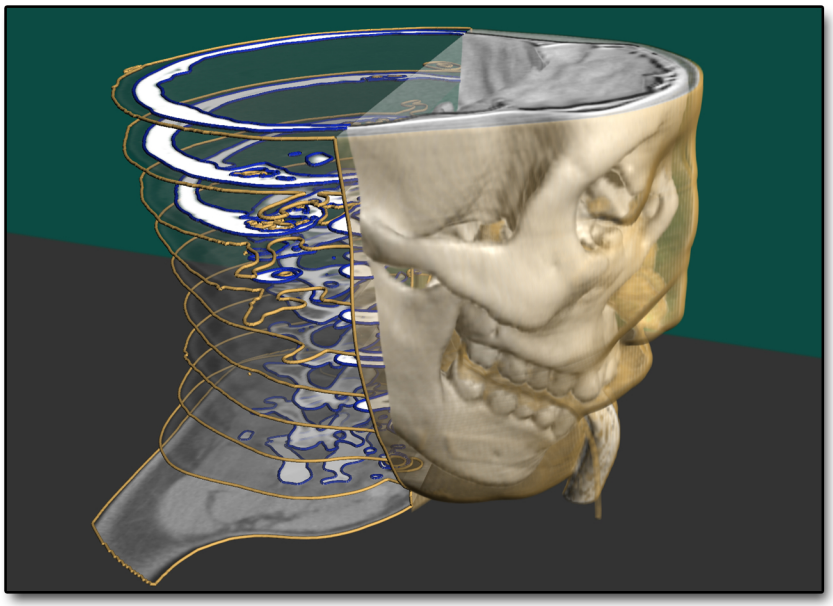
The VTK User's Guide

Install, Use and Extend The Visualization Toolkit

- Covers installation on PC, Unix, and Mac OSX
- Includes example scripts, C++ source code, images and data
- Shows how to extend VTK for your own applications



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Chapter 3

System Overview

The purpose of this chapter is to provide you with an overview of the *Visualization Toolkit* system, and to show you the basic information you'll need to create applications in C++, Java, Tcl, and Python. We begin by introducing basic system concepts and object model abstractions. We close the chapter by demonstrating these concepts and describing what you'll need to know to build applications.

3.1 System Architecture

The *Visualization Toolkit* consists of two basic subsystems: a compiled C++ class library and an "interpreted" wrapper layer that lets you manipulate the compiled classes using the languages Java, Tcl, and Python. See **Figure 3–1**.

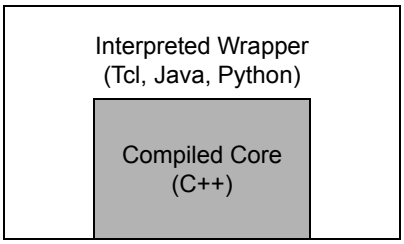

Figure 3–1 The Visualization Toolkit consists of a compiled (C++) core wrapped with various interpreted languages (Java, Tcl, Python).

The advantage of this architecture is that you can build efficient (in both CPU and memory usage) algorithms in the compiled C++ language, and retain the rapid code development features of interpreted languages (avoidance of compile/link cycle, simple but powerful tools, and access to GUI tools). Of course, for those proficient in C++ and who have the tools to do so, applications can be built entirely in C++.

The *Visualization Toolkit* is an object-oriented system. The key to using VTK effectively is to develop a good understanding of the underlying object models. Doing so will remove much of the mystery surrounding the use of the hundreds of objects in the system. With this understanding in place it's much easier to combine objects to build applications. You'll also need to know something about the capabilities of the many objects in the system; this only comes with reviewing code exam-

ples and online documentation. In this User's Guide, we've tried to provide you with useful combinations of VTK objects that you can adapt to your own applications.

In the remainder of this section, we will introduce two major components of the Visualization Toolkit: the visualization pipeline and the rendering engine. The visualization pipeline is used to acquire or create data, process that data, and either write the results to a file or pass the results to the rendering engine for display. The rendering engine is responsible for creating a visual representation of the data. Note that these are not truly rigid architectural components of VTK but are instead conceptual components. The discussion in this chapter will be fairly high-level, but when you combine that with the specific examples in both this chapter and the next, as well as the hundreds of available examples in the VTK source distribution you will gain a good understanding of these components.

Low-Level Object Model

The VTK object model can be thought of as being rooted in the superclass vtkObject. Nearly all VTK classes are derived from this class, or in some special cases from its superclass vtkObjectBase. All VTK must be created using the object's New() method, and must be destroyed using the object's Delete() method. VTK objects cannot be allocated on the stack because the constructor is a protected method. Using a common superclass and a unified method of creating and destroying object, VTK is able to provide several basic object-oriented operations.

Reference Counting. Objects explicitly store a count of the number of pointers referencing them. When an object is created through the static New() method of a class its initial reference count is 1 because a raw pointer must be used to refer to the new object:

```
vtkObjectBase* obj = vtkExampleClass::New();
```

When other references to the object are created or destroyed the reference count is incremented and decremented using the Register() and UnRegister() methods. Usually this is handled automatically by the various "set" methods provided in the object's API:

```
otherObject->SetExample(obj);
```

The reference count is now 2 because both the original pointer and a pointer stored inside the other object both refer to it. When the raw pointer originally storing the object is no longer needed the reference is removed using the Delete() method:

```
obj->Delete();
```

From this point forward it is no longer safe to use the original pointer to access the object because the pointer does not own a reference to it. In order to ensure proper management of object references every call to New() must be paired with a later call to Delete() to be sure no references are leaked.

A "smart pointer" implementation is provided by the class template vtkSmartPointer<> which simplifies object management. The above example may be re-written:

```
vtkSmartPointer<vtkObjectBase> obj =
  vtkSmartPointer<vtkExampleClass>::New();
otherObject->SetExample(obj);
```

In this case the smart pointer automatically manages the reference it owns. When the smart pointer variable goes out-of-scope and is no longer used, such as when a function in which it is a local variable returns, it automatically informs the object by decrementing the reference count. By using the static New() method provided by the smart pointer no raw pointer ever needs to hold a reference to the object, so no call to Delete() is needed.

Run-Time Type Information. In C++ the real type of an object may be different from the type of pointer used to reference it. All classes in the public interface of VTK have simple identifiers for class names (no templates), so a string is sufficient to identify them. The type of a VTK object may be obtained at run-time with the GetClassName() method:

```
const char* type = obj->GetClassName();
```

An object may be tested for whether it is an instance of a particular class or one of its subclasses using the IsA() method:

```
if(obj->IsA("vtkExampleClass")) { ... }
```

A pointer of a superclass type may be safely converted to a more derived type using the static SafeDownCast() method provided by the class of the derived type:

```
vtkExampleClass* example = vtkExampleClass::SafeDownCast(obj)
```

This will succeed at run-time only if the object is truly an instance of the more-derived type and otherwise will return a null pointer.

Object State Display. When debugging it is often useful to display a human-readable description of the current state of an object. This can be obtained for VTK objects using the Print() method:

```
obj->Print(cout);
```

The Rendering Engine

The VTK rendering engine consists of the classes in VTK that are responsible for taking the results of the visualization pipeline and displaying them into a window. This involves the following components. Note that this is not an exhaustive list, but rather a sense of the most commonly used objects in the rendering engine. The subheadings used here are the highest level superclass in VTK that represents this type of object, and in many cases where there are multiple choices these are abstract classes defining the basic API across the various concrete subclasses that implement the functionality..

vtkProp. Visible depictions of data that exist in the scene are represented by a subclass of vtkProp. The most commonly used subclasses of vtkProp for displaying objects in 3D are vtkActor (used to represent geometric data in the scene) and vtkVolume (used to represent volumetric data in the scene). There are also props that represent data in 2D such as vtkActor2D. The vtkProp subclass is generally responsible for knowing its position, size, and orientation in the scene. The parameters used to control the placement of the prop generally depend on whether the prop is for example a 3D object in the scene, or a 2D annotation. For 3D props such as vtkActor and vtkVolume (both subclasses of vtkProp3D which is itself a subclass of vtkProp), you can either directly control parameters such as

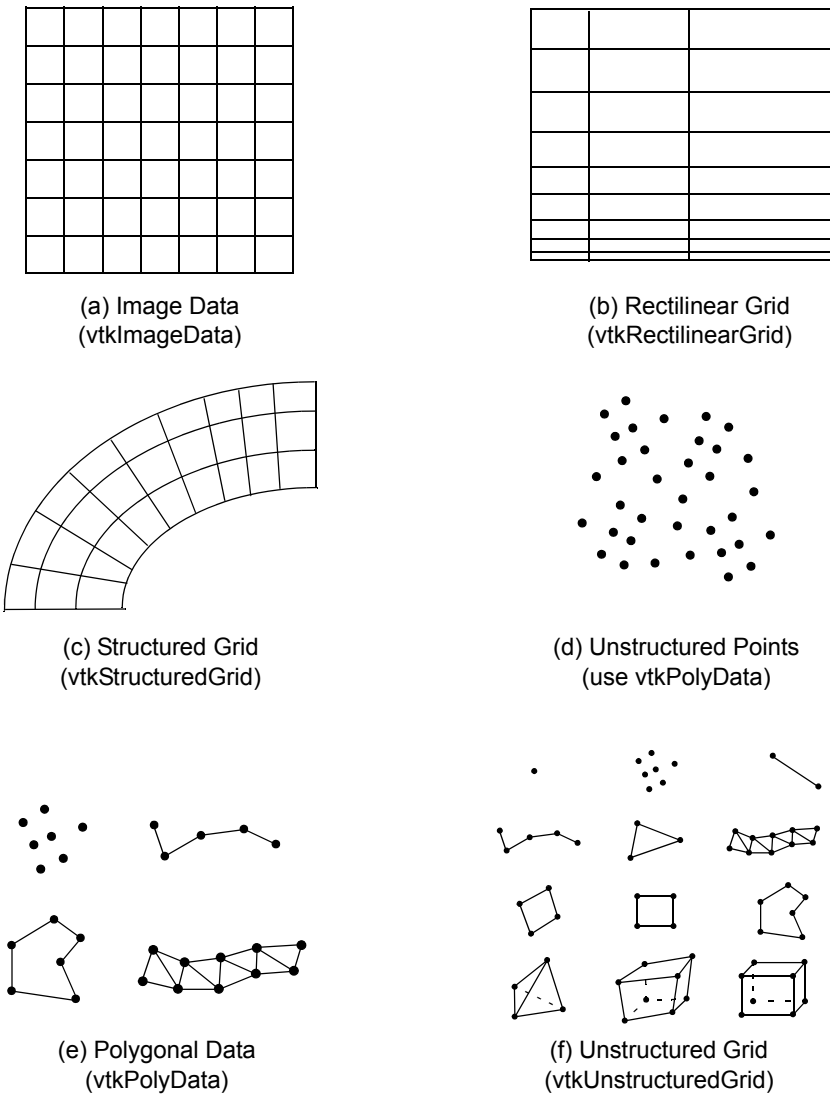

Figure 3–2 Dataset types found in **VTK**. Note that unstructured points can be represented by either polygonal data or unstructured grids, so are not explicitly represented in the system.

the object's 3D position, orientation and scale, or you can use a 4x4 transformation matrix. For 2D props that provide annotation such as the vtkScalarBarActor, the size and position of the annotation can be defined in a variety of ways including specifying a position, width, and height relative to the size of the entire viewport. In addition to providing placement control, props generally have a mapper object that holds the data and knows how to render it, and a property object that controls parameters such as color and opacity.

There are a large number (over 50) of specialized props such as vtkImageActor (used to display an image) and vtkPieChartActor (used to create a pie chart visual representation of an array of data

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About Kitware

Kitware, Inc. is a leader in the creation and support of open-source software and state of the art technology, and is one of the fastest growing software companies in the country. Kitware leverages its open-source communities and diverse technical expertise to provide advanced custom solutions for a host of complex technical problems.

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Part I
An Introduction to VTK

Welcome

Welcome to the *Visualization Toolkit (VTK) User's Guide*. VTK is an open-source, object-oriented software system for computer graphics, visualization, and image processing. Although it is large and complex, VTK is designed to be easy to use once you learn about its basic object-oriented design and implementation methodology. The purpose of this *User's Guide* is to help you learn this methodology, plus familiarize you with a variety of important VTK classes.

If you are a past reader of this guide, you'll note that we are now distinguishing updates of this book based on an edition number rather than a version number for VTK. This is the 11th edition of the *VTK User's Guide*. The *User's Guide* has been in publication for more than eleven years and this edition was published over sixteen years after the start of VTK. Although a version of VTK shortly before the 5.6 release was used when writing this edition, we are fairly confident in saying that nearly all the material covered here will be valid through many future releases. Backwards compatability is taken seriously in VTK, and although new features may be added that are not documented here, it is very rare for an existing feature to change.

VTK is a large system. As a result, it is not possible to completely document all VTK objects and their methods in this guide. Instead, this guide will introduce you to important system concepts and lead you up the learning curve as fast and efficiently as possible. Once you master the basics, we suggest that you take advantage of the many resources available including the Doxygen documentation pages ("Documentation" on page 6) and the community of VTK users (see "Additional Resources" on page 6).

The *Visualization Toolkit* is an open-source software system. What this means is that dozens and perhaps hundreds of generous developers and users like you have contributed to the code base. If you find VTK a useful tool, we encourage you to contribute bug fixes, algorithms, ideas, and/or applications back to the community. (See "How To Contribute Code" on page 299 for more information.) You can also contract with commercial firms such as Kitware to develop and add new features and tools.

1.1 User Guide Organization

This software guide is divided into three parts, each of which is further divided into several stand-alone chapters. Part I is a general introduction to VTK, including—in the next chapter—a description of how to install the *Visualization Toolkit* on your computer. This includes installing pre-compiled libraries and executables or compiling the software from the source code. Part I also introduces basic system concepts including an overview of the system architecture as well as a description of building applications in the C++, Tcl, Java, and Python programming languages. In some ways Part II is the heart of *User's Guide*, since dozens of examples are used to illustrate important system features. Part III is for the advanced VTK user. If you are a developer, Part III explains how to create your own classes, extend the system, and interface to various windowing and GUI systems. Chapter 19 contains simplified object diagrams that provide an overview of the relationship of VTK objects, a summary list of filters, and a description of VTK file formats for reading and writing your own data. Finally, the index is a handy tool for random access into the *User's Guide*.

1.2 How to Learn VTK

There are two broad categories of VTK users. First are class developers, who create classes in C++. Second, application developers use the C++ class library to build turn-key applications. Class developers must be proficient in C++, and if you are extending or modifying VTK, you must also be familiar with VTK's internal structures and design (material covered in Part III). Application developers may or may not use C++, since the compiled C++ class library has been "wrapped" with the interpreted languages Tcl, Python, Visual Basic, and Java. However, as an application developer you must know something about the external interface to the VTK objects, and the relationships between them.

The key to learning how to use VTK is to become familiar with its palette of objects and the ways of combining them. If you are a new *Visualization Toolkit* user, begin by installing the software. If you are a class developer, you'll want to download the source code and then compile it. Application developers may only need the precompiled binaries and executables. We recommend that you learn the system by studying the examples (if you are an application developer) and then studying the source code (if you are a class developer). Start by reading Chapter 3, which provides an overview of some of the key concepts in the system, and then review the examples in Part II. You may also wish to run the dozens of examples distributed with the source code found in the directory `VTK/Examples`. (Please see the file `VTK/Examples/README.txt` for a description of the examples contained in the various subdirectories.) There are also several hundred tests found in the source distribution such as those found in `VTK/Graphics/Testing/Tcl` and `VTK/Graphics/Testing/Cxx`, most of which are undocumented testing scripts. However, they may be useful to see how classes are used together in VTK.

1.3 Software Organization

The following sections describe the directory contents, summarize the software functionality in each directory, and locate the documentation and data.

Obtaining The Software

There are two different ways to access the VTK source code

1. from releases available on the VTK Web site `http://www.vtk.org`; and
2. from direct access to the CVS source code repository (instructions found at `www.vtk.org`).

This user's guide assumes that you are working with an official VTK release. This book was written against VTK as of September 2009. When we wrote this book we were considering both VTK 5.4 and features we were expecting in the 5.6 release. Please note that topics covered in this text will be valid for future releases of VTK as well. Also note that in the past, major releases of VTK were denoted by a major number change (i.e. VTK 4.4 to VTK 5.0) which also indicated that there was some break in backwards compatibility somewhere in the toolkit. However, with more frequent releases we will be faced with releasing a VTK 5.10 (confusing since alpha-numerically that comes before 5.2, but chronologically it comes after 5.8) or releasing VTK 6.0 with no change in backward compatibility. Since it is likely that we will choose to release a VTK 6.0 rather than a VTK 5.10, you may be reading this book while working with VTK 6.0 or later. Although the latest features may not be covered here, the material in this guide will be applicable to future releases. For information on new features specific to future releases, see the VTK mailing lists (http://www.vtk.org/VTK/help/mailing.html) or the *Kitware Source* (http://www.kitware.com/products/thesource.html), Kitware's free, quarterly developer's newsletter.

We highly recommend that you use VTK 5.4 or a later official release. Official releases are stable, consistent, and better tested than the current CVS repository. However, if you must use a more recent version, please be aware of the VTK quality testing dashboard. The *Visualization Toolkit* is heavily tested using the Kitware Software Process (http://www.kitware.com/solutions/softwareprocess.html). Before updating the CVS repository, make sure that the dashboard is "green" indicating stable code. If not green it is possible that your software update is unstable. (Learn more about the VTK quality dashboard in the section "Kitware's Quality Software Process" on page 312.)

Directory Structure

To begin your VTK odyssey, you will first need to know something about VTK's directory structure. Even if you are installing pre-compiled binaries, it is helpful to know enough to navigate through the code base to find examples, code, and documentation. The VTK directory structure is organized as follows.

- `InfoVis` — classes for information visualization.
- Views — specialized classes for viewing data including: filters, visualization, interaction and selection.
- `VTK/CMake` — configuration files for cross-platform building.
- `VTK/Common` — core classes.
- `VTK/Examples` — well-documented examples, grouped by topic.
- `VTK/Filtering` — classes related to data processing in the visualization pipeline.
- `VTK/GenericFiltering` — an adaptor framework to interface VTK to external simulation packages.
- `VTK/GeoVis` — views, sources, and other objects useful in terrain visualization.

- `VTK/Graphics` — filters that process 3D data.
- `VTK/GUISupport` — classes for using VTK with the MFC and Qt user interface packages.
- `VTK/Hybrid` — complex classes that depend on classes in multiple other directories.
- `VTK/Imaging` — image processing filters.
- `VTK/IO` — classes for reading and writing data.
- `VTK/Parallel` — parallel processing support such as MPI.
- `VTK/Rendering` — classes used to render.
- `VTK/Utilities` — supporting software like expat, png, jpeg, tiff, and zlib. The `Doxygen` directory contains scripts and configuration programs for generating the Doxygen documentation.
- `VTK/VolumeRendering` — classes used for volume rendering.
- `VTK/Widgets` — 3D widget classes.
- `VTK/Wrapping` — support for Tcl, Python, and Java wrapping.

Documentation

Besides this text and *The Visualization Toolkit* text (see the next section for more information), there are other documentation resources that you should be aware of.

- **Doxygen Documentation**. The Doxygen documentation is an essential resource when working with VTK. These extensive Web pages describe in detail every class and method in the system. The documentation also contains inheritance and collaboration diagrams, a listing of event invocations, and data members. The documentation is heavily hyper-linked to other classes and to the source code. The Doxygen documentation is available online at `http://www.vtk.org`. Make sure that you have the right documentation for your version of the source code.
- **Header Files.** Each VTK class is implemented with a `.h` and `.cxx` file. All methods found in the `.h` header files are documented and provide a quick way to find documentation for a particular method. (Indeed, Doxygen uses the header documentation to produces its output.)

Data

The data used in VTK examples and tests can be obtained from the download area at vtk.org, and via CVS access. Instructions for CVS access to the data repository are also available at `vtk.org`.

1.4 Additional Resources

This User's Guide is just one resource available to you to learn the Visualization Toolkit. Here is a sampling of some on-line resources, services, software applications and publications that can help you make effective use of this powerful toolkit.

- The companion textbook *The Visualization Toolkit An Object-Oriented Approach to 3D Graphics* covers in detail many of the algorithms and data structures utilized in VTK. The textbook is

published by Kitware, Inc. and is available to purchase either through the Kitware web site or through amazon.com.

- The Source is a quarterly newsletter published by Kitware that covers all of Kitware's open source projects. New functionality added to VTK will typically be covered by an article in the Source, and past issues are a valuable resource for articles and tutorials on a variety of VTK related topics. You can view the source online at kitware.com, and you can subscribe to receive a copy via postal mail.
- The VTK web site at vtk.org contains pointers to many other resources such as online manual pages, the Wiki and FAQ, the dashboard and bug tracker, and a searchable archive of the `vtkusers` mailing list (see below). In particular, the Doxygen manual pages are an invaluable resource for both novice users and experienced developers.
- The `vtkusers` mailing list allows users and developers to ask questions and receive answers; post updates, bug fixes, and improvements; and offer suggestions for improving the system. Please visit the VTK web site for more information on how to join the mailing list.
- Professional training is available from Kitware. Developer's Training Courses covering several of Kitware's open source projects including VTK, ITK, CMake and ParaView are offered typically twice per year in the upstate New York area. In addition, Kitware can bring the course to your site for customized training for your development team. Please see the Kitware web site or send email to courses@kitware.com for further information.
- Commercial support and consulting contracts are available from Kitware. These contracts range from small support efforts where VTK experts assist you in developing your application, to large-scale consulting efforts where Kitware develops an application to your specifications. Please see the Kitware web site or send email to sales@kitware.com for further information.
- ParaView is an open source end-user application focused on scientific visualization that is built on top of VTK. You can find the ParaView web site at paraview.org. Using ParaView is an excellent way to learn VTK since you will have access to the most popular functionality from a graphical user interface. It is also a good reference point for what is possible with VTK since you can load your own data and see what sort of visualization techniques are available and what sort of performance you should expect.
- CMake is an open source build environment for cross platform development. Although basic VTK users will need very little CMake knowledge in order to successfully build VTK on their standard Windows, Linux, or Mac OSX platform, advanced users may find CMake useful in their own development efforts or may require some in-depth CMake knowledge in order to port VTK to a non-standard platform. Visit the CMake web site at cmake.org for more information.
- CDash is an open source testing platform utilized by VTK. You can find a link to the VTK testing dashboard (powered by CDash) on the VTK web site. The dashboard shows the results of nightly and continuous testing on a variety of platforms. Developers who are building on non-standard platforms may with the contribute their own tests results to the dashboard. More information on the Kitware software process can be found in Section 10.8.

Installation

This chapter describes the steps required to install VTK on your computer system. The overall difficulty of this process depends on several factors. On Microsoft Windows, you can install the pre-built vtk.exe and run Tcl scripts using it. For Python or Java usage, to link VTK libraries into your own applications, or to use VTK on any platform other than Microsoft Windows, you must build VTK from source code. (There are too many platform variations – keeping binary distributions up-to-date is too much work, so we focus on making VTK easy to build everywhere.) If you are compiling the VTK source code and building your own libraries, expect to spend one-half hour on faster, multi-processor systems, and several hours on slower, memory limited systems. Also, the time to build depends on how many interpreted languages you wrap around the VTK C++ core, and your system configuration.

You may wish to refer to "System Architecture" on page 19 for an overview of the VTK architecture—this may make the compile process easier to follow. Also, if you run into trouble, you can contact the `vtkusers` mailing list (see "Additional Resources" on page 6).

2.1 Overview

VTK compiles and runs on many different computer platforms. By platform, we are referring to various combinations of operating systems, hardware configurations, and compilers. Because of the large number of combinations possible, binary distributions of VTK are generally not feasible. Therefore, to install VTK, you will have to compile and link the source code to produce libraries and executables. The exception to this process is if you are creating VTK applications using the Tcl interpreted language. In this case, pre-compiled binaries may be available for the Windows platform. Otherwise, you will have to compile the Tcl and Python VTK executables from the source code.

The chapter begins with an overview of CMake, the Cross-platform Make tool. CMake is used on all operating systems to configure the build environment. Next, the chapter is divided into two sections based on the type of operating system that you are installing on: either Windows or UNIX (for

Macintosh OSX or Linux, follow the UNIX instructions). You only need to read the appropriate section for your installation. The *Visualization Toolkit* does not run on older versions of Windows such as Windows 3.1. It also does not run on any Macintosh OS prior to OSX 10.2 (Jaguar).

2.2 CMake

CMake is an open-source, cross-platform tool for configuring and managing the build process. Simple, platform independent files (CMakeLists.txt) are used to describe the build process and capture dependencies. When CMake is run, it produces native build files for the particular compiler/operating system that you are working on. For example, on Windows with Microsoft Visual Studio, solution files and project files are created. On Unix, makefiles are created. This way you can easily compile VTK on any computer using a single source tree and work with the development tools (editors, debuggers, profilers, compilers, etc.) that are natural to the platform that you are working on. (Learn more about CMake from `cmake.org`. Kitware also publishes a book *Mastering CMake* for detailed information.) Download the latest CMake from `http://www.cmake.org`.

Running CMake requires three basic pieces of information: which compiler to use, where the source code directory (i.e. *source tree)* is, and which directory (i.e., *build tree)* to place the object code, libraries, and binaries that the compilation process produces. CMake will read the top-level `CMakeLists.txt` file found in the source tree and produce a cache (`CMakeCache.txt`) in the build tree. Note that CMake handles complex source code directory structures just fine—there will be one `CMakeLists.txt` file in each subdirectory of the source code tree.

Once these basic pieces of information are provided, the user invokes the *configure* step. This causes CMake to read the top-level `CMakeLists.txt` file, determine the system configuration, locate system resources, and descend into subdirectories in the source tree. As CMake runs, it discovers CMake variables and flags (CMake cache entries) that control the build process. These are presented to the user after the configure process ends. If the user desires to change the cache values, CMake provides a simple GUI to do so. After they are changed, another configure invocation is performed. This iterative configuration process continues until no additional changes are required. Once this point is reached, the user invokes the *generate* step. The generate step produces the solutions files, project files or makefiles used to control the build process for the specified compiler.

In the two sections that follow (Windows and Unix), specific instructions for running CMake for each platform are provided. Note that the general instructions described above are applicable to all systems. The CMake user interface may vary based on your platform. Although cmake-gui, the nwe Qt-based interface available in CMake 2.6 and later, is very similar from platform to platform. Also, if at all possible, install precompiled binaries for CMake rather than building CMake from source code.

2.3 Installing VTK on Windows XP, Vista or later

Under Windows there are two types of VTK installations. The first is a binary/executable installation that lets you do development in Tcl by running the pre-compiled executable. The second type is a full source code installation requiring you to compile the VTK source code (to generate C++ libraries) and VTK wrapper code (to generate Java, Tcl, and Python executables). Of the two types of installations, the binary installation is much easier. The source code installation has the advantage that you can monitor, debug, and modify VTK code—which is probably what you want if you are a class developer. Note, however, that even if you choose the binary installation, you can still extend VTK in

Figure 2–1 The VTK installer program for Windows.

a variety of ways—creating your own class (see "Writing A VTK Class: An Overview" on page 305), using run-time programmable filters (see "Programmable Filters" on page 419), and replacing VTK classes at run-time with your own versions of the class (see "Object Factories" on page 307).

Binary Installation

To install vtk.exe, the VTK Tcl/Tk executable, run the installer program vtk-X.X.X-win32.exe, available from the download page of vtk.org which will bring up an installation GUI (see **Figure 2–1**). The "X.X.X" in the installer program's filename represents the version number of VTK used to build it. You may also download corresponding *.zip files of the VTK source tree and the VTKData directory. As we release new versions of VTK, we make them available via links on the vtk.org download page. Watch for release announcements on the vtkusers mailing list.

The VTK source tree contains many *.tcl scripts you may use to learn about how various VTK classes work. Download the vtk-X.X.X.zip and vtkdata-X.X.X.zip files and extract them to your hard drive. In the VTK folder, you will find an "`Examples`" folder. Under the `Examples` folder, there are folders such as `GUI`, `MangledMesa`, and `Parallel`; each of those folders will have a sub folder called `Tcl` that contains various Tcl examples. In addition to the `Examples` folder, there are library folders like `Graphics`, `Imaging`, and `Filtering`. Each of these folders contains a `Testing/Tcl` sub folder containing the regression tests for VTK. Try running any example by double clicking on the Tcl file. When you double-click on a Tcl file (`.tcl` extension) for the first time, a dialog box may appear asking you what to use to open the file. This means that you need to create an association between Tcl files and the `vtk` executable to run them. If this happens, click the "`Select the program from a list`" button on the dialog, and click "`OK`". A new dialog labeled "`Open With`" will appear. Click the "`Browse`" button on this dialog to display a file browser. In the browser, go to the directory where you installed VTK. Normally this is either `C:\Program Files\VTK 5.4` or `C:\Program Files\Documents and Settings\<username>\My Documents\VTK 5.4`. In there you should see a `bin` folder which in turn contains a program called `vtk`. Double-click on `vtk` (or `vtk.exe`). Check that the "`Always use the selected program to open this kind of file`" checkbutton is marked on the "`Open With`" dialog, and then select the `OK` button. Your example should then run. In the future, double-clicking on any Tcl scripts will automatically begin execution of `vtk`.

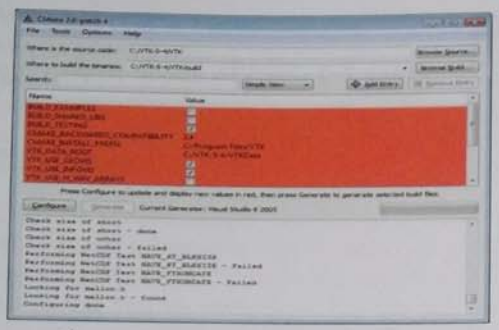


Figure 2–2 CMake is used to generate projects, makefiles, or workspaces for different compilers and operating systems. CMake is cross-platform.

Alternatively, if Tcl files are already associated with the `wish` executable (from installing Tcl/Tk binaries), you will see an error message similar to the following when you double-click on a Tcl file: `can't find package vtk while executing "package require vtk"`. If you receive this error message, right-click on the Tcl file, and select `"Open With..."` from the pop-up menu displayed. The `"Open With"` dialog will appear. Follow the rest of the instructions from the previous paragraph to associate Tcl files with the `vtk` executable.

That completes the binary installation process for Windows. In Chapter 3 we'll go into more detail on how to write your own C++, Tcl, Java and Python applications.

Source Code Installation

To develop C++ applications and extend VTK, you will need to do a source code installation. This is more challenging and may tie up your machine for a few hours as it compiles VTK. First you need to make sure your machine is capable of building a VTK source code release. You must be running Windows XP, Vista or later. You will need a C++ compiler installed on your machine. The instructions in this guide are oriented towards Microsoft Visual Studio 2005 or later, which works well with VTK. We also support the Borland C++ compiler, gcc under Cygwin or MinGW, NMake, Microsoft Visual C++ free editions, and Microsoft Visual C++ 2005. If you have not installed a C++ compiler, then you must do this first.

The next issue to consider is what additional tools you plan to use. If you plan to do development in Java then you must download and install the Java JDK which is available from Sun Microsystems at `http://www.java.sun.com`. If you plan on using Tcl/Tk and you are not using Microsoft Visual C++, then you will need to download and build the source code version of Tcl/Tk from `http://www.tcl.tk` or download and install a Tcl/Tk binary from `http://www.activestate.com/Products/ActiveTcl`. (Note: Tcl/Tk version 8.4 works with VTK version 5.4.0.)

Installing CMake. To compile VTK, you will first need to install CMake. An installer for CMake is available from `http://www.cmake.org`.

Running CMake. After you have setup your C++ compiler, installed CMake, and installed any additional packages such as Tcl, Java, and Python, you are ready to run CMake. To run CMake, there should be a CMake entry in the Start menu under `Programs->CMake->CMakeSetup`. The `CMakeSetup.exe` interface (**Figure 2–2**) is a simple program that allows you to customize the build to your particular machine and desired options for VTK. First you must tell `CMakeSetup` where the source tree for VTK is located and where you want to put the VTK binaries (these are generated as a result of compiling the source code). You can specify those directories with the `Browse` buttons or by

typing in the paths manually. Once the source and binary directories have been selected, you should click on the `Configure` button. The first time you click the `Configure` button, CMake will display a dialog from which you can select the build system you will use for compiling VTK. Then the CMakeSetup GUI will be filled with a list of variables and values found in the CMake cache. When first run, all the variables will be colored red. The red indicates that the cache entry was generated or changed during the previous configure step.

At this point, you can customize your VTK build. For example, if you want to enable the Tcl wrapping feature of VTK, scroll down in the cache values editor to the entry `VTK_WRAP_TCL`, and click on the value to toggle it from `OFF` to `ON`. After that, click the Configure button again. This will cause most of the values to change to gray, and any new values to appear in red. If you installed Tcl/Tk from a binary install, none of the new values should have `NOTFOUND` as values; if they do, you will have to specify those paths manually with the CMake interface. To set any value in the CMake interface, you click to the right of the variable where the value is displayed. Depending on the type of variable, there may be a file chooser, edit box or pull down that will allow you to edit the value.

Some important cache values for VTK are:

- `BUILD_SHARED_LIBS` — If this Boolean value is set to yes, then DLLs or shared libraries will be built. If it is no, then static libraries will be built. The default is static libraries. The static libraries are somewhat easier to work with, since they do not need to be in your path when executables are run. The executables will be self-contained. This is preferred for distribution of VTK based applications.
- `VTK_WRAP_TCL` — This determines if Tcl wrapping will be built.
- `VTK_WRAP_PYTHON` — This determines if Python wrapping will be built.
- `VTK_WRAP_JAVA` — This determines if Java wrapping will be built.

To get on-line help for any variable in CMake, simply click right over the value and select "Help for Cache Entry". Most of the defaults should be correct.

Continue to click on `Configure` until there are no longer any red values and you are happy with all of the values. At this point, you can click the `OK` button. This will cause CMake to write out the build files for the build type selected. For Microsoft, a project file will be located in the binary path you selected. Simply load this project file (`VTK.dsw` into Visual Studio 6.0, `VTK.sln` for .NET), and select the configuration you want to build in the `Build->Set Active Configuration` menu of Visual Studio. You will have the choice of Debug, Release, MinSizeRel (minimum size release), and RelWithDebInfo (release with debug information). You can select the `ALL_BUILD` project, and compile it as you would any other Visual Studio project. For Borland, makefiles are generated, and you have to use the command line make supplied with that compiler. The makefiles are located in the binary directory you specified.

Once VTK has been built all libraries and executables produced will be located in the binary directory you specified to CMake in a sub-folder called bin (unless you changed the `EXECUTABLE_OUTPUT_PATH`, or `LIBRARY_OUTPUT_PATH` variables in CMake).

(**Note:** Do not use the MSVC++ "Rebuild All" menu selection to rebuild the source code. This deletes all `CMakeLists.txt` files which are then automatically regenerated as part of the build process. MSVC will then try reloading them and an error will result. Instead, to rebuild everything, remove your VTK binary directory, rerun CMake, and then do a normal build.)

If you built VTK with BUILD_SHARED_LIBS on, then your client application will need to locate and load the VTK DLLs at runtime. There are many different ways that your application might

find the VTK DLLs at runtime. There are pros and cons associated with each way. The easiest approach is to make sure your application and the VTK DLLs exist in the same directory. You can copy all the VTK DLLs into your application's directory, or build your application into the same directory the VTK DLLs were built in using EXECUTABLE_OUTPUT_PATH in your own application's CMakeLists files. If your application's executable files and the VTK DLLs exist in the same directory, everything should just work. The "pro" of these approaches is their simplicity. The cons are: if you make copies of the VTK DLLs, you'll need to make sure you copy them again if you update and rebuild VTK; if your application's build output is mixed in with VTK's build output, it may be difficult to determine which build product comes from which project if necessary.

Another alternative is to modify the PATH environment variable so that your application can find the VTK DLLs even though they are not in the same directory. However, within this alternative, there are a couple ways to accomplish the task. You can set up a command prompt where the PATH is modified only in that command prompt and then launch your application from there, or you can change the user's PATH environment variable or the system-wide PATH environment variable. Changing the user's or system-wide PATH environment variable is recommended unless you need to have two or more distinct builds of VTK on the same computer.

The KWWidgets project (`http://www.kwwidgets.org`) provides a good example of setting the PATH from a batch script (to avoid changing the PATH environment variable), see the `KWWidgetsSetupPaths.bat` script in the build tree for the KWWidgets project. To obtain source code for KWWidgets, follow the instructions found at `http://www.kwwidgets.org`.

To set up a command prompt that can be used to launch an executable that can find the VTK DLLs, make a shortcut to a command prompt and then set it to call a batch file when it starts up. This is the technique that Visual Studio uses to create a command prompt where you can run the command line compiler or nmake. You can right click on a shortcut in the Windows Start menu and choose Properties to see how other command prompt shortcuts work. You can also drag-and-drop one of them to your desktop while holding down the control key to make a copy of it on your desktop. Then you can modify the properties of the shortcut on your desktop to call your own batch file that sets up your PATH and any other environment settings you may need for your application. Use the "/K batchfilename.bat" argument to the command prompt to run the batch file and then leave the command prompt running. Type "cmd /?" from any Windows command prompt for more information on the /K option.

For further discussion of locating DLLs on Windows, see the Windows SDK documentation for the LoadLibrary and LoadLibraryEx functions.

If you've made it this far, you've successfully built VTK on a PC. It can be a challenging process because of the size and complexity of the software. Please pay careful attention to the instructions given earlier. If you do run into problems, you may wish to join the `vtkusers` mailing list (see "Additional Resources" on page 6) and ask for help there. Commercial support is also available from Kitware.

2.4 Installing VTK on Unix Systems

There are a wide variety of flavors of Unix systems. As a result you will have to compile the VTK source code to build binaries and executables.

Source Code Installation

This section will walk you through the steps required to build VTK on a UNIX system. Unlike Windows, pre-compiled libraries and executables are not available for Unix systems, so you'll have to compile VTK yourself. (Note: check the vtkusers mailing list and other resources as described in "Additional Resources" on page 6—some users maintain binaries on the Web.) Typically, it is a fairly simple process, and it should take about one to four hours depending on the speed of your machine. (High-end, large-memory multi-processor machines using parallel builds can build the C++ and Tcl libraries and executables in under 10 minutes!) Most of this time is spent waiting for the computer to compile the source code. Only about 10-30 minutes of your time will be required. The first step is to make sure you have the necessary resources to build VTK. To be safe, you will need about 300 megabytes of disk space. On some systems, such as SGI, you may need more space, especially if compiling a debug version of VTK. You will also need a C++ compiler since VTK is written in C++. Typically the C++ compiler will be called CC, g++, or acc. If you are not sure that you have a C++ compiler, check with your support staff.

If you are planning to use VTK with Tcl/Tk, Python, or Java, then you will first need to download and install those packages. The Java JDK is available from Sun Microsystems at `http://www.java.sun.com`. If you plan on using Tcl/Tk and it is not already installed on your system, then you will need to download Tcl/Tk from `http://www.tcl.tk`. Python can be downloaded from `http://www.python.org`. Follow the instructions in these packages to build them.

CMake

Similar to the Windows environment, VTK on Unix uses CMake for the build process. (See the previous section on CMake.) There are precompiled binaries of CMake available for many Unix systems; however, you may have to build CMake if binaries are not available. (Go to `http://www.cmake.org` to download precompiled binaries.)

Installing CMake. If pre-compiled binaries are available, download and then extract the `tar` files into your destination directory (typically `/usr/local`). Either make sure that `cmake` and associated executables are in your path, or run cmake and its associated executables by giving their full path.

Building CMake. If a precompiled CMake binary is not available, you will have to build and install CMake. To build and install CMake, simply untar the sources (found at `http://www.cmake.org`) into a directory, and then run (in that directory):

```
./configure
make
make install
```

If you do not have root privileges, you can skip the third step above (i.e., `make install`). The CMake executables will be located at `CMake/bin/`. There are two different CMake executables which can be used to configure VTK: `ccmake` that provides a terminal based interface very similar to `CMakeSetup` described in the Windows installation section, and `cmake` which implements a wizard that requires you to answer a list of questions in order to configure the build.

It is a good idea to tell CMake which C++ and C compilers you want to use. On most Unix systems, you can set the information this way:

```
setenv CXX /your/c++/compiler
setenv CC /your/c/compiler
```

or

```
export CXX=/your/c++/compiler
export CC=/your/c/compiler
```

Otherwise CMake will automatically detect your compiler—however, this may not be the one that you want if you have multiple compilers on your system. Once you have done this, create an empty binary directory (e.g., `VTK-bin`) at the same level as the VTK source directory, and run CMake in it, passing it the path to the VTK source directory as shown below.

```
cd VTK-bin
ccmake ../VTK
```

or

```
cd VTK-bin
cmake -i ../VTK
```

(The instructions in the following two subsections describe the differences between `ccmake` and `cmake -i`.) UNIX developers familiar with configure scripts will notice that CMake and configure are similar in their functionality. However, configure takes command line arguments to control the generation of makefiles whereas in CMake, the build options can be set from a user interface.

Customizing the Build Using the Terminal Based User Interface (ccmake). `ccmake` has a simple terminal based interface that allows you to customize the VTK build to your particular machine and with the desired options. Once you run CMake using `ccmake`, you will be presented with a list of options that can be modified to customize the VTK build. CMake will be able to set most of these options to reasonable default values. To change a value, simply scroll with arrow keys and press `enter` when the desired option is highlighted. You will then be able to edit the option (unless the variable is a boolean, in which case, pressing `enter` will toggle the value). After completing the edit operation, hit `enter` again to resume scrolling through the options. Once you set all the options you want, press '`c`'. CMake will then process the configuration files and if necessary display new options on top (for example, if you turn VTK_WRAP_TCL on, you will be presented with options for the location of Tcl/Tk libraries and include paths). If there are new options, you should set them, (or leave them as they are if you are satisfied with the default values) and re-configure by pressing '`c`' and continue this process until there are no new options. Once this iterative process is completed, there will be new commands available: `Generate` and `Exit`. You can now press '`g`' to have CMake generate new makefiles and exit. If you need to change build options in the future, simply re-run `ccmake` and follow the instructions above.

Customizing the Build Using the Interactive Wizard Mode (cmake -i). On some platforms the terminal based interface provided by `ccmake` may not work. In this case try `cmake` with the `-i` (interactive wizard) option. Once you do so, it will ask you whether you want to see the advanced options. Most users will not have to change the advanced options. Next, CMake will ask you a list of questions. For each option, there will be a line describing what it does and a default (current) value. In

most cases, CMake will be able to generate acceptable default options. However, in certain cases, for example when a library such as OpenGL library is not located in the expected place, you will have to tell CMake the correct setting. Furthermore, by default, the bindings for Tcl, Python and Java are not created. If you want support for one or more of these languages, you will have to turn on the appropriate VTK_WRAP_XXX option on and, if necessary, tell CMake the location of necessary libraries and header files. Once you answer all questions, all your makefiles will be generated and VTK will be ready to build. If you need to change build options in the future, you can re-run CMake in wizard mode and answer all questions again.

Compiling the Source Code

Once CMake has completed running and produced the necessary makefiles, you can type `make` and VTK should compile. Some make utilities such as GNU make (`gmake`) support parallel builds (e.g., `gmake` with the `-j` option). Use parallel make if possible, even if on a single processor system, because usually the process is IO bound and the processor can handle multiple compiles. If you do run into problems, you may wish to join the `vtkusers` mailing list (see "Additional Resources" on page 6) and ask for help there. Commercial support is also available from Kitware.

Building VTK On Multiple Platforms

If you are planning to build VTK for multiple architectures then you can either make a copy of the entire VTK tree for each architecture and follow the instructions above, or you can have one copy of the VTK source tree and produce object code, libraries, and executables for each architecture in a separate directory. This approach requires creating a new build directory for each architecture such as `vtk-solaris` (make sure that you have enough disk space). Assuming that the new directory is created along side of the VTK source code directory, change directory (`cd`) into this directory and then run CMake similar to the following example:

```
cd /yourdisk
ls (output is: VTK vtk-solaris vtk-sgi)
cd vtk-solaris
cmake -i ../VTK
```

or

```
ccmake ../VTK
```

This will create makefiles in the `vtk-solaris` directory. You can now follow the instructions in the previous section for compiling VTK.

Installing VTK

Now that VTK has been built, the executables and libraries will be located in the build directory, in the sub-directory `bin/`. If you plan to share the build with more than one developer on the UNIX system, and you have root privileges, it is often a good idea to run the `make install` command. This will install VTK into `/usr/local`, unless you changed the build option `CMAKE_INSTALL_PREFIX` to another location. Running `make install` will copy all the files you need to compile and run VTK into a directory that other users can share.

This concludes the build and installation section for VTK under UNIX. If you need more information about CMake, see `http://www.cmake.org` or purchase the *Mastering CMake* book from Kitware (`http://www.kitware.com/products/cmakebook.html`). Chapter 3 of this software guide provides more details on how to run examples and create your own applications.

System Overview

The purpose of this chapter is to provide you with an overview of the *Visualization Toolkit* system, and to show you the basic information you'll need to create applications in C++, Java, Tcl, and Python. We begin by introducing basic system concepts and object model abstractions. We close the chapter by demonstrating these concepts and describing what you'll need to know to build applications.

3.1 System Architecture

The *Visualization Toolkit* consists of two basic subsystems: a compiled C++ class library and an "interpreted" wrapper layer that lets you manipulate the compiled classes using the languages Java, Tcl, and Python. See **Figure 3–1**.

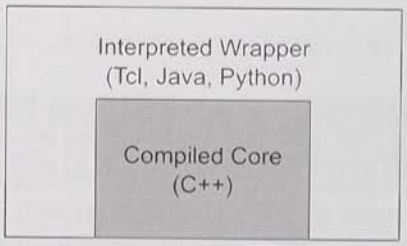


Figure 3–1 The Visualization Toolkit consists of a compiled (C++) core wrapped with various interpreted languages (Java, Tcl, Python).

The advantage of this architecture is that you can build efficient (in both CPU and memory usage) algorithms in the compiled C++ language, and retain the rapid code development features of interpreted languages (avoidance of compile/link cycle, simple but powerful tools, and access to GUI tools). Of course, for those proficient in C++ and who have the tools to do so, applications can be built entirely in C++.

The *Visualization Toolkit* is an object-oriented system. The key to using VTK effectively is to develop a good understanding of the underlying object models. Doing so will remove much of the mystery surrounding the use of the hundreds of objects in the system. With this understanding in place it's much easier to combine objects to build applications. You'll also need to know something about the capabilities of the many objects in the system; this only comes with reviewing code exam-

ples and online documentation. In this User's Guide, we've tried to provide you with useful combinations of VTK objects that you can adapt to your own applications.

In the remainder of this section, we will introduce two major components of the Visualization Toolkit: the visualization pipeline and the rendering engine. The visualization pipeline is used to acquire or create data, process that data, and either write the results to a file or pass the results to the rendering engine for display. The rendering engine is responsible for creating a visual representation of the data. Note that these are not truly rigid architectural components of VTK but are instead conceptual components. The discussion in this chapter will be fairly high-level, but when you combine that with the specific examples in both this chapter and the next, as well as the hundreds of available examples in the VTK source distribution you will gain a good understanding of these components.

Low-Level Object Model

The VTK object model can be thought of as being rooted in the superclass vtkObject. Nearly all VTK classes are derived from this class, or in some special cases from its superclass vtkObjectBase. All VTK must be created using the object's New() method, and must be destroyed using the object's Delete() method. VTK objects cannot be allocated on the stack because the constructor is a protected method. Using a common superclass and a unified method of creating and destroying object, VTK is able to provide several basic object-oriented operations.

Reference Counting. Objects explicitly store a count of the number of pointers referencing them. When an object is created through the static New() method of a class its initial reference count is 1 because a raw pointer must be used to refer to the new object:

```
vtkObjectBase* obj = vtkExampleClass::New();
```

When other references to the object are created or destroyed the reference count is incremented and decremented using the Register() and UnRegister() methods. Usually this is handled automatically by the various "set" methods provided in the object's API:

```
otherObject->SetExample(obj);
```

The reference count is now 2 because both the original pointer and a pointer stored inside the other object both refer to it. When the raw pointer originally storing the object is no longer needed the reference is removed using the Delete() method:

```
obj->Delete();
```

From this point forward it is no longer safe to use the original pointer to access the object because the pointer does not own a reference to it. In order to ensure proper management of object references every call to New() must be paired with a later call to Delete() to be sure no references are leaked.

A "smart pointer" implementation is provided by the class template vtkSmartPointer<> which simplifies object management. The above example may be re-written:

```
vtkSmartPointer<vtkObjectBase> obj =
  vtkSmartPointer<vtkExampleClass>::New();
otherObject->SetExample(obj);
```

In this case the smart pointer automatically manages the reference it owns. When the smart pointer variable goes out-of-scope and is no longer used, such as when a function in which it is a local variable returns, it automatically informs the object by decrementing the reference count. By using the static New() method provided by the smart pointer no raw pointer ever needs to hold a reference to the object, so no call to Delete() is needed.

Run-Time Type Information. In C++ the real type of an object may be different from the type of pointer used to reference it. All classes in the public interface of VTK have simple identifiers for class names (no templates), so a string is sufficient to identify them. The type of a VTK object may be obtained at run-time with the GetClassName() method:

```
const char* type = obj->GetClassName();
```

An object may be tested for whether it is an instance of a particular class or one of its subclasses using the IsA() method:

```
if(obj->IsA("vtkExampleClass")) { ... }
```

A pointer of a superclass type may be safely converted to a more derived type using the static SafeDownCast() method provided by the class of the derived type:

```
vtkExampleClass* example = vtkExampleClass::SafeDownCast(obj)
```

This will succeed at run-time only if the object is truly an instance of the more-derived type and otherwise will return a null pointer.

Object State Display. When debugging it is often useful to display a human-readable description of the current state of an object. This can be obtained for VTK objects using the Print() method:

```
obj->Print(cout);
```

The Rendering Engine

The VTK rendering engine consists of the classes in VTK that are responsible for taking the results of the visualization pipeline and displaying them into a window. This involves the following components. Note that this is not an exhaustive list, but rather a sense of the most commonly used objects in the rendering engine. The subheadings used here are the highest level superclass in VTK that represents this type of object, and in many cases where there are multiple choices these are abstract classes defining the basic API across the various concrete subclasses that implement the functionality..

vtkProp. Visible depictions of data that exist in the scene are represented by a subclass of vtkProp. The most commonly used subclasses of vtkProp for displaying objects in 3D are vtkActor (used to represent geometric data in the scene) and vtkVolume (used to represent volumetric data in the scene). There are also props that represent data in 2D such as vtkActor2D. The vtkProp subclass is generally responsible for knowing its position, size, and orientation in the scene. The parameters used to control the placement of the prop generally depend on whether the prop is for example a 3D object in the scene, or a 2D annotation. For 3D props such as vtkActor and vtkVolume (both subclasses of vtkProp3D which is itself a subclass of vtkProp), you can either directly control parameters such as

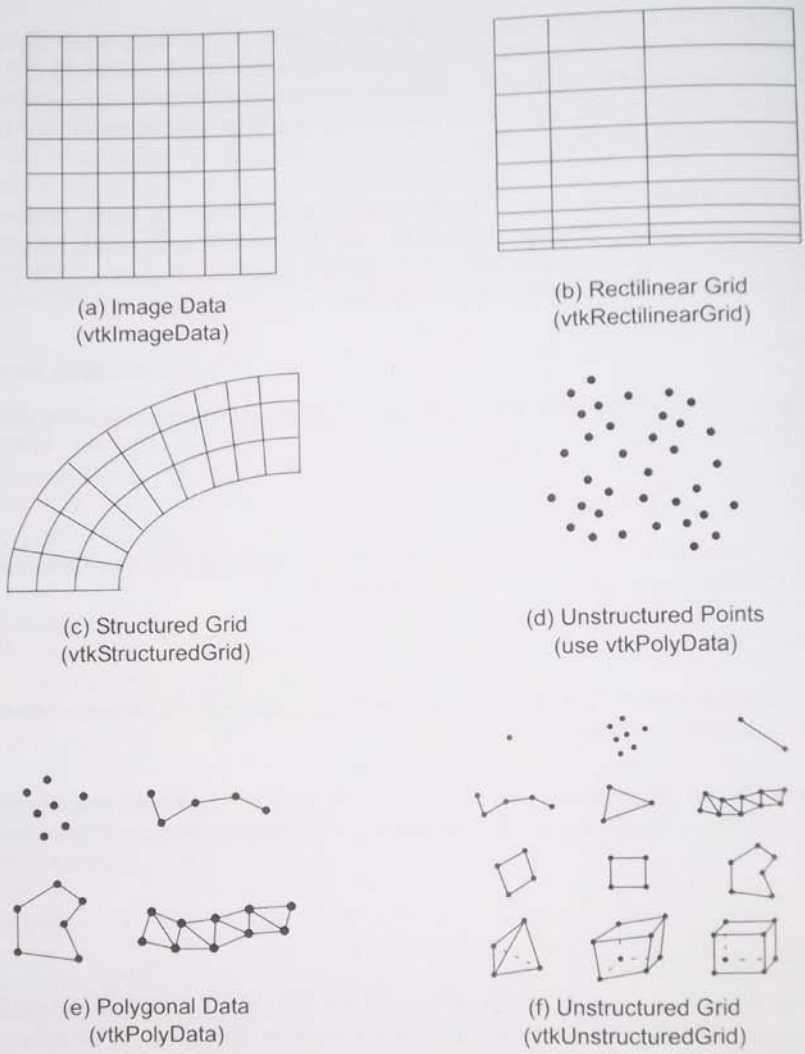


Figure 3–2 Dataset types found in **VTK**. Note that unstructured points can be represented by either polygonal data or unstructured grids, so are not explicitly represented in the system.

the object's 3D position, orientation and scale, or you can use a 4x4 transformation matrix. For 2D props that provide annotation such as the vtkScalarBarActor, the size and position of the annotation can be defined in a variety of ways including specifying a position, width, and height relative to the size of the entire viewport. In addition to providing placement control, props generally have a mapper object that holds the data and knows how to render it, and a property object that controls parameters such as color and opacity.

There are a large number (over 50) of specialized props such as vtkImageActor (used to display an image) and vtkPieChartActor (used to create a pie chart visual representation of an array of data

values). Some of these specialized props directly contain the parameters that control appearance, and directly have a reference to the input data to be rendered, and therefore do not require the use of a property or a mapper. The vtkFollower prop is a specialized subclass of vtkActor that will automatically update its orientation in order to continually face a specified camera. This is useful for displaying billboards or text in the 3D scene and having them remain visible as the user rotates. The vtkLODActor is also a subclass of vtkActor that automatically changes its geometric representation in order to maintain interactive frame rates, and vtkLODProp3D is a subclass of vtkProp3D that selects between a number of different mappers (perhaps even a mixture of volumetric and geometric mappers) in order to provide interactivity. vtkAssembly allows hierarchies of actors, properly managing the transformations when the hierarchy is translated, rotated or scaled.

vtkAbstractMapper. Some props such as vtkActor and vtkVolume use a subclass of vtkAbstractMapper to hold a reference to the input data and to provide the actual rendering functionality. The vtkPolyDataMapper is the primary mapper for rendering polygonal geometry. For volumetric objects, VTK provides several rendering techniques including the vtkFixedPointVolumeRayCastMapper that can be used to rendering vtkImageData, and the vtkProjectedTetrahedra mapper that can be used to render vtkUnstructuredGrid data.

vtkProperty and vtkVolumeProperty. Some props use a separate property object to hold the various parameters that control the appearance of the data. This allows you to more easily share appearance settings between different objects in your scene. The vtkActor object uses a vtkProperty to store parameters such as color, opacity, and the ambient, diffuse, and specular coefficient of the material. The vtkVolume object instead uses a vtkVolumeProperty to capture the parameters that are applicable to a volumetric object, such as the transfer functions that map the scalar value to color and opacity. Many mappers also provide functionality to set clipping planes that can be used to reveal interior structure.

vtkCamera. The vtkCamera contains the parameters that control how you view the scene. The vtkCamera has a position, a focal point, and a vector defining the direction of "up" in the scene. Other parameters control the specific viewing transformation (parallel or perspective), the scale or view angle of the image, and the near and far clipping planes of the view frustum.

vtkLight. When lighting is computed for a scene, one or more vtkLight objects are required. The vtkLight objects store the position and orientation of the light, as well as the color and intensity. Lights also have a type that describes how the light will move with respect to the camera. For example, a Headlight is always located at the camera's position and shines on the camera's focal point, whereas a SceneLight is located at a stationary position in the scene.

vtkRenderer. The objects that make up a scene including the props, the camera and the lights are collected together in a vtkRenderer. The vtkRenderer is responsible for managing the rendering process for the scene. Multiple vtkRenderer objects can be used together in a single vtkRenderWindow. These renderers may render into different rectangular regions (known as viewports) of the render window, or may be overlapping.

vtkRenderWindow. The vtkRenderWindow provides a connection between the operating system and the VTK rendering engine. Platform specific subclasses of vtkRenderWindow are responsible for opening a window in the native windowing system on your computer and managing the display pro-

cess. When you develop with VTK, you simply use the platform-independent vtkRenderWindow which is automatically replaced with the correct platform-specific subclass at runtime. The vtkRenderWindow contains a collection of vtkRenderers, and parameters that control rendering features such as stereo, anti-aliasing, motion blur and focal depth.

vtkRenderWindowInteractor. The vtkRenderWindowInteractor is responsible for processing mouse, key, and timer events and routing these through VTK's implementation of the command / observer design pattern. A vtkInteractorStyle listens for these events and processes them in order to provide motion controls such as rotating, panning and zooming. The vtkRenderWindowInteractor automatically creates a default interactor style that works well for 3D scenes, but you can instead select one for 2D image viewing for example, or create your own custom interactor style.

vtkTransform. Many of the objects in the scene that require placement such as props, lights, and cameras have a vtkTransform parameter that can be used to easily manipulate the position and orientation of the object. The vtkTransform can be used to describe the full range of linear (also known as affine) coordinate transformation in three dimensions, which are internally represented as a 4x4 homogeneous transformation matrix. The vtkTransform object will start with a default identity matrix or you can chain transformation together in a pipeline fashion to create complex behavior. The pipeline mechanism assures that if you modify any transform in the pipeline, all subsequent transforms are updated accordingly.

vtkLookupTable, vtkColorTransferFunction, and vtkPiecewiseFunction. Visualizing scalar data often involves defining a mapping from a scalar value to a color and opacity. This is true both in geometric surface rendering where the opacity will define the translucency of the surface, and in volume rendering where the opacity will represent the opacity accumulated along some length of of ray passing through the volume. For geometric rendering, this mapping is typically created using a vtkLookupTable, and in volume rendering both the vtkColorTransferFunction and the vtkPiecewiseFunction will be utilized.

A minimal example. The following example (adapted from ./VTK/Examples/Rendering/Cxx/Cylinder.cxx) shows how some of these objects can be used to specify and render a scene.

```
vtkCylinderSource *cylinder = vtkCylinderSource::New();

vtkPolyDataMapper *cylinderMapper = vtkPolyDataMapper::New();
cylinderMapper->SetInputConnection(cylinder->GetOutputPort());

vtkActor *cylinderActor = vtkActor::New();
cylinderActor->SetMapper(cylinderMapper);

vtkRenderer *ren1 = vtkRenderer::New();
ren1->AddActor(cylinderActor);

vtkRenderWindow *renWin = vtkRenderWindow::New();
renWin->AddRenderer(ren1);

vtkRenderWindowInteractor *iren = vtkRenderWindowInteractor::New();
iren->SetRenderWindow(renWin);
```

```
renWin->Render();
iren->Start();
```

In this example we have directly created a vtkActor, vtkPolyDataMapper, vtkRenderer, vtkRenderWindow and vtkRenderWindowInteractor. Note that a vtkProperty was automatically created by the actor, and a vtkLight and a vtkCamera were automatically created by the vtkRenderer.

The Visualization Pipeline

The visualization pipeline in VTK can be used to read or create data, analyze and create derivative version of this data, and write the data to disk or pass it along to the rendering engine for display. For example, you may read a 3D volume of data from disk, process it to create a set of triangles representing an isovalued surface through the volume, then write this geometric object back out to disk. Or, you may create a set of spheres and cylinders to represent atoms and bonds, then pass these off to the rendering engine for display.

The *Visualization Toolkit* uses a data flow approach to transform information into graphical data. There are two basic types of objects involved in this approach.

- vtkDataObject
- vtkAlgorithm

Data objects represent data of various types. The class vtkDataObject can be viewed as a generic "blob" of data. Data that has a formal structure is referred to as a dataset (class vtkDataSet). **Figure 3–2** shows the dataset objects supported in VTK. Datasets consist of a geometric and topological structure (points and cells) as illustrated by the figure; they also have associated attribute data such as scalars or vectors. The attribute data can be associated with the points or cells of the dataset. Cells are topological organizations of points; cells form the atoms of the dataset and are used to interpolate information between points. **Figure 19–20** and **Figure 19–21** show twenty-three of the most common cell types supported by VTK. **Figure 3–3** shows the attribute data supported by VTK.

Algorithms, also referred to generally as filters, operate on data objects to produce new data objects. Algorithms and data objects are connected together to form visualization pipelines (i.e., dataflow networks). **Figure 3–4** is a depiction of a visualization pipeline.

This figure together with **Figure 3–5** illustrate some important visualization concepts. Source algorithms produce data by reading (reader objects) or constructing one or more data objects (procedural source objects). Filters ingest one or more data objects and generate one or more data objects on output. Mappers (or in some cases, specialized actors) take the data and convert it into a visual representation that is displayed by the rendering engine. A writer can be thought of as a type of mapper that writes data to a file or stream.

There are several important issues regarding the construction of the visualization pipeline that we will briefly introduce here. First, pipeline topology is constructed using variations of the methods

```
aFilter->SetInputConnection( anotherFilter->GetOutputPort() );
```

which sets the input to the filter `aFilter` to the output of the filter `anotherFilter`. (Filters with multiple inputs and outputs have similar methods.) Second, we must have a mechanism for controlling the execution of the pipeline. We only want to execute those portions of the pipeline necessary to bring the output up to date. The *Visualization Toolkit* uses a lazy evaluation scheme (executes only

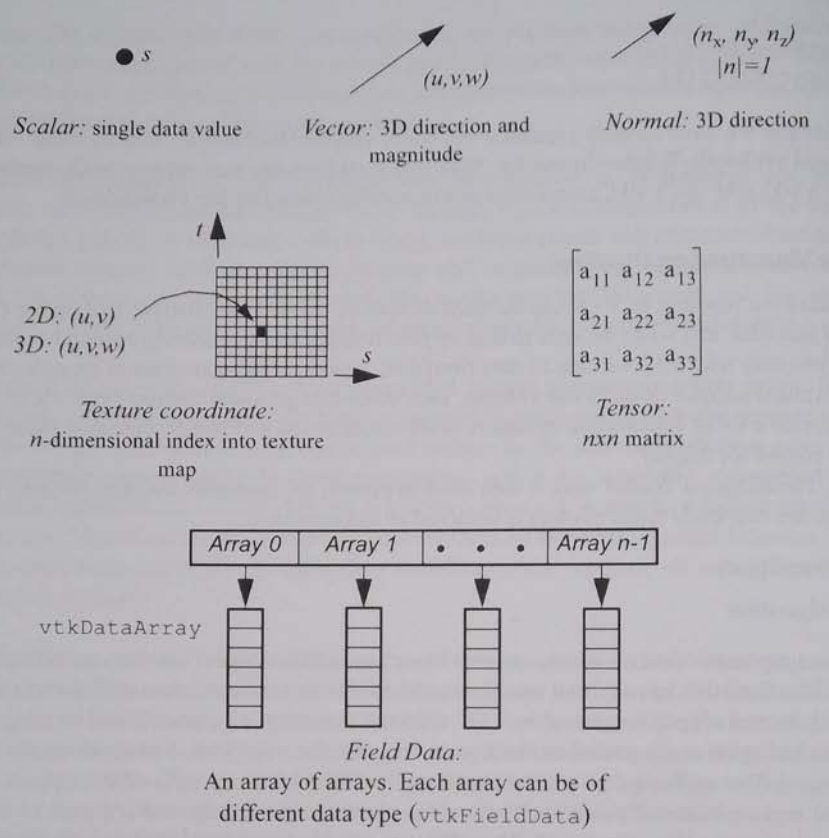


Figure 3–3 Data attributes associated with the points and cells of a dataset.

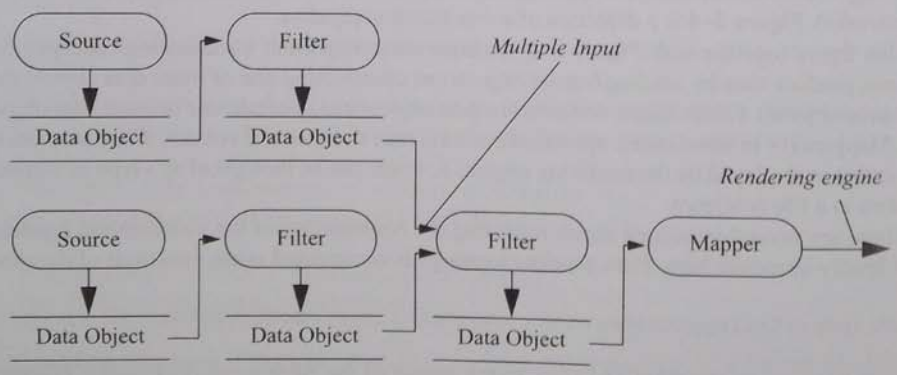


Figure 3–4 Data objects are connected with algorithms (filters) to create the visualization pipeline. The arrows point in the direction of data flow.

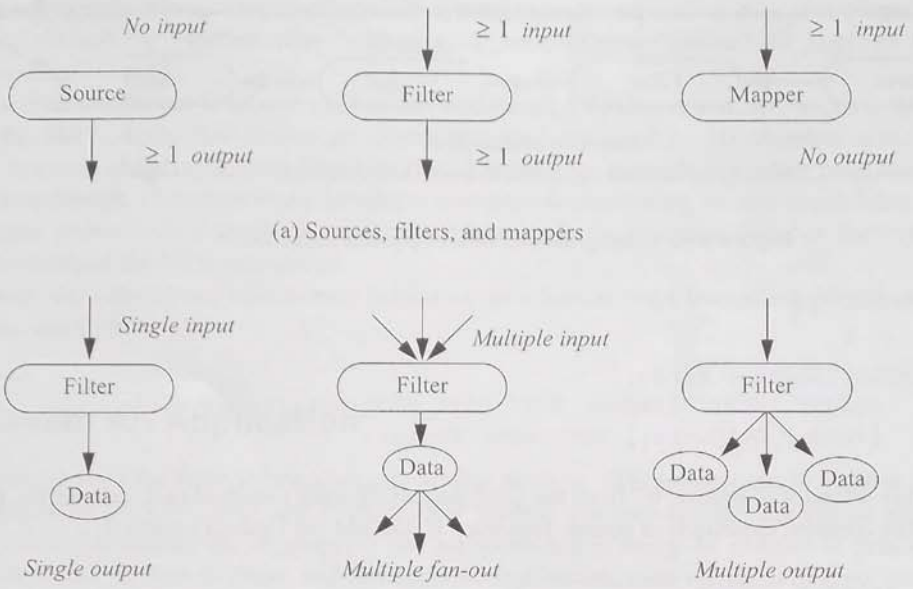


Figure 3–5 Different types of algorithms. Filters ingest one or more inputs and produce one or more output data objects.

when the data is requested) based on an internal modification time of each object. Third, the assembly of the pipeline requires that only those objects compatible with one another can fit together with the `SetInputConnection()` and `GetOutputPort()` methods. VTK produces errors at run-time if the data object types are incompatible. Finally, we must decide whether to cache, or retain, the data objects once the pipeline has executed. Since visualization datasets are typically quite large, this is important to the successful application of visualization tools. VTK offers methods to turn data caching on and off, use of reference counting to avoid copying data, and methods to stream data in pieces if an entire dataset cannot be held in memory. (We recommend that you review the chapter on the Visualization Pipeline in *The Visualization Toolkit An Object-Oriented Approach to 3D Graphics* text for more information.)

Please note that there are many varieties of both algorithm and data objects. **Figure 16–2** shows six of the most common data object types supported by the current version of VTK. Algorithm objects vary in their type(s) of input data and output data and of course in the particular algorithm implemented.

Pipeline Execution. In the previous section we discussed the need to control the execution of the visualization pipeline. In this section we will expand our understanding of some key concepts regarding pipeline execution.

As indicated in the previous section, the VTK visualization pipeline only executes when data is required for computation (lazy evaluation). Consider this example where we instantiate a reader object and ask for the number of points as shown below. (The language shown here is Tcl.)

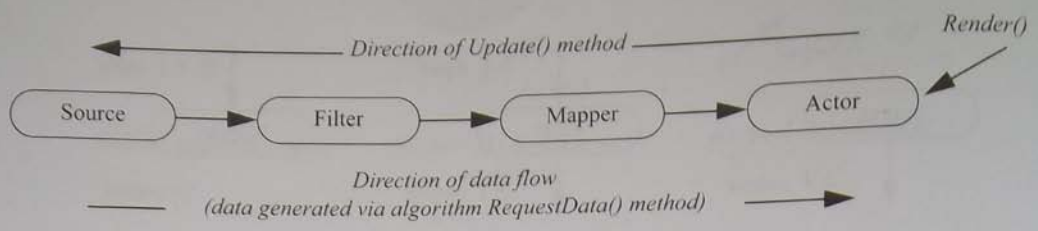


Figure 3–6 Conceptual overview of pipeline execution.

```
vtkPLOT3DReader reader
    reader SetXYZFileName $VTK_DATA_ROOT/Data/combxyz.bin
    [reader GetOutput] GetNumberOfPoints
```

the `reader` object will return "0" from the GetNumberOfPoints() method call, despite the fact that the data file contains thousands of points. However, if you add the Update() method

```
    reader Update
    [reader GetOutput] GetNumberOfPoints
```

the `reader` object will return the correct number. In the first example, the GetNumberOfPoints() methods does not require computation, and the object simply returns the current number of points, which is "0". In the second example, the Update() method forces execution of the pipeline, thereby forcing the reader to execute and read the data from the file indicated. Once the reader has executed, the number of points in its output is set correctly.

Normally, you do not need to manually invoke Update() because the filters are connected into a visualization pipeline. In this case, when the actor receives a request to render itself, it forwards the method to its mapper, and the Update() method is automatically sent through the visualization pipeline. A high-level view of pipeline execution appears in **Figure 3–6**. As this figure illustrates, the Render() method often initiates the request for data; this request is then passed up through the pipeline. Depending on which portions of the pipeline are out-of-date, the filters in the pipeline may re-execute, thereby bringing the data at the end of the pipeline up-to-date; the up-to-date data is then rendered by the actor. (For more information about the execution process, see Chapter 15 "Managing Pipeline Execution" on page 317.)

Image Processing. VTK supports an extensive set of image processing and volume rendering functionality. In VTK, both 2D (image) and 3D (volume) data are referred to as vtkImageData. An image dataset in VTK is one in which the data is arranged in a regular, axis-aligned array. Images, pixmaps, and bitmaps are examples of 2D image datasets; volumes (a stack of 2D images) is a 3D image dataset.

Algorithms in the imaging pipeline always input and output image data objects. Because of the regular and simple nature of the data, the imaging pipeline has other important features. Volume rendering is used to visualize 3D vtkImageData (see "Volume Rendering" on page 139), and special image viewers are used to view 2D vtkImageData. Almost all algorithms in the imaging pipeline are multithreaded and are capable of streaming data in pieces to satisfy a user-specified memory limit. Filters automatically sense the number of cores and processors available on the system and create that

number of threads during execution as well as automatically separating data into pieces that are streamed through the pipeline. (See "vtkStreamingDemandDrivenPipeline" on page 325 for more information.)

This concludes our brief overview of the *Visualization Toolkit* system architecture. We recommend the *The Visualization Toolkit An Object-Oriented Approach to 3D Graphics* text for more details on many of the algorithms found in VTK. Learning by example is another helpful approach. Chapters 4 through 13 contain many annotated examples demonstrating various capabilities of VTK. Also, since source code is available, you may wish to study the examples found in the `VTK/Examples` directory of the VTK source tree.

With this abbreviated introduction behind us, let's look at ways to create applications in C++, Tcl, Java, and Python.

3.2 Create An Application

This section covers the basic information you need to develop VTK applications in the four programming languages Tcl, C++, Java, and Python. After reading this introduction, you should jump to the subsection(s) that discuss the language(s) you are interested in using. In addition to providing you with instructions on how to create and run a simple application, each section will show you how to take advantage of callbacks in that language.

User Methods, Observers, and Commands

Callbacks (or *user methods*) are implemented in VTK using the Subject/Observer and Command design pattern. This means that nearly every class in VTK (every subclass of vtkObject) has an AddObserver() method that can be used to setup callbacks from VTK. The observer looks at every event invoked on an object, and if it matches one of the events that the observer is watching for, then an associated command is invoked (i.e., the callback). For example, all VTK filters invoke a `StartEvent` right before they start to execute. If you add an observer that watches for a `StartEvent` then it will get called every time that filter starts to execute. Consider the following Tcl script that creates an instance of vtkElevationFilter, and adds an observer for the `StartEvent` to call the procedure `PrintStatus`.

```
proc PrintStatus {} {
puts "Starting to execute the elevation filter"
}
vtkElevationFilter foo
foo AddObserver StartEvent PrintStatus
```

This type of functionality (i.e., callback) is available in all the languages VTK supports. Each section that follows will show a brief example of how to use it. Further discussion on user methods is provided in "Integrating With The Windowing System" on page 421. (This section also discusses user interface integration issues.)

To create your own application, we suggest starting with one of the examples that come with VTK. They can be found in `VTK/Examples` in the source distribution. In the source distribution the examples are organized first by topic and then by language. Under `VTK/Examples` you will find directories for different topics, and under the directories there will be subdirectories for different languages such as Tcl.

Tcl

Tcl is one of the easiest languages with which to start creating VTK applications. Once you have installed VTK, you should be able to run the Tcl examples that come with the distribution. Under UNIX you have to compile VTK with Tcl support as mentioned in "Installing VTK on Unix Systems" on page 14. Under Windows you can just install the self-extracting archive as described in "Installing VTK on Windows XP, Vista or later" on page 10.

Windows. Under Windows, you can run a Tcl script just by double clicking on the file (`Cone.tcl` in this example). If nothing happens you might have an error in your script or a problem with associating Tcl files with the vtk.exe executable. To detect this you need to run `vtk.exe` first. `vtk.exe` can be found in your start menu under VTK. Once execution begins, a console window should appear with a prompt in it. At this prompt type in a `cd` command to change to the directory where `Cone.tcl` is located. Two examples are given below:

```
% cd "c:/VTK/Examples/Tutorial/Step1/Tcl"
```

Then you will need to source the example script using the following command.

```
% source Cone.tcl
```

Tcl will try to execute `Cone.tcl`, and you will be able to see errors or warning messages that would otherwise not appear.

Unix. Under UNIX, Tcl development can be done by running the VTK executable (after you have compiled the source code) that can be found in your binary directory (e.g., `VTK-bin/bin/vtk`, `VTK-Solaris/bin/vtk`, etc.) and then providing the Tcl script as the first argument as shown below.

```
unix machine> cd VTK/Examples/Tutorial/Step1/Tcl
unix machine> /home/VTK-Solaris/bin/vtk Cone.tcl
```

User methods can be set up as shown in the introduction of this section. An example can be found in `Examples/Tutorial/Step2/Tcl`/Cone2.tcl. The key changes are shown below.

```
proc myCallback {} {
    puts "Starting to render"
}

vtkRenderer ren1
ren1 AddObserver StartEvent myCallback
```

You may instead simply provide the body of the proc directly to AddObserver().

```
vtkRenderer ren1
ren1 AddObserver StartEvent {puts "Starting to render"}
```

C++

Using C++ as your development language will typically result in smaller, faster, and more easily deployed applications than most any other language. C++ development also has the advantage that

you do not need to compile any additional support for Tcl, Java, or Python. This section will show you how to create a simple VTK C++ application for the PC with Microsoft Visual C++ and also for UNIX using an appropriate compiler. We will start with a simple example called `Cone.cxx` which can be found in `Examples/Tutorial/Step1/Cxx`. For both Windows and UNIX you can use a source code installation of VTK or installed binaries. These examples will work with both.

The first step in building your C++ program is to use CMake to generate a makefile or workspace file, depending on your compiler. The `CMakeList.txt` file that comes with `Cone.cxx` (shown below) makes use of the FindVTK and UseVTK CMake modules. These modules attempt to locate VTK and then setup your include paths and link lines for building C++ programs. If they do not successfully find VTK, you will have to manually specify the appropriate CMake parameters and rerun CMake as necessary.

```
PROJECT (Step1)

FIND_PACKAGE(VTK REQUIRED)
IF(NOT VTK_USE_RENDERING)
 MESSAGE(FATAL_ERROR
          "Example ${PROJECT_NAME} requires VTK_USE_RENDERING.")
ENDIF(NOT VTK_USE_RENDERING)
INCLUDE(${VTK_USE_FILE})

ADD_EXECUTABLE(Cone Cone.cxx)
TARGET_LINK_LIBRARIES(Cone vtkRendering)
```

Microsoft Visual C++. Once you have run CMake for the Cone example you are ready to start Microsoft Visual C++ and load the generated solution file. For current .NET versions of the compile this will be named Cone.sln.You can now select a build type (such as Release or Debug) and build your application. If you want to integrate VTK into an existing project that does not use CMake, you can copy the settings from this simple example into your existing workspaces.

Now consider an example of a true Windows application. The process is very similar to what we did above, except that we create a windows application instead of a console application, as shown in the following. Much of the code is standard Windows code and will be familiar to any Windows developer. This example can be found in `VTK/Examples/GUI/Win32/SimpleCxx/Win32Cone.cxx`. Note that the only significant change to the `CMakeLists.txt` file is the addition of the WIN32 parameter in the `ADD_EXECUTABLE` command.

```
#include "windows.h"
#include "vtkConeSource.h"
#include "vtkPolyDataMapper.h"
#include "vtkRenderWindow.h"
#include "vtkRenderWindowInteractor.h"
#include "vtkRenderer.h"

static HANDLE hinst;
long FAR PASCAL WndProc(HWND, UINT, UINT, LONG);

// define the vtk part as a simple c++ class
class myVTKApp
{
```

```
public:
  myVTKApp(HWND parent);
  ~myVTKApp();
private:
  vtkRenderWindow *renWin;
  vtkRenderer *renderer;
  vtkRenderWindowInteractor *iren;
  vtkConeSource *cone;
  vtkPolyDataMapper *coneMapper;
  vtkActor *coneActor;
};
```

We start by including the required VTK include files. Next we have two standard windows prototypes followed by a small class definition called myVTKApp. When developing in C++, you should try to use object-oriented approaches instead of the scripting programming style found in many of the Tcl examples. Here we are encapsulating the VTK components of the application into a small class.

This is the constructor for myVTKApp. As you can see it allocates the required VTK objects, sets their instance variables, and then connects them to form a visualization pipeline. Most of this is straightforward VTK code except for the vtkRenderWindow. This constructor takes a HWND handle to the parent window that should contain the VTK rendering window. We then use this in the SetParentId() method of vtkRenderWindow so that it will create its window as a child of the window passed to the constructor.

```
myVTKApp::myVTKApp(HWND hwnd)
{
  // Similar to Examples/Tutorial/Step1/Cxx/Cone.cxx
  // We create the basic parts of a pipeline and connect them
  this->renderer = vtkRenderer::New();
  this->renWin = vtkRenderWindow::New();
  this->renWin->AddRenderer(this->renderer);

  // setup the parent window
  this->renWin->SetParentId(hwnd);
  this->iren = vtkRenderWindowInteractor::New();
  this->iren->SetRenderWindow(this->renWin);

  this->cone = vtkConeSource::New();
  this->cone->SetHeight( 3.0 );
  this->cone->SetRadius( 1.0 );
  this->cone->SetResolution( 10 );
  this->coneMapper = vtkPolyDataMapper::New();
  this->coneMapper->SetInputConnection(this->cone->GetOutputPort());
  this->coneActor = vtkActor::New();
  this->coneActor->SetMapper(this->coneMapper);

  this->renderer->AddActor(this->coneActor);
  this->renderer->SetBackground(0.2,0.4,0.3);
  this->renWin->SetSize(400,400);

  // Finally we start the interactor so that event will be handled
```

```
    this->renWin->Render();
  }
```

The destructor simply frees all of the VTK objects that were allocated in the constructor.

```
myVTKApp::~myVTKApp()
{
  renWin->Delete();
  renderer->Delete();
  iren->Delete();
  cone->Delete();
  coneMapper->Delete();
  coneActor->Delete();
}
```

The `WinMain` code here is all standard windows code and has no VTK references in it. As you can see the application has control of the event loop. Events are handled by the `WndProc` described later in this section.

```
int PASCAL WinMain (HINSTANCE hInstance, HINSTANCE hPrevInstance,
                    LPSTR lpszCmdParam, int nCmdShow)
{
  static char szAppName[] = "Win32Cone";
  HWND hwnd ;
  MSG msg ;
  WNDCLASS wndclass ;

  if (!hPrevInstance)
    {
    wndclass.style = CS_HREDRAW | CS_VREDRAW | CS_OWNDC;
    wndclass.lpfnWndProc = WndProc ;
    wndclass.cbClsExtra = 0 ;
    wndclass.cbWndExtra = 0 ;
    wndclass.hInstance = hInstance;
    wndclass.hIcon = LoadIcon(NULL,IDI_APPLICATION);
    wndclass.hCursor = LoadCursor (NULL, IDC_ARROW);
    wndclass.lpszMenuName = NULL;
    wndclass.hbrBackground = (HBRUSH)GetStockObject(BLACK_BRUSH);
    wndclass.lpszClassName = szAppName;
    RegisterClass (&wndclass);
    }
  hinst = hInstance;

  hwnd = CreateWindow ( szAppName,
                        "Draw Window",
                        WS_OVERLAPPEDWINDOW,
                        CW_USEDEFAULT,
                        CW_USEDEFAULT,
                        400,
                        480,
                        NULL,
```

```
                                NULL,
                                hInstance,
                                NULL);
    ShowWindow (hwnd, nCmdShow);
    UpdateWindow (hwnd);
    while (GetMessage (&msg, NULL, 0, 0))
      {
      TranslateMessage (&msg);
      DispatchMessage (&msg);
    }
    return msg.wParam;
  }
```

This WndProc is a very simple event handler. For a full application it would be significantly more complicated, but the key integration issues are the same. At the top of this function we declare a static reference to a myVTKApp instance. When handling the WM_CREATE method we create an Exit button and then construct an instance of myVTKApp passing in the handle to the current window. The vtkRenderWindowInteractor will handle all of the events for the vtkRenderWindow, so you do not need to handle them here. You probably will want to add code to handle resizing events so that the render window resizes appropriately with respect to your overall user interface. If you do not set the ParentId of the vtkRenderWindow, it will show up as a top-level independent window. Everything else should behave the same as before.

```
long FAR PASCAL WndProc (HWND hwnd, UINT message,
UINT wParam, LONG lParam)
{
  static HWND ewin;
  static myVTKApp *theVTKApp;
  switch (message)
    {
    case WM_CREATE:
      {
      ewin = CreateWindow("button","Exit",
                          WS_CHILD | WS_VISIBLE | SS_CENTER,
                          0,400,400,60,
                          hwnd,(HMENU)2,
                         (HINSTANCE)GetWindowLong(hwnd,GWL_HINSTANCE),
                          NULL);
      theVTKApp = new myVTKApp(hwnd);
      return 0;
      }
    case WM_COMMAND:
      switch (wParam)
        {
        case 2:
          PostQuitMessage (0);
          if (theVTKApp)
            {
            delete theVTKApp;
            theVTKApp = NULL;
```

```
            }
          break;
        }
      return 0;

    case WM_DESTROY:
      PostQuitMessage (0);
      if (theVTKApp)
        {
        delete theVTKApp;
        theVTKApp = NULL;
        }
      return 0;
    }
  return DefWindowProc (hwnd, message, wParam, lParam);
}
```

UNIX. Creating a C++ application on UNIX is done by running CMake and then make. CMake creates a makefile that specifies the include paths, link lines, and dependencies. The make program then uses this makefile to compile the application. This should result in a Cone executable that you can run. If `Cone.cxx` does not compile then check the make errors and correct them. Make sure that the values in the top of `CMakeCache.txt` are valid. If it does compile, but you receive errors when you try running it, you might need to set your `LD_LIBRARY_PATH` as described in Chapter 2.

User Methods in C++. You can add user methods (using the observer/command design pattern) in C++ by creating a subclass of vtkCommand that overrides the Execute() method. Consider the following example taken from `VTK/Examples/Tutorial/Step2/Cxx/Cone2.cxx`.

```
class vtkMyCallback : public vtkCommand {
static myCallback *New() {return new vtkMyCallback;}
virtual void Execute(vtkObject *caller, unsigned long, void *)
  {
  vtkRenderer *renderer = reinterpret_cast<vtkRenderer*>(caller);
  cout << renderer->GetActiveCamera()->GetPosition()[0] << " "
       << renderer->GetActiveCamera()->GetPosition()[1] << " "
       << renderer->GetActiveCamera()->GetPosition()[2] << "\n";
  }
};
```

While the Execute() method is always passed the calling object (caller) you are not required to use it. If you do use the caller you will typically want to perform a SafeDownCast() to the actual type. For example:

```
virtual void Execute(vtkObject *caller, unsigned long, void *callData)
{
  vtkRenderer *ren = vtkRenderer::SafeDownCast(caller);
  if (ren) { ren->SetBackground(0.2,0.3,0.4); }
}
```

Once you have created your subclass of vtkCommand you are ready to add an observer that will call your command on certain events. This can be done as follows.

```
// Here is where we setup the observer,
//we do a new and ren1 will eventually free the observer
vtkMyCallback *mo1 = vtkMyCallback::New();
ren1->AddObserver(vtkCommand::StartEvent,mo1);
mo1->Delete();
```

The above code creates an instance of `myCallback` and then adds an observer on `ren1` for the `StartEvent`. Whenever `ren1` starts to render, the Execute() method of `vtkMyCallback` will be called. When `ren1` is deleted, the callback will be deleted as well.

Java

To create Java applications you must first have a working Java development environment. This section provides instructions for using Sun's JDK 1.3 or later on either Windows or UNIX. Once your JDK has been installed and you have installed VTK, you need to set your `CLASSPATH` environment variable to include the VTK classes. Under Microsoft Windows this can be set by right clicking on the My Computer icon, selecting the properties option, then selecting the Advanced tab, and then clicking the Environment Variables button. Then add a `CLASSPATH` environment variable and set it to include your the path to your `vtk.jar` file, your Wrapping/Java directory, and the current directory. For a Windows build it will be something like `"C:\vtk-bin\bin\vtk.jar;C:\vtk-bin\Wrapping\Java;."`. Under UNIX you should set your `CLASSPATH` environment variable to something similar to `"/yourdisk/vtk-bin/bin/vtk.jar;/yourdisk/vtk-bin/Wrapping/Java;."`.

The next step is to byte compile your Java program. For starters try byte compiling (with javac) the `Cone.java` example that comes with VTK under `VTK/Examples/Tutorial/Step1/Java`. Then you should be able to run the resulting application using the java command. It should display a cone which rotates 360 degrees and then exits. The next step is to create your own applications using the examples provided as a starting point.

```
public void myCallback()
{
  System.out.println("Starting a render");
}
```

You set up a callback by passing three arguments. The first is the name of the event you are interested in, the second is an instance of a class, the third is the name of the method you want to invoke. In this example we set up the `StartEvent` to invoke the myCallback method on me (which is an instance of Cone2). The myCallback method must of course be a valid method of Cone2 to avoid an error. (This code fragment is from `VTK/Examples/Tutorial/Step2/Java/cone2.java`.)

```
Cone2 me = new Cone2();
ren1.AddObserver("StartEvent",me,"myCallback");
```

Python

If you have built VTK with Python support, a `vtkpython` executable will be created. Using this executable, you should be able to run `Examples/Tutorial/Step1/Python/Cone.py` as follows.

```
vtkpython Cone.py
```

Creating your own Python scripts is a simple matter of using some of our example scripts as a starting point. User methods can be set up by defining a function and then passing it as the argument to the AddObserver as shown below.

```
def myCallback(obj,event):
    print "Starting to render"
ren1.AddObserver("StartEvent",myCallback)
```

The complete source code for the example shown above is in `VTK/Examples/Tutorial/Step2/Python/Cone2.py`.

3.3 Conversion Between Languages

As we have seen, VTK's core is implemented in C++ and then wrapped with the Tcl, Java, and Python programming languages. This means that you have a language choice when developing applications. Your choice will depend on which language you are most comfortable with, the nature of the application, and whether you need access to internal data structures and/or have special performance requirements. C++ offers several advantages over the other languages when you need to access internal data structure or require the highest-performing application possible. However, using C++ means the extra burden of the compile/link cycle, which often slows the software development process.

You may find yourself developing prototypes in an interpreted language such as Tcl and then converting them to C++. Or, you may discover example code (in the VTK distribution or from other users) that you wish to convert to your implementation language.

Converting VTK code from one language to another is fairly straightforward. Class names and method names remain the same across languages; what changes are the implementation details and GUI interface, if any. For example, the C++ statement

```
anActor->GetProperty()->SetColor(red,green,blue);
```

in Tcl becomes

```
[anActor GetProperty] SetColor $red $green $blue
```

in Java becomes

```
anActor.GetProperty().SetColor(red,green,blue);
```

and in Python becomes

```
anActor.GetProperty().SetColor(red,green,blue)
```

One major limitation you'll find is that some C++ applications cannot be converted to the other three languages because of pointer manipulation.While it is always possible to get and set individual values from the wrapped languages, it is not always possible to obtain a raw pointer to quickly traverse and inspect or modify a large structure. If your application requires this level of data inspection or manipulation, you can either develop directly in C++ or extend VTK at the C++ level with your required high-performance classes, then use these new classes from your preferred interpreted language.

Part II
Learn VTK By Example

The Basics

The purpose of this chapter is to introduce you to some of VTK's capabilities by way of a selected set of examples. Our focus will be on commonly used methods and objects, and combinations of objects. We will also introduce important concepts and useful applications. By no means are all of VTK's features covered; this chapter is meant to give you a broad overview of what's possible. You'll want to refer to online documentation or class `.h` files to learn about other options each class might have.

Most of the examples included here are implemented in the Tcl programming language. They could just as easily be implemented in C++, Java, and Python—the conversion process between the languages is straightforward. (See "Conversion Between Languages" on page 37.) C++ does offer some advantages, mainly access and manipulation of data structures and pointers, and some examples reflect this by being implemented in the C++ language.

Each example presented here includes sample code and often a supplemental image. We indicate the name of the source code file (when one exists in the VTK source tree), so you will not have to enter it manually. We recommend that you run and understand the example and then experiment with object methods and parameters. You may also wish to try suggested alternative methods and/or classes. Often, the *Visualization Toolkit* offers several approaches to achieve similar results. Note also that the scripts are often modified from what's found in the source code distribution. This is done to simplify concepts or remove extraneous code.

Learning an object-oriented system like VTK first requires understanding the programming abstraction, and then becoming familiar with the library of objects and their methods. We recommend that you review "System Architecture" on page 19 for information about the programming abstraction. The examples in this chapter will then provide you with a good overview of the many VTK objects.

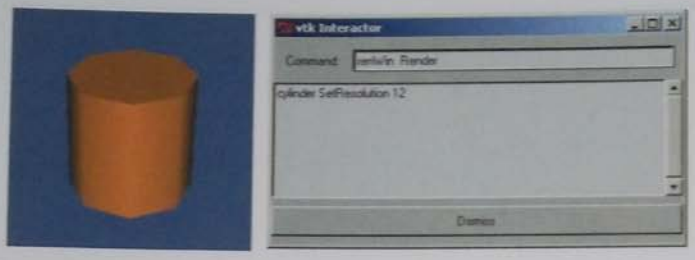


Figure 4–1 Using Tcl/Tk to program an interpreted application.

4.1 Creating Simple Models

The use of the *Visualization Toolkit* typically goes as follows: read/generate some data, filter it, render it, and interact with it. In this section, we'll start by looking at ways to read and generate data.

There are two basic ways to obtain data. The data may exist in a file (or files, streams, etc.) that is read into the system, or the data may be procedurally generated (via an algorithm or mathematical expression). Recall that objects that initiate the processing of data in the visualization pipeline are called source objects (see **Figure 3–5**). Objects that generate data are called procedural (source) objects, and objects that read data are called reader (source) objects.

Procedural Source Object

We'll start off by rendering a simple cylinder. The example code shown below (`VTK/Examples/Rendering/Tcl/Cylinder.tcl`) demonstrates many basic concepts in the visualization pipeline and rendering engine. Refer to **Figure 4–1** to see the results of running the script.

We begin the script by invoking a Tcl command to load the VTK package (`package require vtk`) and create a GUI interpreter (`package require vtkinteraction`) that lets you type commands at run-time. Also, we load `vtktesting` which defines a set of colors, one of which (tomato) is used later in the script.

```
package require vtk
package require vtkinteraction
package require vtktesting
```

We then create a procedural source object: vtkCylinderSource. This source creates a polygonal representation of a cylinder. The output of the cylinder is set as the input to the vtkPolyDataMapper via the method SetInputConnection(). We create an actor (the object that is rendered) that refers to the mapper as its defining geometry. Notice the way objects are constructed in Tcl: we use the class name followed by the desired instance name.

```
vtkCylinderSource cylinder
  cylinder SetResolution 8
vtkPolyDataMapper cylinderMapper
  cylinderMapper SetInputConnection [cylinder GetOutputPort]
vtkActor cylinderActor
  cylinderActor SetMapper cylinderMapper
  eval [cylinderActor GetProperty] SetColor $tomato
    cylinderActor RotateX  30.0
```

```
cylinderActor RotateY -45.0
```

As a reminder of how similar a C++ implementation is to a Tcl (or other interpreted languages) implementation, the same code implemented in C++ is shown below, and can be found in `VTK/Examples/Rendering/Cxx/Cylinder.cxx`.

```
vtkCylinderSource *cylinder = vtkCylinderSource::New();
cylinder->SetResolution(8);

vtkPolyDataMapper *cylinderMapper = vtkPolyDataMapper::New();
cylinderMapper->SetInputConnection(cylinder->GetOutputPort());

vtkActor *cylinderActor = vtkActor::New();
cylinderActor->SetMapper(cylinderMapper);
cylinderActor->GetProperty()->SetColor(1.0000, 0.3882, 0.2784);
cylinderActor->RotateX(30.0);
cylinderActor->RotateY(-45.0);
```

Recall that source objects initiate the visualization pipeline, and mapper objects (or prop objects that include mapping functionality) terminate the pipeline, so in this example we have a pipeline consisting of two algorithms (i.e., a source and mapper). The VTK pipeline uses a lazy evaluation scheme, so even though the pipeline is connected, no generation or processing of data has yet occurred (since we have not yet requested the data).

Next we create graphics objects which will allow us to render the actor. The vtkRenderer instance `ren1` coordinates the rendering process for a viewport of the render window `renWin`. The render window interactor `iren` is a 3D widget that allows us to manipulate the camera.

```
#Create the graphics structure
vtkRenderer ren1
vtkRenderWindow renWin
  renWin AddRenderer ren1
vtkRenderWindowInteractor iren
  iren SetRenderWindow renWin
```

Notice that we've associated the renderer with the render window via the AddRenderer() method. We must also associate the actor with the renderer using the AddActor() method.

```
# Add the actors to the renderer, set the background and size
ren1 AddActor cylinderActor
ren1 SetBackground 0.1 0.2 0.4
renWin SetSize 200 200
```

The SetBackground() method specifies the background color of the rendering window using RGB (red, green, blue) values between (0,1), and SetSize() specifies the window size in pixels. Finally, we conclude this example by associating the GUI interactor with the render window interactor's user-defined method. (The user-defined method is invoked by pressing the `u` key when the mouse focus is in the rendering window. See "Using VTK Interactors" on page 45. Also see "User Methods, Observers, and Commands" on page 29) The Initialize() method begins the event loop, and the Tcl/Tk com-

mand `wm withdraw .` makes sure that the interpreter widget `.vtkInteract` is not visible when the application starts.

```
# Associate the "u" keypress with a UserEvent and start the event loop
iren AddObserver UserEvent {wm deiconify .vtkInteract}
iren Initialize

# suppress the tk window
wm withdraw .
```

When the script is run, the visualization pipeline will execute because the rendering engine will request data. (The window expose event will force the render window to render itself.) Only after the pipeline executes are the filters up-to-date with respect to the input data. If you desire, you can manually cause execution of the pipeline by invoking `renWin Render`.

After you get this example running, you might try a couple of things. First, use the interactor by mousing in the rendering window. Next, change the resolution of the cylinder object by invoking the `cylinder SetResolution 12`. You can do this by editing the example file and re-executing it, or by pressing `u` in the rendering window to bring up the interpreter GUI and typing the command there. Remember, if you are using the Tcl interactor popup, the changes you make are visible only after data is requested, so follow changes with a `renWin Render` command, or by mousing in the rendering window.

Reader Source Object

This example is similar to the previous example except that we read a data file rather than procedurally generating the data. A stereo-lithography file is read (suffix `.stl`) that represents polygonal data using the binary STL data format. (Refer to **Figure 4–2** and the Tcl script `VTK/Examples/Rendering/Tcl/CADPart.tcl`.)

Figure 4–2 Reader source object.

```
vtkSTLReader part
  part SetFileName \
    $VTK_DATA_ROOT/Data/42400-IDGH.stl
vtkPolyDataMapper partMapper
  partMapper SetInputConnection \
    [part GetOutputPort]
vtkLODActor partActor
  partActor SetMapper partMapper
```

Notice the use of the vtkLODActor. This actor changes its representation to maintain interactive performance. Its default behavior is to create a point cloud and wireframe, bounding-box outline to represent the intermediate and low-level representations. (See "Level-Of-Detail Actors" on page 55 for more information.) The model used in this example is small enough that on most computers today you will only see the high-level representation (the full geometry of the model).

Many of the readers do not sense when the input file(s) change and re-execute. For example, if the file `42400-IDGH.stl` changes, the pipeline will not re-execute. You can manually modify objects by invoking the Modified() method on them. This will cause the filter to re-execute, as well as all filters downstream of it.

The *Visualization Toolkit* has limited, built-in modeling capabilities. If you want to use VTK to edit and manipulate complex models (e.g., those created by a solid modeler or modeling tool), you'll typically use a reader (see "Readers" on page 239) to interface to the data. (Another option is importers, which are used to ingest entire scenes. See "Importers" on page 245 for more information.)

4.2 Using VTK Interactors

Once you've visualized your data, you typically want to interact with it. The *Visualization Toolkit* offers several approaches to do this. The first approach is to use the built in class vtkRenderWindowInteractor. The second approach is to create your own interactor by specifying event bindings. And don't forget that if you are using an interpreted language you can type commands at run-time. You may also wish to refer to "Picking" on page 59 to see how to select data from the screen. (Note: Developers can also interface to a windowing system of their choice. See "Integrating With The Windowing System" on page 421.)

vtkRenderWindowInteractor

The simplest way to interact with your data is to instantiate vtkRenderWindowInteractor. This class responds to a pre-defined set of events and actions and provides a way to override the default actions. vtkRenderWindowInteractor allows you to control the camera and actors and offers two interaction styles: position sensitive (i.e., joystick mode) and motion sensitive (i.e., trackball mode). (More about interactor styles in the next section.)

vtkRenderWindowInteractor responds to the following events in the render window. (Remember that multiple renderers can draw into a rendering window and that the renderer draws into a viewport within the render window. Interactors support multiple renderers in a render window.)

- `Keypress j` / `Keypress t` — Toggle between **joystick** (position sensitive) and **trackball** (motion sensitive) styles. In joystick style, motion occurs continuously as long as a mouse button is pressed. In trackball style, motion occurs when the mouse button is pressed and the mouse pointer moves.
- `Keypress c` / `Keypress a` — Toggle between **camera** and **actor** (object) modes. In camera mode, mouse events affect the camera position and focal point. In object mode, mouse events affect the actor that is under the mouse pointer.
- `Button 1` — **Rotate** the camera around its focal point (if camera mode) or rotate the actor around its origin (if actor mode). The rotation is in the direction defined from the center of the renderer's viewport towards the mouse position. In joystick mode, the magnitude of the rotation is determined by the distance between the mouse and the center of the render window.
- `Button 2` — **Pan** the camera (if camera mode) or **translate** the actor (if object mode). In joystick mode, the direction of pan or translation is from the center of the viewport towards the mouse position. In trackball mode, the direction of motion is the direction the mouse moves. (Note: With a 2-button mouse, pan is defined as `<Shift>-Button 1`.)
- `Button 3` — **Zoom** the camera (if camera mode), or **scale** the actor (if object mode). Zoom in/increase scale if the mouse position is in the top half of the viewport; zoom out/decrease scale if the mouse position is in the bottom half. In joystick mode, the amount of zoom is controlled by the distance of the mouse pointer from the horizontal centerline of the window.

- `Keypress 3` — **Toggle** the render window into and out of **stereo mode**. By default, red-blue stereo pairs are created. Some systems support Crystal Eyes LCD stereo glasses; you have to invoke `SetStereoTypeToCrystalEyes()` on the rendering window.
- `Keypress e/q` — **Exit** or **quit** the application.
- `Keypress f` — **Fly-to** the point under the cursor. This sets the focal point and allows rotations around that point.
- `Keypress p` — Perform a **pick** operation. The render window interactor has an internal instance of `vtkPropPicker` that it uses to pick. See "Picking" on page 59 for more information about picking.
- `Keypress r` — **Reset** the camera view along the current view direction. Centers the actors and moves the camera so that all actors are visible.
- `Keypress s` — Modify the representation of all actors so that they are **surfaces**.
- `Keypress u` — Invoke the **user-defined method**. Typically, this keypress will bring up an interactor that you can type commands into.
- `Keypress w` — Modify the representation of all actors so that they are **wireframe**.

The default interaction style is position sensitive (i.e., joystick style)—that is, it manipulates the camera or actor and renders continuously as long as a mouse button is pressed. If you don't like the default behavior, you can change it or write your own. (See "vtkRenderWindow Interaction Style" on page 421 for information about writing your own style.)

vtkRenderWindowInteractor has other useful features. Invoking LightFollowCameraOn() (the default behavior) causes the light position and focal point to be synchronized with the camera position and focal point (i.e., a "headlight" is created). Of course, this can be turned off with LightFollowCameraOff(). A callback that responds to the "u" keypress can be added with "AddObserver(UserEvent) method. It is also possible to set several pick-related methods. AddObserver(StartPickEvent) defines a method to be called prior to picking, and AddObserver(EndPickEvent) defines a method after the pick has been performed. (Please see "User Methods, Observers, and Commands" on page 29 for more information on defining user methods.) You can also specify an instance of a subclass of vtkAbstractPicker to use via the SetPicker() method. (See "Picking" on page 59.)

If you are using a prop that adjusts rendering quality based on desired interactivity, you may wish to set the desired frame rate via SetDesiredUpdateRate() in the interactor. Normally, this is handled automatically. (When the mouse buttons are activated, the desired update rate is increased; when the mouse button is released, the desired update rate is set back down.) Refer to "Level-Of-Detail Actors" on page 55, the "vtkLODProp3D" on page 57, and the chapter on "Volume Rendering" on page 139 for further information on how props and their associated mappers may adjust render style to achieve a desired frame rate..

We've seen how to use vtkRenderWindowInteractor previously, here's a recapitulation.

```
vtkRenderWindowInteractor iren
   iren SetRenderWindow renWin
   iren AddObserver UserEvent {wm deiconify .vtkInteract}
```

Interactor Styles

There are two distinctly different ways to control interaction style in VTK. The first is to use a subclass of vtkInteractorStyle, either one supplied with the system or one that you write. The second

method is to add observers that watch for events on the vtkRenderWindowInteractor and define your own set of callbacks (or commands) to implement the style. (Note: 3D widgets are another, more complex way to interact with data in the scene. See "3D Widgets" on page 72 for more information.)

vtkInteractorStyle. The class vtkRenderWindowInteractor can support different interaction styles. When you type "t" or "j" in the interactor (see the previous section) you are changing between trackball and joystick interaction styles. The way this works is that vtkRenderWindowInteractor translates window-system-specific events it receives (e.g., mouse button press, mouse motion, keyboard events) to VTK events such as MouseMoveEvent, StartEvent, and so on. (See "User Methods, Observers, and Commands" on page 29 for related information.) Different styles then observe particular events and perform the action(s) appropriate to the event. To set the style, use the vtkRenderWindowInteractor::SetInteractorStyle() method. For example:

```
vtkInteractorStyleFlight flightStyle
vtkRenderWindowInteractor iren
    iren SetInteractorStyle flightStyle
```

(Note: When vtkRenderWindowInteractor is instantiated, a window-system specific render window interactor is actually instantiated. For example, on Unix systems the class vtkXRenderWindowInteractor is actually created and returned as an instance of vtkRenderWindowInteractor. On Windows, the class vtkWin32RenderWindowInteractor is instantiated.)

Adding vtkRenderWindowInteractor Observers. While a variety of interactor styles are available in VTK, you may prefer to create your own custom style to meet the needs of a particular application. In C++ the natural approach is to subclass vtkInteractorStyle. (See "vtkRenderWindow Interaction Style" on page 421.) However, in an interpreted language (e.g., Tcl, Python, or Java), this is difficult to do. For interpreted languages the simplest approach is to use observers to define particular interaction bindings. (See "User Methods, Observers, and Commands" on page 29.) The bindings can be managed in any language that VTK supports, including C++, Tcl, Python, and Java. An example of this is found in the Tcl code `VTK/Examples/GUI/Tcl/CustomInteraction.tcl`, which defines bindings for a simple Tcl application. Here's an excerpt to give you an idea of what's going on.

```
vtkRenderWindowInteractor iren
iren SetInteractorStyle ""
iren SetRenderWindow renWin

# Add the observers to watch for particular events. These invoke
# Tcl procedures.

set Rotating 0
set Panning 0
set Zooming 0

iren AddObserver LeftButtonPressEvent {global Rotating; set Rotating 1}
iren AddObserver LeftButtonReleaseEvent \
  {global Rotating; set Rotating 0}
iren AddObserver MiddleButtonPressEvent {global Panning; set Panning 1}
iren AddObserver MiddleButtonReleaseEvent \
  {global Panning; set Panning 0}
```

```
iren AddObserver RightButtonPressEvent {global Zooming; set Zooming 1}
iren AddObserver RightButtonReleaseEvent {global Zooming; set Zooming 0}
iren AddObserver MouseMoveEvent MouseMove
iren AddObserver KeyPressEvent Keypress

proc MouseMove {} {
  ...
  set xypos [iren GetEventPosition]
 set x [lindex $xypos 0]
 set y [lindex $xypos 1]
  ...
}

proc Keypress {} {
 set key [iren GetKeySym]
  if { $key == "e" } {
    vtkCommand DeleteAllObjects
    exit
  }
  ...
}
```

Note that a key step in this example is disabling the default interaction style by invoking SetInteractionStyle(""). Observers are then added to watch for particular events which are tied to the appropriate Tcl procedures.

This example is a simple way to add bindings from a Tcl script. If you would like to create a full GUI using Tcl/Tk, then use the vtkTkRenderWidget, and refer to "Tcl/Tk" on page 433 for more details.

4.3 Filtering Data

The previous example pipelines consisted of a source and mapper object; the pipeline had no filters. In this section we show how to add a filter into the pipeline.

Filters are connected by using the SetInputConnection() and GetOutputPort() methods. For example, we can modify the script in "Reader Source Object" on page 44 to shrink the polygons that make up the model. The script is shown below. (Only the pipeline and other pertinent objects are shown.) The complete script can be found at
`VTK/Examples/Rendering/Tcl/FilterCADPart.tcl`.

```
vtkSTLReader part
    part SetFileName \
        "$VTK_DATA_ROOT/Data/42400-IDGH.stl"
vtkShrinkPolyData shrink
    shrink SetInputConnection [part GetOutputPort]
    shrink SetShrinkFactor 0.85
```

```
vtkPolyDataMapper partMapper
    partMapper SetInputConnection \
      [shrink GetOutputPort]
vtkLODActor partActor
  partActor SetMapper partMapper
```

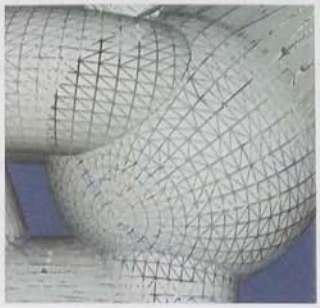


Figure 4–3 Filtering data. Here we use a filter to shrink the polygons forming the model towards their centroid.

As you can see, creating a visualization pipeline is simple. You need to select the right classes for the task at hand, make sure that the input and output type of connected filters are compatible, and set the necessary instance variables. (Input and output types are compatible when the output dataset type of a source or filter is acceptable as input to the next filter or mapper in the pipeline. The output dataset type must either match the input dataset type exactly or be a subclass of it.) Visualization pipelines can contain loops, but the output of a filter cannot be directly connected to its input.

4.4 Controlling The Camera

You may have noticed that in the proceeding scripts no cameras or lights were instantiated. If you're familiar with 3D graphics, you know that lights and cameras are necessary to render objects. In VTK, if lights and cameras are not directly created, the renderer automatically instantiates them.

Instantiating The Camera

The following Tcl script shows how to instantiate and associate a camera with a renderer.

```
vtkCamera cam1
  cam1 SetClippingRange 0.0475572 2.37786
  cam1 SetFocalPoint 0.052665 -0.129454 -0.0573973
  cam1 SetPosition 0.327637 -0.116299 -0.256418
  cam1 ComputeViewPlaneNormal
  cam1 SetViewUp -0.0225386 0.999137 0.034901
ren1 SetActiveCamera cam1
```

Alternatively, if you wish to access a camera that already exists (for example, a camera that the renderer has automatically instantiated), in Tcl you would use

```
set cam1 [ren1 GetActiveCamera]
$cam1 Zoom 1.4
```

Let's review some of the camera methods that we've just introduced. SetClippingPlane() takes two arguments, the distance to the near and far clipping planes along the view plane normal. Recall that all graphics primitives not between these planes are eliminated during rendering, so you need to make sure the objects you want to see lie between the clipping planes. The FocalPoint and Position (in world coordinates) instance variables control the direction and position of the camera. ComputeViewPlaneNormal() resets the normal to the view plane based on the current position and focal point. (If the view plane normal is not perpendicular to the view plane you can get some inter-

esting shearing effects.) Setting the ViewUp controls the "up" direction for the camera. Finally, the Zoom() method magnifies objects by changing the view angle (i.e., SetViewAngle()). You can also use the Dolly() method to move the camera in and out along the view plane normal to either enlarge or shrink the visible actors.

Simple Manipulation Methods

The methods described above are not always the most convenient ones for controlling the camera. If the camera is "looking at" the point you want (i.e., the focal point is set), you can use the Azimuth() and Elevation() methods to move the camera about the focal point.

```
cam1 Azimuth 150
cam1 Elevation 60
```

These methods move the camera in a spherical coordinate system centered at the focal point by moving in the longitude direction (azimuth) and the latitude direction (elevation) by the angle (in degrees) given. These methods do not modify the view-up vector and depend on the view-up vector remaining constant. Note that there are singularities at the north and south poles — the view-up vector becomes parallel with the view plane normal. To avoid this, you can force the view-up vector to be orthogonal to the view vector by using OrthogonalizeViewUp(). However, this changes the camera coordinate system, so if you're flying around an object with a natural horizon or view-up vector (such as terrain), camera manipulation is no longer natural with respect to the data.

Controlling The View Direction

A common function of the camera is to generate a view from a particular direction. You can do this by invoking SetFocalPoint(), SetPosition(), and ComputeViewPlaneNormal() followed by invoking ResetCamera() on the renderer associated with the camera.

```
vtkCamera cam1
  cam1 SetFocalPoint 0 0 0
  cam1 SetPosition 1 1 1
  cam1 ComputeViewPlaneNormal
  cam1 SetViewUp 1 0 0
  cam1 OrthogonalizeViewUp
ren1 SetActiveCamera cam1
ren1 ResetCamera
```

The initial direction (view vector or view plane normal) is computed from the focal point and position of the camera, which, together with ComputeViewPlaneNormal(), defines the initial view vector. Optionally, you can specify an initial view-up vector and orthogonalize it with respect to the view vector. The ResetCamera() method then moves the camera along the view vector so that the renderer's actors are all visible to the camera.

Perspective Versus Orthogonal Views

In the previous examples, we have assumed that the camera is a perspective camera where a view angle controls the projection of the actors onto the view plane during the rendering process. Perspective projection, while generating more natural looking images, introduces distortion that can be unde-

sirable in some applications. Orthogonal (or parallel) projection is an alternative projection method. In orthogonal projection, view rays are parallel, and objects are rendered without distance effects.

To set the camera to use orthogonal projection, use the vtkCamera::ParallelProjectionOn() method. In parallel projection mode, the camera view angle no longer controls zoom. Instead, use the SetParallelScale() method to control the magnification of the actors.

Saving/Restoring Camera State

Another common requirement of applications is the capability to save and restore camera state (i.e., recover a view). To save camera state, you'll need to save (at a minimum) the clipping range, the focal point and position, and the view-up vector. You'll also want to compute the view plane normal (as shown in the example in "Instantiating The Camera" on page 49). Then, to recover camera state, simply instantiate a camera with the saved information, and assign it to the appropriate renderer (i.e., SetActiveCamera()).

In some cases you may need to store additional information. For example, if the camera view angle (or parallel scale) is set, you'll need to save this. Or, if you are using the camera for stereo viewing, the EyeAngle and Stereo flags are required.

4.5 Controlling Lights

Lights are easier to control than cameras. The most frequently used methods are SetPosition(), SetFocalPoint(), and SetColor(). The position and focal point of the light control the direction in which the light points. The color of the light is expressed as an RGB vector. Also, lights can be turned on and off via the SwitchOn() and SwitchOff() methods, and the brightness of the light can be set with the SetIntensity() method.

By default, instances of vtkLight are directional lights. That is, the position and focal point define a vector parallel to which light rays travel, and the light source is assumed to be located at the infinity point. This means that the lighting on an object does not change if the focal point and position are translated identically.

Lights are associated with renderers as follows.

```
vtkLight light
    light SetColor 1 0 0
    light SetFocalPoint [cam1 GetFocalPoint]
    light SetPosition [cam1 GetPosition]

ren1 AddLight light
```

Here we've created a red headlight: a light located at the camera's (`cam1`'s) position and pointing towards the camera's focal point. This is a useful trick, and is used by the interactive renderer to position the light as the camera moves. (See "Using VTK Interactors" on page 45.)

Positional Lights

It is possible to create positional (i.e., spot lights) by using the PositionalOn() method. This method is used in conjunction with the SetConeAngle() method to control the spread of the spot. A cone angle

of 180 degrees indicates that no spot light effects will be applied (i.e., no truncated light cone), only the effects of position.

4.6 Controlling 3D Props

Objects in VTK that are to be drawn in the render window are generically known as "props." (The word prop comes from the vocabulary of theater—a prop is something that appears on stage.) There are several different types of props including vtkProp3D and vtkActor. vtkProp3D is an abstract superclass for those types of props existing in 3D space. The class vtkActor is a type of vtkProp3D whose geometry is defined by analytic primitives such as polygons and lines.

Specifying the Position of a vtkProp3D

We have already seen how to use cameras to move around an object; alternatively, we can also hold the camera steady and transform the props. The following methods can be used to define the position of a vtkProp3D (and its subclasses).

- `SetPosition(x,y,z)` — Specify the position of the vtkProp3D in world coordinates.
- `AddPosition(deltaX,deltaY,deltaZ)` — Translate the prop by the specified amount along each of the x, y, and z axes.
- `RotateX(theta)`, `RotateY(theta)`, `RotateZ(theta)` — Rotate the prop by theta degrees around the *x*, *y*, *z* coordinate axes, respectively.
- `SetOrientation(x,y,z)` — Set the orientation of the prop by rotating about the *z* axis, then about the *x* axis, and then about the *y* axis.
- `AddOrientation(a1,a2,a3)` — Add to the current orientation of the prop.
- `RotateWXYZ(theta,x,y,z)` — Rotate the prop by theta degress around the *x*-*y*-*z* vector defined.
- `SetScale(sx,sy,sz)` — Scale the prop in the *x*, *y*, *z* axes coordinate directions.
- `SetOrigin(x,y,z)` — Specify the origin of the prop. The origin is the point around which rotations and scaling occur.

These methods work together in complex ways to control the resulting transformation matrix. The most important thing to remember is that the operations listed above are applied in a particular order, and the order of application dramatically affects the resulting actor position. The order used in VTK to apply these transformations is as follows:

1. Shift to Origin
2. Scale
3. Rotate Y
4. Rotate X
5. Rotate Z
6. Shift from Origin
7. Translate

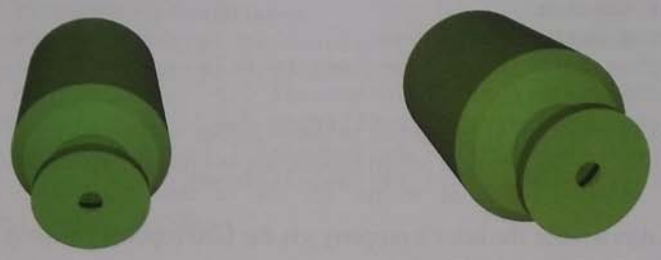


Figure 4–4 The effects of applying rotation in different order. On the left, first an x rotation followed by a y rotation; on the right, first a y rotation followed by an x rotation.

The shift to and from the origin is a negative and positive translation of the Origin value, respectively. The net translation is given by the Position value of the vtkProp3D. The most confusing part of these transformations are the rotations. For example, performing an x rotation followed by a y rotation gives very different results than the operations applied in reverse order (see **Figure 4–4**). For more information about actor transformation, please refer to the *Visualization Toolkit* text.

In the next section we describe a variety of vtkProp3D's—of which the most widely used class in VTK is called vtkActor. Later on (see "Controlling vtkActor2D" on page 62) we will examine 2D props (i.e., vtkActor2D) which tend to be used for annotation and other 2D operations.

Actors

An actor is the most common type of vtkProp3D. Like other concrete subclasses of vtkProp3D, vtkActor serves to group rendering attributes such as surface properties (e.g., ambient, diffuse, and specular color), representation (e.g., surface or wireframe), texture maps, and/or a geometric definition (a mapper).

Defining Geometry. As we have seen in previous examples, the geometry of an actor is specified with the SetMapper() method:

```
vtkPolyDataMapper mapper
   mapper SetInputConnection [aFilter GetOutputPort]
vtkActor anActor
   anActor SetMapper mapper
```

In this case `mapper` is of type vtkPolyDataMapper, which renders geometry using analytic primitives such as points, lines, polygons, and triangle strips. The mapper terminates the visualization pipeline and serves as the bridge between the visualization subsystem and the graphics subsystem.

Actor Properties. Actors refer to an instance of vtkProperty, which in turn controls the appearance of the actor. Probably the most used property is actor color, which we will describe in the next section. Other important features of the property are its representation (points, wireframe, or surface), its shading method (either flat or Gouraud shaded), the actor's opacity (relative transparency), and the ambient, diffuse, and specular color and related coefficients. The following script shows how to set some of these instance variables.

```
vtkActor anActor
   anActor SetMapper mapper
   [anActor GetProperty] SetOpacity 0.25
   [anActor GetProperty] SetAmbient 0.5
   [anActor GetProperty] SetDiffuse 0.6
   [anActor GetProperty] SetSpecular 1.0
   [anActor GetProperty] SetSpecularPower 10.0
```

Notice how we dereference the actor's property via the GetProperty() method. Alternatively, we can create a property and assign it to the actor.

```
vtkProperty prop
   prop SetOpacity 0.25
   prop SetAmbient 0.5
   prop SetDiffuse 0.6
   prop SetSpecular 1.0
   prop SetSpecularPower 10.0
vtkActor anActor
   anActor SetMapper mapper
   anActor SetProperty prop
```

The advantage of the latter method is that we can control the properties of several actors by assigning each the same property.

Actor Color. Color is perhaps the most important property applied to an actor. The simplest procedure for controlling this property is the SetColor() method, used to set the red, green, and blue (RGB) values of the actor. Each value ranges from zero to one.

```
[anActor GetProperty] SetColor 0.1 0.2 0.4
```

Alternatively, you can set the ambient, diffuse, and specular colors separately.

```
vtkActor anActor
   anActor SetMapper mapper
   [anActor GetProperty] SetAmbientColor .1 .1 .1
   [anActor GetProperty] SetDiffuseColor .1 .2 .4
   [anActor GetProperty] SetSpecularColor 1 1 1
```

In this example we've set the ambient color to a dark gray, the diffuse color to a shade of blue, and the specular color to white. (Note: The SetColor() method sets the ambient, diffuse, and specular colors to the color specified.)

Important: The color set in the actor's property only takes effect if there is no scalar data available to the actor's mapper. By default, the mapper's input scalar data colors the actor, and the actor's color is ignored. To ignore the scalar data, use the method ScalarVisibilityOff() as shown in the Tcl script below.

```
vtkPolyDataMapper planeMapper
  planeMapper SetInputConnection [CompPlane GetOutputPort]
  planeMapper ScalarVisibilityOff
vtkActor planeActor
```

```
planeActor SetMapper planeMapper
  [planeActor GetProperty] SetRepresentationToWireframe
  [planeActor GetProperty] SetColor 0 0 0
```

Actor Transparency. Many times it is useful to adjust transparency (or opacity) of an actor. For example, if you wish to show internal organs surrounded by the skin of a patient, adjusting the transparency of the skin allows the user to see the organs in relation to the skin. Use the vtkProperty::SetOpacity() method as follows.

```
vtkActor popActor
  popActor SetMapper popMapper
    [popActor GetProperty] SetOpacity 0.3
  [popActor GetProperty] SetColor .9 .9 .9
```

Please note that transparency is implemented in the rendering library using an α-blending process. This process requires that polygons are rendered in the correct order. In practice, this is very difficult to achieve, especially if you have multiple transparent actors. To order polygons, you should add transparent actors to the end of renderer's list of actors (i.e., add them last). Also, you can use the filter vtkDepthSortPolyData to sort polygons along the view vector. Please see `VTK/Examples/VisualizationAlgorithms/Tcl/DepthSort.tcl` for an example using this filter. For more information on this topic see "Translucent polygonal geometry" on page 79

Miscellaneous Features. Actors have several other important features. You can control whether an actor is visible with the VisibilityOn() and VisibilityOff() methods. If you don't want to pick an actor during a picking operation, use the PickableOff() method. (See "Picking" on page 59 for more information about picking.) Actors also have a pick event that can be invoked when they are picked. Additionally you can get the axis-aligned bounding box of actor with the GetBounds() method.

Level-Of-Detail Actors

One major problem with graphics systems is that they often become too slow for interactive use. To handle this problem, VTK uses level-of-detail actors to achieve acceptable rendering performance at the cost of lower-resolution representations.

In "Reader Source Object" on page 44 we saw how to use a vtkLODActor. Basically, the simplest way to use vtkLODActor is to replace instances of vtkActor with instances of vtkLODActor. In addition, you can control the representation of the levels of detail. The default behavior of vtkLODActor is to create two additional, lower-resolution models from the original mapper. The first is a point cloud, sampled from the points defining the mapper's input. You can control the number of points in the cloud as follows. (The default is 150 points.)

```
vtkLODActor dotActor
  dotActor SetMapper dotMapper
  dotActor SetNumberOfCloudPoints 1000
```

The lowest resolution model is a bounding box of the actor. Additional levels of detail can be added using the AddLODMapper() method. They do not have to be added in order of complexity.

To control the level-of-detail selected by the actor during rendering, you can set the desired frame rate in the rendering window:

```
vtkRenderWindow renWin
   renWin SetDesiredUpdateRate 5.0
```

which translates into five frames per second. The vtkLODActor will automatically select the appropriate level-of-detail to yield the requested rate. (Note: The interactor widgets such as vtkRenderWindowInteractor automatically control the desired update rate. They typically set the frame rate very low when a mouse button is released, and increase the rate when a mouse button is pressed. This gives the pleasing effect of low-resolution/high frame rate models with camera motion, and high-resolution/low frame rate when the camera stops. If you would like more control over the levels-of-detail, see "vtkLODProp3D" on page 57. vtkLODProp3D allow you to specifically set each level.)

Assemblies

Actors are often grouped in hierarchal assemblies so that the motion of one actor affects the position of other actors. For example, a robot arm might consist of an upper arm, forearm, wrist, and end effector, all connected via joints. When the upper arm rotates around the shoulder joint, we expect the rest of the arm to move with it. This behavior is implemented using assemblies, which are a type of (subclass of) vtkActor. The following script shows how it's done (from `VTK/Examples/Rendering/Tcl/assembly.tcl`).

```
# create four parts: a top level assembly and three primitives
vtkSphereSource sphere
vtkPolyDataMapper sphereMapper
  sphereMapper SetInputConnection [sphere GetOutputPort]
vtkActor sphereActor
  sphereActor SetMapper sphereMapper
  sphereActor SetOrigin 2 1 3
  sphereActor RotateY 6
  sphereActor SetPosition 2.25 0 0
  [sphereActor GetProperty] SetColor 1 0 1

vtkCubeSource cube
vtkPolyDataMapper cubeMapper
  cubeMapper SetInputConnection [cube GetOutputPort]
vtkActor cubeActor
  cubeActor SetMapper cubeMapper
  cubeActor SetPosition 0.0 .25 0
  [cubeActor GetProperty] SetColor 0 0 1

vtkConeSource cone
vtkPolyDataMapper coneMapper
  coneMapper SetInputConnection [cone GetOutputPort]
vtkActor coneActor
  coneActor SetMapper coneMapper
  coneActor SetPosition 0 0 .25
  [coneActor GetProperty] SetColor 0 1 0

vtkCylinderSource cylinder
```

```
vtkPolyDataMapper cylinderMapper
  CylinderMapper SetInputConnection [cylinder GetOutputPort]
vtkActor cylinderActor
  cylinderActor SetMapper cylinderMapper
    [cylinderActor GetProperty] SetColor 1 0 0

vtkAssembly assembly
    assembly AddPart cylinderActor
  assembly AddPart sphereActor
  assembly AddPart cubeActor
  assembly AddPart coneActor
  assembly SetOrigin 5 10 15
  assembly AddPosition 5 0 0
  assembly RotateX 15

# Add the actors to the renderer, set the background and size
ren1 AddActor assembly
ren1 AddActor coneActor
```

Notice how we use vtkAssembly's AddPart() method to build the hierarchies. Assemblies can be nested arbitrarily deeply as long as there are not any self-referencing cycles. Note that vtkAssembly is a subclass of vtkProp3D, so it has no notion of properties or of an associated mapper. Therefore, the leaf nodes of the vtkAssembly hierarchy must carry information about material properties (color, etc.) and any associated geometry. Actors may also be used by more than one assembly (notice how `coneActor` is used in the assembly and as an actor). Also, the renderer's AddActor() method is used to associate the top level of the assembly with the renderer; those actors at lower levels in the assembly hierarchy do not need to be added to the renderer since they are recursively rendered.

You may be wondering how to distinguish the use of an actor relative to its context if an actor is used in more than one assembly, or is mixed with an assembly as in the example above. (This is particularly important in activities like picking, where the user may need to know which vtkProp was picked as well as the context in which it was picked.) We address this issue along with the introduction of the class vtkAssemblyPath, which is an ordered list of vtkProps with associated transformation matrices (if any), in detail in "Picking" on page 59.

Volumes

The class vtkVolume is used for volume rendering. It is analogous to the class vtkActor. Like vtkActor, vtkVolume inherits methods from vtkProp3D to position and orient the volume. vtkVolume has an associated property object, in this case a vtkVolumeProperty. Please see "Volume Rendering" on page 116 for a thorough description of the use of vtkVolume and a description of volume rendering.

vtkLODProp3D

The vtkLODProp3D class is similar to vtkLODActor (see "Level-Of-Detail Actors" on page 55) in that it uses different representations of itself in order to achieve interactive frame rates. Unlike vtkLODActor, vtkLODProp3D supports both volume rendering and surface rendering. This means that you can use vtkLODProp3D in volume rendering applications to achieve interactive frame rates. The following example shows how to use the class.

```
vtkLODProp3D lod
   set level1 [lod AddLOD volumeMapper volumeProperty2 0.0]
   set level2 [lod AddLOD volumeMapper volumeProperty 0.0]
   set level3 [lod AddLOD probeMapper_hres probeProperty 0.0]
   set level4 [lod AddLOD probeMapper_lres probeProperty 0.0]
   set level5 [lod AddLOD outlineMapper outlineProperty 0.0]
```

Basically, you create different mappers each corresponding to a different rendering complexity, and add the mappers to the vtkLODProp3D. The AddLOD() method accepts either volume or geometric mappers and optionally a texture map and/or property object. (There are different signatures for this method depending on what information you wish to provide.) The last value in the field is an estimated time to render. Typically you set it to zero to indicate that there is no initial estimate. The method returns an integer id that can be used to access the appropriate LOD (i.e., to select a level or delete it).

vtkLODProp3D measures the time it takes to render each LOD and sorts them appropriately. Then, depending on the render window's desired update rate, vtkLODProp3D selects the appropriate level to render. See "Using a vtkLODProp3D to Improve Performance" on page 135 for more information.

4.7 Using Texture

Texture mapping is a powerful graphics tool for creating realistic and compelling visualizations. The basic idea behind 2D texture mapping is that images can be "pasted" onto a surface during the rendering process, thereby creating richer and more detailed images. Texture mapping requires three pieces of information: a surface to apply the texture to; a texture map, which in VTK is a vtkImageData dataset (i.e., a 2D image); and texture coordinates, which control the positioning of the texture on the surface.

The following example (**Figure 4–5**) demonstrates the use of texture mapping (see `VTK/Examples/Rendering/Tcl/TPlane.tcl`). Notice that the texture map (of class vtkTexture) is associated with the actor, and the texture coordinates come from the plane (the texture coordinates are generated by vtkPlaneSource when the plane is created).

Figure 4–5 Texture map on plane

```
# load in the texture map
vtkBMPReader bmpReader
   bmpReader SetFileName \
          "$VTK_DATA_ROOT/Data/masonry.bmp"
vtkTexture atext
   atext SetInputConnection [bmpReader GetOutputPort]
   atext InterpolateOn

# create a plane source and actor
vtkPlaneSource plane
vtkPolyDataMapper planeMapper
   planeMapper SetInputConnection [plane GetOutputPort]
vtkActor planeActor
   planeActor SetMapper planeMapper
```

```
planeActor SetTexture atext
```

Often times texture coordinates are not available, usually because they are not generated in the pipeline. If you need to generate texture coordinates, refer to "Generate Texture Coordinates" on page 111. Although some older graphics card have limitations on the dimensions of textures (e.g. they must be a power of two and less than 1024 on a side), VTK allows arbitrarily sized textures. At run time, VTK will query the graphics system to determine its capabilities, and will automatically resample your texture to meet the card's requirements.

4.8 Picking

Picking is a common visualization task. Picking is used to select data and actors or to query underlying data values. A pick is made when a display position (i.e., pixel coordinate) is selected and used to invoke vtkAbstractPicker's Pick() method. Depending on the type of picking class, the information returned from the pick may be as simple as an *x-y-z* global coordinate, or it may include cell ids, point ids, cell parametric coordinates, the instance of vtkProp that was picked, and/or assembly paths. The syntax of the pick method is as follows.

```
Pick(selectionX, selectionY, selectionZ, Renderer)
```

Notice that the pick method requires a renderer. The actors associated with the renderer are the candidates for pick selection. Also, `selectionZ` is typically set to 0.0—it relates to depth in the *z*-buffer. (In typical usage, this method is not invoked directly. Rather the user interacts with the class vtkRenderWindowInteractor which manages the pick. In this case, the user would control the picking process by assigning an instance of a picking class to the vtkRenderWindowInteractor, as we will see in a later example.)

The *Visualization Toolkit* supports several types of pickers of varying functionality and performance. (Please see **Figure 19–16** which is an illustration of the picking class hierarchy.) The class vtkAbstractPicker serves as the base class for all pickers. It defines a minimal API which allows the user to retrieve the pick position (in global coordinates) using the GetPickPosition() method.

Two direct subclasses of vtkAbstractPicker exist. The first, vtkWorldPointPicker, is a fast (usually in hardware) picking class that uses the *z*-buffer to return the *x-y-z* global pick position. However, no other information (about the vtkProp that was picked, etc.) is returned. The class vtkAbstractPropPicker is another direct subclass of vtkAbstractPicker. It defines an API for pickers that can pick an instance of vtkProp. There are several convenience methods in this class to allow querying for the return type of a pick.

- `GetProp()` — Return the instance of vtkProp that was picked. If anything at all was picked, then this method will return a pointer to the instance of vtkProp, otherwise `NULL` is returned.
- `GetProp3D()` — If an instance of vtkProp3D was picked, return a pointer to the instance of vtkProp3D.
- `GetActor2D()` — If an instance of vtkActor2D was picked, return a pointer to the instance of vtkActor2D.
- `GetActor()` — If an instance of vtkActor was picked, return a pointer to the instance of vtkActor.

- `GetVolume()` — If an instance of vtkVolume was picked, return a pointer to the instance of vtkVolume.
- `GetAssembly()` — If an instance of vtkAssembly was picked, return a pointer to the instance of vtkAssembly.
- `GetPropAssembly()` — If an instance of vtkPropAssembly was picked, return a pointer to the instance of vtkPropAssembly.

A word of caution about these methods. The class (and its subclass) return information about the *top level of the assembly path* that was picked. So if you have an assembly whose top level is of type vtkAssembly, and whose leaf node is of type vtkActor, the method GetAssembly() will return a pointer to the instance of vtkAssembly, while the GetActor() method will return a `NULL` pointer (i.e., no vtkActor). If you have a complex scene that includes assemblies, actors, and other types of props, the safest course to take is to use the GetProp() method to determine whether anything at all was picked, and then use GetPath().

There are three direct subclasses of vtkAbstractPropPicker. These are vtkPropPicker, vtkAreaPicker, and vtkPicker. vtkPropPicker uses hardware picking to determine the instance of vtkProp that was picked, as well as the pick position (in global coordinates). vtkPropPicker is generally faster than all other decendents of vtkAbstractPropPicker but it cannot return information detailed information about what was picked.

vtkAreaPicker and its hardware picking based descendent vtkRenderedAreaPicker are similarly incapable of determining detailed information, as all three exist for the purpose of identifying entire objects that are shown on screen. The AreaPicker classes differ from all other pickers in that they can determine what lies begin an entire rectangular region of pixels on the screen instead of only what lies behind a single pixel. These classes have an AreaPick(x_min, y_min, x_max, y_max, Renderer) method that can be called in addition to the standard Pick(x,y,z, Renderer) method. If you need detailed information, for example specific cells and points or information about what lies behind an area, review the following picker explanations below.

vtkPicker is a software-based picker that selects vtkProp's based on their bounding box. Its pick method fires a ray from the camera position through the selection point and intersects the bounding box of each prop 3D; of course, more than one prop 3D may be picked. The "closest" prop 3D in terms of its bounding box intersection point along the ray is returned. (The GetProp3Ds() method can be used to get all prop 3D's whose bounding box was intersected.) vtkPicker is fairly fast but cannot generate a single unique pick.

vtkPicker has two subclasses that can be used to retrieve more detailed information about what was picked (e.g., point ids, cell ids, etc.) vtkPointPicker selects a point and returns the point id and coordinates. It operates by firing a ray from the camera position through the selection point, and projecting those points that lie within Tolerance onto the ray. The projected point closest to the camera position is selected, along with its associated actor. (Note: The instance variable Tolerance is expressed as a fraction of the renderer window's diagonal length.) vtkPointPicker is slower than vtkPicker but faster than vtkCellPicker. It cannot always return a unique pick because of the tolerances involved.

vtkCellPicker selects a cell and returns information about the intersection point (cell id, global coordinates, and parametric cell coordinates). It operates by firing a ray and intersecting all cells in each actor's underlying geometry, determining if each intersects this ray, within a certain specified tolerance. The cell closest to the camera position along the specified ray is selected, along with its associated actor. (Note: The instance variable Tolerance is used during intersection calculation, and you may need to experiment with its value to get satisfactory behavior.) vtkCellPicker is the slowest

of all the pickers, but provides the most information. It will generate a unique pick within the tolerance specified.

Several events are defined to interact with the pick operation. The picker invokes StartPickEvent prior to executing the pick operation. EndPickEvent is invoked after the pick operation is complete. The picker's PickEvent and the actor's PickEvent are invoked each time an actor is picked. (Note that no PickEvent is invoked when using vtkWorldPointPicker.)

vtkAssemblyPath

An understanding of the class vtkAssemblyPath is essential if you are to perform picking in a scene with different types of vtkProp's, especially if the scene contains instances of vtkAssembly. vtkAssemblyPath is simply an ordered list of vtkAssemblyNode's, where each node contains a pointer to a vtkProp, as well as an optional vtkMatrix4x4. The order of the list is important: the start of the list represents the root, or top level node in an assembly hierarchy, while the end of the list represents a leaf node in an assembly hierarchy. The ordering of the nodes also affects the associated matrix. Each matrix is a concatenation of the node's vtkProp's matrix with the previous matrix in the list. Thus, for a given vtkAssemblyNode, the associated vtkMatrix4x4 represents the position and orientation of the vtkProp (assuming that the vtkProp is initially untransformed).

Example

Typically, picking is automatically managed by vtkRenderWindowInteractor (see "Using VTK Interactors" on page 45 for more information about interactors). For example, when pressing the `p` key, vtkRenderWindowInteractor invokes a pick with its internal instance of vtkPropPicker. You can then ask the vtkRenderWindowInteractor for its picker, and gather the information you need. You can also specify a particular vtkAbstractPicker instance for vtkRenderWindowInteractor to use, as the following script illustrates. The results on a sample data set are shown in **Figure 4–6**. The script for this example can be found in `VTK/Examples/Annotation/Tcl/annotatePick.tcl`.

```
vtkCellPicker picker
  picker AddObserver EndPickEvent annotatePick
vtkTextMapper textMapper
set tprop [textMapper GetTextProperty]
  $tprop SetFontFamilyToArial
  $tprop SetFontSize 10
  $tprop BoldOn
  $tprop ShadowOn
  $tprop SetColor 1 0 0
vtkActor2D textActor
  textActor VisibilityOff
  textActor SetMapper textMapper
vtkRenderWindowInteractor iren
  iren SetRenderWindow renWin
  iren SetPicker picker

proc annotatePick {} {
  if { [picker GetCellId] < 0 } {
      textActor VisibilityOff
    } else {
      set selPt [picker GetSelectionPoint]
```

Figure 4–6 Annotating a pick operation.

```
        set x [lindex $selPt 0]
        set y [lindex $selPt 1]
        set pickPos [picker GetPickPosition]
        set xp [lindex $pickPos 0]
        set yp [lindex $pickPos 1]
        set zp [lindex $pickPos 2]
        textMapper SetInput "($xp, $yp, $zp)"
        textActor SetPosition $x $y
        textActor VisibilityOn
      }
      renWin Render
    }
    picker Pick 85 126 0 ren1
```

This example uses a vtkTextMapper to draw the world coordinate of the pick on the screen. (See "Text Annotation" on page 63 for more information.) Notice that we register the EndPickEvent to perform setup after the pick occurs. The method is configured to invoke the `annotatePick()` procedure when picking is complete.

4.9 vtkCoordinate and Coordinate Systems

The *Visualization Toolkit* supports several different coordinate systems, and the class vtkCoordinate manages transformations between them. The supported coordinate systems are as follows.

- DISPLAY — *x-y* pixel values in the (rendering) window. (Note that vtkRenderWindow is a subclass of vtkWindow). The origin is the lower-left corner (which is true for all 2D coordinate systems described below).
- NORMALIZED DISPLAY — *x-y* (0,1) normalized values in the window.
- VIEWPORT — *x-y* pixel values in the viewport (or renderer — a subclass of vtkViewport)
- NORMALIZED VIEWPORT — *x-y* (0,1) normalized values in viewport
- VIEW — *x-y-z* (-1,1) values in camera coordinates (*z* is depth)
- WORLD — *x-y-z* global coordinate value
- USERDEFINED - *x-y-z* in user-defined space. The user must provide a transformation method for user defined coordinate systems. See vtkCoordinate for more information.

The class vtkCoordinate can be used to transform between coordinate systems and can be linked together to form "relative" or "offset" coordinate values. Refer to the next section for an example of using vtkCoordinate in an application.

4.10 Controlling vtkActor2D

vtkActor2D is analogous to vtkActor except that it draws on the overlay plane and does not have a 4x4 transformation matrix associated with it. Like vtkActor, vtkActor2D refers to a mapper (vtkMapper2D) and a property object (vtkProperty2D). The most difficult part when working with vtkActor2D is positioning it. To do that, the class vtkCoordinate is used. (See previous section, "vtk-

Figure 4–7 2D (left) and 3D (right) annotation.

Coordinate and Coordinate Systems".) The following script shows how to use the vtkCoordinate object.

```
vtkActor2D bannerActor
  bannerActor SetMapper banner
  [bannerActor GetProperty] SetColor 0 1 0
  [bannerActor GetPositionCoordinate]
                    SetCoordinateSystemToNormalizedDisplay
  [bannerActor GetPositionCoordinate] SetValue 0.5 0.5
```

What's done in this script is to access the coordinate object and define it's coordinate system. Then the appropriate value is set for that coordinate system. In this script a normalized display coordinate system is used, so display coordinates range from zero to one, and the values (0.5,0.5) are set to position the vtkActor2D in the middle of the rendering window. vtkActor2D also provides a convenience method, SetDisplayPosition(), that sets the coordinate system to DISPLAY and uses the input parameters to set the vtkActor2D's position using pixel offsets in the render window. The example in the following section shows how the method is used.

4.11 Text Annotation

The *Visualization Toolkit* offers two ways to annotate images. First, text (and graphics) can be rendered on top of the underlying 3D graphics window (often referred to as rendering in the overlay plane). Second, text can be created as 3D polygonal data and transformed and displayed as any other 3D graphics object. We refer to this as 2D and 3D annotation, respectively. See **Figure 4–7** to see the difference.

2DText Annotation

To use 2D text annotation, we employ 2D actors (vtkActor2D and its subclasses such as vtkScaledTextActor) and mappers (vtkMapper2D and subclasses such as vtkTextMapper). 2D actors and mappers are similar to their 3D counterparts except that they render in the overlay plane on top of underlying graphics or images. Here's an example Tcl script found in `VTK/Examples/Annotation/Tcl/TestText.tcl`; the results are shown on the left side of **Figure 4–7**.

```
vtkSphereSource sphere
vtkPolyDataMapper sphereMapper
  sphereMapper SetInputConnection [sphere GetOutputPort]
```

```
    sphereMapper GlobalImmediateModeRenderingOn
  vtkLODActor sphereActor
    sphereActor SetMapper sphereMapper

  vtkTextActor textActor
    textActor SetTextScaleModeToProp
    textActor SetDisplayPosition 90 50
    textActor SetInput "This is a sphere"
      # Specify an initial size
    [textActor GetPosition2Coordinate] \
                          SetCoordinateSystemToNormalizedViewport
    [textActor GetPosition2Coordinate] SetValue 0.6 0.1

  set tprop [textActor GetTextProperty]
    $tprop SetFontSize 18
    $tprop SetFontFamilyToArial
    $tprop SetJustificationToCentered
    $tprop BoldOn
    $tprop ItalicOn
    $tprop ShadowOn
    $tprop SetColor 0 0 1

  # Create the RenderWindow, Renderer and both Actors
  vtkRenderer ren1
  vtkRenderWindow renWin
    renWin AddRenderer ren1
  vtkRenderWindowInteractor iren
    iren SetRenderWindow renWin

  # Add the actors to the renderer
  ren1 AddViewProp textActor
  ren1 sphereActor
```

Instances of the class vtkTextProperty allow you to control font family (Arial, Courier, or Times), set text color, turn bolding and italics on and off, and apply font shadowing. (Shadowing is used to make the font more readable when placed on top of complex background images.) The position and color of the text is controlled by the associated vtkActor2D. (In this example, the position is set using display or pixel coordinates.)

vtkTextProperty also supports justification (vertical and horizontal) and multi-line text. Use the methods SetJustificationToLeft(), SetJustificationToCentered(), and SetJustificationToRight() to control the horizontal justification. Use the methods SetVerticalJustificationToBottom(), SetVerticalJustificationToCentered(), and SetVerticalJustificationToTop() to control vertical justification. By default, text is left-bottom justified. To insert multi-line text, use the `\n` character embedded in the text. The example in **Figure 4–8** demonstrates justification and multi-line text (taken from `VTK/Examples/Annotation/Tcl/multiLineText.tcl`). The essence of the example is shown below.

```
vtkTextMapper textMapperL
  textMapperL SetInput "This is\nmulti-line\ntext output\n(left-top)"
  set tprop [textMapperL GetTextProperty]
```

Figure 4–8 Justification and use of multi-line text. Use the \n character embedded in the text string to generate line breaks. Both vertical and horizontal justification is supported.

```
  $tprop ShallowCopy multiLineTextProp
  $tprop SetJustificationToLeft
  $tprop SetVerticalJustificationToTop
  $tprop SetColor 1 0 0
vtkActor2D textActorL
  textActorL SetMapper textMapperL
  [textActorL GetPositionCoordinate] \
        SetCoordinateSystemToNormalizedDisplay
  [textActorL GetPositionCoordinate] SetValue 0.05 0.5
```

Note the use of the vtkCoordinate object (obtained by invoking the GetPositionCoordinate() method) to control the position of the actor in the normalized display coordinate system. See the section "vtkCoordinate and Coordinate Systems" on page 62 for more information about placing annotation.

3D Text Annotation and vtkFollower

3D text annotation is implemented using vtkVectorText to create a polygonal representation of a text string, which is then appropriately positioned in the scene. One useful class for positioning 3D text is vtkFollower. This class is a type of actor that always faces the renderer's active camera, thereby insuring that the text is readable. This Tcl script found in `VTK/Examples/Annotation/Tcl/textOrigin.tcl` shows how to do this (**Figure 4–7**). The example creates an axes and labels the origin using an instance of vtkVectorText in combination with a vtkFollower.

```
vtkAxes axes
  axes SetOrigin 0 0 0
vtkPolyDataMapper axesMapper
  axesMapper SetInputConnection [axes GetOutputPort]
vtkActor axesActor
  axesActor SetMapper axesMapper

vtkVectorText atext
  atext SetText "Origin"
vtkPolyDataMapper textMapper
  textMapper SetInputConnection [atext GetOutputPort]
vtkFollower textActor
  textActor SetMapper textMapper
  textActor SetScale 0.2 0.2 0.2
  textActor AddPosition 0 -0.1 0
...etc...after rendering...
textActor SetCamera [ren1 GetActiveCamera]
```

As the camera moves around the axes, the follower will orient itself to face the camera. (Try this by mousing in the rendering window to move the camera.)

4.12 Special Plotting Classes

The *Visualization Toolkit* provides several composite classes that perform supplemental plotting operations. These include the ability to plot scalar bars, perform simple x-y plotting, and place flying axes for 3D spatial context.

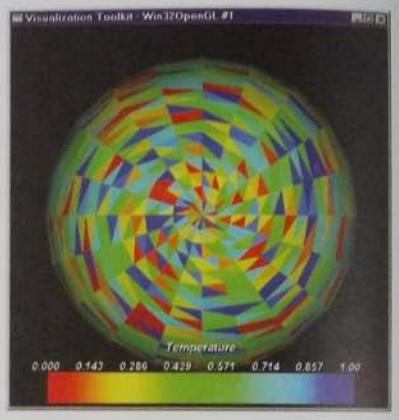


Figure 4–9 vtkScalarBarActor used to create color legends.

Scalar Bar

The class vtkScalarBar is used to create a color-coded key that relates color values to numerical data values as shown in **Figure 4–9**. There are three parts to the scalar bar: a rectangular bar with colored segments, labels, and a title. To use vtkScalarBar, you must reference an instance of vtkLookupTable (defines colors and the range of data values), position and orient the scalar bar on the overlay plane, and optionally specify attributes such as color (of the labels and the title), number of labels, and text string for the title. The following example shows typical usage.

```
vtkScalarBarActor scalarBar
  scalarBar SetLookupTable [mapper GetLookupTable]
  scalarBar SetTitle "Temperature"
  [scalarBar GetPositionCoordinate] \
                    SetCoordinateSystemToNormalizedViewport
  [scalarBar GetPositionCoordinate] SetValue 0.1 0.01
  scalarBar SetOrientationToHorizontal
  scalarBar SetWidth 0.8
  scalarBar SetHeight 0.17
```

The orientation of the scalar bar is controlled by the methods SetOrientationToVertical() and vtkSetOrientationToHorizontal(). To control the position of the scalar bar (i.e., its lower-left corner), set the position coordinate (in whatever coordinate system you desire—see "vtkCoordinate and Coordinate Systems" on page 62), and then specify the width and height using normalized viewport values (or alternatively, specify the Position2 instance variable to set the upper-right corner).

X-Y Plots

The class vtkXYPlotActor generates *x-y* plots from one or more input datasets, as shown in **Figure 4–10**. This class is particularly useful for showing the variation of data across a sequence of points such as a line probe or a boundary edge.

To use vtkXYPlotActor2D, you must specify one or more input datasets, axes, and the plot title, and position the composite actor on the overlay plane. The PositionCoordinate instance variable

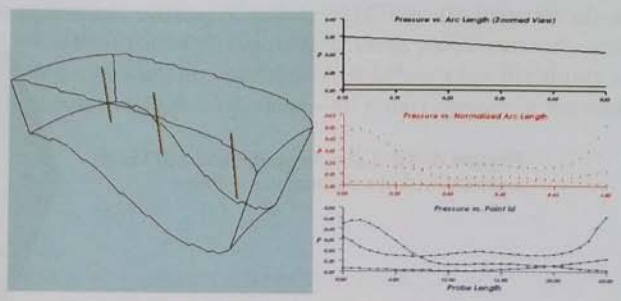


Figure 4–10 Example of using the vtkXYPlotActor2D class to display three probe lines using three different techniques (see VTK/Hybrid/Testing/Tcl/xyPlot.tcl).

defines the location of the lower-left corner of the x-y plot (specified in normalized viewport coordinates), and the Position2Coordinate instance variable defines the upper-right corner. (Note: The Position2Coordinate is relative to PositionCoordinate, so you can move the vtkXYPlotActor around the viewport by setting just the PositionCoordinate.) The combination of the two position coordinates specifies a rectangle in which the plot will lie. The following example (from `VTK/Examples/Annotation/Tcl/xyPlot.tcl`) shows how the class is used.

```
vtkXYPlotActor xyplot
  xyplot AddInput [probe GetOutput]
  xyplot AddInput [probe2 GetOutput]
  xyplot AddInput [probe3 GetOutput]
  [xyplot GetPositionCoordinate] SetValue 0.0 0.67 0
  [xyplot GetPosition2Coordinate] SetValue 1.0 0.33 0
  xyplot SetXValuesToArcLength
  xyplot SetNumberOfXLabels 6
  xyplot SetTitle "Pressure vs. Arc Length (Zoomed View)"
  xyplot SetXTitle ""
  xyplot SetYTitle "P"
  xyplot SetXRange .1 .35
  xyplot SetYRange .2 .4
  [xyplot GetProperty] SetColor 0 0 0
```

Note the x axis definition. By default, the x coordinate is set as the point index in the input datasets. Alternatively, you can use arc length and normalized arc length of lines used as input to vtkXYPlotActor to generate the x values.

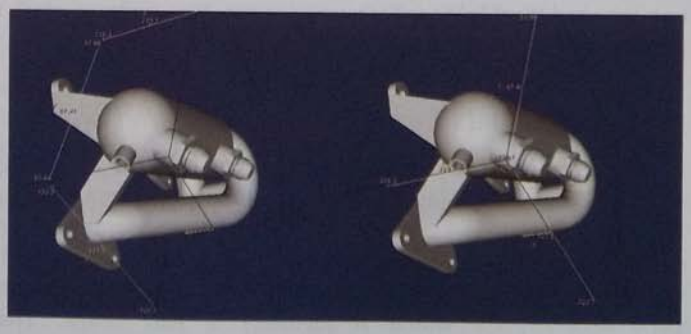


Figure 4–11 Use of vtkCubeAxisActor2D. On the left, outer edges of the cube are used to draw the axes. On the right, the closest vertex to the camera is used.

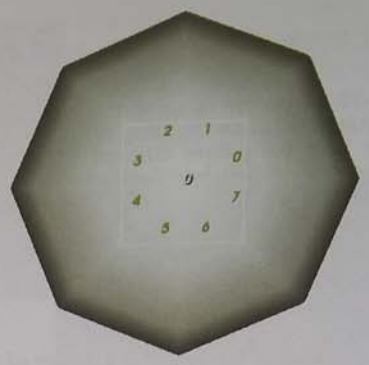


Figure 4–12 Labelling point and cell ids on a sphere within a rectangular window.

Bounding Box Axes (vtkCubeAxesActor2D)

Another composite actor class is vtkCubeAxesActor2D. This class can be used to indicate the position in space that the camera is viewing, as shown in **Figure 4–11**. The class draws axes around the bounding box of the input dataset labeled with *x-y-z* coordinate values. As the camera zooms in, the axes are scaled to fit within the cameras viewport, and the label values are updated. The user can control various font attributes as well as the relative font size (The font size is selected automatically—the method SetFontFactor() can be used to affect the size of the selected font.) The following script demonstrates how to use the class (taken from `VTK/Examples/Annotation/Tcl/cubeAxes.tcl`).

```
vtkTextProperty tprop
    tprop SetColor 1 1 1
    tprop ShadowOn
vtkCubeAxesActor2D axes
  axes SetInput [normals GetOutput]
  axes SetCamera [ren1 GetActiveCamera]
  axes SetLabelFormat "%6.4g"
  axes SetFlyModeToOuterEdges
  axes SetFontFactor 0.8
  axes SetAxisTitleTextProperty tprop
    axis SetAxisLabelTextProperty tprop
```

Note that there are two ways that the axes can be drawn. By default, the outer edges of the bounding box are used (SetFlyModeToOuterEdges()). You can also place the axes at the vertex closest to the camera position (SetFlyModeToClosestTriad()).

Labeling Data

In some applications, you may wish to display numerical values from an underlying data set. The class vtkLabeledDataMapper allows you to label the data associated with the points of a dataset. This includes scalars, vectors, tensors, normals, texture coordinates, and field data, as well as the point ids of the dataset. The text labels are placed on the overlay plane of the rendered image as shown in **Figure 4–12**. The figure was generated from the Tcl script `VTK/Examples/Annotation/Tcl/labeledMesh.tcl` which is included in part below. The script uses three new classes,

vtkCellCenters (to generate points at the parametric centers of cells), vtkIdFilter (to generate ids as scalar or field data from dataset ids), and vtkSelectVisiblePoints (to select those points currently visible), to label the cell and point ids of the sphere. In addition, vtkSelectVisiblePoints has the ability to define a "window" in display (pixel) coordinates in which it operates—all points outside of the window are discarded.

```
# Create a sphere
vtkSphereSource sphere
vtkPolyDataMapper sphereMapper
  sphereMapper SetInputConnection [sphere GetOutputPort]
  sphereMapper GlobalImmediateModeRenderingOn
vtkActor sphereActor
  sphereActor SetMapper sphereMapper
# Generate ids for labeling
vtkIdFilter ids
  ids SetInputConnection [sphere GetOutputPort]
  ids PointIdsOn
  ids CellIdsOn
  ids FieldDataOn

vtkRenderer ren1

# Create labels for points
vtkSelectVisiblePoints visPts
  visPts SetInputConnection [ids GetOutputPort]
  visPts SetRenderer ren1
  visPts SelectionWindowOn
  visPts SetSelection $xmin [expr $xmin + $xLength] \
      $ymin [expr $ymin + $yLength]
vtkLabeledDataMapper ldm
  ldm SetInput [visPts GetOutput]
  ldm SetLabelFormat "%g"
    ldm SetLabelModeToLabelFieldData
vtkActor2D pointLabels
  pointLabels SetMapper ldm

# Create labels for cells
vtkCellCenters cc
  cc SetInputConnection [ids GetOutputPort]
vtkSelectVisiblePoints visCells
  visCells SetInputConnection [cc GetOutputPort]
  visCells SetRenderer ren1
  visCells SelectionWindowOn
  visCells SetSelection $xmin [expr $xmin + $xLength] \
      $ymin [expr $ymin + $yLength]
vtkLabeledDataMapper cellMapper
  cellMapper SetInputConnection [visCells GetOutputPort]
  cellMapper SetLabelFormat "%g"
    cellMapper SetLabelModeToLabelFieldData
    [cellMapper GetLabelTextProperty] SetColor 0 1 0
vtkActor2D cellLabels
```

```
cellLabels SetMapper cellMapper

# Add the actors to the renderer, set the background and size
ren1 AddActor sphereActor
ren1 AddActor2D pointLabels
ren1 AddActor2D cellLabels
```

4.13 Transforming Data

As we saw in the section "Notice how we use vtkAssembly's AddPart() method to build the hierarchies. Assemblies can be nested arbitrarily deeply as long as there are not any self-referencing cycles. Note that vtkAssembly is a subclass of vtkProp3D, so it has no notion of properties or of an associated mapper. Therefore, the leaf nodes of the vtkAssembly hierarchy must carry information about material properties (color, etc.) and any associated geometry. Actors may also be used by more than one assembly (notice how `coneActor` is used in the assembly and as an actor). Also, the renderer's AddActor() method is used to associate the top level of the assembly with the renderer; those actors at lower levels in the assembly hierarchy do not need to be added to the renderer since they are recursively rendered." on page 57, it is possible to position and orient vtkProp3D's in world space. However, in many applications we wish to transform the data prior to using it in the visualization pipeline. For example, to use a plane to cut ("Cutting" on page 98) or clip ("Clip Data" on page 110) an object, the plane must be positioned within the pipeline, not via the actor transformation matrix. Some objects (especially procedural source objects) can be created at a specific position and orientation in space. For example, vtkSphereSource has Center and Radius instance variables, and vtkPlaneSource has Origin, Point1, and Point2 instance variables that allow you to position the plane using three points. However, many classes do not provide this capability without moving data into a new position. In this case, you must transform the data using vtkTransformFilter or vtkTransformPolyDataFilter.

vtkTransformFilter is a filter that takes vtkPointSet dataset objects as input. Datasets that are subclasses of the abstract class vtkPointSet represent points explicitly, that is, an instance of vtkPoints is used to store coordinate information. vtkTransformFilter applies a transformation matrix to the points and create a transformed points array; the rest of the dataset structure (i.e., cell topology) and attribute data (e.g., scalars, vectors, etc.) remains unchanged. vtkTransformPolyDataFilter does the same thing as vtkTransformFilter except that it is more convenient to use in a visualization pipeline containing polygonal data.

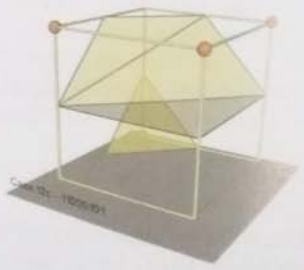


Figure 4–13 Transforming data within the pipeline.

The following example (taken from `VTK/Examples/DataManipulation/Tcl/marching.tcl` with results shown in **Figure 4–13**) uses a vtkTransformPolyDataFilter to reposition a 3D text string. (See "3D Text Annotation and vtkFollower" on page 65 for more information about 3D text.)

```
#define the text for the labels
vtkVectorText caseLabel
 caseLabel SetText "Case 12c - 11000101"
vtkTransform aLabelTransform
```

```
  aLabelTransform Identity
  aLabelTransform Translate -.2 0 1.25
  aLabelTransform Scale .05 .05 .05
vtkTransformPolyDataFilter labelTransform
  labelTransform SetTransform aLabelTransform
  labelTransform SetInputConnection [caseLabel GetOutputPort]
vtkPolyDataMapper labelMapper
  labelMapper SetInputConnection [labelTransform GetOutputPort];
vtkActor labelActor
  labelActor SetMapper labelMapper
```

Notice that vtkTransformPolyDataFilter requires that you supply it with an instance of vtkTransform. Recall that vtkTransform is used by actors to control their position and orientation in space. Instances of vtkTransform support many methods, some of the most commonly used are shown here.

- `RotateX(angle)` — apply rotation (angle in degrees) around the *x* axis
- `RotateY(angle)` — apply rotation around the *y* axis
- `RotateZ(angle)` — apply rotation around the *z* axis
- `RotateWXYZ(angle,x,y,z)` — apply rotation around a vector defined by *x-y-z* components
- `Scale(x,y,z)` — apply scale in the *x*, *y*, and *z* directions
- `Translate(x,y,z)` — apply translation
- `Inverse()` — invert the transformation matrix
- `SetMatrix(m)` — specify the 4x4 transformation matrix directly
- `GetMatrix(m)` — get the 4x4 transformation matrix
- `PostMultiply()` — control the order of multiplication of transformation matrices. If PostMultiply() is invoked, matrix operations are applied on the left hand side of the current matrix.
- `PreMultiply()` — matrix multiplications are applied on the right hand side of the current transformation matrix

The last two methods described above remind us that the order in which transformations are applied dramatically affects the resulting transformation matrix. (See "Notice how we use vtkAssembly's AddPart() method to build the hierarchies. Assemblies can be nested arbitrarily deeply as long as there are not any self-referencing cycles. Note that vtkAssembly is a subclass of vtkProp3D, so it has no notion of properties or of an associated mapper. Therefore, the leaf nodes of the vtkAssembly hierarchy must carry information about material properties (color, etc.) and any associated geometry. Actors may also be used by more than one assembly (notice how `coneActor` is used in the assembly and as an actor). Also, the renderer's AddActor() method is used to associate the top level of the assembly with the renderer; those actors at lower levels in the assembly hierarchy do not need to be added to the renderer since they are recursively rendered." on page 57.) We recommend that you spend some time experimenting with these methods and the order of application to fully understand vtkTransform.

Advanced Transformation

Advanced users may wish to use VTK's extensive transformation hierarchy. (Much of this work was done by David Gobbi.) The hierarchy, of which the class hierarchy is shown in **Figure 19–17**, supports a variety of linear and non-linear transformations.

A wonderful feature of the VTK transformation hierarchy is that different types of transformation can be used in a filter to give very different results. For example, the vtkTransformPolyDataFilter accepts any transform of type vtkAbstractTransform (or a subclass). This includes transformation types ranging from the linear, affine vtkTransform (represented by a 4x4 matrix) to the non-linear, warping vtkThinPlateSplineTransform, which is a complex function representing a correlation between a set of source and target landmarks.

3D Widgets

Interactor styles (see "Using VTK Interactors" on page 45) are generally used to control the camera and provide simple keypress and mouse-oriented interaction techniques. Interactor styles have no representation in the scene; that is, they cannot be "seen" or interacted with, the user must know what the mouse and key bindings are in order to use them. Certain operations, however, are greatly facilitated by the ability to operate directly on objects in the scene. For example, starting a rake of streamlines along a line is easily performed if the endpoints of the line can be interactively positioned.

3D widgets have been designed to provide this functionality. Like the class vtkInteractorStyle, 3D widgets are subclasses of vtkInteractorObserver. That is, they watch for events invoked by vtkRenderWindowInteractor. (Recall that vtkRenderWindowInteractor translates windowing-system specific events into VTK event invocations.) Unlike vtkInteractorStyle, however, 3D widgets represent themselves in the scene in various ways. **Figure 4–14** illustrates some of the many 3D widgets found in VTK.

The following is a list of the most important widgets currently found in VTK and a brief description of their features. Note that some of the concepts mentioned here have not yet been covered in this text. Please refer to "Interaction, Widgets and Selections" on page 255 to learn more about a particular concept and the various widgets available in VTK.

- vtkScalarBarWidget — Manage a vtkScalarBar including positioning, scaling, and orienting it. (See "Scalar Bar" on page 66 for more information about scalar bars.)
- vtkPointWidget — Position a point *x-y-z* location in 3D space. The widget produces a polygonal output. Point widgets are typically used for probing. (See "Probing" on page 100.)
- vtkLineWidget — Place a straight line with a specified subdivision resolution. The widget produces a polygonal output. A common use of the line widget is to probe ("Probing" on page 100) and plot data ("X-Y Plots" on page 66) or produce streamlines ("Streamlines" on page 95) or stream surfaces ("Stream Surfaces" on page 97).
- vtkPlaneWidget — Orient and position a finite plane. The plane resolution is variable, and the widget produces an implicit function and a polygonal output. The plane widget is used for probing ("Probing" on page 100) and seeding streamlines ("Streamlines" on page 95).
- vtkImplicitPlaneWidget — Orient and position an unbounded plane. The widget produces an implicit function and a polygonal output. The polygonal output is created by clipping the plane with a bounding box. The implicit plane widget is typically used for probing ("Probing" on page 100), cutting ("Cutting" on page 98), and clipping data ("Clip Data" on page 110).

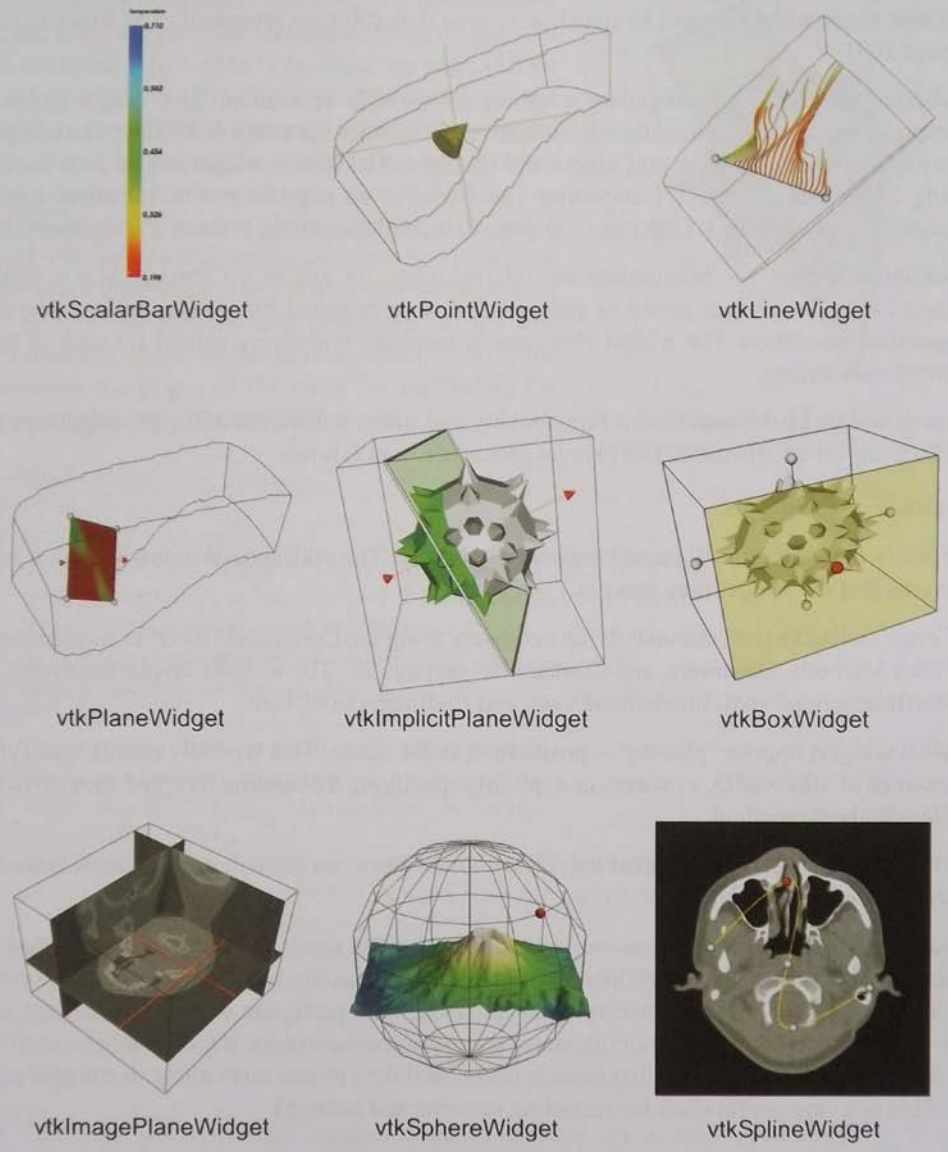


Figure 4–14 Some of the 3D widgets found in VTK.

- vtkBoxWidget — Orient and position a bounding box. The widget produces an implicit function and a transformation matrix. The box widget is used to transform vtkProp3D's and subclasses ("Transforming Data" on page 70) or to cut ("Cutting" on page 98) or clip data ("Clip Data" on page 110).

- vtkImagePlaneWidget — Manipulate three orthogonal planes within a 3D volumetric data set. Probing of the planes to obtain data position, pixel value, and window-level is possible. The image plane widget is used to visualize volume data ("Image Processing and Visualization" on page 103).
- vtkSphereWidget — Manipulate a sphere of variable resolution. The widget produces an implicit function and a transformation matrix and enables the control of focal point and position to support such classes as vtkCamera and vtkLight. The sphere widget can be used for controlling lights and cameras ("Controlling The Camera" on page 49 and "Controlling Lights" on page 51), for clipping ("Clip Data" on page 110), and for cutting ("Cutting" on page 98).
- vtkSplineWidget — Manipulate an interpolating 3D spline ("Creating Movie Files" on page 248). The widget produces polygonal data represented by a series of line segments of specified resolution. The widget also directly manages underlying splines for each of the *x-y-z* coordinate values.

While each widget provides different functionality and offers a different API, 3D widgets are similar in how they are set up and used. The general procedure is as follows.

1. Instantiate the widget.
2. Specify the vtkRenderWindowInteractor to observe. The vtkRenderWindowInteractor invokes events that the widget may process.
3. Create callbacks (i.e., commands) as necessary using the Command/Observer mechanism—see "User Methods, Observers, and Commands" on page 29. The widgets invoke the events StartInteractionEvent, InteractionEvent, and EndInteractionEvent.
4. Most widgets require "placing" – positioning in the scene. This typically entails specifying an instance of vtkProp3D, a dataset, or explicitly specifying a bounding box, and then invoking the PlaceWidget() method.
5. Finally, the widget must be enabled. By default, a `keypress i` will enable the widget and it will appear in the scene.

Note that more than one widget can be enabled at any given time, and the widgets function fine in combination with an instance of vtkInteractorStyle. Thus mousing in the scene not on any particular widget will engage the vtkInteractorStyle, but mousing on a particular widget will engage just that widget—typically no other widget or interactor style will see the events. (One notable exception is the class vtkInteractorEventRecorder that records events and then passes them along. It can also playback events. This is a very useful class for recording sessions and testing.)

The following example (found in `VTK/Examples/GUI/Tcl/ImplicitPlaneWidget.tcl`) demonstrates how to use a 3D widget. The vtkImplicitPlaneWidget will be used to clip an object. (See "Clip Data" on page 110 for more information in clipping.) In this example the vtkProp3D to be clipped is a mace formed from a sphere and cone glyphs located at the sphere points and oriented in the direction of the sphere normals. (See "Glyphing" on page 94 for more information about glyphing.) The mace is clipped with a plane that separates it into two parts, one of which is colored green. The vtkImplicitPlaneWidget is used to control the position and orientation of the clip plane by mousing on the widget normal vector, moving the point defining the origin of the plane, or translating the plane by grabbing the widget bounding box.

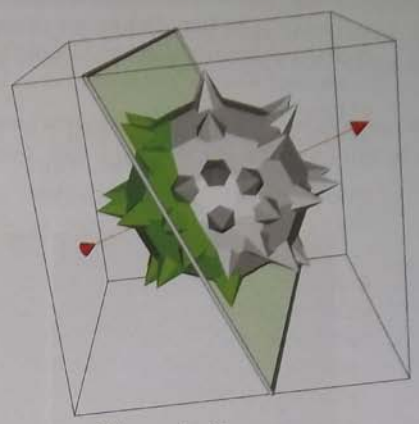


Figure 4–15 Using the implicit plane widget (vtkImplicitPlaneWidget).

```
vtkSphereSource sphere
vtkConeSource cone
vtkGlyph3D glyph
  glyph SetInputConnection [sphere GetOutputPort]
  glyph SetSourceConnection [cone GetOutputPort]
  glyph SetVectorModeToUseNormal
  glyph SetScaleModeToScaleByVector
  glyph SetScaleFactor 0.25

# The sphere and spikes are appended
# into a single polydata.
# This makes things simpler to manage.
vtkAppendPolyData apd
  apd AddInputConnection [glyph GetOutputPort]
  apd AddInputConnection [sphere GetOutputPort]

vtkPolyDataMapper maceMapper
    maceMapper SetInputConnection [apd GetOutputPort]
vtkLODActor maceActor
  maceActor SetMapper maceMapper
  maceActor VisibilityOn

# This portion of the code clips the mace with the vtkPlanes
# implicit function. The clipped region is colored green.
vtkPlane plane
vtkClipPolyData clipper
  clipper SetInputConnection [apd GetOutputPort]
  clipper SetClipFunction plane
  clipper InsideOutOn

vtkPolyDataMapper selectMapper
  selectMapper SetInputConnection [clipper GetOutputPort]

vtkLODActor selectActor
```

```
  selectActor SetMapper selectMapper
  [selectActor GetProperty] SetColor 0 1 0
  selectActor VisibilityOff
  selectActor SetScale 1.01 1.01 1.01
vtkRenderer ren1
vtkRenderWindow renWin
  renWin AddRenderer ren1
vtkRenderWindowInteractor iren
  iren SetRenderWindow renWin

# Associate the line widget with the interactor
vtkImplicitPlaneWidget planeWidget
 planeWidget SetInteractor iren
 planeWidget SetPlaceFactor 1.25
 planeWidget SetInput [glyph GetOutput]
 planeWidget PlaceWidget
 planeWidget AddObserver InteractionEvent myCallback

ren1 AddActor maceActor
ren1 AddActor selectActor

iren AddObserver UserEvent {wm deiconify .vtkInteract}
renWin Render

# Prevent the tk window from showing up then start the event loop.
wm withdraw .

proc myCallback {} {
  planeWidget GetPlane plane
  selectActor VisibilityOn
}
```

As shown above, the implicit plane widget is instantiated and placed. The placing of the widget is with respect to a dataset. (The Tcl statement "[glyph GetOutput]" returns a vtkPolyData, a subclass of vtkDataSet.) The PlaceFactor adjusts the relative size of the widget. In this example the widget is grown 25% larger than the bounding box of the input dataset. The key to the behavior of the widget is the addition of an observer that responds to the InteractionEvent. StartInteraction and EndInteraction are typically invoked by the widget on mouse down and mouse up respectively; the InteractionEvent is invoked on mouse move. The InteractionEvent is tied to the Tcl procedure myCallback that copies the plane maintained by the widget to an instance of vtkPlane—an implicit function used to do the clipping. (See "Implicit Modeling" on page 213.)

The 3D widgets are a powerful feature in VTK that can quickly add complex interaction to any application. We encourage you to explore the examples included with the VTK distribution (in `Examples/GUI` and `Hybrid/Testing/Cxx`) to see the breadth and power of their capabilities.

4.14 Antialiasing

There are two ways to enable antialiasing with VTK: per primitive type or through multisampling. Multisampling usually gives more pleasant result.

Both antialiasing methods are controlled with the vtkRenderWindow API. When multisampling is enabled and supported by the graphics card, the per-primitive-type antialiasing flags are ignored. In both cases, the setting has to be done after the creation of a vtkRenderWindow object but before its initialization on the the screen.

Note that in general, the antialiasing result differs among actual OpenGL implementations. (an OpenGL implementation is either a software implementation, like Mesa, or the combination of a graphics card and its driver)

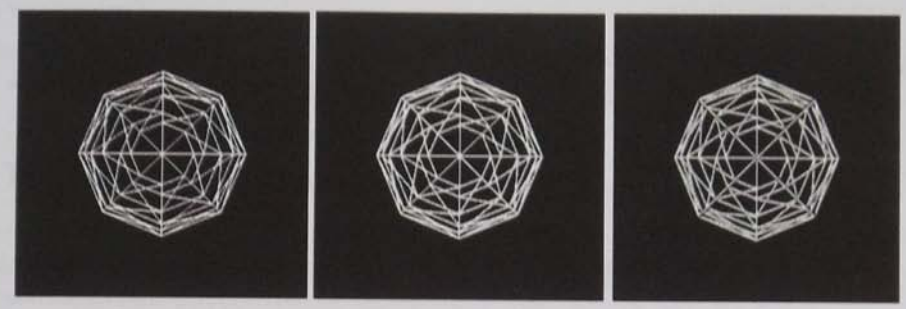


Figure 4–16 Effect of antialiasing techniques on a wireframe sphere.

Per-primitive type antialiasing

Three flags, one for each type of primitive, control antialiasing:

- PointSmoothing,
- LineSmoothing and
- PolygonSmoothing.

Initially, they are all disabled. Here are the 4 steps in required order to enable antialiasing on point primitives:

1. vtkRenderWindow *w=vtkRenderWindow::New();
2. w->SetMultiSamples(0);
3. w->SetPointSmoothing(1);
4. w->Render();

Here is a complete example to display the vertices of a mesh representing a sphere with point antialiasing:

```
#include "vtkRenderWindowInteractor.h"
#include "vtkRenderWindow.h"
#include "vtkRenderer.h"
#include "vtkSphereSource.h"
#include "vtkPolyDataMapper.h"
#include "vtkProperty.h"

int main()
{
```

```
    vtkRenderWindowInteractor *i=vtkRenderWindowInteractor::New();
    vtkRenderWindow *w=vtkRenderWindow::New();
    i->SetRenderWindow(w);

    w->SetMultiSamples(0); // no multisampling
    w->SetPointSmoothing(1); // point antialiasing

    vtkRenderer *r=vtkRenderer::New();
    w->AddRenderer(r);

    vtkSphereSource *s=vtkSphereSource::New();
    vtkPolyDataMapper *m=vtkPolyDataMapper::New();
    m->SetInputConnection(s->GetOutputPort());

    vtkActor *a=vtkActor::New();
    a->SetMapper(m);
    vtkProperty *p=a->GetProperty();
    p->SetRepresentationToPoints(); // we want to see points
    p->SetPointSize(2.0); // big enough to notice antialiasing
    p->SetLighting(0); // don't be disturb by shading
    r->AddActor(a);

    i->Start();

    s->Delete();
    m->Delete();
    a->Delete();
    r->Delete();
    w->Delete();
    i->Delete();
}
```

The following lines are specific to point antialiasing:

```
w->SetPointSmoothing(1);
p->SetRepresentationToPoints();
p->SetPointSize(2.0);
```

You can visualize line antialiasing by changing them to:

```
w->SetLineSmoothing(1);
p->SetRepresentationToWireframe();
p->SetLineWidth(2.0);
```

You can visualize polygon antialiasing with simply:

```
w->PolygonSmoothing(1);
p->SetRepresentationToSurface();
```

Multisampling

Multisampling gives better result than the previous method. Initially, multisampling is enabled. But it is only effective if the graphics card support it. Currently, VTK supports multisampling on X window only. To disable multisampling, set the MultiSamples value (initially set to 8) to 0:

1. 1 vtkRenderWindow *w=vtkRenderWindow::New();
2. 2 w->SetMultiSamples(0); // disable multisampling.
3. 3 w->Render();

Going back to the previous example, if you are using X11, just get rid of line disabling multisampling and we will see the effect of multisampling on points, lines or polygons.

4.15 Translucent polygonal geometry

Rendering the geometry as translucent is a powerful tool for visualization. It allows to "see through" the data. It can be used also to focus on a region of interest; the region of interest is rendered as opaque and the context is renderered as translucent.

Rendering translucent geometry is not trivial: the final color of a pixel on the screen is the contribution of all the geometry primitives visible through the pixel. The color of the pixel is the result of blending operations between the colors of all visible primitives. Blending operations themselves are usually order-dependent (ie not commutative). Therefore, for a correct rendering, depth sorting is required. However, depth sorting has a computational cost.

VTK offers three ways to render translucent polygonal geometry. Each of them is a tradeoff between correctness (quality) and cost (of depth sorting).

Fast and Incorrect. Start ignoring the previous remark about depth sorting. There is then no extra computational cost but the result on the screen is incorrect. However, depending of the application context, the result might be good enough.

Slower and Almost Correct. This method consists in using two filters. First, append all the polygonal geometry with vtkAppendPolyData. Then connect the output port of vtkAppendPolyData to the input port of vtkDepthSortPolyData. Depth sorting is performed per centroid of geometry primitives, not per pixel. For this reason it is not correct but it solves most of the ordering issues and gives a result usually good enough. Look at VTK/Hybrid/Testing/Tcl/depthSort.tcl for an example.

Very Slow and Correct. If the graphics card supports it (nVidia only), use "depth peeling". It performs per pixel sorting (better result) but it is really slow. Before the first Render, ask for alpha bits on the vtkRenderWindow:

```
vtkRenderWindow *w=vtkRenderWindow::New();
w->SetAlphaBitPlanes(1);

Make sure multisampling is disabled:
w->SetMultiSamples(0);
```

On the renderer, enable depth peeling:

```
vtkRenderer *r=vtkRenderer::New();
r->SetUseDepthPeeling(1);
```

Set the depth peeling parameters (the maximum number of rendering passes and the occlusion ratio). The parameters are explained in the next section.

```
r->SetMaximumNumberOfPeels(100);
r->SetOcclusionRatio(0.1);

Render the scene:

w->Render();

Finally, you can check that the graphics card supported depth peeling:

r->GetLastRenderingUsedDepthPeeling();
```

Depth Peeling Parameters. In order to play with the depth peeling parameters, it is necessary to understand the algorithm itself. The algorithm peels the translucent geometry from front to back until there is no more geometry to render. The iteration loop stops either if it reaches the maximum number of iterations set by the user or if the number of pixels modified by the last peel is less than some ratio of the area of the window (this ratio is set by the user, if the ratio is set to 0.0, it means the user wants the exact result. A ratio of 0.2 will render faster than a ratio of 0.1).

OpenGL requirements. The graphics card supports depth peeling, if the following OpenGL extensions are supported:

```
* GL_ARB_depth_texture or OpenGL>=1.4
* GL_ARB_shadow or OpenGL>=1.4
* GL_EXT_shadow_funcs or OpenGL>=1.5
* GL_ARB_vertex_shader or OpenGL>=2.0
* GL_ARB_fragment_shader or OpenGL>=2.0
* GL_ARB_shader_objects or OpenGL>=2.0
* GL_ARB_occlusion_query or OpenGL>=1.5
* GL_ARB_multitexture or OpenGL>=1.3
* GL_ARB_texture_rectangle
* GL_SGIS_texture_edge_clamp, GL_EXT_texture_edge_clamp or OpenGL>=1.2
```

In practice, it works with nVidia GeForce 6 series and above or with Mesa (e.g. 7.4). It does not work with ATI cards.

Example. Here a complete example that uses depth peeling (you can also look for files having DepthPeeling in their name in VTK/Rendering/Testing/Cxx).

```
#include "vtkRenderWindowInteractor.h"
#include "vtkRenderWindow.h"
#include "vtkRenderer.h"
#include "vtkActor.h"

#include "vtkImageSinusoidSource.h"
```

```
#include "vtkImageData.h"
#include "vtkImageDataGeometryFilter.h"
#include "vtkDataSetSurfaceFilter.h"
#include "vtkPolyDataMapper.h"
#include "vtkLookupTable.h"
#include "vtkCamera.h"

int main()
{
  vtkRenderWindowInteractor *iren=vtkRenderWindowInteractor::New();
  vtkRenderWindow *renWin = vtkRenderWindow::New();
  renWin->SetMultiSamples(0);

  renWin->SetAlphaBitPlanes(1);
  iren->SetRenderWindow(renWin);
  renWin->Delete();

  vtkRenderer *renderer = vtkRenderer::New();
  renWin->AddRenderer(renderer);
  renderer->Delete();
  renderer->SetUseDepthPeeling(1);
  renderer->SetMaximumNumberOfPeels(200);
  renderer->SetOcclusionRatio(0.1);

  vtkImageSinusoidSource *imageSource=vtkImageSinusoidSource::New();
  imageSource->SetWholeExtent(0,9,0,9,0,9);
  imageSource->SetPeriod(5);
  imageSource->Update();

  vtkImageData *image=imageSource->GetOutput();
  double range[2];
  image->GetScalarRange(range);

  vtkDataSetSurfaceFilter *surface=vtkDataSetSurfaceFilter::New();

  surface->SetInputConnection(imageSource->GetOutputPort());
  imageSource->Delete();


  vtkPolyDataMapper *mapper=vtkPolyDataMapper::New();
  mapper->SetInputConnection(surface->GetOutputPort());
  surface->Delete();

  vtkLookupTable *lut=vtkLookupTable::New();
  lut->SetTableRange(range);
  lut->SetAlphaRange(0.5,0.5);
  lut->SetHueRange(0.2,0.7);
  lut->SetNumberOfTableValues(256);
  lut->Build();

  mapper->SetScalarVisibility(1);
```

```
    mapper->SetLookupTable(lut);
    lut->Delete();

    vtkActor *actor=vtkActor::New();
    renderer->AddActor(actor);
    actor->Delete();
    actor->SetMapper(mapper);
    mapper->Delete();

    renderer->SetBackground(0.1,0.3,0.0);
    renWin->SetSize(400,400);

    renWin->Render();
    if(renderer->GetLastRenderingUsedDepthPeeling())
      {
      cout<<"depth peeling was used"<<endl;
      }
    else
      {
      cout<<"depth peeling was not used (alpha blending instead)"<<endl;
      }
    vtkCamera *camera=renderer->GetActiveCamera();
    camera->Azimuth(-40.0);
    camera->Elevation(20.0);
    renWin->Render();

    iren->Start();
  }
```

Painter mechanism: customizing the polydata mapper. Sometimes you want full control of the steps used to render a polydata. VTK makes it possible with the use of the painter mechanism. Thanks to the factory design pattern, the following line actually creates a vtkPainterPolyDataMapper:

```
vtkPolyDataMapper *m=vtkPolyDataMapper::New();
```

You can have access to the vtkPainterPolyDataMapper API by downcasting:

```
vtkPainterPolyDataMapper
*m2=vtkPainterPolyDataMapper::SafeDownCast(m);
```

This polydata mapper delegates the rendering to a vtkPainter object. SetPainter() and GetPainter() gives access to this delegate.

vtkPainter itself is just an abstract API shared by concrete Painters. Each of them is responsible for one stage of the rendering. This mechanism allows to choose and combine stages. For example vtkPolygonsPainter is responsible for drawing polygons whereas vtkLightingPainter is responsible for setting lighting parameters. The combination of painters forms a chain of painters. It is a chain because each painter can delegate part of the execution of the rendering to another painter.

Most of the time, you don't need to explicitly set the chain of painters: vtkDefaultPainter already set a standard chain of painters for you.

Writing your own painter. Writing your own painter consists essentially in writing 2 classes: an abstract subclass of vtkPainter, a concrete class with the OpenGL implementation.

Let's take a look at an existing Painter: vtkLightingPainter. vtkLightingPainter derives from vtkPainter and is almost empty. The real implementation is in the concrete class vtkOpenGLLighting-Painter which overrides the protected method RenderInternal().

The arguments of RenderInternal() are essentially the renderer and the actor. Implementing RenderInternal() consists in writing the actual rendering stage code and calling the next Painter in the painter chain (the "delegate") by calling this->Superclass::RenderInternal().

4.16 Animation

- Animation is important component of Visualization System, etc.
- It is possible to create simple animations by writing loops that continuously change some parameter on a filter and render. However such implementations can become complicated when multiple parameter changes are involved.
- VTK provides a framework comprising of vtkAnimationCue and vtkAnimationScene to manage animation setup and playback.
- vtkAnimationCue corresponds to an entity that changes with time e.g. position of an actor; while vtkAnimationScene represents a scene or a setup for the animation comprising of instances of vtkAnimationCue.

Animation Scene (vtkAnimationScene)

vtkAnimationScene represents a scene or a setup for the animation. An animation is generated by rendering frames in a sequence while changing some visualization parameter(s) before rendering each frame. Every frame has an animation time associated with it, which can be used to determine the frame's place in the animation. Animation time is simply a counter that continuously increases over the duration of the animation based on the play-mode.

Following are important methods on a vtkAnimationScene:

`SetStartTime()/SetEndTime()`
: These represent the start and end times of the animation scene. This is the range that the animation time covers during playback.

`SetPlayMode()`
: This is used to control they playback mode i.e. how the animation time is changed. There are two modes available:

`Sequence Mode (PLAYMODE_SEQUENCE)`
: In this mode, the animation time is increased by (1/frame-rate) for every frame until the EndTime is reached. Hence the number of frames rendered in a single run is fixed irrespective of how long each frame takes to render.

`RealTime Mode (PLAYMODE_REALTIME)`
: In this mode, the animation runs for approximately (EndTime-StartTime) seconds, where the animation time at nth frame is given by (animation time and (n-1)th frame + time to render (n-1)th frame). Thus the number of frames rendered changes depending on how

long each frame takes to render.

`SetFrameRate()`
: Frame rate is the number of frames per unit time. This is used only in sequence play-mode.

`AddCue(), RemoveCue(), RemoveAllCue()`
: Methods to add/remove animation cues from the scene.

`SetAnimationTime()`
: SetAnimationTime can be used to explicitly advance to a particular frame.

`GetAnimationTime()`
: GetAnimationTime() can be called during playback to query the animation clock time.

`Play()`
: Starts playing the animation.

`SetLoop()`
: When set to True, Play() results in playing the animation in a loop.

`Animation Cue (vtkAnimationCue)`
: vtkAnimationCue corresponds to an entity that changes in an animation. vtkAnimationCue does not know how to bring about the changes to the parameters. So the user has to either subclass vtkAnimationCue or use event observers to perform the changes as the animation progresses.

A cue has a start-time and an end-time in an animation scene. During playback, a cue is active when the scene's animation time is within the range specified the start and end times for the cue. When the cue is activated, it fires the vtkCommand::StartAnimationCueEvent. For every subsequent frame, it fires the vtkCommand::AnimationCueTickEvent until the end-time is reached when the vtkCommand::EndAnimationCueEvent is fired. Following are the important methods of vtkAnimationCue

`SetTimeMode`
: TimeMode defines how the start and time times are specified. There are two modes available.

`Relative (TIMEMODE_RELATIVE)`
: In this mode the animation cue times are specified relative to the start of the animation scene.

`Normalized (TIMEMODE_NORMALIZED)`
: In this mode, the cue start and end times are always in the range [0, 1] where 0 corresponds to the start and 1 corresponds to the end of the animation scene.

`SetStartTime/SetEndTime`
: These are used to indicate the range of animation time when this cue is active. When the TimeMode is TIMEMODE_RELATIVE, these are specified in the same unit as the animation scene start and end times and are relative to the start of the animation scene. If TimeMode is TIMEMODE_NORMALIZED, these are in the range [0, 1] where 0 corresponds to the start of the animation scene while 1 corresponds to the end of the animation scene.

`GetAnimationTime()`

This is provided for the event handler for vtkCommand::AnimationCueTickEvent. It can be used by the handler to determine how far along in the animation the current frame it. It's value depends on the TimeMode. If TimeMode is Relative, then the value will be number of time units since the cue was activated. If TimeMode is Normalized then it will be value in the range [0, 1] where 0 is the start of the cue, while 1 is the end of the cue.

`GetClockTime()`
: This is same as the animation clock time returned by vtkAnimationScene::GetAnimationTime(). It is valid only in the event handler for vtkCommand::AnimationCueTickEvent.

`GetDeltaTime()`
: This can be used to obtain the change in animation click time from when the previous frame was rendered, if any. Again, this is valid in only in the event handler for vtkCommand::AnimationCueTickEvent.

`TickInternal(double currentime, double deltatime, double clocktime)`
: As mentioned earlier, one can subclasses vtkAnimationCue, instead of writing event handlers to do the animation, in which case you can override this method. The arguments correspond to the values returned by GetAnimationTime(), GetDeltaTime() and GetClockTime() respectively.

`StartCueInternal(), EndCueInternal()`
: These methods can be overridden in subclasses to do setup and cleanup and start and end of the cue during playback. Alternatively, one can add event observers for the vtkCommand::StartAnimationCueEvent and vtkCommand::EndAnimationCueEvent to do the same.

In the following example, we create a simple animation where the StartTheta of a vtkSphereSource is varied over the length of the animation. We use normalized time mode for the animation cue in this example, so that we can change the scene times or the cue times and the code to change the StartTheta value can still remain unchanged.

```
class vtkCustomAnimationCue: public vtkAnimationCue
{
public:
  static vtkCustomAnimationCue* New();
  vtkTypeRevisionMacro(vtkCustomAnimationCue, vtkAnimationCue);

vtkRenderWindow *RenWin;
  vtkSphereSource* Sphere;


protected:
  vtkCustomAnimationCue()
    {
    this->RenWin = 0;
    this->Sphere = 0;
    }

  // Overridden to adjust the sphere's radius depending on the frame we
  // are rendering. In this animation we want to change the StartTheta
```

```
  // of the sphere from 0 to 180 over the length of the cue.
  virtual void TickInternal(double currenttime, double deltatime,
    double clocktime)
    {
    double new_st = currenttime * 180;
     // since the cue is in normalized mode, the currentime will be in the
     // range [0,1], where 0 is start of the cue and 1 is end of the cue.
    this->Sphere->SetStartTheta(new_st);
    this->RenWin->Render();
    }

};
vtkStandardNewMacro(vtkCustomAnimationCue);
vtkCxxRevisionMacro(vtkCustomAnimationCue, "$Revision$");

int main(int argc, char *argv[])
{
  // Create the graphics structure. The renderer renders into the
  // render window.
  vtkRenderer *ren1=vtkRenderer::New();
  vtkRenderWindow *renWin=vtkRenderWindow::New();
  renWin->SetMultiSamples(0);
  renWin->AddRenderer(ren1);

  vtkSphereSource* sphere = vtkSphereSource::New();
  vtkPolyDataMapper* mapper = vtkPolyDataMapper::New();
  mapper->SetInputConnection(sphere->GetOutputPort());
  vtkActor* actor = vtkActor::New();
  actor->SetMapper(mapper);
  ren1->AddActor(actor);

  ren1->ResetCamera();
  renWin->Render();

  // Create an Animation Scene
  vtkAnimationScene *scene = vtkAnimationScene::New();
  scene->SetModeToSequence();
  scene->SetFrameRate(30);
  scene->SetStartTime(0);
  scene->SetEndTime(60);


  // Create an Animation Cue to animate the camera.
  vtkCustomAnimationCue *cue1 = vtkCustomAnimationCue::New();
  cue1->Sphere = sphere;
  cue1->RenWin = renWin;
  cue1->SetTimeModeToNormalized();
  cue1->SetStartTime(0);
  cue1->SetEndTime(1.0);
  scene->AddCue(cue1);
```

```
    scene->Play();
    scene->Stop();

    ren1->Delete();
    renWin->Delete();
    scene->Delete();
    cue1->Delete();
    return 0;
}
```

Chapter 5

Visualization Techniques

Some basic tools to render and interact with data were presented in the previous chapter. In this chapter we'll show you a variety of visualization techniques. These techniques (implemented as filters) are organized according to the type of data they operate on. Some filters are general and can be applied to any type of data—those filters that accept input of class vtkDataSet (or any subclass). Many filters are more specialized to the type of input they accept (e.g., vtkPolyData). There is one class of filters—those that accept input of type vtkImageData (or its obsolete subclass vtkStructuredPoints)—that are not addressed in this chapter. Instead, filters of this type are described in the next chapter ("Image Processing and Visualization" on page 103).

Please keep two things to keep in mind while you read this chapter. First, filters generate a variety of output types, and the output type is not necessarily the same as the input type. Second, filters are used in combination to create complex data processing pipelines. Often there are patterns of usage, or common combinations of filters, that are used. In the following examples you may wish to note these combinations.

5.1 Visualizing vtkDataSet (and Subclasses)

In this section, we'll show you how to perform some common visualization operations on data objects of type vtkDataSet. Recall that vtkDataSet is the superclass for all concrete types of visualization data (see **Figure 3–2**). Therefore, the methods described here are applicable to all of the various data types. (In other words, all filters taking vtkDataSet as input will also accept vtkPolyData, vtkImageData, vtkStructuredGrid, vtkRectilinearGrid, and vtkUnstructuredGrid.)

Working With Data Attributes

Data attributes are information associated with the structure of the dataset (as described in "The Visualization Pipeline" on page 25). In VTK, attribute data is associated with points (point attribute data)

and cells (cell attribute data). Attribute data, along with the dataset structure, are processed by the many VTK filters to generate new structures and attributes. A general introduction to attribute data is beyond the scope of this section, but a simple example will demonstrate the basic ideas. (For more information you may wish to refer to "Field and Attribute Data" on page 362 and **Figure 16–1**.)

Data attributes are simply vtkDataArrays which may be labeled as being one of scalars, vectors, tensors, normals, texture coordinates, global ids (for identifying redundant elements), or pedigree ids (for tracing element history up the pipeline). The points and the cells of a vtkDataSet may have their own independent data attributes. The data attributes may be associated with the points or cells of a vtkDataSet. Every vtkDataArray associated with a vtkDataSet is a concrete subclass of vtkDataArray, such as vtkFloatArray or vtkIntArray. These data arrays can be thought of as contiguous, linear blocks of memory of the named native type. Within this linear block, the data array is thought to consist of subarrays or "tuples." Creating attribute data means instantiating a data array of desired type, specifying the tuple size, inserting data, and associating it with a dataset, as shown in the following Tcl script. The association may have the side effect of labeling the data as scalars, vectors, tensors, texture coordinates, or normals. For example:

```
vtkFloatArray scalars
    scalars InsertTuple1 0 1.0
    scalars InsertTuple1 1 1.2
    ...etc...

vtkDoubleArray vectors
    vectors SetNumberOfComponents 3
    vectors InsertTuple3 0 0.0 0.0 1.0
    vectors InsertTuple3 1 1.2 0.3 1.1
    ...etc...

vtkIntArray justAnArray
    justAnArray SetNumberOfComponents 2
    justAnArray SetNumberOfTuples $numberOfPoints
    justAnArray SetName "Solution Attributes"
    justAnArray SetTuple2 0 1 2
    justAnArray SetTuple2 1 3 4
    ...etc...

vtkPolyData polyData;#A concrete type of vtkDataSet
    [polyData GetPointData] SetScalars scalars
    [polyData GetCellData] SetVectors vectors
    [polyData GetPointData] AddArray justAnArray
```

Here we create three arrays of types `float`, `double`, and `int`. The first array (`scalars`) is instantiated and by default has a tuple size of one. The method InsertTuple1() is used to place data into the array (all methods named Insert___() allocate memory as necessary to hold data). The next data array (`vectors`) is created with a tuple size of three, because vectors are defined as having three components, and InsertTuple3 is used to add data to the array. Finally, we create a general array of tuple size two, and allocate memory using SetNumberOfTuples(). We then use SetTuple2() to add data; this method assumes that memory has been allocated and is therefore faster than the similar Insert__() methods. Notice that the labelling of what is a scalar, vector, etc. occurs when we associate the data arrays with the point data or cell data of the dataset (using the methods SetScalars() and SetVectors()).

Please remember that the number of point attributes (e.g., number of scalars in this example) must equal the number of points in the dataset, and the number of cell attributes (e.g., number of vectors) must match the number of cells in the dataset.

Similarly, to access attribute data, use these methods

```
set scalars [[polyData GetPointData] GetScalars]
set vectors [[polyData GetCellData] GetVectors]
```

You'll find that many of the filters work with attribute data specifically. For example, vtkElevationFilter generates scalar values based on their elevation in a specified direction. Other filters work with the structure of the dataset, and generally ignore or pass the attribute data through the filter (e.g., vtkDecimatePro). And finally, some filters work with (portions of) the attribute data and the structure to generate their output. vtkMarchingCubes is one example. It uses the input scalars in combination with the dataset structure to generate contour primitives (i.e., triangles, lines or points). Other types of attribute data, such as vectors, are interpolated during the contouring process and sent to the output of the filter.

Another important issue regarding attribute data is that some filters will process only one type of attribute (point data versus cell data), ignoring or passing to their output the other attribute data type. You may find that your input data is of one attribute type and you want to process it with a filter that will not handle that type, or you simply want to convert from one attribute type to another. There are two filters that can help you with this: vtkPointDataToCellData and vtkCellDataToPointData, which convert to and from point and cell data attributes. Here's an example of their use (from the Tcl script `VTK/Examples/DataManipulation/Tcl/pointToCellData.tcl`).

```
vtkUnstructuredGridReader reader
  reader SetFileName "$VTK_DATA_ROOT/Data/blow.vtk"
  reader SetScalarsName "thickness9"
  reader SetVectorsName "displacement9"
vtkPointDataToCellData p2c
  p2c SetInputConnection [reader GetOutputPort]
  p2c PassPointDataOn
vtkWarpVector warp
  warp SetInputConnection [p2c GetOutputPort]
vtkThreshold thresh
  thresh SetInputConnection [warp GetOutputPort]
  thresh ThresholdBetween 0.25 0.75
  thresh SetAttributeModeToUseCellData
```

This example is interesting because it demonstrates the conversion between attribute data types (vtkPointDataToCellData), and the use of a filter that can process either cell data or point data (vtkThreshold). The method PassPointDataOn() indicates to vtkPointDataToCellData to create cell data and also pass to its output the input point data. The method SetAttributeModeToUseCellData() configures the vtkThreshold filter to use the cell data to perform the thresholding operation.

The conversion between point and cell data and vice versa is performed using an averaging algorithm. Point data is converted to cell data by averaging the values of the point data associated with the points used by a given cell. Cell data is converted to point data by averaging the cell data associated with the cells that use a given point.

Color Mapping

Probably the single most used visualization technique is coloring objects via scalar value, or color mapping. The ideas behind this technique is simple: scalar values are mapped through a lookup table to obtain a color, and the color is applied during rendering to modify the appearance of points or cells. Before proceeding with this section, make sure that you understand how to control the color of an actor (see "Actor Color" on page 54).

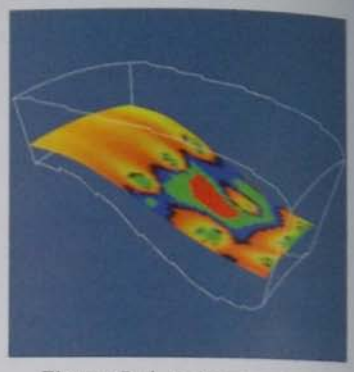


Figure 5–1 Color mapping.

In VTK, color mapping is typically controlled by scalars, which we assume you've created or read from a data file, and the lookup table, which is used by instances of vtkMapper to perform color mapping. It is also possible to use any data array to perform the coloring by using the method ColorByArrayComponent(). If not specified, a default lookup table is created by the mapper, but you can create your own (taken from `VTK/Examples/Rendering/Tcl/rainbow.tcl`—see **Figure 5–1**).

```
vtkLookupTable lut
   lut SetNumberOfColors 64
   lut SetHueRange 0.0 0.667
   lut Build
  for {set i 0} {$i<16} {incr i 1} {
    eval lut SetTableValue [expr $i*16] $red 1
    eval lut SetTableValue [expr $i*16+1] $green 1
    eval lut SetTableValue [expr $i*16+2] $blue 1
    eval lut SetTableValue [expr $i*16+3] $black 1
  }
vtkPolyDataMapper planeMapper
  planeMapper SetLookupTable lut
  planeMapper SetInputConnection [plane GetOutputPort]
  planeMapper SetScalarRange 0.197813 0.710419
vtkActor planeActor
  planeActor SetMapper planeMapper
```

Lookup tables can be manipulated in two different ways, as this example illustrates. First, you can specify a HSVA (Hue-Saturation-Value-Alpha transparency) ramp that is used to generate the colors in the table using linear interpolation in HSVA space (the Build() method actually generates the table). Second, you can manually insert colors at specific locations in the table. Note that the number of colors in the table can be set. In this example we generate the table with the HSVA ramp, and then replace colors in the table with the SetTableValue() method.

The mapper's SetScalarRange() method controls how scalars are mapped into the table. Scalar values greater than the maximum value are clamped to the maximum value. Scalar values less than the minimum value are clamped to the minimum value. Using the scalar range let's you "expand" a region of the scalar data by mapping more colors to it.

Sometimes the scalar data is actually color, and does not need to be mapped through a lookup table. The mapper provides several methods to control the mapping behavior.

- SetColorModeToDefault() invokes the default mapper behavior. The default behavior treats 3 component scalars of data type `unsigned char` as colors and performs no mapping; all other types of scalars are mapped through the lookup table.
- SetColorModeToMapScalars() maps all scalars through the lookup table, regardless of type. If the scalar has more than one component per tuple, then the scalar's zero'th component is used perform the mapping.

Another important feature of vtkMapper is controlling which attribute data (i.e., point or cell scalars, or a general data array) is used to color objects. The following methods let you control this behavior. Note that these methods give strikingly different results: point attribute data is interpolated across rendering primitives during the rendering process, whereas cell attribute data colors the cell a constant value.

- SetScalarModeToDefault() invokes the default mapper behavior. The default behavior uses point scalars to color objects unless they are not available, in which case cell scalars are used, if they are available.
- SetScalarModeToUsePointData() always uses point data to color objects. If no point scalar data is available, then the object color is not affected by scalar data.
- SetScalarModeToUseCellData() always uses cell data to color objects. If no cell scalar data is available, then the object color is not affected by scalar data.
- SetScalarModeToUsePointFieldData() indicates that neither the point or cell scalars are to be used, but rather a data array found in the point attribute data. This method should be used in conjunction with ColorByArrayComponent() to specify the data array and component to use as the scalar.
- SetScalarModeToUseCellFieldData() indicates that neither the point or cell scalars are to be used, but rather a data array found in the cell field data. This method should be used in conjunction with ColorByArrayComponent() to specify the data array and component to use as the scalar.

Normally the default behavior works well, unless both cell and point scalar data is available. In this case, you will probably want to explicitly indicate whether to use point scalars or cell scalars to color your object.

Contouring

Another common visualization technique is generating contours. Contours are lines or surfaces of constant scalar value. In VTK, the filter vtkContourFilter is used to perform contouring as shown in the following Tcl example from `VTK/Examples/VisualizationAlgorithms/Tcl/VisQuad.tcl`—refer to **Figure 5–2**.

```
# Create 5 surfaces in range specified
vtkContourFilter contours
  contours SetInputConnection [sample \
              GetOutputPort]
  contours GenerateValues 5 0.0 1.2
```

Figure 5–2 Generating contours.

```
vtkPolyDataMapper contMapper
  contMapper SetInputConnection [contours GetOutputPort]
  contMapper SetScalarRange 0.0 1.2
vtkActor contActor
  contActor SetMapper contMapper
```

You can specify contour values in two ways. The simplest way is to use the SetValue() method to specify the contour number and its value (multiple values can be specified)

```
contours SetValue 0 0.5
```

The above example demonstrated the second way: via the GenerateValues() method. With this method, you specify the scalar range and the number of contours to be generated in the range (end values inclusive).

Note that there are several objects in VTK that perform contouring specialized to a particular dataset type (and are faster). Examples include vtkSynchronizedTemplates2D and vtkSynchronizedTemplates3D. You do not need to instantiate these directly if you use vtkContourFilter; the filter will select the best contouring function for your dataset type automatically.

Glyphing

Glyphing is a visualization technique that represents data by using symbols, or glyphs (**Figure 5–3**). The symbols can be simple or complex, ranging from oriented cones to show vector data, to complex, multi-variate glyphs such as Chernoff faces (symbolic representations of the human face whose expression is controlled by data values). In VTK, the vtkGlyph3D class allows you to create glyphs that can be scaled, colored, and oriented along a direction. The glyphs are copied to each point of the input dataset. The glyph itself is defined using the second input connection to the filter. (It accepts datasets of type vtkPolyData). The following script demonstrates the use of vtkGlyph3D (the Tcl script is taken from `VTK/Examples/VisualizationAlgorithms/Tcl/spikeF.tcl`).

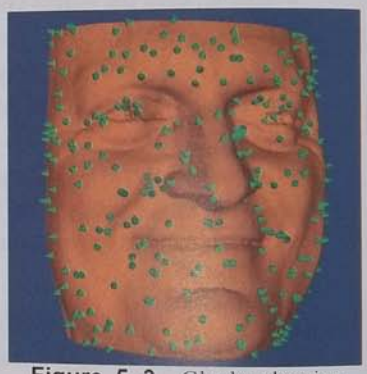


Figure 5–3 Glyphs showing surface normals.

```
vtkPolyDataReader fran
  fran SetFileName "$VTK_DATA_ROOT/Data/fran_cut.vtk"
vtkPolyDataNormals normals
  normals SetInputConnection [fran GetOutputPort]
  normals FlipNormalsOn
vtkPolyDataMapper franMapper
  franMapper SetInputConnection [normals GetOutputPort]
vtkActor franActor
  franActor SetMapper franMapper
    [franActor GetProperty] SetColor 1.0 0.49 0.25

vtkMaskPoints ptMask
  ptMask SetInputConnection [normals GetOutputPort]
```

```
  ptMask SetOnRatio 10
  ptMask RandomModeOn

# In this case we are using a cone as a glyph. We transform the cone so
# its base is at 0,0,0. This is the point where glyph rotation occurs.
vtkConeSource cone
  cone SetResolution 6
vtkTransform transform
  transform Translate 0.5 0.0 0.0
vtkTransformPolyDataFilter transformF
  transformF SetInputConnection [cone GetOutputPort]
  transformF SetTransform transform

vtkGlyph3D glyph
  glyph SetInputConnection [ptMask GetOutputPort]
  glyph SetSourceConnection [transformF GetOutputPort]
  glyph SetVectorModeToUseNormal
  glyph SetScaleModeToScaleByVector
  glyph SetScaleFactor 0.004
vtkPolyDataMapper spikeMapper
  spikeMapper SetInputConnection [glyph GetOutputPort]
vtkActor spikeActor
  spikeActor SetMapper spikeMapper
  eval [spikeActor GetProperty] SetColor 0.0 0.79 0.34
```

The purpose of the script is to indicate the direction of surface normals using small, oriented cones. An input dataset (from a Cyberware laser digitizing system) is read and displayed. Next, the filter vtkMaskPoints is used to subsample the points (and associated point attribute data) from the Cyberware data. This serves as the input to the vtkGlyph3D instance. A vtkConeSource is used as the Source for the glyph instance. Notice that the cone is translated (with vtkTransformPolyDataFilter) so that its base is on the origin (0,0,0) (since vtkGlyph3D rotates the source object around the origin).

The vtkGlyph3D object `glyph` is configured to use the point attribute normals as the orientation vector. (Alternatively, use SetVectorModeToUseVector() to use the vector data instead of the normals.) It also scales the cones by the magnitude of the vector value there, with the given scale factor. (You can scale the glyphs by scalar data or turn data scaling off with the methods SetScaleModeToScaleByScalar() and SetScaleModeToDataScalingOff().)

It is also possible to color the glyphs with scalar or vector data, or by the scale factor. You can also create a table of glyphs, and use scalar or vector data to index into the table. Refer to the online documentation for more information.

Streamlines

A streamline can be thought of as the path that a massless particle takes in a vector field (e.g., velocity field). Streamlines are used to convey the structure of a vector field. Usually multiple streamlines are created to explore interesting features in the field (**Figure 5–4**). Streamlines are computed via numerical integration (integrating the product of velocity times Δt), and are therefore only approximations to the actual streamlines.

Creating a streamline requires specifying a starting point (or points, if multiple streamlines), an integration direction (along the flow, or opposite the flow direction, or in both directions), and other parameters to control its propagation. The following script shows how to create a single streamline. The streamline is wrapped with a tube whose radius is proportional to the inverse of velocity magnitude. This indicates where the flow is slow (fat tube) and where it is fast (thin tube). This Tcl script is extracted from `VTK/Examples/VisualizationAlgorithms/Tcl/officeTube.tcl`.

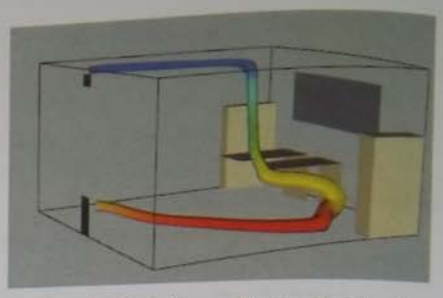


Figure 5–4 Streamline wrapped with a tube.

```
# Read structured grid data
vtkStructuredGridReader reader
  reader SetFileName "$VTK_DATA_ROOT/Data/office.binary.vtk"
  reader Update #force a read to occur

# Create source for streamtubes
vtkRungeKutta4 integ
vtkStreamTracer streamer
  streamer SetInputConnection [reader GetOutputPort]
  streamer SetStartPosition 0.1 2.1 0.5
  streamer SetMaximumPropagation 500
    streamer SetMaximumPropagationUnitToTimeUnit
  streamer SetInitialIntegrationStep 0.05
    streamer SetInitialIntegrationStepUnitToCellLengthUnit
    streamer SetIntegrationDirectionToBoth
    streamer SetIntegrator integ

vtkTubeFilter streamTube
  streamTube SetInputConnection [streamer GetOutputPort]
    streamTube SetInputArrayToProcess 1 0 0 \
          vtkDataObject::FIELD_ASSOCIATION_POINTS vectors
  streamTube SetRadius 0.02
  streamTube SetNumberOfSides 12
  streamTube SetVaryRadiusToVaryRadiusByVector
vtkPolyDataMapper mapStreamTube
  mapStreamTube SetInputConnection [streamTube GetOutputPort]
  eval mapStreamTube SetScalarRange \
    [[[[reader GetOutput] GetPointData] GetScalars] \
                GetRange] #this is why we did an Update
vtkActor streamTubeActor
  streamTubeActor SetMapper mapStreamTube
    [streamTubeActor GetProperty] BackfaceCullingOn
```

In this example we have selected a starting point by specifying the world coordinate (0.1,2.1,0.5). It is also possible to specify a starting location by using cellId, cell subId, and parametric coordinates. The MaximumPropagation instance variable controls the maximum length of the streamline (measured in units specified by the MaximumPropagationUnit instance variable, in this case time). If you want greater accuracy (at the cost of more computation time), set the InitialIntegrationStep instance vari-

able to a smaller value. (In this case, this is specified in terms of cell's length; it is possible to choose time or distance by setting InitialIntegrationStepUnit.) Accuracy can also be controlled by choosing a different subclass of vtkInitialValueProblemSolver such as vtkRungeKutta2 or vtkRungeKutta45 (which allows for adaptive control of the step size). By default, the stream tracer class uses vtkRungeKutta2 to perform the numerical integration. You can also control the direction of integration with the following methods.

- SetIntegrationDirectionToForward()
- SetIntegrationDirectionToBackward()
- SetIntegrationDirectionToBoth()

Lines are often difficult to see and create useful images from. In this example we wrap the lines with a tube filter. The tube filter is configured to vary the radius of the tube inversely proportional to the velocity magnitude (i.e., a flux-preserving relationship if the flow field is incompressible). The SetVaryRadiusToVaryRadiusByVector() enables this. You can also vary the radius by scalar value (SetVaryRadiusToVaryRadiusByScalar()) or turn off the variable radius (SetVaryRadiusToVaryRadiusOff()). Note that the tube filter has to be told which array to use when scaling its radius. In this case, the array with the name "vectors" was selected using SetInputArrayToProcess().

As suggested earlier, we often wish to generate many streamlines simultaneously. One way to do this is to use the SetSourceConnection() method to specify an instance of vtkDataSet whose points are used to seed streamlines. Here is an example of its use (from `VTK/Examples/VisualizationAlgorithms/Tcl/officeTubes.tcl`).

```
vtkPointSource seeds
  seeds SetRadius 0.15
    seeds SetCenter 0.1 2.1 0.5
  seeds SetNumberOfPoints 6
vtkRungeKutta4 integ
vtkStreamTracer streamer
  streamer SetInputConnection [reader GetOutputPort]
  streamer SetSourceConnection [seeds GetOutput]
  streamer SetMaximumPropagationTime 500
    streamer SetMaximumPropagationUnitToTimeUnit
    streamer SetInitialIntegrationStep 0.05
    streamer SetInitialIntegrationStepUnitToCellLengthUnit
    streamer SetIntegrationDirectionToBoth
    streamer SetIntegrator integ
```

Notice that the example uses the source object vtkPointSource to create a spherical cloud of points, which are then set as the source to `streamer`. For every point (inside the input dataset) a streamline will be computed.

Stream Surfaces

Advanced users may want to use VTK's stream surface capability. Stream surfaces are generated in two parts. First, a rake or series of ordered points are used to generate a series of streamlines. Then, vtkRuledSurfaceFilter is used to create a surface from the streamlines. It is very important that the

points (and hence streamlines) are ordered carefully because the vtkRuledSurfaceFilter assumes that the lines lie next to one another, and are within a specified distance (DistanceFactor) of the neighbor to the left and right. Otherwise, the surface tears or you can obtain poor results. The following script demonstrates how to create a stream surface (taken from the Tcl script `VTK/Examples/VisualizationAlgorithms/Tcl/streamSurface.tcl` and shown in **Figure 5–5**).

```
vtkLineSource rake
 rake SetPoint1 15 -5 32
 rake SetPoint2 15 5 32
 rake SetResolution 21
vtkPolyDataMapper rakeMapper
 rakeMapper SetInputConnection [rake
GetOutputPort]
vtkActor rakeActor
 rakeActor SetMapper rakeMapper

vtkRungeKutta4 integ
vtkStreamTracer s1
 s1 SetInputConnection [pl3d GetOutputPort]
 s1 SetSourceConnection [rake GetOutputPort]
 s1 SetIntegrator integ
 s1 SetMaximumPropagation 0.1
  s1 SetMaximumPropagationUnitToTimeUnit
 s1 SetInitialIntegrationStep 0.1
  s1 SetInitialIntegrationStepUnitToCellLengthUnit
 s1 SetIntegrationDirectionToBackward

vtkRuledSurfaceFilter scalarSurface
 scalarSurface SetInputConnection [s1 GetOutputPort]
 scalarSurface SetOffset 0
 scalarSurface SetOnRatio 2
 scalarSurface PassLinesOn
 scalarSurface SetRuledModeToPointWalk
 scalarSurface SetDistanceFactor 30
vtkPolyDataMapper mapper
 mapper SetInputConnection [scalarSurface GetOutputPort]
 eval mapper SetScalarRange [[pl3d GetOutput] GetScalarRange]
vtkActor actor
 actor SetMapper mapper
```

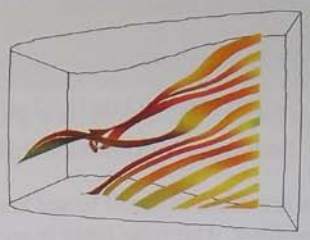


Figure 5–5 Stream surface.

A nice feature of the vtkRuledSurfaceFilter is the ability to turn off strips if multiple lines are provided as input to the filter (the method SetOnRatio()). This helps understand the structure of the surface.

Cutting

Cutting, or slicing, a dataset in VTK entails creating a "cross-section" through the dataset using any type of implicit function. For example, we can slice through a dataset with a plane to create a planar cut. The cutting surface interpolates the data as it cuts, which can then be visualized using any standard visualization technique. The result of cutting is always of type vtkPolyData. (Cutting a n-dimen-

sional cell results in a *(n-1)*-dimensional output primitive. For example, cutting a tetrahedron creates either a triangle or quadrilateral.)

In the following Tcl example, a combustor (structured grid) is cut with a plane as shown in **Figure 5–6**. The example is taken from the Tcl script `VTK/Graphics/Testing/Tcl/probe.tcl`.

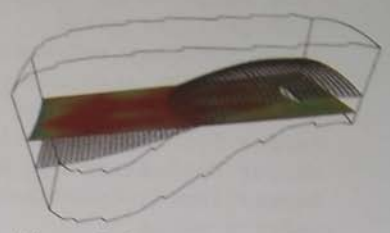


Figure 5–6 Cutting a combustor.

```
vtkPlane plane
  eval plane SetOrigin [[pl3d GetOutput]
GetCenter]
  plane SetNormal -0.287 0 0.9579
vtkCutter planeCut
  planeCut SetInputConnection [pl3d GetOutputPort]
  planeCut SetCutFunction plane
vtkPolyDataMapper cutMapper
  cutMapper SetInputConnection [planeCut GetOutputPort]
  eval cutMapper SetScalarRange \
   [[[[pl3d GetOutput] GetPointData] GetScalars] GetRange]
vtkActor cutActor
  cutActor SetMapper cutMapper
```

vtkCutter requires that you specify an implicit function with which to cut. Also, you may wish to specify one or more cut values using the SetValue() or GenerateValues() methods. These values specify the value of the implicit function used to perform the cutting. (Typically the cutting value is zero, meaning that the cut surface is precisely on the implicit function. Values less than or greater than zero are implicit surfaces below and above the implicit surface. The cut value can also be thought of as a "distance" to the implicit surface, which is only strictly true for vtkPlane.)

Merging Data

Up to this point we have seen simple, linear visualization pipelines. However, it is possible for pipelines to branch, merge and even have loops. It is also possible for pieces of data to move from one leg of the pipeline to another. In this section and the following, we introduce two filters that allow you to build datasets from other datasets. We'll start with vtkMergeFilter.

vtkMergeFilter merges pieces of data from several datasets into a new dataset. For example, you can take the structure (topology and geometry) from one dataset, the scalars from a second, and the vectors from a third dataset, and combine them into a single dataset. Here's an example of its use (From the Tcl script `VTK/Examples/VisualizationAlgorithms/Tcl/imageWarp.tcl`). (Please ignore those filters that you don't recognize, focus on the use of vtkMergeFilter. We'll describe more fully the details of the script in "Warp Based On Scalar Values" on page 106.)

```
vtkBMPReader reader
 reader SetFileName $VTK_DATA_ROOT/Data/masonry.bmp
vtkImageLuminance luminance
 luminance SetInputConnection [reader GetOutputPort]
vtkImageDataGeometryFilter geometry
 geometry SetInputConnection [luminance GetOutputPort]
vtkWarpScalar warp
 warp SetInputConnection [geometry GetOutputPort]
```

```
 warp SetScaleFactor -0.1

# use merge to put back scalars from image file
vtkMergeFilter merge
 merge SetGeometryConnection [warp GetOutputPort]
 merge SetScalarsConnection [reader GetOutputPort]
vtkDataSetMapper mapper
 mapper SetInputConnection [merge GetOutputPort]
 mapper SetScalarRange 0 255
 mapper ImmediateModeRenderingOff
vtkActor actor
 actor SetMapper mapper
```

What's happening here is that the dataset (or geometry) from vtkWarpScalar (which happens to be of type vtkPolyData) is combined with the scalar data from the vtkBMPReader. The pipeline has split and rejoined because the geometry had to be processed separately (in the imaging pipeline) from the scalar data.

When merging data, the number of tuples found in the data arrays that make up the point attribute data must equal the number of points. This is also true for the cell data.

Appending Data

Like vtkMergeFilter, vtkAppendFilter (and its specialized cousin vtkAppendPolyData) builds a new dataset by appending datasets. The append filters take a list of inputs, each of which must be the same type. During the append operation, only those data attributes that are common to all input datasets are appended together. A great example of its application is shown in the example in the following section.

Probing

Probing is a process of sampling one dataset with another dataset. In VTK, you can use any dataset as a probe geometry onto which point data attributes are mapped from another dataset. For example, the following Tcl script (taken from `VTK/Examples/VisualizationAlgorithms/Tcl/probeComb.tcl`) creates three planes (which serve as the probe geometry) used to sample a structured grid dataset. The planes are then processed with vtkContourFilter to generate contour lines.

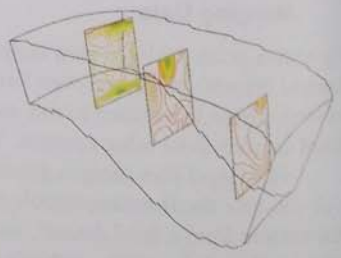


Figure 5–7 Probing data.

```
# Create pipeline
vtkPLOT3DReader pl3d
  pl3d SetXYZFileName "$VTK_DATA_ROOT/Data/combxyz.bin"
  pl3d SetQFileName "$VTK_DATA_ROOT/Data/combq.bin"
  pl3d SetScalarFunctionNumber 100
  pl3d SetVectorFunctionNumber 202
  pl3d Update;#force data read
```

```
# Create the probes. Transform them into right place.
vtkPlaneSource plane
  plane SetResolution 50 50
vtkTransform transP1
  transP1 Translate 3.7 0.0 28.37
  transP1 Scale 5 5 5
  transP1 RotateY 90
vtkTransformPolyDataFilter tpd1
  tpd1 SetInputConnection [plane GetOutputPort]
  tpd1 SetTransform transP1
vtkOutlineFilter outTpd1
  outTpd1 SetInputConnection [tpd1 GetOutputPort]
vtkPolyDataMapper mapTpd1
  mapTpd1 SetInputConnection [outTpd1 GetOutputPort]
vtkActor tpd1Actor
  tpd1Actor SetMapper mapTpd1
  [tpd1Actor GetProperty] SetColor 0 0 0

vtkTransform transP2
  transP2 Translate 9.2 0.0 31.20
  transP2 Scale 5 5 5
  transP2 RotateY 90
vtkTransformPolyDataFilter tpd2
  tpd2 SetInputConnection [plane GetOutputPort]
  tpd2 SetTransform transP2
vtkOutlineFilter outTpd2
  outTpd2 SetInputConnection [tpd2 GetOutputPort]
vtkPolyDataMapper mapTpd2
  mapTpd2 SetInputConnection [outTpd2 GetOutputPort]
vtkActor tpd2Actor
  tpd2Actor SetMapper mapTpd2
  [tpd2Actor GetProperty] SetColor 0 0 0

vtkTransform transP3
  transP3 Translate 13.27 0.0 33.30
  transP3 Scale 5 5 5
  transP3 RotateY 90
vtkTransformPolyDataFilter tpd3
  tpd3 SetInputConnection [plane GetOutputPort]
  tpd3 SetTransform transP3
vtkOutlineFilter outTpd3
  outTpd3 SetInputConnection [tpd3 GetOutputPort]
vtkPolyDataMapper mapTpd3
  mapTpd3 SetInputConnection [outTpd3 GetOutputPort]
vtkActor tpd3Actor
  tpd3Actor SetMapper mapTpd3
  [tpd3Actor GetProperty] SetColor 0 0 0

vtkAppendPolyData appendF
  appendF AddInputConnection [tpd1 GetOutputPort]
  appendF AddInputConnection [tpd2 GetOutputPort]
  appendF AddInputConnection [tpd3 GetOutputPort]
```

```
vtkProbeFilter probe
  probe SetInputConnection [appendF GetOutputPort]
  probe SetSourceConnection [pl3d GetOutputPort]
vtkContourFilter contour
  contour SetInputConnection [probe GetOutputPort]
  eval contour GenerateValues 50 [[pl3d GetOutput]\
                                  GetScalarRange]
vtkPolyDataMapper contourMapper
  contourMapper SetInputConnection [contour GetOutputPort]
  eval contourMapper SetScalarRange [[pl3d GetOutput]\
                                     GetScalarRange]
vtkActor planeActor
  planeActor SetMapper contourMapper
```

Notice that the probe is set using the SetInputConnection() method of vtkProbeFilter, and the dataset to probe is set using the SetSourceConnection() method.

Another useful application of probing is resampling data. For example, if you have an unstructured grid and wish to visualize it with tools specific to vtkImageData (such as volume rendering—see "Volume Rendering" on page 139), you can use vtkProbeFilter to sample the unstructured grid with a volume, and then visualize the volume. It is also possible to probe data with lines (or curves) and use the output to perform *x-y* plotting.

One final note: cutting and probing can give similar results, although there is a difference in resolution. Similar to the example described in "Cutting" on page 98, vtkProbeFilter could be used with a vtkPlaneSource to generate a plane with data attributes from the structured grid. However, cutting creates surfaces with a resolution dependent on the resolution of the input data. Probing creates surfaces (and other geometries) with a resolution independent of the input data. Care must be taken when probing data to avoid under- or oversampling. Undersampling can result in errors in visualization, and oversampling can consume excessive computation time.

Color An Isosurface With Another Scalar

A common visualization task is to generate an isosurface and then color it with another scalar. While you might do this with a probe, there is a much more efficient way when the dataset that you isosurface contains the data you wish to color the isosurface with. This is because the vtkContourFilter (which generates the isosurface) interpolates all data to the isosurface during the generation process. The interpolated data can then be used during the mapping process to color the isosurface. Here's an example from the `VTK/Examples/VisualizationAlgorithms/Tcl/ColorIsosurface.tcl`.

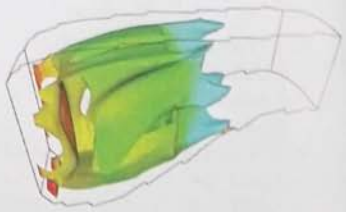


Figure 5–8 Coloring an isosurface with another scalar.

```
vtkPLOT3DReader pl3d
  pl3d SetXYZFileName "$VTK_DATA_ROOT/Data/combxyz.bin"
  pl3d SetQFileName "$VTK_DATA_ROOT/Data/combq.bin"
  pl3d SetScalarFunctionNumber 100
  pl3d SetVectorFunctionNumber 202
  pl3d AddFunction 153
  pl3d Update
```

```
vtkContourFilter iso
  iso SetInputConnection [p13d GetOutputPort]
  iso SetValue 0 .24
vtkPolyDataNormals normals
  normals SetInputConnection [iso GetOutputPort]
  normals SetFeatureAngle 45
vtkPolyDataMapper isoMapper
  isoMapper SetInputConnection [normals GetOutputPort]
  isoMapper ScalarVisibilityOn
  isoMapper SetScalarRange 0 1500
  isoMapper SetScalarModeToUsePointFieldData
  isoMapper ColorByArrayComponent "VelocityMagnitude" 0
vtkLODActor isoActor
  isoActor SetMapper isoMapper
  isoActor SetNumberOfCloudPoints 1000
```

First, the dataset is read with a vtkPLOT3DReader. Here we add a function to be read (function number 153) which we know to be named "Velocity Magnitude." An isosurface is generated which also interpolates all its input data arrays including the velocity magnitude data. We then use the velocity magnitude to color the contour by invoking the method SetScalarModeToUsePointFieldData() and specifying the data array to use to color with the ColorByArrayComponent() method.

Extract Subset of Cells

Visualization data is often large and processing such data can be quite costly in execution time and memory requirements. As a result, the ability to extract pieces of data is important. Many times only a subset of the data contains meaningful information, or the resolution of the data can be reduced without significant loss of accuracy.

The *Visualization Toolkit* offers several tools to extract portions of, or subsample data. We've already seen how vtkProbeFilter can be used to subsample data (see "Probing" on page 100). Other tools include classes to subsample data, and tools to extract cells within a region in space. (Subsampling tools are specific to a type of dataset. See "Subsampling Image Data" on page 105 for information about subsampling image datasets, and "Subsampling Structured Grids" on page 113 for information about subsampling structured grids.) In this section, we describe how to extract pieces of a dataset contained within a region in space.

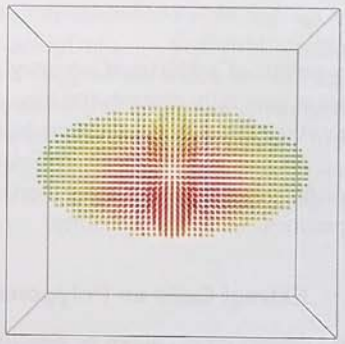


Figure 5–9 Extracting cells.

The class vtkExtractGeometry extracts all cells in a dataset that lie either inside or outside of a vtkImplicitFunction (remember, implicit functions can consist of boolean combinations of other implicit functions). The following script creates a boolean combination of two ellipsoids that is used as the extraction region. A vtkShrinkFilter is also used to shrink the cells so you can see what's been extracted. (The Tcl script is from `VTK/Examples/VisualizationAlgorithms/Tcl/ExtractGeometry.tcl`.)

```
vtkQuadric quadric
  quadric SetCoefficients .5 1 .2 0 .1 0 0 .2 0 0
```

```
vtkSampleFunction sample
  sample SetSampleDimensions 50 50 50
  sample SetImplicitFunction quadric
  sample ComputeNormalsOff
vtkTransform trans
  trans Scale 1 .5 .333
vtkSphere sphere
  sphere SetRadius 0.25
  sphere SetTransform trans
vtkTransform trans2
  trans2 Scale .25 .5 1.0
vtkSphere sphere2
  sphere2 SetRadius 0.25
  sphere2 SetTransform trans2
vtkImplicitBoolean union
  union AddFunction sphere
  union AddFunction sphere2
  union SetOperationType 0;#union

vtkExtractGeometry extract
  extract SetInputConnection [sample GetOutputPort]
  extract SetImplicitFunction union
vtkShrinkFilter shrink
  shrink SetInputConnection [extract GetOutputPort]
  shrink SetShrinkFactor 0.5
vtkDataSetMapper dataMapper
  dataMapper SetInputConnection [shrink GetOutputPort]
vtkActor dataActor
  dataActor SetMapper dataMapper
```

The output of vtkExtractGeometry is always a vtkUnstructuredGrid. This is because the extraction process generally disrupts the topological structure of the dataset, and the most general dataset form (i.e., vtkUnstructuredGrid) must be used to represent the output.

As a side note: implicit functions can be transformed by assigning them a vtkTransform. If specified, the vtkTransform is used to modify the evaluation of the implicit function. You may wish to experiment with this capability.

Extract Cells as Polygonal Data

Most dataset types cannot be directly rendered by graphics hardware or libraries. Only polygonal data (vtkPolyData) is commonly supported by rendering systems. Structured datasets, especially images and sometimes volumes, are also supported by graphics systems. All other datasets require special processing if they are to be rendered. In VTK, one approach to rendering non-polygonal datasets is to convert them to polygonal data. This is the function of vtkGeometryFilter.

vtkGeometryFilter accepts as input any type of vtkDataSet, and generates vtkPolyData on output. It performs the conversion using the following rules. All input cells of topological dimension 2 or less (e.g., polygons, lines, vertices) are passed to the output. The faces of cells of dimension 3 are sent to the output if they are on the boundary of the dataset. (A face is on the boundary if it is used by only one cell.)

The principal use of vtkGeometryFilter is as a conversion filter. The following example from `VTK/Examples/DataManipulation/Tcl/pointToCellData.tcl` uses vtkGeometryFilter to convert a 2D unstructured grid into polygonal data for later processing by filters that accept vtkPolyData as input. Here, the vtkConnectivityFilter extracts data as vtkUnstructuredGrid which is then converted into polygons using vtkGeometryFilter.

```
vtkConnectivityFilter connect2
  connect2 SetInputConnection [thresh GetOutputPort]
vtkGeometryFilter parison
  parison SetInputConnection [connect2 GetOutputPort]
vtkPolyDataNormals normals2
  normals2 SetInputConnection [parison GetOutputPort]
  normals2 SetFeatureAngle 60
vtkLookupTable lut
  lut SetHueRange 0.0 0.66667
vtkPolyDataMapper parisonMapper
  parisonMapper SetInputConnection [normals2 GetOutputPort]
  parisonMapper SetLookupTable lut
  parisonMapper SetScalarRange 0.12 1.0
vtkActor parisonActor
  parisonActor SetMapper parisonMapper
```

In fact, the vtkDataSetMapper mapper uses vtkGeometryFilter internally to convert datasets of any type into polygonal data. (The filter is smart enough to pass input vtkPolyData straight to its output without processing.)

In addition, vtkGeometryFilter has methods that allows you to extract cells based on a range of point ids, cell ids, or whether the cells lie in a particular rectangular region in space. vtkGeometryFilter extracts pieces of datasets based on point and cell ids using the methods PointClippingOn(), SetPointMinimum(), SetPointMaximum() and CellClippingOn(), SetCellMinimum(), SetCellMaximum(). The minimum and maximum values specify a range of ids which are extracted. Also, you can use a rectangular region in space to limit what's extracted. Use the ExtentClippingOn() and SetExtent() methods to enable extent clipping and specify the extent. The extent consists of six values defining a bounding box in space—(x_{min},x_{max}, y_{min},y_{max}, z_{min},z_{max}). You can use point, cell, and extent clipping in any combination. This is a useful feature when debugging data, or when you only want to look at a portion of it.

5.2 Visualizing Polygonal Data

Polygonal data (vtkPolyData) is an important form of visualization data. Its importance is due to its use as the geometry interface into the graphics hardware/rendering engine. Other data types must be converted into polygonal data in order to be rendered with the exception of vtkImageData (images and volumes) which uses special imaging or volume rendering technique). You may wish to refer to "Extract Cells as Polygonal Data" on page 104 to see how this conversion is performed.

Polygonal data (vtkPolyData) consists of combinations of vertices and polyvertices; lines and polylines; triangles, quadrilaterals, and polygons; and triangle strips. Most filters (that input vtkPolyData) will process any combination of this data; however, some filters (like vtkDecimatePro and vtkTubeFilter) will only process portions of the data (triangle meshes and lines).

Manually Create vtkPolyData

Polygonal data can be constructed several different ways. Typically, you'll create a vtkPoints to represent the points, and then one to four vtkCellArrays to represent vertex, line, polygon, and triangle strip connectivity. Here's an example taken from `VTK/Examples/DataManipulation/Tcl/CreateStrip.tcl`. It creates a vtkPolyData with a single triangle strip.

```
vtkPoints points
  points InsertPoint 0 0.0 0.0 0.0
  points InsertPoint 1 0.0 1.0 0.0
  points InsertPoint 2 1.0 0.0 0.0
  points InsertPoint 3 1.0 1.0 0.0
  points InsertPoint 4 2.0 0.0 0.0
  points InsertPoint 5 2.0 1.0 0.0
  points InsertPoint 6 3.0 0.0 0.0
  points InsertPoint 7 3.0 1.0 0.0
vtkCellArray strips
  strips InsertNextCell 8;#number of points
  strips InsertCellPoint 0
  strips InsertCellPoint 1
  strips InsertCellPoint 2
  strips InsertCellPoint 3
  strips InsertCellPoint 4
  strips InsertCellPoint 5
  strips InsertCellPoint 6
  strips InsertCellPoint 7
vtkPolyData profile
  profile SetPoints points
  profile SetStrips strips
vtkPolyDataMapper map
  map SetInput profile
vtkActor strip
  strip SetMapper map
  [strip GetProperty] SetColor 0.3800 0.7000 0.1600
```

In C++, here's another example showing how to create a cube (`VTK/Examples/DataManipulation/Cxx/Cube.cxx`). This time we create six quadrilateral polygons, as well as scalar values at the vertices of the cube.

```
int i;
static double x[8][3]={{0,0,0}, {1,0,0}, {1,1,0}, {0,1,0},
              {0,0,1}, {1,0,1}, {1,1,1}, {0,1,1}};
static vtkIdType pts[6][4]={{0,1,2,3}, {4,5,6,7}, {0,1,5,4},
            {1,2,6,5}, {2,3,7,6}, {3,0,4,7}};

// Create the building blocks of polydata including data attributes.
vtkPolyData *cube = vtkPolyData::New();
vtkPoints *points = vtkPoints::New();
vtkCellArray *polys = vtkCellArray::New();
vtkFloatArray *scalars = vtkFloatArray::New();
```

Figure 5–10 Comparing a mesh with and without surface normals.

```
// Load the point, cell, and data attributes.
for (i=0; i<8; i++) points->InsertPoint(i,x[i]);
for (i=0; i<6; i++) polys->InsertNextCell(4,pts[i]);
for (i=0; i<8; i++) scalars->InsertTuple1(i,i);

// We now assign the pieces to the vtkPolyData.
cube->SetPoints(points);
points->Delete();
cube->SetPolys(polys);
polys->Delete();
cube->GetPointData()->SetScalars(scalars);
scalars->Delete();
```

vtkPolyData can be constructed with any combination of vertices, lines, polygons, and triangle strips. Also, vtkPolyData supports an extensive set of operators that allows you to edit and modify the underlying structure. Refer to "Polygonal Data" on page 345 for more information.

Generate Surface Normals

When you render a polygonal mesh, you may find that the image clearly shows the faceted nature of the mesh (**Figure 5–10**). The image can be improved by using Gouraud shading (see "Actor Properties" on page 53). However, Gouraud shading depends on the existence of normals at each point in the mesh.The vtkPolyDataNormals filter can be used to generate normals on the mesh. The scripts in "Extrusion" on page 217, "Glyphing" on page 94, and "Color An Isosurface With Another Scalar" on page 102 all use vtkPolyDataNormals.

Two important instance variables are Splitting and FeatureAngle. If splitting is on, feature edges (defined as edges where the polygonal normals on either side of the edge make an angle greater than or equal to the feature angle) are "split," that is, points are duplicated along the edge, and the mesh is separated on either side of the feature edge (see *The Visualization Toolkit* text). This creates new points, but allows sharp corners to be rendered crisply. Another important instance variable is FlipNormals. Invoking FlipNormalsOn() causes the filter to reverse the direction of the normals (and the ordering of the polygon connectivity list).

Decimation

Polygonal data, especially triangle meshes, are a common form of graphics data. Filters such as vtkContourFilter generate triangle meshes. Often, these meshes are quite large and cannot be ren-

Figure 5–11 Triangle mesh before (left) and after (right) 90% decimation.

dered or processed quickly enough for interactive application. Decimation techniques have been developed to address this problem. Decimation, also referred to as polygonal reduction, mesh simplification, or multiresolution modeling, is a process to reduce the number of triangles in a triangle mesh, while maintaining a faithful approximation to the original mesh.

VTK supports three decimation methods: vtkDecimatePro, vtkQuadricClustering, and vtkQuadricDecimation. All are similar in usage and application, although they each offer advantages and disadvantages as follows:

- vtkDecimatePro is relatively fast and has the ability to modify topology during the reduction process. It uses an edge collapse process to eliminate vertices and triangles. Its error metric is based on distance to plane/distance to edge. A nice feature of vtkDecimatePro is that you can achieve any level of reduction requested, since the algorithm will begin tearing the mesh into pieces to achieve this (if topology modification is allowed).
- vtkQuadricDecimation uses the quadric error measure proposed by Garland and Heckbert in Siggraph '97 *Surface Simplification Using Quadric Error Metrics*. It uses an edge collapse to eliminate vertices and triangles. The quadric error metric is generally accepted as one of the better error metrics.
- vtkQuadricClustering is the fastest algorithm. It is based on the algorithm presented by Peter Lindstrom in his Siggraph 2000 paper *Out-of-Core Simplification of Large Polygonal Models*. It is capable of quickly reducing huge meshes, and the class supports the ability to process pieces of a mesh (using the StartAppend(), Append(), and EndAppend() methods). This enables the user to avoid reading an entire mesh into memory. This algorithm works well with large meshes; the triangulation process does not work well as meshes become smaller. (Combining this algorithm with one of the other algorithms is a good approach.)

Here's an example using vtkDecimatePro. It's been adapted from the Tcl script `VTK/Examples/VisualizationAlgorithms/Tcl/deciFran.tcl` (**Figure 5–11**).

```
vtkDecimatePro deci
  deci SetInputConnection [fran GetOutputPort]
  deci SetTargetReduction 0.9
  deci PreserveTopologyOn
vtkPolyDataNormals normals
  normals SetInputConnection [fran GetOutputPort]
  normals FlipNormalsOn
vtkPolyDataMapper franMapper
```

Figure 5–12 Smoothing a polygonal mesh. Right image shows the effect of smoothing.

```
  franMapper SetInputConnection [normals GetOutputPort]
vtkActor franActor
  franActor SetMapper franMapper
  eval [franActor GetProperty] SetColor 1.0 0.49 0.25
```

Two important instance variables of vtkDecimatePro are TargetReduction and PreserveTopology. The TargetReduction is the requested amount of reduction (e.g., a value of 0.9 means that we wish to reduce the number of triangles in the mesh by 90%). Depending on whether you allow topology to change or not (PreserveTopologyOn/Off()), you may or may not achieve the requested reduction. If PreserveTopology is off, then vtkDecimatePro will give you the requested reduction.

A final note: the decimation filters take triangle data as input. If you have a polygonal mesh you can convert the polygons to triangles with vtkTriangleFilter.

Smooth Mesh

Polygonal meshes often contain noise or excessive roughness that affect the quality of the rendered image. For example, isosurfacing low resolution data can show aliasing, or stepping effects. One way to treat this problem is to use smoothing. Smoothing is a process that adjusts the positions of points to reduce the noise content in the surface.

VTK offers two smoothing objects: vtkSmoothPolyDataFilter and vtkWindowedSincPolyDataFilter. Of the two, the vtkWindowedSincPolyDataFilter gives the best results and is slightly faster. The following example (taken from `VTK/Examples/VisualizationAlgorithms/Tcl/smoothFran.tcl`) shows how to use the smoothing filter. The example is the same as the one in the previous section, except that a smoothing filter has been added. **Figure 5–12** shows the effects of smoothing on the decimated mesh.

```
# decimate and smooth data
vtkDecimatePro deci
  deci SetInputConnection [fran GetOutputPort]
  deci SetTargetReduction 0.9
  deci PreserveTopologyOn
vtkSmoothPolyDataFilter smoother
  smoother SetInputConnection [deci GetOutputPort]
  smoother SetNumberOfIterations 50
vtkPolyDataNormals normals
  normals SetInputConnection [smoother GetOutputPort]
  normals FlipNormalsOn
```

```
vtkPolyDataMapper franMapper
  franMapper SetInputConnection [normals GetOutputPort]
vtkActor franActor
  franActor SetMapper franMapper
  eval [franActor GetProperty] SetColor 1.0 0.49 0.25
```

Both smoothing filters are used similarly. There are optional methods for controlling the effects of smoothing along feature edges and on boundaries. Check the online documentation and/or `.h` files for more information.

Clip Data

Clipping, like cutting (see "Cutting" on page 98), uses an implicit function to define a surface with which to clip. Clipping separates a polygonal mesh into pieces, as shown in **Figure 5–13**. Clipping will break polygonal primitives into separate parts on either side of the clipping surface. Like cutting, clipping allows you to set a clip value defining the value of the implicit clipping function.

The following example uses a plane to clip a polygonal model of a cow. The clip value is used to move the plane along its normal so that the model can be clipped at different locations. The example Tcl script shown below is taken from `VTK/Examples/VisualizationAlgorithms/Tcl/ClipCow.tcl`.

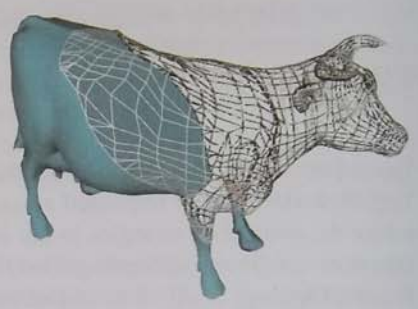


Figure 5–13 Clipping a model.

```
# Read the polygonal data and generate vertex normals
vtkBYUReader cow
 cow SetGeometryFileName "$VTK_DATA_ROOT/Data/Viewpoint/cow.g"
vtkPolyDataNormals cowNormals
 cowNormals SetInputConnection [cow GetOutputPort]

# Define a clip plane to clip the cow in half
vtkPlane plane
  plane SetOrigin 0.25 0 0
  plane SetNormal -1 -1 0
vtkClipPolyData clipper
  clipper SetInputConnection [cowNormals GetOutputPort]
  clipper SetClipFunction plane
    clipper GenerateClippedOutputOn
  clipper SetValue 0.5
vtkPolyDataMapper clipMapper
  clipMapper SetInputConnection [clipper GetOutputPort]
vtkActor clipActor
  clipActor SetMapper clipMapper
  eval [clipActor GetProperty] SetColor $peacock

# Create the rest of the cow in wireframe
vtkPolyDataMapper restMapper
 restMapper SetInputConnection [clipper GetClippedOutputPort]
```

```
vtkActor restActor
 restActor SetMapper restMapper
 [restActor GetProperty] SetRepresentationToWireframe
```

The GenerateClippedOutputOn() method causes the filter to create a second output: the data that was clipped away. This output is shown in wireframe in the figure. If the SetValue() method is used to change the clip value, the implicit function will cut at a point parallel to the original plane, but above or below it. (You could also change the definition of vtkPlane to achieve the same result.)

Generate Texture Coordinates

Several filters are available to generate texture coordinates: vtkTextureMapToPlane, vtkTextureMapToCylinder, and vtkTextureMapToSphere. These objects generated texture coordinates based on a planar, cylindrical, and spherical coordinate system, respectively. Also, the class vtkTransformTextureCoordinates allows you to position the texture map on the surface by translating and scaling the texture coordinates. The following example shows using vtkTextureMapToCylinder to create texture coordinates for an unstructured grid generated from the vtkDelaunay3D object (see "Delaunay Triangulation" on page 218 for more information). The full example can be found at `VTK/Examples/VisualizationAlgorithms/Tcl/GenerateTextureCoords.tcl`.

```
vtkPointSource sphere
 sphere SetNumberOfPoints 25

vtkDelaunay3D del
 del SetInputConnection [sphere GetOutputPort]
 del SetTolerance 0.01

vtkTextureMapToCylinder tmapper
 tmapper SetInputConnection [del GetOutputPort]
 tmapper PreventSeamOn

vtkTransformTextureCoords xform
 xform SetInputConnection [tmapper GetOutputPort]
 xform SetScale 4 4 1

vtkDataSetMapper mapper
 mapper SetInputConnection [xform GetOutputPort]

vtkBMPReader bmpReader
 bmpReader SetFileName "$VTK_DATA_ROOT/Data/masonry.bmp"
vtkTexture atext
 atext SetInputConnection [bmpReader GetOutputPort]
 atext InterpolateOn
vtkActor triangulation
 triangulation SetMapper mapper
 triangulation SetTexture atext
```

In this example a random set of points in the unit sphere is triangulated. The triangulation then has texture coordinates generated over it. These texture coordinates are then scaled in the *i-j* texture coor-

dinate directions in order to cause texture repeats. Finally, a texture map is read in and assigned to the actor.

(As a side note: instances of vtkDataSetMapper are mappers that accept any type of data as input. They use an internal instance of vtkGeometryFilter followed by vtkPolyDataMapper to convert the data into polygonal primitives that can then be passed to the rendering engine. See "Extract Cells as Polygonal Data" on page 104 for further information.)

To learn more about texture coordinates, you may wish to run the example found in `VTK/Examples/Visualization-Algorithms/Tcl/TransformTextureCoords.tcl`. This GUI allows you to select the polygonal model, the texture map, select different texture generation techniques, and provides methods for you to transform the texture using `vtkTransformTexture-Coords`.

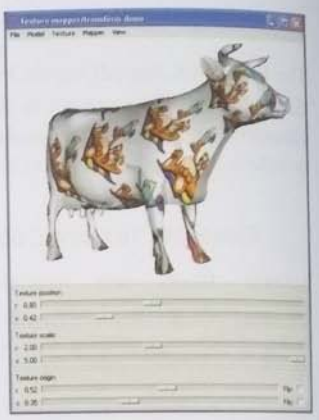


Figure 5–14 Transforming and applying different textures.

5.3 Visualizing Structured Grids

Structured grids are regular in topology, and irregular in geometry (see **Figure 3–2**(c)). Structured grids are often used in numerical analysis (e.g., computational fluid dynamics). The vtkStructuredGrid dataset is composed of hexahedral (vtkHexahedron) or quadrilateral (vtkQuad) cells.

Manually Create vtkStructuredGrid

Structured grids are created by specifying grid dimensions (to define topology) along with a vtkPoints object defining the *x-y-z* point coordinates (to define geometry). This code was derived from `VTK/Examples/DataManipulation/Cxx/SGrid.cxx`.

```
vtkPoints points
   points InsertPoint 0 0.0 0.0 0.0
   ...etc...

vtkStructuredGrid sgrid
   sgrid SetDimensions 13 11 11
   sgrid SetPoints points
```

Make sure that the number of points in the vtkPoints object is consistent with the number of points defined by the product of the three dimension values in the *i*, *j*, and *k* topological directions.

Extract Computational Plane

In most cases, structured grids are processed by filters that accept vtkDataSet as input (see "Visualization Techniques" on page 89). One filter that directly accepts vtkStructuredGrid as input is the vtkStructuredGridGeometryFilter. This filter is used to extract pieces of the grid as points, lines, or polygonal "planes", depending on the specification of the Extent instance variable. (Extent is a 6-vector that describes a (i_{min},i_{max}, j_{min},j_{max}, k_{min},k_{max}) topological region.)

In the following example, we read a structured grid, extract three planes, and warp the planes with the associated vector data (from `VTK/Examples/VisualizationAlgorithms/Tcl/warpComb.tcl`).

```
vtkPLOT3DReader pl3d
  pl3d SetXYZFileName "$VTK_DATA_ROOT/Data/combxyz.bin"
  pl3d SetQFileName "$VTK_DATA_ROOT/Data/combq.bin"
  pl3d SetScalarFunctionNumber 100
  pl3d SetVectorFunctionNumber 202
  pl3d Update
vtkStructuredGridGeometryFilter plane
  plane SetInputConnection [pl3d GetOutputPort]
  plane SetExtent 10 10 1 100 1 100
vtkStructuredGridGeometryFilter plane2
  plane2 SetInputConnection [pl3d GetOutputPort]
  plane2 SetExtent 30 30 1 100 1 100
vtkStructuredGridGeometryFilter plane3
  plane3 SetInputConnection [pl3d GetOutputPort]
  plane3 SetExtent 45 45 1 100 1 100
vtkAppendPolyData appendF
  appendF AddInputConnection [plane GetOutputPort]
  appendF AddInputConnection [plane2 GetOutputPort]
  appendF AddInputConnection [plane3 GetOutputPort]
vtkWarpScalar warp
  warp SetInputConnection [appendF GetOutputPort]
  warp UseNormalOn
  warp SetNormal 1.0 0.0 0.0
  warp SetScaleFactor 2.5
vtkPolyDataNormals normals
  normals SetInputConnection [warp GetOutputPort]
  normals SetFeatureAngle 60
vtkPolyDataMapper planeMapper
  planeMapper SetInputConnection [normals GetOutputPort]
  eval planeMapper SetScalarRange [[pl3d GetOutput] GetScalarRange]
vtkActor planeActor
  planeActor SetMapper planeMapper
```

Subsampling Structured Grids

Structured grids can be subsampled like image data can be (see "Subsampling Image Data" on page 105). The vtkExtractGrid performs the subsampling and data extraction.

```
vtkPLOT3DReader pl3d
  pl3d SetXYZFileName "$VTK_DATA_ROOT/Data/combxyz.bin"
  pl3d SetQFileName "$VTK_DATA_ROOT/Data/combq.bin"
  pl3d SetScalarFunctionNumber 100
  pl3d SetVectorFunctionNumber 202
  pl3d Update
vtkExtractGrid extract
  extract SetInputConnection [pl3d GetOutputPort]
  extract SetVOI 30 30 -1000 1000 -1000 1000
```

```
extract SetSampleRate 1 2 3
extract IncludeBoundaryOn
```

In this example, a subset of the original structured grid (which has dimensions 57x33x25) is extracted with a sampling rate of (1,2,3) resulting in a structured grid with dimensions (1,17,9). The IncludeBoundaryOn method makes sure that the boundary is extracted even if the sampling rate does not pick up the boundary.

5.4 Visualizing Rectilinear Grids

Rectilinear grids are regular in topology, and semi-regular in geometry (see **Figure 3–2**(b)). Rectilinear grids are often used in numerical analysis. The vtkRectilinearGrid dataset is composed of voxel (vtkVoxel) or pixel (vtkPixel) cells.

Manually Create vtkRectilinearGrid

Rectilinear grids are created by specifying grid dimensions (to define topology) along with three scalar arrays to define point coordinates along the *x-y-z* axes (to define geometry). This code was modified from `VTK/Examples/DataManipulation/Cxx/RGrid.cxx`.

```
vtkFloatArray *xCoords = vtkFloatArray::New();

for (i=0; i<47; i++) xCoords->InsertNextValue(x[i]);

vtkFloatArray *yCoords = vtkFloatArray::New();
for (i=0; i<33; i++) yCoords->InsertNextValue(y[i]);

vtkFloatArray *zCoords = vtkFloatArray::New();
for (i=0; i<44; i++) zCoords->InsertNextValue(z[i]);

vtkRectilinearGrid *rgrid = vtkRectilinearGrid::New();
rgrid->SetDimensions(47,33,44);
rgrid->SetXCoordinates(xCoords);
rgrid->SetYCoordinates(yCoords);
rgrid->SetZCoordinates(zCoords);
```

Make sure that the number of scalars in the x, y, and z directions equals the three dimension values in the i, j, and k topological directions.

Extract Computational Plane

In most cases, rectilinear grids are processed by filters that accept vtkDataSet as input (see "Visualization Techniques" on page 89). One filter that directly accepts vtkRectilinearGrid as input is the vtkRectilinearGridGeometryFilter. This filter is used to extract pieces of the grid as points, lines, or polygonal "planes", depending on the specification of the Extent instance variable. (Extent is a 6-vector that describes a (i_{min},i_{max}, j_{min},j_{max}, k_{min},k_{max}) topological region.)

The following example, which we continue from the previous found in `VTK/Examples/DataManipulation/Cxx/RGrid.cxx`, we extract a plane as follows

```
vtkRectilinearGridGeometryFilter *plane =
  vtkRectilinearGridGeometryFilter::New();
plane->SetInput(rgrid);
plane->SetExtent(0,46, 16,16, 0,43);
```

5.5 Visualizing Unstructured Grids

Unstructured grids are irregular in both topology and geometry (see **Figure 3–2**(f)). Unstructured grids are often used in numerical analysis (e.g., finite element analysis). Any and all cell types can be represented in an unstructured grid.

Manually Create vtkUnstructuredGrid

Unstructured grids are created by defining geometry via a vtkPoints instance, and defining topology by inserting cells. (This script was derived from the example `VTK/Examples/DataManipulation/Tcl/BuildUGrid.tcl`.)

```
vtkPoints tetraPoints
 tetraPoints SetNumberOfPoints 4
 tetraPoints InsertPoint 0 0 0 0
 tetraPoints InsertPoint 1 1 0 0
 tetraPoints InsertPoint 2 .5 1 0
 tetraPoints InsertPoint 3 .5 .5 1
vtkTetra aTetra
 [aTetra GetPointIds] SetId 0 0
 [aTetra GetPointIds] SetId 1 1
 [aTetra GetPointIds] SetId 2 2
 [aTetra GetPointIds] SetId 3 3
vtkUnstructuredGrid aTetraGrid
 aTetraGrid Allocate 1 1
 aTetraGrid InsertNextCell [aTetra GetCellType] [aTetra GetPointIds]
 aTetraGrid SetPoints tetraPoints
  ...insert other cells if any...
```

It is mandatory that you invoke the Allocate() method prior to inserting cells into an instance of vtkUnstructuredGrid. The values supplied to this method are the initial size of the data, and the size to extend the allocation by when additional memory is required. Larger values generally give better performance (since fewer memory reallocations are required).

Extract Portions of the Mesh

In most cases, unstructured grids are processed by filters that accept vtkDataSet as input (see "Visualization Techniques" on page 89). One filter that directly accepts vtkUnstructuredGrid as input is the vtkExtractUnstructuredGrid. This filter is used to extract portions of the grid using a range of point ids, cell ids, or geometric bounds (the Extent instance variable which defines a bounding box). This script was derived from the Tcl script `VTK/Examples/VisualizationAlgorithms/Tcl/ExtractUGrid.tcl`.

```
vtkDataSetReader reader
  reader SetFileName "$VTK_DATA_ROOT/Data/blow.vtk"
  reader SetScalarsName "thickness9"
  reader SetVectorsName "displacement9"
vtkCastToConcrete castToUnstructuredGrid
  castToUnstructuredGrid SetInputConnection [reader GetOutputPort]
vtkWarpVector warp
  warp SetInput [castToUnstructuredGrid GetUnstructuredGridOutput]

vtkConnectivityFilter connect
  connect SetInputConnection [warp GetOutputPort]
  connect SetExtractionModeToSpecifiedRegions
  connect AddSpecifiedRegion 0
  connect AddSpecifiedRegion 1
vtkDataSetMapper moldMapper
  moldMapper SetInputConnection [reader GetOutputPort]
  moldMapper ScalarVisibilityOff
vtkActor moldActor
  moldActor SetMapper moldMapper
  [moldActor GetProperty] SetColor .2 .2 .2
  [moldActor GetProperty] SetRepresentationToWireframe

vtkConnectivityFilter connect2
  connect2 SetInputConnection [warp GetOutputPort]
  connect2 SetExtractionModeToSpecifiedRegions
  connect2 AddSpecifiedRegion 2
vtkExtractUnstructuredGrid extractGrid
  extractGrid SetInputConnection [connect2 GetOutputPort]
  extractGrid CellClippingOn
  extractGrid SetCellMinimum 0
  extractGrid SetCellMaximum 23
vtkGeometryFilter parison
  parison SetInputConnection [extractGrid GetOutputPort]
vtkPolyDataNormals normals2
  normals2 SetInputConnection [parison GetOutputPort]
  normals2 SetFeatureAngle 60
vtkLookupTable lut
  lut SetHueRange 0.0 0.66667
vtkPolyDataMapper parisonMapper
  parisonMapper SetInputConnection [normals2 GetOutputPort]
  parisonMapper SetLookupTable lut
  parisonMapper SetScalarRange 0.12 1.0
vtkActor parisonActor
  parisonActor SetMapper parisonMapper
```

In this example, we are using cell clipping (i.e., using cell ids) in combination with a connectivity filter to extract portions of the mesh. Similarly, we could use point ids and a geometric extent to extract portions of the mesh. The vtkConnectivityFilter (and a related class vtkPolyDataConnectivityFilter) are used to extract connected portions of a dataset. (Cells are connected when they share points.) The SetExtractionModeToSpecifiedRegions() method indicates to the filter which connected region to extract. By default, the connectivity filters extract the largest connected regions encountered. How-

ever, it is also possible to specify a particular region as this example does, which of course requires some experimentation to determine which region is which.

Contour Unstructured Grids

A special contouring class is available to generate isocontours for unstructured grids. The class vtkContourGrid is a higher-performing version than the generic vtkContourFilter isocontouring filter. Normally you do not need to instantiate this class directly since vtkContourFilter will automatically create an internal instance of vtkContourGrid if it senses that its input is of type vtkUnstructuredGrid.

This concludes our overview of visualization techniques. You may also wish to refer to the next chapter which describes image processing and volume rendering. Also, see "Summary Of Filters" on page 444 for a summary of the filters in VTK.

Image Processing & Visualization

Image datasets, represented by the class vtkImageData, are regular in topology and geometry as shown in **Figure 6–1**. This data type is structured, meaning that the locations of the data points are implicitly defined using just the few parameters origin, spacing and dimensions. Medical and scientific scanning devices such as CT, MRI, ultrasound scanners, and confocal microscopes often produce data of this type. Conceptually, the vtkImageData dataset is composed of voxel (vtkVoxel) or pixel (vtkPixel) cells. However, the structured nature of this dataset allows us to store the data values in a simple array rather than explicitly creating the vtkVoxel or vtkPixel cells.

In VTK, image data is a special data type that can be processed and rendered in several ways. Although not an exhaustive classification, most of the operations performed on image data in VTK fall into one of the three categories—image processing, geometry extraction, or direct rendering. Dozens of image processing filters exist that can operate on image datasets. These filters take vtkImageData as input and produce vtkImageData as output. Geometry extraction filters exist that convert vtkImageData into vtkPolyData. For example, the vtkContourFilter can extract iso-valued contours in

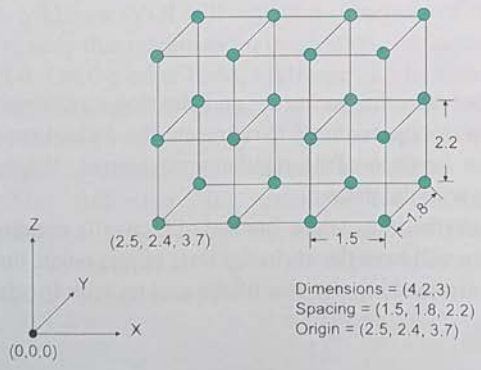


Figure 6–1 The vtkImageData structure is defined by dimensions, spacing, and origin. The dimensions are the number of voxels or pixels along each of the major axes. The origin is the world coordinate position of the lower left corner of the first slice of the data. The spacing is the distance between pixels along each of the three major axes.

triangular patches from the image dataset. Finally, there are various mappers and specialized actors to render vtkImageData, including techniques ranging from simple 2D image display to volume rendering.

In this chapter we examine some important image processing techniques. We will discuss basic image display, image processing, and geometry extraction as elevation maps. Other geometry extraction techniques such as contouring are covered in Chapter 5. Volume rendering of both vtkImageData and vtkUnstructuredGrid is covered in Chapter 7.

6.1 Manually Creating vtkImageData

Creating image data is straightforward: you need only define the dimensions, origin, and spacing of the dataset. The origin is the world coordinate position of the lower left hand corner of the dataset. The dimensions are the number of voxels or pixels along each of the three major axes. The spacing is the height, length, and width of a voxel or the distance between neighboring pixels, depending on whether you view your data as homogeneous boxes or sample points in a continuous function.

In this first example we will assume that we have an array of unsigned character values pointed to by the variable `data`, and containing size[0] by size[1] by size[2] samples. We generated this data outside of VTK, and now we want to get this data into a vtkImageData so that we can use the VTK filtering and rendering operations. We will give VTK a pointer into the memory, but we will manage the deletion of the memory ourselves.

The first thing we need to do is create an array of unsigned chars to store the data. We use the SetArray() method to specify the pointer to the data and its size, with the final argument indicating that VTK should not free this memory.

```
vtkUnsignedCharArray *array = vtkUnsignedCharArray::New();
array->SetArray( data, size[0]*size[1]*size[2], 1);
```

The second step is to create the image data. We must take care that all values match—the scalar type of the image data must be unsigned char, and the dimensions of the image data must match the size of the data.

```
imageData = vtkImageData::New();
imageData->GetPointData()->SetScalars(array);
imageData->SetDimensions(size);
imageData->SetScalarType(VTK_UNSIGNED_CHAR);
imageData->SetSpacing(1.0, 1.0, 1.0 );
imageData->SetOrigin(0.0, 0.0, 0.0 );
```

What's important about image datasets is that because the geometry and topology are implicitly defined by the dimensions, origin, and spacing, the storage required to represent the dataset *structure* is tiny. Also, computation on the structure is fast because of its regular arrangement. What does require storage is the attribute data that goes along with the dataset.

In this next example, we will use C++ to create the image data. Instead of manually creating the data array and associating it with the image data, we will have the vtkImageData object create the scalar data for us. This eliminates the possibility of mismatching the size of the scalars with the dimensions of the image data.

```
// Create the image data
vtkImageData *id = vtkImageData::New();
id->SetDimensions(10,25,100);
id->SetScalarTypeToUnsignedShort();
id->SetNumberOfScalarComponents(1);
id->AllocateScalars();

// Fill in scalar values
unsigned short *ptr = (unsigned short *) id->GetScalarPointer();
for (int i=0; i<10*25*100; i++)
{
*ptr++ = i;
}
```

In this example, the convenience method AllocateScalars() is used to allocate storage for the image data. Notice that this call is made after the scalar type and number of scalar components have been set (up to four scalar components can be set). Then the method GetScalarPointer(), which returns a void*, is invoked and the result is cast to unsigned short. We can do this knowing that the type is unsigned short because we specified this earlier. Imaging filters in VTK work on images of any scalar type. Their RequestData() methods query the scalar type and then switch on the type to a templated function in their implementation. VTK has by design chosen to avoid exposing the scalar type as a template parameter, in its public interface. This makes it easy to provide an interface to wrapped languages, such as Tcl, Java and Python which lack templates.

6.2 Subsampling Image Data

As we saw in "Extract Subset of Cells" on page 103, extracting parts of a dataset is often desirable. The filter vtkExtractVOI extracts pieces of the input image dataset. The filter can also subsample the data, although vtkImageReslice (covered later) provides more flexibility with resampling data. The output of the filter is also of type vtkImageData.

There are actually two similar filters that perform this clipping functionality in VTK: vtkExtractVOI and vtkImageClip. The reason for two separate versions is historical—the imaging pipeline used to be separate from the graphics pipeline, with vtkImageClip working only on vtkImageData in the imaging pipeline and vtkExtractVOI working only on vtkStructuredPoints in the graphics pipeline. These distinctions are gone now, but there are still some differences between these filters. vtkExtractVOI will extract a subregion of the volume and produce a vtkImageData that contains exactly this information. In addition, vtkExtractVOI can be used to resample the volume within the VOI. On the other hand, vtkImageClip by default will pass the input data through to the output unchanged except for the extent information. A flag may be set on this filter to force it to produce the exact amount of data only, in which case the region will be copied into the output vtkImageData. The vtkImageClip filter cannot resample the volume.

The following Tcl example (taken from `VTK/Examples/ImageProcessing/Tcl/Contours2D.tcl`) demonstrates how to use vtkExtractVOI. It extracts a piece of the input volume, and then subsamples it. The output is passed to a vtkContourFilter. (You may want to try removing vtkExtractVOI and compare the results.)

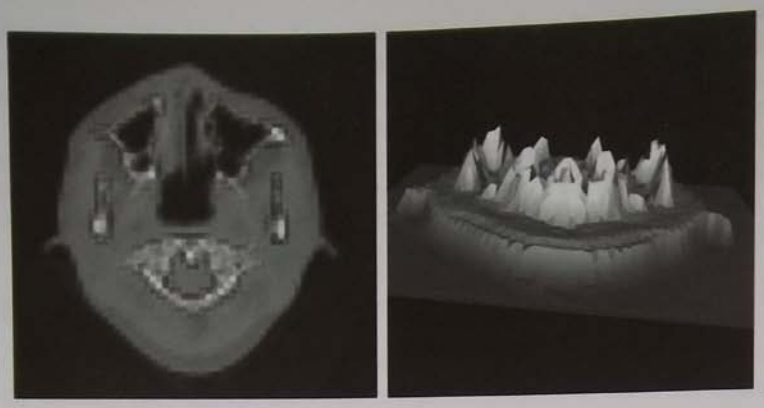


Figure 6–2 Image warped by scalar values.

```
# Quadric definition
vtkQuadric quadric
    quadric SetCoefficients .5 1 .2 0 .1 0 0 .2 0 0
vtkSampleFunction sample
    sample SetSampleDimensions 30 30 30
    sample SetImplicitFunction quadric
    sample ComputeNormalsOff

vtkExtractVOI extract
    extract SetInputConnection [sample GetOutputPort]
    extract SetVOI 0 29 0 29 15 15
    extract SetSampleRate 1 2 3
vtkContourFilter contours
    contours SetInputConnection [extract GetOutputPort]
    contours GenerateValues 13 0.0 1.2
vtkPolyDataMapper contMapper
    contMapper SetInputConnection [contours GetOutputPort]
    contMapper SetScalarRange 0.0 1.2
vtkActor contActor
    contActor SetMapper contMapper
```

Note that this script extracts a plane from the original data by specifying the volume of interest (VOI) as (0,29,0,29,15,15) (i_{min},i_{max}, j_{min},j_{max}, k_{min},k_{max}) and that the sample rate is set differently along each of the *i-j-k* topological axes. You could also extract a subvolume or even a line or point by modifying the VOI specification. (The volume of interest is specified using 0-offset values.)

6.3 Warp Based On Scalar Values

One common use of image data is to store elevation values as an image. These images are frequently called range maps or elevation maps. The scalar value for each pixel in the image represents an elevation, or range value. A common task in visualization is to take such an image and warp it to produce an accurate 3D representation of the elevation or range data. Consider **Figure 6–2** which shows an image that has been warped based on its scalar value. The left image shows the original image while the right view shows the image after warping to produce a 3D surface.

The pipeline to perform this visualization is fairly simple, but there is an important concept to understand. The original data is an image which has implicit geometry and topology. Warping the image will result in a 3D surface where geometry is no longer implicit. To support this we first convert the image to a vtkPolyData representation using vtkImageDataGeometryFilter. Then we perform the warp and connect to a mapper. In the script below you'll note that we also make use of vtkWindowLevelLookupTable to provide a greyscale lookup-table instead of the default red to blue lookup table.

```
vtkImageReader reader
  reader SetDataByteOrderToLittleEndian
  reader SetDataExtent 0 63 0 63 40 40
  reader SetFilePrefix "$VTK_DATA_ROOT/Data/headsq/quarter"
  reader SetDataMask 0x7fff

vtkImageDataGeometryFilter geometry
 geometry SetInputConnection [reader GetOutputPort]

vtkWarpScalar warp
 warp SetInputConnection [geometry GetOutputPort]
 warp SetScaleFactor 0.005

vtkWindowLevelLookupTable wl

vtkPolyDataMapper mapper
 mapper SetInputConnection [warp GetOutputPort]
 mapper SetScalarRange 0 2000
 mapper ImmediateModeRenderingOff
 mapper SetLookupTable wl

vtkActor actor
 actor SetMapper mapper
```

This example is often combined with other techniques. If you want to warp the image with its scalar value and then color it with a different scalar field you would use the vtkMergeFilter. Another common operation is to reduce the number of polygons in the warped surface. Because these surfaces were generated from images they tend to have a large number of polygons. You can use vtkDecimatePro to reduce the number. You should also consider using vtkTriangleFilter followed by vtkStripper to convert the polygons (squares) into triangle strips which tend to render faster and consume less memory.

6.4 Image Display

There are several ways to directly display image data. Two methods that are generally applicable for displaying 2D images are described in this section. Volume rendering is the method for directly displaying 3D images (volumes) and is described in detail in Chapter 7.

Image Viewer

vtkImageViewer2 is a convenient class for displaying images. It replaces an earlier version of the class vtkImageViewer. vtkImageViewer2 internally encapsulates several objects - vtkRenderWindow, vtkRenderer, vtkImageActor and vtkImageMapToWindowLevelColors providing an easy to use class

that can be dropped into your application. This class also creates an interactor style (vtkInteractorStyleImage) customized for images, that allows zooming and panning of images, and supports interactive window/level operations on the image. (See "Interactor Styles" on page 43 and "vtkRenderWindow Interaction Style" on page 283 for more information about interactor styles.) vtkImageViewer2 (unlike vtkImageViewer) uses the 3D rendering and texture mapping engine to draw an image on a plane. This allows for rapid rendering, zooming, and panning. The image is placed in the 3D scene at a depth based on the depth-coordinate of the particular image slice. Each call to SetSlice() changes the image data (slice) displayed and changes the depth of the displayed slice in the 3D scene. This can be controlled by the AutoAdjustCameraClippingRange option on the InteractorStyle. You may also set the orientation to display an XY, YZ or an XZ slice.

An example of using an image viewer to browse through the slices in a volume can be found in Widgets/Testing/Cxx/TestImageActorContourWidget.cxx. The following excerpt illustrates a typical usage of this class.

```
vtkImageViewer2 *ImageViewer = vtkImageViewer2::New();
ImageViewer->SetInput(shifter->GetOutput());
ImageViewer->SetColorLevel(127);
ImageViewer->SetColorWindow(255);
ImageViewer->SetupInteractor(iren);
ImageViewer->SetSlice(40);
ImageViewer->SetOrientationToXY();
ImageViewer->Render();
```

It is possible to mix images and geometry, for instance :

```
viewer->SetInput( myImage );
viewer->GetRenderer()->AddActor( myActor );
```

This can be used to annotate an image with a PolyData of "edges" or highlight sections of an image or display a 3D isosurface with a slice from the volume, etc. Any portions of your geometry that are in front of the displayed slice will be visible; any portions of your geometry that are behind the displayed slice will be obscured.

The window-level transfer function is defined as shown in **Figure 6–3**. The level is the data value that centers the window. The width (i.e., window) defines the range of data values that are mapped to the display. The slope of the resulting transfer function determines the amount of contrast in the final image. All data values outside of the window are clamped to the data values at the boundaries of the window..

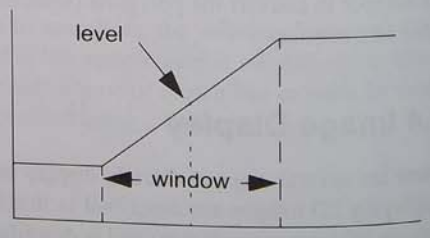


Figure 6–3 Window-level transfer function.

Image Actor

Using a vtkImageViewer is convenient when you would simply like to display the image in a window by itself or accompanied by some simple 2D annotation. The vtkImageActor actor class is useful

when you want to display your image in a 3D rendering window. The image is displayed by creating a polygon representing the bounds of the image and using hardware texture mapping to paste the image onto the polygon. On most platforms this enables you to rotate, pan, and zoom your image with bilinear interpolation in real-time. By changing the interactor to a vtkInteractorStyleImage you can limit rotations so that the 3D render window operates as a 2D image viewer. The advantage to using the 3D render window for image display is that you can easily embed multiple images and complex 3D annotation into one window.

The vtkImageActor object is a composite class that encapsulates both an actor and a mapper into one class. It is simple to use, as can be seen in this example.

```
vtkBMPReader bmpReader
bmpReader SetFileName "$VTK_DATA_ROOT/Data/masonry.bmp"

vtkImageActor imageActor
imageActor SetInput [bmpReader GetOutput]
```

This image actor can then be added to the renderer using the AddProp() method. The vtkImageActor class expects that its input will have a length of 1 along one of the three dimensions, with the image extending along the other two dimensions. This allows the vtkImageActor to be connected to a volume through the use of a clipping filter without the need to reorganize the data if the clip is performed along the X or Y axis. (Note: the input image to vtkImageActor must be of type unsigned char. If your image type is different, you can use vtkImageCast or vtkImageShiftScale to convert to unsigned char.)

vtkImagePlaneWidget

Widgets are covered in "Interaction, Widgets and Selections" on page 255. Suffice it to mention that this widget defines a plane that can be interactively placed in an image volume, with the plane displaying resliced data through the volume. Interpolation options to reslice the data include nearest neighbor, linear and cubic. The plane position and orientation can be interactively manipulated. One can also window level interactively on the resliced plane and optionally display window level and position annotations.

```
vtkImagePlaneWidget* planeWidgetX = vtkImagePlaneWidget::New();
planeWidgetX->SetInteractor( iren);
planeWidgetX->RestrictPlaneToVolumeOn();
planeWidgetX->SetResliceInterpolateToNearestNeighbour();
planeWidgetX->SetInput(v16->GetOutput());
planeWidgetX->SetPlaneOrientationToXAxes();
planeWidgetX->SetSliceIndex(32);
planeWidgetX->DisplayTextOn();
planeWidgetX->On();
```

6.5 Image Sources

There are some image processing objects that produce output but do not take any data objects as input. These are known as image sources, and some of the VTK image sources are described here.

Refer to "Source Objects" on page 444 or to the Doxygen documentation for a more complete list of available image sources.

ImageCanvasSource2D

The vtkImageCanvasSource2D class creates a blank two-dimensional image of a specified size and type and provides methods for drawing various primitives into this blank image. Primitives include boxes, lines, and circles; a flood fill operation is also provided. The following example illustrates the use of this source by creating a 512x512 pixel image and drawing several primitives into it. The resulting image is shown in **Figure 6–4**.

```
#set up the size and type of the image canvas
vtkImageCanvasSource2D imCan
  imCan SetScalarTypeToUnsignedChar
  imCan SetExtent 0 511 0 511 0 0
# Draw various primitives
  imCan SetDrawColor 86
  imCan FillBox 0 511 0 511
  imCan SetDrawColor 0
  imCan FillTube 500 20 30 400 5
  imCan SetDrawColor 255
  imCan DrawSegment 10 20 500 510
  imCan SetDrawColor 0
  imCan DrawCircle 400 350 80.0
  imCan SetDrawColor 255
  imCan FillPixel 450 350
  imCan SetDrawColor 170
  imCan FillTriangle 100 100 300 150 150 300

#Show the resulting image
  vtkImageViewer viewer
  viewer SetInputConnection [imCan GetOutputPort]
  viewer SetColorWindow 256
  viewer SetColorLevel 127.5
```

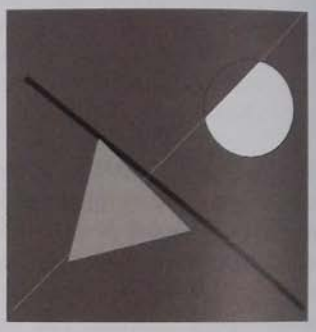


Figure 6–4 The results from a vtkImageCanvasSource2D source after drawing various primitives.

ImageEllipsoidSource

If you would like to write your own image source using a templated execute function, vtkImageEllipsoidSource is a good starting point. This object produces a binary image of an ellipsoid as output based on a center position, a radius along each axis, and the inside and outside values. The output scalar type can also be specified, and this is why the execute function is templated. This source is used internally by some of the imaging filters such as vtkImageDilateErode3D.

If you want to create a vtkImageBoxSource, for example, to produce a binary image of a box, you could start by copying the vtkImageEllipsoidSource source and header files and doing a global search and replace. You would probably change the instance variable Radius to be Length since this is a more appropriate description for a box source. Finally, you would replace the code within the templated function vtkImageBoxSourceExecute to create the box image rather than the ellipsoid image. (For more information on creating image processing filters see "A Threaded Imaging Filter" on page 401.)

ImageGaussianSource

The vtkImageGaussianSource object produces an image with pixel values determined according to a Gaussian distribution using a center location, a maximum value, and a standard deviation. The data type of the output of this image source is always floating point (i.e., `double`).

If you would like to write your own source that produces just one type of output image, for example float, then this might be a good class to use as a starting point. Comparing the source code for vtkImageGaussianSource with that for vtkImageEllipsoidSource, you will notice that the filter implementation is in the RequestData() method for vtkImageGaussianSource, whereas in vtkImageEllipsoidSource the RequestData() method calls a templated function that contains the implementation.

ImageGridSource

If you would like to annotate your image with a 2D grid, vtkImageGridSource can be used to create an image with the grid pattern (**Figure 6–5**). The following example illustrates this use by blending a grid pattern with a slice from a CT dataset. The reader is a vtkImageReader that produces a 64 by 64 image.

Figure 6–5 A grid pattern created by a vtkImageGridSource is overlayed on a slice of a CT dataset.

```
vtkImageGridSource imageGrid
imageGrid SetGridSpacing 16 16 0
imageGrid SetGridOrigin 0 0 0
imageGrid SetDataExtent 0 63 0 63 0 0
imageGrid SetLineValue 4095
imageGrid SetFillValue 0
imageGrid SetDataScalarTypeToShort

vtkImageBlend blend
blend SetOpacity 0 0.5
blend SetOpacity 1 0.5
blend AddInputConnection [reader GetOutputPort]
blend AddInputConnection [imageGrid GetOutputPort]
vtkImageViewer viewer
viewer SetInputConnection [blend GetOutputPort]
viewer SetColorWindow 1000
viewer SetColorLevel 500
viewer Render
```

ImageNoiseSource

The vtkImageNoiseSource image source can be used to generate an image filled with random numbers between some specified minimum and maximum values. The type of the output image is floating point.

One thing to note about vtkImageNoiseSource is that it will produce a different image every time it executes. Normally, this is the desired behavior of a noise source, but this has negative implications in a streaming pipeline with overlap in that the overlapping region will not have the same values across the two requests. For example, assume you set up a pipeline with a vtkImageNoiseSource

connected to an ImageMedianFilter which is in turn connected to a vtkImageDataStreamer. If you specify a memory limit in the streamer such that the image will be computed in two halves, the first request the streamer makes would be for half the image. The median filter would need slightly more than half of the input image (based on the extent of the kernel) to produce the requested output image. When the median filter executes the second time to produce the second half of the output image, it will again request the overlap region, but this region will contain different values, causing any values computed using the overlap region to be inconsistent.

ImageSinusoidSource

The vtkImageSinusoidSource object can be used to create an image of a specified size where the pixel values are determined by a sinusoid function given direction, period, phase, and amplitude values. The output of the sinusoid source is floating point. In the image shown in **Figure 6–6**, the output of the sinusoid source has been converted to unsigned char values and volume rendered. This same output was passed through an outline filter to create the bounding box seen in the image.

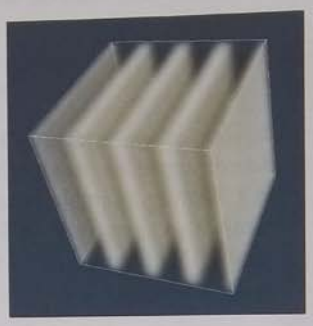


Figure 6–6 The output of the sinusoid source shown on the left has been converted to unsigned char and volume rendered.

```
vtkImageSinusoidSource ss
  ss SetWholeExtent 0 99 0 99 0 99
  ss SetAmplitude 63
  ss SetDirection 1 0 0
  ss SetPeriod 25
```

6.6 Image Processing

Now we will consider a few examples that process image data. This is not an exhaustive description of all filters, but it will get you started using VTK's image processing filters. You may wish to refer to the Doxygen documentation for more information. In addition, a more complete description can be found in "Imaging Filters" on page 450.

Convert Scalar Type

It is sometimes necessary to convert an input image of one scalar type to an output image of another scalar type. For example, certain filters only operate on input of a specific scalar type such as float or integer. Alternatively, you may wish to use an image directly as color values without using a lookup table to map the scalars into color. To do this the image scalar type must be unsigned char.

There are two classes in VTK that can be used to convert the scalar type of an image. The vtkImageCast filter allows you to specify the output scalar type. This filter works well when, for example, you know that your image contains only values between 0 and 255, but is currently stored as unsigned integers. You can then use vtkImageCast to convert the image to unsigned char. If you set the ClampOverflow instance variable to on, then values outside the range of the output scalar type

will be clamped before assignment. For example, if your input image contained a 257, it would be stored in the output image as 255 if ClampOverflow is on; it will be stored as 1 if ClampOverflow is not on.

If you need to convert a floating point image containing intensities in the [-1,1] range to an unsigned char image, vtkImageCast would not work. In this situation, vtkImageShiftScale would be the correct filter to perform the conversion. This filter allows you to specify a shift and scale operation to be performed on the input image pixel values before they are stored in the output image. To perform this conversion, the shift would be set to +1 and the scale would be set to 127.5. This would map the value -1 to (-1+1)*127.5 = 0, and it would map the value +1 to (+1+1)*127.5 = 255.

Change Spacing, Origin, or Extent

A frequent source of confusion in VTK occurs when users needs to change the origin, spacing, or extent of their data. It is tempting to get the output of some filter, and adjust these parameters to the desired values. However, as users quickly note this is only a temporary solution – the next time the pipeline updates, these changes are lost and the data will revert back to its previous shape and location. To change these parameters, it is necessary to introduce a filter into the pipeline to make the change. The vtkImageChangeInformation filter can be used to adjust the origin, spacing, and extent of a vtkImageData. The origin and spacing values can be set explicitly, as can the start of the output whole extent. Since the dimensions of the data do not change, the start of the whole extent fully defines the output whole extent. The vtkImageChangeInformation filter also contains several convenience methods to center the image, translate the extent, or translate and scale the origin and spacing values.

In the following example we use a vtkImageReader to read in the raw medical data for a CT scan. We then pass this data through a 3D vtkImageGradient and display the result as a color image.

```
vtkImageReader reader
  reader SetDataByteOrderToLittleEndian
  reader SetDataExtent 0 63 0 63 1 93
  reader SetFilePrefix "$VTK_DATA_ROOT/Data/headsq/quarter"
  reader SetDataMask 0x7fff

vtkImageGradient gradient
  gradient SetInputConnection [reader GetOutputPort]
  gradient SetDimensionality 3

vtkImageViewer viewer
  viewer SetInputConnection [gradient GetOutputPort]
  viewer SetZSlice 22
  viewer SetColorWindow 400
  viewer SetColorLevel 0
```

Append Images

There are two different classes for appending images in VTK allowing images to be combined either spatially or by concatenating the components. Images may be combined spatially to form a larger image using vtkImageAppend, while vtkImageAppendComponents can be used, for example, to combine independent red, green, and blue images to form a single RGB image.

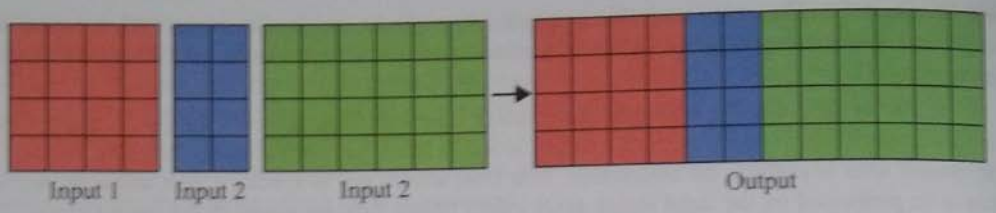


Figure 6–7 Appending three 2D images along the X axis with PreserveExtents off.

Recall that an image may be 1-, 2-, or 3-dimensional. When combined spatially, the output image may increase dimensionality. For example, you can combine multiple independent one-dimensional rows to form a two-dimensional image, or you may combine a stack of 2D images to form a volume. The vtkImageAppend filter combines a set of images spatially using one of two methods. If the PreserveExtents instance variable is turned off, then the images are appended along the axis defined by the AppendAxis instance variable. Except along the AppendAxis, the input images must all have the same dimensions, and they must all have the same scalar type and number of scalar components. The origin and spacing of the output image will be the same as the origin and spacing of the first input image. An example of combining three 2D images along AppendAxis 0 (the X axis) to form a wider 2D image is shown in **Figure 6–7**. In **Figure 6–8** we see an example where a set of 2D XY images are combined along AppendAxis 2 (the Z axis) to form a volume.

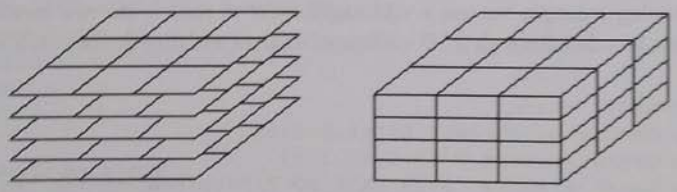


Figure 6–8 Appending 2D (XY) images along the Z axis to form a 3D volume.

If the PreserveExtents instance variable is on, the vtkImageAppend filter will create an output that contains the set of input images based on the union of their whole extents. The origin and spacing are copied from the first input image, and the output image is initialized to 0. Each input image is then copied into the output image. No blending is performed when two input images both define the same pixel in the output image. Instead, the order of the input images determines the value in the output image, with the highest numbered (last added) input image value stored in the output pixel. An example of appending images with PreserveExtents on with three co-planar non-overlapping 2D input images is shown in **Figure 6–9**.

Note that vtkImageAppend considers the pixel or voxel extents of the data rather than world coordinates. This filter functions as if all input images have the same origin and spacing, and therefore the location of each image relative to the other input images is defined solely by the extent of that image.

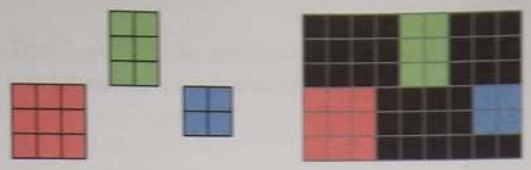


Figure 6–9 Appending 2D images with PreserveExtents on.

The vtkImageAppendComponents filter can be used to combine the components of multiple inputs that all have the same scalar type and dimensions. The origin and spacing of the output image will be obtained from the first input image. The output image will have a number of components equal to the sum of the number of components of all the input images. Frequently this filter is used to combine independent red, green, and blue images into a single color image. An example of this can be seen in **Figure 6–10**.

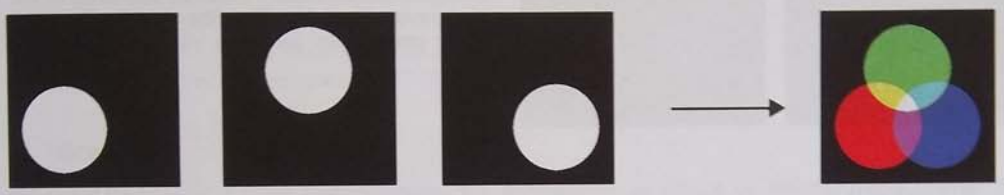


Figure 6–10 Using vtkImageAppendComponents to combine three single-component images into a single color image.

Map Image to Color

vtkImageMapToColors is used for transforming a grayscale image into a color one. (See **Figure 6–11**.) The input's scalar values may be of any data type. A user-selected component (chosen using the SetActiveComponent() method of vtkImageMapToColors) of the input's scalar values is mapped through an instance of vtkScalarsToColors, and the color values from the lookup table are stored in the output image. vtkImageMapToWindowLevelColors, a subclass of vtkImageMapToColors, additionally modulates the color values with a window-level function (see **Figure 6–3**) before storing them in the output image. The scalar type of the output image of either filter is unsigned char.

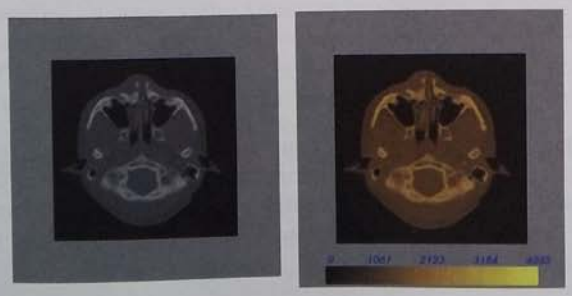


Figure 6–11 The image on the right is the result of passing the image on the left through a vtkImageMapToColors filter. The color map used is shown in the scalar bar at the bottom of the right-hand image.

Image Luminance

The vtkImageLuminance filter is basically the opposite of vtkImageMapToColors. (See **Figure 6–12**.) It converts an RGB image (red, green, and blue color components) to a single-component gray-scale image using the following formula.

```
luminance = 0.3*R + 0.59*G + 0.11*B
```

In this formula, R is the first component (red) of the input image, G is the second component (green), and B is the third component (blue). This calculation computes how bright a given color specified using RGB components appears.

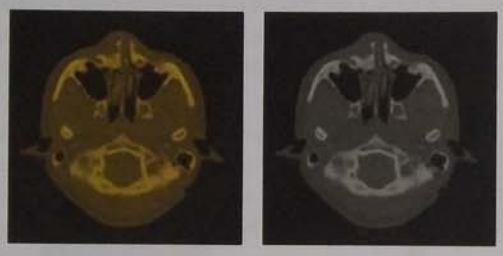


Figure 6–12 The image on the right is the result of passing the image on the left (the output of vtkImageMapToColors in the previous section) through a vtkImageLuminance filter. Note the similarity of the output image from this filter (the right-hand image) and the input image passed to vtkImageMapToColors.

Histogram

vtkImageAccumulate is an image filter that produces generalized histograms of up to four dimensions. This is done by dividing the component space into discrete bins, then counting the number of pixels corresponding to each bin. The input image may be of any scalar type, but the output image will always be of integer type. If the input image has only one scalar component, then the output image will be one-dimensional, as shown in **Figure 6–13**. (This example is taken from `VTK/Examples/ImageProcessing/Tcl/Histogram.tcl`.)

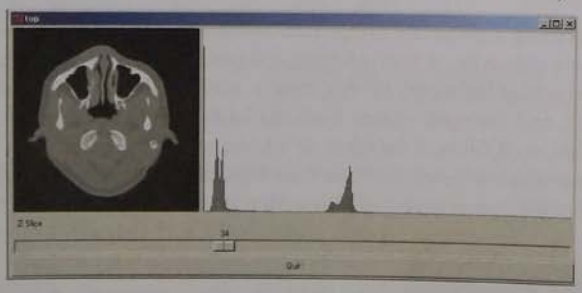


Figure 6–13 The vtkImageAccumulate class is used to generate a one dimensional histogram from a one-component input image.

Image Logic

vtkImageLogic is an image processing filter that takes one or two inputs and performs a boolean logic operation on them (**Figure 6–14**). Most standard operations are supported including AND, OR, XOR, NAND, NOR, and NOT. This filter has two inputs, although for unary operations such as NOT only the first input is required. In the example provided below you will notice we use vtkImageEllipsoidSource to generate the two input images.

```
vtkImageEllipsoidSource sphere1
  sphere1 SetCenter 95 100 0
  sphere1 SetRadius 70 70 70

vtkImageEllipsoidSource sphere2
  sphere2 SetCenter 161 100 0
  sphere2 SetRadius 70 70 70

vtkImageLogic xor
  xor SetInputConnection 0 \
    [sphere1 GetOutputPort]
  xor SetInputConnection 1 [sphere2 \
    GetOutputPort]
  xor SetOutputTrueValue 150
  xor SetOperationToXor

vtkImageViewer viewer
  viewer SetInput [xor GetOutput]
  viewer SetColorWindow 255
  viewer SetColorLevel 127.5
```

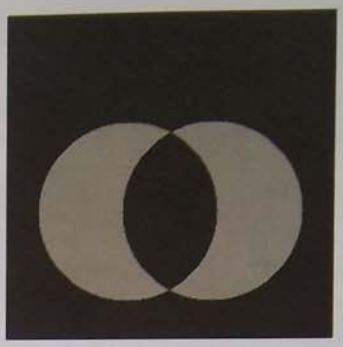


Figure 6–14 Result of image logic.

Gradient

vtkImageGradient is a filter that computes the gradient of an image or volume. You can control whether it computes a two- or three-dimensional gradient using the SetDimensionality() method. It will produce an output with either two or three scalar components per pixel depending on the dimensionality you specify. The scalar components correspond to the x, y, and optionally z components of the gradient vector. If you only want the gradient magnitude you can use the vtkImageGradientMagnitude filter or vtkImageGradient followed by vtkImageMagnitude.

vtkImageGradient computes the gradient by using central differences. This means that to compute the gradient for a pixel we must look at its left and right neighbors. This creates a problem for the pixels on the outside edges of the image since they will be missing one of their two neighbors. There are two solutions to this problem and they are controlled by the HandleBoundaries instance variable. If HandleBoundaries is on, then vtkImageGradient will use a modified gradient calculation for all of the edge pixels. If HandleBoundaries is off, vtkImageGradient will ignore those edge pixels and produce a resulting image that is smaller than the original input image.

Gaussian Smoothing

Smoothing an image with a Gaussian kernel is similar to the gradient calculation done above. It has a dimensionality that controls what dimension Gaussian kernel to convolve against. The class vtkGaussianSmooth also has SetStandardDeviations() and SetRadiusFactors() methods that control the shape of the Gaussian kernel and when to truncate it. The example provided below is very similar to the gradient calculation. We start with a vtkImageReader connected to the vtkImageGaussianSmooth which finally connects to the vtkImageViewer.

```
vtkImageReader reader
  reader SetDataByteOrderToLittleEndian
  reader SetDataExtent 0 63 0 63 1 93
```

```
    reader SetFilePrefix "$VTK_DATA_ROOT/Data/headsq/quarter"
    reader SetDataMask 0x7fff

vtkImageGaussianSmooth smooth
    smooth SetInputConnection [reader GetOutputPort]
    smooth SetDimensionality 2
    smooth SetStandardDeviations 2 10

vtkImageViewer2 viewer
    viewer SetInputConnection [smooth GetOutputPort]
    viewer SetSlice 22
    viewer SetColorWindow 2000
    viewer SetColorLevel 1000
```

Image Flip

The vtkImageFlip filter can be used to reflect the input image data along an axis specified by the FilteredAxis instance variable. By default, the FlipAboutOrigin instance variable is set to 0, and the image will be flipped about its center along the axis specified by the FilteredAxis instance variable (defaults to 0 – the X axis), and the origin, spacing, and extent of the output will be identical to the input. However, if you have a coordinate system associated with the image and you want to use the flip to convert positive coordinate values along one axis to negative coordinate values (and vice versa), then you actually want to flip the image about the coordinate (0,0,0) instead of about the center of the image. If the FlipAboutOrigin instance variable is set to 1, the origin of the output will be adjusted such that the flip occurs about (0,0,0) instead of the center of the image. In **Figure 6–15** we see an input image on the left; the center image shows the results of flipping this image along the Y axis with FlipAboutOrigin off; in the right image, FlipAboutOrigin is on, and all other variables are unchanged from those used to generate the center image.

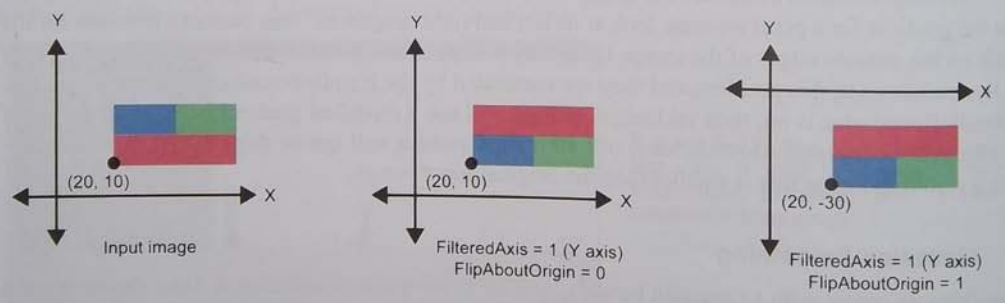


Figure 6–15 Using vtkImageFlip to flip the Y axis of the input image with dimensions (40, 20, 1). The origin of each image (the input and the two outputs) is labelled.

Image Permute

vtkImagePermute allows you to reorder the axes of the input image or volume. (See **Figure 6–16**.) The FilteredAxes instance variable indicates which indicates how the axes should be reordered – which of the input axes will be labelled X, which Y, and which Z in the output.

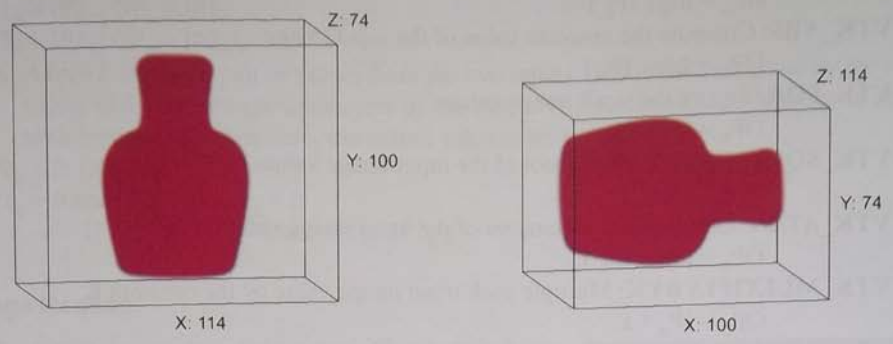


Figure 6–16 Using vtkImagePermute to reorder the axes of a volume dataset. The dimensions of the input volume, shown on the left, are (114, 100, 74). The FilteredAxes instance variable was set to (1, 2, 0), indicating that the Y axis be relabelled as X, Z be relabelled as Y, and X be relabelled as Z. As shown on the right, the dimensions of the output volume are (100, 74, 114).

Image Mathematics

The vtkImageMathematics filter provides basic unary and binary mathematical operations. Depending on the operation set, this filter expects either one or two input images. When two input images are required, they must have the same scalar type and the same number of components, but do not need to have the same dimensions. The output image will have an extent that is the union of the extents of the input images. Origin and spacing of the output image will match the origin and spacing of the first input image.

The unary operations are described below. Note that IP_n is the input pixel value for component n, OP_n is the output pixel value for component n, and C and K are constant values that can be specified as instance variables. DivideByZeroToC is an instance variable that specifies what happens when a divide by zero is encountered. When DivideByZeroToC is on, then the C constant value is the result of a divide by zero; otherwise the maximum value in the range of the output scalar type is used when a divide by zero occurs.

VTK_INVERT: Invert the input. Use C or the maximum output scalar value when a divide by zero is encountered, depending on the value of the DivideByZeroToC instance variable.

if IP_n != 0; $OP_n = 1.0 / IP_n$

if IP_n == 0 and DivideByZeroToC; then $OP_n = C$

if IP_n == 0 and !DivideByZeroToC; then OP_n = *maximum scalar value*

VTK_SIN: Take the sine of the input image.

$OP_n = \sin(IP_n)$

VTK_COS: Calculate the cosine of the input image.

$OP_n = \cos(IP_n)$

VTK_EXP: Calculate the exponential of the input image. This is *e* raised to the power of the input image, where *e* is the base of a natural log, approximately 2.71828.

$OP_n = \exp(IP_n)$

VTK_LOG: Calculate the natural log of the input image (the logarithm base *e*).

$OP_n = \log (IP_n)$

VTK_ABS: Compute the absolute value of the input image.

$OP_n = \text{fabs}(IP_n)$

VTK_SQR: Square the input image values.

$OP_n = IP_c * IP_n$

VTK_SQRT: Take the square root of the input image values.

$OP_n = \text{sqrt}(IP_n)$

VTK_ATAN: Compute the arctangent of the input image values.

$OP_n = \text{atan}(IP_n)$

VTK_MULTIPLYBYK: Multiple each input image value by the constant K.

$OP_n = IP_n * K$

VTK_ADDC: Add the constant C to each input image value.

$OP_n = IP_n + C$

VTK_REPLACECBYK: Replace all input image values that are exactly equal to the constant C, with the constant K.

if $IP_n == C$; $OP_n = K$

if $IP_n != C$; $OP_n = IP_n$

VTK_CONJUGATE: To use this operation, the input image must have two-component scalars. Convert the two-component scalars into a complex conjugate pair.

$OP_0 = IP_0$

$OP_1 = -IP_1$

The binary operations follow. The notation used is similar to that for the unary operations, except that $IP1_n$ is the first input's pixel value for component n, and $IP2_n$ is the second input's pixel value for component n.

VTK_ADD: Add the second input image to the first one.

$OP_n = IP1_n + IP2_n$

VTK_SUBTRACT: Subtract the second input image's values from those of the first input.

$OP_n = IP1_n - IP2_n$

VTK_MULTIPLY: Multiply the first input image's values by those of the second input.

$OP_n = IP1_n * IP2_n$

VTK_DIVIDE: Divide the first input image's values by those of the second input. Use C or the maximum output scalar value when a divide by zero is encountered, depending on the value of the DivideByZeroToC instance variable.

if $IP2_n != 0$; $OP_n = IP1_n / IP2_n$

if $IP2_n == 0$ and DivideByZeroToC; then $OP_n = C$

if $IP2_n == 0$ and !DivideByZeroToC; then OP_n = *maximum scalar value*

VTK_COMPLEX_MULTIPLY: This operation requires that both input images have two-component scalars. The first component is real-valued, and the second component is imaginary. Multiply the first input image's values by those of the second input using complex multiplication.

$OP_0 = IP1_0 * IP2_0 - IP1_1 * IP2_1$

$OP_1 = IP1_1 * IP2_0 + IP1_0 * IP2_1$

VTK_MIN: Compare corresponding values in the two images, and return the smaller value.

if $IP1_n < IP2_n$; $OP_n = IP1_n$

if $IP2_n < IP1_n$; $OP_n = IP2_n$

VTK_MAX: Compare corresponding values in the two images, and return the larger value.
if $IP1_n > IP2_n$; $OP_n = IP1_n$
if $IP2_n > IP1_n$; $OP_n = IP2_n$

VTK_ATAN2: For each pair of values from the two inputs, divide the first value by the second value, and compute the arctangent of the result. If the second input's value is zero, or both inputs' values are zero, the output value is set to 0.
if $IP2_n = 0$; $OP_n = 0$
if $IP1_n = 0$ and $IP2_n = 0$; $OP_n = 0$
$IP2_n$!= 0; $OP_n = atan(IP1_n / IP2_n)$

Image Reslice

vtkImageReslice is a contributed class that offers high-performance image resampling along an arbitrarily-oriented volume (or image). The extent, origin, and sampling density of the output data can also be set. This class provides several other imaging filters: it can permute, flip, rotate, scale, resample, and pad image data in any combination. It can also extract oblique slices from image volumes, which no other VTK imaging filter can do. The following script demonstrates how to use vtkImage-Reslice.

Figure 6–17 Output of vtkImage-Reslice with a gray background level set.

```
vtkBMPReader reader
 reader SetFileName "$VTK_DATA_ROOT/
Data/masonry.bmp"
 reader SetDataExtent 0 255 0 255 0 0
 reader SetDataSpacing 1 1 1
 reader SetDataOrigin 0 0 0
 reader UpdateWholeExtent

vtkTransform transform
 transform RotateZ 45
 transform Scale 1.414 1.414 1.414

vtkImageReslice reslice
 reslice SetInputConnection [reader GetOutputPort]
 reslice SetResliceTransform transform
 reslice SetInterpolationModeToCubic
 reslice WrapOn
 reslice AutoCropOutputOn

vtkImageViewer2 viewer
 viewer SetInputConnection [reslice \
    GetOutputPort]
 viewer SetSlice 0

 viewer SetColorWindow 256.0
 viewer SetColorLevel 127.5
 viewer Render
```

In this example (**Figure 6–17**) a volume of size 64^2 x 93 is read. A transform is used to position a volume on which to resample (or reslice) the data, and cubic interpolation between voxels is used. The wrap-pad feature is turned on, and (by setting the variable AutoCropOutput) the output extent will be resized large enough that none of the resliced data will be cropped. By default, the spacing of the output volume is set at 1.0, and the output origin and extent are adjusted to enclose the input volume. A viewer is used to display one *z*-slice of the resulting volume.

Iterating through an image

VTK also provides STL like iterators to make it convenient to iterate and retrieve / set pixel values in an image. The class vtkImageIterator can be used to accomplish this. It is templated over the datatype of the image. Its constructor takes as argument the subregion over which to iterate over.

```
int subRegion[6] = { 10, 20, 10, 20, 10, 20 };
vtkImageIterator< unsigned char > it( image, subRegion );
while( !it.IsAtEnd() )
 {
 unsigned char *inSI = it.BeginSpan();
 unsigned char *inSIEnd = it.EndSpan();
 while (inSI != inSIEnd)
  {
  *inSI = (255 - *inSI);
  ++inSI;
  }
 it.NextSpan();
 }
}
```

Chapter 7

Volume Rendering

Volume rendering is a term used to describe a rendering process applied to 3D data where information exists throughout a 3D space instead of simply on 2D surfaces defined in 3D space. There is not a clear dividing line between volume rendering and geometric rendering techniques. Often two different approaches can produce similar results, and in some cases one approach may be considered both a volume rendering and a geometric rendering technique. For example, you can use a contouring technique to extract triangles representing an isosurface in an image dataset (see "Contouring" on page 93) and then use geometric rendering techniques to display these triangles, or you can use a volumetric ray casting technique on the image dataset and terminate the ray traversal at a particular isovalue. These two different approaches produce similar (although not necessarily identical) results. Another example is the technique of employing texture mapping hardware in order to perform composite volume rendering. This one method may be considered a volume rendering technique since it works on image data, or a geometric technique since it uses geometric primitives and standard graphics hardware.

In VTK a distinction is made between volume rendering techniques and geometric rendering techniques in order to customize the properties of the data being rendered. As you have seen throughout the many example shown thus far, rendering data typically involves creating a vtkActor, a vtkProperty, and some subclass of a vtkMapper. The vtkActor is used to hold position, orientation and scaling information about the data, as well as a pointer to both the property and the mapper. The vtkProperty object captures various parameters that control the appearance of the data such as the ambient lighting coefficient and whether the object is flat, Gouraud, or Phong shaded. Finally, the vtkMapper subclass is responsible for actually rendering the data. For volume rendering, a different set of classes with very similar functionality are utilized. A vtkVolume is used in place of a vtkActor to represent the data in the scene. Just like the vtkActor, the vtkVolume represents the position, orientation and scaling of the data within the scene. However, a vtkVolume contains references to a vtkVolumeProperty and a vtkAbstractVolumeMapper. The vtkVolumeProperty represents those parameters that affect the appearance of the data in a volume rendering process, which is a different set of parameters than those used during geometric rendering. A vtkAbstractVolumeMapper subclass

is responsible for the volume rendering process and ensures that the input data is of the correct type for the mapper's specific algorithm.

In VTK, volume rendering techniques have been implemented for both regular rectilinear grids (vtkImageData) and unstructured data (vtkUnstructuredGrid). The SetInput() method of the specific subclass of vtkAbstractVolumeMapper that you utilize will accept a pointer to only the correct type of data (vtkImageData or vtkUnstructuredGrid) as appropriate for that mapper. Note that you can resample irregular data into a regular image data format in order to take advantage of the vtkImageData rendering techniques described in this chapter (see "Probing" on page 100). Alternatively, you can tetrahedralize your data to produce an unstructured mesh to use the vtkUnstructuredGrid rendering techniques described in this chapter.

There are several different volume rendering techniques available for each supported data type. We will begin this chapter will some simple examples written using several different rendering techniques. Then we will cover the objects / parameters common to all of these techniques. Next, each of the volume rendering techniques will be discussed in more detail, including information on parameters specific to that rendering method. This will be followed by a discussion on achieving interactive rendering rates that is applicable to all volume rendering methods.

7.1 Historical Note on Supported Data Types

The first volume rendering methods incorporated into VTK were designed solely for vtkImageData. The superclass vtkVolumeMapper was developed to define the API for all vtkImageData volume rendering methods. Later, volume rendering of vtkUnstructuredGrid datasets was added to VTK. In order to preserve backwards compatibility, a new abstract superclass was introduced as the superclass for all types of volume rendering. Hence vtkAbstractVolumeMapper is the superclass of both vtkVolumeMapper (whose subclasses render only vtkImageData datasets) and vtkUnstructuredGridVolumeMapper (whose subclasses render only vtkUnstructuredGrid datasets).

7.2 A Simple Example

Consider the simple volume rendering example shown below and illustrated in **Figure 7–1** (refer to `VTK/Examples/VolumeRendering/Tcl/SimpleRayCast.tcl`). This example is written for volumetric ray casting of vtkImageData, but only the portion of the Tcl script highlighted with bold text is specific to this rendering technique. Following this example you will find the alternate versions of the bold portion of the script that would instead perform the volume rendering task with other mappers, including a texture mapping approach to rendering vtkImageData and a projection-based method for volume rendering vtkUnstructuredGrid datasets. You will notice that switching volume rendering techniques, at least in this simple case, requires only a few minor changes to the script, since most of the functionality is defined in the superclass API and is therefore common to all volume mappers.

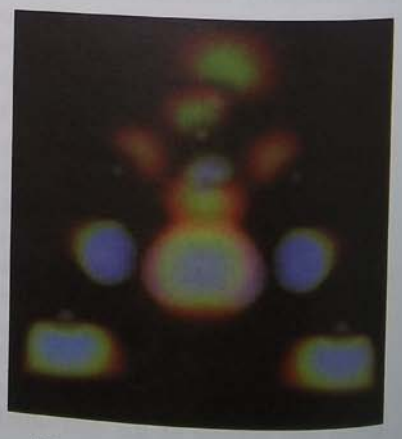


Figure 7–1 Volume rendering.

```
# Create the reader for the data
vtkStructuredPointsReader reader
  reader SetFileName "$VTK_DATA_ROOT/Data/ironProt.vtk"

# Create transfer mapping scalar value to opacity
vtkPiecewiseFunction opacityTransferFunction
  opacityTransferFunction AddPoint 20  0.0
  opacityTransferFunction AddPoint 255 0.2

# Create transfer mapping scalar value to color
vtkColorTransferFunction colorTransferFunction
  colorTransferFunction AddRGBPoint   0.0 0.0 0.0 0.0
  colorTransferFunction AddRGBPoint   64.0 1.0 0.0 0.0
  colorTransferFunction AddRGBPoint  128.0 0.0 0.0 1.0
  colorTransferFunction AddRGBPoint  192.0 0.0 1.0 0.0
  colorTransferFunction AddRGBPoint  255.0 0.0 0.2 0.0

# The property describes how the data will look
vtkVolumeProperty volumeProperty
  volumeProperty SetColor colorTransferFunction
  volumeProperty SetScalarOpacity opacityTransferFunction

# The mapper / ray cast functions know how to render the data
vtkVolumeRayCastCompositeFunction compositeFunction
vtkVolumeRayCastMapper volumeMapper
  volumeMapper SetVolumeRayCastFunction compositeFunction
  volumeMapper SetInputConnection [reader GetOutputPort]

# The volume holds the mapper and the property and
# can be used to position/orient the volume
vtkVolume volume
  volume SetMapper volumeMapper
  volume SetProperty volumeProperty

ren1 AddProp volume
renWin Render
```

In this example we start by reading in a data file from disk. We then define the functions that map scalar value into opacity and color which are used in the vtkVolumeProperty. Next we create the objects specific to volumetric ray casting—a vtkVolumeRayCastCompositeFunction that performs the compositing of samples along the ray, and a vtkVolumeRayCastMapper that performs some of the basic ray casting operations such as transformations and clipping. We set the input of the mapper to the data we read off the disk, and we create a vtkVolume (a subclass of vtkProp3D similar to vtkActor) to hold the mapper and property. Finally, we add the volume to the renderer and render the scene.

If you decided to implement the above script with a 2D texture mapping approach instead of volumetric ray casting, the bold portion of the script would instead be:

```
# Create the objects specific to 2D texture mapping approach
vtkVolumeTextureMapper2D volumeMapper
volumeMapper SetInputConnection [reader GetOutputPort]
```

If your graphics card has the required support for 3D texture mapping (nearly all recent cards do have this support), then you may decide to implement the above script with a 3D texture mapping approach. The bolded portion of the script would instead be:

```
# Create the objects specific to 3D texture mapping approach
vtkVolumeTextureMapper3D volumeMapper
volumeMapper SetInputConnection [reader GetOutputPort]
```

The vtkFixedPointVolumeRayCastMapper is an alternative to the vtkVolumeRayCastMapper, and is for most situations the recommended software mapper. The vtkFixedPointVolumeRayCastMapper handles all data types as well as multicomponent data, and uses fixed pointed computations and space leaping for high performance. However, it is not extensible since the blending operations are hard-coded for performance, rather than customizable by writing new ray cast functions. To change this example over to using the vtkFixedPointVolumeRayCastMapper, the bold portion of the script would instead be:

```
# Create the fixed point ray cast mapper
vtkFixedPointVolumeRayCastMapper volumeMapper volumeMapper
SetInputConnection [reader GetOutputPort]
```

If you would like to use an unstructured grid volume rendering technique instead, the replacement code becomes slightly more complex in order to perform the conversion from vtkImageData to vtkUnstructuredGrid before passing the data as input to the mapper. In this case we will use the unstructured grid rendering method that projects a tetrahedral representation of the grid using the graphics hardware. The replacement code would be:

```
# Convert data to unstructured grid
vtkDataSetTriangleFilter tetraFilter
tetraFilter SetInputConnection [reader GetOutputPort]

# Create the objects specific to the Projected Tetrahedra method
vtkProjectedTetrahedraMapper volumeMapper
volumeMapper SetInputConnection [tetraFilter GetOutputPort]
```

Note that it is not recommended to convert from vtkImageData to vtkUnstructuredGrid for rendering since the mappers that work directly on vtkImageData are typically more efficient, both in memory consumption and rendering performance, than the mappers for vtkUnstructuredGrid data.

7.3 Why Multiple Volume Rendering Techniques?

As you can see, in this simple example the main thing that changes between rendering strategies is the type of volume mapper that is instantiated, and perhaps some rendering-method-specific parameters such as the ray cast function used in the ray casting technique. This may lead you to the following questions: why are there different volume rendering strategies in VTK? Why can't VTK simply pick the "best" strategy? First, it is not always easy to predict which strategy will work best—ray casting may out-perform texture mapping if the image size is reduced, more processors become available, or the graphics hardware is the bottleneck to the rendering rate. These are parameters that differ from

platform to platform, and in fact may change continuously at run time. Second, due to its computational complexity, most volume rendering techniques only produce an approximation of the desired rendering equation. For example, techniques that take samples through the volume and composite them with an alpha blending function are only approximating the true integral through the volume. Under different circumstances, different techniques perform better or worse than others in terms of both quality and speed. In addition, some techniques work only under certain special conditions. For example, some techniques support data with only a single scalar component of unsigned char or unsigned short type, while other techniques support any scalar type and multi-component data. The "best" technique will depend on your specific data, your performance and image quality requirements, and the hardware configuration of the system on which the code is run. In fact, the "best" technique may actually be a combination of techniques. A section of this chapter is dedicated to describing the multi-technique level-of-detail strategies that may be employed to achieve interactive volume rendering in a cross-platform manner.

7.4 Creating a vtkVolume

A vtkVolume is a subclass of vtkProp3D intended for use in volume rendering. Similar to a vtkActor (that is intended for geometric rendering), a vtkVolume holds the transformation information such as position, orientation, and scale, and pointers to a mapper and property. Additional information on how to control the transformation of a vtkVolume is covered in "Controlling 3D Props" on page 52.

The vtkVolume class accepts objects that are subclasses of vtkAbstractVolumeMapper as input to SetMapper(), and accepts a vtkVolumeProperty object as input to SetProperty(). vtkActor and vtkVolume are two separate objects in order to enforce the different types of the mappers and properties. These different types are necessary due to the fact that some parameters of geometric rendering do not make sense in volume rendering and vice versa. For example, the SetRepresentationToWireframe() method of vtkProperty is meaningless in volume rendering, while the SetInterpolationTypeToNearest() method of vtkVolumeProperty has no value in geometric rendering.

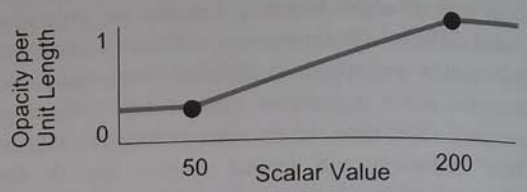
7.5 Using vtkPiecewiseFunction

In order to control the appearance of a 3D volume of scalar values, several mappings or transfer functions must be defined. Generally, two transfer functions are required for all volume rendering techniques. The first required transfer function, known as the *scalar opacity transfer function*, maps the scalar value into an opacity or an opacity per unit length value. The second transfer function, referred to simply as the *color transfer function*, maps the scalar value into a color. An optional transfer function employed in some of the structured volume rendering methods is known as the *gradient opacity transfer function*, which maps the magnitude of the gradient of the scalar value into an opacity multiplier. Any of these mappings can be defined as a single value to single value mapping, which can be represented with a vtkPiecewiseFunction. For the scalar value to color mapping, a vtkColorTransferFunction can also be used to define RGB rather than grayscale colors.

From a user's point of view, vtkPiecewiseFunction has two types of methods—those that add information to the mapping, and those that clear out information from the mapping. When information is added to a mapping, it is considered to be a point sample of the mapping with interpolation

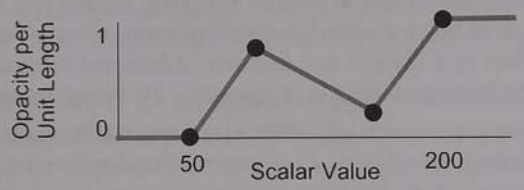
used to determine values between the specified ones. For example, consider the following section of a script on the left that produces the transfer function draw on the right:

```
vtkPiecewiseFunction tfun
  tfun AddPoint  50  0.2
  tfun AddPoint 200  1.0
```

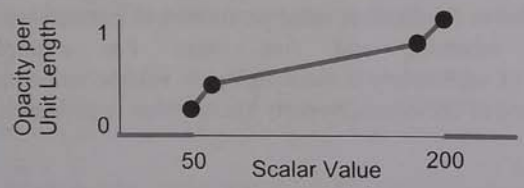


The value of the mapping for the scalar values of 50 and 200 are given as 0.2 and 1.0 respectively, and all other mapping values can be obtained by linearly interpolating between these two values. If Clamping is on (it is by default) then the mapping of any value below 50 will be 0.2, and the mapping of any value above 200 will be 1.0. If Clamping is turned off, then out-of-range values map to 0.0.

Points can be added to the mapping at any time. If a mapping is redefined it replaces the existing mapping. In addition to adding a single point, a segment can be added which will define two mapping points and clear any existing points between the two. As an example, consider the following two modification steps and the corresponding pictorial representations of the transfer functions:




```
tfun RemovePoint  50
tfun AddPoint  50  0.0
tfun AddSegment
    100  0.8  150  0.2
```




```
tfun AddPoint  50  0.2
tfun AddSegment
     60  0.4  190  0.8
tfun ClampingOff
```

In the first step, we change the mapping of scalar value 50 by removing the point and then adding it again, and we add a segment. In the second step, we change the mapping of scalar value 50 by simply adding a new mapping without first removing the old one. We also add a new segment which eliminates the mappings for 100 and 150 since they lie within the new segment, and we turn clamping off.

7.6 Using vtkColorTransferFunction

A vtkColorTransferFunction can be used to specify a mapping of scalar value to color using either an RGB or HSV color space. The methods available are similar to those provided by vtkPiecewiseFunction, but tend to come in two flavors. For example, AddRGBPoint() and AddHSVPoint() both add a point into the transfer function with one accepting an RGB value as input and the other accepting an HSV value as input.

The following Tcl example shows how to specify a transfer function from red to green to blue with RGB interpolation performed for values in between those specified:

```
vtkColorTransferFunction ctfun
  ctfun SetColorSpaceToRGB
  ctfun AddRGBPoint 0 1 0 0
  ctfun AddRGBPoint 127 0 1 0
  ctfun AddRGBPoint 255 0 0 1
```

7.7 Controlling Color / Opacity with a vtkVolumeProperty

In the previous two sections we have discussed the basics of creating transfer functions, but we have not yet discussed how these control the appearance of the volume. Typically, defining the transfer functions is the hardest part of achieving an effective volume visualization since you are essentially performing a classification operation that requires you to understand the meaning of the underlying data values.

For rendering techniques that map a pixel to a single location in the volume (such as an isosurface rendering or a maximum intensity projection) the ScalarOpacity transfer function maps the scalar value to an opacity. When a compositing technique is used, the ScalarOpacity function maps scalar value to an opacity that is accumulated per unit length for a homogenous region of that value. The specific mapper then utilizes a form of compositing to accumulate the continuously changing color and opacity values through the volume to form a final color and opacity that is stored in the corresponding pixel.

The ScalarOpacity and Color transfer functions are typically used to perform a simple classification of the data. Scalar values that are part of the background, or that are considered noise, are mapped to an opacity of 0.0, eliminating them from contributing to the image. The remaining scalar values can be divided into different "materials" which have different opacities and colors. For example, data acquired from a CT scanner can often be categorized as air, soft tissue, or bone based on the density value contained in the data (**Figure 7–2**). The scalar values defined as air would be given an opacity of 0.0, the soft tissue scalar values might be given a light red-brown color and the bone values might be given a white color. By varying the opacity of these last two materials, you can visualize the skin surface or the bone surface, or potentially see the bone through the translucent skin. This process of determining the dividing line between materials in the data can be tedious, and in some cases not possible based on the raw input data values. For example, liver and kidney sample locations may have overlapping CT density values. In this case, a segmentation filter may need to be applied to the volume to either alter the data values so that materials can be classified solely on the basis of the scalar value, or to extract out one specific material type. These segmentation operations can be based on additional information such as location or a comparison to a reference volume.

Figure 7–3 CT head data classified using the ScalarOpacity, Color, and GradientOpacity transfer functions.

Two examples of segmenting CT data using only the transfer functions defined in the vtkVolumeProperty are shown here, one for a torso (**Figure 7–2**) and the other for a head study (**Figure 7–3**). In both of these examples, the third transfer function maps the magnitude of the gradient of the

Figure 7–2 CT torso data classified using the ScalarOpacity, Color, and GradientOpacity transfer functions.

scalar value to an opacity multiplier, and is used to enhance the contribution of transition regions of the volume. For example, a large gradient magnitude can be found where the scalar value transitions from air to soft tissue, or soft tissue to bone, while within the soft tissue and bone regions the magnitude remains relatively small. Below is a code fragment that defines a typical gradient opacity transfer function for 8-bit unsigned data.

```
vtkPiecewiseFunction gtfun
  gtfun AddPoint   0  0.0
  gtfun AddPoint   3  0.0
  gtfun AddPoint   6  1.0
  gtfun AddPoint 255  1.0
```

This function eliminates nearly homogeneous regions by defining an opacity multiplier of 0.0 for any gradient magnitude less than 3. This multiplier follows a linear ramp from 0.0 to 1.0 on gradient magnitudes between 3 and 6, and no change in the opacity value is performed on samples with magnitudes above 6. Noisier data may require a more aggressive edge detection (so the 3 and the 6 would be higher values). Note that the gradient magnitude transfer function is currently only supported in volume mappers that rendering vtkImageData. For volume mappers that render vtkUnstructuredGrid datasets, gradients are not computed and therefore neither the gradient magnitude transfer function nor shading are available in these mappers.

There are a few methods in vtkVolumeProperty that relate to the color and opacity transfer functions. The SetColor() method accepts either a vtkPiecewiseFunction (if your color function defines only grayscale values) or a vtkColorTransferFunction. You can query the number of color channels with GetColorChannels() which will return 1 if a vtkPiecewiseFunction was set as the color, or 3 if a vtkColorTransferFunction was used to specify color. Once you know how many color channels are in use, you can call either GetGrayTransferFunction() or GetRGBTransferFunction() to get the appropriate function.

The SetScalarOpacity() method accepts a vtkPiecewiseFunction to define the scalar opacity transfer function, and there is a corresponding GetScalarOpacity() method that returns this function. Similarly, there are two methods for the gradient opacity transfer function: SetGradientOpacity() and GetGradientOpacity().

The discussion thus far has considered only single component scalar data where one set of transfer functions define the appearance of the data. Alternatively, multi-component data may be rendered in one of two ways. If the components are independent, then one set of transfer functions can be defined per component. An example of independent data may be an unstructured grid produced through a simulation process that produces both temperature and density values on the grid. Another example of independent components is the data produced by confocal microscopy where the specimen is scanned multiple times with different fluorescent dyes used to highlight different structures within the specimen. When rendering multi-component data where the components are independent, you must define the appearance parameters per component. The SetColor(), SetScalarOpacity(), and SetGradientOpacity() methods accept an optional index value as the first argument to set the transfer function for a specific component.

Multi-component data may also represent not independent properties, but instead a set of values that define one property. For example, when utilizing a physical sectioning technique, you may have three or four component data representing RGB or RGBA. Or perhaps you have two components representing luminance and alpha. Volume mappers that support multiple components support two forms of non-independent components. The first is two component data where the first component is passed through the color transfer function in order to determine the sample color, and the second component is passed through the scalar opacity function to define the sample alpha. The second type of non-independent multi-component data is four component data where the first three components are taken directly as RGB, and the fourth is passed through the scalar opacity transfer function in order to define alpha. In both of these non-independent cases, the last component is used to compute gradients, and therefore controls the gradient magnitude opacity transfer function as well.

Note that not all mappers support multi-component data, please consult the mapper-specific documentation provided in the remainder of this chapter for further information on supported functionality. For mappers that do support multiple components, the limit is typically four components.

7.8 Controlling Shading with a vtkVolumeProperty

Controlling shading of a volume with a volume property is similar to controlling the shading of a geometric actor with a property (see "Actor Properties" on page 53 and "Actor Color" on page 54). There is a flag for shading, and four basic parameters: the ambient coefficient, the diffuse coefficient, the specular coefficient and the specular power. Generally, the first three coefficients will sum to 1.0 but exceeding this value is often desirable in volume rendering to increase the brightness of a rendered volume. The exact interpretation of these parameters will depend on the illumination equation used by the specific volume rendering technique that is being used. In general, if the ambient term dominates then the volume will appear unshaded, if the diffuse term dominates then the volume will appear rough (like concrete) and if the specular term dominates then the volume will appear smooth (like glass). The specular power can be used to control how smooth the appearance is (such as brushed metal versus polished metal).

By default, shading is off. You must explicitly call ShadeOn() for the shading coefficients to affect the scene. Setting the shading flag off is generally the same as setting the ambient coefficient to 1.0, the diffuse coefficient to 0.0 and the specular coefficient to 0.0. Note that currently volume mappers that render vtkUnstructuredGrid datasets do not support shading. In addition, some volume rendering techniques for vtkImageData, such as volume ray casting with a maximum intensity ray function, do not consider the shading coefficients regardless of the value of the shading flag.

The shaded appearance of a volume (when the shading flag is on) depends not only on the values of the shading coefficients in the vtkVolumeProperty, but also on the collection of light sources contained in the renderer, and their properties. The appearance of a rendered volume will depend on the number, position, and color of the light sources in the scene.

If possible, the volume rendering technique attempts to reproduce the lighting equations defined by OpenGL. Consider the following example.

```
#Create a geometric sphere
vtkSphereSource sphere
  sphere SetRadius 20
  sphere SetCenter 70 25 25
  sphere SetThetaResolution 50
  sphere SetPhiResolution 50

vtkPolyDataMapper mapper
  mapper SetInput [sphere GetOutput]

vtkActor actor
  actor SetMapper mapper
  [actor GetProperty] SetColor 1 1 1
  [actor GetProperty] SetAmbient 0.01
  [actor GetProperty] SetDiffuse 0.7
  [actor GetProperty] SetSpecular 0.5
  [actor GetProperty] SetSpecularPower 70.0

#Read in a volumetric sphere
vtkSLCReader reader
  reader SetFileName "$VTK_DATA_ROOT/Data/sphere.slc"

# Use this tfun for both opacity and color
vtkPiecewiseFunction opacityTransferFunction
  opacityTransferFunction AddSegment 0 1.0 255 1.0

# Make the volume property match the geometric one
vtkVolumeProperty volumeProperty
  volumeProperty SetColor opacityTransferFunction
  volumeProperty SetScalarOpacity tfun
  volumeProperty ShadeOn
  volumeProperty SetInterpolationTypeToLinear
  volumeProperty SetDiffuse 0.7
  volumeProperty SetAmbient 0.01
  volumeProperty SetSpecular 0.5
  volumeProperty SetSpecularPower 70.0

vtkVolumeRayCastCompositeFunction compositeFunction
vtkVolumeRayCastMapper volumeMapper
  volumeMapper SetInput [reader GetOutput]
  volumeMapper SetVolumeRayCastFunction compositeFunction

vtkVolume volume
  volume SetMapper volumeMapper
```

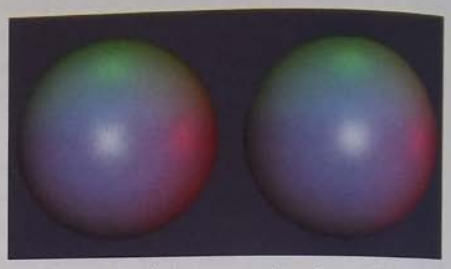


Figure 7–4 A geometric sphere (right) and a volumetric sphere (left) rendered with the same lighting coefficients.

```
  volume SetProperty volumeProperty

# Add both the geometric and volumetric spheres to the renderer
ren1 AddProp volume
ren1 AddProp actor


# Create a red, green, and blue light
vtkLight redlight
  redlight SetColor 1 0 0
  redlight SetPosition 1000 25 25
  redlight SetFocalPoint 25 25 25
  redlight SetIntensity 0.5

vtkLight greenlight
  greenlight SetColor 0 1 0
  greenlight SetPosition 25 1000 25
  greenlight SetFocalPoint 25 25 25
  greenlight SetIntensity 0.5

vtkLight bluelight
  bluelight SetColor 0 0 1
  bluelight SetPosition 25 25 1000
  bluelight SetFocalPoint 25 25 25
  bluelight SetIntensity 0.5

# Add the lights to the renderer
ren1 AddLight redlight
ren1 AddLight greenlight
ren1 AddLight bluelight

#Render it!
renWin Render
```

In the image shown for this example (**Figure 7–4**), the left sphere is rendered with volumetric ray casting, and the right sphere is rendered with OpenGL using surface rendering. Since the vtkProperty used for the vtkActor, and the vtkVolumeProperty used for the vtkVolume were set up with the same ambient, diffuse, specular, and specular power values, and the color of both spheres is white, they have similar appearances.

When rendering data with multiple independent components, you must set the shading parameters per component. Each of the SetAmbient(), SetDiffuse(), SetSpecular(), and SetSpecularPower() methods takes an optional first parameter indicating the component index. Although the vtkVolumeProperty API allows shading to be enable / disabled independently per component, currently no volume mapper in VTK supports this. Therefore all Shade instance variables should be set On or Off.

7.9 Creating a Volume Mapper

vtkAbstractVolumeMapper is an abstract superclass and is never created directly. Instead, you would create a mapper subclass of the specific type desired. In VTK 5.4, the choices for vtkImageData are

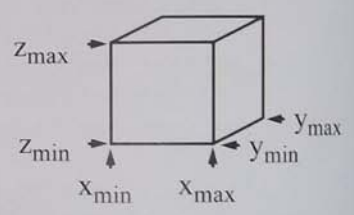
vtkVolumeRayCastMapper, vtkVolumeTextureMapper2D, vtkFixedPointVolumeRayCastMapper, vtkVolumeTextureMapper3D, or VTKVolumeProVP1000Mapper. For vtkUnstructuredGrid datasets, the available mappers are vtkUnstructuredGridVolumeRayCastMapper, vtkUnstructuredGrid-ZSweepMapper, vtkProjectedTetrahedraMapper, or VTKHAVSVolumeMapper.

All volume mappers support the SetInput() method with an argument of a pointer to a vtkImageData object or a vtkUnstructuredGrid object as appropriate. For vtkImageData volume mappers, each of the rendering techniques support only certain types of vtkImageData. For example, the vtkVolumeRayCastMapper and the vtkVolumeTextureMapper2D both support only `VTK_UNSIGNED_CHAR` and `VTK_UNSIGNED_SHORT` data with a single component. The vtkVolumeTextureMapper3D supports any scalar type, but only one component, or multiple non-independent components. The vtkFixedPointVolumeRayCastMapper is the most flexible, supporting all data types and up to four components.

7.10 Cropping a Volume

Since volume rendered images of large, complex volumes can produce images that are difficult to interpret, it is often useful to view only a portion of the volume. The two techniques that can be used to limit the amount of data rendered are known as cropping and clipping.

Cropping is a method of defining visible regions of the structured volume using six planes—two along each of the major axes. Cropping is applicable only to volume mappers that operate on vtkImageData. Clipping is applicable to both vtkImageData and vtkUnstructuredGrid volume mappers. The six axis-aligned cropping planes are defined in data coordinates and are therefore dependent on the origin and spacing of the data, but are independent of any transformation applied to the volume. The most common way to use these six planes is to define a subvolume of interest as shown in the figure to the right.



To crop a subvolume, you must turn cropping on, set the cropping region flags, and set the cropping region planes in the volume mapper as shown below.

```
set xmin 10.0
set xmax 50.0
set ymin 0.0
set ymax 33.0
set zmin 21.0
set zmax 47.0

vtkVolumeRayCastMapper mapper
  mapper CroppingOn
  mapper SetCroppingRegionPlanes $xmin $xmax $ymin $ymax $zmin $zmax
  mapper SetCroppingRegionFlagsToSubVolume
```

Note that the above example is shown for a vtkVolumeRayCastMapper, but it could have instead used any concrete subclass of vtkVolumeMapper since the cropping methods are all defined in the superclass.

The six planes that are defined by the x_{min}, x_{max}, y_{min}, y_{max}, z_{min}, and z_{max} values break the volume into 27 regions (a 3x3 grid). The CroppingRegionFlags is a 27 bit number with one bit representing each of these regions, where a value of 1 indicates that data within that region is visible, and a value of 0 indicating that data within that region will be cropped. The region of the volume that is less than x_{min}, y_{min}, and z_{min} is represented by the first bit, with regions ordered along the x axis first, then the y axis and finally the z axis.

The SetCroppingRegionFlagsToSubVolume() method is a convenience method that sets the flags to 0x0002000—just the center region is visible. Although any 27 bit number can be used to define the cropping operation, in practice there are only a few that are used. Four additional convenience methods are provided for setting these flags: SetCroppingRegionFlagsToFence(), SetCroppingResgionFlagsToInvertedFence(), SetCroppingRegionFlagsToCross(), and SetCroppingRegionFlagsToInvertedCross(), as depicted in **Figure 7–5**.

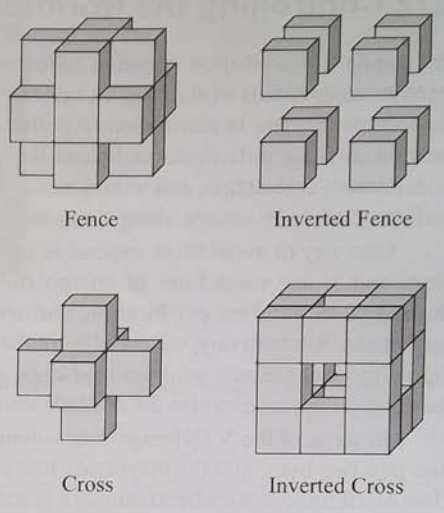


Figure 7–5 Cropping operations.

7.11 Clipping a Volume

In addition to the cropping functionality supplied by the vtkVolumeMapper, arbitrary clipping planes are provided in the vtkAbstractMapper3D. For subclasses of vtkAbstractMapper3D that use OpenGL to perform the clipping in hardware such as vtkPolyDataMapper, vtkVolumeTextureMapper2D, and vtkProjectedTetrahedraMapper, an error message may be displayed if you attempt to use more than the maximum number of clipping planes supported by OpenGL, which is typically 6. Software rendering techniques such as vtkVolumeRayCastMapper can support an arbitrary number of clipping planes. The vtkVolumeProMapper does not support these clipping planes directly, although the class does contain methods for specifying one clipping box using a plane and a thickness value.

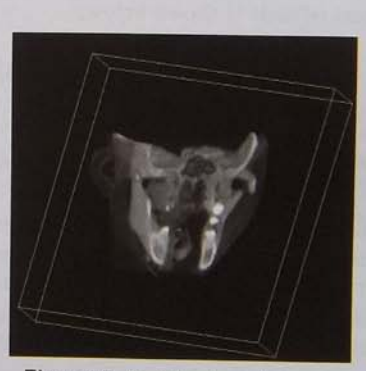


Figure 7–6 Clipping planes are used to define a thick slab.

The clipping planes are specified by creating a vtkPlane, defining the plane parameters, then adding this plane to the mapper using the AddClippingPlane() method. One common use of these arbitrary clipping planes in volume rendering is to specify two planes parallel to each other in order to perform a thick reformatting operation. An example of this applied to CT data is shown in **Figure 7–6**. For unstructured data, clipping planes can be used essentially as cropping planes to view only a subregion of the data, which is often necessary when trying to visualize internal details in a complex structure.

7.12 Controlling the Normal Encoding

The standard illumination equation relies on a surface normal in order to calculate the diffuse and specular components of shading. In volume rendering of vtkImageData, the gradient at a location in the volumetric data is considered to point in the opposite direction of the "surface normal" at that location. A finite differences technique is typically used to estimate the gradient, but this tends to be an expensive calculation, and would make shaded volume rendering prohibitively slow if it had to be performed at every sample along every ray.

One way to avoid these expensive computations is to precompute the normals at the grid locations, and to use some form of interpolation in between. If done naively, this would require three floating point numbers per location, and we would still need to take a square root to determine the magnitude. Alternatively, we could store the magnitude so that each normal would require four floating point values. Since volumes tend to be quite large, this technique requires too much memory, so we must somehow quantize the normals into a smaller number of bytes.

In some of the VTKImageData volume mappers we have chosen to quantize the normal direction into two byes, and the magnitude into one. The calculation of the normal is performed by a subclass of vtkEncodedGradientEstimator (currently only vtkFiniteDifferenceGradientEstimator) and the encoding of the direction into two bytes is performed by a subclass of vtkDirectionEncoder (currently vtkRecursiveSphere-DirectionEncoder and VTKSphericalDirectionEncoder). For mappers that use normal encoding (vtkVolumeRayCastMapper and vtkVolumeTextureMapper2D), these objects are created automatically so the typical user need not be concerned with these objects. In the case where one volume dataset is to be rendered by multiple mappers into the same image, it is often useful to create one gradient estimator for use by all the mappers. This will conserve space and computational time since otherwise there would be one copy of the normal volume per mapper. An example fragment of code is shown below:

```
# Create the gradient estimator
vtkFiniteDifferenceGradientEstimator gradientEstimator

# Create the first mapper
vtkVolumeRayCastMapper volumeMapper1
  volumeMapper1 SetGradientEstimator gradientEstimator
  volumeMapper1 SetInput [reader GetOutput]

# Create the second mapper
vtkVolumeRayCastMapper volumeMapper2
  volumeMapper2 SetGradientEstimator gradientEstimator
  volumeMapper2 SetInput [reader GetOutput]
```

If you set the gradient estimator to the same object in two different mappers, then it is important that these mappers have the same input. Otherwise, the gradient estimator will be out-of-date each time the mapper asks for the normals, and will regenerate them for each volume during every frame rendered. In the above example, the direction encoding objects were not explicitly created, therefore each gradient estimator created its own encoding object. Since this object does not have any significant storage requirements, this is generally an acceptable situation. Alternatively, one vtkRecursiveSphereDirectionEncoder could be created, and the SetDirectionEncoder() method would be used on each estimator.

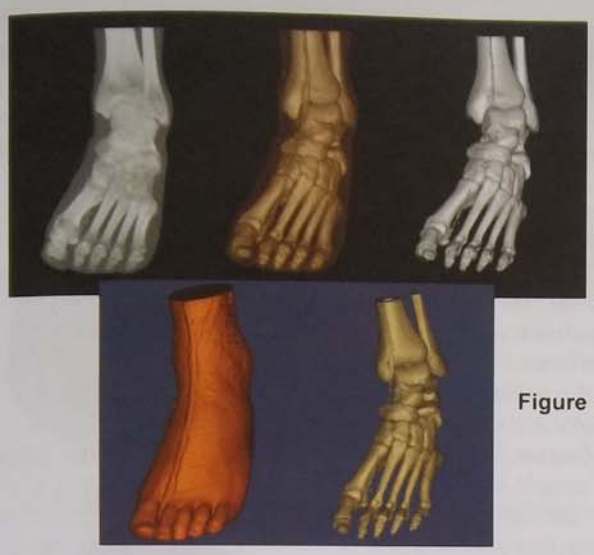


Figure 7–7 Volume rendering via ray casting.

The vtkFixedPointVolumeRayCastMapper class does support shading and does use these same gradient estimators and normal encoders, but these classes are not exposed at the API level and therefore encoded normals cannot be shared between mappers. The vtkVolumeTextureMapper3D class also supports shading, but does so by storing a 3 byte representation of the normal directly in texture memory.

7.13 Volumetric Ray Casting for vtkImageData

The vtkVolumeRayCastMapper is a volume mapper that employs a software ray casting technique to perform volume rendering. It is generally the most accurate mapper, and also the slowest on most platforms. The ray caster is threaded to make use of multiple processors when available.

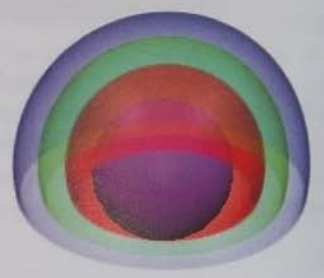
There are a few parameters that are specific to volume ray casting that have not yet been discussed. First, there is the ray cast function that must be set in the mapper. This is the object that does the actual work of considering the data values along the ray and determining a final RGBA value to return. Currently, there are three supported subclasses of vtkVolumeRayCastFunction: the vtkVolumeRayCastIsosurfaceFunction that can be used to render isosurfaces within the volumetric data, the vtkVolumeRayCastMIPFunction that can be used to generate maximum intensity projections of the volume, and vtkVolumeRayCastCompositeFunction that can be used to render the volume with an alpha compositing technique. An example of the images that can be generated using these different methods is **Figure 7–7**. The upper left image was generated using a maximum intensity projection. The other two upper images were generated using compositing, while the lower two images were generated using an isosurface function. Note that it is not always easy to distinguish an image generated using a compositing technique from one generated using an isosurface technique, especially when a sharp opacity ramp is used.

There are some parameters that can be set in each of the ray cast functions that impact the rendering process. In vtkVolumeRayCastIsosurfaceFunction, there is a SetIsoValue() method that can be used to set the value of the rendered isosurface. In vtkVolumeRayCastMIPFunction, you can call

SetMaximizeMethodToScalarValue() (the default) or SetMaximizeMethodToOpacity() to change the behavior of the maximize operation. In the first case, the scalar value is considered at each sample point along the ray. The sample point with the largest scalar value is selected, then this scalar value is passed through the color and opacity transfer functions to produce a final ray value. If the second method is called, the opacity of the sample is computed at each step along the ray, and the sample with the highest opacity value is selected.

In vtkVolumeRayCastCompositeFunction, you can call SetCompositeMethodToInterpolateFirst() (the default) or SetCompositeMethodToClassifyFirst() to change the order of interpolation and classification (**Figure 7–8**). This setting will only have an impact when trilinear interpolation is being used. In the first case, interpolation will be performed to determine the scalar value at the sample point, then this value will be used for classification (the application of the color and opacity transfer functions). In the second case, classification is done at the eight vertices of the cell containing the sample location, then the final RGBA value is interpolated from the computed RGBA values at the vertex locations. Interpolating first generally produces "prettier" images as can be seen on the left where a geometric sphere is contained within a volumetric "distance to point" field, with the transfer functions defined to highlight three concentric spherical shells in the volume. The interpolate first method makes the underlying assumption that if two neighboring data points have values of 10 and 100, then a value of 50 exists somewhere between the two data points. In the case where material is being classified by scalar value, this may not be the case. For example, consider CT data where values below 20 are air (transparent), values from 20 to 80 are soft tissue, and values above 80 are bone. If interpolation is performed first, then bone can never be adjacent to air - there must always be soft tissue between the bone and air. This is not true inside the mouth where teeth meet air. If you render an image with interpolation performed first and a high enough sample rate, it will look like the teeth have a layer of skin on top of them.

Classify First



Interpolate First

Figure 7–8 The effect of interpolation order in composite ray casting.

The value of the interpolation type instance variable in the vtkVolumeProperty is important to ray casting. There are two options: SetInterpolationTypeToNearest() (the default) which will use a nearest neighbor approximation when sampling along the ray, and SetInterpolationTypeToLinear() which will use trilinear interpolation during sampling. Using the trilinear interpolation produces smoother images with less artifacts, but generally takes a bit longer. The difference in image quality obtained with these two methods is shown in **Figure 7–9**. A sphere is voxelized into a 50x50x50 voxel volume, and rendered using alpha compositing with nearest neighbor interpolation on the left and trilinear interpolation on the right. In the image of the full sphere it may be difficult to distinguish between the two interpolation methods, but by zooming up on just a portion of the sphere it is easy to see the individual voxels in the left image.

Another parameter of vtkVolumeRayCastMapper that affects the image is the SampleDistance. This is the distance in world coordinates between sample points for ray functions that take samples. For example, the alpha compositing ray function performs a discrete approximation of the continuous volume rendering integral by sampling along the ray. The accuracy of the approximation increases

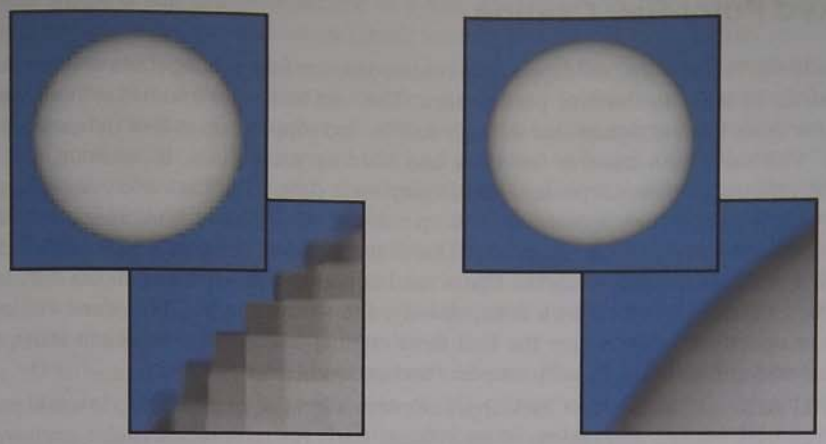


Figure 7–9 Different methods for interpolation. On the left, nearest neighbor interpolation. On the right, trilinear interpolation.

with the number of samples taken, but unfortunately so does the rendering time. The maximum intensity ray function also takes samples to locate the maximum value. The isosurface ray function does not take samples but instead computes the exact location of the intersection according to the current interpolation function.

By default samples are taken 1 unit apart in world coordinates. In practice you should adjust this spacing based on the sample spacing of the 3D data being rendered, and the rate of change of not only the scalar values but also the color and opacity assigned to the scalar values through the transfer functions. An example is shown below of a voxelized vase with a 1x1x1 spacing between samples in the dataset. The scalar values vary smoothly in the data, but a sharp change has been introduced in the transfer functions by having the color change rapidly from black to white. You can clearly see artifacts of the "undersampling" of ray casting in the image created with a step size of 2.0. Even with a step size of 1.0 there are some artifacts since the color of the vase changes significantly within a world space distance of 1.0. If the sample distance is set to 0.1 the image appears smooth. Of course, this smooth image on the left takes nearly 20 times as long to generate as the one on the right.

Step Size = 0.1 Step Size = 1.0 Step Size = 2.0

Figure 7–10 The effects or varying sample distance along the ray. As the sample distance increases, sampling artifacts create the dramatic black and white banding. However, the cost of volume rendering increases inversely proportional to the sample size, i.e., the difference in rendering time for sample distance 0.1 is 20x faster than for 2.0.

7.14 Fixed Point Ray Casting

The vtkFixedPointVolumeRayCastMapper is a volume mapper for vtkImageData that employs fixed point arithmetic in order to improve performance. The vtkFixedPointVolumeRayCastMapper supports all scalar types from unsigned char through double, and supports up to four independent components, each with their own transfer functions and shading parameters. In addition, this mapper supports two varieties of non-independent multi-component data. The first variety is two component data where the first component is used to look up a color, while the second component is used to derive a normal value and to look up opacity. This is useful when some property such as density is stored in the second component, while the first is used as perhaps an index to indicate different material types that can each have their own color, opacity, and shading style. The second variety is four component unsigned char data where the first three components directly represent RGB, with the fourth passed through the scalar opacity transfer function to obtain alpha.

The vtkFixedPointVolumeRayCastMapper employs a form of space leaping to avoid processing in "empty" (entirely transparent) regions of the volume. Early ray termination is also employed to terminate processing once full opacity is reached. Therefore, significant performance improvements can be obtained when rendering data with a sharp "surface" appearance.

7.15 2D Texture Mapping

As an alternative to ray casting, volume rendering of vtkImageData can be performed by texture mapping the volume onto polygons, and projecting these with the graphics hardware. If your graphic board provides reasonable texture mapping acceleration, this method will be significantly faster than ray casting, but at the expense of accuracy since partial accumulation results are stored at the resolution of the framebuffer (usually 8 or less bits per component) rather than in floating point. To use 2D texture mapping, quads are generated along the axis of the volume which is most closely aligned with the viewing direction. As the viewing direction changes, the sample distance between quads will change, and at some point the set of quads will jump to a new axis which may cause temporal artifacts. Generally these artifacts will be most noticeable on small volumes.

The current implementation of vtkVolumeTextureMapper2D supports only alpha compositing. Bilinear interpolation on the slice is used for texture mapping but since quads are only created on the data planes, there is no notion of interpolation between slices. Therefore, the value of the InterpolationType instance variable in the vtkVolumeProperty is ignored by this mapper.

Shading is supported in software for the texture mapping approach. If shading is turned off in the vtkVolumeProperty, then software shading calculations do not need to be performed, and therefore the performance of this mapper will be better than if shading is turned on.

7.16 3D Texture Mapping

Most current graphics cards now support 3D texture mapping where a three-dimensional buffer is stored on the graphics boards and accessed using 3D texture coordinates. A vtkImageData volume may then be rendered by storing this volume as a texture and projecting a set of polygons parallel to the view plane. This removes the "popping" artifacts inherent in the 2D texture mapping approach since there is no longer a sudden change in underlying geometry based on major viewing direction. However, the 3D texture mapping approach currently available in VTK uses the frame buffer for

compositing, which is still generally limited to 8 bits. Therefore with large volumes that are fairly translucent, banding artifacts will occur and small features may be lost in the image.

The 3D texture mapper is a single-pass mapper that requires the entire volume to be in memory. Therefore a limit is placed on the size of the data transferred to the texture memory. This limit is based on the type of the data, the number of components, the texture memory available on the graphics board, and some hard-coded limits used to avoid problems in buggy OpenGL drivers that report the ability to utilize more texture memory than truly available. This is a silent limit - the input data set will be downsampled to fit within the available texture memory with no warning or error messages produced. This mapper supports single component data or any scalar type, and four component dependent data (RGBA) that is unsigned char. For single component data, the hard-coded limit is 256x256x128 voxels, with any aspect ratio provided that each dimension is a power of two. With four component data, the limit is 256x128x128 voxels.

The 3D volume texture mapper supports two main families of graphics hardware: nVidia and ATI. There are two different implementations of 3D texture mapping used - one based on the GL_NV_texture_shader2 and GL_NV_register_combiners2 extensions (supported on some older nVidia cards), and one based on the GL_ARB_fragment_shader extension (supported by most current nVidia and ATI boards). To use this class in an application that will run on various hardware configurations, you should have a back-up volume rendering method. You should create a vtkVolumeTextureMapper3D, assign its input, make sure you have a current OpenGL context (you've rendered at least once), then call IsRenderSupported() with a vtkVolumeProperty as an argument. This method will return 0 if the input has more than one independent component, or if the graphics hardware does not support the set of required extensions for using at least one of the two implemented methods.

7.17 Volumetric Ray Casting for vtkUnstructuredGrid

The vtkUnstructuredGridVolumeRayCastMapper is a volume mapper that employs a software ray casting technique to perform volume rendering on unstructured grids. Using the default ray cast function and integration methods, this mapper is more accurate than the vtkProjectedTetrahedra method, but is also significantly slower. This mapper is generally faster than the vtkUnstructuredGridZSweepMapper, but obtains this speed at the cost of memory consumption and is therefore best used with small unstructured grids. The ray caster is threaded to make use of multiple processors when available. As with all mappers that render vtkUnstructuredGrid data, this mapper requires that the input dataset is composed entirely of tetrahedral elements, and may employ a filter to tetrahedralize the input data if necessary.

This ray cast mapper is customizable in two ways. First, you may specify the method used to traverse the ray through the unstructured grid using the SetRayCastFunction() method. The specified function must be a subclass of vtkUnstructuredGridVolumeRayCastFunction. Currently one such subclass exists within VTK: vtkUnstructuredGridBunykRayCastFunction. This class is based on the method described in "Simple, Fast, Robust Ray Casting of Irregular Grids" by Paul Bunyk, Arie Kaufman, and Claudio Silva. This method is quite memory intensive (with extra explicit copies of the data) and therefore should not be used for very large data.

You may also specify a method for integrating along the ray between the front entry point and back exit point for the length of ray intersecting a tetrahedra using the SetRayIntegrator() method. The specified method must be a subclass of vtkUnstructuredGridVolumeRayIntegrator. Several available subclasses exist in VTK, and when left unspecified the mapper will select an appropriate sub-

Figure 7–11 Comparison of three volume rendering techniques for vtkUnstructuredGrid datasets

class for you. The vtkUnstructuredGridHomogeneousRayIntegrator class is applicable when rendering cell scalars. The vtkUnstructuredGridLinearRayIntegrator performs piecewise linear ray integration. Considering that transfer functions in VTK 5.4 are piecewise linear, this class should give the "correct" integration under most circumstances. However, the computations performed are fairly hefty and should, for the most part, only be used as a benchmark for other, faster methods. The vtkUnstructuredGridPartialPreIntegration also performs piecewise linear ray integration, and will give the same results as vtkUnstructuredGridLinearRayIntegration (with potentially an error due to table lookup quantization), but should be notably faster. The algorithm used is given by Moreland and Angel, "A Fast High Accuracy Volume Renderer for Unstructured Data." The vtkUnstructuredGrid-PreIntegration performs ray integration by looking into a precomputed table. The result should be equivalent to that computed by vtkUnstructuredGridLinearRayIntegrator and vtkUnstructuredGrid-PartialPreIntegration, but faster than either one. The pre-integration algorithm was first introduced by Roettger, Kraus, and Ertl in "Hardware-Accelerated Volume And Isosurface Rendering Based On Cell-Projection."

Similar to the structured ray cast mapper, the unstructured grid ray cast mapper will automatically adjust the number of rays cast in order to achieve a desired update rate. Since this is a software-only technique, this method utilizes multiple processors when available to improve performance.

7.18 ZSweep

The vtkUnstructuredGridVolumeZSweepMapper rendering method is based on an algorithm described in "ZSWEEP: An Efficient and Exact Projection Algorithm for Unstructured Volume Rendering" by Ricardo Farias, Joseph S. B. Mitchell and Claudio T. Silva. This is a software projection technique that will work on any platform, but is generally the slowest of the unstructured grid volume rendering methods available in VTK. It is less memory intensive than the ray cast mapper (using the Bunyk function) and is therefore able to render larger volumes. Similar to the ray cast mapper, the specific ray integrator may be specified using the SetRayIntegrator() method. Again, leaving this as NULL will allow the mapper to select an appropriate integrator for you.

7.19 Projected Tetrahedra

The vtkProjectedTetrahedraMapper rendering method is an implementation of the classic Projected Tetrahedra algorithm presented by Shirley and Tuchman in "A Polygonal Approximation to Direct Scalar Volume Rendering". This method utilizes OpenGL to improve rendering performance by converting tetrahedra into triangles for a given view point, then rendering these triangles with hardware acceleration. However, the OpenGL methods utilized in this class are not necessarily supported by all driver implementations, and may produce artifacts. Typically this mapper will be used in conjunction with either the ray caster or the ZSweep mapper to form a level-of-detail approach that provides fast rendering during interactivity followed by a more accurate technique to produce the final image.

In **Figure 7–11** you can see a comparison of images generated with the three techniques for volume rendering unstructured grids. The projected tetrahedra technique is interactive, while the other two technique require a few seconds per image on a standard desktop system.

The vtkHAVSVolumeMapper is an implementation of the algorithm presented in "Hardware-Assisted Visibility Sorting for Unstructured Volume Rendering" by S. P. Callahan, M. Ikits, J. L. D. Comba, and C. T. Silva.

The code was written and contributed by Steven P. Callahan. The Hardware-Assisted Visibility Sorting (HAVS) algorithm works by first sorting the triangles of the tetrahedral mesh in object space, then they are sorted in image space using a fixed size A-buffer implemented on the GPU called the k-buffer. The HAVS algorithm excels at rendering large datasets quickly. The trade-off is that the algorithm may produce some rendering artifacts due to an insufficient k size (currently 2 or 6 is supported) or read/write race conditions.

A built in level-of-detail (LOD) approach samples the geometry using one of two heuristics (field or area). If LOD is enabled, the amount of geometry that is sampled and rendered changes dynamically to stay within the target frame rate. The field sampling method generally works best for datasets with cell sizes that don't vary much in size. On the contrary, the area sampling approach gives better approximations when the volume has a lot of variation in cell size. For more information on the level-of-detail method, please see "Interactive Rendering of Large Unstructured Grids Using Dynamic Level-of-Detail" by S. P. Callahan, J. L. D. Comba, P. Shirley, and C. T. Silva.

The HAVS algorithm uses several advanced features on graphics hardware. The k-buffer sorting network is implemented using framebuffer objects (FBOs) with multiple render targets (MRTs). Therefore, only cards that support these features can run the algorithm (at least an ATI 9500 or an NVidia NV40 (6600)).

7.20 Speed vs. Accuracy Trade-offs

If you do not have a VolumePro volume rendering board, many fast CPUs, or high-end graphics hardware, you will probably not be satisfied with the rendering rates achieved when one or more volumes are rendered in a scene. It is often necessary to achieve a certain frame rate in order to effectively interact with the data, and it may be necessary to trade off accuracy in order to achieve speed. Fortunately, there are ways to do this for many of the volume rendering approach. In fact, several of them will provide this functionality for you automatically by determining an appropriate accuracy level in order to obtain the desired update rate specified in the vtkRenderWindow.

The support for achieving a desired frame rate for vtkVolumeRayCastMapper, vtkFixedPointVolumeRayCastMapper, vtkUnstructuredGridVolumeRayCastMapper, and vtkUnstructuredGridVolumeZSweepMapper is available by default in VTK. You can set the desired update rate in the

ImageSampleDistance = 1.0 ImageSampleDistance = 2.0 ImageSampleDistance = 4.0

Figure 7–12 The effect of changing image sample distance on image quality.

vtkRenderWindow, or the StillUpdateRate and the DesiredUpdateRate in the interactor if you are using one. Due to the fact that the time required for these rendering techniques is mostly dependent on the size of the image, the mapper will automatically attempt to achieve the desired rendering rate by reducing the number of rays that arecast, or the size of the image is generated. By default, the automatic adjustment is on. In order to maintain interactivity, an abort check procedure should be specified in the render window so that the user will be able to interrupt the higher resolution image in order to interact with the data again.

There are limits on how blocky the image will become in order to achieve the desired update rate. By default, the adjustment will allow the image to become quite blocky - for example, casting only 1 ray for every 10x10 neighborhood of pixels if necessary to achieve the desired update rate. Also by default these mappers will not generate an image larger than necessary to fill the window on the screen. These limits can be adjusted in the mapper by setting the MinimumImageSampleDistance and MaximumImageSampleDistance. In addition AutoAdjustSampleDistances can be turned off, and the specified ImageSampleDistance will be used to represent the spacing between adjacent pixels on the image plane. Results for one example are shown in **Figure 7–12**.

This technique of reducing the number of rays in order to achieve interactive frame rates can be quite effective. For example, consider the full resolution image shown on the left in **Figure 7–12**. This image may require 4 seconds to compute, which is much too slow for data interaction such as rotating or translating the data, or interactively adjusting the transfer function. If we instead subsample every other ray along each axis by setting the ImageSampleDistance to 2.0, we will get an image like the one shown in the middle in only about 1 second. Since this still may be too slow for effective interaction, we could subsample every fourth ray, and achieve rendering rates of nearly 4 frames per second with the image shown on the right. It may be blocky, but it is far easier to rotate a blocky volume at 4 frames per second than a full resolution volume at one frame every four seconds.

There are no built-in automatic techniques for trading off accuracy for speed in a texture mapping approach. This can be done by the user fairly easily by creating a lower resolution volume using vtkImageResample, and rendering this new volume instead. Since the speed of the texture mapping approach is highly dependent on the size of the volume, this will achieve similar results to reducing the number of rays in a ray casting approach. Another option is to reduce the number of planes sampled through the volume. By default, the number of textured quads rendered will be equal to the number of samples along the major axis of the volume (as determined by the viewing direction). You may set the MaximumNumberOfPlanes instance variable to decrease the number of textured quads and

therefore increase performance. The default value is 0 which implies no limit on the number of planes.

7.21 Using a vtkLODProp3D to Improve Performance

The vtkLODProp3D is a 3D prop that allows for the collection of multiple levels-of-detail and decides which to render for each frame based on the allocated rendering time of the prop (see "vtkLODProp3D" on page 57). The allocated rendering time of a prop is dependent on the desired update rate for the rendering window, the number of renderers in the render window, the number of props in the renderer, and any possible adjustment that a culler may have made based on screen coverage or other importance factors.

Using a vtkLODProp3D, it is possible to collect several rendering techniques into one prop, and allow the prop to decide which technique to use. These techniques may span several different classes of rendering including geometric approaches that utilize a vtkPolyDataMapper, and volumetric methods for both structured and unstructured data.

Consider the following simple example of creating a vtkLODProp3D with three different forms of volume rendering for vtkImageData:

```
vtkImageResample resampler
  resampler SetAxisMagnificationFactor 0 0.5
  resampler SetAxisMagnificationFactor 1 0.5
  resampler SetAxisMagnificationFactor 2 0.5


vtkVolumeTextureMapper2D lowresMapper
  lowresMapper SetInput [resampler GetOutput]

vtkVolumeTextureMapper2D medresMapper
  medresMapper SetInput [reader GetOutput]

vtkVolumeRayCastMapper hiresMapper
  hiresMapper SetInput [reader GetOutput]

vtkLODProp3D volumeLOD
  volumeLOD AddLOD lowresMapper volumeProperty 0.0
  volumeLOD AddLOD medresMapper volumeProperty 0.0
  volumeLOD AddLOD hiresMapper volumeProperty 0.0
```

For clarity, many steps of reading the data and setting up visualization parameters have been left out of this example. At render time, one of the three levels-of-detail (LOD) for this prop will be selected based on the estimated time that it will take to render the LODs and the allocated time for this prop. In this case, all three LODs use the same property, but they could have used different properties if desired. Also, in this case all three mappers are subclasses of vtkVolumeMapper, but we could add a bounding box representation as another LOD. If we are rendering a large vtkUnstructuredGrid dataset, we could form an LOD by adding an outline representation using a vtkPolyDataMapper for the lowest resolution, we could resample the data into a vtkImageData and add a level-of-detail that ren-

ders this with 3D texture mapping, and we could add the full resolution unstructured data rendered with the ZSweep mapper as the best level-of-detail.

The last parameter of the AddLOD() method is an initial time to use for the estimated time required to render this level-of-detail. Setting this value to 0.0 requires that the LOD be rendered once before an estimated render time can be determined. When a vtkLODProp3D has to decide which LOD to render, it will choose one with 0.0 estimated render time if there are any. Otherwise, it will choose the LOD with the greatest time that does not exceed the allocated render time of the prop, if it can find such an LOD. Otherwise, it will choose the LOD with the lowest estimated render time. The time required to draw an LOD for the current frame replaces the estimated render time of that LOD for future frames.

Chapter 8

Information Visualization

Visualization techniques may be classified into two broad categories: scientific visualization and information visualization. The two are mainly distinguished by the types of data they represent. Scientific visualization refers to the display of data having inherent spatiotemporal attributes, such as simulations, models, or images. With these types of data, the relative position of elements is known because each element has an inherent structure and placement in a three dimensional space.

Information visualization, on the other hand, is the visualization of all other forms of data. Metadata, relational databases, and general tabular data fall into this category. In these cases, the placement of individual elements is not fixed and an embedding must be performed to place similar or related elements closer together. Consider visualizing a group of people. One simple way to organize the people is to place them in a list or table. If accompanying information is also available, alternative formats may be helpful to the viewer. People could be presented in a 2D view, grouped by similarity in age, gender, occupation, etc. If "friendship" links are known (e.g. from a social networking website), they could be grouped into natural friendship groups formed by these links. If each person's current location is known, they could be arranged on a map ("Geospatial Visualization" on page 207 for VTK's capabilities in that regard).

Other examples of data suitable for information visualization are databases, spreadsheets, XML, and any type of metadata such as demographic information of patients or parameters of simulation runs. For this type of visualization, algorithms such as clustering and graph layout are used to uncover salient relationships or determine a high-level picture of complex, heterogeneous data.

The essential data structures for information visualization are tables, graphs, and trees. A table is simply a two-dimensional array of data, much like a spreadsheet. In VTK, a table consists of a vector of named arrays which serve as the columns of the table. Each column acts much like an attribute in other data objects like vtkImageData. Tables are used to store the results of database queries and contents of delimited text files.

The graph data structure consists of a collection of entities called vertices, along with links between pairs of vertices called edges. Graphs can be used to store many kinds of data. For example,

in a social network, each vertex may represent a person while each edge may signify a friendship between two people. Another example is a biological pathway network where vertices may represent compounds and edges may indicate that chemical reactions can produce one compound from another.

A tree is a type of graph that does not contain any cycles (sequences of connected edges that form a full loop). VTK's tree data structure is a rooted tree, which can be thought of as a hierarchy, with the root vertex on top. Trees can organize large amounts of data by grouping entities into multiple levels.

Tables, graphs, and trees can represent complex data in several ways. The following sections provide some details about how to perform some basic operations and visualizations with these data structures.

8.1 Exploring Relationships in Tabular Data

Tables are a very common form of data. Plain text delimited files, spreadsheets, and relational databases all use tables as the basic data structure. A row in the table normally represents a single entity (a person, an event, a sample, etc.) and columns represent attributes present on those entities. Let's take for example a table of medals from the Summer 2008 Olympics. This table will have the medal winner's name and country, along with the event information. In tabular format, it is not easy to answer questions such as: Who won the most medals? What country excelled in a certain discipline? In order to do this, we want to extract relational information from the table in the form of a graph or tree.

Converting a Table to a Graph

The following python example demonstrates how to take this information, and with vtkTableToGraph, convert it into a vtkGraph data structure and display it in a graph view. Note that the script attempts to find the VTK data path, which may be explicitly defined in this and other examples by adding the parameters "-D <path>" to the command line when running the script. The following example is Python code for converting a simple table into a graph.

```
from vtk import *
import vtk.util.misc
import versionUtil

datapath = vtk.util.misc.vtkGetDataRoot()

reader = vtkDelimitedTextReader()
reader.SetFileName(datapath + '/Data/Infovis/medals.txt')
reader.SetFieldDelimiterCharacters('\t')
reader.SetHaveHeaders(True)

ttg = vtkTableToGraph()
ttg.SetInputConnection(reader.GetOutputPort())
ttg.AddLinkVertex('Name', 'Name', False)
ttg.AddLinkVertex('Country', 'Country', False)
ttg.AddLinkVertex('Discipline', 'Discipline', False)
ttg.AddLinkEdge('Name', 'Country')
ttg.AddLinkEdge('Name', 'Discipline')
```

```
category = vtkStringToCategory()
category.SetInputConnection(ttg.GetOutputPort())
category.SetInputArrayToProcess(0, 0, 0, 4, 'domain')

view = vtkGraphLayoutView()
view.AddRepresentationFromInputConnection(
  category.GetOutputPort())
view.SetLayoutStrategyToSimple2D()
view.SetVertexLabelArrayName('label')
view.VertexLabelVisibilityOn()
view.SetVertexColorArrayName('category')
view.ColorVerticesOn()
view.SetVertexLabelFontSize(18)

theme = vtkViewTheme.CreateMellowTheme()
view.ApplyViewTheme(theme)

rw = versionUtil.SetupView(view)
versionUtil.ShowView(view)]
```

First we create a vtkDelimitedTextReader to read in the medals text file. This reader produces a vtkTable as its output, which is simply a list of named data arrays. The fields in this file are separated by tabs, so we set the field delimiter characters appropriately. We specify SetHaveHeaders(True) in order to assign column names from the first line in the file. Otherwise the columns would have generic names "Field 0", "Field 1", and so on, and data in the table would be assumed to start on the first line.

You will notice the calls to versionUtil.SetupView and versionUtil.ShowView that are used to handle code near the end of this and other examples. This reflects a code change after VTK 5.4 which makes vtkRenderView contain a vtkRenderWindow. This eliminates the need for creating a render window manually and calling SetupRenderWindow(). Also, instead of calling methods such as ResetCamera() and Render() on the render window, these methods have been added to vtkRenderView, and should be called on the view instead. The following listing shows the contents of versionUtil.py. from vtk import * The following code example demonstrates setting up and displaying a VTK view in version 5.4 and later.

```
from vtk import *
def VersionGreaterThan(major, minor):
  v = vtkVersion()
  if v.GetVTKMajorVersion() > major:
    return True
  if v.GetVTKMajorVersion() == major and v.GetVTKMinorVersion() > minor:
    return True
  return False

def SetupView(view):
  if not VersionGreaterThan(5, 4):
    win = vtkRenderWindow()
    view.SetupRenderWindow(win)
    return win
  else:
    return view.GetRenderWindow()
```

```
def ShowView(view):
  if VersionGreaterThan(5, 4):
    view.ResetCamera()
    view.Render()
    view.GetInteractor().Start()
  else:
    view.GetRenderer().ResetCamera()
    view.GetRenderWindow().Render()
    view.GetRenderWindow().GetInteractor().Start()
```

Now we wish to visualize some of the relationships in this table. The table has the following columns: "Name" contains the name of the athlete, "Country" has the athlete's country, and "Discipline" contains the discipline. The table has the following columns: "Name" contains the name of the athlete, "Country" has the athlete's country, and "Discipline" contains the disciplineof the event the athlete participated in (such as swimming, archery, etc.). One method for viewing the relationships in the graph is to use vtkTableToGraph to produce a vtkGraph from the table. vtkTableToGraph takes a vtkTable as input (and optionally a second "vertex table" input described later) and produces a vtkGraph whose structure, vertex attributes, and edge attributes are taken from the table.

The vtkTableToGraph algorithm needs to know what columns should be used to generate vertices, and what pairs of columns should become edges, linking vertices together. So, in our example, we may wish to make a graph whose vertices represent names, countries, and disciplines. To do this we call AddLinkVertex() with the name of a column to make vertices from. All distinct values in that column will become vertices in the graph. So, AddLinkVertex('Country', ...) will make a vertex in the output graph for each distinct country name in the "Country" column of the table. The second argument to AddLinkVertex() provides the domain to be associated with those vertices. Domains are important for entity resolution. If, for example, "Country" and "Name" were given the same domain name, a country named "Chad" would be merged with a person with the name "Chad". Giving each column a different domain will avoid these conflicts. There are situations, however, where two columns of the table should be given the same domain. For example, in a table of communications, there may columns named "From" and "To". These should be assigned the same domain (perhaps named "Person"), so that a person's vertex would be merged into the same vertex regardless of whether that person was a sender or a recipient. The third parameter of AddLinkVertex() is described in "Hidden Vertices" on page 168.

Now that the vertices are defined, we can define the set of edges in the graph with AddLinkEdge(). AddLinkEdge() takes two table column names, and produces an edge between two vertices A and B every time A and B appear together in the same row in those two columns. So the call AddLinkEdge('Name', 'Country') will add an edge in the graph between each athlete and his or her country. Similarly, AddLinkEdge('Name', 'Discipline') will add an edge between an athlete and each discipline he or she participates in. **Figure 8–1** shows the result of converting the table of medals into a graph. The colors of the vertices in the graph indicate the domain to which they belong.Since you may only assign colors with a numeric array, the program uses vtkStringToCategory to convert the domain array (which contains strings), into numeric identifiers for each distinct vertex.

Attributes. The edges in vtkTableToGraph's output have the full set of attributes defined in the table. Namely each edge has associated with it all of the entries in the row of the table that produced the edge.

The vertices, however, have only three attributes associated with them by default. An attribute named "domain" will be a string array containing the domain name of each vertex. The "ids" and "label" attributes both contain the same quantity, but present it in different formats. The quantity that both contain is the content of the particular cell that defines the vertex. The "ids" attribute stores it in the original type, which may vary for vertices that belong to different domains. Hence the "ids" array is stored in a vtkVariantArray in which the data type of each entry is variable. The "label" attribute is a vtkStringArray containing the string equivalents of those values.

vtkTableToGraph accepts an optional second vtkTable input so that the vertices can have additional attributes assigned to them. While the first input to the filter defines connectivity of edges (and hence is called the "edge table"), the second input defines the additional properties for the graph vertices (so is called the "vertex table").

Therefore, to add vertex attributes, you must create a vertex table that contains columns with identifiers matching those of the edge table's columns. The vertex table may have any number of additional columns containing other vertex attributes. In our example, there may be other tables that reside in separate files or in a relational database that define athlete properties (e.g. age, gender), country properties (e.g. population, land area), and discipline properties (e.g. number of events). To add these as vertex properties in the graph, you need to construct a single table containing all these columns. For example, this can be done with a properly formed SQL query or by applying the vtkMergeTables algorithm. When this expanded table is set as the second input to vtkTableToGraph, the domains defined in the second argument of AddLinkVertex() take on a special meaning. The domain name must match the vertex table column name that contains the matching identifiers. So in our example code, the vertex table would need to have arrays named "Name", "Country", and "Discipline" containing values matching those in the edge table.

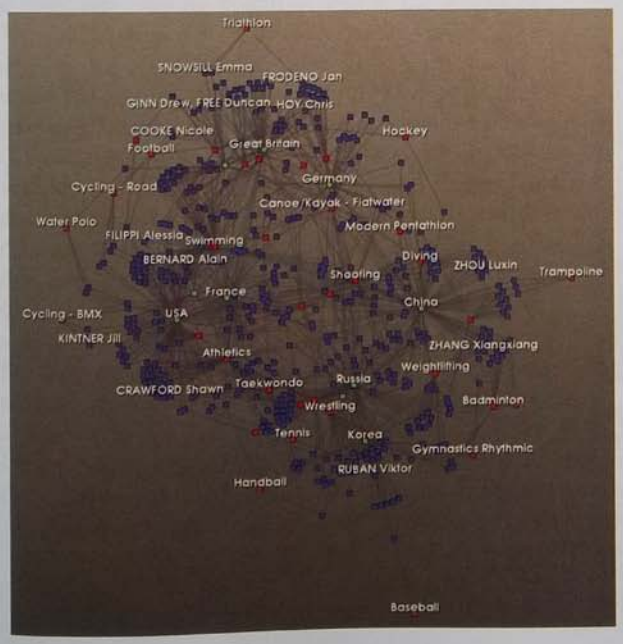


Figure 8–1 The result of performing vtkTableToGraph to visualize a table of 2008 Olympic medals. Medal-winning athletes (blue) are linked to their country (green) and discipline (red).

Hidden Vertices. The third parameter of AddLinkVertex() indicates whether the vertices should be hidden. Most frequently, it is worthwhile to show the vertices, so the default is False. However, setting it to True allows the creation of advanced link effects, for example connecting athletes to other athletes who represent the same country, but without displaying countries explicitly. To do this, you would add "Name" as a non-hidden vertex type, and "Country" as a hidden vertex type. Then you add the pairs ("Name", "Country") and ("Country", "Name") with AddLinkEdge(). Internally vtkTableToGraph creates the graph with name and country vertices, then deletes the country vertices, creating a new edge for each two-edge path that passes through a country vertex. Note that hiding vertices can be prohibitively expensive since the number of edges produced can grow quickly, and can produce large cliques (i.e. collections of vertices where every pair of vertices is connected by an edge). For this reason, this option may be deprecated in the future.

Converting a Table to a Tree

While a graph represents an arbitrarily complex structure, a tree has a much more restricted, and hence simpler, structure. In VTK, a vtkTree contains a rooted tree in which there is a hierarchy of vertices with a single root vertex on top. Outgoing edges flow down the tree, connecting "parent" vertices to "child" vertices. One example use for vtkTrees is to examine the structure of arbitrary XML files. A tree can be generated directly from any XML file simply by using the vtkXMLTreeReader. That reader parses the nested XML elements and creates a vtkTree. You may also create a categorical tree from tabular data. The following python code demonstrates how to use the vtkTableToTreeFilter and vtkGroupLeafVertices algorithms to do this.

```
VERTICES = 4 # Constant for SetInputArrayToProcess
datapath = vtk.util.misc.vtkGetDataRoot()

reader = vtkDelimitedTextReader()
reader.SetFileName(datapath + '/Data/Infovis/medals.txt')
reader.SetFieldDelimiterCharacters('\t')
reader.SetHaveHeaders(True)
if versionUtil.VersionGreaterThan(5,4):
  reader.OutputPedigreeIdsOn()

ttt = vtkTableToTreeFilter()
ttt.SetInputConnection(reader.GetOutputPort())

group_disc = vtkGroupLeafVertices()
group_disc.SetInputConnection(ttt.GetOutputPort())
group_disc.SetInputArrayToProcess(0, 0, 0, VERTICES, 'Discipline')
group_disc.SetInputArrayToProcess(1, 0, 0, VERTICES, 'Name')

group_country = vtkGroupLeafVertices()
group_country.SetInputConnection(group_disc.GetOutputPort())
group_country.SetInputArrayToProcess(0, 0, 0, VERTICES, 'Country')
group_country.SetInputArrayToProcess(1, 0, 0, VERTICES, 'Name')

category = vtkStringToCategory()
category.SetInputArrayToProcess(0, 0, 0, VERTICES, 'Name')
category.SetInputConnection(group_country.GetOutputPort())
```

```
view = vtkTreeRingView()
view.AddRepresentationFromInputConnection(
  category.GetOutputPort())
view.RootAtCenterOn()
view.SetInteriorRadius(1)
view.SetAreaHoverArrayName('Name')
view.SetAreaLabelArrayName('Name')
view.AreaLabelVisibilityOn()
view.SetAreaColorArrayName('category')
if versionUtil.VersionGreaterThan(5,4):
  view.ColorAreasOn()
else:
  view.ColorVerticesOn()
view.SetAreaLabelFontSize(18)
```

The code begins with reading the same tab-delimited file with Olympic medal data described in the previous sections. vtkTableToTreeFilter then performs the first basic step in converting our table into a tree. It produces a new vertex to serve as the root of the tree, then creates a child vertex for every row in the input table, associating the attributes in the table with the child vertices in the tree. This tree is not yet interesting since it only contains a single level with no meaningful structure. In our example, vtkTableToTreeFilter is followed by two instances of vtkGroupLeafVertices. Each of these filters adds a new level to the tree, grouping existing leaf vertices (i.e. vertices with no children) according to matching values in a particular array. The first instance of vtkGroupLeafVertices sets the main input array to be the "Discipline" attribute. This adds a new level below the root that contains one vertex for each unique value in the discipline array. The original leaf vertices are collected under each discipline vertex based on their value for that attribute.

Similarly, the second vtkGroupLeafVertices adds a level representing countries below the disciplines. The data is already split by discipline, so each country may appear several times, once under each discipline where that country won a medal. This is one main difference between converting a table to a graph or a tree. Graphs are a more complex structure, which allows vertices representing the same entity to appear only once. Trees, on the other hand, are simpler structures that are often simpler to comprehend, but often require duplication of data because of their connectivity constraints. The result of converting the table into a tree and visualizing it with a vtkTreeRingView is shown in **Figure 8–2**. The tree ring view and graph layout view are described further in the "Graph Visualization Techniques" on page 170. Simply reversing the two vtkGroupLeafVertices algorithms would produce a tree that was organized first by country, then by discipline.

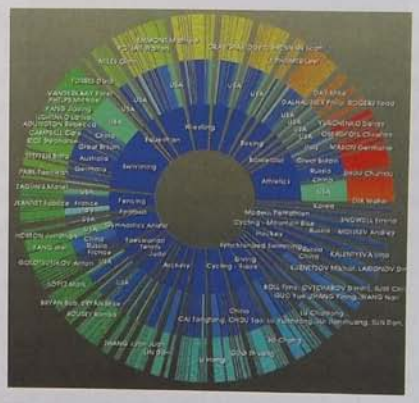


Figure 8–2 A table of Olympic medals visualized in a tree ring view.

These filters are available for processing vtkTables or attribute data in other data objects:

- vtkBoostSplitTableField.cxx - Splits a string attribute into parts by a delimiter and makes duplicate rows for each part, differing only by the split attribute.

- vtkDataObjectToTable.cxx - Converts the point or cell attribute of a vtkDataSet subclass, or vertex or edge data of a vtkGraph subclass into a vtkTable.
- vtkGenerateIndexArray.cxx - Generate a simple zero-based index array and append it to a data object.
- vtkMergeColumns.cxx - Merge multiple columns into a single column.
- vtkMergeTables.cxx - Merge multiple tables into a single table containing the union of all columns.
- vtkStringToCategory.cxx - Convert a string array to an integer array by assigning an integer to each unique string in the array.
- vtkStringToNumeric.cxx - Automatically detects and converts string arrays containing values that may be converted to integer or floating-point values.
- vtkThresholdTable.cxx - Filter out rows from a vtkTable that have attribute values outside a given range.

Other graph transformation algorithms include:

- vtkCollapseGraph.cxx - Combine vertices with matching attribute values into a single vertex.
- vtkPruneTreeFilter.cxx - Remove a sub-tree from a vtkTree.
- vtkRemoveIsolatedVertices.cxx - Delete vertices with no edge connections from a graph.

8.2 Graph Visualization Techniques

Graph visualization is becoming increasingly important as a method for divining relationships between entities, entity clustering, and higher level abstractions. Graphs are typically visualized in two- or three-dimensions, with attempts to inject additional dimensional information through vertex and edge coloring, labeling, annotations, clustering, and icons. Because of the diversity available for displaying graphs including theoretical, heuristic, empirical and manual layout methods, graph visualization has become a mixture of both art and science requiring methods that can handle both flexibility and complexity while maintaining a fair amount of generality. These methods are typically broken down into methods for vertex layout, methods for edge layout and methods which display vertices and relationships with polygonal data structures (e.g., circles, rings, blocks, etc.). In addition to the layout methods, helper functionality for displaying graph attributes is also desirable (e.g., common coloring themes, labeling mechanisms, annotations and selections, etc.). To accommodate this flexibility while maintaining a high level of functionality, the graph visualization tools in VTK utilize `strategy' methods for layout of vertices and edges, and 'view' objects for centralizing common helper functionality associated with the visualization of graphs.

To demonstrate basic capability, we present a simple example uses layouts and views to create graph displays in VTK see **Figure 8–3**. The remainder of this section will discuss additional flexibility available in performing graph visualization. The following code snippet creates a simple graph view of a random graph.

```
from vtk import *

# create a random graph
source = vtkRandomGraphSource()
```

```
source.SetNumberOfVertices(100)
source.SetNumberOfEdges(110)
source.StartWithTreeOn()

#create a view to display the graph
view = vtkGraphLayoutView()
view.SetLayoutStrategyToSimple2D()
view.ColorVerticesOn()
view.SetVertexColorArrayName("vertex id")
view.SetRepresentationFromInputConnection(source.GetOutputPort())

# Apply a theme to the views
theme = vtkViewTheme.CreateMellowTheme()
view.ApplyViewTheme(theme)
theme.FastDelete()

#view.GetRenderWindow().SetSize(500,500)
view.ResetCamera()
view.Render()

view.GetInteractor().Start()
```

A primary step that must take place in information visualization is to embed the data into some drawable space. Recall that vertices in a vtkGraph have no relation to vtkPoints in the more traditional vtkDataSet classes. Points have X, Y and Z coordinates, but vertices to not. Depending on how these assignments are made, the resulting picture will vary greatly, and different characteristics of the underlying data will be easier to discern. A second degree of freedom in information visualization is the exact routing of the edges that connect the vertices.

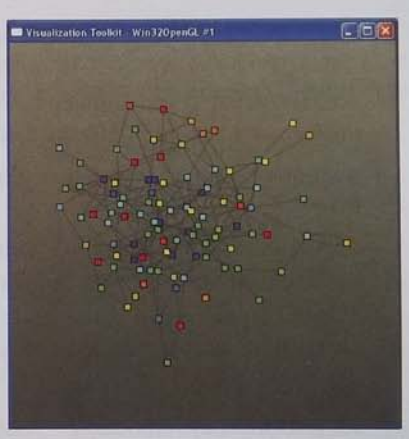


Figure 8–3 A simple graph view

Vertex Layout

To determine where vertices are positioned, one places a vtkGraphLayout class into the pipeline. This class is responsible for the overall task of assigning coordinates to vertices, but it leaves the details of coordinate assignment to a swappable helper class. The helper class is an example of a strategy. This two part structure maximizes flexibility and minimizes complexity. Thus, in a typical graph visualization, a graph is piped into the vtkGraphLayout class after which each vertex has a vtkPoint assigned. The pipeline author can choose amongst a number of strategies. Strategies may vary from spring-based layouts to clustering methods. Each strategy class is subclassed from vtkGraphLayoutStrategy, all of which can be plugged into vtkGraphLayout. Examples of currently available layout strategies include:

- vtkAssignCoordinatesLayoutStrategy - strategy to allow coordinate assignment from arrays designated as the x, y, and z coordinates.
- vtkCircularLayoutStrategy - Assigns points to the vertices around a circle with unit radius.

- vtkClustering2DLayoutStrategy - strategy utilizing a density grid based force directed layout strategy. The layout running time is O(V+E) with an extremely high constant.
- vtkCommunity2DLayoutStrategy - similar to vtkClustering2DLayoutStrategy, but looks for a community array on its input and strengthens edges within a community and weakens edges not within the community.
- vtkConeLayoutStrategy - strategy that positions the nodes of a tree(forest) in 3D space based on the cone-tree approach first described by Robertson, Mackinlay and Card in the proceedings of the ACM Conference on Human Factors in Computing Systems (CHI'91). This implementation also incorporates refinements to the layout developed by Carriere and Kazman, and by Auber.
- vtkConstrained2DLayoutStrategy - similar to vtkClustering2DLayoutStrategy, but looks for a constraint array indicating a level of impedance a node has to the force calculations during the layout optimization.
- vtkCosmicTreeLayoutStrategy - tree layout strategy reminiscent of astronomical systems
- vtkFast2DLayoutStrategy - a simple fast 2D graph layout.
- vtkForceDirectedLayoutStrategy - lays out a graph in 2D or 3D using a force-directed algorithm.
- vtkPassThroughLayoutStrategy - a layout strategy that does absolutely simply passes the graph through without modifying the data.
- vtkRandomLayoutStrategy - randomly places vertices in 2 or 3 dimensions within a bounded range.
- vtkSimple2DLayoutStrategy - an implementation of the Fruchterman & Reingold layout strategy (see "Graph Drawing by Force-directed Placement" Software-Practice and Experience 21(11) 1991)).
- vtkTreeLayoutStrategy - Assigns points to the nodes of a tree in either a standard or radial layout.
- vtkTreeOrbitLayoutStrategy - Assigns points to the nodes of a tree to an orbital layout. Each parent is orbited by its children, recursively.

To simplify the task of visualizing different graphs, the vertex layout strategies can be supplied directly to a view class. This is done by calling vtkGraphLayoutView::SetLayoutStrategy(vtkGraphLayoutStrategy *s) as in the preceding example. Views are discussed in greater depth in "Views and Representations" on page 176.

Edge Layout

To determine how edges are routed, one again uses a strategy abstraction. Every edge layout strategy is subclassed from vtkEdgeLayoutStrategy, which is then plugged into the vtkEdgeLayout class. Examples of currently available edge layout strategies include:

- vtkArcParallelEdgeStrategy - routes single edges as line segments, routes parallel edges as arcs.
- vtkGeoEdgeStrategy - Layout graph edges on a globe as arcs.
- vtkPassThroughEdgeStrategy - a layout strategy that simply passes the graph through without modifying the data.

The edge layout strategies can also be supplied directly to a view class using vtkGraphLayoutView::SetEdgeLayoutStrategy(vtkEdgeLayoutStrategy *s).

Converting Layouts to Geometry

Once the layouts are complete, the graphs must still be converted to geometry: points, lines, polylines, polygons, etc., which can be mapped into actors in order to be displayed in a render window. Classes for helping to accomplish this final conversion include:

- vtkGraphToGlyphs - Converts a vtkGraph to a vtkPolyData containing a glyph (circle, diamond, crosses, etc.) for each vertex.
- vtkGraphMapper - Map vtkGraph and derived classes to graphics primitives.
- vtkGraphToPolyData - Converts the edges of the graph to polydata, assumes vertex data already has associated point data and passes this data along.
- vtkEdgeCenters - generate points at center of graph edges.

The use of the preceding classes is demonstrated here in the following code example of drawing a graph. We are using a single strategy to do the initial graph layout; however, as noted earlier, the strategy classes are interchangeable, and new layout strategies can be applied by swapping out one strategy for another in this example.

```
from vtk import *

# create a random graph
source = vtkRandomGraphSource()
source.SetNumberOfVertices(100)
source.SetNumberOfEdges(110)
source.StartWithTreeOn()
source.Update()

# setup a strategy for laying out the graph
#  NOTE: You can set additional options for each strategy, as desired
strategy = vtkFast2DLayoutStrategy()
#strategy = vtkSimple2DLayoutStrategy()
#strategy = vtkCosmicTreeLayoutStrategy()
#strategy = vtkForceDirectedLayoutStrategy()
#strategy = vtkTreeLayoutStrategy()

# set the strategy on the layout
layout = vtkGraphLayout()
layout.SetLayoutStrategy(strategy)
layout.SetInputConnection(source.GetOutputPort())

# create the renderer to help in sizing glyphs for the vertices
ren = vtkRenderer()

# Pipeline for displaying vertices - glyph -> mapper -> actor -> display
#  mark each vertex with a circle glyph
vertex_glyphs = vtkGraphToGlyphs()
```

```
vertex_glyphs.SetInputConnection(layout.GetOutputPort())
vertex_glyphs.SetGlyphType(7)
vertex_glyphs.FilledOn()
vertex_glyphs.SetRenderer(ren)

# create a mapper for vertex display
vertex_mapper = vtkPolyDataMapper()
vertex_mapper.SetInputConnection(vertex_glyphs.GetOutputPort())
vertex_mapper.SetScalarRange(0,100)
vertex_mapper.SetScalarModeToUsePointFieldData()
vertex_mapper.SelectColorArray("vertex id")

# create the actor for displaying vertices
vertex_actor = vtkActor()
vertex_actor.SetMapper(vertex_mapper)

# Pipeline for displaying edges of the graph - layout -> lines -> mapper
-> actor -> display
#  NOTE: If no edge layout is performed, all edges will be rendered as
#  line segments between vertices in the graph.
edge_strategy = vtkArcParallelEdgeStrategy()

edge_layout = vtkEdgeLayout()
edge_layout.SetLayoutStrategy(edge_strategy)
edge_layout.SetInputConnection(layout.GetOutputPort())

edge_geom = vtkGraphToPolyData()
edge_geom.SetInputConnection(edge_layout.GetOutputPort())

# create a mapper for edge display
edge_mapper = vtkPolyDataMapper()
edge_mapper.SetInputConnection(edge_geom.GetOutputPort())

# create the actor for displaying the
edges
edge_actor = vtkActor()
edge_actor.SetMapper(edge_mapper)
edge_actor.GetProperty().SetColor(0.,0.
,0.)
edge_actor.GetProperty().SetOpacity(0.2
5)
```

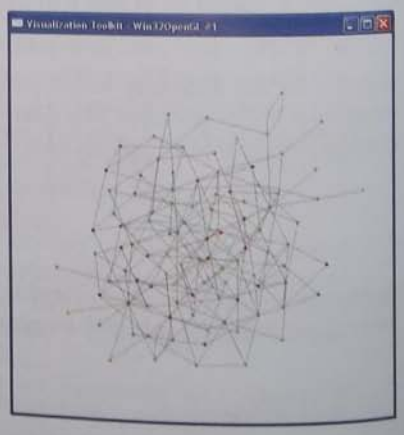


Figure 8–4 The result of executing the code to draw a graph

Despite the flexibility afforded by the above classes, visual clutter is frequently a problem when the number of edges in the graph is large. Especially with straight connections between each pair of related vertices, the displayed graph quickly becomes impossible to interpret. To overcome this problem, VTK includes additional algorithms to reduce the visual clutter. They essentially bend and bundle related edges together. Filters which achieve this include:

- vtkGraphHierarchicalBundle (and the associated vtkGraphHierarchicalBundleEdges) - layout graph edges in arced bundles, following the algorithm developed by Danny Holten in "Hierarchical Edge Bundles: Visualization of Adjacency Relations in Hierarchical Data." IEEE Transactions on Visualization and Computer Graphics, Vol. 12, No. 5, 2006. pp. 741-748.
- vtkSplineGraphEdges - subsample graph edges to make smooth (splined) curves.

Here is an example of performing edge bundling using splines. The following code performs a tree layout, then uses vtkGraphHierarchicalBundle to display bundled edges from the graph on top of the tree (**Figure 8–5**).[

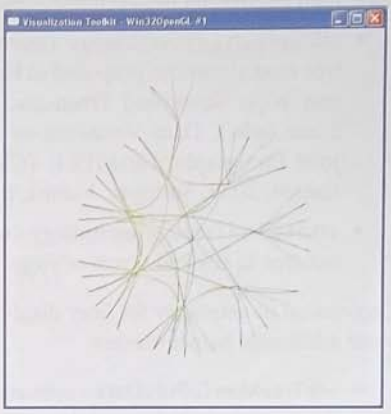


Figure 8–5 The result of bundling graph edges from the code.

```
// Create a standard radial
// tree layout strategy
vtkTreeLayoutStrategy* treeStrategy =
vtkTreeLayoutStrategy::New();
treeStrategy->SetAngle(360.);
treeStrategy->SetRadial(true);
treeStrategy->SetLogSpacingValue(0.8);
treeStrategy->SetLeafSpacing(0.9);

// Layout the vertices of the tree
// using the strategy just created
vtkGraphLayout* treeLayout =
  vtkGraphLayout::New();
treeLayout->SetInput(realTree);
treeLayout->SetLayoutStrategy(treeStrategy);

// Use the tree to control the layout of the graph edges
vtkGraphHierarchicalBundle* bundle =
vtkGraphHierarchicalBundle::New();
bundle->SetInput(0, graph);
bundle->SetInputConnection(1, treeLayout->GetOutputPort(0));
bundle->SetBundlingStrength(0.9);
bundle->SetDirectMapping(true);

// Smooth the edges using with splines
vtkSplineFilter* spline = vtkSplineFilter::New();
spline->SetInputConnection(0, bundle->GetOutputPort(0));
```

Area Layouts

For trees or graphs with embedded hierarchical information (i.e. a graph with an embedded spanning tree), alternative visualization methods convert the displays of the vertices into polygonal based structures (e.g. blocks, rings, circles, etc.). These methods have proven useful in divining out additional structure from the original hierarchy. Examples of these types of graph visualizations include treemaps, radial space-filling trees, and icicle representations (**Figure 8–6**).

For these techniques, each vertex is typically assigned a set of values in a 4-tuple array representing the placement and size of a rectangular region (or circular sector in the case of the tree ring

view). These methods also utilize a layout strategy which is plugged into vtkAreaLayout. Currently available strategies include:

- vtkBoxLayoutStrategy (treemap) - a tree map layout that puts vertices in square-ish boxes by recursive partitioning of the space for children vertices.
- vtkSliceAndDiceLayoutStrategy (treemap) - lays out a tree-map alternating between horizontal and vertical slices.
- vtkSquarifyLayoutStrategy (treemap) - use the squarified tree map algorithm proposed in Bruls, D.M., C. Huizing, J.J. van Wijk. Squarified Treemaps. In: W. de Leeuw, R. van Liere (eds.), Data Visualization 2000, Proceedings of the joint Eurographics and IEEE TCVG Symposium on Visualization, 2000, Springer, Vienna, p. 33-42.
- vtkStackedTreeLayoutStrategy (tree ring and icicle) - lays out tree in stacked boxes or rings.

Conversion to geometry for later display is accomplished through some additional helper classes:

- vtkTreeMapToPolyData - converts a tree with an associated data array to a polygonal data representing a tree map.
- vtkTreeRingToPolyData - converts a tree with an associated data array to a polygonal data representing an icicle or tree ring layout.

These classes utilize the 4-tuple array created in the layout classes and convert this data to the standard polygonal primitives for each vertex represented by the value in the array.

Figure 8–6 Treemap, tree ring, and icicle views displaying the partitioning of classes into libraries, along with links connecting each class to its superclass

8.3 Views and Representations

Views in VTK combine rendering logic, interaction, visualization parameters, and selection into one place. Datasets are displayed in views by adding what are called "representations" to the view. A representation prepares an input dataset to be displayed in a view, and contains options for how that data should be rendered in the view, including colors, icons, layout algorithms, and labels. All views are subclasses of vtkView, and all view representations are subclasses of vtkDataRepresentation. The previous sections have already introduced views such as vtkGraphLayoutView and vtkTreeRingView.

You can add data objects to a view in two ways. One way is to create the appropriate representation, set the inputs on the representation by calling SetInputConnection() or SetInput(), then call AddRepresentation() on the view. The other way that is normally more convenient is to have the view automatically create the default representation for you through calling AddRepresentationFromInput() or AddRepresentationFromInputConnection(). These methods accept a data object or algorithm

output port, create a representation appropriate for the view, add the representation to the view, and return a pointer to the new representation.

The following Python code generates a simple vtkRenderView with a sphere source displayed with a vtkSurfaceRepresentation.

```
from vtk import *
import versionUtil

if versionUtil.VersionGreaterThan(5, 4):
  rep = vtkRenderedSurfaceRepresentation()
else:
  rep = vtkSurfaceRepresentation()

sphere = vtkSphereSource()
sphere.SetPhiResolution(100)
sphere.SetThetaResolution(100)
rep.SetInputConnection(sphere.GetOutputPort())

view = vtkRenderView()
view.AddRepresentation(rep)

rw = versionUtil.SetupView(view)
versionUtil.ShowView(view)
```

Note that the example code reflects the name change from vtkSurfaceRepresentation to vtkRendered-SurfaceRepresentation after VTK 5.4.

An example of using the vtkTreeRingView class for graph visualization is shown below. Note that this view takes two inputs, one for the graph and one for the tree. This code generates the center image in Figure 8-6. The tree ring contains the VTK classes organized by library, while the internal edges show subclass to superclass relationships.

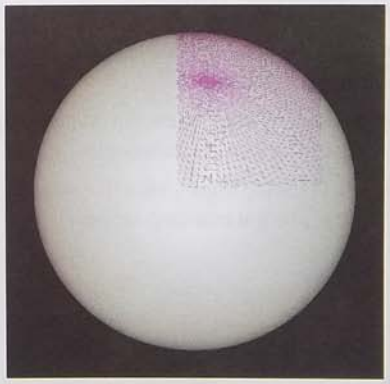


Figure 8–7 A vtkSurfaceRepresentation of a sphere rendered in a vtkRenderView. A rectangular region has been selected and highlighted

```
# Import a grapRush with an embedded
hierarchy (tree).
from vtk import *
import vtk.util.misc
import versionUtil

datapath =
vtk.util.misc.vtkGetDataRoot()

reader1 = vtkXMLTreeReader()
reader1.SetFileName(datapath + "/
Data/Infovis/XML/vtkclasses.xml")
reader1.SetEdgePedigreeIdArrayName("tree edge")
reader1.GenerateVertexPedigreeIdsOff();
reader1.SetVertexPedigreeIdArrayName("id");
```

```
reader2 = vtkXMLTreeReader()
reader2.SetFileName(datapath + "/Data/Infovis/XML/vtklibrary.xml")
reader2.SetEdgePedigreeIdArrayName("graph edge")
reader2.GenerateVertexPedigreeIdsOff();
reader2.SetVertexPedigreeIdArrayName("id");

# Setup the view parameters for displaying the graph
view = vtkTreeRingView()
view.SetTreeFromInputConnection(reader2.GetOutputPort())
view.SetGraphFromInputConnection(reader1.GetOutputPort())
view.SetAreaColorArrayName("VertexDegree")
view.SetEdgeColorToSplineFraction()
view.SetAreaHoverArrayName("id")
view.SetColorEdges(True)
view.SetAreaLabelArrayName("id")
view.SetAreaLabelVisibility(True)
view.SetShrinkPercentage(0.02)
view.SetBundlingStrength(.8)

# Apply a theme to the views
theme = vtkViewTheme.CreateMellowTheme()
view.ApplyViewTheme(theme)

rw = versionUtil.SetupView(view)
versionUtil.ShowView(view)
```

These are the render view subclasses currently implemented in VTK:

- vtkGraphLayoutView - view window for visualizing graphs
- vtkHierarchicalGraphView - view window for visualizing graphs with associated, or derived, hierarchical data.
- vtkIcicleView - view for visualizing trees, or graphs with associated or derived hierarchical data, using an icicle layout.
- vtkTreeMapView - view for visualizing trees, or graphs with associated or derived hierarchical data, using a tree map layout.

- vtkTreeRingView - view for visualizing trees, or graphs with associated or derived hierarchical data, using a radial space filling layout.

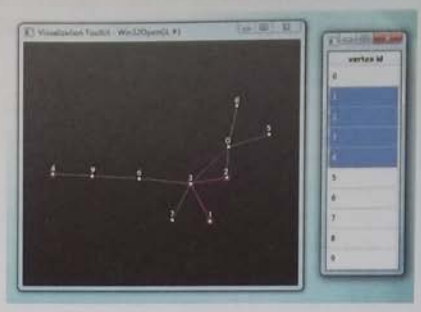


Figure 8–8 A simple application showing linked selection between a graph layout view and a Qt table view.

Selections in Views

Selections are an important component of the VTK view architecture. Refer to "Interaction, Widgets and Selections" on page 255 for a general description of selections in VTK. Most views have the ability to interactively create a selection (e.g. through mouse clicks or rubber-band selections), and also have the capacity to display the current selection through highlighting or some other mechanism.

Views automatically generate selections of the corresponding type when the user performs a selection interaction (e.g. by clicking or dragging a selection box). Selections may be shared across views simply by setting a common vtkSelectionLink object on multiple representations. (In VTK versions after 5.4, vtkSelectionLink has been replaced with the more flexible vtkAnnotationLink. This works in the same way as vtkSelectionLink, but can share annotations on the data between views in addition to a shared selection.)

The following example generates a graph view and table view with linked selection. The table view displays the vertex data of the graph in a Qt widget. Similarly vtkQtTreeView can display the contents of a vtkTree in a Qt tree widget. When rows are selected in the table view, the graph view updates to reflect this, and vice versa.

```
QApplication app(argc, argv);

// Create the graph source and table conversion
vtkRandomGraphSource* src = vtkRandomGraphSource::New();
vtkDataObjectToTable* o2t = vtkDataObjectToTable::New();
o2t->SetInputConnection(src->GetOutputPort());
o2t->SetFieldType(vtkDataObjectToTable::VERTEX_DATA);

// Create Qt table view and add a representation
vtkQtTableView* tv = vtkQtTableView::New();
vtkDataRepresentation* tr;
tr = tv->AddRepresentationFromInputConnection(o2t->GetOutputPort());

// Create graph layout view
vtkGraphLayoutView* gv = vtkGraphLayoutView::New();
gv->SetVertexLabelArrayName("vertex id");
gv->VertexLabelVisibilityOn();
gv->SetLayoutStrategyToSimple2D();

// Add representation to graph view
vtkDataRepresentation* gr;
gr = gv->AddRepresentationFromInputConnection(src->GetOutputPort());
gr->SetSelectionLink(tr->GetSelectionLink());
```

```
// Ensure both views update when selection changes
vtkViewUpdater* vu = vtkViewUpdater::New();
vu->AddView(gv);
vu->AddView(tv);

// Start application
#if VTK_5_4_OR_EARLIER
vtkRenderWindow* win = vtkRenderWindow::New();
gv->SetupRenderWindow(win);
#endif
tv->GetItemView()->show();
app.exec();
}
```

8.4 Graph Algorithms

Graph data structures are an essential part of any informatics application. Many informatics problems consist of a myriad of data sources (people, phone calls, emails, publications) and the relationships between those datatypes. In general, graphs are well suited for the storage, manipulation, and analysis of different entities and the connections between those entities. In semantic graphs entities are represented by the graph vertices and the relationships between entities are represented by the graph edges. The vtkGraph data structure can store arbitrary attributes on both the vertices and edges so properties and types ("semantics") are easily expressed (See Siek, Jeremy, Lie-Quan Lee, and Andrew Lumsdaine. 2001. "The Boost Graph Library: User Guide and Reference Manual". Addison-Wesley Professional).

The effective processing and analysis of graphs require a large set of graph algorithms. The VTK toolkit leverages third party libraries to provide them. These libraries include, the Boost Graph Library (BGL), the Parallel Boost Graph Library (PBGL) and the Multithreaded Graph Library (MTGL)

One of these libraries is the Boost Graph Library (BGL) which provides a generic C++ template interface to many common graph algorithm implementations. VTK provides a 'data-less' adapter which implements the required BGL concepts and allows BGL algorithms to process vtkGraphs directly.

The usage of any graph algorithm follows the VTK pipeline model. The code example shown in Listing <BFS> demonstrates the usage of a graph algorithm. The code includes the header file of the algorithm, creates the VTK filter for the algorithm (in this case vtkBoostBreadthFirstSearch) and puts the algorithm in the pipeline. After the pipeline is updated, the results of that algorithm are available as attributes on the nodes and/or edges of the graph. This example simply labels each vertex with its distance from the starting vertex (labeled "0").

```
#include "vtkBoostBreadthFirstSearch.h"
#include "vtkGraphLayoutView.h"
#include "vtkRandomGraphSource.h"
#include "vtkRenderWindow.h"
#include "vtkRenderWindowInteractor.h"
int main(int argc, char* argv[])
{
```

```
// Create a random graph
vtkRandomGraphSource* source = vtkRandomGraphSource::New();

// Create BGL algorithm and put it in the pipeline
vtkBoostBreadthFirstSearch* bfs = vtkBoostBreadthFirstSearch::New();
bfs->SetInputConnection(source->GetOutputPort());

// Create a view and add the BFS output
vtkGraphLayoutView* view = vtkGraphLayoutView::New();
view->AddRepresentationFromInputConnection(bfs->GetOutputPort());

// Color vertices based on BFS search
view->SetVertexColorArrayName("BFS");
view->ColorVerticesOn();
view->SetVertexLabelArrayName("BFS");
view->VertexLabelVisibilityOn();

// See the start of the Information Visualization chapter
// for information on how this has changed after VTK 5.4.
vtkRenderWindow* window = vtkRenderWindow::New();
view->SetupRenderWindow(window);
window->GetInteractor()->Start();

source->Delete();
bfs->Delete();
view->Delete();
window->Delete();

return 0;
}
```

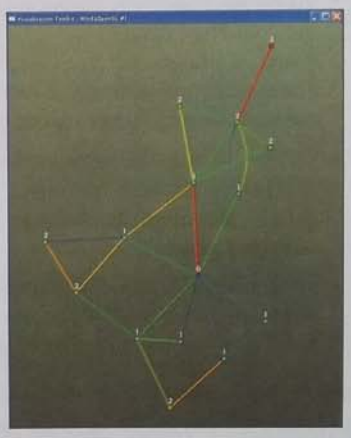


Figure 8–9 The result of computing the breadth-first distance from a starting vertex (labeled "0")

As pipeline components the graph algorithms can also be combined in unique ways. For instance the following python snippet (extracted from VTK\Examples\Infovis\Python\boost_mst.py) shows two graph algorithms working together.

```
# Create a random graph
randomGraph = vtkRandomGraphSource()

# Connect to the centrality filter.
centrality = vtkBoostBrandesCentrality ()
centrality.SetInputConnection(randomGraph.GetOutputPort())

# Find the minimal spanning tree
mstTreeSelection = vtkBoostKruskalMinimumSpanningTree()
mstTreeSelection.SetInputConnection(centrality.GetOutputPort())
mstTreeSelection.SetEdgeWeightArrayName("centrality")
mstTreeSelection.NegateEdgeWeightsOn()

# Create a graph layout view
```

```
view = vtkGraphLayoutView()
view.AddRepresentationFromInputConnection(centrality.GetOutputPort())
```

Here both vertex and edge centrality are computed by the vtkBoostBrandesCentrality filter, the results of that algorithm are feed into the vtkBoostKruskalMinimumSpanningTree filter which computes a 'maximal' spanning tree of the highest centrality edges in the graph (given that the 'NegateEdgeWeights' parameter is set).

Boost Graph Library Algorithms

- vtkBoostBreadthFirstSearch - Performs a breadth first search (BFS) of a graph from some origin node and returns a vtkGraph with new attributes.
- vtkBoostBreadthFirstSearchTree - Performs a BFS of a graph and returns a tree rooted at the origin node.
- vtkBoostBiconnectedComponents - Computes the biconnected components of a vtkGraph.
- vtkBoostBrandesCentrality - Computes graph centrality using the Brandes algorithm.
- vtkBoostConnectedComponents - Discovers the connected components of a vtkGraph. If the graph is undirected this computes the natural connected components, if directed then strongly connected components are computed.
- vtkBoostKruskalMinimumSpanningTree - Uses the Boost Kruskal Minimum Spanning Tree (MST) algorithm to compute the MST on a weighted graph.
- vtkBoostPrimMinimumSpanningTree - Uses the Boost Prim MST algorithm to compute the MST on a positively-weighted vtkGraph.

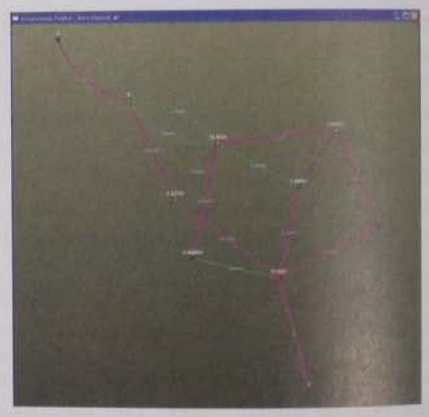


Figure 8–10 Graph showing a minimum spanning tree (purple) based on centrality computed on the graph edges

Many of these algorithms are discussed in this section are demonstrated in the python examples under VTK\Examples\Infovis\Python.

vtkBoostBreadthFirstSearch. This filter implements a vtkGraphAlgorithm that computes the BFS of a vtkGraph which is rooted at some starting node. The starting node can be either a selection or can be specified via its index into the graph. The time complexity of the Boost BFS implementation is O(E+V).

`SetOriginSelection(vtkSelection* s)`
Sets the origin node for this search through a selection cointaining a node in the graph.

`SetOriginSelectionConnection(vtkAlgorithmOutput *)`
Sets the origin node using the output from another VTK filter.

`SetOriginVertex(vtkIdType index)`
Set the index (into the vertex array) of the BFS 'origin' vertex.

`SetOriginVertex(arrayName,value)`
Set the BFS origin vertex. This method allows the application to simply specify an array name and value, instead of having to know the specific index of the vertex.

`SetOriginVertexString(arrayName,value)`
Set the BFS 'origin' vertex given an array name and a string value.

`SetOutputArrayName(string)`
Set the name of the vertex attribute array in the output graph. Default is "BFS".

`SetOriginFromSelection(bool)`
If true/on, use the vtkSelection from input port 1 as the origin vertex. The selection should be an IDs selection with field type POINTS. The first ID in the selection will be used as the 'origin' vertex. Default is OFF.

`SetOutputSelection(bool)`
If true/on, creates an output selection containing the ID of a vertex based on the output selection type. The default is to use the maximum distance from the starting vertex. Default is OFF.

`SetOutputSelectionType(string)`
Set the output selection type. The default is to use the maximum distance from the starting vertex "MAX_DIST_FROM_ROOT". Additional options such as "ROOT", "2D_MAX", etc. may be used.

`vtkBoostBreadthFirstSearchTree`
This VTK class uses the Boost BFS generic algorithm to perform a BFS of a vtkGraph from a given source vertex. The result of this filter is a vtkTree with root node corresponding to the starting node of the search.

`SetOriginVertex(index)`
Sets the index into the vertex array of the origin vertex.

`SetOriginVertex(arrayName,value)`
Set the origin vertex given a value within a named vertex array.

`SetCreateGraphVertexIdArray(bool)`
Stores the graph vertex ids for the tree vertices in an array named "GraphVertexId". Default is OFF.

vtkBoostBiconnectedComponents. This VTK class searches a vtkGraph for biconnected components. The biconnected components of a graph are maximal regions of the graph where the removal of any single vertex from the region will not disconnect the graph. This algorithm returns a vertex attribute array and an edge attribute array containing their biconnected component ids.

Every edge will belong to exactly one biconnected component and will be given in the edge array named "biconnected component" by default. Likewise, the biconnected component id of each vertex is also given in the vertex array named "biconnected component" by default.

Cut vertices (or articulation points) are vertices that belong to multiple biconnected components, and break the graph apart if removed. These are indicated by assigning a component value of -1. To determine the biconnected components that a cut vertex belongs to, traverse its edge list and collect the distinct component ids for its incident edges.

The time complexity of the Boost biconnected components algorithms is O(V+E)

`SetOutputArrayName(string)`
Set the output array name for the vertex and edge arrays. If no output array name is specified, "biconnected component" will be used.

vtkBoostBrandesCentrality. This class uses the Boost brandes_betweenness_centrality algorithm to compute betweenness centrality on a vtkGraph. This filter adds a vertex array and an edge array to the vtkGraph with the name "centrality" and are typed as vtkFloatArray.

The time complexity of Boost Brandes' betweenness centrality is reported as O(VE) for unweighted graphs and O(VE+V(V+E) log V) for weighted graphs. The space complexity is O(VE).

vtkBoostConnectedComponents. Discovers the connected regions of a vtkGraph, assigning to each vertex a component ID in the vertex array "components". If the input graph is an undirected graph the output contains the natural connected components of the graph. Conversely, if the input graph is a directed graph, this filter will discover the strongly connected components of the graph (i.e., the maximal sets of vertices where there is a directed path between any pair of vertices within each set).

For undirected graphs, the time complexity for this algorithm is O(V+E alpha(E,V)) where alpha is the inverse of Ackermann's function. For most practical purposes, the time complexity is only slightly larger than O(V+E). The time complexity of the algorithm used for directed graphs is O(V+E).

vtkBoostKruskalMinimumSpanningTree. This filter finds the Minimum Spanning Tree (MST) of a vtkGraph using the Boost Kruskal MST generic algorithm given a weighting value for each of the edges in the input graph. This algorithm also allows edge weights to be negated to create a maximal spanning tree if desired. This filter produces a vtkSelection containing the edges of the graph that define the MST.

The time complexity for the Boost Kruskal MST algorithm is O(E log E).

`SetEdgeWeightArrayName(string)`
Sets the name of the edge-weight input array, which must be an array that is part of the edge data of the input graph and contains numeric data. If the edge-weight array is not of type vtkDoubleArray it will be copied into a temporary vtkDoubleArray.

`SetOutputSelectionType(string)`
Sets the output selection type. The default is to use the set of minimum spanning tree edges "MINIMUM_SPANNING_TREE_EDGES"'. No other options are currently defined.

`SetNegateEdgeWeights(bool)`
Toggles whether or not the filter should negate edge weights. By negating edge weights this algorithm will attempt to create the 'maximal' spanning tree. A 'maximal' spanning tree is a spanning tree with the highest-weighted edges). Default is OFF.

vtkBoostPrimMinimumSpanningTree. This filter uses the Boost Prim Minimum Spanning Tree generic algorithm to create a MST on an edge-weighted vtkGraph given an origin vertex. This filter differs from Kruskal MST mainly in the following ways:

- An origin vertex must be specified.

- The negate edge weights method cannot be utilized to obtain a 'maximal' spanning tree, and will throw an exception if any negative edge weights exist.
- The boost implementation of the Prim algorithm returns a vertex predecessor map which results in some ambiguity about which edge from the original graph should be utilized if parallel edges exist; for this reason the current VTK implementation does not copy edge data from the graph to the new tree.
- The edge-weight array must be a vtkDataArray type or a child of vtkDataArray giving more generality over the Kruskal variant.

The time complexity of the Boost Prim MST algorithm is O(E log V).

`SetEdgeWeightArrayName(string)`
: Sets the name of the edge-weight input array. The edge-weight array must be a vtkDataArray.

`SetOriginVertex(index)`
: Sets the 'origin' vertex by way of its index into the graph.

`SetCreateGraphVertexIdArray(bool)`
: If enabled, stores the graph vertex ids for the tree vertices in an array named "GraphVertexId". Default is OFF.

`SetNegateEdgeWeights(bool)`
: If on, edge weights are negated. See note in description, this filter will throw an exception if negative edge weights exist. Default is OFF.

Creating Graph Algorithms

n practice anyone can add a graph algorithm to VTK. There are several approaches a developer can take. The first and easiest for a python programmer is to use the vtkProgrammableFilter. The python code in **Figure 8–11** demonstrates the use of the programmable python filter to compute vertex degree (taken from VTK\Examples\Infovis\Python\vertex_degree_programmable.py).

```
def computeVertexDegree():

    input = vertexDegree.GetInput()
    output = vertexDegree.GetOutput()

    output.ShallowCopy(input)

    # Create output array
    vertexArray = vtkIntArray()
    vertexArray.SetName("VertexDegree")
    vertexArray.SetNumberOfTuples(output.GetNumberOfVertices())

    # Loop through all the vertices setting the degree for the new
    # attribute array
    for i in range(output.GetNumberOfVertices()):
        vertexArray.SetValue(i, output.GetDegree(i))

    # Add the new attribute array to the output graph
    output.GetEdgeData().AddArray(vertexArray)
```

```
vertexDegree = vtkProgrammableFilter()
vertexDegree.SetExecuteMethod(computeVertexDegree)

# VTK Pipeline
randomGraph = vtkRandomGraphSource()
vertexDegree.AddInputConnection(randomGraph.GetOutputPort())

view = vtkGraphLayoutView()
view.AddRepresentationFromInputConnection(vertexDegree.GetOutputPort()
)
view.SetVertexLabelArrayName("VertexDegree")
view.SetVertexLabelVisibility(True)
```

Another straightforward approach is to create a regular VTK C++ filter as a graph algorithm. The easiest filter to use as a reference would be vtkVertexDegree (VTK\Infovis\vtkVertexDegree.cxx). The C++ code in vtkVertexDegree.cxx looks remarkably similar to the python example above in Figure X and contains the same functionality. The documentation for vtkGraph and the API for the various ways to access the data structure will also be helpful in the creation of your new filter.

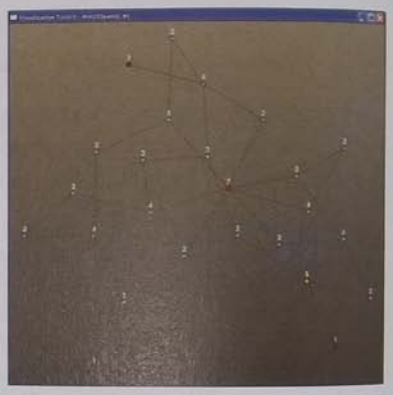


Figure 8–11 A graph labeled by the computed degree of each vertex

Perhaps the most interesting (and advanced) way to create a new graph algorithm in VTK is to contribute an algorithm to the Boost Graph Library and then 'wrap' that algorithm into a VTK class. A good reference is the vtkBoostBreadthFirstSearch filter (VTK\Infovis\vtkBoostBreadthFirstSearch.cxx) and the vtkBoostGraphAdapter.h file. Detailed documentation on the Boost Graph Library can be found at http://www.boost.org/doc/ as well as in the book *The Boost Graph Library: User Guide and Reference Manual*. Although significantly more work, this approach benefits both VTK users and the members of the Boost community as well.

The Parallel Boost Graph Library

As a distributed memory toolkit, VTK currently provides a myriad of functionality around parallel scientific data processing and visualization. The Parallel Boost Graph Library (PBGL) is a generic C++ library for high-performance parallel and distributed graph algorithms. The vtkGraph data structure, along with some distributed helper classes, enables the PBGL functionality to work in the same way as the BGL classes. The integration of PBGL functionality into VTK is currently in the early stages. We would also like to note that PBGL is part of the Boost library with the Boost 1.40 release. VTK has begun including some PBGL based filters which can be found in the Parallel subdirectory.

Multithreaded Graph Library

The MultiThreaded Graph Library (MTGL) targets shared memory platforms such as the massively multi-threaded Cray MTA/XMT and when used in tandem with the Qthreads library chip multiprocessors such as the Sun Niagara and multi-core workstations. MTGL is based on the serial Boost

Graph Library, as data distribution is not an issue on the platforms in question. Shared memory programming is a challenge, and algorithm objects in the MTGL can encapsulate much, but not all, of this challenge. As in the BGL, the visitor pattern enables users to apply methods at key points of algorithm execution. MTGL users write adapters over their graph data structures as BGL users do, but there is no assumption that Boost and STL are available. MTGL codes for connected components on unstructured graphs, a difficult problem for distributed memory architectures, have scaled almost perfectly on the Cray MTA-2.

8.5 Databases

As part of its information visualization capability, VTK 5.4 provides classes for access to SQL databases. Infovis datasets are often a good match for a relational database model. These often contain several smaller datasets linked by common attributes that fit well into tables. Also, a database allows an application to offload the task of managing large data by issuing queries for precisely the subset of interest.

Low-level database access is separated into two abstract classes. The first, vtkSQLDatabase, is responsible for opening and closing databases, reporting whether features such as transactions, prepared statements and triggers are supported, and creating tables using schema objects. The second, vtkSQLQuery, is responsible for sending an SQL statement to the database for execution, checking for errors, and providing access to the results.

The details of connecting to a particular database (MySQL, SQLite, Oracle, etc.) are implemented in concrete subclasses of vtkSQLDatabase. Similarly, the details of executing a query and retrieving results for a particular database are implemented in concrete subclasses of vtkSQLQuery. These concrete subclasses are respectively called "database drivers" and "query drivers".

VTK 5.4 includes drivers for the following databases:

- SQLite 3.4.1
- MySQL 5.0 (and higher)
- PostgreSQL 7.1 (and higher)
- ODBC

A copy of SQLite is included with the VTK source code. In order to interact with other database implementations you must build VTK from source and link against vendor-provided client libraries. If you compiled the database yourself, these libraries were probably built automatically. If you installed a pre-compiled package you may need to download them separately (typically in a "development" package).

Connecting to a Database

In order to connect to a database you must first obtain an instance of an appropriate database driver. There are two ways to do this.

1. Create the driver automatically from a URL:
2. vtkSQLDatabase *db = vtkSQLDatabase::CreateFromURL("sqlite://mydata.db");
3. Instantiate the driver directly:

4. vtkSQLiteDatabase *db = vtkSQLiteDatabase::New();

The CreateFromURL() method will attempt to set all of the supplied parameters (username, server address, server port, database name) on the driver object. If you instantiate the driver directly you must set all of these parameters yourself. If the database requires a password you must supply it in the call to Open(). You may close a connection by calling Close() or by deleting the database driver. If the database connection could not be opened then Open() will return false. You may retrieve information about the reason for the failure using the GetLastErrorText() method. The C++ code for opening a database will generally look like the following:

```
vtkSQLDatabase *db = vtkSQLDatabase::CreateFromURL("sqlite://
mydata.db");
  bool status = db->Open("");
  if (!status)
    {
    cout << "Couldn't open database. Error message: "
         << db->GetLastErrorText() << endl;
    }
```

Once a connection has been established you may call GetTables() to obtain a list of the tables in the database. The GetRecord() function, called with the name of one of those tables, will return a list of the columns in that table. These functions are useful for applications that connect to databases without any foreknowledge of their schemata.

Executing Queries

To actually execute a query you must use an instance of one of the query drivers. Query drivers are never instantiated directly. To obtain one, call GetQueryInstance() on the database driver once the connection has been opened successfully. Set up your query by calling SetQuery() with a string containing the entire SQL statement. It is not necessary to terminate the statement with a semicolon. You must embed all of the query parameters within the string. The query will be sent to the database and executed when you call the Execute() method. Execute() will return true or false depending on whether the query ran successfully or whether it encountered an error. As with the database driver, you may retrieve any error message by calling GetLastErrorText() on the query driver.

```
vtkSQLQuery* query = db->GetQueryInstance();
  const char *queryText = "SELECT name, age, weight "
    "FROM people WHERE age <= 20";
  query->SetQuery(queryText);
  if (!query->Execute())
    {
    cout << "Query failed. Error message: "
         << query->GetLastErrorText() << endl;
    }
```

You may re-use a single query driver for multiple queries. There is no notion of "closing" a currently active query: you may simply set the new query string with SetQuery() and call Execute(). If the driver was in the middle of reading a set of query results they will be cleaned up automatically.

Queries and Threads

Neither vtkSQLQuery nor vtkSQLDatabase are thread-safe. This is more a limitation of the underlying native database APIs, which are themselves rarely thread-safe, than of VTK itself. If your application needs to access a database concurrently from multiple threads you must create a new database connection (via vtkSQLDatabase) for each thread. Each thread may maintain as many vtkSQLQuery objects as necessary. In some installations the database administrator may impose limits on how many concurrent sessions and queries may be open simultaneously. Check with your system administrator to see if this is a concern.

Reading Results

Once a query has been executed successfully, indicated by Execute() returning a value of true, your program may read the query results. There are two kinds of data that may be retrieved here. The query metadata comprises the number of columns, their names, and their data types. These can be retrieved with GetNumberOfColumns(), GetColumnName(int) and GetColumnType(int). VTK will do its best to convert from the database back-end's native data type to standard data types supported in C++, Python and Java.

The result data is read one row at a time. You must call vtkSQLQuery::NextRow() to advance to the next available row. This method will return true if there is another row available to read and false when no more data can be retrieved. Data values within a row may be retrieved either one at a time or all at once. To retrieve the value for a single column, call vtkSQLQuery::DataValue(int) with the index of the column you want to retrieve. The entire process looks like the following.

```
while (query->NextRow())
    {
    for (int field = 0; field < query->GetNumberOfFields(); field++)
      {
      vtkVariant v = query->DataValue(field);
      // Process it
      }
    }
```

To retrieve an entire row at once, call vtkSQLQuery::NextRow(vtkVariantArray *) instead of NextRow(). The values for that row will be stored in the array you supply.

```
vtkVariantArray* va = vtkVariantArray::New();
  while (query->NextRow(va))
    {
    // Process it
    }
```

When processing query results we often wish to store the entire result set in a vtkTable to be passed through the pipeline. The vtkRowQueryToTable filter does exactly this. Use it by obtaining and setting up a query driver, then passing the query to the filter as the argument to SetQuery(). The query will be executed when the filter is updated either manually (by calling Update()) or through a request from further down the pipeline.

```
vtkRowQueryToTable* reader = vtkRowQueryToTable::New();
```

```
reader->SetQuery(query);
reader->Update();
vtkTable* table = reader->GetOutput();
```

Writing Data

Since vtkSQLQuery requires only that the query string be valid SQL it can be used for more operations than just reading from tables. For example, CREATE, UPDATE, INSERT, DROP and TRUNCATE (and others) are all available for use. The only requirement is that if the query returns any output aside from a status code it must be in row format. This excludes commands such as EXPLAIN that return unformatted text.

You may use the SQL INSERT command to write data back to the database. Since each row must be inserted with a separate INSERT statement this is likely to be slow for large amounts of data. Support for prepared statements and bound parameters in the next version of VTK will help eliminate this bottleneck. Meanwhile, if you need to write large datasets back to the database, consider using the database's native interface or bulk loader instead of the VTK access classes. The following example creates a table called PEOPLE and populates it. Error checking is omitted for brevity.

```
vtkStdString createQuery("CREATE TABLE IF NOT EXISTS people "
    "(name TEXT, age INTEGER, weight FLOAT)");
  query->SetQuery( createQuery.c_str() );
  query->Execute();
  for (int i = 0; i < 20; i++)
    {
    char insertQuery[200];
    sprintf( insertQuery,
      "INSERT INTO people (name, age, weight) "
      "VALUES('John Doe %d', %d, %f)",
      i, i, 10.1*i );
    query->SetQuery(insertQuery);
    query->Execute()
    }
```

Table Schemata

VTK provides a class, vtkSQLDatabaseSchema, for representing a relational database schema. This is useful if your program needs to create databases rather than simply accessing existing databases. This class is capable of representing tables, their columns, and their indices in a cross-platform setting. The goal of this class is to make working with multiple database backends simple, not to represent every schema possible with any given database type. For instance, a limited set of column types is supported; extended types such as those available in PostgreSQL are not supported. However, it can store triggers (for databases that support triggers) and preamble statements with an indication of what database backend each trigger or preamble statement was written for, to accommodate backend-specific SQL statements.

Programmatic access to the schema is present so that tables, columns, or indices may be dynamically generated based on some options present in your application. A schema object can contain multiple tables. Each table has a unique integer handle returned by the AddTable method. To add columns, indices, or triggers to a table, you must pass this integer as the first argument to AddColumnToTable(), AddIndexToTable(), or AddTriggerToTable(), respectively.

The AddColumnToTable() function takes a column type (using the enums provided by vtkSQLDatabaseSchema), a column name, an integer field width, and a text string specifying column options such as default values. The field width specifies the storage size for VARCHAR or other variable-size column types and specifies the default column width of printouts for numeric types in MySQL.

The AddIndexToTable() function creates a primary key, unique-value index, or a plain index for a table. Because an index may have multiple columns, you must call AddIndexToTable and then pass the integer index to AddColumnToIndex for each column you would like in the index.

Finally, AddTriggerToTable() allows you to add SQL statements that get executed each time a table's records are modified. Because the syntax for triggers varies from backend to backend, the AddTriggerToTable() method's final argument lets you specify which database backend a trigger is for. The trigger will only be added to databases of the same backend. Because multiple triggers may be added to the schema for each table, you can create different versions of the same trigger for each backend you wish your application to support. Also, some backends such as PostgreSQL require you to specify a trigger as named function. In order to allow you to define functions before triggers are added, the schema class provides AddPreamble(). Statements passed to AddPreamble() are executed before any tables are created. As with AddTriggerToTable(), the final argument of AddPreamble() allows you to specify which backend the statement applies to.

Once you have created a vtkSQLDatabaseSchema object and populated it using the functions above, you may call vtkSQLDatabase::EffectSchema() to translate the schema into a set of tables. The following is an example of how to use the vtkSQLDatabaseSchema class from Python.

```
from vtk import *
schema = vtkSQLDatabaseSchema()
schema.SetName('TestSchema')
url = 'psql://vtk@localhost/vtk_test'

## Values of enums
VTK_SQL_SCHEMA_SERIAL = 0
VTK_SQL_SCHEMA_BIGINT = 3
VTK_SQL_SCHEMA_PRIMARY_KEY = 2

btab = schema.AddTable('btable')
col0 = schema.AddColumnToTable(btab,
  VTK_SQL_SCHEMA_SERIAL, 'tablekey', 0, '')
col1 = schema.AddColumnToTable(btab,
  VTK_SQL_SCHEMA_BIGINT, 'somevalue', 12, 'DEFAULT 0')
idx0 = schema.AddIndexToTable(btab,
  VTK_SQL_SCHEMA_PRIMARY_KEY, '')
i0c0 = schema.AddColumnToIndex(btab, idx0, col0)

# Create a dummy database instance
# so we can call CreateFromURL,
# then replace instance with real thing
db = vtkSQLiteDatabase()
db = db.CreateFromURL(url);

# Try opening the database without a password
if not db.Open(''):
  # Ask the user for a password and try it.
```

```
    from getpass import getpass
    db.Open(getpass('Password for %s' % url))
  if db.IsOpen():
    # If we were able to open the database, effect the schema
    db.EffectSchema(schema, True);
```

A convenience routine, named AddTableMultipleArguments, is available in C++ (but not wrapped languages) to aid in the declaration of a static schema. It uses the cstdarg package so that you may pass an arbitrary number of arguments specifying many table columns, indices, and triggers. The first argument to the function is the name of a table to create. It is followed by any number of tokens, each of which may require additional arguments after it and before the next token. The last argument must be the special vtkSQLDatabaseSchema::END_TABLE_TOKEN. Tokens exist for adding columns, indices, and triggers. Use of AddTableMultipleArguments is shown in Listing 2, which is the example from Listing 1 converted into C++ to illustrate AddTableMultipleArguments.

```
vtkSQLDatabaseSchema* schema = vtkSQLDatabaseSchema::New();
schema->SetName("TestSchema");

tblHandle = schema->AddTableMultipleArguments("btable",
  vtkSQLDatabaseSchema::COLUMN_TOKEN,
  vtkSQLDatabaseSchema::SERIAL, "tablekey",  0, "",
  vtkSQLDatabaseSchema::COLUMN_TOKEN,
  vtkSQLDatabaseSchema::BIGINT, "somevalue", 12, "DEFAULT 0",
  vtkSQLDatabaseSchema::INDEX_TOKEN,
  vtkSQLDatabaseSchema::PRIMARY_KEY, "",
  vtkSQLDatabaseSchema::INDEX_COLUMN_TOKEN, "tablekey",
  vtkSQLDatabaseSchema::END_INDEX_TOKEN,
  vtkSQLDatabaseSchema::END_TABLE_TOKEN
);

vtkSQLDatabase* db = vtkSQLDatabase::CreateFromURL(url);
db->EffectSchema(schema);
```

8.6 Statistics

Statistical characterizations are useful because they can provide not only information on trends in data but also information on the significance of these trends. Also, because datasets continue to increase in both size and complexity, it is important to have tools for characterizing high-dimensional data so that lower-dimensional features can be discovered and visualized with traditional techniques. A number of statistical tools have been implemented in VTK for examining the behavior of individual fields, relationships between pairs of fields, and relationships among any arbitrary number of fields. Each tool acts upon data stored in one or more vtkTable objects; the first table serves as observations and further tables serves as model data. Each row of the first table is an observation, while the form of further tables depends on the type of statistical analysis. Each column of the first table is a variable.

Specifying columns of interest

A univariate statistics algorithm only uses information from a single column and, similarly, a bivariate algorithm from 2 columns. Because an input table may have many more columns than an algo-

rithm can make use of, VTK must provide a way for users to denote columns of interest. Because it may be more efficient to perform multiple analyses of the same type on different sets of columns at once as opposed to one after another, VTK provides a way for users to make multiple analysis requests in a single filter.

As an example, consider **Figure 8–12**. It has 6 observations of 5 variables. If the linear correlations between A, B, and C, and also between B, C and D are desired, two requests, R1 and R2 must be made: The first request R1 would have columns of interest {A,B,C} while R2 would have columns of interest {B,C,D}. Calculating linear correlations for R1 and R2 in one pass is more efficient than computing each separately since the covariances cov(B,B), cov(C,C), and cov(B,C) are required for both requests but need only be computed once.

Row	A	B	C	D	E
1	0	1	0	1	1.03315
2	1	2	2	2	0.76363
3	0	3	4	6	0.49411
4	1	5	6	24	0.04492
5	0	7	8	120	0.58935
6	1	11	10	720	1.66202

Figure 8–12 A table of observations that might serve as input to a statistics algorithm

Phases

Each statistics algorithm performs its computations in a sequence of common phases, regardless of the particular analysis being performed. The VTK statistics algorithms may be configured to perform various subsets of these three operations as desired. These phases can be described as:

- **Learn**: Calculate a "raw" statistical model from an input data set. By "raw", we mean the minimal representation of the desired model, that contains only primary statistics. For example, in the case of descriptive statistics: sample size, minimum, maximum, mean, and centered M2, M3 and M4 aggregates (cf. P. Pébay, Formulas for Robust, One-Pass Parallel Computation of Covariances and Arbitrary-Order Statistical Moments, Sandia Report SAND2008-6212, September 2008, http://infoserve.sandia.gov/sand_doc/2008/086212.pdf). For Table 1 with a request R1={B}, these values are 6, 1, 11, 4.83..., 68.83..., 159.4..., and 1759.8194..., respectively.
- **Derive**: Calculate a "full" statistical model from a raw model. By "full", we mean the complete representation of the desired model, that contains both primary and derived statistics. For example, in the case of descriptive statistics, the following derived statistics are calculated from the raw model: unbiased variance estimator, standard deviation, and two estimators (g and G) for both skewness and kurtosis. For Table 1 with a request R1={B}, these additional values are 13.76..., 3.7103, 0.520253, 0.936456, -1.4524, and -1.73616 respectively.
- **Assess**: Given a statistical model -- from the same or another data set -- mark each datum of a given data set. For example, in the case of descriptive statistics, each datum is marked with its

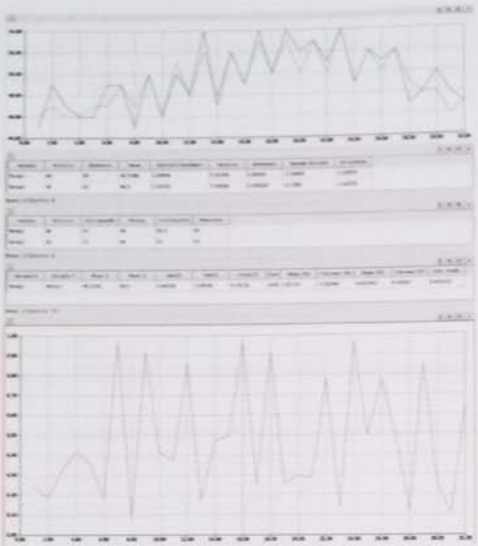


Figure 8–13 An example utilization of VTK's statistics algorithms with the OverView client

relative deviation with respect to the model mean and standard deviation (this amounts to the one-dimensional Mahalanobis distance). Table 1 shows this distance for R1 = {B} in column E.

An example of the utilization of VTK's statistical tools with the Qt application client <description - paraview application tailored to infovis> is illustrated in **Figure 8–13**; specifically, the descriptive, correlative, and order statistics classes are used in conjunction with various table views and plots. With the exception of contingency statistics which can be performed on any type (nominal, cardinal, or ordinal) of variables, all currently implemented algorithms require cardinal or ordinal variables as inputs. The following statistics algorithms are currently available in VTK.

Univariate Algorithms

These algorithms accept a single column (or a set of single columns) and perform an analysis of the distribution of data in that column.

Descriptive statistics.

- Learn: calculate minimum, maximum, mean, and centered M2, M3 and M4 aggregates;
- Derive: calculate unbiased variance estimator, standard deviation, skewness (g1 and G1 estimators), kurtosis (g2 and G2 estimators);
- Assess: mark with relative deviations (one-dimensional Mahlanobis distance).

Order statistics.

- Learn: calculate histogram;
- Derive: calculate arbitrary quantiles, such as 5-point statistics (quartiles) for box plots, deciles, percentiles, etc.;
- Assess: mark with the quantile index.

Bivariate statistics:

These algorithms accept a pair(s) of columns to operate on, and perform a comparative analysis.

Correlative statistics.

- Learn: calculate minima, maxima, means, and centered M2 aggregates;
- Derive: calculate unbiased variance and covariance estimators, Pearson correlation coefficient, and linear regressions (both ways);
- Assess: mark with squared two-dimensional Mahlanobis distance.

Contingency statistics.

- Learn: calculate contingency table;
- Derive: calculate joint, conditional, and marginal probabilities, as well as information entropies;
- Assess: mark with joint and conditional PDF values, as well as pointwise mutual informations.

Multivariate statistics:

These filters all accept multiple requests Ri, each of which is a set of ni variables upon which simultaneous statistics should be computed.

Multi-correlative statistics.

- Learn: calculate means and pairwise centered M2 aggregates;
- Derive: calculate the upper triangular portion of the symmetric ni x ni covariance matrix and its (lower) Cholesky decomposition;
- Assess: mark with squared multi-dimensional Mahlanobis distance.

Principal component analysis (PCA) statistics.

- Learn: identical to the multi-correlative filter;
- Derive: everything the multi-correlative filter provides, plus the ni eigenvalues and eigenvectors of the covariance matrix;
- Assess: perform a change of basis to the principal components (eigenvectors), optionally projecting to the first mi components, where mi <= ni is either some user-specified value or is determined by the fraction of maximal eigenvalues whose sum is above a user-specified threshold. This results in mi additional columns of data for each request Ri.

k-Means statistics (kMeans was added after VTK 5.4).

- Learn: calculate new cluster centers for data using initial cluster centers. When initial cluster centers are provided by the user using an additional input table, multiple sets of new cluster centers are computed. The output metadata is a multiblock dataset containing at a minimum one vtkTable with columns specifying the following for each run: the run ID, number of clusters, number of iterations required for convergence, RMS error associated with the cluster, the num-

ber of elements in the cluster, and the new cluster coordinates;

- Derive: calculates the global and local rankings amongst the sets of clusters computed in the learn phase. The global ranking is the determined by the error amongst all new cluster centers, while the local rankings are computed amongst clusters sets with the same number of clusters. The total error is also reported;
- Assess: mark with closest cluster id and associated distance for each set of cluster centers.

Using statistics algorithms

It is fairly easy to use the statistics classes of VTK. For example, Listing 1 demonstrates how to calculate contingency statistics, on two pairs of column of an input set inData of type vtkTable, with no subsequent data assessment. It is assumed here the input data table has at least 3 columns.

```
// Assume the input dataset is passed to us
  // Also is assume that it has a least 3 columns
  vtkTable* inData = static_cast<vtkTable*>(arg);

  // Create contingency statistics class
  vtkContingencyStatistics* cs = vtkContingencyStatistics::New();

  // Set input data port
  cs->SetInput(0, inData);

  // Select pairs of columns (0,1) and (0,2) in inData
  cs->AddColumnPair(inData->GetColumnName[0], inData-
>GetColumnName[1]);
  cs->AddColumnPair(inData->GetColumnName[0], inData-
>GetColumnName[2]);

  // Calculate statistics with Learn and Derive phases only
#if VTK_5_4_OR_EARLIER
  cs->SetLearn(true);
  cs->SetDerive(true);
  cs->SetAssess(false);
#else
  cs->SetLearnOption(true);
  cs->SetDeriveOption(true);
  cs->SetAssessOption(false);
#endif
  cs->Update();
```

The previous code section's requests for each pair of columns of interest are specified by calling AddColumnPair(), as is done for all bivariate algorithms. Univariate algorithms instead call AddColumn() a number of times to unambiguously specify a set of requests. However, multivariate filters have a slightly different usage pattern. In order to queue a request for multivariate statistics algorithms, SetColumnStatus() should be called to turn on columns of interest (and to turn off any previously-selected columns that are no longer of interest). Once the desired set of columns has been specified, a call to RequestSelectedColumns() should be made. Consider the example from Table 1 where 2

requests are mentioned: {A,B,C} and {B,C,D}. The code snippet in Listing 2 shows how to queue these requests for a vtkPCAStatistics object.

```
vtkPCAStatistics* pps = vtkPCAStatistics::New();

  // Turn on columns of interest
  ps->SetColumnStatus("A", 1);
  ps->SetColumnStatus("B", 1);
  ps->SetColumnStatus("C", 1);
  ps->RequestSelectedColumns();

  // Columns A, B, and C are still selected, so first we turn off
  // column A so it will not appear in the next request.
  ps->SetColumnStatus("A", 0);
  ps->SetColumnStatus("D", 1);
  ps->RequestSelectedColumns();
```

[Listing 2: An example of requesting multiple multi-variate analyses.]

Parallel Statistics Algorithms

One of the purposes of building a full statistical model in three phases is parallel computational efficiency. In our approach, inter-processor communication and updates are performed only for primary statistics. The calculations to obtain derived statistics from primary statistics are typically fast and simple and need only be calculated once, without communication, upon completion of all parallel updates of primary variables. Data to be assessed is assumed to be distributed in parallel across all processes participating in the computation, thus no communication is required as each process assesses its own resident data.

Therefore, in the parallel versions of the statistical engines, inter-processor communication is required only for the Learn phase, while both Derive and Assess are executed in an embarrassingly parallel fashion due to data parallelism. This design is consistent with the data parallelism methodology used to enable parallelism within VTK, most notably in ParaView. The following 5 parallel statistics classes are currently available in VTK:

- vtkPDescriptiveStatistics
- vtkPCorrelativeStatistics
- vtkPContingencyStatistics
- vtkPMultiCorrelativeStatistics
- vtkPPCAStatistics

Each of these parallel algorithms is implemented as a subclass of the respective serial version of the algorithm and contains a vtkMultiProcessController to handle inter-processor communication. Within each of the parallel statistics classes, the Learn phase is the only phase whose behavior is changed (by reimplementing its virtual method) due to the data parallelism inherent in the Derive and Assess phases. The Learn phase of the parallel algorithms performs two primary tasks:

1. Calculate correlative statistics on local data by executing the Learn code of the superclass.
2. If parallel updates are needed (i.e. the number of processes is greater than 1), perform necessary data gathering and aggregation of local statistics into global statistics.

Note that the parallel versions of the statistics algorithms can be used with the same syntax as that which is used for their serial superclasses. All that is required is a parallel build of VTK and a version of MPI installed on your system.

8.7 Processing Multi-Dimensional Data

Many information visualization, scientific, engineering, and economic problems involve data that is either implicitly or explicitly multi-dimensional. In the field of text analysis, a corpus of documents is often represented as a matrix (2D array) that stores the number of times each term (word) in the corpus appears in each document.. This type of term-frequency data can be extended into higher dimensions, as in an analysis of public Wiki edits that encodes the number of times a term is used by a particular author on a specific date as a 3D tensor.

Terms \ Documents	A	B	C
the	2		
quick	1		1
brown	1		
fox	1		
jumped	1		
over	1		
lazy	1	1	
dog	1		
girl		1	
turn			1
around			1

Document A: "The quick brown fox jumped over the lazy dogs."

Document B: "Lazy girl."

Document C: "Quick! Turn around."

Figure 8–14 Mapping two-dimensional term-document frequency data to a matrix for test analysis

In physical experiments, a series of measurements often form a tensor of three or more dimensions, i.e. weather measurements taken at multiple stations across multiple times. In economics, a dataset containing changes in stock value for differing combinations of stock symbol, date, and time horizon could also be represented as a 3D tensor. Although these examples originate in widely varying domains, representing their data using multi-dimensional arrays makes it possible to bring a common set of methods from multi-linear algebra to bear on their analysis. Powerful algorithms such as Singu-

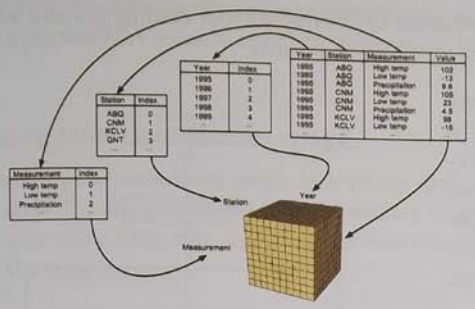


Figure 8–16 Mapping three-dimensional year-station-measurement meterological data to a tensor for analysis.

lar Value Decomposition, PARAFAC, DEDICOM, and TUCKER can be used to seek out correlations in data that would otherwise be hidden from users.

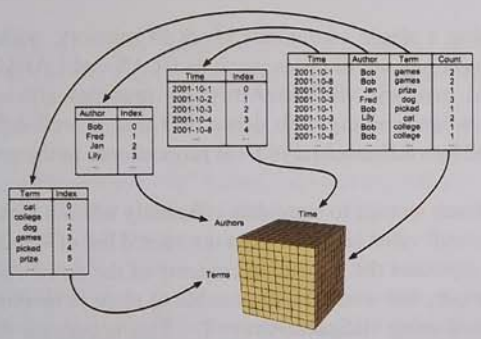


Figure 8–15 Mapping three-dimensional time-author-term data to a tensor for text analysis

Note, in each of these examples the data is likely to be more-or-less "sparse". In the text analysis use-cases, not every term in a corpus will be used in every document; and in scientific experiments, instrument malfunctions may cause data to be undefined or 'null' over varying time ranges. Similarly, stocks enter-and-exit markets on a regular basis, leading to undefined points within the data. Any system that represents multi-dimensional data must be able to explicitly represent these undefined points for efficiency in memory and computation, and to ensure the correctness of calculations. A system that ignores undefined or'null' values will not produce correct results.

Design

To meet the preceding challenges, the vtkArray class and its derivatives provide the functionality to store and manipulate sparse and dense arrays of arbitrary dimension (**Figure 8–17**). Note first that vtkArray and its subclasses are entirely separate from the traditional VTK array types such as vtkDataArray, vtkIntArray, , vtkFloatArray, and other array types derived from vtkAbstractArray. In some future release we plan to unify these two hierarchies.

At the top of the N-Dimensional array hierarchy, vtkArray provides methods and functionality that are common to all arrays, regardless of the type of values stored or the type of storage used. Using vtkArray, you can:

- Create heterogeneous containers of arrays.

- Implement algorithms that convert between arrays of different types.
- Implement algorithms that modify the structure of an array without needing to know what type of value it contains, such as an algorithm to transpose a matrix.

The vtkTypedArray<T> template class derives from vtkArray, and is used to provide strongly-typed access to the values stored in the array while ignoring the type of storage used. Using vtkTypedArray<T>, you can efficiently manipulate arrays that contain a specific type (int, double, string, etc) while ignoring how the array data is stored (dense, sparse, etc).

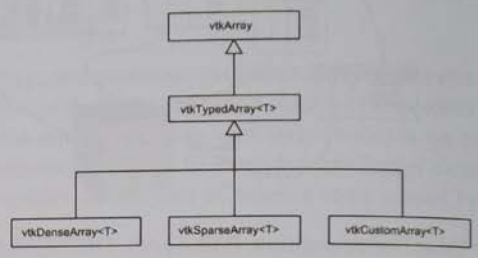


Figure 8–17 VTK N-dimensional array classes

Finally, VTK currently provides two concrete derivatives of vtkTypedArray<T>, vtkDenseArray<T> and vtkSparseArray<T>, that implement specific storage strategies:

vtkDenseArray<T> stores values using a single contiguous block of memory, with Fortran ordering for compatibility with the many linear algebra libraries (such as BLAS and LAPACK) that are designed to work with Fortran-ordered memory. vtkDenseArray<T> provides efficient O(1) retrieval of values and is most appropriate when working with dense data that is well-defined for every location in the array. The memory used by vtkDenseArray<T> is proportional to the product of the array extents along each dimension.

vtkSparseArray<T> uses sparse coordinate storage to store data efficiently when it isn't defined for every location within the array. Each non-null value is stored in an unordered list of values and its coordinates. A single 'null' value is used to represent the remaining contents of the array. As long as it's sufficiently sparse, a high-dimension dataset, that would be impossible to store in memory using vtkDenseArray<T>, can be easily manipulated using vtkSparseArray<T>. This is because the memory used is proportional to the number of non-null values in the array, rather than the size of the array.

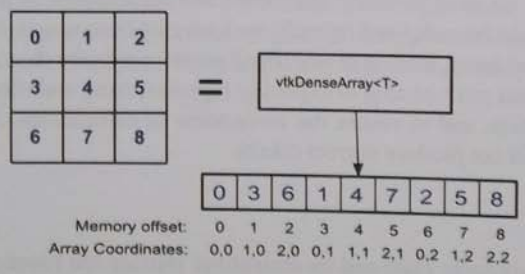


Figure 8–18 How vtkDenseArray<T> stores a 3x3 matirx using Fortran ordering.

The vtkDenseArray<T> and vtkSparseArray<T> storage classes included with VTK are designed to provide good all-around performance in a wide-variety of use-cases, and for arbitrary numbers of dimensions. In practice there may be situations where custom storage classes can provide better performance at the expense of generality, and the vtkArray interfaces are designed with this in mind. Users can create their own array storage classes by deriving from vtkTypedArray<T> and implementing a few pure-virtual methods. A hypothetical use-case for customized array storage might involve creating compressed-row or compressed-column storage for integration with a library that manipu-

lates matrices in one of those formats. Another use-case for custom arrays would be the creation of a read-only 'procedural' array that encapsulates a computed sequence such as the Fibonacci sequence - such an array wouldn't actually store any information, but could be used as an input for other calculations.

Using multi-dimensional arrays

You create multi-dimensional arrays in VTK by instantiating the desired concrete array class (vtkDenseArray<T>, vtkSparseArray<T>, or similar) templated on the type of value you wish to store (int, double, string, etc), then specify the extents (number of dimensions and size along each dimension) of the resulting array:

```
// Creating a dense vector (1D array) of strings:
vtkDenseArray<vtkStdString>* vector =
vtkDenseArray<vtkStdString>::New();
vector->Resize(10);

// Creating a dense 10 x 20 matrix (2D array) of integers:
vtkDenseArray<int>* matrix = vtkDenseArray<int>::New();
matrix->Resize(10, 20);

// Creating a sparse 10 x 20 x 30 x 40 tensor
// (4D array) of floating-point values:
vtkArrayExtents extents;
Extents.SetDimensions(4);
extents[0] = 10;
extents[1] = 20;
extents[2] = 30;
extents[3] = 40;
vtkSparseArray<double>* tensor = vtkSparseArray<double>::New();
tensor->Resize(extents);
```

Note that the vtkArray::Resize() method has been overloaded so that you can easily create one, two, or three-dimensional arrays by simply specifying the size along each dimension. For four-or-more dimensions, you must use an instance of the vtkArrayExtents helper class to encode the number of dimensions and extents.

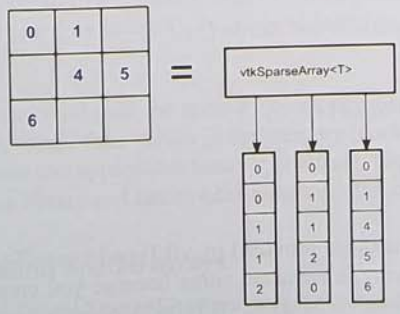


Figure 8–19 How vtkSparseArray<T> stores a sparse 3x3 matrix using coordiante storage.

After resizing, the new arrays must be properly initialized. This process will vary depending on the array storage type - for example, the contents of vtkDenseArray<T> will be undefined after resizing, so vtkDenseArray<T> provides a Fill() method that can be used to overwrite the entire array with a single value:

```
matrix->Fill(0);
```

Sparse arrays will be completely empty (all values will be undefined or 'null' values) after resizing, and it is always a good idea to explicitly specify what the 'null' value (the value that is returned whenever a caller accesses an undefined set of coordinates) should be:

```
tensor->SetNullValue(0.0);
```

Having initialized an array, the next step is to populate it using SetValue():

```
// Overwrite vector[5] with "Hello World!":
vector->SetValue(5, "Hello, World!");

// Overwrite matrix[4, 3] with "22":
matrix->SetValue(4, 3, 22);

// Overwrite tensor[3, 7, 1, 2] with "1.5":
vtkArrayCoordinates
coordinates;
coordinates.SetDimensions(4);
coordinates[0] = 3;
coordinates[1] = 7;
coordinates[2] = 1;
coordinates[3] = 2;
tensor->SetValue(coordinates, 1.5);
```

Note that, as with Resize(), there are overloaded versions of SetValue() that work with one-, two-, or three-dimensional data, and that a helper class - vtkArrayCoordinates - is used to supply coordinates for operations on higher dimension arrays. Not surprisingly, GetValue() is used to retrieve data from an array:

```
// Access array value [5]:
vtkStdString vector_value = vector->GetValue(5);

// Access matrix value [4, 3]:
int matrix_value = matrix->GetValue(4, 3);

// Access tensor value [3, 7, 1, 2]:
double tensor_value = tensor->GetValue(coordinates);
```

SetValue() and GetValue() are strongly-typed methods provided by vtkTypedArray<T>, and assume that you know the type of data stored in the array in advance, either because you created the array yourself, or you used SafeDownCast() to cast from vtkArray to vtkTypedArray<T> for some specific T. For situations where you are working with an array of unknown type, there are SetVariantValue() /

GetVariantValue() methods provided by vtkArray that allow you to conveniently set and get values from any array, regardless of type, albeit with the overhead of conversion to-and-from variant values:

```
// Print value [8] from any one-dimensional array
// to the console, regardless of type:
vtkArray* generic_array = /* Defined elsewhere */
cout << generic_array->GetVariantValue(8).ToString() << endl;
```

In this example, GetVariantValue() returns a vtkVariant object, and the vtkVariant::ToString() method converts the underlying value to a string, regardless of the original type. Similarly, you could use variants to shuffle data within an array without having to know the type of data it contains:

```
// Swap values [3] and [7] within an array, regardless of array type:
vtkVariant temp = generic_array->GetVariantValue(3);
generic_array->SetVariantValue(3, generic_array->GetVariantValue(7));
generic_array->SetVariantValue(7, temp);
```

Performance

Although SetValue() and GetValue() provide an easily-understood, uniform interface to all arrays regardless of their storage type, the convenience of this approach carries an abstraction penalty. In the material that follows, we will cover some important techniques for improving the performance of array-related code.

Populating Dense Arrays

You will often need to manipulate the contents of vtkDenseArray<T> as a simple block of memory, either for I/O operations or for interoperability with other libraries. For these situations, vtkDenseArray<T> provides the GetStorage() method, which returns a pointer to the memory block that stores the array contents. You could use this pointer to write the (binary) contents of an array to a file as a single contiguous block:

```
// Write the contents of a dense int array as binary data to a stream
void WriteDenseArray(vtkDenseArray<int>* array, ostream& stream)
{
  stream.write(
    reinterpret_cast<char*>(array->GetStorage()),
    array->GetSize() * sizeof(int));
}
```

Alternately, you could pass the memory block to a library that performs dense array calculations, so long as the ordering of the values in the memory block (Fortran) match what the library expects. You should try to use this approach whenever practical, since it avoids making deep-copies of your data as you pass it to a library and retrieve the results.

Populating Sparse Arrays

Recall that vtkSparseArray<T> stores values internally using a list of non-null values with their corresponding coordinates. This means that whenever SetValue() is called, vtkSparseArray<T> must

first determine whether an existing value at those coordinates already exists. If it does, the old value is replaced with the new value; otherwise, the new value and its coordinates are appended to the end of the list. This linear search for existing values makes SetValue() an expensive operation for sparse arrays, compared to a constant-time operation on dense arrays. Used naively, SetValue() makes the creation of sparse arrays unacceptably slow.

Fortunately, vtkSparseArray<T> provides the AddValue() method, which appends values to the internal list without performing a search for existing values, and executes in amortized constant time. This provides excellent performance, but means that the caller is responsible to avoid calling AddValue() more than once with the same set of coordinates. In practice, this means that AddValue() should only be used on an array when you are populating it from scratch (as you would do if you were implementing a pipeline source that creates new sparse arrays). Never call AddValue() on an array with unknown contents (such as the input to a filter), since you run the risk of adding values with duplicate coordinates to the array's internal list (which is not allowed). The following code demonstrates using AddValue() to efficiently create a 10000 x 10000 diagonal matrix:

```
vtkSparseArray<double>* array = vtkSparseArray<double>::New();
array->Resize(10000, 10000);
array->SetNullValue(0.0);
for(vtkIdType i = 0; i != 10000; ++i)
    {
    array->AddValue(i, i, 1.0);
    }
```

Iteration

The preceding examples demonstrate how to populate arrays efficiently by avoiding the pitfalls of the SetValue() method. However, similar issues arise when accessing arrays using GetValue() - because vtkSparseArray stores non-null values in an unordered list, GetValue() must perform a linear search every time it is called, leading to unacceptably slow performance. To address this, VTK provides another technique - iteration - that makes it possible to read and write values to dense and sparse arrays in constant time, so long as certain conditions are met. Using iteration, we can:

- Eliminate the cost of linear lookups when getting / setting sparse array values.
- Visit only non-null values in sparse arrays.
- Implement filters using a consistent interface across dense and sparse arrays.
- Implement filters that operate on arbitrary-dimension data.

The iteration interface provided for VTK multi-dimensional arrays works by exposing the values stored in an array as a single unordered list. Each value in the array is assigned an index in the half-open range [0, N), where N is the number of non-null values stored in the array, and the vtkArray and vtkTypedArray<T> classes provide methods for accessing values 'by index': SetValueN(), GetValueN(), and GetCoordinatesN(). Using these methods, you can "visit" every value in an array, regardless of the type of array storage, and regardless of the number of dimensions in the array, using a single loop. For example, the following code efficiently increments every value in an array of integers by one, without any knowledge of its dimensions or whether the array is sparse or dense:

```
vtkTypedArray<int>* array = /* Defined elsewhere */
for(vtkIdType n = 0; n != array->GetNonNullSize(); ++n)
```

```
  {
  array->SetValueN(n, array->GetValueN(n) + 1);
  }
```

Note that the order in which we "visit" the values in the array using GetValueN() / SetValueN() is purposefully undefined, and that the above code works because the order is unimportant - regardless of the type of underlying array, whether dense or sparse, one-dimensional or 11-dimensional, it does not matter whether value[3] is incremented before or after value[300], so long as both are eventually modified in a consistent manner.

Although you cannot control the order in which values are visited, you can use GetCoordinatesN() to discover "where you are at" as you iterate over the contents of any array, and this is usually sufficient for most algorithm implementations. For example, the following code computes the sum of the values in each row in a matrix, storing the results in a dense vector. Although we visit the matrix values in arbitrary order, we can use each value's coordinates as a constant time lookup to accumulate values in our result vector:

```
vtkTypedArray<double>* matrix = /* Defined elsewhere */
vtkIdType row_count = matrix->GetExtents()[0];

vtkTypedArray<double>* vector = vtkDenseArray<double>::New();
vector->Resize(row_count);
vector->Fill(0.0);

for(vtkIdType n = 0; n != matrix->GetNonNullSize(); ++n)
  {
  vtkArrayCoordinates coordinates;
  matrix->GetCoordinatesN(n, coordinates);
  vtkIdType row = coordinates[0];

  vector->SetValue(row, vector->GetValue(row) + matrix->GetValueN(n));
  }
```

The lack of a specific order of iteration may seem limiting at first, but a surprisingly large number of algorithms can be written to work within this constraint, benefiting from constant-time lookups, dimension, and storage-type independence.

Array Data

Now that we can create and manipulate multi-dimension arrays, it's time to move them through the VTK pipeline. Like vtkAbstractArray, vtkArray isn't a vtkDataObject, so it cannot be used directly by the pipeline. Instead, VTK provides vtkArrayData which acts as a container for arrays, and vtkArrayDataAlgorithm which can be used to implement vtkArrayData sources and filters:

Array Sources

- vtkDiagonalMatrixSource - Produces sparse or dense matrices of arbitrary size, with user-assigned values for the diagonal, superdiagonal, and subdiagonal.

- vtkBoostRandomSparseArraySource - Produces sparse matrices with arbitrary size and number of dimensions. Provides separate parameters to control generation of random values and random sparse patterns.
- vtkTableToSparseArray - Converts a vtkTable containing coordinates and values into a sparse array of arbitrary dimensions.

Array Algorithms

- vtkAdjacencyMatrixToEdgeTable - Converts a dense matrix into a vtkTable suitable for use with vtkTableToGraph. Dimension labels in the input matrix are mapped to column names in the output table.
- vtkArrayVectorNorm - Computes an L-norm for each column-vector in a sparse double matrix.
- vtkCosineSimilarity - Treats each row or column in a matrix as a vector, and computes the dot-product similarity between each pair of vectors, producing a vtkTable suitable for use with vtkTableToGraph. Note: In VTK versions after 5.4, vtkCosineSimilarity has been renamed vtkDotProductSimilarity, to better describe its functionality
- vtkDotProductSimilarity -Treats each row or column in a matrix as a vector, and computes the dot-product similarity between each pair of vectors, producing a vtkTable suitable for use with vtkTableToGraph.
- vtkBoostLogWeighting - Replaces each value p in an array with the natural logarithm of p+1. Good example of a filter that works with any array, containing any number of dimensions.
- vtkMatricizeArray - Converts sparse double arrays of arbitrary dimension to sparse matrices. For example, an i x j x k tensor can be converted into an i x jk, j x ik, or ij x k matrix.
- vtkNormalizeMatrixVectors - Normalizes either row vectors or column vectors in a matrix. Good example of a filter that works efficiently with both sparse and dense input matrices. Good example of a filter that works with either row or column vectors.
- vtkTransposeMatrix - Computes the transpose of a matrix.

Geospatial Visualization

Geospatial visualization is a discipline that combines techniques from traditional scientific visualization and information visualization in order to display geographically organized data. VTK's geospatial visualization facilities are currently under development and while VTK 5.4 provides some facilities for rendering high resolution maps, the API is subject to change in the next revision of VTK and may even break backwards compatibility.

9.1 Geographic Views and Representations

The main geospatial visualization functionality provided by VTK is the ability to render extremely large texture images onto geometric representations of the Earth. Both the image data and the geometry it is textured upon must be hierarchical representations that are loaded on demand from disk or a network server because they would otherwise consume too much memory and take too long to load. The following Python snippet shows the easiest way to display a map in VTK, along with a picture of the result. For information on the contents of versionUtil, which resolves some differences between VTK 5.4 and later versions, see "Information Visualization" on page 163. Also note that specifying "-D <path>" will allow the script to find the image data from the VTK data repository.

```
from vtk import *
import vtk.util.misc
import versionUtil

# Read in a small map image from VTKData.
rd = vtkJPEGReader()
datapath = vtk.util.misc.vtkGetDataRoot()
rd.SetFileName(datapath + '/Data/NE2_ps_bath_small.jpg')
rd.Update()
```

```
# Create a GeoView
gv = vtkGeoView()
rw = versionUtil.SetupView(gv)

# Add both image and geometry representations to the view
mi = gv.AddDefaultImageRepresentation(rd.GetOutput())
# Start threads that fetch data as required
gv.GetTerrain().GetSource().Initialize(1)
mi.GetSource().Initialize(1)

# Render and interact with the view.
gv.GetRenderer().SetBackground(1, 1, 1)
gv.GetRenderer().SetBackground2(.5, .5, .5)
gv.GetRenderer().GradientBackgroundOn()
versionUtil.ShowView(gv)
```

The Geovis toolkit provides a specialization of vtkView that creates and manages a set of actors to render a virtual globe textured with the image you provide of the Earth's surface. The vtkGeoView class also includes a compass widget which allows you to rotate the globe about an axis perpendicular to the viewport by clicking and dragging on the compass rose. The compass widget also allows you to zoom in and out using the distance slider and to change the angle between the Earth's surface normal and the camera view vector using the camera tilt slider.

Figure 9–1 3D geospatial view

GeoView's AddDefaultImageRepresentation method creates two representations: one—vtkGeoAlignedImageRepresentation—that takes a high resolution input map image and generates a tile hierarchy; and one—vtkGeoTerraindata that is well-defined—that generates a geometry hierarchy representing a 3-dimensional globe. You are of course free to use different representations. The next two paragraphs show how to manually create and add representations.

The vtkGeoView will accept one geometry representation and multiple aligned image representations. For instance, by adding the following lines to the script above—just before the call to ShowView()—you can display a cloud layer on top of the base map.

```
# Read in a cloud cover image from VTKData.
rd2 = vtkJPEGReader()
datapath = vtk.util.misc.vtkGetDataRoot()
rd2.SetFileName(datapath + '/Data/clouds.jpeg')
rd2.Update()

# Create the texture image hierarchy from the cloud image
mi = vtkGeoAlignedImageRepresentation()
ms = vtkGeoAlignedImageSource()
ms.SetImage(rd2.GetOutput())
ms.Initialize(1) # Start a thread to respond to requests
mi.SetSource(ms)
gv.AddRepresentation(mi) # A GeoView may have multiple textures
```

To add geographically located information to the visualization, vtkGeoView will accept graph representations whose coordinates are specified as latitude and longitude. In VTK 5.4, the representation must be a vtkGeoGraphRepresentation instance but in later versions any vtkRenderedGraphRepresentation whose layout strategy results in latitude and longitude coordinates is acceptable.

Figure 9–2 Using multi-texturing in VTK's geospatial view

```
# Create a graph with lat-long coordinates
gs = vtkGeoRandomGraphSource()
if versionUtil.VersionGreaterThan(5, 4):
  gr = vtkRenderedGraphRepresentation
  gr.SetLayoutStrategyToAssignCoordinates
  ('latitude', 'longitude')
  gr.SetEdgeLayoutStrategyToGeo(0.1)
else:
  gr = vtkGeoGraphRepresentation()
  gr.SetInputConnection( gs.GetOutputPort() )
  gv.AddRepresentation( gr )
```

While the 3-D virtual globe in vtkGeoView is entertaining, in some situations geographic visualizations can be more informative using a cartographic map projection that shows the entire Earth on a flat surface. The vtkGeoView2D subclass of vtkView, the vtkGeoTerrain2D 2-dimensional map geometry representation, and the vtkGeoGraphRepresentation2D graph representation provide a way to produce maps using cartographic projections. The vtkGeoView2D accepts the same image representations as the vtkGeoView, as the following code snippet illustrates.

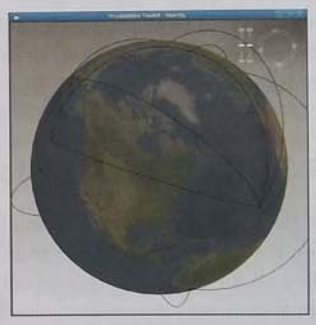


Figure 9–3 A graph drawn on a 3-D globe.

```
gv = vtkGeoView2D()

# Create the terrain geometry
ps = vtkGeoProjectionSource()
ps.Initialize(1)
ps.SetProjection(138) # The "robin" projection
tr = vtkGeoTerrain2D()
tr.SetSource(ps)
gv.SetSurface(tr) # A GeoView can only have one terrain

# Create image representations and graph source
# the same way as previous 3D examples.
# Omitted for brevity ...

# Render and interact with the view.
versionUtil.Show( gv )
```

9.2 Generating Hierarchies

Figure 9–4 Showing the same graph from **Figure 9–3** on VTK's 2D geospatial view

You may have noticed from the examples above that the vtkGeoAlignedImageSource takes the name of a single image file as an input. As the size of the image file increases, generating a set of tiles that can be downloaded to the video card becomes costly. Similarly, sampling cartographic projections—which frequently involves evaluating transcendental functions at each point—in order to generate polygonal tiles can also be burdensome. To avoid performing this work each time a program is started,

- the vtkGeoAlignedImageRepresentation and vtkGeoTerrain classes provide a SaveDatabase() method to save the resulting hierarchy of tiles into a directory, and
- alternative sources named vtkFileImageSource and vtkFileTerrainSource can be used which read these tiles from disk instead of generating them on the fly from the source image or cartographic projection.

Now that we have covered how to use the vtkGeoView and vtkGeoView2D along with their matching representations, the next sections discuss how the representations work with the sources providing the underlying data.

9.3 Hierarchical Data Sources—On-demand resolution

In the examples above, you might have noticed that the image and terrain representations each manage a source object. These source objects are instances of hierarchical image or geometry data and they all inherit from vtkGeoSource. The vtkGeoSource class is an abstract base class that provides a consistent way to perform on-demand loading that allows interactive rendering. Because loading geometry and image data from a disk or network can introduce undesirable latency in rendering, the vtkGeoSource class uses threads to load requested data asynchronously. Each time a render occurs, content that has already been loaded into a vtkGeoSource subclass instance is used for drawing. Whenever this content is not deep enough in the hierarchy to result in a rendering with a sufficient accuracy, new hierarchy nodes are added to a list of requests. The auxiliary thread in the vtkGeoSource subclass is responsible for loading the requested nodes and signaling to the main thread that the new image or geometry node is ready for insertion into the hierarchy.

The vtkGeoAlignedImageSource subclass of vtkGeoSource represents a hierarchy of image tiles. Each tile provides a regularly-sampled image over a rectangular patch in latitude-longitude coordinate-space (lat-long space). These tiles are textured onto geometry (polydata) obtained from another hierarchy. VTK provides 2 sources of geometric hierarchies:

- 3-dimensional coordinates projected into screen space by the rendering pipeline (such as OpenGL®), or
- 2-dimensional coordinates projected into a cartographic space by a traditional map projection.

The 3-dimensional screen-space polydata hierarchy is represented by the class named vtkGeoGlobeSource; the 2-dimensional cartographic space polydata hierarchy is represented by vtkGeoProjection-

Source. These classes generate or read the geometry and present a hierarchy, but they do not determine which nodes in the hierarchy should be used for rendering. That task is reserved for the terrain classes.

9.4 Terrain

A terrain class exists for each case and references a subclass of vtkGeoSource from which it obtains a representation of the Earth's geometry. The terrain classes are representations responsible for requesting geometry from the vtkGeoSource and configuring a list of actors used to render a cut of the hierarchy that has been loaded. The actors created by the terrain classes are reused as different tiles are made available by the vtkGeoSource. In addition to assigning polydata from a tile to an actor, the terrain classes assign image data used to texture the geometry. On hardware that supports multitexturing, multiple lat-long-aligned images may be assigned to each tile.

In the 3-dimensional case, the Earth is represented using the vtkGeoTerrain class that provides rectangular patches that approximate a sphere and are tessellated at varying resolutions depending on a camera's position and orientation. Coordinates are specified in meters.

In the 2-dimensional case, the Earth is represented using the vtkGeoTerrain2D class that provides rectangular patches whose coordinates are in some cartographic space. The units of the cartographic space coordinates vary depending on the map projection used. Because the vtkPoints class requires all points to have 3 coordinates but only 2 are significant, all z coordinate values are 0. The patches are polygonal data which may contain triangles and quadrilaterals. The subset of patches in the hierarchy that are presented for rendering are selected based on the error with which they represent the map projection compared to the viewport pixel size.

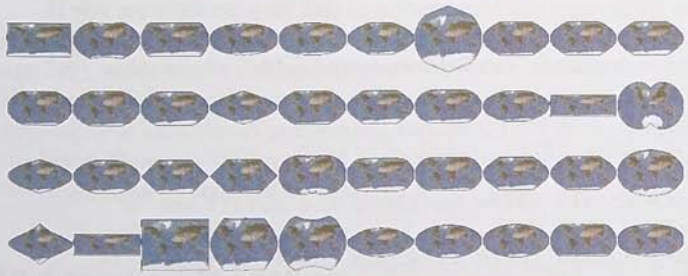


Figure 9–5 Some interesting cartographic projections provided by libproj4

9.5 Cartographic Projections

The cartographic projections applied in the 2-dimensional case are provided by the vtkGeoProjection class. To transform to or from cartographic coordinates, the vtkGeoTransform class takes a source and destination vtkGeoProjection instance and uses the libproj4 library in VTK/Utilities to transform points. Because vtkGeoTransform inherits from the vtkAbstractTransform class, the vtkTransformFilter may be used to transform any data you wish to or from cartographic space. By default, new vtkGeoProjection instances are set to the natural cartographic transform named "latlong". Over 180 projections are provided, a few of which are shown in **Figure 9–5**. Note that many projections are not intended for use over the entire globe, but rather over a small lat-long region. If you attempt to use these projections on a domain that is too large, the results will often be confusing and incoherent.

The example below illustrates how a cartographic projection can be used to transform vector data from lat-long space into cartographic space. The vector data in the example is provided by the vtkGeoGraticule class, which generates a grid covering the globe with lines of constant latitude and longitude. The graticule is sampled at a lower rate near the poles to avoid clutter.

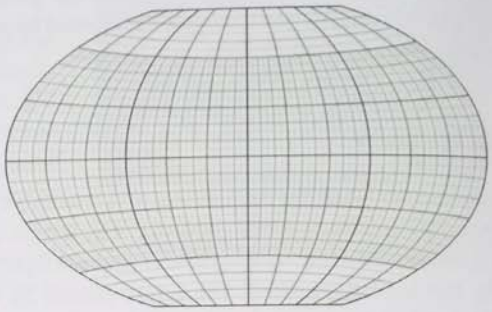


Figure 9–6 A grid of equal latitude/longitude lines sent through a 2D projection

```
# The default is latlong
# (no projection at all)
ps = vtkGeoProjection()

# Interesting destination
# projections to try:
#  wintri, rouss, robin, eckl
pd.SetName('wintri') # Use the Robinson projection
pd.SetCentralMeridian(0)

# The vtkGeoTransform class moves points from one projection to
# another by applying the inverse of the source projection and
# the forward projection of the destination to each point.
gt = vtkGeoTransform()
gt.SetSourceProjection(ps)
gt.SetDestinationProjection(pd)

# We will obtain points in lat-long coordinates from the
# vtkGeoGraticule. It creates a grid that covers the globe in
# lat-long coordinates.
gg = vtkGeoGraticule()
gg.SetLongitudeBounds(-180, 180)
gg.SetLatitudeBounds(-90, 90)
# How many grid points should there be along the latitude?
gg.SetLatitudeLevel(3)
# How many grid points should there be along the longitude?
gg.SetLongitudeLevel(3)

# The vtkTransformFilter is a vtkAlgorithm that uses a transform
# to map points from one coordinate system to another.
tr = vtkTransformFilter()
tr.SetTransform(gt)
tr.SetInputConnection(gg.GetOutputPort())

# Create a mapper, actor, renderer, to display the results.
```

Chapter 10

Building Models

We have seen how to use source objects (both readers and procedural objects) to create geometry. (See "Creating Simple Models" on page 42.) VTK provides several other techniques to generate more complex models. Three techniques covered in this chapter are implicit modeling, extrusion, and surface reconstruction from unorganized points.

If you are working with data in a form that lacks topological or geometric structure, VTK can represent this information as field data (using class vtkDataObject, see "Working With Field Data" on page 249), which can be further processed to produce datasets for visualization with the techniques in this chapter. For example, an n-dimensional financial record can be reduced to three dimensions by choosing three variables as independent variables. Then the techniques described here—Delaunay triangulation, Gaussian splatting, and surface reconstruction—can be used to create structure suitable for visualization by standard methods.

10.1 Implicit Modeling

Implicit modeling is a powerful technique employing 3D contouring (isosurface generation) to create polygonal surface meshes. The contouring operation is applied to a vtkImageData dataset (a regular volume) whose scalar values have been synthetically generated. The key to implicit modeling is that the scalar field can be generated using a wide variety of techniques. These techniques include producing a distance field from generating primitives (e.g., a field representing the distance from a set of lines and/or polygons) as well as using boolean set operations to combine the scalar fields.

Creating An Implicit Model

Here's an example that uses some lines to generate a complex, polygonal surface. The lines are arranged to spell the word "HELLO" and serve as the generating seed geometry (**Figure 10–1**). (The Tcl script is taken from `VTK/Examples/Modelling/Tcl/hello.tcl`.)

Figure 10–1 Implicit modeling from lines spelling the word "hello."

```
# create lines
vtkPolyDataReader reader
    reader SetFileName "$VTK_DATA_ROOT/Data/hello.vtk"
vtkPolyDataMapper lineMapper
    lineMapper SetInputConnection [reader GetOutputPort]
vtkActor lineActor
    lineActor SetMapper lineMapper
    eval [lineActor GetProperty] SetColor $red

# create implicit model
vtkImplicitModeller imp
  imp SetInputConnection [reader GetOutputPort]
  imp SetSampleDimensions 110 40 20
  imp SetMaximumDistance 0.25
  imp SetModelBounds -1.0 10.0 -1.0 3.0 -1.0 1.0
vtkContourFilter contour
  contour SetInputConnection [imp GetOutputPort]
  contour SetValue 0 0.25
vtkPolyDataMapper impMapper
  impMapper SetInputConnection [contour GetOutputPort]
  impMapper ScalarVisibilityOff
vtkActor impActor
  impActor SetMapper impMapper
  eval [impActor GetProperty] SetColor $peacock
  [impActor GetProperty] SetOpacity 0.5
```

What's happening in this script is that the lines that stroke out the word "hello" serve as the generating primitives. The vtkImplicitModeller class computes the distance from the lines (taking the closest distance to any line) to the points in the output vtkImageData and assigns this distance as the scalar value at each point in the dataset. The output is then passed to the vtkContourFilter which generates a polygonal isosurface. (The isosurface value is the distance from the generating primitives.)

There are a couple of important parameters in vtkImplicitModeller. The MaximumDistance instance variable controls how far from the generating primitives to continue the distance calculation. This instance variable, expressed as a fraction of the grid length, has a great effect on the speed of calculation: smaller values result in faster computation, but the isosurface may become choppy or break up if the values are too small. The SampleDimensions instance variable controls the resolution of the output vtkImageData, and ModelBounds controls the position and size of the dataset in space.

Sampling Implicit Functions

Another powerful modeling technique is the use of implicit functions. Implicit functions have the form

$$F(x,y,z) = constant$$

Spheres, cones, ellipsoids, planes, and many other useful geometric entities can be described with implicit functions. For example, a sphere S of radius R centered at the origin can be described by the equation $F(x,y,z) = R^2 - x^2 - y^2 - z^2$. When $F(x,y,z)=0$, the equation describes S exactly. When $F(x,y,z) < 0$, we describe a sphere that lies inside the sphere S, and when $F(x,y,z) > 0$, we describe a sphere that lies outside the sphere S. As its name implies, an implicit function defines a surface implicitly; producing an explicit representation of the surface (e.g., polygons) requires sampling the function over a volume and then performing an isocontouring operation as demonstrated in the next example.

Figure 10–2 Implicit modeling using boolean combinations.

Besides modeling, implicit functions can also be combined using the set operations union, intersection, and difference. These operations allow you to create complex geometry using combinations of implicit functions. Here's an example script that models an ice cream cone by using a sphere (ice cream), a cone intersected by two planes (to create a cone of finite extent), and another sphere to simulate the "bite" out of the ice cream. The script is taken from `VTK/Examples/Modelling/Tcl/iceCream.tcl`.

```
# create implicit function primitives
vtkCone cone
  cone SetAngle 20
vtkPlane vertPlane
  vertPlane SetOrigin .1 0 0
  vertPlane SetNormal -1 0 0
vtkPlane basePlane
  basePlane SetOrigin 1.2 0 0
  basePlane SetNormal 1 0 0
vtkSphere iceCream
  iceCream SetCenter 1.333 0 0
  iceCream SetRadius 0.5
vtkSphere bite
  bite SetCenter 1.5 0 0.5
  bite SetRadius 0.25

# combine primitives to build ice-cream cone
vtkImplicitBoolean theCone
    theCone SetOperationTypeToIntersection
  theCone AddFunction cone
  theCone AddFunction vertPlane
  theCone AddFunction basePlane
```

```
# take a bite out of the ice cream
vtkImplicitBoolean theCream
  theCream SetOperationTypeToDifference
  theCream AddFunction iceCream
  theCream AddFunction bite

# iso-surface to create geometry of the cone
vtkSampleFunction theConeSample
  theConeSample SetImplicitFunction theCone
  theConeSample SetModelBounds -1 1.5 -1.25 1.25 -1.25 1.25
  theConeSample SetSampleDimensions 60 60 60
  theConeSample ComputeNormalsOff
vtkContourFilter theConeSurface
  theConeSurface SetInputConnection [theConeSample GetOutputPort]
  theConeSurface SetValue 0 0.0
vtkPolyDataMapper coneMapper
  coneMapper SetInputConnection [theConeSurface GetOutputPort]
  coneMapper ScalarVisibilityOff
vtkActor coneActor
  coneActor SetMapper coneMapper
  eval [coneActor GetProperty] SetColor $chocolate

# iso-surface to create geometry of the ice cream
vtkSampleFunction theCreamSample
  theCreamSample SetImplicitFunction theCream
  theCreamSample SetModelBound 0 2.5 -1.25 1.25 -1.25 1.25
    theCreamSample SetSampleDimensions 60 60 60
  theCreamSample ComputeNormalsOff
vtkContourFilter theCreamSurface
  theCreamSurface SetInputConnection [theCreamSample GetOutputPort]
  theCreamSurface SetValue 0 0.0
vtkPolyDataMapper creamMapper
  creamMapper SetInputConnection [theCreamSurface GetOutputPort]
  creamMapper ScalarVisibilityOff
vtkActor creamActor
  creamActor SetMapper creamMapper
  eval [creamActor GetProperty] SetColor $mint
```

The classes vtkSampleFunction and vtkContourFilter are the keys to building the polygonal geometry. vtkSampleFunction evaluates the implicit function (actually the boolean combination of implicit functions) to generate scalars across a volume (vtkImageData) dataset. vtkContourFilter is then used to generate an isosurface which approximates the implicit function. The accuracy of the approximation depends on the nature of the implicit function, as well as the resolution of the volume generated by vtkSampleFunction (specified using the SetSampleDimensions() method).

A couple of usage notes: Boolean combinations can be nested to arbitrary depth. Just make sure the hierarchy does not contain self-referencing loops. Also, you may wish to use vtkDecimatePro to reduce the number of primitives output by the contour filter since the number of triangles can be quite large. See "Decimation" on page 107 for more information.

10.2 Extrusion

Extrusion is a modeling technique that sweeps a generating object along a path to create a surface. For example, we can sweep a line in a direction perpendicular to it to create a plane.

Figure 10–3 Rotational extrusion.

The *Visualization Toolkit* offers two methods of extrusion: linear extrusion and rotational extrusion. In VTK, the generating object is a vtkPolyData dataset. Lines, vertices, and "free edges" (edges used by only one polygon) are used to generate the extruded surface. The vtkLinearExtrusionFilter sweeps the generating primitives along a straight line path; the vtkRotationalExtrusionFilter sweeps them along a rotational path. (Translation during rotation is also possible.)

In this example we will use an octagonal polygon (i.e., an approximation to a disk) to sweep out a combined rotational/translational path to model a "spring" (**Figure 10–3**). The filter extrudes its input (generating primitives) around the *z* axis while also translating (during rotation) along the *z* axis and adjusting the sweep radius. By default, the instance variable Capping is on, so the extruded surface (a hollow tube) is capped by the generating primitive. Also, we must set the Resolution instance variable to generate a reasonable approximation. (The vtkPolyDataNormals filter used in the following example is described in "Generate Surface Normals" on page 107.)

```
# create spring profile (a disk)
vtkPoints points
  points InsertPoint 0 1.0 0.0 0.0
  points InsertPoint 1 1.0732 0.0 -0.1768
  points InsertPoint 2 1.25 0.0 -0.25
  points InsertPoint 3 1.4268 0.0 -0.1768
  points InsertPoint 4 1.5 0.0 0.00
  points InsertPoint 5 1.4268 0.0 0.1768
  points InsertPoint 6 1.25 0.0 0.25
  points InsertPoint 7 1.0732 0.0 0.1768
vtkCellArray poly
  poly InsertNextCell 8;#number of points
  poly InsertCellPoint 0
  poly InsertCellPoint 1
  poly InsertCellPoint 2
  poly InsertCellPoint 3
  poly InsertCellPoint 4
  poly InsertCellPoint 5
  poly InsertCellPoint 6
  poly InsertCellPoint 7
vtkPolyData profile
  profile SetPoints points
  profile SetPolys poly

# extrude profile to make spring
vtkRotationalExtrusionFilter extrude
  extrude SetInput profile
```

```
    extrude SetResolution 360
    extrude SetTranslation 6
    extrude SetDeltaRadius 1.0
    extrude SetAngle 2160.0;#six revolutions

  vtkPolyDataNormals normals
    normals SetInputConnection [extrude GetOutputPort]
    normals SetFeatureAngle 60
  vtkPolyDataMapper map
    map SetInputConnection [normals GetOutputPort]
  vtkActor spring
    spring SetMapper map
    [spring GetProperty] SetColor 0.6902 0.7686 0.8706
    [spring GetProperty] SetDiffuse 0.7
    [spring GetProperty] SetSpecular 0.4
    [spring GetProperty] SetSpecularPower 20
    [spring GetProperty] BackfaceCullingOn
```

The vtkLinearExtrusionFilter is similar, but it is simpler to use than vtkRotationalExtrusionFilter. Linear extrusion can be performed along a user-specified vector (SetExtrusionTypeToVectorExtrusion()) or towards a user-specified point (SetExtrusionTypeToPointExtrusion()); or the extrusion can be performed in the direction of the surface normals of the generating surface (SetExtrusionTypeToNormalExtrusion()).

10.3 Constructing Surfaces

Often we wish to construct a surface from a set of unstructured points or other data. The points may come from a laser digitizing system or may be assembled from multi-variate data. In this section we examine techniques to build new surfaces from data of this form. You may also wish to refer to "Building Models" on page 213 for other methods to create surfaces from generating primitives (i.e., implicit modeling).

Delaunay Triangulation

The Delaunay triangulation is widely used in computational geometry. The basic application of the Delaunay triangulation is to create a simplicial mesh (i.e., triangles in 2D, tetrahedra in 3D) from a set of points. The resulting mesh can then be used in a variety of ways, including processing with standard visualization techniques. In VTK, there are two objects for creating Delaunay triangulations: vtkDelaunay2D and vtkDelaunay3D.

Note: Delaunay triangulation is numerically sensitive. The current version of vtkDelaunay3D may not be robust enough to reliably handle large numbers of points. This will be improved in the near future.

vtkDelaunay2D. The vtkDelaunay2D object takes vtkPointSet (or any of its subclasses) as input and generates a vtkPolyData on output. Typically the output is a triangle mesh, but if you use a non-zero Alpha value it is possible to generate meshes consisting of triangles, lines, and vertices. (This parameter controls the "size" of output primitives. The size of the primitive is measured by an n-dimensional circumsphere; only those pieces of the mesh whose circumsphere has a circumradius less than

or equal to the alpha value are sent to the output. For example, if an edge of length L is less than 2*Alpha, the edge would be output).

In the following Tcl example we generate points using a random distribution in the (0,1) x-y plane. (vtkDelaunay2D ignores the z-component during execution, although it does output the z value.) To create a nicer picture we use vtkTubeFilter and vtkGlyph3D to create tubes around mesh edges and spheres around the mesh points. The script comes from `VTK/Examples/Modelling/Tcl/DelMesh.tcl`.

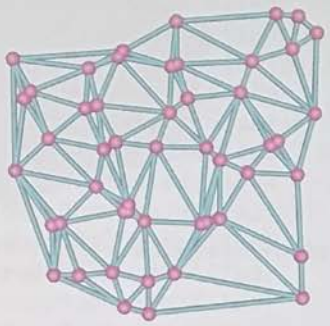


Figure 10–4 2D Delaunay triangulation

```
# create some points
vtkMath math
vtkPoints points
for {set i 0} {$i<50} {incr i 1} {
  eval points InsertPoint $i [math Random 0 1] \
                             [math Random 0 1] 0.0
}
vtkPolyData profile
  profile SetPoints points

# triangulate them
vtkDelaunay2D del
  del SetInput profile
  del SetTolerance 0.001
vtkPolyDataMapper mapMesh
  mapMesh SetInputConnection [del GetOutputPort]
vtkActor meshActor
  meshActor SetMapper mapMesh
    [meshActor GetProperty] SetColor .1 .2 .4
vtkExtractEdges extract
  extract SetInputConnection [del GetOutputPort]
vtkTubeFilter tubes
  tubes SetInputConnection [extract GetOutputPort]
  tubes SetRadius 0.01
  tubes SetNumberOfSides 6
vtkPolyDataMapper mapEdges
  mapEdges SetInputConnection [tubes GetOutputPort]
vtkActor edgeActor
  edgeActor SetMapper mapEdges
    eval [edgeActor GetProperty] SetColor $peacock
  [edgeActor GetProperty] SetSpecularColor 1 1 1
  [edgeActor GetProperty] SetSpecular 0.3
  [edgeActor GetProperty] SetSpecularPower 20
  [edgeActor GetProperty] SetAmbient 0.2
  [edgeActor GetProperty] SetDiffuse 0.8

vtkSphereSource ball
  ball SetRadius 0.025
  ball SetThetaResolution 12
```

```
  ball SetPhiResolution 12
vtkGlyph3D balls
  balls SetInputConnection [del GetOutputPort]
  balls SetSourceConnection [ball GetOutputPort]
vtkPolyDataMapper mapBalls
  mapBalls SetInputConnection [balls GetOutputPort]
vtkActor ballActor
  ballActor SetMapper mapBalls
  eval [ballActor GetProperty] SetColor $hot_pink
  [ballActor GetProperty] SetSpecularColor 1 1 1
  [ballActor GetProperty] SetSpecular 0.3
  [ballActor GetProperty] SetSpecularPower 20
  [ballActor GetProperty] SetAmbient 0.2
  [ballActor GetProperty] SetDiffuse 0.8
```

The Tolerance instance variable is used to determine whether points are coincident. Points located a distance Tolerance apart (or less) are considered coincident, and one of the points may be discarded. Tolerance is expressed as a fraction of the length of the diagonal of the bounding box of the input points.

Another useful feature of vtkDelaunay2D is the ability to define constraint edges and polygons. Normally, vtkDelaunay2D will generate a Delaunay triangulation of an input set of points satisfying the circumsphere criterion. However, in many cases additional information specifying edges in the triangulation (constraint edges) or "holes" in the data (constraint polygons) may be available. By specifying constraint edges and polygons, vtkDelaunay2D can be used to generate sophisticated triangulations of points. The following example (taken from `VTK/Examples/Modelling/Tcl/constrainedDelaunay.tcl`) demonstrates this.

```
vtkPoints points
  points InsertPoint 0 1 4 0
  points InsertPoint 1 3 4 0
  points InsertPoint 2 7 4 0
    ...(more points defined)...
vtkCellArray polys
  polys InsertNextCell 12
  polys InsertCellPoint 0
  polys InsertCellPoint 1
  polys InsertCellPoint 2
    ...(a total of two polygons defined)...
vtkPolyData polyData
  polyData SetPoints points
  polyData SetPolys polys

# generate constrained triangulation
vtkDelaunay2D del
  del SetInput polyData
  del SetSource polyData
vtkPolyDataMapper mapMesh
  mapMesh SetInputConnection [del GetOutputPort]
vtkActor meshActor
  meshActor SetMapper mapMesh
```

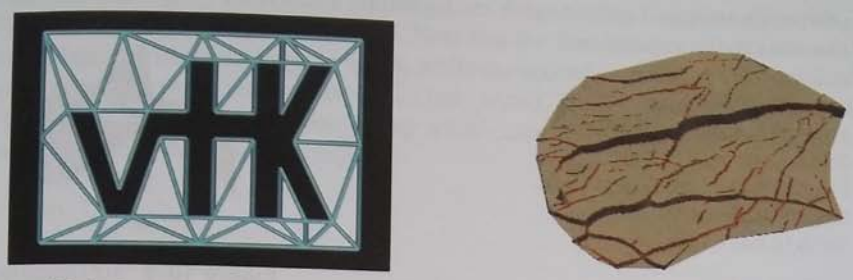


Figure 10–5 Constrained Delaunay triangulation. On the left, a constraint polygon defines a hole in the triangulation. On the right, constraint edges define fault lines in a geological horizon.

```
# tubes around mesh
vtkExtractEdges extract
  extract SetInputConnection [del GetOutputPort]
vtkTubeFilter tubes
  tubes SetInputConnection [extract GetOutputPort]
  tubes SetRadius 0.1
  tubes SetNumberOfSides 6
vtkPolyDataMapper mapEdges
  mapEdges SetInputConnection [tubes GetOutputPort]
vtkActor edgeActor
  edgeActor SetMapper mapEdges
  eval [edgeActor GetProperty] SetColor $peacock
  [edgeActor GetProperty] SetSpecularColor 1 1 1
  [edgeActor GetProperty] SetSpecular 0.3
  [edgeActor GetProperty] SetSpecularPower 20
  [edgeActor GetProperty] SetAmbient 0.2
  [edgeActor GetProperty] SetDiffuse 0.8
```

In this example (resulting image shown on the left of **Figure 10–5**), a second input to vtkDelaunay2D has been defined (with the SetSource() method). This input defines two polygons, one ordered counter-clockwise and defining the outer rectangular boundary, and the second clockwise-ordered polygon defining the "vtk" hole in the triangulation.

Using constraint edges is much simpler since the ordering of the edges is not important. Referring to the example `VTK/Examples/Modelling/Tcl/faultLines.tcl`, constraint edges (lines and polylines provided to the second input Source) are used to constrain the triangulation along a set of edges. (See the right side of **Figure 10–5**.)

vtkDelaunay3D. vtkDelaunay3D is similar to vtkDelaunay2D. The major difference is that the output of vtkDelaunay3D is an unstructured grid dataset (i.e., a tetrahedral mesh).

```
vtkMath math
vtkPoints points
for {set i 0} {$i<25} {incr i 1} {
    points InsertPoint $i [math Random 0 1]\
         [math Random 0 1] [math Random 0 1]}
```

```
vtkPolyData profile
  profile SetPoints points

# triangulate them
vtkDelaunay3D del
  del SetInput profile
  del BoundingTriangulationOn
  del SetTolerance 0.01
  del SetAlpha 0.2

# shrink the result to help see it better
vtkShrinkFilter shrink
  shrink SetInputConnection [del
GetOutputPort]
  shrink SetShrinkFactor 0.9
vtkDataSetMapper map
  map SetInputConnection [shrink GetOutputPort]
vtkActor triangulation
  triangulation SetMapper map
  [triangulation GetProperty] SetColor 1 0 0
```

Figure 10–6 3D Delaunay triangulation with non-zero alpha.

In this example (taken from `VTK/Examples/Modelling/Tcl/Delaunay3D.tcl`) we triangulate a random set of points in 3D space ranging between (0,1) along each of the coordinate axes. A non-zero Alpha is used, so the mesh consists of a collection of tetrahedra, triangles, lines, and points. The resulting tetrahedral mesh is shrunk with vtkShrinkFilter and mapped with vtkDataSetMapper.

Gaussian Splatting

Many times data has no inherent structure, or the dimension of the data is high relative to what 2D, 3D, or 4D (3D with animation) visualization techniques can represent. An example of one such data set is scalar values (i.e., temperature) located at random points in space from a thermocouple measuring system. Multidimensional financial data (i.e., many records each record having several variables), is another example. One of the simplest and most robust procedures that can used to treat such data is to resample the data on a volume (i.e., vtkImageData dataset) and then visualize the resampled dataset. In the following C++ example (`VTK/Examples/Modelling/Cxx/finance.cxx`) we show how to do this with multivariate financial data. You may wish to refer to "Working With Field Data" on page 249 for an alternative way to work with this data.

The data consists of an ASCII text file with 3188 financial records. Each record contains the following information: the time late in paying the loan (`TIME_LATE`); the monthly payment of the loan (`MONTHLY_PAYMENT`); the principal left on the loan (`UNPAID_PRINCIPAL`); the original amount of the loan (`LOAN_AMOUNT`); the interest rate on the loan (`INTEREST_RATE`); and the monthly income of the loanee (`MONTHLY_INCOME`).

The purpose of the visualization is to understand the relationship of these variables to the variable of major concern: `TIME_LATE`. Building a mathematical model or understanding of this data helps financial institutions make less risky loans. What we will do in the example is to show the late paying loans in context with the total loan population. We begin by choosing `MONTHLY_PAYMENT` as the x-axis, `INTEREST_RATE` as the y-axis, and `LOAN_AMOUNT` as the z-axis, and then choose `TIME_LATE` as the dependent variable (i.e., we reduce the dimensionality of the data by selecting three variables and ignoring the others). The class vtkGaussianSplatter is used to take the reduced

financial data and "splat" them into a vtkImageData dataset using Gaussian ellipsoids. Then vtkContourFilter is used to generate an isosurface. Note that the first instance of vtkGaussianSplatter splats the entire dataset without scaling the splats, while the second instance of vtkGaussianSplatter scales the splats according to the scalar value (i.e., TIME_LATE). The late loans are rendered in red while the total population is rendered in a translucent white color. (See **Figure 10–7**.) Following is the C++ code demonstrating Gaussian splatting.

```
main ()
{
 double bounds[6];
  vtkDataSet *dataSet;

...read data...
if ( ! dataSet ) exit(0);

 // construct pipeline for original
population
 vtkGaussianSplatter *popSplatter =
vtkGaussianSplatter::New();
  popSplatter->SetInput(dataSet);
  popSplatter-
>SetSampleDimensions(50,50,50);
  popSplatter->SetRadius(0.05);
  popSplatter->ScalarWarpingOff();
 vtkContourFilter *popSurface = vtkContourFilter::New();
  popSurface->SetInputConnection(popSplatter->GetOutputPort());
  popSurface->SetValue(0,0.01);
 vtkPolyDataMapper *popMapper = vtkPolyDataMapper::New();
  popMapper->SetInputConnection(popSurface->GetOutputPort());
  popMapper->ScalarVisibilityOff();
 vtkActor *popActor = vtkActor::New();
  popActor->SetMapper(popMapper);
  popActor->GetProperty()->SetOpacity(0.3);
  popActor->GetProperty()->SetColor(.9,.9,.9);

  // construct pipeline for delinquent population
 vtkGaussianSplatter *lateSplatter = vtkGaussianSplatter::New();
  lateSplatter->SetInput(dataSet);
  lateSplatter->SetSampleDimensions(50,50,50);
  lateSplatter->SetRadius(0.05);
  lateSplatter->SetScaleFactor(0.005);
 vtkContourFilter *lateSurface = vtkContourFilter::New();
  lateSurface->SetInputConnection(lateSplatter->GetOutputPort());
  lateSurface->SetValue(0,0.01);
 vtkPolyDataMapper *lateMapper = vtkPolyDataMapper::New();
  lateMapper->SetInputConnection(lateSurface->GetOutputPort());
  lateMapper->ScalarVisibilityOff();
 vtkActor *lateActor = vtkActor::New();
  lateActor->SetMapper(lateMapper);
  lateActor->GetProperty()->SetColor(1.0,0.0,0.0);
```

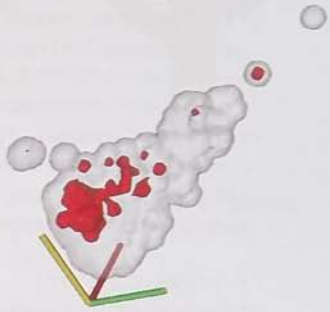


Figure 10–7 Splatting data.

```
// create axes
popSplatter->Update();
popSplatter->GetOutput()->GetBounds(bounds);
vtkAxes *axes = vtkAxes::New();
 axes->SetOrigin(bounds[0], bounds[2], bounds[4]);
 axes->SetScaleFactor(
                popSplatter->GetOutput()->GetLength()/5);
vtkTubeFilter *axesTubes = vtkTubeFilter::New();
 axesTubes->SetInputConnection(axes->GetOutputPort());
 axesTubes->SetRadius(axes->GetScaleFactor()/25.0);
 axesTubes->SetNumberOfSides(6);
vtkPolyDataMapper *axesMapper = vtkPolyDataMapper::New();
 axesMapper->SetInputConnection(axesTubes->GetOutputPort());
vtkActor *axesActor = vtkActor::New();
 axesActor->SetMapper(axesMapper);

// graphics stuff
vtkRenderer *renderer = vtkRenderer::New();
vtkRenderWindow *renWin = vtkRenderWindow::New();
 renWin->AddRenderer(renderer);
vtkRenderWindowInteractor *iren =
                    vtkRenderWindowInteractor::New();
 iren->SetRenderWindow(renWin);

// read data, set up renderer
renderer->AddActor(lateActor);
renderer->AddActor(axesActor);
renderer->AddActor(popActor);
renderer->SetBackground(1,1,1);
renWin->SetSize(300,300);

// interact with data
iren->Initialize();
iren->Start();
...clean up...
}
```

What's interesting about this example is that the majority of late payments occur in a region of a high interest rate (expected) and lower monthly payment amount. Therefore, it's the smaller loans with higher interest rates which are the problem in this data.

Another filter for resampling data into a volume is vtkShepardMethod. You may wish to modify the previous C++ example to use this class.

Surfaces from Unorganized Points

In computer graphics applications, surfaces are often represented as three-dimensional unorganized points. Laser and other digitizers are often the source of these point sets. Reconstructing surfaces from point clouds is both computationally and algorithmically challenging. While the methods described previously (Delaunay triangulation and Gaussian splatting) may be used with varying lev-

els of success to reconstruct surfaces from point clouds, VTK has a class designed specifically for this purpose.

vtkSurfaceReconstructionFilter can be used to reconstruct surfaces from point clouds. This filter takes as input a vtkDataSet defining points assumed to lie on the surface of a 3D object. The following script (`VTK/Examples/Modelling/Tcl/reconstructSurface.tcl`) shows how to use the filter. **Figure 10–8** shows the results.

Figure 10–8 Surface reconstruction.

```
vtkProgrammableSource pointSource
  pointSource SetExecuteMethod readPoints
proc readPoints {} {
  set output [pointSource GetPolyDataOutput]
  vtkPoints points
  $output SetPoints points
   set file [open "$VTK_DATA_ROOT/Data/
cactus.3337.pts" r]
  while { [gets $file line] != -1 } {
   scan $line "%s" firstToken
   if { $firstToken == "p" } {
     scan $line "%s %f %f %f" firstToken x y z
     points InsertNextPoint $x $y $z
   }
  }
  points Delete; #okay, reference counting
}

# Construct the surface and create isosurface
vtkSurfaceReconstructionFilter surf
  surf SetInputConnection [pointSource GetOutputPort]
vtkContourFilter cf
  cf SetInputConnection [surf GetOutputPort]
  cf SetValue 0 0.0
vtkReverseSense reverse
   reverse SetInputConnection [cf GetOutputPort]
    reverse ReverseCellsOn
   reverse ReverseNormalsOn
vtkPolyDataMapper map
  map SetInputConnection [reverse GetOutputPort]
  map ScalarVisibilityOff
vtkActor surfaceActor
  surfaceActor SetMapper map
```

The example begins by reading points from a file using vtkProgrammableSource filter. (See "Programmable Filters" on page 419 for more information.) vtkSurfaceReconstructionFilter takes the points and generates a volumetric representation (similar to what vtkGaussianSplatter did in the previous section). The volume is contoured (with an isosurface value=0.0) to generate a surface and vertex normals. Because of the nature of the data, the vertex normals point inward so vtkReverseSense is used to reverse the normals and polygon ordering. (On some systems inward pointing normals will result in black surfaces during rendering.)

The algorithm works reasonably well as long as the points are close enough together. The instance variable SampleSpacing can be set to control the dimensions of the output volume. If SampleSpacing is given a negative value, the algorithm makes a guess at the voxel size. The output volume bounds the input point cloud.

Time Varying Data

11.1 Introduction to temporal support

The visualization toolkit was created for the purpose of allowing people to visualize and thus explore features in data with spatial extent. It allows people to answer questions, such as "Where are the regions of maximum value located within this data?? "What shape and value do they have?" and "How are those shapes distributed throughout?" VTK provides a plethora of techniques for displaying and analyzing data, as it exists at a single moment in time. Exploration of data that has temporal extent is also important. One would also like to answer questions such as. "How do those shapes grow, move and shrink over time?"

That goal is complicated by the fact that VTK represents a point with only X, Y and Z coordinate values. Adding T is impractical because of backward compatibility requirements and the need to conserve RAM in the most common case in which T unimportant. With previous versions of the visualization toolkit, people implemented a variety of workarounds to overcome the basic lack of support for time. For instance, multiple attribute array sets (one set for each time step) were sometimes loaded and filters were told to iterate through the sets.

Creating such workarounds was difficult not only because of the lack of support in VTK but also because of the variety of formats in which time varying data is stored. Some practitioners store an entire dataset in a sequentially named file for each (regularly or irregularly sampled) point in time. Others store just the time varying portions of the data in one or many separate files. Some store the T coordinates alongside the X, Y, and Z coordinates as suggested above, and some store the data in highly compressed encoded formats.

As compute power has grown and become widespread, exploration and analysis of time varying scientific data has become commonplace. Since release 5.2, VTK has included a general-purpose infrastructure for time varying visualization. The infrastructure is not wasteful of memory and is backward compatible. In the common case when time is immaterial, no additional RAM or disk space is consumed, and the majority of filters that are time insensitive did not need any modification. The infrastructure is also opening ended and extensible. In addition to supporting flipbook style anima-

tions, which would allow one to answer the temporal question posed above, it also allows one to programmatically answer quantitative questions such as:

- "At what time do the shapes take on a maximum volume?"
- "At what point do they move most quickly?"
- "What are the average attribute values over a particular region of time?"
- "What does a 2D plot of values for particular elements or locations look like?"

To do so, one finds, or creates a vtkAlgorithm that takes into account the temporal dimension to answer the question, and then builds a pipeline that exercises it. A time-aware filter is one that is capable of: requesting one or more specific time steps from the pipeline behind it, doing some processing once supplied with the requested data objects, and producing an answer (in the form of another data object) for the downstream filters.

The many varieties of temporal representations are facilitated because of the reader abstraction. A reader, as described in Chapter 12, is responsible for reading a file or set of files on the file system, interpreting a specific file format, and producing one or more data objects. A time aware reader is one that additionally tells the pipeline what the available temporal domain is, and is capable of producing an answer (again in the form of a data object) for the specific time (or times) that the downstream pipeline has requested of it.

11.2 VTK's implementation of time support

VTK supports time varying data at the pipeline level. vtkExecutives are the glue that hold neighboring vtkAlgorithms together and thus make up the pipeline. Besides linking Algorithms together, Executives are also responsible for telling each Algorithm exactly what to do. The Executives do so by communicating meta-information, small pieces of data (stored in vtkInformation containers), up and down the pipeline before causing their attached Algorithms to execute. For example, each Algorithm is given a vtkInformation object that specifies where, or what spatial sub domain it is to fill. When doing temporal visualization, Executives also tell each Algorithm when, or at what point in time they are to do so. This each Algorithm can now be given a vtkInformation object that specifies what temporal sub domain that processing is supposed to take place in.

To be exact, the pipeline now supports temporal visualization because it recognizes the following meta-information keys, and understands how and when to transport them and react to their presence in order to drive filter execution.

TIME_RANGE

This key is injected into the pipeline by a reader of time varying data, at the source or beginning of the pipeline. It contains two floating-point numbers, which are the minimum and maximum times that the reader can produce data within, or in other words, the extent of the temporal domain.

TIME_STEPS

When the data produced by the reader is exact at discrete points in time, this key is also injected into the pipeline by a reader of time varying data. It contains any number of floating point numbers which may be regularly or irregularly placed within the temporal domain.

UPDATE_TIME_STEPS

This key is injected into the pipeline at downstream end of the pipeline. It contains one or more floating point numbers that correspond to the set of times that are to be processed by the pipeline update.

DATA_TIME_STEPS

When the update request reaches the reader, it may or may not be able to provide results for exactly that time. For example the renderer may ask for a time that lies between two points in the TIME_STEPS. The reader injects this key into the pipeline to indicate the exact data time that corresponds to the data it produces in response to the request.

CONTINUE_EXECUTING

This flag is injected into the pipeline to cause the pipeline to keep iterating in order to fulfill a set of time requests.

Because time support was added at the pipeline level, one must know something about how the visualization pipeline executes in order to understand the actions that the above meta information cause, and thus understand what VTK's time support can be used for. VTK's standard streaming demand driven pipeline operates in four stages. The same four passes are used for time varying visualization, but they are often (either for a subset of or for the full pipeline) iterated in a loop.

During the first pass, called REQUEST_DATA_OBJECT , each Executive creates an empty DataObject of whatever type is needed for the Algorithm. A vtkJPEGReader for example, produces an empty vtkImageData. When a time aware filter requests multiple time steps from a non-time aware filter upstream, the Executive will change the filter's output type to be a vtkTemporalDataSet. That output acts as a cache for the actual datasets produces for each requested time.

During the second pass, called REQUEST_INFORMATION, filters produce whatever lightweight meta-information they can about the data they are about to create. A vtkJPEGReader would provide an image extent for example. This pass starts at the upstream end and works forward toward the display. It is during this pass when time aware readers are required to inject their TIME_RANGE and TIME_STEPS keys, which downstream filters and the application can use to guide their actions.

During the third pass, called REQUEST_UPDATE_EXTENT, the filters agree, starting at the downstream end and working back toward the reader, what portion of their input will be required to produce the output they are themselves being asked for. It is at this pass that the UPDATE_TIME_STEPS request moves backwards.

During the last pass, called REQUEST_DATA, Algorithms actually do the work requested of them, which means for time varying data, producing data at the time requested and filling in the DATA_TIME_STEPS parameter.

At first this appears to still be a brute force approach. One still makes a flipbook animation by stepping through time, updating the pipeline to draw an image at each time. In older versions of VTK iterating over a loop in which a time parameter was set on the reader and then the display was rendered often did this. In modern VTK this is done similarly. The only difference from the user's standpoint is that the requested time is set on the renderer instead of the reader. However, several details in the implementation make VTK's new time support more efficient, easier to use and more flexible than it was previously.

First, Algorithms are free to request and provide multiple times. This makes it possible for any filter to consider more that one time step together, in effect merging a temporal pipeline. This enables

more advanced time varying visualizations than flip books, such as interpolation between time steps and advanced motion blur like effects (time trails).

Second, the Executive has the ability to automatically iterate portions of the pipeline that are not time aware. This makes it unnecessary for the programmer to explicitly control individual Algorithms in the pipeline. To compute a running average, one would simply set the width or support as a parameter on an averaging filter and then tell the pipeline to execute once. Before this would have been done by explicitly updating the pipeline over multiple passes and at each pass telling the reader exactly what time is required for the active portion of the running average.

Third, the Executive, and even Algorithms themselves, are able to manipulate the meta-information keys, which enable techniques such as temporal shifting, scaling and reversion. These are useful in cases such as normalize data sources to a common frame of reference.

Finally, the pipeline will, and it is possible to manually cause, caching of temporal results, and to do so without keeping all results from the reader in memory simultaneously. Caching can give substantial speedups and makes techniques like comparative visualization of the same pipeline at different points in time effective.

Using time support

The default pipeline created by VTK programs consists of Algorithms connected by vtkStreamingDemandDrivenPipeline Executives. This Executive does not do automatic iteration or temporal caching. Thus the first step in doing temporal analysis with VTK is to replace the default pipeline with a newer Executive class that does. The following code fragment does this. To use it, simply place these two lines at the top of your program, before creating any filters.

```
vtkSmartPointer<vtkCompositeDataPipeline> cdp =
vtkSmartPointer<vtkCompositeDataPipeline>::New();
vtkAlgorithm::SetDefaultExecutivePrototype(cdp);
```

As with any other type of data, the most important step towards using VTK to visualize time varying data is to get the data into a format that the VTK pipeline can process. As Chapter 9 explains, this essentially means finding a reader, which can read the file that you are working with. If the data is time varying, you must also be sure that that the reader knows about the new pipeline features described in (2 above), or in other words is time aware.

There are a growing number of readers in VTK, which are time aware. Examples include (along with subclasses and relatives of the following):

- vtkExodusReader - readers for Sandia National Lab's Exodus file format
- vtkEnsightReader - readers CEI's EnSight file format
- vtkLSDynaReader - reader for Livermore Software Technology Corporation's multiphysics simulation software package files
- vtkXMLReader - readers for Kitware's newer XML based file format

Once you find such a reader, using it then becomes a matter of instantiating the reader, setting a filename, and calling update. You can programmatically get the available temporal domain from the file by calling UpdateInformation on the reader, and can tell it to update at a specific time by calling SetUpdateTimeStep(int port, double time), followed by a call to Update().

The following code segment illustrates how to instantiate a time aware reader and query it for the time domain in a file.

```
vtkSmartPointer<vtkGenericEnSightReader> r =
vtkSmartPointer<vtkGenericEnSightReader>::New();
r->SetCaseFileName("../VTKData/Data/EnSight/naca.bin.case");

// Update meta-data. This reads time information and other meta-data.
r->UpdateInformation();

// The meta-data is in the output information
vtkInformation* outInfo = r->GetExecutive()->GetOutputInformation(0);

if (outInfo.Has(vtkStreamingDemandDrivenPipeline::TIME_STEPS()))
  {
  cout << "Times are:" << endl;
  for(int i=0; i<outInfo-
>Length(vtkStreamingDemandDrivenPipeline::TIME_STEPS()), i++)
    {
   cout << outInfo->Get(vtkStreamingDemandDrivenPipeline::TIME_STEPS(),
i) << endl;
    }
  }
else
  {
  cout << "That file has not time content." << endl;
  }
```

There are a growing number of readers in VTK which are time aware, but there are many more readers that are not. And there are still more file formats for which no reader yet exists. What exactly must a reader do to support temporal visualization? It must do at least two things. It must announce the temporal range that it has data for, and it must respect the time that is requested of it by the pipeline.

Announcing the range happens during the REQUEST_INFORMATION pipeline pass. Do this by populating the TIME_STEPS and TIME_RANGE keys.

```
int vtkTimeAwareReader::RequestInformation(
  vtkInformation* vtkNotUsed(request),
  vtkInformationVector** vtkNotUsed(inputVector),
  vtkInformationVector* outputVector )
{
  vtkInformation* outInfo = outputVector->GetInformationObject(0);

  // Read the time information from the file here.
  // ...

  // Let timeValues be an array of times (type double)
  // nSteps is the number of time steps in the array.
  outInfo->Set(vtkStreamingDemandDrivenPipeline::TIME_STEPS(),
timeValue, nSteps);
  double timeRange[2];
```

```
  timeRange[0] = timeValue[0];
  timeRange[1] = timeValue[nSteps - 1];
  outInfo->Set(vtkStreamingDemandDrivenPipeline::TIME_RANGE(),
timeRange, 2);

  return 1;
}
```

The reader finds out during the REQUEST_DATA pass, what time or times it is being asked of at present and responds accordingly. The time request comes in the UPDATE_TIME_STEPS key.

```
int vtkTimeAwareReader::RequestData(
  vtkInformation* vtkNotUsed(request),
  vtkInformationVector** vtkNotUsed(inputVector),
  vtkInformationVector* outputVector )
{
  vtkInformation* outInfo = outputVector->GetInformationObject(0);

  if (outInfo->Has(
vtkStreamingDemandDrivenPipeline::UPDATE_TIME_STEPS()))
    {
    // Get the requested time steps.
    int numRequestedTimeSteps = outInfo-
>Length(vtkStreamingDemandDrivenPipeline::UPDATE_TIME_STEPS());
    double* requestedTimeValues = outInfo-
>Get(vtkStreamingDemandDrivenPipeline::UPDATE_TIME_STEPS());

    double firstTime = requestedTimeValues[0];
    double lastTime = requestedTimeValues[numRequestedTimeSteps-1];
    // ...
    }

  // ..

  return 1;
}
```

The reader is free to interpret this request however it likes. Most use a floor function to find the nearest lesser exact time value for which they have data. For this reason it is useful to provide the exact time the data produced by the reader actually corresponds to. Placing the DATA_TIME_STEPS key in the output data object does this.

```
double myAnswerTime = this->Floor_in_timeValue(firstTime);
vtkDataObject *output= outInfo->Get(vtkDataObject::DATA_OBJECT());
output->GetInformation()->Set(vtkDataObject::DATA_TIME_STEPS(),
&myAnswerTime, 1);
```

Many readers can satisfy only a single time request in any given call. In this case they are free to produce any particular vtkDataSet subclass. They typically only honor the first requested value as in the preceding code. Other readers can efficiently satisfy multiple time requests. An example might be a

reader for a file format the stores only changed values in subsequent time steps. In that case shallow copies of the constant portions of the data are effective. When the reader can provide data at multiple times, it must produce a vtkTemporalDataSet and fill it with the data for each answer. Here is how a filter would create a temporal dataset that has data at times 0.1 and 0.3.

```
vtkSmartPointer<vtkTemporalDataSet>tds =
vtkSmartPointer<vtkTemporalDataSet>::New();

vtkSmartPointer<vtkPolyData> pd0 = vtkSmartPointer<vtkPolyData>::New();
pd0->GetInformation()->Append(vtkDataObject::DATA_TIME_STEPS(), 0.1);

tds->SetTimeStep(0, pd0);

vtkSmartPointer<vtkPolyData> pd1 = vtkSmartPointer<vtkPolyData>::New();
pd1->GetInformation()->Append(vtkDataObject::DATA_TIME_STEPS(), 0.3);

tds->SetTimeStep(1, pd1);

4) Time aware filters

(Time aware filters using)
```

There are also a growing number of time aware filters in VTK. The temporal statistics filter is an example. It computes statistics such as the average, minimum, and maximum values as well as the standard deviation of, all attribute values for every point and cell in the input data over all time steps. For the most part, given that you are using the proper Executive and have a time aware source or reader somewhere in the pipeline, using a time aware filter is no different than using any standard filter. Simply set up the pipeline and call update. The following code illustrates.

```
vtkSmartPointer<vtkTemporalStatistics> ts =
vtkSmartPointer<vtkTemporalStatistics>::New()
ts->SetInputConnection(r->GetOutputPort())
ts->Update()

cout
  << ts->GetOutput()->GetBlock(0)->GetPointData()->GetArray(1)-
>GetName()
  << endl;
cout
  << ts->GetOutput()->GetBlock(0)->GetPointData()->GetArray(1)-
>GetTuple1(0)
  << endl;

(Time aware filters creating)
```

Although the number of time aware filters in VTK is growing, it will never cover every possible temporal analysis technique. When you find that the toolkit lacks a technique that you need, you can write a new filter.

A time aware filter must be able to cooperate with the Executive in order to manipulate the temporal dimension in order to do its work. For example, the temporal statistics filter examines all time

steps on its input and summarizes the information. In doing so, it removes time from consideration from downstream filters. A graphing filter that plots value changes over time does the same. The output graph, which has time along the X-axis, is "timeless" and does not itself change as time moves. Filters that act like that should remove the TIME keys from their output in the REQUEST_INFORMATION pass.

```
int vtkTemporalStatistics::RequestInformation(
  vtkInformation *vtkNotUsed(request),
  vtkInformationVector **vtkNotUsed(inputVector),
  vtkInformationVector *outputVector)
{
  vtkInformation *outInfo = outputVector->GetInformationObject(0);

  // The output data of this filter has no time associated with it.  It
is the
  // result of computations that happen over all time.
  outInfo->Remove(vtkStreamingDemandDrivenPipeline::TIME_STEPS());
  outInfo->Remove(vtkStreamingDemandDrivenPipeline::TIME_RANGE());

  return 1;
}
```

The temporal statistics filter produces a single value, but it needs to ask its own input to produce all of the time steps that it can. It populates the UPDATE_TIME_STEPS key to ask the input filter what times to produce data for. Note, this filter only needs to examine one time step at a time, in effect streaming time as it aggregates results. Thus in this example we ask for only the next time step. Other filters may request more than one time step, or all of them, but should be careful not to overrun memory when doing so.

```
int vtkTemporalStatistics::RequestUpdateExtent(
   vtkInformation *vtkNotUsed(request),
   vtkInformationVector **inputVector,
   vtkInformationVector *vtkNotUsed(outputVector))
{
  vtkInformation *inInfo = inputVector[0]->GetInformationObject(0);

  // The RequestData method will tell the pipeline Executive to iterate
the
  // upstream pipeline to get each time step in order.  On every
iteration,
  // this method will be called first which gives this filter the
opportunity
  // to ask for the next  time step.
  double *inTimes = inInfo-
>Get(vtkStreamingDemandDrivenPipeline::TIME_STEPS());
  if (inTimes)
    {
    inInfo->Set(vtkStreamingDemandDrivenPipeline::UPDATE_TIME_STEPS(),
                        &inTimes[this->CurrentTimeIndex], 1);
    }
```

```
    return 1;
  }
```

This filter examines one time step at a time, so it needs to iterate over all the time steps to produce the correct result. The application does not have to do the iteration for us, because the filter can tell the Executive to do it on its own. It sets the CONTINUE_EXECUTING() flag to make the Executive loop. On the first call, the filter sets up the loop and set the flag. That causes the REQUEST_UPDATE_EXTENT and REQUEST_DATA passes to happen continuously until the filter decides to remove the flag. At each iteration, the filter asks for a different time step (see RequestUpdateExtent above). After examining all time steps, it clears the flag. At this point the output will have the computed overall statistics.

```
int vtkTemporalStatistics::RequestData(vtkInformation *request,
  vtkInformationVector **inputVector,
  vtkInformationVector *outputVector)
{
  vtkInformation *inInfo = inputVector[0]->GetInformationObject(0);
  vtkInformation *outInfo = outputVector->GetInformationObject(0);

  vtkDataObject *input = vtkDataObject::GetData(inInfo);
  vtkDataObject *output = vtkDataObject::GetData(outInfo);

  if (this->CurrentTimeIndex == 0)
    {
    // First execution, initialize arrays.
    this->InitializeStatistics(input, output);
    }
  else
    {
    // Subsequent execution, accumulate new data.
    this->AccumulateStatistics(input, output);
    }

  this->CurrentTimeIndex++;

  if (  this->CurrentTimeIndex
        < inInfo-
>Length(vtkStreamingDemandDrivenPipeline::TIME_STEPS()))
    {
    // There is still more to do.
    request-
>Set(vtkStreamingDemandDrivenPipeline::CONTINUE_EXECUTING(), 1);
    }
  else
    {
    // We are done.  Finish up.
    this->PostExecute(input, output);
    request-
>Remove(vtkStreamingDemandDrivenPipeline::CONTINUE_EXECUTING());
```

```
      this->CurrentTimeIndex = 0;
      }

    return 1;
  }
```

In the previous example, the filter was written to operate by looking at one time step at a time. For other operation, that may not be practical, geometric interpolation for example requires two time steps. This example demonstrates how a filter can request multiple time steps simultaneously and process them together. To request multiple time steps, you set UPDATE_TIME_STEPS to contain more than one value during the REQUEST_UPDATE_EXTENT pass.

```
int vtkSimpleTemporalInterpolator::RequestUpdateExtent (
   vtkInformation * vtkNotUsed(request),
   vtkInformationVector **inputVector,
   vtkInformationVector *outputVector)
{
  // get the info objects
  vtkInformation* outInfo = outputVector->GetInformationObject(0);
  vtkInformation *inInfo = inputVector[0]->GetInformationObject(0);

  // Find the time step requested by downstream
  if (outInfo-
>Has(vtkStreamingDemandDrivenPipeline::UPDATE_TIME_STEPS()))
    {
    if (outInfo-
>Length(vtkStreamingDemandDrivenPipeline::UPDATE_TIME_STEPS()) != 1)
      {
      vtkErrorMacro("This filter can only handle 1 time request");
      return 0;
      }
    upTime =
      outInfo-
>Get(vtkStreamingDemandDrivenPipeline::UPDATE_TIME_STEPS())[0];

    double inUpTimes[2];
// Find two time steps that surround upTime here and set inUpTimes
// This requests two time steps from upstream.

    inInfo->Set(vtkStreamingDemandDrivenPipeline::UPDATE_TIME_STEPS(),
                        inUpTimes, 2);
    }

  return 1;
}
```

Now REQUEST_DATA will be called only once, but when it does it will be given a temporal data set which contains two time steps. These can be extracted and processed as in the following:

```
int vtkSimpleTemporalInterpolator::RequestData(
   vtkInformation *vtkNotUsed(request),
```

```
    vtkInformationVector **inputVector,
    vtkInformationVector *outputVector)
{
  vtkInformation *inInfo = inputVector[0]->GetInformationObject(0);
  vtkInformation *outInfo = outputVector->GetInformationObject(0);

  vtkTemporalDataSet *inData = vtkTemporalDataSet::SafeDownCast(
    inInfo->Get(vtkDataObject::DATA_OBJECT()));
  vtkTemporalDataSet *outData = vtkTemporalDataSet::SafeDownCast(
    outInfo->Get(vtkDataObject::DATA_OBJECT()));

  // get the input times
  double *inTimes = inData->GetInformation()-
>Get(vtkDataObject::DATA_TIME_STEPS());
  int numInTimes = inData->GetInformation()-
>Length(vtkDataObject::DATA_TIME_STEPS());

  // get the requested update time
  upTime =
    outInfo-
>Get(vtkStreamingDemandDrivenPipeline::UPDATE_TIME_STEPS())[0];

  vtkDataObject *in0 = inData->GetTimeStep(0);
  vtkDataObject *in1 = inData->GetTimeStep(1);

  // Interpolate in0 and in1 at upTime and produce outData here.

  // set the resulting time
  outData->GetInformation()->Set(vtkDataObject::DATA_TIME_STEPS(),
     upTime, 1);

  return 1;
}
```

Chapter 12

Reading and Writing Data

In this chapter we briefly describe various ways to read, write, import, and export data. Readers ingest a single dataset, while importers create an entire scene, which may include one or more datasets, actors, lights, cameras, and so on. Writers output a single dataset to disk (or stream), and exporters output an entire scene. In some cases, you may want to interface to data that is not in standard VTK format, or in any other common format that VTK supports. In such circumstances, you may wish to treat data as field data, and convert it in the visualization pipeline into datasets that the standard visualization techniques can properly handle.

12.1 Readers

We saw in "Reader Source Object" on page 44 how to use a reader to bring data into the visualization pipeline. Using a similar approach, we can read many other types of data. Using a reader involves instantiating the reader, supplying a filename, and calling Update() somewhere down the pipeline.

There are many different readers in the VTK library, all of which exist to read files and produce data structures that can be processed and visualized by the rest of the visualization pipeline. A reader then, is any vtkAlgorithm, which does not require input connections and which knows how to read files to produce vtkDataObjects.

There are many different readers in VTK because there are many important file formats for scientific data. The different file formats exist to make permanent different varieties of data such as structured, unstructured, polygonal, tabular, or graph. As a user of VTK, an important task is to determine what VTK data structure corresponds to the data of interest to you and then to find a reader that reads in the files you work with to produce that structure. This section introduces some of the available readers.

There are some points to make note of before diving into the list of readers. For all VTK data structure types there exists one or two VTK native reader classes. These classes were written in concert with developing or extending the corresponding data type. The older native reader class reads

files with the ".vtk" extension, and the newer reads XML based files with the ".vt?" extension (where ? describes the type). Both old and new formats support writing data in text or binary formats. The newer format is more involved, but it fully supports the most recent vtk features including named arrays, 32 bit / 64 bit encoding, streamed processing and the all of the latest data structures. Both formats have parallel processing extensions, which are implemented with meta files which refer to external serial files that are meant to be read independently. See "VTK File Formats" on page 469., for details of the native file formats.

This chapter lists the VTK native readers for each data type as well as a selection of the readers that interface with the more well known third party file formats and produce that type.

Finally note that, if a suitable reader does not exist one can write one in C++, or use the techniques described in"Working With Field Data" on page 249 to coerce the output of the most generic reader, vtkProgrammableDataObjectSource, into the proper data type.

Data Object Readers

- vtkProgrammableDataObjectSource - an algorithm that executes a user specified function to produce a vtkDataObject.. The user specified function can be written to read in any particular file format, or procedurally generate data without reading any file.
- vtkGenericDataObjectReader - read a ".vtk" file, the legacy file format for all of VTK's data structures and populate a vtkDataObject or the most specific subclass thereof with the structure defined in the file. This reader will produce vtkTable for example, if the .vtk file contains Tabular Data, and vtkUnstructuredGrid if the chosen .vtk file contains an Unstructured Grid. This class reads the header information to find out what type of data is in the file and then delegates the rest of the processing to one of the more specific classes described below.
- vtkDataObjectReader - read a ".vtk" file and populate a DataObject with Field associated arrays. This differs from vtkGenericDataObjectReader in that it will not produce the specific data structure best suited to the contents of the file and instead always produces the most general one, vtkDataObject.

Data Set Readers

These readers produce generic vtkDataSet as output. Typically, the reader requires an Update() invocation to determine what kind of concrete vtkDataSet subclass is created.

- vtkDataSetReader - like vtkDataObjectReader, but this class is limited to the more common vtkDataSet subclasses.
- vtkPDataSetReader - like vtkDataSetReader, but reads parallel vtk (.pvtk) format files, which are meta files that references several legacy .vtk files which are meant to be processed by different processors simultaneously
- vtkGenericEnSightReader (and subclasses) - read EnSight files

Image and Volume Readers

- vtkStructuredPointsReader - reads ".vtk" legacy format files containing image data
- vtkXMLImageDataReader - reads ".vti" files, one of the newer XML based VTK file formats

- vtkXMLPImageDataReader - reads ".pvti" XML based parallel partitioned files that reference individual ".vti" files
- vtkImageReader - reads raw image data. Since the file format is a raw dump, you must specify the image extent, byte ordering, scalar type etc in order to get the correct result from the file.
- vtkDICOMImageReader - reads DICOM (Digital Imaging and Communications in Medicine) images
- vtkGESignaReader - reads GE Signa Imaging files
- vtkMINCImageReader - a netCDF based reader for MINC (Montreal Neurological Institute Center) files
- vtkSTLReader - read stereo-lithography files
- vtkJPEGReader - reads JPEG files
- vtkPNMReader - reads PNM files
- vtkTIFFReader - reads TIFF files

Rectilinear Grid Readers

- vtkRectilinearGridReader - reads ".vtk" legacy format files containing rectilinear grid data
- vtkXMLRectilinearGridReader - reads ".vtr" XML based VTK files
- vtkXMLPRectilinearGridDataReader - reads ".pvtr" XML based parallel partitioned files that reference individual ".vtr" files
- vtkSESAMEReader - reads Los Alamos National Lab Equation of state data base files (http://t1web.lanl.gov/doc/SESAME_3Ddatabase_1992.html)

Structured Grid Readers

- vtkStructuredGridReader - reads ".vtk" legacy format files containing structured grid data
- vtkXMLStructuredGridReader - reads ".vts" XML based VTK files
- vtkXMLPStructuredGridReader - reads ".pvts" XML based parallel partitioned files that reference individual ".vts" files
- vtkPLOT3DReader - reads NASA PLOT3D structured CFD computation datasets (http://people.nas.nasa.gov/~rogers/plot3d/intro.html)

Polygonal Data Readers

- vtkPolyDataReader - reads ".vtk" legacy format files containing polygonal data
- vtkXMLPolyDataReader - reads ".vtp" XML based VTK files
- vtkXMLPPolyDataReader - reads ".pvtp" XML based parallel partitioned files that reference individual ".vtp" files
- vtkOBJReader - reads Wavefront .obj files
- vtkPLYReader - reads Stanford University .ply files
- vtkParticleReader - reads particle with scalar data x,y,z,value in ascii or binary format

- vtkSimplePointsReader - example reader, reads points written as X Y Z floating point form and produce edges and vtk_vertex cells in vtkPolyData (PD)
- vtkSLACParticleReader - reads netCDF files written with conventions for Stanford Linear Accelerator Center processing tools. Output corresponds to particles in space. This differs from vtkNetCDFReader in that although both understand the NetCDF format, this reader adds conventions suited to a particular area of scientific research.

Unstructured Grid Readers

- vtkUnstructuredGridReader - reads ".vtk" legacy format files containing unstructured grid data
- vtkXMLUnstructuredGridReader - reads ".vtu" XML based VTK files
- vtkXMLPUnstructuredGridReader - reads ".pvtu" XML based parallel partitioned files that reference individual ".vtu" files
- vtkCosmoReader - read Los Alamos National Lab cosmology binary data format files
- vtkExodusReader - read Sandia National Lab Exodus format files
- vtkPExodusReader - parallel processing specialization of vtkExodusReader in which each processor reads its own portion of the blocks from the file simultaneously
- vtkChacoReader - reads Sandia Chaco graph package format files and produces UnstructuredGrid data
- vtkPChacoReader - reads Sandia Chaco graph format packages on one processor and internally distributes portions of the data to other parallel processors

Graph Readers

- vtkGraphReader - read ".vtk" legacy format files containing general Graph data
- vtkTreeReader - read ".vtk" legacy format files to produce more specialized Trees
- vtkXMLTreeReader - reads XML based VTK files
- vtkChacoGraphReader - reads a file written in the Sandia Chaco graph package format. This differs from vtkChacoReader in that it produces a vtkUndirectedGraph instead of the more spatially oriented vtkUnstructuredGrid.
- vtkPBGLGraphSQLReader - read vertex and edge tables from an Parallel Boost Graph Library SQL database
- vtkSQLGraphReader - read vertex and edge tables from an SQL database
- vtkRISReader - read a RIS format bibliographic citation file and produce a vtkTable (TA)

Table Readers

- vtkTableReader - - read ".vtk" legacy format files containing general tabular data
- vtkDelimitedTextReader - read text files in which newlines separate each row and a single user specified delimiter character, for example, comma, tab or space, separates columns
- vtkFixedWidthTextReader - read text files in which newlines separate each row and where each column has a fixed width

- vtkISIReader - read bibliographic citation records in ISI format

Composite Data Readers

vtkCompositeDataSet's concrete subclasses vtkMultiPieceDataSet, vtkHierarchicalBoxDataSet, and vtkMultiBlockDataSet are VTK's way of representing compound data objects, or data objects which contain other data objects. These structures are useful in parallel processing, for adaptively refined simulations and to represent hierarchical relationships between related parts. Several readers import complex data and produce composite data outputs. The contents of the composite data may be any or all of the above atomic types, and/or additional composite data objects.

- vtkXMLCompositeDataReader - and its subclasses read XML based VTK files. The standard extensions for these files include ".vtm", ".vth" and ".vtb".
- vtkExodusIIReader - read Sandia Exodus2 format files and directly produce MultiBlock datasets. This differs from vtkExodusReader in that the output is not converted to a single vtkUnstructuredGrid, which can potentially conserve memory when the data is regular.
- vtkPExodusIIReader- parallel processing specialization of the preceding each processor independently and simultaneously reads its own subset of the blocks
- vtkOpenFOAMReader - read file written in OpenFOAM (computational fluid dynamics) format

12.2 Writers

Writers output vtkDataObjects to the file system. A writer is any vtkAlgorithm which takes in a vtkDataObject, usually one produced by the vtkAlgorithm connected to the writer's input, and writes it to the file system in some standard format. There are many different writers in VTK because there are many important file formats.

Typically, using a writer involves setting an input and specifying and output file name (or sometimes names) as shown in the following.

```
vtkPolyDataWriter writer
    writer SetInput [aFilter GetOutput]
    writer SetFileName "outFile.vtk"
    writer SetFileTypeToBinary
    writer Write
```

The legacy VTK writers offer you the option of writing binary (SetFileTypeToBinary()) or ASCII (SetFileTypeToASCII()) files. (Note: binary files may not be transportable across computers. VTK takes care of swapping bytes, but does not handle transport between 64-bit and 32-bit computers.)

The VTK XML writers also allow you to write in binary (SetDataModeToBinary()) or ASCII (SetDataModeToAscii()); and appended binary mode is also available (SetDataModeToAppended()). The VTK XML readers and writers do handle transporting data between 32-bit and 64-bit computers in addition to taking care of byte swapping.

The following is a list of available writers.

Data Object Writers

- vtkGenericDataObjectWriter - Writes any type of vtkDataObject to file in the legacy ".vtk" file format.
- vtkDataObjectWriter -- Write only the vtkDataObject's field data in legacy ".vtk" file format.

Data Set Writers

- vtkDataSetWriter - Writes any type of vtkDataSet to file in legacy ".vtk" file format
- vtkPDataSetWriter - Writes any type of vtkDataSet to file in legacy ".pvtk" parallel partitioned file format
- vtkXMLDataSetWriters - Writes any type of vtkDataSet to file in the newer XML based ".vt?" format.

Image and Volume Writers

- vtkStructuredPointsWriter - Write image data in legacy ".vtk" format
- vtkPImageWriter - A parallel processing specialization of the preceding
- vtkXMLImageDataWriter - Write image data in XML based ".vti" format
- vtkMINCImageWriter - A netCDF based writer for MINC (Montreal Neurological Institute Center) files
- vtkPostScriptWriter - write image into post script format
- vtkJPEGWriter - write into JPEG format
- vtkPNMWriter - write into PNM format
- vtkTIFFWriter - write into TIFF format

Rectilinear Grid Writers

- vtkRectilinearGridWriter - Write rectilinear grid in legacy ".vtk" format
- vtkXMLRectilinearGridWriter - Write rectilinear grid in XML based ".vtr" format
- vtkXMLPRectilinearGridWriter - A parallel processing specialization of the preceding

Structured Grid Writers

- vtkStructuredGridWriter - Write structured grid in legacy ".vtk" format
- vtkXMLStructuredGridWriter - Write structured grid in XML based ".vts" format
- vtkXMLPStructuredGridWriter - A parallel processing specialization of the preceding

Polygonal Data Writers

- vtkPolyDataWriter - Write polygonal data in legacy ".vtk" format
- vtkXMLPolyDataWriter - Write polygonal data in XML based ".vtp" format

- vtkXMLPPolyDataWriter - A parallel processing specialization of the preceding
- vtkSTLWriter - Write stereo-lithography files
- vtkIVWriter - Write into OpenInventor 2.0 format
- vtkPLYWriter - Writer Stanford University ".ply" files

Unstructured Grid Writers

- vtkUnstructuredGridWriter - Write unstructured data in legacy ".vtk" format
- vtkXMLUnstructuredGridWriter - Write unstructured data in XML based ".vtu" format
- vtkXMLPUnstructuredGridWriter - A parallel processing specialization of the preceding
- vtkEnSightWriter - Write vtk unstructured grid data as an EnSight file

Graph Writers

- vtkGraphWriter - write vtkGraph data to a file in legacy ".vtk" format
- vtkTreeWriter - write vtkTree data to a file in legacy ".vtk" format

Table Writers

- vtkTableWriter - write vtkTable data to file in legacy ".vtk" format

Composite Data Writers

- vtkXMLCompositeDataWriter (and its subclasses) - writers for composite data structures including hierarchical box (multires image data) and multi-block (related datasets) data types
- vtkExodusIIWriter - Write composite data in Exodus II format

12.3 Importers

Importers accept data files that contain multiple datasets and/or the objects that compose a scene (i.e., lights, cameras, actors, properties, transformation matrices, etc.). Importers will either generate an instance of vtkRenderWindow and/or vtkRenderer, or you can specify them. If specified, the importer will create lights, cameras, actors, and so on, and place them into the specified instance(s). Otherwise, it will create instances of vtkRenderer and vtkRenderWindow, as necessary. The following example shows how to use an instance of vtkImporter (in this case a vtk3DSImporter—imports 3D Studio files). This Tcl script was taken from `VTK/Examples/IO/Tcl/flamingo.tcl` (see **Figure 12–1**).

Figure 12–1 Importing a file.

```
vtk3DSImporter importer
 importer ComputeNormalsOn
 importer SetFileName \
     "$VTK_DATA_ROOT/Data/iflamigm.3ds"
 importer Read

set renWin [importer GetRenderWindow]
vtkRenderWindowInteractor iren
 iren SetRenderWindow $renWin
```

The *Visualization Toolkit* supports the following importers. (Note that the superclass vtkImporter is available for developing new subclasses.)

- vtk3DSImporter — import 3D Studio files
- vtkVRMLImporter — import VRML version 2.0 files

12.4 Exporters

Exporters output scenes in various formats. Instances of vtkExporter accept an instance of vtkRenderWindow, and write out the graphics objects supported by the exported format.

```
vtkRIBExporter exporter
    exporter SetRenderWindow renWin
    exporter SetFilePrefix "anExportedFile"
    exporter Write
```

The vtkRIBExporter shown above writes out multiple files in RenderMan format. The FilePrefix instance variable is used to write one or more files (geometry and texture map(s), if any).

The *Visualization Toolkit* supports the following exporters.

- vtkGL2PSExporter — export a scene as a PostScript file using GL2PS
- vtkIVExporter — export an Inventor scene graph
- vtkOBJExporter — export a Wavefront `.obj` files
- vtkOOGLExporter — export a scene into GeomView OOGL format
- vtkRIBExporter — export RenderMan files
- vtkVRMLExporter — export VRML version 2.0 files
- vtkPOVExporter - export into file format for the Persistence of Vision Raytracer (www.povray.org)
- vtkX3DExporter - export into X3D format (an XML based 3d scene format similar to VRML)

12.5 Creating Hardcopy

Creating informative images is a primary objective of VTK, and to document what you've done, saving images and series of images (i.e., animations) is important. This section describes various ways to create graphical output.

Saving Images

The simplest way to save images is to use the vtkWindowToImageFilter which grabs the output buffer of the render window and converts it into vtkImageData. This image can then be saved using one of the image writers (see "Writers" on page 164 for more information). Here is an example

```
vtkWindowToImageFilter w2i
 w2i SetInput renWin

vtkJPEGWriter writer
 writer SetInput [w2i GetOutput]
 writer SetFileName "DelMesh.jpg"
 writer Write
```

Note that it is possible to use the off-screen mode of the render window when saving an image. The off-screen mode can be turned on by setting OffScreenRenderingOn() for the render window.

Saving Large (High-Resolution) Images

The images saved via screen capture or by saving the render window vary greatly in quality depending on the graphics hardware and screen resolution supported on your computer. To improve the quality of your images, there are two approaches that you can try. The first approach allows you to use the imaging pipeline to render pieces of your image and then combine them into a very high-resolution final image. We'll refer to this as tiled imaging. The second approach requires external software to perform high resolution rendering. We'll refer to this as the RenderMan solution.

Tiled Rendering. Often we want to save an image of resolution greater than the resolution of the computer hardware. For example, generating an image of 4000 x 4000 pixels is not easy on a 1280x1024 computer display. The *Visualization Toolkit* makes this trivial with the class vtkRenderLargeImage. This class breaks up the rendering process into separate pieces, each piece containing just a portion of the final image. The pieces are assembled into a final image, which can be saved to file using one of the VTK image writers. Here's how it works (Tcl script taken from `VTK/Examples/Rendering/Tcl/RenderLargeImage.tcl`).

```
vtkRenderLargeImage renderLarge
 renderLarge SetInput ren
 renderLarge SetMagnification 4

vtkTIFFWriter writer
 writer SetInputConnection [renderLarge GetOutputPort]
 writer SetFileName largeImage.tif
 writer Write
```

The Magnification instance variable (an integer value) controls how much to magnify the input renderer's current image. If the renderer's image size is (400,400) and the magnification factor is 5, the final image will be of resolution (2000,2000). In this example, the resulting image is written to a file with an instance of vtkTIFFWriter. Of course, other writer types could be used.

RenderMan. RenderMan is a high-quality software rendering system currently sold by Pixar, the graphics animation house that created the famous *Toy Story* movie. RenderMan is a commercial package. A license for a single computer RenderMan rendering plugin for Maya costs $995 at the time of this writing.. Fortunately, there is at least one modestly priced (or free system if you're non-commercial) RenderMan compatible system that you can download and use: Pixie (Blue Moon Ray Tracer). Pixie is slower than RenderMan, but it also offers several features that RenderMan does not.

In an earlier section ("Exporters" on page 166) we saw how to export a RenderMan `.rib` file (and associated textures). You can adjust the size of the image RenderMan produces using the SetSize() method in the vtkRIBExporter. This method adds a line to the rib file that causes RenderMan (or RenderMan compatible system such as Pixie) to create an output TIFF image of size (`xres`, `yres`) pixels.

12.6 Creating Movie Files

In addition to writing a series of images, VTK also has three classes that allow you to write movie files directly: vtkAVIWriter, vtkFFMPEGWriter and vtkMPEG2Writer. Both are subclasses of vtkGenericMovieWriter. vtkAVIWriter uses Microsoft's multimedia API to create movie files, and is thus only available on Windows machines. The FFMPEG and MPEG2 media formats are available on all platforms, but because of license incompatibilities are provided only in source code format, and not within the VTK library itself. To use either of these interface classes you must manually download and compile the library on your machine and then configure and build VTK to link to them. Instructions for doing so and the library source code are available at http://www.vtk.org/VTK/resources/software.html#addons. Both of these classes take a 2D vtkImageData as input – often the output of the vtkWindowToImageFilter. The important methods in these classes are as follows.

- Start — Call this method once to start writing a movie file.
- Write— Call this method once per frame added to the movie file.
- End — Call this method once to end the writing process.

Similar to the other writers, the movie writers also have SetInput and SetFileName methods. Example Tcl code for writing a movie file with 100 frames follows.

```
vtkMPEG2Writer writer
  writer SetInput [aFilter GetOutput]
  writer SetFileName "movie.mpg"
  writer Start

for {set i 0} {$i < 100} {incr i} {
  writer Write

  # modify input to create next frame of movie
  ...
}

writer End
```

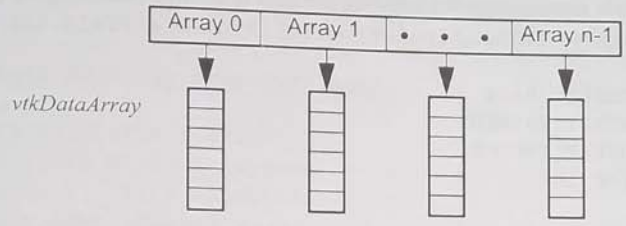


Figure 12–2 Structure of field data—an array of arrays. Each array may be of a different native data type and may have one or more components.

12.7 Working With Field Data

Many times data is organized in a form different from that found in VTK. For example, your data may be tabular, or possibly even higher-dimensional. And sometimes you'd like to be able to rearrange your data, assigning some data as scalars, some as point coordinates, and some as other attribute data. In such situations VTK's field data, and the filters that allow you to manipulate field data, are essential.

To introduce this topic a concrete example is useful. In the previous chapter ("Gaussian Splatting" on page 156) we saw an example that required writing custom code to read a tabular data file, then extracting specified data to form points and scalars (look at the function ReadFinancialData() found in `VTK/Examples/Modelling/Cxx/finance.cxx`). While this works fine for this example, it does require a lot of work and is not very flexible. In the following example we'll do the same thing using field data.

The data is in the following tabular format.

```
NUMBER_POINTS 3188
TIME_LATE
 29.14  0.00  0.00 11.71  0.00  0.00  0.00  0.00
 0.00 29.14  0.00  0.00  0.00  0.00  0.00  0.00
....
MONTHLY_PAYMENT
 7.26  5.27  8.01 16.84  8.21 15.75 10.62 15.47
 5.63  9.50 15.29 15.65 11.51 11.21 10.33 10.78
....
```

This format repeats for each of the following fields: time late in paying the loan (`TIME_LATE`); the monthly payment of the loan (`MONTHLY_PAYMENT`); the principal left on the loan (`UNPAID_PRINCIPAL`); the original amount of the loan (`LOAN_AMOUNT`); the interest rate on the loan (`INTEREST_RATE`); and the monthly income of the borrower (`MONTHLY_INCOME`). These six fields form a matrix of 3188 rows and 6 columns.

We start by parsing the data file. The class vtkProgrammableDataObjectSource is useful for defining special input methods without having to modify VTK. All we need to do is to define a function that parses the file and puts the results into a VTK data object. (Recall that vtkDataObject is the

most general form of data representation.) Reading the data is the most challenging part of this example, found in `VTK/Examples/DataManipulation/Tcl/FinancialField.tcl`.

```
set xAxis INTEREST_RATE
set yAxis MONTHLY_PAYMENT
set zAxis MONTHLY_INCOME
set scalar TIME_LATE

# Parse an ascii file and manually create a field. Then construct a
# dataset from the field.
vtkProgrammableDataObjectSource dos
  dos SetExecuteMethod parseFile

proc parseFile {} {
  global VTK_DATA_ROOT

  # Use Tcl to read an ascii file
  set file [open "$VTK_DATA_ROOT/Data/financial.txt" r]
  set line [gets $file]
  scan $line "%*s %d" numPts
  set numLines [expr (($numPts - 1) / 8) + 1 ]

  # Get the data object's field data and allocate
  # room for 4 fields
  set fieldData [[dos GetOutput] GetFieldData]
  $fieldData AllocateArrays 4

  # read TIME_LATE - dependent variable
  # search the file until an array called TIME_LATE is found
  while { [gets $file arrayName] == 0 } {}
  # Create the corresponding float array
  vtkFloatArray timeLate
  timeLate SetName TIME_LATE
  # Read the values
  for {set i 0} {$i < $numLines} {incr i} {
   set line [gets $file]
   set m [scan $line "%f %f %f %f %f %f %f %f" \
  v(0) v(1) v(2) v(3) v(4) v(5) v(6) v(7)]
   for {set j 0} {$j < $m} {incr j} {timeLate InsertNextValue $v($j)}
  }
  # Add the array
  $fieldData AddArray timeLate

  # MONTHLY_PAYMENT - independent variable
  while { [gets $file arrayName] == 0 } {}
  vtkFloatArray monthlyPayment
  monthlyPayment SetName MONTHLY_PAYMENT
  for {set i 0} {$i < $numLines} {incr i} {
   set line [gets $file]
   set m [scan $line "%f %f %f %f %f %f %f %f" \
  v(0) v(1) v(2) v(3) v(4) v(5) v(6) v(7)]
```

```
    for {set j 0} {$j < $m} {incr j} {monthlyPayment InsertNextValue
$v($j)}
  }
  $fieldData AddArray monthlyPayment

  # UNPAID_PRINCIPLE - skip
  while { [gets $file arrayName] == 0 } {}
  for {set i 0} {$i < $numLines} {incr i} {
   set line [gets $file]
  }

  # LOAN_AMOUNT - skip
  while { [gets $file arrayName] == 0 } {}
  for {set i 0} {$i < $numLines} {incr i} {
   set line [gets $file]
  }

  # INTEREST_RATE - independent variable
  while { [gets $file arrayName] == 0 } {}
  vtkFloatArray interestRate
  interestRate SetName INTEREST_RATE
  for {set i 0} {$i < $numLines} {incr i} {
   set line [gets $file]
   set m [scan $line "%f %f %f %f %f %f %f %f" \
  v(0) v(1) v(2) v(3) v(4) v(5) v(6) v(7)]
   for {set j 0} {$j < $m} {incr j} {interestRate InsertNextValue $v($j)}
  }
  $fieldData AddArray interestRate

  # MONTHLY_INCOME - independent variable
  while { [gets $file arrayName] == 0 } {}
  vtkIntArray monthlyIncome
  monthlyIncome SetName MONTHLY_INCOME
  for {set i 0} {$i < $numLines} {incr i} {
   set line [gets $file]
   set m [scan $line "%d %d %d %d %d %d %d %d" \
  v(0) v(1) v(2) v(3) v(4) v(5) v(6) v(7)]
   for {set j 0} {$j < $m} {incr j} {monthlyIncome InsertNextValue $v($j)}
  }
  $fieldData AddArray monthlyIncome
}
```

Now that we've read the data, we have to rearrange the field data contained by the output vtkDataObject into a form suitable for processing by the visualization pipeline (i.e., the vtkGaussianSplatter). This means creating a subclass of vtkDataSet, since vtkGaussianSplatter takes an instance of vtkDataSet as input. There are two steps required. First, the filter vtkDataObjectToDataSetFilter is used to convert the vtkDataObject to type vtkDataSet. Then, vtkRearrangeFields and vtkAssignAttribute are used to move a field from the vtkDataObject to the vtkPointData of the newly created vtkDataSet and label it as the active scalar field.

```
vtkDataObjectToDataSetFilter do2ds
  do2ds SetInputConnection [dos GetOutputPort]
  do2ds SetDataSetTypeToPolyData
  do2ds DefaultNormalizeOn
  do2ds SetPointComponent 0 $xAxis 0
  do2ds SetPointComponent 1 $yAxis 0
  do2ds SetPointComponent 2 $zAxis 0

vtkRearrangeFields rf
  rf SetInputConnection [do2ds GetOutputPort]
  rf AddOperation MOVE $scalar DATA_OBJECT POINT_DATA

vtkAssignAttribute aa
  aa SetInputConnection [rf GetOutputPort]
  aa Assign $scalar SCALARS POINT_DATA
  aa Update
```

There are several import techniques in use here.

1. All filters pass their input vtkDataObject through to their output unless instructed otherwise (or unless they modify vtkDataObject). We will take advantage of this in the downstream filters.
2. We set up vtkDataObjectToDataSetFilter tocreate an instance of vtkPolyData as its output, with the three named arrays of the field data serving as *x*, *y*, and *z* coordinates. In this case we use vtkPolyData because the data is unstructured and consists only of points.
3. We normalize the field values to range between (0,1) because the axes' ranges are different enough that we create a better visualization by filling the entire space with data.
4. The filter vtkRearrangeFields copies/moves fields between vtkDataObject, vtkPointData and vtkCellData. In this example, an operation to move the field called $scalar from the data object of the input to the point data of the output is added.
5. The filter vtkAssignAttribute labels fields as attributes. In this example, the field called $scalar (in the point data) is labeled as the active scalar field.

The Set___Component() methods are the key methods of vtkDataObjectToDataSetFilter. These methods refer to the data arrays in the field data by name and by component number. (Recall that a data array may have more than one component.) It is also possible to indicate a (min,max) tuple range from the data array, and to perform normalization. However, make sure that the number of tuples extracted matches the number of items in the dataset structure (e.g., the number of points or cells).

There are several related classes that do similar operations. These classes can be used to rearrange data arbitrarily to and from field data, into datasets, and into attribute data. These filters include:

- vtkDataObjectToDataSetFilter — Create a vtkDataSet, building the dataset's geometry, topology and attribute data from the chosen arrays within the vtkDataObject's field data.
- vtkDataSetToDataObjectFilter — Transform vtkDataSet into vtkFieldData contained in a vtkDataObject.
- vtkRearrangeFields — Move/copy fields between field data, point data, and cell data.
- vtkAssignAttribute — Label a field as an attribute.

- vtkMergeFields — Merge multiple fields into one.
- vtkSplitField — Split a field into multiple single component fields.
- vtkDataObjectReader — Read a VTK formatted field data file.
- vtkDataObjectWriter — Write a VTK formatted field data file.
- vtkProgrammableDataObjectSource — Define a method to read data of arbitrary form and represent it as field data (i.e., place it in a vtkDataObject).

Interaction, Widgets and Selections

The greatest power in a visualization system is not in its ability to process data or create an image, but rather in its mechanism for allowing the user to interact with the scene in order to guide the visualization in new directions. In VTK this interaction comes in a variety of forms from basic mouse and keyboard interaction allowing you rotate, translate and zoom, to the interactive widget elements in the scene that can be manipulated to control various parameters of the visualization, to the selection mechanism for identifying portions of the data. This chapter will cover the basics of interaction and introduce you to the tools you can use to develop your own customized interaction model for your application.

13.1 Interactors

Once you've visualized your data, you typically want to interact with it. The Visualization Toolkit offers several approaches to do this. The first approach is to use the built in class vtkRenderWindowInteractor. The second approach is to create your own interactor by specifying event bindings. And don't forget that if you are using an interpreted language you can type commands at run-time. You may also wish to refer to "Picking" on page 59 to see how to select data from the screen. (Note: Developers can also interface to a windowing system of their choice. See "Integrating With The Windowing System" on page 421.)

vtkRenderWindowInteractor

vtkRenderWindowInteractor provides a platform-independent interaction mechanism for mouse/key/time events. Platform specific subclasses intercept messages from the windowing system that occur within the render window and convert them to platform independent events. Specific classes may observe the interactor for these user events and respond to them. One such class is vtkInteractorObserver. (Remember that multiple renderers can draw into a rendering window and that the renderer

draws into a viewport within the render window. Interactors support multiple renderers in a render window). We've seen how to use vtkRenderWindowInteractor previously, here's a recapitulation.

```
vtkRenderWindowInteractor iren
  iren SetRenderWindow renWin
  iren AddObserver UserEvent {wm deiconify .vtkInteract}
```

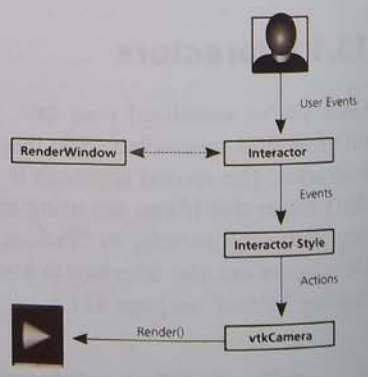
Apart from providing a platform independent interaction, vtkRenderWindowInteractor also provides functionality for frame rate control. The class maintains a notion of two kinds of requested frame rates: "DesiredUpdateRate" and "StillUpdateRate". The rationale for this is that during interaction, one is willing to sacrifice some amount of rendering quality for better interactivity. Hence, the interactor (to be more exact the interactor styles as you will see in the next section), sets the target frame rate to the DesiredUpdateRate during interaction. After interaction, the target frame rate is set back to the StillUpdateRate. Typically the DesiredUpdateRate is much larger than the StillUpdateRate. If a vtkLODActor is present in the scene ("Level-Of-Detail Actors" on page 55), it will then switch to a level of detail low enough to meet the target rate. A volume mapper (See "Volume Rendering" on page 139.) can cast fewer rays, or skip texture planes to meet the desired frame rate. Users may set these rates using the methods SetDesiredUpdateRate() and SetStillUpdateRate() on the interactor.

Interactor Styles

Everyone has a favorite way of interacting with data. There are two distinctly different ways to control interaction style in VTK. The first (and the recommended method) is to use a subclass of vtkInteractorStyle, either one supplied with the system or one that you write. The second method is to add observers that watch for events on the vtkRenderWindowInteractor and define your own set of callbacks (or commands) to implement the style. (Note: 3D widgets are another, more complex way to interact with data in the scene.)

vtkInteractorStyle

The class vtkRenderWindowInteractor can support different interaction styles. When you type "t" or "j" in the interactor (see the previous section) you are changing between trackball and joystick interaction styles. The way this works is that vtkRenderWindowInteractor translates window-system-specific events it receives (e.g., mouse button press, mouse motion, keyboard events) to VTK events such as MouseMoveEvent, StartEvent, and so on. (See "User Methods, Observers, and Commands" on page 29.) Different styles then observe particular events and perform the action(s) appropriate to the event, typically some form of camera manipulation. To set the style, use the vtkRenderWindowInteractor's SetInteractorStyle() method. For example:




```
vtkInteractorStyleFlight flightStyle
  vtkRenderWindowInteractor iren
  iren SetInteractorStyle flightStyle
```

A variety of interactor styles are provided with the toolkit. Below, we list some of the interactor styles found in the toolkit:

- vtkInteractorStyleTrackballActor - Allows the user to interact with (rotate, pan, etc.) actors in the scene independent of each other in a trackball based style. The trackball style is motion sensitive, ie. the magnitude of the mouse motion is proportional to the camera motion associated with a particular mouse binding.
- vtkInteractorStyleTrackballCamera - Allows the user to interactively manipulate (rotate, pan, etc.) the camera, the viewpoint of the scene in a trackball based style.
- vtkInteractorStyleJoystickActor - allows the user to interact with actors in a joystick style. The joystick style is position sensitive; ie. the position of the mouse relative to the center of the object, rather than the velocity of the mouse motion, determines the speed of the object's motion.
- vtkInteractorStyleJoystickCamera - Manipulate the camera in a joystick style.
- vtkInteractorStyleFlight - Provides flight motion routines. It is suitable for a fly through interaction (for instance through the colon in virtual colonoscopy), or a fly over (for instance over a terrain, or height field).
- vtkInteractorStyleImage - The style is specially designed to work with images that are being rendered with vtkImageActor. Its interactions support window/level etc.
- vtkInteractorStyleRubberbandZoom - This interactor style allows the user to draw a rectangle (rubberband) in the render window and zooms the camera appropriately into the selected region.
- vtkGeoInteractorStyle - Tailored for interaction with a geographic view (for instance a globe). Its interaction capabilities include orbit, zoom and tilt. It also features a compass widget for changing view parameters.
- vtkInteractorStyleTreeMapHover - works with a tree map (See "Information Visualization" on page 163.). Interactions allow 2D pan/zoom and balloon annotations for nodes on the tree map, node selection capabilities etc.
- vtkInteractorStyleAreaSelectHover - Similar to vtkInteractorStyleTreeMapHover except that it works with an area layout (See "Area Layouts" on page 175.)
- vtkInteractorStyleUnicam - Single mouse button, context sensitive interaction.

Adding vtkRenderWindowInteractor Observers

While a variety of interactor styles are available in VTK, you may prefer to create your own custom style to meet the needs of a particular application. In C++ the natural approach is to subclass vtkInteractorStyle. (See "vtkRenderWindowInteractor" on page 255.) However, in an interpreted language (e.g., Tcl, Python, or Java), this is difficult to do. For interpreted languages the simplest approach is to use observers to define particular interaction bindings. (See "User Methods, Observers, and Commands" on page 29.) The bindings can be managed in any language that VTK supports, including C++, Tcl, Python, and Java. An example of this is found in the Tcl code VTK/Examples/GUI/Tcl/CustomInteraction.tcl, which defines bindings for a simple Tcl application. Here's an excerpt to give you an idea of what's going on.

```
vtkRenderWindowInteractor iren
  iren SetInteractorStyle ""
  iren SetRenderWindow renWin

# Add the observers to watch for particular events
# These invoke Tcl procedures
set Rotating 0
set Panning 0
set Zooming 0


iren AddObserver LeftButtonPressEvent {global Rotating; set Rotating 1}
iren AddObserver LeftButtonReleaseEvent \
  {global Rotating; set Rotating 0}
iren AddObserver MiddleButtonPressEvent {global Panning; set Panning 1}
iren AddObserver MiddleButtonReleaseEvent \
  {global Panning; set Panning 0}
iren AddObserver RightButtonPressEvent {global Zooming; set Zooming 1}
iren AddObserver RightButtonReleaseEvent {global Zooming; set Zooming 0}
iren AddObserver MouseMoveEvent MouseMove
iren AddObserver KeyPressEvent Keypress

proc MouseMove {} {
  ...
  set xypos [iren GetEventPosition]
  set x [lindex $xypos 0]
  set y [lindex $xypos 1]
  ...
  }

proc Keypress {} {
  set key [iren GetKeySym]
  if { $key == "e" } {
    vtkCommand DeleteAllObjects
    exit
    }
  ...
  }
```

Note that a key step in this example is disabling the default interaction style by invoking SetInteractionStyle(""). Observers are then added to watch for particular events which are tied to the appropriate Tcl procedures. This example is a simple way to add bindings from a Tcl script. If you would like to create a full GUI using Tcl/Tk, then use the vtkTkRenderWidget, and refer to "Tcl/Tk" on page 433 for more details.

13.2 Widgets

Interactor styles are generally used to control the camera and provide simple keypress and mouse-oriented interaction techniques. Interactor styles have no representation in the scene; that is, they cannot be "seen" or interacted with, the user must know what the mouse and key bindings are in order to use

them. Certain operations, however, are greatly facilitated by the ability to operate directly on objects in the scene. For example, starting a rake of streamlines along a line is easily performed if the end-points of the line can be interactively positioned.

VTK's 3D widgets have been designed to provide this functionality. Like the class vtkInteractorStyle, VTK's widgets are subclasses of vtkInteractorObserver. That is, they listen to mouse and keyboard events invoked by vtkRenderWindowInteractor. Unlike vtkInteractorStyle, however, these widgets have some geometrical representation in the scene, with which the user typically interacts. VTK provides numerous widgets tailored to perform tasks that range from measurements and annotations to segmentations, scene parameter manipulation, probing etc.

Since their inception into VTK, the widget architecture has undergone a redesign. The older widgets derive from vtk3DWidget. Below, we will discuss the architecture of the newer widgets. These derive from vtkAbstractWidget, which derives from vtkInteractorObserver. This class defines the behavior of the widget (its interaction, etc). The widget's geometry (how it appears in the scene) is encapsulated in the form of a prop. This is a class that derives from vtkWidgetRepresentation, which derives from vtkProp. This decoupling of the behavior (interaction) from the representation (geometry) allows one to create multiple representations for the same widget. This allows users to override existing representations with their own representations without having to reimplement event processing. They are useful in a parallel, distributed computing world where the capabilities for event processing may not exist. A vtkHandleWidget that is used to represent a seed has four geometric representations namely: vtkPointHandleRepresentation2D, vtkPointHandleRepresentation3D, vtkSphereHandleRepresentation and vtkPolygonalHandleRepresentation. These render a handle as a 2D crosshair, 3D crosshair, a sphere or a user supplied polygonal shape respectively. The following snippet found in Widgets/Testing/Cxx/TestHandleWidget.cxx shows how to create a widget and tie it to its representation. Here, we'll create a handle widget that can be moved around in a 3D world. The handle is represented via a 3D crosshair, as dictated by its representation.

```
// Create a render window interactor
vtkRenderWindowInteractor *iren = vtkRenderWindowInteractor::New();
  iren->SetRenderWindow(renderWindow);

// Create a 3D cross hair representation for a handle
double worldPos[3] = {-0.0417953, 0.202206, -0.0538641};
vtkPointHandleRepresentation3D *handleRep
  = vtkPointHandleRepresentation3D::New();
  handleRep->SetHandleSize(10);
  handleRep->SetWorldPosition(worldPos);

// Create the handle widget.
vtkHandleWidget *handleWidget = vtkHandleWidget::New();
  handleWidget->SetInteractor(iren);
  handleWidget->SetRepresentation(handleRep);
  handleWidget->EnabledOn();
```

While each widget provides different functionality and offers a different API, the 3D widgets are similar in how they are set up and used. The general procedure is as follows.

1. Instantiate the widget
2. Specify the render window interactor that the widget will observe for user events

3. Create callbacks (i.e., commands) as necessary using the Command/Observer mechanism.See "User Methods, Observers, and Commands" on page 29. The widgets typically invoke the generic events indicating that they are being interacted with and also widget specific events during interaction, such as StartInteractionEvent, InteractionEvent, and EndInteractionEvent. The user typically observes these events to update data, visualization parameters or the application's user interface.
4. Create the appropriate representation and provide it to the widget using SetRepresentation, or use the default representation provided by the widget.
5. Finally the widget must be enabled, so that it is visible on the scene. By default, a keypress "i" will enable the widget and it will appear in the scene.

While SetEnabled toggles the visibility of a widget, in some cases, it may be necessary to disable a widget's interaction, while keeping it visible in the scene. Event processing for the newer widgets can be disabled via:

```
widget->ProcessEventsOff();
```

This will cause the widget to stop responding to interactions, which will end up being processed by the underlying interactor style.

Reconfigurable Bindings

Users may also like to customize mouse / keyboard bindings for a widget, due to personal preference or when a different interaction device is used. The newly architected widgets allow you to reconfigure bindings. All user events are associated with specific widget actions. The widgets use an intermediate class called an "event translator" to translate user events to widget specific events. In turn, the widget event is mapped into a method invocation on the widget. The event translator can be used to change the default bindings as shown in the following code excerpt from Widgets/Testing/Cxx/TestSliderWidget.cxx

```
vtkWidgetEventTranslator *translator =
  sliderWidget->GetEventTranslator();
  translator->SetTranslation(
    vtkCommand::RightButtonPressEvent, vtkWidgetEvent::Select);
  translator->SetTranslation(
    vtkCommand::RightButtonReleaseEvent, vtkWidgetEvent::EndSelect);
```

As a result, the user can manipulate the slider's notch using the right mouse button in addition to the default left button. The user may also remove existing bindings using the RemoveTranslation method.

```
translator->RemoveTranslation( vtkCommand::LeftButtonPressEvent );
translator->RemoveTranslation( vtkCommand::LeftButtonReleaseEvent );
```

A list of translations associated with a widget can be obtained by exercising its Print statement:

```
translator->Print( std::cout );
```

Cursor Management and Highlighting

Most widgets also manage the cursor, changing its shape appropriately when hovering over a portion of the widget to indicate an action. Highlighting is another common feature, for instance the handle of a box widget will change color when hovered upon / selected to indicate its ability to be manipulated.

Widget Hierarchies

Widgets also support hierarchies. A widget may be "parented" by another widget to enable creation of composite widgets, using one or more existing widgets. For instance a vtkDistanceWidget internally comprises two vtkHandleWidgets, as its children, representing the end points. The children listen to their parent for events, instead of the render window interactor, thereby allowing the parent to modify their behavior if necessary. Within VTK, the handle widget is used as a child in several other widgets such as the Angle, BiDimensional, Box, Parallelopiped, Line and Seed widgets.

Timers

Apart from responding to events, from the user, VTK's widgets can also respond to other events, such as timer events. For instance a vtkBalloonWidget is used to popup text / image annotations when the mouse hovers over an actor for a user specified time. To do this, the widget observes the interactor for the MouseMoveEvent and the TimerEvent, so that the widget may take action when the mouse stagnates over an actor for a time exceeding a user specified "TimerDuration".

The following excerpt from Rendering/Testing/Cxx/TestInteractorTimers.cxx illustrates how to request and observe the render window interactor for timers.

```
// Observe the interactor for timers with a callback
iren->AddObserver(vtkCommand::TimerEvent, myCallback);

// Create a timer that repeats every 3 milliseconds
tid = iren->CreateRepeatingTimer(3);

// Create a timer that fires once after 1 second.
tid = iren->CreateOneShotTimer(10000);
```

Priorities

Several classes may observe the render window interactor simultaneously for user events. These include all subclasses of vtkInteractorObserver, such as the interactor style and one or more widgets in the scene. Mousing in the scene, not on any particular widget will engage the vtkInteractorStyle, but mousing on a particular widget will engage just that widget-typically no other widget or interactor style will see the events. (One notable exception is the class vtkInteractorEventRecorder that records events and then passes them along. This class can also playback events, thereby making it useful for recording sessions. The class is used in VTK to exercise regression tests for the widgets.). Such a scenario may result in event competition. Competition for user events is handled through "priorities". All subclasses of vtkInteractorObserver can be assigned a priority using the SetPriority method. Objects with a higher priority are given the opportunity to process events before those with a lower priority. They may also choose to abort event processing for a given event, and in effect grab "focus".

In fact, the reason the widgets handle event processing before the interactor style is due to their having a higher priority than the interactor styles.

Point Placers

Note that interactions happen in a 2D window. 3D widgets may need to translate 2D coordinates to coordinates in a 3D world. For instance, consider the use of a vtkHandleWidget to drop a seed point on a render window. At what depth in the 3D scene should the seed be placed? VTK provides a few standard ways define this mapping and a framework to create your own mapping. This is accomplished via a class called vtkPointPlacer. The contour widget and the handle widget have representations that accept a point placer to which they delegate the responsibility of translating from 2D to 3D co-ordinates. One may use these to specify constraints on where a node may be moved. For instance, the following excerpt found in Widgets/Testing/Cxx/TestSurfaceConstrainedHandleWidget.cxx restricts the placement and interaction of seeds to a polygonal surface:

```
vtkHandleWidget *widget = vtkHandleWidget::New();
vtkPointHandleRepresentation3D *rep =
  vtkPointHandleRepresentation3D::SafeDownCast(
  widget->GetRepresentation());

// Restrict the placement of seeds to the polygonal surface defined by
// "polydata" and rendered as "actor"
vtkPolygonalSurfacePointPlacer * pointPlacer
  = vtkPolygonalSurfacePointPlacer::New();
  pointPlacer->AddProp(actor);
  pointPlacer->GetPolys()->AddItem( polydata );
  rep->SetPointPlacer(pointPlacer);
```

Similarly, one may use the class vtkImageActorPointPlacer to restrict the placement of control points of a contour widget to a slice of an image as shown in the following excerpt from Widgets/Testing/Cxx/TestImageActorContourWidget.cxx.

```
vtkOrientedGlyphContourRepresentation *rep =
  vtkOrientedGlyphContourRepresentation::New();

vtkImageActorPointPlacer * imageActorPointPlacer =
  vtkImageActorPointPlacer::New();
  imageActorPointPlacer->SetImageActor(ImageViewer->GetImageActor());
rep->SetPointPlacer(imageActorPointPlacer);
```

13.3 A tour of the widgets

The following is a selected list of widgets currently found in VTK and a brief description of their features. Note that some of the concepts mentioned here have not yet been covered in this text. Please refer to the appropriate cross-reference to learn more about a particular concept.

Measurement Widgets

vtkDistanceWidget. The vtkDistanceWidget is used to measure the distance between two points in 2D, for instance to measure the diameter of a tumor in a medical image. The two end points can be positioned independently, and when they are released, a PlacePointEvent is invoked so that you can perform custom operations to reposition the point (snap to grid, snap to an edge, etc.) The widget has two different modes of interaction: the first mode is used when you initially define the measurement

(i.e., placing the two points) and then a manipulate mode is used to allow you to adjust the position of the two points.

To use this widget, specify an instance of vtkDistanceWidget and a representation (a subclass of vtkDistanceRepresentation). The widget is implemented using two instances of vtkHandleWidget which are used to position the end points of the line. The representations for these two handle widgets are provided by the vtkDistanceRepresentation. The following is an example of vtkDistanceWidget taken from VTK/Widgets/Testing/Cxx/TestDistanceWidget.cxx.

vtkDistanceWidget

```
vtkPointHandleRepresentation2D *handle =
  vtkPointHandleRepresentation2D::New();
vtkDistanceRepresentation2D *rep =
vtkDistanceRepresentation2D::New();
  rep->SetHandleRepresentation(handle);

vtkDistanceWidget *widget = vtkDistanceWidget::New();
  widget->SetInteractor(iren);
  widget->SetRepresentation(rep);
```

vtkAngleWidget. The vtkAngleWidget is used to measure the angle between two rays (defined by three points). The three points (two end points and a center) can be positioned independently in either 2D or 3D. Similar to vtkDistanceWidget, a PlacePointEvent is invoked when one of the handle positions is altered so that you can adjust the position of the point to snap to a grid or to perform other specialized placement options. Also similar to the vtkDistanceWidget, the vtkAngleWidget has two modes of operation. The first is in effect as the angle widget is being defined and the three points are initially placed. After that the widget switches to the manipulation interaction mode, allowing you to adjust the placement of each of the three points defining the angle.

vtkAngleWidget

To use this widget, specify an instance of vtkAngleWidget and a representation (a subclass of vtkAngleRepresentation). The widget is implemented using three instances of vtkHandleWidget which are used to position the three points. The representations for these handle widgets are provided by the vtkAngleRepresentation. The following is an example of the vtkAngleWidget taken from VTK/Widgets/Testing/Cxx/TestAngleWidget3D.cxx.

```
vtkPointHandleRepresentation3D *handle =
  vtkPointHandleRepresentation3D::New();
vtkAngleRepresentation3D *rep = vtkAngleRepresentation3D::New();
  rep->SetHandleRepresentation(handle);

vtkAngleWidget *widget = vtkAngleWidget::New();
  widget->SetInteractor(iren);
  widget->SetRepresentation(rep);
```

Similarly one may instantiate the representation vtkAngleRepresentation2D to measure angles in 2D

```
vtkPointHandleRepresentation2D *handle =
  vtkPointHandleRepresentation2D::New();
vtkAngleRepresentation2D *rep = vtkAngleRepresentation2D::New();
  rep->SetHandleRepresentation(handle);
widget->SetRepresentation(rep);
```

vtkBiDimensionalWidget. The vtkBiDimensionalWidget is used to measure the bidimensional length of an object. The bi-dimensional measure is defined by two finite, orthogonal lines that intersect within the finite extent of both lines. The lengths of these two lines gives the bidimensional measure. Each line is defined by two handle widgets at the end points of each line.

vtkBiDimensionalWidget

The orthogonal constraint on the two lines limits how the four end points can be positioned. The first two points can be placed arbitrarily to define the first line (similar to vtkDistanceWidget). The placement of the third point is limited by the finite extent of the first line. As the third point is placed, the fourth point is placed on the opposite side of the first line. Once the third point is placed, the second line is defined since the fourth point is defined at the same time, but the fourth point can be moved along the second line (i.e., maintaining the orthogonal relationship between the two lines). Once defined, any of the four points can be moved along their constraint line. Also, each line can be translated along the other line (in an orthogonal direction), and the whole bi-dimensional widget can be rotated about its center point. Finally, by selecting the point where the two orthogonal axes intersect the entire widget can be translated in any direction.

Placement of any point results in a special PlacePointEvent invocation so that special operations may be performed to reposition the point. Motion of any point, moving the lines, or rotating the widget cause InteractionEvents to be invoked. Note that the widget has two fundamental modes: a define mode (when initially placing the points) and a manipulate mode (after the points are placed). Line translation and rotation are only possible in manipulate mode.

To use this widget, specify an instance of vtkBiDimensionalWidget and a representation (e.g., vtkBiDimensionalRepresentation2D). The widget is implemented using four instances of vtkHandleWidget which are used to position the end points of the two intersecting lines. The representations for these handle widgets are provided by the vtkBiDimensionalRepresentation2D class. An example taken from VTK/Widgets/TestBiDimensionalWidget.cxx is shown below:

```
vtkBiDimensionalRepresentation2D *rep =
  vtkBiDimensionalRepresentation2D::New();

vtkBiDimensionalWidget *widget = vtkBiDimensionalWidget::New();
  widget->SetInteractor(iren);
  widget->SetRepresentation(rep);
```

Widgets for probing or manipulating underlying data

vtkHandleWidget. The vtkHandleWidget provides a handle that can be interactively positioned in 2D or 3D space. They may also be used as fiducials. Several geometrical representations are provided that enable creation of various shapes in 2D and 3D. The handle can be translated in 2D/3D space with the left mouse button. Dragging it with the shift key depressed constrains its translation along one of the coordinate axes; the axes being determined as the one most aligned with the mouse motion vector. The handle may be resized using the right mouse button. The widget invokes an InteractionEvent during manipulation of the handles and an EndInteractionEvent after interaction, allowing users to respond if necessary.

vtkHandleWidget

vtkHandleRepresentation is the abstract superclass for the handle's many representations. vtkPointHandleRepresentation3D represents the handle via a 3D cross hair. vtkPointHandleRepresentation2D represents it via a 2D cross hair on the overlay plane. vtkSphereHandleRepresentation represents it via a 3D sphere. vtkPolygonalHandleRepresentation3D allows the users to plug in an instance of vtkPolyData so to render the handle in a user defined shape. The myriad representations allow one to represent the end points of the distance, angle and bidimensional widgets in various shapes. An example:

```
vtkHandleWidget *widget = vtkHandleWidget::New();
vtkPointHandleRepresentation3D *rep =
  vtkPointHandleReprentation3D::New()
widget->SetRepresentation(rep);
```

Constraints on handle placement and movement may be optionally placed via a subclass of vtkPointPlacer. A vtkPolygonalSurfacePointPlacer will restrict the handles to the surfaces of a vtkPolyData.

```
// Restrict the placement of seeds to the polygonal surface defined by
// "polydata" and rendered as "actor"

vtkPolygonalSurfacePointPlacer * pointPlacer =
  vtkPolygonalSurfacePointPlacer::New();
  pointPlacer->AddProp(actor);
  pointPlacer->GetPolys()->AddItem( polydata );
rep->SetPointPlacer(pointPlacer);
```

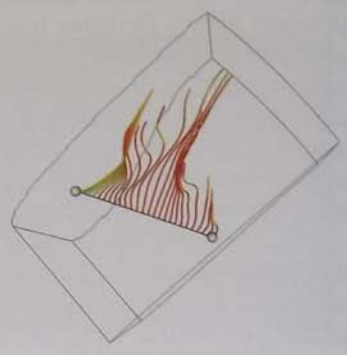
Similarly, a vtkTerrainDataPointPlacer may be used to restrict the handles to a height field (a Digital Elevation Map).

```
vtkTerrainDataPointPlacer * placer = vtkTerrainDataPointPlacer::New();
  placer->SetHeightOffset( 5.0 );
  // height over the terrain to constrain the points to
  placer->AddProp( demActor ); // prop representing the DEM.
rep->SetPointPlacer( placer );
```

A vtkImageActorPointPlacer will restrict the handles to an image, represented by an instance of vtkImageActor. Bounds may in addition be placed on this placer to further restrict the points within the image actor via SetBounds.

```
vtkImageActorPointPlacer *placer = vtkImageActorPointPlacer::New();
 placer->SetImageActor( imageActor );
```

vtkLineWidget2. The class vtkLineWidget2 allows the define and manipulate a finite straight line in 3D space. The line can be picked at its endpoints, (represented by instances of vtkHandleWidget) to orient and stretch the line. It can also be picked anywhere along the line so as to translate it in the scene. Much like vtkHandleWidget, the movement of the end-points or the center can be constrained to one of the axes by dragging with the shift key depressed. The line can be scaled about its center using the right mouse button. By moving the mouse "up" the render window the line will be made bigger; by moving "down" the render window the line gets smaller. A common use of the line widget is to probe ("Probing" on page 100) and plot data ("X-Y Plots" on page 66) or produce streamlines ("Streamlines" on page 95) or stream surfaces ("Stream Surfaces" on page 97). vtkLineRepresentation provides the geometry for the line widget. One may also enable annotation of the length of the line. The widget invokes an InteractionEvent during the manipulation of the line and an EndInteractionEvent after interaction, allowing users to respond if necessary. Here's an excerpt from Widgets/Testing/Cxx/TestLineWidget2.cxx.



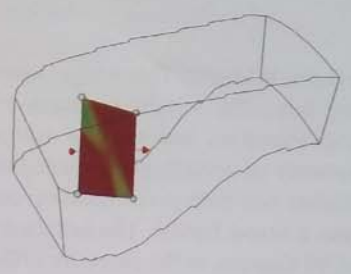
vtkLineWidget2

```
vtkLineRepresentation *rep = vtkLineRepresentation::New();
 p[0] = 0.0; p[1] = -1.0; p[2] = 0.0;
 rep->SetPoint1WorldPosition(p);
 p[0] = 0.0; p[1] =  1.0; p[2] = 0.0;
 rep->SetPoint2WorldPosition(p);
 rep->PlaceWidget(pl3d->GetOutput()->GetBounds());
 rep->GetPolyData(seeds); // used to seed a streamline later
 rep->DistanceAnnotationVisibilityOn();

vtkLineWidget2 *lineWidget = vtkLineWidget2::New();
 lineWidget->SetInteractor(iren);
 lineWidget->SetRepresentation(rep);
 lineWidget->AddObserver(vtkCommand::InteractionEvent,myCallback);
```

vtkPlaneWidget. This widget can be used to orient and position a finite plane. The plane resolution is variable. The widget produces an implicit function, which may be queried via the GetPlane method and a polygonal output, which may be queried via the GetPolyData methods The plane widget may be used for probing and seeding streamlines. The plane has four handles (at its corner vertices), a normal vector, and the plane itself. By grabbing one of the four handles (use the left mouse button), the plane can be resized. By grabbing the plane itself, the entire plane can be arbitrarily translated. Pressing Control while grabbing the plane will spin the plane around the normal. If you select the normal vec-

tor, the plane can be arbitrarily rotated. Selecting any part of the widget with the middle mouse button enables translation of the plane along its normal.

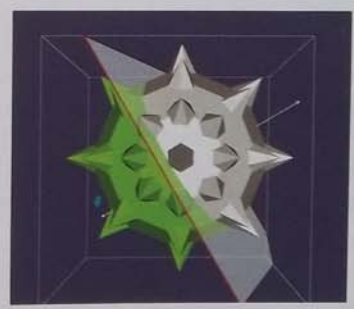
(Once selected using middle mouse, moving the mouse in the direction of the normal translates the plane in the direction of the normal; moving in the direction opposite the normal translates the plane in the direction opposite the normal.) Scaling (about the center of the plane) is achieved by using the right mouse button, dragging "up" the render window to make the plane bigger; and "down" to make it smaller. The public API of the widget also allows the user to change the property of the plane and the handle. One can also constrain the plane normal to one of the coordinate axes, as is shown in the code snippet below. The widget invokes an InteractionEvent during manipulation and an EndInteractionEvent after interaction. The following excerpt from Widgets/Testing/Cxx/TestPlaneWidget.cxx illustrates the usage of this widget.



vtkPlaneWidget

```
vtkPlaneWidget *planeWidget = vtkPlaneWidget::New();
  planeWidget->SetInteractor(iren);
  planeWidget->SetInput(pl3d->GetOutput());
  planeWidget->NormalToXAxisOn();
  planeWidget->SetResolution(20);
  planeWidget->SetRepresentationToOutline();
  planeWidget->PlaceWidget();
  planeWidget->AddObserver(vtkCommand::InteractionEvent,myCallback);
```

vtkImplicitPlaneWidget2. This widget can be used to orient and position an unbounded plane. An implicit function as well as a polygonal output can be queried from this widget. The widget consists of four parts: 1) a plane contained in a 2) bounding box, with a 3) plane normal, which is rooted at a 4) point on the plane. The widget may be scaled using the right mouse button. The normal can be picked and dragged to orient the plane. The root of the normal can also be translated to change the origin of the normal. The entire widget may be translated using the middle mouse button. The polygonal output is created by clipping the plane with a bounding box. The widget is often used to "cutting" and "clipping". One can change various properties on the plane. The SetTubing can be used to display a tubed outline of the plane. This excerpt from Widgets/Testing/Cxx/TestImplicitPlaneWidget2.cxx illustrates the use of vtkImplicitPlaneWidget2 along with an instance of vtkImplicitPlaneRepresentation

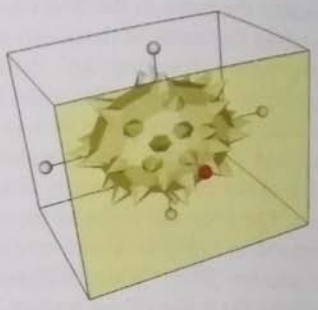


vtkImplicitPlaneWidget2

```
vtkImplicitPlaneRepresentation *rep =
  vtkImplicitPlaneRepresentation::New();
  rep->SetPlaceFactor(1.25);
  rep->PlaceWidget(glyph->GetOutput()->GetBounds());
```

```
vtkImplicitPlaneWidget2 *planeWidget = vtkImplicitPlaneWidget2::New();
  planeWidget->SetInteractor(iren);
  planeWidget->SetRepresentation(rep);
  planeWidget->AddObserver(vtkCommand::InteractionEvent,myCallback);
```

vtkBoxWidget2. This widget orients and positions a bounding box. The widget produces an implicit function and a transformation matrix. The widget is used along with an instance of a vtkBoxRepresentation. The representation represents box with seven handles: one on each of the six faces, plus a center handle. The hexahedron has interior face angles of 90 degrees, ie the faces are orthogonal. Each of the 7 handles that can be moused on and manipulated. A bounding box outline is shown, the "faces" of which can be selected for object scaling. During interaction, the corresponding face or the handle becomes highlighted, providing enhanced visual cues. One can use the PlaceWidget() method to initially position the widget. By grabbing the six face handles (using the left mouse button), faces can be moved. By grabbing the center handle (with the left mouse button), the entire hexahedron can be translated. (Translation can also be employed by using the "shift-left-mouse-button" combination inside of the widget.) Scaling is achieved by using the right mouse button; "up" the render window (makes the widget bigger) or "down" the render window (makes the widget smaller).



vtkBoxWidget2

The vtkBoxWidget2 may be used to select, cut, clip, or perform any other operation that depends on an implicit function (use the GetPlanes() method on the representation); or it can be used to transform objects using a linear transformation (use the GetTransform() method on the representation). The widget is also typically used to define a region of interest, which may be used for annotation or for cropping a dataset. The widget invokes a StartInteractionEvent, InteractionEvent, and EndInteractionEvent events before, during and after interaction. One can turn on/off the display of the outline between the handles using the SetOutlineCursorWires in vtkBoxRepresentation. The box widget is used to transform vtkProp3D's and sub-classes ("Transforming Data" on page 70) or to cut ("Cutting" on page 98) or clip data ("Clip Data" on page 110). This excerpt from VTK/Widgets/Testing/Cxx/BoxWidget2.cxx shows how this widget may be used to transform other props in the scene.

```
// Callback for the interaction
class vtkBWCallback2 : public vtkCommand
{
 virtual void Execute(vtkObject *caller, unsigned long, void*)
  {
    vtkBoxWidget2 *boxWidget = reinterpret_cast<vtkBoxWidget2*>(caller);
    vtkBoxRepresentation *boxRep =
      reinterpret_cast<vtkBoxRepresentation*>(boxWidget->
      GetRepresentation());
      boxRep->GetTransform(this->Transform);
      this->Actor->SetUserTransform(this->Transform);
  }
 vtkTransform *Transform;
 vtkActor     *Actor;
};
```

```
...

vtkBoxRepresentation *boxRep = vtkBoxRepresentation::New();
  boxRep->SetPlaceFactor( 1.25 );
  boxRep->PlaceWidget(glyph->GetOutput()->GetBounds());

vtkBoxWidget2 *boxWidget = vtkBoxWidget2::New();
  boxWidget->SetRepresentation( boxRep );
  boxWidget->AddObserver(vtkCommand::InteractionEvent,myCallback);

vtkTransform *t = vtkTransform::New();
vtkBWCallback2 *myCallback = vtkBWCallback2::New();
  myCallback->Transform = t;
  myCallback->Actor = maceActor;
```

vtkAffineWidget. This widget provides support for interactively defining affine transformations (shear / rotation / scaling / translation). The widget used along with an instance of vtkAffineRepresentation. vtkAffineRepresentation2D is a concrete subclass of vtkAffineRepresentation to represent affine transformations in 2D. This representation's geometry consists of three parts: a box, a circle, and a cross. The box is used for scaling and shearing. The left mouse button can be used to stretch the box along one of the axes by clicking on the edges, or to stretch along both axes by picking the corner. The circle is used for rotation. The central cross may be picked to achieve translation. During manipulation of the box, circle and cross respectively, the scale, angle or translation component of the affine transform can optionally displayed as accompanying annotation. All the geometry is drawn on the overlay plane by vtkAffineRepresentation maintaining a constant size (width and height) specified in terms of normalized viewport coordinates.

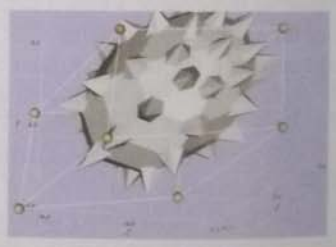
vtkAffineWidget

The representation maintains a transformation matrix, which may be queried by users using the GetTransform() method, so as to apply transformations to underlying props or datasets. The transformations generated by this widget assume that the representation lies in the x-y plane. If this is not the case, the user is responsible for transforming this representation's matrix into the correct coordinate space (by judicious matrix multiplication). Note that the transformation matrix returned by GetTransform() is relative to the last PlaceWidget() invocation. (The PlaceWidget() method sets the origin around which rotation and scaling occurs the origin is the center point of the bounding box provided.). VTK/Widgets/Testing/Cxx/TestAffineWidget.cxx shows how the affine widget may be used to apply a transform to the underlying image. The widget invokes an InteractionEvent during interaction and an EndInteractionEvent after interaction.

```
class vtkAffineCallback : public vtkCommand
  {
  virtual void Execute(vtkObject *caller, unsigned long, void*)
   {
   this->AffineRep->GetTransform(this->Transform);
   this->ImageActor->SetUserTransform(this->Transform);
   }
  vtkImageActor *ImageActor;
```

```
  vtkAffineRepresentation2D *AffineRep;
  vtkTransform *Transform;
};

vtkAffineRepresentation2D *rep = vtkAffineRepresentation2D::New();
  rep->SetBoxWidth(100);
  rep->SetCircleWidth(75);
  rep->SetAxesWidth(60);
  rep->DisplayTextOn();
  rep->PlaceWidget(bounds);

vtkAffineWidget *widget = vtkAffineWidget::New();
  widget->SetInteractor(iren);
  widget->SetRepresentation(rep);

vtkAffineCallback *acbk = vtkAffineCallback::New();
  acbk->AffineRep = rep;
  acbk->ImageActor = imageActor;

widget->AddObserver(vtkCommand::InteractionEvent,acbk);
widget->AddObserver(vtkCommand::EndInteractionEvent,acbk);
```

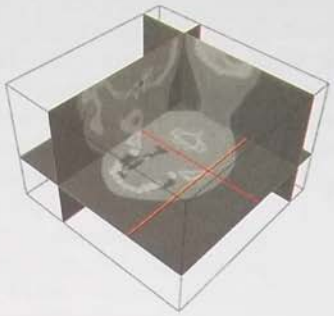
vtkParallelopipedWidget. A vtkParallelopipedWidget can be used interactively manipulate a parallelopiped in 3D. It is meant to be used along with an instance of vtkParallelopiped-Representation. The parallelopiped is represented by 8 handles and 6 faces. The handles can be picked and dragged so as to manipulate the parallelopiped. The handles are instances of vtkHandleWidget, represented as spheres (vtkSphereHandle-Representation). Left clicking on a handle and dragging it moves the handle in space, the handles along faces shared by this handle may also move so as to maintain topology as a parallelopiped. Dragging a handle with the shift button pressed resizes the parallelopiped along an axis.The parallelopiped widget also has a special mode, designed for probing the underlying data and displaying a cut through it. By ctrl-left-click on a handle, it buckles inwards to carve a "chair" out of the parallelopiped. In this mode, the parallelopiped has 14 handles and 9 faces. These handles can again be picked to manipulate the parallelopiped or the depression of the chair. The following excerpt from VTK/Widgets/Testing/Cxx/TestParallelopiped-Widget.cxx illustrates the use of the vtkParallelopipedWidget.



vtkParallelopipedWidget

```
vtkParallelopipedWidget *widget = vtkParallelopipedWidget::New();
vtkParallelopipedRepresentation *rep =
  vtkParallelopipedRepresentation::New();
widget->SetRepresentation(rep);
widget->SetInteractor( iren );
rep->SetPlaceFactor( 0.5 );
rep->PlaceWidget(parallelopipedPts);
```

vtkImagePlaneWidget. This widget defines a plane in a 3D scene to reslice image volumes interactively. The plane orientation may be interactively defined. Additional functionality includes the ability to window-level the resliced data and defining the degree of interpolation while reslicing. Internally, the widget contains an instance of vtkImageReslice. This slices through the underlying volumetric image data based on the defined plane. The output of this class is texture mapped onto the plane, creating an "image plane widget". Selecting the widget with the middle mouse button with and without holding the shift or control keys enables complex reslicing capablilites. A set of 'margins' (left, right, top, bottom) are shown as a set of plane-axes aligned lines. Without keyboard modifiers: selecting towards the middle of the plane margins enables translation of the plane along its normal. Selecting one of the corners within the margins enables spinning around the plane's normal at its center. Selecting within a margin allows rotating about the center of the plane around an axis aligned with the margin (i.e., selecting the left margin enables rotation around the plane's local y-prime axis). With the control key modifier: margin selection enables edge translation (i.e., a constrained form of scaling). Selecting within the margins enables translation of the entire plane. With shift key modifier: uniform plane scaling is enabled. Moving the mouse up enlarges the plane while downward movement shrinks it. When selected the plane outline is highlighted to provide visual cues.



vtkImagePlaneWidget

Window-level is achieved by using the right mouse button. Window-level values can be reset by shift + 'r' or control + 'r'. One can reset the camera by pressing 'r' or 'R'. The left mouse button can be used to query the underlying image data with a snap-to cross-hair cursor. The nearest point in the input image data to the mouse cursor generates the cross-hairs. With oblique slicing, this behavior may appear unsatisfactory. Text annotations display the window-level and image coordinates/data values. The text annotation may be toggled on and off with SetDisplayText. The widget invokes a StartInteractionEvent, InteractionEvent and EndInteractionEvent at the beginning, during and end of an interaction. The events StartWindowLevelEvent, WindowLevelEvent, EndWindowLevelEvent and ResetWindowLevelEvent are invoked during their corresponding actions.

The vtkImagePlaneWidget has additional public API that allow it to be used has several methods that can be used in conjunction with other VTK objects. The GetPolyData() method can be used to get the polygonal representation of the plane and can be used as input for other VTK objects. Some additional features of this class include the ability to control the properties of the widget. You can set the properties of: the selected and unselected representations of the plane's outline; the text actor via its vtkTextProperty; the cross-hair cursor. In addition there are methods to constrain the plane so that it is aligned along the x-y-z axes. Finally, one can specify the degree of interpolation used for reslicing the data: nearest neighbor, linear, and cubic. One can also choose between voxel centered or continuous cursor probing. With voxel centered probing, the cursor snaps to the nearest voxel and the reported cursor coordinates are extent based. With continuous probing, voxel data is interpolated using vtkDataSetAttributes' InterpolatePoint method and the reported coordinates are 3D spatial continuous. VTK/Widgets/Testing/Cxx/ImagePlaneWidget.cxx uses vtkImagePlaneWidget to interactively display axial, coronal and sagittal slices in a 3D volume. The following excerpt illustrates the usage of this widget.

```
vtkImagePlaneWidget* planeWidgetX = vtkImagePlaneWidget::New();
  planeWidgetX->SetInteractor( iren);
  planeWidgetX->SetKeyPressActivationValue('x');
  planeWidgetX->SetPicker(picker);
  planeWidgetX->RestrictPlaneToVolumeOn();
  planeWidgetX->GetPlaneProperty()->SetColor(1,0,0);
  planeWidgetX->SetTexturePlaneProperty(ipwProp);
  planeWidgetX->TextureInterpolateOff();
  planeWidgetX->SetResliceInterpolateToNearestNeighbour();
  planeWidgetX->SetInput(v16->GetOutput());
  planeWidgetX->SetPlaneOrientationToXAxes();
  planeWidgetX->SetSliceIndex(32);
  planeWidgetX->DisplayTextOn();
  planeWidgetX->On();
```

vtkTensorProbeWidget. This widget can be used to probe tensors along a trajectory. The trajectory is represented via a polyline (vtkPolyLine). The class is intended to be used with an instance of vtkTensorProbeRepresentation. The representation class is also responsible for rendering the tensors. vtkEllipsoidTensorProbeRepresentation renders the tensors as ellipsoids. The orientation and radii of the ellipsoids illustrate the major, medium, and minor eigenvalues/eigenvectors of the tensors. The interactions of the widget are controlled by the left mouse button. A left click on the tensor selects it. It can dragged around the trajectory to probe the tensors on it. The following is an example taken from Widgets/Testing/Cxx/TestTensorProbeWidget.cxx.

vtkTensorProbeWidget

```
vtkTensorProbeWidget *w = vtkTensorProbeWidget::New();
  w->SetInteractor(iren);
vtkTensorProbeRepresentation * rep =
  vtkTensorProbeRepresentation::SafeDownCast(w->GetRepresentation());
  rep->SetTrajectory(pd);
```

Annotation widgets

vtkScalarBarWidget. This class provides support for interactively manipulating the position, size, and orientation of a scalar bar. This widget is typically used to display a color legend in the scene. The legend is displayed in the overlay plane.vtkScalarBarWidget is meant to be used in conjunction with an instance of vtkScalarBarRepresentation. The widget allows the scalar bar to be resized, repositioned or reoriented. If the cursor is over an edge or a corner of the scalar bar it will change the cursor shape to a resize edge / corner shape. A drag with the left button then resizes the scalar bar. Similarly, if the cursor is within the scalar bar, it changes shape to indicate that it can be translated. The scalar bar can also be repositioned by pressing the middle mouse button. If the position of a scalar bar is moved to be close

vtkScalarBarWidget

to the center of one of the four edges of the viewport, then the scalar bar will change its orientation to align with that edge. This orientation is sticky in that it will stay that orientation until the position is moved close to another edge. The orientation may also be programmatically specified. The scalar bar itself text annotations can be queried or specified by retrieving or setting the scalar bar from the widget or the representation. One can then set the lookuptable or properties such as text annotations. One can also disable resizing by setting the SetResizable() method in the widget. Similarly one can disable repositioning using the SetSelectable() flag in the widget. This excerpt from VTK/Widgets/Testing/Cxx/TestScalarBarWidget.cxx illustrates its usage.

```
vtkScalarBarWidget *scalarWidget = vtkScalarBarWidget::New();
  scalarWidget->SetInteractor(iren);
  scalarWidget->GetScalarBarActor()->SetTitle("Temperature");
  scalarWidget->GetScalarBarActor()->
    SetLookupTable(outlineMapper->GetLookupTable());
```

vtkCaptionWidget. This widget provides support for interactively placing a textual caption on the 2D overlay plane, along with a leader (e.g., arrow) that points from the text to the point in the scene to be annotated. The caption is represented by a vtkCaptionRepresentation. One can interactively anchor the placement of the leader. The widget-representation internally contains an instance of vtkCaptionActor2D to display the caption. One can set the caption actor directly on the widget. The caption box automatically adjusts itself to fit the text based on its font size, justification and other text properties. The widget invokes a StartInteractionEvent, InteractionEvent and EndInteractionEvent at the beginning, during and end of an interaction. When the caption text is selected, the widget emits a ActivateEvent that observers can watch for. This is useful for opening GUI dialogs to adjust font characteristics, etc. The following excerpt from VTK/Widgets/Testing/Cxx/TestCaptionWidget.cxx shows how this widget is used to annotate a scene.

vtkCaptionWidget

```
// Create the widget
vtkCaptionActor2D *rep = vtkCaptionActor2D::New();
  rep->SetCaption("This is a test\nAnd it has two lines");
  rep->GetTextActor()->GetTextProperty()->
    SetJustificationToCentered();
  rep->GetTextActor()->GetTextProperty()->
    SetVerticalJustificationToCentered();

vtkCaptionWidget *widget = vtkCaptionWidget::New();
  widget->SetInteractor(iren);
  widget->SetCaptionActor2D(rep);
```

vtkOrientationMarkerWidget. The vtkOrientationMarkerWidget provides support for interactively manipulating the position, size, and orientation of a prop representing an orientation marker. The input orientation marker is rendered as an overlay on the parent renderer, thus it appears superposed over all provided props in the parent's scene. The camera view of the orientation marker is made to match that of the parent, so that it matches the scene's orientation. This class maintains its own ren-

derer which is added to the parent render window on a different layer. The camera view of the orientation marker is made to match that of the parent by means of a command-observer mechanism. This gives the illusion that the marker's orientation reflects that of the prop(s) in the parent's scene.

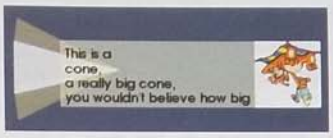
The widget listens to left mouse button and mouse movement events. It will change the cursor shape based on its location. If the cursor is over the overlay renderer, it will change the cursor shape to a SIZEALL shape. With a click followed by a drag, the orientation marker can be translated, (along with the overlay viewport). If the mouse cursor is near a corner, the cursor changes to a resize corner shape (e.g., SIZENW). With a click and a drag, the viewport, along with the orientation marker it contains is resized. The aspect ratio is maintained after releasing the left mouse button, to enforce the overlay renderer to be square, by making both sides equal to the minimum edge size. The widget also highlights itself when the mouse cursor is over it, by displaying an outline of the orientation marker.The widget requires an instance of an orientation marker prop to be set. The marker prop itself can be any subclass of vtkProp. Specifically, vtkAxesActor and vtkAnnoatedCubeActor are two classes that are designed to serve as orientation props. The former provides annotation in the form of annotated XYZ axes. The latter appears as a cube, with the 6 faces annotated with textures created from user specified text. A composite orientation marker can also be generated by adding instances of vtkAxesActor and vtkAnnoatedCubeActor to a vtkPropAssembly, which can then be set as the input orientation marker. The widget can be also be set up programmatically, in a non-interactive fashion by setting Interactive to Off and sizing/placing the overlay renderer in its parent viewport by calling the widget's SetViewport method. The following illustrates a typical usage; for a more complex use case see VTK/Widgets/Testing/Cxx/TestOrientationMarkerWidget.cxx.

vtkOrientationMarkerWidget

```
vtkAnnotatedCubeActor* cube = vtkAnnotatedCubeActor::New();
  cube->SetXPlusFaceText ( "A" );
  cube->SetXMinusFaceText( "P" );
  cube->SetYPlusFaceText ( "L" );
  cube->SetYMinusFaceText( "R" );
  cube->SetZPlusFaceText ( "S" );
  cube->SetZMinusFaceText( "I" );
  cube->SetFaceTextScale( 0.666667 );
  cube->SetFaceTextScale( 0.65 );
property = cube->GetCubeProperty();
property->SetColor( 0.5, 1, 1 );
property = cube->GetTextEdgesProperty();
property->SetLineWidth( 1 );
property->SetDiffuse( 0 );
property->SetAmbient( 1 );
property->SetColor( 0.1800, 0.2800, 0.2300 );

// this static function improves the appearance of the text edges
// since they are overlaid on a surface rendering of the cube's faces
vtkMapper::SetResolveCoincidentTopologyToPolygonOffset();

vtkOrientationMarkerWidget* widget = vtkOrientationMarkerWidget::New();
```

```
widget->SetOutlineColor( 0.9300, 0.5700, 0.1300 );
widget->SetOrientationMarker( cube );
widget->SetInteractor( iren );
widget->SetViewport( 0.0, 0.0, 0.4, 0.4 );
widget->SetEnabled( 1 );
```

vtkBalloonWidget. This widget is used to popup annotations when the mouse hovers over an actor for a specified time. The annotation may be text and/or an images annotation when the mouse hovers over an actor for a specified time. The widget keeps track of user chosen props by associating an instance of a vtkProp with an instance of a "balloon". The balloon encapsulates annotations (text and/or images). The balloon is brought up with user specified properties near the vtkProp when the mouse cursor hovers over it for a specified delay. An instance of vtkBalloonRepresentation is used to draw the balloon. To use this widget, first specify an instance of vtkBalloonWidget and the representation. Then list all instances of vtkProp, a text string, and/or an instance of vtkImageData to be associated with each vtkProp. (Note that you can specify both text and an image, or just one or the other.) You may also wish to specify the hover delay. The widget invokes a WidgetActivateEvent before a balloon pops up, that observers can watch for. VTK/Widgets/Testing/Cxx/TestBalloonWidget.cxx illustrates a typical usage.



vtkBalloonWidget

```
class vtkBalloonCallback : public vtkCommand
  {
  virtual void Execute(vtkObject *caller, unsigned long, void*)
    {
      vtkBalloonWidget *balloonWidget =
        reinterpret_cast<vtkBalloonWidget*>(caller);
      if ( balloonWidget->GetCurrentProp() != NULL )
        {
        cout << "Prop selected\n";
        }
    }
  };

...

vtkBalloonRepresentation *rep = vtkBalloonRepresentation::New();
  rep->SetBalloonLayoutToImageRight();

vtkBalloonWidget *widget = vtkBalloonWidget::New();
  widget->SetInteractor(iren);
  widget->SetRepresentation(rep);
  widget->SetTimerDuration( 3000 ); // hover delay in ms.
  widget->AddBalloon(sph,"This is a sphere",NULL);
  widget->AddBalloon(cyl,"This is a\ncylinder",image1->GetOutput());
  widget->AddBalloon(cone,"This is a\ncone,\na really big cone,\nyou
    wouldn't believe how big",image1->GetOutput());

vtkBalloonCallback *cbk = vtkBalloonCallback::New();
  widget->AddObserver(vtkCommand::WidgetActivateEvent,cbk);
```

vtkTextWidget

vtkTextWidget. This class provides support for interactively placing text on the 2D overlay plane. The text is defined by an instance of vtkTextActor. It derives from vtkBorderWidget and inherits its border selection and resizing capabilities. The text border may be selected with the left mouse button. A click and a drag resizes the border along a particular direction, determined by the corner or face along which the text boundary is selected. The text along with its boundary may also be translated using the selecting the text box near the center. One can disable resizing and moving by turning the Selectable flag on the widget. In addition, when the text is selected, the widget emits a WidgetActivateEvent that observers can watch for. This is useful for opening GUI dialogues to adjust font characteristics, etc. The widget also invokes a StartInteractionEvent, an InteractionEvent and an EndInteractionEvent prior to, during and after user interaction with the widget.

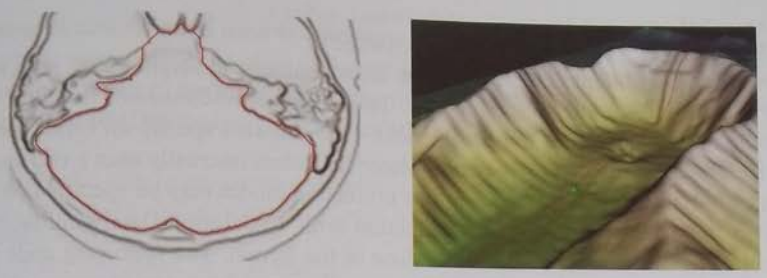
One can retrieve the text property (vtkTextProperty) from the text actor managed by the widget to change the properties of the text (font, font size, justification etc.). The following excerpt from VTK/Widgets/Testing/Cxx/TestTextWidget.cxx illustrates this widget's usage.

```
vtkTextActor *ta = vtkTextActor::New();
  ta->SetInput("This is a test");

vtkTextWidget *widget = vtkTextWidget::New();
  widget->SetInteractor(iren);
  widget->SetTextActor(ta);
  widget->SelectableOff();
```

Segmentation / Registration widgets

vtkContourWidget. The contour widget is a very flexible class which may be used to draw closed or open contours by interactively defining a set of control points. The widget has two modes. When enabled, one enters a "define" mode through which the user can place control points in succession by clicking the left mouse button. A contour is drawn passing through the nodes and interpolated between the nodes according to some interpolation kernel. After the user has placed the points, he presses the right mouse button. This takes the widget into a "manipulate" mode. The widget may also enter the "manipulate" mode if the user closes the contour by clicking near the first control point. In this mode, the user can interactively manipulate the contour. Mousing over a control point will highlight the control point; users can click on a control point and move it around. This moves the node and its associated lines, satisfying the constraint imposed by the interpolator. Clicking on the contour (but not on the node), adds a node at that point. That node may be further manipulated. Mousing over a node and hitting the "Delete" or "Backspace" key removes the node and re-interpolates the lines with the remaining nodes.

The contour widget is designed to work with a subclass of vtkContourRepresentation. Several representations are provided. Two important ancillary classes used by the contour widget are the "vtkContourLineInterpolator" and "vtkPointPlacer". The class vtkContourLineInterpolator is an abstract class that enables the user to specify the interpolation used to define curves between nodes. The class



vtkContourWidget

vtkPointPlacer allows the user to impose constraints on the placement of the control points. Several point placers and interpolators are provided. For instance, the class vtkBezierContourLineInterpolator, constrains the interpolation between nodes to be a bezier curve.

```
vtkOrientedGlyphContourRepresentation *contourRep =
  vtkOrientedGlyphContourRepresentation::New();
vtkContourWidget *contourWidget = vtkContourWidget::New();
  contourWidget->SetInteractor(iren);
  contourWidget->SetRepresentation(contourRep);
vtkBezierContourLineInterpolator * interpolator =
  vtkBezierContourLineInterpolator::New();
contourRep->SetLineInterpolator(interpolator);
contourWidget->SetEnabled(1);
```

A user can draw contours on polygonal surfaces using vtkPolygonalSurfaceContourLineInterpolator. This interpolator places its lines on the surface of a specified vtkPolyData. It is meant to be used in conjunction with a vtkPolygonalSurfacePointPlacer. This placer constrains the placement of control point nodes on the surface of the polydata. The interpolator internally uses a Dijkstra single source shortest path algorithm to compute the shortest path from one control point to the next. The costs for the paths are determined by the edge lengths in the mesh. The resulting path traverses along the edges of the mesh from one node to the next. This example from VTK/Widgets/Testing/Cxx/TestDijkstraGraphGeodesicPath.cxx illustrates its usage.

```
vtkContourWidget *contourWidget = vtkContourWidget::New();
contourWidget->SetInteractor(iren);
vtkOrientedGlyphContourRepresentation *rep =
  vtkOrientedGlyphContourRepresentation::SafeDownCast(
    contourWidget->GetRepresentation());

vtkPolygonalSurfacePointPlacer * pointPlacer
  = vtkPolygonalSurfacePointPlacer::New();
  pointPlacer->AddProp(demActor);
  pointPlacer->GetPolys()->AddItem( pd );
rep->SetPointPlacer(pointPlacer);

vtkPolygonalSurfaceContourLineInterpolator * interpolator =
  vtkPolygonalSurfaceContourLineInterpolator::New();
```

```
    interpolator->GetPolys()->AddItem( pd );
  rep->SetLineInterpolator(interpolator);
```

Using vtkTerranContourLineInterpolator, one can draw contours on height fields, such as Digital Elevation Maps vtkTerrainContourLineInterpolator. This interpolator constrains the lines between control points to lie on the surface of the height field. One can also specify an offset for the lines, by using the SetHeightOffset method on the interpolator. The class internally uses a vtkProjectedTerrainPath to project a polyline on the surface. Various projection modes may be specified on the projector. This interpolator is meant to be used in conjunction with a vtkTerrainDataPointPlacer, which constrains the control point nodes to lie on the surface of the terrain. The following code snippet, from VTK/Widgets/Testing/Cxx/TerrainPolylineEditor.cxx illustrates how one may use this interpolator and point placer.

```
vtkContourWidget *contourWidget = vtkContourWidget::New();
vtkOrientedGlyphContourRepresentation *rep =
  vtkOrientedGlyphContourRepresentation::SafeDownCast(
    contourWidget->GetRepresentation());

vtkTerrainDataPointPlacer * pointPlacer =
  vtkTerrainDataPointPlacer::New();
  pointPlacer->AddProp(demActor); // the actor(s) containing the terrain
rep->SetPointPlacer(pointPlacer);

// Set a terrain interpolator. Interpolates points as they are placed,
// so that they lie on the terrain.
vtkTerrainContourLineInterpolator *interpolator =
  vtkTerrainContourLineInterpolator::New();
rep->SetLineInterpolator(interpolator);
interpolator->SetImageData(demReader->GetOutput());

// Set the default projection mode to hug the terrain, unless user
// overrides it.
interpolator->GetProjector()->SetProjectionModeToHug();
interpolator->GetProjector()->SetHeightOffset(20.0);
pointPlacer->SetHeightOffset(20.0);
```

Of particular interest is the "live wire" interpolator (vtkDijkstraImageContourLineInterpolator) where the lines between the control points are interpolated based on the shortest path through the gradient cost function computed on the image, resulting in the contours being attracted to the edges of the image. As the control points are moved around, a new shortest path is computed. This is ideal for interactive segmentation of organs, etc. This interpolator internally uses a vtkDijkstraImageGeodesicPath, which generates a single source shortest path through a cost function image by treating it as a graph with VTK_PIXEL cells. The user is free to plug in the cost function. A typical cost function for a gray scale image might be generated by the following pipeline:

```
Image --> vtkImageGradientMagnitude --> vtkImageShiftScale
```

The gradient magnitude image is inverted, so that strong edges have low cost value. Costs in moving from one vertex to another are calculated using a weighted additive scheme. One can set the edge length weight, the curvature weight and the weight associated with the normalized image cost. These

affect the computed cost function used to determine the shortest path. The contours are meant to be placed on an image actor, hence the class vtkImageActorPointPlacer is used. This restricts the placement of control point nodes to the plane containing the image. The following code snippet from VTK/Widgets/Testing/Cxx/TestDijkstraImageGeodesicPath.cxx illustrates its usage.

```
vtkOrientedGlyphContourRepresentation *rep =
  vtkOrientedGlyphContourRepresentation::New();
vtkImageActorPointPlacer *placer = vtkImageActorPointPlacer::New();
placer->SetImageActor( actor );
rep->SetPointPlacer( placer );

vtkDijkstraImageContourLineInterpolator *interpolator =
  vtkDijkstraImageContourLineInterpolator::New();
  interpolator->SetCostImage( gradInvert->GetOutput() );
rep->SetLineInterpolator( interpolator );

vtkDijkstraImageGeodesicPath* path =
  interpolator->GetDijkstraImageGeodesicPath();
  path->StopWhenEndReachedOn();

// prevent contour segments from overlapping
path->RepelPathFromVerticesOn();

// weights are scaled from 0 to 1 as are associated cost components
path->SetCurvatureWeight( 0.15 );
path->SetEdgeLengthWeight( 0.8 );
path->SetImageWeight( 1.0 );
```

vtkImageTracerWidget. This widget provides support to trace free form contours through a planar surface (i.e., manually tracing over image data). The user can click the left button over the image, hold and drag to draw a freehand line. Clicking the left button and releasing erases the widget line, if it exists, and repositions the first handle. A middle button click starts a snap drawn line. The line can be terminated by clicking the middle button while depressing the ctrl key. The contour loop being traced will be automatically closed when the user clicks the last cursor position within a specified tolerance to the first handle. The user can drag a handle (and its associated line segments) by clicking the right button on any handle that is part of a snap drawn line. If the path is open and the flag AutoClose is set to On, the path can be closed by repositioning the first and last points over one another. A handle can be erased by pressing the ctrl key along with the right button on the handle. Again, the snap drawn line segments are updated. If the line was formed by continuous tracing, the line is deleted leaving one handle. A handle can be inserted by pressing the shift key and the right button on any snap drawn line segment. This will insert a handle at the cursor position. The line segment is split accordingly on either side of the cursor. One can disable interaction on the widget by using the SetInteraction method.

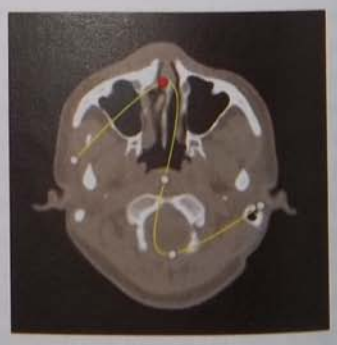
vtkImageTracerWidget

Since the widget exists on a plane, (the handles, etc. are 2D glyphs), one must specify the plane on which the widget lies. This is done by specifying the projection normal vector, via SetProjectionNormal and the plane's position via SetProjectionPosition. In the excerpt below, the projection normal is set to the X axis. The user can force snapping to the image data while tracing by using the flag SnapToImage. The user can change the handle and line properties, using the methods SetHandleProperty and SetLineProperty, or the SetSelectedHandleProperty and SetSelectedLineProperty.

The widget invokes InteractionEvent and EndInteractionEvents. At this point, the current path may be retrieved as a polydata via the GetPath method, so that segmentation etc may be performed on the underlying image. The widget can also be initialized from a user specified set of control points, by using the method InitializeHandles. This takes a pointer to a vtkPoints instance, containing the list of points. VTK/Widgets/Testing/Cxx/TestImageTracerWidget.cxx illustrates how one may use the vkImageTracerWidget and a vtkSplineWidget to segment images. The following is an excerpt.

```
vtkImageTracerWidget* imageTracerWidget = vtkImageTracerWidget::New();
  imageTracerWidget->SetDefaultRenderer(ren1);
  imageTracerWidget->SetCaptureRadius(1.5);
  imageTracerWidget->GetGlyphSource()->SetColor(1, 0, 0);
  imageTracerWidget->GetGlyphSource()->SetScale(3.0);
  imageTracerWidget->GetGlyphSource()->SetRotationAngle(45.0);
  imageTracerWidget->GetGlyphSource()->Modified();
  imageTracerWidget->ProjectToPlaneOn();
  imageTracerWidget->SetProjectionNormalToXAxes();
  imageTracerWidget->SetProjectionPosition(imageActor1->
    GetBounds()[0]);
  imageTracerWidget->SetViewProp(imageActor1);
  imageTracerWidget->SetInput(shifter->GetOutput());
  imageTracerWidget->SetInteractor(iren);
  imageTracerWidget->PlaceWidget();
  imageTracerWidget->SnapToImageOff();
  imageTracerWidget->AutoCloseOn();
```

vtkSplineWidget. This is another widget that can be used to trace contours using a spline kernel. The widget predates the rearchitecturing efforts that culminated in vtkContourWidget. It derives from vtk3DWidget. The spline has handles, the number of which can be changed, plus it can be picked on the spline itself to translate or rotate it in the scene. The widget responds to the following keyboard and mouse modifiers. 1) left button down on and drag one of the spherical handles to change the shape of the spline: the handles act as "control points". 2) left button or middle button down on a line segment forming the spline allows uniform translation of the widget. 3) ctrl + middle button down on the widget enables spinning of the widget about its center. 4) right button down on the widget enables scaling of the widget. By moving the mouse "up" the render window the spline will be made bigger; by moving "down" the render window the widget will be made smaller. 5) ctrl key + right button down on any handle will erase it providing



vtkSplineWidget

there will be two or more points remaining to form a spline. 6) shift key + right button down on any line segment will insert a handle onto the spline at the cursor position.

The vtkSplineWidget has several methods that can be used in conjunction with other VTK objects. The Set/GetResolution() methods control the number of subdivisions of the spline. The GetPolyData() method can be used to get the polygonal representation and for things like seeding streamlines or probing other datasets. Typically the widget is used to make use of the StartInteractionEvent, InteractionEvent, and EndInteractionEvent events. The InteractionEvent is called on mouse motion, the other two events are called on button down and button up (either left or right button).

Some additional features of this class include the ability to control the properties of the widget. You can set the properties of the selected and unselected representations of the spline. For example, you can set the property for the handles and spline. In addition there are methods to constrain the spline so that it is aligned with a plane. As with vtkImageTracerWidget, one can specify the plane on which the widget lies. This is done by specifying the projection normal vector, via SetProjectionNormal and the plane's position via SetProjectionPosition. The GetSummedLength returns the approximate arc length of the spline by summing the line segments making up the spline. The SetClosed method can be used to close the spline loop.

Using the SetParametricSpline method, one can also set the parametric spline object. Through vtkParametricSpline's API, the user can supply and configure one of currently two types of spline: vtkCardinalSpline or vtkKochanekSpline. The widget controls the open or closed configuration of the spline. The following excerpt from VTK/Widgets/Testing/Cxx/TestSplineWidget.cxx illustrates the usage of this widget.

```
vtkSplineWidget* spline = vtkSplineWidget::New();
  spline->SetInput(v16->GetOutput());
  spline->SetPriority(1.0);
  spline->KeyPressActivationOff();
  spline->PlaceWidget();
  spline->ProjectToPlaneOn();
  spline->SetProjectionNormal(0);
  spline->SetProjectionPosition(102.4); //initial plane position
  spline->SetProjectionNormal(3); //allow oblique orientations
  spline->SetPlaneSource(
static_cast<vtkPlaneSource*>(ipw->GetPolyDataAlgorithm()));

// Specify the type of spline (change from default vtkCardinalSpline)
vtkKochanekSpline* xspline = vtkKochanekSpline::New();
vtkKochanekSpline* yspline = vtkKochanekSpline::New();
vtkKochanekSpline* zspline = vtkKochanekSpline::New();

vtkParametricSpline* para = spline->GetParametricSpline();
  para->SetXSpline(xspline);
  para->SetYSpline(yspline);
  para->SetZSpline(zspline);

vtkPolyData* poly = vtkPolyData::New();
spline->GetPolyData(poly);
```

vtkCheckerboardWidget. The checkerboard widget is used to interactively control a checkerboard through an image actor displaying two images. This is useful in evaluating the quality of an image registration. The user can adjust the number of checkerboard divisions in each of the i-j directions in a 2D image. The widget is meant to be used in conjunction with a vtkCheckerboardRepresentation. When enabled, a frame appears around the vtkImageActor with sliders along each side of the frame. A total of 4 sliders are provided for the two checkerboards, along both the i and j directions. (This internally uses a vtkSliderRepresentation3D). The user can interactively adjust the sliders (see vtkSliderWidget) to the desired number of checkerboard subdivisions. The user can override the default slider representations by setting their own slider representations on the widget. The widget needs an instance of a vtkImageCheckerBoard which, in turn, takes two images as input to generate the checkerboard. The following example from VTK/Widgets/Testing/Cxx/TestCheckerboardWidget.cxx illustrates a typical usage.

vtkCheckerboardWidget

```
vtkImageCheckerboard *checkers = vtkImageCheckerboard::New();
  checkers->SetInput(0,image1);
  checkers->SetInput(1,image2);
  checkers->SetNumberOfDivisions(10,6,1);

vtkImageActor *checkerboardActor = vtkImageActor::New();
  checkerboardActor->SetInput(checkers->GetOutput());

vtkCheckerboardRepresentation *rep =
  vtkCheckerboardRepresentation::New();
  rep->SetImageActor(checkerboardActor);
  rep->SetCheckerboard(checkers);

vtkCheckerboardWidget *checkerboardWidget =
  vtkCheckerboardWidget::New();
  checkerboardWidget->SetInteractor(iren);
  checkerboardWidget->SetRepresentation(rep);
```

vtkRectilinearWipeWidget. The vtkRectilinearWipeWidget displays a split view (2x2 checkerboard) of a pair of images allowing one to control the location of the split. This is useful in comparing two images, typically the registered image from the source image in an image registration pipeline. A rectilinear wipe is a 2x2 checkerboard pattern created by combining two separate images, where various combinations of the checker squares are possible. It must be noted that although the this widget appears similar in functionality to the checkerboard widget, there are important differences. Using this widget, the user can adjust the layout of the checker pattern, such as moving the center point, moving the horizontal separator, or moving the vertical separator. The location of the wipe (interface between the two images) can be changed to any point in the image, unlike the checkerboard widget, where one can interactively only change the resolution the checkerboard.?One can select the horizontal separator and the vertical separator by selecting the separator using the left mouse button. Dragging with the button depressed moves the separators. Selecting the center point allows you to move

the horizontal and vertical separators simultaneously. To use this widget, specify its representation (by default the representation is an instance of vtkRectilinearWipeProp).

The representation requires that you specify an instance of vtkImageRectilinearWipe and an instance of vtkImageActor. One can specify various "wipe" modes on the vtkImageRectilinearWipe instance. These modes determine how the two input images are combined together. The first is a quad mode, using the method SetWipeToQuad. In this mode, the inputs alternate horizontally and vertically. One can get a purely horizontal or a vertical wipe using SetWipeToHorizontal or SetWipeToVertical. In this mode, one half of the image comes from one input, and the other half from the other input. One can also get a corner wipe, with 3 inputs coming from one input image and one coming from the other input image, by using the methods SetWIpeToLowerLeft, SetWipeToLowerRight, SetWipeToUpperLeft and SetWipeToUpperRight. The following excerpt from VTK/Widgets/Testing/Cxx/TestRectilinearWipeWidget.cxx illustrates its usage.

vtkRectilinearWipeWidget

```
vtkImageRectilinearWipe *wipe = vtkImageRectilinearWipe::New();
  wipe->SetInput(0,pad1->GetOutput());
  wipe->SetInput(1,pad2->GetOutput());
  wipe->SetPosition(100,256);
  wipe->SetWipeToQuad();

vtkImageActor *wipeActor = vtkImageActor::New();
  wipeActor->SetInput(wipe->GetOutput());

vtkRectilinearWipeWidget *wipeWidget = vtkRectilinearWipeWidget::New();
vtkRectilinearWipeRepresentation *wipeWidgetRep=
  static_cast<vtkRectilinearWipeRepresentation *>(
    wipeWidget->GetRepresentation());

wipeWidgetRep->SetImageActor(wipeActor);
wipeWidgetRep->SetRectilinearWipe(wipe);
wipeWidgetRep->GetProperty()->SetLineWidth(2.0);
wipeWidgetRep->GetProperty()->SetOpacity(0.75);
```

vtkSeedWidget. The vtkSeedWidget can be used to place multiple seed points. These are typically used for operations such as connectivity, segmentation, region growing, fiducials for image registration. This widget works in conjunction with an instance of a vtkSeedRepresentation (a subclass of vtkSeedRepresentation). The widget internally contains instances of vtkHandleWidget, to represent each seed. The handle widgets can, in turn, be represented by any subclass of vtkHandleRepresentation. vtkPointHandleRepresentation2D can be used to define seeds on a 2D overlay plane. vtkPointHandleRepresentation3D can be used to represent

vtkSeedWidget

seeds in a 3D scene. One can set the appropriate handle representation using the SetHandleRepresentation method in vtkSeedRepresentation.

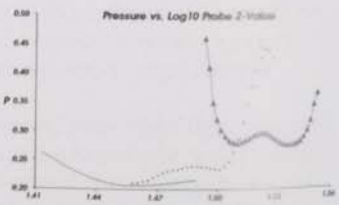
Once a vtkSeedWidget is enabled, the user can drop seed points by pressing the left mouse button. After the user has finished dropping seeds, a click of the right button terminates placing and sends the widget into a "manipulate" mode. In this mode, the user can select a seed by clicking on it with the left mouse button and drag it around with the button depressed, to translate it. Much like the handle widget, the seeds responds to translation along an axis, by dragging it with the shift key depressed; the axes being determined as the one most aligned with the mouse motion vector. One can delete the currently selected handle by pressing the "Delete" key. If no seed was selected, pressing the delete key, removes the last added seed.

When a seed is placed, the widget invokes an PlacePointEvent, that observers can watch for. Much like the other widgets, the vtkSeedWidget also invokes StartInteractionEvent, InteractionEvent and EndInteractionEvent before, during and after user interaction. The following excerpt from VTK/Widgets/Testing/Cxx/TestSeedWidget2.cxx illustrates a typical usage.

```
vtkPointHandleRepresentation2D *handle =
  vtkPointHandleRepresentation2D::New();
  handle->GetProperty()->SetColor(1,0,0);
vtkSeedRepresentation *rep = vtkSeedRepresentation::New();
  rep->SetHandleRepresentation(handle);

vtkSeedWidget *widget = vtkSeedWidget::New();
  widget->SetInteractor(iren);
  widget->SetRepresentation(rep);
```

Miscellaneous

vtkXYPlotWidget. The vtkXYPlotWidget provides support for interactively manipulating the position, size, and orientation of a XY Plot. The widget is typically used to generate XY plots from one or more input data sets or field data. It internally contains an instance of a vtkXYPlotActor to perform to plotting functionality. One can retrieve this instance via GetXYPlotActor(). The x-axis values in vtkXYPlotActor are generated by taking the point ids, computing a cumulative arc length, or a normalized arc length. More than one input data set can be specified to generate multiple plots. Alternatively, if field data is supplied as input, the class plots one component against another. The user must specify which component to use as the x-axis and which for the y-axis.



vtkXYPlotWidget

To use this class to plot dataset(s), the user specifies one or more input datasets containing scalar and point data. To use this class to plot field data, the user specifies one or more input data objects with its associated field data. When plotting field data, the x and y values are used directly (i.e., there are no options to normalize the components). Users have the ability to specify axes labels, label format and plot title, using the methods SetTitle, SetXTitle and SetYTitle. One can also manually specify the x and y plot ranges (by default they are computed automatically) using the methods SetXRange and SetYRange. Data outside the specified range is clipped. One can also specify the number of specify the number of annotation labels along the axes using SetNumberOfXLabels and SetNumberOfY-

Labels methods. Similarly the number of X and Y minor ticks can be controlled using the methods SetNumberOfXMinorTicks and SetNumberOfYMinorTicks. The Border instance variable is used to create space between the boundary of the plot window, the region that can be resized interactively. The font property of the plot title can be modified using SetTitleTextProperty. The font property of the axes titles and labels can also be modified using SetAxisTitleTextProperty and SetAxisLabelTextProperty. Users can also use the GetXAxisActor2D or GetYAxisActor2D methods to access each individual axis actor to modify their font properties. This returns instances of vtkAxisActor2D. In the same way, the GetLegendBoxActor method can be used to access the legend box actor to modify its font properties.

Users can also assign per curve properties (such as color and a plot symbol). Users may choose to is to add a plot legend that graphically indicates the correspondence between the curve, curve symbols, and the data source. The legend can be turned on/off using LegendOn/Off(). Users can also exchange the x and y axes to re-orient the plot by using the method ExchangeAxis. Users can also reverse the X and Y axis by using the method ReverseXAxis and ReverseYAxis. Users can plot on a log scale with LogXOn().

The widget allows the actor to be interactively resized and repositioned. It listens to Left mouse events and mouse movement. It will change the cursor shape based on its location. If the cursor is over an edge of the plot it will change the cursor shape to the appropriate resize edge shape. Users can then left click and drag to resize. If the cursor hovers near the center, the cursor will change to a four way translate shape. Users can then left click and drag to reposition the plot. If the position of a XY plot is moved to be close to the center of one of the four edges of the viewport, then the XY plot will change its orientation to align with that edge. This orientation is sticky in that it will stay that orientation until the position is moved close to another edge. The following code excerpt shows how one may use this widget.

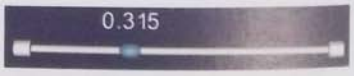
```
vtkXYPlotWidget * widget = vtkXYPlotWidget::New();
 widget->SetInteractor(iren);

// Get the plot actor so we can adjust properties on the actor.
vtkXYPlotActor *plotActor = widget->GetXYPlotActor();
xyplot->AddInput(probe->GetOutput());
xyplot->AddInput(probe2->GetOutput());
xyplot->AddInput(probe3->GetOutput());
xyplot->GetPositionCoordinate()->SetValue(0.0, 0.67, 0);
xyplot->GetPosition2Coordinate()->SetValue(1.0, 0.33, 0);

// relative to Position
xyplot->SetXValuesToArcLength();
xyplot->SetNumberOfXLabels(6);
xyplot->SetTitle("Pressure vs. Arc Length - Zoomed View");
xyplot->SetXTitle(""); // no X title
xyplot->SetYTitle("P");
xyplot->SetXRange(.1, .35);
xyplot->SetYRange(.2, .4);
xyplot->GetProperty()->SetColor(0, 0, 0);
xyplot->GetProperty()->SetLineWidth(2);

vtkTextProperty *tprop = xyplot->GetTitleTextProperty();
  tprop->SetColor(xyplot->GetProperty()->GetColor());
```

```
xyplot->SetAxisTitleTextProperty(tprop);
xyplot->SetAxisLabelTextProperty(tprop);
xyplot->SetLabelFormat("%-#6.2f");
widget->SetEnabled(1);
```

vtkCompassWidget

vtkCompassWidget. The compass widget provides support for interactively annotating and manipulating the orientation of a geo-spatial scene. The class also features zoom and tilt controls to position oneself in a geospatial view. This widget is used in the GeoVis views of VTK ("Geospatial Visualization" on page 207). You may drag the heading wheel to change the widget's heading, and may pull the sliders to animate the zoom level or tilt of the widget. The widget is most readily used in conjunction with a vtkGeoCamera, which retains camera positions in terms of the three parameters heading, tilt, and zoom. The following code shows how the widget's properties can be linked to a vtkGeoCamera in the event handler of the widget's InteractionEvent.

```
vtkGeoCamera* camera = vtkGeoCamera::New();
vtkCompassWidget* widget = vtkCompassWidget::New();
  widget->CreateDefaultRepresentation();

// In callback for InteractionEvent:
camera->SetHeading(widget->GetHeading()*360.0);
camera->SetTilt(widget->GetTilt());
camera->SetDistance(widget->GetDistance());
```



vtkSliderWidget

vtkSliderWidget. This widget provides functionality to manipulate a slider along a 1D range. The widget is meant to be used in conjunction with an instance of vtkSliderRepresentation. Two concrete representations are provided with the toolkit: vtkSliderRepresentation2D and vtkSliderRepresentation3D. vtkSliderRepresentation2D, renders the slider on the overlay plane, while vtkSliderRepresentation3D renders the slider in 3D space. The range is represented by a tube, with a bead for the slider, and two caps at the ends delineating the lower and upper bounds. These properties may be changed by using the methods SetSliderWidth(), SetSliderLength(), SetTubeWidth(), SetEndCapLength() and SetEndCapWidth() on vtkSliderRepresentation. The properties of the caps / tubes, etc. can also be retrieved and modified. Similarly, the slider properties can also be modified both when its selected and when its not.

One optionally can display a title next to the slider using the methods SetTitleText(). One can also display the current slider value next to it using the method ShowSliderLabelOn().

Lower and upper bounds on the slider value may be set using SetMinimumValue() and SetMaximumValue(). The SetValue() method itself can be used to programmatically set the current value of the slider.

The slider is selected using the left button. A drag with the left button depressed moves the slider along the tube. If the tube or one of the two endcaps is selected, the slider jumps or animates to the selected location. The user may choose the desired behavior by using the methods, SetAnimationModeToJump() or SetAnimationModeToAnimate(). The number of steps used for animation (if the

mode is animate) may be controlled using SetNumberOfAnimationSteps(). Alternatively, one may disable this behavior altogether by using SetAnimationModeToOff().

The widget invokes StartInteractionEvent, InteractionEvent and EndInteractionEvent before, during and after user interaction. The following excerpt from VTK/Widgets/Testing/Cxx/TestSliderWidget.cxx illustrates the usage of the vtkSliderWidget in conjunction with a vtkSliderRepresentation3D.

```
vtkSliderRepresentation3D *sliderRep =
  vtkSliderRepresentation3D::New();
  sliderRep->SetValue(0.25);
  sliderRep->SetTitleText("Spike Size");
  sliderRep->GetPoint1Coordinate()->SetCoordinateSystemToWorld();
  sliderRep->GetPoint1Coordinate()->SetValue(0,0,0);
  sliderRep->GetPoint2Coordinate()->SetCoordinateSystemToWorld();
  sliderRep->GetPoint2Coordinate()->SetValue(2,0,0);
  sliderRep->SetSliderLength(0.075);
  sliderRep->SetSliderWidth(0.05);
  sliderRep->SetEndCapLength(0.05);

vtkSliderWidget *sliderWidget = vtkSliderWidget::New();
  sliderWidget->SetInteractor(iren);
  sliderWidget->SetRepresentation(sliderRep);
  sliderWidget->SetAnimationModeToAnimate();
  sliderWidget->EnabledOn();
```

The following excerpt from VTK/Widgets/Testing/Cxx/TestSliderWidget2D illustrates the usage of vtkSliderWidget in conjunction with vtkSliderRepresentation2D to render the slider on the overlay plane.

```
vtkSliderRepresentation2D *sliderRep =
  vtkSliderRepresentation2D::New();
  sliderRep->SetValue(0.25);
  sliderRep->SetTitleText("Spike Size");
  sliderRep->GetPoint1Coordinate()->
    SetCoordinateSystemToNormalizedDisplay();
  sliderRep->GetPoint1Coordinate()->SetValue(0.2,0.1);
  sliderRep->GetPoint2Coordinate()->
    SetCoordinateSystemToNormalizedDisplay();
  sliderRep->GetPoint2Coordinate()->SetValue(0.8,0.1);
  sliderRep->SetSliderLength(0.02);
  sliderRep->SetSliderWidth(0.03);
  sliderRep->SetEndCapLength(0.01);
  sliderRep->SetEndCapWidth(0.03);
  sliderRep->SetTubeWidth(0.005);

vtkSliderWidget *sliderWidget = vtkSliderWidget::New();
  sliderWidget->SetInteractor(iren);
  sliderWidget->SetRepresentation(sliderRep);
  sliderWidget->SetAnimationModeToAnimate();
```

vtkCenteredSliderWidget. PThe vtkCenteredSliderWidget is similar to the vtkSliderWidget. Its interactions however provide joystick based control on the slider. The widget is meant to be used in conjunction with an instance of vtkCenteredSliderRepresentation. When unselected, the slider always stays at the center. The user can select the slider by pressing the left button. The user can then drag and move the slider upwards or downwards with the button depressed, thereby increasing or decreasing the value the slider represents. The increase (or decrease) is proportional to both the time the the slider is depressed and held away from the center and to the magnitude of deviation of the slider from its center. Upon releasing, the slider returns to the midpoint. The representation is used internally in vtkCompassRepresentation to represent the tilt and the distance values of the compass. Thus one can move the slider gently upwards to watch the camera tilt slowly forward. Alternatively one can yank the slider upwards to tilt the camera rapidly forward. The vtkCenteredSliderWidget like other widgets invokes StartInteractionEvent, InteractionEvent and EndInteractionEvent before, during and after user interaction. Usage of the centered slider widget is very similar to vtkSliderWidget. The GetValue() method on the widget can be used to query the value at any instant.

vtkCenteredSliderWidget

vtkCameraWidget. The vtkCameraWidget provides support for interactively saving and playing a series of camera views into an interpolated path. The interpolation itself is done using an instance of vtkCameraInterpolator. The user can use the widget to record a series of views and then play back interpolated camera views using the vtkCameraInterpolator. To use this widget, the user specifies a camera to interpolate, and then starts recording by hitting the "record" button. Then one manipulates the camera (by using an interactor, direct scripting, or any other means). After completion of interaction, one then saves the camera view. One can repeat this process to record a series of views.

vtkCameraWidget

The widget is meant to be used in conjunction with an instance of vtkCameraRepresentation. The representation's geometry consists of a camera icon, a play-stop icon and a delete icon. These are rendered on the overlay plane. Pressing the camera icon adds the view defined by the current camera parameters to the interpolated camera path. Pressing the play button interpolates frames along the current path. The camera interpolator can be retrieved by using the method GetCameraInterpolator on the representation. One can use the interpolator to set the interpolation type (linear or spline). The SetNumberOfFrames method on the representation can be used to control the number of frames used for interpolation between two camera nodes while animating the camera path. The following excerpt from VTK/Widgets/Testing/Cxx/TestCameraWidget.cxx illustrates a typical usage.

```
vtkCameraRepresentation *rep = vtkCameraRepresentation::New();
  rep->SetNumberOfFrames(2400);

vtkCameraWidget *widget = vtkCameraWidget::New();
  widget->SetInteractor(iren);
  widget->SetRepresentation(rep);
```

vtkPlaybackWidget. pThe vtkPlaybackWidget provides support for interactively controlling the playback of a serial stream of information (e.g., animation sequence, video). Controls for play, stop, advance one step forward, advance one step backward, jump to beginning, and jump to end are available. The widget works in conjunction with an instance of vtkPlaybackRepresentation. The representation exists on the overlay plane and derives from vtkBorderWidget. It can be interactively resized or repositioned using the corners/edges or near the center. Six controls, in the form of icons, are provided by the playback widget. These controls allow for (a) Jumping to the beginning of the frame (b) Reverting one frame (c) Stop playback (d) Play (e) Jump forward one frame (f) Jump to the end. The implementation is left to the subclass. ie. Users are expected to subclass vtkPlaybackRepresentation to provide their own implementations for the 6 controls above. The following excerpt from VTK/Widgets/Testing/Cxx/TestPlaybackWidget.cxx illustrates a typical usage.

vtkPlaybackWidget

```
class vtkSubclassPlaybackRepresentation : public
  vtkPlaybackRepresentation
  {
  public:
  static vtkSubclassPlaybackRepresentation *New()
    {return new vtkSubclassPlaybackRepresentation;}
  virtual void Play() {cout << "play\n";}
  virtual void Stop() {cout << "stop\n";}
  virtual void ForwardOneFrame() {cout << "forward one frame\n";}
  virtual void BackwardOneFrame() {cout << "backward one frame\n";}
  virtual void JumpToBeginning() {cout << "jump to beginning\n";}
  virtual void JumpToEnd() {cout << "jump to end\n";}
  };

...

vtkSubclassPlaybackRepresentation *rep =
  vtkSubclassPlaybackRepresentation::New();
vtkPlaybackWidget *widget = vtkPlaybackWidget::New();
  widget->SetInteractor(iren);
  widget->SetRepresentation(rep);
```

An Example

The following example from Widgets/Testing/Cxx/TestAffineWidget.cxx uses a vtkAffineWidget to transform (shear / rotate / translate / scale) a 2D image interactively. We will observe the widget for interactions with the class vtkAffineCallback in order to update the transform on the image actor.

```
class vtkAffineCallback : public vtkCommand
{
public:
  static vtkAffineCallback *New()
    { return new vtkAffineCallback; }
  virtual void Execute(vtkObject *caller, unsigned long, void*);
  vtkAffineCallback():ImageActor(0),AffineRep(0)
```

```
    {this->Transform = vtkTransform::New();}
  ~vtkAffineCallback()
    {this->Transform->Delete();}
  vtkImageActor *ImageActor;
  vtkAffineRepresentation2D *AffineRep;
  vtkTransform *Transform;
};

void vtkAffineCallback::Execute(vtkObject*, unsigned long, void*)
  {
  this->AffineRep->GetTransform(this->Transform);
  this->ImageActor->SetUserTransform(this->Transform);
  }

int TestAffineWidget( int argc, char *argv[] )
  {
  // Create the pipeline
  char* fname = vtkTestUtilities::ExpandDataFileName(
    argc, argv, "Data/headsq/quarter");

vtkVolume16Reader* v16 = vtkVolume16Reader::New();
  v16->SetDataDimensions(64, 64);
  v16->SetDataByteOrderToLittleEndian();
  v16->SetImageRange(1, 93);
  v16->SetDataSpacing(3.2, 3.2, 1.5);
  v16->SetFilePrefix(fname);
  v16->ReleaseDataFlagOn();
  v16->SetDataMask(0x7fff);
  v16->Update();
delete[] fname;

double range[2];
v16->GetOutput()->GetScalarRange(range);

vtkImageShiftScale* shifter = vtkImageShiftScale::New();
  shifter->SetShift(-1.0*range[0]);
  shifter->SetScale(255.0/(range[1]-range[0]));
  shifter->SetOutputScalarTypeToUnsignedChar();
  shifter->SetInputConnection(v16->GetOutputPort());
  shifter->ReleaseDataFlagOff();
  shifter->Update();

vtkImageActor* imageActor = vtkImageActor::New();
  imageActor->SetInput(shifter->GetOutput());
  imageActor->VisibilityOn();
  imageActor->SetDisplayExtent(0, 63, 0, 63, 46, 46);
  imageActor->InterpolateOn();

double bounds[6];
imageActor->GetBounds(bounds);
```

```
// Create the RenderWindow, Renderer and both Actors
vtkRenderer *ren1 = vtkRenderer::New();
vtkRenderWindow *renWin = vtkRenderWindow::New();
  renWin->AddRenderer(ren1);

vtkRenderWindowInteractor *iren = vtkRenderWindowInteractor::New();
  iren->SetRenderWindow(renWin);

vtkInteractorStyleImage *style = vtkInteractorStyleImage::New();
iren->SetInteractorStyle(style);

// VTK widgets consist of two parts: event processing and the
// representation that defines how the widget appears in the scene
vtkAffineRepresentation2D *rep = vtkAffineRepresentation2D::New();
  rep->SetBoxWidth(100);
  rep->SetCircleWidth(75);
  rep->SetAxesWidth(60);
  rep->DisplayTextOn();
  rep->PlaceWidget(bounds);

vtkAffineWidget *widget = vtkAffineWidget::New();
  widget->SetInteractor(iren);
  widget->SetRepresentation(rep);

vtkAffineCallback *acbk = vtkAffineCallback::New();
  acbk->AffineRep = rep;
  acbk->ImageActor = imageActor;
widget->AddObserver(vtkCommand::InteractionEvent,acbk);
widget->AddObserver(vtkCommand::EndInteractionEvent,acbk);

// Add the actors to the renderer, set the background and size
  ren1->AddActor(imageActor);
  ren1->SetBackground(0.1, 0.2, 0.4);
  renWin->SetSize(300, 300);

  iren->Initialize();
  renWin->Render();
  iren->Start();
}
```

13.4 Selections

In its most general sense, a selection is a data structure that specifies a subset of something else. This subset may be highlighted to show a feature in the data, or may be extracted to analyze a portion of the data in more detail. VTK provides a framework for generating, processing, and sharing selections in applications using the vtkSelection class, along with related selection sources, filters, and views.

vtkSelection is a container class holding one or more vtkSelectionNode objects. Each node contains information indicating what part of the data is selected. A compound selection is interpreted as the union of the individual node selections. We allow selections to consist of multiple nodes so that in

one place we can represent selections on multiple parts of the data. For example, a selection on geometry may contain a vtkSelectionNode for both points and cells. Another use case is to collect selections from multiple datasets in the same renderer into one place.

13.5 Types of selections

Each vtkSelectionNode has a selection type which indicates how the selection is to be interpreted. The selection types are constants defined in vtkSelectionNode.h. Values associated with a selection are stored in an array retrieved by GetSelectionList(). For convenience, we will use the term "element" to refer to the basic building-blocks of datasets to which attributes may be assigned. For vtkDataSet subclasses, the elements are points and cells. The elements of vtkGraph subclasses are vertices and edges. For vtkTable, the elements are the rows of the table.

Index selections

This is the most basic type of selection. An index selection's selection list is a vtkIdTypeArray containing the raw zero-based indices of the selected elements in a dataset, using the dataset's internal ordering. Since these indices may change as a dataset is processed or filtered, an index selection is generally only applicable to a single data set. You should not share an index selection between datasets with different topologies.

Pedigree ID selections

A pedigree ID is an identifier assigned to each element in a dataset at its source, and is propagated down the pipeline. You specify pedigree IDs on a dataset in the same way that other special attributes like scalars and vectors are specified, by calling SetPedigreeIds() on a dataset's attributes. Pedigree ID arrays may be of any type, including vtkStringArray and vtkVariantArray. A pedigree ID selection contains a list of values from a dataset's pedigree ID array. Both pedigree ID and global ID selections refer to elements by name, instead of by a dataset-specific offset used in index selections, which makes them more robust across different datasets which originate from the same source.

Global ID selections

Global ID selections are much like pedigree ID selections, except that they refer to the global ID attribute (set with SetGlobalIds()). Global IDs are used in a way similar to pedigree IDs, except that they must be numeric, and some filters re-assign global IDs to ensure that IDs are never repeated.

Frustum selections

Frustum selections simply store the geometry of a frustum in the selection. All elements within the frustum are considered selected. This is most useful in the case that the user drag-selects a region in a 3D scene. The rectangular region on the screen translates into a frustum in the 3D scene. The selection list for this type of selection must be a vtkDoubleArray with eight four-component tuples. The points, in the form (x,y,z,1), should be in the following order:

1. near lower left
2. far lower left
3. near upper left
4. far upper left
5. near lower right
6. far lower right
7. near upper right
8. far upper right

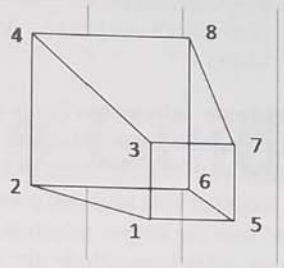


Figure 13–1 The expected order of the points in a view frustum selection.

Value selections

A value selection is a selection that refers to elements in an arbitrary array. In a value selection you must set the name of the selection list to the name of the array that you want to select. For example, if you have a dataset where the points contain an integer attribute "type" which varies from 0 to 10. To select only points with values 1, 3, and 7, create a vtkIntArray, add the desired values to it, then set the name of the array to "type". Finally, call node->SetSelectionList(arr) with the array you created.

Threshold selections

Threshold selections work just like value selections, except you indicate value ranges with each pair of elements in the array. While value selections may be of any type, threshold selections only work on numeric arrays, and the selection list must be a vtkDoubleArray. To select points with type in the range 0-5, create a vtkDoubleArray and add the elements 0 and 5. You may add additional ranges to the threshold selection by adding more pairs of numbers.

Location selections

As the name suggests, you provide this type of selection with the 3D locations that you want selected. A location selection must be a vtkDoubleArray with 3 components per tuple. A location selection is often used to select cells that contain a point. For location selections referring to the points of a dataset, there is a way to specify the maximum distance a selected dataset point can be to a point in the selection list:

```
n->GetProperties()->Set(vtkSelectionNode::EPSILON(), distance);
```

Block selections

The VTK data object, vtkMultiBlockDataset, can store a collection of datasets. A block selection allows you to specify which blocks to select. The selection list must be a vtkUnsignedIntArray.

Using the hardware selector. VTK provides the class vtkHardwareSelector to assist you in generating selections from a rectangular region of the screen. This process is similar to AreaPicking ("Picking" on page 59), but is able to return finer grained details about what is picked.

```
vtkHardwareSelector* hs = vtkHardwareSelector::New();
```

```
hs->SetRenderer(ren);
 hs->SetArea(xmin, ymin, xmax, ymax);
vtkSelection* s = hs->Select();
```

The hardware selector performs special rendering passes in order to determine which datasets in the renderer are selected, and which cells within those datasests are selected. Any cell that is rendered to at least one pixel within the selection area is inserted into the output selection. The output selection contains one vtkSelectionNode for each selected actor. These nodes are cell index selections by default, although the hardware selector can also be configured to select points. You can retrieve the pointer to the associated actor in the scene by accessing the PROP property of the selection node.

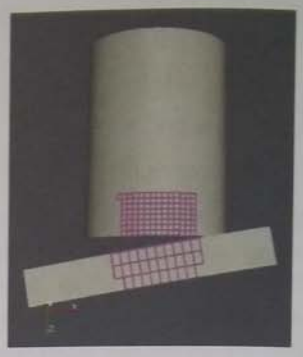


Figure 13–2 The result of a hardware cell selection on two actors.

Extracting selections. Now that we know how to define a selection, we must use it in some way. One of the most common tasks is to extract the selection from a dataset. To do this, use the vtkExtractSelection filter for vtkDataSets or vtkMultiBlockDataSets, or use vtkExtractSelectedGraph for vtkGraphs. Both filters work in similar ways, and accept a selection of any type. To extract a selection from a vtkPolyData, we can do the following:

```
vtkPolyData* pd = vtkPolyData::New();
// Populate the poly data here
vtkSelection* s = vtkSelection::New();
// Populate the selection here
vtkExtractSelection* ex = vtkExtractSelection::New();
  ex->SetInput(0, pd);
  ex->SetInput(1, s);
  ex->Update();
vtkUnstructuredGrid* extracted = ex->GetOutput();
```

Note that because vtkExtractSelection accepts any vtkDataSet subclass, the output is the most general dataset, vtkUnstructuredGrid. The output type cannot match the input type because, for example, a selection, which denotes an arbitrary subset, on a structured type like vtkImageData might no longer be structured. If you desire to simply mark selected elements of a dataset, call ex->PreserveTopologyOn() before updating the filter. This will pass the data structurally unchanged to the output, with the same data type. Instead of culling away rejected elements, the filter adds a boolean flag to each element indicating whether it is selected or not.

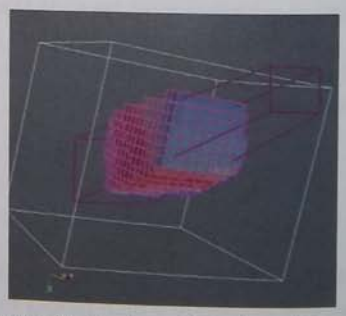


Figure 13–3 A portion of a vtkImageData extracted by a frustum selection.

Part III
VTK Developer's Guide

Contributing Code

The previous chapters offered an introduction to VTK by way of example. By now it should be apparent that VTK offers the functionality to create powerful graphics, imaging, and visualization applications. In addition, because you have access to the source code, you can extend VTK by adding your own classes. In Part III of the *User's Guide*, we show how to extend VTK to suit the needs of your application. We begin in this chapter by introducing coding conventions that you may consider adopting—especially if you wish to contribute code to the VTK community. We also describe standard conventions and methods that your objects must implement to be incorporated into VTK. Later in Part III we describe implementation details for algorithm and data objects, as well as methods for controlling the execution of the visualization pipeline; we also discuss ways to interface VTK to various windowing systems.

14.1 Coding Considerations

If you develop your own filter or other addition to the *Visualization Toolkit*, we encourage you to contribute the source code. You will have to consider what it means to contribute code from a legal point of view, what coding styles and conventions to use, and how to go about contributing code.

Conditions on Contributing Code To VTK

When you contribute code to VTK, two things are bound to happen. First, many people will see the code—dissecting, improving, and modifying it; second, you will in some sense "lose control" of the code due to the modifications that will inevitably occur to it. You will not want to release proprietary code or code you cannot relinquish control over (also, patented code is not allowed), and you'll want to carefully craft the code so that others can understand and improve it.

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If these restrictions are acceptable, you can consider contributing code. However, you will need to meet other criteria before your code is accepted. These criteria are not formalized, but have to do with the usefulness, simplicity, and compatibility with the rest of the system. Important questions to ask are:

- Does the code meet the VTK coding standards (also see "Coding Style" on page 299)?
- Is the code documented and commented?
- Is the code general? Or is it specific to a narrow application?
- Does it require extensive modification to the system? (For example, modifications to widely-used object APIs.)
- Does the code duplicate existing functionality?
- Is the code robust?
- Does the code belong in a visualization toolkit?

If you can answer these questions favorably, chances are that the code is a good candidate for inclusion in VTK.

Coding Style

There are many useful coding styles, but we insist that you follow just one. We know this is a contentious issue, but we have found that it is very important to maintain a consistent style. Consistent style means that the code is easier to read, debug, maintain, test, and extend. It also means that the automated documentation facilities operate correctly, and other automated functions are available to all users of VTK.

Here's a summary of the coding style. You may wish to examine VTK source code to see what it looks like.

- Variables, methods, and class names use changing capitalization to indicate separate words. Instance variables and methods always begin with a capital letter. Static variables are discouraged, but should also begin with a capital letter. Local variables begin with a lower-case letter. SetNumberOfPoints() or PickList are examples of a method name and instance variable.
- Class names are prefixed with `vtk` followed by the class name starting with a capital letter. For example, vtkActor or vtkPolyData are class names. The `vtk` prefix allows the VTK class library to be mixed with other libraries.
- Class names and files names are the same. For example, `vtkObject.h` and `vtkObject.cxx` are the source files for vtkObject.
- Explicit `this->` pointers are used in methods. Examples include `this->Visibility` and `this->Property` and `this->Update()`. We have found that the use of explicit `this->` pointers improves code understanding and readability.
- Variable, method, and class names should be spelled out. Common abbreviations can be used, but the abbreviation should be entirely in capital letters. For example, vtkPolyDataConnectivityFilter and vtkLODActor are acceptable class names.
- Preprocessor variables are written in capital letters. These variables are the only one to use the underscore "_" to separate words. Preprocessor variables should also begin with `VTK_` as in `VTK_LARGE_FLOAT`.
- Instance variables are typically `protected` or `private` class members. Access to instance variables is through `Set/Get` methods. Note that VTK provides `Set/Get` macros which should be used whenever possible. (Look in `VTK/Common/vtkSetGet.h` for the implementation, and `.h` header files for example usage.)
- The indentation style can be characterized as the "indented brace" style. Indentations are two spaces, and the curly brace (scope delimiter) is placed on the following line and indented along with the code (i.e., the curly brace lines up with the code).
- Use `//` to comment code. Methods are commented by adding `// Description:` followed by lines each beginning with `//`.

How To Contribute Code

Contributing code is fairly easy once you've created your class or classes following the coding convention described above. First, include the copyright notice in both the `.cxx` and `.h` source files. You may wish to place your name, organization, and/or other identifying information in the "`Thanks:`" field of the copyright notice. (See `VTK/Graphics/vtkCurvatures.h` for an example). Next, send e-mail to `kitware@kitware.com` with an explanation of what the code does, sample data (if

needed), test code (in either C++, Tcl, or Python), and the source code (a single `.h` and `.cxx` file per class). Another method is to send the same information to the `vtkusers` mailing list. (See "Additional Resources" on page 6 for information about joining the list.) The advantage of sending contributed code to the mailing list is that users can take advantage of the code immediately.

There is no guarantee that contributed code will be incorporated into official VTK releases. This depends upon the quality, usefulness, and generality of the code as outlined in "Conditions on Contributing Code To VTK" on page 297.

14.2 Standard Methods: Creating and Deleting Objects

Almost every object in VTK responds to a set of standard methods. Many of these methods are implemented in vtkObject or vtkObjectBase, from which most VTK classes are derived. However, subclasses typically require that you extend or implement the inherited methods for proper behavior. For example, the New() method should be implemented by every concrete (i.e., non-abstract, instantiable) class, while the Delete() method is generally inherited from its superclass's vtkObject. Before you develop any code you should become familiar with these standard methods, and make sure your own classes support them.

`New()`
: This static class method is used to instantiate objects. We refer to this method as an "object factory" since it is used to create instances of a class. In VTK, every New() method should be paired with a Delete() method. (See also "Object Factories" on page 307.)

`instance = NewInstance()`
: This method is a virtual constructor. That is, invoking this method causes an object to create an instance of the same type as itself and then return a pointer to the new object. (The macro vtkTypeMacro found in `VTK/Common/vtkSetGet.h` defines this method.)

`Delete()`
: Use this method to delete a VTK object created with the New() or NewInstance() method. Depending upon the nature of the object being deleted, this may or may not actually delete the object. For example, reference-counted objects will only be deleted if their reference count goes to zero.

`DebugOn()/DebugOff()`
: Turn debugging information on or off. These methods are inherited from vtkObject.

`Print()`
: Print out the object including superclass information. The Print() method, which is defined in vtkObjectBase, requires implementation of a PrintSelf() method for each class. The PrintSelf() method is invoked in a chain, each subclass calling its superclass's PrintSelf() and then printing its own instance variables.

`PrintSelf(ostream, indent)`
: Each class should implement this method. The method invokes its parent's PrintSelf(), followed by the code required to print itself.

`name = GetClassName()`
: Return the name of the class as a character string. This method is used for debugging

information. (The macro vtkTypeMacro found in `VTK/Common/tkSetGet.h` defines this method.)

`flag = IsA(`*className*`)`
Return non-zero if the named class is a superclass of, or the same type as, this class. (The macro vtkTypeMacro found in `VTK/Common/vtkSetGet.h` defines this method.)

`<class> *ptr = <class>::SafeDownCast(vtkObject *o)`
This static class method is available in C++ for performing safe down casts (i.e., casting a general class to a more specialized class). If `ptr` is returned `NULL`, then the down cast failed, otherwise `ptr` points to an instance of the class `<class>`. For example, `ptr=vtkActor::SafeDownCast(prop)` will return non-`NULL` if `prop` is a vtkActor or a subclass of vtkActor. (The macro vtkTypeMacro found in `VTK/Common/vtkSetGet.h` defines this method.)

`void Modified()`
This updates the internal modification time stamp for the object. The value is guaranteed to be unique and monotonically increasing.

`mtime = GetMTime()`
Return the last modification time of an object. Normally this method is inherited from vtkObject, however in some cases you'll want to overload it. See "Compute Modified Time" on page 391 for more information.

The most important information you can take from this section is this: instances should be created with the New() method and destroyed with the Delete() method, and for every New() there should be a Delete() method. For example, to create an instance of an actor do the following

```
vtkActor *anActor = vtkActor::New();
... (more stuff)
anActor->Delete();
```

In addition to ::New and ::Delete, VTK provides a smart pointer class that can be used to manage VTK objects. The smart pointer will automatically increment and decrement the reference count of the object being pointed to. This can make the code more less likely to leak VTK objects. The smart pointer class is a template class and is used as follows:

```
#include <vtkSmartPointer.h>
...
vtkSmartPointer<vtkActor> anActor = vtkSmartPointer<vtkActor>::New();
... (more stuff)
// when anActor goes out of scope the reference count for that
// vtkActor will be decremented.
```

The New() method is called an object factory: it's a class method used to create instances of the class. Typically, the New() method first asks the vtkObjectFactory to create an instance of the object, and if that fails, it simply invokes the C++ `new` operator. This is done by adding the vtkStandardNewMacro (found in `VTK/Common/vtkSetGet.h`) to a .cxx file as is shown below for vtkSphereSource.

```
vtkStandardNewMacro(vtkSphereSource);
```

However, the New() method can be more complex, for example, to instantiate device-independent classes. For example, in `vtkGraphicsFactory.cxx`, the code used to instantiate a vtkActor looks like the following.

```
if(strcmp(vtkclassname, "vtkActor") == 0)
  {
  return vtkOpenGLActor::New();
  }
```

Here the New() method is used to create a device-*dependent* subclass of vtkActor (i.e., OpenGL), which is then returned as a pointer to a device-*independent* vtkActor. For example, depending on the compile-time flags (e.g., `VTK_USE_OGLR`) and possibly other information such as environment variables, different actor types corresponding to the rendering libraries (e.g., OpenGL, Mesa, et.c) are created transparently to the user. Using this mechanism we can create device-independent applications, or at run-time select different classes to use in the application. (See "Object Factories" on page 307 for more information.)

14.3 Copying Objects and Protected Methods

The constructor, destructor, operator=, and copy constructor methods are either protected or private members of most every VTK class. This means that for VTK class `vtkX`, the methods

- `vtkX()` — constructor
- `~vtkX()` — destructor

are protected, and the methods

- `operator=(const vtkX &)` — equivalence operator, and
- `vtkX(const vtkX &)` — copy constructor

are private. In addition, the assignment operator and copy constructors should be declared only, and not implemented. This prevents the compiler from creating one automatically, and does not generate code that cannot be covered in the testing process. This means that you cannot use these methods in your application. (The reason for this is to prevent potentially dangerous misuse of these methods. For example, reference counting can be broken by using the constructor and destructor rather than the standard `New()` and `Delete()` methods described in the previous section.)

Since the copy constructor and operator= methods are private, other methods must be used to copy instances of an object. The methods to use are `DeepCopy()` and/or `ShallowCopy()` as shown below.

```
vtkActor *a1 = vtkActor::New();
vtkActor *a2 = vtkActor::New();
a2->ShallowCopy(a1);
```

A shallow copy is a copy of an object that copies references to objects (via reference counting) rather than the objects themselves. For example, instances of the class `vtkActor` refer to a `vtkMapper` object (the mapper represents the geometry for the actor). In a shallow copy, replication of data is avoided, and just the reference to the `vtkMapper` is copied. However, any changes to the shared map-

per indirectly affects all instances of `vtkActor` that refer to it. Alternatively, a `DeepCopy()` can be used to copy an instance, including any data it represents, without any references to other objects. Here's an examples:

```
vtkIntArray *ia1 = vtkIntArray::New();
vtkIntArray *ia2 = vtkIntArray::New();
ia1->DeepCopy(ia2);
```

In this example, the data in `ia2` is copied into `ia1`. From this point on, `ia1` and `ia2` can be modified without affecting each other.

At the current time, VTK does not support `DeepCopy()` and `ShallowCopy()` in all classes. This will be added in the future.

14.4 Using STL

The Standard Template Library (STL) is a C++ library that provides a set of easily composable C++ container classes and generic algorithms (templated functions).

- The container classes include vectors, lists, deques, sets, multisets, maps, multimaps, stacks, queues, and priority queues.
- The generic algorithms include a broad range of fundamental algorithms for the most common kinds of data manipulations, such as searching, sorting, merging, copying, and transforming.

While STL definitely has a lot to offer C++ programmers, it suffers several implementation issues (especially in cross-platform use) requiring VTK programmers to be careful when using STL. Some of these issues including namespace management, DLL (dynamic link library) boundary problems, and threading issues. To address these issues, VTK has a policy in place describing how STL is to be used in conjunction with VTK. Here are the tenets of the policy.

1. STL is for implementation, not interface. All STL references should be contained in a `.cxx` class implementation file, never in the `.h` header file.
2. Use the PIMPL idiom to forward reference/contain STL classes. STL-derived classes should be private, not protected or public, to avoid dll boundary issues. DLL boundary issues would arise if a subclass of a class using the PIMPL idiom is in a different VTK kit than the parent class. In some VTK classes that have no subclasses are using the PIMPL idiom, the STL-derived classes are in the `protected` section instead of the `private` one. (The PIMPL idiom is a technique for private implementation of class members. Search the Web for "pimpl idiom C++" for more information.)
3. Use the `vtkstd::` namespace to refer to STL classes and functions.

Here's an example (from the class vtkInterpolatedVelocityField). In the class `.h` file create the PIMPL by forward declaring a class and using it to define a data member as follows.

```
class vtkInterpolatedVelocityFieldDataSetsType;
class VTK_FILTERING_EXPORT vtkInterpolatedVelocityField : public
vtkFunctionSet
{
```

```
protected:
  vtkInterpolatedVelocityFieldDataSetsType* DataSets;
};
```

In the `.cxx` file define the class (here deriving from the STL vector container).

```
typedef vtkstd::vector< vtkDataSet* > DataSetsTypeBase;
class vtkInterpolatedVelocityFieldDataSetsType:
                                        public DataSetsTypeBase {};
```

(The first typedef is used as a convenience to shorten the definition of the class.) Next, in the `.cxx` file construct and destruct the class as follows:

```
vtkInterpolatedVelocityField::vtkInterpolatedVelocityField()
{
  this->DataSets = new vtkInterpolatedVelocityFieldDataSetsType;
}
vtkInterpolatedVelocityField::~vtkInterpolatedVelocityField()
{
  delete this->DataSets;
}
```

Since the class is derived from a STL container, it can be used as that type of container.

```
for ( DataSetsTypeBase::iterator i = this->DataSets->begin();
      i != this->DataSets->end(); ++i)
  {
  ds = *i;
  ....
  }
```

14.5 Managing Include Files

Software systems have inherent inter-module dependencies. In C++ this occurs because subclasses depend on their superclasses, or access to structures or classes requires knowledge of the API and data offsets. These dependencies show up in implementation as `#include` statements that include header files defining classes, structures, and interfaces. In the build process, whenever any one of the header files changes, all the code that depends on that file must be recompiled. By including header files within header files that are in turn included in other files, this can result in excessive inter-code dependencies resulting in prolonged compilation time when code changes. In some compilers, too many include files will even cause the compiler to fail. In order to address these issues, the VTK developer community has developed a policy regarding include files. The basic rule is simple: *a class definition (`.h`) file should include at most one other #include file—its superclass definition file.* All other `#include`'s should be placed in the class implementation (`.cxx`) file. However, the policy requires following particular coding conventions.

First, classes must contain *pointers* to other classes or structures, and not instances of them. And second, in-line code that invokes class methods (other than the superclass) must be avoided. All of these operations require access to the class definition and hence the associated `#include` file. In

particular, the older VTK macro `vtkSetObjectMacro()` is no longer used. This macro invokes several methods on any class used as a data member and thereby required including its class definition file. The current approved procedure is to declare the set method, and implement the method in the `.cxx` file using the `vtkCxxSetObjectMacro()`. For example, the class vtkCutter has a data member that is a pointer to a vtkImplicitFunction. In the definition file `VTK/Graphics/vtkCutter.h` the SetCutFunction() is declared

```
virtual void SetCutFunction(vtkImplicitFunction*);
```

and in the `.cxx` file the method is implemented

```
vtkCxxSetObjectMacro(vtkCutter,CutFunction,vtkImplicitFunction);
```

Of course, all rules are made to be broken. In some cases performance concerns or other issues may require additional `#include` files. However, this is to be avoided whenever possible. When it cannot be avoided, put a comment on the line with the `#include` explaining why it is required. See the example below from `VTK/Graphics/vtkSynchronizedTemplates3D.h`

```
#include "vtkPolyDataAlgorithm.h"
#include "vtkContourValues.h" // Passes calls through
```

14.6 Writing A VTK Class: An Overview

In this section we give a broad overview of how to write a VTK class. If you are writing a new filter, you'll also want to refer to Chapter 17 "How To Write an Algorithm for VTK" on page 385, and of course, you should read the previous portion of this chapter.

Probably the hardest part about writing a VTK class is figuring out if you need it, and if so, where it fits into the system. These decisions come easier with experience. In the mean time, you probably want to start by working with other VTK developers, or posting to the `vtkusers` mailing list. (See "Additional Resources" on page 6.) If you determine that a class is needed, you'll want to look at the following issues.

Find A Similar Class

The best place to start is to find a class that does something similar to what you want to do. This will often guide the creation of the object API, and/or the selection of a superclass.

Identify A Superclass

Most classes should derive from vtkObject or one of vtkObject's descendants. Exceptions to this rule are few, since vtkObject (or its superclass, vtkObjectBase) implements important functionality such as reference counting, command/observer user methods, print methods, and debugging flags. All VTK classes use single inheritance. While this is a contentious issue, there are good reasons for this policy including Java support (Java allows only single inheritance) and simplification of the wrapping process as well as the code. You may wish to refer to the object diagrams found in "Object Diagrams" on page 437. These provide a succinct overview of many inheritance relationships found in VTK.

Single Class Per .h File

Classes in VTK are implemented one class per `.h` header file, along with any associated `.cxx` implementation file. There are some exceptions to this rule—for example, when you have to define internal helper classes. However, in these exceptions the helper class is not visible outside of the principle class. If it is, it should placed into its own `.h/.cxx` files.

Required Methods

Several methods and macros must be defined by every VTK class as follows. See "Standard Methods: Creating and Deleting Objects" on page 300 for a description of these methods.

- `New()` — Every non-abstract class (i.e., a class that does not implement a pure virtual function) must define the `New()` method.
- `vtkTypeMacro(className,superclassName)` — This macro is a convenient way to define methods used at run-time to determine the type of an instance, or to perform safe down casting. vtkTypeMacro is defined in the file `vtkSetGet.h`. The macro defines the methods `IsTypeOf()`, `IsA()`, `GetClassName()`, `SafeDownCast()`, and the virtual constructor `NewInstance()`.
- `PrintSelf()` — Print out instance variables in an intelligent manner.
- Constructor (must be `protected`)
- Destructor (must be `protected`)
- Copy Constructor (must be `private` and not implemented)
- `operator=` (must be `private` and not implemented)

The constructor, copy constructor, destructor, and `operator=` must not be public. The `New()` method should use the procedure outlined in "Object Factories" on page 307. Of course, depending upon the superclass(es) of your class, there may be additional methods to implement to satisfy the class API (i.e., fill in pure virtual functions).

Document Code

The documentation of VTK classes depends upon proper use of documentation directives. Each `.h` class file should have a `// .NAME` description, which includes the class name and a single-line description of what the class does. In addition, the header file should have a `// .SECTION Description` section, which is a multi-paragraph description (delimited with the C++ comment indicator `//`) giving detailed information about the class and how it works. Other possible information is contained in the `// .SECTION Caveats` section, which describes quirks and limitations of the class, and the `// .SECTION See Also` section, which refers to other, related classes.

Methods should also be documented. If a method satisfies a superclass API, or overloads a superclass method, you may not need to document the method. Those methods that you do document use the following construct:

```
// Description:
// This is a description...
```

Of course, you may want to embed other documentation, comments, etc. into the code to help other developers and users understand what you've done.

Use SetGet Macros

Whenever possible, use the `SetGet` macros found in `VTK/Common/vtkSetGet.h` to define access methods to instance variables. Also, you'll want to use the debugging macros and additional `#defines` (e.g., `VTK_LARGE_FLOAT`) in your code, as necessary.

Add Class To VTK

Once you've created your class, you'll want to decide whether you want it to be incorporated into the VTK build or separated in your own application. If you add your class to VTK, modify the `CMakeLists.txt` file in the appropriate subdirectory. You'll then have to re-run CMake (as described in "CMake" on page 10), and then recompile. You can add an entire new library by creating a file called `LocalUser.cmake` in the top level of your VTK source tree. This file is used only if it exits. You can put a CMake `add_subdirectory` command into the file, telling CMake to go into the new library's directory. Inside the directory, you will need to create a new `CMakeLists.txt` file that contains CMake commands for building your library. If you are using one of the wrapped languages like Tcl, you can either add your library into the VTK executable with another `LocalUser.cmake` file in the `Wrapping/Tcl` directory, or you will have to build shared libraries, and load the new library at run time into the Tcl environment. To add classes that simply use VTK, see "C++" on page 30 for example `CMakeLists.txt` files.

14.7 Object Factories

VTK Version 3.0 and later has a potent capability that allows you to extend VTK at run time. Using *object factories*, you can replace a VTK object with one of your own creation. For example, if you have special hardware, you can use your own special high-performance filter at *run-time* by replacing object(s) in VTK with your own objects. So, if you wanted to replace the vtkImageFFT filter with a filter that performed FFT in hardware, or replace the cell vtkTetra with a high-performance, assembly code implementation, you could do this. Here are the benefits of using object factories.

- Allow sub-classes to be used in place of parent classes in existing code.
- Your application can dynamically load new object implementations.
- You can extend VTK at run-time.
- Proprietary extensions can be isolated from the public VTK builds.
- Removes the need for many `#ifdefs` in C++ code; for example, an OpenGL factory could replace all of the `#ifdefs` in vtkRenderer and vtkRenderWindow.
- An object factory can be used as a debugging aid. For example, a factory can be created that does nothing except track the invocation of `New()` for each class.
- Implementation of accelerated or alternative VTK objects on different hardware similar to the plug-in model of Netscape and Photoshop is easier.

Overview

The key class when implementing an object factory is vtkObjectFactory. vtkObjectFactory maintains a list of "registered" factories. It also defines a static class method used to create VTK objects by string name—the method CreateInstance()—which takes as an argument a `const char*`. The create method iterates over the registered factories asking each one in turn to create the object. If the factory returns an object, that object is returned as the created instance. Thus, the first factory returning an object is the one used to create the object.

An example will help illustrate how the object factory is used. The New() method from the class vtkVertex is shown below (after expansion of the vtkStandardNewMacro defined in `VTK/Common/vtkSetGet.h`).

```
vtkVertex* vtkVertex::New()
{
  // First try to create the object from the vtkObjectFactory
  vtkObject* ret = vtkObjectFactory::CreateInstance("vtkVertex");
  if(ret)
    {
    return static_cast<vtkVertex*>(ret);
    }

  // If the factory was unable to create the object, then create it
  return new vtkVertex;
}
```

The implementation of this New() method is similar to most all other New() methods found in VTK. If the object factory does not return an instance of class vtkVertex, then the constructor for vtkVertex is used. Note that the factory must return an instance of a class that is a subclass of the invoking class (i.e., vtkVertex).

How To Write A Factory

The first thing you need to do is to create a subclass of vtkObjectFactory. You must implement two virtual functions in your factory: GetVTKSourceVersion() and GetDescription().

```
virtual const char* GetVTKSourceVersion();
virtual const char* GetDescription();
```

GetDescription() returns a string defining the functionality of the object factory. The method GetVTKSourceVersion() should return `VTK_SOURCE_VERSION` and should NOT call vtkVersion::GetVTKSourceVersion(). You cannot call vtkVersion functions, because the version must be compiled into your factory, if you did call vtkVersion functions, it would just use the VTK version that the factory was loaded into and not the one it was built with. This method is used to check the version numbers of the factory and the objects it creates against the installed VTK. If the software versions are different, a warning will be produced and there's a good chance that a serious program error will follow.

There are two ways for a factory to create objects. The most convenient method is to use the protected method of vtkObjectFactory called RegisterOverride().

```
void RegisterOverride(const char* classOverride,
                      const char* overrideClassName,
                      const char* description,
                      int enableFlag,
                      CreateFunction createFunction);
```

This method should be called in your constructor once for each object your factory provides. The following are descriptions of the arguments.

- classOverride — This is the name of the class you are replacing.
- overrideClassName — This is the name of the class that will replace classOverride
- description — This is a text based description of what your replacement class does. This can be useful from a GUI if you want to select which object to use at run-time.
- enableFlag — This is a Boolean flag that should be 0 or 1. If it is 0, this override will not be used. Note, it is possible to change these flags at run-time from the vtkObjectFactory class interface.
- createFunction — This is a pointer to a function that will create your class. The function must look like this:

  ```
  vtkObject* createFunction();
  ```

  You can write your own function or use the `VTK_CREATE_CREATE_FUNCTION` macro provided in vtkObjectFactory.h. (See `VTK/Parallel/vtkParallelFactory.cxx` for an example if using this macro.)

The second way in which an object factory can create objects is the virtual function CreateObject():

```
virtual vtkObject* CreateObject(const char* vtkclassname);
```

The function should return NULL if your factory does not want to handle the class name it is being asked to create. It should return a sub-class of the named VTK class if it wants to override the class. Since the CreateObject() method returns a vtkObject* there is not much type safety other than that the object must be a vtkObject, so be careful to only return sub-classes of the object to avoid run-time errors. A factory can handle as many objects as it wants. If many objects are to be created, it would be best to use a hash table to map from the string names to the object creation. The method should be as fast as possible since it may be invoked frequently. Also note that this method will not allow a GUI to selectively enable and disable individual objects like the RegisterOverride() method does.

How To Install A Factory

How factories are installed depends on whether they are compiled into your VTK library or application or whether they are dynamically loaded DLLs or shared libraries. Compiled-in factories need only call

```
vtkObjectFactory::RegisterFactory ( MyFactory::New() );
```

For dynamically loaded factories, a shared library or DLL must be created that contains the object factory subclass. The library should include the macro VTK_FACTORY_INTER-

FACE_IMPLEMENT(factoryName). This macro defines three external "C" linkage functions named vtkGetFactoryCompilerUsed(), vtkGetFactoryVersion(), and vtkLoad() that returns an instance of the factory provided by the library.

```
#define VTK_FACTORY_INTERFACE_IMPLEMENT(factoryName) \
extern "C"                                  \
VTK_FACTORY_INTERFACE_EXPORT                \
const char* vtkGetFactoryCompilerUsed()     \
{                                           \
 return VTK_CXX_COMPILER;                   \
}                                           \
extern "C"                                  \
VTK_FACTORY_INTERFACE_EXPORT                \
const char* vtkGetFactoryVersion()          \
{                                           \
 return VTK_SOURCE_VERSION;                 \
}                                           \
extern "C"                                  \
VTK_FACTORY_INTERFACE_EXPORT                \
vtkObjectFactory* vtkLoad()                 \
{                                           \
 return factoryName ::New();                \
}
```

The library must then be put in the VTK_AUTOLOAD_PATH. This variable follows the convention of PATH on your machine using the separation delimiters ";" on Windows, and ":" on Unix. The first time the vtkObjectFactory is asked to create an object, it loads all shared libraries or DLLs in the VTK_AUTOLOAD_PATH. For each library in the path, vtkLoad() is called to create an instance of vtkObjectFactory. This is only done the first time to avoid performance problems. However, it is possible to re-check the path for new factories at run time by calling

```
vtkObjectFactory::ReHash();
```

(Note that the VTK class vtkDynamicLoader handles operating system independent loading of shared libraries or DLLs.)

Example Factory

Here is a simple factory that uses OLE automation on the Windows operating system to redirect all VTK debug output to a Microsoft Word document. To use this factory, just compile the code into a DLL, and put it in your VTK_AUTOLOAD_PATH.

```
#include "vtkOutputWindow.h"
#include "vtkObjectFactory.h"
#pragma warning (disable:4146)
#import "mso9.dll"
#pragma warning (default:4146)
#import "vbe6ext.olb"
#import "msword9.olb" rename("ExitWindows", "WordExitWindows")
// This class is exported from the vtkWordOutputWindow.dll
```

```
class vtkWordOutputWindow : public vtkOutputWindow {
public:
 vtkWordOutputWindow();
 virtual void DisplayText(const char*);
 virtual void PrintSelf(vtkOstream& os, vtkIndent indent);
 static vtkWordOutputWindow* New() { return new vtkWordOutputWindow;}
protected:
 Word::_ApplicationPtr m_pWord;
 Word::_DocumentPtr m_pDoc;
};

class vtkWordOutputWindowFactory : public vtkObjectFactory
{
public:
 vtkWordOutputWindowFactory();
 virtual const char* GetVTKSourceVersion();
 virtual const char* GetDescription();
};

// vtkWordOutputWindow.cpp : the entry point for the DLL application.
//
#include "vtkWordOutputWindow.h"
#include "vtkVersion.h"
BOOL APIENTRY DllMain( HANDLE hModule,
            DWORD ul_reason_for_call,
            LPVOID lpReserved )
{
  if(ul_reason_for_call == DLL_PROCESS_ATTACH)
  {
   CoInitialize(NULL);
  }
  return TRUE;
}

void vtkWordOutputWindow::PrintSelf(vtkOstream& os, vtkIndent indent)
{
 vtkOutputWindow::PrintSelf(os, indent);
 os << indent << "vtkWordOutputWindow " << endl;
}

// This is the constructor of a class that has been exported.
// see vtkWordOutputWindow.h for the class definition
vtkWordOutputWindow::vtkWordOutputWindow()
{
  try
   {
   HRESULT hr = m_pWord.CreateInstance(__uuidof(Word::Application));
   if(hr != 0) throw _com_error(hr);

   m_pWord->Visible = VARIANT_TRUE;
   m_pDoc = m_pWord->Documents->Add();
```

```
    }
   catch (_com_error& ComError)
    {
    cerr << ComError.ErrorMessage() << endl;
    }
}

void vtkWordOutputWindow::DisplayText(const char* text)
{
 m_pDoc->Content->InsertAfter(text);
}

// Use the macro to create a function to return a vtkWordOutputWindow
VTK_CREATE_CREATE_FUNCTION(vtkWordOutputWindow);

// Register the one override in the constructor of the factory
vtkWordOutputWindowFactory::vtkWordOutputWindowFactory()
{
  this->RegisterOverride("vtkOutputWindow",
                         "vtkWordOutputWindow",
                         "OLE Word Window",
                         1,
                         vtkObjectFactoryCreatevtkWordOutputWindow);
}


// Methods to load and insure factory compatibility.
VTK_FACTORY_INTERFACE_IMPLEMENT(vtkWordOutputWindowFactory);

// return the version of VTK that the factory was built with
const char* vtkWordOutputWindowFactory::GetVTKSourceVersion()
{
 return VTK_SOURCE_VERSION;
}

// return a text description of the factory
const char* vtkWordOutputWindowFactory::GetDescription()
{
 return "vtk debug output to Word via OLE factory";
}
```

14.8 Kitware's Quality Software Process

An outstanding feature of VTK is the software process used to develop, maintain, and test the toolkit. The *Visualization Toolkit* software continues to evolve rapidly due to the efforts of developers and users located around the world, so the software process is essential to maintaining its quality. If you are planning to contribute to VTK or to use the CVS source code repository, you need to know something about this process. (See "Obtaining The Software" on page 5.) This information will help you know when and how to update and work with the software as it changes. The following sections describe key elements of the process.

CVS Source Code Repository

VTK source code, data, and examples are maintained in a source code version control system called CVS (Concurrent Versions System). The primary purpose of CVS is to keep track of changes to software. CVS date- and version-stamps every addition to the repository—also providing for special user-specified tags—so that it is possible to return to a particular state or point of time whenever desired. The differences between any two points is represented by a "diff" file, which is a compact, incremental representation of change. CVS supports concurrent development so that two developers can edit the same file at the same time; these edits are then (usually) merged together without incident (and marked if there is a conflict). In addition, branches off of the main development trunk provide parallel development of software.

The principal advantage of a system like CVS is that it frees developers to try new ideas and changes without fear of losing a previous working version of the software. It also provides a simple way to incrementally update code as new features are added to the repository.

CDash Regression Testing System

One of the unique features of the VTK software process is the CDash regression testing system (`http://www.cdash.org`). In a nutshell, what CDash does is to provide quantifiable feedback to developers as they check in new code and make changes. The feedback consists of the results of a variety of tests, and the results are posted on a publicly-accessible Web page (to which we refer as a *dashboard* as shown in **Figure 14–1**); VTK's dashboard is accessible from `http://www.cdash.org/CDash/index.php?project=VTK`. All users and developers of VTK can view the dashboard which produces considerable peer-pressure on developers who check in code with problems. The Dart dashboard serves as the vehicle for developer communication and should be viewed whenever you consider updating software via CVS.

CDash supports a variety of test types. These include the following.

- **Compilation.** All source code is compiled and linked. Any resulting errors and warnings are reported.
- **Regression.** Most VTK tests produce images as output. Testing requires comparing each test's output against a valid image. If the images match then the test passes. The comparison must be performed carefully since many 3D graphics systems (e.g., OpenGL) produce slightly different results on different platforms.
- **Memory.** One of the nastiest of problems to find in any computer program are those related to memory. Memory leakage, uninitialized memory, and reads and writes beyond allocated space are all examples of this sort of problem. VTK checks memory using Purify (a commercial package produced by Rational) or Valgrind (an open-source memory debugger for x86-Linux programs).
- **PrintSelf.** All classes in VTK are expected to print out all their instance variables correctly. This test checks to make sure that this is the case.
- **SetGet.** Often developers make assumptions about the values of instance variables; i.e., they assume that they are non-NULL, etc. The SetGet tests perform a Get on all instance variables with a Get__() method, followed by a Set method on the instance variable with the value returned from the Get__() method. It's surprising how many times this test identifies problems.

Site	Build Name	Update		Configure			Build			Test				Build Time
		Files	Min	Error	Warn	Min	Error	Warn	Min	NotRun	Fail	Pass	Min	
u20n17.pbm.ihost.com	AIX00C518-xlC	60	0.7	0	0	2.0	0	0	88	0	0	616	23.2	2009-05-27T01:56:46 EDT
heart	HP-UXia64-aCC	5	0.3	0	0	1.8	0	1	31.4	0	0	47	0.5	2009-05-27T03:16:16 EDT
blackrose.sandia.gov	Linux-g++-debug	5	1.4	0	0	0.3	0	0	18.6	0	0	1090	25.8	2009-05-26T23:03:29 EDT
RogueResearch5	Mac10.5-VTKBS-dbg	0	0.4	0	0	1.8	0	0	9.6	0	0	268	18.9	2009-05-27T03:29:03 EDT
RogueResearch5	Mac10.5-VTKBS-rel	0	0.9	0	0	1.7	0	0	8.3	0	0	268	16.8	2009-05-27T03:00:44 EDT
DASH2.kitware	Win32-64-ds-nmake70	5	3.7	0	0	0.3	0	0	32.4	0	0	273	31.8	2009-05-27T01:44:55 EDT
dash19.kitware	Win32-bcc32	0	0.6	0	0	0.3	0	0	58.1	0	0	267	8.3	2009-05-27T04:55:55 EDT
dash19.kitware	Win32-bcc32-WrapTCL	5	1.2	0	0	0.5	0	0	99.3	0	0	670	21.2	2009-05-27T02:51:36 EDT

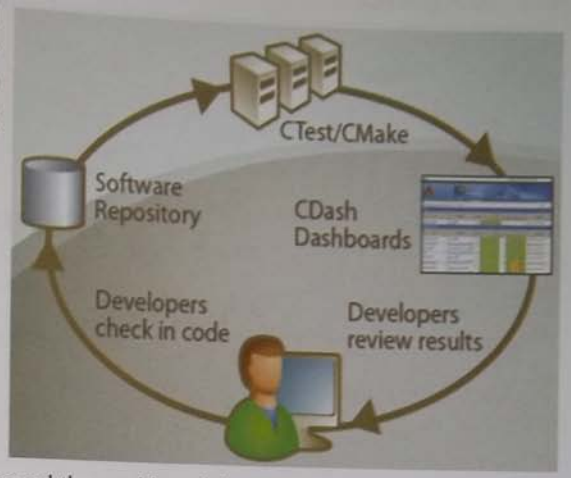
Figure 14–1 CDash regression testing dashboard. Tests are submitted from client sites around the world. The dashboard summarizes the results of hundreds of tests, and makes those results available as hyperlinked Web pages that is publicly viewable.

- **TestEmptyInput.** This deceptively simple test catches many problems due to developers assuming that the input to an algorithm is non-NULL, or that the input data object contains some data. TestEmptyInput simply exercises these two conditions on each subclass of vtkAlgorithm and reports problems if encountered.
- **Coverage.** There is a saying among VTK developers: "If it isn't covered, then it's broken." What this means is that code that is not executed during testing is likely to be wrong. The coverage tests identify lines that are not executed in the *Visualization Toolkit* test suite, reporting a total percentage covered at the end of the test. While it is nearly impossible to bring the coverage to 100% because of error handling code and similar constructs that are rarely encountered in practice, the coverage numbers should be 75% or higher. Code that is not covered well enough requires additional tests.

Another nice feature of CDash is that it maintains a history of changes to the source code (by coordinating with CVS) and summarizes the changes as part of the dashboard. This is useful for tracking problems and keeping up to date with new additions to VTK.

Working The Process

The VTK software process functions across three cycles—the *continuous* cycle, the *daily* cycle, and the *release* cycle.



The continuous cycle revolves around the actions of developers as they check code into CVS. When changed or new code is checked into CVS, the CDash continuous testing process kicks in. A small number of tests are performed (including compilation), and if something breaks, email is sent to all developers who checked code in during the continuous cycle. Developers are expected to fix the problem immediately.

The daily cycle occurs over a 24-hour period. Changes to the source base made during the day are extensively tested by the nightly CDash regression testing sequence. These tests occur on different combinations of computers and operating systems located around the world, and the results are posted every day to the CDash dashboard. Developers who checked in code are expected to visit the dashboard and ensure their changes are acceptable—that is, they do not introduce compilation errors or warnings or break any other tests including regression, memory, print self, and Set/Get. Developers are expected to fix problems immediately.

The release cycle occurs a small number of times a year. This requires tagging and branching the CVS repository, updating documentation, and producing new release packages. Although additional testing is performed to insure the consistency of the package, keeping the daily releases error free minimizes the work required to cut a release.

VTK users typically work with releases, since they are the most stable. Developers work with the CVS repository, or sometimes with periodic snapshots (a particular daily release) in order to take advantage of a newly-added feature. It is extremely important that developers watch the dashboard carefully, and *update their software only when the dashboard is in good condition (i.e., is "green").* Failure to do so can cause significant disruption if a particular day's software release is unstable.

The Effectiveness of the Process

The effectiveness of this process is profound. By providing immediate feedback to developers through email and Web pages (i.e., the dashboard), the quality of VTK is exceptionally high, especially considering the complexity of the algorithms and system. Errors, when accidently introduced, are caught quickly, as compared to catching them at the point of release. To wait to the point of release is to wait too long, since the causal relationship between a code change or addition and a bug is lost. The process is so powerful that it routinely catches errors in vendor's graphics drivers (e.g., OpenGL drivers) or changes to external subsystems such as the Mesa OpenGL software library. All of these tools that make up the process (CMake, CVS, and CDash are open-source). Many large and small systems such as ITK (the Insight Segmentation and Registration Toolkit `http://www.itk.org`) use the same process with similar results. We encourage the adoption of the process in your environment. (Note: Commercial support, consulting, and training for this process is available from Kitware, Inc. at `kitware@kitware.com`.)

Managing Pipeline Execution

The Visualization Toolkit uses a very general execution mechanism. Filters are divided into two basic parts: algorithm and executive objects. An *algorithm* object, whose class is derived from vtkAlgorithm, is responsible for processing information and data. An *executive* object, whose class is derived from vtkExecutive, is responsible for telling an algorithm when to execute and what information and data to process. The executive component of a filter may be created independently of the algorithm component allowing custom pipeline execution mechanisms without modifying core VTK classes.

Information and data produced by a filter are stored in one or more *output ports*. An output port corresponds to one logical output of the filter. For example, a filter producing a color image and a corresponding binary mask image would define two output ports each holding one of the images. Pipeline-related information is stored in an instance of vtkInformation on each output port. The data for an output port is stored in an instance of a class derived from vtkDataObject.

Information and data consumed by a filter are retrieved through one or more *input ports*. An input port corresponds to one logical input of the filter. For example, a glyph filter would define one input port for the glyph itself and another input port providing the geometry specifying glyph placement. Input ports store *input connections* which reference the output ports of other filters providing information and data. Each input connection provides one data object and its corresponding information obtained from the output port to which the connection is made. Since connections are stored through logical ports and not in the data flowing through those ports the data type need not be known when the connection is made. This is particularly useful for creation of pipelines whose source is a reader that does not know its output data type until the file is read.

Figure 15–1 depicts the layout of a filter from two viewpoints. The top diagram shows the filter as viewed from the algorithm object. This view of the filter is independent of the pipeline and contains all the information about the interface of the algorithm. The second diagram shows the filter as viewed from the executive object. This view of the filter is independent of the details of the algorithm and contains all the information about pipeline connections and the data sent through them.

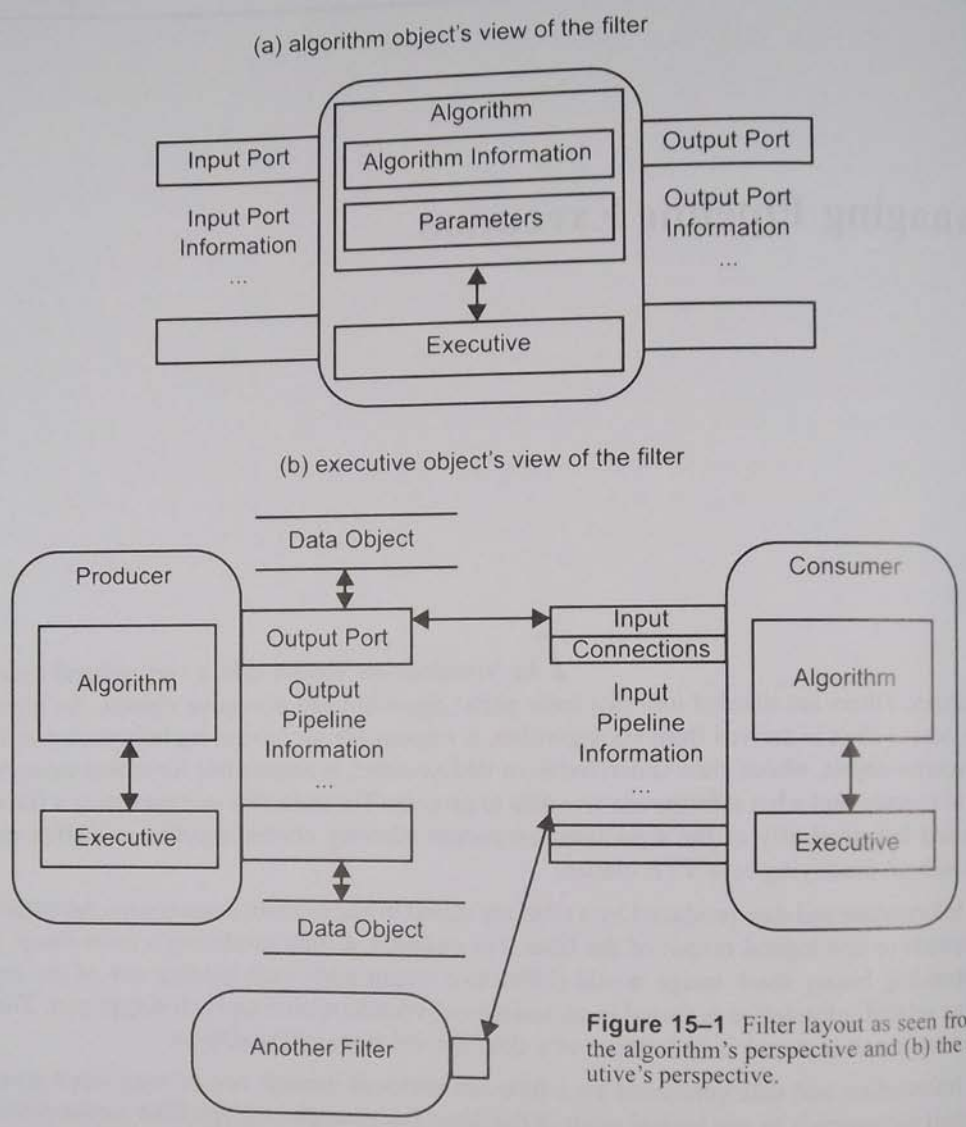


Figure 15–1 Filter layout as seen from (a) the algorithm's perspective and (b) the executive's perspective.

15.1 Information Objects

Information objects are the basic containers used throughout a VTK pipeline to hold a wide variety of information. All information objects are instances of the class vtkInformation. They are heterogeneous key-to-value maps in which the type of the key determines the type of the value. The following is an enumeration of the places information objects are used.

- **Pipeline Information** objects hold information for pipeline execution. They are stored in instances of vtkExecutive or a subclass and are accessible via the method vtkExecutive::GetOutputInformation(). There is one pipeline information object per output port. It contains an entry pointing to the output vtkDataObject on the corresponding port (if it has been created).

The vtkDataObject contains a pointer back to its corresponding pipeline information object, accessible via vtkDataObject::GetPipelineInformation(). The pipeline information object also holds information about what will populate the data object when the filter executes and generates the output. The actual information contained is determined by the output data type and the execution model in use. Pipeline information objects for input connections are accessible via the method vtkExecutive::GetInputInformation(), and they are the pipeline information objects on the output ports to which the input ports are connected.

- **Port Information** objects hold information about the data types produced on output ports and consumed by input ports. They are stored by instances of vtkAlgorithm. There is one input port information object per input port and one output port information object per output port. They are accessible via the methods vtkAlgorithm::GetInputPortInformation() and vtkAlgorithm::GetOutputPortInformation(). Port information objects are usually created and populated by subclasses of vtkAlgorithm in order to specify the interface of the filter.
- **Request Information** objects hold information about a specific request being sent to an executive or algorithm. There is one entry indicating what request is being sent and possibly other entries giving additional details about the specific request. These information objects are not accessible via any public method but are passed to ProcessRequest() methods that implement the requests.
- **Data Information** objects hold information about what is currently stored in a vtkDataObject. There is one data information object in each data object, accessible via vtkDataObject::GetInformation(). The actual information contained is determined by the data object type.
- **Algorithm Information** objects hold information about an instance of vtkAlgorithm. There is one algorithm information object per algorithm object, accessible via vtkAlgorithm::GetInformation(). The actual information contained is determined by the algorithm object type.

15.2 Pipeline Execution Models

The fundamental pipeline update mechanism is the *request*. A request is the basic pipeline operation (or "pipeline pass") which generally asks for certain information to be propagated through the pipeline. An *execution model* is a set of requests defined by a specific executive.

Requests are generated by the executive object of a filter that has been explicitly asked to update by its algorithm due to some user call. For example, when the Write() method of a writer is called, the algorithm object asks its executive to update the pipeline, and execute the writer, by calling this->GetExecutive()->Update(). Several requests may be sent through the pipeline in order to bring it up to date.

A request is implemented as an information object. There is one key of type vtkInformationRequestKey specifying the request itself. This key is typically defined by the executive's class. Additional information about the request may also be stored in the request information object.

Requests are propagated through the pipeline by the executives of each filter. The vtkExecutive::ProcessRequest() method is invoked on an executive and given the request information object. This method is implemented by each executive and is responsible for fulfilling the request as it sees fit. Many requests may be fulfilled for a filter only after it has been fulfilled for the filters providing its inputs. For these requests the executive will pass the request on to the executives of these upstream filters and then handle the request itself.

An executive often asks its algorithm object for help in fulfilling a request. It sends the request to the algorithm object by invoking the vtkAlgorithm::ProcessRequest() method. This method is implemented by all algorithms and is responsible for handling the request. Input and output pipeline information objects are provided as arguments to the method. The algorithm must handle the request using only its own filter parameter settings and the pipeline information objects given. An algorithm is not allowed to ask its executive for any additional information.

Figure 15–2 shows a typical path taken by a request as it is sent through a pipeline. Typically the request originates in a consumer at the end of the pipeline. It is sent back through the pipeline by the executives. Each executive asks its algorithm to help handle the request.

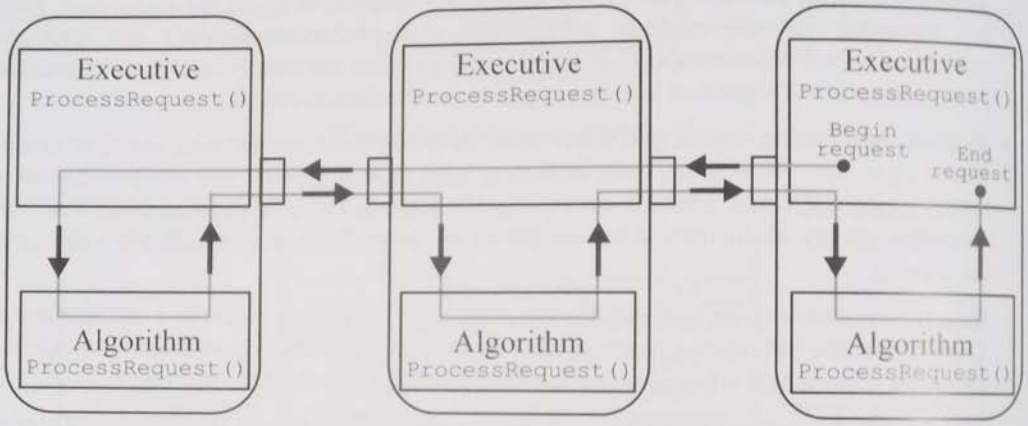


Figure 15–2 Path of a request sent through a pipeline. For example, assume the consumer (at the far right) needs only a single piece of this data (e.g., piece 1 of 4); also assume that the producer (on the far left) is a reader that can partition its data into pieces. The consumer passes this request upstream, and it continues upstream (via executives) until it reaches a producer which can fulfill the request. When the reader algorithm is asked for a piece of the data, it provides it, and passes the new data back (with the information that it is piece 1 of 4) down the pipeline. It stops when it reaches the consumer who made the request.

15.3 Pipeline Information Flow

Information flows through VTK pipelines one filter at a time. While handling a request a filter may modify the pipeline information given with the request. Modification of the output pipeline information is known as *downstream* flow because information is sent down the pipeline toward the consumers, terminating at a mapper. Similarly, modification of the input pipeline information is known as *upstream* flow because information is sent up the pipeline toward the producers, terminating with the sources at the beginning of the pipeline.

Each request defined by an executive asks for certain information to be propagated through the pipeline. Requests that ask filters to send information downstream are known as *downstream requests*, and those that ask filters to send information upstream are known as *upstream requests*. For example, an image processing filter might be given a downstream request for information about the geometry of the image. If the filter does not modify this geometry it may simply copy the image origin and spacing (using the keys vtkDataObject::ORIGIN() and vtkDataObject::SPACING()) from its input pipeline information to its output pipeline information. Similarly, a filter may be given an upstream request for information about the region of the image required to satisfy a consumer. The

filter may simply copy the requested image extent from its output pipeline information to its input pipeline information or it may change the extent if it needs extra input to complete its computation.

Information about the data being processed by a filter is usually handled by the filter implementation simply because it would not otherwise function. Some algorithms may wish to send additional information through a pipeline. For example, a mapper might decide that it needs information about the number of timesteps available from the source. This mapper can modify the default information request by overriding a virtual method and asking for additional information. This extended request is propagated to the source without the knowledge of intermediate filters. The source is then free to generate the information and if it does so, the pipeline will propagate it downstream.

15.4 Interface of Information Objects

The vtkInformation class provides a heterogeneous key-to-value map. Keys to this map are instances of the abstract class vtkInformationKey. The address of a key object is used to store and retrieve values in the map, and the type of a key object is used to interpret the values. A key is named by the static class method that returns it. An interface for storing and retrieving values with a key is provided by the key itself. For example, consider these information keys defined by vtkDataObject:

```
vtkInformationStringKey* FIELD_NAME();
vtkInformationDoubleVectorKey* ORIGIN();
```

We can create an vtkInformation instance with which to work.

```
vtkSmartPointer<vtkInformation> info =
  vtkSmartPointer<vtkInformation>::New();
```

FIELD_NAME is a key accessing a value with type "String":

```
vtkInformationStringKey* FIELD_NAME = vtkDataObject::FIELD_NAME();
FIELD_NAME->Has(info);     // returns 0
FIELD_NAME->Set(info, "ABC"); // sets info{FIELD_NAME} to "ABC"
FIELD_NAME->Has(info);     // returns 1
FIELD_NAME->Get(info);     // returns a pointer to "ABC"
FIELD_NAME->Remove(info);    // removes info{FIELD_NAME}
FIELD_NAME->Has(info);     // returns 0
```

ORIGIN is a key accessing a value with type "DoubleVector":

```
double origin[3] = {1,2,3};
vtkInformationDoubleVectorKey* ORIGIN = vtkDataObject::ORIGIN();
ORIGIN->Has(info);         // returns 0
ORIGIN->Set(info, origin, 3); // sets info{ORIGIN} to {1,2,3}
ORIGIN->Has(info);         // returns 1
ORIGIN->Get(info);         // returns a pointer to {1,2,3}
ORIGIN->Get(info, origin);    // stores {1,2,3} in origin
ORIGIN->Length(info);      // returns 3
ORIGIN->Remove(info);      // removes info{ORIGIN}
ORIGIN->Has(info);         // returns 0
```

Since the access interface is provided by the key new key types may be defined without modifying the class vtkInformation itself. However, the syntax is somewhat unintuitive because the key object is not modified but instead modifies the given information object. In order to simplify access to information objects in the common case, vtkInformation provides a convenience interface for most of the key types defined in VTK. The above examples may instead be written

```
vtkInformationStringKey* FIELD_NAME = vtkDataObject::FIELD_NAME();
info->Has(FIELD_NAME);     // returns 0
info->Set(FIELD_NAME, "ABC"); // sets info{FIELD_NAME} to "ABC"
info->Has(FIELD_NAME);     // returns 1
info->Get(FIELD_NAME);     // returns a pointer to "ABC"
info->Remove(FIELD_NAME);    // removes info{FIELD_NAME}
info->Has(FIELD_NAME);     // returns 0

double origin[3] = {1,2,3};
vtkInformationDoubleVectorKey* ORIGIN = vtkDataObject::ORIGIN();
info->Has(ORIGIN);         // returns 0
info->Set(ORIGIN, origin, 3); // sets info{ORIGIN} to {1,2,3}
info->Has(ORIGIN);         // returns 1
info->Get(ORIGIN);         // returns a pointer to {1,2,3}
info->Get(ORIGIN, origin);    // stores {1,2,3} in origin
info->Length(ORIGIN);      // returns 3
info->Remove(ORIGIN);      // removes info{ORIGIN}
info->Has(ORIGIN);         // returns 0
```

Key instances may be defined by classes by creating a static method naming the key and implementing the method using the vtkInformationKeyMacro or vtkInformationKeyRestrictedMacro. The latter form may be used for key types whose constructors accept an additional argument that specifies some restriction on the values allowed. For example, vtkDataObject implements its static methods FIELD_NAME() and ORIGIN() using this code:

```
#include "vtkInformationStringKey.h"
#include "vtkInformationDoubleVectorKey.h"
vtkInformationKeyMacro(vtkDataObject, FIELD_NAME, String);
vtkInformationKeyRestrictedMacro(vtkDataObject, ORIGIN, DoubleVector,
                                 3);
```

The first line states that FIELD_NAME is a key with type "String", and the second line states that ORIGIN is a key with type "DoubleVector" whose length must always be 3. Key type names are transformed to information key class names by adding the prefix "vtkInformation" and suffix "Key". In the above example FIELD_NAME has key type vtkInformationStringKey. Class authors must include the header for each key type used in key definitions.

Debugging pipeline execution and algorithm implementations may be simplified if the "watch" feature available in most debuggers is used to break when a particular information entry changes. Since most information entries are not stored in instance variables getting the proper memory address to watch is non-obvious. Some information key types provide a protected method GetWatchAddress() which returns the proper address to watch. Every key instance is stored by a global variable whose name is constructed from the name of the class defining the key, followed by an underscore, followed by the name of the key. For example, in order to watch the WHOLE_EXTENT entry in a pipeline

information object one may obtain the memory address from the following expression in the debugger.

```
vtkStreamingDemandDrivenPipeline::WHOLE_EXTENT()
->GetWatchAddress(info)
```

In this example the argument "info" may be a local variable in the scope at which the debugger has stopped the program. The returned address may be used to automatically break when the whole extent changes.

15.5 Standard Executives

VTK provides some standard extremely powerful executives. Most applications can achieve desired pipeline update behavior using one of the executives reviewed here.

vtkDemandDrivenPipeline

This executive implements a basic demand-driven implicit execution model. Each filter maintains a modification time as its parameters change. The executive tracks the time at which the information and data on each output port of its filter were last generated. Filters are executed on-demand when their output is requested and is out of date.

The following requests are defined by this executive. All of them are downstream requests. A default implementation is provided for each request that simplifies filters in the common case. The burden of maintaining pipeline information is removed from filters that do not change it.

ComputePipelineMTime asks that the pipeline modification time be computed for a filter. This is the highest (most recent) modification time of all the filter parameters and its inputs. The time computed will be compared to that of any output requested from the filter to determine whether it is up to date. Since the request is sent through the entire pipeline on every update no matter what filters will execute, it must be fast. The implementation is optimized in a special way: the request is implemented by the ComputePipelineMTime() method instead of ProcessRequest(). Common information needed for the request is passed directly in arguments to the method. Both executives and algorithms that wish to replace the default implementation of this request should override the ComputePipelineMTime() method. The special design of this request is purely an optimization for its performance-critical nature and should not be used as a model for the design of other requests.

REQUEST_DATA_OBJECT asks for a vtkDataObject to be created, but not populated, and stored in the output pipeline information of all output ports. The data objects will be populated later by REQUEST_DATA. A default implementation is provided by vtkDemandDrivenPipeline which uses the data object type specified by the key vtkDataObject::DATA_TYPE_NAME() in the corresponding output port information. Filters that vary their output type based on input type and parameter settings must implement this request and compute the proper type. The data object should be stored in the output pipeline information using the key vtkDataObject::DATA_OBJECT().

REQUEST_INFORMATION asks for output pipeline information about the data object in each output port. This is information about what will be stored in the data object, not what is currently in the data object. An example of this information is the origin and spacing of an image or uniform grid, stored with the keys vtkDataObject::ORIGIN() and vtkDataObject::SPACING() respectively. A default implementation is provided by vtkDemandDrivenPipeline which copies information from each output data object's data information to the corresponding pipeline information by calling vtk-

DataObject::CopyInformationToPipeline(). Then if any input connection exists information is copied from the first connection to each output pipeline information object. Sources that have no input or filters that change this information from that in the input must implement this request to compute the proper information.

REQUEST_DATA asks for the output data object to be populated with the actual output data on the output port through which the request arrived. This output port number is given by the key vtkExecutive::FROM_OUTPUT_PORT() in the request information object. The data object in the output port given in the request must be populated, but data objects in other output ports may optionally be populated also. (Most filters always populate all outputs.) When processing a REQUEST_DATA the vtkDemandDrivenPipeline proceeds with the following steps.

- Send a vtkDemandDrivenPipeline::REQUEST_DATA_NOT_GENERATED() request to the algorithm part of the filter. The request contains all the information in the original REQUEST_DATA, including the vtkExecutive::FROM_OUTPUT_PORT() key. Filters that do not always populate all outputs must implement this request to store a vtkDemandDrivenPipeline::DATA_NOT_GENERATED() with value 1 in the pipeline information of all output ports whose data will not be populated. This tells the executive that those outputs will not be generated by this REQUEST_DATA. Most filters can ignore this request.
- For output ports whose pipeline information does not contain the vtkDemandDrivenPipeline::DATA_NOT_GENERATED() mark, the output data objects are initialized by calling vtkDataObject::PrepareForNewData. These objects were previously created by a REQUEST_DATA_OBJECT and are re-initialized to an empty state by this step. Pipeline information that was previously set by a REQUEST_INFORMATION and corresponding to each data object is copied to the objects' data information by calling vtkDataObject::CopyInformationFromPipeline.
- Invoke the StartEvent on the algorithm object, clear the AbortExecute flag, and update the progress to 0.
- Send REQUEST_DATA to the algorithm. All algorithms must implement this request to populate the data objects in output pipeline information for ports not marked by vtkDemandDrivenPipeline::DATA_NOT_GENERATED().
- Update the progress to 1 if the AbortExecute flag is not set and then always invoke the EndEvent on the algorithm object.
- For output ports whose pipeline information does not contain the vtkDemandDrivenPipeline::DATA_NOT_GENERATED() mark, the output data objects are marked as generated by calling vtkDataObject::DataHasBeenGenerated().
- Remove vtkDemandDrivenPipeline::DATA_NOT_GENERATED() marks from all output pipeline information.
- For any input connections whose pipeline information contains a vtkDemandDrivenPipeline::RELEASE_DATA() mark, data are released by calling vtkDataObject::ReleaseData().

This default sequence of events handles most of the pipeline-related part of filter execution. The algorithm implementation needs only to process the actual data and compute information about the data that it is changing from input to output.

vtkStreamingDemandDrivenPipeline

This executive is a subclass of vtkDemandDrivenPipeline that adds streaming capability to pipelines. It implements the traditional VTK pipeline update rules and is the default executive assigned to algorithms not explicitly given one by the user.

The following requests are defined by this executive in addition to those defined by vtkDemandDrivenPipeline. All of them are downstream requests except for REQUEST_UPDATE_EXTENT, which is an upstream request.

REQUEST_INFORMATION is extended from that defined by vtkDemandDrivenPipeline. It asks for information about the amount of data available to be stored in the pipeline information of each output port. In the case of structured data this would be the whole extent, stored by vtkStreamingDemandDrivenPipeline::WHOLE_EXTENT(). In the case of unstructured data this would be the maximum number of pieces and the bounding box of the whole data set, stored by vtkStreamingDemandDrivenPipeline::MAXIMUM_NUMBER_OF_PIECES() and vtkStreamingDemandDrivenPipeline::WHOLE_BOUNDING_BOX() respectively. For filters that can produce data with time, the information includes information about the number of discrete time steps available or the continuous time range stored by vtkStreamingDemandDrivenPipeline::TIME_STEPS() or vtkStreamingDemandDrivenPipeline::TIME_RANGE() resepectively. A default implementation is provided by vtkStreamingDemandDrivenPipeline that copies this information first from the data object currently in the output and then from the first input connection if it exists. If the pipeline information on a port does not have a key vtkStreamingDemandDrivenPipeline::UPDATE_EXTENT_INITIALIZED() storing a non-zero value, the vtkStreamingDemandDrivenPipeline will initialize the update extent to the whole extent. This will cause all data to be processed if no consumer requests a specific update extent.

REQUEST_UPDATE_EXTENT asks for the input update extent necessary to produce a given output update extent stored in the input pipeline information. The output update extent to be satisfied must be obtained from the output pipeline information on the port through which the request arrived. This port number is given by vtkExecutive::FROM_OUTPUT_PORT() in the request information object. The update extent is stored using vtkStreamingDemandDrivenPipeline::UPDATE_EXTENT() for structured data and vtkStreamingDemandDrivenPipeline::UPDATE_PIECE_NUMBER(), vtkStreamingDemandDrivenPipeline::UPDATE_NUMBER_OF_PIECES(), and vtkStreamingDemandDrivenPipeline::UPDATE_NUMBER_OF_GHOST_LEVELS() for unstructured data. If a filter requires the exact extent it requests from an input connection to execute properly, it must store the key vtkStreamingDemandDrivenPipeline::EXACT_EXTENT() with value 1 in that input pipeline information for that connection. The time request is stored using vtkStreamingDemanDrivenPipeline::UPDATE_TIME_STEPS(). A default implementation is provided by vtkStreamingDemandDrivenPipeline that will copy the update extent from the output pipeline information to all input connections. If the output is unstructured data and an input connection is structured data, the extent translator stored in the output pipeline information with the key vtkStreamingDemandDrivenPipeline::EXTENT_TRANSLATOR() is used.

REQUEST_UPDATE_EXTENT_INFORMATION asks for information about the data that will be generated within the update extent. This is an advanced feature used to help the pipeline do extra analysis for choosing how to execute certain filters.

REQUEST_DATA is extended from that defined by vtkDemandDrivenPipeline. It enables streaming by giving algorithms the option of executing the request multiple times with different update extents requested of its input. When a streaming filter first receives a

REQUEST_UPDATE_EXTENT it stores only the update extent of the first piece of input data it will process. Then when it receives a REQUEST_DATA it processes the current piece and stores the key vtkStreamingDemandDrivenPipeline::CONTINUE_EXECUTING() with value 1 in the request information object itself. This tells the vtkStreamingDemandDrivenPipeline to send additional pairs of REQUEST_UPDATE_EXTENT and REQUEST_DATA. The filter responds to these subsequent requests by requesting and processing the remaining pieces of input data one at a time. After processing the last piece it removes the vtkStreamingDemandDrivenPipeline::CONTINUE_EXECUTING() mark from the request information object.

vtkCompositeDataPipeline

This executive is a subclass of vtkStreamingDemandDrivenPipeline that adds support for processing composite datasets. Composite datasets are datasets that comprise of other datasets e.g. multi-block datasets, AMR (adaptive mesh refinement) datasets. This executive supports algorithms that are aware of composite datasets as well as those that aren't. Algorithms that are not composite dataset aware need to support all the dataset types that can be part of the input composite dataset otherwise incompatible input type errors will be thrown at run-time.

For composite dataset aware algorithms i.e. those algorithms that indicate that they can accept vtkCompositeDataSet or any of its subclass as an input dataset, this executive behaves exactly like vtkStreamingDemandDrivenPipeline. Extra complication comes only when handling noncomposite aware algorithms. Due to the nature of composite datasets, typically correct result can be obtained by simply executing the noncomposite aware filter on each dataset in the input composite dataset and then combining the result produced by each execution into an output composite dataset with structure similar to that of the input. That's exactly how vtkCompositeDataPipeline deals with such algorithms.

REQUEST_DATA is extended to call REQUEST_DATA on the superclass vtkStreamingDemandDrivePipeline in a loop, passing a different noncomposite block from the input composite dataset as the current input and then collecting the results in a composite dataset with a structure similar to the input.

15.6 Choosing the Default Executive

A vtkAlgorithm subclass can override CreateDefaultExecute() to create the executive suitable for that algorithm. By default, vtkStreamingDeamandDrivenPipeline is used as the executive. One can use vtkAlgorithm::SetDefaultExecutivePrototype() to set the prototype for the executive to use by default. For example, if the application deals with composite datasets, one would want to change the executive to vtkCompositeDataPipeline so that non-composite aware filters can be used.

Interfacing To VTK Data Objects

In this section we provide detailed information describing the interface to the many data objects in VTK. This ranges from datasets, which are processed by the filter objects in visualization pipelines, to data arrays, which are used to represent a portion of a dataset (e.g., the scalar data).

To understand the relationship of data objects in VTK, refer to the diagrams in **Figure 19–1** through **Figure 19–5**.

16.1 Data Arrays

Data arrays, implemented in the superclass vtkDataArray and its many subclasses, are the foundation upon which many of the VTK data objects are built. For example, vtkPolyData, the data structure that VTK uses to represent polygonal graphics data, contains data arrays that store geometric (within vtkPoints), topological (within vtkCellArray) and attribute (within vtkField, vtkPointData and vtkCellData) information. It is essential then to learn how to manipulate vtkDataArrays in order to manipulate VTK Data Objects. vtkDataArrays are primarily used to store numerical information, and always for information that is not heterogeneous. They also assume that the information content that will be stored in the array is not sparse. VTK also provides vtkAbstractArrays (the superclass of vtkDataArray), and vtkArrays (reference section 12.16 vtkArray) later on in chapter) for working with less rigidly defined contents. Data arrays inherit from their vtkAbstractArray superclass an interfacebased on a tuple abstraction

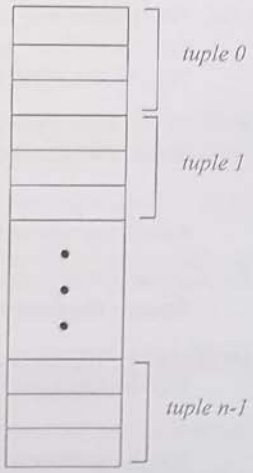


Figure 16–1 Data array structure. In this example, each tuple consists of three components.

(refer to **Figure 16–1**). Data arrays have the ability to manage internal memory by dynamic allocation and yet also provide raw pointer based access to their contents for efficiency.

In the tuple abstraction, vtkDataArray represents data as an array of tuples, each tuple consisting of the same number of components and each of the same native data type. In implementation, the tuples are actually subarrays within a contiguous array of data, as shown in the figure.

The power of data arrays and the tuple abstraction is that data can be represented in native type, and visualization data can be represented as a tuple. For example, we can represent vector data of native type `float` by creating a vtkFloatArray (a subclass of vtkDataArray) of tuple size (i.e., number of components) equal to 3. In this case, the number of vectors is simply the number of tuples; or alternatively, the number of float values divided by the number of components (for a vector, the number of components is always three).

vtkDataArray Methods

The following is a summary of the methods of vtkDataArray. Note that these are the methods required by all subclasses of vtkDataArray; there are several other methods specialized to each subclass. The special methods (which deal mainly with pointers and data specific information) for one subclass, vtkFloatArray, are shown immediately following the vtkDataArray method summary.

`dataArray = NewInstance()`
: Create an instance (`dataArray`) of the same type as the current data array. Also referred to as a "virtual" constructor.

`type = GetDataType()`
: Return the native type of data as an integer token (tokens are defined in `vtkType.h`). The possible types are `VTK_VOID`, `VTK_BIT`, `VTK_CHAR`, `VTK_SIGNED_CHAR`, `VTK_UNSIGNED_CHAR`, `VTK_SHORT`, `VTK_UNSIGNED_SHORT`, `VTK_INT`, `VTK_UNSIGNED_INT`, `VTK_LONG`, `VTK_UNSIGNED_LONG`, `VTK_LONG_LONG`, `VTK_UNSIGNED_LONG_LONG`, `VTK___INT64`, `VTK_UNSIGNED___INT64`, `VTK_FLOAT`, `VTK_DOUBLE`, and `VTK_ID_TYPE`.

`size = GetDataTypeSize()`
: Return the size of the underlying data type. 1 is returned for `VTK_BIT`.

`size = GetDataType(type)`
: Return the size of the specified data type. 1 is returned for `VTK_BIT`.

`SetNumberOfComponents(numComp)`
: Specify the number of components per tuple.

`GetNumberOfComponents()`
: Get the number of components per tuple.

`SetNumberOfTuples(number)`
: Set the number of tuples in the data array. This method allocates storage, and depends on prior invocation of the method SetNumberOfComponents() for proper allocation.

`numTuples = GetNumberOfTuples()`
: Return the number of tuples in the data array.

`tuple = GetTuple(i)`
: Return a pointer to an array that represents a particular tuple in the data array. This

method is not thread-safe, and data may be cast to a common type (i.e., `double`).

`GetTuple(i, tuple)`
Fill in a user-provided tuple (previously allocated) with data.

`GetTuples(ids, output)`
Given a list of ids (indices), return an array of corresponding tuples in the user-provided output array. The output array must be allocated (by the user) with enough memory for the data.

`GetTuples(id1, id2, output)`
Fill the user-provided output array with the tuples for the ranges of ids (indices) specified (id1 to id2, inclusive). The output array must be allocated (by the user) with enough memory for the data.

`SetTuple(i, tuple)`
Specify the tuple at array location `i`. This method does not do range checking, and is faster than methods that do (e.g., InsertTuple()). You must invoke SetNumberOfTuples() prior to inserting data with this method.

`InsertTuple(i, tuple)`
Insert data at the tuple location `i`. This method performs range checking, and will allocate memory if necessary.

`i = InsertNextTuple(tuple)`
Insert data at the end of the data array, and return its position in the array. This method performs range checking, and will allocate memory if necessary.

`c = GetComponent(i, j)`
Get the component value as a `double` at tuple location `i` and component `j` (of the ith tuple).

`SetComponent(i, j, c)`
Set the jth component value at tuple location `i`. This method does not perform range checking, you must have previously allocated memory with the method SetNumberOfTuples().

`InsertComponent(i, j, c)`
Insert the jth component value at tuple location `i`. This method performs range checking and will allocate memory as necessary.

`FillComponent(j, c)`
Fill the jth component of a data array with the specified value (`c`) for all tuples. This can be used to initialize a single component of a multi-component array.

`CopyComponent(j, array, c)`
Fill the jth component of a data array with the value from the cth component of `array`. This can be used to copy a component (column) from one data array to another.

`GetData(tupleMin, tupleMax, compMin, compMax, data)`
Extract a rectangular array of data (into `data`). The array `data` must have been pre-allocated. The rectangle is defined from the minimum and maximum ranges of the components and tuples.

`DeepCopy(dataArray)`
Perform a deep copy of another object. Deep copy means that the data is actually copied, not reference counted.

`ptr = GetVoidPointer(id)`
Return a pointer to the data as a `void *` pointer. This can be used, in conjunction with the method GetDataType(), to cast data to and from the appropriate type.

`ptr = WriteVoidPointer(id, number)`
Prepare the array for `number` writes starting at location `id`. Return the address of a particular data index (`id`). Make sure memory is allocated for `number` items. Set the `MaxId` instance variable according to the number of values requested.

`Allocate(size)`
Allocate memory for this array.

`Squeeze()`
Reclaim any unused memory the data array may have allocated. This method is typically used when you use Insert() methods and cannot exactly specify the amount of data at initial allocation.

`Resize(numTuples)`
Resize the array to the size specified by `numTuples`. Any data contained in the array will be preserved.

`Reset()`
Modify the data array so it looks empty but retains allocated storage. Useful to avoid excessive allocation and deallocation.

`size = GetSize()`
Return the size (number of elements) of the array.

`Initialize()`
Reset the data array to its initial state and release allocated storage.

`CreateDefaultLookupTable()`
If no lookup table is specified, and a lookup table is needed, then a default table is created.

`SetLookupTable(lut)`
Specify a lookup table to use for mapping array values to colors.

`lut = GetLookupTable()`
Return the lookup table to use for mapping array values to colors.

`GetTuples(ids, array)`
Given a list of ids, fill the user-provided array with tuples corresponding to those ids. For example, the ids might be the ids defining a cell and the return list contains the point scalars.

`id = GetMaxId()`
Return the maximum id currently in the array (number of elements - 1).

`SetVoidArray(array, size, save)`

Directly set the data array (specified as a void*) from an outside source. This method is useful when you are interfacing to data and want to pass the data into VTK's pipeline. The save flag indicates whether the array passed in should be deleted when the data array is destructed. A value of 1 indicates that VTK should not delete the data array when it is done using it.

`ExportToVoidPointer(ptr)`
Copy the data array to the void pointer specified by the user. It is the user's responsibility to allocate enough memory for the void pointer.

`sz = GetActualMemorySize()`
Return the memory (in kilobytes) used by this data array.

`SetName(name)`
Specify a name for the data array.

`name = GetName()`
Return the name of the data array.

`ComputeRange(comp)`
Determine the range of values contained in the specified component (`comp`) of the data array.

`range = GetRange(i)`
Return the range (min,max) of the ith component. This method is not thread safe.

`GetRange(range, i)`
Fill in the minimum/maximum values of the ith component in a user-provided array.

`range = GetRange()`
Return the range (min, max) of the 0th component. This method is not thread safe.

`GetRange(range)`
Fill in the minimum/maximum values of the 0th component in a user-provided array.

`GetDataTypeRange(range)`
Fill in the minimum/maximum values that can be specified using the underlying data type.

`GetDataTypeRange(type, range)`
Fill in the minimum/maximum values that can be specified using the data type indicated by type.

`min = GetDataTypeMin()`
Return the minimum value that can be specified using the underlying data type.

`min = GetDataTypeMin(type)`
Return the minimum value that can be specified using the data type indicated by type.

`max = GetDataTypeMax()`
Return the maximum value that can be specified using the underlying data type.

`max = GetDataTypeMax(type)`
Return the maximum value that can be specified using the data type indicated by type.

`norm = GetMaxNorm()`
Return the maximum norm value over all the tuples. This value is computed each time GetMaxNorm() is called.

`array = CreateDataArray(type)`
Create an array of the specified data type. The user is responsible for deleting the data array returned.

The following methods are from vtkFloatArray, which is a subclass of vtkDataArray. Note that there is overlap between the functionality available from the superclass vtkDataArray and its concrete subclasses. The is because the superclass provides some generic functionality useful for quick/compact coding, while the subclasses let you get at the data directly, which can be manipulated via pointer manipulation and/or templated functions.

`v = GetValue(i)`
Return the value at the ith data location in the array.

`SetNumberOfValues(number)`
Set the number of values in the array. This method performs memory allocation.

`SetValue(i, value)`
Set the value at the ith data location in the array. This method requires prior invocation of SetNumberOfValues() or WritePointer(). The method is faster than the insertion methods because no range checking is performed.

`InsertValue(i, f)`
Insert the value at the ith data location in the array. This method perform range checking and allocates memory as necessary.

`id = InsertNextValue(f)`
Insert the value `f` at the end of the data array, and return its position in the array. This method performs range checking, and will allocate memory if necessary.

`void GetTupleValue(i, tuple)`
Copy the ith tuple into the user-provided array.

`SetTupleValue(i, tuple)`
Set the tuple at the ith position in the data array.

`InsertTupleValue(i, tuple)`
Insert the tuple into the ith position in the data array. Memory allocation is performed if necessary.

`InsertNextTupleValue(tuple)`
Insert the tuple at the end of the data array. Memory allocation is performed if necessary.

`ptr = GetPointer(i)`
Return the pointer to the data array. The pointer is returned from the ith data location (usually `i=0` and the method returns the pointer at the beginning of the array).

`ptr = WritePointer(i, number)`
Allocate memory and prepare the array for `number` direct writes starting at data location `i`. A pointer to the data starting at location `i` is returned.

`SetArray(array, size, save)`
Directly set the data array from an outside source. This method is useful when you are interfacing to data and want to pass the data into VTK's pipeline. The `save` flag indicates whether the `array` passed in should be deleted when the data array is destructed. A value

of one indicates that VTK should not delete the data array when it is done using it.

16.2 Datasets

Often times the hardest part about writing a filter is interfacing to the VTK data objects. Chances are that as a filter developer, you are intimately familiar with the algorithm. It's learning how to manipulate VTK datasets—reading the input and creating the output—that is the key to writing an efficient, robust, and useful filter. Probably the single most important step in learning how to manipulate datasets is understanding the data model. **Figure 16–2** summarizes the dataset types in VTK. If you're not familiar with these objects, you'll want to read *The Visualization Toolkit* text, and/or spend some time reading the code to understand the data model. The following paragraphs highlight some of the important features of the data model.

One important aspect of VTK's data model is the relationship between the *structure* and the *data attributes* of a dataset. vtkDataSet is a subclass of vtkDataObject. The difference between the two classes is that data objects represent completely arbitrary data (see the "The Visualization Pipeline" on page 25) and datasets represent data that has an inherent spatial structure. Several vtkDataObject types that are not vtkDataSet including vtkSelection, vtkGraph, and vtkTable are described later in this chapter. The dataset structure then describes the geometric and topological relationship of points and cells to one another. When we refer to dataset type, we are actually referring to the structure of the data, that is how the geometry and topology is defined, stored and manipulated.

This spatial structure is the framework to which the dataset attributes are attached. Whereas a vtkDataObject will contain information in one instance of vtkFieldData, vtkDataSet has three instances. One for data set wide, general purpose information, one for values that are associated with each point and the last for values that are associated with each cell. These point and cell associated values are called dataset attributes and store information such as scalars, vectors, tensors, normals, texture coordinates, and ids. Regardless of the type of dataset, these topologically and geometrically associated data attributes are created and manipulated in the same way.

Another important feature of VTK's data model is the relationship of datasets to cells, and whether cells are represented implicitly or explicitly. Cells can be thought of as the atoms that form a dataset. Cells are a topological organization of the dataset points (*x-y-z* positions) into an ordered list, or connectivity array. For example, in a polygonal dataset (vtkPolyData), the polygons are the cells of the dataset, and each polygonal cell is represented as an ordered list of points (i.e., the vertices of the polygon). Some datasets represent points and cells explicitly (e.g., a list of points and cells in vtkPolyData), while others represent the points and cells implicitly (e.g., an image represented in vtkImageData by its dimensions, spacing, and origin). Implicit representation means that we do not explicitly store point coordinates or cell connectivity. Instead, this information is derived as necessary. You may wish to refer to **Figure 19–20** to view the cell types found in VTK.

Assuming that you have a thorough understanding of VTK's data model, you'll need to know how to get data from the datasets, and how to create and put data into the datasets. These activities are dependent on the type of dataset—different datasets have different preferred ways to interface to them. Also, datasets can be accessed at different levels of abstraction corresponding to the inheritance hierarchy. For example, to get the coordinates of a point in a vtkPolyData, we can invoke the superclass method vtkDataSet::GetPoint(), or we can retrieve the points array in vtkPolyData with pts=vtkPolyData::GetPoints(), followed by access to the point coordinates via pts->GetPoint(). Both approaches are valid, and both are used, depending on the circumstances. As a filter writer, you'll have to determine the correct level of abstraction by which to interface with the datasets.

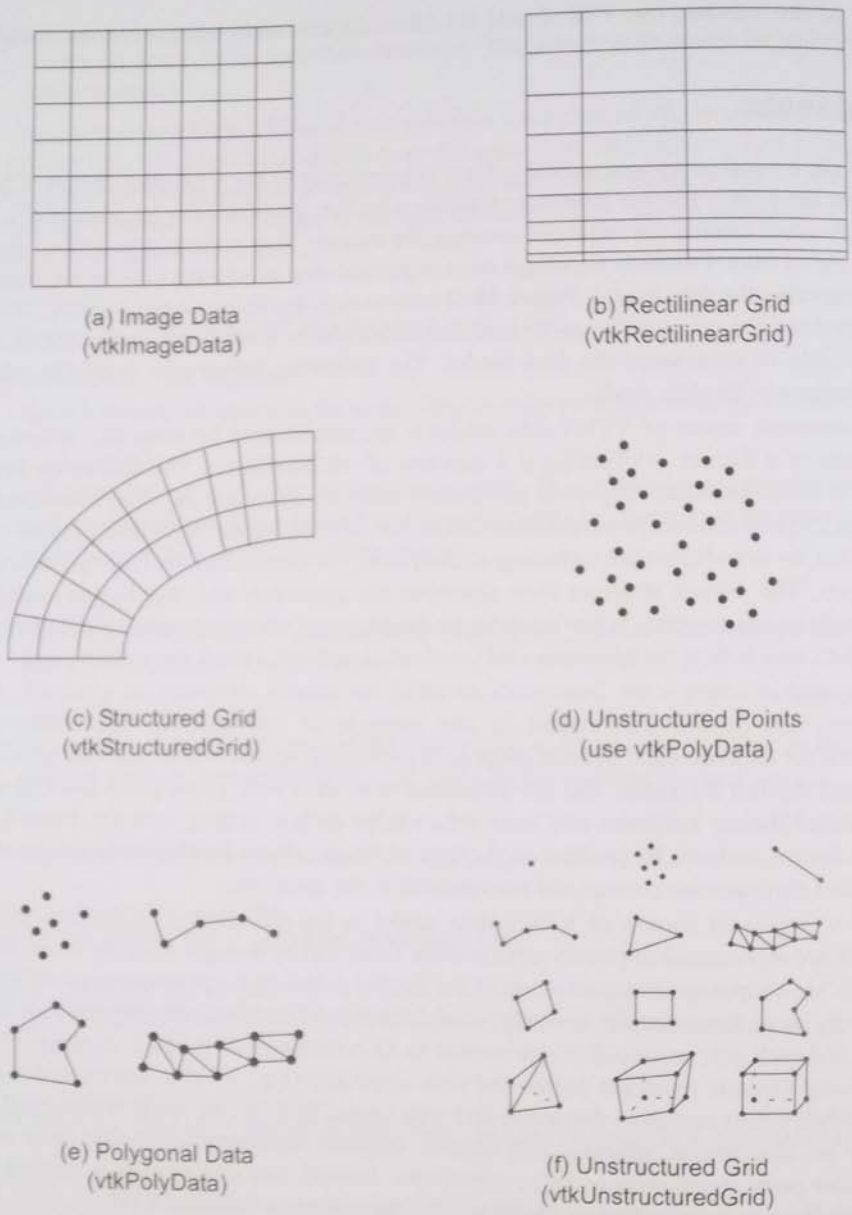


Figure 16–2 Fundamental dataset types found in VTK. Note that unstructured points can be represented by either polygonal data or unstructured grids, so are not explicitly represented in the system.

Note: for the fastest access, you could get the pointer to the points array and then use templated methods to process the data. For example:

```
void *ptr = pts->GetData()->GetVoidPointer(0);
switch (pts->GetData()->GetDataType())
```

```
{
case VTK_FLOAT:
  float *fptr = static_cast<float*>ptr;
  ...etc...
}
```

The next sections summarize how to manipulate the various types of datasets. You'll need this information if you're going to write a filter. Once you understand the interface to vtkDataSet, the actual construction of a graphics filter is relatively straightforward. As you read this material, you may wish to refer to the inheritance hierarchy (**Figure 19–4**). The summary information for each dataset is broken into three parts:

1. a general description of the dataset,
2. methods to create, manipulate, and extract information from the dataset,
3. one or more examples demonstrating important concepts.

vtkDataSet is an abstract dataset type. vtkDataSet exists to define a set of accessor methods that all of its concrete dataset sub-classes inherit. Abstract objects are used as to refer to concrete objects in general settings, in which the specific concrete type is unknown or unimportant.

Note that abstract objects cannot be (directly) instantiated. Therefore it is common practice to use vtkDataSet's NewInstance() method to create a new instance of a concrete class given a pre-existing vtkDataSet object. This is almost always followed by the CopyStructure() method, which makes a copy of the geometric and topological structure of the dataset. (You may also wish to copy the dataset attributes, see "Field and Attribute Data" on page 362 for more information.)

vtkDataSet Methods

In practice, the accessor methods that vtkDataSet defines are used within general filters that operate on any type of dataset, without regard for their specific structural characteristics. The following methods can be called on any vtkDataSet subclass.

`dataSet = NewInstance()`
: Create an instance of the same type as the current dataset. Also referred to as a "virtual" constructor.

`CopyStructure(dataSet)`
: Update the current structure definition (i.e., geometry and topology) with the supplied dataset. Note that copying is done using reference counting.

`type = GetDataObjectType()`
: Return the type of data object (e.g., vtkDataObject, vtkPolyData, vtkImageData, vtkStructuredGrid, vtkRectilinearGrid, or vtkUnstructuredGrid).

`numPoints = GetNumberOfPoints()`
: Return the number of points in the dataset.

`numCells = GetNumberOfCells()`
: Return the number of cells in the dataset.

`x = GetPoint(ptId)`
: Given a point id, return a pointer to the *(x,y,z)* coordinates of the point.

`GetPoint(ptId,x)`
Given a point id, copy the *(x,y,z)* coordinates of the point into the array `x` provided. This is a thread-safe variant of the previous method.

`cell = GetCell(cellId)`
Given a cell id, return a pointer to a cell object.

`GetCell(cellId, genericCell)`
Given a cell id, return a cell in the user-provided instance of type vtkGenericCell. This is a thread-safe variant of the previous GetCell() method.

`type = GetCellType(cellId)`
Return the type of the cell given by cell id. The type is an integer flag defined in the include file `vtkCellType.h`.

`GetCellTypes(types)`
Generate a list of types of cells (supplied in `types`) that compose the dataset.

`GetPointCells(ptId, cellIds)`
Given a point id, return a list of cells that use this point.

`GetCellPoints(cellId, ptIds)`
Given a cell id, return the point ids (e.g., connectivity list) defining the cell.

`GetCellNeighbors(cellId, ptIds, neighbors)`
Given a cell id and a list of points composing a boundary face or edge of the cell, return the neighbor(s) of that cell sharing the points.

`pointId = FindPoint(x)`
Locate the closest point to the global coordinate `x`. Return the closest point or `-1` if the point `x` is outside of the dataset.

`foundCellId = FindCell(x, cell, cellId, tol2, subId, pcoords, weights)`
Given a coordinate value `x`, an initial search cell defined by `cell` and `cellId`, and a tolerance measure (squared), return the cell id and sub-id of the cell containing the point and its interpolation function weights. The initial search cell (if `cellId>=0`) is used to speed up the search process when the position `x` is known to be near the cell. If no cell is found, `foundCellId` < 0 is returned.

`foundCellId = FindCell(x, cell, genericCell, cellId, tol2, subIc, pcoords, weights)`
Same as previous, but the user-provided instance of vtkGenericCell is used in any internal calls to GetCell().

`cell = FindAndGetCell(x, cell, cellId, tol2, subId, pcoords, weights)`
This is a variation of the previous method (FindCell()) that returns a pointer to the cell instead of the cell id.

`pointData = GetPointData()`
Return a pointer to the object maintaining point attribute data. This includes scalars, vectors, normals, tensors, texture coordinates, and field data.

`cellData = GetCellData()`

Return a pointer to the object maintaining cell attribute data. This includes scalars, vectors, normals, tensors, texture coordinates, and field data.

`bounds = GetBounds()`
Get the bounding box of the dataset. The return value is an array of $(x_{min}, x_{max}, y_{min}, y_{max}, z_{min}, z_{max})$.

`GetBounds(bounds)`
Get the bounding box of the dataset. The return value is an array of $(x_{min}, x_{max}, y_{min}, y_{max}, z_{min}, z_{max})$. This is a thread-safe variant of the previous method.

`length = GetLength()`
Return the length of the diagonal of the bounding box of the dataset.

`center = GetCenter()`
Get the center of the bounding box of the dataset.

`GetCenter(center)`
Get the center of the bounding box of the dataset. This is a thread-safe variant of the previous method.

`range = GetScalarRange()`
A convenience method to return the (minimum, maximum) range of the scalar attribute data associated with the dataset.

`GetScalarRange(range)`
A thread-safe variant of the previous method.

`Squeeze()`
Reclaim any extra memory used to store data. Typically used after creating and inserting data into the dataset.

`GetCellBounds(cellId, bounds)`
Store the bounds of the cell with the given cellId in the user-provided array.

`ComputeBounds()`
Determine the bounding box of the dataset.

`Initialize()`
Return the dataset to its initial state.

`size = GetMaxCellSize()`
Return the size (defined by number of points in the cell) of the largest cell in the dataset.

`size = GetActualMemorySize()`
Return the size of the dataset in kilobytes.

`ShallowCopy(src)`
Copy the `src` dataset to this dataset using reference counting.

`DeepCopy(src)`
Copy the `src` dataset to this dataset, making a second copy of the data.

`mismatch = CheckAttributes()`
Check whether the length of the cell and point attribute arrays matches the number of

points/cells in the geometry. Return 1 if there is a mismatch; return 0 otherwise.

`GenerateGhostLevelArray()`

This method computes the ghost arrays for the points of a given dataset.

vtkDataSet Examples

Here's a typical example of using the vtkDataSet API. The code fragment is modified from vtkProbeFilter. vtkProbeFilter samples data attribute values from one dataset onto the points of another (the filter has two inputs). Please ignore the references to point data attributes for now; these methods will be explained in "Field and Attribute Data" on page 362.

```
numPts = input->GetNumberOfPoints();
pd = source->GetPointData();

// Allocate storage for output PointData
outPD = output->GetPointData();
outPD->InterpolateAllocate(pd);

// Use tolerance as a function of size of source data
tol2 = source->GetLength();
tol2 = tol2*tol2 / 1000.0;

// Loop over all input points, interpolating source data
for (ptId=0; ptId < numPts; ptId++)
  {
  // Get the xyz coordinate of the point in the input dataset
  x = input->GetPoint(ptId);
  // Find the cell that contains xyz and get it
  cell = source->FindAndGetCell(x,NULL,
                        -1,tol2,subId,pcoords,weights);
  if (cell)
    {
    // Interpolate the point data
    outPD->InterpolatePoint(pd,ptId,
                            cell->PointIds,weights);
    }
  else
    {
    outPD->NullPoint(ptId);
    }
  }
 delete [] weights;
```

The following example shows how to create a reference-counted copy of a dataset using the vtkDataSet API. Both the variables newDataSet and `dataSet` are pointers to vtkDataSet.

```
newDataSet = dataSet->NewInstance();
newDataSet->CopyStructure(dataSet);
newDataSet->GetPointData()->
              PassData(dataSet->GetPointData());
```

```
newDataSet->GetCellData()->
                PassData(dataSet->GetCellData());
```

Now that we've covered the abstract API to vtkDataSet, we move to the concrete dataset types. Remember, every concrete subclass inherits the methods of its superclasses, including vtkDataSet.

16.3 Image Data

vtkImageData is a concrete dataset type representing a regular, *x-y-z* axis-aligned array of points. vtkImageData can represent 1D arrays, 2D images, and 3D volumes. Both the geometry and topology of the dataset structure are regular, and both are represented implicitly. A vtkImageData dataset is defined by data dimensions, interpoint spacing, and the origin (i.e., lower-left corner) of the dataset. If the dimension of the dataset is two, then we call the vtkImageData dataset an image, and it is composed of vtkPixel cell types. If the dimension of the dataset is three, then we call the vtkImageData dataset a volume, and it is composed of vtkVoxel cells.

vtkImageData Methods

`SetExtent(x1, x2, y1, y2, z1, z2)`
Set the extent of the image dataset. On each axis, the extent is defined by the index of the first point and the index of the last point.

`SetExtent(extent)`
An alternative to the previous method where extent is an integer array of size 6.

`ext = GetExtent()`
Return a pointer to an integer array of size 6 containing the extent (x_{min}, x_{max}, y_{min}, y_{max}, z_{min}, z_{max}) of the image dataset

`GetExtent(ext)`
A thread-safe alternative to the previous method.

`SetDimensions(i, j, k)`
Set the dimensions of the image dataset in terms of number of points, not cells. This is shorthand for the common case when the data starts at 0, 0, 0 and is equivalent to SetExtent(0, i-1, 0, j-1, 0, k-1).

`SetDimensions(dim)`
An alternative form of the previous method where `dim` is an array of size three.

`dims = GetDimensions()`
Return a pointer to an array of size three containing the *i-j-k* dimensions of the image dataset.

`GetDimensions(dims)`
Thread-safe form of previous method.

`SetSpacing(sx, sy, sz)`
Set the spacing of the image dataset.

`SetSpacing(spacing)`

An alternative form of the previous method where `spacing` is an array of size three.

`spacing = GetSpacing()`
Return a pointer to an array of size three containing the spacing of the dataset.

`GetSpacing(spacing)`
Thread-safe form of previous method.

`SetOrigin(x, y, z)`
Set the origin of the image dataset.

`SetOrigin(origin)`
An alternative form of the previous method where `origin` is an array of size three.

`origin = GetOrigin()`
Return a pointer to an array of size three containing the origin of the image dataset.

`GetOrigin(origin)`
Thread-safe form of previous method.

`ComputeStructuredCoordinates(x, ijk, pcoords)`
Given a point *x* in the 3D modeling coordinate system, determine the structured coordinates *i-j-k* specifying which cell the point is in, as well as the parametric coordinates inside the cell.

`GetVoxelGradient(i, j, k, scalars, gradient)`
Given a cell specified by *i-j-k* structured coordinates, and the scalar data for the image data dataset, compute the gradient at each of the eight points defining the voxel.

`GetPointGradient(i, j, k, scalars, gradient)`
Given a point specified by *i-j-k* structured coordinates, and the scalar data for the image data dataset, compute the gradient at the point (an array of size three).

`d = GetDataDimension()`
Return the dimensionality of the dataset ranging from (0,3).

`pointId = ComputePointId(int ijk[3])`
Given a point specified by *i-j-k* structured coordinates, return the point id.

`cellId = ComputeCellId(int ijk[3])`
Given a cell specified by *i-j-k* structured coordinates, return the cell id of the point.

`size = GetEstimatedMemorySize()`
Return the estimated memory size of the vtkImageData dataset in kilobytes.

vtkImageData Example

In this example, which is taken from the filter vtkExtractVOI, we subsample the input data to generate output data. In the initial portion of the filter (not shown), the dimensions, spacing, and origin of the output are determined and then set (shown). We then configure the output and copy the associated point attribute data.

```
int *inExt = input->GetExtent();
```

```
 output->SetDimensions(outDims);
output->SetSpacing(outAR);
output->SetOrigin(outOrigin);

 // If output same as input, just pass data through
 //
if ( outDims[0] == dims[0] && outDims[1] == dims[1] &&
 outDims[2] == dims[2] &&
rate[0] == 1 && rate[1] == 1 && rate[2] == 1 )
 {
 output->GetPointData()->PassData(input->GetPointData());
   output->GetCellData()->PassData(input->GetCellData());
 vtkDebugMacro(<<"Passed data through bacause input
                        and output are the same");
 return;
 }

 // Allocate necessary objects
outPD->CopyAllocate(pd,outSize,outSize);
 outCD->CopyAllocate(cd, outSize, outSize);
sliceSize = dims[0]*dims[1];

 // Traverse input data and copy point attributes to output
 //
newIdx = 0;
for ( k=voi[4]; k <= voi[5]; k += rate[2] )
 {
 kOffset = (k-inExt[4]) * sliceSize;
 for ( j=voi[2]; j <= voi[3]; j += rate[1] )
  {
  jOffset = (j-inExt[2]) * dims[0];
  for ( i=voi[0]; i <= voi[1]; i += rate[0] )
   {
   idx = (i-inExt[0]) + jOffset + kOffset;
   outPD->CopyData(pd, idx, newIdx++);
   }
  }
 }
```

16.4 Rectilinear Grids

vtkRectilinearGrid is a concrete dataset that represents information arranged on a topologically regular and geometrically semi-regular array of points. The points are defined by three vectors that contain coordinate values for the x, y, and z axes—thus the points are axis-aligned and only partially represented. The cells that make up vtkRectilinearGrid are implicitly represented and are of type vtkVoxel (3D) or vtkPixel (2D).

Creating a vtkRectilinearGrid requires specifying the dataset dimensions and three arrays defining the coordinates in the x, y, z directions. (These arrays are represented by the XCoordinates,

YCoordinates, and ZCoordinates instance variables.) Make sure that the number of coordinate values is consistent with the dimensions specified.

vtkRectilinearGrid Methods

The class vtkRectilinearGrid defines several methods beyond the methods inherited from vtkDataSet.

`SetExtent(x1, x2, y1, y2, z1, z2)`
Set the extent of the vtkRectilinearGrid dataset. On each axis, the extent is defined by the index of the first point and the index of the last point. Note that the ranges must match the number of values found in the XCoordinates, YCoordinates, and ZCoordinates arrays.

`SetExtent(extent)`
An alternative to the previous method where extent is an integer array of size 6.

`extent = GetExtent()`
Return a pointer to an integer array of size 6 containing the extent (x_{min}, x_{max}, y_{min}, y_{max}, z_{min}, z_{max}) of the vtkRectilinearGrid dataset.

`GetExtent(extent)`
A thread-safe alternative to the previous method.

`SetDimensions(i, j, k)`
Set the dimensions of the rectilinear grid dataset. This is shorthand for the common case when the data starts at 0, 0, 0 and is equivalent to SetExtent (0, i-1, 0, j-1, 0, k-1).

`SetDimensions(dim)`
An alternative form of the previous method where `dim` is an array of size 3.

`dims = GetDimensions()`
Return a pointer to an array of size 3 containing the *i-j-k* dimensions of the dataset.

`GetDimensions(dims)`
Thread-safe form of previous method.

`ComputeStructuredCoordinates(x, ijk, pcoords)`
Given a point in the 3D modeling coordinate system, determine the structured coordinates *i-j-k* specifying which cell the point is in, as well as the parametric coordinates inside the cell.

`d = GetDataDimension()`
Return the dimensionality of the dataset ranging from (0,3).

`pointId = ComputePointId(int ijk[3])`
Given a point specified by *i-j-k* structured coordinates, return the point id of the point.

`cellId = ComputeCellId(int ijk[3])`
Given a cell specified by *i-j-k* structured coordinates, return the cell id of the cell.

`SetXCoordinates(xcoords)`
Specify the array of values which define the *x* coordinate values. The array `xcoords` is of type vtkDataArray.

`SetYCoordinates(ycoords)`

Specify the array of values which define the *y* coordinate values. The array `ycoords` is of type vtkDataArray.

`SetZCoordinates(zcoords)`
Specify the array of values which define the *z* coordinate values.The array `zcoords` is of type vtkDataArray.

`xCoord = GetXCoordinates()`
Get the vtkDataArray specifying the values which define the x coordinate values.

`GetXCoordinates(xCoord)`
A thread-safe alternative to the previous method.

`yCoord = GetYCoordinates()`
Get the vtkDataArray specifying the values which define the y coordinate values.

`GetYCoordinates(yCoord)`
A thread-safe alternative to the previous method.

`zCoord = GetZCoordinates()`
Get the vtkDataArray specifying the values which define the z coordinate values.

`GetZCoordinates(zCoord)`
A thread-safe alternative to the previous method.

16.5 Point Sets

vtkPointSet is an abstract superclass for those classes that explicitly represent points (i.e., vtkPolyData, vtkStructuredGrid, vtkUnstructuredGrid). The basic function of vtkPointSet is to implement those vtkDataSet methods that access or manipulate points (e.g., GetPoint() or FindPoint()).

vtkPointSet Methods

There are several access methods defined, but most overload vtkDataSet's API. Note that because this object is abstract, there are no direct creation methods. Refer to the vtkDataSet::NewInstance() creation method (see "vtkDataSet Methods" on page 335 for more information).

`points = GetPoints()`
Return a pointer to an object of type vtkPoints. This class explicitly represents the points in the dataset.

`SetPoints(points)`
Specify the explicit point representation for this object. The parameter `points` is an instance of vtkPoints.

vtkPointSet Example

Here's an example of a filter that exercises the vtkPointSet API. The following code performs the operation defined by the class vtkWarpVector. (Note: vtkWarpVector has been templated for performance.)

```
 inPts = input->GetPoints();
pd = input->GetPointData();
if ( !pd->GetVectors() || !inPts )
 {
 vtkErrorMacro(<<"No input data");
 return;
 }
inVectors = pd->GetVectors();
numPts = inPts->GetNumberOfPoints();
newPts = vtkPoints::New();
newPts->SetNumberOfPoints(numPts);

 // Loop over all points, adjusting locations
for (ptId=0; ptId < numPts; ptId++)
 {
 x = inPts->GetPoint(ptId);
 v = inVectors->GetTuple(ptId);
 for (i=0; i<3; i++)
  {
  newX[i] = x[i] + this->ScaleFactor * v[i];
  }
 newPts->SetPoint(ptId, newX);
 }
```

The method to focus on is vtkPointSet::GetPoints(), which returns a pointer to a vtkPoints instance (inPts). Also, notice that we use the invocation vtkPoints::GetPoint() to return the point coordinates of a particular point. We could replace this call with vtkPointSet::GetPoint() and achieve the same result.

16.6 Structured Grids

vtkStructuredGrid is a concrete dataset that represents information arranged on a topologically regular but geometrically irregular array of points. The cells are of type vtkHexahedron (in 3D) and of type vtkQuad (in 2D), and are represented implicitly with the Dimensions instance variable. The points are represented explicitly by the superclass vtkPointSet.

vtkStructuredGrid Methods

Most of vtkStructuredGrid's methods are inherited from its superclasses vtkPointSet and vtkDataSet.

`SetExtent(x1, x2, y1, y2, z1, z2)`
: Set the extent of the vtkStructuredGrid dataset. On each axis, the extent is defined by the index of the first point and the index of the last point.

`SetExtent(extent)`
: An alternative to the previous method where extent is an integer array of size 6.

`ext = GetExtent()`
: Return a pointer to an integer array of size 6 containing the extent (x_{min}, x_{max}, y_{min}, y_{max}, z_{min}, z_{max}) of the vtkStructuredGrid dataset.

`GetExtent(ext)`

A thread-safe alternative to the previous method.

`SetDimensions(i, j, k)`

Specify the *i-j-k* dimensions of the structured grid. The number of points for the grid, specified by the product *i*j*k*, must match the number of points returned from vtkPointSet::GetNumberOfPoints().This is shorthand for the common case when the data starts at 0, 0, 0 and is equivalent to SetExtent(0, i-1, 0, j-1, 0, k-1).

`SetDimensions(dim)`

An alternative form of the previous method. Dimensions are specified with an array of three integer values.

`dims = GetDimensions()`

Return a pointer to an array of size three containing *i-j-k* dimensions of dataset.

`GetDimensions(dims)`

Thread-safe form of the previous method.

`dim = GetDataDimension()`

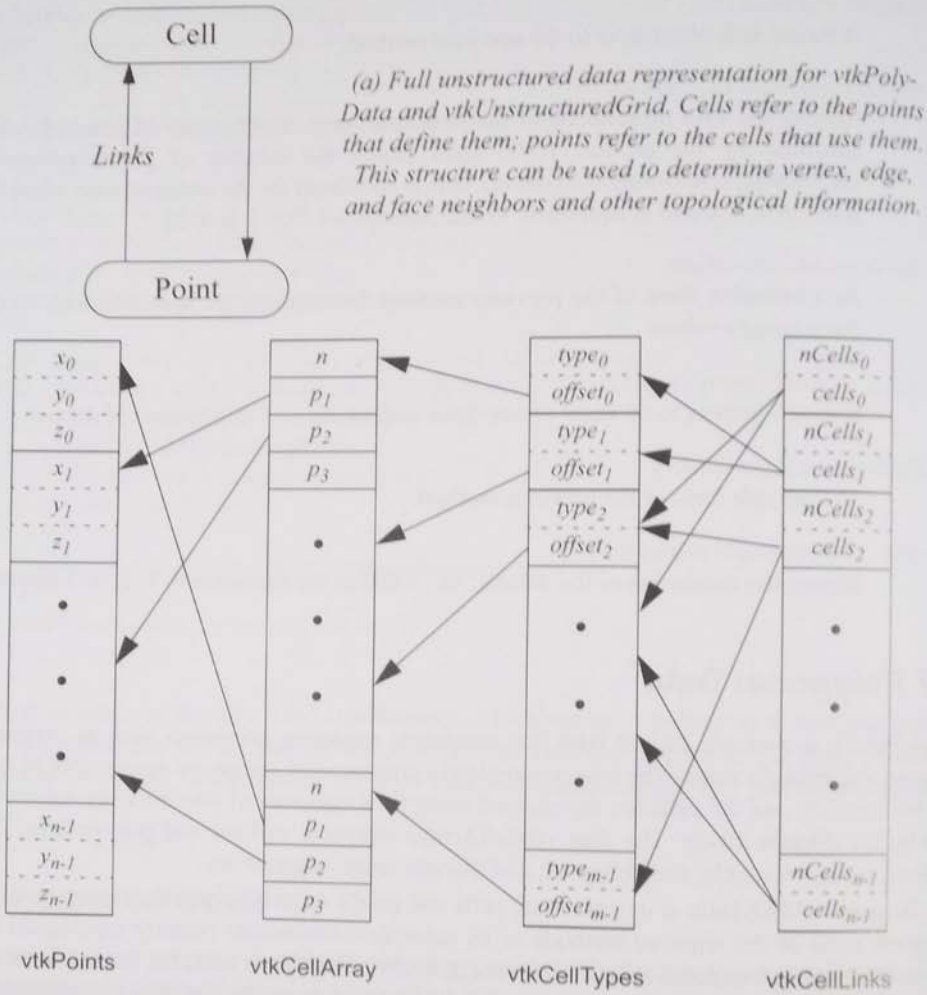
Return the dimension of the dataset, i.e., whether the dataset is 0, 1, 2, or 3-dimensional.

16.7 Polygonal Data

vtkPolyData is a concrete dataset type that represents rendering primitives such as vertices, lines, polygons, and triangle strips. The data is completely unstructured: points are represented in the superclass vtkPointSet, and the cells are represented using four instances of vtkCellArray, which is a connectivity list (**Figure 16–3**). The four vtkCellArrays represent vertices and polyvertices; lines and polylines; triangles, quads, and polygons; and triangle strips, respectively.

Because vtkPolyData is unstructured, cells and points must be explicitly represented. In order to support some of the required methods of its superclass vtkDataSet (mainly topological methods such as GetPointCells() and GetCellNeighbors()), vtkPolyData has a complex internal data structure as shown in **Figure 16–3**. Besides vtkPoints and the vtkCellArrays, the data structure consists of a list of cell types (vtkCellTypes) and cell links (vtkCellLinks). The cell types array allows random access into the cells. This is necessary because vtkCellArray cannot support random access due to the fact that individual cells may vary in size. The cell links array supports topological operations by maintaining references to all cells that use a particular vertex. (See *The Visualization Toolkit* text for more information.) Instances of these two classes, vtkCellTypes and vtkCellLinks, are only instantiated if needed. That is, if random access to cells is required vtkCellTypes is instantiated; or if topological information is required, vtkCellLinks is instantiated.

While this structure is fairly complex, the good news is that for the most part the management of the internal structure is taken care of for you. Normally you'll never need to directly manipulate the structure as long as you use vtkDataSet's API to interface the information. In some cases, writing a filter or using some of the vtkPolyData or vtkUnstructuredGrid methods, you may have to explicitly create the cell types and/or cell links arrays using the BuildCells() and BuildLinks() methods. In rare cases you may want to directly manipulate the structure—deleting points or cells, and/or modifying the link array to reflect changing topology. Refer to section "Supporting Objects for Data Sets" on page 355 for more information. Examples of code demonstrating the use these complex operators



(a) Full unstructured data representation for vtkPolyData and vtkUnstructuredGrid. Cells refer to the points that define them; points refer to the cells that use them. This structure can be used to determine vertex, edge, and face neighbors and other topological information.

(b) Unstructured data is represented by points (geometry and position in 3D space), a cell array (cell connectivity), cell types (provides random access to cells), and cell links (provides topological information). The cell types and cell links arrays are created on demand.

Figure 16–3 Representing unstructured data. This structure is used to represent polygonal and unstructured grid datasets.

include the classes Graphics/vtkDecimatePro, Graphics/vtkDelaunay2D, and Graphics/vtkDelaunay3D.

vtkPolyData Methods

The class vtkPolyData is fairly complex, overloading many of the methods inherited from its superclasses vtkDataSet and vtkPointSet. Most of the complexity is due to the definition of vertices, lines,

polygons, and triangle strips in separate vtkCellArrays, and special (geometric) methods for operating on the mesh.

`SetVerts (verts)`
Specify the list of vertices, verts. The parameter verts is an instance of vtkCellArray. Note: the difference between vertices and points are that Points define geometry; while vertices represent cells that contain a single point. Cells are directly renderable in VTK and points are not.

`verts = GetVerts()`
Get the list of vertices. The list is an instance of vtkCellArray.

`SetLines (lines)`
Specify the list of lines, `lines`. The parameter `lines` is an instance of vtkCellArray.

`lines = GetLines()`
Get the list of lines. The list is an instance of vtkCellArray.

`SetPolys(polys)`
Specify the list of polygons, `polys`. The parameter `polys` is an instance of vtkCellArray.

`polys = GetPolys()`
Get the list of polygons. The list is an instance of vtkCellArray.

`SetStrips(strips)`
Specify the list of triangle strips, `strips`. The parameter `strips` is an instance of vtkCellArray.

`strips = GetStrips()`
Get the list of triangle strips. The list is an instance of vtkCellArray.

`numVerts = GetNumberOfVerts()`
Return the number of vertices.

`numLines = GetNumberOfLines()`
Return the number of lines.

`numPolys = GetNumberOfPolys()`
Return the number of polygons.

`numStrips = GetNumberOfStrips()`
Return the number of triangle strips.

`Allocate(numCells, extend)`
Perform initial memory allocation prior to invoking the InsertNextCell() methods (described in next two items). The parameter `numCells` is an estimate of the number of cells to be inserted; `extend` is the size by which to extend the internal structure (if needed).

`Allocate(inPolyData, numCells, extend)`
Similar to the above method, this method allocates initial storage for vertex, line, polygon, and triangle strip arrays. However, it examines the supplied inPolyData to determine which of these arrays to allocate; they are only allocated if there is data in the corresponding arrays in inPolyData.

`cellId = InsertNextCell(type, npts, pts)`
Given a cell type, `type`, number of points in the cell, `npts`, and an integer list of point ids, `pts`, insert a cell and return its cell id. See **Figure 19–20** for a definition of type values. Make sure to invoke Allocate() prior to invoking this method.

`cellId = InsertNextCell(type, pts)`
Given a cell type, `type` and instance of vtkIdList, `pts`, insert a cell and return its cell id. Make sure to invoke Allocate() prior to invoking this method.

`Reset()`
Restores this instance of vtkPolyData to its initial condition without releasing allocated memory.

`BuildCells()`
Build the internal vtkCellTypes array. This allows random access to cells (e.g., GetCell() and other special vtkPolyData methods). Normally you don't need to invoke this method unless you are doing specialized operations on vtkPolyData.

`BuildLinks()`
Build the internal vtkCellLinks array. This enables access to topological information such as neighborhoods (e.g., vertex, edge, face neighbors). Normally you don't need to invoke this method unless you are doing special operations on vtkPolyData.

`DeleteCells()`
Release the memory for the internal vtkCellTypes array which allows random access of the cells. This method implicitly deletes the cell links too since they are no longer valid.

`DeleteLinks()`
Release the memory for the internal vtkCellLinks array.

`GetPointCells(ptId, ncells, cells)`
Given a point id (`ptId`), return the number of cells using the point (`ncells`), and an integer array of cell ids that use the point (`cells`).

`GetCellEdgeNeighbors(cellId, p1, p2, cellIds)`
Given a cell (`cellId`) and two points (`p1` and `p2`) forming an edge of the cell, fill in a user-supplied list of all cells using the edge (`p1,p2`).

`GetCellPoints(cellId, npts, pts)`
Given a cell (`cellId`), return the number of points (`npts`) and an integer list of point ids which define the cell connectivity. This is a specialized version of the method GetCellPoints(npts, ptIds) inherited from its superclass vtkDataSet.

`flag = IsTriangle(p1, p2, p3)`
A special method meant for triangle meshes. Returns a 0/1 flag indicating whether the three points listed (`p1,p2,p3`) form a triangle in the mesh.

`flag = IsEdge(p1, p2)`
Returns a 0/1 flag indicating whether the two points listed (`p1,p2`) form an edge in the mesh.

`flag = IsPointUsedByCell(ptId,cellId)`
Return a 0/1 flag indicating whether a particular point given by `ptId` is used by a partic-

ular cell (`cellId`).

`ReplaceCell(cellId, npts, pts)`
Redefine a cell (`cellId`) with a new connectivity list (`pts`). Note that the number of points (`npts`) must be equal to the original number of points in the cell.

`ReplaceCellPoint(cellId, oldPtId, newPtId)`
Redefine a cell's connectivity list by replacing one point id (`oldPtId`) with a new point id (`newPtId`).

`ReverseCell(cellId)`
Reverse the order of the connectivity list definition for the cell (`cellId`). For example, if a triangle is defined (`p1,p2,p3`), after invocation of this method it will be defined by the points (`p3,p2,p1`).

`DeletePoint(ptId)`
Delete the point by removing all links from it to cells using it. This method does not actually remove the point from the vtkPoints object.

`DeleteCell(cellId)`
Delete a cell by marking its type as `VTK_EMPTY_CELL`. This operator only modifies the vtkCellTypes array, it does not actually remove the cell's connectivity from the vtkCellArray object.

`ptId = InsertNextLinkedPoint(x, numLinks)`
If the instance of vtkCellLinks has been built, and you wish to insert a new point into the mesh, use this method. The parameter `numLinks` is the initial size of the list of cells using the point.

`ptId = InsertNextLinkedPoint(numLinks)`
Similar to the above method, this method is used for allocating memory to add a new point in vtkCellLinks. However, this method only allocates memory; it does not insert the point.

`cellId = InsertNextLinkedCell(type, npts, pts)`
Insert a new cell into the vtkPolyData after the cell links and cell types structures have been built (i.e., BuildCells() and BuildLinks() have been invoked).

`ReplaceLinkedCell(cellId, npts, pts)`
Replace one linked cell with another cell. Note that `npts` must be the same size for the replaced and replacing cell.

`RemoveCellReference(cellId)`
Remove all references to the cell `cellId` from the cell links structure. This effectively topologically disconnects the cell from the data structure.

`AddCellReference(cellId)`
Add references to the cell `cellId` into the cell links structure. That is, the links from all points are modified to reflect the use by the cell `cellId`.

`RemoveReferenceToCell(ptId,cellId)`
Remove the reference from the links of `ptId` to the cell `cellId`.

`AddReferenceToCell(ptId,cellId)`
Add a reference to the cell `cellId` into the point `ptId`'s link list.

`ResizeCellList(ptId, size)`
Resize the link list for the point `ptId` and make it of size `size`.

`CopyCells(pd, idList, locator)`
Copy cells listed in idList (a vtkIdList) from pd (a vtkPolyData), including points, point data, and cell data. This method assumes that point and cell data have been allocated. If a point locator is passed in, then the points will not be duplicated in the output.

`RemoveGhostCells(level)`
Remove any cell that has a ghost level array value at least as large as the level indicated. This method does not remove unused points. Ghost levels represent partition boundaries in parallel processing applications.

16.8 Unstructured Grids

vtkUnstructuredGrid is a concrete dataset type that represents all possible combinations of VTK cells (i.e., all those shown on **Figure 19–20**). The data is completely unstructured. Points are represented by the superclass vtkPointSet, and cells are represented by a combinations of objects including vtkCellArray, vtkCellTypes, and vtkCellLinks. Typically, these objects (excluding vtkPoints) are used internally, and you do not directly manipulate them. Refer to the previous section "Polygonal Data" on page 345 for additional information about the unstructured data structure in VTK. Also, see "Supporting Objects for Data Sets" on page 355 for detailed interface information about vtkCellArray, vtkCellTypes, and vtkCellLinks.

Although vtkUnstructuredGrid and vtkPolyData are similar, there are substantial differences. vtkPolyData can only represent cells of topological dimension 2 or less (i.e., triangle strips, polygons, lines, vertices) while vtkUnstructuredGrid can represent cells of dimension 3 and less. Also, vtkUnstructuredGrid maintains an internal instance of vtkCellTypes to allow random access to its cells, while vtkPolyData instantiates vtkCellTypes only when random access is required. Finally, vtkUnstructuredGrid maintains a single internal instance of vtkCellArray to represent cell connectivity; vtkPolyData maintains four arrays corresponding to triangle strips, polygons, lines, and vertices.

vtkUnstructuredGrid Methods

`Allocate(numCells, extend)`
Perform initial memory allocation prior to invoking the InsertNextCell() methods (described in the following two items). The parameter `numCells` is an estimate of the number of cells to be inserted; `extend` is the size by which to extend the internal structure (if needed).

`cellId = InsertNextCell(type, npts, pts)`
Given a cell type (`type`), number of points in the cell (`npts`), and an integer list of point ids (`pts`), insert a cell and return its cell id. See **Figure 19–20** for a definition of type values. Make sure to invoke Allocate() prior to invoking this method.

`cellId = InsertNextCell(type, ptIds)`
Given a cell type (`type`) and instance of vtkIdList, `ptIds`, insert a cell and return its cell

id. Make sure to invoke Allocate() prior to invoking this method.

`Reset()`
Restores this instance of vtkUnstructuredGrid to its initial condition without releasing allocated memory.

`SetCells(types, cells)`
This is a high performance method that allows you to define a set of cells all at once. You specify an integer list of cell types, `types`, followed by an instance of vtkCellArray.

`SetCells(type, cells)`
This method is similar to the one above, but you specify a single cell type instead of a list of them.

`SetCells(cellTypes, cellLocations, cells)`
This method is similar to the two above, but in addition to specifying a list of cell types, a list of cell locations (a vtkIdTypeArray) is provided as well.

`cells = GetCells()`
Return a pointer to the cell connectivity list. The return value `cells` is of type vtkCellArray.

`types = GetCellTypesArray()`
Return a pointer to the cell types array. The return value, types, is of type vtkUnsigned-CharArray.

`locs = GetCellLocationsArray()`
Return a pointer to the cell locations array used for indexing into the Connectivity array. The return value, locs, is of type vtkIdTypeArray.

`links = GetCellLinks()`
Return a pointer to the cell links array. The return value, links, is of type vtkCellLinks.

`BuildLinks()`
Build the internal vtkCellLinks array. This enables access to topological information such as neighborhoods (e.g., vertex, edge, face neighbors). Normally you don't need to invoke this method unless you are doing specialized operations on vtkUnstructuredGrid.

`GetCellPoints(cellId, npts, pts)`
Given a cell (`cellId`), return the number of points (`npts`) and an integer list of point ids that define the cell connectivity. This is a specialized version of the method inherited from vtkUnstructuredGrid's superclass GetCellPoints(npts, ptIds) method.

`ReplaceCell(cellId, npts, pts)`
Redefine the cell `cellId` with a new connectivity list `pts`. Note that the number of points `npts` must be equal to the original number of points in the cell.

`cellId = InsertNextLinkedCell(type, npts, pts)`
Insert a new cell into the vtkUnstructuredGrid after the cell links structure has been built (i.e., the method BuildLinks() has been invoked).

`RemoveReferenceToCell(ptId, cellId)`
Remove the reference from the links of `ptId` to the cell `cellId`.

`AddReferenceToCell(ptId, cellId)`
Add a reference to the cell `cellId` into the point `ptId`'s link list.

`ResizeCellList(ptId, size)`
Resize the link list for the point `ptId` and make it of size `size`.

`GetIdsOfCellsOfType(type, array)`
Fill the specified array (a vtkIdTypeArray) with the ids of all the cells with the specified type.

`stat = IsHomogeneous()`
Determine whether the vtkUnstructuredGrid dataset is composed only of cells of a single type. Return 1 if this is true; return 0 otherwise.

`RemoveGhostCells(level)`
Remove any cell that has a ghost level array value at least as large as the level indicated. Ghost levels represent partition boundaries in parallel processing applications.

16.9 Cells

Cells are the atoms of datasets. They are used to perform local operations within the dataset such as interpolation, coordinate transformation and searching, and various geometric operations. Cells are often used as a "handle" into a dataset, returning local information necessary to the execution of an algorithm. To obtain a cell from a dataset, the method GetCell(int cellId) is used, and the returned cell can then be processed.

The class vtkCell represents data using an instance of vtkPoints and vtkIdList (representing point coordinates and point ids, respectively). These two instance variables are publicly accessible, one of the few exceptions in VTK where instance variables are public. The following methods are available to all subclasses of vtkCell.

vtkCell Methods

`type = GetCellType()`
Return the type of the cell as defined in `vtkCellType.h`.

`dim = GetCellDimension()`
Return the topological dimensional of the cell (0,1,2, or 3).

`flag = IsLinear()`
Return whether the cell interpolation is linear or not. Usually linear (=1).

`points = GetPoints()`
Get the point coordinates for the cell.

`numPts = GetNumberOfPoints()`
Return the number of points in the cell.

`numEdges = GetNumberOfEdges()`
Return the number of edges in the cell.

`numFaces = GetNumberOfFaces()`

Return the number of faces in the cell.

`ptIds = GetPointIds()`
Return the list of point ids defining the cell.

`id = GetPointId(ptId)`
For cell point ptId, return the actual point id.

`edge = GetEdge(edgeId)`
Return the edge cell from the `edgeId` of the cell.

`cell = GetFace(faceId)`
Return the face cell from the `faceId` of the cell.

`status = CellBoundary(subId, pcoords[3], pts)`
Given parametric coordinates of a point, return the closest cell boundary, and whether the point is inside or outside of the cell. The cell boundary is defined by a list of points (pts) that specify a face (3D cell), edge (2D cell), or vertex (1D cell). If the return value of the method is != 0, then the point is inside the cell.

`status = EvaluatePosition(x[3], closestPoint[3], subId, pcoords[3], dist2, weights[])`
Given a point `x[3]` return inside(=1) or outside(=0) cell; evaluate parametric coordinates, sub-cell id (!=0 only if cell is composite), distance squared of point `x[3]` to cell (in particular, the sub-cell indicated), closest point on cell to `x[3]`, and interpolation weights in cell. (The number of weights is equal to the number of points defining the cell). Note: on rare occasions a -1 is returned from the method. This means that numerical error has occurred and all data returned from this method should be ignored.

`EvaluateLocation(subId, pcoords[3], x[3], weights[])`
Determine global coordinates (`x[3]`) from `subId` and parametric coordinates. Also returns interpolation weights. (The number of weights is equal to the number of points in the cell.)

`Contour(value, cellScalars, locator, verts, lines, polys, inPd, outPd, inCd, cellId, outCd)`
Generate contouring primitives. The scalar list `cellScalars` contains scalar values at each cell point. The `locator` is essentially a points list that merges points as they are inserted (i.e., prevents duplicates). Contouring primitives can be vertices, lines, or polygons. It is possible to interpolate point data along the edge by providing input and output point data; if `outPd` is NULL, then no interpolation is performed. Also, if the output cell data (`outCd`) is non-NULL, the cell data from the contoured cell is passed to the generated contouring primitives.

`Clip(value, cellScalars, locator, connectivity, inPd, outPd, inCd, cellId, outCd, insideOut)`
Cut (or clip) the cell based on the input `cellScalars` and the specified value. The output of the clip operation will be one or more cells of the same topological dimension as the original cell. The flag `insideOut` controls what part of the cell is considered inside - normally cell points whose scalar value is greater than "value" are considered inside. If `insideOut` is on, this is reversed. Also, if the output cell data (`outCd`) is non-NULL, the

cell data from the clipped cell is passed to the generated clipped primitives.

`status = IntersectWithLine(p1[3], p2[3], tol, t, x[3], pcoords[3], subId)`

Intersect with the ray defined by `p1` and `p2`. Return parametric coordinates (both line and cell). A non-zero return value indicates that an intersection has occurred. You can specify a tolerance `tol` on the intersection operation.

`status = Triangulate(index, ptIds, pts)`

Generate simplices of the appropriate dimension that approximate the geometry of this cell. 3D cells will generate tetrahedra,; 2D cells triangles; and so on. If triangulation failure occurs, a zero is returned.

`Derivatives(subId, pcoords[3], values, dim, derivs)`

Compute the derivatives of the values given for this cell.

`GetBounds(bounds[6])`

Set the $(x_{min}, x_{max}, y_{min}, y_{max}, z_{min}, z_{max})$ bounding box values of the cell.

`bounds = GetBounds()`

Return a pointer to the bounds of the cell.

`length2 = GetLength2()`

Return the length squared of the cell (the length is the diagonal of the cell's bounding box).

`status = GetParametricCenter(pcoords[3])`

Return the parametric coordinates of the center of the cell. If the cell is a composite cell, the particular subId that the center is in is returned.

`pcoords = GetParametricCoords()`

Return the parametric coordinates for the points that define this cell.

`distance = GetParametricDistance(pcoords[3])`

Return the distance to the cell given a parametric value.

`void ShallowCopy(cell)`

Perform shallow (reference counted) copy of the cell.

`void DeepCopy(cell)`

Perform deep (copy of all data) copy of the cell.

`Initialize(npts, pts, p)`

Initialize the cell from outside with the point ids (`pts`) and point coordinates (`p`, an instance of vtkPoints) specified. The `npts` parameter indicates the number of points in the cell.

`req = RequiresInitialization()`

Returns whether a cell requires initialization prior to access. (For example, the cell may need to triangulate itself or set up internal data structures.)

`Initialize()`

Allow the cell to initialize itself as mentioned in the description for the previous method.

`exp = IsExplicitCell()`
Returns whether a cell is explicit (i.e., whether it requires additional representational information beyond cell type and connectivity). Most cells in VTK are implicit rather than explicit.

`pri = IsPrimaryCell()`
Returns whether a cell has a fixed topology. For example, a vtkTriangle is a primary cell, but a vtkTriangleStrip is not.

16.10 Supporting Objects for Data Sets

We saw earlier that some dataset types required instantiation and manipulation of component objects. For example, vtkStructuredGrid requires the creation of an instance of vtkPoints to define its point locations, and vtkPolyData requires the instantiation of vtkCellArray to define cell connectivity. In this section we describe the interface to these supporting objects. Refer to **Figure 16–3** for additional information describing the relationship of these objects.

vtkPoints Methods

vtkPoints represents *x-y-z* point coordinate information. Instances of vtkPoints are used to explicitly represent points. vtkPoints depends on an internal instance of vtkDataArray, thereby supporting data of different native types (i.e., `int`, `float`, etc.) The methods for creating and manipulating `vtkPoints` are shown below.

`num = GetNumberOfPoints()`
Return the number of points in the array.

`x = GetPoint(int id)`
Return a pointer to an array of three doubles: the *x-y-z* coordinate position. This method is not thread safe.

`GetPoint(id, x)`
Given a point id `id`, fill in a user-provided `double` array of length three with the *x-y-z* coordinate position.

`SetNumberOfPoints(number)`
Specify the number of points in the array, allocating memory if necessary. Use this method in conjunction with SetPoint() to put data into the vtkPoints array.

`SetPoint(id, x)`
Directly set the point coordinate `x` at the location `id` specified. Range checking is not performed, and as a result this method is faster than the insertion methods. Make sure SetNumberOfPoints() is invoked prior to using this method.

`SetPoint(id, x, y, z)`
Directly set the point coordinate (`x`, `y`, `z`) at the location id specified. Range checking is not performed and as a result, this method is faster than the insertion methods. Make sure SetNumberOfPoints() is invoked prior to using this method.

`InsertPoint(id, x)`

Insert the point coordinate `x` at the location `id` specified. Range checking is performed, and memory is allocated as necessary.

`InsertPoint(id, x, y, z)`
Insert the point coordinate (`x,y,z`) at the location `id` specified. Range checking is performed and memory allocated as necessary.

`pointId = InsertNextPoint(x)`
Insert the point coordinate `x` at the end of the array, returning its point id. Range checking is performed and memory allocated as necessary.

`pointId = InsertNextPoint(x, y, z)`
Insert the point coordinate (`x,y,z`) at the end of the array, returning its point id. Range checking is performed and memory allocated as necessary.

`GetPoints(ptIds, pts)`
Given a list of points `ptIds`, fill-in a user-provided vtkPoints instance with corresponding coordinate values.

`bounds = GetBounds()`
Return a pointer to an array of size six containing the $(x_{min}, x_{max}, y_{min}, y_{max}, z_{min}, z_{max})$ bounds of the points. This method is not thread-safe.

`GetBounds(bounds)`
Fill in a user-provided array of size six with the $(x_{min}, x_{max}, y_{min}, y_{max}, z_{min}, z_{max})$ bounds of the points.

`Allocate(size, extend)`
Perform initial memory allocation. The parameter size is an estimate of the number of points to be inserted; extend is the size by which to extend the internal structure (if needed).

`Initialize()`
Return the object to its state at instantiation, including freeing memory.

`SetData(pts)`
Set the underlying vtkDataArray (`pts`) specifying the point coordinates. The number of components in the vtkDataArray must be 3.

`pts = GetData()`
Return the underlying vtkDataArray containing the point coordinates.

`dType = GetDataType()`
Return an integer indicating the data type of the point coordinates.

`SetDataType(dType)`
Set the data type of the point coordinates. See `vtkType.h` for a list of possible types.

`ptr = GetVoidPointer(id)`
Return a void pointer to the data contained in the underlying data array starting at the indicated index (`id`).

`Squeeze()`
Reclaim any extra memory in the data structure.

`Reset()`
Set the object to its initial state, but do not free memory.

`DeepCopy(pts)`
Copy the given vtkPoints (`pts`) to this instance of vtkPoints, making a second copy of the data.

`ShallowCopy(pts)`
Copy the given vtkPoints (`pts`) to this instance of vtkPoints using reference counting.

`size = GetActualMemorySize()`
Return the size of this instance of vtkPoints in kilobytes.

`ComputeBounds()`
Determine the bounding box of the point coordinates contained in this instance of vtkPoints.

vtkCellArray Methods

vtkCellArray represents the topology (i.e., connectivity) information of cells. The connectivity of a cell is defined by an ordered integer list of point ids. The methods for creating and manipulating vtkCellArrays are shown below.

`Allocate(size, extend)`
Perform initial memory allocation prior to invoking the InsertNextCell() methods. The parameter `size` is the number of entries in the list to be inserted; `extend` is the size by which to extend the internal structure (if needed).

`Initialize()`
Set the object to its original state, releasing memory that may have been allocated.

`size = EstimateSize(numCells, PtsPerCell)`
Estimate the size of the data to insert based on the number of cells, and the expected number of points per cell. This method returns an estimate; use it in conjunction with the Allocate() method to perform the initial memory allocation.

`void InitTraversal()`
Initialize the traversal of the connectivity array. Used in conjunction with GetNextCell().

`nonEmpty = GetNextCell(npts, pts)`
Get the next cell in the list, returning the number of points `npts` and an integer array of point ids `pts`. If the list is empty, return 0; return non-zero otherwise.

`size = GetSize()`
Return the number of entries allocated in the list.

`numEntries = GetNumberOfConnectivityEntries()`
Return the total number of data values added to the list thus far.

`GetCell(loc, npts, pts)`
A special method to return the cell at location offset `loc`. This method is typically used by unstructured data for random access into the cell array. Note that `loc` is not the same as a cell id, it is a offset into the cell array. See GetCellLocation(id) on page 360

`cellId = InsertNextCell(cell)`
Insert a cell into the array. The parameter `cell` is of type vtkCell. Return the cell id.

`cellId = InsertNextCell(npts, pts)`
Insert a cell into the array by specifying the number of points `npts` and an integer list of cell ids. Return the cell id.

`cellId = InsertNextCell(pts)`
Insert a cell into the array by supplying an id list (vtkIdList). Return the cell id.

`cellId = InsertNextCell(npts)`
Insert a cell into the cell array by specifying the number of cell points. This method is generally followed by multiple invocations of InsertCellPoint() to define the cell points, and possibly UpdateCellCount() to specify the final number of points.

`InsertCellPoint(id)`
Insert a cell point into the cell array. This method requires prior invocation of InsertNext-Cell(npts).

`UpdateCellCount(npts)`
Specify the final number of points defining a cell after invoking InsertNextCell(npts) and InsertCellPoint(). This method allows you to adjust the number of points after estimating an initial point count with InsertNextCell(npts).

`location = GetInsertLocation(npts)`
Return the current insertion location in the cell array. The insertion location is used by methods such as InsertNextCell(). The location is an offset into the cell array.

`location = GetTraversalLocation(npts)`
Return the current traversal location in the cell array. The insertion location is used by methods such as GetCell(). The location is an offset into the cell array.

`ReverseCell(loc)`
Reverse the order of the connectivity list definition for the cell `cellId`. For example, if a triangle is defined (`p1,p2,p3`), after invocation of this method it will be defined by the points (`p3,p2,p1`).

`ReplaceCell(loc, npts, pts)`
Redefine the cell at offset location `loc` with a new connectivity list `pts`. Note that the number of points `npts` must be equal to the original number of points in the cell array.

`maxSize = GetMaxCellSize()`
Return the maximum size, in terms of the number of points which definte it, of any cell in the cell array connectivity list.

`ptr = GetPointer()`
Return an integer pointer to the cell array. The structure of the data in the returned data is the number of points in a cell, followed by its connectivity list, which repeats for each cell: (npts, p_0, p_1, p_2, . . . , p_{npts-1}; npts, p_0, p_1, p_2, . . . , p_{npts-1}, . . .).

`ptr = WritePointer(ncells, size)`
Allocate memory for a cell array with `ncells` cells and of size specified. The `size` includes the connectivity entries as well as the count for each cell.

`Reset()`
Restore the object to its initial state with the exception that previously allocated memory is not released.

`Squeeze()`
Recover any unused space in the array.

`SetNumberOfCells(numCells)`
Set the number of cells in the array. This method does not allocate memory.

`numCells = GetNumberOfCells()`
Return the number of cells in the cell array.

`SetTraversalLocation(loc)`
Set the current traversal location within the array. The traversal location is an offset into the cell array; it is used by the GetNextCell() method.

`loc = GetTraversalLocation()`
Get the current traversal location within the array.

`SetCells(ncells, cells)`
Define multiple cells (number given by `ncells`) by providing a connectivity list (`cells`, a vtkIdTypeArray). The cells array is in the form (npts, p0, p1, ..., p(npts-1)), repeated for each cell. When this method is used, it overwrites anything that was previously stored in this array, so anything referring to these cells becomes invalid. The traversal location is set to the beginning of the list, and the insertion location is set to the end of the list.

`DeepCopy(ca)`
Copy the given vtkCellArray (`ca`) to this vtkCellArray, making a second copy of the data.

`array = GetData()`
Return a pointer to the underlying data array (a vtkIdTypeArray).

`size = GetActualMemorySize()`
Return the memory in kilobytes used by this cell array.

vtkCellTypes Methods

The class vtkCellTypes provides random access to cells. Instances of vtkCellTypes are always associated with at least one instance of vtkCellArray, which actually defines the connectivity list for the cells. The information contained in the vtkCellTypes is (for each cell) the cell type specified (an integer flag as defined in **Figure 19–20**) and a location offset, which is an integer value representing an offset into the associated vtkCellArray.

`Allocate(size, extend)`
Perform initial memory allocation prior to invoking the InsertNextCell() methods. The parameter `size` is an estimate of the number of cells to be inserted; `extend` is the size by which to extend the internal structure (if needed).

`InsertCell(id, type, loc)`
Given a cell type `type` and its location offset in an associated vtkCellArray, insert the cell type at the location (`id`) specified.

`cellId = InsertNextCell(type, loc)`
Given a cell type `type` and its location offset in an associated vtkCellArray, insert the cell type at the end of the array and return its cell id.

`DeleteCell(cellId)`
Delete a cell by marking its type as `VTK_EMPTY_CELL`.

`numTypes = GetNumberOfTypes()`
Return the number of entries (i.e., cell types) in the list.

`IsType(type)`
Return 1 if the type specified is contained in the vtkCellTypes array; return zero otherwise.

`cellId = InsertNextType(type)`
Add the type specified to the end of the list, returning its cell id.

`type = GetCellType(id)`
Return the type of the cell give by `id`.

`loc = GetCellLocation(id)`
Get the offset location into an associated vtkCellArray instance for the cell given by `id`.

`Squeeze()`
Recover any unused space in the array.

`Reset()`
Restore the object to its initial state with the exception that previously allocated memory is not released.

`SetCellTypes(ncells, cellTypes, cellLocations)`
Specify a group of cell types (number given by `ncells`) by providing a cell type list (`cellTypes`, a vtkUnsignedCharArray) and a cell location list (`cellLocations`, a vtkIntArray). When this method is used, it overwrites anything that was previously stored in this array.

`size = GetActualMemorySize()`
Return the memory in kilobytes used by this instance of vtkCellTypes.

`DeepCopy(ct)`
Copy the vtkCellTypes instance (`ct`) to this vtkCellTypes instance, making a second copy of the data.

vtkCellLinks Methods

The class vtkCellLinks provides topological information describing the use of points by cells. Think of the vtkCellLinks object as a list of lists of cells using a particular point. (See **Figure 16–3**.) This information is used to derive secondary topological information such as face, edge, and vertex neighbors. Instances of vtkCellLinks are always associated with a vtkPoints instance, and access to the cells is through vtkCellTypes and vtkCellArray objects.

`link_s = GetLink(ptId)`
Return a pointer to a structure containing the number of cells using the point `pointId`

and a pointer to a list of cells using the point.

`ncells = GetNcells(pointId)`
Return the number of cells using the point `pointId`.

`BuildLinks(dataset)`
Given a pointer to a VTK dataset, build the link topological structure.

`BuildLinks(dataset, connectivity)`
Given a pointer to a VTK dataset and a vtkCellArray (`connectivity`), build the link topological structure. Use the connectivity array to determine which cells reference which points.

`cellList = GetCells(ptId)`
Return a pointer to the list of cells using the point `ptId`.

`ptId = InsertNextPoint(numLinks)`
Allocate (if necessary) and insert space for a link at the end of the cell links array. The parameter `numLinks` is the initial size of the list.

`InsertNextCellReference(ptId, cellId)`
Insert a reference to the cell `cellId` for the point `ptId`. This implies that `cellId` uses the point `ptId` in its definition.

`DeletePoint(ptId)`
Delete the point by removing all links from it to cells using it. This method does not actually remove the point from the vtkPoints object.

`RemoveCellReference(cellId, ptId)`
Remove all references to the cell `cellId` from the point `ptId`'s list of cells using it.

`AddCellReference(cellId, ptId)`
Add a reference to the cell `cellId` in the point `ptId`'s list of cells using it.

`ResizeCellList(ptId, size)`
Allocate (if necessary) and resize the list of cells using the point `ptId` to the size given.

`Squeeze()`
Recover any unused space in the array.

`Reset()`
Restore the object to its initial state with the exception that previously allocated memory is not released.

`Allocate(numLinks, extend)`
Perform initial memory allocation. The number of links specified by numLinks will be allocated. The extend parameter is not used.

`size = GetActualMemorySize()`
Return the memory in kilobytes used by this instance of vtkCellLinks.

`DeepCopy(cl)`
Copy the given vtkCellLinks (`cl`) to this vtkCellLinks, making a second copy of the data.

16.11 Field and Attribute Data

The previous sections described how to create, access, and generate the structure of datasets, including underlying objects such as vtkPoints and vtkCellArray. In this section we describe vtkFieldData and vtkDataSetAttributes, two classes used to manage the processing of data values (scalars, vectors, tensors, normals, and texture coordinates) and arbitrary information. Those classes provide a number of convenience methods for copying, interpolating, and passing data from a filter's input to its output. vtkDataSets contain 3 instances of these classes, one field data to store non aligned values, and one dataset attribute for the point and cell associated values.

vtkFieldData Methods

vtkFieldData is a container for arrays. As of VTK 4.0, vtkFieldData is the superclass of vtkDataSetAttributes (and therefore of vtkPointData and vtkCellData which inherit from vtkDataSetAttributes). Therefore, all fields and attributes (scalars, vectors, normals, tensors, and texture coordinates) are stored in the field data and can be easily interchanged (see "Working With Field Data" on page 249for more information on manipulating fields). It is now possible to associate a field (vtkDataArray) to, for example, vtkPointData and label it as the active vector array afterwards.

`PassData(fromData)`
: Copy the field data from the input (fromData) to the output. Reference counting is used, and the copy flags (e.g., CopyFieldOn/Off) control which fields are copied or omitted.

`num = GetNumberOfArrays()`
: Get the number of arrays currently in the field data.

`array = GetArray(index)`
: Given an index, return the corresponding array.

`array = GetArray(name)`
: Given a name, return the corresponding array.

`array = GetArray(name, index)`
: Given a name, return the corresponding array. Return the index of the array in the index parameter provided. This parameter is set to -1 if the array is not found.

`val = HasArray(name)`
: If an array with the given name exists in this vtkFieldData, return 1. Otherwise return 0.

`name = GetArrayName(index)`
: Return the name of the array at the given index.

`AddArray(array)`
: Add a field (vtkDataArray).

`RemoveArray(name)`
: Remove the array with the given name.

`DeepCopy(data)`
: Copy the input data (a vtkFieldData). Performs a deep copy, which means duplicating allocated memory.

`ShallowCopy(data)`

Copy the input data (a vtkFieldData). Performs a shallow copy, which means reference counting underlying data objects.

`Squeeze()`
Recover any extra space in each data array.

`mtime = GetMTime()`
Return the modified time of this object by examining its own modified time as well as the modified time of the associated fields (arrays).

`CopyFieldOn/Off(name)`
These methods are used to control the copying and interpolation of individual fields from the input to the output. If off, the field with the given name is not copied or interpolated.

`CopyAllOn/Off()`
Control whether all of the arrays in this vtkFieldData are copied and interpolated from the input to the output. If off, no arrays will be copied or interpolated; if on, all will be. The flags set by CopyFieldOn/Off override this.

`Initialize()`
Set this instance of vtkFieldData to its initial state, including releasing allocated memory.

`Allocate(size, extend)`
Allocate memory for each vtkDataArray in this instance of vtkFieldData. The `size` and `extend` parameters are passed to each vtkDataArray.

`CopyStructure(fd)`
Set the structure of this instance of vtkFieldData from the one given (`fd`). Any existing data arrays are removed. The arrays from the input vtkFieldData will be created in this vtkFieldData, and they will have the same types, names, and widths, but they will contain no data.

`AllocateArrays(num)`
Specify the number of data arrays contained in this vtkFieldData.

`Reset()`
Reset each data array in this vtkFieldData, but do not release memory.

`size = GetActualMemorySize()`
Return the amount of memory in kilobytes used by this vtkFieldData.

`GetField(ptIds, f)`
Fill the provided instance of vtkFieldData (`f`) with the tuples at the ids specified in `ptIds` (a vtkIdList). The provided vtkFieldData should have the same number and type of vtkDataArrays as this one.

`numComps = GetNumberOfComponents()`
Return the number of components in this vtkFieldData. This is determined by summing the number of components in each non-NULL data array in this vtkFieldData.

`arrayNum = GetArrayContainingComponent(N, arrayComp)`
Return the index of the array containing the N'th global component of this vtkFieldData. (Return -1 if this vtkFieldData does not contain that component.) In the `arrayComp`

parameter, returns the particular component of the data array which matches the requested global component.

`numTups = GetNumberOfTuples()`
Return the number of tuples in this vtkFieldData. (The number of tuples in the first data array is returned.)

`SetNumberOfTuples(num)`
Set the number of tuples (`num`) of each data array in this vtkFieldData.

`tuple = GetTuple(index)`
Return a tuple consisting of a concatenation of the specified tuple in each data array contained in this vtkFieldData. The returned array is of type double, so all the data values are converted to double before being returned.

`GetTuple(index, tuple)`
This method provides the same functionality as the one above, but the tuple is returned in a user-provided data array. Be sure that the provided array has enough memory allocated.

`SetTuple(index, tuple)`
Set the tuple at the specified index. No range checking is performed.

`InsertTuple(index, tuple)`
Insert the tuple at the specified index. Range checking is performed, and memory is allocated as necessary.

`id = InsertNextTuple(tuple)`
Insert the tuple at the end of this vtkFieldData. Range checking is performed, and memory is allocated as necessary. The id of this tuple is returned.

`comp = GetComponent(i, j)`
Return the value (as a double) at the ith tuple and j^{th} component.

`SetComponent(i, j, comp)`
Set the value at the ith tuple and j^{th} component. Range checking is not performed.

`InsertComponent(i, j, comp)`
Insert the value at the ith tuple and j^{th} component. Range checking is performed, and memory is allocated as necessary.

vtkDataSetAttributes Methods

Recall that there are two types of attributes: those associated with the points of the dataset (vtkPointData) and those associated with the cells of the dataset (vtkCellData). Both of these classes are subclasses of vtkDataSetAttributes (which is a subclass of vtkFieldData) and have nearly identical interfaces. The following methods are defined by vtkDataSetAttributes and are common to both vtkPointData and vtkCellData. Remember: all datasets have attribute data (both cell and point), so all datasets' attribute data respond to these methods.

`PassData(fromData)`
Copy the attribute data from the input (fromData) to the output attribute data. Reference counting is used, and the copy flags (e.g., CopyScalars) are used to control which attribute data is copied.

`CopyAllocate(fromData, size, extend)`
Allocate memory and initialize the copy process. The copy process involves copying data on an item by item basis (e.g., point-by-point or cell-by-cell). The initial allocated size of each vtkAttributeData object is given by `size`; if the objects must be dynamically resized during the copy process, then the objects are extended by `extend`.

`CopyData(fromData, fromId, toId)`
Copy the input attribute data (fromData) at location fromId to location toId in the output attribute data.

`InterpolateAllocate(fromData, size, extend)`
Allocate memory and initialize the interpolation process. The interpolation process involves interpolating data across a cell or cell topological feature (e.g., an edge). The initial allocated size of each vtkAttributeData object is given by `size`; if the objects must be dynamically resized during the interpolate process, then the objects are extended by `extend`.

`InterpolatePoint(fromData, toId, Ids, weights)`
Interpolate from the dataset attributes given (`fromData`) to the point specified (`toId`). The interpolation is performed by summing the product of the attribute values given at each point in the list `Ids` with the interpolation `weights` provided.

`InterpolateEdge(fromData, toId, id1, id2, t)`
Similar to the previous method, except that the interpolation is performed between `id1` and `id2` using the parametric coordinate `t`.

`DeepCopy(data)`
Copy the input data (a vtkDataSetAttributes). Performs a deep copy, which means duplicating allocated memory.

`ShallowCopy(data)`
Copy the input data (a vtkDataSetAttributes). Performs a shallow copy, which means reference counting underlying data objects.

`SetScalars(scalars)`
Specify that the provided vtkDataArray is to be considered the active scalar array. Many filters operate on the active array unless directed otherwise.

`SetActiveScalars(name)`
Specify that the array with the given name is to be the scalar attribute data.

`scalars = GetScalars()`
Retrieve the active scalar (vtkDataArray) attribute data.

`scalars = GetScalars(name)`
Get the array with the specified name. If `name` is NULL, or no array matches that name, then the active scalar attribute data array is returned.

`SetVectors(vectors)`
Specify that the provided vtkDataArray is to be considered the active vector array. Many filters operate on the active array unless directed otherwise.

`SetActiveVectors(name)`

Set the active array with the given name to be the vector attribute data.

`vectors = GetVectors()`
Retrieve the active vector (vtkDataArray) attribute data.

`vectors = GetVectors(name)`
Get the array with the specified name. If `name` is NULL, or no array matches that name, then the vector attribute data array is returned.

`SetTensors(tensors)`
Specify that the provided vtkDataArray is to be considered the active tensor array. Many filters operate on the active array unless directed otherwise.

`SetActiveTensors(name)`
Set the active array with the given name to be the tensor attribute data.

`tensors = GetTensors()`
Retrieve the active tensor (vtkDataArray) attribute data.

`tensors = GetTensors(name)`
Get the array with the specified name. If `name` is NULL, or no array matches that name, then the tensor attribute data array is returned.

`SetNormals(normals)`
Specify that the provided vtkDataArray is to be considered the active normal array. Many filters operate on the active array unless directed otherwise.

`SetActiveNormals(name)`
Set the active array with the given name to be the normal attribute data.

`normals = GetNormals()`
Retrieve the active normal (vtkDataArray) attribute data.

`normals = GetNormals(name)`
Get the array with the specified name. If `name` is NULL, or no array matches that name, then the normal attribute data array is returned.

`SetTCoords(tcoords)`
Specify that the provided vtkDataArray is to be considered the active texture coordinate array. Many filters operate on the active array unless directed otherwise.

`SetActiveTCoords(name)`
Set the active array with the given name to be the texture coordinate attribute data.

`tcoords = GetTCoords()`
Retrieve the active texture coordinate (vtkDataArray) attribute data.

`tcoords = GetTCoords(name)`
Get the array with the specified name. If `name` is NULL, or no array matches that name, then the texture coordinate attribute data array is returned.

`SetGlobalIds(GlobalIds)`
Global Ids are used to assign unique names to every cell and/or point. Global Ids are preserved by filters whenever possible, and never interpolated, because they represent identi-

ties instead of numerical quantities. Any two cells (or points) that share a global id are considered to be the same thing. Specify that the provided vtkDataArray is to be considered the active global id array.

`SetActiveGlobalIds(name)`
Specify that the array with the given name is to be the global id attribute data.

`globalids = GetGlobalIds()`
Retrieve the active global id (vtkDataArray) attribute data.

`globalids = GetGlobalIds(name)`
Get the array with the specified name. If `name` is NULL, or no array matches that name, then the active global id attribute data array is returned.

`SetPedigreeIds(PedigreeIds)`
Pedigree Ids, like global ids are used assign names to every cell and/or point. Pedigree ids are treated similarly by filters in the pipeline, but instead of being unique - pedigree ids are used to maintain ancestry information. With pedigree ids, an output cell (or point) can be traced back to the original cell (or point) that contributed to it. Specify that the provided vtkDataArray is to be considered the active pedigree id array.

`SetActivePedigreeIds(name)`
Specify that the array with the given name is to be the pedigree id attribute data.

`pedigreeids = GetPedigreeIds()`
Retrieve the active pedigree id (vtkDataArray) attribute data.

`pedigreeids = GetPedigreeIds(name)`
Get the array with the specified name. If `name` is NULL, or no array matches that name, then the active pedigree id attribute data array is returned.

`CopyScalarsOn/Off()`
These methods are used to control the copying and interpolation of scalar data from the input to the output. If off, scalar data is not copied or interpolated.

`CopyVectorsOn/Off()`
These methods are used to control the copying and interpolation of vector data from the input to the output. If off, vector data is not copied or interpolated.

`CopyTensorsOn/Off()`
These methods are used to control the copying and interpolation of tensor data from the input to the output. If off, tensor data is not copied or interpolated.

`CopyNormalsOn/Off()`
These methods are used to control the copying and interpolation of normal data from the input to the output. If off, normal data is not copied or interpolated.

`CopyTCoordsOn/Off()`
These methods are used to control the copying and interpolation of texture coordinate data from the input to the output. If off, texture coordinate data is not copied or interpolated.

`CopyGlobalIdsOn/Off()`

These methods are used to control the copying and interpolation of global id data from the input to the output. If off, global id data is not copied or interpolated.

`CopyPedigreeIdsOn/Off()`
: These methods are used to control the copying and interpolation of pedigree id data from the input to the output. If off, pedigree id data is not copied or interpolated.

`CopyAllOn/Off()`
: These convenience methods set all the copy flags on or off at the same time.

`CopyStructuredData(inData, inExt, outExt)`
: Copy the attribute data from the input vtkDataSetAttributes (`inData`) for the points/cells in the given input extent (`inExt`) to this vtkDataSetAttributes for the points/cells in the given output extent (`outExt`).

`InterpolateTime(fromData1, fromData2, id, t)`
: For the given point or cell id (`id`), interpolate between the two dataset attributes given (`fromData1` and `fromData2`) at the specified time t (ranging between 0 and 1). Be sure that the InterpolateAllocate method has been invoked before calling this method.

`idx = SetActiveAttribute(name, attributeType)`
: Set the array with the given name to be the specified active attribute (scalars = 0, vectors = 1, normals = 2, texture coordinates = 3, tensors = 4, global ids=5, pedigree ids=6). The index of the array with the given name is returned. If no array exists in this vtkDataSetAttributes with the specified name, -1 is returned.

`idx = SetActiveAttribute(index, attributeType)`
: Similar to the above method, but the array is specified by index rather than by name.

`SetCopyAttribute(index, value)`
: Specify whether to copy the data set attribute indicated by the index. A value of 0 indicates that the array will not be copied; a value of 1 indicates that it will be. The indices corresponding to the different attribute types are given in the description of the first SetActiveAttribute method above.

`CopyTuple(fromData, toData, fromId, toId)`
: Copy the tuple at the `fromId` index in the `fromData` data array to the tuple at the `toId` index in the `toData` data array.

`GetAttributeIndices(indexArray)`
: Fill the user-provided index array (an array of int) with the indices of the arrays corresponding to scalars, vectors, etc. The indices corresponding to the different attribute types (used for indexing into the provided array) are given in the description of the first SetActiveAttribute method above.

`attr = IsArrayAnAttribute(index)`
: Determine whether the data array at the specified index is a data set attribute. If it is, return an index indicating which attribute it is (scalars = 0, vectors = 1, normals = 2, texture coordinates = 3, tensors = 4).

`array = GetAttribute(attributeType)`
: Return the data array corresponding to the given attribute type.

`RemoveArray(name)`
Remove the array with the given name from the list of arrays in this vtkDataSetAttributes.

`attr = GetAttributeTypeAsString(attributeType)`
Given an index corresponding to an attribute type, return the attribute type as a string.

16.12 Selections

A vtkSelection provides ways to represent a subset of a data object. These include lists of indices or identifiers, attribute value ranges, locations, frustums, or blocks. A selection may be applied to a particular data object to extract its selected data, or may be modified through filters to expand, reduce, or otherwise change the nature of the selection. Selections are generated by classes such as vtkSelectionSource, which produces a selection based on filter parameters, and vtkHardwareSelector, which uses graphics hardware to select items rendered within a rectangular region of the screen.

vtkSelection is simply a container of vtkSelectionNode objects. Each selection node contains all the information about its part of the selection. This two level structure allows a single selection to combine information from different parts of a data object, such as selection on both points and cells, and allows a selection to maintain selection information on different blocks of a multi-block dataset.

vtkSelection Methods

`n = GetNumberOfNodes()`
Return the number of vtkSelectionNode objects in the selection.

`node = GetNode(i)`
Return the i-th vtkSelectionNode.

`AddNode(node)`
Append the vtkSelectionNode to the end of the list of nodes.

`RemoveNode(i)`
Remove the i-th vtkSelectionNode.

`RemoveNode(node)`
Remove the specified vtkSelectionNode if it exists in the selection.

`RemoveAllNodes()`
Remove all vtkSelectionNode objects, leaving an empty selection.

`Union(sel)`
Union this selection with the specified vtkSelection. Attempts to append to existing nodes if properties of the nodes match exactly. Otherwise, it adds new selection nodes to the selection.

`Union(node)`
Union this selection with the specified vtkSelectionNode. Attempts to append to an existing node if properties of the node match exactly. Otherwise, it adds a new selection node to the selection.

vtkSelectionNode Methods

Fundamentally, a vtkSelectionNode is simply a collection of arrays (normally a single array). Additional properties of the selection node indicate exactly how the values in the arrays should be interpreted.

`SetSelectionList(arr)`
Set the array that will be used as the list of selected items, or interpreted in other ways based on the content type.

`arr = GetSelectionList()`
Return the selection list.

`SetSelectionData(data)`
Set a collection of arrays for the selection node stored in a vtkDataSetAttributes instance. The first array is interpreted in the same way that a normal selection list's single array is. For VALUES type selections only, the additional arrays are used as further qualifiers so that more than one data array can be matched with simultaneously.

`data = GetSelectionData()`
Return the collection of arrays for the selection node as a vtkDataSetAttributes instance.

`SetContentType(type)`
Set the content type to one of the constants SELECTIONS, GLOBALIDS, PEDIGREEIDS, VALUES, INDICES, FRUSTUM, LOCATIONS, THRESHOLDS, BLOCKS defined in vtkSelectionNode. The content type defines how the selection list is to be interpreted. The meaning of each type is described in [ref: Selection section].

`type = GetContentType()`
Return the content type.

`SetFieldType(type)`
Set the field type to one of the constants CELL, POINT, FIELD, VERTEX, EDGE, ROW defined in vtkSelectionNode. This determines what parts of a data object the selection refers to (points or cells in vtkDataSet subclasses, field data of vtkDataObject, vertices or edges of vtkGraph, or rows of a vtkTable).

`type = GetFieldType()`
Return the field type.

`UnionSelectionList(node)`
Merge the selection list of another vtkSelectionNode into this node. This assumes that both nodes have identical properties.

vtkSelectionNode Property Methods

`info = GetProperties()`
Return the properties of the selection node stored in a vtkInformation general purpose container object.

`eq = EqualProperties(node, full)`
Return true if all the properties in this node are also set to the same values in the node given as an argument. The second argument is a flag indicating whether to also fully

check properties in the opposite direction before returning true (i.e. that this node contains all properties of the node passed as an argument).

`GetProperties()->Set(vtkSelectionNode:: INVERSE(), inv)`
Whether the selection should be inverted, in which case the selection defines what is not of interest rather than what is.

`GetProperties()->Set(vtkSelectionNode::EPSILON(), eps)`
For content type LOCATION, this is a tolerance (geometric distance) within which items are accepted and outside of which they are rejected.

`GetProperties()->Set(vtkSelectionNode:: CONTAINING_CELLS(), c)`
This flag tells the extraction filter, when the field type is POINT, that it should also extract the cells that contain any of the extracted points.

`GetProperties()->Set(vtkSelectionNode:: PIXEL_COUNT(), count)`
A helper for screen space selection, this is the number of pixels covered by the actor whose cells are listed in the selection node.

`GetProperties()->Set(vtkSelectionNode:: SOURCE(), alg)`
Pointer to the data or algorithm the selection belongs to.

`GetProperties()->Set(vtkSelectionNode:: SOURCE_ID(), id)`
ID of the data or algorithm the selection belongs to. What the ID means is application specific.

`GetProperties()->Set(vtkSelectionNode:: PROP(), obj)`
Pointer to the prop the selection belongs to.

`GetProperties()->Set(vtkSelectionNode:: PROP_ID(), id)`
ID of the prop the selection belongs to. What the ID means is application specific.

`GetProperties()->Set(vtkSelectionNode:: PROCESS_ID(), id)`
Process ID the selection refers to.

`GetProperties()->Set(vtkSelectionNode:: COMPOSITE_INDEX(), i)`
Used to identify a node in composite datasets.

`GetProperties()->Set(vtkSelectionNode:: HIERARCHICAL_LEVEL(), level)`
Used to identify the level of a dataset in a hiererchical box (AMR) dataset.

`GetProperties()->Set(vtkSelectionNode:: HIERARCHICAL_INDEX(), i)`
Used to identify the index of a dataset in a hiererchical box (AMR) dataset.

16.13 Graphs

The hierarchy for graph classes is shown in [Figure graph-hierachy]. At the top level, we distinguish between graphs whose edges have inherent order from source to target (directed graphs) and graphs whose edges do not indicate direction (undirected graphs). The directed graph subclasses are naturally structured by specialization. A directed acyclic graph (i.e. a graph with no paths that lead back to the same place) is a subset of the class of all directed graphs. A vtkTree further restricts this by enforcing a hierarchy: every vertex but the root must have exactly one parent (incoming edge). The

mutable classes are used to create or modify graphs. The structure of a graph may be copied into any other graph instance, if it first passes a compatibility test.

This hierarchy gives us several advantages. Filters that operate on vtkGraph will work for all graph types. So one can send a vtkTree or a vtkDirectedAcyclicGraph into a filter that takes the more general vtkGraph as an input type (such as vtkVertexDegree). The subclasses also enable filters to be specific about input type: if a filter requires a tree, that can be specified as the input type. The separate mutable classes allow VTK to enforce that all instances of graph data structures are valid at all times. If vtkGraph itself was mutable, it would have methods for adding edges and vertices. Due to inheritance, this method would exist in all subclasses, including vtkTree. The result would be that vtkTree could at times hold a structure that is not a valid tree. It would be prohibitively expensive in time and complexity to check for a valid tree after every edge or vertex addition.

An additional feature of the graph data structures is copy-on-write. Since all graphs share the same internal representation, multiple objects, even those of different types, may share the same structure. A deep copy of the structure is only made if the user modifies a graph whose structure is shared with other graphs. To the caller, the graph instances behave as though they were independent of other graphs, while internally memory usage is optimized.

The user may assign an arbitrary number of arrays to the vertices and edges of the graph, in much the same way that attributes are assigned to points and cells in vtkDataSet subclasses. These attributes may be used in various ways to alter the visualization of the graph, i.e. using them to color or label the graph.

vtkGraph Methods

vtkGraph is the superclass of all graph types. Since it is not mutable, it only provides read access to the structure of the graph.

`data = GetVertexData()`
Return the vtkDataSetAttributes structure containing all vertex attributes.

`data = GetEdgeData()`
Return the vtkDataSetAttributes structure containing all edge attributes.

pt = GetPoint(id)
Return the location of a particular vertex as a pointer to an array containing x-y-z coordinates.

`GetPoint(id, pt)`
An alternative form of the previous method. The coordinates are set in the variable passed as the second argument.

`pts = GetPoints()`
Return the locations of the vertices as a vtkPoints object.

`SetPoints(pts)`
Set the vertex locations.

`ComputeBounds()`
Compute the current bounding box of the graph.

`bds = GetBounds()`
Return the graph bounds as a six component array with values x_min, x_max, y_min,

y_max, z_min, z_max.

`GetBounds(bds)`
An alternate form of the previous method. The bounds are set the variable passed as an argument.

`GetOutEdges(v, it)`
Initialize an iterator of type vtkOutEdgeIterator to iterate over all outgoing edges of vertex v. For an undirected graph, this returns all incident edges.

`deg = GetDegree(v)`
Return the degree of a vertex, which is the total number of edges connected to it.

`deg = GetOutDegree(v)`
Return the number of outgoing edges connected to a vertex. In an undirected graph, this is the total number of edges connected to it.

`edge = GetOutEdge(v, i)`
Return the i-th outgoing edge of a vertex as a vtkOutEdgeType structure.

`GetOutEdge(v, i, edge)`
This is an alternate form of the previous method, which will work for wrapped languages. Return the outgoing edge in the variable passed as the third argument, which is of type vtkGraphEdge.

`GetInEdges(v, it)`
Initialize an iterator of type vtkInEdgeIterator to iterate over all incoming edges of vertex v. For an undirected graph, this returns all incident edges.

`deg = GetInDegree(v)`
Return the number of incoming edges connected to a vertex. In an undirected graph, this is the total number of edges connected to it.

`edge = GetInEdge(v, i)`
Return the i-th incoming edge of a vertex as a vtkOutEdgeType structure.

`GetInEdge(v, i, edge)`
This is an alternate form of the previous method, which will work for wrapped languages. Return the incoming edge in the variable passed as the third argument, which is of type vtkGraphEdge.

`GetAdjacentVertices(v, it)`
Initialize an iterator of type vtkAdjacentVertexIterator to iterate over all outgoing vertices of a vertex. For an undirected graph, this returns all adjacent vertices.

`GetEdges(it)`
Initializes an iterator of type vtkEdgeListIterator to iterate over all edges in the graph.

`m = GetNumberOfEdges()`
Return the number of edges in the graph.

`GetVertices(it)`
Initializes an iterator of type vtkVertexListIterator to iterate over all vertices in the graph.

`n = GetNumberOfVertices()`
Return the number of vertices in the graph.

`SetDistributedGraphHelper(helper)`
Set the distributed graph helper for the graph that makes the graph capable of being spread over multiple processors. Helper's type is vtkDistributedGraphHelper. The current implementation is vtkPBGLDistribtuedGraphHelper, which implements distributed graphs using the Parallel Boost Graph Library. See the documentation of these classes for details on using distributed graphs.

`helper = GetDistributedGraphHelper()`
Return the distributed graph helper.

`v = FindVertex(pedigree_id)`
Return the vertex whose pedigree ID matches the argument. The ID is passed as a vtkVariant which can take any type that that can be stored in a VTK array. Return -1 if no vertex with that ID is found.

`success = CheckedShallowCopy(g)`
Perform a shallow copy of the graph g if the graph meets the constraints of the graph, otherwise just returns false. For vtkGraph, this check always succeeds, but subclasses override this behavior to ensure that the incoming graph passes additional tests.

`success = CheckedDeepCopy(g)`
Perform a deep copy of the graph g if the graph meets the constraints of the graph, otherwise just returns false. For vtkGraph, this check always succeeds, but subclasses override this behavior to ensure that the incoming graph passes additional tests.

`ReorderOutVertices(v, list)`
Reorder the outgoing vertices of a vertex according to a list stored in a vtkIdTypeArray. This does not change the topology of the graph, just the internal ordering in the data structure.

`v = GetSourceVertex(e)`
Retrieve the source vertex index given an edge index. The first time this or GetTargetVertex() is called, the graph will build a mapping array from edge index to source and target vertex for all edges. If you have access to an edge type such as vtkOutEdgeType, vtkInEdgeType, vtkEdgeType, or vtkGraphEdge, these should be used in preference to this method, which will consume additional memory.

`v = GetTargetVertex(e)`
Similar to GetSourceVertex(), but retrieves the source vertex of the edge.

`SetEdgePoints(e, npts, pts)`
Set the points for routing edge e by providing a number of points and a 3-x-npts array containing the x, y, z coodinates of each point.

`GetEdgePoints(e, npts, pts)`
Get the points for routing edge e by setting the number of points and array of points passed as the second and third arguments.

`n = GetNumberOfEdgePoints(e)`

Return the number of edge points along an edge.

`pt = GetEdgePoint(e, i)`
Get the i-th point along an edge's path as a pointer to x, y, z coordinate values.

`ClearEdgePoints(e)`
Clear the edge points associated with an edge.

`SetEdgePoint(e, i, pt)`
Set the i-th point along an edge's path as an array holding x, y, z coordinate values.

`SetEdgePoint(e, i, x, y, z)`
An alternate form of the previous method that passes the x, y, z coordinates as separate arguments.

`AddEdgePoint(e, pt)`
Add a point to the end of an edge's path as an array holding x, y, z coordinate values.

`AddEdgePoint(e, x, y, z)`
An alternate form of the previous method that passes the x, y, z coordinates as separate arguments.

vtkDirectedGraph

vtkDirectedGraph is the superclass of all graphs that impose ordering on edges, so the edge (A,B) is treated as distinct from (B,A). When copying a graph with methods like CheckedShallowCopy(), this type ensures that the graph structure is a valid directed graph. There are no additional public methods.

vtkUndirectedGraph

vtkUndirectedGraph is the superclass of all graphs that do not impose ordering on edges, so the edge (A,B) is equivalent to an edge (B,A). When copying a graph with methods like CheckedShallowCopy(), this type ensures that the graph structure is a valid undirected graph. There are no additional public methods.

vtkMutableDirectedGraph and vtkMutableUndirectedGraph Methods

Mutable graph classes are the only graph classes whose structure may be edited programmatically. This refers only to the structure of the graph, since it is possible to add and remove vertex and edge attributes, including vertex and edge locations, in all graph classes.

`v = AddVertex()`
Add a vertex to the graph and return its index.

`v = AddVertex(properties)`
Add a vertex to the graph with properties stored in a vtkVariantArray and return its index. The order of the properties must match the order that arrays were added to the graph's vertex data.

`v = AddVertex(pedigree_id)`
Add a vertex to the graph with the specified pedigree id stored in a vtkVariant and return its index.

`e = AddEdge(u, v)`
Add an edge from vertex u to vertex v and return the edge as a vtkEdgeType structure.

`edge = AddGraphEdge(u, v)`
Add an edge from vertex u to vertex v and return the edge as a vtkGraphEdge object. This method provides the functionality of AddEdge(u, v) to wrapped languages.

`e = AddEdge(u, v, properties)`
Add an edge from vertex u to vertex v with edge properties stored in a vtkVariantArray, and return the edge as a vtkEdgeType structure. The order of the properties must match the order that arrays were added to the graph's edge data.

`e = AddEdge(u_pedigree, v, properties)`
Functions just like AddEdge(u, v, properties) except that the first vertex is specified by its pedigree ID.

`e = AddEdge(u, v_pedigree, properties)`
Functions just like AddEdge(u, v, properties) except that the second vertex is specified by its pedigree ID.

`e = AddEdge(u_pedigree, v_pedigree, properties)`
Functions just like AddEdge(u, v, properties) except that the both vertices are specified by their pedigree IDs.

`child = AddChild(parent)`
Available in vtkMutableDirectedGraph only. Add an outgoing edge from the parent vertex to a new child vertex, and return the new child vertex index. This is useful when building trees with vtkMutableDirectedGraph.

`child = AddChild(parent, properties)`
Available in vtkMutableDirectedGraph only. Add an outgoing edge from the parent vertex to a new child vertex with properties stored in a vtkVariantArray, and return the new child vertex index. The order of the properties must match the order that arrays were added to the graph's vertex data.

In addition to the methods mentioned above, vtkMutableDirectedGraph and vtkMutableUndirectedGraph have a set of similar methods designed to support distributed graphs. These methods are:

```
LazyAddVertex()
LazyAddVertex(properties)
LazyAddVertex(pedigree_id)
LazyAddEdge(u, v, properties)
LazyAddEdge(u_pedigree, v, properties)
LazyAddEdge (u, v_pedigree, properties)
LazyAddEdge (u_pedigree, v_pedigree, properties)
```

These methods are only valid on a distributed graph (i.e. a graph whose distributed helper is non-null). All these methods work just like their counterparts without the prepended "Lazy", except that the addition is performed asynchronously if the new vertex or edge will be owned by a remote processor. Calling Synchronize() on the distributed helper will flush all pending edits. In the case of adding an edge where both endpoints are nonlocal, this may require two Synchronize() calls.

vtkDirectedAcyclicGraph

vtkDirectedAcyclicGraph is a constrained directed graph where edges do not form a directed cycle. A cycle is a sequence of adjacent edges that forms a full loop in the graph. A directed acyclic graph defines a partial ordering over a set of elements. Other than the added constraint in CheckedShallowCopy(), this class is identical to vtkDirectedGraph.

To generate a vtkDirectedAcyclicGraph, first create an instance of vtkMutableDirectedGraph. After adding the appropriate vertices and edges to create the tree, call CheckedShallowCopy() on an instance of vtkDirectedAcyclicGraph, passing the mutable graph as an argument. This method will do one of two things. If the graph is a valid directed acyclic graph, it will set the structure via a shallow copy and return true. If the graph is found to contain a cycle, the method will return false. There are no additional public methods.

vtkTree

A tree is a special type of directed acyclic graph that is connected (i.e. has no disjoint pieces), and each vertex has exactly one incoming edge, except for one vertex with no incoming edges which is called the root of the tree. The result of these constraints is that a tree is a hierarchy with the root vertex at the top, and edges directed downward toward the lower levels of the tree. Other than the added constraints in CheckedShallowCopy(), this class is identical to vtkDirectedGraph.

To generate a vtkTree, first create an instance of vtkMutableDirectedGraph. After adding the appropriate vertices and edges to create the tree, call CheckedShallowCopy() on an instance of vtkTree, passing the mutable graph as an argument. This method will do one of two things. If the tree is valid, it will set the structure via a shallow copy and return true. If it is not a valid tree, it will return false. There are no additional public methods.

16.14 Tables

vtkTable is simply a collection of columns stored in arrays. Each column is accessed by name, and columns may be added, altered, or removed by algorithms. As part of the support for vtkTable the toolkit now includes discriminated-union (vtkVariant, vtkVariantArray) and string (vtkStdString, and vtkStringArray) types in addition to the numeric types already in VTK.

vtkTable Methods

`Dump(width)`
: Write the table to standard output using the specified column width.

`data = GetRowData()`
: Return the columns of the table as a vtkDataSetAttributes object.

`SetRowData(data)`
: Set the full data in the table from a vtkDataSetAttributes object.

`n = GetNumberOfRows()`
: The number of rows in the table.

`row = GetRow(i)`
: Retrieve the i-th row of the table as a vtkVariantArray.

`GetRow(i, row)`
Retrieve the i-th row of the table into the vtkVariantArray variable specified as the second argument.

`SetRow(i, row)`
Set the i-th row of the table from a vtkVariantArray.

`i = InsertNextBlankRow()`
Insert a new row with empty values (numeric values of zero and/or empty strings) at the bottom of the table and return the index of the new row.

`i = InsertNextRow(row)`
Insert a new row with values from a vtkVariantArray to the bottom of the table and return the index of the new row.

`RemoveRow(i)`
Remove the i-th row from the table. Rows below the deleted row are shifted up.

`m = GetNumberOfColumns()`
The number of columns in the table.

`name = GetColumnName(j)`
Return the name of the j-th column.

`arr = GetColumnByName(name)`
Return the column with a specified name as a vtkAbstractArray, or null if none exists.

`arr = GetColumn(j)`
Return the j-th column as a vtkAbstractArray.

`AddColumn(arr)`
Add an column to the table from a vtkAbstractArray.

`RemoveColumnByName(name)`
Remove the column with a particular name if it exists.

`RemoveColumn(j)`
Remove the j-th column from the table. Columns to the right of the deleted column are shifted left.

`val = GetValue(i, j)`
Return the value at row i and column j as a vtkVariant.

`val = GetValueByName(i, name)`
Return the value at a row i and column name as a vtkVariant.

`SetValue(i, j, val)`
Set the value at a row i and column j as a vtkVariant.

`SetValueByName(i, name, val)`
Set the value at a row i and column name as a vtkVariant.

16.15 Multi-Dimensional Arrays

The new vtkArray class forms the base of a hierarchy of sparse and dense arrays that can store data with arbitrary dimensionality. Unlike vtkAbstractArray derivatives that are limited to storing a one-dimension array of tuples, vtkArray dimension can store vector (one-dimension), matrix (two-dimensions), or tensor (three-or-more dimensions) data using a variety of storage schemes. VTK currently provides dense and sparse-coordinate storage for multi-dimensional arrays. Future versions of VTK may use vtkArray to store field and attribute data.

Please note that you must set VTK_USE_N_WAY_ARRAYS "ON" when building VTK, to enable the multi-dimensional array classes. Currently, the multi-dimensional array classes are not wrapped for use in languages other than C++.

vtkArray Methods

vtkArray is a pure-virtual base class that declares methods common to all multi-dimensional arrays, regardless of how they store their data or what type of value they store. Of particular importance are functions to resize arrays that specify both the number of dimensions in the array, and the size of the array along each dimension.

`extents = GetExtents()`
: Returns the extents (the number of dimensions and size along each dimension) of the array.

`dimensions = GetDimensions()`
: Returns the number of dimensions stored in the array. Note that this is the same as calling GetExtents().GetDimensions().

`size = GetSize()`
: Returns the number of values stored in the array. Note that this is the same as calling GetExtents().GetSize(), and represents the maximum number of values that could ever be stored using the current extents. This is equal to the number of values stored in a dense array, and is greater-than-or-equal to the number of values stored in a sparse array.

`size = GetNonNullSize()`
: Returns the number of non-null values stored in the array. Note that this value will equal GetSize() for dense arrays, and will be less-than-or-equal to GetSize() for sparse arrays.

`SetDimensionLabel(i, label)`
: Sets the label for the i-th array dimension.

`label = GetDimensionLabel(i)`
: Returns the label for the i-th array dimension.

`GetCoordinatesN(n, coordinates)`
: Returns the coordinates of the n-th value in the array, where n is in the range [0, GetNonNullSize()). Note that the order in which coordinates are visited is undefined, but is guaranteed to match the order in which values are visited using other index-based array value accessors.

`value = GetVariantValueN(n)`
: Returns the n-th value stored in the array, where n is in the range [0, GetNonNullSize()).

This is useful for efficiently visiting every value in the array. Note that the order in which values are visited is undefined, but is guaranteed to match the order used by vtkArray::GetCoordinatesN().

`SetVariantValueN(n, value)`

Overwrites the n-th value stored in the array, where n is in the range [0, GetNonNullSize()). This is useful for efficiently visiting every value in the array. Note that the order in which values are visited is undefined, but is guaranteed to match the order used by vtkArray::GetCoordinatesN().

`array = DeepCopy()`

Returns a new array that is a deep copy of this array.

```
Resize(i)
Resize(i, j)
Resize(i, j, k)
Resize(extents)
```

Resizes the array to the given extents (number of dimensions and size of each dimension). Note that concrete implementations of vtkArray may place constraints on the the extents that they will store, so you cannot assume that GetExtents() will always return the same value passed to Resize(). The contents of the array are undefined after calling Resize() - you should initialize its contents accordingly. In particular, dimension-labels will be undefined, dense array values will be undefined, and sparse arrays will be empty.

```
value = GetVariantValue(i)
value = GetVariantValue(i, j)
value = GetVariantValue(i, j, k)
value = GetVariantValue(coordinates)
```

Returns the value stored in the array at the given coordinates. Note, the number of dimensions in the supplied coordinates must match the number of dimensions in the array.

```
SetVariantValue(i, value)
SetVariantValue(i, j, value)
SetVariantValue(i, j, k, value)
SetVariantValue(coordinates, value)
```

Overwrites the value stored in the array at the given coordinates. Note, the number of dimensions in the supplied coordinates must match the number of dimensions in the array.

```
CopyValue(source, source_coordinates, target_coordinates)
CopyValue(source, source_index, target_coordinates)
CopyValue(source, source_coordinates, target_index)
```

Where coordinates are provided, they must match the number of dimensions in the corresponding array. Overwrites a value with a value retrieved from another array. Both arrays must store the same data types.

vtkTypedArray Methods

vtkTypedArray provides a type-specific interface for retrieving and updating data in an arbitrary-dimension array. It derives from vtkArray and is templated on the type of value stored in the array.

Methods are provided for retrieving and updating array values based either on their array coordinates, or on a 1-dimensional integer index. The latter approach can be used to iterate over the values in an array in arbitrary order, which is useful when writing filters that operate efficiently on sparse

arrays and arrays that can have any number of dimensions. Special overloaded methods provide simple access for arrays with one, two, or three dimensions.

`value = GetValueN(n)`
: Returns the n-th value stored in the array, where n is in the range [0, GetNonNullSize()). This is useful for efficiently visiting every value in the array. Note that the order in which values are visited is undefined, but is guaranteed to match the order used by vtkArray::GetCoordinatesN().

`SetValueN(n, value)`
: Overwrites the n-th value stored in the array, where n is in the range [0, GetNonNullSize()). This is useful for efficiently visiting every value in the array. Note that the order in which values are visited is undefined, but is guaranteed to match the order used by vtkArray::GetCoordinatesN().

`value = GetValue(i)`
`value = GetValue(i, j)`
`value = GetValue(i, j, k)`
`value = GetValue(coordinates)`
: Returns the value stored in the array at the given coordinates. Note, the number of dimensions in the supplied coordinates must match the number of dimensions in the array.

`SetValue(i, value)`
`SetValue(i, j, value)`
`SetValue(i, j, k, value)`
`SetValue(coordinates, value)`
: Overwrites the value stored in the array at the given coordinates. Note, the number of dimensions in the supplied coordinates must match the number of dimensions in the array.

vtkDenseArray Methods

vtkDenseArray is a concrete vtkArray implementation that stores values using a contiguous block of memory. Values are stored with fortran ordering, meaning that if you iterated over the memory block, the left-most coordinates would vary the fastest. In addition to the retrieval and update methods provided by vtkTypedArray, vtkDenseArray provides methods to:

- fill the entire array with a specific value, and
- retrieve a raw pointer to the storage memory block.

`Fill(value)`
: Fills every element in the array with the given value.

`reference = operator[](coordinates)`
: Returns a value by-reference, which is useful for performance and code-clarity.

`ptr = GetStorage()`
: Returns a mutable reference to the underlying storage. Values are stored contiguously with fortran ordering. Use at your own risk!

vtkSparseArray Methods

vtkSparseArray is a concrete vtkArray implementation that stores values using sparse coordinate storage. This means that the array stores the complete set for sparse storage of coordinates and the value for each non-null value in the array, an approach that generalizes well for arbitrary numbers of dimensions. In addition to the value retrieval and update methods provided by vtkTypedArray, vtkSparseArray provides methods to:

- get and set a special 'null' value that will be returned when retrieving values for undefined coordinates;
- clear the contents of the array so that every set of coordinates is undefined;
- add values to the array in amortized-constant time;
- resize the array extents so that they bound the largest
- set of non-NULL values along each dimension; and
- retrieve pointers to the value- and coordinate-storage memory blocks.

`SetNullValue(value)`
: Set the value that will be returned by GetValue() for NULL areas of the array.

`value = GetNullValue()`
: Returns the value that will be returned by GetValue() for NULL areas of the array.

`Clear()`
: Remove all non-null elements from the array, leaving the number of dimensions, the extent of each dimension, and the label for each dimension unchanged.

`ptr = GetCoordinateStorage()`
: Return a mutable reference to the underlying coordinate storage.In VTK 5.4, GetCoordinateStorage() returns the array coordinates as a contiguous one-dimensional array, organized so that the coordinates for each value are adjacent in memory. After VTK 5.4, this method has been changed to take a zero-based dimension as an argument, returning a contiguous array of coordinates for that dimension. Use at your own risk!

`ptr = GetValueStorage()`
: Return a mutable reference to the underlying value storage. Values are stored contiguously, but in arbitrary order. Use GetCoordinateStorage() if you need to get the corresponding coordinates for a value. Use at your own risk!

`ReserveStorage(value_count)`
: Reserve storage for a specific number of values. This is useful for reading external data using GetCoordinateStorage() and GetValueStorage(), when the total number of non-NULL values in the array can be determined in advance. Note that after calling ReserveStorage(), all coordinates and values will be undefined, so you must ensure that every set of coordinates and values is overwritten. It is the caller's responsibility to ensure that duplicate coordinates are not inserted into the array.

`ResizeToContents()`
: Update the array extents to match its contents, so that the extent along each dimension matches the maximum index value along that dimension. Note: ResizeToContents() was relabelled 'SetExtentsFromContents()' in VTK versions after VTK 5.4.

```
AddValue(i, value)
AddValue(i, j, value)
AddValue(i, j, k, value)
AddValue(coordinates, value)
```

Adds a new non-null element to the array. Does not test to see if an element with matching coordinates already exists. Useful for providing fast initialization of the array as long as the caller is prepared to guarantee that no duplicate coordinates are ever used.

vtkArrayData Methods

Because vtkArray does not derive from vtkDataObject, the multi-dimensional array classes cannot be processed directly by the pipeline. Instead, the new vtkArrayData class is a vtkDataObject that acts as a "container" for multi-dimensional arrays. There is a corresponding vtkArrayDataAlgorithm class that is used to implement pipeline sources and filters that operate on vtkArrayData.

Please note that in VTK 5.4, vtkArrayData is a vtkDataObject that stores a single vtkArray, and vtkFactoredArrayData is a vtkDataObject that stores one-or-more vtkArray instances. In subsequent versions of VTK, the two classes have been merged so that vtkArrayData is a container for one-or-more vtkArray instances.

```
array = GetArray()
```

Returns the vtkArray stored by this vtkArrayData.

```
SetArray(array)
```

Sets the vtkArray stored by this vtkArrayData.

How To Write an Algorithm for VTK

This section describes how to create your own algorithms in VTK. Algorithms are objects that produce data (sources), operate on data to generate new data (filters), and interface the data to graphics systems and/or other systems (mappers). (One may also refer to algorithms generically as filters.) You may want to review "The Visualization Pipeline" on page 25 for information about the graphics pipeline. Pipeline execution is discussed in more detail in Chapter 19.

17.1 Overview

Implementing an algorithm or process as a VTK filter requires three basic steps.

1. Set up the pipeline interface. This specifies the number and type of inputs and/or outputs that are consumed and/or produced by the filter.
2. Set up the user interface. This provides users of the filter a means by which to tune or control algorithm parameters.
3. Write methods to fulfill pipeline requests. These provide the core functionality of the filter and contain the algorithm implementation.

The Pipeline Interface

A filter's pipeline interface determines how it may be connected and used in a VTK pipeline. Filters that consume data define one or more *input ports*, and those that produce data define one or more *output ports*. Each port corresponds to a logical input or output of the algorithm implemented by the filter.

The first part of defining the pipeline interface is to choose the proper superclass from which to derive the class implementing the new algorithm. All filters derive directly or indirectly from vtkAl-

gorithm, but direct derivation is used only by advanced filters in rare cases. Several subclasses of vtkAlgorithm are provided by VTK that define pipeline interfaces for most common cases. Filters derive from the class defining the most suitable pipeline interface for their algorithm. The proper superclass depends on the filter's purpose and the kind of geometry and data it is meant to process. The superclass name is intended to indicate the type of vtkDataObject it produces, though this is often the type it consumes as well.

- Graphics filters almost always derive from vtkPolyDataAlgorithm or vtkUnstructuredGridAlgorithm.
- Imaging filters almost always derive from vtkImageAlgorithm or vtkThreadedImageAlgorithm.
- Filters that process scientific simulation results may derive from vtkRectilinearGridAlgorithm, vtkStructuredGridAlgorithm, or vtkUnstructuredGridAlgorithm depending on the data set type supported.
- Abstract filters may derive from vtkDataObjectAlgorithm, vtkDataSetAlgorithm, or vtkPointSetAlgorithm in order to process data objects of a variety of types.
- There are a few other superclasses meant for filters that process advanced data set types beyond the scope of this book.

All of these superclasses define by default a pipeline interface consisting of one input port and one output port. The number of ports is set by calling the methods SetNumberOfInputPorts() and/or SetNumberOfOutputPorts() when a filter is constructed. For example, the constructor of vtkPolyDataAlgorithm contains the following code.

```
vtkPolyDataAlgorithm::vtkPolyDataAlgorithm()
 {
  ...
  this->SetNumberOfInputPorts(1);
  this->SetNumberOfOutputPorts(1);
 }
```

Filters may change this number in their constructors. For example, vtkSphereSource does not consume any data (i.e., it is a source object) so its constructor sets the number of input ports to zero.

```
vtkSphereSource::vtkSphereSource()
 {
  ...
  this->SetNumberOfInputPorts(0);
 }
```

Port requirements are stored in *port information* objects. These information objects are populated by the methods FillInputPortInformation() and FillOutputPortInformation(). The above superclasses provide a default implementation of these methods that simply requires one data object of the corresponding type on each input port and provides one such data object on each output port. For example, vtkPolyDataAlgorithm specifies that each input port consumes one vtkPolyData and each output port produces one vtkPolyData.

```
int
vtkPolyDataAlgorithm
 ::FillInputPortInformation(int, vtkInformation* info)
 {
  info->Set(vtkAlgorithm::INPUT_REQUIRED_DATA_TYPE(),
       "vtkPolyData");
  return 1;
 }

int
vtkPolyDataAlgorithm
::FillOutputPortInformation(int, vtkInformation* info)
{
 info->Set(vtkDataObject::DATA_TYPE_NAME(),
      "vtkPolyData");
 return 1;
}
```

One logical input to an algorithm may actually allow an arbitrary number of data objects, each provided by a different input connection. If an input port allows zero connections the port is said to be *optional*. If it allows more than one connection it is said to be *repeatable*. For example, vtkGlyph3D consumes two logical inputs: one providing the geometry describing glyph placement, and one providing zero or more glyphs to place. Its constructor sets the number of input ports to two.

```
vtkGlyph3D::vtkGlyph3D()
 {
  ...
  this->SetNumberOfInputPorts(2);
  ...
 }
```

Then vtkGlyph3D implements FillInputPortInformation() to specify the requirements of each input port. Specifically, input port zero requires exactly one connection with a data set of any type derived from vtkDataSet, and input port one supports zero or more connections providing vtkPolyData objects.

```
int vtkGlyph3D::FillInputPortInformation(int port,
                                         vtkInformation *info)
 {
  if (port == 0)
   {
   info->Set(vtkAlgorithm::INPUT_REQUIRED_DATA_TYPE(),
        "vtkDataSet");
   return 1;
   }
  else if (port == 1)
   {
   info->Set(vtkAlgorithm::INPUT_IS_REPEATABLE(), 1);
   info->Set(vtkAlgorithm::INPUT_IS_OPTIONAL(), 1);
```

```
    info->Set(vtkAlgorithm::INPUT_REQUIRED_DATA_TYPE(), "vtkPolyData");
    return 1;
    }
  return 0;
}
```

The User Interface

Many algorithms define parameters that tune their behavior. A VTK filter may define parameters stored by instance variables in its class. Methods to set and get the parameter values are defined by "Set/Get" macros. These macros implement the methods to automatically update the filter object's modified time when parameters change.

For example, the vtkGlyph3D filter provides a "ScaleFactor" parameter that controls the amount by which to scale input glyphs when placing them in the output. The class defines a member variable storing the parameter and uses vtkSetMacro and vtkGetMacro to define the user interface methods SetScaleFactor() and GetScaleFactor().

```
class vtkGlyph3D
{
public:
  ...
  vtkSetMacro(ScaleFactor,double);
  vtkGetMacro(ScaleFactor,double);
  ...
protected:
  double ScaleFactor;
};
```

Parameters are initialized with a default value by the constructor of a filter. In the vtkGlyph3D implementation the constructor initializes the ScaleFactor parameter to 1.0.

```
vtkGlyph3D::vtkGlyph3D()
{
  ...
  this->ScaleFactor = 1.0;
  ...
}
```

All VTK classes define a PrintSelf() method that prints information about the current state of an instance of the class. In the case of algorithm implementations the parameters of the algorithm should be included. For example, vtkGlyph3D prints the value of the ScaleFactor in its PrintSelf() method.

```
void vtkGlyph3D::PrintSelf(ostream& os, vtkIndent indent)
{
  this->Superclass::PrintSelf(os,indent);
  ...
  os << indent << "Scale Factor: "
    << this->ScaleFactor << "\n";
  ...
}
```

Fulfilling Pipeline Requests

Once the pipeline and user interfaces have been established it is possible to include a new filter in a VTK pipeline. The last step is to implement the actual algorithm.

When a pipeline updates, a filter may receive requests asking it to process some information and/or data. These requests are first sent to the executive object of a filter which may then send them to the algorithm implementation by calling the virtual method vtkAlgorithm::ProcessRequest(). This method is given the request information object and a set of input and output pipeline information objects on which to operate. It is responsible for attempting to fulfill the request and reporting success or failure. An implementation of ProcessRequest() must be provided by every algorithm object as it is the entry point for algorithm execution.

Many filters may be implemented without providing the ProcessRequest() method directly. The standard filter superclasses provide a default implementation of ProcessRequest() that implements the most common requests by transforming them into calls to request-specific methods. For example, vtkPolyDataAlgorithm implements ProcessRequest() as follows.

```
int
vtkPolyDataAlgorithm
::ProcessRequest(vtkInformation* request,
                 vtkInformationVector** inputVector,
                 vtkInformationVector* outputVector)
{
  if(request->Has(vtkDemandDrivenPipeline::REQUEST_INFORMATION()))
    {
    return this->RequestInformation(request, inputVector,
                                    outputVector);
    }
  if(request->Has(
      vtkStreamingDemandDrivenPipeline::REQUEST_UPDATE_EXTENT()))
    {
    return this->RequestUpdateExtent(request, inputVector,
                                     outputVector);
    }
  if(request->Has(vtkDemandDrivenPipeline::REQUEST_DATA()))
    {
    return this->RequestData(request, inputVector, outputVector);
    }
  return this->Superclass::ProcessRequest(request, inputVector,
                                          outputVector);
}
```

When using a standard superclass a filter needs only to implement the RequestData() method to contain its actual algorithm implementation. The RequestInformation() and RequestUpdateExtent() methods may also be implemented if a filter needs to transform requested extent between its output and input. The pipeline information passed to these methods contains all the input and output data objects on which they should operate. For example, vtkGlyph3D implements RequestData() as follows.

```
int vtkGlyph3D::RequestData(vtkInformation* request,
                            vtkInformationVector** inputVector,
```

```
                                vtkInformationVector* outputVector)
{
  vtkInformation* inInfo = inputVector[0]->GetInformationObject(0);
  vtkInformation* outInfo = outputVector->GetInformationObject(0);
  vtkDataSet* input = vtkDataSet::SafeDownCast(
    inInfo->Get(vtkDataObject::DATA_OBJECT()));
  vtkPolyData* output = vtkPolyData::SafeDownCast(
    outInfo->Get(vtkDataObject::DATA_OBJECT()));
  ...
  int numberOfSources =
    inputVector[1]->GetNumberOfInformationObjects();
  for(int i=0; i < numberOfSources; ++i)
    {
    vtkInformation* sourceInfo =
      inputVector[1]->GetInformationObject(i);
    vtkPolyData* source = vtkPolyData::SafeDownCast(
      sourceInfo->Get(vtkDataObject::DATA_OBJECT()));
    ...
    }
  ...
}
```

The inputVector contains the input pipeline information. Each element of the array represents one input port. It is a vtkInformationVector whose entries are the input pipeline information objects for the connections on the corresponding input port. The outputVector is a vtkInformationVector containing one output pipeline information object for each output port of the filter. Each pipeline information object for both input and output contains a vtkDataObject stored with the key vtkDataObject::DATA_OBJECT(). Once an implementation of RequestData() has retrieved its input and output data objects from the pipeline information it may proceed with its algorithm implementation.

17.2 Laws of VTK Algorithms

Never Modify Input Data

One of the most important guidelines for any filter writer is to never modify the input to the filter. The reason for this is simple: the proper execution of the pipeline requires that filters create and modify their own output. Remember, other filters may be using the input data as well; if you modify a filter's input, you can be potentially corrupting the data with respect to other filters that use it or the filter that created it.

Reference Count Data

If the input data to a filter is sent to the output of the filter unchanged be sure to share the representation by using reference counting. This reduces the memory cost of the pipeline which can be quite high for large visualization data. Typically, if one uses Get__() and Set__() methods to get and set data, reference counting is automatically handled. Alternatively the Register() and UnRegister() methods of an object may be called directly. The vtkSmartPointer<> template may be used to hold references to objects as local variables, but it should not be used in the public interface of a class. See

"Low-Level Object Model" on page 20 for more information about reference counting and smart pointers. Filter authors may wish to use specialized methods for passing data through a filter, see "Field and Attribute Data" on page 362 for more information.

Use Debug Macros

Filters should provide debugging information when the object's Debug flag is set. This is conveniently done using VTK's debug macros defined in `VTK/Common/vtkSetGet.h`. At a minimum, a filter should report the initiation of execution similar to the following (from `VTK/Graphics/vtkContourFilter.cxx`).

```
vtkDebugMacro(<< "Executing contour filter");
```

You may also wish to provide other information as the filter executes, for example, a summary of execution (again from `vtkContourFilter.cxx`):

```
vtkDebugMacro(<<"Created: "
              << newPts->GetNumberOfPoints() << " points, "
              << newVerts->GetNumberOfCells() << " verts, "
              << newLines->GetNumberOfCells() << " lines, "
              << newPolys->GetNumberOfCells() << " triangles");
```

Do not place debugging macros in the inner portions of a loop, since the macro invokes an `if` check that may affect performance. Also, if debugging is turned on in an inner loop, too much information will be output to be meaningfully interpreted.

Reclaim/Delete Allocated Memory

One common mistake that filter writers make is introducing memory leaks or using excessive memory. Memory leaks can be avoided by pairing New() and Delete() methods for all VTK objects and `new` and `delete` methods for all native or non-VTK objects. (See "Standard Methods: Creating and Deleting Objects" on page 300.)

Another way to reduce memory usage is to use the Squeeze() methods provided by vtkDataArray and subclasses. This method reclaims excess memory that an object may be using. Use the Squeeze() method whenever the size of the data object can only be estimated upon initial allocation.

Compute Modified Time

One of the trickiest parts of writing a filter is making sure that its modified time is properly managed. As you may recall, modified time is an internal time stamp that each object maintains in response to changes in its internal state. Typically, modified time changes when a Set__() method is invoked. For example, the method vtkTubeFilter::SetNumberOfSides(num) causes the vtkTubeFilter's modified time to change when this method is invoked, as long as `num` is different than the tube filter's current instance variable value.

Normally, the modified time of a filter is maintained without requiring intervention. For example, if you use the vtkSet/Get macros defined in `VTK/Common/vtkSetGet.h` to get and set instance variable values, modified time is properly managed, and the inherited method vtkObject::GetMTime() returns the correct value. However, if you define your own Set__() methods,

or include methods that modify the internal state of the object, you will have to invoke Modified() (i.e., change the internal modified time) on the filter as appropriate. And, if your object definition includes references to other objects, the correct modified time of the filter includes both the filter and objects it depends on. This requires overloading the GetMTime() method.

vtkCutter is an example of a filter demonstrating this behavior. This filter makes reference to another object, (i.e., the CutFunction), an instance of vtkImplicitFunction. When the implicit function definition changes, we expect the cutter to reexecute. Thus, the GetMTime() method of the filter must reflect this by considering the modified time of the implicit function; the GetMTime() method inherited from its superclass vtkObject must be overloaded. The implementation of the vtkCutter::GetMTime() method is as follows. It's actually more complicated than suggested here because vtkCutter depends on two other objects (vtkLocator and vtkContourValues) as shown below.

```
unsigned long vtkCutter::GetMTime()
{
 unsigned long mTime=this->Superclass::GetMTime();
 unsigned long contourValuesMTime=this->ContourValues->GetMTime();
 unsigned long time;

 mTime = ( contourValuesMTime > mTime ?
                                contourValuesMTime : mTime );
 if ( this->CutFunction != NULL )
  {
  time = this->CutFunction->GetMTime();
  mTime = ( time > mTime ? time : mTime );
  }
 if ( this->Locator != NULL )
  {
  time = this->Locator->GetMTime();
  mTime = ( time > mTime ? time : mTime );
  }
 return mTime;
}
```

The class vtkLocator is used to merge coincident points as the filter executes; vtkContourValues is a helper class used to generate contour values for those functions using isosurfacing as part of their execution process. The GetMTime() method must check all objects that vtkCutter depends on, returning the largest modified time it finds.

Although the use of modified time and the implicit execution model of the VTK visualization pipeline is simple, there is one common source of confusion. That is, you must distinguish between a filter's modified time and its dependency on the data stream. Remember, filters will execute either when they are modified (the modified time changes), or the input to the filter changes (dependency on data stream). Modified time only reflects changes to a filter or dependencies on other objects independent of the data stream.

Use ProgressEvent and AbortExecute

The ProgressEvent is invoked at regular intervals during the execution of a source, filter, or mapper object (i.e., any algorithm). Progress user methods typically perform such functions as updating an application user interface (e.g., imagine manipulating a progress bar in the GUI). (See "General

Guidelines for GUI Interaction" on page 423 and "User Methods, Observers, and Commands" on page 29 for more information.)

A progress user method is created by invoking AddObserver() with an event type of vtkCommand::ProgressEvent. When the progress method is invoked, the filter also sets the current progress value (a decimal fraction between (0,1) retrieved with the GetProgress() method). The progress method can be used in combination with the vtkAlgorithm's invocation of StartEvent and EndEvent. For example, `Examples/Tutorial/Step2` shows how to use these methods. Here's a code fragment to show how it works.

```
vtkDecimatePro deci
   deci AddObserver StartEvent {StartProgress deci "Decimating..."}
   deci AddObserver ProgressEvent {ShowProgress deci "Decimating..."}
   deci AddObserver EndEvent EndProgress
```

Not all filters invoke ProgressEvents or invoke them infrequently (depending on the filter implementation). The progress value may not be a true measure of the actual work done by the filter because it is difficult to measure progress in some filters and/or the filter implementor may choose to update the filter at key points in the algorithm (e.g., after building internal data structures, reading in a piece of data, etc.).

Related to progress methods is the concept of a flag that is used to stop execution of a filter. This flag, defined in vtkAlgorithm, is called the AbortExecute flag. When set, some filters will terminate their execution, sending to their output some portion of the result of their execution (or possibly nothing). Typically, the flag is set during invocation of a ProgressEvent and is used to prematurely terminate execution of a filter when it is taking too long or the application is attempting to keep up with user input events. Not all filters support the AbortExecute flag. Check the source code to be sure which ones support the flag. (Most do, and those that don't will in the near future.) An example use of progress user methods and the abort flag is shown in the following code fragment taken from `VTK/Graphics/vtkDecimatePro.cxx`.

```
for ( ptId=0; ptId < npts && !abortExecute ; ptId++ )
{
if ( ! (ptId % 10000) )
 {
 vtkDebugMacro(<<"Inserting vertex #" << ptId);
 this->UpdateProgress (0.25*ptId/npts);//25% inserting
 if (this->GetAbortExecute())
  {
  abortExecute = 1;
  break;
  }
 }
this->Insert(ptId);
}
```

Note that the filter implementor made some arbitrary decisions: the progress methods are invoked every 10,000 points; and the portion of the RequestData() method shown is assumed to take approximately 25% of the total execution time. Also, some debug output is combined with the execution of the progress method, as well as a status check on the abort flag. This points out an important guide-

line: as a filter implementor you do not want to invoke progress methods too often because they can affect overall performance.

Implement PrintSelf() Methods

All VTK classes implement a PrintSelf() method that prints the state of the object in a human-readable format. An implementation of this method must first pass the call to the superclass's implementation of the method and then print the state of the class's instance variables. If one of these instance variables is itself a VTK class then that object's PrintSelf() method should be invoked with an incremented level of indentation. For example, vtkCutter implements PrintSelf() as follows.

```
void vtkCutter::PrintSelf(ostream& os, vtkIndent indent)
{
 this->Superclass::PrintSelf(os,indent);
 os << indent << "Cut Function: " << this->CutFunction << "\n";
 os << indent << "Sort By: " << this->GetSortByAsString() << "\n";
 if ( this->Locator )
  {
  os << indent << "Locator: " << this->Locator << "\n";
  }
 else
  {
  os << indent << "Locator: (none)\n";
  }
 this->ContourValues->PrintSelf(os, indent.GetNextIndent());
 os << indent << "Generate Cut Scalars: "
   << (this->GenerateCutScalars ? "On\n" : "Off\n");
}
```

Get Input/Output Data From Pipeline Information

Many filters provide GetInput() and GetOutput() methods that are useful for users to get the inputs and outputs of a filter they create. It is tempting to use these methods from within the implementation of ProcessRequest() or one of the methods it calls, but this should not be done. The pipeline information objects passed to ProcessRequest() and related methods contain the data objects that should be used. These may be different from the data objects returned by GetInput() or GetOutput(), particularly when one filter is used internally in the implementation of another filter.

17.3 Example Algorithms

In this section a few example VTK filters are given. We show how to implement the filters by following the steps outlined above.

A Graphics Filter

The class vtkShrinkFilter defines a simple graphics filter. Its purpose is to shrink all cells of an input data set in order to visualize the structure of each cell. Since all standard VTK cell types are supported, the output type must be vtkUnstructuredGrid. We also want one input port for the input data set and one output port for the output data set. This makes vtkUnstructuredGridAlgorithm a suitable

choice for the superclass. The algorithm defines one parameter, ShrinkFactor, indicating the fraction of the original cell size that should be used for each output cell. The class declaration appears in VTK/Graphics/vtkShrinkFilter.h as follows.

```
#ifndef __vtkShrinkFilter_h
#define __vtkShrinkFilter_h
#include "vtkUnstructuredGridAlgorithm.h"
class VTK_GRAPHICS_EXPORT vtkShrinkFilter : public
            vtkUnstructuredGridAlgorithm
{
public:
 static vtkShrinkFilter* New();
 vtkTypeRevisionMacro(vtkShrinkFilter,
           vtkUnstructuredGridAlgorithm);
 void PrintSelf(ostream& os, vtkIndent indent);
 // Description:
 // Get/Set the fraction of shrink for each cell.
 vtkSetClampMacro(ShrinkFactor, double, 0.0, 1.0);
 vtkGetMacro(ShrinkFactor, double);
protected:
 vtkShrinkFilter();
 ~vtkShrinkFilter() {}
 virtual int FillInputPortInformation(int port,
            vtkInformation* info);
 virtual int RequestData(vtkInformation*,
           vtkInformationVector**,
           vtkInformationVector*);
 double ShrinkFactor;
private:
 vtkShrinkFilter(const vtkShrinkFilter&);
 void operator=(const vtkShrinkFilter&);
};
#endif
```

To complete the definition of the class, we need to implement the constructor and the FillInputPortInformation(), PrintSelf(), and RequestData() methods. These implementations, excerpted from the VTK/Graphics/vtkShrinkFilter.cxx file, are shown in the following. (Note: VTK_GRAPHICS_EXPORT is a #define macro that is used by some compilers to export symbols from shared libraries.)

The constructor initializes the ShrinkFactor parameter to a default value. Since the superclass vtkUnstructuredGridAlgorithm sets the number of input ports and output ports to one this constructor need not change it.

```
vtkShrinkFilter::vtkShrinkFilter()
{
 this->ShrinkFactor = 0.5;
}
```

The PrintSelf() method prints the setting of the ShrinkFactor parameter.

```
void vtkShrinkFilter::PrintSelf(ostream& os, vtkIndent indent)
{
 this->Superclass::PrintSelf(os,indent);
 os << indent << "Shrink Factor: "
        << this->ShrinkFactor << "\n";
}
```

The FillInputPortInformation() method overrides the default from vtkUnstructuredGridAlgorithm to specify support for accepting any vtkDataSet as input.

```
int vtkShrinkFilter::FillInputPortInformation(
            int, vtkInformation* info)
{
 info->Set(vtkAlgorithm::INPUT_REQUIRED_DATA_TYPE(),
      "vtkDataSet");
 return 1;
}
```

Finally, the RequestData() method implements the cell shrink algorithm.

```
int vtkShrinkFilter::RequestData(
 vtkInformation*,
 vtkInformationVector** inputVector,
 vtkInformationVector* outputVector)
{
 // Get input and output data.
 vtkDataSet* input =
  vtkDataSet::GetData(inputVector[0]);
 vtkUnstructuredGrid* output =
  vtkUnstructuredGrid::GetData(outputVector);

 // We are now executing this filter.
 vtkDebugMacro("Shrinking cells");

 // Skip execution if there is no input geometry.
 vtkIdType numCells = input->GetNumberOfCells();
 vtkIdType numPts = input->GetNumberOfPoints();
 if(numCells < 1 || numPts < 1)
  {
  vtkDebugMacro("No data to shrink!");
  return 1;
  }

 // Allocate working space for new and old cell
 // point lists.
 vtkSmartPointer<vtkIdList> ptIds =
  vtkSmartPointer<vtkIdList>::New();
 vtkSmartPointer<vtkIdList> newPtIds =
  vtkSmartPointer<vtkIdList>::New();
 ptIds->Allocate(VTK_CELL_SIZE);
 newPtIds->Allocate(VTK_CELL_SIZE);
```

```
// Allocate approximately the space needed for the output cells.
output->Allocate(numCells);

// Allocate space for a new set of points.
vtkSmartPointer<vtkPoints> newPts =
    vtkSmartPointer<vtkPoints>::New();
newPts->Allocate(numPts*8, numPts);

// Allocate space for data associated with the
// new set of points.
vtkPointData* inPD = input->GetPointData();
vtkPointData* outPD = output->GetPointData();
outPD->CopyAllocate(inPD, numPts*8, numPts);

// Support progress and abort.
vtkIdType tenth =
 (numCells >= 10? numCells/10 : 1);
double numCellsInv = 1.0/numCells;
int abort = 0;

// Traverse all cells, obtaining node
// coordinates. Compute "center" of cell, then
// create new vertices shrunk towards center.
for(vtkIdType cellId = 0;
  cellId < numCells && !abort;
  ++cellId)
 {
 // Get the list of points for this cell.
 input->GetCellPoints(cellId, ptIds);
 vtkIdType numIds = ptIds->GetNumberOfIds();

 // Periodically update progress and check for
 // an abort request.
 if(cellId % tenth == 0)
  {
  this->UpdateProgress((cellId+1)*numCellsInv);
  abort = this->GetAbortExecute();
  }

 // Compute the center of mass of the cell
 // points.
 double center[3] = {0,0,0};
 for(vtkIdType i=0; i < numIds; ++i)
  {
  double p[3];
  input->GetPoint(ptIds->GetId(i), p);
  for(int j=0; j < 3; ++j)
   {
   center[j] += p[j];
   }
  }
```

```
    for(int j=0; j < 3; ++j)
     {
     center[j] /= numIds;
     }

    // Create new points for this cell.
    newPtIds->Reset();
    for(vtkIdType i=0; i < numIds; ++i)
     {
     // Get the old point location.
     double p[3];
     input->GetPoint(ptIds->GetId(i), p);

     // Compute the new point location.
     double newPt[3];
     for(int j=0; j < 3; ++j)
      {
      newPt[j] =
       (center[j] +
        this->ShrinkFactor*(p[j] - center[j]));
      }

     // Create the new point for this cell.
     vtkIdType newId =
      newPts->InsertNextPoint(newPt);
     newPtIds->InsertId(i, newId);

     // Copy point data from the old point.
     vtkIdType oldId = ptIds->GetId(i);
     outPD->CopyData(inPD, oldId, newId);
     }

    // Store the new cell in the output.
    output->InsertNextCell(
     input->GetCellType(cellId), newPtIds);
    }

   // Store the new set of points in the output.
   output->SetPoints(newPts);

   // Just pass cell data through because we still
   // have the same number and type of cells.
   output->GetCellData()
    ->PassData(input->GetCellData());

   // Avoid keeping extra memory around.
   output->Squeeze();

   return 1;
  }
```

The vtkShrinkFilter example is typical of graphics filters. Simpler filters supporting only polygonal cell types may use the superclass vtkPolyDataAlgorithm instead.

A Simple Imaging Filter

The class vtkSimpleImageFilterExample defines a very simple imaging filter. It simply copies image data from its input to its output, and is intended to be copied and modified by users wishing to implement very simple image processing tasks in VTK filters. A special superclass vtkSimpleImageToImageFilter provides a pipeline interface suitable for such simple imaging filters. It even implements the RequestData() method and transforms it into a call to the very simple method SimpleExecute(). The class declaration appears in `VTK/Imaging/vtkSimpleImageFilterExample.h` as follows.

```
#ifndef __vtkSimpleImageFilterExample_h
#define __vtkSimpleImageFilterExample_h
#include "vtkSimpleImageToImageFilter.h"
class VTK_IMAGING_EXPORT vtkSimpleImageFilterExample
 : public vtkSimpleImageToImageFilter
{
public:
 static vtkSimpleImageFilterExample* New();
 vtkTypeRevisionMacro(vtkSimpleImageFilterExample,
            vtkSimpleImageToImageFilter);
protected:
 vtkSimpleImageFilterExample() {}
 ~vtkSimpleImageFilterExample() {}
 virtual void SimpleExecute(vtkImageData* input,
               vtkImageData* output);
private:
 vtkSimpleImageFilterExample(
  const vtkSimpleImageFilterExample&);
 void operator=(
  const vtkSimpleImageFilterExample&);
};
#endif
```

To complete the definition of the class, we need to implement the SimpleExecute() method. Its implementation appears in `VTK/Imaging/vtkSimpleImageFilterExample.cxx` as shown here. (Note: VTK_IMAGING_EXPORT is a #define macro that is used by some compilers to export symbols from shared libraries.)

VTK image data may be represented using any of several scalar data types. Image processing filters are usually implemented using a function template. Pointers to the input and output image data arrays are given in the last two arguments. In this example we assume that the output data type will be the same as the input data type though this may not always be the case in practice.

```
template <class IT>
void vtkSimpleImageFilterExampleExecute(
 vtkImageData* input, vtkImageData* output,
 IT* inPtr, IT* outPtr)
{
 int dims[3];
```

```
  input->GetDimensions(dims);
  if (input->GetScalarType() !=
    output->GetScalarType())
   {
   vtkGenericWarningMacro(
    << "Execute: input ScalarType, "
    << input->GetScalarType()
    << ", must match out ScalarType "
    << output->GetScalarType());
   return;
   }
  int size = dims[0]*dims[1]*dims[2];
  for(int i=0; i<size; i++)
   {
   outPtr[i] = inPtr[i];
   }
}
```

The SimpleExecute() method is called by the RequestData() method defined by vtkSimpleImageToImageFilter. The superclass has already extracted the input and output data objects from the input and output pipeline information it was given. These data objects are passed as arguments to the SimpleExecute() method. In order to support all possible image scalar types the vtkTemplateMacro is used in a switch statement to instantiate calls to the above function template.

```
void vtkSimpleImageFilterExample::SimpleExecute(
 vtkImageData* input, vtkImageData* output)
{
 void* inPtr = input->GetScalarPointer();
 void* outPtr = output->GetScalarPointer();
 switch(output->GetScalarType())
  {
  // This is simply a #define for a big case list.
  // It handles all data types VTK supports.
  vtkTemplateMacro(
   vtkSimpleImageFilterExampleExecute(
   input, output,
   (VTK_TT*)(inPtr), (VTK_TT*)(outPtr)));
  default:
   vtkGenericWarningMacro(
    "Execute: Unknown input ScalarType");
   return;
  }
}
```

While the vtkSimpleImageToImageFilter superclass makes writing an imaging filter extremely simple, it also leaves out support for many advanced VTK pipeline features. Filters written using this superclass will work in VTK pipelines but may not be particularly efficient. Serious image filter implementations should subclass directly from vtkImageAlgorithm and support streaming, or even vtkThreadedImageAlgorithm to support threaded processing as well.

A Threaded Imaging Filter

The class vtkImageShiftScale defines a threaded imaging filter. Its purpose is to scale and shift the range of pixel values from input to output. An example application of such a filter is to convert a floating-point image to an unsigned 8-bit integer representation before writing to a file. Since the input and output type is vtkImageData, we may wish to choose vtkImageAlgorithm as a superclass. However, since the shifting and scaling is a per-pixel operation it is trivial to support a threaded implementation. This makes vtkThreadedImageAlgorithm an ideal choice of superclass for this filter. The algorithm defines four parameters specifying the amount to shift and scale, the output scalar type, and whether to clamp values to the range of the output type. The class declaration appears in `VTK/Imaging/vtkImageShiftScale.h` as follows.

```
#ifndef __vtkImageShiftScale_h
#define __vtkImageShiftScale_h
#include "vtkThreadedImageAlgorithm.h"
class VTK_IMAGING_EXPORT vtkImageShiftScale
 : public vtkThreadedImageAlgorithm
{
public:
 static vtkImageShiftScale* New();
 vtkTypeRevisionMacro(vtkImageShiftScale,
            vtkThreadedImageAlgorithm);
 void PrintSelf(ostream& os, vtkIndent indent);

 // Description:
 // Set/Get the shift value.
 vtkSetMacro(Shift,double);
 vtkGetMacro(Shift,double);

 // Description:
 // Set/Get the scale value.
 vtkSetMacro(Scale,double);
 vtkGetMacro(Scale,double);

 // Description:
 // Set the desired output scalar type. The result of the shift
 // and scale operations is cast to the type specified.
 vtkSetMacro(OutputScalarType, int);
 vtkGetMacro(OutputScalarType, int);
 void SetOutputScalarTypeToDouble()
  {this->SetOutputScalarType(VTK_DOUBLE);}
 void SetOutputScalarTypeToFloat()
  {this->SetOutputScalarType(VTK_FLOAT);}
 void SetOutputScalarTypeToLong()
  {this->SetOutputScalarType(VTK_LONG);}
 void SetOutputScalarTypeToUnsignedLong()
  {this->SetOutputScalarType(VTK_UNSIGNED_LONG);};
 void SetOutputScalarTypeToInt()
  {this->SetOutputScalarType(VTK_INT);}
 void SetOutputScalarTypeToUnsignedInt()
  {this->SetOutputScalarType(VTK_UNSIGNED_INT);}
```

```
  void SetOutputScalarTypeToShort()
   {this->SetOutputScalarType(VTK_SHORT);}
  void SetOutputScalarTypeToUnsignedShort()
   {this->SetOutputScalarType(VTK_UNSIGNED_SHORT);}
  void SetOutputScalarTypeToChar()
   {this->SetOutputScalarType(VTK_CHAR);}
  void SetOutputScalarTypeToUnsignedChar()
   {this->SetOutputScalarType(VTK_UNSIGNED_CHAR);}

  // Description:
  // When the ClampOverflow flag is on, the data is thresholded so that
  // the output value does not exceed the max or min of the data type.
  // By default, ClampOverflow is off.
  vtkSetMacro(ClampOverflow, int);
  vtkGetMacro(ClampOverflow, int);
  vtkBooleanMacro(ClampOverflow, int);
 protected:
  vtkImageShiftScale();
  ~vtkImageShiftScale() {}

  double Shift;
  double Scale;
  int OutputScalarType;
  int ClampOverflow;

  virtual
  int RequestInformation(vtkInformation*,
             vtkInformationVector**,
             vtkInformationVector*);

  virtual
  void ThreadedRequestData(vtkInformation*,
              vtkInformationVector**,
              vtkInformationVector*,
              vtkImageData*** inData,
              vtkImageData** outData,
              int outExt[6],
              int threadId);
 private:
  vtkImageShiftScale(const vtkImageShiftScale&);
  void operator=(const vtkImageShiftScale&);
 };
 #endif
```

To complete the definition of the class, we need to implement the constructor and the PrintSelf(), RequestInformation(), and ThreadedRequestData() methods. These implementations, excerpted from the `VTK/Imaging/vtkImageShiftScale.cxx` file, are shown in the following. (Note: VTK_IMAGING_EXPORT is a #define macro that is used by some compilers to export symbols from shared libraries. Also, the large number of variants of SetOutputScalarType() allow the parameter to be set easily from Tcl, Python, or Java wrappers, and are not critical.)

The constructor initializes the parameter values to reasonable defaults.

```
vtkImageShiftScale::vtkImageShiftScale()
{
 this->Shift = 0.0;
 this->Scale = 1.0;
 this->OutputScalarType = -1;
 this->ClampOverflow = 0;
}
```

The PrintSelf() method prints the settings of the parameters.

```
void vtkImageShiftScale::PrintSelf(
 ostream& os, vtkIndent indent)
{
 this->Superclass::PrintSelf(os,indent);
 os << indent << "Shift: " << this->Shift << "\n";
 os << indent << "Scale: " << this->Scale << "\n";
 os << indent << "Output Scalar Type: "
   << this->OutputScalarType << "\n";
 os << indent << "ClampOverflow: "
   << (this->ClampOverflow? "On" : "Off") << "\n";
}
```

The RequestInformation() method changes the output type to that specified by the OutputScalarType parameter if it has been set.

```
int vtkImageShiftScale::RequestInformation(
 vtkInformation*,
 vtkInformationVector**,
 vtkInformationVector* outputVector)
{
 // Set the image scalar type for the output.
 if(this->OutputScalarType != -1)
  {
  vtkInformation* outInfo =
   outputVector->GetInformationObject(0);
  vtkDataObject::SetPointDataActiveScalarInfo(
   outInfo, this->OutputScalarType, -1);
  }
 return 1;
}
```

In order to support any combination of input and output scalar type, the core of the algorithm is implemented in a function template vtkImageShiftScaleExecute. The function is used only inside the class implementation file and does not need to be declared in the header. It should be defined and implemented just before it is needed. The template keyword before the function definition indicates that it is a templated function, and that it is templated over the type `T`. If you are not familiar with C++ templates, you can think of `T` as a string that gets replaced by `int`, `short`, `float`, etc. at compile time much like a C macro. Notice that `T` is used as the data type for `inPtr` and `outPtr`. Since these

are functions instead of methods, they do not have access to the `this` pointer and its associated instance variables. Instead, we pass in the this pointer as a variable called `self`. The `self` argument can then be used to access the values of the class as is done in the examples shown here. For example, in the following we obtain the value of `Scale` from the instance and place it into a local variable called `scale`. The template will be instantiated and called by the ThreadedRequestData() method for all possible combinations. Each thread is given a region of the output image for which it is responsible. This region is specified by the `outExt` argument.

This code also introduces a new concept: image iterators. In VTK, several convenience classes are available for looping (or iterating) over the pixels in an image. The class vtkImageIterator is templated over the type of the image, and unlike most other classes in VTK is not instantiated with the New() factory method. Instead, the image iterator is instantiated on the stack with the standard C++ constructor. The constructor takes two arguments: a pointer to an instance of vtkImageData and the associated extent over which to iterate.

The vtkImageProgressIterator is another convenience class similar to the vtkImageIterator (it is a subclass of vtkImageIterator). However, vtkImageProgressIterator requires two additional parameters for instantiation: a pointer to the filter instantiating the progress iterator (i.e., self in the example) and the thread id. What the vtkImageProgressIterator does is to first insure that the thread id is zero (to limit the number of callbacks to a single thread), and periodically invoke UpdateProgress() on the filter. It also checks the AbortExecute flag on the filter each time IsAtEnd() is called and reports the end of data early if the flag is set.

Note how the BeginSpan() and EndSpan() methods are used to process one row of pixels at a time. The image iterator method IsAtEnd() is used to halt the processing of the image when all pixels have been processed.

```
template <class IT, class OT>
void vtkImageShiftScaleExecute(vtkImageShiftScale* self,
                               vtkImageData* inData,
                               vtkImageData* outData,
                               int outExt[6], int id,
                               IT*, OT*)
{
 // Create iterators for the input and output extents assigned to
 // this thread.
 vtkImageIterator<IT> inIt(inData, outExt);
 vtkImageProgressIterator<OT> outIt(outData, outExt, self, id);

 // Get the shift and scale parameters values.
 double shift = self->GetShift();
 double scale = self->GetScale();

 // Clamp pixel values within the range of the output type.
 double typeMin = outData->GetScalarTypeMin();
 double typeMax = outData->GetScalarTypeMax();
 int clamp = self->GetClampOverflow();

 // Loop through output pixels.
 while (!outIt.IsAtEnd())
  {
  IT* inSI = inIt.BeginSpan();
```

```
    OT* outSI = outIt.BeginSpan();
    OT* outSIEnd = outIt.EndSpan();
    if (clamp)
     {
     while (outSI != outSIEnd)
      {
      // Pixel operation
      double val = ((double)(*inSI) + shift) * scale;
      if (val > typeMax)
       {
       val = typeMax;
       }
      if (val < typeMin)
       {
       val = typeMin;
       }
      *outSI = (OT)(val);
      ++outSI;
      ++inSI;
      }
     }
    else
     {
     while (outSI != outSIEnd)
      {
      // Pixel operation
      *outSI = (OT)(((double)(*inSI) + shift) * scale);
      ++outSI;
      ++inSI;
      }
     }
    inIt.NextSpan();
    outIt.NextSpan();
    }
  }
```

The vtkTemplateMacro is used by ThreadedRequestData() below to call the function template vtkImageShiftScaleExecute1() for each possible input scalar data type. This function uses the vtkTemplateMacro to call the above function template vtkImageShiftScaleExecute() for each possible output scalar data type given an input scalar data type. The two uses of vtkTemplateMacro dispatch calls to the vtkImageShiftScaleExecute() function template for all possible combinations of input and output scalar types.

```
template <class T>
void vtkImageShiftScaleExecute1(
 vtkImageShiftScale* self,
 vtkImageData* inData,
 vtkImageData* outData,
 int outExt[6], int id, T*)
{
 switch (outData->GetScalarType())
```

```
    {
    vtkTemplateMacro(
     vtkImageShiftScaleExecute(self, inData,
                 outData, outExt, id,
                 static_cast<T*>(0),
                 static_cast<VTK_TT*>(0)));
    default:
     vtkErrorWithObjectMacro(
      self, "ThreadedRequestData: Unknown output ScalarType");
     return;
    }
  }
```

Finally, the ThreadedRequestData() method is the entry point for the filter implementation in each thread. The superclass vtkThreadedImageAlgorithm implements the RequestData() method and creates some number of helper threads. In each thread this ThreadedRequestData() method is called.

```
void vtkImageShiftScale::ThreadedRequestData(
 vtkInformation*,
 vtkInformationVector**,
 vtkInformationVector*,
 vtkImageData*** inData,
 vtkImageData** outData,
 int outExt[6],
 int threadId)
{
 vtkImageData* input = inData[0][0];
 vtkImageData* output = outData[0];
 switch(input->GetScalarType())
  {
  vtkTemplateMacro(
   vtkImageShiftScaleExecute1(this, input, output, outExt, threadId,
                static_cast<VTK_TT*>(0)));
  default:
   vtkErrorMacro("ThreadedRequestData: Unknown input ScalarType");
   return;
  }
}
```

For simplicity the input and output image data objects for every input connection and every output port are extracted from their pipeline information objects and passed in arrays to this method. This filter uses only one input connection and one output, so only the first entries of these arrays are used.

Non-threaded filters may be implemented similarly to this example. They should use vtkImageAlgorithm as a superclass, and implement RequestData() instead of ThreadedRequestData(). These two superclasses are sufficient for implementation of most image processing algorithms.

A Simple Reader

The class vtkSimplePointsReader provides a simple example of how to write a reader. Its purpose is to read a list of points from an ASCII file. Each point is specified on one line by three floating point

values. The reader has zero input ports and one output port producing vtkPolyData. This makes vtkPolyDataAlgorithm a suitable choice for superclass. There is one parameter called FileName specifying the name of the file from which to read points. The class declaration appears in `VTK/IO/vtkSimplePointsReader.h` as follows.

```
#ifndef __vtkSimplePointsReader_h
#define __vtkSimplePointsReader_h
#include "vtkPolyDataAlgorithm.h"
class VTK_IO_EXPORT vtkSimplePointsReader
 : public vtkPolyDataAlgorithm
{
public:
 static vtkSimplePointsReader* New();
 vtkTypeRevisionMacro(vtkSimplePointsReader,
            vtkPolyDataAlgorithm);
 void PrintSelf(ostream& os, vtkIndent indent);

 // Description: Set/Get the name of the file from which to read points.
 vtkSetStringMacro(FileName);
 vtkGetStringMacro(FileName);

protected:
 vtkSimplePointsReader();
 ~vtkSimplePointsReader();
 char* FileName;
 int RequestData(vtkInformation*,
        vtkInformationVector**,
        vtkInformationVector*);
private:
 vtkSimplePointsReader(
  const vtkSimplePointsReader&);
 void operator=(const vtkSimplePointsReader&);
};
```

Note that the vtkSetStringMacro() and vtkGetStringMacro() invocations define the methods SetFileName() and GetFileName() which automatically manage the memory for the file name string. The constructor shown below initializes FileName to a NULL pointer and the destructor releases any allocated string by setting FileName back to NULL.

To complete the definition of the class, we need to implement the constructor and destructor, and the PrintSelf() and RequestData() methods. These implementations, excerpted from the `VTK/IO/vtkSimplePointsReader.cxx` file, are shown in the following. (Note: VTK_IO_EXPORT is a #define macro that is used by some compilers to export symbols from shared libraries.) The constructor initializes the parameter value to a reasonable default. It also changes the number of input ports to zero since the reader consumes no input.

```
vtkSimplePointsReader::vtkSimplePointsReader()
{
 this->FileName = 0;
 this->SetNumberOfInputPorts(0);
}
```

The destructor frees memory consumed by the FileName parameter.

```
vtkSimplePointsReader::~vtkSimplePointsReader()
{
 this->SetFileName(0);
}
```

The PrintSelf() method prints the value of the FileName parameter.

```
void vtkSimplePointsReader::PrintSelf(ostream& os, vtkIndent indent)
{
 this->Superclass::PrintSelf(os,indent);
 os << indent << "FileName: "
   << (this->FileName ? this->FileName : "(none)") << "\n";
}
```

Finally, the RequestData() method contains the reader implementation.

```
int vtkSimplePointsReader::RequestData(
 vtkInformation*,
 vtkInformationVector**,
 vtkInformationVector* outputVector)
{
 // Make sure we have a file to read.
 if(!this->FileName)
  {
  vtkErrorMacro("A FileName must be specified.");
  return 0;
  }

 // Open the input file.
 ifstream fin(this->FileName);
 if(!fin)
  {
  vtkErrorMacro("Error opening file "
         << this->FileName);
  return 0;
  }

 // Allocate objects to hold points and
 // vertex cells.
 vtkSmartPointer<vtkPoints> points =
  vtkSmartPointer<vtkPoints>::New();
 vtkSmartPointer<vtkCellArray> verts =
  vtkSmartPointer<vtkCellArray>::New();

 // Read points from the file.
 vtkDebugMacro("Reading points from file "
        << this->FileName);
 double x[3];
 while(fin >> x[0] >> x[1] >> x[2])
```

```
    {
    vtkIdType id = points->InsertNextPoint(x);
    verts->InsertNextCell(1, &id);
    }
  vtkDebugMacro("Read "
          << points->GetNumberOfPoints()
          << " points.");

  // Store the points and cells in the output
  // data object.
  vtkPolyData* output =
   vtkPolyData::GetData(outputVector);
  output->SetPoints(points);
  output->SetVerts(verts);

  return 1;
}
```

Reader implementations must deal with input files that may not exist or may be the wrong format. This leads to many potential cases of failure. When a RequestData() method fails the reason should be reported using vtkErrorMacro and the method should return 0. When a RequestData() method is successful, it should return 1. Note the use of the vtkSmartPointer<> template to create and hold the point and vertex objects. This avoids the need to explicitly call Delete() on these objects after handing them to the vtkPolyData object. Since the reference held by a smart pointer is freed by its destructor all possible exit paths from the method will automatically release the objects.

A Streaming Filter

The class vtkImageGradient provides a filter that computes an approximate image gradient using central differencing. It serves as a good example for filters that change the image size from input to output. In order to provide the gradient direction at all pixels in a requested extent of the output the filter must ask for one extra layer of pixels surrounding this extent from the input. A filter parameter HandleBoundaries specifies how to handle the image boundaries. If enabled, the algorithm works as if boundary pixels are duplicated so that central differencing works for the boundary pixels. If disabled, the output whole extent of the image is reduced by a one pixel border along every axis. The class is defined by `VTK/Imaging/vtkImageGradient.h` and implemented by `VTK/Imaging/vtkImageGradient.cxx`. Below the implementation of two key methods is shown.

The RequestInformation() method shrinks the image by one pixel if boundary handling is not enabled. This amounts to changing the whole extent from the input pipeline information and storing it in the output pipeline information.

```
int vtkImageGradient::RequestInformation(
 vtkInformation*,
 vtkInformationVector** inputVector,
 vtkInformationVector* outputVector)
{
 // Get input and output pipeline information.
 vtkInformation* outInfo =
  outputVector->GetInformationObject(0);
```

```
  vtkInformation* inInfo =
   inputVector[0]->GetInformationObject(0);

  // Get the input whole extent.
  int extent[6];
  inInfo->Get(
  vtkStreamingDemandDrivenPipeline::WHOLE_EXTENT(),
   extent);

  // Shrink output image extent by one pixel if
  // not handling boundaries.
  if(!this->HandleBoundaries)
   {
   for(int idx = 0;
     idx < this->Dimensionality;
     ++idx)
    {
    extent[idx*2] += 1;
    extent[idx*2 + 1] -= 1;
    }
   }

  // Store the new whole extent for the output.
  outInfo->Set(
  vtkStreamingDemandDrivenPipeline::WHOLE_EXTENT(),
   extent, 6);

  // Set the number of point data componets to the
  // number of components in the gradient vector.
  vtkDataObject::SetPointDataActiveScalarInfo(
   outInfo, VTK_DOUBLE, this->Dimensionality);

  return 1;
}
```

The RequestUpdateExtent() method grows the extent requested by a consumer of the output by one pixel around the boundary to generate the extent needed from the input. In the case that boundary handling is enabled the grown extent must be clipped by the whole extent of the input image to avoid accessing non-existent pixels.

```
int vtkImageGradient::RequestUpdateExtent(
 vtkInformation*,
 vtkInformationVector** inputVector,
 vtkInformationVector* outputVector)
{
 // Get input and output pipeline information.
 vtkInformation* outInfo =
  outputVector->GetInformationObject(0);
 vtkInformation* inInfo =
  inputVector[0]->GetInformationObject(0);
```

```
  // Get the input whole extent.
  int wholeExtent[6];
  inInfo->Get(
  vtkStreamingDemandDrivenPipeline::WHOLE_EXTENT(),
   wholeExtent);

  // Get the requested update extent from the output.
  int inUExt[6];
  outInfo->Get(
  vtkStreamingDemandDrivenPipeline::UPDATE_EXTENT(),
   inUExt);

  // In order to do central differencing we need
  // one more layer of input pixels than we are
  // producing output pixels.
  for(int idx = 0;
    idx < this->Dimensionality;
    ++idx)
   {
   inUExt[idx*2] -= 1;
   inUExt[idx*2+1] += 1;

   // If handling boundaries instead of shrinking
   // the image then we must clip the needed
   // extent within the whole extent of the input.
   if (this->HandleBoundaries)
    {
    if(inUExt[idx*2] < wholeExtent[idx*2])
     {
     inUExt[idx*2] = wholeExtent[idx*2];
     }
    if(inUExt[idx*2+1] > wholeExtent[idx*2+1])
     {
     inUExt[idx*2+1] = wholeExtent[idx*2+1];
     }
    }
   }

  // Store the update extent needed from the intput.
  inInfo->Set(
  vtkStreamingDemandDrivenPipeline::UPDATE_EXTENT(),
   inUExt, 6);

  return 1;
 }
```

During pipeline execution the RequestInformation() method will be called first. This will inform consumers of the output image of its adjusted size. Later the RequestUpdateExtent() method will be called to ask the filter how much of the input image it needs to produce the requested output extent. Finally the RequestData() method will be called to actually compute the gradient. We omit it here for

brevity. (Actually vtkImageGradient is threaded so it uses vtkThreadedImageAlgorithm as its superclass and implements ThreadedRequestData().)

An Abstract Filter

The class vtkElevationFilter defines an abstract graphics filter. Its purpose is to generate scalar data on the points of a data set by projecting their position onto a one-dimensional parametric space. Reference counting is used to avoid allocating a duplicate copy of all the input geometry and data. Since only attribute data (e.g., scalars) are modified and the underlying geometry of the data set is not changed, there is no need to require a specific input or output data set type. The filter accepts any vtkDataSet and produces a duplicate of the data set as output but with the addition of the elevation data. This makes vtkDataSetAlgorithm a suitable choice of superclass. The algorithms defines three input parameters defining the mapping from 3D to the 1D parameter space and then to the output scalar range. The class declaration appears in `VTK/Graphics/vtkElevationFilter.h` as follows.

```
#ifndef __vtkElevationFilter_h
#define __vtkElevationFilter_h
#include "vtkDataSetAlgorithm.h"
class VTK_GRAPHICS_EXPORT vtkElevationFilter
 : public vtkDataSetAlgorithm
{
public:
 static vtkElevationFilter* New();
 vtkTypeRevisionMacro(vtkElevationFilter,
            vtkDataSetAlgorithm);
 void PrintSelf(ostream& os, vtkIndent indent);

 // Description:
 // Define one end of the line
 // (small scalar values). Default is (0,0,0).
 vtkSetVector3Macro(LowPoint,double);
 vtkGetVectorMacro(LowPoint,double,3);

 // Description:
 // Define other end of the line
 // (large scalar values). Default is (0,0,1).
 vtkSetVector3Macro(HighPoint,double);
 vtkGetVectorMacro(HighPoint,double,3);

 // Description:
 // Specify range to map scalars into.
 // Default is [0, 1].
 vtkSetVector2Macro(ScalarRange,double);
 vtkGetVectorMacro(ScalarRange,double,2);

protected:
 vtkElevationFilter();
 ~vtkElevationFilter() {}
```

```
  int RequestData(vtkInformation*,
          vtkInformationVector**,
          vtkInformationVector*);

  double LowPoint[3];
  double HighPoint[3];
  double ScalarRange[2];
 private:
  vtkElevationFilter(const vtkElevationFilter&);
  void operator=(const vtkElevationFilter&);
 };
 #endif
```

To complete the definition of the class, we need to implement the constructor and the PrintSelf() and RequestData() methods. These implementations, excerpted from the `VTK/Graphics/vtkElevationFilter.cxx` file, are shown in the following. (Note: VTK_GRAPHICS_EXPORT is a #define macro that is used by some compilers to export symbols from shared libraries.)

The constructor initializes the parameters to default values. Since the superclass vtkDataSetAlgorithm sets the number of input ports and output ports to one this constructor need not change it.

```
vtkElevationFilter::vtkElevationFilter()
{
 this->LowPoint[0] = 0.0;
 this->LowPoint[1] = 0.0;
 this->LowPoint[2] = 0.0;
 this->HighPoint[0] = 0.0;
 this->HighPoint[1] = 0.0;
 this->HighPoint[2] = 1.0;
 this->ScalarRange[0] = 0.0;
 this->ScalarRange[1] = 1.0;
}
```

The PrintSelf() method prints the parameter values.

```
void vtkElevationFilter::PrintSelf(
 ostream& os, vtkIndent indent)
{
 this->Superclass::PrintSelf(os,indent);
 os << indent << "Low Point: ("
   << this->LowPoint[0] << ", "
   << this->LowPoint[1] << ", "
   << this->LowPoint[2] << ")\n";
 os << indent << "High Point: ("
   << this->HighPoint[0] << ", "
   << this->HighPoint[1] << ", "
   << this->HighPoint[2] << ")\n";
 os << indent << "Scalar Range: ("
   << this->ScalarRange[0] << ", "
   << this->ScalarRange[1] << ")\n";
}
```

Finally, the RequestData() method implements the algorithm.

```
int vtkElevationFilter::RequestData(
 vtkInformation*,
 vtkInformationVector* outputVector)
{
 // Get the input and output data objects.
 vtkDataSet* input =
  vtkDataSet::GetData(inputVector[0]);
 vtkDataSet* output =
  vtkDataSet::GetData(outputVector);

 // Check the size of the input.
 vtkIdType numPts = input->GetNumberOfPoints();
 if(numPts < 1)
  {
  vtkDebugMacro("No input!");
  return 1;
  }

 // Allocate space for the elevation scalar data.
 vtkSmartPointer<vtkFloatArray> newScalars =
  vtkSmartPointer<vtkFloatArray>::New();
 newScalars->SetNumberOfTuples(numPts);

 // Set up 1D parametric system and make sure it
 // is valid.
 double diffVector[3] =
  { this->HighPoint[0] - this->LowPoint[0],
   this->HighPoint[1] - this->LowPoint[1],
   this->HighPoint[2] - this->LowPoint[2] };
 double length2 = vtkMath::Dot(diffVector,
                 diffVector);
 if(length2 <= 0)
  {
  vtkErrorMacro("Bad vector, using (0,0,1).");
  diffVector[0] = 0;
  diffVector[1] = 0;
  diffVector[2] = 1;
  length2 = 1.0;
  }

 // Support progress and abort.
 vtkIdType tenth = (numPts >= 10? numPts/10 : 1);
 double numPtsInv = 1.0/numPts;
 int abort = 0;

 // Compute parametric coordinate and map into
 // scalar range.
 double diffScalar =
  this->ScalarRange[1] - this->ScalarRange[0];
```

```
    vtkDebugMacro("Generating elevation scalars!");
    for(vtkIdType i=0; i < numPts && !abort; ++i)
     {
     // Periodically update progress and check for
     // an abort request.
     if(i % tenth == 0)
      {
      this->UpdateProgress((i+1)*numPtsInv);
      abort = this->GetAbortExecute();
      }

     // Project this input point into the 1D system.
     double x[3];
     input->GetPoint(i, x);
     double v[3] = { x[0] - this->LowPoint[0],
             x[1] - this->LowPoint[1],
             x[2] - this->LowPoint[2] };
     double s =
      vtkMath::Dot(v, diffVector) / length2;
     s = (s < 0.0 ? 0.0 : s > 1.0 ? 1.0 : s);

     // Store the resulting scalar value.
     newScalars->SetValue(
      i, this->ScalarRange[0] + s*diffScalar);
     }

    // Copy all the input geometry and data to
    // the output.
    output->CopyStructure(input);
    output->GetPointData()
     ->PassData(input->GetPointData());
    output->GetCellData()
     ->PassData(input->GetCellData());

    // Add the new scalars array to the output.
    newScalars->SetName("Elevation");
    output->GetPointData()->AddArray(newScalars);
    output->GetPointData()
     ->SetActiveScalars("Elevation");

    return 1;
   }
```

Note that the filter only computes scalar data and then passes it to the output. The actual generation of the output structure is done using the CopyStructure() method. This method makes a reference-counted copy of the input geometric structure and original attribute data.

vtkPointSetAlgorithm works in a similar fashion, except that the point coordinates are modified or generated and sent to the output. See vtkTransformFilter if you'd like to see a concrete example of vtkPointSetAlgorithm.

When writing a filter that modifies attribute data, or modifies point positions without changing the number of points or cells, either vtkDataSetAlgorithm or vtkPointSetAlgorithm is a suitable superclass.

Composite Dataset Aware Filters

The class vtkExtractBlock is a filter that extracts blocks from a multi-block dataset. The filter takes in a multi-block dataset and produces a multiblock dataset. Hence it's a vtkMultiBlockDataSetAlgorithm subclass. The user selects the blocks to be extracted using the AddIndex(), RemoveIndex(), RemoveAllIndices() API. vtkExtractBlock has a property PruneOutput, which when set results in the output multi-block being pruned to not have any empty branches. To keep it simple, we will ignore the tree pruning component of this algorithm, the reader is encouraged to look at the source for details for the pruning algorithm. The class declaration in VTK/Graphics/vtkExtractBlock.h, minus the tree pruning code is as follows:

```
#ifndef __vtkExtractBlock_h
#define __vtkExtractBlock_h
#include "vtkMultiBlockDataSetAlgorithm.h"
class vtkCompositeDataIterator;
class vtkMultiPieceDataSet;
class VTK_GRAPHICS_EXPORT vtkExtractBlock : public
vtkMultiBlockDataSetAlgorithm
{
public:
  static vtkExtractBlock* New();
  vtkTypeRevisionMacro(vtkExtractBlock, vtkMultiBlockDataSetAlgorithm);
  void PrintSelf(ostream& os, vtkIndent indent);

  // Description: Select the block indices to extract.
  // Each node in the multi-block tree is identified by an \c index.
  // The index can be obtained by performing a preorder traversal of the
  // tree (including empty nodes). eg. A(B (D, E), C(F, G)).
  // Inorder traversal yields: A, B, D, E, C, F, G
  // Index of A is 0, while index of C is 4.
  void AddIndex(unsigned int index);
  void RemoveIndex(unsigned int index);
  void RemoveAllIndices();

//BTX
protected:
  vtkExtractBlock();
  ~vtkExtractBlock();

  // Implementation of the algorithm.
  virtual int RequestData(vtkInformation *,
    vtkInformationVector **, vtkInformationVector *);

  // Extract subtree
  void CopySubTree(vtkCompositeDataIterator* loc,
```

```
    vtkMultiBlockDataSet* output, vtkMultiBlockDataSet* input);

private:
  vtkExtractBlock(const vtkExtractBlock&); // Not implemented.
  void operator=(const vtkExtractBlock&); // Not implemented.

  class vtkSet;
  vtkSet *Indices;
  vtkSet *ActiveIndices;
//ETX
};

#endif
```

Following are the excerpts from the VTK/Graphics/vtkExtractBlock.cxx file (minus the tree pruning code) which shows the implementations for the various methods.

The constructor initializes the default parameters, which includes allocation of the sets used to indices to be extracted.

```
{
this->Indices = new vtkExtractBlock::vtkSet();
this->ActiveIndices = new vtkExtractBlock::vtkSet();
}
```

Here vtkSet is merely a subclass of STL set, defined as such to avoid the inclusion of STL headers in the VTK header file, as follows:

```
#include <vtkstd/set>
class vtkExtractBlock::vtkSet : public vtkstd::set<unsigned int>
{
};
The destructor releases the memory allocated for sets.
vtkExtractBlock::~vtkExtractBlock()
{
delete this->Indices;
delete this->ActiveIndices;
}
```

The RequestData() method is where the filter's crux is implemented. Following is an extract from the same:

```
Author: utkarsh Subject: Inserted Text Date: 5/26/2009 12:02:34 PM
int vtkExtractBlock::RequestData(
vtkInformation *vtkNotUsed(request),
vtkInformationVector **inputVector,
vtkInformationVector *outputVector)
{
vtkMultiBlockDataSet *input =
vtkMultiBlockDataSet::GetData(inputVector[0], 0);
vtkMultiBlockDataSet *output =
```

```
vtkMultiBlockDataSet::GetData(outputVector, 0);
if (this->Indices->find(0) != this->Indices->end())
{
// trivial case.
output->ShallowCopy(input);
return 1;
}
output->CopyStructure(input);
(*this->ActiveIndices) = (*this->Indices);
// Copy selected blocks over to the output.
vtkCompositeDataIterator* iter = input->NewIterator();
iter->VisitOnlyLeavesOff();
for (iter->InitTraversal();
!iter->IsDoneWithTraversal() && this->ActiveIndices->size()>0;
iter->GoToNextItem())
{
if (this->ActiveIndices->find(iter->GetCurrentFlatIndex()) !=
this->ActiveIndices->end())
{
this->ActiveIndices->erase(iter->GetCurrentFlatIndex());
// This removed the visited indices from this->ActiveIndices.
this->CopySubTree(iter, output, input);
}
}
iter->Delete();
this->ActiveIndices->clear();
...
return 1;
}
```

Note that unlike CopyStructure() on a vtkDataSet used earlier, CopyStructure on a vtkCompositeDataSet merely copies the structure for the composite tree and not the input geometric structure. Once we have an output composite tree with the same structure as the input, we use the vtkCompositeDataIterator to iterate over the input and copying only the blocks for the chosen indices to the output. CopySubTree() is a method that compies the entire sub tree over, as follows:

```
void vtkExtractBlock::CopySubTree(vtkCompositeDataIterator* loc,
  vtkMultiBlockDataSet* output, vtkMultiBlockDataSet* input)
{
  vtkDataObject* inputNode = input->GetDataSet(loc);
  if (!inputNode->IsA("vtkCompositeDataSet"))
    {
    vtkDataObject* clone = inputNode->NewInstance();
    clone->ShallowCopy(inputNode);
    output->SetDataSet(loc, clone);
    clone->Delete();
    }

  else
    {
    vtkCompositeDataSet* cinput =
```

```
    vtkCompositeDataSet::SafeDownCast(inputNode);
    vtkCompositeDataSet* coutput = vtkCompositeDataSet::SafeDownCast(
      outut->GetDataSet(loc));
    vtkCompositeDataIterator* iter = cinput->NewIterator();
    iter->VisitOnlyLeavesOff();
    for (iter->InitTraversal(); !iter->IsDoneWithTraversal();
      iter->GoToNextItem())
      {
      vtkDataObject* curNode = iter->GetCurrentDataObject();
      vtkDataObject* clone = curNode->NewInstance();
      clone->ShallowCopy(curNode);
      coutput->SetDataSet(iter, clone);
      clone->Delete();

      this->ActiveIndices->erase(loc->GetCurrentFlatIndex() +
        iter->GetCurrentFlatIndex());
      }
    iter->Delete();
    }
}
```

Typically filters dealing with composite datasets use the vtkCompositeDataIterator to iterate over the nodes in the composite tree. Concrete subclasses of vtkCompositeDataSet also provide additional API to access the tree eg. vtkMultiBlockDataSet has GetBlock() API. When writing a filter that deals with composite datasets, ensure that the executive created is vtkCompositeDataPipeline. This is done by overriding vtkAlgorithm::CreateDefaultExecutive() which is already implemented in vtkMultiBlockDataSetAlgorithm and hence we don't do it in this filter.

Programmable Filters

An alternative to developing a filter in C++ is to use programmable algorithms. These objects allow you to create a function that is invoked during the execution of the algorithm (i.e., during the RequestData() method). The advantage of programmable filters is that you do not have to rebuild the VTK libraries, or even use C++. In fact, you can use the supported interpreted languages Tcl, Java, and Python to create a filter!

Programmable sources and filters are algorithms that enable you to create new filters at runtime. There is no need to create a C++ class or rebuild object libraries. Programmable objects take care of the overhead of hooking into the visualization pipeline, requiring only that you write the body of the filter's RequestData() method.

The programmable objects are vtkProgrammableSource, vtkProgrammableFilter, vtkProgrammableGlyphFilter, vtkProgrammableAttributeDataFilter, and vtkProgrammableDataObjectSource. vtkProgrammableSource is a source object that supports and can generate an output of any of the VTK dataset types. vtkProgrammableFilter allows you to set input and retrieve output of any dataset type (e.g., GetPolyDataOutput()). The filter vtkProgrammableAttributeDataFilter allows one or more inputs of the same or different types, and can generate an output of any dataset type.

An example will clarify the application of these filters. This excerpted code is from `VTK/Examples/Modelling/Tcl/expCos.tcl`.

```
vtkProgrammableFilter besselF
   besselF SetInputConnection [transF GetOutputPort]
```

```
  besselF SetExecuteMethod bessel

proc bessel {} {
  set input [besselF GetPolyDataInput]
    set numPts [$input GetNumberOfPoints]
    vtkPoints newPts
    vtkFloatArray derivs

    for {set i 0} {$i < $numPts} {incr i} {
       set x [$input GetPoint $i]
       set x0 [lindex $x 0]
       set x1 [lindex $x 1]

       set r [expr sqrt($x0*$x0 + $x1*$x1)]
       set x2 [expr exp(-$r) * cos(10.0*$r)]
       set deriv [expr -exp(-$r) * (cos(10.0*$r) + 10.0*sin(10.0*$r))]

       newPts InsertPoint $i $x0 $x1 $x2
       eval derivs InsertValue $i $deriv
    }

    set output [besselF GetPolyDataOutput]
    $output CopyStructure $input
    $output SetPoints newPts
    [$output GetPointData] SetScalars derivs

  newPts Delete; #reference counting - it's ok
    derivs Delete
}

vtkWarpScalar warp
    warp SetInput [besselF GetPolyDataOutput]
    warp XYPlaneOn
    warp SetScaleFactor 0.5
```

This example instantiates a vtkProgrammableFilter and then the Tcl proc bessel() serves as the function to compute the Bessel functions and derivatives. Note that bessel() works directly with the output of the filter obtained with the method GetPolyDataOutput(). This is because the output of besselF can be of any VTK supported dataset type, and we have to indicate to objects working with the output which type to use.

We hope that this chapter helps you write your own filters in VTK. You may wish to build on the information given here by studying the source code in other filters. It's particularly helpful if you can find an algorithm that you understand, and then look to see how VTK implements it.

Chapter 18

Integrating With The Windowing System

At some point in your use of VTK you will probably want to modify the default interaction behavior (in vtkRenderWindowInteractor) or add a graphical user interface (GUI) to your VTK based application. This section will explain how to do this for many common user interface toolkits. Up-to-date and new examples will be found in the `VTK/Examples/GUI` source directory. To use this chapter effectively, we recommend that you begin by reading the next section on managing interaction style. Then (to embed VTK into a GUI) look at "General Guidelines for GUI Interaction" on page 423 and then only the subsection appropriate to your user interface. If you are using a GUI other than the ones covered here, read the subsections that are similar to your GUI.

18.1 vtkRenderWindow Interaction Style

The class vtkRenderWindowInteractor captures mouse and keyboard events in the render window, translates window system specific events into VTK events (these are defined in `Common/vtkCommand.h`) and then dispatches the translated VTK events to another class—the interactor style. Therefore, to add a new style of interaction to VTK, you need to derive a new class from vtkInteractorStyle. For example, the class vtkInteractorStyleTrackball implements the trackball style interaction described in "vtkRenderWindowInteractor" on page 45. vtkInteractorStyleJoystickActor or vtkInteractorStyleJoystickCamera implements the joystick interaction style described in the same section. Another option is to use the class vtkInteractorStyleUser. This class allows users to define a new interactor style without subclassing.

Basically, the way this works is as follows. vtkRenderWindowInteractor intercepts events occurring in the vtkRenderWindow with which it is associated. Recall that on instantiation, vtkRenderWindowInteractor actually instantiates a device/windowing-specific implementation—either vtkXRenderWindowInteractor (Unix) or vtkWin32RenderWindowInteractor (Windows). The event intercepts are enabled when the vtkRenderWindowInteractor::Start() method is called. These

events are in turn forwarded to the vtkRenderWindowInteractor::InteractorStyle instance. The interactor style processes the events as appropriate.

Here is a list of the available interactor styles with a brief description of what each one does.

- vtkInteractorStyleJoystickActor — implements joystick style for actor manipulation.
- vtkInteractorStyleJoystickCamera — implements joystick style for camera manipulation.
- vtkInteractorStyleTrackballActor — implements trackball style for actor manipulation.
- vtkInteractorStyleTrackballCamera — implements trackball style for camera manipulation.
- vtkInteractorStyleSwitch — manages the switching between trackball and joystick mode, and camera and object (actor) mode. It does this by intercepting keystrokes and internally switching to one of the modes listed above. (Recall from "vtkRenderWindowInteractor" on page 45 that `Keypress j` / `Keypress t` toggles between the trackball and joystick modes, and `Keypress c` / `Keypress a` toggles between camera and actor mode.)
- vtkInteractorStyleFlight — a special class that allows the user to "fly-through" complex scenes.
- vtkInteractorStyleImage — a specially designed interactor style for 2D images. This class performs window and level adjustment via mouse motion, as well as pan and dolly constrained to the *x*-*y* plane.
- vtkInteractorStyleUnicam — single button camera manipulation. Rotation, zoom, and pan can all be performed with one mouse button.
- vtkInteractorStyleTerrain — Moves the camera around an object with a constant view-up vector (in the *z*-direction). The camera is moved with combinations of elevation, azimuth and zoom.
- vtkInteractorStyleRubberBandZoom — supports zooming in on an object by drawing a rectangle in the render window.

If one of these interactor styles does not suit your needs, you can create your own interactor style. There are two approaches to create your own. First, you can subclass from vtkInteractorStyle and override the appropriate virtual methods. Second, you can create observers that directly observe the vtkRenderWindowInteractor (see "Adding vtkRenderWindowInteractor Observers" on page 47) and take the appropriate actions as registered events are observed.

Subclassing from vtkInteractorStyle requires overriding the following methods (as described in `VTK/Rendering/vtkInteractorStyle.h`):

```
 // Description:
// Generic event bindings must be overridden in subclasses.
virtual void OnMouseMove() {}
virtual void OnLeftButtonDown() {}
virtual void OnLeftButtonUp() {}
virtual void OnMiddleButtonDown() {}
virtual void OnMiddleButtonUp() {}
virtual void OnRightButtonDown() {}
virtual void OnRightButtonUp() {}
 virtual void OnMouseWheelForward() {}
 virtual void OnMouseWheelBackward() {}

// Description:
// OnChar implements keyboard functions, but subclasses can override
```

```
 // this behavior.
virtual void OnChar()
virtual void OnKeyDown() {}
virtual void OnKeyUp() {}
virtual void OnKeyPress() {}
virtual void OnKeyRelease() {}

// Description:
// These are more esoteric events, but are useful in some cases.
 virtual void OnExpose() {}
 virtual void OnConfigure() {}
virtual void OnEnter() {}
virtual void OnLeave() {}
```

Then to use the interactor style, associate it with vtkRenderWindowInteractor via the SetInteractorStyle() method.

The second approach for developing your own style involves creating a set of command/observers to implement the desired behavior (see "Adding vtkRenderWindowInteractor Observers" on page 47 for an example). This provides greater flexibility and the capability to tie together code without the constraints of object inheritance.

18.2 General Guidelines for GUI Interaction

For the most part VTK has been designed to isolate the functional objects from the user interface. This has been done for portability and flexibility. But sooner or later you will need to create a user interface, so we have provided a number of hooks to help in this process. These hooks are called *user methods* and they are discussed in Chapter 3 (see "User Methods, Observers, and Commands" on page 29). Recall that the essence of user methods in VTK is that any class can invoke an event. If an observer is registered with the class that invokes the event, then an instance of vtkCommand is executed which is the implementation of the callback. There are a variety of events invoked by different VTK classes that come in handy when developing a user interface. A partial list of the more useful events is provided below.

The subclasses of vtkInteractorStyle and vtk3DWidget (subclasses of vtkInteractorObserver) invoke these events:

- StartInteractionEvent
- InteractionEvent
- EndInteractionEvent

In general, these events are invoked when you might expect. Pressing a mouse button starts the interaction (StartInteractionEvent), moving the mouse requires interactive response (InteractionEvent), and releasing the mouse ends the interaction (EndInteractionEvent). These events are designed to provide the necessary control to change the level-of-detail (see "Level-Of-Detail Actors" on page 55) or to otherwise ensure interactive rendering performance.

All filters (subclasses of vtkAlgorithm) invoke these events:

- StartEvent

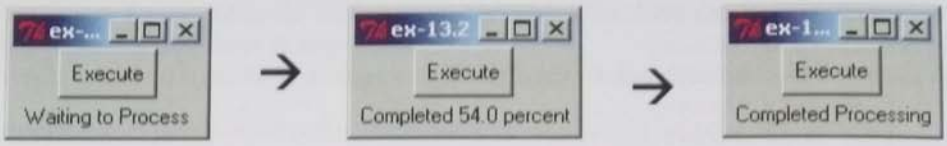


Figure 18–1 GUI feedback as a result of invoking the StartEvent, ProgressEvent, and EndEvent as a filter executes.

- EndEvent
- ProgressEvent

The class vtkRenderWindow invokes this event (while rendering):

- AbortCheckEvent

The classes (and subclasses of) vtkActor, vtkVolume, vtkPropPicker, vtkPicker, and vtkWorldPointPicker invoke these events while picking:

- PickEvent
- StartPickEvent (available in the picking classes only)
- EndPickEvent (available in the picking classes only)

The class vtkRenderWindowInteractor invokes these events:

- StartPickEvent — while picking
- EndPickEvent — while picking
- UserEvent — in response to "u" keypress in the render window
- ExitEvent — in response to the "e" keypress in the render window

And don't forget that you can define your own vtkInteractorStyle with its own set of special callbacks.

The StartEvent, EndEvent, and ProgressEvent invocations can be used to provide feedback to the user on what the application is doing and how much longer it will take. The vtkDemandDrivenPipeline invokes StartEvent and EndEvent on all filters. ProgressEvents are supported by imaging filters, some readers, and many (but not all) of the visualization filters. The AbortCheckEvent can be used to allow the user to interrupt a render that is taking too long (requires the use of vtkLODActors). The pick events in combination with virtual methods can be used to override the default VTK interactor behavior so that you can create your own custom interaction style.

To help you get started, consider the following two examples that incorporate user methods. Both are written in Tcl but can be easily converted to other languages. The first defines a `proc` that catches the ProgressEvent to display the progress of the vtkImageGaussianSmooth filter. It then catches the EndEvent to update the display to indicate the processing is complete (**Figure 18–1**). The code is based on `VTK/Examples/GUI/Tcl/ProgressEvent.tcl`.

```
# Demonstrate filter ProgressEvent and GetProgress
package require vtk

# Image pipeline
```

```
vtkImageReader reader
    reader SetDataByteOrderToLittleEndian
    reader SetDataExtent 0 255 0 255 1 93
    reader SetFilePrefix $env(VTK_DATA_ROOT)/Data/headsq/quarter
    reader SetDataMask 0x7fff

vtkImageGaussianSmooth smooth
    smooth SetInputConnection [reader GetOutputPort]
    smooth AddObserver ProgressEvent {
      .text configure -text \
                Completed [expr [smooth GetProgress]*100.0] percent
      update
    }
    smooth AddObserver EndEvent {
     .text configure -text Completed Processing
     update
    }

button .run -text Execute -command{
    smooth Modified
    smooth Update
}
label .text -text Waiting to Process
pack .run .text
```

For pipelines consisting of multiple filters, each filter could provide an indication of its progress. You can also create generic Tcl `procs` (rather than define them in-line as here) and assign them to multiple filters.

The second example makes use of the AbortCheckEvent to interrupt a long render if a mouse event is pending. (The script is based on `VTK/Examples/Rendering/Tcl/AbortCheckEvent.tcl`.) Most of the code is typical VTK code. The critical changes are that you must use instances of vtkLODActor; it is best if you turn on GlobalImmediateModeRendering() since the abort method cannot be invoked in the middle of display list processing; and finally you must add a few lines of code to process the abort check. In this example we define a simple procedure called TkCheckAbort which invokes the GetEventPending() method of vtkRenderWindow and then sets the AbortRender instance variable to 1 if an event is pending. The resolution of the mace model has been dramatically increased (**Figure 18–2**(left)) so that you can see the effects of using the AbortRender logic. Feel free to adjust the resolution of the sphere to suit your system. If everything is working properly then you should be able to quickly rotate and then zoom without waiting for the full resolution sphere to render in between the two actions (**Figure 18–2**(right)).

```
package require vtk
package require vtkinteraction
# Create the RenderWindow, Renderer and both Actors
vtkRenderer ren1
vtkRenderWindow renWin
    renWin AddRenderer ren1
vtkRenderWindowInteractor iren
    iren SetRenderWindow renWin
```

Figure 18–2 Aborting the rendering process. This is used to improve overall interaction with VTK. Rendering can be aborted whenever an event is pending. Make sure that you are using immediate mode rendering.

```
# Create a sphere source and actor
vtkSphereSource sphere
    sphere SetThetaResolution 40
    sphere SetPhiResolution 40
vtkPolyDataMapper sphereMapper
    sphereMapper SetInputConnection [sphere GetOutputPort]
    sphereMapper GlobalImmediateModeRenderingOn
vtkLODActor sphereActor
    sphereActor SetMapper sphereMapper

# Create the spikes using a cone source and the sphere source
#
vtkConeSource cone
vtkGlyph3D glyph
    glyph SetInputConnection [sphere GetOutputPort]
    glyph SetSourceConnection [cone GetOutputPort]
    glyph SetVectorModeToUseNormal
    glyph SetScaleModeToScaleByVector
    glyph SetScaleFactor 0.25
vtkPolyDataMapper spikeMapper
    spikeMapper SetInput Connection [glyph GetOutput Port]
vtkLODActor spikeActor
    spikeActor SetMapper spikeMapper

# Add the actors to the renderer, set the background and size
ren1 AddActor sphereActor
ren1 AddActor spikeActor
ren1 SetBackground 0.1 0.2 0.4
renWin SetSize 300 300

iren AddObserver UserEvent {wm deiconify .vtkInteract}

set cam1 [ren1 GetActiveCamera]
$cam1 Zoom 1.4
iren Initialize

proc TkCheckAbort {} {
  if {[renWin GetEventPending] != 0} {renWin SetAbortRender 1}
}
renWin AddObserver AbortCheckMethod TkCheckAbort
```

```
# Prevent the tk window from appearing; start the event loop
wm withdraw .
```

18.3 X Windows, Xt, and Motif

Figure 18–3 Simple Motif application using VTK.

Most traditional UNIX based applications use either Xt or Motif as their widget set. Many of those that don't directly use Xt or Motif end up using Xt at a lower level. There are two common ways to integrate VTK into your Xt (or Motif) based application. These examples can be found in the `VTK/Examples/GUI/Motif` source directory. First we will look at an example (`Example1.cxx`) where the VTK rendering window and the application UI are in separate windows (**Figure 18–3**). This helps avoid some problems that can occur if VTK and the UI do **not** use the same X visual. Both windows will use the same X event loop. Consider the following example application. It draws a mace into a VTK render window and then creates a Motif push button and associated callback in a separate window.

```
// Include OS specific include file to mix in X code

#include "vtkActor.h"
#include "vtkConeSource.h"
#include "vtkGlyph3D.h"
#include "vtkPolyData.h"
#include "vtkPolyDataMapper.h"
#include "vtkRenderWindow.h"
#include "vtkRenderer.h"
#include "vtkSphereSource.h"
#include "vtkXRenderWindowInteractor.h"

#include <Xm/PushB.h>
// void quit_cb(Widget,XtPointer,XtPointer);
// main (int argc, char *argv[])
{
 // X window stuff
 XtAppContext app;
 Widget toplevel, button;
 Display *display;
 // VTK stuff
 vtkRenderWindow *renWin;
 vtkRenderer *ren1;
 vtkActor *sphereActor1, *spikeActor1;
 vtkSphereSource *sphere;
 vtkConeSource *cone;
 vtkGlyph3D *glyph;
 vtkPolyDataMapper *sphereMapper, *spikeMapper;
 vtkXRenderWindowInteractor *iren;
```

The first section of code simply includes the required header files and prototypes a simple callback called quit_cb. Then we enter the main function and declare some standard X/Motif variables. Then we declare the VTK objects we will need as before. The only significant change here is the use of the vtkXRenderWindowInteractor subclass instead of the typical vtkRenderWindowInteractor. This subclass allows us to access some additional methods specific to the vtkXRenderWindowInteractor class.

```
 renWin = vtkRenderWindow::New();
ren1 = vtkRenderer::New();
renWin->AddRenderer(ren1);

sphere = vtkSphereSource::New();
sphereMapper = vtkPolyDataMapper::New();
sphereMapper->SetInputConnection(sphere->GetOutputPort());
sphereActor1 = vtkActor::New();
sphereActor1->SetMapper(sphereMapper);
cone = vtkConeSource::New();
glyph = vtkGlyph3D::New();
glyph->SetInputConnection(sphere->GetOutputPort());
glyph->SetSourceConnection(cone->GetOutputPort());
glyph->SetVectorModeToUseNormal();
glyph->SetScaleModeToScaleByVector();
glyph->SetScaleFactor(0.25);
spikeMapper = vtkPolyDataMapper::New();
spikeMapper->SetInputConnection(glyph->GetOutputPort());
spikeActor1 = vtkActor::New();
spikeActor1->SetMapper(spikeMapper);
ren1->AddProp(sphereActor1);
ren1->AddProp(spikeActor1);
ren1->SetBackground(0.4,0.1,0.2);
```

The above code is standard VTK code to create a mace.

```
 // Do the xwindow ui stuff
XtSetLanguageProc(NULL,NULL,NULL);
toplevel = XtVaAppInitialize(&app,"Sample",NULL,0,
                             &argc,argv,NULL,NULL);

// Get the display connection and give it to the renderer
display = XtDisplay(toplevel);
renWin->SetDisplayId(display);

// We use an X specific interactor
// since we have decided to make this an X program
iren = vtkXRenderWindowInteractor::New();
iren->SetRenderWindow(renWin);
iren->Initialize(app);

button = XtVaCreateManagedWidget("Exit",
                                 xmPushButtonWidgetClass,
                                 toplevel,XmNwidth, 50,
                                 XmNheight, 50,NULL);
```

```
 XtRealizeWidget(toplevel);
 XtAddCallback(button,XmNactivateCallback,quit_cb,NULL);
 XtAppMainLoop(app);
}

// Simple quit callback
void quit_cb(Widget w,XtPointer client_data,XtPointer call_data)
{
 exit(0);
}
```

Finally we perform the standard Xt initialization and create our toplevel shell. The next few lines are very important. We obtain the X display id from the toplevel shell and tell the render window to use the same display id. Next we create the vtkXRenderWindowInteractor, set its render window and finally initialize it using the X application context from our earlier XtVaAppInitialize() call. Then we use standard Xt/Motif calls to create a push button, realize the toplevel shell, and assign a callback to the pushbutton. The last step is to start the XtAppMainLoop. The `quit_cb` is a simple callback that just exits the application. It is critical in this type of approach that the VTK render window interactor is initialized prior to creating the rest of your user interface. Otherwise some events may not be handled correctly.

Now we will modify the preceding example so that the rendering window is part of the user interface (**Figure 18–4**). (The modified source code is in `VTK/Examples/GUI/Motif/Example2.cxx`.) This will require that we create a toplevel shell with a visual that VTK can use for rendering. Fortunately vtkXOpenGLRenderWindow includes some methods for helping you create an appropriate toplevel shell. Much of the code in the following example is the same as the previous example. The differences will be discussed shortly.

Figure 18–4 Simple Motif application with integrated VTK render window.

```
// Include OS specific file to mix in X code

#include "vtkActor.h"
#include "vtkConeSource.h"
#include "vtkGlyph3D.h"
#include "vtkPolyData.h"
#include "vtkPolyDataMapper.h"
#include "vtkRenderer.h"
#include "vtkSphereSource.h"
#include "vtkXOpenGLRenderWindow.h"
#include "vtkXRenderWindowInteractor.h"

#include <Xm/PushB.h>
#include <Xm/Form.h>

void quit_cb(Widget,XtPointer,XtPointer);

main (int argc, char *argv[])
{
 // X window stuff
 XtAppContext app;
```

```
Widget toplevel, form, toplevel2, vtk;
Widget button;
int depth;
Visual *vis;
Display *display;
Colormap col;

// VTK stuff
vtkXOpenGLRenderWindow *renWin;
vtkRenderer *ren1;
vtkActor *sphereActor1, *spikeActor1;
vtkSphereSource *sphere;
vtkConeSource *cone;
vtkGlyph3D *glyph;
vtkPolyDataMapper *sphereMapper, *spikeMapper;
vtkXRenderWindowInteractor *iren;

renWin = vtkXOpenGLRenderWindow::New();
ren1 = vtkRenderer::New();
renWin->AddRenderer(ren1);

sphere = vtkSphereSource::New();
sphereMapper = vtkPolyDataMapper::New();
sphereMapper->SetInputConnection(sphere->GetOutputPort());
sphereActor1 = vtkActor::New();
sphereActor1->SetMapper(sphereMapper);
cone = vtkConeSource::New();
glyph = vtkGlyph3D::New();
glyph->SetInputConnection(sphere->GetOutputPort());
glyph->SetSourceConnection(cone->GetOutputPort());
glyph->SetVectorModeToUseNormal();
glyph->SetScaleModeToScaleByVector();
glyph->SetScaleFactor(0.25);
spikeMapper = vtkPolyDataMapper::New();
spikeMapper->SetInputConnection(glyph->GetOutputPort());
spikeActor1 = vtkActor::New();
spikeActor1->SetMapper(spikeMapper);
ren1->AddActor(sphereActor1);
ren1->AddActor(spikeActor1);
ren1->SetBackground(0.4,0.1,0.2);

// Do the xwindow ui stuff
XtSetLanguageProc(NULL,NULL,NULL);
toplevel = XtVaAppInitialize(&app,"Sample",NULL,0,
                             &argc,argv,NULL,NULL);
```

The initial code is relatively unchanged. In the beginning we have included an additional Motif header file to support the Motif form widget. In the main function we have added some additional variables to store some additional X properties.

```
// Get the display connection and give it to the renderer
```

```
    display = XtDisplay(toplevel);
    renWin->SetDisplayId(display);
    depth = renWin->GetDesiredDepth();
    vis = renWin->GetDesiredVisual();
    col = renWin->GetDesiredColormap();

    toplevel2 = XtVaCreateWidget("top2",
          topLevelShellWidgetClass,toplevel,
       XmNdepth, depth,
       XmNvisual, vis,
       XmNcolormap, col,
       NULL);
```

Here is where the significant changes begin. We use the first toplevel shell widget to get an X display connection. We then set the render window to use that display connection and then query what X depth, visual, and colormap would be best for it to use. Then we create another toplevel shell widget this time explicitly specifying the depth, colormap, and visual. That way the second toplevel shell will be suitable for VTK rendering. All of the child widgets of this toplevel shell will have the same depth, colormap, and visual as `toplevel2`.

```
     form = XtVaCreateWidget("form",xmFormWidgetClass, toplevel2, NULL);
    vtk  = XtVaCreateManagedWidget("vtk",
        xmPrimitiveWidgetClass, form,
      XmNwidth, 300, XmNheight, 300,
      XmNleftAttachment, XmATTACH_FORM,
      XmNrightAttachment, XmATTACH_FORM,
      XmNtopAttachment, XmATTACH_FORM,
      NULL);
    button = XtVaCreateManagedWidget("Exit",
         xmPushButtonWidgetClass, form,
      XmNheight, 40,
      XmNbottomAttachment, XmATTACH_FORM,
      XmNtopAttachment, XmATTACH_WIDGET,
      XmNtopWidget, vtk,
      XmNleftAttachment, XmATTACH_FORM,
      XmNrightAttachment, XmATTACH_FORM,
      NULL);

    XtAddCallback(button,XmNactivateCallback,quit_cb,NULL);
    XtManageChild(form);
    XtRealizeWidget(toplevel2);
    XtMapWidget(toplevel2);

    // We use a X specific interactor
    // since we have decided to make this an X program
    iren = vtkXRenderWindowInteractor::New();
    iren->SetRenderWindow(renWin);
    iren->SetWidget(vtk);
    iren->Initialize(app);
    XtAppMainLoop(app);
}
```

Figure 18–5 A sample built as an MFC MDI application.

```
/* quit when the Exit button is clicked*/
void quit_cb(Widget w,XtPointer client_data,XtPointer call_data)
{
 exit(0);
}
```

Finally we create a few Motif widgets including a xmPrimitiveWidgetClass which is what VTK will render into. The form widget has been added simply to handle layout of the button and the rendering window. The SetWidget() call is used in this example to tell the interactor (and hence the render window) what widget to use for rendering.

18.4 Microsoft Windows / Microsoft Foundation Classes (MFC)

The basics of integration of VTK within the Windows environment has been shown previously (see "Create An Application" on page 29). You can also develop MFC-based applications that make use of VTK in two different ways. The first way to use VTK within an MFC based application is following the code from `VTK/Examples/GUI/Win32/SimpleCxx/Win32Cone.cxx`. Create a vtkRenderWindow in the MFC application and if desired, parent it with a MFC-based window. The second way is to make use of the vtkMFCView, vtkMFCRenderView and vtkMFCDocument classes that are provided in the `Examples/GUI/Win32/SampleMFC` subdirectory. In fact, the `Sample.exe` application is a sample MFC-based application that demonstrates the use of these classes. This MDI application (Multi-Document Interface) shows how to open several VTK data files and interact with them through the GUI (**Figure 18–5**). You may copy these classes as a starting point for your own new MFC applications.

18.5 Tcl/Tk

Integrating VTK with Tcl/Tk user interfaces is typically a fairly easy process thanks to classes such as vtkTkRenderWidget, and vtkTkImageViewerWidget. These classes can be used just like you would use any other Tk widget. Up-to-date information and new examples may be found both in the `VTK/Examples/GUI/Tcl` and `VTK/Wrapping/Tcl` source directories. Consider the following example taken from `VTK/Examples/GUI/Tcl/vtkTkRenderWidgetDemo.tcl`. **Figure 18–6** shows the result of running this script.

```
package require vtk
package require vtkinteraction
# This script uses a vtkTkRenderWidget to
# create a Tk widget that is associated with
# a vtkRenderWindow.

# Create the GUI: a render widget and a quit
# button
wm withdraw .
toplevel .top
frame .top.f1
vtkTkRenderWidget .top.f1.r1 \
     -width 400 -height 400
button .top.btn -text Quit -command exit
pack .top.f1.r1 -side left -padx 3 -pady 3 -fill both \
     -expand t
pack .top.f1 -fill both -expand t
pack .top.btn -fill x
# Get the render window associated with the widget.
set renWin [.top.f1.r1 GetRenderWindow]
vtkRenderer ren1
$renWin AddRenderer ren1

# Bind the mouse events
BindTkRenderWidget .top.f1.r1

# Create a Cone source and actor
vtkConeSource cone
vtkPolyDataMapper coneMapper
  coneMapper SetInputConnection [cone GetOutputPort]
  coneMapper GlobalImmediateModeRenderingOn
vtkLODActor coneActor
  coneActor SetMapper coneMapper
# Add the actors to the renderer, set the background
#
ren1 AddProp coneActor
ren1 SetBackground 0.1 0.2 0.4
```

Figure 18–6 Tcl/Tk example.

The first line is the standard `package require vtk` command that is used to load the VTK Tcl package. The `vtkinteraction` package contains default bindings for handling mouse and keyboard events for a render widget. Specifically it defines the `BindTkRenderWidget proc` which sets up

those bindings for a particular vtkTkRenderWidget. Next we withdraw the default toplevel widget and create a new one called `.top`. On some systems you may need to create `.top` with the following line instead of the one given above.

```
toplevel .top -visual best
```

Next we create and pack the frame, vtkTkRenderWidget, and a button in the traditional Tk manner. The next line queries the vtkTkRenderWidget for the underlying render window that it is using. We store this in a variable called `renWin`. We then create a renderer, associate it with the render window, and then bind the mouse events to the vtkRenderWidget using the `BindTkRenderWidget proc`. Finally we create a cone and actor in the normal manner. If you wish, the render window can be provided as an argument on the creation of the vtkTkRenderWidget as follows:

```
vtkRenderWindow renWin
vtkTkRenderWidget .top.f1.r1 \
    -width 400 -height 400 -rw renWin
```

Then simply use `renWin` instead of `$renWin` since it is now an instance, not a variable reference.

For your application development you will probably want to customize the event handling. The best way to do this is to make a copy of `bindings-rw.tcl` and `bindings.tcl` located in `VTK/Wrapping/Tcl/vtkinteraction` and then edit it to suit your preferences. The format of the first file is fairly straightforward. It defines the `BindTkRenderWidget proc` that associates events with specific Tcl procedures. The other file defines these procedures. The same techniques used with vtkTkRenderWidget can be used with vtkTkImageViewerWidget for image processing. Instead of having a `-rw` option and GetRenderWindow() method, vtkTkImageViewerWidget supports `-iv` and GetImageViewer().

When using the vtkTkWidget classes you should not use the interactor classes such as vtkRenderWindowInteractor. Normally you should use either an interactor or a vtkTkWidget but never both for a given window.

18.6 Java

The *Visualization Toolkit* includes a class specially designed to help you integrate VTK into your Java based application. This is a fairly tricky procedure since Java does not provide any "public" classes to support native code integration. It is made more difficult by the fact that Java is a multithreaded language and yet windowing systems such as X11R5 do not support multithreaded user interfaces. To help overcome these difficulties, we have provided a Java class called `vtkPanel`. This class works with Java to make a vtkRenderWindow appear like a normal Java AWT Canvas. The `SimpleVTK.java` example is in the `VTK/Wrapping/Java` subdirectory. It makes use of the `vtkPanel` class. `vtkPanel.java` is in `VTK/Wrapping/Java/vtk`.

18.7 Using VTK with Qt

VTK now contains many classes that make it easy to integrate VTK functionality into Qt applications. The VTK source files related to Qt are located under the VTK/GUISupport/Qt directory. Qt related VTK examples are located under the VTK/Examples/GUI/Qt directory. The Qt support in

VTK is not enabled by default, so when you configure VTK, you have to turn on the Qt support by setting the following set of CMake variables:

- "VTK_USE_GUISUPPORT:BOOL=ON
- "VTK_USE_QT:BOOL=ON
- "DESIRED_QT_VERSION:STRING=4
- "QT_QMAKE_EXECUTABLE:FILEPATH=C:/full/path/to/qmake

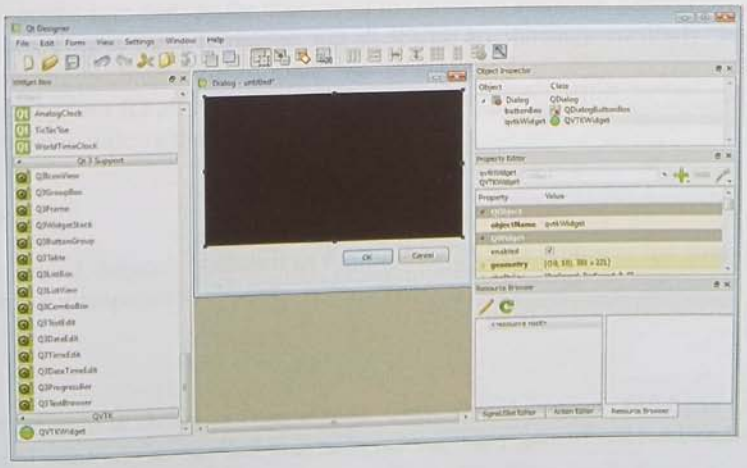
If you turn on BUILD_EXAMPLES in addition to setting all the required Qt variables, then all the examples in the VTK/Examples/GUI/Qt directory will also be built when you build VTK. Or you can build them individually after building VTK.

If you start from scratch with a new VTK build tree, follow these instructions to make these settings interactively in cmake-gui or ccmake:

- "Configure vtk
- "Turn on VTK_USE_GUISUPPORT (advanced) and VTK_USE_QT
- "Configure vtk again
- "Set DESIRED_QT_VERSION (to 4 or 3)
- "Configure vtk again
- "Set QT_QMAKE_EXECUTABLE
- "Optionally turn on BUILD_EXAMPLES
- "Configure & generate

If you want to use the QVTKPluginWidget in the Qt designer application, be sure to build a configuration that matches designer. By default, use the Release configuration in a Visual Studio or Xcode build, or set CMAKE_BUILD_TYPE to "Release" for a makefile based build.

After building, copy the file QVTKWidgetPlugin.dll (or the *.so or *.dylib equivalent on Linux or Mac) to the "plugins/designer" folder of your Qt installation. Then, when you open up designer, you should have "QVTKWidget" available in the Widget Box of Qt designer, as seen in the following screenshot:



The vtkEventQtSlotConnect class is an adapter class that allows you to connect vtkObject based events to your QObject based slots such that when the vtkObject event is invoked, your slot is called. Example use of this class is located in the Form1::init method in the file VTK/Examples/GUI/Qt/Events/GUI.ui.h. This code snippet from that example demonstrates how easy it is to connect your slot method to a vtkObject based event:

```
connections = vtkEventQtSlotConnect::New();

  // get right mouse pressed with high priority
  connections->Connect(qVTK1->GetRenderWindow()->GetInteractor(),
                       vtkCommand::RightButtonPressEvent,
                       this,SLOT(popup( vtkObject*, unsigned long,
                                        void*, void*, vtkCommand*)),
                       popup1, 1.0);
```

Coding Resources

This chapter provides information to make the job of building VTK applications and classes a little easier. Object diagrams are useful when you'd like an overview of the objects in the system; they are included here in symbolic form known as object modeling diagrams. The diagrams we use here are simplified to mainly show inheritance, but some associations between classes are shown as well. Succinct filter descriptions are provided to help you find the right filter to do the job at hand. This chapter also documents the VTK legacy and XML file formats.

19.1 Object Diagrams

The following section contains abbreviated object diagrams using the OMT graphical language. The purpose of this section is to convey the essence of the software structure, particularly inheritance and object associations. Due to space limitation, not all objects are shown, particularly "leaf" (i.e., bottom of the inheritance tree) objects. Instead, we choose a single leaf object to represent other sibling objects. (Object diagrams for all classes in VTK are provided in the online documentation.) The organization of the objects follows that of the synopsis.

Foundation

The foundation object diagram is shown in **Figure 19–1**. These represent the core data objects, as well as other object manipulation classes.

Cells

The cell object diagram is shown in **Figure 19–3**. Currently, 21 concrete cell types are supported in VTK. The special class vtkGenericCell is used to represent any type of cell (i.e., supports the thread-

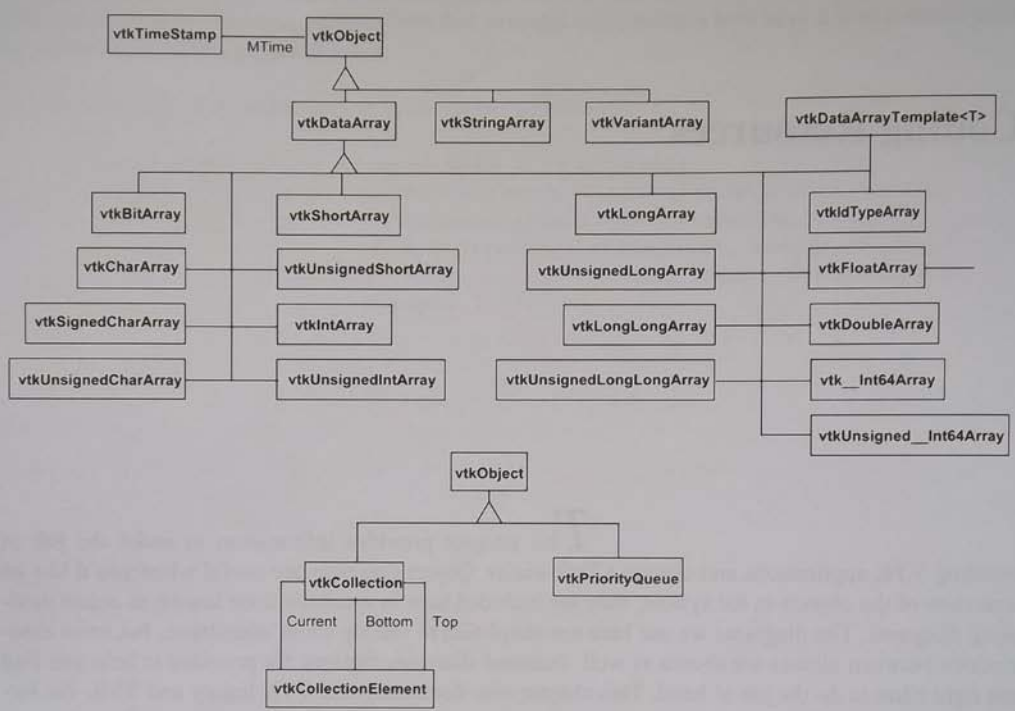


Figure 19–1 Foundation object diagram.

safe vtkDataSet::GetCell() method). The class vtkEmptyCell is used to indicate the presence of a deleted or NULL cell.

Datasets

The data object diagram is shown in **Figure 19–2**, and the dataset object diagram is shown in **Figure 19–4**. Currently, six concrete dataset types are supported. Unstructured point data can be represented

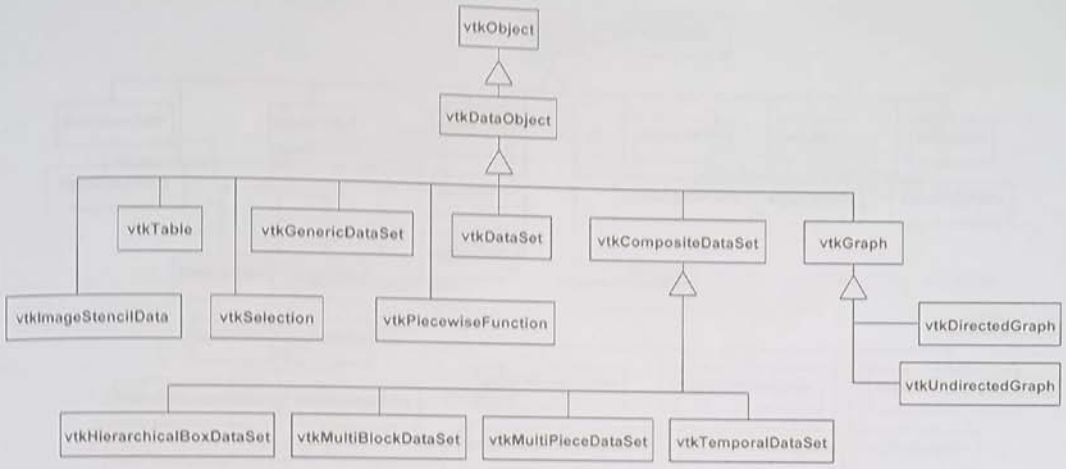


Figure 19–2 Data object diagram.

by any of the subclasses of vtkPointSet. vtkImageData used to be vtkStructuredPoints, and represents 2D image and 3D volume data.

Topology and Attribute Data

The object diagram for topology and attribute data objects is shown in **Figure 19–5**. These are the core objects to represent data.

Pipeline

The object diagram for the classes in VTK's pipeline architecture is shown in **Figure 19–6**. This includes executive and information objects.

Sources and Filters

The source and filter object diagram is shown in **Figure 19–7**.

Mappers

The mapper object diagram is shown in **Figure 19–8**. There are basically two types: graphics mappers that map visualization data to the graphics system and writers that write data to an output file (or other I/O device).

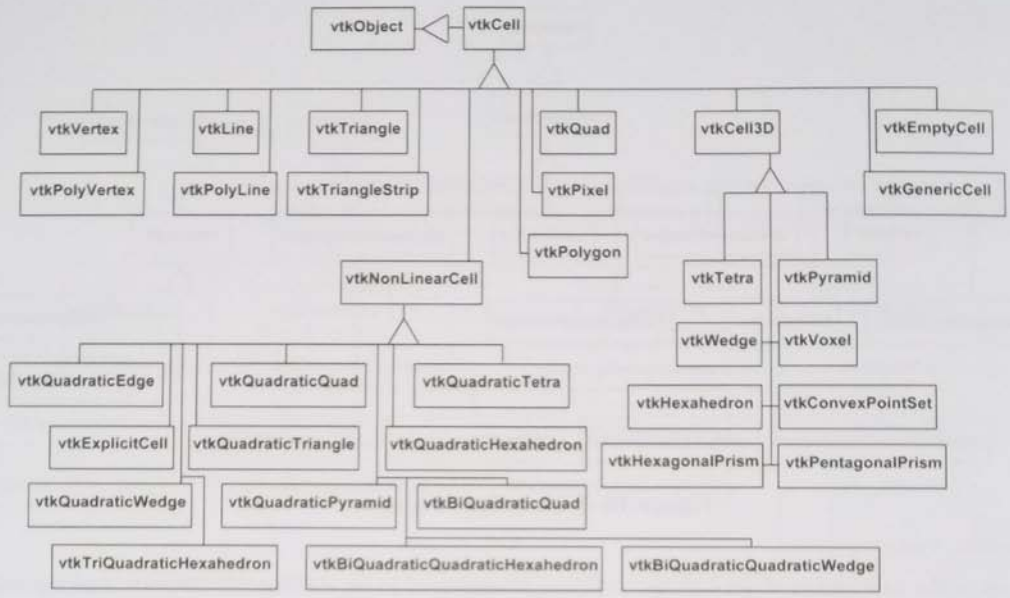


Figure 19–3 Cell object diagram.

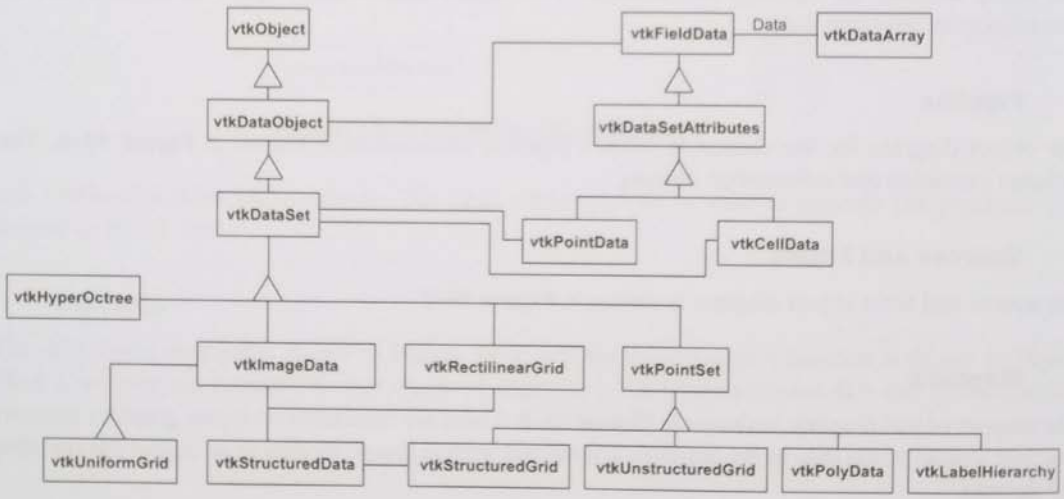


Figure 19–4 Dataset object diagram.

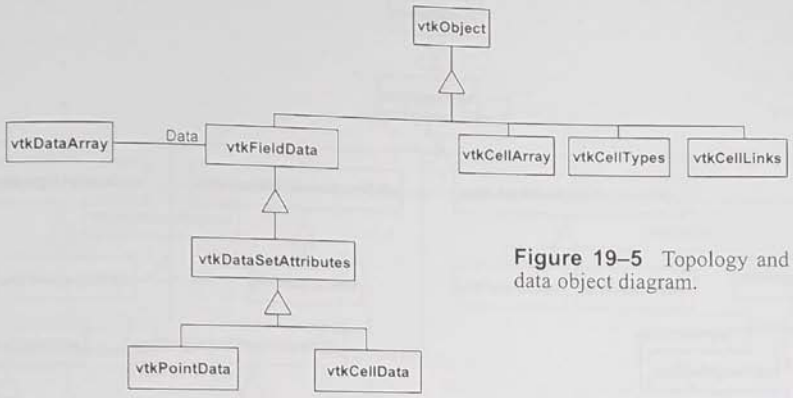


Figure 19–5 Topology and attribute data object diagram.

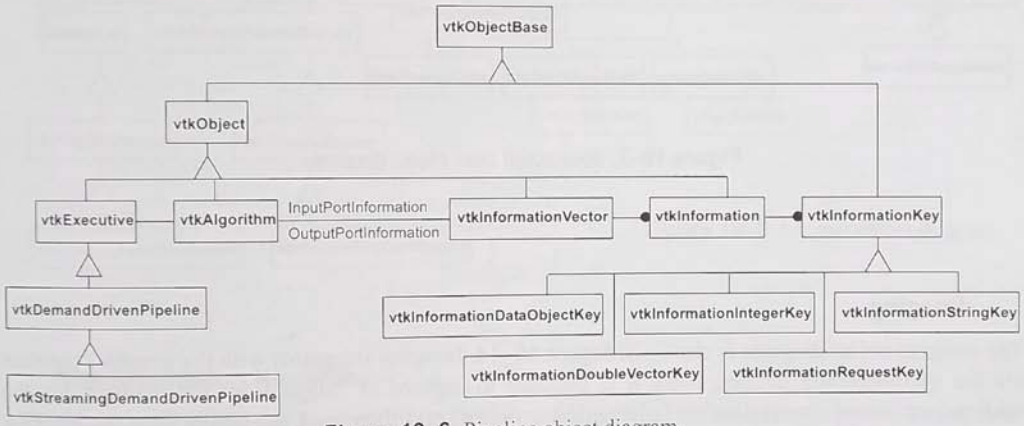


Figure 19–6 Pipeline object diagram.

Graphics

The graphics object diagram is shown in **Figure 19–10**. The diagram has been extended to include some associations with objects in the system. If you are unfamiliar with the object-oriented graphics notation see Rumbaugh et al., *Object-Oriented Modeling and Design*.

Volume Rendering

The volume rendering class hierarchy is shown in **Figure 19–11**. The hierarchy for structured volume rendering is shown in **Figure 19–12**, and the one for unstructured grid volume rendering is shown in **Figure 19–13**. Note that VTK's volume rendering process supports mixing volumes, surfaces, and annotation. Just make sure that the surface geometry is opaque.

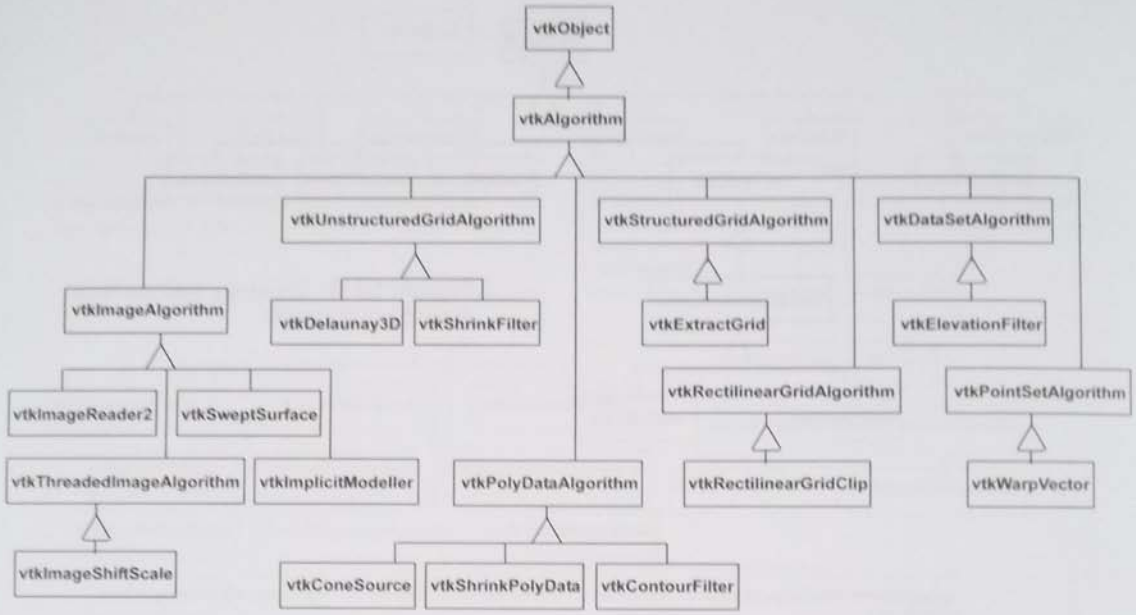


Figure 19–7 Source and filter object diagram.

Imaging

The imaging object diagram is shown in **Figure 19–14**. Imaging integrates with the graphics pipeline via the vtkImageData dataset. Also, it is possible to capture an image from the renderer via the vtkRendererSource or vtkWindowToImageFilter object, and then feed the image into the imaging pipeline.

OpenGL Renderer

The OpenGL renderer object diagram is shown in **Figure 19–15**. Note that there are other rendering libraries in VTK. The OpenGL object diagram is representative of these other libraries.

Picking

The picking class hierarchy is shown in **Figure 19–16**. vtkPropPicker and vtkWorldPointPicker are the fastest (hardware-based) pickers. All pickers can return a global x-y-z from a selection point in the render window. vtkCellPicker uses software ray casting to return information about cells (cell id, parametric coordinate of intersection). vtkPointPicker returns a point id. vtkPropPicker indicates which instance of vtkProp was picked as well as returning the pick coordinates.

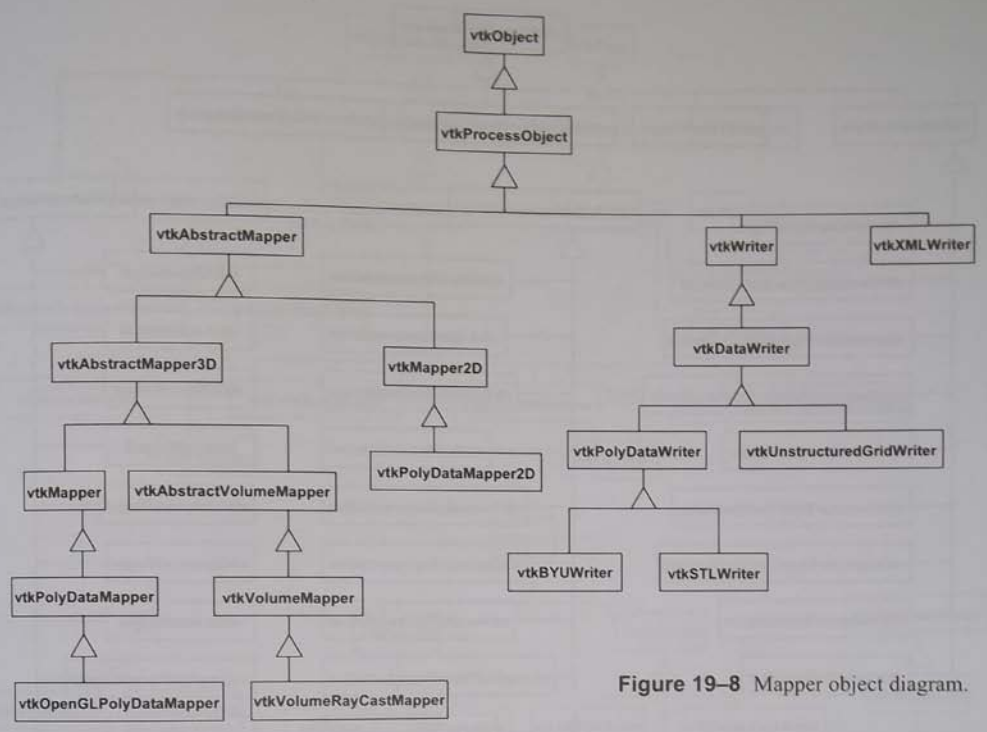


Figure 19–8 Mapper object diagram.

Transformation Hierarchy

VTK provides an extensive, powerful transformation hierarchy. This hierarchy supports linear, non-linear, affine, and homogeneous transformations. The transformation object diagram is shown in **Figure 19–17**.

Widgets and Interaction Style

VTK provides an extensive suite of interactive widgets and interaction styles. Widgets may appear in the scene as 2D or 3D props (known as representations) that respond to user interaction. Note that an interaction style is similar to a widget except that no representation is associated with an interactor

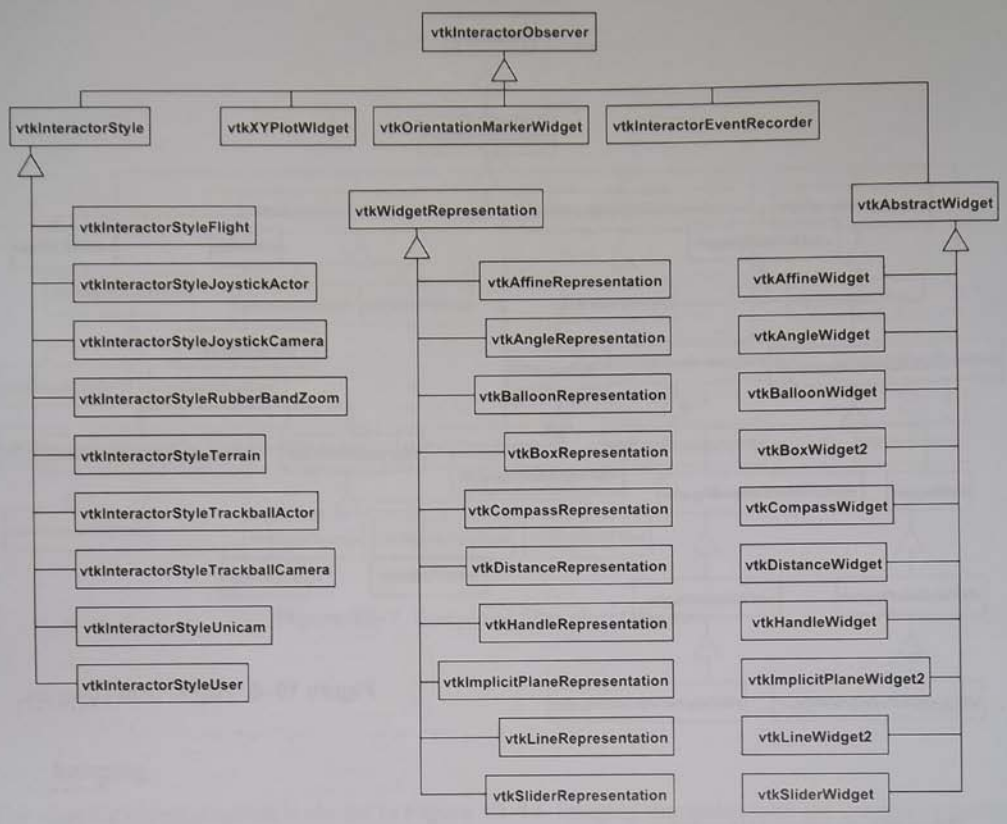


Figure 19–9 Widget and interaction style object diagram. Note that only a portion of the widgets and interactor styles are shown

(typically interactors are used to control cameras). The widget and interaction style object diagrams are shown in **Figure 19–9**.

19.2 Summary Of Filters

In this section we provide a brief summary of VTK filters. The section is divided into three parts: an overview of source objects, a list of imaging filters, and a description of visualization filters. Classes used to interface with data (i.e., readers, writers, importers, and exporters) are described in Chapter 12 "Reading and Writing Data" on page 239.

Source Objects

In this section we provide a brief description of source objects. Source objects initiate the visualization pipeline. Note that readers (source objects that read files) are not listed here. Instead, find them in

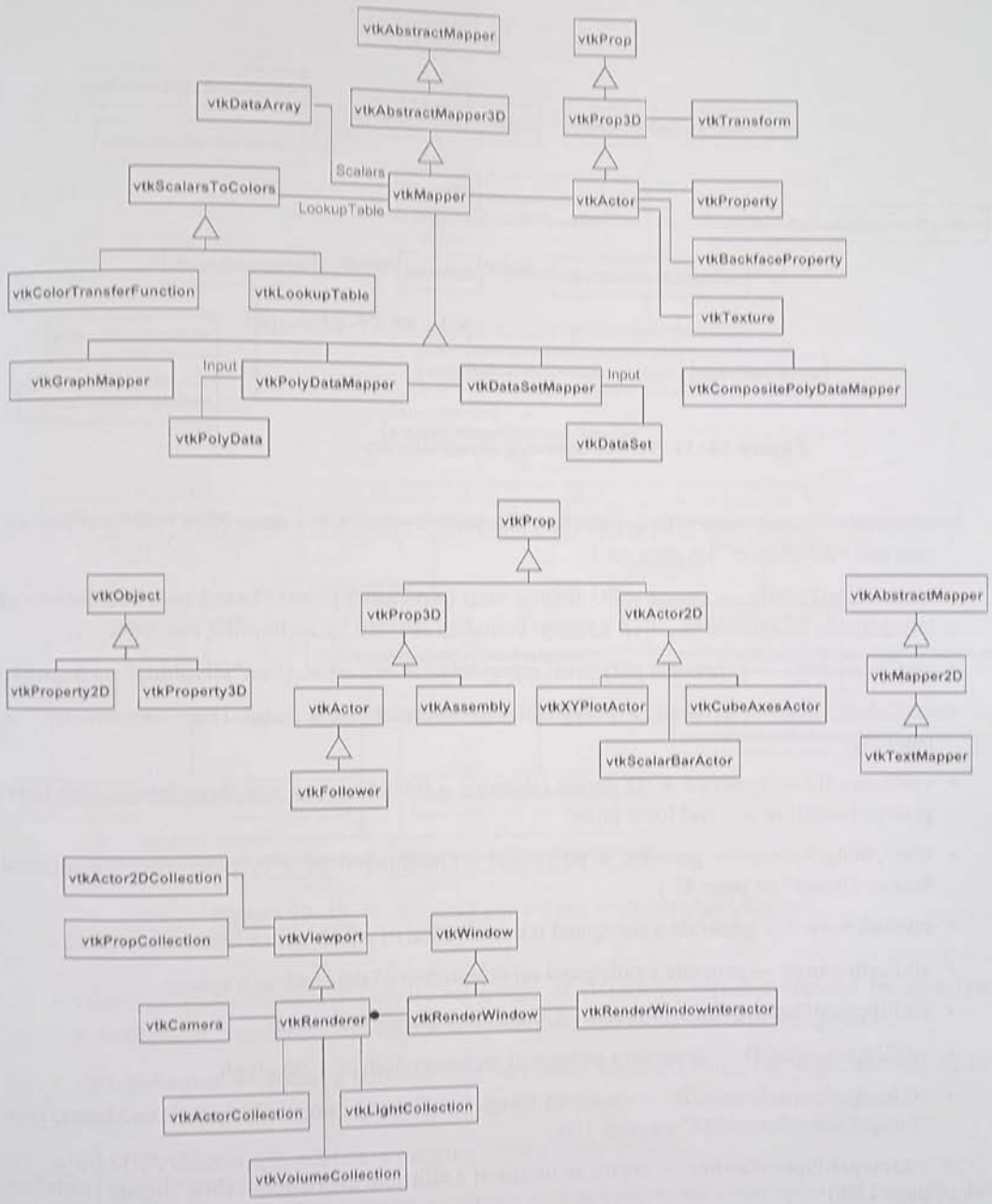


Figure 19–10 Graphics object diagram.

Chapter 12 "Reading and Writing Data" on page 239. Each entry includes a brief description including the type of output it generates.

- vtkArrowSource — generate a polygonal representation of an arrow.

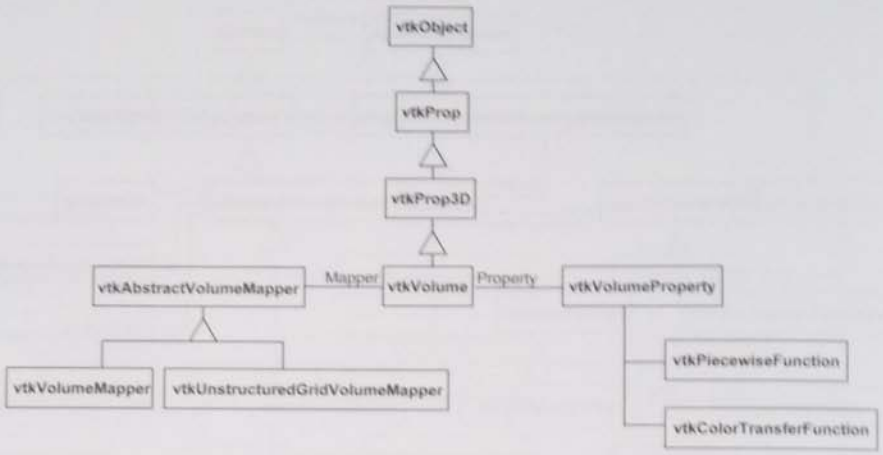


Figure 19–11 Volume rendering object diagram.

- vtkAxes — create three orthogonal lines that form a set of x-y-z axes. (See "3D Text Annotation and vtkFollower" on page 65.)
- vtkBooleanTexture — create a 2D texture map (structured points) based on combinations of being inside of, outside of, or on a region boundary defined by an implicit function.
- vtkConeSource — generate a polygonal representation of a cone. (See "Glyphing" on page 94.)
- vtkCubeSource — generate a polygonal representation of a cube. (See "Assemblies" on page 56.)
- vtkCursor3D — generate a 3D cursor (showing a bounding box and three intersecting lines) given a bounding box and focal point.
- vtkCylinderSource — generate a polygonal representation of a cylinder. (See "Procedural Source Object" on page 42.)
- vtkDiskSource — generate a polygonal representation of a disk with a hole in the center.
- vtkEarthSource — generate a polygonal representation of the earth as a sphere.
- vtkEllipticalButtonSource — create an ellipsoidal-shaped 3D button.
- vtkGlyphSource2D — generate a polygonal representation of a 2D glyph.
- vtkImageCanvasSource2D — create an image by drawing into it with primitive shapes. (See "ImageCanvasSource2D" on page 126.)
- vtkImageEllipsoidSource — create an image of a ellipsoid distribution. (See "Image Logic" on page 132.)
- vtkImageGaussianSource — create an image of a Gaussian distribution.
- vtkImageGridSource — create an image of an axis-aligned grid.
- vtkImageMandelbrotSource — create an image of the Mandelbrot set.
- vtkImageNoiseSource — create an image filled with random, uniform noise.

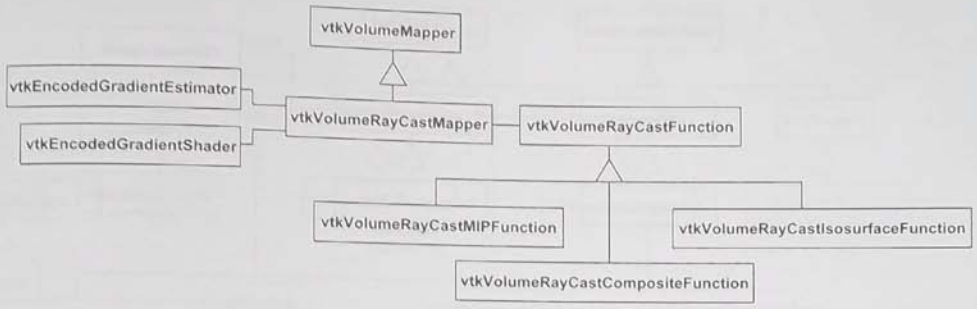


Figure 19–12 Structured volume rendering object diagram.

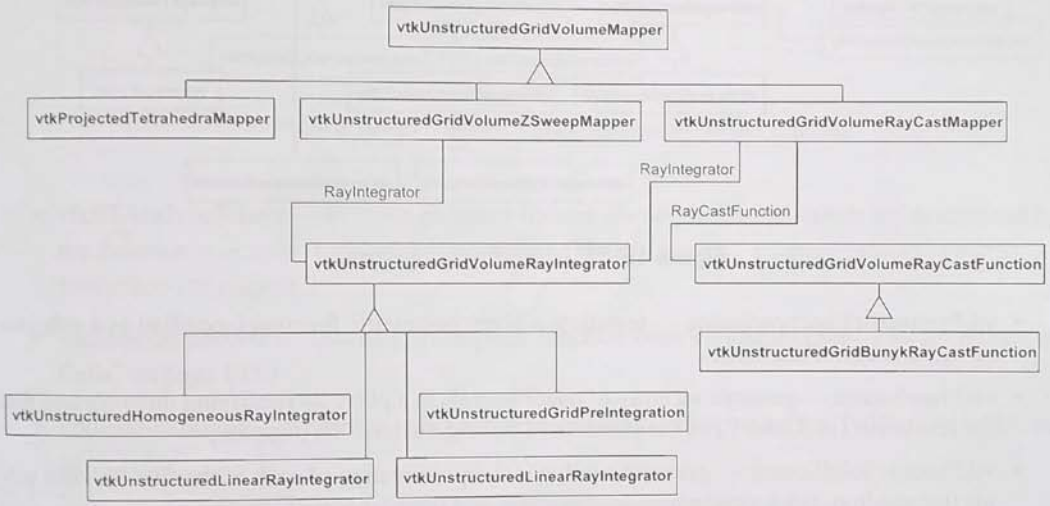


Figure 19–13 Unstructured grid volume rendering object diagram.

- vtkImageSinusoidSource — create an image of sinusoidal values computed by specifying period, phase, amplitude, and direction. (See "ImageSinusoidSource" on page 128.)
- vtkLineSource — create a polyline with *resolution* number of line segments, defined by two end points. (See "Stream Surfaces" on page 97.)
- vtkMILVideoSource — Matrox imaging library frame grabber.
- vtkOutlineCornerSource — create wireframe outline corners for a user-specified bounding box (similar to vtkOutlineCornerFilter, but explicitly specifying a bounding box instead of specifying an input dataset from which to determine a bounding box).
- vtkOutlineSource — generate a wireframe outline around a user-specified bounding box (similar to vtkOutlineFilter, but explicitly specifying a bounding box instead of specifying an input dataset from which to determine a bounding box).

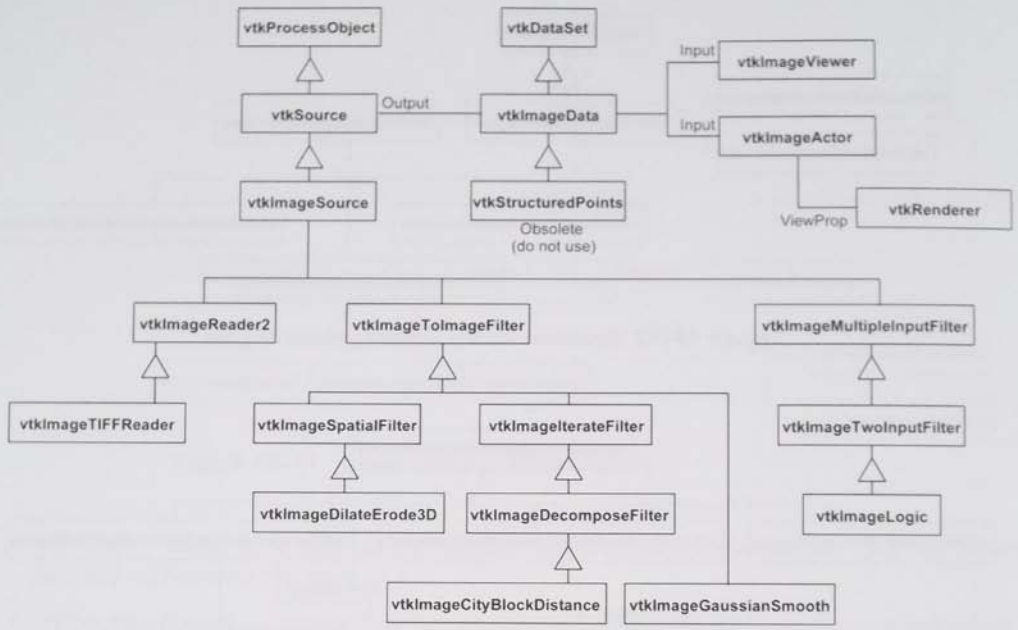


Figure 19–14 Imaging object diagram.

- vtkParametricFunctionSource — tessellate a given parametric function (specified as a subclass of vtkParametricFunction).
- vtkPlaneSource — generate an array of quadrilaterals in a plane by specifying three corners and the resolution (in X and Y) of the plane. (See "Using Texture" on page 58.)
- vtkPlatonicSolidSource — generate a polygonal representation of each of the five Platonic solids (tetrahedron, cube, octahedron, icosahedron, and dodecahedron).
- vtkPointLoad — generate a tensor field from a point load on a semi-infinite domain.
- vtkPointSource — generate a random cloud of points within a specified radius. (See "Streamlines" on page 95.)
- vtkProgrammableDataObjectSource — a filter that can be programmed at run-time to read or generate a vtkDataObject (i.e., a field). (See "Working With Field Data" on page 249.)
- vtkProgrammableSource — a filter that can be programmed at run-time to read or generate any type of vtkDataSet. (See "Surfaces from Unorganized Points" on page 224.)
- vtkPSphereSource — a subclass of vtkSphereSource that can handle a request for a piece of the data.
- vtkRectangularButtonSource — create a rectangular-shaped 3D button.
- vtkRegularPolygonSource — create a regular, n-sided polygon and/or a polyline. This is useful for seeding streamlines or defining regions for clipping/cutting.
- vtkRendererSource — an imaging filter that takes the renderer or render window into the imaging pipeline (great for screen capture).

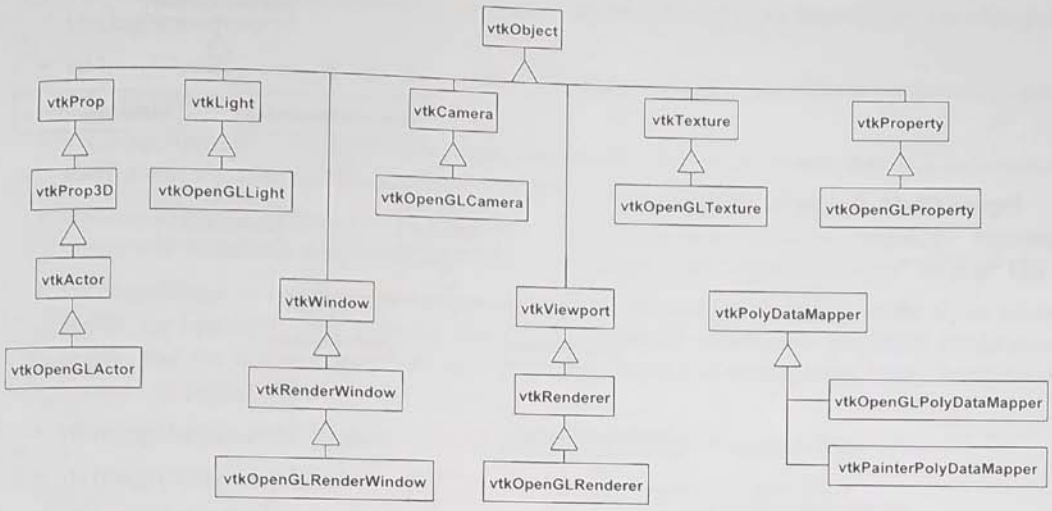


Figure 19–15 OpenGL / graphics interface object diagram.

- vtkRTAnalyticSource — produce an image dataset whose pixel/voxel values are determined by the function `Maximum*Gaussian + XMag*sin(XFreq*X) + YMag*sin(YFreq*Y) + ZMag*cos(ZFreq*Z)`.
- vtkSampleFunction — evaluate an implicit function over a volume. (See "Extract Subset of Cells" on page 103.)
- vtkSphereSource — generate a polygonal representation of a sphere. (See "vtkDelaunay2D" on page 218.)
- vtkSuperquadricSource — generates a polygonal representation of a superquadric.
- vtkTextSource — create a polygonal representation of input text.
- vtkTexturedSphereSource — create a polygonal representation of a sphere with associated texture coordinates.
- vtkTransformToGrid — sample a user-specified transform onto a 3D uniform grid.
- vtkTriangularTexture — generate a triangular 2D texture map.
- vtkVectorText — create a polygonal representation of text. (See "Transforming Data" on page 70.)
- vtkVideoSource — grabs video signals as an image.
- vtkWin32VideoSource — Video-for-Windows video digitizer.
- vtkWindowToImageFilter — capture the contents of a vtkWindow as input to image pipeline. (See "Saving Images" on page 247.)

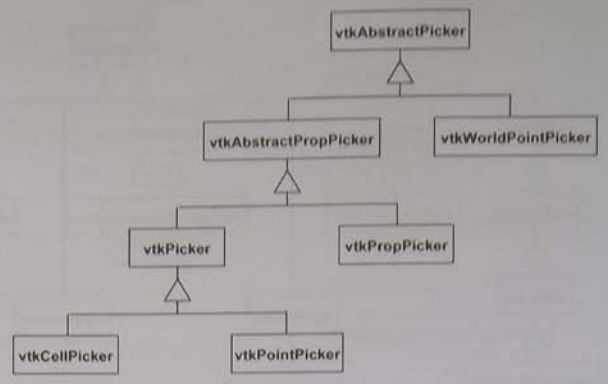


Figure 19–16 Picking object diagram.

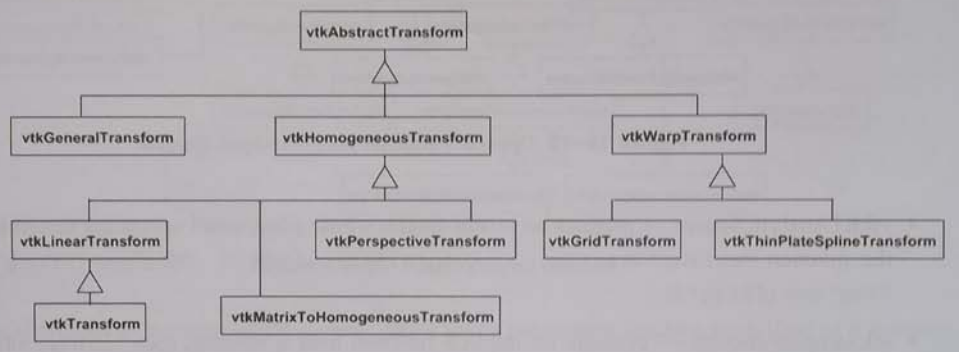


Figure 19–17 Transformation object diagram.

Imaging Filters

In this section we provide a brief summary of imaging filters. Note that descriptions of other visualization filters are found in "Visualization Filters" on page 455. Classes used to interface with data are described in Chapter 12 "Reading and Writing Data" on page 239.

All the filters described here take vtkImageData (or obsolete vtkStructuredPoints) as input, and typically produce the same type of output.

- vtkClipVolume — clip a volume with an implicit function to generate a tetrahedral mesh.
- vtkDiscreteMarchingCubes — a subclass of vtkMarchingCubes that (if computing scalars) will store the output scalar value as cell-centered data.
- vtkExtractVOI — extract a volume of interest (a subset of the volume) and/or subsample the volume. (See "Subsampling Image Data" on page 121.)
- vtkGreedyTerrainDecimation — approximates a height field with a triangle mesh (triangulated irregular network - TIN). (See "Gaussian Splatting" on page 222.)
- vtkImageAccumulate — generate a histogram of the input image. (See "Histogram" on page 132.)

- vtkImageAnisotropicDiffusion2D — iteratively apply a 2D diffusion filter to perform edge-preserving smoothing.
- vtkImageAnisotropicDiffusion3D — iteratively apply a 3D diffusion filter to perform edge-preserving smoothing.
- vtkImageAppend — merge multiple input images into one output image; they will be concatenated along a user-specified axis. (See "Append Images" on page 129.)
- vtkImageAppendComponents — merge the components from two input images; the resulting image will contain all the components from both images. (See "Append Images" on page 129.)
- vtkImageBlend — combine the components of multiple images according to the alpha values and/or the opacity setting for each input; the number of components per input image must match, and the output image will also have this number of components. (See "ImageGridSource" on page 127.)
- vtkImageButterworthHighPass — apply a frequency-domain high pass filter.
- vtkImageButterworthLowPass — apply a frequency-domain low pass filter.
- vtkImageCacheFilter — cache (store) images for future use to avoid pipeline re-execution.
- vtkImageCast — change the scalar type of an image by casting from the input scalar type to a user-specified output scalar type. (See "Convert Scalar Type" on page 128.)
- vtkImageChangeInformation — modify the spacing, origin, or extent of the data without changing the data itself. (See "Change Spacing, Origin, or Extent" on page 129.)
- vtkImageCheckerboard — show two images at once using a checkerboard pattern.
- vtkImageCityBlockDistance — create a distance map (distance to the nearest 0-valued pixel/voxel) using the city block (or Manhattan) metric (i.e., stepping along pixel/voxel edges, never through the middle of a cell).
- vtkImageClip — reduce the size (extent) of the input image. (See "Subsampling Image Data" on page 121.)
- vtkImageConstantPad — change the extent of the image, setting any pixels outside the original extent to a constant user-specified value.
- vtkImageContinuousDilate3D — evaluate the maximum value in an ellipsoidal neighborhood.
- vtkImageContinuousErode3D — evaluate the minimum value in an ellipsoidal neighborhood.
- vtkImageConvolve — convolution of an image with a kernel.
- vtkImageCorrelation — create a correlation image for two input images.
- vtkImageCursor3D — add a cursor to the input image, modifying the pixels/voxels covered by the cursor.
- vtkImageDataGeometryFilter — extract geometry (points, lines, planes) as vtkPolyData. (See "Warp Based On Scalar Values" on page 122.)
- vtkImageDataStreamer — initiate streaming for image data; to satisfy a request for data, this filter calls Update() on its input many times, each time requesting a different piece of the data. This is helpful when operating on large data that cannot be stored in memory with all the additional information required by a filter operating on this image/volume data. (See "ImageNoiseSource" on page 127.)

- vtkImageDifference — generate a difference image / error value for two images.
- vtkImageDilateErode3D — increase the size of regions with one scalar value while decreasing the size of regions with another scalar value along the boundary between the two.
- vtkImageDivergence — create a scalar field that represents the rate of change of the input vector field.
- vtkImageDotProduct — create a dot product image from two vector images.
- vtkImageEuclideanDistance — create a distance map (i.e., distance to the nearest 0-valued pixel/voxel) 3D Euclidean distance (i.e., straight-line distance).
- vtkImageEuclideanToPolar — convert 2D Euclidean coordinates to polar coordinates.
- vtkImageExport — pass the data in a vtkImageData to a C programming language array, providing applications with direct access to the image data in memory. This is the reverse of vtkImageImport.
- vtkImageExtractComponents — extract a subset of the components of the input image.
- vtkImageFFT — perform a Fast Fourier Transform (i.e., transform from the spatial to the frequency domain).
- vtkImageFlip — flip an image about a specified axis (i.e., right becomes left, etc.). (See "Image Flip" on page 134.)
- vtkImageFourierCenter — shift the zero frequency from the origin to the center.
- vtkImageGaussianSmooth — perform 1D, 2D, or 3D Gaussian convolution to smooth the input image. (See "Gaussian Smoothing" on page 133.)
- vtkImageGradient — compute the gradient vector in 2D or 3D at each point of an image; the vector results are stored in the output image as scalar components. (See "Gradient" on page 133.)
- vtkImageGradientMagnitude — similar to vtkImageGradient, but the magnitude of the gradient vector at each point in the image is stored in the output image. (See "Gradient" on page 133.)
- vtkImageHSIToRGB — convert images stored using the HSI (hue, saturation, intensity) color model to the RGB (red, green, blue) one.
- vtkImageHSVToRGB — convert images stored using the HSV (hue, saturation, value) color model to the RGB (red, green, blue) one.
- vtkImageHybridMedian2D — perform a median (middle value) filter while preserving lines / corners.
- vtkImageIdealHighPass — perform a simple frequency domain high pass filter.
- vtkImageIdealLowPass — perform a simple frequency domain low pass filter.
- vtkImageImport — create a vtkImageData from data in a C programming language array. This is the reverse of vtkImageExport.
- vtkImageIslandRemoval2D — remove small clusters with a specified value from the image.
- vtkImageLaplacian — compute the Laplacian (divergence of the gradient).
- vtkImageLogarithmicScale — perform a log function on each pixel.

- vtkImageLogic — perform a logic operation: AND, OR, XOR, NAND, NOR, NOT; the first four operations require two input images; the last two only require one. (See "Image Logic" on page 132.)
- vtkImageLuminance — calculate luminance of an RGB image (luminance = 0.3*R + 0.59*G + 0.11*B). (See "Image Luminance" on page 132.)
- vtkImageMagnify — increase the size of the image by an integer scale factor.
- vtkImageMagnitude — compute a magnitude image from the scalar components of an input image. (See "Gradient" on page 133.)
- vtkImageMapToColors — map a single-component image through a lookup table. (See "Map Image to Color" on page 131.)
- vtkImageMapToWindowLevelColors — map the single-component input image through a lookup table and window / level it (i.e., modulate the color from the lookup table based on (S - (L - W/2)) / W, where S is the scalar value, L is the level value, and W is the window value). This allows you to highlight scalars in a specified range. (See "Map Image to Color" on page 131.)
- vtkImageMarchingCubes — a streaming version of marching cubes.
- vtkImageMask — Combine a mask image with an input image. If a mask pixel is non-zero, the output pixel is unchanged from the input; if a mask pixel is zero, the input pixel is et to a user-specified "masked value".
- vtkImageMaskBits — specify four unsigned int values, and use them to compute bitwise logical operations on each component of each input pixel (one unsigned int value per component).
- vtkImageMathematics — apply basic mathematical operations to one or two images. (See "Image Mathematics" on page 135.)
- vtkImageMedian3D — compute a median (middle value) filter in a rectangular neighborhood.
- vtkImageMirrorPad — change the extent of the image; mirror the original image at its boundaries to fill pixels outside the original extent.
- vtkImageNonMaximumSuppression — set non-maximum (i.e., not a peak) pixel values to 0.
- vtkImageNormalize — normalize the vector defined by the scalar components of an image.
- vtkImageOpenClose3D — perform opening or closing (image morphology operations) using two dilate / erode operations.
- vtkImagePermute — reorder the axes of an image; use SetFilteredAxes() to specify how the X, Y, and Z axes should be relabelled. (See "Image Permute" on page 134.)
- vtkImageQuantizeRGBToIndex — from an RGB (red, green, blue) image, create an index image and a lookup table. The indices in the output image, when passed through the lookup table, return the corresponding RGB values of the input image. This filter does not support streaming because it must operate on the entire image.
- vtkImageRange3D — compute the range (max - min) in an ellipsoidal neighborhood.
- vtkImageRectilinearWipe — make a rectilinear combination of two images.
- vtkImageResample — resample an image to increase or decrease its size. (See "Speed vs. Accuracy Trade-offs" on page 159.)

- vtkImageReslice — permute, rotate, flip, scale, resample, deform, and/or pad image data in any combination with reasonably high efficiency. (See "Image Reslice" on page 137.)
- vtkImageRFFT — perform a Reverse Fast Fourier Transform (i.e., transform from the frequency to the spatial domain).
- vtkImageRGBToHSI — convert images stored using the RGB (red, green, blue) color model to the HSI (hue, saturation, intensity) one.
- vtkImageRGBToHSV — convert images stored using the RGB (red, green, blue) color model to the HSV (hue, saturation, value) one.
- vtkImageSeedConnectivity — label the regions connected to user-specified seeds by pixel/voxels with a specified value.
- vtkImageSeparableConvolution — compute three, 1D convolutions on an image (one along each of the X, Y, and Z axes).
- vtkImageShiftScale — Shift the scalar values of the input image by a specified amount, and then multiply them by the specified scale value. (See "Convert Scalar Type" on page 128.)
- vtkImageShrink3D — shrink (reduce the extent of) an image by subsampling on a uniform grid.
- vtkImageSkeleton2D — perform a skeleton operation in 2D.
- vtkImageSobel2D — compute the vector field of an image showing the gradient of the intensity at each pixel using Sobel functions.
- vtkImageSobel3D — compute the vector field of a volume showing the gradient of the intensity at each voxel using Sobel functions.
- vtkImageStencil — combine images via a cookie-cutter operation.
- vtkImageToImageStencil — converts vtkImageData into an image that can be used with vtkImageStencil or other VTK classes that apply a stencil to an image.
- vtkImageToPolyDataFilter — convert an image to polygons.
- vtkImageThreshold — perform binary or continuous thresholding, replacing scalar values that do or do not meet the thresholding criteria with user-specified values.
- vtkImageTranslateExtent — shift the whole extent, but does not change the data, similar to vtkImageChangeInformation.
- vtkImageVariance3D — compute an approximation of the variance within an ellipsoidal neighborhood (i.e., the average of the difference squared between each pixel/voxel in the neighborhood and the center pixel/voxel value).
- vtkImageWrapPad — pad an image using a mod operation on the pixel index so that the original image is tiled across the new image.
- vtkLinkEdgels — link edgels together to form digital curves.
- vtkMarchingCubes — high-performance isocontouring algorithm. (See "Working With Data Attributes" on page 89.)
- vtkMarchingSquares — high-performance isocontouring algorithm in 2D.
- vtkMemoryLimitImageDataStreamer — a subclass of vtkImageDataStreamer that determines the number of pieces to use for streaming based on a user-specified memory limit.
- vtkRecursiveDividingCubes — generate an isocontour as a cloud of points.

- vtkSimpleImageFilterExample — just copies the input image to the output; provided as a simple example of an imaging filter. Its superclass, vtkSimpleImageToImageFilter hides much of the complexity of vtkImageAlgorithm. (See "A Simple Imaging Filter" on page 399.)
- vtkSynchronizedTemplates2D — high-performance isocontouring algorithm in 2D.
- vtkSynchronizedTemplates3D — high-performance isocontouring algorithm in 3D.
- vtkSynchronizedTemplatesCutter3D — generate a cut surface (by specifying a cut function) from an image/volume dataset.

Visualization Filters

The classes listed below are organized to the type of data they input. Each class contains a brief description of what it does and any special notations regarding multiple inputs or outputs.

Input Type vtkDataSet. These filters will process any type of dataset (that is, subclasses of vtkDataSet).

- vtkAppendFilter — appends one or more datasets into a single unstructured grid. (See "Appending Data" on page 100.)
- vtkArrayCalculator — perform mathematical operations on data in field data arrays.
- vtkAssignAttribute — label a data array as an attribute (scalars, vectors, etc.). (See "Working With Field Data" on page 249.)
- vtkAttributeDataToFieldDataFilter — transform attribute data (either point or cell) into field data.
- vtkBoxClipDataSet — generate an unstructured grid dataset consisting only of the cells (and pieces of cells) contained in a user-specified box.
- vtkBrownianPoints — assign random vectors to points.
- vtkCastToConcrete — cast an abstract type of input (e.g., vtkDataSet) to a concrete form (e.g., vtkPolyData). (See "Extract Portions of the Mesh" on page 115.)
- vtkCellCenters — generate points (vtkPolyData) marking cell centers. (See "Labeling Data" on page 68.)
- vtkCellDataToPointData — convert cell data to point data. (See "Working With Data Attributes" on page 89.)
- vtkCellDerivatives — compute derivatives of scalar and vectors.
- vtkClipDataSet — cut through the cells of arbitrary vtkDataSets, returning everything contained within a user-specified implicit function (or having a scalar value greater than the one specified).
- vtkConnectivityFilter — extract geometrically connected cells into an unstructured grid. (See "Extract Cells as Polygonal Data" on page 104.)
- vtkContourFilter — generate isosurface(s). (See "Contouring" on page 93.)
- vtkCutMaterial — computes cut plane for a (material, array) pair.
- vtkCutter — generate an n-1 dimensional cut surface from an n-dimensional dataset. (See "Cutting" on page 98.)

- vtkDashedStreamLine — generate a streamline with dashes representing elapsed time. (Although this is a subclass of vtkStreamer, vtkStreamTracer does not duplicate its functionality.)
- vtkDataSetSurfaceFilter — extract surface geometry from a dataset (faster version of vtkGeometryFilter, but with less options).
- vtkDataSetToDataObjectFilter — converts a dataset into a general data object.
- vtkDataSetTriangleFilter — triangulate any type of dataset.
- vtkDicer — abstract superclass for generating data values based on spatial (or other) segregation.
- vtkDistributedDataFilter — redistribute data among processors in a parallel application into spatially contiguous unstructured grid datasets. This filter is sometimes referred to as "D3" for "distributed data decomposition".
- vtkDistributedStreamTracer — generates streamlines by integrating a vector field for a dataset distributed across processors.
- vtkEdgePoints — generate points along cell edges that intersect an isosurface.
- vtkElevationFilter — generate scalars according to projection along a vector. (See "An Abstract Filter" on page 412.)
- vtkExtractEdges — extract the cell edges of a dataset as lines. (See "vtkDelaunay2D" on page 218.)
- vtkExtractGeometry — extract cells that lie either entirely inside or outside of an implicit function. (See "Extract Subset of Cells" on page 103.)
- vtkExtractTensorComponents — extract the components of a tensor as scalars, vectors, normals, or texture coordinates.
- vtkExtractVectorComponents — extract components of vector as separate scalars.
- vtkFieldDataToAttributeDataFilter — convert general field data into point or cell attribute data.
- vtkGaussianSplatter — generate a scalar field in a volume by splatting points (injecting points into a volume, distributing values to nearby voxels) with an elliptical, Gaussian distribution. (See "Gaussian Splatting" on page 222.)
- vtkGeometryFilter — extract surface geometry from a dataset, and store the output as vtkPolyData. (See "Extract Cells as Polygonal Data" on page 104.)
- vtkGlyph2D — a 2D specialization of vtkGlyph3D. Translation, rotation, and scaling of the glyphs is constrained to the x-y plane.
- vtkGlyph3D — copy a polygonal glyph (second input to the filter defines the glyph) to every point in the (first) input. (See "Glyphing" on page 94.)
- vtkHedgeHog — generate scaled and oriented lines at each point from the associated vector field (basically a specialization of vtkGlyph3D).
- vtkHyperStreamline — use tensor data to generate a streamtube; the tube cross section is warped according to eigenvectors.
- vtkIdFilter — generate scalars or field data from integer point or cells id values (useful for plotting). (See "Labeling Data" on page 68.)

- vtkImplicitModeller — generate a distance field by computing the distance from the input geometry to the points of an image/volume dataset. (See "Creating An Implicit Model" on page 213.)
- vtkImplicitTextureCoords — create texture coordinates based on an implicit function.
- vtkInterpolateDataSetAttributes — interpolate point- and cell-centered attribute data (scalars, vectors, etc.) between two datasets (useful for animation).
- vtkMarchingContourFilter — generate isosurfaces/isolines from scalar values. This filter calls vtkMarchingSquares, vtkMarchingCubes, vtkImageMarchingCubes, or vtkContourFilter (depending on the type of the input dataset) to perform the contouring.
- vtkMaskFields — allow control of which fields are passed to the output.
- vtkMaskPoints — select a subset of input points. This filter is often used in conjunction with vtkGlyph3D to limit the number of glyphs produced. (See "Glyphing" on page 94.)
- vtkMergeDataObjectFilter — merge a data object and dataset to form a new dataset (useful for combining data stored separately as geometry and solution files).
- vtkMergeFields — merge components from multiple arrays (all in one of cell data, point data, or general field data) to form a new array.
- vtkMergeFilter — merge components of data (e.g., geometry, scalars, vectors, etc.) from different datasets into a single dataset. (See "Merging Data" on page 99.)
- vtkMeshQuality — calculate the geometric quality of tetrahedral meshes.
- vtkOBBDicer — divide a dataset into pieces using oriented bounding boxes.
- vtkOutlineCornerFilter — create wireframe outline corners for arbitrary input dataset (similar to vtkOutlineCornerSource, but using the bounding box of the dataset).
- vtkOutlineFilter — create a wireframe outline around the input dataset (similar to vtkOutlineSource, but using the bounding box of the dataset). (See "Probing" on page 100.)
- vtkPassThroughFilter — filter which shallow copies its input to its output.
- vtkPCellDataToPointData — a subclass of vtkCellDataToPointData that can operate on pieces of the data and produce piece-invariant results.
- vtkPointDataToCellData — convert point data to cell data. (See "Working With Data Attributes" on page 89.)
- vtkPOutlineCornerFilter — performs the functionality of vtkOutlineCornerFilter on polygonal data distributed across processes. It ensures that the outline corners are drawn around the corners of the bounding box of the whole dataset, not around the corners of the bounding box for each piece of the data.
- vtkPProbeFilter — a parallel version of vtkProbeFilter.
- vtkProbeFilter — probe, or resample, one dataset with another. (See "Probing" on page 100.)
- vtkProcessIdScalars — store in a point or cell scalar array the process id of the process containing this portion of the data. This is useful for visually displaying the partitioning of data across processors.
- vtkProgrammableAttributeDataFilter — a run-time programmable filter that operates on data attributes.

- vtkProgrammableFilter — a run-time programmable filter. (See "Programmable Filters" on page 419.)
- vtkProgrammableGlyphFilter — a run-time programmable filter that can generate glyphs that vary arbitrarily based on data value.
- vtkProjectedTexture — generate texture coordinates projected onto an arbitrary surface.
- vtkRearrangeFields — move and/or copy data arrays (fields) between general field data, point data, and cell data. (See "Working With Field Data" on page 249.)
- vtkReflectionFilter — reflects a dataset across a plane.
- vtkSelectVisiblePoints — select the subset of points that are visible; hidden points are culled (not passed to the output). (See "Labeling Data" on page 68.)
- vtkShepardMethod — resample a set of points into a volume.
- vtkShrinkFilter — shrink the cells of a dataset by moving the vertices of each cell toward that cell's centroid (average position of the vertices); this causes the cells to break apart from one another. (See "Extract Subset of Cells" on page 103.)
- vtkSimpleElevationFilter — generate scalars from dot product of points with user-specified vector.
- vtkSpatialRepresentationFilter — create a polygonal representation of a spatial search (i.e., locator) object.
- vtkSplitField — Split a multi-component field (data array) into multiple single-component fields.
- vtkStreamer — abstract superclass performs vector field particle integration. Deprecated; use vtkStreamTracer and its subclasses instead.
- vtkStreamLine — generate a streamline from a vector field. Deprecated; use vtkStreamTracer and its subclasses instead.
- vtkStreamPoints — generate a set of points along a streamline from a vector field. Deprecated; use vtkStreamTracer and its subclasses instead.
- vtkStreamTracer — generates streamlines by integrating a vector field. (See "Streamlines" on page 95.)
- vtkSurfaceReconstructionFilter — constructs a surface from unorganized points. (See "Surfaces from Unorganized Points" on page 224.)
- vtkTensorGlyph — generate glyphs based on tensor eigenvalues and eigenvectors.
- vtkTextureMapToCylinder — generate 2-D texture coordinates by projecting data onto a cylinder. (See "Generate Texture Coordinates" on page 111.)
- vtkTextureMapToPlane — generate 2-D texture coordinates by projecting data onto a plane.
- vtkTextureMapToSphere — generate 2-D texture coordinates by projecting data onto a sphere.
- vtkThreshold — extract cells whose scalar values lie below, above, or between a threshold range. (See "Working With Data Attributes" on page 89.)
- vtkThresholdPoints — extract points whose scalar values lie below, above, or between a threshold range.

- vtkThresholdTextureCoords — compute texture coordinates based on satisfying a threshold criterion.
- vtkTransformTextureCoords — transform (e.g., scale, shift, etc.) texture coordinates. (See "Generate Texture Coordinates" on page 111.)
- vtkVectorDot — store a scalar per point computed from the dot product between the vector and normal at that point.
- vtkVectorNorm — compute scalars from the Euclidean norm of vectors.
- vtkVoxelModeller — convert an arbitrary dataset into a voxel (image/volume) representation. This filter is similar to vtkImplicitModeller, but it stores occupancy instead of distance.

Input Type vtkPointSet. These filters will process datasets that are a subclass of vtkPointSet. (These classes explicitly represent their points with an instance of vtkPoints.)

- vtkDelaunay2D — create constrained and unconstrained Delaunay triangulations including alpha shapes. (See "vtkDelaunay2D" on page 218.)
- vtkDelaunay3D — create 3D Delaunay triangulation including alpha shapes. (See "vtkDelaunay3D" on page 221.)
- vtkExtractDataOverTime — extract point data from a time sequence for a specified point id.
- vtkPCAAnalysisFilter — performs principal component analysis of a set of aligned pointsets.
- vtkProcrustesAlignmentFilter — aligns a set of pointset datasets together in a least squares sense to their mutual mean.
- vtkTransformFilter — reposition the points in a vtkPointSet using a 4x4 transformation matrix. (See "Transforming Data" on page 70.)
- vtkWarpLens — transform points according to lens distortion.
- vtkWarpScalar — modify point coordinates by scaling according to scalar values. (See "Warp Based On Scalar Values" on page 122.)
- vtkWarpTo — modify point coordinates by warping towards a point.
- vtkWarpVector — modify point coordinates by scaling in the direction of the point vectors.
- vtkWeightedTransformFilter — transform based on per-point or per-cell weighting functions.

Input Type vtkPolyData. The input type must be vtkPolyData. Remember that filters that accept vtkDataSet and vtkPointSet will also process vtkPolyData.

- vtkAppendPolyData — collect one or more vtkPolyData datasets into a single vtkPolyData. (See "Appending Data" on page 100.)
- vtkApproximatingSubdivisionFilter — a superclass for classes that subdivide the cells of a polygonal surface using an approximating scheme.
- vtkArcPlotter — plot data along an arbitrary polyline.
- vtkBandedPolyDataContourFilter — generate filled contours (bands of cells that all have the same cell scalar value).

- vtkButterflySubdivisionFilter — subdivide a triangular, polygonal surface using a butterfly subdivision scheme; four new triangles are created for each triangle of the polygonal surface.
- vtkCleanPolyData — merge coincident points, remove degenerate primitives.
- vtkClipPolyData — clip a polygonal dataset with an implicit function (or scalar value), returning all the cells within the implicit function (or greater than the scalar value). (See "Clip Data" on page 110.)
- vtkCollectPolyData — when performing distributed processing of the dataset, collect the distributed polygonal datasets to the 0th process.
- vtkCurvatures — compute the curvature (Gauss and mean) of a vtkPolyData object at each point in the dataset.
- vtkDecimatePro — reduce the number of triangles in a triangle mesh. (See "Decimation" on page 107.)
- vtkDepthSortPolyData — Sort polygons based on depth (distance from the camera); used for translucent rendering. (See "Actor Transparency" on page 55.)
- vtkDuplicatePolyData — when using a distributed tiled display, put an entire copy of the dataset on every process. The filter is used at the end of a pipeline for driving a tiled display.
- vtkExtractPolyDataGeometry — extract polygonal cells that lie entirely inside or outside of an implicit function. This is very similar to the functionality of vtkClipPolyData.
- vtkExtractPolyDataPiece — extract a piece of a polygonal dataset as requested by a downstream filter or mapper.
- vtkFeatureEdges — extract edges of cells in a polygonal dataset that meet certain conditions (feature, boundary, manifold, non-manifold edges).
- vtkGraphLayoutFilter — distribute an undirected graph network into pleasing arrangement.
- vtkHull — generate a convex hull of a polygonal dataset using six or more independent planes to bound the dataset.
- vtkLinearExtrusionFilter — generate polygonal data by sweeping a vtkPolyData according to a specified straight-line extrusion function. (See "Extrusion" on page 217.)
- vtkLinearSubdivisionFilter — subdivide a triangular, polygonal surface using a linear subdivision scheme; four new triangles are created for each triangle of the polygonal surface.
- vtkLoopSubdivisionFilter — subdivide a triangular, polygonal surface using Loop's subdivision scheme (described in *Loop, C., "Smooth Subdivision surfaces based on triangles.", Masters Thesis, University of Utah, August 1987*).
- vtkMaskPolyData — create a new vtkPolyData by selecting every n^{th} cell of the input vtkPolyData; n is user-specified.
- vtkPLinearExtrusionFilter — a subclass of vtkLinearExtrusionFilter that can produce piece-invariant results.
- vtkPolyDataConnectivityFilter — extract geometrically connected regions of the dataset. (See "Extract Portions of the Mesh" on page 115.)
- vtkPolyDataNormals — generate surface normal vectors (i.e., vectors perpendicular to the geometric surface) at each point in the dataset. (See "Generate Surface Normals" on page 107.)

- vtkPolyDataStreamer — request pieces one-by-one from the input (upstream filters), and append the resulting polygonal data (using vtkAppendPolyData) to form a single output dataset.
- vtkPolyDataToImageStencil — converts vtkPolyData into an image that can be used with vtkImageStencil or other VTK classes that apply a stencil to an image.
- vtkPPolyDataNormals — a subclass of vtkPolyDataNormals that can produce piece-invariant results.
- vtkProjectedTerrainPath — project an input polyline onto a terrain image (a 2D vtkImageData whose scalars are height data).
- vtkQuadricClustering — a decimation algorithm (using spatial binning) for very large datasets. (See "Decimation" on page 107)
- vtkQuadricDecimation — a decimation algorithm using the quadric error measure. (See "Decimation" on page 107.)
- vtkQuantizePolyDataPoints — quantizes *x-y-z* coordinates of points (i.e., converts the coordinates to integer-valued coordinates) in addition to inherited functionality of vtkCleanPolyData.
- vtkReverseSense — reverse the connectivity order of points in a cell and/or the direction of surface normals. (See "Surfaces from Unorganized Points" on page 224.)
- vtkRibbonFilter — create oriented ribbons from lines in a polygonal dataset.
- vtkRotationalExtrusionFilter — generate polygonal data by sweeping a vtkPolyData according to a specified rotational path. (See "Extrusion" on page 217.)
- vtkRuledSurfaceFilter — construct a polygonal surface from two or more "parallel" lines. This filter is typically used to create stream surfaces from a rake of streamlines. (See "Stream Surfaces" on page 97.)
- vtkSelectPolyData — select polygonal data by drawing a loop (i.e., creating a list of x-y-z point coordinates). The polygonal output is either the cells contained within the loop or unchanged geometry with a new scalar array indicating the selected points.
- vtkShrinkPolyData — shrink polygonal data by moving the points of each cell towards the cell's centroid, causing the polygonal cells to disconnect from one another.
- vtkSmoothPolyDataFilter — use Laplacian smoothing to "relax" the polygonal mesh, making the cells "better-shaped" and the vertices more evenly distributed. (See "Smooth Mesh" on page 109.)
- vtkSplineFilter — generate uniformly subdivided polylines from an input dataset containing polylines using a vtkSpline.
- vtkStripper — generate triangle strips from input triangles and polylines from input lines in the polygonal mesh. (See "Warp Based On Scalar Values" on page 122.)
- vtkSubPixelPositionEdgels — adjust edgel (line) positions in the input polygonal dataset based on gradients contained in the second input (a vtkImageData).
- vtkTransformPolyDataFilter — reposition the points in a polygonal dataset according to a 4x4 transformation matrix. This filter is like vtkTransformFilter, but it is specialized for vtkPolyData. (See "Transforming Data" on page 70.)

- vtkTransmitPolyDataPiece — when working in a distributed environment and all the polygonal data is initially on process 0, break the dataset into pieces (one per process), and send each process its corresponding piece.
- vtkTriangleFilter — generate triangles from polygons or triangle strips.
- vtkTriangularTCoords — generate texture coordinates for the triangles in a polygonal dataset.
- vtkTubeFilter — wrap lines with geometric tubes. (See "vtkDelaunay2D" on page 218.)
- vtkVoxelContoursToSurfaceFilter — convert line contours (stored in a polygonal dataset as vtkPolygon cells) into a surface.
- vtkWindowedSincPolyDataFilter — smooths meshes using a windowed sinc function (a standard signal processing low-pass filter). (See "Smooth Mesh" on page 109.)

Input Type vtkStructuredGrid. The input type must be vtkStructuredGrid. Remember that filters that accept vtkDataSet and vtkPointSet will also process vtkStructuredGrid.

- vtkBlankStructuredGrid — convert a specified point scalar array into a blanking field (i.e., an array containing 0's for points considered "off" and 1's for points considered "on"). A point is blanked (marked "off") if its scalar value lies within a specified scalar range; it is not blanked (i.e., marked "on") otherwise.
- vtkBlankStructuredGridWithImage — create a blanking field (i.e., an array containing 0's for points considered "off" and 1's for points considered "on") for a structured grid with an image whose dimensions are the same as those of the structured grid. Zero values in the image indicate that the output point is blanked; non-zero values indicate that the output point is visible.
- vtkExtractGrid — extract a region of interest and/or subsample a vtkStructuredGrid. (See "Subsampling Structured Grids" on page 113.)
- vtkGridSynchronizedTemplates3D — high-performance isocontouring algorithm specialized for structured grid datasets.
- vtkStructuredGridClip — reduce the extent of the input structured grid. This filter's functionality is very similar to vtkImageClip, but it operates on a structured grid instead of an image or volume.
- vtkStructuredGridGeometryFilter — extract a region of the structured grid (by specifying the extents of this region) as polygonal geometry (points, lines, surfaces). (See "Extract Computational Plane" on page 112.)
- vtkStructuredGridOutlineFilter — generate a wireframe outline of the boundaries of the structured grid. This is similar to the vtkOutlineFilter, but the edges of the outline will follow the curves of the boundaries of the vtkStructuredGrid.

Input Type vtkUnstructuredGrid. These filters take vtkUnstructuredGrid as input. Remember that filters that accept vtkDataSet and vtkPointSet will also process vtkUnstructuredGrid's.

- vtkContourGrid — generate isosurfaces/isolines from scalar values, specialized for unstructured grids. (See "Contour Unstructured Grids" on page 117.)
- vtkExtractUnstructuredGrid — extract a subset of an unstructured grid either by region of interest, by point ids, or by cell ids. (See "Extract Portions of the Mesh" on page 115.)

- vtkExtractUnstructuredGridPiece — extract a piece of an unstructured grid dataset as requested by a downstream filter or mapper.
- vtkExtractUserDefinedPiece — a subclass of vtkExtractUnstructuredGridPiece where the cells composing a piece are defined by a user-specified function.
- vtkSubdivideTetra — subdivide a tetrahedral mesh into 12 tetrahedra for every original tetrahedron.
- vtkTransmitUnstructuredGridPiece — when working in a distributed environment and all the unstructured grid data is initially on process 0, break the dataset into pieces (one per process), and send each process its corresponding piece.

Input Type vtkRectilinearGrid. The input type must be vtkRectilinearGrid. Remember that filters that accept vtkDataSet will also process vtkRectilinearGrid.

- vtkExtractRectilinearGrid — extract a sub-grid (Volume of Interest, or VOI) from the structured rectilinear dataset.
- vtkRectilinearGridClip — reduce the size (extent) of the input rectilinear grid dataset.
- vtkRectilinearGridGeometryFilter — extract a region of the rectilinear grid (by specifying the extents of this region) as polygonal geometry (points, lines, surfaces). (See "Extract Computational Plane" on page 112.)
- vtkRectilinearGridOutlineFilter — create a wireframe outline around the boundaries of a rectilinear grid.
- vtkRectilinearGridToTetrahedra — create a tetrahedral mesh (vtkUnstructuredGrid) from a rectilinear grid.
- vtkRectilinearSynchronizedTemplates — generate isosurface from scalar values, specialized for rectilinear grids.

Mapper Objects

In this section we provide a brief description of mapper objects. Mapper objects terminate the visualization pipeline. Note that writers (mapper objects that write files) are not listed here. Instead, find them in "Reading and Writing Data" on page 239. Each entry includes a brief description including the type of input it requires.

- vtkDataSetMapper — maps any type of dataset to the graphics system. (See "Extract Cells as Polygonal Data" on page 104.)
- vtkFixedPointVolumeRayCastMapper — maps a volume (vtkImageData) to an image via software ray casting (using 15-bit fixed-point precision for calculations) for volumes containing up to 4-component scalar of any data type.
- vtkImageMapper — 2D image display.
- vtkLabeledDataMapper — generates 3D text labels for a dataset based on underlying data values. (See "Labeling Data" on page 68.)
- vtkPolyDataMapper — maps polygonal data to the graphics system. (See "Defining Geometry" on page 53 as well as many of the code examples in this book.)

- vtkPolyDataMapper2D — draws vtkPolyData into the overlay plane.
- vtkProjectedTetrahedraMapper — maps an unstructured grid to an image using the volume rendering technique described by Shirley and Tuchman in "*A Polygonal Approximation to Direct Scalar Volume Rendering*" in Computer Graphics, December 1990.
- vtkTextMapper — displays 2D text annotation. (See "2DText Annotation" on page 63.)
- vtkUnstructuredGridVolumeRayCastMapper — maps an unstructured grid to an image via software ray casting.
- vtkUnstructuredGridVolumeZSweepMapper — maps an unstructured grid to an image using the ZSweep technique described by Ricardo Farias, Joseph S. B. Mitchell, and Claudio T. Silva in "*ZSWEEP: An Efficient and Exact Projection Algorithm for Unstructured Volume Rendering*" in 2000 Volume Visualization Symposium, pages 91--99, October 2000.
- vtkVolumeRayCastMapper — maps a volume (vtkImageData) to an image via software ray casting for volumes containing single-component unsigned short or unsigned char scalars.
- vtkVolumeTextureMapper2D — maps a volume (vtkImageData) to an image via 2D textures.
- vtkVolumeTextureMapper3D — maps a volume (vtkImageData) to an image via 3D textures, taking advantage of current graphics hardware to perform the 3D texture mapping.

Actor (Prop) Objects

The following is a brief description of the various types of vtkProp (e.g., vtkProp3D and vtkActor) available in the system.

- vtkActor — a type of vtkProp3D whose geometry is defined by analytic primitives such as polygons and lines; it is often used for representing a dataset in a 3D scene. (See "Actors" on page 53.)
- vtkActor2D — type of prop drawn in the overlay plane. (See "Controlling vtkActor2D" on page 62 and "Text Annotation" on page 63.)
- vtkAnnotatedCubeActor — a subclass of vtkProp3D that displays a 3D cube with face labels indicating coordinate directions. It is intended for use with vtkOrientationMarkerWidget to indicate direction in a 3D scene.
- vtkAssembly — an ordered grouping (hierarchy) of vtkProp3D's with a shared transformation matrix. (See "Assemblies" on page 56.)
- vtkAxesActor — a subclass of vtkProp3D that displays three labeled coordinate axes. It is intended for use with vtkOrientationMarkerWIdget to indicate direction in a 3D scene.
- vtkAxisActor2D — a single labeled axis drawn in the overlay plane.
- vtkCaptionActor2D — attach a text caption to an object.
- vtkCornerAnnotation — display text in the four corners of a viewport.
- vtkCubeAxesActor2D — draw the x-y-z axes around a bounding box (specified using a vtkDataSet, a vtkProp, or manually specifying the bound). Each axis is labeled with the range of the coordinates of the bounding box in its associated dimension. (See "Bounding Box Axes (vtkCubeAxesActor2D)" on page 68.)

- vtkFollower — a vtkActor that always faces the camera. (See "3D Text Annotation and vtkFollower" on page 65.)
- vtkImageActor — a special type of vtkProp3D that draws an image as a texture map on a single polygon. (See "Image Actor" on page 124.)
- vtkLegendBoxActor — used by vtkXYPlotActor to draw curve legends; combines text, symbols, and lines into a curve legend for labeling the curves in the vtkXYPlotActor.
- vtkLODActor — a simple level-of-detail scheme for rendering 3D geometry. (See "Level-Of-Detail Actors" on page 55.)
- vtkLODProp3D — level-of-detail method for vtkProp3D's. It is more general-purpose than vtkLODActor because it supports any type of vtkProp3D, including vtkVolume (for volume rendering). (See "vtkLODProp3D" on page 57.)
- vtkParallelCoordinatesActor — multivariate visualization technique for displaying a vtkDataObject. Parallel coordinates represent N-dimensional data by using a set of N parallel axes (not orthogonal like the usual x-y-z Cartesian axes). Each N-dimensional point is plotted as a polyline, where each of the N components of the point lie on one of the N axes, and the components are connected by straight lines.
- vtkPropAssembly — an ordered grouping (hierarchy) of vtkProps.
- vtkProp3D — a transformable (i.e., has a matrix) type of vtkProp. (See "Controlling 3D Props" on page 52.)
- vtkScalarBarActor — a labeled, colored bar that visually expresses the relationship between color and scalar value. (See "Scalar Bar" on page 66.)
- vtkTextActor — text drawn in the overlay plane that can be set to scale as the viewport changes size. (See "2DText Annotation" on page 63.)
- vtkTextActor3D — a subclass of vtkProp3D for displaying text. Unlike vtkTextActor, it supports oriented text.
- vtkVolume — a vtkProp3D used for volume rendering.
- vtkXYPlotActor — draw an *x-y* plot of scalar data contained in one or more vtkDataSets. (See "X-Y Plots" on page 66.)

Views and Informatics

VTK version 5.4 and later have extensive support for informatics (information visualization) and related classes (e.g., vtkView). **Figure 19–18** shows informatics-related object diagrams. Note that is support for Qt charting is built into a portion of the view hierarchy (only if VTK is compiled against Qt). Finally, many of the classes here require that the Boost Graph Library (http://www.boost.org/doc/libs/1_39_0/libs/graph/doc/index.html) or Parallel Boost Graph Library (PBGL) is built with VTK, which of courses requires enabling this option in the associated CMake build process. For more information on the Information Visualization capabilities of VTK See "Information Visualization" on page 163.

vtkGraph Algorithms. The following are algorithms that produce the data object type vtkGraph. By default the algorithms take vtkGraph as input, but this can be changed by overriding the method FillInputPortInfo().

- vtkBoostBrandesCentrality — compute Brandes betweenness centrality on a vtkGraph.
- vtkBoostBreadthFirstSearch — perform a breadth-first search.
- vtkBoostConnectedComponents — find the connected components of a graph.
- vtkCollapseGraph — collapses vertices onto their neighbors based on an input selection.
- vtkCollectGraph — collect a distributed graph onto vertex 0.
- vtkEdgeLayout — layout a graph using complex edge placement (including curved edges). This is different than vtkGraphLayout which places vertices (connected by straight lines). Multiple strategies are supported.
- vtkExtractSelectedGraph — return a subgraph of the input graph based on a selection.
- vtkGraphHierarchicalBundleEdges — layout a graph with reference to a supplementary vtkTree. The vtkGraph defines the topology of the graph; vtkTree defines the geometry.
- vtkGraphLayout — layout a graph's vertices using a variety of strategies.
- vtkPBGLBreadthFirstSearch — perform a breadth-first search on a distributed graph using PBGL.
- vtkPBGLCollapseGraph — collapse multiple vertices (with the same value) onto the same vertex in a distributed graph using PBGL.
- vtkPBGLCollapseParallelEdges — collapse multiple vertices into a single vertex using PBGL.
- vtkPBGLCollectGraph — collects all the pieces of a distributed vtkGraph onto a single, non-distributed vtkGraph.
- vtkPBGLConnectedComponents — compute connected components on a distributed graph using PBGL.
- vtkPBGLGraphSQLReader — create a graph using two SQL tables. The edge table must have one row for each edge, with two columns that define the edge source and target. The vertex table has one romw for each vertex, with field values that match those in the edge table.
- vtkPBGLMinimumSpanningTree — compute the minimal spanning tree in a distributed graph.
- vtkPBGLRandomGraphSource — generate a distributed graph with random edges.
- vtkPBGLRMATGraphSource — generate a distributed, random graph built according to the recursive matrix (R-MAT) model.
- vtkPBGLShortestPaths — compute the shortest path from an origin vertex to all other vertices in a distributed graph.
- vtkPBGLVertexColoring — compute a vertex coloring for a distributed, undirected graph where each vertex has a color distinct from its adjacent vertices.
- vtkPerturbCoincidentVertices — moves vertices slightly so they do not overlap.
- vtkRandomGraphSource — generate a random graph with a specified number of vertices.
- vtkRemoveIsolatedVertices — remove vertices of a graph with degree zero.
- vtkSplineGraphEdges — subsample graph edges to make smooth curves.
- vtkSQLDatabaseGraphSource — generate a graph from a SQL query.
- vtkSQLGraphReader — read a graph from a SQL database.

- vtkTableToGraph — convert a vtkTable into a vtkGraph using an auxilliarry link graph.
- vtkVertexDegree — adds an attribute data array with the degree of each vertex.

vtkTable Algorithms. The following are algorithms that produce the data object type vtkTable. By default the algorithms take vtkTable as input, but this can be changed by overriding the method FillInputPortInfo().

- vtkBoostSplitTableField — splits table fields by creating new rows containined delimited data.
- vtkCollectTable — collect a distributed table.
- vtkDataObjectToTable — extract VTK field data as a table.
- vtkDelimitedTextReader — reader for parsing a text file. A delimiter (which can be any character) is used to separate entries in the table.
- vtkExtractSelectedRows — return the selected rows of a table.
- vtkExtractTemporalFieldData — extract temporal arrays from input field data.
- vtkFixedWidthTextReader — read text files with fixed-width fields.
- vtkISIReader — read ISI files. ISI is a tagged format for expressing bibliographic citations.
- vtkMergeColumns — merge two columns into a single column. If the data is numeric, the values are summed in the merged column. If the data arrays are strings, the values are concatenated with a separating space (if both strings are non-empty).
- vtkMergeTables — combine two tables.
- vtkRISReader — read RIS files. RIS is a tagged format for expressing bibliographic citations.
- vtkRowQueryToTable — execute a SQL query and place the results into a table.
- vtkSQLDatabaseTableSource — generate a table from an SQL query.
- vtkStatisticsAlgorithm — this is the base class for statistics algorithms including bivariate, means, multi-correlative, and univariate statistics.
- vtkThresholdTable — threshold table rows using user-specified minimum and maximum values.

vtkTree Algorithms. The following are algorithms that produce the data object type vtkTree. By default the algorithms take vtkTree as input, but this can be changed by overriding the method FillInputPortInfo().

- vtkAreaLayout — create a tree ring based on a variety of area layout strategies.
- vtkBoostBreadthFirstSearchTree — perform a breadth-first-search from a given source vertex using BGL.
- vtkBoostPrimMinimumSpanningTree — construct a minimum spanning tree from a graph, starting vertex, and an edge weighting array.
- vtkGroupLeafVertices — a filter that expands a tree and categorizes leaf vertices.
- vtkNetworkHierarchy — generate a tree from a graph from network IP addressed contained in the graph.
- vtkPruneTreeFilter — removes a subtree rooted at a particular vertex in a vtkTree.

- vtkStahlerMetric — compute the Stahler metric for a tree. This metric characterizes the complexity of the sub-tree rooted at each node.
- vtkTableToTreeFilter — convert a vtkTable into a vtkTree.
- vtkTreeFieldAggregator — assign field data values to all the vertices in the tree, working from the leaves on up.
- vtkTreeLevelsFilter — add level and leaf fields (i.e., data arrays) to a vtkTree.
- vtkTreeMapLayout — layout a tree into a tree map. Each vertex in the tree corresponds to a rectangular region in the tree map.
- vtkXMLTreeReader — read an XML file into a vtkTree.

vtkUndirectedGraph Algorithms. The following are algorithms that produce the data object type vtkUndirectedGraph. By default the algorithms take vtkGraph as input, but this can be changed by overriding the method FillInputPortInfo().

- vtkBoostConnectedComponents — find the bi-connected components of a graph using BGL.
- vtkChacoGraphReader — read Chaco graph files.
- vtkTulipReader — read Tulip graph files.
- vtkXGMLReader — read XGML graph files.

vtkDirectedGraph Algorithms. The following are algorithms that produce the data object type vtkDirectedGraph. By default the algorithms take vtkGraph as input, but this can be changed by overriding the method FillInputPortInfo().

- vtkPipelineGraphSource — construct a graph from a VTK pipeline.

vtkPassInputType Algorithms. The following are algorithms that produce the same data object type as their input type. By default the algorithms take vtkDataObject as input, but this can be changed by overriding the method FillInputPortInfo().

- vtkAddMembershipArray — add an array to the output indicating membership within an input selection.
- vtkApplyColors — color a dataset using default colors, lookup tables, annotations, and/or a selection.
- vtkApplyIcons — generate icons for a dataset using default colors, lookup tables, annotations, and/or a selection.
- vtkArrayMap — map values in an input array to different values in an output array of (possibly) different type.
- vtkAssignAttribute — labels a field as an attribute.
- vtkAssignCoordinates — given two or three arrays take those values in those arrays and use them as the *x-y-z* coordinates.
- vtkConvertSelectionDomain — convert a selection from one domain to another using known domain mappings.
- vtkDataRepresentation — a general superclass for all data representations.

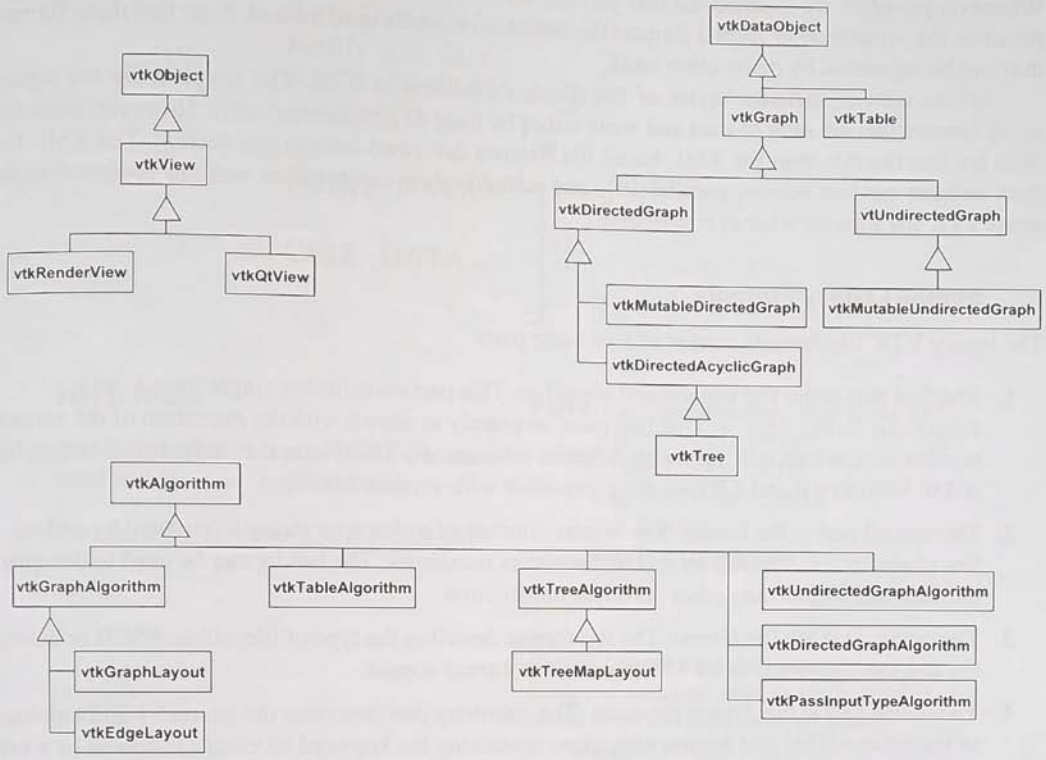


Figure 19–18 Informatics and vtkView hierarchy.

- vtkGeoAssignCoordinates — given latitude and longitude, take those values and convert them to *x-y-z* world coordinates.
- vtkPassThrough — shallow copies the input to the output.
- vtkProgrammableFilter — a general-purpose, user-programmable filter.
- vtkRemoveHiddenData — remove rows/edges/vertices of input data flagged by annotation.
- vtkTemporalStatistics — compute statistics of point or cell data as it changes over time.
- vtkTransferAttributes — transfer data from a graph representation to a tree representation using direct mapping or pedigree ids.

19.3 VTK File Formats

The *Visualization Toolkit* provides a number of source and writer objects to read and write popular data file formats. The *Visualization Toolkit* also provides some of its own file formats. The main reason for creating yet another data file format is to offer a consistent data representation scheme for a variety of dataset types, and to provide a simple method to communicate data between software.

Whenever possible, we recommend that you use formats that are more widely used. But if this is not possible, the *Visualization Toolkit* formats described here can be used instead. Note that these formats may not be supported by many other tools.

There are two different styles of file formats available in VTK. The simplest are the legacy, serial formats that are easy to read and write either by hand or programmatically. However, these formats are less flexible than the XML based file formats described later in this section. The XML formats support random access, parallel I/O, and portable data compression and are preferred to the serial VTK file formats whenever possible.

Simple Legacy Formats

The legacy VTK file formats consist of five basic parts.

1. The first part is the file version and identifier. This part contains the single line: `# vtk DataFile Version x.x`. This line must be exactly as shown with the exception of the version number `x.x`, which will vary with different releases of VTK. (Note: the current version number is 3.0. Version 1.0 and 2.0 files are compatible with version 3.0 files.)
2. The second part is the header. The header consists of a character string terminated by end-of-line character `\n`. The header is 256 characters maximum. The header can be used to describe the data and include any other pertinent information.
3. The next part is the file format. The file format describes the type of file, either ASCII or binary. On this line the single word `ASCII` or `BINARY` must appear.
4. The fourth part is the dataset structure. The geometry part describes the geometry and topology of the dataset. This part begins with a line containing the keyword `DATASET` followed by a keyword describing the type of dataset. Then, depending upon the type of dataset, other keyword/data combinations define the actual data.
5. The final part describes the dataset attributes. This part begins with the keywords `POINT_DATA` or `CELL_DATA`, followed by an integer number specifying the number of points or cells, respectively. (It doesn't matter whether `POINT_DATA` or `CELL_DATA` comes first.) Other keyword/data combinations then define the actual dataset attribute values (i.e., scalars, vectors, tensors, normals, texture coordinates, or field data).

An overview of the file format is shown in **Figure 19–19**. The first three parts are mandatory, but the other two are optional. Thus you have the flexibility of mixing and matching dataset attributes and geometry, either by operating system file manipulation or using VTK filters to merge data. Keywords are case insensitive, and may be separated by whitespace.

Before describing the data file formats please note the following.

- *dataType* is one of the types `bit`, `unsigned_char`, `char`, `unsigned_short`, `short`, `unsigned_int`, `int`, `unsigned_long`, `long`, `float`, or `double`. These keywords are used to describe the form of the data, both for reading from file, as well as constructing the appropriate internal objects. Not all data types are supported for all classes.
- All keyword phrases are written in ASCII form whether the file is binary or ASCII. The binary section of the file (if in binary form) is the data proper; i.e., the numbers that define points coordinates, scalars, cell indices, and so forth.
- Indices are 0-offset. Thus the first point is point id 0.

```
# vtk DataFile Version 2.0                ](1)
Really cool data                          ](2)
ASCII | BINARY                            ](3)
DATASET type   ]
...            ]  (4)
POINT_DATA n   ]
...            ]  (5)
CELL_DATA n    ]
...            ]
```

Part 1: Header

Part 2: Title (256 characters maximum, terminated with newline `\n` character)

Part 3: Data type, either ASCII or BINARY

Part 4: Geometry/topology. *Type* is one of:

```
STRUCTURED_POINTS
STRUCTURED_GRID
UNSTRUCTURED_GRID
POLYDATA
RECTILINEAR_GRID
FIELD
```

Part 5: Dataset attributes. The number of data items *n* of each type must match the number of points or cells in the dataset. (If *type* is `FIELD`, point and cell data should be omitted.

Figure 19–19 Overview of five parts of VTK data file format.

- If both the data attribute and geometry/topology part are present in the file, then the number of data values defined in the data attribute part must exactly match the number of points or cells defined in the geometry/topology part.
- Cell types and indices are of type `int`.
- Binary data must be placed into the file immediately after the "newline" (`\n`) character from the previous ASCII keyword and parameter sequence.
- The geometry/topology description must occur prior to the data attribute description.

Binary Files. Binary files in VTK are portable across different computer systems as long as you observe two conditions. First, make sure that the byte ordering of the data is correct, and second, make sure that the length of each data type is consistent.

Most of the time VTK manages the byte ordering of binary files for you. When you write a binary file on one computer and read it in from another computer, the bytes representing the data will be automatically swapped as necessary. For example, binary files written on a Sun are stored in big endian order, while those on a PC are stored in little endian order. As a result, files written on a Sun workstation require byte swapping when read on a PC. (See the class vtkByteSwap for implementation details.) The VTK data files described here are written in big endian form.

Some file formats, however, do not explicitly define a byte ordering form. You will find that data read or written by external programs, or the classes vtkVolume16Reader, vtkMCubesReader, and vtkMCubesWriter may have a different byte order depending on the system of origin. In such cases, VTK allows you to specify the byte order by using the methods

```
SetDataByteOrderToBigEndian()
SetDataByteOrderToLittleEndian()
```

Another problem with binary files is that systems may use a different number of bytes to represent an integer or other native type. For example, some 64-bit systems will represent an integer with 8-bytes, while others represent an integer with 4-bytes. Currently, the *Visualization Toolkit* cannot handle transporting legacy binary files across systems with incompatible data length. In this case, use ASCII file formats instead.

Dataset Format. The *Visualization Toolkit* supports five different dataset formats: structured points (i.e., vtkImageData), structured grid, rectilinear grid, unstructured grid, and polygonal data. Unlike the VTK XML files (described later in this chapter), by convention legacy VTK files use the .vtk file extension regardless of the dataset type contained in the file. Data with implicit topology (structured data such as vtkImageData and vtkStructuredGrid) are ordered with x increasing fastest, then y, then z. These formats are as follows.

- Structured Points
  The file format supports 1D, 2D, and 3D structured point datasets. The dimensions n_x, n_y, n_z must be greater than or equal to 1. The data spacing s_x, s_y, s_z must be greater than 0. (Note: in the version 1.0 data file, spacing was referred to as "aspect ratio". `ASPECT_RATIO` can still be used in version 2.0 data files, but is discouraged.)

  `DATASET STRUCTURED_POINTS`
  `DIMENSIONS` $n_x\ n_y\ n_z$
  `ORIGIN` $x\ y\ z$
  `SPACING` $s_x\ s_y\ s_z$

- Structured Grid
  The file format supports 1D, 2D, and 3D structured grid datasets. The dimensions n_x, n_y, n_z must be greater than or equal to 1. The point coordinates are defined by the data in the `POINTS` section. This consists of x-y-z data values for each point.

  `DATASET STRUCTURED_GRID`
  `DIMENSIONS` $n_x\ n_y\ n_z$
  `POINTS` n *dataType*
  $p_{0x}\ p_{0y}\ p_{0z}$
  $p_{1x}\ p_{1y}\ p_{1z}$
  ...
  $p_{(n-1)x}\ p_{(n-1)y}\ p_{(n-1)z}$

- Rectilinear Grid
  A rectilinear grid defines a dataset with regular topology, and semi-regular geometry aligned

along the x-y-z coordinate axes. The geometry is defined by three lists of monotonically increasing coordinate values, one list for each of the x-y-z coordinate axes. The topology is defined by specifying the grid dimensions, which must be greater than or equal to 1.

DATASET RECTILINEAR_GRID
DIMENSIONS $n_x\ n_y\ n_z$
X_COORDINATES n_x *dataType*
$x_0\ x_1 \ldots x_{(nx-1)}$
Y_COORDINATES n_y *dataType*
$y_0\ y_1 \ldots y_{(ny-1)}$
Z_COORDINATES n_z *dataType*
$z_0\ z_1 \ldots z_{(nz-1)}$

- Polygonal Data

The polygonal dataset consists of arbitrary combinations of surface graphics primitives: vertices (and polyvertices), lines (and polylines), polygons (of various types), and triangle strips. Polygonal data is defined by the POINTS, VERTICES, LINES, POLYGONS, or TRIANGLE_STRIPS sections. The POINTS definition is the same as we saw for structured grid datasets. The VERTICES, LINES, POLYGONS, or TRIANGLE_STRIPS keywords define the polygonal dataset topology. Each of these keywords requires two parameters: the number of cells n and the size of the cell list *size*. The cell list size is the total number of integer values required to represent the list (i.e., sum of *numPoints* and connectivity indices over each cell). None of the keywords VERTICES, LINES, POLYGONS, or TRIANGLE_STRIPS are required.

DATASET POLYDATA
POINTS n *dataType*
$p_{0x}\ p_{0y}\ p_{0z}$
$p_{1x}\ p_{1y}\ p_{1z}$
...
$p_{(n-1)x}\ p_{(n-1)y}\ p_{(n-1)z}$

VERTICES n *size*
$numPoints_0, i_0, j_0, k_0, \ldots$
$numPoints_1, i_1, j_1, k_1, \ldots$
...
$numPoints_{n-1}, i_{n-1}, j_{n-1}, k_{n-1}, \ldots$

LINES n *size*
$numPoints_0, i_0, j_0, k_0, \ldots$
$numPoints_1, i_1, j_1, k_1, \ldots$
...
$numPoints_{n-1}, i_{n-1}, j_{n-1}, k_{n-1}, \ldots$

POLYGONS n *size*
$numPoints_0, i_0, j_0, k_0, \ldots$
$numPoints_1, i_1, j_1, k_1, \ldots$

...
$numPoints_{n-1}, i_{n-1}, j_{n-1}, k_{n-1}, \ldots$

`TRIANGLE_STRIPS` *n size*
$numPoints_0, i_0, j_0, k_0, \ldots$
$numPoints_1, i_1, j_1, k_1, \ldots$
...
$numPoints_{n-1}, i_{n-1}, j_{n-1}, k_{n-1}, \ldots$

- Unstructured Grid
  The unstructured grid dataset consists of arbitrary combinations of any possible cell type. Unstructured grids are defined by points, cells, and cell types. The `CELLS` keyword requires two parameters: the number of cells *n* and the size of the cell list *size*. The cell list size is the total number of integer values required to represent the list (i.e., sum of *numPoints* and connectivity indices over each cell). The `CELL_TYPES` keyword requires a single parameter: the number of cells *n*. This value should match the value specified by the `CELLS` keyword. The cell types data is a single integer value per cell that specified cell type (see `vtkCell.h` or **Figure 19–20**).

`DATASET UNSTRUCTURED_GRID`
`POINTS` *n dataType*
$p_{0x}\, p_{0y}\, p_{0z}$
$p_{1x}\, p_{1y}\, p_{1z}$
...
$p_{(n-1)x}\, p_{(n-1)y}\, p_{(n-1)z}$

`CELLS` *n size*
$numPoints_0, i, j, k, l, \ldots$
$numPoints_1, i, j, k, l, \ldots$
$numPoints_2, i, j, k, l, \ldots$
...
$numPoints_{n-1}, i, j, k, l, \ldots$

`CELL_TYPES` *n*
$type_0$
$type_1$
$type_2$
...
$type_{n-1}$

- Field
  Field data is a general format without topological and geometric structure, and without a particular dimensionality. Typically field data is associated with the points or cells of a dataset. However, if the `FIELD` *type* is specified as the dataset type (see **Figure 19–19**), then a general VTK data object is defined. Use the format described in the next section to define a field. Also see "Working With Field Data" on page 249 and the fourth of the examples starting in "Examples" on page 477.

Dataset Attribute Format. The *Visualization Toolkit* supports the following dataset attributes: scalars (one to four components), color scalars, vectors, normals, texture coordinates (1D, 2D, and 3D), 3×3 tensors, and field data. In addition, a lookup table using the RGBA color specification, associated with the scalar data, can be defined as well. Dataset attributes are supported for both points and cells.

Each type of attribute data has a *dataName* associated with it. This is a character string (without embedded whitespace) used to identify a particular data. The *dataName* is used by the VTK readers to extract data. As a result, more than one attribute data of the same type can be included in a file. For example, two different scalar fields defined on the dataset points, pressure and temperature, can be contained in the same file. (If a matching *dataName* is not specified in the VTK reader, then the first data of that type is extracted from the file.)

- Scalars

  Scalar definition includes specification of a lookup table. The definition of a lookup table is optional. If not specified, the default VTK table will be used (and *tableName* should be "`default`"). Also note that the *numComp* variable is optional—by default the number of components is equal to one. (The parameter *numComp* must range between (1,4) inclusive; in versions of VTK prior to vtk2.3 this parameter was not supported.)

  `SCALARS` *dataName dataType numComp*
  `LOOKUP_TABLE` *tableName*
  s_0
  s_1
  ...
  s_{n-1}

- Color Scalars

  The definition of color scalars (i.e., `unsigned char` values directly mapped to color) varies depending upon the number of values (*nValues*) per scalar. If the file format is `ASCII`, the color scalars are defined using *nValues* `float` values between (0,1). If the file format is `BINARY`, the stream of data consists of *nValues* `unsigned char` values per scalar value.

  `COLOR_SCALARS` *dataName nValues*
  $c_{00}\ c_{01} \cdots c_{0(nValues-1)}$
  $c_{10}\ c_{11} \cdots c_{1(nValues-1)}$
  ...
  $c_{(n-1)0}\ c_{(n-1)1} \cdots c_{(n-1)(nValues-1)}$

- Lookup Table

  The *tableName* field is a character string (without imbedded white space) used to identify the lookup table. This label is used by the VTK reader to extract a specific table.

  Each entry in the lookup table is a `rgba[4]` (*red-green-blue-alpha*) array (*alpha* is opacity where *alpha=0* is transparent). If the file format is `ASCII`, the lookup table values must be `float` values between (0,1). If the file format is `BINARY`, the stream of data must be four unsigned char values per table entry.

LOOKUP_TABLE *tableName size*
$r_0\, g_0\, b_0\, a_0$
$r_1\, g_1\, b_1\, a_1$
...
$r_{size-1}\, g_{size-1}\, b_{size-1}\, a_{size-1}$

- Vectors

VECTORS *dataName dataType*
$v_{0x}\, v_{0y}\, v_{0z}$
$v_{1x}\, v_{1y}\, v_{1z}$
...
$v_{(n-1)x}\, v_{(n-1)y}\, v_{(n-1)z}$

- Normals
  Normals are assumed normalized $|n| = 1$.

NORMALS *dataName dataType*
$n_{0x}\, n_{0y}\, n_{0z}$
$n_{1x}\, n_{1y}\, n_{1z}$
...
$n_{(n-1)x}\, n_{(n-1)y}\, n_{(n-1)z}$

- Texture Coordinates
  Texture coordinates of 1, 2, and 3 dimensions are supported.

TEXTURE_COORDINATES *dataName dim dataType*
$t_{00}\, t_{01} \cdots t_{0(dim-1)}$
$t_{10}\, t_{11} \cdots t_{1(dim-1)}$
...
$t_{(n-1)0}\, t_{(n-1)1} \cdots t_{(n-1)(dim-1)}$

- Tensors
  Currently only 3×3 real-valued, symmetric tensors are supported.

TENSORS *dataName dataType*
$t^0_{00}\, t^0_{01}\, t^0_{02}$
$t^0_{10}\, t^0_{11}\, t^0_{12}$
$t^0_{20}\, t^0_{21}\, t^0_{22}$

$t^1_{00}\, t^1_{01}\, t^1_{02}$
$t^1_{10}\, t^1_{11}\, t^1_{12}$
$t^1_{20}\, t^1_{21}\, t^1_{22}$
...
$t^{n-1}_{00}\, t^{n-1}_{01}\, t^{n-1}_{02}$
$t^{n-1}_{10}\, t^{n-1}_{11}\, t^{n-1}_{12}$

$t^{n-1}_{20}\, t^{n-1}_{21}\, t^{n-1}_{22}$

- Field Data
  Field data is essentially an array of data arrays. Defining field data means giving a name to the field and specifying the number of arrays it contains. Then, for each array, the name of the array *arrayName(i)*, the number of components of the array, *numComponents*, the number of tuples in the array, *numTuples*, and the data type, *dataType*, are defined.

  FIELD *dataName numArrays*
  arrayName0 numComponents numTuples dataType
  $f_{00} f_{01} \cdots f_{0(numComponents-1)}$
  $f_{10} f_{11} \cdots f_{1(numComponents-1)}$
  ...
  $f_{(numTuples-1)0} f_{(numTuples-1)1} \cdots f_{(numTuples-1)(numComponents-1)}$

  arrayName1 numComponents numTuples dataType
  $f_{00} f_{01} \cdots f_{0(numComponents-1)}$
  $f_{10} f_{11} \cdots f_{1(numComponents-1)}$
  ...
  $f_{(numTuples-1)0} f_{(numTuples-1)1} \cdots f_{(numTuples-1)(numComponents-1)}$

  ...
  arrayName(numArrays-1) numComponents numTuples dataType
  $f_{00} f_{01} \cdots f_{0(numComponents-1)}$
  $f_{10} f_{11} \cdots f_{1(numComponents-1)}$
  ...
  $f_{(numTuples-1)0} f_{(numTuples-1)1} \cdots f_{(numTuples-1)(numComponents-1)}$

Examples. The first example is a cube represented by six polygonal faces. We define a single-component scalar, normals, and field data on the six faces. There are scalar data associated with the eight vertices. A lookup table of eight colors, associated with the point scalars, is also defined.

```
# vtk DataFile Version 2.0
Cube example
ASCII
DATASET POLYDATA
POINTS 8 float
0.0 0.0 0.0
1.0 0.0 0.0
1.0 1.0 0.0
0.0 1.0 0.0
0.0 0.0 1.0
1.0 0.0 1.0
1.0 1.0 1.0
0.0 1.0 1.0
POLYGONS 6 30
4 0 1 2 3
```

```
4 4 5 6 7
4 0 1 5 4
4 2 3 7 6
4 0 4 7 3
4 1 2 6 5

CELL_DATA 6
SCALARS cell_scalars int 1
LOOKUP_TABLE default
0
1
2
3
4
5
NORMALS cell_normals float
0 0 -1
0 0 1
0 -1 0
0 1 0
-1 0 0
1 0 0
FIELD FieldData 2
cellIds 1 6 int
0 1 2 3 4 5
faceAttributes 2 6 float
0.0 1.0 1.0 2.0 2.0 3.0 3.0 4.0 4.0 5.0 5.0 6.0

POINT_DATA 8
SCALARS sample_scalars float 1
LOOKUP_TABLE my_table
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
LOOKUP_TABLE my_table 8
0.0 0.0 0.0 1.0
1.0 0.0 0.0 1.0
0.0 1.0 0.0 1.0
1.0 1.0 0.0 1.0
0.0 0.0 1.0 1.0
1.0 0.0 1.0 1.0
0.0 1.0 1.0 1.0
1.0 1.0 1.0 1.0
```

The next example is a volume of dimension $3 \times 4 \times 6$. Since no lookup table is defined, either the user must create one in VTK, or the default lookup table will be used.

```
# vtk DataFile Version 2.0
Volume example
ASCII
DATASET STRUCTURED_POINTS
DIMENSIONS 3 4 6
SPACING 1 1 1
ORIGIN 0 0 0
POINT_DATA 72
SCALARS volume_scalars char 1
LOOKUP_TABLE default
0 0 0 0 0 0 0 0 0 0 0 0
0 5 10 15 20 25 25 20 15 10 5 0
0 10 20 30 40 50 50 40 30 20 10 0
0 10 20 30 40 50 50 40 30 20 10 0
0 5 10 15 20 25 25 20 15 10 5 0
0 0 0 0 0 0 0 0 0 0 0 0
```

The third example is an unstructured grid containing eight VTK cell types (see **Figure 19–20** and **Figure 19–21**). The file contains scalar and vector data.

```
# vtk DataFile Version 2.0
Unstructured Grid Example
ASCII

DATASET UNSTRUCTURED_GRID
POINTS 27 float
0 0 0   1 0 0   2 0 0   0 1 0   1 1 0   2 1 0
0 0 1   1 0 1   2 0 1   0 1 1   1 1 1   2 1 1
0 1 2   1 1 2   2 1 2   0 1 3   1 1 3   2 1 3
0 1 4   1 1 4   2 1 4   0 1 5   1 1 5   2 1 5
0 1 6   1 1 6   2 1 6

CELLS 11 60
8 0 1 4 3 6 7 10 9
8 1 2 5 4 7 8 11 10
4 6 10 9 12
4 5 11 10 14
6 15 16 17 14 13 12
6 18 15 19 16 20 17
4 22 23 20 19
3 21 22 18
3 22 19 18
2 26 25
1 24

CELL_TYPES 11
12
12
10
10
7
```

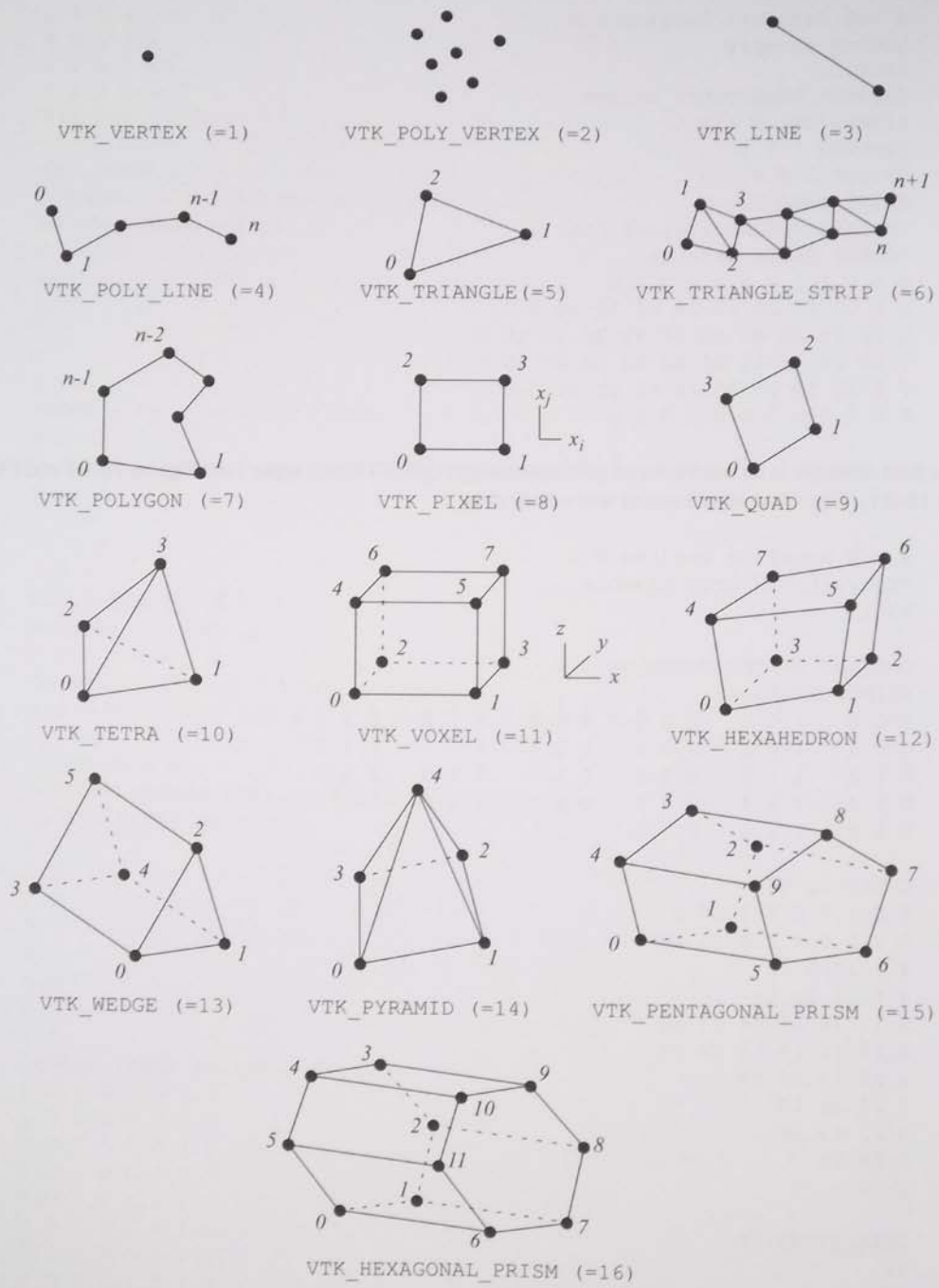


Figure 19–20 Linear cell types found in VTK. Use the include file vtkCellType.h to manipulate cell types.

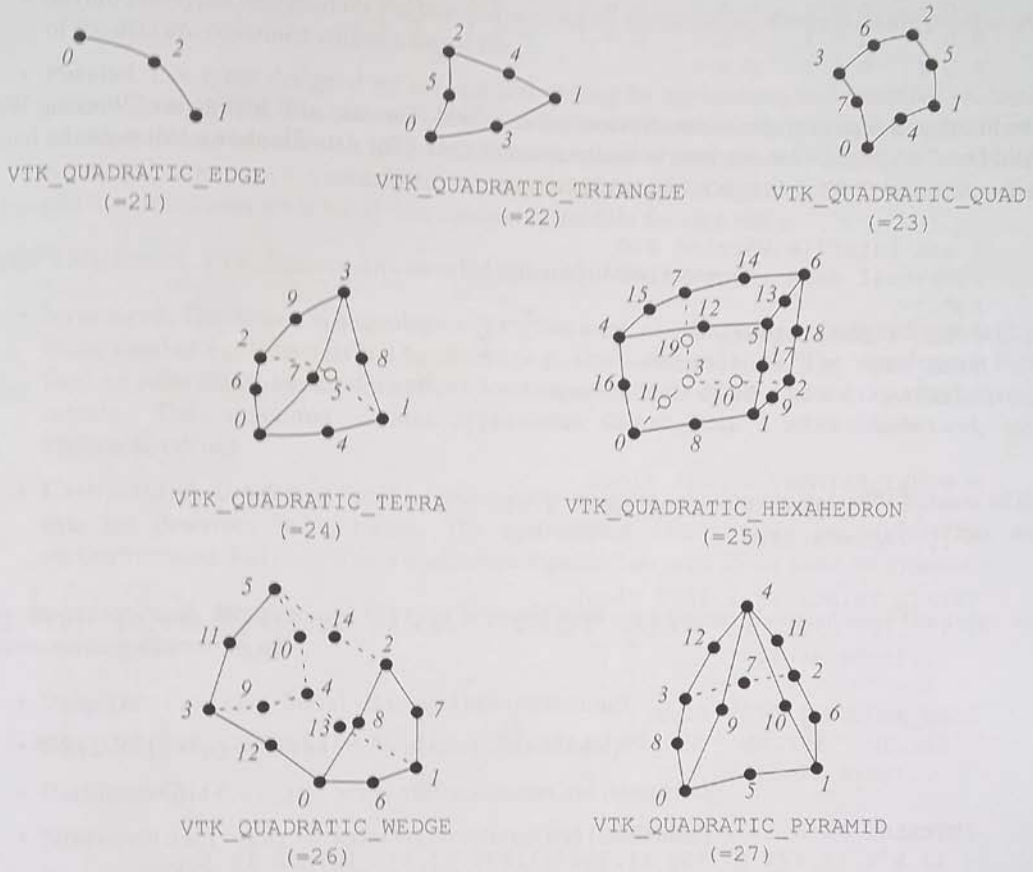


Figure 19–21 Non-linear cell types found in VTK.

```
6
9
5
5
3
1


POINT_DATA 27
SCALARS scalars float 1
LOOKUP_TABLE default
0.0   1.0   2.0   3.0   4.0   5.0
6.0   7.0   8.0   9.0   10.0   11.0
12.0   13.0   14.0   15.0   16.0   17.0
18.0   19.0   20.0   21.0   22.0   23.0
24.0   25.0   26.0
VECTORS vectors float
1 0 0   1 1 0   0 2 0   1 0 0   1 1 0   0 2 0
1 0 0   1 1 0   0 2 0   1 0 0   1 1 0   0 2 0
```

```
0 0 1   0 0 1   0 0 1   0 0 1   0 0 1   0 0 1
0 0 1   0 0 1   0 0 1   0 0 1   0 0 1   0 0 1
0 0 1   0 0 1   0 0 1
```

The fourth and final example is data represented as a field. You may also wish to see "Working With Field Data" on page 249 to see how to manipulate this data. (The data file shown below can be found in its entirety in `$VTK_DATA_ROOT/Data/financial.vtk`.)

```
# vtk DataFile Version 2.0
Financial data in vtk field format
ASCII
FIELD financialData 6
TIME_LATE 1 3188 float
 29.14   0.00   0.00  11.71   0.00   0.00   0.00   0.00
...(more stuff - 3188 total values)...

MONTHLY_PAYMENT 1 3188 float
  7.26   5.27   8.01  16.84   8.21  15.75  10.62  15.47
  ...(more stuff)...

UNPAID_PRINCIPLE 1 3188 float
  430.70   380.88   516.22  1351.23   629.66  1181.97   888.91  1437.83
  ...(more stuff)...

LOAN_AMOUNT 1 3188 float
  441.50   391.00   530.00  1400.00   650.00  1224.00   920.00  1496.00
  ...(more stuff)...

INTEREST_RATE 1 3188 float
  13.875 13.875 13.750 11.250 11.875 12.875 10.625 10.500
  ...(more stuff)...

MONTHLY_INCOME 1 3188 unsigned_short
 39  51  51  38  35  49  45  56
  ...(more stuff)...
```

In this example, a field is represented using six arrays. Each array has a single component and 3,188 tuples. Five of the six arrays are of type `float`, while the last array is of type `unsigned_short`. Additional examples are available in the data directory.

XML File Formats

VTK provides another set of data formats using XML syntax. While these formats are much more complicated than the original VTK format described previously (see "Simple Legacy Formats" on page 470), they support many more features. The major motivation for their development was to facilitate data streaming and parallel I/O. Some features of the format include support for compression, portable binary encoding, random access, big endian and little endian byte order, multiple file representation of piece data, and new file extensions for different VTK dataset types. XML provides many features as well, especially the ability to extend a file format with application specific tags. There are two types of VTK XML data files: parallel and serial as described in the following.

- **Serial.** File types designed for reading and writing by applications of only a single process. All of the data are contained within a single file.
- **Parallel.** File types designed for reading and writing by applications with multiple processes executing in parallel. The dataset is broken into pieces. Each process is assigned a piece or set of pieces to read or write. An individual piece is stored in a corresponding serial file type. The parallel file type does not actually contain any data, but instead describes structural information and then references other serial files containing the data for each piece.

In the XML format, VTK datasets are classified into one of two categories.

- **Structured.** The dataset is a topologically regular array of cells such as pixels and voxels (e.g., image data) or quadrilaterals and hexahedra (e.g., structured grid) (see "The Visualization Pipeline" on page 25 for more information). Rectangular subsets of the data are described through extents. The structured dataset types are vtkImageData, vtkRectilinearGrid, and vtkStructuredGrid.
- **Unstructured.** The dataset forms a topologically irregular set of points and cells. Subsets of the data are described using pieces. The unstructured dataset types are vtkPolyData and vtkUnstructuredGrid (see "The Visualization Pipeline" on page 25 for more information).

By convention, each data type and file type is paired with a particular file extension. The types and corresponding extensions are

- ImageData (`.vti`) — Serial vtkImageData (structured).
- PolyData (`.vtp`) — Serial vtkPolyData (unstructured).
- RectilinearGrid (`.vtr`) — Serial vtkRectilinearGrid (structured).
- StructuredGrid (`.vts`) — Serial vtkStructuredGrid (structured).
- UnstructuredGrid (`.vtu`) — Serial vtkUnstructuredGrid (unstructured).
- PImageData (`.pvti`) — Parallel vtkImageData (structured).
- PPolyData (`.pvtp`) — Parallel vtkPolyData (unstructured).
- PRectilinearGrid (`.pvtr`) — Parallel vtkRectilinearGrid (structured).
- PStructuredGrid (`.pvts`) — Parallel vtkStructuredGrid (structured).
- PUnstructuredGrid (`.pvtu`) — Parallel vtkUnstructuredGrid (unstructured).

All of the VTK XML file types are well-formed XML documents.* The document-level element is `VTKFile`:

```
<VTKFile type="ImageData" version="0.1" byte_order="LittleEndian">
  ...
</VTKFile>
```

The attributes of the element are:

*There is one case in which the file is not a well-formed XML document. When the AppendedData section is not encoded as base64, raw binary data is present that may violate the XML specification. This is not default behavior, and must be explicitly enabled by the user.

`type` — The type of the file (the bulleted items in the previous list).

`version` — File version number in "major.minor" format.

`byte_order` — Machine byte order in which data are stored. This is either "BigEndian" or "LittleEndian".

`compressor` — Some data in the file may be compressed. This specifies the subclass of vtkDataCompressor that was used to compress the data.

Nested inside the `VTKFile` element is an element whose name corresponds to the type of the data format (i.e., the `type` attribute). This element describes the topology of the dataset, and is different for the serial and parallel formats, which are described as follows.

Serial XML File Formats. The `VTKFile` element contains one element whose name corresponds to the type of dataset the file describes. We refer to this as the dataset element, which is one of `ImageData`, `RectilinearGrid`, `StructuredGrid`, `PolyData`, or `UnstructuredGrid`. The dataset element contains one or more `Piece` elements, each describing a portion of the dataset. Together, the dataset element and `Piece` elements specify the entire dataset.

Each piece of a dataset must specify the geometry (points and cells) of that piece along with the data associated with each point or cell. Geometry is specified differently for each dataset type, but every piece of every dataset contains `PointData` and `CellData` elements specifying the data for each point and cell in the piece.

The general structure for each serial dataset format is as follows:

- **ImageData** — Each `ImageData` piece specifies its extent within the dataset's whole extent. The points and cells are described implicitly by the extent, origin, and spacing. Note that the origin and spacing are constant across all pieces, so they are specified as attributes of the `ImageData` XML element as follows.

```
<VTKFile type="ImageData" ...>
  <ImageData WholeExtent="x1 x2 y1 y2 z1 z2"
   Origin="x0 y0 z0" Spacing="dx dy dz">
    <Piece Extent="x1 x2 y1 y2 z1 z2">
      <PointData>...</PointData>
      <CellData>...</CellData>
    </Piece>
  </ImageData>
</VTKFile>
```

- **RectilinearGrid** — Each `RectilinearGrid` piece specifies its extent within the dataset's whole extent. The points are described by the `Coordinates` element. The cells are described implicitly by the extent.

```
<VTKFile type="RectilinearGrid" ...>
  <RectilinearGrid WholeExtent="x1 x2 y1 y2 z1 z2">
    <Piece Extent="x1 x2 y1 y2 z1 z2">
      <PointData>...</PointData>
      <CellData>...</CellData>
```

```
      <Coordinates>...</Coordinates>
    </Piece>
  </RectilinearGrid>
</VTKFile>
```

- **StructuredGrid** — Each `StructuredGrid` piece specifies its extent within the dataset's whole extent. The points are described explicitly by the `Points` element. The cells are described implicitly by the extent.

```
<VTKFile type="StructuredGrid" ...>
  <StructuredGrid WholeExtent="x1 x2 y1 y2 z1 z2">
    <Piece Extent="x1 x2 y1 y2 z1 z2">
      <PointData>...</PointData>
      <CellData>...</CellData>
      <Points>...</Points>
    </Piece>
  </StructuredGrid>
</VTKFile>
```

- **PolyData** — Each `PolyData` piece specifies a set of points and cells independently from the other pieces. The points are described explicitly by the `Points` element. The cells are described explicitly by the `Verts`, `Lines`, `Strips`, and `Polys` elements.

```
<VTKFile type="PolyData" ...>
  <PolyData>
    <Piece  NumberOfPoints="#"  NumberOfVerts="#"  NumberOfLines="#"
     NumberOfStrips="#" NumberOfPolys="#">
      <PointData>...</PointData>
      <CellData>...</CellData>
      <Points>...</Points>
      <Verts>...</Verts>
      <Lines>...</Lines>
      <Strips>...</Strips>
      <Polys>...</Polys>
    </Piece>
  </PolyData>
</VTKFile>
```

- **UnstructuredGrid** — Each `UnstructuredGrid` piece specifies a set of points and cells independently from the other pieces. The points are described explicitly by the `Points` element. The cells are described explicitly by the `Cells` element.

```
<VTKFile type="UnstructuredGrid" ...>
  <UnstructuredGrid>
    <Piece NumberOfPoints="#" NumberOfCells="#">
      <PointData>...</PointData>
```

```
      <CellData>...</CellData>
      <Points>...</Points>
      <Cells>...</Cells>
    </Piece>
  </UnstructuredGrid>
</VTKFile>
```

Every dataset describes the data associated with its points and cells with `PointData` and `CellData` XML elements as follows:

```
<PointData Scalars="Temperature" Vectors="Velocity">
  <DataArray Name="Velocity" .../>
  <DataArray Name="Temperature" .../>
  <DataArray Name="Pressure" .../>
</PointData>
```

VTK allows an arbitrary number of data arrays to be associated with the points and cells of a dataset. Each data array is described by a `DataArray` element which, among other things, gives each array a name. The following attributes of `PointData` and `CellData` are used to specify the active arrays by name:

`Scalars` — The name of the active scalars array, if any.

`Vectors` — The name of the active vectors array, if any.

`Normals` — The name of the active normals array, if any.

`Tensors` — The name of the active tensors array, if any.

`TCoords` — The name of the active texture coordinates array, if any.

Some datasets describe their points and cells using different combinations of the following common elements:

- **Points** — The `Points` element explicitly defines coordinates for each point individually. It contains one `DataArray` element describing an array with three components per value, each specifying the coordinates of one point.

  ```
  <Points>
    <DataArray NumberOfComponents="3" .../>
  </Points>
  ```

  `Coordinates` — The `Coordinates` element defines point coordinates for an extent by specifying the ordinate along each axis for each integer value in the extent's range. It contains three `DataArray` elements describing the ordinates along the *x*-*y*-*z* axes, respectively.

  ```
  <Coordinates>
    <DataArray .../>
    <DataArray .../>
    <DataArray .../>
  </Coordinates>
  ```

- **Verts**, **Lines**, **Strips**, and **Polys** — The `Verts`, `Lines`, `Strips`, and `Polys` elements define cells explicitly by specifying point connectivity. Cell types are implicitly known by the type of element in which they are specified. Each element contains two `DataArray` elements. The first array specifies the point connectivity. All the cells' point lists are concatenated together. The second array specifies the offset into the connectivity array for the end of each cell.

```
<Verts>
  <DataArray type="Int32" Name="connectivity" .../>
  <DataArray type="Int32" Name="offsets" .../>
</Verts>
```

- **Cells** — The `Cells` element defines cells explicitly by specifying point connectivity and cell types. It contains three `DataArray` elements. The first array specifies the point connectivity. All the cells' point lists are concatenated together. The second array specifies the offset into the connectivity array for the end of each cell. The third array specifies the type of each cell. (Note: the cell types are defined in **Figure 19–20** and **Figure 19–21**.)

```
<Cells>
  <DataArray type="Int32" Name="connectivity" .../>
  <DataArray type="Int32" Name="offsets" .../>
  <DataArray type="UInt8" Name="types" .../>
</Cells>
```

All of the data and geometry specifications use `DataArray` elements to describe their actual content as follows:

- **DataArray** — The `DataArray` element stores a sequence of values of one type. There may be one or more components per value.

```
<DataArray type="Float32" Name="vectors" NumberOfComponents="3"
           format="appended" offset="0"/>
<DataArray type="Float32" Name="scalars" format="binary">
           bAAAAAAAAAAAAIA/AAAAQAAAQEAAAIBA... </DataArray>
<DataArray type="Int32" Name="offsets" format="ascii">
           10 20 30 ... </DataArray>
```

The attributes of the `DataArray` elements are described as follows:

`type` — The data type of a single component of the array. This is one of `Int8`, `UInt8`, `Int16`, `UInt16`, `Int32`, `UInt32`, `Int64`, `UInt64`, `Float32`, `Float64`.

`Name` — The name of the array. This is usually a brief description of the data stored in the array.

`NumberOfComponents` — The number of components per value in the array.

`format` — The means by which the data values themselves are stored in the file. This is "ascii", "binary", or "appended".

`offset` — If the format attribute is "appended", this specifies the offset from the beginning of the appended data section to the beginning of this array's data.

`RangeMin`, `RangeMax` — These optional attributes specify the minimum and maximum values present in the `DataArray`.

The `format` attribute chooses among the three ways in which data values can be stored:

`format="ascii"` — The data are listed in ASCII directly inside the `DataArray` element. Whitespace is used for separation.

`format="binary"` — The data are encoded in base64 and listed contiguously inside the `DataArray` element. Data may also be compressed before encoding in base64. The byte-order of the data matches that specified by the `byte_order` attribute of the `VTKFile` element.

`format="appended"` — The data are stored in the appended data section. Since many `DataArray` elements may store their data in this section, the offset attribute is used to specify where each `DataArray's` data begins. This format is the default used by VTK's writers.

The appended data section is stored in an `AppendedData` element that is nested inside `VTKFile` after the dataset element:

```
<VTKFile ...>
  ...
  <AppendedData encoding="base64">
    _QMwEAAAAAAAAA...
  </AppendedData>
</VTKFile>
```

The appended data section begins with the first character after the underscore inside the `AppendedData` element. The underscore is not part of the data, but is always present. Data in this section is always in binary form, but can be compressed and/or base64 encoded. The byte-order of the data matches that specified by the `byte_order` attribute of the `VTKFile` element. Each `DataArray`'s data are stored contiguously and appended immediately after the previous `DataArray`'s data without a seperator. The `DataArray`'s `offset` attribute indicates the file position offset from the first character after the underscore to the beginning its data.

Parallel File Formats. The parallel file formats do not actually store any data in the file. Instead, the data are broken into pieces, each of which is stored in a serial file of the same dataset type.

The `VTKFile` element contains one element whose name corresponds to the type of dataset the file describes, but with a "P" prefix. We refer to this as the parallel dataset element, which is one of PImageData, PRectilinearGrid, PStructuredGrid, PPolyData, or PUnstructuredGrid.

The parallel dataset element and those nested inside specify the types of the data arrays used to store points, point data, and cell data (the type of arrays used to store cells is fixed by VTK). The element does not actually contain any data, but instead includes a list of `Piece` elements that specify the source from which to read each piece. Individual pieces are stored in the corresponding serial file format. The parallel file needs to specify the type and structural information so that readers can update pipeline information without actually reading the pieces' files.

The general structure for each parallel dataset format is as follows:

- **PImageData** — The `PImageData` element specifies the whole extent of the dataset and the number of ghost-levels by which the extents in the individual pieces overlap. The `Origin` and `Spacing` attributes implicitly specify the point locations. Each `Piece` element describes the extent of one piece and the file in which it is stored.

```
<VTKFile type="PImageData" ...>
  <PImageData WholeExtent="x1 x2 y1 y2 z1 z2"
              GhostLevel="#" Origin="x0 y0 z0" Spacing="dx dy dz">
    <PPointData>...</PPointData>
    <PCellData>...</PCellData>
    <Piece Extent="x1 x2 y1 y2 z1 z2" Source="imageData0.vti"/>
    ...
  </PImageData>
</VTKFile>
```

- **PRectilinearGrid** — The `PRectilinearGrid` element specifies the whole extent of the dataset and the number of ghost-levels by which the extents in the individual pieces overlap. The `PCoordinates` element describes the type of arrays used to specify the point ordinates along each axis, but does not actually contain the data. Each `Piece` element describes the extent of one piece and the file in which it is stored.

```
<VTKFile type="PRectilinearGrid" ...>
  <PRectilinearGrid WholeExtent="x1 x2 y1 y2 z1 z2"
                    GhostLevel="#">
    <PPointData>...</PPointData>
    <PCellData>...</PCellData>
    <PCoordinates>...</PCoordinates>
    <Piece Extent="x1 x2 y1 y2 z1 z2"
           Source="rectilinearGrid0.vtr"/>
    ...
  </PRectilinearGrid>
</VTKFile>
```

- **PStructuredGrid** — The `PStructuredGrid` element specifies the whole extent of the dataset and the number of ghost-levels by which the extents in the individual pieces overlap. The `PPoints` element describes the type of array used to specify the point locations, but does not actually contain the data. Each `Piece` element describes the extent of one piece and the file in which it is stored.

```
<VTKFile type="PStructuredGrid" ...>
  <PStructuredGrid WholeExtent="x1 x2 y1 y2 z1 z2"
                   GhostLevel="#">
    <PPointData>...</PPointData>
    <PCellData>...</PCellData>
```

```
    <PPoints>...</PPoints>
    <Piece Extent="x1 x2 y1 y2 z1 z2"
           Source="structuredGrid0.vts"/>
    ...
  </PStructuredGrid>
</VTKFile>
```

- **PPolyData** — The `PPolyData` element specifies the number of ghost-levels by which the individual pieces overlap. The `PPoints` element describes the type of array used to specify the point locations, but does not actually contain the data. Each `Piece` element specifies the file in which the piece is stored.

```
<VTKFile type="PPolyData" ...>
  <PPolyData GhostLevel="#">
    <PPointData>...</PPointData>
    <PCellData>...</PCellData>
    <PPoints>...</PPoints>
    <Piece Source="polyData0.vtp"/>
    ...
  </PPolyData>
</VTKFile>
```

- **PUnstructuredGrid** — The `PUnstructuredGrid` element specifies the number of ghost-levels by which the individual pieces overlap. The `PPoints` element describes the type of array used to specify the point locations, but does not actually contain the data. Each `Piece` element specifies the file in which the piece is stored.

```
<VTKFile type="PUnstructuredGrid" ...>
  <PUnstructuredGrid GhostLevel="0">
    <PPointData>...</PPointData>
    <PCellData>...</PCellData>
    <PPoints>...</PPoints>
    <Piece Source="unstructuredGrid0.vtu"/>
    ...
  </PUnstructuredGrid>
</VTKFile>
```

Every dataset uses PPointData and PCellData elements to describe the types of data arrays associated with its points and cells.

- **PPointData** and **PCellData** — These elements simply mirror the `PointData` and `CellData` elements from the serial file formats. They contain `PDataArray` elements describing the data arrays, but without any actual data.

```
<PPointData Scalars="Temperature" Vectors="Velocity">
  <PDataArray Name="Velocity" .../>
```

```
    <PDataArray Name="Temperature" .../>
    <PDataArray Name="Pressure" .../>
  </PPointData>
```

For datasets that need specification of points, the following elements mirror their counterparts from the serial file format:

- **PPoints** — The `PPoints` element contains one `PDataArray` element describing an array with three components. The data array does not actually contain any data.

```
<PPoints>
  <PDataArray NumberOfComponents="3" .../>
</PPoints>
```

- **PCoordinates** — The `PCoordinates` element contains three `PDataArray` elements describing the arrays used to specify ordinates along each axis. The data arrays do not actually contain any data.

```
<PCoordinates>
  <PDataArray .../>
  <PDataArray .../>
  <PDataArray .../>
</PCoordinates>
```

All of the data and geometry specifications use `PDataArray` elements to describe the data array types:

- **PDataArray** — The `PDataArray` element specifies the `type`, `Name`, and optionally the `NumberOfComponents` attributes of the `DataArray` element. It does not contain the actual data. This can be used by readers to create the data array in their output without needing to read any real data, which is necessary for efficient pipeline updates in some cases.

```
<PDataArray type="Float32" Name="vectors" NumberOfComponents="3"/>
```

Example. The following is a complete example specifying a `vtkPolyData` representing a cube with some scalar data on its points and faces.

```
<?xml version="1.0"?>
<VTKFile type="PPolyData" version="0.1" byte_order="LittleEndian">
  <PPolyData GhostLevel="0">
    <PPointData Scalars="my_scalars">
      <PDataArray type="Float32" Name="my_scalars"/>
    </PPointData>
    <PCellData Scalars="cell_scalars" Normals="cell_normals">
      <PDataArray type="Int32" Name="cell_scalars"/>
      <PDataArray type="Float32" Name="cell_normals"
NumberOfComponents="3"/>
```

```
      </PCellData>
      <PPoints>
        <PDataArray type="Float32" NumberOfComponents="3"/>
      </PPoints>
      <Piece Source="polyEx0.vtp"/>
    </PPolyData>
  </VTKFile>


  <?xml version="1.0"?>
  <VTKFile type="PolyData" version="0.1" byte_order="LittleEndian">
    <PolyData>
      <Piece NumberOfPoints="8" NumberOfVerts="0" NumberOfLines="0"
             NumberOfStrips="0" NumberOfPolys="6">
        <Points>
         <DataArray type="Float32" NumberOfComponents="3" format="ascii">
            0 0 0 1 0 0 1 1 0 0 1 0 0 0 1 1 0 1 1 1 1 0 1 1
          </DataArray>
        </Points>
        <PointData Scalars="my_scalars">
          <DataArray type="Float32" Name="my_scalars" format="ascii">
            0 1 2 3 4 5 6 7
          </DataArray>
        </PointData>
        <CellData Scalars="cell_scalars" Normals="cell_normals">
          <DataArray type="Int32" Name="cell_scalars" format="ascii">
            0 1 2 3 4 5
          </DataArray>
          <DataArray type="Float32" Name="cell_normals"
                     NumberOfComponents="3" format="ascii">
            0 0 -1 0 0 1 0 -1 0 0 1 0 -1 0 0 1 0 0
          </DataArray>
        </CellData>
        <Polys>
          <DataArray type="Int32" Name="connectivity" format="ascii">
            0 1 2 3 4 5 6 7 0 1 5 4 2 3 7 6 0 4 7 3 1 2 6 5
          </DataArray>
          <DataArray type="Int32" Name="offsets" format="ascii">
            4 8 12 16 20 24
          </DataArray>
        </Polys>
      </Piece>
    </PolyData>
  </VTKFile>
```

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