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VTK-m Users' Guide Version 0.0

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Prepared by

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Abstract

[WRITE THIS.]

Acknowledgement

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Chapter 1

Introduction

[WRITE THIS. COMBINATION OF CHAPTERS 1 AND 2 IN THE DAX REPORT PLUS ADDED FEATURES LIKE DATASETS AND FILTERS.]

[ALSO INCLUDE THE FOLLOWING.]

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. [VERIFY THAT DOES NOT CHANGE BY VERSION 1.0] This is typically necessary of template libraries, which need to be compiled with template parameters that are not known until they are used. This also provides the convenience of allowing the compiler to inline user code for better performance.

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 the Dax toolkit are printed in **red**.
- Identifiers from the Dax toolkit are printed in **blue**.
- Signatures, described in Section ??, and the tags used in them are printed in **green**.

Chapter 2

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.

2.1 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 ??, 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 11), 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.

[PROBABLY PUT A PARAGRAPH ON FILTERS HERE AND MOVE THIS PARAGRAPH LOWER.]

Worklets provided by VTK-m, described in Chapter ??, are contained in the `vtkm::worklet` package. Although the operation of a worklet happens exclusively in the execution

[MAKE A GRAPHIC OF THE PACKAGE HIERARCHY.]

Figure 2.1: VTK-m package hierarchy.

environment, worklets are typically initialized in the control environment. Thus, the `vtkm::worklet` package is not encapsulated in either `vtkm::cont` or `vtkm::exec`.

VTK-m provides a base set of library functions that are ported to the various systems and compilers on which it is used. These functions are located in the `vtkm::math` package. The features in `vtkm::math` are available in both the control and execution environments, but they are typically used in the execution environment.

VTK-m contains code that uses specialized compiler features, such as those with CUDA and OpenMP, 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: `vtkm::cuda`, `vtkm::openmp`, and `vtkm::tbb`. Within each one of these packages, there will be `cont` and `exec` namespaces as necessary to denote features that are accessible in only one environment or the other. [I'M THINKING OF REVERSING THIS TO PUT THE DEVICE-SPECIFIC NAMESPACES UNDER `vtkm::cont`. WE HAVE YET TO NEED A DEVICE-SPECIFIC THING IN `vtkm::exec`.]

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 2.1 provides a diagram of the 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.

2.2 Function and Method Exports

Any function or method defined by VTK-m must come with an export modifier that determines in which environments the function may be run. These export 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 export macros, `VTKM_CONT_EXPORT`, `VTKM_EXEC_EXPORT`, and `VTKM_EXEC_CONT_EXPORT`, 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 export 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 exported to both places.

Example 2.1: Usage of export macro.

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

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

There is one additional export 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_EXPORT` 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 export currently has no effect on any other compiler.

Finally, it is sometimes the case that a function declared as `VTKM_EXEC_CONT_EXPORT` has to call a method declared as `VTKM_EXEC_EXPORT` or `VTKM_CONT_EXPORT`. Generally functions should not call other functions with incompatible control/execution exports, but sometimes a generic `VTKM_EXEC_CONT_EXPORT` function calls another function determined by the template parameters, and the export 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 export macro.

2.3 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`.

2.3.1 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 2.3.2). 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.

2.3.2 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 2.2: 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 typedefs of `vtkm::Vec<vtkm::Id,2>` and `vtkm::Vec<vtkm::Id,3>`. 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.

Example 2.3: A Longer Vector.

```
vtkm::Vec<vtkm::Float32, 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 2.4: 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 2.5: 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, 0.866));
```

2.3.3 Extents

`vtkm::Extent3` is a simple structure that holds the extent information for structured data (data defined on a regular grid). It contains two `vtkm::Id3` fields named `Min` and `Max` that define the minimum and maximum 3D index. `Min` and `Max` are *inclusive* point indices.

Although less used, there also exists `vtkm::Extent2`, which is the same as `vtkm::Extent3` except for structured grids with 2 topological dimensions. The two structures are exactly the same except that `vtkm::Extent2` uses `vtkm::Id2` objects for its `Min` and `Max` instead of `vtkm::Id3`. There is also a generic structure named `vtkm::Extent` that takes a single integer argument to make the structured extent for some arbitrary topological dimension.

`vtkm::Extent3` and the other extent structures are defined in the `vtkm/Extent.h` header. This header also contains the following helper functions.

`vtkm::ExtentPointDimensions` Takes an extent object as an argument and returns a `vtkm::Id3` (or other appropriately sized tuple) giving the number of points in each topological dimension.

`vtkm::ExtentCellDimensions` Takes an extent object as an argument and returns a `vtkm::Id3` (or other appropriately sized tuple) giving the number of cells in each topological dimension. The number of cells is one less than the number of points in each dimensions.

`vtkm::ExtentNumberOfPoints` Takes an extent object as an argument and returns the number of points in an associated structured mesh.

`vtkm::ExtentNumberOfCells` Takes an extent object as an argument and returns the number of cells in an associated structured mesh.

vtkm::ExtentPointFlatIndexToTopologyIndex Elements in structured grids have a single index with 0 being the entry at the minimum extent in every direction and then increasing first in the r direction, then the s direction, and then the t direction. This function takes a flat point index as its first argument and an extent as its second argument and returns the r, s, t topological coordinates in a **vtkm::Id3** (or other appropriately sized tuple).

vtkm::ExtentCellFlatIndexToTopologyIndex Takes a flat cell index as its first argument and an extent as its second argument and returns the r, s, t topological coordinates in a **vtkm::Id3** (or other appropriately sized tuple).

vtkm::ExtentPointTopologyIndexToFlatIndex Takes topological point coordinates as the first argument and an extent as the second argument and returns the equivalent flat point index.

vtkm::ExtentCellTopologyIndexToFlatIndex Takes topological cell coordinates as the first argument and an extent as the second argument and returns the equivalent flat cell index.

vtkm::ExtentFirstPointOnCell Takes a flat cell index as its first argument and returns the flat index to the first point incident on that cell. This is a convenience function for some operations that relate cells to points.

The following example demonstrates using a **vtkm::Extent3** and the supporting functions. Extents of different dimensions work correspondingly.

Example 2.6: Creating and using an **Extent3**.

```
#include <vtkm/Extent.h>
#include <vtkm/Types.h>

void ExtentExample()
{
    // Make an extent that defines a grid that has 5x5x3 points and "centered"
    // at index (0,0,0).
    vtkm::Extent3 extent(vtkm::Id3(-2,-2,-1), vtkm::Id3(2,2,1));

    vtkm::Id3 minIndices = extent.Min; // Is (-2,-2,-1)
    vtkm::Id3 maxIndices = extent.Max; // Is (2,2,1)

    vtkm::Id3 pointDims = vtkm::ExtentPointDimensions(extent); // Returns (5,5,3)
    vtkm::Id3 cellDims = vtkm::ExtentCellDimensions(extent); // Returns (4,4,2)

    vtkm::Id numPoints = vtkm::ExtentNumberOfPoints(extent); // Returns 75
    vtkm::Id numCells = vtkm::ExtentNumberOfCells(extent); // Returns 32

    // Returns (-1,-1,0)
    vtkm::Id3 pointIndexA = vtkm::ExtentPointFlatIndexToTopologyIndex(31, extent);

    // Returns (1,1,0)
    vtkm::Id3 cellIndexA = vtkm::ExtentCellFlatIndexToTopologyIndex(31, extent);

    // Returns 33
    vtkm::Id pointIndexB =
        vtkm::ExtentPointTopologyIndexToFlatIndex(vtkm::Id3(1,-1,0), extent);
}
```

```

// Returns 23
vtkm::Id cellIndexB =
    vtkm::ExtentCellTopologyIndexToFlatIndex(vtkm::Id3(1,-1,0), extent);

// Returns 33
vtkm::Id firstPoint = vtkm::ExtentFirstPointOnCell(23, extent);
}

```

2.3.4 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.

2.4 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 Meyers for a description of traits classes and their uses.

2.4.1 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 2.3. `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 look something like this.

Example 2.7: 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 2.8: Using `TypeTraits` for a generic remainder.

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

#include <vtkm/Math.h>

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

namespace detail {

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

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

} // namespace detail
```

```

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

```

2.4.2 Vector Traits

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`.

NUM_COMPONENTS An integer specifying how many components are contained in the vector.

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.

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.

ToVec A static method that converts a vector of the given type to a `vtkm::Vec`.

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

Example 2.9: Definition of `vtkm::VecTraits<vtkm::Id3>`.

```

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

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

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

```

```

}

VTKM_EXEC_CONT_EXPORT
static vtkm::Vec<vtkm::Id,3> ToTuple(const vtkm::Id3 &vector) {
    return vector;
}
};

} // 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 2.10: 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_EXPORT
    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_EXPORT
    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;
    }
}

```

```
};
```

2.5 List Tags

VTK-m internally uses template metaprogramming, which utilizes the C++ template 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 2.5.2 or the storage lists specified in Section ???. 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.)

2.5.1 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 concatenates 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 2.11: 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> { };
```

2.5.2 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 Section 6.3).

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 2.5.1 as demonstrated in the following example.

Example 2.12: 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** (Section 6.3). 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 2.12 also contains an example of overriding the `VTKM_DEFAULT_TYPE_LIST_TAG` macro.

2.5.3 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 converting 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 Section 6.3).

Example 2.13: 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());
}
```

}

Chapter 3

File I/O

[WRITE THIS.]

Chapter 4

Provided Filters

[WRITE THIS ONCE SOME FILTERS ARE PROVIDED. SHOULD ALSO MAKE A REFERENCE TO USING WORKLETS (CHAPTER 8).]

Chapter 5

Rendering

[WRITE THIS ONCE THE RENDERING MODULE IS IMPLEMENTED.]

Chapter 6

Control Environment

The control environment is where code interfaces with applications and I/O devices. The associated API is designed for users that want to use VTK-m to analyze their data using provided or supplied worklets. Code for the control environment is designed to run on a single thread (or one single thread per process in an MPI job).

Most users of VTK-m will have some interaction with the control environment, for you cannot define data structures or execute any algorithms without it.

6.1 Device Adapter Tag

VTK-m uses a feature called a device adapter to define what type of device will be used to run algorithms. The device adapter encapsulates the device-specific code required to port to various devices. More information on the function of the device adapter is given in Section ??.

The 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.

6.1.1 Default Device Adapter

A default device adapter tag is specified in `vtkm/cont/DeviceAdapter.h` (although it can also be 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 6.1: Macros to port VTK-m code among different devices

```
// Uncomment one (and only one) of the following to reconfigure the Dax
// 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>
```


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.

6.1.2 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`.

[ADD EXAMPLE. I WOULD LIKE TO HAVE A SIMPLE EXAMPLE INVOLVING A FILTER, BUT THAT INTERFACE IS STILL IN FLUX.]

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 has a (rather artificial) declaration of a helper class for executing the elevation filter.

[ADD EXAMPLE WHEN FILTERS ARE SETTLED.]

6.2 Array Handle

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.

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.

6.2.1 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 this section, and for now we will use the default value.

Example 6.2: 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 6.3: Creating an `ArrayHandle` for output data.

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

Constructing an `vtkm::cont::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 6.4: 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 6.5: 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 `vtkm::cont::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 6.5 were to be placed within a callable function or method, it could cause the `vtkm::cont::ArrayHandle` to become invalid.

Example 6.6: Invalidating an `ArrayHandle` by letting the source `std::vector` leave scope.

```
VTKM_CONT_EXPORT
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_EXPORT
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.
}

```

6.2.2 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 6.7: 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_EXPORT
    SimpleScalarArrayPortal(ValueType *array, vtkm::Id numberOfValues)
        : Array(array), NumberOfValues(numberOfValues) { }

```

```

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

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

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

VTKM_EXEC_CONT_EXPORT
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 convenient 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 6.8: Using `ArrayPortalToIterators`.

```

template<typename PortalType>
VTKM_CONT_EXPORT
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 6.9: Using [ArrayPortalToIteratorBegin](#) and [ArrayPortalToIteratorEnd](#).

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

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

`vtkm::cont::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.

`vtkm::cont::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 an 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 `vtkm::cont::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 6.10: 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;
        }
    }
}
```

6.2.3 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 worklets [OR FILTERS?], 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 6.1 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 6.7, but here is a quick example of using these execution array portals in a simple functor.

Example 6.11: 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_EXPORT
    DoubleFunctor(InputPortalType inputPortal, OutputPortalType outputPortal)
```

```

    : InputPortal(inputPortal), OutputPortal(outputPortal) { }

    VTKM_EXEC_EXPORT
    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.

6.2.4 Basic Storage

As previously discussed, `vtkm::cont::ArrayHandle` takes two template arguments.

Example 6.12: 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. 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 6.13: 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.

6.2.5 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.

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 6.14: Fictitious field storage used in custom array storage examples.

```
#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 6.2.2 and is generally straightforward for simple containers like this. Here is an example implementation for our `FooFieldsDeque` container.

Example 6.15: Array portal to adapt a third-party container to VTK-m.

```

#include <vtkm/cont/Assert.h>
#include <vtkm/cont/internal/IteratorFromArrayPortal.h>

// DequeType expected to be either FooFieldsDeque or const FooFieldsDeque
template<typename DequeType>
class ArrayPortalFooPressure
{
public:
    typedef float ValueType;

    VTKM_CONT_EXPORT
    ArrayPortalFooPressure() : Container(NULL) { }

    VTKM_CONT_EXPORT
    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_EXPORT
    ArrayPortalFooPressure(const ArrayPortalFooPressure<OtherDequeType> &other)
        : Container(other.GetContainer()) { }

    VTKM_CONT_EXPORT
    vtkm::Id GetNumberOfValues() const {
        return static_cast<vtkm::Id>(this->Container->size());
    }

    VTKM_CONT_EXPORT
    ValueType Get(vtkm::Id index) const {
        VTKM_ASSERT_CONT(index >= 0);
        VTKM_ASSERT_CONT(index < this->GetNumberOfValues());
        return (*this->Container)[index].Pressure;
    }

    VTKM_CONT_EXPORT
    void Set(vtkm::Id index, ValueType value) const {
        VTKM_ASSERT_CONT(index >= 0);
        VTKM_ASSERT_CONT(index < this->GetNumberOfValues());
        (*this->Container)[index].Pressure = value;
    }

    // Here for the copy constructor.
    VTKM_CONT_EXPORT
    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 6.16: 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 managed 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. Any 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 6.15.

Example 6.17: 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_EXPORT
    Storage() : Container(NULL) { }

    VTKM_CONT_EXPORT
    Storage(FooFieldsDeque *container) : Container(container) { }

    VTKM_CONT_EXPORT
    PortalType GetPortal() { return PortalType(this->Container); }

    VTKM_CONT_EXPORT
    PortalConstType GetPortalConst() const {
        return PortalConstType(this->Container);
    }

    VTKM_CONT_EXPORT
    vtkm::Id GetNumberOfValues() const {
        return static_cast<vtkm::Id>(this->Container->size());
    }

    VTKM_CONT_EXPORT
    void Allocate(vtkm::Id numberOfValues) {
        this->Container->resize(numberOfValues);
    }

    VTKM_CONT_EXPORT
    void Shrink(vtkm::Id numberOfValues) {
        this->Container->resize(numberOfValues);
    }

    VTKM_CONT_EXPORT
    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 6.18: 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_EXPORT
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 6.18 is not templated, so it uses the `VTKM_ARRAY_HANDLE_SUBCLASS_NT` macro. (The other macro is described in Section 6.2.7 on page 57). 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.]

[ALTHOUGH THIS EXAMPLE WAS ORIGINALLY WRITTEN WITH EXECUTING WORKLETS IN MIND, AT THIS LEVEL OF THE USER'S GUIDE IT WOULD PROBABLY BE BETTER TO HAVE AN EXAMPLE THAT USES A FILTER. ONCE THE FILTERS ARE SETTLED, THAT IS.]

Example 6.19: Using an `ArrayHandle` with custom container.

```

template<typename GridType>
VTKM_CONT_EXPORT
void GetElevationAirPressure(const GridType &grid, FooFieldsDeque *fields)
{
    // Make an array handle that points to the pressure values in the fields.
    ArrayHandleFooPressure pressureHandle(fields);

    // This is currently commented out because worklets are not yet implemented.
    // // Run an elevation worklet.
    // vtkm::worklet::Elevation elevation(vtkm::make_Vector3(0.0, 0.0, 0.0),
    //                                   vtkm::make_Vector3(0.0, 0.0, 10.0),
    //                                   vtkm::make_Vector2(0.02, 0.0));
    // vtkm::cont::DispatcherMapField<vtkm::worklet::Elevation>
    //     dispatcher(elevation);
    // dispatcher.Invoke(grid.GetPointCoordinates(), pressureHandle);

    // Make sure the values are flushed back to the control environment.
    pressureHandle.GetPortalConstControl();

    // Now the pressure field is in the fields container.
}

```

6.2.6 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, ...]` (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.

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 6.20: Functor that doubles an index.

```
struct DoubleIndexFunctor
{
    VTKM_EXEC_CONT_EXPORT
    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 6.21: 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 6.22: Using `make_ArrayHandleImplicit`.

```
vtkm::cont::make_ArrayHandleImplicit<vtkm::Id>(DoubleIndexFunc(), 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 6.23: Custom implicit array handle for even numbers.

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

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

  VTKM_CONT_EXPORT
  ArrayHandleDoubleIndex(vtkm::Id numberOfValues)
    : Superclass(DoubleIndexFunc(), 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 6.23 is not templated, so it uses the `VTKM_ARRAY_HANDLE_SUBCLASS_NT` macro. (The other macro is described in Section 6.2.7 on page 57). 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.

VTk-m comes with some examples of implicit storage. `vtkm::cont::ArrayHandleConstant` returns the same value for every index in the array. The constant array is useful when an algorithm that can work on a variable field is used on a constant value. `vtkm::cont::ArrayHandleIndex` returns the index as the value. `vtkm::cont::ArrayHandleCounting` is an array that starts from a given value and then counts with a given step. The index and counting arrays are useful for generating fields of identifiers or for indexing operations. `vtkm::cont::ArrayHandleUniformPointCoordinates` generates the position of points in axis-aligned uniform rectilinear grids. It is used internally by VTK-m to create point coordinates for these types of data structures.

6.2.7 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 6.24: Functor to scale and bias a value.

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

    VTKM_EXEC_CONT_EXPORT
    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 6.25: 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 6.26: 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_EXPORT
    ArrayHandleScaleBias(const ArrayHandleType &array,
                        ValueType scale,
                        ValueType bias)
        : Superclass(array, ScaleBiasFunctor<ValueType>(scale, bias)) { }
};

template<typename ArrayHandleType>
VTKM_CONT_EXPORT
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 6.26 is templated, so it uses the `VTKM_ARRAY_-`

`HANDLE_SUBCLASS` macro. (The other macro is described in Section 6.2.5 on page 53). 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.

6.2.8 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 copying 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 6.27: Using `ArrayHandlePermutation`.

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

typedef vtkm::cont::ArrayHandle<vtkm::Float32> 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 6.28: Using `make_ArrayHandlePermutation`.

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

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.

6.2.9 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.

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 6.29: Using `ArrayHandleZip`.

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

typedef vtkm::cont::ArrayHandle<vtkm::Float32> 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::Float32> 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 6.30: Using `make_ArrayHandleZip`.

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

6.2.10 Derived Storage

So far, we have discussed using the array storage mechanism to adapt to particular memory layout and to create implicit and other special fancy arrays. Yet another option is to create a *derived storage*. A derived storage allows you to declare your own type of fancy array. A derived storage takes one or more other arrays and changes their behavior in some way. Their implementation is similar to adapting a memory layout, but some of the details are different.

In this section we will demonstrate the steps required to create a derived storage. A transform, permutation, and zip arrays, documented in Sections 6.2.7, 6.2.8, and 6.2.9, respectively, provide specific forms of a derived storage. When applicable, it is much easier to create a derived array using these pre-implemented 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 6.31: Derived array portal for concatenated arrays.

```
#include <vtkm/cont/ArrayHandle.h>
#include <vtkm/cont/ArrayPortal.h>
#include <vtkm/cont/Assert.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_EXPORT
    ArrayPortalConcatenate() : Portal1(), Portal2() { }

    VTKM_SUPPRESS_EXEC_WARNINGS
    VTKM_EXEC_CONT_EXPORT
    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_EXPORT
ArrayPortalConcatenate(const ArrayPortalConcatenate<OtherP1,OtherP2> &src)
    : Portal1(src.GetPortal1()), Portal2(src.GetPortal2()) { }

VTKM_SUPPRESS_EXEC_WARNINGS
VTKM_EXEC_CONT_EXPORT
vtkm::Id GetNumberOfValues() const {
    return
        this->Portal1.GetNumberOfValues() + this->Portal2.GetNumberOfValues();
}

VTKM_SUPPRESS_EXEC_WARNINGS
VTKM_EXEC_CONT_EXPORT
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_EXPORT
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_EXPORT
const PortalType1 &GetPortal1() const { return this->Portal1; }
VTKM_EXEC_CONT_EXPORT
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 6.32: `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_EXPORT
    Storage() : Valid(false) { }

    VTKM_CONT_EXPORT
    Storage(const ArrayHandleType1 array1, const ArrayHandleType2 array2)
        : Array1(array1), Array2(array2), Valid(true) { }

    VTKM_CONT_EXPORT
    PortalType GetPortal() {
        VTKM_ASSERT_CONT(this->Valid);
        return PortalType(this->Array1.GetPortalControl(),
            this->Array2.GetPortalControl());
    }

    VTKM_CONT_EXPORT
    PortalConstType GetPortalConst() const {
        VTKM_ASSERT_CONT(this->Valid);
        return PortalConstType(this->Array1.GetPortalConstControl(),
            this->Array2.GetPortalConstControl());
    }

    VTKM_CONT_EXPORT
    vtkm::Id GetNumberOfValues() const {
        VTKM_ASSERT_CONT(this->Valid);
        return this->Array1.GetNumberOfValues() + this->Array2.GetNumberOfValues();
    }

    VTKM_CONT_EXPORT
    void Allocate(vtkm::Id numberOfValues) {
        VTKM_ASSERT_CONT(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_EXPORT
    void Shrink(vtkm::Id numberOfValues) {
        VTKM_ASSERT_CONT(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_EXPORT
void ReleaseResources() {
    VTKM_ASSERT_CONT(this->Valid);
    this->Array1.ReleaseResources();
    this->Array2.ReleaseResources();
}

// Required for later use in ArrayTransfer class.
VTKM_CONT_EXPORT
const ArrayHandleType1 &GetArray1() const {
    VTKM_ASSERT_CONT(this->Valid);
    return this->Array1;
}
VTKM_CONT_EXPORT
const ArrayHandleType2 &GetArray2() const {
    VTKM_ASSERT_CONT(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 6.33: 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 6.33, the prototype for the constructor must be equivalent to the following.

Example 6.34: 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 6.31 and 6.32, the following provides an `ArrayTransfer` appropriate for the derived storage.

Example 6.35: `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_EXPORT
ArrayTransfer(StorageType *storage)
    : Array1(storage->GetArray1()), Array2(storage->GetArray2())
{ }

VTKM_CONT_EXPORT
vtkm::Id GetNumberOfValues() const {
    return this->Array1.GetNumberOfValues() + this->Array2.GetNumberOfValues();
}

VTKM_CONT_EXPORT
PortalConstExecution PrepareForInput(bool vtkmNotUsed(updateData)) {
    return PortalConstExecution(this->Array1.PrepareForInput(Device()),
                                this->Array2.PrepareForInput(Device()));
}

VTKM_CONT_EXPORT
PortalExecution PrepareForInPlace(bool vtkmNotUsed(updateData)) {
    return PortalExecution(this->Array1.PrepareForInPlace(Device()),
                            this->Array2.PrepareForInPlace(Device()));
}

VTKM_CONT_EXPORT
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_EXPORT
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_EXPORT
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_EXPORT
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 6.36: `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_EXPORT
    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 6.36 is templated, so it uses the `VTKM_ARRAY_HANDLE_SUBCLASS` macro. (The other macro is described in Section 6.2.5 on page 53). 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.

6.3 Dynamic Array Handle

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-time 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 6.37: Creating a `DynamicArrayHandle`.

```
VTKM_CONT_EXPORT
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;
}
```

6.3.1 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 6.38: 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 executing a worklet [OR FILTER?] on one or more fields, it is common to generate an output field, and it is furthermore usually desirable for the output type to match the input type. 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 6.39: 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 `IsArrayHandleType` and `IsTypeAndStorage` method. `IsArrayHandleType` takes an example array handle type and returns whether the underlying array matches the given static array. `IsTypeAndStorage` takes an example component type and an example storage type as arguments and returns whether the underlying array matches both types.

Example 6.40: 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.IsArrayHandleType(concreteHandle);

// This returns false
bool isIdArray = dynamicHandle.IsArrayHandleType(
    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::internal::StorageTagError());

```

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 Section 6.2. This is done with the `CastToArrayHandle` 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 `CastToArrayHandle` throws a `vtkm::cont::ErrorControlBadValue` exception.

Example 6.41: Casting a `DynamicArrayHandle` to a concrete `ArrayHandle`.

```
dynamicHandle.CastToArrayHandle(concreteHandle);
```

6.3.2 Casting to Unknown Types

Using `CastToArrayHandle` 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 6.42: Operating on `DynamicArrayHandle` with `CastAndCall`.

```

struct PrintArrayContentsFunctor
{
    template<typename T, typename Storage>
    VTKM_CONT_EXPORT
    void operator()(const vtkm::cont::ArrayHandle<T,Storage> &array) const
    {
        this->PrintArrayPortal(array.GetPortalConstControl());
    }
}

private:

```

```

template<typename PortalType>
VTKM_CONT_EXPORT
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());
}

```

6.3.3 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 2.5. There are separate lists for component types and for storage types.

Common type lists for components are defined in `vtkm/TypeListTag.h` and are documented in Section 2.5.2. This header also defines `VTKM_DEFAULT_TYPE_LIST_TAG`, which defines the default list of component 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 2.5.1.

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 6.42, 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 6.42 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 6.43: 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 6.44: Specifying a single component type in a `DynamicArrayHandle`.

```
PrintArrayContents(dynamicArray.ResetTypeList(vtkm::TypeListTagId()));
```

Storage type lists can be changed similarly.

Example 6.45: 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()));
}
```

Both the component type list and the storage type list can be modified by chaining these reset calls.

Example 6.46: Specifying both component and storage types in a `DynamicArrayHandle`.

```
PrintArrayContents(dynamicArray.
    ResetTypeList(vtkm::TypeListTagId()).
    ResetStorageList(MyIdStorageList()));
```


6.4 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.

6.4.1 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.

Creating Uniform Grids

[I AM EXPECTING TO CHANGE `vtkm::cont::DataSetBuilderRegular` TO `vtkm::cont::DataSetBuilderUniform`. CHANGE THIS DOCUMENTATION WHEN THAT HAPPENS.]

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::DataSetBuilderRegular` class can be used to easily create 2- or 3-dimensional uniform grids. `DataSetBuilderRegular` 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 6.47: Creating a uniform grid.

```
vtkm::cont::DataSetBuilderRegular 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 6.48: Creating a uniform grid with custom origin and spacing.

```
vtkm::cont::DataSetBuilderRegular 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));
```

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`.
[SUPPORT ARRAYHANDLE AS WELL?]

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 6.49: 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 range from -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);
```

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 6.1 shows an example of an explicit mesh and the arrays that can be used to define it.

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 6.1.

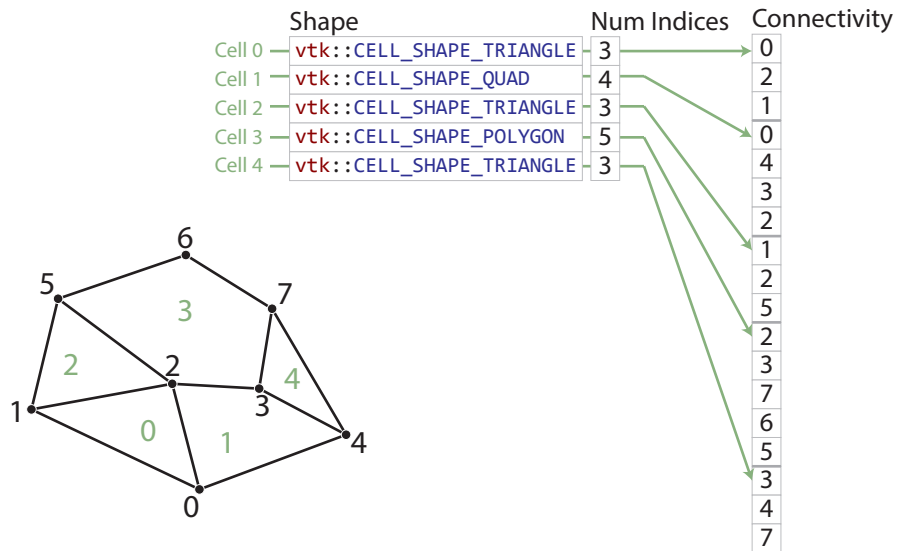


Figure 6.1: An example explicit mesh.

Example 6.50: 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 6.1 except this time using `DataSetBuilderExplicitIterative`.

Example 6.51: 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();
```

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 `DataSets` 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::vectors`, 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 6.52: 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::DataSetBuilderRegular 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);

```

6.4.2 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.) 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 7.5.1 starting on page 100.

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.

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 6.2 demonstrates this arrangement.

The big advantage of using `vtkm::cont::CellSetStructured` to define a cell set is that

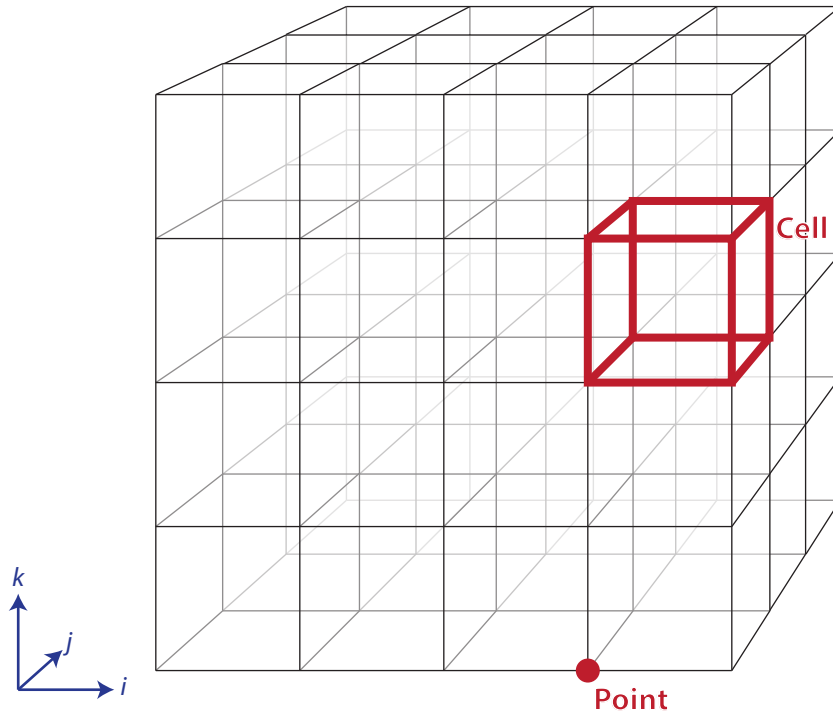


Figure 6.2: The arrangement of points and cells in a 3D structured grid.

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 6.4.4 starting on page 84.

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.

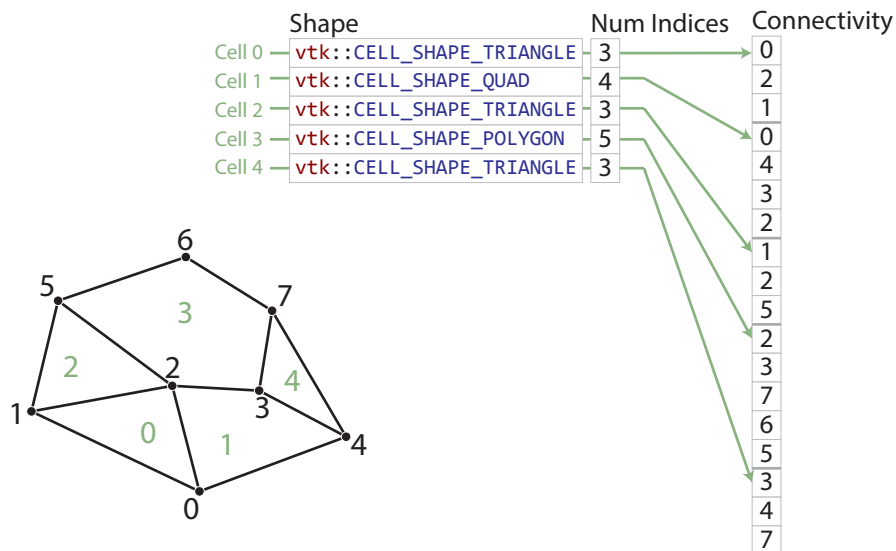


Figure 6.3: Example of cells in a `CellSetExplicit` and the arrays that define them.

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 7.5.1 starting on page 100.) 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 6.3 shows a simple example of an explicit cell set.

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.

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. Note that 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 6.53: Subsampling a data set with `CellSetPermutation`.

```
// Create a simple data set.
vtkm::cont::DataSetBuilderRegular dataSetBuilder;
vtkm::cont::DataSet originalDataSet =
    dataSetBuilder.Create(vtkm::Id3(33,33,26));
vtkm::cont::CellSetStructured<3> originalCellSet =
    originalDataSet.GetCellSet().CastTo(vtkm::cont::CellSetStructured<3>());

// 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::ArrayHandleCounting<vtkm::Id>,
    vtkm::cont::CellSetStructured<3> >
    permutedCellSet(permutationArray, originalCellSet);
```

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 Section 6.3 starting on page 68) 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.

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.

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.

6.4.3 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 managed 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.

6.4.4 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.

6.5 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.

[THIS EXAMPLE NEEDS TO BE UPDATED WHEN SOMETHING INTERESTING CAN BE INVOKED.]

Example 6.54: Using `vtkm::cont::Timer`.

```

vtkm::cont::ArrayHandle<vtkm::Float32> results;
// vtkm::cont::DispatchMapField<vtkm::worklet::Elevation> dispatcher;

vtkm::cont::Timer<> timer;

// dispatcher.Invoke(grid.GetPointCoordinates(), results);

// This call makes sure data is pulled back to the host in a host/device
// architecture.
results.GetPortalConstControl();

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

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

```

6.6 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 6.55: 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 two subclasses to `vtkm::cont::Error`. These are `vtkm::cont::ErrorExecution` and `vtkm::cont::ErrorControl`, and they represent errors that happen in the

respective execution and control environments.

Readers familiar with parallel programming will probably note the difficulty in raising errors in multi-threaded execution like what happens in the execution environment. In fact some devices, like CUDA devices, do not support exceptions at all. VTK-m handles the error reporting in the execution environment by flagging an error when it occurs and then throwing an error in the control environment after all threads have terminated. This means that the amount of execution that happens after an error is flagged is indeterminate and any output values should be considered incorrect.

The `vtkm::cont::ErrorControl` class is also broken down into several subclasses that can be independently caught to handle different types of errors. The following control errors exist and may be thrown.

`vtkm::cont::ErrorControlAssert` Thrown when an assertion fails, meaning a VTK-m operation reached an unexpected state. The header file `vtkm/cont/Assert.h` defines a macro named `VTKM_ASSERT_CONT` that behaves much like the POSIX C `assert` macro except that a `ErrorControlAssert` is thrown rather than killing the application outright.

`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::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.

6.7 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 6.56: 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.

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::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.

6.8 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/con-`

t/cxx11/DeviceAdapterCxx11Thread.h. The contents are the following (with minutia like include guards removed).

Example 6.57: 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.

6.8.1 Tag

The device adapter tag, as described in Section 6.1 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 6.58: 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);
```

6.8.2 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 6.59: 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 6.60: 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_EXPORT
    ArrayManagerExecution(typename Superclass::StorageType *storage)
        : Superclass(storage) { }
};
};
};
```

```
};
}
}
} // namespace vtkm::cont::internal
```

6.8.3 Algorithms

A device adapter implementation must also provide a specialization of `vtkm::cont::DeviceAdapterAlgorithm`, which is documented in Section 6.7. 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.

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 7.3, 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.

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 6.61: 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_EXPORT
        ScheduleKernel1D(const FunctorType &functor)
            : Functor(functor)
        { }

        VTKM_EXEC_EXPORT
        void operator()() const
        {
            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; }
            }
        }

        FunctorType Functor;
        vtkm::exec::internal::ErrorMessageBuffer ErrorMessage;
        vtkm::Id BeginId;
        vtkm::Id EndId;
    };

    template<typename FunctorType>
    struct ScheduleKernel3D
    {
        VTKM_CONT_EXPORT
        ScheduleKernel3D(const FunctorType &functor, vtkm::Id3 maxRange)
            : Functor(functor), MaxRange(maxRange)
        { }

        VTKM_EXEC_EXPORT
        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]));

            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;
                }
            }
        }

        FunctorType Functor;
        vtkm::Id3 MaxRange;
    };
};

```

```

        threadId3D[1]++;
        if (threadId3D[1] >= MaxRange[1])
        {
            threadId3D[1] = 0;
            threadId3D[2]++;
        }
    }
}

FunctorType Functor;
vtkm::exec::internal::ErrorMessageBuffer ErrorMessage;
vtkm::Id BeginId;
vtkm::Id EndId;
vtkm::Id3 MaxRange;
};

template<typename KernelType>
VTKM_CONT_EXPORT
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_EXPORT
static void Schedule(FunctorType functor, vtkm::Id numInstances)
{
    DoSchedule(ScheduleKernel1D<FunctorType>(functor), numInstances);
}

template<typename FunctorType>
VTKM_CONT_EXPORT
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_EXPORT
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

```

6.8.4 Timer Implementation

The VTK-m timer, described in Section 6.5, delegates to an internal class named `vtkm::cont::DeviceAdapterTimerImplementation`. 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 6.62: Specialization of `DeviceAdapterTimerImplementation`.

```

#include <chrono>

namespace vtkm {
namespace cont {

template<>
class DeviceAdapterTimerImplementation<vtkm::cont::DeviceAdapterTagCxx11Thread>

```



```

{
public:
    VTKM_CONT_EXPORT
    DeviceAdapterTimerImplementation()
    {
        this->Reset();
    }

    VTKM_CONT_EXPORT
    void Reset()
    {
        vtkm::cont::DeviceAdapterAlgorithm<vtkm::cont::DeviceAdapterTagCxx11Thread>
            ::Synchronize();
        this->StartTime = std::chrono::high_resolution_clock::now();
    }

    VTKM_CONT_EXPORT
    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 7

Execution Environment

[WRITE THIS.]

7.1 Simple Scheduling

7.2 Creating Worklets

7.3 Error Handling

7.4 Math

7.5 Working with Topology

In the control environment, data is defined in mesh structures that comprise a set of finite cells. (See Section 6.4.2 starting on page 79 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.

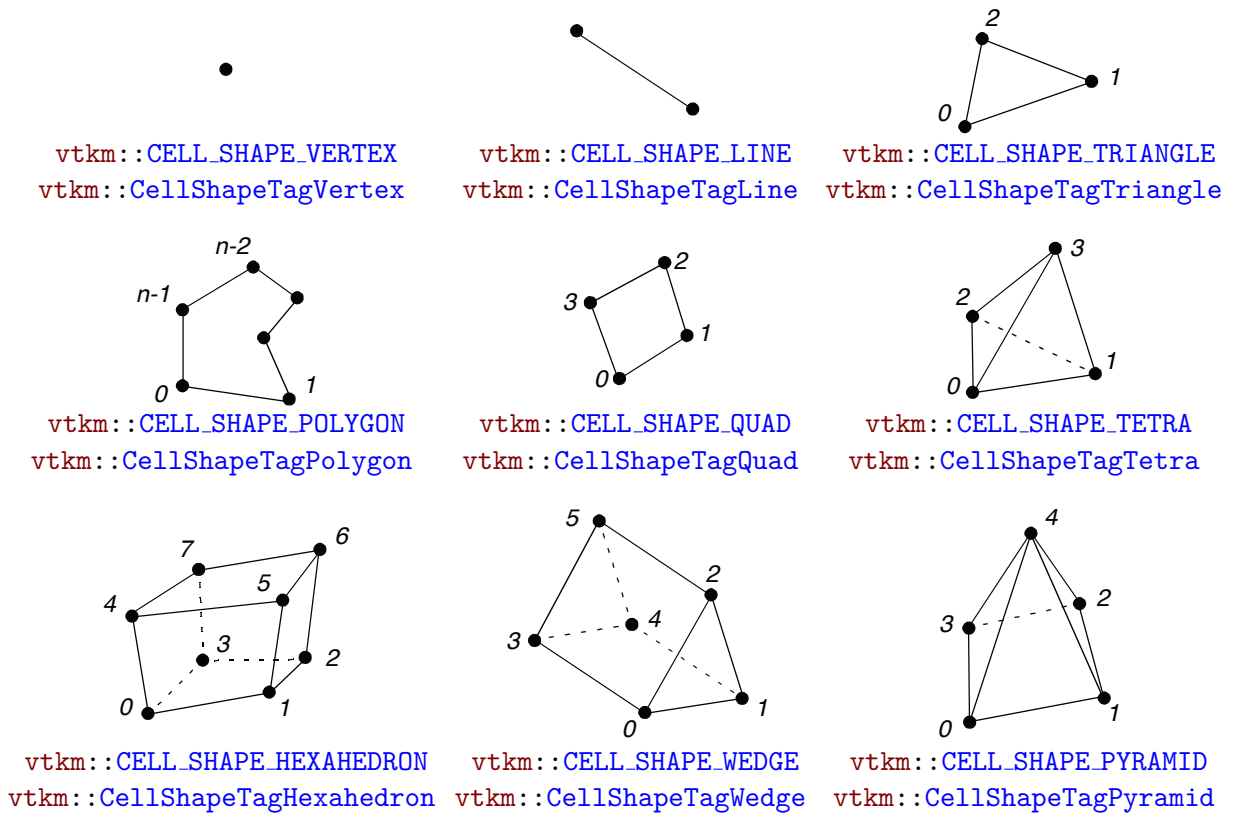


Figure 7.1: Basic Cell Shapes

7.5.1 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 7.1 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.

[ADD OTHER BASIC CELL SHAPE FEATURES SUCH AS TRAITS, CONVERTING BACK AND FORTH, AND `VTKMGENERICCELLSHAPEMACRO`.]

7.5.2 Parametric and World Coordinates

7.5.3 Interpolation

7.5.4 Derivatives

Chapter 8

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.

8.1 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 8.4.5. It is also possible to create new worklet types in VTK-m. This is an advanced topic covered in Chapter 9.

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.

8.2 Dispatchers

Worklets, both those provided by VTK-m as listed in Section 8.3 and ones created by a user as described in Section 8.4, 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 8.3. Also, for any worklet, the `Invoke` arguments can be gleaned from the control signature, which is described in Section 8.4.1.

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 8.1. Many examples of using these dispatchers are provided in Section 8.3.

`vtkm::worklet::DispatcherMapField` The dispatcher used in conjunction with a worklet that subclasses `vtkm::worklet::WorkletMapField`. The class has two template arguments: the worklet type and the device adapter (optional).

8.3 Provided Worklets

[WRITE THIS ONCE SOME WORKLETS ARE PROVIDED.]

8.4 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 must contain an overload of the parenthesis operator, which is the method that is executed in the execution environment.
5. The class must publicly inherit from a base worklet class that specifies the type of operation being performed.

[PERHAPS HAVE AN ANNOTATED EXAMPLE OF A WORKLET DECLARATION LIKE THE ONE IN FIGURE 3.3 OF THE DAX REPORT.]

8.4.1 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 8.1: 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 8.4.5.

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.

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 2.5.2 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.

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`.

The signature tags and their modifiers are described in greater detail in the following section on worklet types.

8.4.2 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 8.4.4) in terms of arity and argument semantics.

Example 8.2: 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.

8.4.3 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 `typedefed` 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 8.3: An `InputDomain` declaration.

```
typedef _1 InputDomain;
```

8.4.4 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.

[IT MIGHT BE BETTER TO HAVE AN EXAMPLE WITH A MORE STRAIGHTFORWARD TEMPLATE.]

Example 8.4: An overloaded parenthesis operator of a worklet.

```
template<typename T, vtkm::IdComponent Size>
VTKM_EXEC_EXPORT
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_EXPORT` (or `VTKM_EXEC_CONT_EXPORT`) modifier. Third, the method must be declared `const` to help preserve thread safety.

8.4.5 Worklet Types

There are multiple worklet types provided by VTK-m, each designed to support a particular type of operation. This section will define each of the worklet types, identify the generic superclass that a worklet instance should derive, identify the signature tags and their meanings, and give an example of the worklet in use.

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 its `ControlSignature`:

FieldIn An input field. This tag corresponds to a `vtkm::cont::ArrayHandle` passed to `Invoke`, and each invocation of the worklet gets a single value in this array. Dynamic

classes like `vtkm::cont::DynamicArrayHandle` and `vtkm::cont::DynamicPointCoordinates` that are implicitly cast to `ArrayHandles` are also supported. `FieldIn` is templated with a single argument that specifies the types that can be in an array. Any type list tag can be used for this argument, but the most common entries are described in Section 8.4.1 starting on page 105.

FieldOut An output field. This tag corresponds to a `vtkm::cont::ArrayHandle` or `vtkm::cont::DynamicArrayHandle` passed to `Invoke`. The array is resized appropriately, and each invocation of the worklet sets a single value in this array. `FieldOut` is templated with a single argument that specifies the types that can be in an array. Any type list tag can be used for this argument, but the most common entries are described in Section 8.4.1 starting on page 105.

ExecObject An execution object, which is passed directly from the control environment to the execution environment and then passed to each invocation of the worklet. The execution object must derive `vtkm::exec::ExecutionObjectBase`.

A field map worklet supports the following tags in its `ExecutionSignature`.

`_1, _2, _3,...` The numeric tags point to arguments in the `ControlSignature`. The data passed to the worklet come from this identified argument.

WorkIndex A unique identifier for the invocation instance of the worklet. The work index corresponds to the index of the domain.

Field maps most commonly perform basic calculator arithmetic, as demonstrated in the following example.

Example 8.5: Declaration 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>

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_EXPORT
    T operator()(const vtkm::Vec<T,Size> &inVector) const
    {
        return vtkm::Magnitude(inVector);
    }
};
```

```

}
};

VTKM_CONT_EXPORT
vtkm::cont::DynamicArrayHandle
InvokeMagnitude(vtkm::cont::DynamicArrayHandle input)
{
    vtkm::cont::ArrayHandle<vtkm::Float64> output;

    vtkm::worklet::DispatcherMapField<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 and the `ExecObject` control signature tag can be used to pass execution objects directly to the worklet.

The `ExecObject` parameter can be used in conjunction with the `vtkm::exec::ExecutionWholeArray` class to pass an entire array into a worklet. `ExecutionWholeArray` takes an `ArrayHandle` object in the control environment and converts it to an execution environment object that is compatible with the `ExecObject` tag. This allows you to have random access to the array. (You can also use `vtkm::exec::ExecutionWholeArrayConst` for read only access.) Care should be taken when directly accessing an array like this. Be sure to avoid invalid indexing or memory race conditions, which can be hard to debug.

The following example uses the random access of `ExecutionWholeArray` to make a worklet that copies an array in reverse order.

Example 8.6: Using `ExecutionWholeArray` for random array access.

```

struct ReverseArrayCopy : vtkm::worklet::WorkletMapField
{
    typedef void ControlSignature(FieldIn<> inputArray,
                                 ExecObject outputArray);
    typedef void ExecutionSignature(_1, _2, WorkIndex);
    typedef _1 InputDomain;

    template<typename InputType, typename OutputArrayPortalType>
    VTKM_EXEC_EXPORT
    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.");
        }
    }
};

template<typename T, typename Storage>
VTKM_CONT_EXPORT

```

```
vtkm::cont::ArrayHandle<T>
InvokeReverseArrayCopy(const vtkm::cont::ArrayHandle<T,Storage> &inArray)
{
    vtkm::cont::ArrayHandle<T> outArray;
    vtkm::exec::ExecutionWholeArray<T>
        outArrayExecObject(outArray, inArray.GetNumberOfValues());

    vtkm::worklet::DispatcherMapField<ReverseArrayCopy> dispatcher;
    dispatcher.Invoke(inArray, outArrayExecObject);

    return outArray;
}
```


Chapter 9

Advanced Worklet Customization

Chapter 8 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.

9.1 Transferring Arguments from Control to Execution

From the `ControlSignature` and `ExecutionSignature` defined in worklets, VTK-m uses template meta-programming 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.]

9.1.1 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 9.1: 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 =
        TypeCheck<TypeCheckTagArray<vtkm::TypeListTagField>, ArrayType>::value; // true
    bool check4 =
        TypeCheck<TypeCheckTagArray<vtkm::TypeListTagIndex>, ArrayType>::value; // false
    bool check5 = TypeCheck<TypeCheckTagExecObject, ArrayType>::value;          // false
}
```

9.1.2 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 9.2: 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);
}

```

9.1.3 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.

9.2 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`.

9.2.1 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 9.3: 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 provides 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 9.4: Using `vtkm::internal::make_FunctionInterface`.

```

const char *s = "Hello World";
static const size_t BUFFER_SIZE = 100;
char buffer[BUFFER_SIZE];

strlenInterface =
    vtkm::internal::make_FunctionInterface<size_t>(s);

strncpyInterface =
    vtkm::internal::make_FunctionInterface<char *>(buffer, s, BUFFER_SIZE);

```

9.2.2 Parameters

Once 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 9.5: Getting the arity of a `FunctionInterface`.

```

BOOST_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 9.6: Using `FunctionInterface::GetParameter()`.

```

void GetFirstParameterResolved(
    const vtkm::internal::FunctionInterface<void(const char *)> &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 `SetParameter` method for changing parameters. The same rules for indexing and template specification apply.

Example 9.7: Using `FunctionInterface::SetParameter()`.

```

void SetFirstParameterResolved(
    vtkm::internal::FunctionInterface<void(const char *)> &interface,
    const char *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>());
}

```

9.2.3 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 separate 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 9.8: Invoking a `FunctionInterface`.

```

vtkm::internal::FunctionInterface<size_t(const char *)> strlenInterface =
    vtkm::internal::make_FunctionInterface<size_t>("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 9.9: Invoking a [FunctionInterface](#) with a transform.

```
// Our transform converts C strings to integers, leaves everything else alone.
struct TransformFunctor
{
    template<typename T>
    VTKM_CONT_EXPORT
    const T &operator()(const T &x) const
    {
        return x;
    }

    VTKM_CONT_EXPORT
    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_EXPORT
    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>("42", 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 9.10: Getting return value from [FunctionInterface](#) safely.

```
template<typename ResultType, bool Valid> struct PrintReturnFunctor;

template<typename ResultType>
struct PrintReturnFunctor<ResultType, true>
{
```



```

    VTKM_CONT_EXPORT
    void operator()(
        const vtkm::internal::FunctionInterfaceReturnContainer<ResultType> &x)
    const
    {
        std::cout << x.Value << std::endl;
    }
};

template<typename ResultType>
struct PrintReturnFunctor<ResultType, false>
{
    VTKM_CONT_EXPORT
    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());
}

```

9.2.4 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 9.11: Appending parameters to a [FunctionInterface](#).

```

using vtkm::internal::FunctionInterface;
using vtkm::internal::make_FunctionInterface;

typedef FunctionInterface<void(const char *, vtkm::Id)>
    InitialFunctionInterfaceType;
InitialFunctionInterfaceType initialFunctionInterface =
    make_FunctionInterface<void>("Hello World", vtkm::Id(42));

typedef FunctionInterface<void(const char *, vtkm::Id, const char *)>
    AppendedFunctionInterfaceType1;
AppendedFunctionInterfaceType1 appendedFunctionInterface1 =
    initialFunctionInterface.Append("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 parameters 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 9.12: Replacing parameters in a `FunctionInterface`.

```

using vtkm::internal::FunctionInterface;
using vtkm::internal::make_FunctionInterface;

typedef FunctionInterface<void(const char *, vtkm::Id)>
    InitialFunctionInterfaceType;
InitialFunctionInterfaceType initialFunctionInterface =
    make_FunctionInterface<void>("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, const char *>::type
    ReplacedFunctionInterfaceType2;
ReplacedFunctionInterfaceType2 replacedFunctionInterface2 =
    initialFunctionInterface.Replace<2>("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 9.13: 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;
}

```

}

9.2.5 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 9.14: 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_EXPORT
    const T *operator()(const T &x, vtkm::internal::IndexTag<Index>) const {
        return &x;
    }
};

template<typename FunctionInterfaceType>
VTKM_CONT_EXPORT
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 9.15: Using a dynamic transform of a function interface.

```

struct UnpackNumbersTransformFunctor {
    template<typename InputType,
            typename ContinueFunctor,
            vtkm::IdComponent Index>
    VTKM_CONT_EXPORT
    void operator()(const InputType &input,
                  const ContinueFunctor &continueFunction,
                  vtkm::internal::IndexTag<Index>) const
    {
        continueFunction(input);
    }

    template<typename ContinueFunctor, vtkm::IdComponent Index>
    VTKM_CONT_EXPORT
    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_EXPORT
    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 9.16: Using `DynamicTransform` to cast dynamic arrays in a function interface.

```

template<typename Device>
struct ArrayCopyFunctor {
    template<typename Signature>
    VTKM_CONT_EXPORT
    void operator()(
        vtkm::internal::FunctionInterface<Signature> functionInterface) const
    {
        functionInterface.InvokeCont(*this);
    }

    template<typename T, class CIn, class COut>
    VTKM_CONT_EXPORT
    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_EXPORT
    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>());
}

```

9.2.6 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 9.17: Using the `ForEach` feature of `FunctionInterface`.

```

struct PrintArgumentFunctor{
    template<typename T, vtkm::IdComponent Index>
    VTKM_CONT_EXPORT
    void operator()(const T &argument, vtkm::internal::IndexTag<Index>) const
    {
        std::cout << Index << ":" << argument << " ";
    }
};

template<typename FunctionInterfaceType>
VTKM_CONT_EXPORT
void PrintArguments(const FunctionInterfaceType &functionInterface)
{
    std::cout << "( ";
    functionInterface.ForEachCont(PrintArgumentFunctor());
    std::cout << ")" << std::endl;
}

```

9.3 Invocation Objects

9.4 Creating New `ControlSignature` Tags

9.5 Creating New `ExecutionSignature` Tags

9.6 Creating New Worklet Types

9.6.1 New Worklet Superclasses

9.6.2 Dispatch Workflow

9.6.3 New Dispatch Classes

Chapter 10

OpenGL Interoperability

Chapter 11

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:

```
//=====
// Copyright (c) Kitware, Inc.
// All rights reserved.
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//=====
```

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 `typedefs`. 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 rationale 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.)
- 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++03 and C++11 specifications. It must also compile on older compilers that support C++98. Code that uses language features not available in C++98 must have a second implementation that works around the limitations of C++98. The `VTKM_FORCE_ANSI` turns on a compiler check for ANSI compatibility in gcc and clang compilers.
- 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::exec::CellField` and `vtkm::math::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 the Dax toolkit should be declared with `VTKM_EXPORT`, `VTKM_EXEC_EXPORT`, or `VTKM_EXEC_CONT_EXPORT`.

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.

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