reader("data/cow.vtk");
    surfaceData = reader.ReadDataSet();
  }
  catch (vtkm::io::ErrorIO &error)
  {
    std::cout << "Could not read file:" << std::endl
              << error.GetMessage() << std::endl;
  }
  catch (...)
  {
    throw;
  }

  vtkm::rendering::Actor actor(surfaceData.GetCellSet(),
                               surfaceData.GetCoordinateSystem(),
                               surfaceData.GetField("RandomPointScalars"));

  vtkm::rendering::Scene scene;
  scene.AddActor(actor);

  vtkm::rendering::MapperGL mapper;
  vtkm::rendering::CanvasGL canvas;

  gViewPointer = new vtkm::rendering::View3D(scene, mapper, canvas);
  gViewPointer->Initialize();

  // Start the GLUT rendering system. This function typically does not return.
  glutMainLoop();

  return 0;
}
```

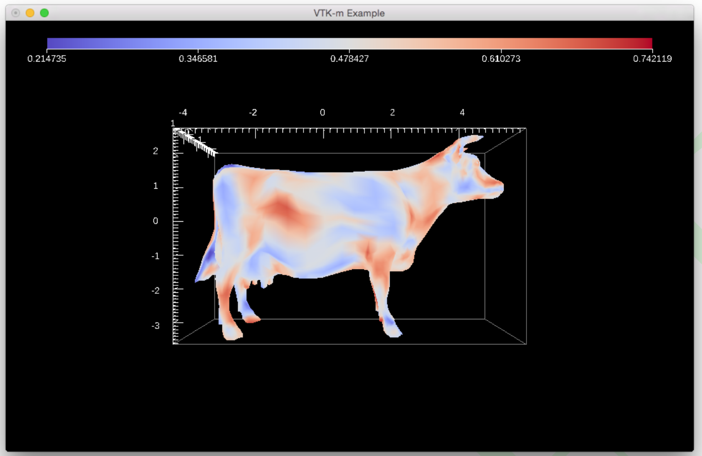


Figure 5.1: Output of the rendering program listed in Example 5.3.

5.1.2 Creating an Off Screen Rendering Canvas

Another use case for rendering in VTK-m is rendering to an off screen buffer. This is the preferred method when doing automated visualization such as when running visualization in situ with a simulation. VTK-m comes built in with multiple methods to create off screen rendering contexts. There are multiple subclasses to `vtkm::rendering::Canvas` that, when constructed, create their own rendering contexts, so can be used immediately. All of these classes take as parameters to their constructors the width and height of the image to create.

The following classes, when constructed, create an off screen rendering buffer.

`vtkm::rendering::CanvasEGL` Creates an off screen OpenGL rendering buffer using EGL. EGL provides an interface to create a context for OpenGL rendering software without engaging the operating-system-specific windowing system. For this to be available, VTK-m must have been configured to use the EGL library.

`vtkm::rendering::CanvasOSMesa` Creates an off screen OpenGL rendering buffer using the OSMesa library. For this to be available, VTK-m must have been configured to use the OSMesa library. Also, be aware that OSMesa contexts do not use GPU hardware.

`vtkm::rendering::CanvasRayTracer` Creates the frame buffers required for ray tracing. When invoking this canvas, you must use other ray tracing component where applicable. OpenGL rendering does not work with the `CanvasRayTracer`.

By their nature, when writing to an off screen canvas, you cannot directly see the result. Typically, programs using off screen rendering save rendered images as files to be viewed later. For convenience, `Canvas` has a method named `SaveAs` that will write the contents of the last saved image to a file. The files are written in portable pixel map (PPM) format, which are also valid portable anymap format (PNM) files. This is a very simple format that is easy to read and write. PPM files are supported by the ImageMagick[1] software suite as well as many other image software tools.

Example 5.4: Saving an image rendered in a Canvas to a file.

```
canvas.SaveAs("MyVis.ppm");
```

Alternately, the rendered image can be retrieved directly from the Canvas by first calling the RefreshColorBuffer method and then calling GetColorBuffer. This retrieves the raw image data as a vtkm::cont::ArrayHandle. ArrayHandles are documented later in Chapter 7.

5.2 Scenes and Actors

The primary intent of the rendering package in VTK-m is to visually display the data that is loaded and processed. Data are represented in VTK-m by vtkm::cont::DataSet objects. DataSet is presented in Chapters 3 and 4. For now we treat DataSet mostly as an opaque object that can be passed around readers, writers, filters, and rendering units. Detailed documentation for DataSet is provided in Chapter 12.

To render a DataSet, the data are wrapped in a vtkm::rendering::Actor class. The Actor holds the components of the DataSet to render (a cell set, a coordinate system, and a field). A color table can also be optionally be specified, but a default color table will be specified otherwise.

Actors are collected together in an object called vtkm::rendering::Scene. An Actor is added to a Scene with the AddActor method. The following example demonstrates creating a Scene with one Actor.

Example 5.5: Creating an Actor and adding it to a Scene.

```
vtkm::rendering::Actor actor(surfaceData.GetCellSet(),
                             surfaceData.GetCoordinateSystem(),
                             surfaceData.GetField("RandomPointScalars"));

vtkm::rendering::Scene scene;
scene.AddActor(actor);
```

5.3 Mappers

A *mapper* is a unit that converts data (managed by an Actor) and issues commands to the rendering subsystem to generate images. All mappers in VTK-m are a subclass of vtkm::rendering::Mapper. Different rendering systems (as established by the Canvas) often require different mappers. Also, different mappers could render different types of data in different ways. For example, one mapper might render polygonal surfaces whereas another might render polyhedra as a translucent volume. Thus, a mapper should be picked to match both the rendering system of the Canvas and the data in the Actor.

The following mappers are provided by VTK-m.

vtkm::rendering::MapperGL Uses OpenGL to render surfaces. If the data contain polyhedra, then their faces are rendered. MapperGL only works in conjunction with CanvasGL or one of its subclasses.

vtkm::rendering::MapperRayTracer Uses VTK-m's built in ray tracing system to render the visible surface of a mesh. MapperRayTracer only works in conjunction with CanvasRayTracer.

vtkm::rendering::MapperVolume Uses VTK-m's built in ray tracing system to render polyhedra as a translucent volume. MapperVolume only works in conjunction with CanvasRayTracer.

[1]http://imagemagick.org

5.4 Views

A *view* is a unit that collects all the structures needed to perform rendering. It contains everything needed to take a Scene (Section 5.2) and use a Mapper (Section 5.3) to render it onto a Canvas (Section 5.1). The view also annotates the image with spatial and scalar properties.

The base class for all views is vtkm::rendering::View. View is an abstract class, and you must choose one of the two provided subclasses, vtkm::rendering::View3D and vtkm::rendering::View2D, depending on the type of data being presented. (All three classes are defined in the vtkm/rendering/View.h header file.) Both View3D and View2D take a Scene, a Mapper, and a Canvas as arguments to their constructor.

Example 5.6: Constructing a View.

```
vtkm::rendering::Actor actor(surfaceData.GetCellSet(),
                             surfaceData.GetCoordinateSystem(),
                             surfaceData.GetField("RandomPointScalars"));

vtkm::rendering::Scene scene;
scene.AddActor(actor);

vtkm::rendering::MapperGL mapper;
vtkm::rendering::CanvasGL canvas;

gViewPointer = new vtkm::rendering::View3D(scene, mapper, canvas);
gViewPointer->Initialize();
```

The View constructors also take an optional fourth argument for the background color. The background color (like other colors) is specified using the vtkm::rendering::Color helper class, which manages the red, green, and blue color channels as well as an optional alpha channel. These channel values are given as floating point values between 0 and 1.

Example 5.7: Creating a View with a background color.

```
    new vtkm::rendering::View3D(
      scene, mapper, canvas, vtkm::rendering::Color(1.0f, 1.0f, 1.0f));
```

Once the View is created but before it is used to render, the Initialize method should be called. This is demonstrated in Example 5.6.

Once the Initialize method is called, the View is ready to render the scene. This happens by calling the Paint method, which will render the data into the contained canvas. When using GLUT, as in Example 5.3, or with most other GUI-based systems, Paint is called in the display callback.

Example 5.8: Using Canvas::Paint in a display callback.

```
void DisplayCallback()
{
  gViewPointer->Paint();
  glutSwapBuffers();
}
```

5.5 Manipulating the Camera

The vtkm::rendering::View uses an object called vtkm::rendering::Camera to describe the vantage point from which to draw the geometry. The camera can be retrieved from the View's GetCamera method. That retrieved camera can be directly manipulated or a new camera can be provided by calling SetCamera on the View.

A Camera operates in one of two major modes: 2D mode or 3D mode. 2D mode is designed for looking at flat geometry (or close to flat geometry) that is parallel to the x-y plane. 3D mode provides the freedom to place the camera anywhere in 3D space. The different modes can be set with `SetModeTo2D` and `SetModeTo3D`, respectively. The interaction with the camera in these two modes is very different.

5.5.1 2D Camera Mode

The 2D camera is restricted to looking at some region of the x-y plane.

View Range

The vantage point of a 2D camera can be specified by simply giving the region in the x-y plane to look at. This region is specified by calling `SetViewRange2D` on Camera. This method takes the left, right, bottom, and top of the region to view. Typically these are set to the range of the geometry in world space as shown in Figure 5.2.

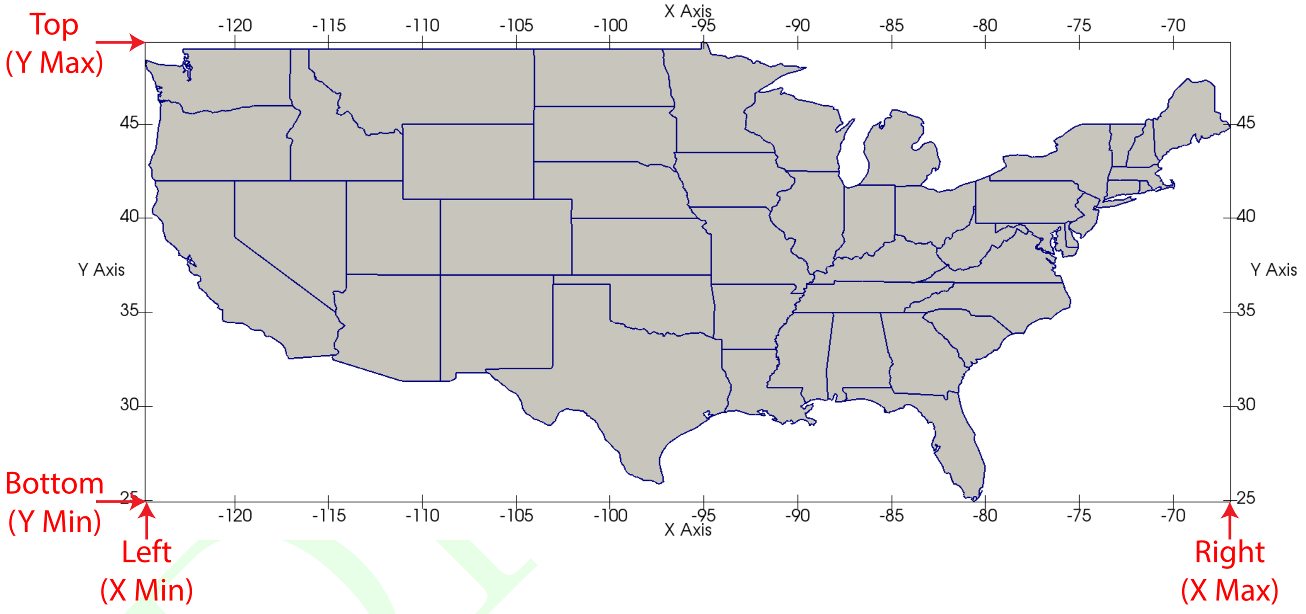


Figure 5.2: The view range bounds to give a Camera.

There are 3 overloaded versions of the `SetViewRange2D` method. The first version takes the 4 range values, left, right, bottom, and top, as separate arguments in that order. The second version takes two `vtkm::Range` objects specifying the range in the x and y directions, respectively. The third version trakes a single `vtkm::Bounds` object, which completely specifies the spatial range. (The range in z is ignored.) The Range and Bounds objects are documented later in Sections 6.4.4 and 6.4.5, respectively.

Pan

A camera pan moves the viewpoint left, right, up, or down. A camera pan is performed by calling the `Pan` method on Camera. `Pan` takes two arguments: the amount to pan in x and the amount to pan in y.

The pan is given with respect to the projected space. So a pan of 1 in the x direction moves the camera to focus on the right edge of the image whereas a pan of -1 in the x direction moves the camera to focus on the left edge of the image. When using `Pan` to respond to mouse movements, a natural pan will divide the distance traveled by the mouse pointer by the width and height of the screen as demonstrated in the following example.

Example 5.9: Pan the view based on mouse movements.

```
void DoMousePan(vtkm::rendering::View &view,
                vtkm::Id mouseStartX,
                vtkm::Id mouseStartY,
                vtkm::Id mouseEndX,
                vtkm::Id mouseEndY)
{
  vtkm::Id screenWidth = view.GetCanvas().GetWidth();
  vtkm::Id screenHeight = view.GetCanvas().GetHeight();

  // Convert the mouse position coordinates, given in pixels from 0 to
  // width/height, to normalized screen coordinates from -1 to 1. Note that y
  // screen coordinates are usually given from the top down whereas our
  // geometry transforms are given from bottom up, so you have to reverse the y
  // coordiantes.
  vtkm::Float32 startX = (2.0f*mouseStartX)/screenWidth - 1.0f;
  vtkm::Float32 startY = -((2.0f*mouseStartY)/screenHeight - 1.0f);
  vtkm::Float32 endX = (2.0f*mouseEndX)/screenWidth - 1.0f;
  vtkm::Float32 endY = -((2.0f*mouseEndY)/screenHeight - 1.0f);

  view.GetCamera().Pan(endX-startX, endY-startY);
}
```

Zoom

A camera zoom draws the geometry larger or smaller. A camera zoom is performed by calling the `Zoom` method on `Camera`. `Zoom` takes a single argument specifying the zoom factor. A positive number draws the geometry larger (zoom in), and larger zoom factor results in larger geometry. Likewise, a negative number draws the geometry smaller (zoom out). A zoom factor of 0 has no effect.

When using `Zoom` to respond to mouse movements, a natural zoom will divide the distance traveled by the mouse pointer by the width or height of the screen as demonstrated in the following example.

Example 5.10: Zoom the view based on mouse movements.

```
void DoMouseZoom(vtkm::rendering::View &view,
                 vtkm::Id mouseStartY,
                 vtkm::Id mouseEndY)
{
  vtkm::Id screenHeight = view.GetCanvas().GetHeight();

  // Convert the mouse position coordinates, given in pixels from 0 to height,
  // to normalized screen coordinates from -1 to 1. Note that y screen
  // coordinates are usually given from the top down whereas our geometry
  // transforms are given from bottom up, so you have to reverse the y
  // coordiantes.
  vtkm::Float32 startY = -((2.0f*mouseStartY)/screenHeight - 1.0f);
  vtkm::Float32 endY = -((2.0f*mouseEndY)/screenHeight - 1.0f);

  view.GetCamera().Zoom(endY-startY);
}
```

5.5.2 3D Camera Mode

The 3D camera is a free-form camera that can be placed anywhere in 3D space and can look in any direction. The projection of the 3D camera is based on the pinhole camera model in which all viewing rays intersect a single point. This single point is the camera's position.

Position and Orientation

The position of the camera, which is the point where the observer is viewing the scene, can be set with the SetPosition method of Camera. The direction the camera is facing is specified by giving a position to focus on. This is called either the "look at" point or the focal point and is specified with the SetLookAt method of Camera. Figure 5.3 shows the relationship between the position and look at points.

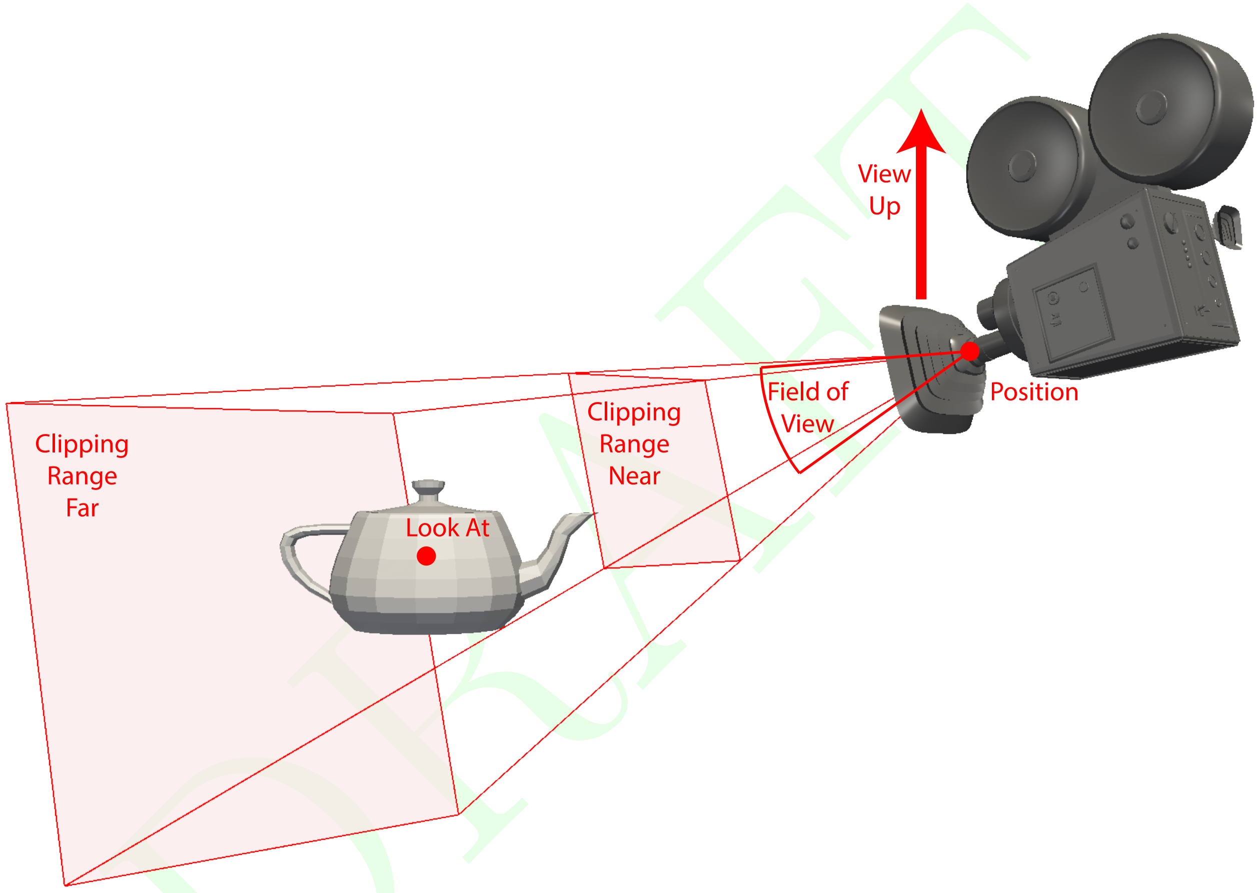


Figure 5.3: The position and orientation parameters for a Camera.

In addition to specifying the direction to point the camera, the camera must also know which direction is considered "up." This is specified with the view up vector using the SetViewUp method in Camera. The view up vector points from the camera position (in the center of the image) to the top of the image. The view up vector in relation to the camera position and orientation is shown in Figure 5.3.

Another important parameter for the camera is its field of view. The field of view specifies how wide of a region the camera can see. It is specified by giving the angle in degrees of the cone of visible region emanating from the pinhole of the camera to the SetFieldOfView method in the Camera. The field of view angle in relation to the camera orientation is shown in Figure 5.3. A field of view angle of 60° usually works well.

Finally, the camera must specify a clipping region that defines the valid range of depths for the object. This is a pair of planes parallel to the image that all visible data must lie in. Each of these planes is defined simply by their distance to the camera position. The near clip plane is closer to the camera and must be in front of all geometry. The far clip plane is further from the camera and must be behind all geometry. The distance to both the near and far planes are specified with the `SetClippingRange` method in `Camera`. Figure 5.3 shows the clipping planes in relationship to the camera position and orientation.

Example 5.11: Directly setting `vtkm::rendering::Camera` position and orientation.

```
camera.SetPosition(vtkm::make_Vec(10.0, 6.0, 6.0));
camera.SetLookAt(vtkm::make_Vec(0.0, 0.0, 0.0));
camera.SetViewUp(vtkm::make_Vec(0.0, 1.0, 0.0));
camera.SetFieldOfView(60.0);
camera.SetClippingRange(0.1, 100.0);
```

Movement

In addition to specifically setting the position and orientation of the camera, `vtkm::rendering::Camera` contains several convenience methods that move the camera relative to its position and look at point.

Two such methods are elevation and azimuth, which move the camera around the sphere centered at the look at point. `Elevation` raises or lowers the camera. Positive values raise the camera up (in the direction of the view up vector) whereas negative values lower the camera down. `Azimuth` moves the camera around the look at point to the left or right. Positive values move the camera to the right whereas negative values move the camera to the left. Both `Elevation` and `Azimuth` specify the amount of rotation in terms of degrees. Figure 5.4 shows the relative movements of `Elevation` and `Azimuth`.

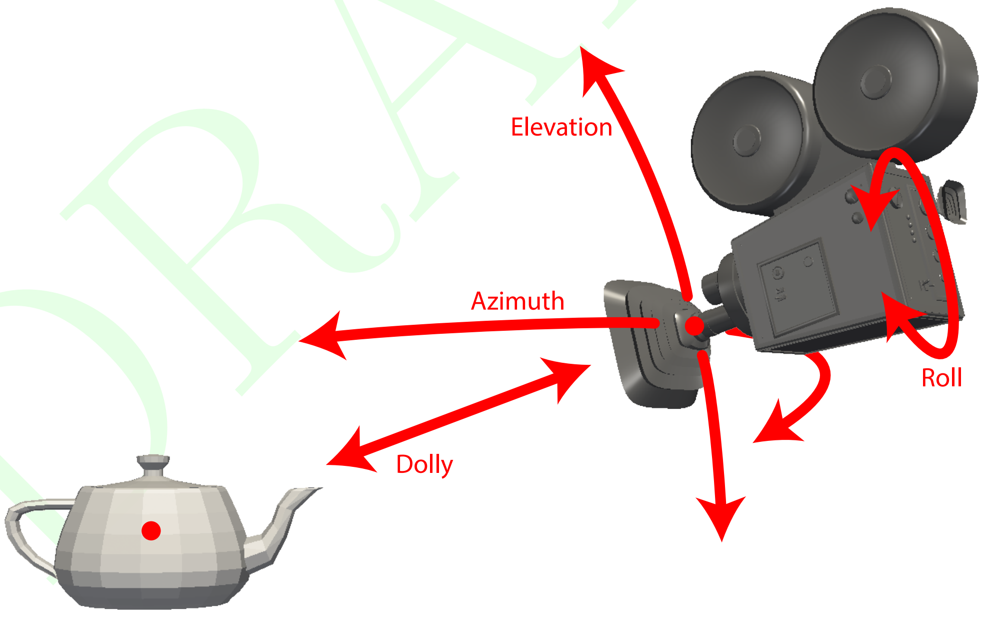


Figure 5.4: `Camera` movement functions relative to position and orientation.

Example 5.12: Moving the camera around the look at point.

```
view.GetCamera().Azimuth(45.0);
view.GetCamera().Elevation(45.0);
```

Common Errors

The `Elevation` *and* `Azimuth` *methods change the position of the camera, but not the view up vector. This can cause some wild camera orientation changes when the direction of the camera view is near parallel to the view up vector, which often happens when the elevation is raised or lowered by about 90 degrees.*

In addition to rotating the camera around the look at point, you can move the camera closer or further from the look at point. This is done with the `Dolly` method. The `Dolly` method takes a single value that is the factor to scale the distance between camera and look at point. Values greater than one move the camera away, values less than one move the camera closer. The direction of dolly movement is shown in Figure 5.4.

Finally, the `Roll` method rotates the camera around the viewing direction. It has the effect of rotating the rendered image. The `Roll` method takes a single value that is the angle to rotate in degrees. The direction of roll movement is shown in Figure 5.4.

Interactive Rotations

A common and important mode of interaction with 3D views is to allow the user to rotate the object under inspection by dragging the mouse. To facilitate this type of interactive rotation, `vtkm::rendering::Camera` provides a convenience method named `TrackballRotate`. The `TrackballRotate` method takes a start and end position of the mouse on the image and rotates viewpoint as if the user grabbed a point on a sphere centered in the image at the start position and moved under the end position.

The `TrackballRotate` method is typically called from within a mouse movement callback. The callback must record the pixel position from the last event and the new pixel position of the mouse. Those pixel positions must be normalized to the range -1 to 1 where the position (-1,-1) refers to the lower left of the image and (1,1) refers to the upper right of the image. The following example demonstrates the typical operations used to establish rotations when dragging the mouse.

Example 5.13: Interactive rotations through mouse dragging with `Camera::TrackballRotate`.

```
void DoMouseRotate(vtkm::rendering::View &view,
                   vtkm::Id mouseStartX,
                   vtkm::Id mouseStartY,
                   vtkm::Id mouseEndX,
                   vtkm::Id mouseEndY)
{
  vtkm::Id screenWidth = view.GetCanvas().GetWidth();
  vtkm::Id screenHeight = view.GetCanvas().GetHeight();

  // Convert the mouse position coordinates, given in pixels from 0 to
  // width/height, to normalized screen coordinates from -1 to 1. Note that y
  // screen coordinates are usually given from the top down whereas our
  // geometry transforms are given from bottom up, so you have to reverse the y
  // coordiantes.
  vtkm::Float32 startX = (2.0f*mouseStartX)/screenWidth - 1.0f;
  vtkm::Float32 startY = -((2.0f*mouseStartY)/screenHeight - 1.0f);
  vtkm::Float32 endX = (2.0f*mouseEndX)/screenWidth - 1.0f;
  vtkm::Float32 endY = -((2.0f*mouseEndY)/screenHeight - 1.0f);

  view.GetCamera().TrackballRotate(startX, startY, endX, endY);
}
```

Pan

A camera pan moves the viewpoint left, right, up, or down. A camera pan is performed by calling the `Pan` method on `Camera`. `Pan` takes two arguments: the amount to pan in x and the amount to pan in y.

The pan is given with respect to the projected space. So a pan of 1 in the x direction moves the camera to focus on the right edge of the image whereas a pan of −1 in the x direction moves the camera to focus on the left edge of the image. When using `Pan` to respond to mouse movements, a natural pan will divide the distance traveled by the mouse pointer by the width and height of the screen as demonstrated in the following example.

Example 5.14: Pan the view based on mouse movements.

```
void DoMousePan(vtkm::rendering::View &view,
                vtkm::Id mouseStartX,
                vtkm::Id mouseStartY,
                vtkm::Id mouseEndX,
                vtkm::Id mouseEndY)
{
  vtkm::Id screenWidth = view.GetCanvas().GetWidth();
  vtkm::Id screenHeight = view.GetCanvas().GetHeight();

  // Convert the mouse position coordinates, given in pixels from 0 to
  // width/height, to normalized screen coordinates from -1 to 1. Note that y
  // screen coordinates are usually given from the top down whereas our
  // geometry transforms are given from bottom up, so you have to reverse the y
  // coordiantes.
  vtkm::Float32 startX = (2.0f*mouseStartX)/screenWidth - 1.0f;
  vtkm::Float32 startY = -((2.0f*mouseStartY)/screenHeight - 1.0f);
  vtkm::Float32 endX = (2.0f*mouseEndX)/screenWidth - 1.0f;
  vtkm::Float32 endY = -((2.0f*mouseEndY)/screenHeight - 1.0f);

  view.GetCamera().Pan(endX-startX, endY-startY);
}
```

`Pan` operates in image space, not world space. Panning does not change the camera position or orientation. Thus the look at point will be off center with respect to the image.

Zoom

A camera zoom draws the geometry larger or smaller. A camera zoom is performed by calling the `Zoom` method on `Camera`. `Zoom` takes a single argument specifying the zoom factor. A positive number draws the geometry larger (zoom in), and larger zoom factor results in larger geometry. Likewise, a negative number draws the geometry smaller (zoom out). A zoom factor of 0 has no effect.

When using `Zoom` to respond to mouse movements, a natural zoom will divide the distance traveled by the mouse pointer by the width or height of the screen as demonstrated in the following example.

Example 5.15: Zoom the view based on mouse movements.

```
void DoMouseZoom(vtkm::rendering::View &view,
                 vtkm::Id mouseStartY,
                 vtkm::Id mouseEndY)
{
  vtkm::Id screenHeight = view.GetCanvas().GetHeight();

  // Convert the mouse position coordinates, given in pixels from 0 to height,
  // to normalized screen coordinates from -1 to 1. Note that y screen
  // coordinates are usually given from the top down whereas our geometry
  // transforms are given from bottom up, so you have to reverse the y
  // coordiantes.
  vtkm::Float32 startY = -((2.0f*mouseStartY)/screenHeight - 1.0f);
  vtkm::Float32 endY = -((2.0f*mouseEndY)/screenHeight - 1.0f);

  view.GetCamera().Zoom(endY-startY);
}
```

`Zoom` operates in image space, not world space. Zooming differs from `Dolly` in that the reported position of the camera does not change. Instead, the image gets magnified or shrunk.

Reset

Setting a specific camera position and orientation can be frustrating, particularly when the size, shape, and location of the geometry is not known a priori. Typically this involves querying the data and finding a good camera orientation.

To make this process simpler, `vtkm::rendering::Camera` has a convenience method named `ResetToBounds` that automatically positions the camera based on the spatial bounds of the geometry. The most expedient method to find the spatial bounds of the geometry being rendered is to get the `vtkm::rendering::Scene` object and call `GetSpatialBounds`. The `Scene` object can be retrieved from the `vtkm::rendering::View`, which, as described in Section 5.4, is the central object for managing rendering.

Example 5.16: Resetting a `Camera` to view geometry.

```
void ResetCamera(vtkm::rendering::View &view)
{
  vtkm::Bounds bounds = view.GetScene().GetSpatialBounds();
  view.GetCamera().ResetToBounds(bounds);
}
```

The `ResetToBounds` method operates by placing the look at point in the center of the bounds and then placing the position of the camera relative to that look at point. The position is such that the view direction is the same as before the call to `ResetToBounds` and the distance between the camera position and look at point has the bounds roughly fill the rendered image. This behavior is a convenient way to update the camera to make the geometry most visible while still preserving the viewing position. If you want to reset the camera to a new viewing angle, it is best to set the camera to be pointing in the right direction and then calling `ResetToBounds` to adjust the position.

Example 5.17: Resetting a `Camera` to be axis aligned.

```
  view.GetCamera().SetPosition(vtkm::make_Vec(0.0, 0.0, 0.0));
  view.GetCamera().SetLookAt(vtkm::make_Vec(0.0, 0.0, -1.0));
  view.GetCamera().SetViewUp(vtkm::make_Vec(0.0, 1.0, 0.0));
  vtkm::Bounds bounds = view.GetScene().GetSpatialBounds();
  view.GetCamera().ResetToBounds(bounds);
```

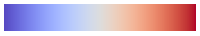
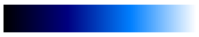
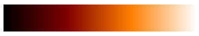
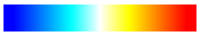
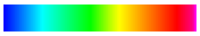
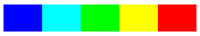
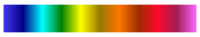
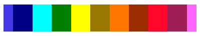
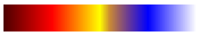
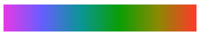
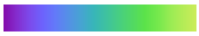
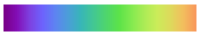
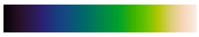
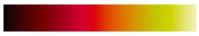
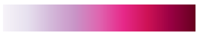
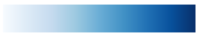
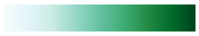
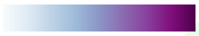
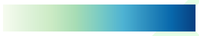
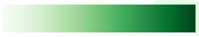
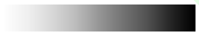
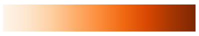
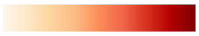
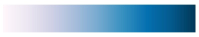
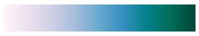
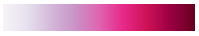
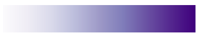
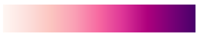
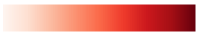
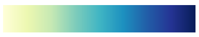
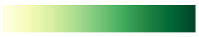
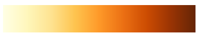
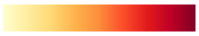
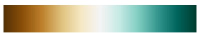
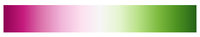
5.6 Color Tables

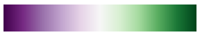
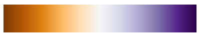
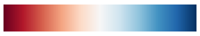
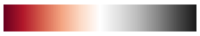
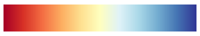
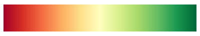
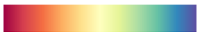
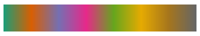
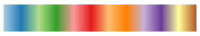
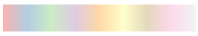
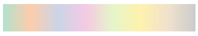
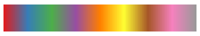
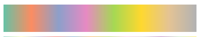
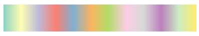
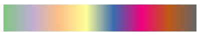
An important feature of VTK-m's rendering units is the ability to pseudocolor objects based on scalar data. This technique maps each scalar to a potentially unique color. This mapping from scalars to colors is defined by a `vtkm::rendering::ColorTable` object. A `ColorTable` can be specified as an optional argument when constructing a `vtkm::rendering::Actor`. (Use of `Actor`s is discussed in Section 5.2.)

Example 5.18: Specifying a `ColorTable` for an `Actor`.

```
  vtkm::rendering::Actor actor(surfaceData.GetCellSet(),
                               surfaceData.GetCoordinateSystem(),
                               surfaceData.GetField("RandomPointScalars"),
                               vtkm::rendering::ColorTable("thermal"));
```

The easiest way to create a ColorTable is to provide the name of one of the many predefined sets of color provided by VTK-m. A list of all available predefined color tables is provided below.

	cool2warm	A color table designed to be perceptually even, to work well on shaded 3D surfaces, and to generally perform well across many uses. This is also the default color map and will be used if no ColorTable is given to an Actor or if "default" is specified.
	blue	A monochromatic blue color map.
	orange	A monochromatic orange color map.
	temperature	A very saturated diverging color map.
	rainbow	There have been many scientific perceptual studies on the effectiveness of different color maps, and this rainbow color map is by far the most studied. These perceptual studies uniformly agree that this rainbow color map is terrible. Never use it.
	levels	A map of 5 distinct colors.
	dense	This is similar to the rainbow color map but with an intentional variation in brightness. This probably makes the map more effective, but not by much.
	sharp	A map of 11 fairly distinct colos.
	thermal	A diverging color map of heat-based colors.
	IsoL	An isoluminant (constant brightness) color map of varying hues. Isoluminant color maps are sometimes recommended for 3D surfaces, but they have poor perceptual resolution.
	CubicYF	A modification to the rainbow color map to make it more perceptually uniform. This corrects some (but not all) of the problems with the rainbow color map.
	CubicL	Similar to CubicYF but extends the hues to red at the expense of some perceptual non-linearity.
	LinearL	Runs throught the same hues as the rainbow color map but also adjusts the brightness from minimum (black) to maximum (white) in a perceptually linear manner. This is sometimes referred to as the Kindlmann color map.
	LinHhot	Based on the colors for black body radiation, but modified to be perceptually linear.
	PuRd	A sequential color map from unsaturated purple to red.
	Blues	A sequential color map of blue varied by saturation.
	BuGn	A sequential color map from unsaturated blue to green.
	BuPu	A sequential color map from unsaturated blue to purple.
	GnBu	A sequential color map from unsaturated green to blue.
	Greens	A sequential color map of green varied by saturation.
	Greys	A sequential color map of grays of different lightness.
	Oranges	A sequential color map of orange varied by saturation.
	OrRd	A sequential color map from unsaturated orange to red.
	PuBu	A sequential color map from unsaturated purple to blue.
	PuBuGn	A sequential color map from unsaturated purple to blue to green.
	PuRd	A sequential color map from unsaturated purple to red.
	Purples	A sequential color map of purple varied by saturation.
	RdPu	A sequential color map from unsaturated red tu purple.
	Reds	A sequential color map of red varied by saturation.
	YlGnBu	A sequential color map from yellow to green to blue.
	YlGn	A sequential color map from yellow to green.
	YlOrBr	A sequential color map from yellow to orange to brown.
	YlOrRd	A sequential color map from yellow to orange to red.
	BrBG	A diverging color map from brown to greenish blue.
	PiYG	A diverging color map from pink to yellowish green.

	PRGn	A diverging color map from purple to green.
	PuOr	A diverging color map from orange to purple.
	RdBu	A diverging color map from red to blue.
	RdGy	A diverging color map from red to gray.
	RdYlBu	A diverging color map from red to blue through yellow.
	RdYlGn	A diverging color map from red to green through yellow.
	Spectral	A diverging color map incorporating most of the spectral hues.
	Dark2	A collection of 8 distinct dark colors.
	Paired	A collection of 12 distinct colors paired into light and dark versions of 6 different hues.
	Pastel1	A collection of 9 distinct pastel (light) colors.
	Pastel2	A collection of 8 distinct pastel (light) colors.
	Set1	A collection of 9 distinct colors.
	Set2	A collection of 8 distinct colors.
	Set3	A collection of 12 distinct colors.
	Accent	A collection of 8 colors.

[There is more functionality to document in `ColorTable`. In particular, building color tables by adding control points. However, I am not bothering to document that right now because (1) I don't think many people will use it and (2) it is pretty clear from the Doxygen.]

Part II

Using VTK-m

CHAPTER

SIX

BASIC PROVISIONS

This section describes the core facilities provided by VTK-m. These include macros, types, and classes that define the environment in which code is run, the core types of data stored, and template introspection. We also start with a description of package structure used by VTK-m.

6.1 General Approach

VTK-m is designed to provide a *pervasive parallelism* throughout all its visualization algorithms, meaning that the algorithm is designed to operate with independent concurrency at the finest possible level throughout. VTK-m provides this pervasive parallelism by providing a programming construct called a *worklet*, which operates on a very fine granularity of data. The worklets are designed as serial components, and VTK-m handles whatever layers of concurrency are necessary, thereby removing the onus from the visualization algorithm developer. Worklet operation is then wrapped into *filters*, which provide a simplified interface to end users.

A worklet is essentially a small functor or kernel designed to operate on a small element of data. (The name "worklet" means a small amount of work. We mean small in this sense to be the amount of data, not necessarily the amount of instructions performed.) The worklet is constrained to contain a serial and stateless function. These constraints form three critical purposes. First, the constraints on the worklets allow VTK-m to schedule worklet invocations on a great many independent concurrent threads and thereby making the algorithm pervasively parallel. Second, the constraints allow VTK-m to provide thread safety. By controlling the memory access the toolkit can insure that no worklet will have any memory collisions, false sharing, or other parallel programming pitfalls. Third, the constraints encourage good programming practices. The worklet model provides a natural approach to visualization algorithm design that also has good general performance characteristics.

VTK-m allows developers to design algorithms that are run on massive amounts of threads. However, VTK-m also allows developers to interface to applications, define data, and invoke algorithms that they have written or are provided otherwise. These two modes represent significantly different operations on the data. The operating code of an algorithm in a worklet is constrained to access only a small portion of data that is provided by the framework. Conversely, code that is building the data structures needs to manage the data in its entirety, but has little reason to perform computations on any particular element.

Consequently, VTK-m is divided into two *environments* that handle each of these use cases. Each environment has its own API, and direct interaction between the environments is disallowed. The environments are as follows.

Execution Environment This is the environment in which the computational portion of algorithms are executed. The API for this environment provides work for one element with convenient access to information such as connectivity and neighborhood as needed by typical visualization algorithms. Code for the execution environment is designed to always execute on a very large number of threads.

Control Environment This is the environment that is used to interface with applications, interface with I/O devices, and schedule parallel execution of the algorithms. The associated API is designed for users that want to use VTK-m to analyze their data using provided or supplied filters. Code for the control environment is designed to run on a single thread (or one single thread per process in an MPI job).

These dual programming environments are partially a convenience to isolate the application from the execution of the worklets and are partially a necessity to support GPU languages with host and device environments. The control and execution environments are logically equivalent to the host and device environments, respectively, in CUDA and other associated GPU languages.

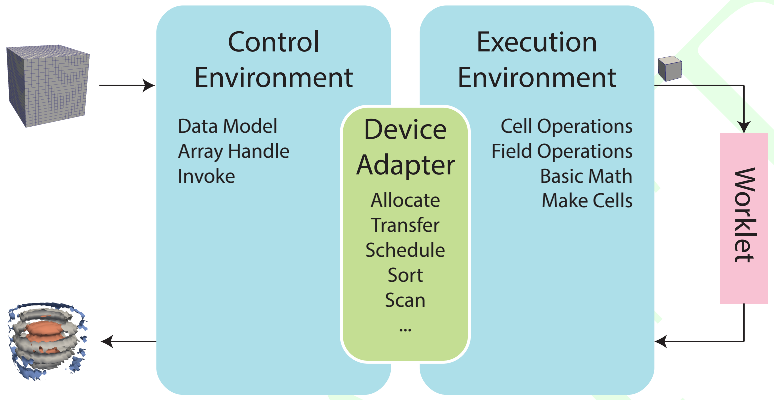


Figure 6.1: Diagram of the VTK-m framework.

Figure 6.1 displays the relationship between the control and execution environment. The typical workflow when using VTK-m is that first the control thread establishes a data set in the control environment and then invokes a parallel operation on the data using a filter. From there the data is logically divided into its constituent elements, which are sent to independent invocations of a worklet. The worklet invocations, being independent, are run on as many concurrent threads as are supported by the device. On completion the results of the worklet invocations are collected to a single data structure and a handle is returned back to the control environment.

Did you know?
Are you only planning to use filters in VTK-m that already exist? If so, then everything you work with will be in the control environment. The execution environment is only used when implementing algorithms for filters.

6.2 Package Structure

VTK-m is organized in a hierarchy of nested packages. VTK-m places definitions in *namespaces* that correspond to the package (with the exception that one package may specialize a template defined in a different namespace).

The base package is named `vtkm`. All classes within VTK-m are placed either directly in the `vtkm` package or in a package beneath it. This helps prevent name collisions between VTK-m and any other library.

As described in Section 6.1, the VTK-m API is divided into two distinct environments: the control environment and the execution environment. The API for these two environments are located in the `vtkm::cont` and `vtkm::exec` packages, respectively. Items located in the base `vtkm` namespace are available in both environments.

Although it is conventional to spell out names in identifiers (see the coding conventions in Chapter A), there is an exception to abbreviate control and execution to `cont` and `exec`, respectively. This is because it is also part of the coding convention to declare the entire namespace when using an identifier that is part of the corresponding package. The shorter names make the identifiers easier to read, faster to type, and more feasible to pack lines in 80 column displays. These abbreviations are also used instead of more common abbreviations (e.g. ctrl for control) because, as part of actual English words, they are easier to type.

Further functionality in VTK-m is built on top of the base `vtkm`, `vtkm::cont`, and `vtkm::exec` packages. Support classes for building worklets, described in Chapter 14, are contained in the `vtkm::worklet` package. Other facilities in VTK-m are provided in their own packages such as `vtkm::io`, `vtkm::filter`, and `vtkm::rendering`. These packages are described in Part I.

VTK-m contains code that uses specialized compiler features, such as those with CUDA, or libraries, such as Intel Threading Building Blocks, that will not be available on all machines. Code for these features are encapsulated in their own packages under the `vtkm::cont` namespace: `vtkm::cont::cuda` and `vtkm::cont::tbb`.

VTK-m contains OpenGL interoperability that allows data generated with VTK-m to be efficiently transferred to OpenGL objects. This feature is encapsulated in the `vtkm::opengl` package.

Figure 6.2 provides a diagram of the VTK-m package hierarchy.

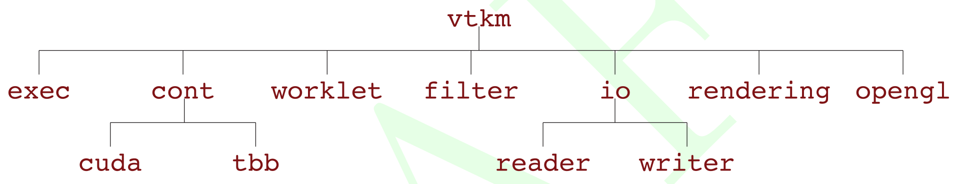


Figure 6.2: VTK-m package hierarchy.

By convention all classes will be defined in a file with the same name as the class name (with a .h extension) located in a directory corresponding to the package name. For example, the `vtkm::cont::ArrayHandle` class is found in the vtkm/cont/ArrayHandle.h header. There are, however, exceptions to this rule. Some smaller classes and types are grouped together for convenience. These exceptions will be noted as necessary.

Within each namespace there may also be `internal` and `detail` sub-namespaces. The `internal` namespaces contain features that are used internally and may change without notice. The `detail` namespaces contain features that are used by a particular class but must be declared outside of that class. Users should generally ignore classes in these namespaces.

6.3 Function and Method Environment Modifiers

Any function or method defined by VTK-m must come with a modifier that determines in which environments the function may be run. These modifiers are C macros that VTK-m uses to instruct the compiler for which architectures to compile each method. Most user code outside of VTK-m need not use these macros with the important exception of any classes passed to VTK-m. This occurs when defining new worklets, array storage, and device adapters.

VTK-m provides three modifier macros, `VTKM_CONT`, `VTKM_EXEC`, and `VTKM_EXEC_CONT`, which are used to declare functions and methods that can run in the control environment, execution environment, and both environments, respectively. These macros get defined by including just about any VTK-m header file, but including vtkm/Types.h will ensure they are defined.

The modifier macro is placed after the template declaration, if there is one, and before the return type for the function. Here is a simple example of a function that will square a value. Since most types you would use this function on have operators in both the control and execution environments, the function is declared for both places.

Example 6.1: Usage of an environment modifier macro on a function.

```
template<typename ValueType>
VTKM_EXEC_CONT
ValueType Square(const ValueType &inValue)
{
  return inValue * inValue;
}
```

The primary function of the modifier macros is to inject compiler-specific keywords that specify what architecture to compile code for. For example, when compiling with CUDA, the control modifiers have `__host__` in them and execution modifiers have `__device__` in them.

There is one additional modifier macro that is not used for functions but rather used when declaring a constant data object that is used in the execution environment. This macro is named `VTKM_EXEC_CONSTANT` and is used to declare a constant lookup table used when executing a worklet. Its primary reason for existing is to add a `__constant__` keyword when compiling with CUDA. This modifier currently has no effect on any other compiler.

Finally, it is sometimes the case that a function declared as `VTKM_EXEC_CONT` has to call a method declared as `VTKM_EXEC` or `VTKM_CONT`. Generally functions should not call other functions with incompatible control/execution modifiers, but sometimes a generic `VTKM_EXEC_CONT` function calls another function determined by the template parameters, and the valid environments of this subfunction may be inconsistent. For cases like this, you can use the `VTKM_SUPPRESS_EXEC_WARNINGS` to tell the compiler to ignore the inconsistency when resolving the template. When applied to a templated function or method, `VTKM_SUPPRESS_EXEC_WARNINGS` is placed before the `template` keyword. When applied to a non-templated method in a templated class, `VTKM_SUPPRESS_EXEC_WARNINGS` is placed before the environment modifier macro.

Example 6.2: Suppressing warnings about functions from mixed environments.

```
VTKM_SUPPRESS_EXEC_WARNINGS
template<typename Functor>
VTKM_EXEC_CONT
void OverlyComplicatedForLoop(Functor &functor, vtkm::Id numInterations)
{
  for (vtkm::Id index = 0; index < numInterations; index++)
  {
    functor();
  }
}
```

6.4 Core Data Types

Except in rare circumstances where precision is not a concern, VTK-m does not directly use the core C types like `int`, `float`, and `double`. Instead, VTK-m provides its own core types, which are declared in vtkm/Types.h.

6.4.1 Single Number Types

To ensure portability across different compilers and architectures, VTK-m provides `typedef`s for the following basic types with explicit precision: `vtkm::Float32`, `vtkm::Float64`, `vtkm::Int8`, `vtkm::Int16`, `vtkm::Int32`, `vtkm::Int64`, `vtkm::UInt8`, `vtkm::UInt16`, `vtkm::UInt32`, and `vtkm::UInt64`. Under most circumstances when using VTK-m (and performing visualization in general) the type of data is determined by the source of the data or resolved through templates. In the case where a specific type of data is required, these VTK-m–defined types should be preferred over basic C types like `int` or `float`.

Many of the structures in VTK-m require indices to identify elements like points and cells. All indices for arrays and other lists use the type `vtkm::Id`. By default this type is a 32-bit wide integer but can be easily changed by compile options. The CMake configuration option VTKM_USE_64BIT_IDS can be used to change `vtkm::Id` to be 64 bits wide. This configuration can be overridden by defining the C macro `VTKM_USE_64BIT_IDS` or `VTKM_NO_64BIT_IDS` to force `vtkm::Id` to be either 64 or 32 bits. These macros must be defined before any VTK-m header files are included to take effect.

There is also a secondary index type named `vtkm::IdComponent` that is used to index components of short vectors (discussed in Section 6.4.2). This type is an integer that might be a shorter width than `vtkm::Id`.

There is also the rare circumstance in which an algorithm in VTK-m computes data values for which there is no indication what the precision should be. For these circumstances, the type `vtkm::FloatDefault` is provided. By default this type is a 32-bit wide floating point number but can be easily changed by compile options. The CMake configuration option VTKM_USE_DOUBLE_PRECISION can be used to change `vtkm::FloatDefault` to be 64 bits wide. This configuration can be overridden by defining the C macro `VTKM_USE_DOUBLE_PRECISION` or `VTKM_NO_DOUBLE_PRECISION` to force `vtkm::FloatDefault` to be either 64 or 32 bits. These macros must be defined before any VTK-m header files are included to take effect.

For convenience, you can include either vtkm/internal/ConfigureFor32.h or vtkm/internal/ConfigureFor64.h to force both `vtkm::Id` and `vtkm::FloatDefault` to be 32 or 64 bits.

6.4.2 Vector Types

Visualization algorithms also often require operations on short vectors. Arrays indexed in up to three dimensions are common. Data are often defined in 2-space and 3-space, and transformations are typically done in homogeneous coordinates of length 4. To simplify these types of operations, VTK-m provides the `vtkm::Vec<T,Size>` templated type, which is essentially a fixed length array of a given type.

The default constructor of `vtkm::Vec` objects leaves the values uninitialized. All vectors have a constructor with one argument that is used to initialize all components. All `vtkm::Vec` objects with a size of 4 or less is specialized to also have a constructor that allows you to set the individual components. Likewise, there is a `vtkm::make_Vec` function that builds initialized vector types of up to 4 components. Once created, you can use the bracket operator to get and set component values with the same syntax as an array.

Example 6.3: Creating vector types.

```
vtkm::Vec<vtkm::Float32,3> A(1);                     // A is (1, 1, 1)
A[1] = 2;                                            // A is now (1, 2, 1)
vtkm::Vec<vtkm::Float32,3> B(1, 2, 3);               // B is (1, 2, 3)
vtkm::Vec<vtkm::Float32,3> C = vtkm::make_Vec(3, 4, 5); // C is (3, 4, 5)
```

The types `vtkm::Id2` and `vtkm::Id3` are `typedef`s of `vtkm::Vec<vtkm::Id,2>` and `vtkm::Vec<vtkm::Id,2>`. These are used to index arrays of 2 and 3 dimensions, which is common.

Vectors longer than 4 are also supported, but independent component values must be set after construction. The `vtkm::Vec` class contains a constant named `NUM_COMPONENTS` to specify how many components are in the vector. The class also has a `GetNumberOfComponents` method that also returns the number of components that are in the vector.

Example 6.4: A Longer Vector.

```
vtkm::Vec<vtkm::Float64, 5> A(2); // A is (2, 2, 2, 2, 2)
for (vtkm::IdComponent index = 1; index < A.NUM_COMPONENTS; index++)
```

```
{
  A[index] = A[index-1] * 1.5;
}
// A is now (2, 3, 4.5, 6.75, 10.125)
```

vtkm::Vec supports component-wise arithmetic using the operators for plus (+), minus (-), multiply (*), and divide (/). It also supports scalar to vector multiplication with the multiply operator. The comparison operators equal (==) is true if every pair of corresponding components are true and not equal (!=) is true otherwise. A special vtkm::dot function is overloaded to provide a dot product for every type of vector.

Example 6.5: Vector operations.

```
vtkm::Vec<vtkm::Float32,3> A(1, 2, 3);
vtkm::Vec<vtkm::Float32,3> B(4, 5, 6.5);
vtkm::Vec<vtkm::Float32,3> C = A + B;         // C is (5, 7, 9.5)
vtkm::Vec<vtkm::Float32,3> D = 2.0f * C;      // D is (10, 14, 19)
vtkm::Float32 s = vtkm::dot(A, B);            // s is 33.5
bool b1 = (A == B);                           // b1 is false
bool b2 = (A == vtkm::make_Vec(1, 2, 3));     // b2 is true
```

These operators, of course, only work if they are also defined for the component type of the vtkm::Vec. For example, the multiply operator will work fine on objects of type vtkm::Vec<char,3>, but the multiply operator will not work on objects of type vtkm::Vec<std::string,3> because you cannot multiply objects of type std::string.

In addition to generalizing vector operations and making arbitrarily long vectors, vtkm::Vec can be repurposed for creating any sequence of homogeneous objects. Here is a simple example of using vtkm::Vec to hold the state of a polygon.

Example 6.6: Repurposing a vtkm::Vec.

```
vtkm::Vec<vtkm::Vec<vtkm::Float32,2>, 3> equilateralTriangle(
                                           vtkm::make_Vec(0.0, 0.0),
                                           vtkm::make_Vec(1.0, 0.0),
                                           vtkm::make_Vec(0.5, 0.8660254));
```

The vtkm::Vec class provides a convenient structure for holding and passing small vectors of data. However, there are times when using Vec is inconvenient or inappropriate. For example, the size of vtkm::Vec must be known at compile time, but there may be need for a vector whose size is unknown until compile time. Also, the data populating a vtkm::Vec might come from a source that makes it inconvenient or less efficient to construct a vtkm::Vec. For this reason, VTK-m also provides several *Vec-like* objects that behave much like vtkm::Vec but are a different class. These Vec-like objects have the same interface as vtkm::Vec except that the NUM_COMPONENTS constant is not available on those that are sized at run time. Vec-like objects also come with a CopyInto method that will take their contents and copy them into a standard Vec class. (The standard Vec class also has a CopyInto method for consistency.)

The first Vec-like object is vtkm::VecC, which exposes a C-type array as a Vec. The constructor for vtkm::VecC takes a C array and a size of that array. There is also a constant version of VecC named vtkm::VecCConst, which takes a constant array and cannot be mutated. The vtkm/Types.h header defines both VecC and VecCConst as well as multiple versions of vtkm::make_VecC to easily convert a C array to either a VecC or VecCConst.

The following example demonstrates converting values from a constant table into a vtkm::VecCConst for further consumption. The table and associated methods define how 8 points come together to form a hexahedron.

Example 6.7: Using vtkm::VecCConst with a constant array.

```
VTKM_EXEC_CONSTANT
static const vtkm::IdComponent HexagonIndexToIJKTable[8][3] = {
  { 0, 0, 0 },
  { 1, 0, 0 },
  { 1, 1, 0 },
  { 0, 1, 0 },
  { 0, 0, 1 },
  { 1, 0, 1 },
  { 1, 1, 1 },
  { 0, 1, 1 }
};

VTKM_EXEC_CONSTANT
static const vtkm::IdComponent HexagonIJKToIndexTable[2][2][2] = {
  { // i=0
    { 0, 4 }, // j=0
    { 3, 7 }, // j=1
  },
  { // i=1
    { 1, 5 }, // j=0
    { 2, 6 }, // j=1
  }
};

VTKM_EXEC
vtkm::VecCConst<vtkm::IdComponent> HexagonIndexToIJK(vtkm::IdComponent index)
{
  return vtkm::make_VecC(HexagonIndexToIJKTable[index], 3);
}

VTKM_EXEC
vtkm::IdComponent HexagonIJKToIndex(vtkm::VecCConst<vtkm::IdComponent> ijk)
{
  return HexagonIJKToIndexTable[ijk[0]][ijk[1]][ijk[2]];
}
```

Common Errors

The vtkm::VecC *and* vtkm::VecCConst *classes only hold a pointer to a buffer that contains the data. They do not manage the memory holding the data. Thus, if the pointer given to* vtkm::VecC *or* vtkm::VecCConst *becomes invalid, then using the object becomes invalid. Make sure that the scope of the* vtkm::VecC *or* vtkm::VecCConst *does not outlive the scope of the data it points to.*

The next Vec-like object is vtkm::VecVariable, which provides a Vec-like object that can be resized at run time to a maximum value. Unlike VecC, VecVariable holds its own memory, which makes it a bit safer to use. But also unlike VecC, you must define the maximum size of VecVariable at compile time. Thus, VecVariable is really only appropriate to use when there is a predetermined limit to the vector size that is fairly small.

The following example uses a vtkm::VecVariable to store the trace of edges within a hexahedron. This example uses the methods defined in Example 6.7.

Example 6.8: Using vtkm::VecVariable.

```
vtkm::VecVariable<vtkm::IdComponent,4>
HexagonShortestPath(vtkm::IdComponent startPoint, vtkm::IdComponent endPoint)
{
  vtkm::VecCConst<vtkm::IdComponent> startIJK = HexagonIndexToIJK(startPoint);
  vtkm::VecCConst<vtkm::IdComponent> endIJK = HexagonIndexToIJK(endPoint);

  vtkm::Vec<vtkm::IdComponent,3> currentIJK;
  startIJK.CopyInto(currentIJK);

  vtkm::VecVariable<vtkm::IdComponent,4> path;
  path.Append(startPoint);
  for (vtkm::IdComponent dimension = 0; dimension < 3; dimension++)
  {
    if (currentIJK[dimension] != endIJK[dimension])
    {
      currentIJK[dimension] = endIJK[dimension];
      path.Append(HexagonIJKToIndex(currentIJK));
    }
  }

  return path;
}
```

VTK-m provides further examples of Vec-like objects as well. For example, the vtkm::VecFromPortal and vtkm::VecFromPortalPermute objects allow you to treat a subsection of an arbitrarily large array as a Vec. These objects work by attaching to array portals, which are described in Section 7.2. Another example of a Vec-like object is vtkm::VecRectilinearPointCoordinates, which efficiently represents the point coordinates in an axis-aligned hexahedron. Such shapes are common in structured grids. These and other data sets are described in Chapter 12.

6.4.3 Pair

VTK-m defines a vtkm::Pair<T1,T2> templated object that behaves just like std::pair from the standard template library. The difference is that vtkm::Pair will work in both the execution and control environment, whereas the STL std::pair does not always work in the execution environment.

The VTK-m version of vtkm::Pair supports the same types, fields, and operations as the STL version. VTK-m also provides a vtkm::make_Pair function for convenience.

6.4.4 Range

VTK-m provides a convenience structure named vtkm::Range to help manage a range of values. The Range struct contains two data members, Min and Max, which represent the ends of the range of numbers. Min and Max are both of type vtkm::Float64. Min and Max can be directly accessed, but Range also comes with the following helper functions to make it easier to build and use ranges. Note that all of these functions treat the minimum and maximum value as inclusive to the range.

IsNonEmpty Returns true if the range covers at least one value.

Contains Takes a single number and returns true if that number is contained within the range.

Length Returns the distance between Min and Max. Empty ranges return a length of 0. Note that if the range is non-empty and the length is 0, then Min and Max must be equal, and the range contains exactly one number.

Center Returns the number equidistant to Min and Max. If the range is empty, NaN is returned.

Include Takes either a single number or another range and modifies this range to include the given number or range. If necessary, the range is grown just enough to encompass the given argument. If the argument is already in the range, nothing changes.

Union A nondestructive version of Include, which builds a new Range that is the union of this range and the argument. The + operator is also overloaded to compute the union.

The following example demonstrates the operation of vtkm::Range.

Example 6.9: Using vtkm::Range.

```
vtkm::Range range;                      // default constructor is empty range
bool b1 = range.IsNonEmpty();           // b1 is false

range.Include(0.5);                     // range now is [0.5 .. 0.5]
bool b2 = range.IsNonEmpty();           // b2 is true
bool b3 = range.Contains(0.5);          // b3 is true
bool b4 = range.Contains(0.6);          // b4 is false

range.Include(2.0);                     // range is now [0.5 .. 2]
bool b5 = range.Contains(0.5);          // b3 is true
bool b6 = range.Contains(0.6);          // b4 is true

range.Include(vtkm::Range(-1, 1));      // range is now [-1 .. 2]

range.Include(vtkm::Range(3, 4));       // range is now [-1 .. 4]

vtkm::Float64 lower = range.Min;        // lower is -1
vtkm::Float64 upper = range.Max;        // upper is 4
vtkm::Float64 length = range.Length();  // length is 5
vtkm::Float64 center = range.Center();  // center is 1.5
```

6.4.5 Bounds

VTK-m provides a convenience structure named vtkm::Bounds to help manage an axis-aligned region in 3D space. Among other things, this structure is often useful for representing a bounding box for geometry. The Bounds struct contains three data members, X, Y, and Z, which represent the range of the bounds along each respective axis. All three of these members are of type vtkm::Range, which is discussed previously in Section 6.4.4. X, Y, and Z can be directly accessed, but Bounds also comes with the following helper functions to make it easier to build and use ranges.

IsNonEmpty Returns true if the bounds cover at least one value.

Contains Takes a vtkm::Vec of size 3 and returns true if those point coordinates are contained within the range.

Center Returns the point at the center of the range as a vtkm::Vec<vtkm::Float64,3>.

Include Takes either a vtkm::Vec of size 3 or another bounds and modifies this bounds to include the given point or bounds. If necessary, the bounds are grown just enough to encompass the given argument. If the argument is already in the bounds, nothing changes.

Union A nondestructive version of Include, which builds a new Bounds that is the union of this bounds and the argument. The + operator is also overloaded to compute the union.

The following example demonstrates the operation of vtkm::Bounds.

Example 6.10: Using vtkm::Bounds.

```
vtkm::Bounds bounds;                       // default constructor makes empty
bool b1 = bounds.IsNonEmpty();             // b1 is false

bounds.Include(vtkm::make_Vec(0.5, 2.0, 0.0));    // bounds contains only
                                                  // the point [0.5, 2, 0]
bool b2 = bounds.IsNonEmpty();                            // b2 is true
bool b3 = bounds.Contains(vtkm::make_Vec(0.5, 2.0, 0.0)); // b3 is true
bool b4 = bounds.Contains(vtkm::make_Vec(1, 1, 1));       // b4 is false
```

```
  bool b5 = bounds.Contains(vtkm::make_Vec(0, 0, 0));       // b5 is false

  bounds.Include(vtkm::make_Vec(4, -1, 2)); // bounds is region [0.5 .. 4] in X,
                                            //                  [-1 .. 2] in Y,
                                            //              and [0 .. 2] in Z
  bool b6 = bounds.Contains(vtkm::make_Vec(0.5, 2.0, 0.0)); // b6 is true
  bool b7 = bounds.Contains(vtkm::make_Vec(1, 1, 1));       // b7 is true
  bool b8 = bounds.Contains(vtkm::make_Vec(0, 0, 0));       // b8 is false

  vtkm::Bounds otherBounds(vtkm::make_Vec(0, 0, 0), vtkm::make_Vec(3, 3, 3));
                              // otherBounds is region [0 .. 3] in X, Y, and Z
  bounds.Include(otherBounds);  // bounds is now region [0 .. 4] in X,
                                //                      [-1 .. 3] in Y,
                                //                  and [0 .. 3] in Z

  vtkm::Vec<vtkm::Float64,3> lower(bounds.X.Min, bounds.Y.Min, bounds.Z.Min);
                                                        // lower is [0, -1, 0]
  vtkm::Vec<vtkm::Float64,3> upper(bounds.X.Max, bounds.Y.Max, bounds.Z.Max);
                                                        // upper is [4, 3, 3]

  vtkm::Vec<vtkm::Float64,3> center = bounds.Center();  // center is [2, 1, 1.5]
```

6.5 Traits

When using templated types, it is often necessary to get information about the type or specialize code based on general properties of the type. VTK-m uses traits classes to publish and retrieve information about types. A traits class is simply a templated structure that provides typedefs for tag structures, empty types used for identification. The traits classes might also contain constant numbers and helpful static functions. See *Effective C++ Third Edition* by Scott Mayers for a description of traits classes and their uses.

6.5.1 Type Traits

The `vtkm::TypeTraits<T>` templated class provides basic information about a core type. These type traits are available for all the basic C++ types as well as the core VTK-m types described in Section 6.4. `vtkm::TypeTraits` contains the following elements.

`NumericTag` This type is set to either `vtkm::TypeTraitsRealTag` or `vtkm::TypeTraitsIntegerTag` to signal that the type represents either floating point numbers or integers.

`DimensionalityTag` This type is set to either `vtkm::TypeTraitsScalarTag` or `vtkm::TypeTraitsVectorTag` to signal that the type represents either a single scalar value or a tuple of values.

The definition of `vtkm::TypeTraits` for `vtkm::Float32` could like something like this.

Example 6.11: Definition of `vtkm::TypeTraits<vtkm::Float32>`.

```
namespace vtkm {

template<>
struct TypeTraits<vtkm::Float32>
{
  typedef vtkm::TypeTraitsRealTag NumericTag;
  typedef vtkm::TypeTraitsScalarTag DimensionalityTag;
};

}
```

Here is a simple example of using vtkm::TypeTraits to implement a generic function that behaves like the remainder operator (%) for all types including floating points and vectors.

Example 6.12: Using TypeTraits for a generic remainder.

```
#include <vtkm/TypeTraits.h>

#include <vtkm/Math.h>

template<typename T>
T AnyRemainder(const T &numerator, const T &denominator);

namespace detail {

template<typename T>
T AnyRemainderImpl(const T &numerator,
                   const T &denominator,
                   vtkm::TypeTraitsIntegerTag,
                   vtkm::TypeTraitsScalarTag)
{
  return numerator % denominator;
}

template<typename T>
T AnyRemainderImpl(const T &numerator,
                   const T &denominator,
                   vtkm::TypeTraitsRealTag,
                   vtkm::TypeTraitsScalarTag)
{
  // The VTK-m math library contains a Remainder function that operates on
  // floating point numbers.
  return vtkm::Remainder(numerator, denominator);
}

template<typename T, typename NumericTag>
T AnyRemainderImpl(const T &numerator,
                   const T &denominator,
                   NumericTag,
                   vtkm::TypeTraitsVectorTag)
{
  T result;
  for (int componentIndex = 0;
       componentIndex < T::NUM_COMPONENTS;
       componentIndex++)
  {
    result[componentIndex] =
        AnyRemainder(numerator[componentIndex], denominator[componentIndex]);
  }
  return result;
}

} // namespace detail

template<typename T>
T AnyRemainder(const T &numerator, const T &denominator)
{
  return detail::AnyRemainderImpl(
        numerator,
        denominator,
        typename vtkm::TypeTraits<T>::NumericTag(),
        typename vtkm::TypeTraits<T>::DimensionalityTag());
}
```

6.5.2 Vector Traits

The templated vtkm::Vec class contains several items for introspection (such as the component type and its size). However, there are other types behave similarly to Vec objects but have different ways to perform this introspection. For example, VTK-m contains Vec-like objects that essentially behave the same but might have different features such as a variable number of components. Also, there may be reason to interchangeably use basic scalar values, like an integer or floating point number, with vectors.

To provide a consistent interface to access these multiple types that represents vectors, the vtkm::VecTraits<T> templated class provides information and accessors to vector types. It contains the following elements.

ComponentType This type is set to the type for each component in the vector. For example, a vtkm::Id3 has ComponentType defined as vtkm::Id.

IsSizeStatic This type is set to either vtkm::VecTraitsTagSizeStatic if the vector has a static number of components that can be determined at compile time or set to vtkm::VecTraitsTagSizeVariable if the size of the vector is determined at run time. If IsSizeStatic is set to VecTraitsTagSizeVariable, then VecTraits will be missing some information that cannot be determined at compile time.

HasMultipleComponents This type is set to either vtkm::VecTraitsTagSingleComponent if the vector length is size 1 or vtkm::VecTraitsTagMultipleComponents otherwise. This tag can be useful for creating specialized functions when a vector is really just a scalar. If the vector type is of variable size (that is, IsSizeStatic is VecTraitsTagSizeVariable), then HasMultipleComponents might be VecTraitsTag-MultipleComponents even when at run time there is only one component.

NUM_COMPONENTS An integer specifying how many components are contained in the vector. NUM_COMPONENTS is not available for vector types of variable size (that is, IsSizeStatic is VecTraitsTagSizeVariable).

GetNumberOfComponents A static method that takes an instance of a vector and returns the number of components the vector contains. The result of GetNumberOfComponents is the same value of NUM_COMPONENTS for vector types that have a static size (that is, IsSizeStatic is VecTraitsTagSizeStatic). But unlike NUM_COMPONENTS, GetNumberOfComponents works for vectors of any type.

GetComponent A static method that takes a vector and returns a particular component.

SetComponent A static method that takes a vector and sets a particular component to a given value.

CopyInto A static method that copies the components of a vector to a vtkm::Vec.

The definition of vtkm::VecTraits for vtkm::Id3 could look something like this.

Example 6.13: Definition of vtkm::VecTraits<vtkm::Id3>.

```
namespace vtkm {

template<>
struct VecTraits<vtkm::Id3>
{
  typedef vtkm::Id ComponentType;
  static const int NUM_COMPONENTS = 3;
  typedef vtkm::VecTraitsTagSizeStatic IsSizeStatic;
  typedef VecTraitsTagMultipleComponents HasMultipleComponents;

  VTKM_EXEC_CONT
  static vtkm::IdComponent GetNumberOfComponents(const VecType &vec) {
    return NUM_COMPONENTS;
  }

  VTKM_EXEC_CONT
  static vtkm::Id &GetComponent(vtkm::Id3 &vector, int component) {
    return vector[component];
  }

  VTKM_EXEC_CONT
  static void SetComponent(vtkm::Id3 &vector, int component, vtkm::Id value) {
    vector[component] = value;
  }

  template<vtkm::IdComponent destSize>
  VTKM_EXEC_CONT
  static void
  CopyInto(const VecType &src, vtkm::Vec<vtkm::Id,destSize> &dest)
  {
    for (vtkm::IdComponent index = 0;
         (index < NUM_COMPONENTS) && (index < OtherSize);
         index++)
    {
      dest[index] = src[index];
    }
  }
};

} // namespace vtkm
```

The real power of vector traits is that they simplify creating generic operations on any type that can look like a vector. This includes operations on scalar values as if they were vectors of size one. The following code uses vector traits to simplify the implementation of less functors that define an ordering that can be used for sorting and other operations.

Example 6.14: Using VecTraits for less functors.

```
#include <vtkm/VecTraits.h>

// This functor provides a total ordering of vectors. Every compared vector
// will be either less, greater, or equal (assuming all the vector components
// also have a total ordering).
template<typename T>
struct LessTotalOrder
{
  VTKM_EXEC_CONT
  bool operator()(const T &left, const T &right)
  {
    for (int index = 0; index < vtkm::VecTraits<T>::NUM_COMPONENTS; index++)
    {
      typedef typename vtkm::VecTraits<T>::ComponentType ComponentType;
      const ComponentType &leftValue =
          vtkm::VecTraits<T>::GetComponent(left, index);
      const ComponentType &rightValue =
          vtkm::VecTraits<T>::GetComponent(right, index);
      if (leftValue < rightValue) { return true; }
      if (rightValue < leftValue) { return false; }
    }
    // If we are here, the vectors are equal (or at least equivalent).
    return false;
  }
};

// This functor provides a partial ordering of vectors. It returns true if and
// only if all components satisfy the less operation. It is possible for
// vectors to be neither less, greater, nor equal, but the transitive closure
// is still valid.
template<typename T>
```

```
struct LessPartialOrder
{
  VTKM_EXEC_CONT
  bool operator()(const T &left, const T &right)
  {
    for (int index = 0; index < vtkm::VecTraits<T>::NUM_COMPONENTS; index++)
    {
      typedef typename vtkm::VecTraits<T>::ComponentType ComponentType;
      const ComponentType &leftValue =
          vtkm::VecTraits<T>::GetComponent(left, index);
      const ComponentType &rightValue =
          vtkm::VecTraits<T>::GetComponent(right, index);
      if (!(leftValue < rightValue)) { return false; }
    }
    // If we are here, all components satisfy less than relation.
    return true;
  }
};
```

6.6 List Tags

VTK-m internally uses template metaprogramming, which utilizes C++ templates to run source-generating programs, to customize code to various data and compute platforms. One basic structure often uses with template metaprogramming is a list of class names (also sometimes called a tuple or vector, although both of those names have different meanings in VTK-m).

Many VTK-m users only need predefined lists, such as the type lists specified in Section 6.6.2. Those users can skip most of the details of this section. However, it is sometimes useful to modify lists, create new lists, or operate on lists, and these usages are documented here.

VTK-m uses a tag-based mechanism for defining lists, which differs significantly from lists in many other template metaprogramming libraries such as with `boost::mpl::vector` or `boost::vector`. Rather than enumerating all list entries as template arguments, the list is referenced by a single tag class with a descriptive name. The intention is to make fully resolved types shorter and more readable. (Anyone experienced with template programming knows how insanely long and unreadable types can get in compiler errors and warnings.)

6.6.1 Building List Tags

List tags are constructed in VTK-m by defining a `struct` that publicly inherits from another list tags. The base list tags are defined in the vtkm/ListTag.h header.

The most basic list is defined with `vtkm::ListTagEmpty`. This tag represents an empty list.

`vtkm::ListTagBase<T, ...>` represents a list of the types given as template parameters. `vtkm::ListTagBase` supports a variable number of parameters with the maximum specified by `VTKM_MAX_BASE_LIST`.

Finally, lists can be combined together with `vtkm::ListTagJoin<ListTag1,ListTag2>`, which concatinates two lists together.

The following example demonstrates how to build list tags using these base lists classes. Note first that all the list tags are defined as `struct` rather than `class`. Although these are roughly synonymous in C++, `struct` inheritance is by default public, and public inheritance is important for the list tags to work. Note second that these tags are created by inheritance rather than using `typedef`. Although `typedef` will work, it will lead to much uglier type names defined by the compiler.

Example 6.15: Creating list tags.

```
#include <vtkm/ListTag.h>

// Placeholder classes representing things that might be in a template
// metaprogram list.
class Foo;
class Bar;
class Baz;
class Qux;
class Xyzzy;

// The names of the following tags are indicative of the lists they contain.

struct FooList : vtkm::ListTagBase<Foo> { };

struct FooBarList : vtkm::ListTagBase<Foo,Bar> { };

struct BazQuxXyzzyList : vtkm::ListTagBase<Baz,Qux,Xyzzy> { };

struct QuxBazBarFooList : vtkm::ListTagBase<Qux,Baz,Bar,Foo> { };

struct FooBarBazQuxXyzzyList
    : vtkm::ListTagJoin<FooBarList, BazQuxXyzzyList> { };
```

6.6.2 Type Lists

One of the major use cases for template metaprogramming lists in VTK-m is to identify a set of potential data types for arrays. The vtkm/TypeListTag.h header contains predefined lists for known VTK-m types. Although technically all these lists are of C++ types, the types we refer to here are those data types stored in data arrays. The following lists are provided.

`vtkm::TypeListTagId` Contains the single item `vtkm::Id`.

`vtkm::TypeListTagId2` Contains the single item `vtkm::Id2`.

`vtkm::TypeListTagId3` Contains the single item `vtkm::Id3`.

`vtkm::TypeListTagIndex` A list of all types used to index arrays. Contains `vtkm::Id`, `vtkm::Id2`, and `vtkm::Id3`.

`vtkm::TypeListTagFieldScalar` A list containing types used for scalar fields. Specifically, it contains floating point numbers of different widths (i.e. `vtkm::Float32` and `vtkm::Float64`).

`vtkm::TypeListTagFieldVec2` A list containing types for values of fields with 2 dimensional vectors. All these vectors use floating point numbers.

`vtkm::TypeListTagFieldVec3` A list containing types for values of fields with 3 dimensional vectors. All these vectors use floating point numbers.

`vtkm::TypeListTagFieldVec3` A list containing types for values of fields with 3 dimensional vectors. All these vectors use floating point numbers.

`vtkm::TypeListTagField` A list containing all the types generally used for fields. It is the combination of `vtkm::TypeListTagFieldScalar`, `vtkm::TypeListTagFieldVec2`, `vtkm::TypeListTagFieldVec3`, and `vtkm::TypeListTagFieldVec4`.

`vtkm::TypeListTagScalarAll` A list of all scalar types. It contains signed and unsigned integers of widths from 8 to 64 bits. It also contains floats of 32 and 64 bit widths.

vtkm::TypeListTagVecCommon A list of the most common vector types. It contains all vtkm::Vec class of size 2 through 4 containing components of unsigned bytes, signed 32-bit integers, signed 64-bit integers, 32-bit floats, or 64-bit floats.

vtkm::TypeListTagVecAll A list of all vtkm::Vec classes with standard integers or floating points as components and lengths between 2 and 4.

vtkm::TypeListTagAll A list of all types included in vtkm/Types.h with vtkm::Vecs with up to 4 components.

vtkm::TypeListTagCommon A list containing only the most used types in visualization. This includes signed integers and floats that are 32 or 64 bit. It also includes 3 dimensional vectors of floats. This is the default list used when resolving the type in dynamic arrays (described in Chapter 11).

If these lists are not sufficient, it is possible to build new type lists using the existing type lists and the list bases from Section 6.6.1 as demonstrated in the following example.

Example 6.16: Defining new type lists.

```
#define VTKM_DEFAULT_TYPE_LIST_TAG MyCommonTypes

#include <vtkm/ListTag.h>
#include <vtkm/TypeListTag.h>

// A list of 2D vector types.
struct Vec2List
    : vtkm::ListTagBase<vtkm::Id2,
                        vtkm::Vec<vtkm::Float32,2>,
                        vtkm::Vec<vtkm::Float64,2> > {  };

// An application that uses 2D geometry might commonly encounter this list of
// types.
struct MyCommonTypes : vtkm::ListTagJoin<Vec2List,vtkm::TypeListTagCommon> {  };
```

The vtkm/TypeListTag.h header also defines a macro named VTKM_DEFAULT_TYPE_LIST_TAG that defines a default list of types to use in classes like vtkm::cont::DynamicArrayHandle (Chapter 11). This list can be overridden by defining the VTKM_DEFAULT_TYPE_LIST_TAG macro *before* any VTK-m headers are included. If included after a VTK-m header, the list is not likely to take effect. Do not ignore compiler warnings about the macro being redefined, which you will not get if defined correctly. Example 6.16 also contains an example of overriding the VTKM_DEFAULT_TYPE_LIST_TAG macro.

6.6.3 Operating on Lists

VTK-m template metaprogramming lists are typically just passed to VTK-m methods that internally operate on the lists. Although not typically used outside of the VTK-m library, these operations are also available.

The vtkm/ListTag.h header comes with a vtkm::ListForEach function that takes a functor object and a list tag. It then calls the functor object with the default object of each type in the list. This is most typically used with C++ run-time type information to convert a run-time polymorphic object to a statically typed (and possibly inlined) call.

The following example shows a rudimentary version of coverting a dynamically-typed array to a statically-typed array similar to what is done in VTK-m classes like vtkm::cont::DynamicArrayHandle (which is documented in Chapter 11).

Example 6.17: Converting dynamic types to static types with ListForEach.

```
struct MyArrayBase {
  // A virtual destructor makes sure C++ RTTI will be generated. It also helps
  // ensure subclass destructors are called.
  virtual ~MyArrayBase() {  }
};

template<typename T>
struct MyArrayImpl : public MyArrayBase {
  std::vector<T> Array;
};

template<typename T>
void PrefixSum(std::vector<T> &array)
{
  T sum(typename vtkm::VecTraits<T>::ComponentType(0));
  for (typename std::vector<T>::iterator iter = array.begin();
       iter != array.end();
       iter++)
  {
    sum = sum + *iter;
    *iter = sum;
  }
}

struct PrefixSumFunctor {
  MyArrayBase *ArrayPointer;

  PrefixSumFunctor(MyArrayBase *arrayPointer) : ArrayPointer(arrayPointer) {  }

  template<typename T>
  void operator()(T) {
    typedef MyArrayImpl<T> ConcreteArrayType;
    ConcreteArrayType *concreteArray =
        dynamic_cast<ConcreteArrayType *>(this->ArrayPointer);
    if (concreteArray != NULL)
    {
      PrefixSum(concreteArray->Array);
    }
  }
};

void DoPrefixSum(MyArrayBase *array)
{
  PrefixSumFunctor functor = PrefixSumFunctor(array);
  vtkm::ListForEach(functor, vtkm::TypeListTagCommon());
}
```

6.7 Error Handling

VTK-m uses exceptions to report errors. All exceptions thrown by VTK-m will be a subclass of `vtkm::cont::Error`. For simple error reporting, it is possible to simply catch a `vtkm::cont::Error` and report the error message string reported by the `GetMessage` method.

Example 6.18: Simple error reporting.

```
int main(int argc, char **argv)
{
  try
  {
    // Do something cool with VTK-m
    // ...
  }
  catch (vtkm::cont::Error error)
  {
    std::cout << error.GetMessage() << std::endl;
    return 1;
  }
  return 0;
}
```

There are several subclasses to vtkm::cont::Error. The specific subclass gives an indication of the type of error that occured when the exception was thrown. Catching one of these subclasses may help a program better recover from errors.

vtkm::cont::ErrorControlBadAllocation Thrown when there is a problem accessing or manipulating memory. Often this is thrown when an allocation fails because there is insufficient memory, but other memory access errors can cause this to be thrown as well.

vtkm::cont::ErrorControlBadType Thrown when VTK-m attempts to perform an operation on an object that is of an incompatible type.

vtkm::cont::ErrorControlBadValue Thrown when a VTK-m function or method encounters an invalid value that inhibits progress.

vtkm::cont::ErrorExecution Throw when an error is signaled in the execution environment for example when a worklet is being executed.

vtkm::cont::ErrorControlInternal Thrown when VTK-m detects an internal state that should never be reached. This error usually indicates a bug in VTK-m or, at best, VTK-m failed to detect an invalid input it should have.

vtkm::io::ErrorIO Thrown by a reader or writer when a file error is encountered.

In addition to the aforementioned error signaling, the vtkm/Assert.h header file defines a macro named VTKM_ASSERT. This macro behaves the same as the POSIX assert macro. It takes a single argument that is a condition that is expected to be true. If it is not true, the program is halted and a message is printed. Asserts are useful debugging tools to ensure that software is behaving and being used as expected.

Example 6.19: Using VTKM_ASSERT.

```
template<typename T>
VTKM_CONT
T GetArrayValue(vtkm::cont::ArrayHandle<T> arrayHandle, vtkm::Id index)
{
  VTKM_ASSERT(index >= 0);
  VTKM_ASSERT(index < arrayHandle.GetNumberOfValues());
```

Did you know?

Like the POSIX assert, if the NDEBUG macro is defined, then VTKM_ASSERT will become an empty expression. Typically NDEBUG is defined with a compiler flag (like -DNDEBUG) for release builds to better optimize the code. CMake will automatically add this flag for release builds.

Common Errors

A helpful warning provided by many compilers alerts you of unused variables. (This warning is commonly enabled on VTK-m regression test nightly builds.) If a function argument is used only in a VTKM_ASSERT*, then it will be required for debug builds and be unused in release builds. To get around this problem, add a statement to the function of the form* (void)*variableName*;*. This statement will have no effect on the code generated but will suppress the warning for release builds.*

Because VTK-m makes heavy use of C++ templates, it is possible that these templates could be used with inappropriate types in the arguments. Using an unexpected type in a template can lead to very confusing errors, so it is better to catch such problems as early as possible. The VTKM_STATIC_ASSERT macro, defined in vtkm/StaticAssert.h makes this possible. This macro takes a constant expression that can be evaluated at compile time and verifies that the result is true.

In the following example, VTKM_STATIC_ASSERT and its sister macro VTKM_STATIC_ASSERT_MSG, which allows you to give a descriptive message for the failure, are used to implement checks on a templated function that is designed to work on any scalar type that is represented by 32 or more bits.

Example 6.20: Using VTKM_STATIC_ASSERT.

```
template<typename T>
VTKM_EXEC_CONT
void MyMathFunction(T &value)
{
  VTKM_STATIC_ASSERT(
        (std::is_same<typename vtkm::TypeTraits<T>::DimensionalityTag,
                      vtkm::TypeTraitsScalarTag>::value));

  VTKM_STATIC_ASSERT_MSG(
        sizeof(T) >= 4, "MyMathFunction needs types with at least 32 bits.");
```

Did you know?

In addition to the several trait template classes provided by VTK-m to introspect C++ types, the C++ standard type_traits *header file contains several helpful templates for general queries on types. Example 6.20 demonstrates the use of one such template:* std::is_same*.*

Common Errors

Many templates used to introspect types resolve to the tags std::true_type *and* std::false_type *rather than the constant values* true *and* false *that* VTKM_STATIC_ASSERT *expects. The* std::true_type *and* std::false_type *tags can be converted to the Boolean literal by adding* ::value *to the end of them. Failing to do so will cause* VTKM_STATIC_ASSERT *to behave incorrectly. Example 6.20 demonstrates getting the Boolean literal from the result of* std::is_same*.*

CHAPTER

SEVEN

ARRAY HANDLES

An *array handle*, implemented with the vtkm::cont::ArrayHandle class, manages an array of data that can be accessed or manipulated by VTK-m algorithms. It is typical to construct an array handle in the control environment to pass data to an algorithm running in the execution environment. It is also typical for an algorithm running in the execution environment to allocate and populate an array handle, which can then be read back in the control environment. It is also possible for an array handle to manage data created by one VTK-m algorithm and passed to another, remaining in the execution environment the whole time and never copied to the control environment.

Did you know?

The array handle may have up to two copies of the array, one for the control environment and one for the execution environment. However, depending on the device and how the array is being used, the array handle will only have one copy when possible. Copies between the environments are implicit and lazy. They are copied only when an operation needs data in an environment where the data is not.

vtkm::cont::ArrayHandle behaves like a shared smart pointer in that when the C++ object is copied, each copy holds a reference to the same array. These copies are reference counted so that when all copies of the vtkm::cont::ArrayHandle are destroyed, any allocated memory is released.

7.1 Creating Array Handles

vtkm::cont::ArrayHandle is a templated class with two template parameters. The first template parameter is the only one required and specifies the base type of the entries in the array. The second template parameter specifies the storage used when storing data in the control environment. Storage objects are discussed later in Chapter 10, and for now we will use the default value.

Example 7.1: Declaration of the vtkm::cont::ArrayHandle templated class.

```
template<
    typename T,
    typename StorageTag = VTKM_DEFAULT_STORAGE_TAG>
class ArrayHandle;
```

There are multiple ways to create and populate an array handle. The default vtkm::cont::ArrayHandle constructor will create an empty array with nothing allocated in either the control or execution environment. This is convenient for creating arrays used as the output for algorithms.

Example 7.2: Creating an ArrayHandle for output data.

```
vtkm::cont::ArrayHandle<vtkm::Float32> outputArray;
```

Constructing an ArrayHandle that points to a provided C array or `std::vector` is straightforward with the `vtkm::cont::make_ArrayHandle` functions. These functions will make an array handle that points to the array data that you provide.

Example 7.3: Creating an ArrayHandle that points to a provided C array.

```
  vtkm::Float32 dataBuffer[50];
  // Populate dataBuffer with meaningful data. Perhaps read data from a file.

  vtkm::cont::ArrayHandle<vtkm::Float32> inputArray =
      vtkm::cont::make_ArrayHandle(dataBuffer, 50);
```

Example 7.4: Creating an ArrayHandle that points to a provided `std::vector`.

```
  std::vector<vtkm::Float32> dataBuffer;
  // Populate dataBuffer with meaningful data. Perhaps read data from a file.

  vtkm::cont::ArrayHandle<vtkm::Float32> inputArray =
      vtkm::cont::make_ArrayHandle(dataBuffer);
```

Be aware that `vtkm::cont::make_ArrayHandle` makes a shallow pointer copy. This means that if you change or delete the data provided, the internal state of ArrayHandle becomes invalid and undefined behavior can ensue. The most common manifestation of this error happens when a `std::vector` goes out of scope. This subtle interaction will cause the `vtkm::cont::ArrayHandle` to point to an unallocated portion of the memory heap. For example, if the code in Example 7.4 where to be placed within a callable function or method, it could cause the `vtkm::cont::ArrayHandle` to become invalid.

Common Errors

Because ArrayHandle does not manage data provided by make_ArrayHandle, you should only use these as temporary objects. Example 7.5 demonstrates a method of copying one of these temporary arrays into safe managed memory, and Section 7.3 describes how to put data directly into an ArrayHandle object.

Example 7.5: Invalidating an ArrayHandle by letting the source `std::vector` leave scope.

```
VTKM_CONT
vtkm::cont::ArrayHandle<vtkm::Float32> BadDataLoad()
{
  std::vector<vtkm::Float32> dataBuffer;
  // Populate dataBuffer with meaningful data. Perhaps read data from a file.

  vtkm::cont::ArrayHandle<vtkm::Float32> inputArray =
      vtkm::cont::make_ArrayHandle(dataBuffer);

  return inputArray;
  // THIS IS WRONG! At this point dataBuffer goes out of scope and deletes its
  // memory. However, inputArray has a pointer to that memory, which becomes an
  // invalid pointer in the returned object. Bad things will happen when the
  // ArrayHandle is used.
}

VTKM_CONT
vtkm::cont::ArrayHandle<vtkm::Float32> SafeDataLoad()
{
  std::vector<vtkm::Float32> dataBuffer;
  // Populate dataBuffer with meaningful data. Perhaps read data from a file.

  vtkm::cont::ArrayHandle<vtkm::Float32> tmpArray =
      vtkm::cont::make_ArrayHandle(dataBuffer);

  // This copies the data from one ArrayHandle to another (in the execution
  // environment). Although it is an extraneous copy, it is usually pretty fast
  // on a parallel device. Another option is to make sure that the buffer in
  // the std::vector never goes out of scope before all the ArrayHandle
  // references, but this extra step allows the ArrayHandle to manage its own
  // memory and ensure everything is valid.
  vtkm::cont::ArrayHandle<vtkm::Float32> inputArray;
  vtkm::cont::DeviceAdapterAlgorithm<VTKM_DEFAULT_DEVICE_ADAPTER_TAG>::Copy(
      tmpArray, inputArray);

  return inputArray;
  // This is safe.
}
```

7.2 Array Portals

An array handle defines auxiliary structures called *array portals* that provide direct access into its data. An array portal is a simple object that is somewhat functionally equivalent to an STL-type iterator, but with a much simpler interface. Array portals can be read-only (const) or read-write and they can be accessible from either the control environment or the execution environment. All these variants have similar interfaces although some features that are not applicable can be left out.

An array portal object contains each of the following:

ValueType A **typedef** of the type for each item in the array.

GetNumberOfValues A method that returns the number of entries in the array.

Get A method that returns the value at a given index.

Set A method that changes the value at a given index. This method does not need to exist for read-only (const) array portals.

The following code example defines an array portal for a simple C array of scalar values. This definition has no practical value (it is covered by the more general vtkm::cont::internal::ArrayPortalFromIterators), but demonstrates the function of each component.

Example 7.6: A simple array portal implementation.

```
template<typename T>
class SimpleScalarArrayPortal
{
public:
  typedef T ValueType;

  // There is no specification for creating array portals, but they generally
  // need a constructor like this to be practical.
  VTKM_EXEC_CONT
  SimpleScalarArrayPortal(ValueType *array, vtkm::Id numberOfValues)
    : Array(array), NumberOfValues(numberOfValues) {  }

  VTKM_EXEC_CONT
  SimpleScalarArrayPortal() : Array(NULL), NumberOfValues(0) {  }

  VTKM_EXEC_CONT
  vtkm::Id GetNumberOfValues() const { return this->NumberOfValues; }

  VTKM_EXEC_CONT
  ValueType Get(vtkm::Id index) const { return this->Array[index]; }

  VTKM_EXEC_CONT
  void Set(vtkm::Id index, ValueType value) const {
    this->Array[index] = value;
  }

private:
  ValueType *Array;
  vtkm::Id NumberOfValues;
};
```

Although array portals are simple to implement and use, and array portals' functionality is similar to iterators, there exists a great deal of code already based on STL iterators and it is often convienient to interface with an array through an iterator rather than an array portal. The `vtkm::cont::ArrayPortalToIterators` class can be used to convert an array portal to an STL-compatible iterator. The class is templated on the array portal type and has a constructor that accepts an instance of the array portal. It contains the following features.

`IteratorType` A `typedef` of an STL-compatible random-access iterator that can provide the same access as the array portal.

`GetBegin` A method that returns an STL-compatible iterator of type `IteratorType` that points to the beginning of the array.

`GetEnd` A method that returns an STL-compatible iterator of type `IteratorType` that points to the end of the array.

Example 7.7: Using `ArrayPortalToIterators`.

```
template<typename PortalType>
VTKM_CONT
std::vector<typename PortalType::ValueType>
CopyArrayPortalToVector(const PortalType &portal)
{
  typedef typename PortalType::ValueType ValueType;
  std::vector<ValueType> result(portal.GetNumberOfValues());

  vtkm::cont::ArrayPortalToIterators<PortalType> iterators(portal);

  std::copy(iterators.GetBegin(), iterators.GetEnd(), result.begin());

  return result;
}
```

As a convenience, vtkm/cont/ArrayPortalToIterators.h also defines a pair of functions named `ArrayPortalToIteratorBegin` and `ArrayPortalToIteratorEnd` that each take an array portal as an argument and return a begin and end iterator, respectively.

Example 7.8: Using `ArrayPortalToIteratorBegin` and `ArrayPortalToIteratorEnd`.

```
  std::vector<vtkm::Float32> myContainer(portal.GetNumberOfValues());

  std::copy(vtkm::cont::ArrayPortalToIteratorBegin(portal),
            vtkm::cont::ArrayPortalToIteratorEnd(portal),
            myContainer.begin());
```

ArrayHandle contains two typedefs for array portal types that are capable of interfacing with the underlying data in the control environment. These are PortalControl and PortalConstControl, which define read-write and read-only (const) array portals, respectively.

ArrayHandle also contains similar typedefs for array portals in the execution environment. Because these types are dependent on the device adapter used for execution, these typedefs are embedded in a templated class named ExecutionTypes. Within ExecutionTypes are the typedefs Portal and PortalConst defining the read-write and read-only (const) array portals, respectively, for the execution environment for the given device adapter tag.

Because vtkm::cont::ArrayHandle is control environment object, it provides the methods GetPortalControl and GetPortalConstControl to get the associated array portal objects. These methods also have the side effect of refreshing the control environment copy of the data, so this can be a way of synchronizing the data. Be aware that when an ArrayHandle is created with a pointer or std::vector, it is put in a read-only mode, and GetPortalControl can fail (although GetPortalConstControl will still work). Also be aware that calling GetPortalControl will invalidate any copy in the execution environment, meaning that any subsequent use will cause the data to be copied back again.

Example 7.9: Using portals from an ArrayHandle.

```
template<typename T>
void SortCheckArrayHandle(vtkm::cont::ArrayHandle<T> arrayHandle)
{
  typedef typename vtkm::cont::ArrayHandle<T>::PortalControl
      PortalType;
  typedef typename vtkm::cont::ArrayHandle<T>::PortalConstControl
      PortalConstType;

  PortalType readwritePortal = arrayHandle.GetPortalControl();
  // This is actually pretty dumb. Sorting would be generally faster in
  // parallel in the execution environment using the device adapter algorithms.
  std::sort(vtkm::cont::ArrayPortalToIteratorBegin(readwritePortal),
            vtkm::cont::ArrayPortalToIteratorEnd(readwritePortal));

  PortalConstType readPortal = arrayHandle.GetPortalConstControl();
  for (vtkm::Id index = 1; index < readPortal.GetNumberOfValues(); index++)
  {
    if (readPortal.Get(index-1) > readPortal.Get(index))
    {
      std::cout << "Sorting is wrong!" << std::endl;
      break;
    }
  }
}
```

Did you know?

Most operations on arrays in VTK-m should really be done in the execution environment. Keep in mind that whenever doing an operation using a control array portal, that operation will likely be slow for large arrays. However, some operations, like performing file I/O, make sense in the control environment.

7.3 Allocating and Populating Array Handles

vtkm::cont::ArrayHandle is capable of allocating its own memory. The most straightforward way to allocate memory is to call the Allocate method. The Allocate method takes a single argument, which is the number of elements to make the array.

Example 7.10: Allocating an ArrayHandle.

```
vtkm::cont::ArrayHandle<vtkm::Float32> arrayHandle;

const vtkm::Id ARRAY_SIZE = 50;
arrayHandle.Allocate(ARRAY_SIZE);
```

Common Errors

The ability to allocate memory is a key difference between ArrayHandle *and many other common forms of smart pointers. When one* ArrayHandle *allocates new memory, all other* ArrayHandles *pointing to the same managed memory get the newly allocated memory. This can be particularly surprising when the originally managed memory is empty. For example, older versions of* std::vector *initialized all its values by setting them to the same object. When a* vector *of* ArrayHandles *was created and one entry was allocated, all entries changed to the same allocation.*

Once an ArrayHandle is allocated, it can be populated by using the portal returned from GetPortalControl, as described in Section 7.2. This is roughly the method used by the readers in the I/O package (Chapter 3).

Example 7.11: Populating a newly allocated ArrayHandle.

```
vtkm::cont::ArrayHandle<vtkm::Float32> arrayHandle;

const vtkm::Id ARRAY_SIZE = 50;
arrayHandle.Allocate(ARRAY_SIZE);

typedef vtkm::cont::ArrayHandle<vtkm::Float32>::PortalControl PortalType;
PortalType portal = arrayHandle.GetPortalControl();

for (vtkm::Id index = 0; index < ARRAY_SIZE; index++)
{
  portal.Set(index, GetValueForArray(index));
}
```

7.4 Interface to Execution Environment

One of the main functions of the array handle is to allow an array to be defined in the control environment and then be used in the execution environment. When using an ArrayHandle with filters or worklets, this transition is handled automatically. However, it is also possible to invoke the transfer for use in your own scheduled algorithms.

The ArrayHandle class manages the transition from control to execution with a set of three methods that allocate, transfer, and ready the data in one operation. These methods all start with the prefix Prepare and are meant to be called before some operation happens in the execution environment. The methods are as follows.

PrepareForInput Copies data from the control to the execution environment, if necessary, and readies the data for read-only access.

PrepareForInPlace Copies the data from the control to the execution environment, if necessary, and readies the data for both reading and writing.

PrepareForOutput Allocates space (the size of which is given as a parameter) in the execution environment, if necessary, and readies the space for writing.

The PrepareForInput and PrepareForInPlace methods each take a single argument that is the device adapter tag where execution will take place (see Section 8.1 for more information on device adapter tags). PrepareForOutput takes two arguments: the size of the space to allocate and the device adapter tag. Each of these methods returns an array portal that can be used in the execution environment. PrepareForInput returns an object of type ArrayHandle::ExecutionTypes<*DeviceAdapterTag*>::PortalConst whereas PrepareForInPlace and PrepareForOutput each return an object of type ArrayHandle::ExecutionTypes<*DeviceAdapterTag*>::Portal.

Although these Prepare methods are called in the control environment, the returned array portal can only be used in the execution environment. Thus, the portal must be passed to an invocation of the execution environment. Typically this is done with a call to Schedule in vtkm::cont::DeviceAdapterAlgorithm. This and other device adapter algorithms are described in detail in Section 8.2, but here is a quick example of using these execution array portals in a simple functor.

Example 7.12: Using an execution array portal from an ArrayHandle.

```
template<typename T, typename Device>
struct DoubleFunctor : public vtkm::exec::FunctorBase
{
  typedef typename vtkm::cont::ArrayHandle<T>::
      template ExecutionTypes<Device>::PortalConst InputPortalType;
  typedef typename vtkm::cont::ArrayHandle<T>::
      template ExecutionTypes<Device>::Portal OutputPortalType;

  VTKM_CONT
  DoubleFunctor(InputPortalType inputPortal, OutputPortalType outputPortal)
    : InputPortal(inputPortal), OutputPortal(outputPortal) {  }

  VTKM_EXEC
  void operator()(vtkm::Id index) const {
    this->OutputPortal.Set(index, 2*this->InputPortal.Get(index));
  }

  InputPortalType InputPortal;
  OutputPortalType OutputPortal;
};

template<typename T, typename Device>
void DoubleArray(vtkm::cont::ArrayHandle<T> inputArray,
                 vtkm::cont::ArrayHandle<T> outputArray,
                 Device)
{
  vtkm::Id numValues = inputArray.GetNumberOfValues();

  DoubleFunctor<T, Device> functor(
        inputArray.PrepareForInput(Device()),
        outputArray.PrepareForOutput(numValues, Device()));

  vtkm::cont::DeviceAdapterAlgorithm<Device>::Schedule(functor, numValues);
}
```

It should be noted that the array handle will expect any use of the execution array portal to finish before the next call to any ArrayHandle method. Since these Prepare methods are typically used in the process of scheduling an algorithm in the execution environment, this is seldom an issue.

Common Errors

There are many operations on `ArrayHandle` *that can invalidate the array portals, so do not keep them around indefinitely. It is generally better to keep a reference to the* `ArrayHandle` *and use one of the* `Prepare` *each time the data are accessed in the execution environment.*

CHAPTER

EIGHT

DEVICE ADAPTERS

As multiple vendors vie to provide accelerator-type processors, a great variance in the computer architecture exists. Likewise, there exist multiple compiler environments and libraries for these devices such as CUDA, OpenMP, and various threading libraries. These compiler technologies also vary from system to system.

To make porting among these systems at all feasible, we require a base language support, and the language we use is C++. The majority of the code in VTK-m is constrained to the standard C++ language constructs to minimize the specialization from one system to the next.

Each device and device technology requires some level of code specialization, and that specialization is encapsulated in a unit called a *device adapter*. Thus, porting VTK-m to a new architecture can be done by adding only a device adapter.

The device adapter is shown diagrammatically as the connection between the control and execution environments in Figure 6.1 on page 46. The functionality of the device adapter comprises two main parts: a collection of parallel algorithms run in the execution environment and a module to transfer data between the control and execution environments.

This chapter describes how tags are used to specify which devices to use for operations within VTK-m. The chapter also outlines the features provided by a device adapter that allow you to directly control a device. Finally, we document how to create a new device adapter to port or specialize VTK-m for a different device or system.

8.1 Device Adapter Tag

A device adapter is identified by a *device adapter tag*. This tag, which is simply an empty struct type, is used as the template parameter for several classes in the VTK-m control environment and causes these classes to direct their work to a particular device.

There are two ways to select a device adapter. The first is to make a global selection of a default device adapter. The second is to specify a specific device adapter as a template parameter.

8.1.1 Default Device Adapter

A default device adapter tag is specified in vtkm/cont/DeviceAdapter.h (although it can also by specified in many other VTK-m headers via header dependencies). If no other information is given, VTK-m attempts to choose a default device adapter that is a best fit for the system it is compiled on. VTK-m currently select the default device adapter with the following sequence of conditions.

- If the source code is being compiled by CUDA, the CUDA device is used.

- If the CUDA compiler is not being used and the current compiler supports OpenMP, then the OpenMP device is used. [TECHNICALLY, OPENMP IS NOT YET SUPPORTED IN VTK-M, SO THIS WILL NEVER ACTUALLY BE PICKED. BUT ONCE IT IS IMPLEMENTED, THIS WILL BE THE CHAIN.]
- If the compiler supports neither CUDA nor OpenMP and VTK-m was configured to use Intel Threading Building Blocks, then that device is used.
- If no parallel device adapters are found, then VTK-m falls back to a serial device.

You can also set the default device adapter specifically by setting the `VTKM_DEVICE_ADAPTER` macro. This macro must be set *before* including any VTK-m files. You can set `VTKM_DEVICE_ADAPTER` to any one of the following.

`VTKM_DEVICE_ADAPTER_SERIAL` Performs all computation on the same single thread as the control environment. This device is useful for debugging. This device is always available.

`VTKM_DEVICE_ADAPTER_CUDA` Uses a CUDA capable GPU device. For this device to work, VTK-m must be configured to use CUDA and the code must be compiled by the CUDA `nvcc` compiler.

`VTKM_DEVICE_ADAPTER_OPENMP` Uses OpenMP compiler extensions to run algorithms on multiple threads. For this device to work, VTK-m must be configured to use OpenMP and the code must be compiled with a compiler that supports OpenMP pragmas. [NOT CURRENTLY IMPLEMENTED.]

`VTKM_DEVICE_ADAPTER_TBB` Uses the Intel Threading Building Blocks library to run algorithms on multiple threads. For this device to work, VTK-m must be configured to use TBB and the executable must be linked to the TBB library.

These macros provide a useful mechanism for quickly reconfiguring code to run on different devices. The following example shows a typical block of code at the top of a source file that could be used for quick reconfigurations.

Example 8.1: Macros to port VTK-m code among different devices

```
// Uncomment one (and only one) of the following to reconfigure the VTK-m
// code to use a particular device. Comment them all to automatically pick a
// device.
#define VTKM_DEVICE_ADAPTER VTKM_DEVICE_ADAPTER_SERIAL
//#define VTKM_DEVICE_ADAPTER VTKM_DEVICE_ADAPTER_CUDA
//#define VTKM_DEVICE_ADAPTER VTKM_DEVICE_ADAPTER_OPENMP
//#define VTKM_DEVICE_ADAPTER VTKM_DEVICE_ADAPTER_TBB

#include <vtkm/cont/DeviceAdapter.h>
```

Did you know?

Filters do not actually use the default device adapter tag. They have a more sophisticated device selection mechanism that determines the devices available at runtime and will attempt running on multiple devices.

The default device adapter can always be overridden by specifying a device adapter tag, as described in the next section. There is actually one more internal default device adapter named `VTKM_DEVICE_ADAPTER_ERROR` that will cause a compile error if any component attempts to use the default device adapter. This feature is most often used in testing code to check when device adapters should be specified.

8.1.2 Specifying Device Adapter Tags

In addition to setting a global default device adapter, it is possible to explicitly set which device adapter to use in any feature provided by VTK-m. This is done by providing a device adapter tag as a template argument to VTK-m templated objects. The following device adapter tags are available in VTK-m.

`vtkm::cont::DeviceAdapterTagSerial` Performs all computation on the same single thread as the control environment. This device is useful for debugging. This device is always available. This tag is defined in vtkm/cont/DeviceAdapterSerial.h.

`vtkm::cont::DeviceAdapterTagCuda` Uses a CUDA capable GPU device. For this device to work, VTK-m must be configured to use CUDA and the code must be compiled by the CUDA nvcc compiler. This tag is defined in vtkm/cont/cuda/DeviceAdapterCuda.h.

`vtkm::cont::DeviceAdapterTagOpenMP` Uses OpenMP compiler extensions to run algorithms on multiple threads. For this device to work, VTK-m must be configured to use OpenMP and the code must be compiled with a compiler that supports OpenMP pragmas. This tag is defined in vtkm/openmp/cont/DeviceAdapterOpenMP.h. [NOT CURRENTLY IMPLEMENTED.]

`vtkm::cont::DeviceAdapterTagTBB` Uses the Intel Threading Building Blocks library to run algorithms on multiple threads. For this device to work, VTK-m must be configured to use TBB and the executable must be linked to the TBB library. This tag is defined in vtkm/cont/tbb/DeviceAdapterTBB.h.

The following example uses the tag for the Intel Threading Building blocks device adapter to prepare an output array for that device. In this case, the device adapter tag is passed as a parameter for the `PrepareForOutput` method of `vtkm::cont::ArrayHandle`.

Example 8.2: Specifying a device using a device adapter tag.

```
  arrayHandle.PrepareForOutput(50, vtkm::cont::DeviceAdapterTagTBB());
```

When structuring your code to always specify a particular device adapter, consider setting the default device adapter (with the `VTKM_DEVICE_ADAPTER` macro) to `VTKM_DEVICE_ADAPTER_ERROR`. This will cause the compiler to produce an error if any object is instantiated with the default device adapter, which checks to make sure the code properly specifies every device adapter parameter.

VTK-m also defines a macro named `VTKM_DEFAULT_DEVICE_ADAPTER_TAG`, which can be used in place of an explicit device adapter tag to use the default tag. This macro is used to create new templates that have template parameters for device adapters that can use the default. The following example defines a functor to be used with the `Schedule` operation (to be described later) that is templated on the device it uses.

Example 8.3: Specifying a default device for template parameters.

```
template<typename Device = VTKM_DEFAULT_DEVICE_ADAPTER_TAG>
struct SetPortalFunctor : vtkm::exec::FunctorBase
{
  VTKM_IS_DEVICE_ADAPTER_TAG(Device);

  typedef typename vtkm::cont::ArrayHandle<vtkm::Id>::
      ExecutionTypes<Device>::Portal ExecPortalType;
  ExecPortalType Portal;

  VTKM_CONT
  SetPortalFunctor(vtkm::cont::ArrayHandle<vtkm::Id> array, vtkm::Id size)
    : Portal(array.PrepareForOutput(size, Device()))
  {  }

  VTKM_EXEC
  void operator()(vtkm::Id index) const
  {
    typedef typename ExecPortalType::ValueType ValueType;
    this->Portal.Set(index, TestValue(index, ValueType()));
  }
};
```

Common Errors

A device adapter tag is a class just like every other type in C++. Thus it is possible to accidently use a type that is not a device adapter tag when one is expected. This leads to unexpected errors in strange parts of the code. To help identify these errors, it is good practice to use the `VTKM_IS_DEVICE_ADAPTER_TAG` *macro to verify the type is a valid device adapter tag. Example 8.3 uses this macro on line 4.*

8.2 Device Adapter Algorithms

VTK-m comes with the templated class `vtkm::cont::DeviceAdapterAlgorithm` that provides a set of algorithms that can be invoked in the control environment and are run on the execution environment. The template has a single argument that specifies the device adapter tag.

Example 8.4: Prototype for `vtkm::cont::DeviceAdapterAlgorithm`.

```
namespace vtkm {
namespace cont {

template<typename DeviceAdapterTag>
struct DeviceAdapterAlgorithm;

}
} // namespace vtkm::cont
```

`DeviceAdapterAlgorithm` contains no state. It only has a set of static methods that implement its algorithms. The following methods are available.

Did you know?

Many of the following device adapter algorithms take input and output `ArrayHandle`*s, and these functions will handle their own memory management. This means that it is unnecessary to allocate output arrays. For example, it is unnecessary to call* `ArrayHandle::Allocate()` *for the output array passed to the* `Copy` *method.*

`Copy` Copies data from an input array to an output array. The copy takes place in the execution environment.

`LowerBounds` The `LowerBounds` method takes three arguments. The first argument is an `ArrayHandle` of sorted values. The second argument is another `ArrayHandle` of items to find in the first array. `LowerBounds` find the index of the first item that is greater than or equal to the target value, much like the `std::lower_bound` STL algorithm. The results are returned in an `ArrayHandle` given in the third argument.

There are two specializations of LowerBounds. The first takes an additional comparison function that defines the less-than operation. The second takes only two parameters. The first is an ArrayHandle of sorted vtkm::Ids and the second is an ArrayHandle of vtkm::Ids to find in the first list. The results are written back out to the second array. This second specialization is useful for inverting index maps.

Reduce The Reduce method takes an input array, initial value, and a binary function and computes a "total" of applying the binary function to all entries in the array. The provided binary function must be associative (but it need not be commutative). There is a specialization of Reduce that does not take a binary function and computes the sum.

ReduceByKey The ReduceByKey method works similarly to the Reduce method except that it takes an additional array of keys, which must be the same length as the values being reduced. The arrays are partitioned into segments that have identical adjacent keys, and a separate reduction is performed on each partition. The unique keys and reduced values are returned in separate arrays.

ScanInclusive The ScanInclusive method takes an input and an output ArrayHandle and performs a running sum on the input array. The first value in the output is the same as the first value in the input. The second value in the output is the sum of the first two values in the input. The third value in the output is the sum of the first three values of the input, and so on. ScanInclusive returns the sum of all values in the input. There are two forms of ScanInclusive: one performs the sum using addition whereas the other accepts a custom binary function to use as the sum operator.

ScanExclusive The ScanExclusive method takes an input and an output ArrayHandle and performs a running sum on the input array. The first value in the output is always 0. The second value in the output is the same as the first value in the input. The third value in the output is the sum of the first two values in the input. The fourth value in the output is the sum of the first three values of the input, and so on. ScanExclusive returns the sum of all values in the input. There are two forms of ScanExclusive: one performs the sum using addition whereas the other accepts a custom binary function to use as the sum operator and a custom initial value to use in the running sum.

Schedule The Schedule method takes a functor as its first argument and invokes it a number of times specified by the second argument. It should be assumed that each invocation of the functor occurs on a separate thread although in practice there could be some thread sharing.

There are two versions of the Schedule method. The first version takes a vtkm::Id and invokes the functor that number of times. The second version takes a vtkm::Id3 and invokes the functor once for every entry in a 3D array of the given dimensions.

The functor is expected to be an object with a const overloaded parentheses operator. The operator takes as a parameter the index of the invocation, which is either a vtkm::Id or a vtkm::Id3 depending on what version of Schedule is being used. The functor must also subclass vtkm::exec::FunctorBase, which provides the error handling facilities for the execution environment. FunctorBase contains a public method named RaiseError that takes a message and will cause a vtkm::cont::ErrorExecution exception to be thrown in the control environment.

Sort The Sort method provides an unstable sort of an array. There are two forms of the Sort method. The first takes an ArrayHandle and sorts the values in place. The second takes an additional argument that is a functor that provides the comparison operation for the sort.

SortByKey The SortByKey method works similarly to the Sort method except that it takes two ArrayHandles: an array of keys and a corresponding array of values. The sort orders the array of keys in ascending values and also reorders the values so they remain paired with the same key. Like Sort, SortByKey has a version that sorts by the default less-than operator and a version that accepts a custom comparison functor.

`StreamCompact` The `StreamCompact` method selectively removes values from an array. The first argument is an `ArrayHandle` to be compacted and the second argument is an `ArrayHandle` of equal size with flags indicating whether the corresponding input value is to be copied to the output. The third argument is an output `ArrayHandle` whose length is set to the number of true flags in the stencil and the passed values are put in order to the output array.

There is also a second form of `StreamCompact` that only has the stencil and output as arguments. In this version, the output gets the corresponding index of where the input should be taken from.

`Synchronize` The `Synchronize` method waits for any asynchronous operations running on the device to complete and then returns.

`Unique` The `Unique` method removes all duplicate values in an `ArrayHandle`. The method will only find duplicates if they are adjacent to each other in the array. The easiest way to ensure that duplicate values are adjacent is to sort the array first.

There are two versions of `Unique`. The first uses the equals operator to compare entries. The second accepts a binary functor to perform the comparisons.

`UpperBounds` The `UpperBounds` method takes three arguments. The first argument is an `ArrayHandle` of sorted values. The second argument is another `ArrayHandle` of items to find in the first array. `UpperBounds` find the index of the first item that is greater than to the target value, much like the `std::upper_bound` STL algorithm. The results are returned in an `ArrayHandle` given in the third argument.

There are two specializations of `UpperBounds`. The first takes an additional comparison function that defines the less-than operation. The second takes only two parameters. The first is an `ArrayHandle` of sorted `vtkm::Id`s and the second is an `ArrayHandle` of `vtkm::Id`s to find in the first list. The results are written back out to the second array. This second specialization is useful for inverting index maps.

CHAPTER

NINE

TIMERS

It is often the case that you need to measure the time it takes for an operation to happen. This could be for performing measurements for algorithm study or it could be to dynamically adjust scheduling.

Performing timing in a multi-threaded environment can be tricky because operations happen asynchronously. In the VTK-m control environment timing is simplified because the control environment operates on a single thread. However, operations invoked in the execution environment may run asynchronously to operations in the control environment.

To ensure that accurate timings can be made, VTK-m provides a vtkm::cont::Timer class that is templated on the device adapter to provide an accurate measurement of operations that happen on the device. If not template parameter is provided, the default device adapter is used.

The timing starts when the Timer is constructed. The time elapsed can be retrieved with a call to the GetElapsedTime method. This method will block until all operations in the execution environment complete so as to return an accurate time. The timer can be restarted with a call to the Reset method.

Example 9.1: Using vtkm::cont::Timer.

```
vtkm::filter::PointElevation elevationFilter;

vtkm::cont::Timer<> timer;

vtkm::filter::ResultField result =
    elevationFilter.Execute(dataSet, dataSet.GetCoordinateSystem());

// This code makes sure data is pulled back to the host in a host/device
// architecture.
vtkm::cont::ArrayHandle<vtkm::Float64> outArray;
result.FieldAs(outArray);
outArray.GetPortalConstControl();

vtkm::Float64 elapsedTime = timer.GetElapsedTime();

std::cout << "Time to run: " << elapsedTime << std::endl;
```

Common Errors

Make sure the Timer being used is match to the device adapter used for the computation. This will ensure that the parallel computation is synchronized.

Common Errors

Some device require data to be copied between the host CPU and the device. In this case you might want to measure the time to copy data back to the host. This can be done by "touching" the data on the host by getting a control portal.

CHAPTER

TEN

FANCY ARRAY STORAGE

Chapter 7 introduces the vtkm::cont::ArrayHandle class. In it, we learned how an ArrayHandle manages the memory allocation of an array, provides access to the data via array portals, and supervises the movement of data between the control and execution environments.

In addition to these data management features, ArrayHandle also provides a configurable *storage* mechanism that allows you, through efficient template configuration, to redefine how data are stored and retrieved. The storage object provides an encapsulated interface around the data so that any necessary strides, offsets, or other access patterns may be handled internally. The relationship between array handles and their storage object is shown in Figure 10.1.

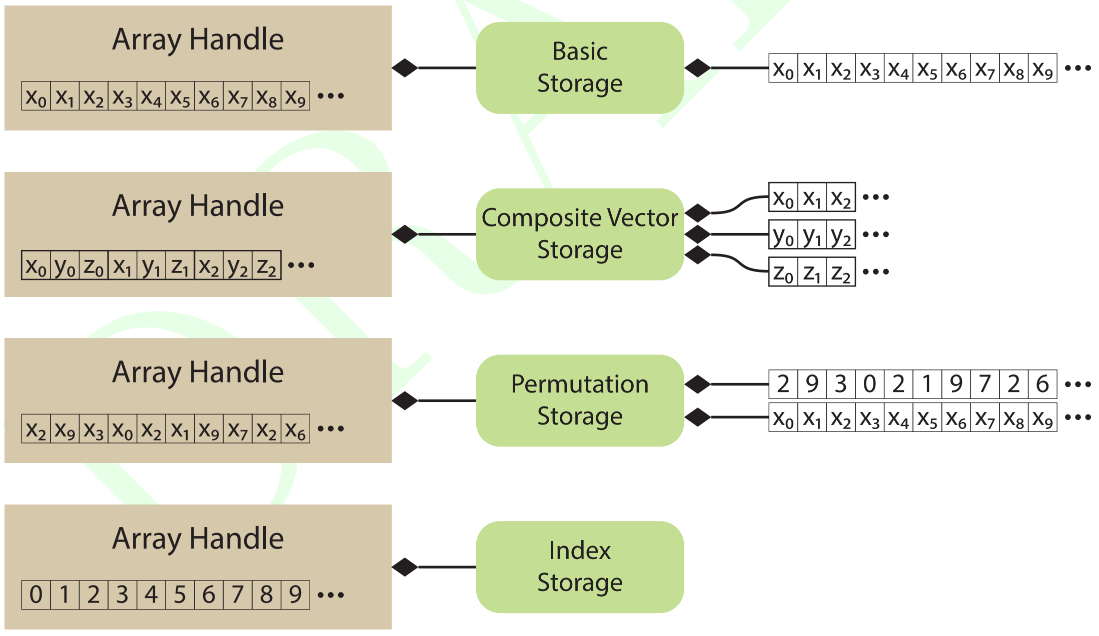


Figure 10.1: Array handles, storage objects, and the underlying data source.

One interesting consequence of using a generic storage object to manage data within an array handle is that the storage can be defined functionally rather than point to data stored in physical memory. Thus, implicit array handles are easily created by adapting to functional "storage." For example, the point coordinates of a uniform rectilinear grid are implicit based on the topological position of the point. Thus, the point coordinates for uniform rectilinear grids can be implemented as an implicit array with the same interface as explicit arrays (where unstructured grid points would be stored). In this chapter we explore the many ways you can manipulate the ArrayHandle storage.

Did you know?

VTK-m comes with many "fancy" array handles that can change the data in other arrays without modifying the memory or can generate data on the fly to behave like an array without actually using any memory. These fancy array handles are documented later in this chapter, and they can be very handy when developing with VTK-m.

10.1 Basic Storage

As previously discussed in Chapter 7, vtkm::cont::ArrayHandle takes two template arguments.

Example 10.1: Declaration of the vtkm::cont::ArrayHandle templated class (again).

```
template<
    typename T,
    typename StorageTag = VTKM_DEFAULT_STORAGE_TAG>
class ArrayHandle;
```

The first argument is the only one required and has been demonstrated multiple times before. The second (optional) argument specifies something called a storage, which provides the interface between the generic vtkm::cont::ArrayHandle class and a specific storage mechanism in the control environment.

In this and the following sections we describe this storage mechanism. A default storage is specified in much the same way as a default device adapter is defined (as described in Section 8.1.1. It is done by setting the VTKM_STORAGE macro. This macro must be set before including any VTK-m header files. Currently the only practical storage provided by VTK-m is the basic storage, which simply allocates a continuous section of memory of the given base type. This storage can be explicitly specified by setting VTKM_STORAGE to VTKM_STORAGE_BASIC although the basic storage will also be used as the default if no other storage is specified (which is typical).

The default storage can always be overridden by specifying an array storage tag. The tag for the basic storage is located in the vtkm/cont/StorageBasic.h header file and is named vtkm::cont::StorageTagBasic. Here is an example of specifying the storage type when declaring an array handle.

Example 10.2: Specifying the storage type for an ArrayHandle.

```
vtkm::cont::ArrayHandle<vtkm::Float32,vtkm::cont::StorageTagBasic> arrayHandle;
```

VTK-m also defines a macro named VTKM_DEFAULT_STORAGE_TAG that can be used in place of an explicit storage tag to use the default tag. This macro is used to create new templates that have template parameters for storage that can use the default.

10.2 Provided Fancy Arrays

The generic array handle and storage templating in VTK-m allows for any type of operations to retrieve a particular value. Typically this is used to convert an index to some location or locations in memory. However, it is also possible to do many other operations. Arrays can be augmented on the fly by mutating their indices or values. Or values could be computed directly from the index so that no storage is required for the array at all. This modified behavior for arrays is called "fancy" arrays.

VTK-m provides many of the fancy arrays, which we explore in this section. Later Section 10.3 describes many different ways in which new fancy arrays can be implemented.

10.2.1 Constant Arrays

A constant array is a fancy array handle that has the same value in all of its entries. The constant array provides this array without actually using any memory.

Specifying a constant array in VTK-m is straightforward. VTK-m has a class named vtkm::cont::ArrayHandleConstant. ArrayHandleConstant is a templated class with a single template argument that is the type of value for each element in the array. The constructor for ArrayHandleConstant takes the value to provide by the array and the number of values the array should present. The following example is a simple demonstration of the constant array handle.

Example 10.3: Using ArrayHandleConstant.

```
// Create an array of 50 entries, all containing the number 3. This could be
// used, for example, to represent the sizes of all the polygons in a set
// where we know all the polygons are triangles.
vtkm::cont::ArrayHandleConstant<vtkm::Id> constantArray(3, 50);
```

The vtkm/cont/ArrayHandleConstant.h header also contains the templated convenience function vtkm::cont::make_ArrayHandleConstant that takes a value and a size for the array. This function can sometimes be used to avoid having to declare the full array type.

Example 10.4: Using make_ArrayHandleConstant.

```
// Create an array of 50 entries, all containing the number 3.
vtkm::cont::make_ArrayHandleConstant(3, 50)
```

10.2.2 Counting Arrays

A counting array is a fancy array handle that provides a sequence of numbers. These fancy arrays can represent the data without actually using any memory.

VTK-m provides two versions of a counting array. The first version is an index array that provides a specialized but common form of a counting array called an index array. An index array has values of type vtkm::Id that start at 0 and count up by 1 (i.e. $0, 1, 2, 3, \ldots$). The index array mirrors the array's index.

Specifying an index array in VTK-m is done with a class named vtkm::cont::ArrayHandleIndex. The constructor for ArrayHandleIndex takes the size of the array to create. The following example is a simple demonstration of the index array handle.

Example 10.5: Using ArrayHandleIndex.

```
// Create an array containing [0, 1, 2, 3, ..., 49].
vtkm::cont::ArrayHandleIndex indexArray(50);
```

The vtkm::cont::ArrayHandleCounting class provides a more general form of counting. ArrayHandleCounting is a templated class with a single template argument that is the type of value for each element in the array. The constructor for ArrayHandleCounting takes three arguments: the start value (used at index 0), the step from one value to the next, and the length of the array. The following example is a simple demonstration of the counting array handle.

Example 10.6: Using ArrayHandleCounting.

```
// Create an array containing [-1.0, -0.9, -0.8, ..., 0.9, 1.0]
vtkm::cont::ArrayHandleCounting<vtkm::Float32> sampleArray(-1.0f, 0.1f, 21);
```

Did you know?

In addition to being simpler to declare, `ArrayHandleIndex` *is slightly faster than* `ArrayHandleCounting`*. Thus, when applicable, you should prefer using* `ArrayHandleIndex`*.*

The vtkm/cont/ArrayHandleCounting.h header also contains the templated convenience function `vtkm::cont::make_ArrayHandleCounting` that also takes the start value, step, and length as arguments. This function can sometimes be used to avoid having to declare the full array type.

Example 10.7: Using `make_ArrayHandleCounting`.

```
  // Create an array of 50 entries, all containing the number 3.
  vtkm::cont::make_ArrayHandleCounting(-1.0f, 0.1f, 21)
```

There are no fundamental limits on how `ArrayHandleCounting` counts. For example, it is possible to count backwards.

Example 10.8: Counting backwards with `ArrayHandleCounting`.

```
  // Create an array containing [49, 48, 47, 46, ..., 0].
  vtkm::cont::ArrayHandleCounting<vtkm::Id> backwardIndexArray(49, -1, 50);
```

It is also possible to use `ArrayHandleCounting` to make sequences of `vtkm::Vec` values with piece-wise counting in each of the components.

Example 10.9: Using `ArrayHandleCounting` with `vtkm::Vec` objects.

```
  // Create an array containg [(0,-3,75), (1,2,25), (3,7,-25)]
  vtkm::cont::make_ArrayHandleCounting(vtkm::make_Vec(0, -3, 75),
                                       vtkm::make_Vec(1, 5, -50),
                                       3)
```

10.2.3 Cast Arrays

A cast array is a fancy array that changes the type of the elements in an array. The cast array provides this re-typed array without actually copying or generating any data. Instead, casts are performed as the array is accessed.

VTK-m has a class named `vtkm::cont::ArrayHandleCast` to perform this implicit casting. `ArrayHandleCast` is a templated class with two template arguments. The first argument is the type to cast values to. The second argument is the type of the original `ArrayHandle`. The constructor to `ArrayHandleCast` takes the `ArrayHandle` to modify by casting.

Example 10.10: Using `ArrayHandleCast`.

```
template<typename T>
VTKM_CONT
void Foo(const std::vector<T> &inputData)
{
  vtkm::cont::ArrayHandle<T> originalArray =
      vtkm::cont::make_ArrayHandle(inputData);

  vtkm::cont::ArrayHandleCast<vtkm::Float64, vtkm::cont::ArrayHandle<T> >
      castArray(originalArray);
```

The vtkm/cont/ArrayHandleCast.h header also contains the templated convenience function `vtkm::cont::make_ArrayHandleCast` that constructs the cast array. The first argument is the original `ArrayHandle` original array to cast. The optional second argument is of the type to cast to (or you can optionally specify the cast-to type as a template argument.

Example 10.11: Using make_ArrayHandleCast.

```
vtkm::cont::make_ArrayHandleCast<vtkm::Float64>(originalArray)
```

10.2.4 Permuted Arrays

A permutation array is a fancy array handle that reorders the elements in an array. Elements in the array can be skipped over or replicated. The permutation array provides this reordered array without actually coping any data. Instead, indices are adjusted as the array is accessed.

Specifying a permutation array in VTK-m is straightforward. VTK-m has a class named vtkm::cont::ArrayHandlePermutation that takes two arrays: an array of values and an array of indices that maps an index in the permutation to an index of the original values. The index array is specified first. The following example is a simple demonstration of the permutation array handle.

Example 10.12: Using ArrayHandlePermutation.

```
typedef vtkm::cont::ArrayHandle<vtkm::Id> IdArrayType;
typedef IdArrayType::PortalControl IdPortalType;

typedef vtkm::cont::ArrayHandle<vtkm::Float64> ValueArrayType;
typedef ValueArrayType::PortalControl ValuePortalType;

// Create array with values [0.0, 0.1, 0.2, 0.3]
ValueArrayType valueArray;
valueArray.Allocate(4);
ValuePortalType valuePortal = valueArray.GetPortalControl();
valuePortal.Set(0, 0.0);
valuePortal.Set(1, 0.1);
valuePortal.Set(2, 0.2);
valuePortal.Set(3, 0.3);

// Use ArrayHandlePermutation to make an array = [0.3, 0.0, 0.1].
IdArrayType idArray1;
idArray1.Allocate(3);
IdPortalType idPortal1 = idArray1.GetPortalControl();
idPortal1.Set(0, 3);
idPortal1.Set(1, 0);
idPortal1.Set(2, 1);
vtkm::cont::ArrayHandlePermutation<IdArrayType,ValueArrayType>
    permutedArray1(idArray1, valueArray);

// Use ArrayHandlePermutation to make an array = [0.1, 0.2, 0.2, 0.3, 0.0]
IdArrayType idArray2;
idArray2.Allocate(5);
IdPortalType idPortal2 = idArray2.GetPortalControl();
idPortal2.Set(0, 1);
idPortal2.Set(1, 2);
idPortal2.Set(2, 2);
idPortal2.Set(3, 3);
idPortal2.Set(4, 0);
vtkm::cont::ArrayHandlePermutation<IdArrayType,ValueArrayType>
    permutedArray2(idArray2, valueArray);
```

The vtkm/cont/ArrayHandlePermutation.h header also contains the templated convenience function vtkm::cont::make_ArrayHandlePermutation that takes instances of the index and value array handles and returns a permutation array. This function can sometimes be used to avoid having to declare the full array type.

Example 10.13: Using make_ArrayHandlePermutation.

```
vtkm::cont::make_ArrayHandlePermutation(idArray,valueArray)
```

Common Errors

When using an `ArrayHandlePermutation`*, take care that all the provided indices in the index array point to valid locations in the values array. Bad indices can cause reading from or writing to invalid memory locations, which can be difficult to debug.*

Did you know?

You can write to a `ArrayHandlePermutation` *by, for example, using it as an output array. Writes to the* `ArrayHandlePermutation` *will go to the respective location in the source array. However,* `ArrayHandlePermutation` *cannot be resized.*

10.2.5 Zipped Arrays

A zip array is a fancy array handle that combines two arrays of the same size to pair up the corresponding values. Each element in the zipped array is a `vtkm::Pair` containing the values of the two respective arrays. These pairs are not stored in their own memory space. Rather, the pairs are generated as the array is used. Writing a pair to the zipped array writes the values in the two source arrays.

Specifying a zipped array in VTK-m is straightforward. VTK-m has a class named `vtkm::cont::ArrayHandleZip` that takes the two arrays providing values for the first and second entries in the pairs. The following example is a simple demonstration of creating a zip array handle.

Example 10.14: Using `ArrayHandleZip`.

```
typedef vtkm::cont::ArrayHandle<vtkm::Id> ArrayType1;
typedef ArrayType1::PortalControl PortalType1;

typedef vtkm::cont::ArrayHandle<vtkm::Float64> ArrayType2;
typedef ArrayType2::PortalControl PortalType2;

// Create an array of vtkm::Id with values [3, 0, 1]
ArrayType1 array1;
array1.Allocate(3);
PortalType1 portal1 = array1.GetPortalControl();
portal1.Set(0, 3);
portal1.Set(1, 0);
portal1.Set(2, 1);

// Create a second array of vtkm::Float32 with values [0.0, 0.1, 0.2]
ArrayType2 array2;
array2.Allocate(3);
PortalType2 portal2 = array2.GetPortalControl();
portal2.Set(0, 0.0);
portal2.Set(1, 0.1);
portal2.Set(2, 0.2);

// Zip the two arrays together to create an array of
// vtkm::Pair<vtkm::Id, vtkm::Float64> with values [(3,0.0), (0,0.1), (1,0.2)]
vtkm::cont::ArrayHandleZip<ArrayType1,ArrayType2> zipArray(array1, array2);
```

The vtkm/cont/ArrayHandleZip.h header also contains the templated convenience function `vtkm::cont::make_ArrayHandleZip` that takes instances of the two array handles and returns a zip array. This function can sometimes be used to avoid having to declare the full array type.

Example 10.15: Using make_ArrayHandleZip.

```
vtkm::cont::make_ArrayHandleZip(array1,array2)
```

10.2.6 Coordinate System Arrays

Many of the data structures we use in VTK-m are described in a 3D coordinate system. Although, as we will see in Chapter 12, we can use any ArrayHandle to store point coordinates, including a raw array of 3D vectors, there are some common patterns for point coordinates that we can use specialized arrays to better represent the data.

There are two fancy array handles that each handle a special form of coordinate system. The first such array handle is vtkm::cont::ArrayHandleUniformPointCoordinates, which represents a uniform sampling of space. The constructor for ArrayHandleUniformPointCoordinates takes three arguments. The first argument is a vtkm::Id3 that specifies the number of samples in the x, y, and z directions. The second argument, which is optional, specifies the origin (the location of the first point at the lower left corner). If not specified, the origin is set to $[0,0,0]$. The third argument, which is also optional, specifies the distance between samples in the x, y, and z directions. If not specified, the spacing is set to 1 in each direction.

Example 10.16: Using ArrayHandleUniformPointCoordinates.

```
// Create a set of point coordinates for a uniform grid in the space between
// -5 and 5 in the x direction and -3 and 3 in the y and z directions. The
// uniform sampling is spaced in 0.08 unit increments in the x direction (for
// 126 samples), 0.08 unit increments in the y direction (for 76 samples) and
// 0.24 unit increments in the z direction (for 26 samples). That makes
// 248,976 values in the array total.
vtkm::cont::ArrayHandleUniformPointCoordinates uniformCoordinates(
      vtkm::Id3(126, 76, 26),
      vtkm::make_Vec<vtkm::FloatDefault>(-5.0f, -3.0f, -3.0f),
      vtkm::make_Vec<vtkm::FloatDefault>(0.08f, 0.08f, 0.24f)
      );
```

The second fancy array handle for special coordinate systems is vtkm::cont::ArrayHandleCartesianProduct, which represents a rectilinear sampling of space where the samples are axis aligned but have variable spacing. Sets of coordinates of this type are most efficiently represented by having a separate array for each component of the axis, and then for each $[i,j,k]$ index of the array take the value for each component from each array using the respective index. This is equivalent to performing a Cartesian product on the arrays.

ArrayHandleCartesianProduct is a templated class. It has three template parameters, which are the types of the arrays used for the x, y, and z axes. The constructor for ArrayHandleCartesianProduct takes the three arrays.

Example 10.17: Using a ArrayHandleCartesianProduct.

```
typedef vtkm::cont::ArrayHandle<vtkm::Float32> AxisArrayType;
typedef AxisArrayType::PortalControl AxisPortalType;

// Create array for x axis coordinates with values [0.0, 1.1, 5.0]
AxisArrayType xAxisArray;
xAxisArray.Allocate(3);
AxisPortalType xAxisPortal = xAxisArray.GetPortalControl();
xAxisPortal.Set(0, 0.0f);
xAxisPortal.Set(1, 1.1f);
xAxisPortal.Set(2, 5.0f);

// Create array for y axis coordinates with values [0.0, 2.0]
AxisArrayType yAxisArray;
yAxisArray.Allocate(2);
AxisPortalType yAxisPortal = yAxisArray.GetPortalControl();
```

```
  yAxisPortal.Set(0, 0.0f);
  yAxisPortal.Set(1, 2.0f);

  // Create array for z axis coordinates with values [0.0, 0.5]
  AxisArrayType zAxisArray;
  zAxisArray.Allocate(2);
  AxisPortalType zAxisPortal = zAxisArray.GetPortalControl();
  zAxisPortal.Set(0, 0.0f);
  zAxisPortal.Set(1, 0.5f);

  // Create point coordinates for a "rectilinear grid" with axis-aligned points
  // with variable spacing by taking the Cartesian product of the three
  // previously defined arrays. This generates the following 3x2x2 = 12 values:
  //
  // [0.0, 0.0, 0.0], [1.1, 0.0, 0.0], [5.0, 0.0, 0.0],
  // [0.0, 2.0, 0.0], [1.1, 2.0, 0.0], [5.0, 2.0, 0.0],
  // [0.0, 0.0, 0.5], [1.1, 0.0, 0.5], [5.0, 0.0, 0.5],
  // [0.0, 2.0, 0.5], [1.1, 2.0, 0.5], [5.0, 2.0, 0.5]
  vtkm::cont::ArrayHandleCartesianProduct<
      AxisArrayType,AxisArrayType,AxisArrayType>rectilinearCoordinates(
        xAxisArray, yAxisArray, zAxisArray);
```

The vtkm/cont/ArrayHandleCartesianProduct.h/header also contains the templated convenience function vtkm::cont::make_ArrayHandleCartesianProduct that takes the three axis arrays and returns an array of the Cartesian product. This function can sometimes be used to avoid having to declare the full array type.

Example 10.18: Using make_ArrayHandleCartesianProduct.

```
  vtkm::cont::make_ArrayHandleCartesianProduct(xAxisArray,yAxisArray,zAxisArray)
```

Did you know?

These specialized arrays for coordinate systems greatly reduce the code duplication in VTK-m. Most scientific visualization systems need separate implementations of algorithms for uniform, rectilinear, and unstructured grids. But in VTK-m an algorithm can be written once and then applied to all these different grid structures by using these specialized array handles and letting the compiler's templates optimize the code.

10.2.7 Composite Vector Arrays

A composite vector array is a fancy array handle that combines two to four arrays of the same size and value type and combines their corresponding values to form a vtkm::Vec. A composite vector array is similar in nature to a zipped array (described in Section 10.2.5) except that values are combined into vtkm::Vecs instead of vtkm::Pairs. The created vtkm::Vecs are not stored in their own memory space. Rather, the Vecs are generated as the array is used. Writing Vecs to the composite vector array writes values into the components of the source arrays.

A composite vector array can be created using the vtkm::cont::ArrayHandleCompositeVector class. This class has a single template argument that is a "signature" for the arrays to be combined. These signatures can be tricky to prototype, so vtkm/cont/ArrayHandleCompositeVector.h/header also contains a helper struct named vtkm::cont::ArrayHandleCompositeVectorType to define the type. ArrayHandleCompositeVectorType takes a variable number of ArrayHandle types that compose the vector. ArrayHandleCompositeVectorType has an internal type named type that is the appropriately defined ArrayHandleCompositeVector.

The constructor for ArrayHandleCompositeVector takes instances of the array handles to combine along with the component from each array to use. If the array handles being combined contain scalar data, then the appropriate component to use is 0.

Example 10.19: Using ArrayHandleCompositeVector.

```cpp
// Create an array with [0, 1, 2, 3, 4]
typedef vtkm::cont::ArrayHandleIndex ArrayType1;
ArrayType1 array1(5);

// Create an array with [3, 1, 4, 1, 5]
typedef vtkm::cont::ArrayHandle<vtkm::Id> ArrayType2;
ArrayType2 array2;
array2.Allocate(5);
ArrayType2::PortalControl arrayPortal2 = array2.GetPortalControl();
arrayPortal2.Set(0, 3);
arrayPortal2.Set(1, 1);
arrayPortal2.Set(2, 4);
arrayPortal2.Set(3, 1);
arrayPortal2.Set(4, 5);

// Create an array with [2, 7, 1, 8, 2]
typedef vtkm::cont::ArrayHandle<vtkm::Id> ArrayType3;
ArrayType3 array3;
array3.Allocate(5);
ArrayType2::PortalControl arrayPortal3 = array3.GetPortalControl();
arrayPortal3.Set(0, 2);
arrayPortal3.Set(1, 7);
arrayPortal3.Set(2, 1);
arrayPortal3.Set(3, 8);
arrayPortal3.Set(4, 2);

// Create an array with [0, 0, 0, 0]
typedef vtkm::cont::ArrayHandleConstant<vtkm::Id> ArrayType4;
ArrayType4 array4(0, 5);

// Use ArrayhandleCompositeVector to create the array
// [(0,3,2,0), (1,1,7,0), (2,4,1,0), (3,1,8,0), (4,5,2,0)].
typedef vtkm::cont::ArrayHandleCompositeVectorType<
    ArrayType1, ArrayType2, ArrayType3, ArrayType4>::type CompositeArrayType;
CompositeArrayType compositeArray(array1, 0,
                                  array2, 0,
                                  array3, 0,
                                  array4, 0);
```

The vtkm/cont/ArrayHandleCompositeVector.h header also contains the templated convenience function vtkm::cont::make_ArrayHandleCompositeVector which takes two to four array handles and returns an ArrayHandleCompositeVector. This function can sometimes be used to avoid having to declare the full array type.

Example 10.20: Using make_ArrayHandleCompositeVector.

```cpp
vtkm::cont::make_ArrayHandleCompositeVector(array1, 0,
                                            array2, 0,
                                            array3, 0,
                                            array4, 0)
```

ArrayHandleCompositeVector is often used to combine scalar arrays into vector arrays, but it can also be used to pull components out of other vector arrays. The following example uses this feature to convert an array of 2D x, y coordinates and an array of elevations to 3D x, y, z coordinates.

Example 10.21: Combining vector components with ArrayHandleCompositeVector.

```cpp
template<typename CoordinateArrayType, typename ElevationArrayType>
VTKM_CONT
```

```
typename vtkm::cont::ArrayHandleCompositeVectorType<
    CoordinateArrayType, CoordinateArrayType, ElevationArrayType>::type
ElevateCoordianteArray(const CoordinateArrayType &coordinateArray,
                       const ElevationArrayType &elevationArray)
{
  VTKM_IS_ARRAY_HANDLE(CoordinateArrayType);
  VTKM_IS_ARRAY_HANDLE(ElevationArrayType);

  return vtkm::cont::make_ArrayHandleCompositeVector(coordinateArray, 0,
                                                      coordinateArray, 1,
                                                      elevationArray, 0);
}
```

10.2.8 Grouped Vector Arrays

A grouped vector array is a fancy array handle that groups consecutive values of an array together to form a vtkm::Vec. The source array must be of a length that is divisible by the requested Vec size. The created vtkm::Vecs are not stored in their own memory space. Rather, the Vecs are generated as the array is used. Writing Vecs to the grouped vector array writes values into the the source array.

A grouped vector array is created using the vtkm::cont::ArrayHandleGroupVec class. This templated class has two template arguments. The first argument is the type of array being grouped and the second argument is an integer specifying the size of the Vecs to create (the number of values to group together).

Example 10.22: Using ArrayHandleGroupVec.

```
  // Create an array containing [0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]
  typedef vtkm::cont::ArrayHandleIndex ArrayType;
  ArrayType sourceArray(12);

  // Create an array containing [(0,1), (2,3), (4,5), (6,7), (8,9), (10,11)]
  vtkm::cont::ArrayHandleGroupVec<ArrayType,2> vec2Array(sourceArray);

  // Create an array containing [(0,1,2), (3,4,5), (6,7,8), (9,10,11)]
  vtkm::cont::ArrayHandleGroupVec<ArrayType,3> vec3Array(sourceArray);
```

The vtkm/cont/ArrayHandleGroupVec.h header also contains the templated convenience function vtkm::cont::make_ArrayHandleGroupVec that takes an instance of the array to group into Vecs. You must specify the size of the Vecs as a template parameter when using vtkm::cont::make_ArrayHandleGroupVec.

Example 10.23: Using make_ArrayHandleGroupVec.

```
  // Create an array containing [(0,1,2,3), (4,5,6,7), (8,9,10,11)]
  vtkm::cont::make_ArrayHandleGroupVec<4>(sourceArray)
```

10.3 Implementing Fancy Arrays

Although the behavior of fancy arrays might seem complicated, they are actually straightforward to implement. VTK-m provides several mechanisms to implement fancy arrays.

10.3.1 Implicit Array Handles

The generic array handle and storage templating in VTK-m allows for any type of operations to retrieve a particular value. Typically this is used to convert an index to some location or locations in memory. However, it is also possible to compute a value directly from an index rather than look up some value in memory. Such an array is completely functional and requires no storage in memory at all. Such a functional array is called an *implicit array handle*. Implicit arrays are an example of *fancy array handles*, which are array handles that behave like regular arrays but do special processing under the covers to provide values.

Specifying a functional or implicit array in VTK-m is straightforward. VTK-m has a special class named `vtkm::cont::ArrayHandleImplicit` that makes an implicit array containing values generated by a user-specified *functor*. A functor is simply a C++ class or struct that contains an overloaded parenthesis operator so that it can be used syntactically like a function.

To demonstrate the use of `ArrayHandleImplicit`, let us say we want an array of even numbers. The array has the values $[0, 2, 4, 6, \ldots]$ (double the index) up to some given size. Although we could easily create this array in memory, we can save space and possibly time by computing these values on demand.

Did you know?

VTK-m already comes with an implicit array handle named `vtkm::cont::ArrayHandleCounting` *that can make implicit even numbers as well as other more general counts. So in practice you would not have to create a special implicit array, but we are doing so here for demonstrative purposes.*

The first step to using `ArrayHandleImplicit` is to declare a functor. The functor's parenthesis operator should accept a single argument of type `vtkm::Id` and return a value appropriate for that index. The parenthesis operator should also be declared `const` because it is not allowed to change the class' state.

Example 10.24: Functor that doubles an index.

```
struct DoubleIndexFunctor
{
  VTKM_EXEC_CONT
  vtkm::Id operator()(vtkm::Id index) const
  {
    return 2*index;
  }
};
```

Once the functor is defined, an implicit array can be declared using the templated `vtkm::cont::ArrayHandleImplicit` class. The first template argument is the type of the array's values (which should match the return value for the functor), and the second template argument is the functor type.

Example 10.25: Declaring a `ArrayHandleImplicit`.

```
  vtkm::cont::ArrayHandleImplicit<vtkm::Id, DoubleIndexFunctor>
      implicitArray(DoubleIndexFunctor(), 50);
```

For convenience, vtkm/cont/ArrayHandleImplicit.h also declares the `vtkm::cont::make_ArrayHandleImplicit` function. This function takes a functor and the size of the array and returns the implicit array. When using this function, you also have to declare the first template argument, which is the array's value type, since this type does not appear in any of the arguments.

Example 10.26: Using `make_ArrayHandleImplicit`.

```
  vtkm::cont::make_ArrayHandleImplicit<vtkm::Id>(DoubleIndexFunctor(), 50);
```

If the implicit array you are creating tends to be generally useful and is something you use multiple times, it might be worthwhile to make a convenience subclass of `vtkm::cont::ArrayHandleImplicit` for your array.

Example 10.27: Custom implicit array handle for even numbers.

```
#include <vtkm/cont/ArrayHandleImplicit.h>

class ArrayHandleDoubleIndex
    : public vtkm::cont::ArrayHandleImplicit<vtkm::Id, DoubleIndexFunctor>
{
public:
  VTKM_ARRAY_HANDLE_SUBCLASS_NT(
      ArrayHandleDoubleIndex,
      (vtkm::cont::ArrayHandleImplicit<vtkm::Id,DoubleIndexFunctor>));

  VTKM_CONT
  ArrayHandleDoubleIndex(vtkm::Id numberOfValues)
    : Superclass(DoubleIndexFunctor(), numberOfValues) {  }
};
```

Subclasses of ArrayHandle provide constructors that establish the state of the array handle. All array handle subclasses must also use either the VTKM_ARRAY_HANDLE_SUBCLASS macro or the VTKM_ARRAY_HANDLE_SUBCLASS_NT macro. Both of these macros define the typedefs Superclass, ValueType, and StorageTag as well as a set of constructors and operators expected of all ArrayHandle classes. The difference between these two macros is that VTKM_ARRAY_HANDLE_SUBCLASS is used in templated classes whereas VTKM_ARRAY_HANDLE_SUBCLASS_NT is used in non-templated classes.

The ArrayHandle subclass in Example 10.27 is not templated, so it uses the VTKM_ARRAY_HANDLE_SUBCLASS_NT macro. (The other macro is described in Section 10.3.2 on page 94). This macro takes two parameters. The first parameter is the name of the subclass where the macro is defined and the second parameter is the immediate superclass including the full template specification. The second parameter of the macro must be enclosed in parentheses so that the C pre-processor correctly handles commas in the template specification.

10.3.2 Transformed Arrays

Another type of fancy array handle is the transformed array. A transformed array takes another array and applies a function to all of the elements to produce a new array. A transformed array behaves much like a map operation except that a map operation writes its values to a new memory location whereas the transformed array handle produces its values on demand so that no additional storage is required.

Specifying a transformed array in VTK-m is straightforward. VTK-m has a special class named vtkm::cont::ArrayHandleTransform that takes an array handle and a functor and provides an interface to a new array comprising values of the first array applied to the functor.

To demonstrate the use of ArrayHandleTransform, let us say that we want to scale and bias all of the values in a target array. That is, each value in the target array is going to be multiplied by a given scale and then offset by adding a bias value. (The scale and bias are uniform across all entries.) We could, of course, easily create a worklet to apply this scale and bias to each entry in the target array and save the result in a new array, but we can save space and possibly time by computing these values on demand.

The first step to using ArrayHandleTransform is to declare a functor. The functor's parenthesis operator should accept a single argument of the type of the target array and return the transformed value. For more generally applicable transform functors, it is often useful to make the parenthesis operator a template. The parenthesis operator should also be declared const because it is not allowed to change the class' state.

Example 10.28: Functor to scale and bias a value.

```
template<typename T>
struct ScaleBiasFunctor
{
  VTKM_EXEC_CONT
  ScaleBiasFunctor(T scale = T(1), T bias = T(0))
    : Scale(scale), Bias(bias) {  }

  VTKM_EXEC_CONT
  T operator()(T x) const
  {
    return this->Scale*x + this->Bias;
  }

  T Scale;
  T Bias;
};
```

Once the functor is defined, a transformed array can be declared using the templated vtkm::cont::ArrayHandleTransform class. The first template argument is the type of the array's values (which should match the return value for the functor). The second template argument is the type of array being transformed. The third and final template argument is the type of functor used for the transformation.

That said, it is generally easier to use the vtkm::cont::make_ArrayHandleTransform convenience function. This function takes an array and a functor and returns a transformed array. When using this function, you also have to declare the first template argument, which is the transformed array's value type, since this type does not appear in any of the arguments.

Example 10.29: Using make_ArrayHandleTransform.

```
  vtkm::cont::make_ArrayHandleTransform<vtkm::Float32>(
          array, ScaleBiasFunctor<vtkm::Float32>(2,3))
```

If the transformed array you are creating tends to be generally useful and is something you use multiple times, it might be worthwhile to make a convenience subclass of vtkm::cont::ArrayHandleTransform or convenience make_ArrayHandle* function for your array.

Example 10.30: Custom transform array handle for scale and bias.

```
#include <vtkm/cont/ArrayHandleTransform.h>

template<typename ArrayHandleType>
class ArrayHandleScaleBias
    : public vtkm::cont::ArrayHandleTransform<
          typename ArrayHandleType::ValueType,
          ArrayHandleType,
          ScaleBiasFunctor<typename ArrayHandleType::ValueType> >
{
public:
  VTKM_ARRAY_HANDLE_SUBCLASS(
      ArrayHandleScaleBias,
      (ArrayHandleScaleBias<ArrayHandleType>),
      (vtkm::cont::ArrayHandleTransform<
         typename ArrayHandleType::ValueType,
         ArrayHandleType,
         ScaleBiasFunctor<typename ArrayHandleType::ValueType> >)
      );

  VTKM_CONT
  ArrayHandleScaleBias(const ArrayHandleType &array,
                       ValueType scale,
                       ValueType bias)
    : Superclass(array, ScaleBiasFunctor<ValueType>(scale, bias)) {  }
};

template<typename ArrayHandleType>
VTKM_CONT
ArrayHandleScaleBias<ArrayHandleType>
```

```
make_ArrayHandleScaleBias(const ArrayHandleType &array,
                          typename ArrayHandleType::ValueType scale,
                          typename ArrayHandleType::ValueType bias)
{
  return ArrayHandleScaleBias<ArrayHandleType>(array, scale, bias);
}
```

Subclasses of ArrayHandle provide constructors that establish the state of the array handle. All array handle subclasses must also use either the VTKM_ARRAY_HANDLE_SUBCLASS macro or the VTKM_ARRAY_HANDLE_SUBCLASS_NT macro. Both of these macros define the typedefs Superclass, ValueType, and StorageTag as well as a set of constructors and operators expected of all ArrayHandle classes. The difference between these two macros is that VTKM_ARRAY_HANDLE_SUBCLASS is used in templated classes whereas VTKM_ARRAY_HANDLE_SUBCLASS_NT is used in non-templated classes.

The ArrayHandle subclass in Example 10.30 is templated, so it uses the VTKM_ARRAY_HANDLE_SUBCLASS macro. (The other macro is described in Section 10.4 on page 105). This macro takes three parameters. The first parameter is the name of the subclass where the macro is defined, the second parameter is the type of the subclass including the full template specification, and the third parameter is the immediate superclass including the full template specification. The second and third parameters of the macro must be enclosed in parentheses so that the C pre-processor correctly handles commas in the template specification.

10.3.3 Derived Storage

A *derived storage* is a type of fancy array that takes one or more other arrays and changes their behavior in some way. A transformed array (Section 10.3.2) is a specific type of derived array with a simple mapping. In this section we will demonstrate the steps required to create a more general derived storage. When applicable, it is much easier to create a derived array as a transformed array or using the other fancy arrays than to create your own derived storage. However, if these pre-existing fancy arrays do not work work, for example if your derivation uses multiple arrays or requires general lookups, you can do so by creating your own derived storage. For the purposes of the example in this section, let us say we want 2 array handles to behave as one array with the contents concatenated together. We could of course actually copy the data, but we can also do it in place.

The first step to creating a derived storage is to build an array portal that will take portals from arrays being derived. The portal must work in both the control and execution environment (or have a separate version for control and execution).

Example 10.31: Derived array portal for concatenated arrays.

```
#include <vtkm/cont/ArrayHandle.h>
#include <vtkm/cont/ArrayPortal.h>

template<typename P1, typename P2>
class ArrayPortalConcatenate
{
public:
  typedef P1 PortalType1;
  typedef P2 PortalType2;
  typedef typename PortalType1::ValueType ValueType;

  VTKM_SUPPRESS_EXEC_WARNINGS
  VTKM_EXEC_CONT
  ArrayPortalConcatenate() : Portal1(), Portal2() {  }

  VTKM_SUPPRESS_EXEC_WARNINGS
  VTKM_EXEC_CONT
  ArrayPortalConcatenate(const PortalType1 &portal1, const PortalType2 portal2)
    : Portal1(portal1), Portal2(portal2) {  }

  /// Copy constructor for any other ArrayPortalConcatenate with a portal type
  /// that can be copied to this portal type. This allows us to do any type
  /// casting that the portals do (like the non-const to const cast).
  VTKM_SUPPRESS_EXEC_WARNINGS
  template<typename OtherP1, typename OtherP2>
  VTKM_EXEC_CONT
  ArrayPortalConcatenate(const ArrayPortalConcatenate<OtherP1,OtherP2> &src)
    : Portal1(src.GetPortal1()), Portal2(src.GetPortal2()) {  }

  VTKM_SUPPRESS_EXEC_WARNINGS
  VTKM_EXEC_CONT
  vtkm::Id GetNumberOfValues() const {
    return
        this->Portal1.GetNumberOfValues() + this->Portal2.GetNumberOfValues();
  }

  VTKM_SUPPRESS_EXEC_WARNINGS
  VTKM_EXEC_CONT
  ValueType Get(vtkm::Id index) const {
    if (index < this->Portal1.GetNumberOfValues())
    {
      return this->Portal1.Get(index);
    }
    else
    {
      return this->Portal2.Get(index - this->Portal1.GetNumberOfValues());
    }
  }

  VTKM_SUPPRESS_EXEC_WARNINGS
  VTKM_EXEC_CONT
  void Set(vtkm::Id index, const ValueType &value) const {
    if (index < this->Portal1.GetNumberOfValues())
    {
      this->Portal1.Set(index, value);
    }
    else
    {
      this->Portal2.Set(index - this->Portal1.GetNumberOfValues(), value);
    }
  }

  VTKM_EXEC_CONT
  const PortalType1 &GetPortal1() const { return this->Portal1; }
  VTKM_EXEC_CONT
  const PortalType2 &GetPortal2() const { return this->Portal2; }

private:
  PortalType1 Portal1;
  PortalType2 Portal2;
};
```

Like in an adapter storage, the next step in creating a derived storage is to define a tag for the adapter. We shall call ours `StorageTagConcatenate` and it will be templated on the two array handle types that we are deriving. Then, we need to create a specialization of the templated `vtkm::cont::internal::Storage` class. The implementation for a `Storage` for a derived storage is usually trivial compared to an adapter storage because the majority of the work is deferred to the derived arrays.

Example 10.32: `Storage` for derived container of concatenated arrays.

```
template<typename ArrayHandleType1, typename ArrayHandleType2>
struct StorageTagConcatenate {  };

namespace vtkm {
```

```
namespace cont {
namespace internal {

template<typename ArrayHandleType1, typename ArrayHandleType2>
class Storage<
    typename ArrayHandleType1::ValueType,
    StorageTagConcatenate<ArrayHandleType1, ArrayHandleType2> >
{
public:
  typedef typename ArrayHandleType1::ValueType ValueType;

  typedef ArrayPortalConcatenate<
      typename ArrayHandleType1::PortalControl,
      typename ArrayHandleType2::PortalControl> PortalType;
  typedef ArrayPortalConcatenate<
      typename ArrayHandleType1::PortalConstControl,
      typename ArrayHandleType2::PortalConstControl> PortalConstType;

  VTKM_CONT
  Storage() : Valid(false) {  }

  VTKM_CONT
  Storage(const ArrayHandleType1 array1, const ArrayHandleType2 array2)
    : Array1(array1), Array2(array2), Valid(true) {  }

  VTKM_CONT
  PortalType GetPortal() {
    VTKM_ASSERT(this->Valid);
    return PortalType(this->Array1.GetPortalControl(),
                      this->Array2.GetPortalControl());
  }

  VTKM_CONT
  PortalConstType GetPortalConst() const {
    VTKM_ASSERT(this->Valid);
    return PortalConstType(this->Array1.GetPortalConstControl(),
                           this->Array2.GetPortalConstControl());
  }

  VTKM_CONT
  vtkm::Id GetNumberOfValues() const {
    VTKM_ASSERT(this->Valid);
    return this->Array1.GetNumberOfValues() + this->Array2.GetNumberOfValues();
  }

  VTKM_CONT
  void Allocate(vtkm::Id numberOfValues) {
    VTKM_ASSERT(this->Valid);
    // This implementation of allocate, which allocates the same amount in both
    // arrays, is arbitrary. It could, for example, leave the size of Array1
    // alone and change the size of Array2. Or, probably most likely, it could
    // simply throw an error and state that this operation is invalid.
    vtkm::Id half = numberOfValues/2;
    this->Array1.Allocate(numberOfValues-half);
    this->Array2.Allocate(half);
  }

  VTKM_CONT
  void Shrink(vtkm::Id numberOfValues) {
    VTKM_ASSERT(this->Valid);
    if (numberOfValues < this->Array1.GetNumberOfValues())
    {
      this->Array1.Shrink(numberOfValues);
      this->Array2.Shrink(0);
    }
    else
    {
      this->Array2.Shrink(numberOfValues - this->Array1.GetNumberOfValues());
    }
  }

  VTKM_CONT
  void ReleaseResources() {
    VTKM_ASSERT(this->Valid);
    this->Array1.ReleaseResources();
    this->Array2.ReleaseResources();
  }

  // Requried for later use in ArrayTransfer class.
  VTKM_CONT
  const ArrayHandleType1 &GetArray1() const {
    VTKM_ASSERT(this->Valid);
    return this->Array1;
  }
  VTKM_CONT
  const ArrayHandleType2 &GetArray2() const {
    VTKM_ASSERT(this->Valid);
    return this->Array2;
  }

private:
  ArrayHandleType1 Array1;
  ArrayHandleType2 Array2;
  bool Valid;
};

}
}
} // namespace vtkm::cont::internal
```

One of the responsibilities of an array handle is to copy data between the control and execution environments. The default behavior is to request the device adapter to copy data items from one environment to another. This might involve transferring data between a host and device. For an array of data resting in memory, this is necessary. However, implicit storage (described in the previous section) overrides this behavior to pass nothing but the functional array portal. Likewise, it is undesirable to do a raw transfer of data with derived storage. The underlying arrays being derived may be used in other contexts, and it would be good to share the data wherever possible. It is also sometimes more efficient to copy data independently from the arrays being derived than from the derived storage itself.

The mechanism that controls how a particular storage gets transferred to and from the execution environment is encapsulated in the templated vtkm::cont::internal::ArrayTransfer class. By creating a specialization of vtkm::cont::internal::ArrayTransfer, we can modify the transfer behavior to instead transfer the arrays being derived and use the respective copies in the control and execution environments.

vtkm::cont::internal::ArrayTransfer has three template arguments: the base type of the array, the storage tag, and the device adapter tag.

Example 10.33: Prototype for vtkm::cont::internal::ArrayTransfer.

```
namespace vtkm {
namespace cont {
namespace internal {

template<typename T,typename StorageTag,typename DeviceAdapterTag>
class ArrayTransfer;

}
}
} //namespace vtkm::cont::internal
```

All vtkm::cont::internal::ArrayTransfer implementations must have a constructor method that accepts a pointer to a vtkm::cont::internal::Storage object templated to the same base type and storage tag as the ArrayTransfer object. Assuming that an ArrayHandle is templated using the parameters in Example 10.33, the prototype for the constructor must be equivalent to the following.

Example 10.34: Prototype for ArrayTransfer constructor.

```
ArrayTransfer(vtkm::cont::internal::Storage<T, StorageTag> *storage);
```

Typically the constructor either saves the Storage pointer or other relevant objects from the Storage for later use in the methods.

In addition to this non-default constructor, the vtkm::cont::internal::ArrayTransfer specialization must define the following items.

`ValueType` A `typedef` of the type for each item in the array. This is the same type as the first template argument.

`PortalControl` The type of an array portal that is used to access the underlying data in the control environment.

`PortalConstControl` A read-only (const) version of `PortalControl`.

`PortalExecution` The type of an array portal that is used to access the underlying data in the execution environment.

`PortalConstExecution` A read-only (const) version of `PortalExecution`.

`GetNumberOfValues` A method that returns the number of values currently allocated in the execution environment. The results may be undefined if none of the load or allocate methods have yet been called.

`PrepareForInput` A method responsible for transferring data from the control to the execution for input. `PrepareForInput` has one Boolean argument that controls whether this transfer should actually take place. When true, data from the Storage object given in the constructor should be transferred to the execution environment; otherwise the data should not be copied. An ArrayTransfer for a derived array typically ignores this parameter since the arrays being derived manages this transfer already. Regardless of the Boolean flag, a `PortalConstExecution` is returned.

`PrepareForInPlace` A method that behaves just like `PrepareForInput` except that the data in the execution environment is used for both reading and writing so the method returns a PortalExecution. If the array is considered read-only, which is common for derived arrays, then this method should throw a vtkm::cont::ErrorControlBadValue.

`PrepareForOutput` A method that takes a size (in a vtkm::Id) and allocates an array in the execution environment of the specified size. The initial memory can be uninitialized. The method returns a `PortalExecution` for the allocated data. If the array is considered read-only, which is common for derived arrays, then this method should throw a vtkm::cont::ErrorControlBadValue.

`RetrieveOutputData` This method takes an array storage pointer (which is the same as that passed to the constructor, but provided for convenience), allocates memory in the control environment, and copies data from the execution environment into it. If the derived array is considered read-only and both `PrepareForInPlace` and `PrepareForOutput` throw exceptions, then this method should never be called. If it is, then that is probably a bug in ArrayHandle, and it is OK to throw vtkm::cont::ErrorControlInternal.

`Shrink` A method that adjusts the size of the array in the execution environment to something that is a smaller size. All the data up to the new length must remain valid. Typically, no memory is actually reallocated. Instead, a different end is marked. If the derived array is considered read-only, then this method should throw a `vtkm::cont::ErrorControlBadValue`.

`ReleaseResources` A method that frees any resources (typically memory) in the execution environment.

Continuing our example derived storage that concatenates two arrays started in Examples 10.31 and 10.32, the following provides an `ArrayTransfer` appropriate for the derived storage.

Example 10.35: `ArrayTransfer` for derived storage of concatenated arrays.

```
namespace vtkm {
namespace cont {
namespace internal {

template<typename ArrayHandleType1,
         typename ArrayHandleType2,
         typename Device>
class ArrayTransfer<
    typename ArrayHandleType1::ValueType,
    StorageTagConcatenate<ArrayHandleType1,ArrayHandleType2>,
    Device>
{
public:
  typedef typename ArrayHandleType1::ValueType ValueType;

private:
  typedef StorageTagConcatenate<ArrayHandleType1,ArrayHandleType2>
      StorageTag;
  typedef vtkm::cont::internal::Storage<ValueType,StorageTag>
      StorageType;

public:
  typedef typename StorageType::PortalType PortalControl;
  typedef typename StorageType::PortalConstType PortalConstControl;

  typedef ArrayPortalConcatenate<
      typename ArrayHandleType1::template ExecutionTypes<Device>::Portal,
      typename ArrayHandleType2::template ExecutionTypes<Device>::Portal>
    PortalExecution;
  typedef ArrayPortalConcatenate<
      typename ArrayHandleType1::template ExecutionTypes<Device>::PortalConst,
      typename ArrayHandleType2::template ExecutionTypes<Device>::PortalConst>
    PortalConstExecution;

  VTKM_CONT
  ArrayTransfer(StorageType *storage)
    : Array1(storage->GetArray1()), Array2(storage->GetArray2())
  {  }

  VTKM_CONT
  vtkm::Id GetNumberOfValues() const {
    return this->Array1.GetNumberOfValues() + this->Array2.GetNumberOfValues();
  }

  VTKM_CONT
  PortalConstExecution PrepareForInput(bool vtkmNotUsed(updateData)) {
    return PortalConstExecution(this->Array1.PrepareForInput(Device()),
                                this->Array2.PrepareForInput(Device()));
  }

  VTKM_CONT
  PortalExecution PrepareForInPlace(bool vtkmNotUsed(updateData)) {
    return PortalExecution(this->Array1.PrepareForInPlace(Device()),
                           this->Array2.PrepareForInPlace(Device()));
  }

  VTKM_CONT
  PortalExecution PrepareForOutput(vtkm::Id numberOfValues)
  {
    // This implementation of allocate, which allocates the same amount in both
    // arrays, is arbitrary. It could, for example, leave the size of Array1
    // alone and change the size of Array2. Or, probably most likely, it could
    // simply throw an error and state that this operation is invalid.
    vtkm::Id half = numberOfValues/2;
    return PortalExecution(
          this->Array1.PrepareForOutput(numberOfValues-half, Device()),
          this->Array2.PrepareForOutput(half, Device()));
  }

  VTKM_CONT
  void RetrieveOutputData(StorageType *vtkmNotUsed(storage)) const {
    // Implementation of this method should be unnecessary. The internal
    // array handles should automatically retrieve the output data as
    // necessary.
  }

  VTKM_CONT
  void Shrink(vtkm::Id numberOfValues) {
    if (numberOfValues < this->Array1.GetNumberOfValues())
    {
      this->Array1.Shrink(numberOfValues);
      this->Array2.Shrink(0);
    }
    else
    {
      this->Array2.Shrink(numberOfValues - this->Array1.GetNumberOfValues());
    }
  }

  VTKM_CONT
  void ReleaseResources() {
    this->Array1.ReleaseResourcesExecution();
    this->Array2.ReleaseResourcesExecution();
  }

private:
  ArrayHandleType1 Array1;
  ArrayHandleType2 Array2;
};

}
}
} // namespace vtkm::cont::internal
```

The final step to make a derived storage is to create a mechanism to construct an `ArrayHandle` with a storage derived from the desired arrays. This can be done by creating a trivial subclass of `vtkm::cont::ArrayHandle` that simply constructs the array handle to the state of an existing storage. It uses a protected constructor of `vtkm::cont::ArrayHandle` that accepts a constructed storage.

Example 10.36: `ArrayHandle` for derived storage of concatenated arrays.

```
template<typename ArrayHandleType1, typename ArrayHandleType2>
class ArrayHandleConcatenate
    : public vtkm::cont::ArrayHandle<
        typename ArrayHandleType1::ValueType,
        StorageTagConcatenate<ArrayHandleType1,ArrayHandleType2> >
{
public:
  VTKM_ARRAY_HANDLE_SUBCLASS(
      ArrayHandleConcatenate,
      (ArrayHandleConcatenate<ArrayHandleType1,ArrayHandleType2>),
      (vtkm::cont::ArrayHandle<
         typename ArrayHandleType1::ValueType,
         StorageTagConcatenate<ArrayHandleType1,ArrayHandleType2> >));

private:
  typedef vtkm::cont::internal::Storage<ValueType,StorageTag> StorageType;

public:
  VTKM_CONT
  ArrayHandleConcatenate(const ArrayHandleType1 &array1,
                         const ArrayHandleType2 &array2)
    : Superclass(StorageType(array1, array2)) {  }
};
```

Subclasses of ArrayHandle provide constructors that establish the state of the array handle. All array handle subclasses must also use either the VTKM_ARRAY_HANDLE_SUBCLASS macro or the VTKM_ARRAY_HANDLE_SUBCLASS_NT macro. Both of these macros define the typedefs Superclass, ValueType, and StorageTag as well as a set of constructors and operators expected of all ArrayHandle classes. The difference between these two macros is that VTKM_ARRAY_HANDLE_SUBCLASS is used in templated classes whereas VTKM_ARRAY_HANDLE_SUBCLASS_NT is used in non-templated classes.

The ArrayHandle subclass in Example 10.36 is templated, so it uses the VTKM_ARRAY_HANDLE_SUBCLASS macro. (The other macro is described in Section 10.4 on page 105). This macro takes three parameters. The first parameter is the name of the subclass where the macro is defined, the second parameter is the type of the subclass including the full template specification, and the third parameter is the immediate superclass including the full template specification. The second and third parameters of the macro must be enclosed in parentheses so that the C pre-processor correctly handles commas in the template specification.

vtkm::cont::ArrayHandleCompositeVector is an example of a derived array handle provided by VTK-m. It references some fixed number of other arrays, pulls a specified component out of each, and produces a new component that is a tuple of these retrieved components.

10.4 Adapting Data Structures

The intention of the storage parameter for vtkm::cont::ArrayHandle is to implement the strategy design pattern to enable VTK-m to interface directly with the data of any third party code source. VTK-m is designed to work with data originating in other libraries or applications. By creating a new type of storage, VTK-m can be entirely adapted to new kinds of data structures.

Common Errors

Keep in mind that memory layout used can have an effect on the running time of algorithms in VTK-m. Different data layouts and memory access can change cache performance and introduce memory affinity problems. The example code given in this section will likely have poorer cache performance than the basic storage provided by VTK-m. However, that might be an acceptable penalty to avoid data copies.

In this section we demonstrate the steps required to adapt the array handle to a data structure provided by a third party. For the purposes of the example, let us say that some fictitious library named "foo" has a simple structure named `FooFields` that holds the field values for a particular part of a mesh, and then maintain the field values for all locations in a mesh in a `std::deque` object.

Example 10.37: Fictitious field storage used in custom array storage examples.

```cpp
#include <deque>

struct FooFields {
  float Pressure;
  float Temperature;
  float Velocity[3];
  // And so on...
};

typedef std::deque<FooFields> FooFieldsDeque;
```

VTK-m expects separate arrays for each of the fields rather than a single array containing a structure holding all of the fields. However, rather than copy each field to its own array, we can create a storage for each field that points directly to the data in a `FooFieldsDeque` object.

The first step in creating an adapter storage is to create a control environment array portal to the data. This is described in more detail in Section 7.2 and is generally straightforward for simple containers like this. Here is an example implementation for our `FooFieldsDeque` container.

Example 10.38: Array portal to adapt a third-party container to VTK-m.

```cpp
#include <vtkm/cont/internal/IteratorFromArrayPortal.h>
#include <vtkm/Assert.h>

// DequeType expected to be either FooFieldsDeque or const FooFieldsDeque
template<typename DequeType>
class ArrayPortalFooPressure
{
public:
  typedef float ValueType;

  VTKM_CONT
  ArrayPortalFooPressure() : Container(NULL) {  }

  VTKM_CONT
  ArrayPortalFooPressure(DequeType *container) : Container(container) {  }

  // Required to copy compatible types of ArrayPortalFooPressure. Really needed
  // to copy from non-const to const versions of array portals.
  template<typename OtherDequeType>
  VTKM_CONT
  ArrayPortalFooPressure(const ArrayPortalFooPressure<OtherDequeType> &other)
    : Container(other.GetContainer()) {  }

  VTKM_CONT
  vtkm::Id GetNumberOfValues() const {
    return static_cast<vtkm::Id>(this->Container->size());
  }

  VTKM_CONT
  ValueType Get(vtkm::Id index) const {
    VTKM_ASSERT(index >= 0);
    VTKM_ASSERT(index < this->GetNumberOfValues());
    return (*this->Container)[index].Pressure;
  }

  VTKM_CONT
  void Set(vtkm::Id index, ValueType value) const {
    VTKM_ASSERT(index >= 0);
    VTKM_ASSERT(index < this->GetNumberOfValues());
    (*this->Container)[index].Pressure = value;
  }

  // Here for the copy constructor.
  VTKM_CONT
  DequeType *GetContainer() const { return this->Container; }

private:
  DequeType *Container;
};
```

The next step in creating an adapter storage is to define a tag for the adapter. We shall call ours StorageTagFooPressure. Then, we need to create a specialization of the templated vtkm::cont::internal::Storage class. The ArrayHandle will instantiate an object using the array container tag we give it, and we define our own specialization so that it runs our interface into the code.

vtkm::cont::internal::Storage has two template arguments: the base type of the array and the storage tag.

Example 10.39: Prototype for vtkm::cont::internal::Storage.

```
namespace vtkm {
namespace cont {
namespace internal {

template<typename T, class StorageTag>
class Storage;

}
}
} // namespace vtkm::cont::internal
```

The vtkm::cont::internal::Storage must define the following items.

ValueType A typedef of the type for each item in the array. This is the same type as the first template argument.

PortalType The type of an array portal that can be used to access the underlying data. This array portal needs to work only in the control environment.

PortalConstType A read-only (const) version of PortalType.

GetPortal A method that returns an array portal of type PortalType that can be used to access the data manged in this storage.

GetPortalConst Same as GetPortal except it returns a read-only (const) array portal.

GetNumberOfValues A method that returns the number of values the storage is currently allocated for.

Allocate A method that allocates the array to a given size. An values stored in the previous allocation may be destroyed.

Shrink A method like Allocate with two differences. First, the size of the allocation must be smaller than the existing allocation when the method is called. Second, any values currently stored in the array will be valid after the array is resized. This constrained form of allocation allows the array to be resized and values valid without ever having to copy data.

ReleaseResources A method that instructs the storage to free all of its memory.

The following provides an example implementation of our adapter to a `FooFieldsDeque`. It relies on the `ArrayPortalFooPressure` provided in Example 10.38.

Example 10.40: Storage to adapt a third-party container to VTK-m.

```
// Includes or definition for ArrayPortalFooPressure

struct StorageTagFooPressure {  };

namespace vtkm {
namespace cont {
namespace internal {

template<>
class Storage<float, StorageTagFooPressure>
{
public:
  typedef float ValueType;

  typedef ArrayPortalFooPressure<FooFieldsDeque> PortalType;
  typedef ArrayPortalFooPressure<const FooFieldsDeque> PortalConstType;

  VTKM_CONT
  Storage() : Container(NULL) {  }

  VTKM_CONT
  Storage(FooFieldsDeque *container) : Container(container) {  }

  VTKM_CONT
  PortalType GetPortal() { return PortalType(this->Container); }

  VTKM_CONT
  PortalConstType GetPortalConst() const {
    return PortalConstType(this->Container);
  }

  VTKM_CONT
  vtkm::Id GetNumberOfValues() const {
    return static_cast<vtkm::Id>(this->Container->size());
  }

  VTKM_CONT
  void Allocate(vtkm::Id numberOfValues) {
    this->Container->resize(numberOfValues);
  }

  VTKM_CONT
  void Shrink(vtkm::Id numberOfValues) {
    this->Container->resize(numberOfValues);
  }

  VTKM_CONT
  void ReleaseResources() { this->Container->clear(); }

private:
  FooFieldsDeque *Container;
};

}
}
} // namespace vtkm::cont::internal
```

The final step to make a storage adapter is to make a mechanism to construct an `ArrayHandle` that points to a particular storage. This can be done by creating a trivial subclass of `vtkm::cont::ArrayHandle` that simply constructs the array handle to the state of an existing container.

Example 10.41: Array handle to adapt a third-party container to VTK-m.

```
class ArrayHandleFooPressure
    : public vtkm::cont::ArrayHandle<float, StorageTagFooPressure>
{
private:
  typedef vtkm::cont::internal::Storage<float, StorageTagFooPressure>
      StorageType;

public:
  VTKM_ARRAY_HANDLE_SUBCLASS_NT(
      ArrayHandleFooPressure,
      (vtkm::cont::ArrayHandle<float, StorageTagFooPressure>));

  VTKM_CONT
  ArrayHandleFooPressure(FooFieldsDeque *container)
    : Superclass(StorageType(container)) {  }
};
```

Subclasses of ArrayHandle provide constructors that establish the state of the array handle. All array handle subclasses must also use either the VTKM_ARRAY_HANDLE_SUBCLASS macro or the VTKM_ARRAY_HANDLE_SUBCLASS_NT macro. Both of these macros define the typedefs Superclass, ValueType, and StorageTag as well as a set of constructors and operators expected of all ArrayHandle classes. The difference between these two macros is that VTKM_ARRAY_HANDLE_SUBCLASS is used in templated classes whereas VTKM_ARRAY_HANDLE_SUBCLASS_NT is used in non-templated classes.

The ArrayHandle subclass in Example 10.41 is not templated, so it uses the VTKM_ARRAY_HANDLE_SUBCLASS_NT macro. (The other macro is described in Section 10.3.2 on page 94). This macro takes two parameters. The first parameter is the name of the subclass where the macro is defined and the second parameter is the immediate superclass including the full template specification. The second parameter of the macro must be enclosed in parentheses so that the C pre-processor correctly handles commas in the template specification.

With this new version of ArrayHandle, VTK-m can now read to and write from the FooFieldsDeque structure directly. Note, however, that when writing to an array handle, it is necessary to call GetPortalControl or GetPortalConstControl to flush data from the execution environment to the control environment. [SHOULD PROBABLY MAKE THIS EASIER.]

Example 10.42: Using an ArrayHandle with custom container.

```
VTKM_CONT
void GetElevationAirPressure(vtkm::cont::DataSet grid, FooFieldsDeque *fields)
{
  // Make an array handle that points to the pressure values in the fields.
  ArrayHandleFooPressure pressureHandle(fields);

  // Use the elevation worklet to estimate atmospheric pressure based on the
  // height of the point coordinates. Atmospheric pressure is 101325 Pa at
  // sea level and drops about 12 Pa per meter.
  vtkm::worklet::PointElevation elevation;
  elevation.SetLowPoint(vtkm::make_Vec(0.0, 0.0, 0.0));
  elevation.SetHighPoint(vtkm::make_Vec(0.0, 0.0, 2000.0));
  elevation.SetRange(101325.0, 77325.0);

  vtkm::worklet::DispatcherMapField<vtkm::worklet::PointElevation>
      dispatcher(elevation);
  dispatcher.Invoke(grid.GetCoordinateSystem().GetData(), pressureHandle);

  // Make sure the values are flushed back to the control environment.
  pressureHandle.GetPortalConstControl();

  // Now the pressure field is in the fields container.
}
```

Most of the code in VTK-m will create `ArrayHandle`s using the default storage, which is set to the basic storage if not otherwise specified. If you wish to replace the default storage used, then set the `VTKM_STORAGE` macro to `VTKM_STORAGE_UNDEFINED` and set the `VTKM_DEFAULT_STORAGE_TAG` to your tag class. These definitions have to happen *before* including any VTK-m header files. You will also have to declare the tag class (or at least a prototype of it) before including VTK-m header files.

Example 10.43: Redefining the default array handle storage.

```
#define VTKM_STORAGE VTKM_STORAGE_UNDEFINED
#define VTKM_DEFAULT_STORAGE_TAG StorageTagFooPressure

struct StorageTagFooPressure;
```

Common Errors

`ArrayHandle`s are often stored in dynamic objects like dynamic arrays (Chapter 11) or data sets (Chapter 12). When this happens, the array's type information, including the storage used, is lost. VTK-m will have to guess the storage, and if you do not tell VTK-m to try your custom storage, you will get a runtime error when the array is used. The most common ways of doing this are to change the default storage tag (described here), adding the storage tag to the default storage list (Section 11.3) or specifying the storage tag in the policy when executing filters ([ADD REFERENCE WHEN DOCUMENTED.]*).*

CHAPTER

ELEVEN

DYNAMIC ARRAY HANDLES

The ArrayHandle class uses templating to make very efficient and type-safe access to data. However, it is sometimes inconvenient or impossible to specify the element type and storage at run-time. The DynamicArrayHandle class provides a mechanism to manage arrays of data with unspecified types.

vtkm::cont::DynamicArrayHandle holds a reference to an array. Unlike ArrayHandle, DynamicArrayHandle is *not* templated. Instead, it uses C++ run-type type information to store the array without type and cast it when appropriate.

A DynamicArrayHandle can be established by constructing it with or assigning it to an ArrayHandle. The following example demonstrates how a DynamicArrayHandle might be used to load an array whose type is not known until run-time.

Example 11.1: Creating a DynamicArrayHandle.

```
VTKM_CONT
vtkm::cont::DynamicArrayHandle
LoadDynamicArray(const void *buffer, vtkm::Id length, std::string type)
{
  vtkm::cont::DynamicArrayHandle handle;
  if (type == "float")
  {
    vtkm::cont::ArrayHandle<vtkm::Float32> concreteArray =
        vtkm::cont::make_ArrayHandle(
          reinterpret_cast<const vtkm::Float32*>(buffer), length);
    handle = concreteArray;
  } else if (type == "int") {
    vtkm::cont::ArrayHandle<vtkm::Int32> concreteArray =
        vtkm::cont::make_ArrayHandle(
          reinterpret_cast<const vtkm::Int32*>(buffer), length);
    handle = concreteArray;
  }
  return handle;
}
```

11.1 Querying and Casting

Data pointed to by a DynamicArrayHandle is not directly accessible. However, there are a few generic queries you can make without directly knowing the data type. The GetNumberOfValues method returns the length of the array with respect to its base data type. It is also common in VTK-m to use data types, such as vtkm::Vec, with multiple components per value. The GetNumberOfComponents method returns the number of components in a vector-like type (or 1 for scalars).

Example 11.2: Non type-specific queries on DynamicArrayHandle.

```
std::vector<vtkm::Float32> scalarBuffer(10);
vtkm::cont::DynamicArrayHandle scalarDynamicHandle(
      vtkm::cont::make_ArrayHandle(scalarBuffer));

// This returns 10.
vtkm::Id scalarArraySize = scalarDynamicHandle.GetNumberOfValues();

// This returns 1.
vtkm::IdComponent scalarComponents =
    scalarDynamicHandle.GetNumberOfComponents();

std::vector<vtkm::Vec<vtkm::Float32,3> > vectorBuffer(20);
vtkm::cont::DynamicArrayHandle vectorDynamicHandle(
      vtkm::cont::make_ArrayHandle(vectorBuffer));

// This returns 20.
vtkm::Id vectorArraySize = vectorDynamicHandle.GetNumberOfValues();

// This returns 3.
vtkm::IdComponent vectorComponents =
    vectorDynamicHandle.GetNumberOfComponents();
```

It is also often desirable to create a new array based on the underlying type of a DynamicArrayHandle. For example, when a filter creates a field, it is common to make this output field the same type as the input. To satisfy this use case, DynamicArrayHandle has a method named NewInstance that creates a new empty array with the same underlying type as the original array.

Example 11.3: Using DynamicArrayHandle::NewInstance().

```
std::vector<vtkm::Float32> scalarBuffer(10);
vtkm::cont::DynamicArrayHandle dynamicHandle(
      vtkm::cont::make_ArrayHandle(scalarBuffer));

// This creates a new empty array of type Float32.
vtkm::cont::DynamicArrayHandle newDynamicArray = dynamicHandle.NewInstance();
```

Before the data with a DynamicArrayHandle can be accessed, the type and storage of the array must be established. This is usually done internally within VTK-m when a worklet [OR FILTER?] is invoked. However, it is also possible to query the types and cast to a concrete ArrayHandle.

You can query the component type and storage type using the IsType, IsSameType, and IsTypeAndStorage methods. IsType takes an example array handle type and returns whether the underlying array matches the given static array type. IsSameType behaves the same as IsType but accepts an instance of an ArrayHandle object to automatically resolve the template parameters. IsTypeAndStorage takes an example component type and an example storage type as arguments and returns whether the underlying array matches both types.

Example 11.4: Querying the component and storage types of a DynamicArrayHandle.

```
std::vector<vtkm::Float32> scalarBuffer(10);
vtkm::cont::ArrayHandle<vtkm::Float32> concreteHandle =
    vtkm::cont::make_ArrayHandle(scalarBuffer);
vtkm::cont::DynamicArrayHandle dynamicHandle(concreteHandle);

// This returns true
bool isFloat32Array = dynamicHandle.IsSameType(concreteHandle);

// This returns false
bool isIdArray =
    dynamicHandle.IsType<vtkm::cont::ArrayHandle<vtkm::Id> >();

// This returns true
```

```
  bool isFloat32 =
      dynamicHandle.IsTypeAndStorage<vtkm::Float32,VTKM_DEFAULT_STORAGE_TAG>();

  // This returns false
  bool isId =
      dynamicHandle.IsTypeAndStorage<vtkm::Id,VTKM_DEFAULT_STORAGE_TAG>();

  // This returns false
  bool isErrorStorage = dynamicHandle.IsTypeAndStorage<
      vtkm::Float32,
      vtkm::cont::ArrayHandleCounting<vtkm::Float32>::StorageTag>();
```

Once the type of the DynamicArrayHandle is known, it can be cast to a concrete ArrayHandle, which has access to the data as described in Chapter 7. The easiest way to do this is to use the CopyTo method. This templated method takes a reference to an ArrayHandle as an argument and sets that array handle to point to the array in DynamicArrayHandle. If the given types are incorrect, then CopyTo throws a vtkm::cont::-ErrorControlBadValue exception.

Example 11.5: Casting a DynamicArrayHandle to a concrete ArrayHandle.

```
  dynamicHandle.CopyTo(concreteHandle);
```

Common Errors

Remember that ArrayHandle and DynamicArrayHandle represent pointers to the data, so this "copy" is a shallow copy. There is still only one copy of the data, and if you change the data in one array handle that change is reflected in the other.

11.2 Casting to Unknown Types

Using CopyTo is fine as long as the correct types are known, but often times they are not. For this use case DynamicArrayHandle has a method named CastAndCall that attempts to cast the array to some set of types.

The CastAndCall method accepts a functor to run on the appropriately cast array. The functor must have an overloaded const parentheses operator that accepts an ArrayHandle of the appropriate type.

Example 11.6: Operating on DynamicArrayHandle with CastAndCall.

```
struct PrintArrayContentsFunctor
{
  template<typename T, typename Storage>
  VTKM_CONT
  void operator()(const vtkm::cont::ArrayHandle<T,Storage> &array) const
  {
    this->PrintArrayPortal(array.GetPortalConstControl());
  }

private:
  template<typename PortalType>
  VTKM_CONT
  void PrintArrayPortal(const PortalType &portal) const
  {
    for (vtkm::Id index = 0; index < portal.GetNumberOfValues(); index++)
    {
      // All ArrayPortal objects have ValueType for the type of each value.
      typedef typename PortalType::ValueType ValueType;

      ValueType value = portal.Get(index);

      vtkm::IdComponent numComponents =
          vtkm::VecTraits<ValueType>::GetNumberOfComponents(value);
      for (vtkm::IdComponent componentIndex = 0;
           componentIndex < numComponents;
           componentIndex++)
      {
        std::cout << " "
                  << vtkm::VecTraits<ValueType>::GetComponent(value,
                                                              componentIndex);
      }
      std::cout << std::endl;
    }
  }
};

template<typename DynamicArrayType>
void PrintArrayContents(const DynamicArrayType &array)
{
  array.CastAndCall(PrintArrayContentsFunctor());
}
```

Common Errors

It is possible to store any form of ArrayHandle *in a* DynamicArrayHandle*, but it is not possible for* CastAndCall *to check every possible form of* ArrayHandle*. If* CastAndCall *cannot determine the* ArrayHandle *type, then an* ErrorControlBadValue *is thrown. The following section describes how to specify the forms of* ArrayHandle *to try.*

11.3 Specifying Cast Lists

The CastAndCall method can only check a finite number of types. The default form of CastAndCall uses a default set of common types. These default lists can be overridden using the VTK-m list tags facility, which is discussed at length in Section 6.6. There are separate lists for value types and for storage types.

Common type lists for value are defined in vtkm/TypeListTag.h and are documented in Section 6.6.2. This header also defines VTKM_DEFAULT_TYPE_LIST_TAG, which defines the default list of value types tried in CastAndCall.

Common storage lists are defined in vtkm/cont/StorageListTag.h. There is only one common storage distributed with VTK-m: StorageBasic. A list tag containing this type is defined as vtkm::cont::StorageListTagBasic.

As with other lists, it is possible to create new storage type lists using the existing type lists and the list bases from Section 6.6.1.

The vtkm/cont/StorageListTag.h header also defines a macro named VTKM_DEFAULT_STORAGE_LIST_TAG that defines a default list of types to use in classes like DynamicArrayHandle. This list can be overridden by defining the VTKM_DEFAULT_STORAGE_LIST_TAG macro *before* any VTK-m headers are included. If included after a VTK-m header, the list is not likely to take effect. Do not ignore compiler warnings about the macro being redefined, which you will not get if defined correctly.

There is a form of `CastAndCall` that accepts tags for the list of component types and storage types. This can be used when the specific lists are known at the time of the call. However, when creating generic operations like the `PrintArrayContents` function in Example 11.6, passing these tags is inconvenient at best.

To address this use case, `DynamicArrayHandle` has a pair of methods named `ResetTypeList` and `ResetStorageList`. These methods return a new object with that behaves just like a `DynamicArrayHandle` with identical state except that the cast and call functionality uses the specified component type or storage type instead of the default. (Note that `PrintArrayContents` in Example 11.6 is templated on the type of `DynamicArrayHandle`. This is to accommodate using the objects from the `Reset*List` methods, which have the same behavior but different type names.)

So the default component type list contains a subset of the basic VTK-m types. If you wanted to accommodate more types, you could use `ResetTypeList`.

Example 11.7: Trying all component types in a `DynamicArrayHandle`.

```
  PrintArrayContents(dynamicArray.ResetTypeList(vtkm::TypeListTagAll()));
```

Likewise, if you happen to know a particular type of the dynamic array, that can be specified to reduce the amount of object code created by templates in the compiler.

Example 11.8: Specifying a single component type in a `DynamicArrayHandle`.

```
  PrintArrayContents(dynamicArray.ResetTypeList(vtkm::TypeListTagId()));
```

Storage type lists can be changed similarly.

Example 11.9: Specifying different storage types in a `DynamicArrayHandle`.

```
struct MyIdStorageList :
    vtkm::ListTagBase<
        vtkm::cont::StorageTagBasic,
        vtkm::cont::ArrayHandleIndex::StorageTag>
{ };

void PrintIds(vtkm::cont::DynamicArrayHandle array)
{
  PrintArrayContents(array.ResetStorageList(MyIdStorageList()));
}
```

Common Errors

The `ResetTypeList` *and* `ResetStorageList` *do not change the object they are called on. Rather, they return a new object with different type information. Calling these methods has no effect unless you do something with the returned value.*

Both the component type list and the storage type list can be modified by chaining these reset calls.

Example 11.10: Specifying both component and storage types in a `DynamicArrayHandle`.

```
  PrintArrayContents(dynamicArray.
                       ResetTypeList(vtkm::TypeListTagId()).
                       ResetStorageList(MyIdStorageList()));
```

The `ResetTypeList` and `ResetStorageList` work by returning a `vtkm::cont::DynamicArrayHandleBase` object. `DynamicArrayHandleBase` specifies the value and storage tag lists as template arguments and otherwise behaves just like `DynamicArrayHandle`.

Did you know?

I lied earlier when I said at the beginning of this chapter that DynamicArrayHandle *is a class that is not templated. This symbol is really just a* typedef *of* DynamicArrayHandleBase*. Because the* DynamicArrayHandle *fully specifies the template arguments, it behaves like a class, but if you get a compiler error it will show up as* DynamicArrayHandleBase*.*

Most code does not need to worry about working directly with DynamicArrayHandleBase. However, it is sometimes useful to declare it in templated functions that accept dynamic array handles so that works with every type list. The function in Example 11.6 did this by making the dynamic array handle class itself the template argument. This will work, but it is prone to error because the template will resolve to any type of argument. When passing objects that are not dynamic array handles will result in strange and hard to diagnose errors. Instead, we can define the same function using DyamicArrayHandleBase so that the template will only match dynamic array handle types.

Example 11.11: Using DynamicArrayHandleBase to accept generic dynamic array handles.

```
template<typename TypeList, typename StorageList>
void PrintArrayContents(
    const vtkm::cont::DynamicArrayHandleBase<TypeList,StorageList> &array)
{
  array.CastAndCall(PrintArrayContentsFunctor());
}
```

CHAPTER

TWELVE

DATA SETS

A *data set*, implemented with the vtkm::cont::DataSet class, contains and manages the geometric data structures that VTK-m operates on. A data set comprises the following 3 data structures.

Cell Set A cell set describes topological connections. A cell set defines some number of points in space and how they connect to form cells, filled regions of space. A data set must have at least one cell set, but can have more than one cell set defined. This makes it possible to define groups of cells with different properties. For example, a simulation might model some subset of elements as boundary that contain properties the other elements do not. Another example is the representation of a molecule that requires atoms and bonds, each having very different properties associated with them.

Field A field describes numerical data associated with the topological elements in a cell set. The field is represented as an array, and each entry in the field array corresponds to a topological element (point, edge, face, or cell). Together the cell set topology and discrete data values in the field provide an interpolated function throughout the volume of space covered by the data set. A cell set can have any number of fields.

Coordinate System A coordinate system is a special field that describes the physical location of the points in a data set. Although it is most common for a data set to contain a single coordinate system, VTK-m supports data sets with no coordinate system such as abstract data structures like graphs that might not have positions in a space. DataSet also supports multiple coordinate systems for data that have multiple representations for position. For example, geospatial data could simultaneously have coordinate systems defined by 3D position, latitude-longitude, and any number of 2D projections.

12.1 Building Data Sets

Before we go into detail on the cell sets, fields, and coordinate systems that make up a data set in VTK-m, let us first discuss how to build a data set. One simple way to build a data set is to load data from a file using the vtkm::io module. Reading files is discussed in detail in Chapter 3.

This section describes building data sets of different types using a set of classes named `DataSetBuilder*`, which provide a convenience layer on top of vtkm::cont::DataSet to make it easier to create data sets.

12.1.1 Creating Uniform Grids

Uniform grids are meshes that have a regular array structure with points uniformly spaced parallel to the axes. Uniform grids are also sometimes called regular grids or images.

The vtkm::cont::DataSetBuilderUniform class can be used to easily create 2- or 3-dimensional uniform grids. DataSetBuilderUniform has several versions of a method named Create that takes the number of points in each dimension, the origin, and the spacing. The origin is the location of the first point of the data (in the lower left corner), and the spacing is the distance between points in the x, y, and z directions. The Create methods also take an optional name for the coordinate system and an optional name for the cell set.

The following example creates a vtkm::cont::DataSet containing a uniform grid of $101 \times 101 \times 26$ points.

Example 12.1: Creating a uniform grid.

```
vtkm::cont::DataSetBuilderUniform dataSetBuilder;

vtkm::cont::DataSet dataSet = dataSetBuilder.Create(vtkm::Id3(101, 101, 26));
```

If not specified, the origin will be at the coordinates $(0,0,0)$ and the spacing will be 1 in each direction. Thus, in the previous example the width, height, and depth of the mesh in physical space will be 100, 100, and 25, respectively, and the mesh will be centered at $(50,50,12.5)$. Let us say we actually want a mesh of the same dimensions, but we want the z direction to be stretched out so that the mesh will be the same size in each direction, and we want the mesh centered at the origin.

Example 12.2: Creating a uniform grid with custom origin and spacing.

```
vtkm::cont::DataSetBuilderUniform dataSetBuilder;

vtkm::cont::DataSet dataSet =
    dataSetBuilder.Create(
      vtkm::Id3(101, 101, 26),
      vtkm::Vec<vtkm::FloatDefault,3>(-50.0, -50.0, -50.0),
      vtkm::Vec<vtkm::FloatDefault,3>(1.0, 1.0, 4.0));
```

12.1.2 Creating Rectilinear Grids

A rectilinear grid is similar to a uniform grid except that a rectilinear grid can adjust the spacing between adjacent grid points. This allows the rectilinear grid to have tighter sampling in some areas of space, but the points are still constrained to be aligned with the axes and each other. The irregular spacing of a rectilinear grid is specified by providing a separate array each for the x, y, and z coordinates.

The vtkm::cont::DataSetBuilderRectilinear class can be used to easily create 2- or 3-dimensional rectilinear grids. DataSetBuilderRectilinear has several versions of a method named Create that takes these coordinate arrays and builds a vtkm::cont::DataSet out of them. The arrays can be supplied as either standard C arrays or as std::vector objects, in which case the data in the arrays are copied into the DataSet. These arrays can also be passed as ArrayHandle objects, in which case the data are shallow copied.

The following example creates a vtkm::cont::DataSet containing a rectilinear grid with $201 \times 201 \times 101$ points with different irregular spacing along each axis.

Example 12.3: Creating a rectilinear grid.

```
// Make x coordinates range from -4 to 4 with tighter spacing near 0.
std::vector<vtkm::Float32> xCoordinates;
for (vtkm::Float32 x = -2.0f; x <= 2.0f; x += 0.02f)
{
  xCoordinates.push_back(vtkm::CopySign(x*x, x));
}

// Make y coordinates range from 0 to 2 with tighter spacing near 2.
std::vector<vtkm::Float32> yCoordinates;
for (vtkm::Float32 y = 0.0f; y <= 4.0f; y += 0.02f)
{
  yCoordinates.push_back(vtkm::Sqrt(y));
}

// Make z coordinates rangefrom -1 to 1 with even spacing.
std::vector<vtkm::Float32> zCoordinates;
for (vtkm::Float32 z = -1.0f; z <= 1.0f; z += 0.02f)
{
  zCoordinates.push_back(z);
}

vtkm::cont::DataSetBuilderRectilinear dataSetBuilder;

vtkm::cont::DataSet dataSet = dataSetBuilder.Create(xCoordinates,
                                                    yCoordinates,
                                                    zCoordinates);
```

12.1.3 Creating Explicit Meshes

An explicit mesh is an arbitrary collection of cells with arbitrary connections. It can have multiple different types of cells. Explicit meshes are also known as unstructured grids.

The cells of an explicit mesh are defined by providing the shape, number of indices, and the points that comprise it for each cell. These three things are stored in separate arrays. Figure 12.1 shows an example of an explicit mesh and the arrays that can be used to define it.

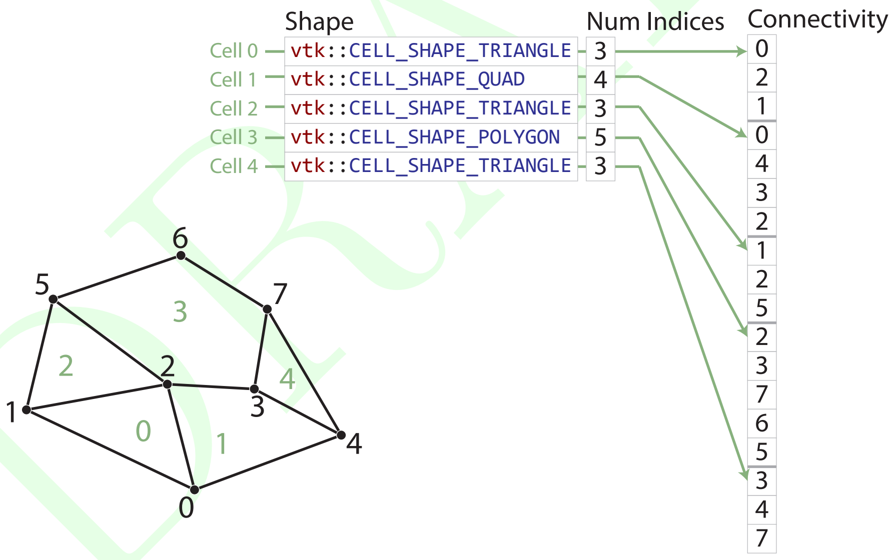


Figure 12.1: An example explicit mesh.

The vtkm::cont::DataSetBuilderExplicit class can be used to create data sets with explicit meshes. DataSetBuilderExplicit has several versions of a method named Create. Generally, these methods take the shapes, number of indices, and connectivity arrays as well as an array of point coordinates. These arrays can be given in std::vector objects, and the data are copied into the DataSet created.

The following example creates a mesh like the one shown in Figure 12.1.

Example 12.4: Creating an explicit mesh with DataSetBuilderExplicit.

```
  // Array of point coordinates.
```

```
std::vector<vtkm::Vec<vtkm::Float32,3> > pointCoordinates;
pointCoordinates.push_back(vtkm::Vec<vtkm::Float32,3>(1.1f, 0.0f, 0.0f));
pointCoordinates.push_back(vtkm::Vec<vtkm::Float32,3>(0.2f, 0.4f, 0.0f));
pointCoordinates.push_back(vtkm::Vec<vtkm::Float32,3>(0.9f, 0.6f, 0.0f));
pointCoordinates.push_back(vtkm::Vec<vtkm::Float32,3>(1.4f, 0.5f, 0.0f));
pointCoordinates.push_back(vtkm::Vec<vtkm::Float32,3>(1.8f, 0.3f, 0.0f));
pointCoordinates.push_back(vtkm::Vec<vtkm::Float32,3>(0.4f, 1.0f, 0.0f));
pointCoordinates.push_back(vtkm::Vec<vtkm::Float32,3>(1.0f, 1.2f, 0.0f));
pointCoordinates.push_back(vtkm::Vec<vtkm::Float32,3>(1.5f, 0.9f, 0.0f));

// Array of shapes.
std::vector<vtkm::UInt8> shapes;
shapes.push_back(vtkm::CELL_SHAPE_TRIANGLE);
shapes.push_back(vtkm::CELL_SHAPE_QUAD);
shapes.push_back(vtkm::CELL_SHAPE_TRIANGLE);
shapes.push_back(vtkm::CELL_SHAPE_POLYGON);
shapes.push_back(vtkm::CELL_SHAPE_TRIANGLE);

// Array of number of indices per cell.
std::vector<vtkm::IdComponent> numIndices;
numIndices.push_back(3);
numIndices.push_back(4);
numIndices.push_back(3);
numIndices.push_back(5);
numIndices.push_back(3);

// Connectivity array.
std::vector<vtkm::Id> connectivity;
connectivity.push_back(0); // Cell 0
connectivity.push_back(2);
connectivity.push_back(1);
connectivity.push_back(0); // Cell 1
connectivity.push_back(4);
connectivity.push_back(3);
connectivity.push_back(2);
connectivity.push_back(1); // Cell 2
connectivity.push_back(2);
connectivity.push_back(5);
connectivity.push_back(2); // Cell 3
connectivity.push_back(3);
connectivity.push_back(7);
connectivity.push_back(6);
connectivity.push_back(5);
connectivity.push_back(3); // Cell 4
connectivity.push_back(4);
connectivity.push_back(7);

// Copy these arrays into a DataSet.
vtkm::cont::DataSetBuilderExplicit dataSetBuilder;

vtkm::cont::DataSet dataSet = dataSetBuilder.Create(pointCoordinates,
                                                    shapes,
                                                    numIndices,
                                                    connectivity);
```

Often it is awkward to build your own arrays and then pass them to `DataSetBuilderExplicit`. There also exists an alternate builder class named `vtkm::cont::DataSetBuilderExplicitIterative` that allows you to specify each cell and point one at a time rather than all at once. This is done by calling one of the versions of **`AddPoint`** and one of the versions of **`AddCell`** for each point and cell, respectively. The next example also builds the mesh shown in Figure 12.1 except this time using `DataSetBuilderExplicitIterative`.

Example 12.5: Creating an explicit mesh with `DataSetBuilderExplicitIterative`.

```
vtkm::cont::DataSetBuilderExplicitIterative dataSetBuilder;
```

```

  dataSetBuilder.AddPoint(1.1, 0.0, 0.0);
  dataSetBuilder.AddPoint(0.2, 0.4, 0.0);
  dataSetBuilder.AddPoint(0.9, 0.6, 0.0);
  dataSetBuilder.AddPoint(1.4, 0.5, 0.0);
  dataSetBuilder.AddPoint(1.8, 0.3, 0.0);
  dataSetBuilder.AddPoint(0.4, 1.0, 0.0);
  dataSetBuilder.AddPoint(1.0, 1.2, 0.0);
  dataSetBuilder.AddPoint(1.5, 0.9, 0.0);

  dataSetBuilder.AddCell(vtkm::CELL_SHAPE_TRIANGLE);
  dataSetBuilder.AddCellPoint(0);
  dataSetBuilder.AddCellPoint(2);
  dataSetBuilder.AddCellPoint(1);

  dataSetBuilder.AddCell(vtkm::CELL_SHAPE_QUAD);
  dataSetBuilder.AddCellPoint(0);
  dataSetBuilder.AddCellPoint(4);
  dataSetBuilder.AddCellPoint(3);
  dataSetBuilder.AddCellPoint(2);

  dataSetBuilder.AddCell(vtkm::CELL_SHAPE_TRIANGLE);
  dataSetBuilder.AddCellPoint(1);
  dataSetBuilder.AddCellPoint(2);
  dataSetBuilder.AddCellPoint(5);

  dataSetBuilder.AddCell(vtkm::CELL_SHAPE_POLYGON);
  dataSetBuilder.AddCellPoint(2);
  dataSetBuilder.AddCellPoint(3);
  dataSetBuilder.AddCellPoint(7);
  dataSetBuilder.AddCellPoint(6);
  dataSetBuilder.AddCellPoint(5);

  dataSetBuilder.AddCell(vtkm::CELL_SHAPE_TRIANGLE);
  dataSetBuilder.AddCellPoint(3);
  dataSetBuilder.AddCellPoint(4);
  dataSetBuilder.AddCellPoint(7);

  vtkm::cont::DataSet dataSet = dataSetBuilder.Create();
```

12.1.4 Add Fields

In addition to creating the geometric structure of a data set, it is usually important to add fields to the data. Fields describe numerical data associated with the topological elements in a cell. They often represent a physical quantity (such as temperature, mass, or volume fraction) but can also represent other information (such as indices or classifications).

The easiest way to define fields in a data set is to use the `vtkm::cont::DataSetFieldAdd` class. This class works on `DataSet`s of any type. It has methods named `AddPointField` and `AddCellField` that define a field for either points or cells. Every field must have an associated field name.

Both `AddPointField` and `AddCellField` are overloaded to accept arrays of data in different structures. Field arrays can be passed as standard C arrays or as `std::vector`s, in which case the data are copied. Field arrays can also be passed in a `ArrayHandle`, in which case the data are not copied.

The following (somewhat contrived) example defines fields for a uniform grid that identify which points and cells are on the boundary of the mesh.

Example 12.6: Adding fields to a `DataSet`.

```
  // Make a simple structured data set.
  const vtkm::Id3 pointDimensions(20, 20, 10);
  const vtkm::Id3 cellDimensions = pointDimensions - vtkm::Id3(1, 1, 1);
  vtkm::cont::DataSetBuilderUniform dataSetBuilder;
  vtkm::cont::DataSet dataSet = dataSetBuilder.Create(pointDimensions);

  // This is the helper object to add fields to a data set.
  vtkm::cont::DataSetFieldAdd dataSetFieldAdd;

  // Create a field that identifies points on the boundary.
  std::vector<vtkm::UInt8> boundaryPoints;
  for (vtkm::Id zIndex = 0; zIndex < pointDimensions[2]; zIndex++)
  {
    for (vtkm::Id yIndex = 0; yIndex < pointDimensions[1]; yIndex++)
    {
      for (vtkm::Id xIndex = 0; xIndex < pointDimensions[0]; xIndex++)
      {
        if ( (xIndex == 0) || (xIndex == pointDimensions[0]-1) ||
             (yIndex == 0) || (yIndex == pointDimensions[1]-1) ||
             (zIndex == 0) || (zIndex == pointDimensions[2]-1) )
        {
          boundaryPoints.push_back(1);
        }
        else
        {
          boundaryPoints.push_back(0);
        }
      }
    }
  }

  dataSetFieldAdd.AddPointField(dataSet, "boundary_points", boundaryPoints);

  // Create a field that identifies cells on the boundary.
  std::vector<vtkm::UInt8> boundaryCells;
  for (vtkm::Id zIndex = 0; zIndex < cellDimensions[2]; zIndex++)
  {
    for (vtkm::Id yIndex = 0; yIndex < cellDimensions[1]; yIndex++)
    {
      for (vtkm::Id xIndex = 0; xIndex < cellDimensions[0]; xIndex++)
      {
        if ( (xIndex == 0) || (xIndex == cellDimensions[0]-1) ||
             (yIndex == 0) || (yIndex == cellDimensions[1]-1) ||
             (zIndex == 0) || (zIndex == cellDimensions[2]-1) )
        {
          boundaryCells.push_back(1);
        }
        else
        {
          boundaryCells.push_back(0);
        }
      }
    }
  }

  dataSetFieldAdd.AddCellField(dataSet, "boundary_cells", boundaryCells);
```

12.2 Cell Sets

A cell set determines the topological structure of the data in a data set. Fundamentally, any cell set is a collection of cells, which typically (but not always) represent some region in space. 3D cells are made up of points, edges, and faces. (2D cells have only points and edges, and 1D cells have only points.) Figure 12.2 shows the relationship between a cell's shape and these topological elements. The arrangement of these points, edges, and faces is defined by the *shape* of the cell, which prescribes a specific ordering of each. The basic cell shapes provided by VTK-m are discussed in detail in Section 17.1 starting on page 173.

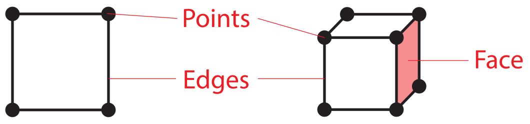


Figure 12.2: The relationship between a cell shape and its topological elements (points, edges, and faces).

There are multiple ways to express the connections of a cell set, each with different benefits and restrictions. These different cell set types are managed by different cell set classes in VTK-m. All VTK-m cell set classes inherit from `vtkm::cont::CellSet`. The two basic types of cell sets are structured and explicit, and there are several variations of these types.

12.2.1 Structured Cell Sets

A `vtkm::cont::CellSetStructured` defines a 1-, 2-, or 3-dimensional grid of points with lines, quadrilaterals, or hexahedra, respectively, connecting them. The topology of a `CellSetStructured` is specified by simply providing the dimensions, which is the number of points in the i, j, and k directions of the grid of points. The number of points is implicitly $i \times j \times k$ and the number of cells is implicitly $(i-1) \times (j-1) \times (k-1)$ (for 3D grids). Figure 12.3 demonstrates this arrangement.

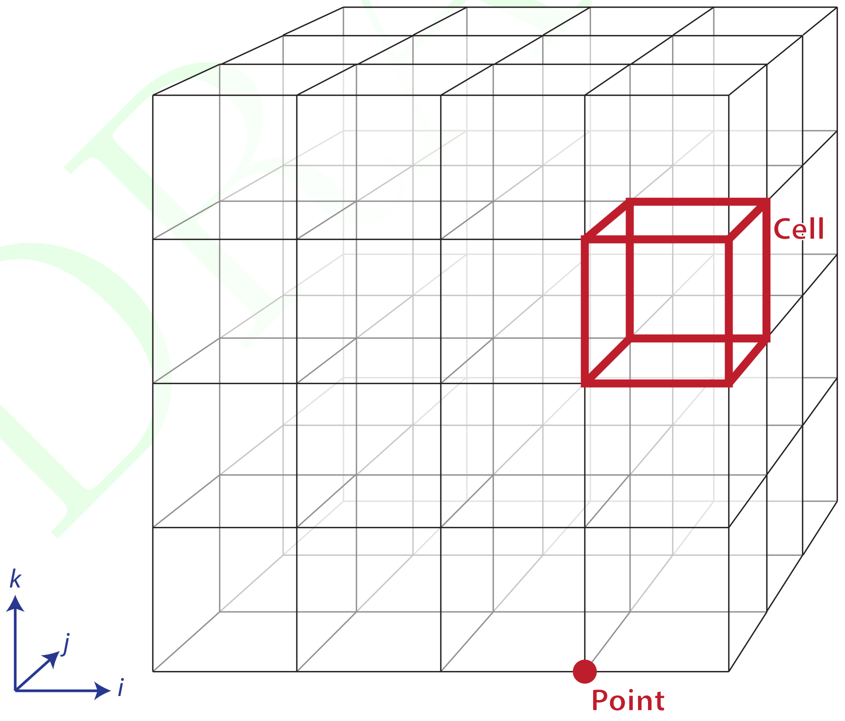


Figure 12.3: The arrangement of points and cells in a 3D structured grid.

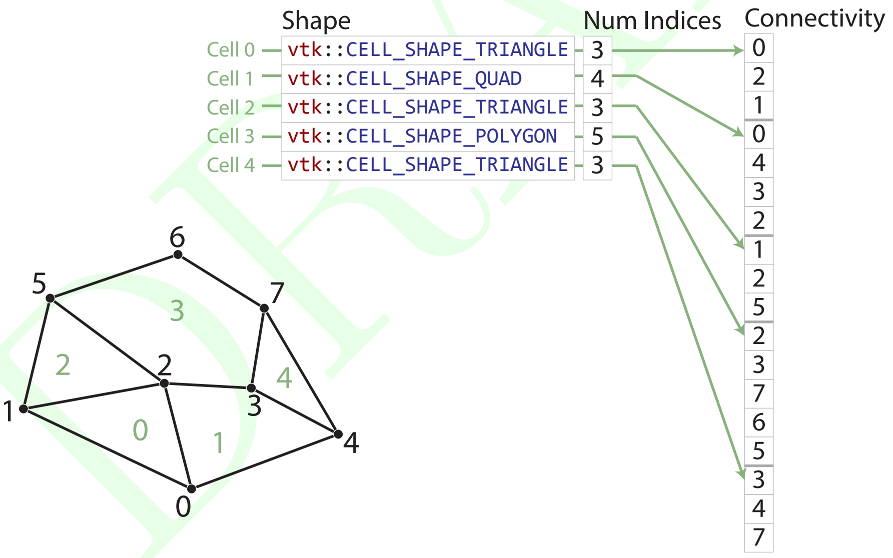
The big advantage of using `vtkm::cont::CellSetStructured` to define a cell set is that it is very space efficient because the entire topology can be defined by the three integers specifying the dimensions. Also algorithms can be optimized for CellSetStructured's regular nature. However, CellSetStructured's strictly regular grid structure also limits its applicability. A structured cell set can only be a dense grid of lines, quadrilaterals, or hexahedra. It cannot represent irregular data well.

Many data models in other software packages, such as the one for VTK, make a distinction between uniform, rectilinear, and curvilinear grids. VTK-m's cell sets do not. All three of these grid types are represented by CellSetStructured. This is because in a VTK-m data set the cell set and the coordinate system are defined independently and used interchangeably. A structured cell set with uniform point coordinates makes a uniform grid. A structured cell set with point coordinates defined irregularly along coordinate axes makes a rectilinear grid. And a structured cell set with arbitrary point coordinates makes a curvilinear grid. The point coordinates are defined by the data set's coordinate system, which is discussed in Section 12.4 starting on page 123.

12.2.2 Explicit Cell Sets

A vtkm::cont::CellSetExplicit defines an irregular collection of cells. The cells can be of different types and connected in arbitrary ways. This is done by explicitly providing for each cell a sequence of points that defines the cell.

An explicit cell set is defined with a minimum of three arrays. The first array identifies the shape of each cell. (Cell shapes are discussed in detail in Section 17.1 starting on page 173.) The second array identifies how many points are in each cell. The third array has a sequence of point indices that make up each cell. Figure 12.4 shows a simple example of an explicit cell set.



Shape
Num Indices
Connectivity
Cell 0 vtk::CELL_SHAPE_TRIANGLE 3
Cell 1 vtk::CELL_SHAPE_QUAD 4
Cell 2 vtk::CELL_SHAPE_TRIANGLE 3
Cell 3 vtk::CELL_SHAPE_POLYGON 5
Cell 4 vtk::CELL_SHAPE_TRIANGLE 3
0 2 1 0 4 3 2 1 2 5 2 3 7 6 5 3 4 7

Figure 12.4: Example of cells in a CellSetExplict and the arrays that define them.

An explicit cell set may also have other topological arrays such as an array of offsets of each cell into the connectivity array or an array of cells incident on each point. Although these arrays can be provided, they are optional and can be internally derived from the shape, num indices, and connectivity arrays.

vtkm::cont::ExplicitCellSet is a powerful representation for a cell set because it can represent an arbitrary collection of cells. However, because all connections must be explicitly defined, ExplicitCellSet requires a significant amount of memory to represent the topology.

An important specialization of an explicit cell set is vtkm::cont::CellSetSingleType. CellSetSingleType is an explicit cell set constrained to contain cells that all have the same shape and all have the same number of points. So for example if you are creating a surface that you know will contain only triangles, CellSetSingleType is a good representation for these data.

Using CellSetSingleType saves memory because the array of cell shapes and the array of point counts no longer need to be stored. CellSetSingleType also allows VTK-m to skip some processing and other storage required for general explicit cell sets.

12.2.3 Cell Set Permutations

A vtkm::cont::CellSetPermutation rearranges the cells of one cell set to create another cell set. This restructuring of cells is not done by copying data to a new structure. Rather, CellSetPermutation establishes a look-up from one cell structure to another. Cells are permuted on the fly while algorithms are run.

A CellSetPermutation is established by providing a mapping array that for every cell index provides the equivalent cell index in the cell set being permuted. CellSetPermutation is most often used to mask out cells in a data set so that algorithms will skip over those cells when running.

Did you know?

Although CellSetPermutation can mask cells, it cannot mask points. All points from the original cell set are available in the permuted cell set regardless of whether they are used.

The following example uses vtkm::cont::CellSetPermutation with a counting array to expose every tenth cell. This provides a simple way to subsample a data set.

Example 12.7: Subsampling a data set with CellSetPermutation.

```
// Create a simple data set.
vtkm::cont::DataSetBuilderUniform dataSetBuilder;
vtkm::cont::DataSet originalDataSet =
    dataSetBuilder.Create(vtkm::Id3(33,33,26));
vtkm::cont::CellSetStructured<3> originalCellSet;
originalDataSet.GetCellSet().CopyTo(originalCellSet);

// Create a permutation array for the cells. Each value in the array refers
// to a cell in the original cell set. This particular array selects every
// 10th cell.
vtkm::cont::ArrayHandleCounting<vtkm::Id> permutationArray(0, 10, 2560);

// Create a permutation of that cell set containing only every 10th cell.
vtkm::cont::CellSetPermutation<
      vtkm::cont::CellSetStructured<3>,
      vtkm::cont::ArrayHandleCounting<vtkm::Id> >
    permutedCellSet(permutationArray, originalCellSet);
```

12.2.4 Dynamic Cell Sets

vtkm::cont::DataSet must hold an arbitrary collection of vtkm::cont::CellSet objects, which it cannot do while knowing their types at compile time. To manage storing CellSets without knowing their types, DataSet actually holds references using vtkm::cont::DynamicCellSet.

DynamicCellSet is similar in nature to DynamicArrayHandle except that it, of course, holds CellSets instead of ArrayHandles. The interface for the two classes is similar, and you should review the documentation for DynamicArrayHandle (in Chapter 11 starting on page 107) to understand DynamicCellSet.

vtkm::cont::DynamicCellSet has a method named GetCellSet that returns a const reference to the held cell set as the abstract CellSet class. This can be used to easily access the virtual methods in the CellSet interface. You can also create a new instance of a cell set with the same type using the NewInstance method.

The DynamicCellSet::IsType() method can be used to determine whether the cell set held in the dynamic cell set is of a given type. If the cell set type is known, DynamicCellSet::CastTo() can be used to safely downcast the cell set object.

When a typed version of the cell set stored in the DynamicCellSet is needed but the type is not known, which happens regularly in the internal workings of VTK-m, the CastAndCall method can be used to make this transition. CastAndCall works by taking a functor and calls it with the appropriately cast cell set object.

The CastAndCall method works by attempting to cast to a known set of types. This set of types used is defined by the macro VTKM_DEFAULT_CELL_SET_LIST_TAG, which is declared in vtkm/cont/CellSetListTag.h. This list can be overridden globally by defining the VTKM_DEFAULT_CELL_SET_LIST_TAG macro *before* any VTK-m headers are included.

The set of types used in a CastAndCall can also be changed only for a particular instance of a dynamic cell set by calling its ResetCellSetList. This method takes a list of cell types and returns a new dynamic array handle of a slightly different type that will use this new list of cells for dynamic casting.

12.2.5 Blocks and Assemblies

Rather than just one cell set, a vtkm::cont::DataSet can hold multiple cell sets. This can be used to construct multiblock data structures or assemblies of parts. Multiple cell sets can also be used to represent subsets of the data with particular properties such as all cells filled with a material of a certain type. Or these multiple cells might represent particular features in the data, such as the set of faces representing a boundary in the simulation.

12.2.6 Zero Cell Sets

It is also possible to construct a vtkm::cont::DataSet that contains no cell set objects whatsoever. This can be used to manage data that does not contain any topological structure. For example, a collection of series that come from columns in a table could be stored as multiple fields in a data set with no cell set.

12.3 Fields

A field on a data set provides a value on every point in space on the mesh. Fields are often used to describe physical properties such as pressure, temperature, mass, velocity, and much more. Fields are represented in a VTK-m data set as an array where each value is associated with a particular element type of a mesh (such as points or cells). This association of field values to mesh elements and the structure of the cell set determines how the field is interpolated throughout the space of the mesh.

Fields are manged by the vtkm::cont::Field class. Field holds its data with a DynamicArrayHandle, which itself is a container for an ArrayHandle. Field also maintains the association and, optionally, the name of a cell set for which the field is valid.

The data array can be retrieved as a DynamicArrayHandle using the GetData method of Field. Field also has a convenience method named GetBounds that finds the range of values stored in the field array.

12.4 Coordinate Systems

A coordinate system determines the location of a mesh's elements in space. The spatial location is described by providing a 3D vector at each point that gives the coordinates there. The point coordinates can then be interpolated throughout the mesh.

Coordinate systems are managed by the `vtkm::cont::CoordinateSystem` class. In actuality, a coordinate system is just a field with a special meaning, and so the `CoordinateSystem` class inherits from the `Field` class. `CoordinateSystem` constrains the field to be associated with points and typically has 3D floating point vectors for values.

It is typical for a `DataSet` to have one coordinate system defined, but it is possible to define multiple coordinate systems. This is helpful when there are multiple ways to express coordinates. For example, positions in geographic may be expressed as Cartesian coordinates or as latitude-longitude coordinates. Both are valid and useful in different ways.

It is also valid to have a `DataSet` with no coordinate system. This is useful when the structure is not rooted in physical space. For example, if the cell set is representing a graph structure, there might not be any physical space that has meaning for the graph.

CHAPTER

THIRTEEN

FILTER POLICES

In Chapter 4 we explored the set of filter classes in VTK-m, which provide a convenient interface for running the algorithms that come with VTK-m. That chapter describes methods like `Execute` and `MapFieldOntoOutput`, which take data process it in parallel. What is not described in Chapter 4 is how the filter chooses data types and what computing device (e.g. CPU or GPU) to use.

These decisions are determined by *policies*. A policy defines the behavior of how a filter interprets dynamic data and what devices it should use. The methods previously described in 4 implicitly use a default policy that tries the most common types and a group of basic devices. However, each of these methods have an alternate form that allows you to specify a customized policy. In this chapter we describe policies and demonstrate how to create and use your own policies.

13.1 Default Policy

The default policy is specified by the `vtkm::filter::DefaultPolicy` class, which is defined in the vtkm/filter/-DefaultPolicy.h header file. The default policy can be used any place a standard policy is used, although generally this is unnecessary as the default policy is used automatically if no policy is specified.

Did you know?

The `vtkm::filter::DefaultPolicy` class makes for a good reference on what a policy contains and how to construct a new policy. The contents of the default policy can also be used when creating new policies where only some of the properties need be different (as is done in the examples here).

[It would be nice if you could create a new policy that inherited all of the default policies rather than require you to define every one. If that were implemented, then the description above would change as would pretty much all the examples here.]

13.2 Policy Contents

A policy is a traits-like object that contains the following typedefs. [Most of?] These typedefs are list tag objects. List tags are described in Section 6.6.

FieldTypeList A type list tag containing a list of all possible types of values in field arrays used as input to the filter. The default policy sets this to VTKM_DEFAULT_TYPE_LIST_TAG, which corresponds to vtkm::Int32, vtkm::Int64, vtkm::Float32, vtkm::Float64, vtkm::Vec<vtkm::Float32,3>, and vtkm::Vec<vtkm::Float64,3>.

FieldStorageList A type list tag containing a list of all possible storage types for field arrays used as input to the filter. The default policy sets this to VTKM_DEFAULT_STORAGE_LIST_TAG, which corresponds to a list containing only vtkm::cont::StorageTagBasic (the default storage for vtkm::cont::ArrayHandle objects).

CoordinateTypeList A type list tag containing a list of all possible types of values in field arrays used as input to the filter when the field array comes from the coordinates of the data set. The default policy sets this to VTKM_DEFAULT_COORDINATE_SYSTEM_TYPE_LIST_TAG, which corresponds to vtkm::Vec<vtkm::Float32,3> and vtkm::Vec<vtkm::Float64,3>.

CoordinateStorageList A type list tag containing a list of all possible storage types for field arrays used as input to the filter when the field array comes from the coordinates of the data set. The default policy sets this to VTKM_DEFAULT_COORDINATE_SYSTEM_STORAGE_LIST_TAG, which corresponds to a list containing the basic ArrayHandle storage as well as structures for vtkm::cont::ArrayHandleUniformPointCoordinates, vtkm::cont::ArrayHandleCompositeVector, and vtkm::cont::ArrayHandleCartesianProduct.

StructuredCellSetList A type list tag containing a list of all possible cell sets classes used when representing structured cell sets. The default policy sets this to vtkm::cont::CellSetListTagStructured, which corresponds to a list containing vtkm::cont::CellSetStructured<2> and vtkm::cont::CellSetStructured<3>.

UnstructuredCellSetList A type list tag containing a list of all possible cell set classes used when representing unstructured cell sets. The default policy sets this to vtkm::cont::CellSetListTagUnstructured, which corresponds to a list containing vtkm::cont::CellSetExplicit and vtkm::cont::CellSetSingleType.

AllCellSetList A type list tag containing a list of all possible cell set classes. This is usually a union of StructuredCellSetList and UnstructuredCellSetList. The default policy sets this to VTKM_DEFAULT_CELL_SET_LIST_TAG, which corresponds to a list containing vtkm::cont::CellSetStructured<2>, vtkm::cont::CellSetStructured<3>, vtkm::cont::CellSetExplicit, and vtkm::cont::CellSetSingleType

DeviceAdapterList A type list tag containing a list of device adapter tags for the devices to try to run the algorithm on. The devices are tried in the order they are listed in DeviceAdapterList, so the "best" devices should be listed first. The default policy sets this to VTKM_DEFAULT_DEVICE_ADAPTER_LIST_TAG, which corresponds to a list containing vtkm::cont::DeviceAdapterTagCuda, vtkm::cont::DeviceAdapterTagTBB, and vtkm::cont::DeviceAdapterTagSerial.

Common Errors

Just because a device is listed in DeviceAdapterList *there is no guarantee that such a device will ever be used. For example, if the Cuda device is listed (as in the default) but the filter is not compiled by the Cuda compiler, then that device will always be skipped.*

13.3 Creating Policies

Creating a policy is as simple as creating a subclass of `vtkm::filter::PolicyBase` that provides typedefs for each of the expected policy information types. `PolicyBase` is a templated class that takes as its single template parameter the type of the subclass. For example, a policy object named `PolicyFoo` will subclass `PolicyBase<PolicyFoo>`.

Did you know?

The convention of having a subclass be templated on the derived class' type is known as the Curiously Recurring Template Pattern (CRTP). In the case of policies, VTK-m uses this CRTP behavior to allow methods to have templates that accept any policy type but nothing that is not a policy.

After inheriting from `PolicyBase`, the custom policy class adds definitions for the type names listed in Section 13.2. The following examples show type typical structure for some common instances of policies. Although these custom policies are separated by use case, there is no real restriction on combining them.

[The VTK-m source is moving from using `typedef` to `using =`. Perhaps we should go through and change all of the examples.]

[Maybe I will hold off on implementing this. If the virtual method branch gets accepted, then the policies will change significantly.]

Part III

Developing with VTK-m

CHAPTER

FOURTEEN

WORKLETS

The simplest way to implement an algorithm in VTK-m is to create a *worklet*. A worklet is fundamentally a functor that operates on an element of data. Thus, it is a `class` or `struct` that has an overloaded parenthesis operator (which must be declared `const` for thread safety). However, worklets are also embedded with a significant amount of metadata on how the data should be managed and how the execution should be structured. This chapter explains the basic mechanics of defining and using worklets.

14.1 Worklet Types

Different operations in visualization can have different data access patterns, perform different execution flow, and require different provisions. VTK-m manages these different accesses, execution, and provisions by grouping visualization algorithms into common classes of operation and supporting each class with its own worklet type.

Each worklet type has a generic superclass that worklets of that particular type must inherit. This makes the type of the worklet easy to identify. The following list describes each worklet type provided by VTK-m and the superclass that supports it. Details on how to create worklets of each type are given in Section 14.5. It is also possible to create new worklet types in VTK-m. This is an advanced topic covered in Chapter 20.

Field Map A worklet deriving `vtkm::worklet::WorkletMapField` performs a basic mapping operation that applies a function (the operator in the worklet) on all the field values at a single point or cell and creates a new field value at that same location. Although the intention is to operate on some variable over a mesh, a `WorkletMapField` may actually be applied to any array. Thus, a field map can be used as a basic map operation.

Topology Map A worklet deriving `vtkm::worklet::WorkletMapTopology` or one of its sibling classes performs a mapping operation that applies a function (the operator in the worklet) on all elements of a particular type (such as points or cells) and creates a new field for those elements. The basic operation is similar to a field map except that in addition to access fields being mapped on, the worklet operation also has access to incident fields.

There are multiple convenience classes available for the most common types of topology mapping. `vtkm::worklet::WorkletMapPointToCell` calls the worklet operation for each cell and makes every incident point available. This type of map also has access to cell structures and can interpolate point fields.

14.2 Dispatchers

Worklets, both those provided by VTK-m as listed in Section 14.3 and ones created by a user as described in Section 14.4, are instantiated in the control environment and run in the execution environment. This means that the control environment must have a means to *invoke* worklets that start running in the execution environment.

This invocation is done through a set of *dispatcher* objects. A dispatcher object is an object in the control environment that has an instance of a worklet and can invoke that worklet with a set of arguments. There are multiple types of dispatcher objects, each corresponding to a type of worklet object. All dispatcher objects have at least two template parameters: the worklet class being invoked, which is always the first argument, and the device adapter tag, which is always the last argument and will be set to the default device adapter if not specified.

All dispatcher classes have a method named `Invoke` that launches the worklet in the execution environment. The arguments to `Invoke` must match those expected by the worklet, which is specified by something called a *control signature*. The expected arguments for worklets provided by VTK-m are documented in Section 14.3. Also, for any worklet, the `Invoke` arguments can be gleaned from the control signature, which is described in Section 14.4.1.

The following is a list of the dispatchers defined in VTK-m. The dispatcher classes correspond to the list of worklet types specified in Section 14.1. Many examples of using these dispatchers are provided in Section 14.3.

`vtkm::worklet::DispatcherMapField` The dispatcher used in conjunction with a worklet that subclasses `vtkm::worklet::WorkletMapField`. The dispatcher class has two template arguments: the worklet type and the device adapter (optional).

`vtkm::worklet::DispatcherMapTopology` The dispatcher used in conjunction with a worklet that subclasses `vtkm::worklet::WorkletMapTopology` or one of its sibling classes (such as `vtkm::worklet::WorkletMapPointToCell`). The dispatcher class has two template arguments: the worklet type and the device adapter (optional).

14.3 Provided Worklets

VTK-m comes with several worklet implementations. These worklet implementations for the most part provide the underlying implementations of the filters described in Chapter 4. The easiest way to execute a filter is to run it from the associated filter class. However, if your data is not in a `vtkm::cont::DataSet` structure or you have knowledge of the specific data types used in the `DataSet`, it might be more efficient to run the worklet directly. Note that many of the filters use multiple worklets under the covers to implement the full functionality.

The following example demonstrates using the simple `vtkm::worklet::PointElevation` worklet directly.

Example 14.1: Using the provided `PointElevation` worklet.

```
VTKM_CONT
vtkm::cont::ArrayHandle<vtkm::FloatDefault>
ComputeAirPressure(
    vtkm::cont::ArrayHandle<vtkm::Vec<vtkm::FloatDefault,3> > pointCoordinates)
{
  vtkm::worklet::PointElevation elevationWorklet;

  // Use the elevation worklet to estimate atmospheric pressure based on the
  // height of the point coordinates. Atmospheric pressure is 101325 Pa at
  // sea level and drops about 12 Pa per meter.
  elevationWorklet.SetLowPoint(vtkm::Vec<vtkm::Float64,3>(0.0, 0.0, 0.0));
  elevationWorklet.SetHighPoint(vtkm::Vec<vtkm::Float64,3>(0.0, 0.0, 2000.0));
  elevationWorklet.SetRange(101325.0, 77325.0);

  vtkm::worklet::DispatcherMapField<vtkm::worklet::PointElevation>
      elevationDispatcher(elevationWorklet);

  vtkm::cont::ArrayHandle<vtkm::FloatDefault> pressure;

  elevationDispatcher.Invoke(pointCoordinates, pressure);

  return pressure;
}
```

14.4 Creating Worklets

A worklet is created by implementing a `class` or `struct` with the following features.

1. The class must contain a `ControlSignature` `typedef`, which specifies what arguments are expected when invoking the class with a dispatcher in the control environment.
2. The class must contain an `ExecutionSignature` `typedef`, which specifies how the data gets passed from the arguments in the control environment to the worklet running in the execution environment.
3. The class must contain an `InputDomain` `typedef`, which identifies which input parameter defines the input domain of the data.
4. The class may define a scatter operation to override a 1:1 mapping from input to output.
5. The class must contain an overload of the parenthesis operator, which is the method that is executed in the execution environment.
6. The class must publicly inherit from a base worklet class that specifies the type of operation being performed.

Figure 14.1 demonstrates all of the required components of a worklet.

14.4.1 Control Signature

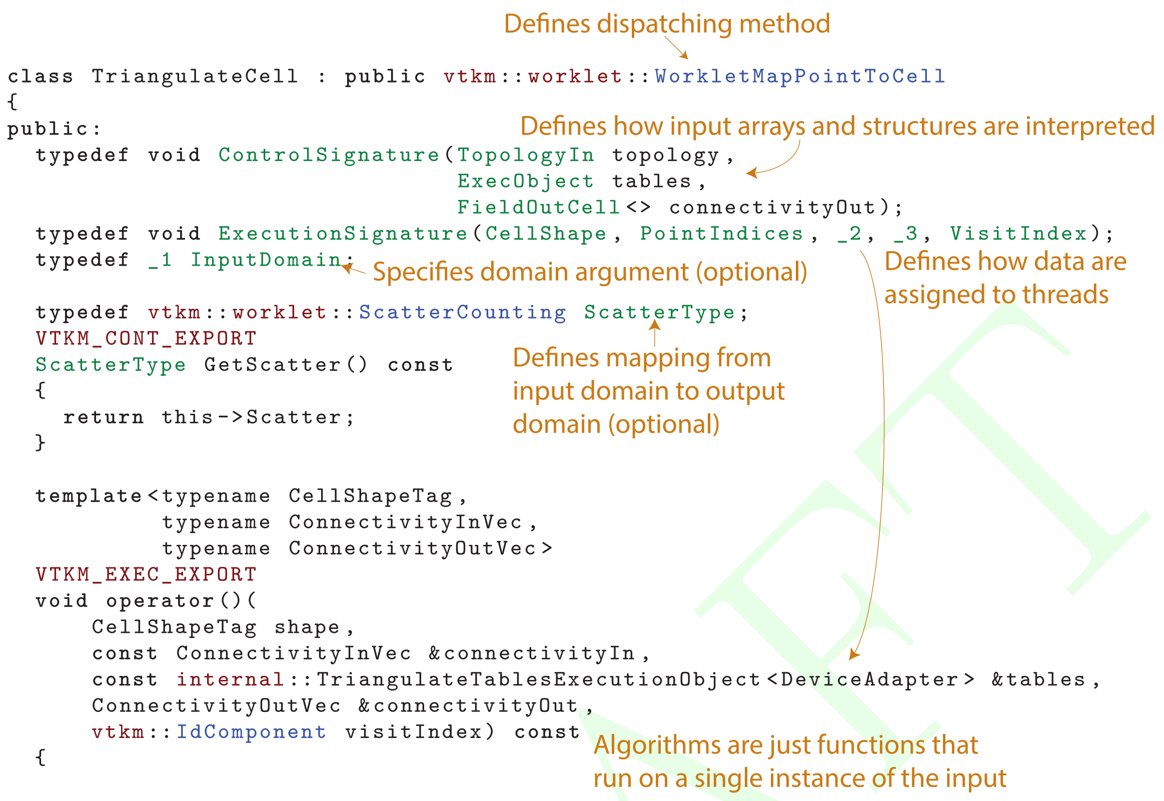
The control signature of a worklet is the `typedef` of a function prototype named `ControlSignature`. The function prototype matches the calling specification used with the dispatcher `Invoke` function.

Example 14.2: A `ControlSignature`.

```
  typedef void ControlSignature(FieldIn<VecAll> inputVectors,
                                FieldOut<Scalar> outputMagnitudes);
```

The return type of the function prototype is always `void` because the dispatcher `Invoke` functions do not return values. The parameters of the function prototype are *tags* that identify the type of data that is expected to be passed to invoke. `ControlSignature` tags are defined by the worklet type and the various tags are documented more fully in Section 14.5.

By convention, `ControlSignature` tag names start with the base concept (e.g. `Field` or `Topology`) followed by the domain (e.g. `Point` or `Cell`) followed by `In` or `Out`. For example, `FieldPointIn` would specify values for a field on the points of a mesh that are used as input (read only). Although they should be there in most cases, some tag names might leave out the domain or in/out parts if they are obvious or ambiguous.


Defines dispatching method
Defines how input arrays and structures are interpreted
Specifies domain argument (optional)
Defines how data are assigned to threads
Defines mapping from input domain to output domain (optional)
Algorithms are just functions that run on a single instance of the input

```
class TriangulateCell : public vtkm::worklet::WorkletMapPointToCell
{
public:
  typedef void ControlSignature(TopologyIn topology,
                                ExecObject tables,
                                FieldOutCell<> connectivityOut);
  typedef void ExecutionSignature(CellShape, PointIndices, _2, _3, VisitIndex);
  typedef _1 InputDomain;

  typedef vtkm::worklet::ScatterCounting ScatterType;
  VTKM_CONT_EXPORT
  ScatterType GetScatter() const
  {
    return this->Scatter;
  }

  template<typename CellShapeTag,
           typename ConnectivityInVec,
           typename ConnectivityOutVec>
  VTKM_EXEC_EXPORT
  void operator()(
      CellShapeTag shape,
      const ConnectivityInVec &connectivityIn,
      const internal::TriangulateTablesExecutionObject<DeviceAdapter> &tables,
      ConnectivityOutVec &connectivityOut,
      vtkm::IdComponent visitIndex) const
  {
```

Figure 14.1: Annotated example of a worklet declaration.

Type List Tags

Some tags are templated to have modifiers. For example, `Field` tags have a template argument that is set to a type list tag defining what types of field data are supported. (See Section 6.6.2 for a description of type lists.) In fact, this type list modifier is so common that the following convenience subtags used with `Field` tags are defined for all worklet types.

Did you know?

Any type list will work as modifiers for `ControlSignature` tags. However, these common type lists are provided for convenience and to make the `ControlSignature` shorter and more readable.

`AllTypes` All possible types.

`CommonTypes` The most used types in visualization. This includes signed integers and floats that are 32 or 64 bit. It also includes 3 dimensional vectors of floats. The same as `vtkm::TypeListTagCommon`.

`IdType` Contains the single item `vtkm::Id`. The same as `vtkm::TypeListTagId`.

`Id2Type` Contains the single item `vtkm::Id2`. The same as `vtkm::TypeListTagId2`.

`Id3Type` Contains the single item `vtkm::Id3`. The same as `vtkm::TypeListTagId3`.

Index All types used to index arrays. Contains vtkm::Id, vtkm::Id2, and vtkm::Id3. The same as vtkm::-TypeListTagIndex.

FieldCommon A list containing all the types generally used for fields. It is the combination of Scalar, Vec2, Vec3, and Vec4. The same as vtkm::TypeListTagField.

Scalar Types used for scalar fields. Specifically, it contains floating point numbers of different widths (i.e. vtkm::Float32 and vtkm::Float64). The same as vtkm::TypeListTagFieldScalar.

ScalarAll All scalar types. It contains signed and unsigned integers of widths from 8 to 64 bits. It also contains floats of 32 and 64 bit widths. The same as vtkm::TypeListTagScalarAll.

Vec2 Types for values of fields with 2 dimensional vectors. All these vectors use floating point numbers. The same as vtkm::TypeListTagFieldVec2.

Vec3 Types for values of fields with 3 dimensional vectors. All these vectors use floating point numbers. The same as vtkm::TypeListTagFieldVec3.

Vec4 Types for values of fields with 4 dimensional vectors. All these vectors use floating point numbers. The same as vtkm::TypeListTagFieldVec4.

VecAll All vtkm::Vec classes with standard integers or floating points as components and lengths between 2 and 4. The same as vtkm::TypeListTagVecAll.

VecCommon The most common vector types. It contains all vtkm::Vec class of size 2 through 4 containing components of unsigned bytes, signed 32-bit integers, signed 64-bit integers, 32-bit floats, or 64-bit floats. The same as vtkm::TypeListTagVecCommon.

14.4.2 Execution Signature

Like the control signature, the execution signature of a worklet is the typedef of a function prototype named ExecutionSignature. The function prototype must match the parenthesis operator (described in Section 14.4.4) in terms of arity and argument semantics.

Example 14.3: An ExecutionSignature.

```
  typedef _2 ExecutionSignature(_1);
```

The arguments of the ExecutionSignature's function prototype are tags that define where the data come from. The most common tags are an underscore followed by a number, such as _1, _2, etc. These numbers refer back to the corresponding argument in the ControlSignature. For example, _1 means data from the first control signature argument, _2 means data from the second control signature argument, etc.

Unlike the control signature, the execution signature optionally can declare a return type if the parenthesis operator returns a value. If this is the case, the return value should be one of the numeric tags (i.e. _1, _2, etc.) to refer to one of the data structures of the control signature. If the parenthesis operator does not return a value, then ExecutionSignature should declare the return type as void.

In addition to the numeric tags, there are other execution signature tags to represent other types of data. For example, the WorkIndex tag identifies the instance of the worklet invocation. Each call to the worklet function will have a unique WorkIndex. Other such tags exist and are described in the following section on worklet types where appropriate.

14.4.3 Input Domain

All worklets represent data parallel operations that are executed over independent elements in some domain. The type of domain is inherent from the worklet type, but the size of the domain is dependent on the data being operated on. One of the arguments given to the dispatcher's `Invoke` in the control environment must specify the domain.

A worklet identifies the argument specifying the domain with a `typedef` named `InputDomain`. The `InputDomain` must be `typedef`ed to one of the execution signature numeric tags (i.e. `_1`, `_2`, etc.). By default, the `InputDomain` points to the first argument, but a worklet can override that to point to any argument.

Example 14.4: An `InputDomain` declaration.

```
typedef _1 InputDomain;
```

Different types of worklets can have different types of domain. For example a simple field map worklet has a `FieldIn` argument as its input domain, and the size of the input domain is taken from the size of the associated field array. Likewise, a worklet that maps topology has a `CellSetIn` argument as its input domain, and the size of the input domain is taken from the cell set.

Specifying the `InputDomain` is optional. If it is not specified, the first argument is assumed to be the input domain.

14.4.4 Worklet Operator

A worklet is fundamentally a functor that operates on an element of data. Thus, the algorithm that the worklet represents is contained in or called from the parenthesis operator method.

Example 14.5: An overloaded parenthesis operator of a worklet.

```
template<typename T, vtkm::IdComponent Size>
VTKM_EXEC
T operator()(const vtkm::Vec<T,Size> &inVector) const
{
```

There are some constraints on the parenthesis operator. First, it must have the same arity as the `ExecutionSignature`, and the types of the parameters and return must be compatible. Second, because it runs in the execution environment, it must be declared with the `VTKM_EXEC` (or `VTKM_EXEC_CONT`) modifier. Third, the method must be declared `const` to help preserve thread safety.

14.5 Worklet Type Reference

There are multiple worklet types provided by VTK-m, each designed to support a particular type of operation. Section 14.1 gave a brief overview of each type of worklet. This section gives a much more detailed reference for each of the worklet types including identifying the generic superclass that a worklet instance should derive, listing the signature tags and their meanings, and giving an example of the worklet in use.

14.5.1 Field Map

A worklet deriving `vtkm::worklet::WorkletMapField` performs a basic mapping operation that applies a function (the operator in the worklet) on all the field values at a single point or cell and creates a new field value at that same location. Although the intention is to operate on some variable over the mesh, a `WorkletMapField` can actually be applied to any array.

A WorkletMapField subclass is invoked with a vtkm::worklet::DispatcherMapField. This dispatcher has two template arguments. The first argument is the type of the worklet subclass. The second argument, which is optional, is a device adapter tag.

A field map worklet supports the following tags in the parameters of its ControlSignature.

FieldIn This tag represents an input field. A FieldIn argument expects an ArrayHandle or a DynamicArrayHandle in the associated parameter of the dispatcher's Invoke. Each invocation of the worklet gets a single value out of this array.

FieldIn has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

The worklet's InputDomain can be set to a FieldIn argument. In this case, the input domain will be the size of the array.

FieldOut This tag represents an output field. A FieldOut argument expects an ArrayHandle or a DynamicArrayHandle in the associated parameter of the dispatcher's Invoke. The array is resized before scheduling begins, and each invocation of the worklet sets a single value in the array.

FieldOut has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

FieldInOut This tag represents field that is both an input and an output. A FieldInOut argument expects an ArrayHandle or a DynamicArrayHandle in the associated parameter of the dispatcher's Invoke. Each invocation of the worklet gets a single value out of this array, which is replaced by the resulting value after the worklet completes.

FieldInOut has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

The worklet's InputDomain can be set to a FieldInOut argument. In this case, the input domain will be the size of the array.

WholeArrayIn This tag represents an array where all entries can be read by every worklet invocation. A WholeArrayIn argument expects an ArrayHandle in the associated parameter of the dispatcher's Invoke. An array portal capable of reading from any place in the array is given to the worklet. Whole arrays are discussed in detail in Section 14.6 starting on page 149.

WholeArrayIn has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

WholeArrayOut This tag represents an array where any entry can be written by any worklet invocation. A WholeArrayOut argument expects an ArrayHandle in the associated parameter of the dispatcher's Invoke. An array portal capable of writing to any place in the array is given to the worklet. Developers should take care when using writable whole arrays as introducing race conditions is possible. Whole arrays are discussed in detail in Section 14.6 starting on page 149.

WholeArrayOut has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

WholeArrayInOut This tag represents an array where any entry can be read or written by any worklet invocation. A WholeArrayInOut argument expects an ArrayHandle in the associated parameter of the dispatcher's Invoke. An array portal capable of reading from or writing to any place in the array is given to the worklet. Developers should take care when using writable whole arrays as introducing race conditions is possible. Whole arrays are discussed in detail in Section 14.6 starting on page 149.

WholeArrayInOut has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

ExecObject This tag represents an execution object that is passed directly from the control environment to the worklet. A ExecObject argument expects a subclass of vtkm::exec::ExecutionObjectBase, and this same object is given to the worklet. Execution objects are discussed in detail in Section 14.7 starting on page 151.

A field map worklet supports the following tags in the parameters of its ExecutionSignature.

_1, _2,... These reference the corresponding parameter in the ControlSignature.

WorkIndex This tag produces a vtkm::Id that uniquely identifies the invocation of the worklet.

VisitIndex This tag produces a vtkm::IdComponent that uniquely identifies when multiple worklet invocations operate on the same input item, which can happen when defining a worklet with scatter (as described in Section 14.8).

Field maps most commonly perform basic calculator arithmetic, as demonstrated in the following example.

Example 14.6: Implementation and use of a field map worklet.

```
#include <vtkm/worklet/DispatcherMapField.h>
#include <vtkm/worklet/WorkletMapField.h>

#include <vtkm/cont/ArrayHandle.h>
#include <vtkm/cont/DynamicArrayHandle.h>

#include <vtkm/VectorAnalysis.h>

namespace vtkm {
namespace worklet {

class Magnitude : public vtkm::worklet::WorkletMapField
{
public:
  typedef void ControlSignature(FieldIn<VecAll> inputVectors,
                                FieldOut<Scalar> outputMagnitudes);
  typedef _2 ExecutionSignature(_1);

  typedef _1 InputDomain;

  template<typename T, vtkm::IdComponent Size>
  VTKM_EXEC
  T operator()(const vtkm::Vec<T,Size> &inVector) const
  {
    return vtkm::Magnitude(inVector);
  }
};

}
} // namespace vtkm::worklet

VTKM_CONT
vtkm::cont::DynamicArrayHandle
InvokeMagnitude(vtkm::cont::DynamicArrayHandle input)
{
  vtkm::cont::ArrayHandle<vtkm::FloatDefault> output;

  vtkm::worklet::DispatcherMapField<vtkm::worklet::Magnitude> dispatcher;
  dispatcher.Invoke(input, output);

  return vtkm::cont::DynamicArrayHandle(output);
}
```

Although simple, the WorkletMapField worklet type can be used (and abused) as a general parallel-for/scheduling mechanism. In particular, the WorkIndex execution signature tag can be used to get a unique index, the WholeArray* tags can be used to get random access to arrays, and the ExecObject control signature tag can be used to pass execution objects directly to the worklet. Whole arrays and execution objects are talked about in more detail in Sections 14.6 and 14.7, respectively, in more detail, but here is a simple example that uses the random access of WholeArrayOut to make a worklet that copies an array in reverse order.

Example 14.7: Leveraging field maps and field maps for general processing.
```
namespace vtkm {
namespace worklet {

struct ReverseArrayCopy : vtkm::worklet::WorkletMapField
{
  typedef void ControlSignature(FieldIn<> inputArray,
                                WholeArrayOut<> outputArray);
  typedef void ExecutionSignature(_1, _2, WorkIndex);
  typedef _1 InputDomain;

  template<typename InputType, typename OutputArrayPortalType>
  VTKM_EXEC
  void operator()(const InputType &inputValue,
                  const OutputArrayPortalType &outputArrayPortal,
                  vtkm::Id workIndex) const
  {
    vtkm::Id outIndex = outputArrayPortal.GetNumberOfValues() - workIndex - 1;
    if (outIndex >= 0)
    {
      outputArrayPortal.Set(outIndex, inputValue);
    }
    else
    {
      this->RaiseError("Output array not sized correctly.");
    }
  }
};

}
} // namespace vtkm::worklet

template<typename T, typename Storage>
VTKM_CONT
vtkm::cont::ArrayHandle<T>
InvokeReverseArrayCopy(const vtkm::cont::ArrayHandle<T,Storage> &inArray)
{
  vtkm::cont::ArrayHandle<T> outArray;
  outArray.Allocate(inArray.GetNumberOfValues());

  vtkm::worklet::DispatcherMapField<vtkm::worklet::ReverseArrayCopy> dispatcher;
  dispatcher.Invoke(inArray, outArray);

  return outArray;
}
```

14.5.2 Topology Map

A topology map performs a mapping that it applies a function (the operator in the worklet) on all the elements of a DataSet of a particular type (i.e. point, edge, face, or cell). While operating on the element, the worklet has access to data from all incident elements of another type.

There are several versions of topology maps that differ in what type of element being mapped from and what type of element being mapped to. The subsequent sections describe these different variations of the topology maps. Regardless of their names, they are all defined in vtkm/worklet/WorkletMapTopology.h and are all invoked with `vtkm::worklet::DispatcherMapTopology`.

Point to Cell Map

A worklet deriving `vtkm::worklet::WorkletMapPointToCell` performs a mapping operation that applies a function (the operator in the worklet) on all the cells of a `DataSet`. While operating on the cell, the worklet has access to fields associated both with the cell and with all incident points. Additionally, the worklet can get information about the structure of the cell and can perform operations like interpolation on it.

A `WorkletMapPointToCell` subclass is invoked with a `vtkm::worklet::DispatcherMapTopology`. This dispatcher has two template arguments. The first argument is the type of the worklet subclass. The second argument, which is optional, is a device adapter tag.

A point to cell map worklet supports the following tags in the parameters of its `ControlSignature`.

`CellSetIn` This tag represents the cell set that defines the collection of cells the map will operate on. A `CellSetIn` argument expects a `CellSet` subclass or a `DynamicCellSet` in the associated parameter of the dispatcher's `Invoke`. Each invocation of the worklet gets a cell shape tag. (Cell shapes and the operations you can do with cells are discussed in Chapter 17.)

There must be exactly one `CellSetIn` argument, and the worklet's `InputDomain` must be set to this argument.

`FieldInPoint` This tag represents an input field that is associated with the points. A `FieldInPoint` argument expects an `ArrayHandle` or a `DynamicArrayHandle` in the associated parameter of the dispatcher's `Invoke`. The size of the array must be exactly the number of points.

Each invocation of the worklet gets a Vec-like object containing the field values for all the points incident with the cell being visited. The order of the entries is consistent with the defined order of the vertices for the visited cell's shape. If the field is a vector field, then the provided object is a Vec of Vecs.

`FieldInPoint` has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

`FieldInCell` This tag represents an input field that is associated with the cells. A `FieldInCell` argument expects an `ArrayHandle` or a `DynamicArrayHandle` in the associated parameter of the dispatcher's `Invoke`. The size of the array must be exactly the number of cells. Each invocation of the worklet gets a single value out of this array.

`FieldInCell` has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

`FieldOutCell` This tag represents an output field, which is necessarily associated with cells. A `FieldOut-Cell` argument expects an `ArrayHandle` or a `DynamicArrayHandle` in the associated parameter of the dispatcher's `Invoke`. The array is resized before scheduling begins, and each invocation of the worklet sets a single value in the array.

`FieldOutCell` has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

`FieldOut` is an alias for `FieldOutCell` (since output arrays can only be defined on cells).

`FieldInOutCell` This tag represents field that is both an input and an output, which is necessarily associated with cells. A `FieldInOutCell` argument expects an `ArrayHandle` or a `DynamicArrayHandle` in the associated parameter of the dispatcher's `Invoke`. Each invocation of the worklet gets a single value out of this array, which is replaced by the resulting value after the worklet completes.

FieldInOutCell has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

FieldInOut is an alias for FieldInOutCell (since output arrays can only be defined on cells).

WholeArrayIn This tag represents an array where all entries can be read by every worklet invocation. A WholeArrayIn argument expects an ArrayHandle in the associated parameter of the dispatcher's Invoke. An array portal capable of reading from any place in the array is given to the worklet. Whole arrays are discussed in detail in Section 14.6 starting on page 149.

WholeArrayIn has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

WholeArrayOut This tag represents an array where any entry can be written by any worklet invocation. A WholeArrayOut argument expects an ArrayHandle in the associated parameter of the dispatcher's Invoke. An array portal capable of writing to any place in the array is given to the worklet. Developers should take care when using writable whole arrays as introducing race conditions is possible. Whole arrays are discussed in detail in Section 14.6 starting on page 149.

WholeArrayOut has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

WholeArrayInOut This tag represents an array where any entry can be read or written by any worklet invocation. A WholeArrayInOut argument expects an ArrayHandle in the associated parameter of the dispatcher's Invoke. An array portal capable of reading from or writing to any place in the array is given to the worklet. Developers should take care when using writable whole arrays as introducing race conditions is possible. Whole arrays are discussed in detail in Section 14.6 starting on page 149.

WholeArrayInOut has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

ExecObject This tag represents an execution object that is passed directly from the control environment to the worklet. A ExecObject argument expects a subclass of vtkm::exec::ExecutionObjectBase, and this same object is given to the worklet. Execution objects are discussed in detail in Section 14.7 starting on page 151.

A field map worklet supports the following tags in the parameters of its ExecutionSignature.

_1, _2,... These reference the corresponding parameter in the ControlSignature.

CellShape This tag produces a shape tag corresponding to the shape of the visited cell. (Cell shapes and the operations you can do with cells are discussed in Chapter 17.) This is the same value that gets provided if you reference the CellSetIn parameter.

PointCount This tag produces a vtkm::IdComponent equal to the number of points incident on the cell being visited. The Vecs provided from a FieldInPoint parameter will be the same size as PointCount.

PointIndices This tag produces a Vec-like object of vtkm::Ids giving the indices for all incident points. Like values from a FieldInPoint parameter, the order of the entries is consistent with the defined order of the vertices for the visited cell's shape.

WorkIndex This tag produces a vtkm::Id that uniquely identifies the invocation of the worklet.

VisitIndex This tag produces a vtkm::IdComponent that uniquely identifies when multiple worklet invocations operate on the same input item, which can happen when defining a worklet with scatter (as described in Section 14.8).

Point to cell field maps are a powerful construct that allow you to interpolate point fields throughout the space of the data set. The following example provides a simple demonstration that finds the geometric center of each cell by interpolating the point coordinates to the cell centers.

Example 14.8: Implementation and use of a map point to cell worklet.

```
#include <vtkm/worklet/DispatcherMapTopology.h>
#include <vtkm/worklet/WorkletMapTopology.h>

#include <vtkm/cont/DataSet.h>
#include <vtkm/cont/DataSetFieldAdd.h>

#include <vtkm/exec/CellInterpolate.h>
#include <vtkm/exec/ParametricCoordinates.h>

namespace vtkm {
namespace worklet {

class CellCenter : public vtkm::worklet::WorkletMapPointToCell
{
public:
  typedef void ControlSignature(CellSetIn cellSet,
                                FieldInPoint<> inputPointField,
                                FieldOut<> outputCellField);
  typedef _3 ExecutionSignature(_1, PointCount, _2);

  typedef _1 InputDomain;

  template<typename CellShape,
           typename InputPointFieldType>
  VTKM_EXEC
  typename InputPointFieldType::ComponentType
  operator()(CellShape shape,
             vtkm::IdComponent numPoints,
             const InputPointFieldType &inputPointField) const
  {
    vtkm::Vec<vtkm::FloatDefault,3> parametricCenter =
        vtkm::exec::ParametricCoordinatesCenter(numPoints, shape, *this);
    return vtkm::exec::CellInterpolate(inputPointField,
                                       parametricCenter,
                                       shape,
                                       *this);
  }
};

}
} // namespace vtkm::worklet

VTKM_CONT
void FindCellCenters(vtkm::cont::DataSet &dataSet)
{
  vtkm::cont::ArrayHandle<vtkm::Vec<vtkm::FloatDefault,3> > cellCentersArray;

  vtkm::worklet::DispatcherMapTopology<vtkm::worklet::CellCenter> dispatcher;
  dispatcher.Invoke(dataSet.GetCellSet(),
                    dataSet.GetCoordinateSystem().GetData(),
                    cellCentersArray);

  vtkm::cont::DataSetFieldAdd dataSetFieldAdd;
  dataSetFieldAdd.AddCellField(dataSet, "cell_center", cellCentersArray);
}
```

Cell To Point Map

A worklet deriving vtkm::worklet::WorkletMapCellToPoint performs a mapping operation that applies a function (the operator in the worklet) on all the points of a DataSet. While operating on the point, the worklet has access to fields associated both with the point and with all incident cells.

A WorkletMapCellToPoint subclass is invoked with a vtkm::worklet::DispatcherMapTopology. This dispatcher has two template arguments. The first argument is the type of the worklet subclass. The second argument, which is optional, is a device adapter tag.

A cell to point map worklet supports the following tags in the parameters of its ControlSignature.

CellSetIn This tag represents the cell set that defines the collection of points the map will operate on. A CellSetIn argument expects a CellSet subclass or a DynamicCellSet in the associated parameter of the dispatcher's Invoke.

There must be exactly one CellSetIn argument, and the worklet's InputDomain must be set to this argument.

FieldInCell This tag represents an input field that is associated with the cells. A FieldInCell argument expects an ArrayHandle or a DynamicArrayHandle in the associated parameter of the dispatcher's Invoke. The size of the array must be exactly the number of cells.

Each invocation of the worklet gets a Vec-like object containing the field values for all the cells incident with the point being visited. The order of the entries is arbitrary but will be consistent with the values of all other FieldInCell arguments for the same worklet invocation. If the field is a vector field, then the provided object is a Vec of Vecs.

FieldInCell has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

FieldInPoint This tag represents an input field that is associated with the points. A FieldInPoint argument expects an ArrayHandle or a DynamicArrayHandle in the associated parameter of the dispatcher's Invoke. The size of the array must be exactly the number of points. Each invocation of the worklet gets a single value out of this array.

FieldInPoint has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

FieldOutPoint This tag represents an output field, which is necessarily associated with points. A FieldOutPoint argument expects an ArrayHandle or a DynamicArrayHandle in the associated parameter of the dispatcher's Invoke. The array is resized before scheduling begins, and each invocation of the worklet sets a single value in the array.

FieldOutPoint has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

FieldOut is an alias for FieldOutPoint (since output arrays can only be defined on points).

FieldInOutPoint This tag represents field that is both an input and an output, which is necessarily associated with points. A FieldInOutPoint argument expects an ArrayHandle or a DynamicArrayHandle in the associated parameter of the dispatcher's Invoke. Each invocation of the worklet gets a single value out of this array, which is replaced by the resulting value after the worklet completes.

FieldInOutPoint has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

FieldInOut is an alias for FieldInOutPoint (since output arrays can only be defined on points).

WholeArrayIn This tag represents an array where all entries can be read by every worklet invocation. A WholeArrayIn argument expects an ArrayHandle in the associated parameter of the dispatcher's Invoke. An array portal capable of reading from any place in the array is given to the worklet. Whole arrays are discussed in detail in Section 14.6 starting on page 149.

WholeArrayIn has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

WholeArrayOut This tag represents an array where any entry can be written by any worklet invocation. A WholeArrayOut argument expects an ArrayHandle in the associated parameter of the dispatcher's Invoke. An array portal capable of writing to any place in the array is given to the worklet. Developers should take care when using writable whole arrays as introducing race conditions is possible. Whole arrays are discussed in detail in Section 14.6 starting on page 149.

WholeArrayOut has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

WholeArrayInOut This tag represents an array where any entry can be read or written by any worklet invocation. A WholeArrayInOut argument expects an ArrayHandle in the associated parameter of the dispatcher's Invoke. An array portal capable of reading from or writing to any place in the array is given to the worklet. Developers should take care when using writable whole arrays as introducing race conditions is possible. Whole arrays are discussed in detail in Section 14.6 starting on page 149.

WholeArrayInOut has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

ExecObject This tag represents an execution object that is passed directly from the control environment to the worklet. A ExecObject argument expects a subclass of vtkm::exec::ExecutionObjectBase, and this same object is given to the worklet. Execution objects are discussed in detail in Section 14.7 starting on page 151.

A field map worklet supports the following tags in the parameters of its ExecutionSignature.

_1, _2,... These reference the corresponding parameter in the ControlSignature.

CellCount This tag produces a vtkm::IdComponent equal to the number of cells incident on the point being visited. The Vecs provided from a FieldInCell parameter will be the same size as CellCount.

CellIndices This tag produces a Vec-like object of vtkm::Ids giving the indices for all incident cells. The order of the entries is arbitrary but will be consistent with the values of all other FieldInCell arguments for the same worklet invocation.

WorkIndex This tag produces a vtkm::Id that uniquely identifies the invocation of the worklet.

VisitIndex This tag produces a vtkm::IdComponent that uniquely identifies when multiple worklet invocations operate on the same input item, which can happen when defining a worklet with scatter (as described in Section 14.8).

Cell to point field maps are typically used for converting fields associated with cells to points so that they can be interpolated. The following example does a simple averaging, but you can also implement other strategies such as a volume weighted average.

Example 14.9: Implementation and use of a map cell to point worklet.

```
#include <vtkm/worklet/DispatcherMapTopology.h>
#include <vtkm/worklet/WorkletMapTopology.h>
```

```

#include <vtkm/cont/DataSet.h>
#include <vtkm/cont/DataSetFieldAdd.h>
#include <vtkm/cont/DynamicArrayHandle.h>
#include <vtkm/cont/DynamicCellSet.h>
#include <vtkm/cont/Field.h>

namespace vtkm {
namespace worklet {

class AverageCellField : public vtkm::worklet::WorkletMapCellToPoint
{
public:
  typedef void ControlSignature(CellSetIn cellSet,
                                FieldInCell<> inputCellField,
                                FieldOut<> outputPointField);
  typedef void ExecutionSignature(CellCount, _2, _3);

  typedef _1 InputDomain;

  template<typename InputCellFieldType, typename OutputFieldType>
  VTKM_EXEC
  void
  operator()(vtkm::IdComponent numCells,
             const InputCellFieldType &inputCellField,
             OutputFieldType &fieldAverage) const
  {
    // TODO: This trickery with calling DoAverage with an extra fabricated type
    // is to handle when the dynamic type resolution provides combinations that
    // are incompatible. On the todo list for VTK-m is to allow you to express
    // types that are the same for different parameters of the control
    // signature. When that happens, we can get rid of this hack.
    typedef typename InputCellFieldType::ComponentType InputComponentType;
    this->DoAverage(numCells,
                    inputCellField,
                    fieldAverage,
                    vtkm::ListTagBase<InputComponentType,OutputFieldType>());
  }

private:
  template<typename InputCellFieldType, typename OutputFieldType>
  VTKM_EXEC
  void DoAverage(vtkm::IdComponent numCells,
                 const InputCellFieldType &inputCellField,
                 OutputFieldType &fieldAverage,
                 vtkm::ListTagBase<OutputFieldType,OutputFieldType>) const
  {
    fieldAverage = OutputFieldType(0);

    for (vtkm::IdComponent cellIndex = 0; cellIndex < numCells; cellIndex++)
    {
      fieldAverage = fieldAverage + inputCellField[cellIndex];
    }

    fieldAverage = fieldAverage / OutputFieldType(numCells);
  }

  template<typename T1, typename T2, typename T3>
  VTKM_EXEC
  void DoAverage(vtkm::IdComponent, T1, T2, T3) const
  {
    this->RaiseError("Incompatible types for input and output.");
  }
};

}
} // namespace vtkm::worklet

VTKM_CONT
vtkm::cont::DataSet
ConvertCellFieldsToPointFields(const vtkm::cont::DataSet &inData)
{
  vtkm::cont::DataSet outData;

  // Copy parts of structure that should be passed through.
  for (vtkm::Id cellSetIndex = 0;
       cellSetIndex < inData.GetNumberOfCellSets();
       cellSetIndex++)
  {
    outData.AddCellSet(inData.GetCellSet(cellSetIndex));
  }
  for (vtkm::Id coordSysIndex = 0;
       coordSysIndex < inData.GetNumberOfCoordinateSystems();
       coordSysIndex++)
  {
    outData.AddCoordinateSystem(inData.GetCoordinateSystem(coordSysIndex));
  }

  // Copy all fields, converting cell fields to point fields.
  for (vtkm::Id fieldIndex = 0;
       fieldIndex < inData.GetNumberOfFields();
       fieldIndex++)
  {
    vtkm::cont::Field inField = inData.GetField(fieldIndex);
    if (inField.GetAssociation() == vtkm::cont::Field::ASSOC_CELL_SET)
    {
      vtkm::cont::DynamicArrayHandle inFieldData = inField.GetData();
      vtkm::cont::DynamicCellSet inCellSet =
          inData.GetCellSet(inField.GetAssocCellSet());

      vtkm::cont::DynamicArrayHandle outFieldData = inFieldData.NewInstance();
      vtkm::worklet::DispatcherMapTopology<vtkm::worklet::AverageCellField>
          dispatcher;
      dispatcher.Invoke(inCellSet, inFieldData, outFieldData);

      vtkm::cont::DataSetFieldAdd::AddCellField(outData,
                                                inField.GetName(),
                                                outFieldData,
                                                inField.GetAssocCellSet());
    }
    else
    {
      outData.AddField(inField);
    }
  }

  return outData;
}
```

General Topology Maps

A worklet deriving vtkm::worklet::WorkletMapTopology performs a mapping operation that applies a function (the operator in the worklet) on all the elements of a specified type from a DataSet. While operating on each element, the worklet has access to fields associated both with that element and with all incident elements of a different specified type.

The WorkletMapTopology class is a template with two template parameters. The first template parameter specifies the "from" topology element, and the second template parameter specifies the "to" topology element. The worklet is scheduled such that each instance is associated with a particular "to" topology element and has access to incident "from" topology elements.

These from and to topology elements are specified with topology element tags, which are defined in the vtkm/-TopologyElementTag.h header file. The available topology element tags are vtkm::TopologyElementTagCell, vtkm::TopologyElementTagPoint, vtkm::TopologyElementTagEdge, and vtkm::TopologyElementTagFace, which represent the cell, point, edge, and face elements, respectively.

WorkletMapTopology is a generic form of a topology map, and it can perform identically to the aforementioned forms of topology map with the correct template parameters. For example,

> vtkm::worklet::WorkletMapTopology<vtkm::TopologyElementTagPoint, vtkm::TopologyElementTagCell>

is equivalent to the vtkm::worklet::WorkletMapPointToCell class except the signature tags have different names. The names used in the specific topology map superclasses (such as WorkletMapPointToCell) tend to be easier to read and are thus preferable. However, the generic WorkletMapTopology is available for topology combinations without a specific superclass or to support more general mappings in a worklet.

The general topology map worklet supports the following tags in the parameters of its ControlSignature, which are equivalent to tags in the other topology maps but with different (more general) names.

CellSetIn This tag represents the cell set that defines the collection of elements the map will operate on. A CellSetIn argument expects a CellSet subclass or a DynamicCellSet in the associated parameter of the dispatcher's Invoke. Each invocation of the worklet gets a cell shape tag. (Cell shapes and the operations you can do with cells are discussed in Chapter 17.)

There must be exactly one CellSetIn argument, and the worklet's InputDomain must be set to this argument.

FieldInFrom This tag represents an input field that is associated with the "from" elements. A FieldInFrom argument expects an ArrayHandle or a DynamicArrayHandle in the associated parameter of the dispatcher's Invoke. The size of the array must be exactly the number of "from" elements.

Each invocation of the worklet gets a Vec-like object containing the field values for all the "from" elements incident with the "to" element being visited. If the field is a vector field, then the provided object is a Vec of Vecs.

FieldInFrom has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

FieldInTo This tag represents an input field that is associated with the "to" element. A FieldInTo argument expects an ArrayHandle or a DynamicArrayHandle in the associated parameter of the dispatcher's Invoke. The size of the array must be exactly the number of cells. Each invocation of the worklet gets a single value out of this array.

FieldInTo has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

FieldOut This tag represents an output field, which is necessarily associated with "to" elements. A FieldOut argument expects an ArrayHandle or a DynamicArrayHandle in the associated parameter of the dispatcher's Invoke. The array is resized before scheduling begins, and each invocation of the worklet sets a single value in the array.

FieldOut has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

FieldInOut This tag represents field that is both an input and an output, which is necessarily associated with "to" elements. A FieldInOut argument expects an ArrayHandle or a DynamicArrayHandle in the associated parameter of the dispatcher's Invoke. Each invocation of the worklet gets a single value out of this array, which is replaced by the resulting value after the worklet completes.

FieldInOut has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

WholeArrayIn This tag represents an array where all entries can be read by every worklet invocation. A WholeArrayIn argument expects an ArrayHandle in the associated parameter of the dispatcher's Invoke. An array portal capable of reading from any place in the array is given to the worklet. Whole arrays are discussed in detail in Section 14.6 starting on page 149.

WholeArrayIn has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

WholeArrayOut This tag represents an array where any entry can be written by any worklet invocation. A WholeArrayOut argument expects an ArrayHandle in the associated parameter of the dispatcher's Invoke. An array portal capable of writing to any place in the array is given to the worklet. Developers should take care when using writable whole arrays as introducing race conditions is possible. Whole arrays are discussed in detail in Section 14.6 starting on page 149.

WholeArrayOut has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

WholeArrayInOut This tag represents an array where any entry can be read or written by any worklet invocation. A WholeArrayInOut argument expects an ArrayHandle in the associated parameter of the dispatcher's Invoke. An array portal capable of reading from or writing to any place in the array is given to the worklet. Developers should take care when using writable whole arrays as introducing race conditions is possible. Whole arrays are discussed in detail in Section 14.6 starting on page 149.

WholeArrayInOut has a single template parameter that specifies what data types are acceptable for the array. The type tags are described in Section 14.4.1 starting on page 134.

ExecObject This tag represents an execution object that is passed directly from the control environment to the worklet. A ExecObject argument expects a subclass of vtkm::exec::ExecutionObjectBase, and this same object is given to the worklet. Execution objects are discussed in detail in Section 14.7 starting on page 151.

A general topology map worklet supports the following tags in the parameters of its ExecutionSignature.

_1, _2,... These reference the corresponding parameter in the ControlSignature.

CellShape This tag produces a shape tag corresponding to the shape of the visited "to" element. (Cell shapes and the operations you can do with cells are discussed in Chapter 17.) This is the same value that gets provided if you reference the CellSetIn parameter.

If the "to" element is cells, the CellShape clearly will match the shape of each cell. Other elements will have shapes to match their structures. Points have vertex shapes, edges have line shapes, and faces have some type of polygonal shape.

FromCount This tag produces a vtkm::IdComponent equal to the number of "from" elements incident on the "to" element being visited. The Vecs provided from a FieldInFrom parameter will be the same size as FromCount.

`FromIndices` This tag produces a Vec-like object of `vtkm::Id`s giving the indices for all incident "from" elements. The order of the entries is consistent with the values of all other `FieldInFrom` arguments for the same worklet invocation.

`WorkIndex` This tag produces a `vtkm::Id` that uniquely identifies the invocation of the worklet.

`VisitIndex` This tag produces a `vtkm::IdComponent` that uniquely identifies when multiple worklet invocations operate on the same input item, which can happen when defining a worklet with scatter (as described in Section 14.8).

14.6 Whole Arrays

As documented in Section 14.5, each worklet type has a set of parameter types that can be used to pass data to and from the worklet invocation. But what happens if you want to pass data that cannot be expressed in these predefined mechanisms. Chapter 20 describes how to create completely new worklet types and parameter tags. However, designing such a system for a one-time use is overkill.

Instead, all VTK-m worklets provide a couple of mechanisms that allow you to pass arbitrary data to a worklet. In this section, we will explore a *whole array* argument that provides random access to an entire array. In the following section we describe an even more general mechanism to describe any execution object.

We have already seen a demonstration of using a whole array in Example 14.7 to perform a simple array copy. Here we will construct a more thorough example of building functionality that requires random array access.

Let's say we want to measure the quality of triangles in a mesh. A common method for doing this is using the equation

$$q = \frac{4a\sqrt{3}}{h_1^2 + h_2^2 + h_3^2}$$

where a is the area of the triangle and h_1, h_2, and h_3 are the lengths of the sides. We can easily compute this in a cell to point map, but what if we want to speed up the computations by reducing precision? After all, we probably only care if the triangle is good, reasonable, or bad. So instead, let's build a lookup table and then retrieve the triangle quality from that lookup table based on its sides.

The following example demonstrates creating such a table lookup in an array and using a worklet argument tagged with `WholeArrayIn` to make it accessible.

Example 14.10: Using `WholeArrayIn` to access a lookup table in a worklet.

```
#include <vtkm/cont/ArrayHandle.h>
#include <vtkm/cont/DataSet.h>

#include <vtkm/worklet/DispatcherMapTopology.h>
#include <vtkm/worklet/WorkletMapTopology.h>

#include <vtkm/CellShape.h>
#include <vtkm/Math.h>
#include <vtkm/VectorAnalysis.h>

static const vtkm::Id TRIANGLE_QUALITY_TABLE_DIMENSION = 8;
static const vtkm::Id TRIANGLE_QUALITY_TABLE_SIZE =
    TRIANGLE_QUALITY_TABLE_DIMENSION*TRIANGLE_QUALITY_TABLE_DIMENSION;

VTKM_CONT
vtkm::cont::ArrayHandle<vtkm::Float32> GetTriangleQualityTable()
{
  // Use these precomputed values for the array. A real application would
  // probably use a larger array, but we are keeping it small for demonstration
  // purposes.
  static vtkm::Float32 triangleQualityBuffer[TRIANGLE_QUALITY_TABLE_SIZE] = {
    0, 0,        0,        0,        0,        0,        0,        0,
    0, 0,        0,        0,        0,        0,        0,        0.24431f,
    0, 0,        0,        0,        0,        0,        0.43298f, 0.47059f,
    0, 0,        0,        0,        0,        0.54217f, 0.65923f, 0.66408f,
    0, 0,        0,        0,        0.57972f, 0.75425f, 0.82154f, 0.81536f,
    0, 0,        0,        0.54217f, 0.75425f, 0.87460f, 0.92567f, 0.92071f,
    0, 0,        0.43298f, 0.65923f, 0.82154f, 0.92567f, 0.97664f, 0.98100f,
    0, 0.24431f, 0.47059f, 0.66408f, 0.81536f, 0.92071f, 0.98100f, 1
  };

  return vtkm::cont::make_ArrayHandle(triangleQualityBuffer,
                                      TRIANGLE_QUALITY_TABLE_SIZE);
}

template<typename T>
VTKM_EXEC_CONT
vtkm::Vec<T,3> TriangleEdgeLengths(const vtkm::Vec<T,3> &point1,
                                   const vtkm::Vec<T,3> &point2,
                                   const vtkm::Vec<T,3> &point3)
{
  return vtkm::make_Vec(vtkm::Magnitude(point1-point2),
                        vtkm::Magnitude(point2-point3),
                        vtkm::Magnitude(point3-point1));
}

VTKM_SUPPRESS_EXEC_WARNINGS
template<typename PortalType, typename T>
VTKM_EXEC_CONT
vtkm::Float32 LookupTriangleQuality(const PortalType &triangleQualityPortal,
                                    const vtkm::Vec<T,3> &point1,
                                    const vtkm::Vec<T,3> &point2,
                                    const vtkm::Vec<T,3> &point3)
{
  vtkm::Vec<T,3> edgeLengths = TriangleEdgeLengths(point1, point2, point3);

  // To reduce the size of the table, we just store the quality of triangles
  // with the longest edge of size 1. The table is 2D indexed by the length
  // of the other two edges. Thus, to use the table we have to identify the
  // longest edge and scale appropriately.
  T smallEdge1 = vtkm::Min(edgeLengths[0], edgeLengths[1]);
  T tmpEdge = vtkm::Max(edgeLengths[0], edgeLengths[1]);
  T smallEdge2 = vtkm::Min(edgeLengths[2], tmpEdge);
  T largeEdge = vtkm::Max(edgeLengths[2], tmpEdge);

  smallEdge1 /= largeEdge;
  smallEdge2 /= largeEdge;

  // Find index into array.
  vtkm::Id index1 = static_cast<vtkm::Id>(
        vtkm::Floor(smallEdge1*(TRIANGLE_QUALITY_TABLE_DIMENSION-1)+0.5));
  vtkm::Id index2 = static_cast<vtkm::Id>(
        vtkm::Floor(smallEdge2*(TRIANGLE_QUALITY_TABLE_DIMENSION-1)+0.5));
  vtkm::Id totalIndex = index1 + index2*TRIANGLE_QUALITY_TABLE_DIMENSION;

  return triangleQualityPortal.Get(totalIndex);
}

struct TriangleQualityWorklet : vtkm::worklet::WorkletMapPointToCell
{
  typedef void ControlSignature(CellSetIn cells,
                                FieldInPoint<Vec3> pointCoordinates,
                                WholeArrayIn<Scalar> triangleQualityTable,
                                FieldOutCell<Scalar> triangleQuality);
  typedef _4 ExecutionSignature(CellShape, _2, _3);
  typedef _1 InputDomain;

  template<typename CellShape,
           typename PointCoordinatesType,
           typename TriangleQualityTablePortalType>
  VTKM_EXEC
  vtkm::Float32 operator()(
      CellShape shape,
      const PointCoordinatesType &pointCoordinates,
      const TriangleQualityTablePortalType &triangleQualityTable) const
  {
    if (shape.Id != vtkm::CELL_SHAPE_TRIANGLE)
    {
      this->RaiseError("Only triangles are supported for triangle quality.");
      return vtkm::Nan32();
    }

    return LookupTriangleQuality(triangleQualityTable,
                                 pointCoordinates[0],
                                 pointCoordinates[1],
                                 pointCoordinates[2]);
  }
};

// Normally we would encapsulate this call in a filter, but for demonstrative
// purposes we are just calling the worklet directly.
template<typename DeviceAdapterTag>
VTKM_CONT
vtkm::cont::ArrayHandle<vtkm::Float32>
RunTriangleQuality(vtkm::cont::DataSet dataSet,
                   DeviceAdapterTag)
{
  vtkm::cont::ArrayHandle<vtkm::Float32> triangleQualityTable =
      GetTriangleQualityTable();

  vtkm::cont::ArrayHandle<vtkm::Float32> triangleQualities;

  vtkm::worklet::DispatcherMapTopology<TriangleQualityWorklet,DeviceAdapterTag>
      dispatcher;
  dispatcher.Invoke(dataSet.GetCellSet(),
                    dataSet.GetCoordinateSystem().GetData(),
                    triangleQualityTable,
                    triangleQualities);

  return triangleQualities;
}
```

14.7 Execution Objects

Although passing whole arrays into a worklet is a convenient way to provide data to a worklet that is not divided by the input or output domain, it is sometimes not the best structure to represent data. Thus, all worklets support a second type of argument called an *execution object*, or exec object for short, that passes the given object directly to each invocation of the worklet. This is defined by an ExecObject tag in the ControlSignature.

The execution object must be a subclass of vtkm::exec::ExecutionObjectBase. Also, it must be possible to copy the object from the control environment to the execution environment and be usable in the execution environment, and any method of the execution object used within the worklet must be declared with VTKM_EXEC or VTKM_EXEC_CONT.

An execution object can refer to an array, but the array reference must be through an array portal for the execution environment. This can be retrieved from the PrepareForInput method in vtkm::cont::ArrayHandle as described in Section 7.4. Other VTK-m data objects, such as the subclasses of vtkm::cont::CellSet, have similar methods.

Returning to the example we have in Section 14.6, we are computing triangle quality quickly by looking up the value in a table. In Example 14.10 the table is passed directly to the worklet as a whole array. However, there is some additional code involved to get the appropriate index into the table for a given triangle. Let us say that we want to have the ability to compute triangle quality in many different worklets. Rather than pass in a raw array, it would be better to encapsulate the functionality in an object.

We can do that by creating an execution object that has the table stored inside and methods to compute the triangle quality. The following example uses the table built in Example 14.10 to create such an object.

Example 14.11: Using ExecObject to access a lookup table in a worklet.

```cpp
template<typename DeviceAdapterTag>
class TriangleQualityTable : public vtkm::exec::ExecutionObjectBase
{
public:
  VTKM_CONT
  TriangleQualityTable()
  {
    this->TablePortal =
        GetTriangleQualityTable().PrepareForInput(DeviceAdapterTag());
  }

  template<typename T>
  VTKM_EXEC
  vtkm::Float32 GetQuality(const vtkm::Vec<T,3> &point1,
                           const vtkm::Vec<T,3> &point2,
                           const vtkm::Vec<T,3> &point3) const
  {
    return LookupTriangleQuality(this->TablePortal, point1, point2, point3);
  }

private:
  typedef vtkm::cont::ArrayHandle<vtkm::Float32> TableArrayType;
  typedef typename TableArrayType::ExecutionTypes<DeviceAdapterTag>::PortalConst
      TableArrayPortalType;
  TableArrayPortalType TablePortal;
};

struct TriangleQualityWorklet2 : vtkm::worklet::WorkletMapPointToCell
{
  typedef void ControlSignature(CellSetIn cells,
                                FieldInPoint<Vec3> pointCoordinates,
                                ExecObject triangleQualityTable,
                                FieldOutCell<Scalar> triangleQuality);
  typedef _4 ExecutionSignature(CellShape, _2, _3);
  typedef _1 InputDomain;

  template<typename CellShape,
           typename PointCoordinatesType,
           typename TriangleQualityTableType>
  VTKM_EXEC
  vtkm::Float32 operator()(
      CellShape shape,
      const PointCoordinatesType &pointCoordinates,
      const TriangleQualityTableType &triangleQualityTable) const
  {
    if (shape.Id != vtkm::CELL_SHAPE_TRIANGLE)
    {
      this->RaiseError("Only triangles are supported for triangle quality.");
      return vtkm::Nan32();
    }

    return triangleQualityTable.GetQuality(pointCoordinates[0],
                                           pointCoordinates[1],
                                           pointCoordinates[2]);
  }
};

// Normally we would encapsulate this call in a filter, but for demonstrative
// purposes we are just calling the worklet directly.
template<typename DeviceAdapterTag>
VTKM_CONT
vtkm::cont::ArrayHandle<vtkm::Float32>
RunTriangleQuality2(vtkm::cont::DataSet dataSet,
                    DeviceAdapterTag)
{
  TriangleQualityTable<DeviceAdapterTag> triangleQualityTable;

  vtkm::cont::ArrayHandle<vtkm::Float32> triangleQualities;

  vtkm::worklet::DispatcherMapTopology<TriangleQualityWorklet2,DeviceAdapterTag>
      dispatcher;
  dispatcher.Invoke(dataSet.GetCellSet(),
                    dataSet.GetCoordinateSystem().GetData(),
                    triangleQualityTable,
                    triangleQualities);

  return triangleQualities;
}
```

14.8 Scatter

The default scheduling of a worklet provides a 1 to 1 mapping from the input domain to the output domain. For example, a `vtkm::worklet::WorkletMapField` gets run once for every item of the input array and produces one item for the output array. Likewise, `vtkm::worklet::WorkletMapPointToCell` gets run once for every cell in the input topology and produces one associated item for the output field.

However, there are many operations that do not fall well into this 1 to 1 mapping procedure. The operation might need to pass over elements that produce no value or the operation might need to produce multiple values for a single input element.

Such non 1 to 1 mappings can be achieved by defining a *scatter* for a worklet. The following types of scatter are provided by VTK-m.

`vtkm::worklet::ScatterIdentity` Provides a basic 1 to 1 mapping from input to output. This is the default scatter used if none is specified.

`vtkm::worklet::ScatterUniform` Provides a 1 to many mapping from input to output with the same number of outputs for each input. The worklet provides a number at runtime that defines the number of output values to produce per input.

`vtkm::worklet::ScatterCounting` Provides a 1 to any mapping from input to output with different numbers of outputs for each input. The worklet provides an `ArrayHandle` that is the same size as the input containing the count of output values to produce for each input. Values can be zero, in which case that input will be skipped.

To define a scatter procedure, the worklet must provide two items. The first item is a `typedef` named `ScatterType`. The `ScatterType` must be `typedef`ed to one of the aforementioned `Scatter*` classes. The second item is a `const` method named `GetScatter` that returns an object of type `ScatterType`.

Example 14.12: Declaration of a scatter type in a worklet.

```
  typedef vtkm::worklet::ScatterCounting ScatterType;

  VTKM_CONT
  ScatterType GetScatter() const { return this->Scatter; }
```

When using a scatter that produces multiple outputs for a single input, the worklet is invoked multiple times with the same input values. In such an event the worklet operator needs to distinguish these calls to produce the correct associated output. This is done by declaring one of the `ExecutionSignature` arguments as `VisitIndex`. This tag will pass a `vtkm::IdComponent` to the worklet that identifies which invocation is being called.

To demonstrate using scatters with worklets, we provide some contrived but illustrative examples. The first example is a worklet that takes a pair of input arrays and interleaves them so that the first, third, fifth, and so on entries come from the first array and the second, fourth, sixth, and so on entries come from the second array. We achieve this by using a `vtkm::cont::ScatterUniform` of size 2 and using the `VisitIndex` to determine from which array to pull a value.

Example 14.13: Using `ScatterUniform`.

```
struct InterleaveArrays : vtkm::worklet::WorkletMapField
{
  typedef void ControlSignature(FieldIn<>, FieldIn<>, FieldOut<>);
  typedef void ExecutionSignature(_1, _2, _3, VisitIndex);
  typedef _1 InputDomain;

  typedef vtkm::worklet::ScatterUniform ScatterType;

  VTKM_CONT
  ScatterType GetScatter() const { return vtkm::worklet::ScatterUniform(2); }

  template<typename T>
  VTKM_EXEC
  void operator()(const T &input0,
                  const T &input1,
                  T &output,
                  vtkm::IdComponent visitIndex) const
  {
    if (visitIndex == 0)
    {
      output = input0;
    }
    else // visitIndex == 1
    {
      output = input1;
    }
  }
};
```

The second example takes a collection of point coordinates and clips them by an axis-aligned bounding box. It does this using a `vtkm::cont::ScatterCounting` with an array containing 0 for all points outside the bounds and 1 for all points inside the bounds. As is typical with this type of operation, we use another worklet with a default identity scatter to build the count array.

Example 14.14: Using ScatterCounting.

```
class ClipPointsCount : public vtkm::worklet::WorkletMapField
{
public:
  typedef void ControlSignature(FieldIn<Vec3> points,
                                FieldOut<IdComponentType> count);
  typedef _2 ExecutionSignature(_1);
  typedef _1 InputDomain;

  template<typename T>
  VTKM_CONT
  ClipPointsCount(const vtkm::Vec<T,3> &boundsMin,
                  const vtkm::Vec<T,3> &boundsMax)
    : BoundsMin(boundsMin[0], boundsMin[1], boundsMin[2]),
      BoundsMax(boundsMax[0], boundsMax[1], boundsMax[2])
  {  }

  template<typename T>
  VTKM_EXEC
  vtkm::IdComponent operator()(const vtkm::Vec<T,3> &point) const
  {
    return static_cast<vtkm::IdComponent>((this->BoundsMin[0] < point[0]) &&
                                          (this->BoundsMin[1] < point[1]) &&
                                          (this->BoundsMin[2] < point[2]) &&
                                          (this->BoundsMax[0] > point[0]) &&
                                          (this->BoundsMax[1] > point[1]) &&
                                          (this->BoundsMax[2] > point[2]));
  }

private:
  vtkm::Vec<vtkm::FloatDefault,3> BoundsMin;
  vtkm::Vec<vtkm::FloatDefault,3> BoundsMax;
};

class ClipPointsGenerate : public vtkm::worklet::WorkletMapField
{
public:
  typedef void ControlSignature(FieldIn<Vec3> inPoints,
                                FieldOut<Vec3> outPoints);
  typedef void ExecutionSignature(_1, _2);
  typedef _1 InputDomain;

  typedef vtkm::worklet::ScatterCounting ScatterType;

  VTKM_CONT
  ScatterType GetScatter() const { return this->Scatter; }

  template<typename CountArrayType, typename DeviceAdapterTag>
  VTKM_CONT
  ClipPointsGenerate(const CountArrayType &countArray, DeviceAdapterTag)
    : Scatter(countArray, DeviceAdapterTag())
  {
    VTKM_IS_ARRAY_HANDLE(CountArrayType);
  }

  template<typename InType, typename OutType>
  VTKM_EXEC
  void operator()(const vtkm::Vec<InType,3> &inPoint,
                  vtkm::Vec<OutType,3> &outPoint) const
  {
    // The scatter ensures that this method is only called for input points
    // that are passed to the output (where the count was 1). Thus, in this
    // case we know that we just need to copy the input to the output.
    outPoint = vtkm::Vec<OutType,3>(inPoint[0], inPoint[1], inPoint[2]);
  }

private:
  ScatterType Scatter;
};

// Normally we would encapsulate these calls in a filter, but for demonstrative
// purposes we are just calling the worklet directly.
template<typename T, typename Storage, typename DeviceAdapterTag>
VTKM_CONT
vtkm::cont::ArrayHandle<vtkm::Vec<T,3> >
RunClipPoints(const vtkm::cont::ArrayHandle<vtkm::Vec<T,3>, Storage> &pointArray,
              vtkm::Vec<T,3> boundsMin,
              vtkm::Vec<T,3> boundsMax,
              DeviceAdapterTag)
{
  vtkm::cont::ArrayHandle<vtkm::IdComponent> countArray;

  ClipPointsCount workletCount(boundsMin, boundsMax);
  vtkm::worklet::DispatcherMapField<ClipPointsCount, DeviceAdapterTag>
      dispatcherCount(workletCount);
  dispatcherCount.Invoke(pointArray, countArray);

  vtkm::cont::ArrayHandle<vtkm::Vec<T,3> > clippedPointsArray;

  ClipPointsGenerate workletGenerate(countArray, DeviceAdapterTag());
  vtkm::worklet::DispatcherMapField<ClipPointsGenerate, DeviceAdapterTag>
      dispatcherGenerate(workletGenerate);
  dispatcherGenerate.Invoke(pointArray, clippedPointsArray);

  return clippedPointsArray;
}
```

14.9 Error Handling

It is sometimes the case during the execution of an algorithm that an error condition can occur that causes the computation to become invalid. At such a time, it is important to raise an error to alert the calling code of the problem. Since VTK-m uses an exception mechanism to raise errors, we want an error in the execution environment to throw an exception.

However, throwing exceptions in a parallel algorithm is problematic. Some accelerator architectures, like CUDA, do not even support throwing exceptions. Even on architectures that do support exceptions, throwing them in a thread block can cause problems. An exception raised in one thread may or may not be thrown in another, which increases the potential for deadlocks, and it is unclear how uncaught exceptions progress through thread blocks.

VTK-m handles this problem by using a flag and check mechanism. When a worklet (or other subclass of `vtkm::exec::FunctorBase`) encounters an error, it can call its `RaiseError` method to flag the problem and record a message for the error. Once all the threads terminate, the scheduler checks for the error, and if one exists it throws a `vtkm::cont::ErrorExecution` exception in the control environment. Thus, calling `RaiseError` looks like an exception was thrown from the perspective of the control environment code that invoked it.

Example 14.15: Raising an error in the execution environment.

```
struct SquareRoot : vtkm::worklet::WorkletMapField
{
public:
  typedef void ControlSignature(FieldIn<Scalar>, FieldOut<Scalar>);
  typedef _2 ExecutionSignature(_1);

  template<typename T>
  VTKM_EXEC
  T operator()(T x) const
  {
    if (x < 0)
      {
      this->RaiseError("Cannot take the square root of a negative number.");
      }
    return vtkm::Sqrt(x);
  }
};
```

It is also worth noting that the VTKM_ASSERT macro described in Section 6.7 also works within worklets and other code running in the execution environment. Of course, a failed assert will terminate execution rather than just raise an error so is best for checking invalid conditions for debugging purposes.

CHAPTER

FIFTEEN

CREATING FILTERS

In Chapter 14 we discuss how to implement an algorithm in the VTK-m framework by creating a worklet. Worklets might be straightforward to implement and invoke for those well familiar with the appropriate VTK-m API. However, novice users have difficulty using worklets directly. For simplicity, worklet algorithms are generally wrapped in what are called filter objects for general usage. Chapter 4 introduces the concept of filters and documents those that come with the VTK-m library. In this chapter we describe how to build new filter objects using the worklet examples introduced in Chapter 14.

Unsurprisingly, the base filter objects are contained in the `vtkm::filter` package. The basic implementation of a filter involves subclassing one of the base filter objects and implementing the `DoExecute` method. The `DoExecute` method performs the operation of the filter and returns the appropriate result object.

As with worklets, there are several flavors of filter types to address different operating behaviors although their is not a one-to-one relationship between worklet and filter types. This chapter is sectioned by the different filter types with an example of implementations for each.

15.1 Field Filters

As described in Section 4.1 (starting on page 17), field filters are a category of filters that generate a new fields. These new fields are typically derived from one or more existing fields or point coordinates on the data set. For example, mass, volume, and density are interrelated, and any one can be derived from the other two.

Field filters are implemented in classes that derive the `vtkm::filter::FilterField` base class. `FilterField` is a templated class that has a single template argument, which is the type of the concrete subclass.

Did you know?

The convention of having a subclass be templated on the derived class' type is known as the Curiously Recurring Template Pattern (CRTP). In the case of `FilterField` *and other filter base classes, VTK-m uses this CRTP behavior to allow the general implementation of these algorithms to run* `DoExecute` *in the subclass, which as we see in a moment is itself templated.*

All `FilterField` subclasses must implement a `DoExecute` method. The `FilterField` base class implements an `Execute` method (actually several overloaded versions of `Execute`), processes the arguments, and then calls the `DoExecute` method of its subclass. The `DoExecute` method has the following 5 arguments.

- An input data set contained in a `vtkm::cont::DataSet` object. (See Chapter 12 for details on `DataSet` objects.)

- The field from the DataSet specified in the Execute method to operate on. The field is always passed as an instance of vtkm::cont::ArrayHandle. (See Chapter 7 for details on ArrayHandle objects.) The type of the ArrayHandle is generally not known until the class is used and requires a template type.

- A vtkm::filter::FieldMetadata object that contains the associated metadata of the field not contained in the ArrayHandle of the second argument. The FieldMetadata contains information like the name of the field and what topological element the field is associated with (such as points or cells).

- A policy class. (See Chapter 13 for details on policy classes.) The type of the policy is generally to known until the class is used and requires a template type.

- A device adapter tag. (See Chapter 8 for details on device adapters and their tags.) The type of the device adapter is generally to known until the class is used and requires a template type.

In this section we provide an example implementation of a field filter that wraps the "magnitude" worklet provided in Example 14.6 (listed on page 138). By convention, filter implementations are split into two files. The first file is a standard header file with a .h extension that contains the declaration of the filter class without the implementation. So we would expect the following code to be in a file named FieldMagnitude.h.

Example 15.1: Header declaration for a field filter.

```
namespace vtkm {
namespace filter {

class FieldMagnitude : public vtkm::filter::FilterField<FieldMagnitude>
{
public:
  VTKM_CONT
  FieldMagnitude();

  template<typename ArrayHandleType, typename Policy, typename DeviceAdapter>
  VTKM_CONT
  vtkm::filter::ResultField
  DoExecute(const vtkm::cont::DataSet &inDataSet,
            const ArrayHandleType &inField,
            const vtkm::filter::FieldMetadata &fieldMetadata,
            vtkm::filter::PolicyBase<Policy>,
            DeviceAdapter);
};

template<>
class FilterTraits<vtkm::filter::FieldMagnitude>
{
public:
  struct InputFieldTypeList :
      vtkm::ListTagBase<vtkm::Vec<vtkm::Float32,2>,
                        vtkm::Vec<vtkm::Float64,2>,
                        vtkm::Vec<vtkm::Float32,3>,
                        vtkm::Vec<vtkm::Float64,3>,
                        vtkm::Vec<vtkm::Float32,4>,
                        vtkm::Vec<vtkm::Float64,4> >
  { };
};

}
} // namespace vtkm::filter
```

Notice that in addition to declaring the class for FieldMagnitude, Example 15.1 also specializes the vtkm::-filter::FilterTraits templated class for FieldMagnitude. The FilterTraits class, declared in vtkm/filter/-

FilterTraits.h, provides hints used internally in the base filter classes to modify its behavior based on the subclass. A `FilterTraits` class is expected to define the following types.

`InputFieldTypeList` A type list containing all the types that are valid for the input field. For example, a filter operating on positions in space might limit the types to three dimensional vectors. Type lists are discussed in detail in Section 6.6.2.

In the particular case of our `FieldMagnitude` filter, the filter expects to operate on some type of vector field. Thus, the `InputFieldTypeList` is modified to a list of all standard floating point `Vec`s.

Once the filter class and (optionally) the `FilterTraits` are declared in the .h file, the implementation filter is by convention given in a separate .hxx file. So the continuation of our example that follows would be expected in a file named FieldMagnitude.hxx. The .h file near its bottom needs an include line to the .hxx file. This convention is set up because a near future version of VTK-m will allow the building of filter libraries containing default policies that can be used by only including the header declaration.

The implementation of `DoExecute` is straightforward. A worklet is invoked to compute a new field array. `DoExecute` then returns a newly constructed `vtkm::filter::ResultField` object. The constructor to `ResultField` takes the following 5 arguments.

- The input data set. This is the same data set passed to the first argument of `DoExecute`.
- The array containing the data for the new field, which was presumably computed by the filter.
- The name of the new field.
- The topological association (e.g. points or cells) of the new field. In the case where the filter is a simple operation on a field array, the association can usually be copied from the `FieldMetadata` passed to `DoExecute`.
- The name of the element set the new field is associated with. This only has meaning if the new field is associated with cells. This usually can be copied from the `FieldMetadata` passed to `DoExecute`.

Note that all fields need a unique name, which is the reason for the third argument to the `ResultField` constructor. The `vtkm::filter::FilterField` base class contains a pair of methods named `SetOutputFieldName` and `GetOutputFieldName` to allow users to specify the name of output fields. The `DoExecute` method should respect the given output field name. However, it is also good practice for the filter to have a default name if none is given. This might be simply specifying a name in the constructor, but it is worthwhile for many filters to derive a name based on the name of the input field.

Example 15.2: Implementation of a field filter.

```
namespace vtkm {
namespace filter {

VTKM_CONT
FieldMagnitude::FieldMagnitude()
{
  this->SetOutputFieldName("");
}

template<typename ArrayHandleType, typename Policy, typename DeviceAdapter>
VTKM_CONT
vtkm::filter::ResultField
FieldMagnitude::DoExecute(const vtkm::cont::DataSet &inDataSet,
                          const ArrayHandleType &inField,
                          const vtkm::filter::FieldMetadata &fieldMetadata,
                          vtkm::filter::PolicyBase<Policy>,
                             DeviceAdapter)
{
  VTKM_IS_ARRAY_HANDLE(ArrayHandleType);
  VTKM_IS_DEVICE_ADAPTER_TAG(DeviceAdapter);

  using ComponentType = typename ArrayHandleType::ValueType::ComponentType;
  vtkm::cont::ArrayHandle<ComponentType> outField;

  vtkm::worklet::DispatcherMapField<vtkm::worklet::Magnitude, DeviceAdapter>
      dispatcher;
  dispatcher.Invoke(inField, outField);

  std::string outFieldName = this->GetOutputFieldName();
  if (outFieldName == "")
  {
    outFieldName = fieldMetadata.GetName() + "_magnitude";
  }

  return vtkm::filter::ResultField(inDataSet,
                                   outField,
                                   outFieldName,
                                   fieldMetadata.GetAssociation(),
                                   fieldMetadata.GetCellSetName());
}

}
} // namespace vtkm::filter
```

15.2 Field Filters Using Cell Connectivity

A special subset of field filters are those that take into account the connectivity of a cell set to compute derivative fields. These types of field filters should be implemented in classes that derive the `vtkm::filter::FilterCell` base class. `FilterCell` is itself a subclass of `vtkm::filter::FilterField` and behaves essentially the same. `FilterCell` adds the pair of methods `SetActiveCellSet` and `GetActiveCellSetIndex`. [Why is there a mismatch in the naming? Should they be changed? If they are, update the documentation here and in the ProvidedFilters chapter.] The `SetActiveCellSet` method allows users to specify which cell set of the given `DataSet` to use. Likewise, `FilterCell` subclasses should use `GetActiveCellSetIndex` when retrieving a cell set from the given `DataSet`.

Like `FilterField`, `FilterCell` is a templated class that takes as its single template argument the type of the derived class. Also like `FilterField`, a `FilterCell` subclass must implement a method named `DoExecute` with 5 arguments: an input `vtkm::cont::DataSet` object, a `vtkm::cont::ArrayHandle` of the input field, a `vtkm::filter::FieldMetadata` information object, a policy class, and a device adapter tag.

In this section we provide an example implementation of a field filter on cells that wraps the "cell center" worklet provided in Example 14.8 (listed on page 142). By convention, filter implementations are split into two files. The first file is a standard header file with a .h extension that contains the declaration of the filter class without the implementation. So we would expect the following code to be in a file named CellCenter.h.

Example 15.3: Header declaration for a field filter using cell topology.

```
namespace vtkm {
namespace filter {

class CellCenters : public vtkm::filter::FilterCell<CellCenters>
{
public:
  VTKM_CONT
  CellCenters();

  template<typename ArrayHandleType, typename Policy, typename DeviceAdapter>
  VTKM_CONT
  vtkm::filter::ResultField
  DoExecute(const vtkm::cont::DataSet &inDataSet,
            const ArrayHandleType &inField,
            const vtkm::filter::FieldMetadata &FieldMetadata,
            vtkm::filter::PolicyBase<Policy>,
            DeviceAdapter);
};

}
} // namespace vtkm::filter
```

Did you know?

You may have noticed that Example 15.1 provided a specialization for `vtkm::filter::FilterTraits` *but Example 15.3 provides no such specialization. This demonstrates that declaring filter traits is optional. If a filter only works on some limited number of types, then it can use* `FilterTraits` *to specify the specific types it supports. But if a filter is generally applicable to many field types, it can simply use the default filter traits.*

Once the filter class and (optionally) the `FilterTraits` are declared in the .h file, the implementation filter is by convention given in a separate .hxx file. So the continuation of our example that follows would be expected in a file named CellCenter.hxx. The .h file near its bottom needs an include line to the .hxx file. This convention is set up because a near future version of VTK-m will allow the building of filter libraries containing default policies that can be used by only including the header declaration.

Like with a `FilterField`, a subclass of `FilterCell` implements `DoExecute` by invoking a worklet to compute a new field array and then return a newly constructed `vtkm::filter::ResultField` object.

Example 15.4: Implementation of a field filter using cell topology.

```
namespace vtkm {
namespace filter {

VTKM_CONT
CellCenters::CellCenters()
{
  this->SetOutputFieldName("");
}

template<typename ArrayHandleType, typename Policy, typename DeviceAdapter>
VTKM_CONT
vtkm::filter::ResultField
CellCenters::DoExecute(const vtkm::cont::DataSet &inDataSet,
                       const ArrayHandleType &inField,
                       const vtkm::filter::FieldMetadata &fieldMetadata,
                       vtkm::filter::PolicyBase<Policy>,
                       DeviceAdapter)
{
  VTKM_IS_ARRAY_HANDLE(ArrayHandleType);
  VTKM_IS_DEVICE_ADAPTER_TAG(DeviceAdapter);

  if (!fieldMetadata.IsPointField())
  {
    throw vtkm::cont::ErrorControlBadType(
          "Cell Centers filter operates on point data.");
  }

  vtkm::cont::DynamicCellSet cellSet =
      inDataSet.GetCellSet(this->GetActiveCellSetIndex());

  using ValueType = typename ArrayHandleType::ValueType;
  vtkm::cont::ArrayHandle<ValueType> outField;

  vtkm::worklet::DispatcherMapTopology<vtkm::worklet::CellCenter, DeviceAdapter>
      dispatcher;

  dispatcher.Invoke(vtkm::filter::ApplyPolicy(cellSet, Policy()),
                    inField,
                    outField);

  std::string outFieldName = this->GetOutputFieldName();
  if (outFieldName == "")
  {
    outFieldName = fieldMetadata.GetName() + "_center";
  }

  return vtkm::filter::ResultField(inDataSet,
                                   outField,
                                   outFieldName,
                                   vtkm::cont::Field::ASSOC_CELL_SET,
                                   cellSet.GetName());
}

}
} // namespace vtkm::filter
```

Common Errors

The policy passed to the `DoExecute` *method contains information on what types of cell sets should be supported by the execution. This list of cell set types could be different than the default types specified the* `DynamicCellSet` *returned from* `DataSet::GetCellSet()`*. Thus, it is important to apply the policy to the cell set before passing it to the dispatcher's invoke method. The policy is applied by calling the* `vtkm::filter::ApplyPolicy` *function on the* `DynamicCellSet`*. The use of* `ApplyPolicy` *is demonstrated in Example 15.4.* [THE DETAILS OF THIS MAY CHANGE WHEN MOVING TO VIRTUAL METHODS.]

[ADD DOCUMENTATION FOR `vtkm::filter::FilterDataSet` AND `vtkm::filter::FilterDataSetWithField`. THESE WILL MAKE MORE SENSE ONCE WE HAVE WORKLET TYPES THAT SUPPORT CREATING NEW TOPOLOGIES.]

CHAPTER

SIXTEEN

MATH

VTK-m comes with several math functions that tend to be useful for visualization algorithms. The implementation of basic math operations can vary subtly on different accelerators, and these functions provide cross platform support.

All math functions are located in the `vtkm` package. The functions are most useful in the execution environment, but they can also be used in the control environment when needed.

16.1 Basic Math

The vtkm/Math.h header file contains several math functions that replicate the behavior of the basic POSIX math functions as well as related functionality.

Did you know?

When writing worklets, you should favor using these math functions provided by VTK-m over the standard math functions in math.h*. VTK-m's implementation manages several compiling and efficiency issues when porting.*

`vtkm::Abs` Returns the absolute value of the single argument. If given a vector, performs a component-wise operation.

`vtkm::ACos` Returns the arccosine of a ratio in radians. If given a vector, performs a component-wise operation.

`vtkm::ACosH` Returns the hyperbolic arccossine. If given a vector, performs a component-wise operation.

`vtkm::ASin` Returns the arcsine of a ratio in radians. If given a vector, performs a component-wise operation.

`vtkm::ASinH` Returns the hyperbolic arcsine. If given a vector, performs a component-wise operation.

`vtkm::ATan` Returns the arctangent of a ratio in radians. If given a vector, performs a component-wise operation.

`vtkm::ATan2` Computes the arctangent of y/x where y is the first argument and x is the second argument. `ATan2` uses the signs of both arguments to determine the quadrant of the return value. `ATan2` is only defined for floating point types (no vectors).

`vtkm::ATanH` Returns the hyperbolic arctangent. If given a vector, performs a component-wise operation.

`vtkm::Cbrt` Takes one argument and returns the cube root of that argument. If called with a vector type, returns a component-wise cube root.

`vtkm::Ceil` Rounds and returns the smallest integer not less than the single argument. If given a vector, performs a component-wise operation.

`vtkm::CopySign` Copies the sign of the second argument onto the first argument and returns that. If the second argument is positive, returns the absolute value of the first argument. If the second argument is negative, returns the negative absolute value of the first argument.

`vtkm::Cos` Returns the cosine of an angle given in radians. If given a vector, performs a component-wise operation.

`vtkm::CosH` Returns the hyperbolic cosine. If given a vector, performs a component-wise operation.

`vtkm::Epsilon` Returns the difference between 1 and the least value greater than 1 that is representable by a floating point number. Epsilon is useful for specifying the tolerance one should have when considering numerical error. The `Epsilon` method is templated to specify either a 32 or 64 bit floating point number. The convenience methods `Epsilon32` and `Epsilon64` are non-templated versions that return the precision for a particular precision.

`vtkm::Exp` Computes e^x where x is the argument to the function and e is Euler's number (approximately 2.71828). If called with a vector type, returns a component-wise exponent.

`vtkm::Exp10` Computes 10^x where x is the argument. If called with a vector type, returns a component-wise exponent.

`vtkm::Exp2` Computes 2^x where x is the argument. If called with a vector type, returns a component-wise exponent.

`vtkm::ExpM1` Computes $e^x - 1$ where x is the argument to the function and e is Euler's number (approximately 2.71828). The accuracy of this function is good even for very small values of x. If called with a vector type, returns a component-wise exponent.

`vtkm::Floor` Rounds and returns the largest integer not greater than the single argument. If given a vector, performs a component-wise operation.

`vtkm::FMod` Computes the remainder on the division of 2 floating point numbers. The return value is $numerator - n \cdot denominator$, where *numerator* is the first argument, *denominator* is the second argument, and n is the quotient of *numerator* divided by *denominator* rounded towards zero to an integer. For example, `FMod(6.5,2.3)` returns 1.9, which is $6.5 - 2 \cdot 4.6$. If given vectors, `FMod` performs a component-wise operation. `FMod` is similar to `Remainder` except that the quotient is rounded toward 0 instead of the nearest integer.

`vtkm::Infinity` Returns the representation for infinity. The result is greater than any other number except another infinity or NaN. When comparing two infinities or infinity to NaN, neither is greater than, less than, nor equal to the other. The `Infinity` method is templated to specify either a 32 or 64 bit floating point number. The convenience methods `Infinity32` and `Infinity64` are non-templated versions that return the precision for a particular precision.

`vtkm::IsFinite` Returns true if the argument is a normal number (neither a NaN nor an infinite).

`vtkm::IsInf` Returns true if the argument is either positive infinity or negative infinity.

`vtkm::IsNan` Returns true if the argument is not a number (NaN).

`vtkm::IsNegative` Returns true if the single argument is less than zero, false otherwise.

`vtkm::Log` Computes the natural logarithm (i.e. logarithm to the base e) of the single argument. If called with a vector type, returns a component-wise logarithm.

`vtkm::Log10` Computes the logarithm to the base 10 of the single argument. If called with a vector type, returns a component-wise logarithm.

`vtkm::Log1P` Computes $\ln(1+x)$ where x is the single argument and ln is the natural logarithm (i.e. logarithm to the base e). The accuracy of this function is good for very small values. If called with a vector type, returns a component-wise logarithm.

`vtkm::Log2` Computes the logarithm to the base 2 of the single argument. If called with a vector type, returns a component-wise logarithm.

`vtkm::Max` Takes two arguments and returns the argument that is greater. If called with a vector type, returns a component-wise maximum.

`vtkm::Min` Takes two arguments and returns the argument that is lesser. If called with a vector type, returns a component-wise minimum.

`vtkm::ModF` Returns the integral and fractional parts of the first argument. The second argument is a reference in which the integral part is stored. The return value is the fractional part. If given vectors, `ModF` performs a component-wise operation.

`vtkm::Nan` Returns the representation for not-a-number (NaN). A NaN represents an invalid value or the result of an invalid operation such as 0/0. A NaN is neither greater than nor less than nor equal to any other number including other NaNs. The `NaN` method is templated to specify either a 32 or 64 bit floating point number. The convenience methods `Nan32` and `NaN64` are non-templated versions that return the precision for a particular precision.

`vtkm::NegativeInfinity` Returns the representation for negative infinity. The result is less than any other number except another negative infinity or NaN. When comparing two negative infinities or negative infinity to NaN, neither is greater than, less than, nor equal to the other. The `NegativeInfinity` method is templated to specify either a 32 or 64 bit floating point number. The convenience methods `NagativeInfinity32` and `NegativeInfinity64` are non-templated versions that return the precision for a particular precision.

`vtkm::Pi` Returns the constant π (about 3.14159).

`vtkm::Pi_2` Returns the constant $\pi/2$ (about 1.570796).

`vtkm::Pi_3` Returns the constant $\pi/3$ (about 1.047197).

`vtkm::Pi_4` Returns the constant $\pi/4$ (about 0.785398).

`vtkm::Pow` Takes two arguments and returns the first argument raised to the power of the second argument. This function is only defined for `vtkm::Float32` and `vtkm::Float64`.

`vtkm::RCbrt` Takes one argument and returns the cube root of that argument. The result of this function is equivalent to `1/Cbrt(x)`. However, on some devices it is faster to compute the reciprocal cube root than the regular cube root. Thus, you should use this function whenever dividing by the cube root.

`vtkm::Remainder` Computes the remainder on the division of 2 floating point numbers. The return value is $numerator - n \cdot denominator$, where *numerator* is the first argument, *denominator* is the second argument, and n is the quotient of *numerator* divided by *denominator* rounded towards the nearest integer. For example, `FMod(6.5,2.3)` returns -0.4, which is $6.5 - 3 \cdot 2.3$. If given vectors, `Remainder` performs a component-wise operation. `Remainder` is similar to `FMod` except that the quotient is rounded toward the nearest integer instead of toward 0.

vtkm::RemainderQuotient Performs an operation identical to Reminder. In addition, this function takes a third argument that is a reference in which the quotient is given.

vtkm::Round Rounds and returns the integer nearest the single argument. If given a vector, performs a component-wise operation.

vtkm::RSqrt Takes one argument and returns the square root of that argument. The result of this function is equivalent to `1/Sqrt(x)`. However, on some devices it is faster to compute the reciprocal square root than the regular square root. Thus, you should use this function whenever dividing by the square root.

vtkm::SignBit Returns a nonzero value if the single argument is negative.

vtkm::Sin Returns the sine of an angle given in radians. If given a vector, performs a component-wise operation.

vtkm::SinH Returns the hyperbolic sine. If given a vector, performs a component-wise operation.

vtkm::Sqrt Takes one argument and returns the square root of that argument. If called with a vector type, returns a component-wise square root. On some hardware it is faster to find the reciprocal square root, so RSqrt should be used if you actually plan to divide byt the square root.

vtkm::Tan Returns the tangent of an angle given in radians. If given a vector, performs a component-wise operation.

vtkm::TanH Returns the hyperbolic tangent. If given a vector, performs a component-wise operation.

vtkm::TwoPi Returns the constant 2π (about 6.283185).

16.2 Vector Analysis

Visualization and computational geometry algorithms often perform vector analysis operations. The vtkm/-VectorAnalysis.h header file provides functions that perform the basic common vector analysis operations.

vtkm::Cross Returns the cross product of two vtkm::Vec of size 3.

vtkm::Lerp Given two values x and y in the first two parameters and a weight w as the third parameter, interpolates between x and y. Specifically, the linear interpolation is $(y-x)w+x$ although Lerp might compute the interpolation faster than using the independent arithmetic operations. The two values may be scalars or equal sized vectors. If the two values are vectors and the weight is a scalar, all components of the vector are interpolated with the same weight. If the weight is also a vector, then each component of the value vectors are interpolated with the respective weight component.

vtkm::Magnitude Returns the magnitude of a vector. This function works on scalars as well as vectors, in which case it just returns the scalar. It is usually much faster to compute MagnitudeSquared, so that should be substituted when possible (unless you are just going to take the square root, which would be besides the point). On some hardware it is also faster to find the reciprocal magnitude, so RMagnitude should be used if you actually plan to divide by the magnitude.

vtkm::MagnitudeSquared Returns the square of the magnitude of a vector. It is usually much faster to compute the square of the magnitude than the length, so you should use this function in place of Magnitude or RMagnitude when needing the square of the magnitude or any monotonically increasing function of a magnitude or distance. This function works on scalars as well as vectors, in which case it just returns the square of the scalar.

`vtkm::Normal` Returns a normalized version of the given vector. The resulting vector points in the same direction as the argument but has unit length.

`vtkm::Normalize` Takes a reference to a vector and modifies it to be of unit length. `Normalize(v)` is functionally equivalent to `v *= RMagnitude(v)`.

`vtkm::RMagnitude` Returns the reciprocal magnitude of a vector. On some hardware `RMagnitude` is faster than `Magnitude`, but neither is as fast as `MagnitudeSquared`. This function works on scalars as well as vectors, in which case it just returns the reciprocal of the scalar.

`vtkm::TriangleNormal` Given three points in space (contained in `vtkm::Vec`s of size 3) that compose a triangle return a vector that is perpendicular to the triangle. The magnitude of the result is equal to twice the area of the triangle. The result points away from the "front" of the triangle as defined by the standard counter-clockwise ordering of the points.

16.3 Matrices

Linear algebra operations on small matrices that are done on a single thread are located in vtkm/Matrix.h.

This header defines the `vtkm::Matrix` templated class. The template parameters are first the type of component, then the number of rows, then the number of columns. The overloaded parentheses operator can be used to retrieve values based on row and column indices. Likewise, the bracket operators can be used to reference the `Matrix` as a 2D array (indexed by row first). The following example builds a `Matrix` that contains the values

$$\begin{vmatrix} 0 & 1 & 2 \\ 10 & 11 & 12 \end{vmatrix}$$

Example 16.1: Creating a `Matrix`.

```cpp
vtkm::Matrix<vtkm::Float32, 2, 3> matrix;

// Using parenthesis notation.
matrix(0,0) = 0.0f;
matrix(0,1) = 1.0f;
matrix(0,2) = 2.0f;

// Using bracket notation.
matrix[1][0] = 10.0f;
matrix[1][1] = 11.0f;
matrix[1][2] = 12.0f;
```

The vtkm/Matrix.h header also defines the following functions that operate on matrices.

`vtkm::MatrixDeterminant` Takes a square `Matrix` as its single argument and returns the determinant of that matrix.

`vtkm::MatrixGetColumn` Given a `Matrix` and a column index, returns a `vtkm::Vec` of that column. This function might not be as efficient as `vtkm::MatrixRow`. (It performs a copy of the column).

`vtkm::MatrixGetRow` Given a `Matrix` and a row index, returns a `vtkm::Vec` of that row.

`vtkm::MatrixIdentity` Returns the identity matrix. If given no arguments, it creates an identity matrix and returns it. (In this form, the component type and size must be explicitly set.) If given a single square matrix argument, fills that matrix with the identity.

vtkm::MatrixInverse Finds and returns the inverse of a given matrix. The function takes two arguments. The first argument is the matrix to invert. The second argument is a reference to a Boolean that is set to true if the inverse is found or false if the matrix is singular and the returned matrix is incorrect.

vtkm::MatrixMultiply Performs a matrix-multiply on its two arguments. Overloaded to work for matrix-matrix, vector-matrix, or matrix-vector multiply.

vtkm::MatrixSetColumn Given a Matrix, a column index, and a vtkm::Vec, sets the column of that index to the values of the Tuple.

vtkm::MatrixSetRow Given a Matrix, a row index, and a vtkm::Vec, sets the row of that index to the values of the Tuple.

vtkm::MatrixTranspose Takes a Matrix and returns its transpose.

vtkm::SolveLinearSystem Solves the linear system $Ax = b$ and returns x. The function takes three arguments. The first two arguments are the matrix A and the vector b, respectively. The third argument is a reference to a Boolean that is set to true if a single solution is found, false otherwise.

16.4 Newton's Method

VTK-m's matrix methods (documented in Section 16.3) provide a method to solve a small linear system of equations. However, sometimes it is necessary to solve a small nonlinear system of equations. This can be done with the vtkm::NewtonsMethod function defined in the vtkm/NewtonsMethod.h header.

The NewtonsMethod function assumes that the number of variables equals the number of equations. Newton's method operates on an iterative evaluate and search. Evaluations are performed using the functors passed into the NewtonsMethod. The function takes the following 6 parameters (three of which are optional).

1. A functor whose operation takes a vtkm::Vec and returns a vtkm::Matrix containing the math function's Jacobian vector at that point.
2. A functor whose operation takes a vtkm::Vec and returns the evaluation of the math function at that point as another vtkm::Vec.
3. The vtkm::Vec that represents the desired output of the function.
4. A vtkm::Vec to use as the initial guess. If not specified, the origin is used.
5. The convergence distance. If the iterative method changes all values less than this amount, then it considers the solution found. If not specified, set to 10^{-3}.
6. The maximum amount of iterations to run before giving up and returning the best solution. If not specified, set to 10.

Example 16.2: Using NewtonsMethod to solve a small system of nonlinear equations.

```
// A functor for the mathematical function f(x) = [dot(x,x),x[0]*x[1]]
struct FunctionFunctor
{
  template<typename T>
  VTKM_EXEC_CONT
  vtkm::Vec<T,2> operator()(const vtkm::Vec<T,2> &x) const
  {
    return vtkm::make_Vec(vtkm::dot(x,x), x[0]*x[1]);
  }
};

// A functor for the Jacobian of the mathematical function
// f(x) = [dot(x,x),x[0]*x[1]], which is
//   | 2*x[0] 2*x[1] |
//   |   x[1]   x[0] |
struct JacobianFunctor
{
  template<typename T>
  VTKM_EXEC_CONT
  vtkm::Matrix<T,2,2> operator()(const vtkm::Vec<T,2> &x) const
  {
    vtkm::Matrix<T,2,2> jacobian;
    jacobian(0,0) = 2*x[0];
    jacobian(0,1) = 2*x[1];
    jacobian(1,0) = x[1];
    jacobian(1,1) = x[0];

    return jacobian;
  }
};

VTKM_EXEC
void SolveNonlinear()
{
  // Use Newton's method to solve the nonlinear system of equations:
  //
  //    x^2 + y^2 = 2
  //    x*y = 1
  //
  // There are two possible solutions, which are (x=1,y=1) and (x=-1,y=-1).
  // The one found depends on the starting value.
  vtkm::Vec<vtkm::Float32,2> answer1 =
      vtkm::NewtonsMethod(JacobianFunctor(),
                          FunctionFunctor(),
                          vtkm::make_Vec(2.0f, 1.0f),
                          vtkm::make_Vec(1.0f, 0.0f));
  // answer1 is [1,1]

  vtkm::Vec<vtkm::Float32,2> answer2 =
      vtkm::NewtonsMethod(JacobianFunctor(),
                          FunctionFunctor(),
                          vtkm::make_Vec(2.0f, 1.0f),
                          vtkm::make_Vec(0.0f, -2.0f));
  // answer2 is [-1,-1]
}
```

CHAPTER

SEVENTEEN

WORKING WITH CELLS

In the control environment, data is defined in mesh structures that comprise a set of finite cells. (See Section 12.2 starting on page 118 for information on defining cell sets in the control environment.) When worklets that operate on cells are scheduled, these grid structures are broken into their independent cells, and that data is handed to the worklet. Thus, cell-based operations in the execution environment exclusively operate on independent cells.

Unlike some other libraries such as VTK, VTK-m does not have a cell class that holds all the information pertaining to a cell of a particular type. Instead, VTK-m provides tags or identifiers defining the cell shape, and companion data like coordinate and field information are held in separate structures. This organization is designed so a worklet may specify exactly what information it needs, and only that information will be loaded.

17.1 Cell Shape Tags and Ids

Cell shapes can be specified with either a tag (defined with a struct with a name like `CellShapeTag*`) or an enumerated identifier (defined with a constant number with a name like `CELL_SHAPE_*`). These shape tags and identifiers are defined in vtkm/CellShape.h and declared in the `vtkm` namespace (because they can be used in either the control or the execution environment). Figure 17.1 gives both the identifier and the tag names.

In addition to the basic cell shapes, there is a special "empty" cell with the identifier `vtkm::CELL_SHAPE_EMPTY` and tag `vtkm::CellShapeTagEmpty`. This type of cell has no points, edges, or faces and can be thought of as a placeholder for a null or void cell.

There is also a special cell shape "tag" named `vtkm::CellShapeTagGeneric` that is used when the actual cell shape is not known at compile time. `CellShapeTagGeneric` actually has a member variable named `Id` that stores the identifier for the cell shape. There is no equivalent identifier for a generic cell; cell shape identifiers can be placed in a `vtkm::IdComponent` at runtime.

When using cell shapes in templated classes and functions, you can use the `VTKM_IS_CELL_SHAPE_TAG` to ensure a type is a valid cell shape tag. This macro takes one argument and will produce a compile error if the argument is not a cell shape tag type.

17.1.1 Converting Between Tags and Identifiers

Every cell shape tag has a member variable named `Id` that contains the identifier for the cell shape. This provides a convenient mechanism for converting a cell shape tag to an identifier. Most cell shape tags have their `Id` member as a compile-time constant, but `CellShapeTagGeneric` is set at run time.

vtkm/CellShape.h also declares a templated class named `vtkm::CellShapeIdToTag` that converts a cell shape

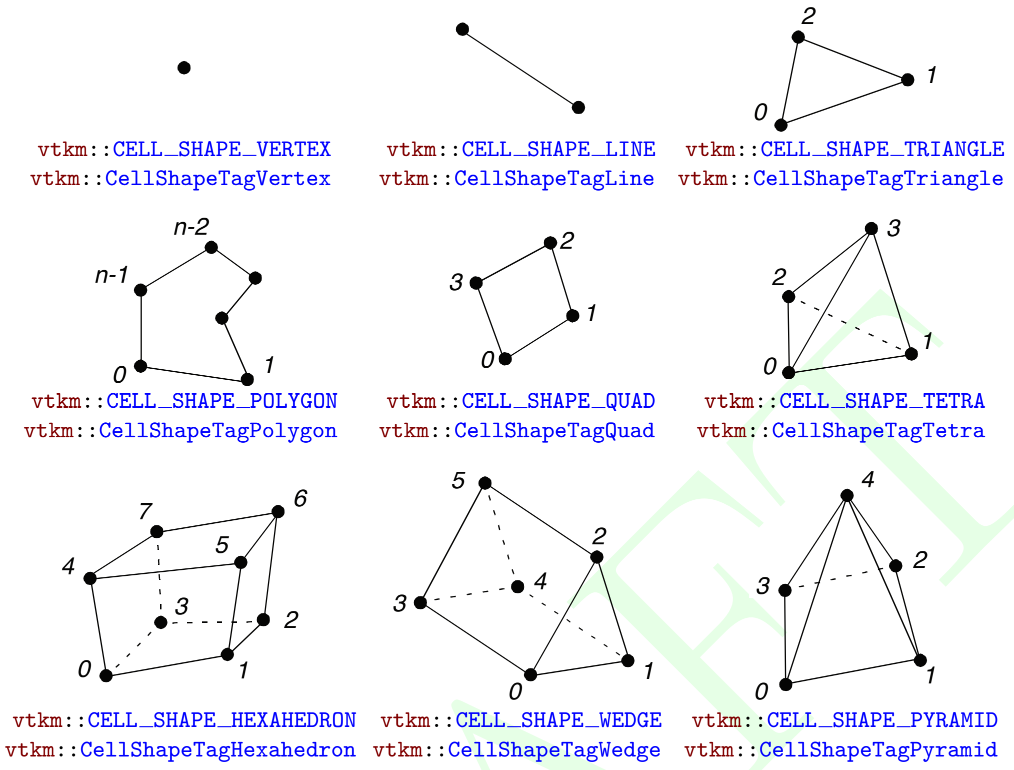


Figure 17.1: Basic Cell Shapes

identifier to a cell shape tag. CellShapeIdToTag has a single template argument that is the identifier. Inside the class is a type named Tag that is the type of the correct tag.

Example 17.1: Using CellShapeIdToTag.

```
void CellFunction(vtkm::CellShapeTagTriangle)
{
  std::cout << "In CellFunction for triangles." << std::endl;
}

void DoSomethingWithACell()
{
  // Calls CellFunction overloaded with a vtkm::CellShapeTagTriangle.
  CellFunction(vtkm::CellShapeIdToTag<vtkm::CELL_SHAPE_TRIANGLE>::Tag());
}
```

However, CellShapeIdToTag is only viable if the identifier can be resolved at compile time. In the case where a cell identifier is stored in a variable or an array or the code is using a CellShapeTagGeneric, the correct cell shape is not known at run time. In this case, vtkmGenericCellShapeMacro can be used to check all possible conditions. This macro is embedded in a switch statement where the condition is the cell shape identifier. vtkmGenericCellShapeMacro has a single argument, which is an expression to be executed. Before the expression is executed, a type named CellShapeTag is defined as the type of the appropriate cell shape tag. Often this method is used to implement the condition for a CellShapeTagGeneric in a function overloaded for cell types. A demonstration of vtkmGenericCellShapeMacro is given in Example 17.2.

17.1.2 Cell Traits

The vtkm/CellTraits.h header file contains a traits class named vtkm::CellTraits that provides information about a cell. Each specialization of CellTraits contains the following members.

TOPOLOGICAL_DIMENSIONS Defines the topological dimensions of the cell type. This is 3 for polyhedra, 2 for polygons, 1 for lines, and 0 for points.

TopologicalDimensionsTag A type set to either vtkm::CellTopologicalDimensionsTag<3>, CellTopologicalDimensionsTag<2>, CellTopologicalDimensionsTag<1>, or CellTopologicalDimensionsTag<0>. The number is consistent with TOPOLOGICAL_DIMENSIONS. This tag is provided for convenience when specializing functions.

IsSizeFixed Set to either vtkm::CellTraitsTagSizeFixed for cell types with a fixed number of points (for example, triangle) or vtkm::CellTraitsTagSizeVariable for cell types with a variable number of points (for example, polygon).

NUM_POINTS A vtkm::IdComponent set to the number of points in the cell. This member is only defined when there is a constant number of points (i.e. IsSizeFixed is set to vtkm::CellTraitsTagSizeFixed).

Example 17.2: Using CellTraits to implement a polygon normal estimator.

```
namespace detail {

VTKM_SUPPRESS_EXEC_WARNINGS
template<typename PointCoordinatesVector, typename WorkletType>
VTKM_EXEC_CONT
typename PointCoordinatesVector::ComponentType
CellNormalImpl(const PointCoordinatesVector &pointCoordinates,
               vtkm::CellTopologicalDimensionsTag<2>,
               const WorkletType &worklet)
{
  if (pointCoordinates.GetNumberOfComponents() >= 3)
  {
    return vtkm::TriangleNormal(pointCoordinates[0],
                                pointCoordinates[1],
                                pointCoordinates[2]);
  }
  else
  {
    worklet.RaiseError("Degenerate polygon.");
    return typename PointCoordinatesVector::ComponentType();
  }
}

VTKM_SUPPRESS_EXEC_WARNINGS
template<typename PointCoordinatesVector,
         vtkm::IdComponent Dimensions,
         typename WorkletType>
VTKM_EXEC_CONT
typename PointCoordinatesVector::ComponentType
CellNormalImpl(const PointCoordinatesVector &,
               vtkm::CellTopologicalDimensionsTag<Dimensions>,
               const WorkletType &worklet)
{
  worklet.RaiseError("Only polygons supported for cell normals.");
  return typename PointCoordinatesVector::ComponentType();
}

} // namespace detail
```

```

VTKM_SUPPRESS_EXEC_WARNINGS
template<typename CellShape,
         typename PointCoordinatesVector,
         typename WorkletType>
VTKM_EXEC_CONT
typename PointCoordinatesVector::ComponentType
CellNormal(CellShape,
           const PointCoordinatesVector &pointCoordinates,
           const WorkletType &worklet)
{
  return detail::CellNormalImpl(
        pointCoordinates,
        typename vtkm::CellTraits<CellShape>::TopologicalDimensionsTag(),
        worklet);
}

VTKM_SUPPRESS_EXEC_WARNINGS
template<typename PointCoordinatesVector,
         typename WorkletType>
VTKM_EXEC_CONT
typename PointCoordinatesVector::ComponentType
CellNormal(vtkm::CellShapeTagGeneric shape,
           const PointCoordinatesVector &pointCoordinates,
           const WorkletType &worklet)
{
  switch(shape.Id)
  {
    vtkmGenericCellShapeMacro(
          return CellNormal(CellShapeTag(), pointCoordinates, worklet));
    default:
      worklet.RaiseError("Unknown cell type.");
      return typename PointCoordinatesVector::ComponentType();
  }
}
```

17.2 Parametric and World Coordinates

Each cell type supports a one-to-one mapping between a set of parametric coordinates in the unit cube (or some subset of it) and the points in 3D space that are the locus contained in the cell. Parametric coordinates are useful because certain features of the cell, such as vertex location and center, are at a consistent location in parametric space irrespective of the location and distortion of the cell in world space. Also, many field operations are much easier with parametric coordinates.

The vtkm/exec/ParametricCoordinates.h header file contains the following functions for working with parametric coordinates.

`vtkm::exec::ParametricCoordinatesCenter` Returns the parametric coordinates for the center of a given shape. It takes 4 arguments: the number of points in the cell, a `vtkm::Vec` of size 3 to store the results, a shape tag, and a worklet object (for raising errors). A second form of this method takes 3 arguments and returns the result as a `vtkm::Vec<vtkm::FloatDefault,3>` instead of passing it as a parameter.

`vtkm::exec::ParametricCoordinatesPoint` Returns the parametric coordinates for a given point of a given shape. It takes 5 arguments: the number of points in the cell, the index of the point to query, a `vtkm::Vec` of size 3 to store the results, a shape tag, and a worklet object (for raising errors). A second form of this method takes 3 arguments and returns the result as a `vtkm::Vec<vtkm::FloatDefault,3>` instead of passing it as a parameter.

vtkm::exec::ParametricCoordinatesToWorldCoordinates Given a vector of point coordinates (usually given by a FieldPointIn worklet argument), a vtkm::Vec of size 3 containing parametric coordinates, a shape tag, and a worklet object (for raising errors), returns the world coordinates.

vtkm::exec::WorldCoordinatesToParametricCoordinates Given a vector of point coordinates (usually given by a FieldPointIn worklet argument), a vtkm::Vec of size 3 containing world coordinates, a shape tag, and a worklet object (for raising errors), returns the parametric coordinates. This function can be slow for cell types with nonlinear interpolation (which is anything that is not a simplex).

17.3 Interpolation

The shape of every cell is defined by the connections of some finite set of points. Field values defined on those points can be interpolated to any point within the cell to estimate a continuous field.

The vtkm/exec/CellInterpolate.h header contains the function vtkm::exec::CellInterpolate that takes a vector of point field values (usually given by a FieldPointIn worklet argument), a vtkm::Vec of size 3 containing parametric coordinates, a shape tag, and a worklet object (for raising errors). It returns the field interpolated to the location represented by the given parametric coordinates.

Example 17.3: Interpolating field values to a cell's center.

```
struct CellCenters : vtkm::worklet::WorkletMapPointToCell
{
  typedef void ControlSignature(CellSetIn,
                                FieldInPoint<> inputField,
                                FieldOutCell<> outputField);
  typedef void ExecutionSignature(CellShape, PointCount, _2, _3);
  typedef _1 InputDomain;

  template<typename CellShapeTag,typename FieldInVecType,typename FieldOutType>
  VTKM_EXEC
  void operator()(CellShapeTag shape,
                  vtkm::IdComponent pointCount,
                  const FieldInVecType &inputField,
                  FieldOutType &outputField) const
  {
    vtkm::Vec<vtkm::FloatDefault,3> center =
        vtkm::exec::ParametricCoordinatesCenter(pointCount, shape, *this);
    outputField = vtkm::exec::CellInterpolate(inputField, center, shape, *this);
  }
};
```

17.4 Derivatives

Since interpolations provide a continuous field function over a cell, it is reasonable to consider the derivative of this function. The vtkm/exec/CellDerivative.h header contains the function vtkm::exec::CellDerivative that takes a vector of scalar point field values (usually given by a FieldPointIn worklet argument), a vtkm::Vec of size 3 containing parametric coordinates, a shape tag, and a worklet object (for raising errors). It returns the field derivative at the location represented by the given parametric coordinates. The derivative is return in a vtkm::Vec of size 3 corresponding to the partial derivatives in the x, y, and z directions. This derivative is equivalent to the gradient of the field.

Example 17.4: Computing the derivative of the field at cell centers.

```
struct CellDerivatives : vtkm::worklet::WorkletMapPointToCell
{
  typedef void ControlSignature(CellSetIn,
                                FieldInPoint<> inputField,
                                FieldInPoint<Vec3> pointCoordinates,
                                FieldOutCell<> outputField);
  typedef void ExecutionSignature(CellShape, PointCount, _2, _3, _4);
  typedef _1 InputDomain;

  template<typename CellShapeTag,
           typename FieldInVecType,
           typename PointCoordVecType,
           typename FieldOutType>
  VTKM_EXEC
  void operator()(CellShapeTag shape,
                  vtkm::IdComponent pointCount,
                  const FieldInVecType &inputField,
                  const PointCoordVecType &pointCoordinates,
                  FieldOutType &outputField) const
  {
    vtkm::Vec<vtkm::FloatDefault,3> center =
        vtkm::exec::ParametricCoordinatesCenter(pointCount, shape, *this);
    outputField = vtkm::exec::CellDerivative(inputField,
                                             pointCoordinates,
                                             center,
                                             shape,
                                             *this);
  }
};
```

17.5 Edges and Faces

As explained earlier in this chapter, a cell is defined by a collection of points and a shape identifier that describes how the points come together to form the structure of the cell. The cell shapes supported by VTK-m are documented in Section 17.1. It contains Figure 17.1 on page 174, which shows how the points for each shape form the structure of the cell.

Most cell shapes can be broken into subelements. 2D and 3D cells have pairs of points that form *edges* at the boundaries of the cell. Likewise, 3D cells have loops of edges that form *faces* that encase the cell. Figure 17.2 demonstrates the relationship of these constituent elements for some example cell shapes.

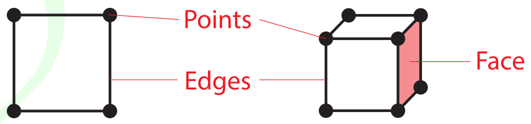


Figure 17.2: The constituent elements (points, edges, and faces) of cells.

The header file vtkm/exec/CellEdge.h contains a collection of functions to help identify the edges of a cell. The first such function is `vtkm::exec::CellEdgeNumberOfEdges`. This function takes the number of points in the cell, the shape of the cell, and an instance of the calling worklet (for error reporting). It returns the number of edges the cell has (as a `vtkm::IdComponent`).

The second function is `vtkm::exec::CellEdgeLocalIndices`. This function takes the number of points, the local index of the edge (0 to the number of edges in the cell), the shape of the cell, and an instance of the calling worklet. It returns a `vtkm::Vec<vtkm::IdComponent,2>` containing the local indices of the two points forming the edge. These local indices are consistent with the point labels in Figure 17.2. To get the point indices relative to the data set, the edge indices should be used to reference a PointIndices list.

The following example demonstrates a pair of worklets that use the cell edge functions. As is typical for operations of this nature, one worklet counts the number of edges in each cell and another uses this count to generate the data. [ONCE DONE, SHOULD REFERENCE MORE COMPLETE DOCUMENTATION OF THIS CODE IN A CHAPTER ON HOW TO GENERATE TOPOLOGY.]

Example 17.5: Using cell edge functions.

```
struct EdgesCount : vtkm::worklet::WorkletMapPointToCell
{
  typedef void ControlSignature(CellSetIn,
                                FieldOutCell<> numEdgesInCell);
  typedef _2 ExecutionSignature(CellShape, PointCount);
  typedef _1 InputDomain;

  template<typename CellShapeTag>
  VTKM_EXEC
  vtkm::IdComponent
  operator()(CellShapeTag shape, vtkm::IdComponent numPointsInCell) const
  {
    return vtkm::exec::CellEdgeNumberOfEdges(numPointsInCell, shape, *this);
  }
};

struct EdgesExtract : vtkm::worklet::WorkletMapPointToCell
{
  typedef void ControlSignature(CellSetIn,
                                FieldOutCell<> edgeIndices);
  typedef void ExecutionSignature(CellShape, PointIndices, VisitIndex, _2);
  typedef _1 InputDomain;

  typedef vtkm::worklet::ScatterCounting ScatterType;
  VTKM_CONT ScatterType GetScatter() const { return this->Scatter; }

  VTKM_CONT
  EdgesExtract(const ScatterType &scatter)
    : Scatter(scatter) {  }

  template<typename CellShapeTag,
           typename PointIndexVecType,
           typename EdgeIndexVecType>
  VTKM_EXEC
  void operator()(CellShapeTag shape,
                  const PointIndexVecType &pointIndices,
                  vtkm::IdComponent visitIndex,
                  EdgeIndexVecType &edgeIndices) const
  {
    vtkm::Vec<vtkm::IdComponent,2> localEdgeIndices =
        vtkm::exec::CellEdgeLocalIndices(pointIndices.GetNumberOfComponents(),
                                         visitIndex,
                                         shape,
                                         *this);
    edgeIndices[0] = pointIndices[localEdgeIndices[0]];
    edgeIndices[1] = pointIndices[localEdgeIndices[1]];
  }

private:
  ScatterType Scatter;
};
```

The header file vtkm/exec/CellFace.h contains a collection of functions to help identify the faces of a cell. The first such function is vtkm::exec::CellFaceNumberOfFaces. This function takes the shape of the cell and an instance of the calling worklet (for error reporting). It returns the number of faces the cell has (as a vtkm::-IdComponent).

The second function is vtkm::exec::CellFaceNumberOfPoints. This function takes the local index of the face (0 to the number of faces in the cell), the shape of the cell, and an instance of the calling worklet. It returns the number of points the specified face has (as a vtkm::IdComponent).

The third function is vtkm::exec::CellFaceLocalIndices. This function takes the local index of the face, the shape of the cell, and an instance of the calling worklet. It returns a vtkm::VecCConst<vtkm::IdComponent> containing the local indices of the points forming the face. The points are given in counterclockwise order when viewing the face from the outside of the cell. These local indices are consistent with the point labels in Figure 17.2. To get the point indices relative to the data set, the face indices should be used to reference a PointIndices list.

The following example demonstrates a triple of worklets that use the cell face functions. As is typical for operations of this nature, the worklets are used in steps to first count entities and then generate new entities. In this case, the first worklet counts the number of faces and the second worklet counts the points in each face. The third worklet generates cells for each face. [ONCE DONE, SHOULD REFERENCE MORE COMPLETE DOCUMENTATION OF THIS CODE IN A CHAPTER ON HOW TO GENERATE TOPOLOGY.]

Example 17.6: Using cell face functions.

```
struct FacesCount : vtkm::worklet::WorkletMapPointToCell
{
  typedef void ControlSignature(CellSetIn,
                                FieldOutCell<> numFacesInCell);
  typedef _2 ExecutionSignature(CellShape);
  typedef _1 InputDomain;

  template<typename CellShapeTag>
  VTKM_EXEC
  vtkm::IdComponent
  operator()(CellShapeTag shape) const
  {
    return vtkm::exec::CellFaceNumberOfFaces(shape, *this);
  }
};

struct FacesCountPoints : vtkm::worklet::WorkletMapPointToCell
{
  typedef void ControlSignature(CellSetIn,
                                FieldOutCell<> numPointsInFace,
                                FieldOutCell<> faceShape);
  typedef void ExecutionSignature(CellShape, VisitIndex, _2, _3);
  typedef _1 InputDomain;

  typedef vtkm::worklet::ScatterCounting ScatterType;
  VTKM_CONT ScatterType GetScatter() const { return this->Scatter; }

  VTKM_CONT
  FacesCountPoints(const ScatterType &scatter)
    : Scatter(scatter) {  }

  template<typename CellShapeTag>
  VTKM_EXEC
  void operator()(CellShapeTag shape,
                  vtkm::IdComponent visitIndex,
                  vtkm::IdComponent &numPointsInFace,
                  vtkm::UInt8 &faceShape) const
  {
    numPointsInFace =
        vtkm::exec::CellFaceNumberOfPoints(visitIndex, shape, *this);
    switch (numPointsInFace)
    {
      case 3: faceShape = vtkm::CELL_SHAPE_TRIANGLE; break;
      case 4: faceShape = vtkm::CELL_SHAPE_QUAD; break;
      default: faceShape = vtkm::CELL_SHAPE_POLYGON; break;
    }
  }

private:
  ScatterType Scatter;
};

struct FacesExtract : vtkm::worklet::WorkletMapPointToCell
{
  typedef void ControlSignature(CellSetIn,
                                FieldOutCell<> faceIndices);
  typedef void ExecutionSignature(CellShape, PointIndices, VisitIndex, _2);
  typedef _1 InputDomain;

  typedef vtkm::worklet::ScatterCounting ScatterType;
  VTKM_CONT ScatterType GetScatter() const { return this->Scatter; }

  VTKM_CONT
  FacesExtract(const ScatterType &scatter)
    : Scatter(scatter) {  }

  template<typename CellShapeTag,
           typename PointIndexVecType,
           typename FaceIndexVecType>
  VTKM_EXEC
  void operator()(CellShapeTag shape,
                  const PointIndexVecType &pointIndices,
                  vtkm::IdComponent visitIndex,
                  FaceIndexVecType &faceIndices) const
  {
    vtkm::VecCConst<vtkm::IdComponent> localFaceIndices =
        vtkm::exec::CellFaceLocalIndices(visitIndex,
                                         shape,
                                         *this);

    vtkm::IdComponent numPoints = faceIndices.GetNumberOfComponents();
    VTKM_ASSERT(numPoints == localFaceIndices.GetNumberOfComponents());
    for (vtkm::IdComponent localPointIndex = 0;
         localPointIndex < numPoints;
         localPointIndex++)
    {
      faceIndices[localPointIndex] =
          pointIndices[localFaceIndices[localPointIndex]];
    }
  }

private:
  ScatterType Scatter;
};
```

Part IV

Advanced Development

CHAPTER

EIGHTEEN

IMPLEMENTING DEVICE ADAPTERS

VTK-m comes with several implementations of device adapters so that it may be ported to a variety of platforms. It is also possible to provide new device adapters to support yet more devices, compilers, and libraries. A new device adapter provides a tag, a class to manage arrays in the execution environment, a collection of algorithms that run in the execution environment, and (optionally) a timer.

Most device adapters are associated with some type of device or library, and all source code related directly to that device is placed in a subdirectory of vtkm/cont. For example, files associated with CUDA are in vtkm/cont/cuda and files associated with the Intel Threading Building Blocks (TBB) are located in vtkm/cont/tbb. The documentation here assumes that you are adding a device adapter to the VTK-m source code and following these file conventions. However, it is also possible to define a device adapter outside of the core VTK-m, in which case the file paths might be different.

For the purposes of discussion in this section, we will give a simple example of implementing a device adapter using the `std::thread` class provided by C++11. We will call our device `Cxx11Thread` and place it in the directory vtkm/cont/cxx11.

By convention the implementation of device adapters within VTK-m are divided into 3 header files with the names DeviceAdapterTag∗.h, ArrayManagerExecution∗.h and DeviceAdapterAlgorithm∗.h, which are hidden in internal directories. The DeviceAdapter∗.h that most code includes is a trivial header that simply includes these other three files. For our example `std::thread` device, we will create the base header at vtkm/cont/cxx11/DeviceAdapterCxx11Thread.h. The contents are the following (with minutia like include guards removed).

Example 18.1: Contents of the base header for a device adapter.

```
#include <vtkm/cont/cxx11/internal/DeviceAdapterTagCxx11Thread.h>
#include <vtkm/cont/cxx11/internal/ArrayManagerExecutionCxx11Thread.h>
#include <vtkm/cont/cxx11/internal/DeviceAdapterAlgorithmCxx11Thread.h>
```

The reason VTK-m breaks up the code for its device adapters this way is that there is an interdependence between the implementation of each device adapter and the mechanism to pick a default device adapter. Breaking up the device adapter code in this way maintains an acyclic dependence among header files.

18.1 Tag

The device adapter tag, as described in Section 8.1 is a simple empty type that is used as a template parameter to identify the device adapter. Every device adapter implementation provides one. The device adapter tag is typically defined in an internal header file with a prefix of DeviceAdapterTag.

The device adapter tag should be created with the macro `VTKM_VALID_DEVICE_ADAPTER`. This adapter takes an abbreviated name that it will append to `DeviceAdapterTag` to make the tag structure. It will also create some support classes that allow VTK-m to introspect the device adapter. The macro also expects a unique integer identifier that is usually stored in a macro prefixed with `VTKM_DEVICE_ADAPTER_`. These identifiers for the device adapters provided by the core VTK-m are declared in vtkm/cont/internal/DeviceAdapterTag.h.

The following example gives the implementation of our custom device adapter, which by convention would be placed in the vtkm/cont/cxx11/internal/DeviceAdapterTagCxx11Thread.h header file.

Example 18.2: Implementation of a device adapter tag.

```
#include <vtkm/cont/internal/DeviceAdapterTag.h>

// If this device adapter were to be contributed to VTK-m, then this macro
// declaration should be moved to DeviceAdapterTag.h and given a unique
// number.
#define VTKM_DEVICE_ADAPTER_CXX11_THREAD 101

VTKM_VALID_DEVICE_ADAPTER(Cxx11Thread, VTKM_DEVICE_ADAPTER_CXX11_THREAD);
```

18.2 Array Manager Execution

VTK-m defines a template named `vtkm::cont::internal::ArrayManagerExecution` that is responsible for allocating memory in the execution environment and copying data between the control and execution environment. The execution array manager is typically defined in an internal header file with a prefix of ArrayManagerExecution.

Example 18.3: Prototype for `vtkm::cont::internal::ArrayManagerExecution`.

```
namespace vtkm {
namespace cont {
namespace internal {

template<typename T, typename StorageTag, typename DeviceAdapterTag>
class ArrayManagerExecution;

}
}
} // namespace vtkm::cont::internal
```

A device adapter must provide a partial specialization of `ArrayManagerExecution` for its device adapter tag. The implementation for `ArrayManagerExecution` is expected to manage the resources for a single array. All `ArrayManagerExecution` specializations must have a constructor that takes a pointer to a `vtkm::cont::internal::Storage` object. The `ArrayManagerExecution` should store a reference to this `Storage` object and use it to pass data between control and execution environments. Additionally, `ArrayManagerExecution` must provide the following elements.

`ValueType` A `typedef` of the type for each item in the array. This is the same type as the first template argument.

`PortalType` The type of an array portal that can be used in the execution environment to access the array.

`PortalConstType` A read-only (const) version of `PortalType`.

`GetNumberOfValues` A method that returns the number of values stored in the array. The results are undefined if the data has not been loaded or allocated.

`PrepareForInput` A method that ensures an array is allocated in the execution environment and valid data is there. The method takes a `bool` flag that specifies whether data needs to be copied to the execution environment. (If false, then data for this array has not changed since the last operation.) The method returns a `PortalConstType` that points to the data.

PrepareForInPlace A method that ensures an array is allocated in the execution environment and valid data is there. The method takes a bool flag that specifies whether data needs to be copied to the execution environment. (If false, then data for this array has not changed since the last operation.) The method returns a PortalType that points to the data.

PrepareForOutput A method that takes an array size and allocates an array in the execution environment of the specified size. The initial memory may be uninitialized. The method returns a PortalType to the data.

RetrieveOutputData This method takes a storage object, allocates memory in the control environment, and copies data from the execution environment into it. If the control and execution environments share arrays, then this can be a no-operation.

CopyInto This method takes an STL-compatible iterator and copies data from the execution environment into it.

Shrink A method that adjusts the size of the array in the execution environment to something that is a smaller size. All the data up to the new length must remain valid. Typically, no memory is actually reallocated. Instead, a different end is marked.

ReleaseResources A method that frees any resources (typically memory) in the execution environment.

Specializations of this template typically take on one of two forms. If the control and execution environments have separate memory spaces, then this class behaves by copying memory in methods such as PrepareForInput and RetrieveOutputData. This might require creating buffers in the control environment to efficiently move data from control array portals.

However, if the control and execution environments share the same memory space, the execution array manager can, and should, delegate all of its operations to the Storage it is constructed with. VTK-m comes with a class called vtkm::cont::internal::ArrayManagerExecutionShareWithControl that provides the implementation for an execution array manager that shares a memory space with the control environment. In this case, making the ArrayManagerExecution specialization be a trivial subclass is sufficient. Continuing our example of a device adapter based on C++11's std::thread class, here is the implementation of ArrayManagerExecution, which by convention would be placed in the vtkm/cont/cxx11/internal/ArrayManagerExecutionCxx11Thread.h header file.

Example 18.4: Specialization of ArrayManagerExecution.

```
#include <vtkm/cont/cxx11/internal/DeviceAdapterTagCxx11Thread.h>

#include <vtkm/cont/internal/ArrayManagerExecution.h>
#include <vtkm/cont/internal/ArrayManagerExecutionShareWithControl.h>

namespace vtkm {
namespace cont {
namespace internal {

template<typename T, typename StorageTag>
class ArrayManagerExecution<
      T, StorageTag, vtkm::cont::DeviceAdapterTagCxx11Thread>
    : public vtkm::cont::internal::ArrayManagerExecutionShareWithControl<
        T, StorageTag>
{
  typedef vtkm::cont::internal::ArrayManagerExecutionShareWithControl
      <T, StorageTag> Superclass;

public:
  VTKM_CONT
  ArrayManagerExecution(typename Superclass::StorageType *storage)
    : Superclass(storage) {  }
};

}
}
} // namespace vtkm::cont::internal
```

18.3 Algorithms

A device adapter implementation must also provide a specialization of vtkm::cont::DeviceAdapterAlgorithm, which is documented in Section 8.2. The implementation for the device adapter algorithms is typically placed in a header file with a prefix of DeviceAdapterAlgorithm.

Although there are many methods in DeviceAdapterAlgorithm, it is seldom necessary to implement them all. Instead, VTK-m comes with vtkm::cont::internal::DeviceAdapterAlgorithmGeneral that provides generic implementation for most of the required algorithms. By deriving the specialization of DeviceAdapterAlgorithm from DeviceAdapterAlgorithmGeneral, only the implementations for Schedule and Synchronize need to be implemented. All other algorithms can be derived from those.

That said, not all of the algorithms implemented in DeviceAdapterAlgorithmGeneral are optimized for all types of devices. Thus, it is worthwhile to provide algorithms optimized for the specific device when possible. In particular, it is best to provide specializations for the sort, scan, and reduce algorithms.

It is standard practice to implement a specialization of DeviceAdapterAlgorithm by having it inherit from vtkm::cont::internal::DeviceAdapterAlgorithmGeneral and specializing those methods that are optimized for a particular system. DeviceAdapterAlgorithmGeneral is a templated class that takes as its single template parameter the type of the subclass. For example, a device adapter algorithm structure named DeviceAdapterAlgorithm<DeviceAdapterTagFoo> will subclass DeviceAdapterAlgorithmGeneral<DeviceAdapterAlgorithm<DeviceAdapterTagFoo> >.

Did you know?

The convention of having a subclass be templated on the derived class' type is known as the Curiously Recurring Template Pattern (CRTP). In the case of DeviceAdapterAlgorithmGeneral*, VTK-m uses this CRTP behavior to allow the general implementation of these algorithms to run* Schedule *and other specialized algorithms in the subclass.*

One point to note when implementing the Schedule methods is to make sure that errors handled in the execution environment are handled correctly. As described in Section 14.9, errors are signaled in the execution environment by calling RaiseError on a functor or worklet object. This is handled internally by the vtkm::exec::internal::ErrorMessageBuffer class. ErrorMessageBuffer really just holds a small string buffer, which must be provided by the device adapter's Schedule method.

So, before Schedule executes the functor it is given, it should allocate a small string array in the execution environment, initialize it to the empty string, encapsulate the array in an ErrorMessageBuffer object, and set this buffer object in the functor. When the execution completes, Schedule should check to see if an error exists in this buffer and throw a vtkm::cont::ErrorExecution if an error has been reported.

Common Errors

Exceptions are generally not supposed to be thrown in the execution environment, but it could happen on devices that support them. Nevertheless, few thread schedulers work well when an exception is thrown in them. Thus, when implementing adapters for devices that do support exceptions, it is good practice to catch them within the thread and report them through the `ErrorMessageBuffer`*.*

The following example is a minimal implementation of device adapter algorithms using C++11's `std::thread` class. Note that no attempt at providing optimizations has been attempted (and many are possible). By convention this code would be placed in the vtkm/cont/cxx11/internal/DeviceAdapterAlgorithmCxx11Thread.h header file.

Example 18.5: Minimal specialization of `DeviceAdapterAlgorithm`.

```
#include <vtkm/cont/cxx11/internal/DeviceAdapterTagCxx11Thread.h>

#include <vtkm/cont/DeviceAdapterAlgorithm.h>
#include <vtkm/cont/internal/DeviceAdapterAlgorithmGeneral.h>

#include <thread>

namespace vtkm {
namespace cont {

template<>
struct DeviceAdapterAlgorithm<vtkm::cont::DeviceAdapterTagCxx11Thread>
    : vtkm::cont::internal::DeviceAdapterAlgorithmGeneral<
          DeviceAdapterAlgorithm<vtkm::cont::DeviceAdapterTagCxx11Thread>,
          vtkm::cont::DeviceAdapterTagCxx11Thread>
{
private:
  template<typename FunctorType>
  struct ScheduleKernel1D
  {
    VTKM_CONT
    ScheduleKernel1D(const FunctorType &functor)
      : Functor(functor)
    {  }

    VTKM_EXEC
    void operator()() const
    {
      try
      {
        for (vtkm::Id threadId = this->BeginId;
             threadId < this->EndId;
             threadId++)
        {
          this->Functor(threadId);
          // If an error is raised, abort execution.
          if (this->ErrorMessage.IsErrorRaised()) { return; }
        }
      }
      catch (vtkm::cont::Error error)
      {
        this->ErrorMessage.RaiseError(error.GetMessage().c_str());
      }
      catch (std::exception error)
      {
        this->ErrorMessage.RaiseError(error.what());
      }
      catch (...)
      {
        this->ErrorMessage.RaiseError("Unknown exception raised.");
      }
    }

    FunctorType Functor;
    vtkm::exec::internal::ErrorMessageBuffer ErrorMessage;
    vtkm::Id BeginId;
    vtkm::Id EndId;
  };

  template<typename FunctorType>
  struct ScheduleKernel3D
  {
    VTKM_CONT
    ScheduleKernel3D(const FunctorType &functor, vtkm::Id3 maxRange)
      : Functor(functor), MaxRange(maxRange)
    {  }

    VTKM_EXEC
    void operator()() const
    {
      vtkm::Id3 threadId3D(this->BeginId%this->MaxRange[0],
                           (this->BeginId/this->MaxRange[0])%this->MaxRange[1],
                           this->BeginId/(this->MaxRange[0]*this->MaxRange[1]));

      try
      {
        for (vtkm::Id threadId = this->BeginId;
             threadId < this->EndId;
             threadId++)
        {
          this->Functor(threadId3D);
          // If an error is raised, abort execution.
          if (this->ErrorMessage.IsErrorRaised()) { return; }

          threadId3D[0]++;
          if (threadId3D[0] >= MaxRange[0])
          {
            threadId3D[0] = 0;
            threadId3D[1]++;
            if (threadId3D[1] >= MaxRange[1])
            {
              threadId3D[1] = 0;
              threadId3D[2]++;
            }
          }
        }
      }
      catch (vtkm::cont::Error error)
      {
        this->ErrorMessage.RaiseError(error.GetMessage().c_str());
      }
      catch (std::exception error)
      {
        this->ErrorMessage.RaiseError(error.what());
      }
      catch (...)
      {
        this->ErrorMessage.RaiseError("Unknown exception raised.");
      }
    }

    FunctorType Functor;
    vtkm::exec::internal::ErrorMessageBuffer ErrorMessage;
    vtkm::Id BeginId;
    vtkm::Id EndId;
    vtkm::Id3 MaxRange;
  };

  template<typename KernelType>
  VTKM_CONT
  static void DoSchedule(KernelType kernel,
                         vtkm::Id numInstances)
  {
    if (numInstances < 1) { return; }

    const vtkm::Id MESSAGE_SIZE = 1024;
    char errorString[MESSAGE_SIZE];
    errorString[0] = '\0';
    vtkm::exec::internal::ErrorMessageBuffer errorMessage(errorString,
                                                          MESSAGE_SIZE);
    kernel.Functor.SetErrorMessageBuffer(errorMessage);
    kernel.ErrorMessage = errorMessage;

    vtkm::Id numThreads =
        static_cast<vtkm::Id>(std::thread::hardware_concurrency());
    if (numThreads > numInstances)
    {
      numThreads = numInstances;
    }
    vtkm::Id numInstancesPerThread = (numInstances+numThreads-1)/numThreads;

    std::thread *threadPool = new std::thread[numThreads];
    vtkm::Id beginId = 0;
    for (vtkm::Id threadIndex = 0; threadIndex < numThreads; threadIndex++)
    {
      vtkm::Id endId = std::min(beginId+numInstancesPerThread, numInstances);
      KernelType threadKernel = kernel;
      threadKernel.BeginId = beginId;
      threadKernel.EndId = endId;
      std::thread newThread(threadKernel);
      threadPool[threadIndex].swap(newThread);
      beginId = endId;
    }

    for (vtkm::Id threadIndex = 0; threadIndex < numThreads; threadIndex++)
    {
      threadPool[threadIndex].join();
    }

    delete[] threadPool;

    if (errorMessage.IsErrorRaised())
    {
      throw vtkm::cont::ErrorExecution(errorString);
    }
  }

public:
  template<typename FunctorType>
  VTKM_CONT
  static void Schedule(FunctorType functor, vtkm::Id numInstances)
  {
    DoSchedule(ScheduleKernel1D<FunctorType>(functor), numInstances);
  }

  template<typename FunctorType>
  VTKM_CONT
  static void Schedule(FunctorType functor, vtkm::Id3 maxRange)
  {
    vtkm::Id numInstances = maxRange[0]*maxRange[1]*maxRange[2];
    DoSchedule(ScheduleKernel3D<FunctorType>(functor, maxRange), numInstances);
  }

  VTKM_CONT
  static void Synchronize()
  {
    // Nothing to do. This device schedules all of its operations using a
    // split/join paradigm. This means that the if the control thread is
    // calling this method, then nothing should be running in the execution
    // environment.
  }
};

}
} // namespace vtkm::cont
```

18.4 Timer Implementation

The VTK-m timer, described in Chapter 9, delegates to an internal class named vtkm::cont::DeviceAdapter-TimerImplementation. The interface for this class is the same as that for vtkm::cont::Timer. A default implementation of this templated class uses the system timer and the Synchronize method in the device adapter algorithms.

However, some devices might provide alternate or better methods for implementing timers. For example, the TBB and CUDA libraries come with high resolution timers that have better accuracy than the standard system timers. Thus, the device adapter can optionally provide a specialization of DeviceAdapterTimerImplementation, which is typically placed in the same header file as the device adapter algorithms.

Continuing our example of a custom device adapter using C++11's std::thread class, we could use the default timer and it would work fine. But C++11 also comes with a std::chrono package that contains some portable time functions. The following code demonstrates creating a custom timer for our device adapter using this package. By convention, DeviceAdapterTimerImplementation is placed in the same header file as DeviceAdapterAlgorithm.

Example 18.6: Specialization of DeviceAdapterTimerImplementation.

```
#include <chrono>

namespace vtkm {
namespace cont {

template<>
class DeviceAdapterTimerImplementation<vtkm::cont::DeviceAdapterTagCxx11Thread>
{
public:
  VTKM_CONT
  DeviceAdapterTimerImplementation()
  {
    this->Reset();
  }

  VTKM_CONT
  void Reset()
  {
    vtkm::cont::DeviceAdapterAlgorithm<vtkm::cont::DeviceAdapterTagCxx11Thread>
        ::Synchronize();
    this->StartTime = std::chrono::high_resolution_clock::now();
  }

  VTKM_CONT
  vtkm::Float64 GetElapsedTime()
  {
    vtkm::cont::DeviceAdapterAlgorithm<vtkm::cont::DeviceAdapterTagCxx11Thread>
        ::Synchronize();
    std::chrono::high_resolution_clock::time_point endTime =
        std::chrono::high_resolution_clock::now();

    std::chrono::high_resolution_clock::duration elapsedTicks =
        endTime - this->StartTime;

    std::chrono::duration<vtkm::Float64> elapsedSeconds(elapsedTicks);

    return elapsedSeconds.count();
  }

private:
  std::chrono::high_resolution_clock::time_point StartTime;
};

}
} // namespace vtkm::cont
```

CHAPTER

NINETEEN

OPENGL INTEROPERABILITY

CHAPTER

TWENTY

ADVANCED WORKLET CUSTOMIZATION

[This chapter should be split up.]

Chapter 14 describes the basics of creating and using worklets. Many visualization algorithms can be implemented using VTK-m's existing worklet types and features. However, new algorithms and designs may require features not provided by VTK-m's current worklet set. In such cases it is possible to directly design filters using the lower level device adapter operations [as described in section bla]. But by adding features to the worklet mechanisms, new designs can be integrated better with the other VTK-m features and can be repurposed in interesting ways for other algorithms.

This chapter provides the information necessary to create new mechanisms for worklets. It first describes the interface for getting data from the control environment objects to the data passed to a worklet invocation and back. It then describes how to modify these mechanisms to create new data movement structures and new worklet types.

20.1 Transferring Arguments from Control to Execution

From the `ControlSignature` and `ExecutionSignature` defined in worklets, VTK-m uses template metaprogramming to build the code required to manage data from control to execution environment. This management is handled by three classes that provide type checking, transportation, and fetching.

[I've been thinking that one more feature that these classes should provide is the ability to return the size of the domain. That would make things simpler and safer for getting the input domain size and checking the remaining domain sizes.]

20.1.1 Type Checks

Before attempting to move data from the control to the execution environment, the VTK-m dispatchers check the input types to ensure that they are compatible with the associated `ControlSignature` concept. This is done with the `vtkm::cont::arg::TypeCheck` `struct`.

The `TypeCheck` `struct` is templated with two parameters. The first parameter is a tag that identifies which check to perform. The second parameter is the type of the control argument (after any dynamic casts). The `TypeCheck` class contains a static constant Boolean named `value` that is `true` if the type in the second parameter is compatible with the tag in the first or `false` otherwise.

Type checks are implemented with a defined type check tag (which, by convention, is defined in the `vtkm::-cont::arg` namespace and starts with `TypeCheckTag`) and a partial specialization of the `vtkm::cont::arg::-`

TypeCheck structure. The following type checks (identified by their tags) are provided in VTK-m.

vtkm::cont::arg::TypeCheckTagArray True if the type is a vtkm::cont::ArrayHandle. TypeCheckTagArray also has a template parameter that is a type list. The ArrayHandle must also have a value type contained in this type list.

vtkm::cont::arg::TypeCheckTagExecObject True if the type is an execution object. All execution objects must derive from vtkm::exec::ExecutionObjectBase and must be copyable through memcpy or similar mechanism.

Here are some trivial examples of using TypeCheck. Typically these checks are done internally in the base VTK-m dispatcher code, so these examples are for demonstration only.

Example 20.1: Behavior of vtkm::cont::arg::TypeCheck.

```
struct MyExecObject : vtkm::exec::ExecutionObjectBase { vtkm::Id Value; };

void DoTypeChecks()
{
  using vtkm::cont::arg::TypeCheck;
  using vtkm::cont::arg::TypeCheckTagArray;
  using vtkm::cont::arg::TypeCheckTagExecObject;

  bool check1 = TypeCheck<TypeCheckTagExecObject, MyExecObject>::value; // true
  bool check2 = TypeCheck<TypeCheckTagExecObject, vtkm::Id>::value;     // false

  typedef vtkm::cont::ArrayHandle<vtkm::Float32> ArrayType;

  bool check3 =                                                         // true
      TypeCheck<TypeCheckTagArray<vtkm::TypeListTagField>, ArrayType>::value;
  bool check4 =                                                         // false
      TypeCheck<TypeCheckTagArray<vtkm::TypeListTagIndex>, ArrayType>::value;
  bool check5 = TypeCheck<TypeCheckTagExecObject, ArrayType>::value;    // false
}
```

20.1.2 Transport

After all the argument types are checked, the base dispatcher must load the data into the execution environment before scheduling a job to run there. This is done with the vtkm::cont::arg::Transport struct.

The Transport struct is templated with three parameters. The first parameter is a tag that identifies which transport to perform. The second parameter is the type of the control parameter (after any dynamic casts). The third parameter is a device adapter tag for the device on which the data will be loaded.

A Transport contains a typedef named ExecObjectType that is the type used after data is moved to the execution environment. A Transport also has a const parenthesis operator that takes the control-side object and the size of the domain and returns an execution-side object. This operator is called in the control environment, and the returned object must be ready to be passed to the execution environment.

Transports are implemented with a defined transport tag (which, by convention, is defined in the vtkm::cont::-arg namespace and starts with TransportTag) and a partial specialization of the vtkm::cont::arg::Transport structure. The following transports (identified by their tags) are provided in VTK-m.

vtkm::cont::arg::TransportTagArrayIn Loads data from a vtkm::cont::ArrayHandle onto the specified device using the array handle's PrepareForInput method. The returned execution object is an array portal.

vtkm::cont::arg::TransportTagArrayOut Allocates data onto the specified device for a vtkm::cont::ArrayHandle using the array handle's PrepareForOutput method. The returned execution object is an array portal.

vtkm::cont::arg::TransportTagExecObject Simply returns the given execution object, which should be ready to load onto the device.

Here are some trivial examples of using Transport. Typically this movement is done internally in the base VTK-m dispatcher code, so these examples are for demonstration only.

Example 20.2: Behavior of vtkm::cont::arg::Transport.

```
struct MyExecObject : vtkm::exec::ExecutionObjectBase { vtkm::Id Value; };

typedef vtkm::cont::ArrayHandle<vtkm::Id> ArrayType;

void DoTransport(const MyExecObject &inExecObject,
                 const ArrayType &inArray,
                 const ArrayType &outArray)
{
  typedef VTKM_DEFAULT_DEVICE_ADAPTER_TAG Device;

  using vtkm::cont::arg::Transport;
  using vtkm::cont::arg::TransportTagArrayIn;
  using vtkm::cont::arg::TransportTagArrayOut;
  using vtkm::cont::arg::TransportTagExecObject;

  // The executive object transport just passes the object through.
  typedef Transport<TransportTagExecObject,MyExecObject,Device>
      ExecObjectTransport;
  MyExecObject passedExecObject = ExecObjectTransport()(inExecObject, 10);

  // The array in transport returns a read-only array portal.
  typedef Transport<TransportTagArrayIn,ArrayType,Device> ArrayInTransport;
  ArrayInTransport::ExecObjectType inPortal = ArrayInTransport()(inArray, 10);

  // The array out transport returns an allocated array portal.
  typedef Transport<TransportTagArrayOut,ArrayType,Device> ArrayOutTransport;
  ArrayOutTransport::ExecObjectType outPortal =ArrayOutTransport()(outArray,10);
}
```

20.1.3 Fetch

Before the function of a worklet is invoked, the VTK-m internals pull the appropriate data out of the execution object and pass it to the worklet function. A class named vtkm::exec::arg::Fetch is responsible for pulling this data out and putting computed data in to the execution objects.

The Fetch struct is templated with four parameters. The first parameter is a tag that identifies which type of fetch to perform. The second parameter is a different tag that identifies the aspect of the data to fetch. The third parameter is an Invocation type that provides details about how the worklet is being dispatched including a list of execution object parameters passed to the invocation. The fourth parameter is a vtkm::IdComponent that points to the invocation parameter that the data should be fetched from.

A Fetch contains a typedef named ValueType that is the type of data that is passed to and from the worklet function. A Fetch also has a pair of methods named Load and Store that get data from and add data to the execution object at a given domain or thread index.

Fetches are specified with a pair of fetch and aspect tags. Fetch tags are by convention defined in the vtkm::exec::arg namespace and start with FetchTag. Likewise, aspect tags are also defined in the vtkm::exec::arg namespace and start with AspectTag. The Fetch typedef is partially specialized on these two tags.

The most common aspect tag is vtkm::exec::arg::AspectTagDefault, and all fetch tags should have a specialization of vtkm::exec::arg::Fetch with this tag. The following list of fetch tags describes the execution objects they work with and the data they pull for each aspect tag they support.

[Don't forget to add index entries for both fetch and aspect where appropriate.]

vtkm::exec::arg::FetchTagArrayDirectIn Loads data from an array portal. This fetch only supports the AspectTagDefault aspect. The Load gets data directly from the domain (thread) index. The Store does nothing.

vtkm::exec::arg::FetchTagArrayDirectOut Stores data to an array portal. This fetch only supports the AspectTagDefault aspect. The Store sets data directly to the domain (thread) index. The Load does nothing.

vtkm::exec::arg::FetchTagExecObject Simply returns an execution object. This fetch only supports the AspectTagDefault aspect. The Load returns the executive object in the associated parameter. The Store does nothing.

In addition to the aforementioned aspect tags that are explicitly paired with fetch tags, VTK-m also provides some aspect tags that either modify the behavior of a general fetch or simply ignore the type of fetch.

vtkm::exec::arg::AspectTagWorkIndex Simply returns the domain (or thread) index ignoring any associated data. This aspect is used to implement the WorkIndex execution signature tag.

20.2 Function Interface Objects

For flexibility's sake a worklet is free to declare a ControlSignature with whatever number of arguments are sensible for its operation. The Invoke method of the dispatcher is expected to support arguments that match these arguments, and part of the dispatching operation may require these arguments to be augmented before the worklet is scheduled. This leaves dispatchers with the tricky task of managing some collection of arguments of unknown size and unknown types.

[FunctionInterface is in the vtkm::internal interface. I still can't decide if it should be moved to the vtkm interface.]

To simplify this management, VTK-m has the vtkm::internal::FunctionInterface class. FunctionInterface is a templated class that manages a generic set of arguments and return value from a function. An instance of FunctionInterface holds an instance of each argument. You can apply the arguments in a FunctionInterface object to a functor of a compatible prototype, and the resulting value of the function call is saved in the FunctionInterface.

20.2.1 Declaring and Creating

vtkm::internal::FunctionInterface is a templated class with a single parameter. The parameter is the *signature* of the function. A signature is a function type. The syntax in C++ is the return type followed by the argument types encased in parentheses.

Example 20.3: Declaring vtkm::internal::FunctionInterface.

```
// FunctionInterfaces matching some common POSIX functions.
vtkm::internal::FunctionInterface<size_t(const char *)>
    strlenInterface;

vtkm::internal::FunctionInterface<char *(char *, const char *s2, size_t)>
    strncpyInterface;
```

The vtkm::internal::make_FunctionInterface function provies an easy way to create a FunctionInterface and initialize the state of all the parameters. make_FunctionInterface takes a variable number of arguments, one for each parameter. Since the return type is not specified as an argument, you must always specify it as a template parameter.

Example 20.4: Using vtkm::internal::make_FunctionInterface.

```
const char *s = "Hello World";
static const size_t BUFFER_SIZE = 100;
char *buffer = (char *)malloc(BUFFER_SIZE);

strlenInterface =
    vtkm::internal::make_FunctionInterface<size_t>(s);

strncpyInterface =
    vtkm::internal::make_FunctionInterface<char *>(buffer, s, BUFFER_SIZE);
```

20.2.2 Parameters

One created, FunctionInterface contains methods to query and manage the parameters and objects associated with them. The number of parameters can be retrieved either with the constant field ARITY or with the GetArity method.

Example 20.5: Getting the arity of a FunctionInterface.

```
VTKM_STATIC_ASSERT(
      vtkm::internal::FunctionInterface<size_t(const char *)>::ARITY == 1);

vtkm::IdComponent arity = strncpyInterface.GetArity();  // arity = 3
```

To get a particular parameter, FunctionInterface has the templated method GetParameter. The template parameter is the index of the parameter. Note that the parameters in FunctionInterface start at index 1. Although this is uncommon in C++, it is customary to number function arguments starting at 1.

There are two ways to specify the index for GetParameter. The first is to directly specify the template parameter (e.g. GetParameter<1>()). However, note that in a templated function or method where the type is not fully resolved the compiler will not register GetParameter as a templated method and will fail to parse the template argument without a template keyword. The second way to specify the index is to provide a vtkm::internal::IndexTag object as an argument to GetParameter. Although this syntax is more verbose, it works the same whether the FunctionInterface is fully resolved or not. The following example shows both methods in action.

Example 20.6: Using FunctionInterface::GetParameter().

```
void GetFirstParameterResolved(
    const vtkm::internal::FunctionInterface<void(std::string)> &interface)
{
  // The following two uses of GetParameter are equivalent
  std::cout << interface.GetParameter<1>() << std::endl;
  std::cout << interface.GetParameter(vtkm::internal::IndexTag<1>())
            << std::endl;
}

template<typename FunctionSignature>
```

```
void GetFirstParameterTemplated(
    const vtkm::internal::FunctionInterface<FunctionSignature> &interface)
{
  // The following two uses of GetParameter are equivalent
  std::cout << interface.template GetParameter<1>() << std::endl;
  std::cout << interface.GetParameter(vtkm::internal::IndexTag<1>())
            << std::endl;
}
```

Likewise, there is a `SetParmeter` method for changing parameters. The same rules for indexing and template specification apply.

Example 20.7: Using `FunctionInterface::SetParameter()`.

```
void SetFirstParameterResolved(
    vtkm::internal::FunctionInterface<void(std::string)> &interface,
    const std::string &newFirstParameter)
{
  // The following two uses of SetParameter are equivalent
  interface.SetParameter<1>(newFirstParameter);
  interface.SetParameter(newFirstParameter, vtkm::internal::IndexTag<1>());
}

template<typename FunctionSignature, typename T>
void SetFirstParameterTemplated(
    vtkm::internal::FunctionInterface<FunctionSignature> &interface,
    T newFirstParameter)
{
  // The following two uses of SetParameter are equivalent
  interface.template SetParameter<1>(newFirstParameter);
  interface.SetParameter(newFirstParameter, vtkm::internal::IndexTag<1>());
}
```

20.2.3 Invoking

`FunctionInterface` can invoke a functor of a matching signature using the parameters stored within. If the functor returns a value, that return value will be stored in the `FunctionInterface` object for later retrieval. There are several versions of the invoke method. There are always seperate versions of invoke methods for the control and execution environments so that functors for either environment can be executed. The basic version of invoke passes the parameters directly to the function and directly stores the result.

Example 20.8: Invoking a `FunctionInterface`.

```
  vtkm::internal::FunctionInterface<size_t(const char *)> strlenInterface;
  strlenInterface.SetParameter<1>("Hello world");

  strlenInterface.InvokeCont(strlen);

  size_t length = strlenInterface.GetReturnValue();   // length = 11
```

Another form of the invoke methods takes a second transform functor that is applied to each argument before passed to the main function. If the main function returns a value, the transform is applied to that as well before being stored back in the `FunctionInterface`.

Example 20.9: Invoking a `FunctionInterface` with a transform.

```
// Our transform converts C strings to integers, leaves everything else alone.
struct TransformFunctor
{
  template<typename T>
  VTKM_CONT
  const T &operator()(const T &x) const
  {
    return x;
  }

  VTKM_CONT
  const vtkm::Int32 operator()(const char *x) const
  {
    return atoi(x);
  }
};

// The function we are invoking simply compares two numbers.
struct IsSameFunctor
{
  template<typename T1, typename T2>
  VTKM_CONT
  bool operator()(const T1 &x, const T2 &y) const
  {
    return x == y;
  }
};

void TryTransformedInvoke()
{
  vtkm::internal::FunctionInterface<bool(const char *, vtkm::Int32)>
      functionInterface =
        vtkm::internal::make_FunctionInterface<bool>((const char *)"42",
                                                      (vtkm::Int32)42);

  functionInterface.InvokeCont(IsSameFunctor(), TransformFunctor());

  bool isSame = functionInterface.GetReturnValue();     // isSame = true
}
```

As demonstrated in the previous examples, FunctionInterface has a method named GetReturnValue that returns the value from the last invoke. Care should be taken to only use GetReturnValue when the function specification has a return value. If the function signature has a void return type, using GetReturnValue will cause a compile error.

FunctionInterface has an alternate method named GetReturnValueSafe that returns the value wrapped in a templated structure named vtkm::internal::FunctionInterfaceReturnContainer. This structure always has a static constant Boolean named VALID that is false if there is no return type and true otherwise. If the container is valid, it also has an entry named Value containing the result.

Example 20.10: Getting return value from FunctionInterface safely.

```
template<typename ResultType, bool Valid> struct PrintReturnFunctor;

template<typename ResultType>
struct PrintReturnFunctor<ResultType, true>
{
  VTKM_CONT
  void operator()(
      const vtkm::internal::FunctionInterfaceReturnContainer<ResultType> &x)
  const
  {
    std::cout << x.Value << std::endl;
  }
};

template<typename ResultType>
struct PrintReturnFunctor<ResultType, false>
```

```
{
  VTKM_CONT
  void operator()(
      const vtkm::internal::FunctionInterfaceReturnContainer<ResultType> &)
  const
  {
    std::cout << "No return type." << std::endl;
  }
};

template<typename FunctionInterfaceType>
void PrintReturn(const FunctionInterfaceType &functionInterface)
{
  typedef typename FunctionInterfaceType::ResultType ResultType;
  typedef vtkm::internal::FunctionInterfaceReturnContainer<ResultType>
      ReturnContainerType;

  PrintReturnFunctor<ResultType, ReturnContainerType::VALID> printReturn;
  printReturn(functionInterface.GetReturnValueSafe());
}
```

20.2.4 Modifying Parameters

In addition to storing and querying parameters and invoking functions, FunctionInterface also contains multiple ways to modify the parameters to augment the function calls. This can be used in the same use case as a chain of function calls that generally pass their parameters but also augment the data along the way.

The Append method returns a new FunctionInterface object with the same parameters plus a new parameter (the argument to Append) to the end of the parameters. There is also a matching AppendType templated structure that can return the type of an augmented FunctionInterface with a new type appended.

Example 20.11: Appending parameters to a FunctionInterface.

```
  using vtkm::internal::FunctionInterface;
  using vtkm::internal::make_FunctionInterface;

  typedef FunctionInterface<void(std::string, vtkm::Id)>
      InitialFunctionInterfaceType;
  InitialFunctionInterfaceType initialFunctionInterface =
      make_FunctionInterface<void>(std::string("Hello World"), vtkm::Id(42));

  typedef FunctionInterface<void(std::string, vtkm::Id, std::string)>
      AppendedFunctionInterfaceType1;
  AppendedFunctionInterfaceType1 appendedFunctionInterface1 =
      initialFunctionInterface.Append(std::string("foobar"));
  // appendedFunctionInterface1 has parameters ("Hello World", 42, "foobar")

  typedef InitialFunctionInterfaceType::AppendType<vtkm::Float32>::type
      AppendedFunctionInterfaceType2;
  AppendedFunctionInterfaceType2 appendedFunctionInterface2 =
      initialFunctionInterface.Append(vtkm::Float32(3.141));
  // appendedFunctionInterface2 has parameters ("Hello World", 42, 3.141)
```

Replace is a similar method that returns a new FunctionInterface object with the same paraemters except with a specified parameter replaced with a new parameter (the argument to Replace). There is also a matching ReplaceType templated structure that can return the type of an augmented FunctionInterface with one of the parameters replaced.

Example 20.12: Replacing parameters in a FunctionInterface.

```
  using vtkm::internal::FunctionInterface;
  using vtkm::internal::make_FunctionInterface;

  typedef FunctionInterface<void(std::string, vtkm::Id)>
      InitialFunctionInterfaceType;
  InitialFunctionInterfaceType initialFunctionInterface =
      make_FunctionInterface<void>(std::string("Hello World"), vtkm::Id(42));

  typedef FunctionInterface<void(vtkm::Float32, vtkm::Id)>
      ReplacedFunctionInterfaceType1;
  ReplacedFunctionInterfaceType1 replacedFunctionInterface1 =
      initialFunctionInterface.Replace<1>(vtkm::Float32(3.141));
  // replacedFunctionInterface1 has parameters (3.141, 42)

  typedef InitialFunctionInterfaceType::ReplaceType<2, std::string>::type
      ReplacedFunctionInterfaceType2;
  ReplacedFunctionInterfaceType2 replacedFunctionInterface2 =
      initialFunctionInterface.Replace<2>(std::string("foobar"));
  // replacedFunctionInterface2 has parameters ("Hello World", "foobar")
```

It is sometimes desirable to make multiple modifications at a time. This can be achieved by chaining modifications by calling `Append` or `Replace` on the result of a previous call.

Example 20.13: Chaining `Replace` and `Append` with a `FunctionInterface`.

```
template<typename FunctionInterfaceType>
void FunctionCallChain(const FunctionInterfaceType &parameters,
                       vtkm::Id arraySize)
{
  // In this hypothetical function call chain, this function replaces the
  // first parameter with an array of that type and appends the array size
  // to the end of the parameters.

  typedef typename FunctionInterfaceType::template ParameterType<1>::type
      ArrayValueType;

  // Allocate and initialize array.
  ArrayValueType value = parameters.template GetParameter<1>();
  ArrayValueType *array = new ArrayValueType[arraySize];
  for (vtkm::Id index = 0; index < arraySize; index++)
  {
    array[index] = value;
  }

  // Call next function with modified parameters.
  NextFunctionChainCall(
        parameters.template Replace<1>(array).Append(arraySize));

  // Clean up.
  delete[] array;
}
```

20.2.5 Transformations

Rather than replace a single item in a `FunctionInterface`, it is sometimes desirable to change them all in a similar way. `FunctionInterface` supports two basic transform operations on its parameters: a static transform and a dynamic transform. The static transform determines its types at compile-time whereas the dynamic transform happens at run-time.

The static transform methods (named `StaticTransformCont` and `StaticTransformExec`) operate by accepting a functor that defines a function with two arguments. The first argument is the `FunctionInterface` parameter to transform. The second argument is an instance of the `vtkm::internal::IndexTag` templated class that statically identifies the parameter index being transformed. An IndexTag object has no state, but the class contains a static integer named INDEX. The function returns the transformed argument.

The functor must also contain a templated class named ReturnType with an internal type named type that defines the return type of the transform for a given parameter type. ReturnType must have two template parameters. The first template parameter is the type of the FunctionInterface parameter to transform. It is the same type as passed to the operator. The second template parameter is a vtkm::IdComponent specifying the index.

The transformation is only applied to the parameters of the function. The return argument is unaffected.

The return type can be determined with the StaticTransformType template in the FunctionInterface class. StaticTransformType has a single parameter that is the transform functor and contains a type named type that is the transformed FunctionInterface.

In the following example, a static transform is used to convert a FunctionInterface to a new object that has the pointers to the parameters rather than the values themselves. The parameter index is always ignored as all parameters are uniformly transformed.

Example 20.14: Using a static transform of function interface class.

```
struct ParametersToPointersFunctor {
  template<typename T, vtkm::IdComponent Index>
  struct ReturnType {
    typedef const T *type;
  };

  template<typename T, vtkm::IdComponent Index>
  VTKM_CONT
  const T *operator()(const T &x, vtkm::internal::IndexTag<Index>) const {
    return &x;
  }
};

template<typename FunctionInterfaceType>
VTKM_CONT
typename FunctionInterfaceType::
    template StaticTransformType<ParametersToPointersFunctor>::type
ParametersToPointers(const FunctionInterfaceType &functionInterface)
{
  return functionInterface.StaticTransformCont(ParametersToPointersFunctor());
}
```

There are cases where one set of parameters must be transformed to another set, but the types of the new set are not known until run-time. That is, the transformed type depends on the contents of the data. The DynamicTransformCont method achieves this using a templated callback that gets called with the correct type at run-time.

The dynamic transform works with two functors provided by the user code (as opposed to the one functor in static transform). These functors are called the transform functor and the finish functor. The transform functor accepts three arguments. The first argument is a parameter to transform. The second argument is a continue function. Rather than return the transformed value, the transform functor calls the continue function, passing the transformed value as an argument. The third argument is a vtkm::internal::IndexTag for the index of the argument being transformed.

Unlike its static counterpart, the dynamic transform method does not return the transformed FunctionInterface. Instead, it passes the transformed FunctionInterface to the finish functor passed into DynamicTransformCont.

In the following contrived but illustrative example, a dynamic transform is used to convert strings containing numbers into number arguments. Strings that do not have numbers and all other arguments are passed through. Note that because the types for strings are not determined till run-time, this transform cannot be determined at compile time with meta-template programming. The index argument is ignored because all arguments are transformed the same way.

Example 20.15: Using a dynamic transform of a function interface.

```cpp
struct UnpackNumbersTransformFunctor {
  template<typename InputType,
           typename ContinueFunctor,
           vtkm::IdComponent Index>
  VTKM_CONT
  void operator()(const InputType &input,
                  const ContinueFunctor &continueFunction,
                  vtkm::internal::IndexTag<Index>) const
  {
    continueFunction(input);
  }

  template<typename ContinueFunctor, vtkm::IdComponent Index>
  VTKM_CONT
  void operator()(const std::string &input,
                  const ContinueFunctor &continueFunction,
                  vtkm::internal::IndexTag<Index>) const
  {
    if ((input[0] >= '0') && (input[0] <= '9'))
    {
      std::stringstream stream(input);
      vtkm::FloatDefault value;
      stream >> value;
      continueFunction(value);
    }
    else
    {
      continueFunction(input);
    }
  }
};

struct UnpackNumbersFinishFunctor {
  template<typename FunctionInterfaceType>
  VTKM_CONT
  void operator()(FunctionInterfaceType &functionInterface) const
  {
    // Do something
  }
};

template<typename FunctionInterfaceType>
void DoUnpackNumbers(const FunctionInterfaceType &functionInterface)
{
  functionInterface.DynamicTransformCont(UnpackNumbersTransformFunctor(),
                                         UnpackNumbersFinishFunctor());
}
```

One common use for the FunctionInterface dynamic transform is to convert parameters of virtual polymorphic type like vtkm::cont::DynamicArrayHandle and vtkm::cont::DynamicPointCoordinates. This use case is handled with a functor named vtkm::cont::internal::DynamicTransform. When used as the dynamic transform functor, it will convert all of these dynamic types to their static counterparts.

Example 20.16: Using DynamicTransform to cast dynamic arrays in a function interface.

```cpp
template<typename Device>
struct ArrayCopyFunctor {
  template<typename Signature>
  VTKM_CONT
  void operator()(
      vtkm::internal::FunctionInterface<Signature> functionInterface) const
  {
    functionInterface.InvokeCont(*this);
  }

  template<typename T, class CIn, class COut>
  VTKM_CONT
  void operator()(const vtkm::cont::ArrayHandle<T, CIn> &input,
                  vtkm::cont::ArrayHandle<T, COut> &output) const
  {
    vtkm::cont::DeviceAdapterAlgorithm<Device>::Copy(input, output);
  }

  template<typename TIn, typename TOut, class CIn, class COut>
  VTKM_CONT
  void operator()(const vtkm::cont::ArrayHandle<TIn, CIn> &,
                  vtkm::cont::ArrayHandle<TOut, COut> &) const
  {
    throw vtkm::cont::ErrorControlBadType(
          "Arrays to copy must be the same type.");
  }
};

template<typename Device>
void CopyDynamicArrays(vtkm::cont::DynamicArrayHandle input,
                       vtkm::cont::DynamicArrayHandle output,
                       Device)
{
  vtkm::internal::FunctionInterface<void(vtkm::cont::DynamicArrayHandle,
                                         vtkm::cont::DynamicArrayHandle)>
      functionInterface =
        vtkm::internal::make_FunctionInterface<void>(input, output);

  functionInterface.DynamicTransformCont(
        vtkm::cont::internal::DynamicTransform(), ArrayCopyFunctor<Device>());
}
```

20.2.6 For Each

The invoke methods (principally) make a single function call passing all of the parameters to this function. The transform methods call a function on each parameter to convert it to some other data type. It is also sometimes helpful to be able to call a unary function on each parameter that is not expected to return a value. Typically the use case is for the function to have some sort of side effect. For example, the function might print out some value (such as in the following example) or perform some check on the data and throw an exception on failure.

This feature is implemented in the for each methods of FunctionInterface. As with all the FunctionInterface methods that take functors, there are separate implementations for the control environment and the execution environment. There are also separate implementations taking const and non-const references to functors to simplify making functors with side effects.

Example 20.17: Using the ForEach feature of FunctionInterface.

```
struct PrintArgumentFunctor{
  template<typename T, vtkm::IdComponent Index>
  VTKM_CONT
  void operator()(const T &argument, vtkm::internal::IndexTag<Index>) const
  {
    std::cout << Index << ":" << argument << " ";
  }
};

template<typename FunctionInterfaceType>
VTKM_CONT
void PrintArguments(const FunctionInterfaceType &functionInterface)
{
  std::cout << "( ";
  functionInterface.ForEachCont(PrintArgumentFunctor());
  std::cout << ")" << std::endl;
}
```

20.3 Invocation Objects

20.4 Creating New ControlSignature Tags

20.5 Creating New ExecutionSignature Tags

20.6 Creating New Worklet Types

20.6.1 New Worklet Superclasses

20.6.2 Dispatch Workflow

20.6.3 New Dispatch Classes

Part V

Appendix

APPENDIX

A

CODING CONVENTIONS

Several developers contribute to VTK-m and we welcome others who are interested to also contribute to the project. To ensure readability and consistency in the code, we have adopted the following coding conventions. Many of these conventions are adapted from the coding conventions of the VTK project. This is because many of the developers are familiar with VTK coding and because we expect VTK-m to have continual interaction with VTK.

- All code contributed to VTK-m must be compatible with VTK-m's BSD license.
- Copyright notices should appear at the top of all source, configuration, and text files. The statement should have the following form (with the year replaced with the year the file was created):

  ```
  //============================================================================
  //  Copyright (c) Kitware, Inc.
  //  All rights reserved.
  //  See LICENSE.txt for details.
  //  This software is distributed WITHOUT ANY WARRANTY; without even
  //  the implied warranty of MERCHANTABILITY or FITNESS FOR A PARTICULAR
  //  PURPOSE.  See the above copyright notice for more information.
  //
  //  Copyright 2014 Sandia Corporation.
  //  Copyright 2014 UT-Battelle, LLC.
  //  Copyright 2014. Los Alamos National Security
  //
  //  Under the terms of Contract DE-AC04-94AL85000 with Sandia Corporation,
  //  the U.S. Government retains certain rights in this software.
  //
  //  Under the terms of Contract DE-AC52-06NA25396 with Los Alamos National
  //  Laboratory (LANL), the U.S. Government retains certain rights in
  //  this software.
  //============================================================================
  ```

  The CopyrightStatement test checks all files for a similar statement. The test will print out a suggested text that can be copied and pasted to any file that has a missing copyright statement (with appropriate replacement of comment prefix). Exceptions to this copyright statement (for example, third-party files with different but compatible statements) can be added to LICENSE.txt.

- All include files should use include guards. starting right after the copyright statement. The naming convention of the include guard macro is that it should start with `vtk_m` be followed with the path name, starting from the top-level source code directory under vtkm, with non alphanumeric characters, such as `/` and `.` replaced with underscores. The `#endif` part of the guard at the bottom of the file should include the guard name in a comment. For example, the vtkm/cont/ArrayHandle.h header contains the guard

```
#ifndef vtk_m_cont_ArrayHandle_h
#define vtk_m_cont_ArrayHandle_h
```

at the top and

```
#endif //vtk_m_cont_ArrayHandle_h
```

- VTK-m has several nested namespaces. The declaration of each namespace should be on its own line, and the code inside the namespace bracket should not be indented. The closing brace at the bottom of the namespace should be documented with a comment identifying the namespace. Namespaces can be grouped as desired. The following is a valid use of namespaces.

```
namespace vtkm {
namespace cont {

namespace detail {

class InternalClass;

} // namespace detail

class ExposedClass;

}
} // namespace vtkm::cont
```

- Multiple inheritance is not allowed in VTK-m classes.
- Any functional public class should be in its own header file with the same name as the class. The file should be in a directory that corresponds to the namespace the class is in. There are several exceptions to this rule.
  - Templated classes and template specialization often require the implementation of the class to be broken into pieces. Sometimes a specialization is placed in a header with a different name.
  - Many VTK-m toolkit features are not encapsulated in classes. Functions may be collected by purpose or co-located with associated class.
  - Although tags are technically classes, they behave as an enumeration for the compiler. Multiple tags that make up this enumeration are collected together.
  - Some classes, such as `vtkm::Vec` are meant to behave as basic types. These are sometimes collected together as if they were related `typedef`s. The `vtkm/Types.h` header is a good example of this.
- The indentation follows the Allman style. The curly brace (scope delimiter) for a block is placed on the line following the prototype or control statement and is indented with the outer scope (i.e. the curly brace does not line up with the code in the block). This differs from VTK style, but was agreed on by the developers as the more common style. Indentations are two spaces.
- Conditional clauses (including loop conditionals such as `for` and `while`) must be in braces below the conditional. That is, instead of

```
if (test) { clause; }
```

use

```
if (test)
{
  clause;
}
```

The rational for this requirement is to make it obvious whether the clause is executed when stepping through the code with the debugger. The one exception to this rule is when the clause contains a control-flow statement with obvious side effects such as `return` or `break`. However, even if the clause contains a single statement and is on the same line, the clause should be surrounded by braces.

- Use two space indentation.
- Tabs are not allowed. Only use spaces for indentation. No one can agree on what the size of a tab stop is, so it is better to not use them at all.
- There should be no trailing whitespace in any line.
- Use only alphanumeric characters in names. Use capitalization to demarcate words within a name (camel case). The exception is preprocessor macros and constant numbers that are, by convention, represented in all caps and a single underscore to demarcate words.
- Namespace names are in all lowercase. They should be a single word that designates its meaning.
- All class, method, member variable, and functions should start with a capital letter. Local variables should start in lower case and then use camel case. Exceptions can be made when such naming would conflict with previously established conventions in other library. (For example, `make_ArrayHandle` corresponds to `make_pair` in the standard template library.)
- All class, function, and member names that have multiple words in their descriptions should be listed from general to specific. For example, if a class is a k-d tree that is used to locate points, the preferred name would be `LocatorPointKDTree`. This naming convention makes it easier to find both known and unknown classes in alphabetic lists.
- Always spell out words in names; do not use abbreviations except in cases where the shortened form is widely understood and a name in its own right (e.g. OpenMP).
- Always use descriptive names in all identifiers, including local variable names. Particularly avoid meaningless names of a few characters (e.g. `x`, `foo`, or `tmp`) or numbered names with no meaning to the number or order (e.g. `value1`, `value2`,...). Also avoid the meaningless for loop variable names `i`, `j`, `k`, etc. Instead, use a name that identifies what type of index is being referenced such as `pointIndex`, `vertexIndex`, `componentIndex`, etc.
- Classes are documented with Doxygen-style comments before classes, methods, and functions.
- Exposed classes should not have public instance variables outside of exceptional situations. Access is given by convention through methods with names starting with `Set` and `Get` or through overloaded operators.
- References to classes and functions should be fully qualified with the namespace. This makes it easier to establish classes and functions from different packages and to find source and documentation for the referenced class. As an exception, if one class references an internal or detail class clearly associated with it, the reference can be shortened to `internal::` or `detail::`.
- use `this->` inside of methods when accessing class methods and instance variables to distinguish between local variables and instance variables.
- Include statements should generally be in alphabetical order. They can be grouped by package and type.
- Namespaces should not be brought into global scope or the scope of any VTK-m package namespace with the "using" keyword. It should also be avoided in class, method, and function scopes (fully qualified namespace references are preferred).
- All code must be valid by the C++11 specification.
- Limit all lines to 80 characters whenever possible.
- New code must include regression tests that will run on the dashboards. Generally a new class will have an associated "UnitTest" that will test the operation of the test directly. There may be other tests necessary that exercise the operation with different components or on different architectures.

- All code must compile and run without error or warning messages on the nightly dashboards, which should include Windows, Mac, and Linux.
- Use `vtkm::Id` in lieu of `int` or `long` for data structure indices and `vtkm::IdComponent` for component indices of `vtkm::Vec` and related classes (like `vtkm::VecVariable` and `vtkm::Matrix`).
- Whenever possible, use templates to resolve data types like `float`, `double`, or vectors to make code as flexible as possible. If a specific data type is required, prefer the VTK-m–provided types like `vtkm::Float32` and `vtkm::Float64` over the standard C types like `float` or `double`. `vtkm::FloatDefault` can be used in cases where there is no reasonable way to specify data precision (for example, when generating coordinates for uniform grids), but should be use sparingly.
- All functions and methods defined within VTK-m should be declared with `VTKM_CONT`, `VTKM_EXEC`, or `VTKM_EXEC_CONT`.

We should note that although these conventions impose a strict statute on VTK-m coding, these rules (other than those involving licensing and copyright) are not meant to be dogmatic. Examples can be found in the existing code that break these conventions, particularly when the conventions stand in the way of readability (which is the point in having them in the first place). For example, it is often the case that it is more readable for a complicated `typedef` to stretch a few characters past 80 even if it pushes past the end of a display.

INDEX