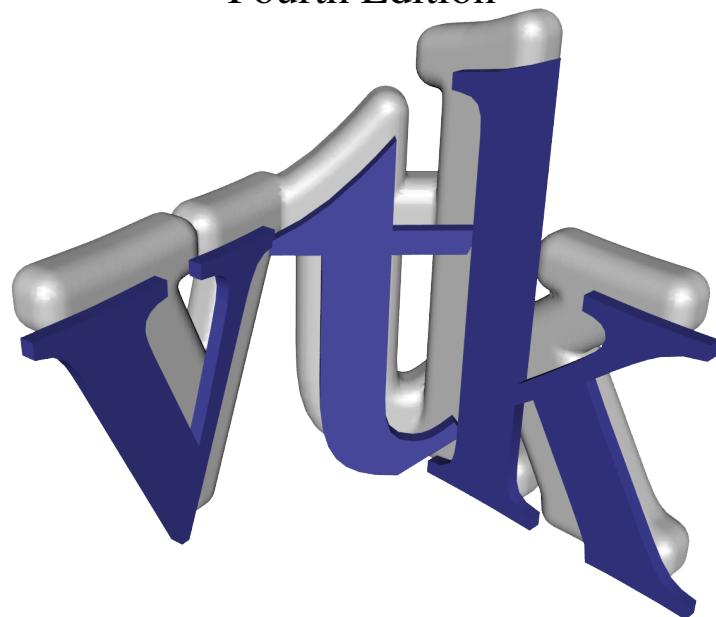


The Visualization Toolkit
An Object-Oriented Approach To 3D Graphics
Fourth Edition



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2006 Revised 26 April 2005

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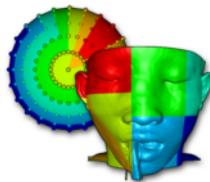
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Preface



Visualization is a great field to work in these days. Advances in computer hardware and software have brought this technology into the reach of nearly every computer system. Even the ubiquitous personal computer now offers specialized 3D graphics hardware at discount prices. And with recent releases of the Windows operating systems such as XP, OpenGL has become the de facto standard API for 3D graphics.

We view visualization and visual computing as nothing less than a new form of communication. All of us have long known the power of images to convey information, ideas, and feelings. Recent trends have brought us 2D images and graphics as evidenced by the variety of graphical user interfaces and business plotting software. But 3D images have been used sparingly, and often by specialists using specialized systems. Now this is changing. We believe we are entering a new era where 3D images, visualizations, and animations will begin to extend, and in some cases, replace the current communication paradigm based on words, mathematical symbols, and 2D images. Our hope is that along the way the human imagination will be freed like never before.

This text and companion software offers one view of visualization. The field is broad, including elements of computer graphics, imaging, computer science, computational geometry, numerical analysis, statistical methods, data analysis, and studies in human perception. We certainly do not pretend to cover the field in its entirety. However, we feel that this text does offer you a great opportunity to learn about the fundamentals of visualization. Not only can you learn from the written word and companion images, but the included software will allow you to *practice* visualization. You can start by using the sample data we have provided here, and then move on to your own data and applications. We believe that you will soon appreciate visualization as much as we do.

In this, the third edition of *Visualization Toolkit* textbook, we have added several new features since the first and second editions. Volume rendering is now extensively supported, including the ability to combine opaque surface graphics with volumes. We have added an extensive image processing pipeline that integrates conventional 3D visualization and graphics with imaging. Besides several new filters such as clipping, smoothing, 2D/3D Delaunay triangulation, and new decimation algorithms, we have added several readers and writers, and better support net-based tools such as Java and VRML. VTK now supports cell attributes, and attributes have been generalized into data arrays that are labeled as being scalars, vectors, and so on. Parallel processing, both shared-memory and distributed models, is a major addition. For example, VTK has been used on a large 1024-processor computer at the US National Labs to process nearly a pet-a-pat of data. A suite of 3D widgets is now available in VTK, enabling powerful data interaction techniques. Finally,

VTK's cross-platform support has greatly improved with the addition of CMake—a very nice tool for managing the compile process ([CMake](#)).

The additions of these features required the support of three special contributors to the text: Lisa Sobierajski Avila, Rick Avila, and C. Charles Law. Rick and Lisa worked hard to create an object-oriented design for volume rendering, and to insure that the design and software is fully compatible with the surface-based rendering system. Charles is the principle architect and implementer for the imaging pipeline. We are proud of the streaming and caching capability of the architecture: It allows us to handle large data sets despite limited memory resources.

Especially satisfying has been the response from users of the text and software. Not only have we received a warm welcome from these wonderful people, but many of them have contributed code, bug fixes, data, and ideas that greatly improved the system. In fact, it would be best to categorize these people as co-developers rather than users of the system. We would like to encourage anyone else who is interested in sharing their ideas, code, or data to contact the VTK user community at [VTK](#), or one of the authors. We would very much welcome any contributions you have to make. Contact us at [Kitware](#).

Acknowledgments

During the creation of the *Visualization Toolkit* we were fortunate to have the help of many people. Without their aid this book and the associated software might never have existed. Their contributions included performing book reviews, discussing software ideas, creating a supportive environment, and providing key suggestions for some of our algorithms and software implementations.

We would like to first thank our management at the General Electric Corporate R&D Center who allowed us to pursue this project and utilize company facilities: Peter Meenan, Manager of the Computer Graphics and Systems Program, and Kirby Vosburgh, Manager of the Electronic Systems Laboratory. We would also like to thank management at GE Medical Systems who worked with us on the public versus proprietary software issues: John Lalonde, John Heinen, and Steve Roehm.

We thank our co-workers at the R&D Center who have all been supportive: Matt Turek, for proof reading much of the second edition; also Majeid Alyassin, Russell Blue, Jeanette Bruno, Shane Chang, Nelson Corby, Rich Hammond, Margaret Kelliher, Tim Kelliher, Joyce Langan, Paul Miller, Chris Nafis, Bob Tatar, Chris Volpe, Boris Yamrom, Bill Hoffman (now at Kitware), Harvey Cline and Siegwalt Ludke. We thank former co-workers Skip Montanaro (who created a FAQ for us), Dan McLachlan and Michelle Barry. We'd also like to thank our friends and co-workers at GE Medical Systems: Ted Hudacko (who managed the first VTK users mailing list), Darin Okerlund, and John Skinner. Many ideas, helpful hints, and suggestions to improve the system came from this delightful group of people.

The third edition is now published by Kitware, Inc. We very much appreciate the efforts of the many contributors at Kitware who have helped make VTK one of the leading visualization systems in the world today. Sébastien Barré, Andy Cedilnik, Berk Geveci, Amy Henderson, and Brad King have each made significant contributions. Thank also to the folks at GE Global Research such as Jim Miller who continue to push the quality of the system, particularly with the creation of the DART system for regression testing. The US National Labs, led by Jim Ahrens of Los Alamos, has been instrumental in adding parallel processing support to VTK. An additional special thanks to Kitware for accepting the challenge of publishing this book.

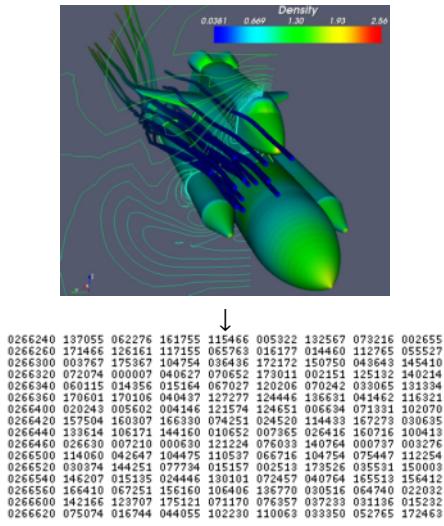
Many of the bug fixes and improvements found in the second and third editions came from talented people located around the world. Some of these people are acknowledged in the software and elsewhere in the text, but most of them have contributed their time, knowledge, code, and data without regard for recognition and acknowledgment. It is this exchange of ideas and information with people like this that makes the *Visualization Toolkit* such a fun and exciting project to work on. In particular we would like to thank John Biddicombe, Charl P. Botha, David Gobbi, Tim Hutton, Dean Inglis, and Prabhu Ramachandran. Thank you very much.

A special thanks to the software and text reviewers who spent their own time to track down some nasty bugs, provide examples, and offer suggestions and improvements. Thank you Tom Citriniti, Mark Miller, George Petras, Hansong Zhang, Penny Rheingans, Paul Hinken, Richard Ellson, and Roger Crawfis. We'd also like to mention that Tom Citriniti at Rensselaer, and Penny Rheingans at the University of Mississippi (now at the University of Maryland Baltimore County)

were the first faculty members to teach from early versions of this text. Thank you Penny and Tom for your feedback and extra effort.

Most importantly we would like to thank our friends and loved ones who supported us patiently during this project. We know that you shouldered extra load for us. You certainly saw a lot less of us! But we're happy to say that we're back. Thank you.

1.0 **Introduction**



Visualization transforms numbers to images.

Visualization 2: the act or process of interpreting in visual terms or of putting into visual form,
Websters Ninth New Collegiate Dictionary."

1.1 What Is Visualization?

Visualization is a part of our everyday life. From weather maps to the exciting computer graphics of the entertainment industry, examples of visualization abound. But what is visualization? Informally, visualization is the transformation of data or information into pictures. Visualization engages the primary human sensory apparatus, vision, as well as the processing power of the human mind. The result is a simple and effective medium for communicating complex and/or voluminous information

1.1.1 Terminology

Different terminology is used to describe visualization. Scientific visualization is the formal name given to the field in computer science that encompasses user interface, data representation and processing algorithms, visual representations, and other sensory presentation such as sound or touch.

[3]. The term data visualization is another phrase used to describe visualization. Data visualization is generally interpreted to be more general than scientific visualization, since it implies treatment of data sources beyond the sciences and engineering. Such data sources include financial, marketing, or business data. In addition, the term data visualization is broad enough to include application of statistical methods and other standard data analysis techniques [2]. Another recently emerging term is information visualization. This field endeavors to visualize abstract information such as hyper-text documents on the World Wide Web, directory/ file structures on a computer, or abstract data structures [15]. A major challenge facing information visualization researchers is to develop coordinate systems, transformation methods, or structures that meaningfully organize and represent data.

Another way to classify visualization technology is to examine the context in which the data exists. If the data is spatial-temporal in nature (up to three spatial coordinates and the time dimension) then typically methods from scientific visualization are used. If the data exists in higher dimensional spaces, or abstract spaces, then methods from information visualization are used. This distinction is important, because the human perceptual system is highly tuned to space-time relationships. Data expressed in this coordinate system is inherently understood with little need for explanation. Visualization of abstract data typically requires extensive explanations as to what is being viewed. This is not to say that there is no overlap between scientific and information visualization often the first step in the information visualization process is to project abstract data into the spatial-temporal domain, and then use the methods of scientific visualization to view the results. The projection process can be quite complex, involving methods of statistical graphics, data mining, and other techniques, or it may be as simple as selecting a lower-dimensional subset of the original data.

In this text we use the term data visualization instead of the more specific terms scientific visualization or information visualization. We feel that scientific visualization is too narrow a description of the field, since visualization techniques have moved beyond the scientific domain and into areas of business, social science, demographics, and information management in general. We also feel that the term data visualization is broad enough to encompass the term information visualization.

1.1.2 Examples of Visualization

Perhaps the best definition of visualization is offered by example. In many cases visualization is influencing peoples' lives and performing feats that a few years ago would have been unimaginable. A prime example of this is its application to modern medicine.

Computer imaging techniques have become an important diagnostic tool in the practice of modern medicine. These include techniques such as X-ray *Computed Tomography* (CT) and *Magnetic Resonance Imaging* (MRI). These techniques use a sampling or data acquisition process to capture information about the internal anatomy of a living patient. This information is in the form of *slice-planes* or cross-sectional images of a patient, similar to conventional photographic X-rays. CT imaging uses many pencil thin X-rays to acquire the data, while MRI combines large magnetic fields with pulsed radio waves. Sophisticated mathematical techniques are used to reconstruct the slice-planes. Typically, many such closely spaced slices are gathered together into a *volume* of data to complete the study.

As acquired from the imaging system, a slice is a series of numbers representing the attenuation of X-rays (CT) or the relaxation of nuclear spin magnetization (MRI) [8]. On any given slice these numbers are arranged in a matrix, or regular array. The amount of data is large, so large that it is not possible to understand the data in its raw form. However, by assigning to these numbers a gray scale value, and then displaying the data on a computer screen, structure emerges. This structure results from the interaction of the human visual system with the spatial organization of the data

and the gray-scale values we have chosen. What the computer represents as a series of numbers, we see as a cross section through the human body: skin, bone, and muscle. Even more impressive results are possible when we extend these techniques into three dimensions. Image slices can be gathered into volumes and the volumes can be processed to reveal complete anatomical structures. Using modern techniques, we can view the entire brain, skeletal system, and vascular system on a living patient without interventional surgery. Such capability has revolutionized modern medical diagnostics, and will increase in importance as imaging and visualization technology matures.

Another everyday application of visualization is in the entertainment industry. Movie and television producers routinely use computer graphics and visualization to create entire worlds that we could never visit in our physical bodies. In these cases we are visualizing other worlds as we imagine them, or past worlds we suppose existed. It's hard to watch the movies such as *Jurassic Park* and *Toy Story* and not gain a deeper appreciation for the awesome Tyrannosaurus Rex, or to be charmed by Toy Story's heroic Buzz Lightyear.

Morphing is another popular visualization technique widely used in the entertainment industry. Morphing is a smooth blending of one object into another. One common application is to morph between two faces. Morphing has also been used effectively to illustrate car design changes from one year to the next. While this may seem like an esoteric application, visualization techniques are used routinely to present the daily weather report. The use of isovalue, or contour, lines to display areas of constant temperature, rainfall, and barometric pressure has become a standard tool in the daily weather report.

Many early uses of visualization were in the engineering and scientific community. From its inception the computer has been used as a tool to simulate physical processes such as ballistic trajectories, fluid flow, and structural mechanics. As the size of the computer simulations grew, it became necessary to transform the resulting calculations into pictures. The amount of data overwhelmed the ability of the human to assimilate and understand it. In fact, pictures were so important that early visualizations were created by manually plotting data. Today, we can take advantage of advances in computer graphics and computer hardware. But, whatever the technology, the application of visualization is the same: to display the results of simulations, experiments, measured data, and fantasy; and to use these pictures to communicate, understand, and entertain.

1.2 Why Visualize?

Visualization is a necessary tool to make sense of the flood of information in today's world of computers. Satellites, supercomputers, laser digitizing systems, and digital data acquisition systems acquire, generate, and transmit data at prodigious rates. The Earth-Orbiting Satellite (EOS) transmits terabytes of data every day. Laser scanning systems generate over 500,000 points in a 15 second scan [19]. Supercomputers model weather patterns over the entire earth [5]. In the first four months of 1995, the New York Stock Exchange processed, on average, 333 million transactions per day [16]. Without visualization, most of this data would sit unseen on computer disks and tapes. Visualization offers some hope that we can extract the important information hidden within the data.

There is another important element to visualization: It takes advantage of the natural abilities of the human vision system. Our vision system is a complex and powerful part of our bodies. We use it and rely on it in almost everything we do. Given the environment in which our ancestors lived, it is not surprising that certain senses developed to help them survive. As we described earlier in the example of a 2D MRI scan, visual representations are easier to work with. Not only do we have strong 2D visual abilities, but also we are adept at integrating different viewpoints and other visual clues into a mental image of a 3D object or plot. This leads to interactive visualization, where we can manipulate our viewpoint. Rotating about the object helps to achieve a better understanding. Likewise, we have a talent for recognizing temporal changes in an image. Given an animation

consisting of hundreds of frames, we have an uncanny ability to recognize trends and spot areas of rapid change.

With the introduction of computers and the ability to generate enormous amounts of data, visualization offers the technology to make the best use of our highly developed visual senses. Certainly other technologies such as statistical analysis, artificial intelligence, mathematical filtering, and sampling theory will play a role in large-scale data processing. However, because visualization directly engages the vision system and human brain, it remains an unequaled technology for understanding and communicating data.

Visualization offers significant financial advantages as well. In today's competitive markets, computer simulation teamed with visualization can reduce product cost and improve time to market. A large cost of product design has been the expense and time required to create and test design prototypes. Current design methods strive to eliminate these physical prototypes, and replace them with digital equivalents. This digital prototyping requires the ability to create and manipulate product geometry, simulate the design under a variety of operating conditions, develop manufacturing techniques, demonstrate product maintenance and service procedures, and even train operators on the proper use of the product before it is built. Visualization plays a role in each case. Already CAD systems are used routinely to model product geometry and design manufacturing procedures. Visualization enables us to view the geometry, and see special characteristics such as surface curvature. For instance, analysis techniques such as finite element, finite difference, and boundary element techniques are used to simulate product performance; and visualization is used to view the results. Recently, human ergonomics and anthropometry are being analyzed using computer techniques in combination with visualization [9]. Three-dimensional graphics and visualization are being used to create training sequences. Often these are incorporated into a hypertext document or World Wide Web (WWW) pages. Another practical use of graphics and visualization has been in-flight simulators. This has been shown to be a significant cost savings as compared to flying real airplanes and is an effective training method.

1.3 Imaging, Computer Graphics, and Visualization

There is confusion surrounding the difference between imaging, computer graphics, and visualization. We offer these definitions.

- *Imaging*, or image processing, is the study of 2D pictures, or images. This includes techniques to transform (e.g., rotate, scale, shear), extract information from, analyze, and enhance images.

The resulting data is mapped to a graphics system for display.

- *Computer graphics* is the process of creating images using a computer. This includes both 2D paint-and-draw techniques as well as more sophisticated 3D drawing (or rendering) techniques.
- *Visualization* is the process of exploring, transforming, and viewing data as images (or other sensory forms) to gain understanding and insight into the data.

Based on these definitions we see that there is overlap between these fields. The output of computer graphics is an image, while the output of visualization is often produced using computer graphics. Sometimes visualization data is in the form of an image, or we wish to visualize object geometry using realistic rendering techniques from computer graphics.

Generally speaking we distinguish visualization from computer graphics and image processing in three ways.

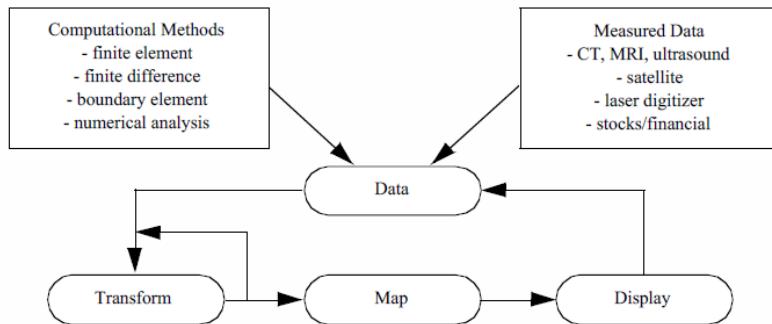


Figure 1.1: The visualization process. Data from various sources is repeatedly transformed to extract, derive, and enhance information. The resulting data is mapped to a graphics system for display.

1. The dimensionality of data is three dimensions or greater. Many well-known methods are available for data of two dimensions or less; visualization serves best when applied to data of higher dimension.
2. Visualization concerns itself with data transformation. That is, information is repeatedly created and modified to enhance the meaning of the data.
3. Visualization is naturally interactive, including the human directly in the process of creating, transforming, and viewing data.

Another perspective is that visualization is an activity that encompasses the process of exploring and understanding data. This includes both imaging and computer graphics as well as data processing and filtering, user interface methodology, computational techniques, and software design. **Figure 1.1** depicts this process.

As this figure illustrates we see that the visualization process focuses on data. In the first step data is acquired from some source. Next, the data is transformed by various methods, and then mapped to a form appropriate for presentation to the user. Finally, the data is rendered or displayed, completing the process. Often, the process repeats as the data is better understood or new models are developed. Sometimes the results of the visualization can directly control the generation of the data. This is often referred to as *analysis steering*. Analysis steering is an important goal of visualization because it enhances the interactivity of the overall process.

1.4 Origins of Data Visualization

The origin of visualization as a formal discipline dates to the 1987 NSF report *Visualization in Scientific Computing* [3]. That report coined the term *scientific visualization*. Since then the field has grown rapidly with major conferences, such as IEEE Visualization, becoming well established. Many large computer graphics conferences, for example ACM SIGGRAPH, devote large portions of their program to visualization technology.

Of course, data visualization technology had existed for many years before the 1987 report referenced [18]. The first practitioners recognized the value of presenting data as images. Early pictorial data representations were created during the eighteenth century with the arrival of statistical graphics. It was only with the arrival of the digital computer and the development of the field of computer graphics, that visualization became a practicable discipline.

The future of data visualization and graphics appears to be explosive. Just a few decades ago, the field of data visualization did not exist and computer graphics was viewed as an offshoot of the more formal discipline of computer science. As techniques were created and computer power increased, engineers, scientists, and other researchers began to use graphics to understand and communicate data. At the same time, user interface tools were being developed. These forces have now converged to the point where we expect computers to adapt to humans rather than the other way around. As such, computer graphics and data visualization serve as the window into the computer, and more importantly, into the data that computers manipulate. Now, with the visualization window, we can extract information from data and analyze, understand, and manage more complex systems than ever before.

Dr. Fred Brooks, Kenan Professor of Computer Science at the University of North Carolina at Chapel Hill and recipient of the John von Neumann Medal of the IEEE, puts it another way. At the award presentation at the ACM SIGGRAPH '94, Dr. Brooks stated that computer graphics and visualization offer "intelligence amplification" (IA) as compared to artificial intelligence (AI). Besides the deeper philosophical issues surrounding this issue (e.g., human before computer), it is a pragmatic observation. While the long-term goal of AI has been to develop computer systems that could replace humans in certain applications, the lack of real progress in this area has lead some researchers to view the role of computers as amplifiers and assistants to humans. In this view, computer graphics and visualization play a significant role, since arguably the most effective human/computer interface is visual. Recent gains in computer power and memory are only accelerating this trend, since it is the interface between the human and the computer that often is the obstacle to the effective application of the computer.

1.5 Purpose of This Book

There currently exist texts that define and describe data visualization, many of them using case studies to illustrate techniques and typical applications. Some provide high-level descriptions of algorithms or visualization system architectures. Detailed descriptions are left to academic journals or conference proceedings. What these texts lack is a way to *practice* visualization. Our aim in this text is to go beyond descriptions and provide tools to learn about and apply visualization to your own application area. In short, the purpose of the book is fourfold.

1. Describe visualization algorithms and architectures in detail.
2. Demonstrate the application of data visualization to a broad selection of case studies.
3. Provide a working architecture and software design for application of data visualization to real-world problems.
4. Provide effective software tools packaged in a C++ class library. We also provide language bindings for the interpreted languages Tcl, Python, and Java.

Taken together, we refer to the text and software as the *Visualization Toolkit*, or VTK for short. Our hope is that you can use the text to learn about the fundamental concepts of visualization, and then adapt the computer code to your own applications and data.

1.6 What This Book Is Not

The purpose of this book is not to provide a rigorous academic treatise on data visualization. Nor do we intend to include an exhaustive survey of visualization technology. Our goal is to bridge

the formal discipline of data visualization with practical application, and to provide a solid technical overview of this emerging technology. In many cases we refer you to the included software to understand implementation details. You may also wish to refer to the appropriate references for further information.

1.7 Intended Audience

Our primary audience is computer users who create, analyze, quantify, and/or process data. We assume a minimal level of programming skill. If you can write simple computer code to import data and know how to run a computer program, you can practice data visualization with the software accompanying this book.

As we wrote this book we also had in mind educators and students of introductory computer graphics and visualization courses. In more advanced courses this text may not be rigorous enough to serve as sole reference. In these instances, this book will serve well as a companion text, and the software is well suited as a foundation for programming projects and class exercises.

Educators and students in other disciplines may also find the text and software to be valuable tools for presenting results. Courses in numerical analysis, computer science, business simulation, chemistry, dynamic systems, and engineering simulations, to name a few, often require large-scale programming projects that create large amounts of data. The software tools provided here are easy to learn and readily adapted to different data sources. Students can incorporate this software into their work to display and analyze their results.

1.8 How to Use This Book

There are a number of approaches you can take to make effective use of this book. The particular approach depends on your skill level and goals. Three likely paths are as follows:

Novice. You're a novice if you lack basic knowledge of graphics, visualization, or object-oriented principles. Start by reading Chapter 2 if you are unfamiliar with object-oriented principles, Chapter 3 if you are unfamiliar with computer graphics, and Chapter 4 if you are unfamiliar with visualization. Continue by reading the application studies in Chapter 12. You can then move on to the CD-ROM and try out some programming examples. Leave the more detailed treatment of algorithms and data representation until you are familiar with the basics and plan to develop your own applications.

Hacker. You're a hacker if you are comfortable writing your own code and editing other's. Review the examples in Chapter 3, Chapter 4, and Chapter 12. At this point you will want to acquire the companion software guide to this text (*The VTK User's Guide*) or become familiar with the programming resources at [VTK](#). Then retrieve the examples from the CD-ROM and start practicing.

Researcher/Educator. You're a researcher if you develop computer graphics and/or visualization algorithms or if you are actively involved in using and evaluating such systems. You're an educator if you cover aspects of computer graphics and/or visualization within your courses. Start by reading Chapter 2, Chapter 3, and Chapter 4. Select appropriate algorithms from the text and examine the associated source code. If you wish to extend the system, we recommend that you acquire the companion software guide to this text (*The VTK User's Guide*) or become familiar with the programming resources at [VTK](#).

1.9 Software Considerations and Example Code

In writing this book we have attempted to strike a balance between practice and theory. We did not want the book to become a user manual, yet we did want a strong correspondence between algorithmic presentation and software implementation. (Note: *The VTK User's Guide* published by Kitware, Inc. <http://www.kitware.com> is recommended as a companion text to this book.) As a result of this philosophy, we have adopted the following approach:

Application versus Design. The book's focus is the application of visualization techniques to real-world problems. We devote less attention to software design issues. Some of these important design issues include: memory management, deriving new classes, shallow versus deep object copy, single versus multiple inheritance, and interfaces to other graphics libraries. Software issues are covered in the companion text *The VTK User's Guide* published by Kitware, Inc.

Theory versus Implementation. Whenever possible, we separate the theory of data visualization from our implementation of it. We felt that the book would serve best as a reference tool if the theory sections were independent of software issues and terminology. Toward the end of each chapter there are separate implementation or example sections that are implementation specific. Earlier sections are implementation free.

Documentation. This text contains documentation considered essential to understanding the software architecture, including object diagrams and condensed object descriptions. More extensive documentation of object methods and data members is embedded in the software (in the.h header files) and on CD-ROM or online at [VTK](#). In particular, the Doxygen generated manual pages contain detailed descriptions of class relationships, methods, and other attributes.

We use a number of conventions in this text. Imported computer code is denoted with a typewriter font, as are external programs and computer files. To avoid conflict with other C++ class libraries, all class names in VTK begin with the "vtk" prefix. Methods are differentiated from variables with the addition of the "()" postfix. (Other conventions are listed in *VTK User's Guide*.)

All images in this text have been created using the *Visualization Toolkit* software and data found on the included CD-ROM or from the Web site <http://www.vtk.org>. In addition, every image has source code (sometimes in C++ and sometimes a Tcl script). We decided against using images from other researchers because we wanted you to be able to practice visualization with every example we present. Each computer generated image indicates the originating file. Files ending in.cxx are C++ code, files ending in.tcl are Tcl scripts. Hopefully these examples can serve as a starting point for you to create your own applications.

To find the example code you will want to search in one of three areas. The standard VTK distribution includes an VTK/Examples directory where many well-documented examples are found. The VTK testing directories VTK/Testing, for example, VTK/Graphics/Testing/Tcl, contain some of the example code used in this text. These examples use the data found in the VTKData distribution. Finally, a separate software distribution, the VTKTextbook distribution, contains examples and data that do not exist in the standard VTK distribution. The VTK, VTKData, and VTKTextbook distributions are found on the included CD-ROM and/or on the web site at [VTK](#).

1.10 Chapter-by-Chapter Overview

Chapter 2: Object-Oriented Design

This chapter discusses some of the problems with developing large and/or complex software systems and describes how object-oriented design addresses many of these problems. This chapter defines the key terms used in object-oriented modelling and design and works through a real-world

example. The chapter concludes with a brief look at some object-oriented languages and some of the issues associated with object-oriented visualization.

Chapter 3: Computer Graphics Primer

Computer graphics is the means by which our visualizations are created. This chapter covers the fundamental concepts of computer graphics from an application viewpoint. Common graphical entities such as cameras, lights, and geometric primitives are described along with some of the underlying physical equations that govern lighting and image generation. Issues related to currently available graphics hardware are presented, as they affect how and what we choose to render. Methods for interacting with data are introduced.

Chapter 4: The Visualization Pipeline

This chapter explains our methodology for transforming raw data into a meaningful representation that can than be rendered by the graphics system. We introduce the notion of a visualization pipeline, which is similar to a data flow diagram from software engineering. The differences between process objects and data objects are covered, as well as how we resolved issues between performance and memory usage. We explain the advantages to a pipeline network topology regarding execution ordering, result caching, and reference counting.

Chapter 5: Basic Data Representation

There are many types of data produced by the variety of fields that apply visualization. This chapter describes the data objects that we use to represent and access such data. A flexible design is introduced where the programmer can interact with most any type of data using one consistent interface. The three high level components of data (structure, cells, and data attributes) are introduced, and their specific subclasses and components are discussed.

Chapter 6: Fundamental Algorithms

Where the preceding chapter deals with data objects, this one introduces process objects. These objects encompass the algorithms that transform and manipulate data. This chapter looks at commonly used techniques for isocontour extraction, scalar generation, color mapping, and vector field display, among others. The emphasis of this chapter is to provide the reader with a basic understanding of the more common and important visualization algorithms.

Chapter 7: Advanced Computer Graphics

This chapter covers advanced topics in computer graphics. The chapter begins by introducing transparency and texture mapping, two topics important to the main thrust of the chapter: volume rendering. Volume rendering is a powerful technique to see inside of 3D objects, and is used to visualize volumetric data. We conclude the chapter with other advanced topics such as stereoscopic rendering, special camera effects, and 3D widgets.

Chapter 8: Advanced Data Representation

Part of the function of a data object is to store the data. The first chapter on data representation discusses this aspect of data objects. This chapter focuses on basic geometric and topological access methods, and computational operations implemented by the various data objects. The chapter

covers such methods as coordinate transformations for data sets, interpolation functions, derivative calculations, topological adjacency operations, and geometric operations such as line intersection and searching.

Chapter 9: Advanced Algorithms

This chapter is a continuation of *Fundamental Algorithms* and covers algorithms that are either more complex or less widely used. Scalar algorithms such as dividing cubes are covered along with vector algorithms such as stream ribbons. A large collection of modelling algorithms is discussed, including triangle strip generation, polygon decimation, feature extraction, and implicit modelling. We conclude with a look at some visualization algorithms that utilize texture mapping.

Chapter 10: Image Processing

While 3D graphics and visualization is the focus of the book, image processing is an important tool for preprocessing and manipulating data. In this chapter we focus on several important image processing algorithms, as well as describe how we use a streaming data representation to process large datasets.

Chapter 11: Visualization on the Web

The Web is one of the best places to share your visualizations. In this chapter we show you how to write Java-based visualization applications, and how to create VRML (Virtual Reality Modelling Language) data files for inclusion in your own Web content.

Chapter 12: Applications

In this chapter we tie the previous chapters together by working through a series of case studies from a variety of application areas. For each case, we briefly describe the application and what information we expect to obtain through the use of visualization. Then, we walk through the design and resulting source code to demonstrate the use of the tools described earlier in the text.

1.11 Legal Considerations

We make no warranties, expressly or implied, that the computer code contained in this text is free of error or will meet your requirements for any particular application. Do not use this code in any application where coding errors could result in injury to a person or loss of property. If you do use the code in this way, it is at your own risk. The authors and publisher disclaim all liability for direct or consequential damages resulting from your use of this code.

The computer code contained in this text is copyrighted. We grant permission for you to use, copy, and distribute this software for any purpose. However, you may not modify and then redistribute the software. Some of the algorithms presented here are implementations of patented software. If you plan to use this software for commercial purposes, please insure that applicable patent laws are observed.

Some of the data on the CD-ROM may be freely distributed or used (with appropriate acknowledgment). Refer to the local README files or other documentation for details.

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is a trademark of the Massachusetts Institute of Technology. Starbase and HP are trademarks of Hewlett-Packard Inc. Silicon Graphics and OpenGL, are trademarks of Silicon Graphics, Inc. Macintosh is a trademark of Apple Computer. RenderMan is a trademark of Pixar.

1.12 Bibliographic Notes

A number of visualization texts are available. The first six texts listed in the reference section are good general references ([10], [11], [1], [21], [2], and [6]). Gallagher [6] is particularly valuable if you are from a computational background. Wolff and Yaeger [21] contains many beautiful images and is oriented towards Apple Macintosh users. The text includes a CD-ROM with images and software.

You may also wish to learn more about computer graphics and imaging. Foley and van Dam [7] is the basic reference for computer graphics.

Another recommended text is [4]. Suggested reference books on computer imaging are [12] and [20].

Two texts by Tufte [18] [17] are particularly impressive. Not only are the graphics superbly done, but the fundamental philosophy of data visualization is articulated. He also describes the essence of good and bad visualization techniques.

Another interesting text is available from Siemens, a large company offering medical imaging systems [8]. This text describes the basic concepts of imaging technology, including MRI and CT. This text is only for those users with a strong mathematical background. A less mathematical overview of MRI is available from [14].

To learn more about programming with Visualization Toolkit, we recommend the text The VTK Users Guide [13]. This text has an extensive example suite as well as descriptions of the internals of the software. Programming resources including a detailed description of APIs, VTK file formats, and class descriptions are provided.

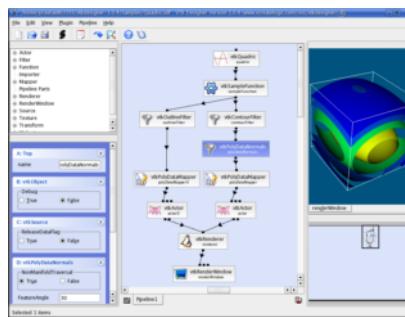
Bibliography

- [1] K. W. Brodlie et al. *Scientific Visualization Techniques and Applications*. Springer-Verlag, Berlin, 1992.
- [2] L. Rosenblum et al. *Scientific Visualization Advances and Challenges*. Harcourt Brace & Company, London, 1994.
- [3] B. H. McCormick, T. A. DeFanti, and M. D. Brown. *Visualization in Scientific Computing*. Report of the NSF Advisory Panel on Graphics, Image Processing and Workstations, 1987.
- [4] P. Burger and D. Gillies. *Interactive Computer Graphics Functional, Procedural and Device-Level Methods*. Addison-Wesley Publishing Company, Reading, MA, 1989.
- [5] P. C. Chen. “A Climate Simulation Case Study”. In: *Proceedings of Visualization '93*. IEEE Computer Society Press, Los Alamitos, 1993, pp. 391–401.
- [6] R. S. Gallagher, ed. *Computer Visualization Graphics Techniques for Scientific and Engineering Analysis*. CRC Press, Boca Raton, FL, 1995.
- [7] J. D. Foley, A. van Dam, S. K. Feiner, and J. F. Hughes. *Computer Graphics Principles and Practice (2d Ed)*. Addison-Wesley, Reading, MA, 1990.
- [8] E. Krestel, ed. *Imaging Systems for Medical Diagnostics*. Siemens-Aktienges, Munich, 1990.
- [9] *McDonnell Douglas Human Modeling System Reference Manual*. Version 2.1. Report MDC 93K0281. Mc-Donnell Douglas Corporation, Human Factors Technology. July 1993.
- [10] G. M. Nielson and B. Shriver, eds. *Visualization in Scientific Computing*. IEEE Computer Society Press, Los Alamitos, 1990.
- [11] N. M. Patrikalakis, ed. *Scientific Visualization of Physical Phenomena*. Springer-Verlag, Berlin, 1991.
- [12] T. Pavlidis. *Graphics and Image Processing*. Computer Science Press, Rockville, MD, 1982.
- [13] Will Schroeder, Ken Martin, and Bill Lorensen. *The VTK User's Guide*. Ed. by W. Schroeder. Kitware, 2006. ISBN: 1-930934-19-X. URL: <https://www.amazon.com/Visualization-Toolkit-Object-Oriented-Approach-Graphics/dp/193093419X?SubscriptionId=0JYN1NVW651KCA56C102&tag=techkie-20&linkCode=xm2&camp=2025&creative=165953&creativeASIN=193093419X>.
- [14] H. J. Smith and F. N. Ranallo. *A Non-Mathematical Approach to Basic MRI*. Medical Physics Publishing Corporation, Madison, WI, 1989.
- [15] *The First Information Visualization Symposium*. IEEE Computer Society Press, 1995.
- [16] *The New York Times Business Day, Tuesday, May 2 (1990)*.
- [17] E. R. Tufte. *Envisioning Information*. Graphics Press, Cheshire, CT, 1999.
- [18] E. R. Tufte. *The Visual Display of Quantitative Information*. Graphics Press, Cheshire, CT, 1990.

- [19] K. Waters and D. Terzopoulos. “Modeling and Animating Faces Using Scanned Data”. In: *Visualization and Computer Animation*. 2. 1991, pp. 123–128.
- [20] G. Wolberg. *Digital Image Warping*. IEEE Computer Society Press, Los Alamitos, CA, 1990.
- [21] R. S. Wolff and L. Yaeger. *Visualization of Natural Phenomena TELOS*. Springer-Verlag, Santa Clara, CA, 1993.

2.0

Object-Oriented Design



VTK Designer image courtesy of vcreatelogic.com.

O

bject-oriented systems are becoming widespread in the computer industry for good reason.

Object-oriented systems are more modular, easier to maintain, and easier to describe than traditional procedural systems. Since the *Visualization Toolkit* has been designed and implemented using object-oriented design, we devote this chapter to summarizing the concepts and practice of object-oriented design and implementation.

2.1 Introduction

Todays software systems try to solve complex, real-world problems. A rigorous software design and implementation methodology can ease the burden of this complexity. Without such a methodology, software developers can find it difficult to meet a systems specifications. Furthermore, as specifications change and grow, a software system that does not have a solid, underlying architecture and design will have difficulty adapting to these expanding requirements.

Our visualization system is a good example of complex software that needs to be designed with extensibility in mind. Data visualization is a rapidly expanding field, with visualization techniques being introduced each year. Any system that hopes to incorporate future innovations must have an underlying design that supports the addition of new material without a significant impact on the existing system.

Object-oriented design is a software engineering methodology that deals comfortably with complexity and provides a framework for later changes and additions. The object-oriented design process attempts to divide a complex task into small and simple pieces called objects. The objects are computer abstractions that model physical or abstract pieces of the system being simulated. Object-oriented design methodologies provide mechanisms to identify the abstractions that exist within a system and to model the behavior of the objects.

2.2 Goals of Good Software Design

The quality of a software design is difficult to measure, but some qualitative aspects can guide us. A good software design should be robust, understandable, extendible, modular, maintainable, and reusable.

A robust system handles exceptional conditions gracefully and behaves consistently. Robustness gives software developers confidence that the underlying components of the system will behave as expected, even when the system is used under different circumstances than the original implementor intended.

An understandable system can be used by someone other than the original implementor. The use of the system should seem logical and sensible. The names of the components of the system should be derived from the problem domain.

Extendable systems accept new tasks while still doing the tasks they were originally intended to perform. A system should accept new forms of data and new algorithms without disrupting existing software. Adding a new primitive to the system should not cause large portions of the system to be modified. Experience shows that the more existing code that is modified in a system, the more likely errors will be introduced.

Modular software systems minimize the number of relationships that exist between components of a system. System components that are tightly coupled should be grouped together logically and obey common naming conventions and protocols.

Software maintenance is often ignored during system design. Nevertheless, the total cost of a system includes maintenance as well as the original development. A software system is maintainable if problems are easily isolated and the repair of one problem does not introduce problems in unrelated parts of the system.

Finally, the economics of software development require that we leverage as much of our past work as possible. In an ideal world, the implementation of a new technique in an existing system should be a simple task. This is seldom the case in software systems. Creation of reusable software components can reduce duplication of effort and promote consistent interfaces within a system. However, as we see throughout this book, creating software that can be reused often takes extra effort. A short-term view of productivity by one individual conflicts with the long-term view of the productivity of a software development organization.

2.3 Object-Oriented Concepts

Objects are the dominating concepts in object-oriented systems. Objects are abstractions that encapsulate the properties and behavior of the entities within a system. Each object has an identity that distinguishes it from other objects in the system. Often, the distinguishable aspects of an object are obvious. For example, a difference in color, location on a screen, size, or contents distinguishes one window from another on a computer desktop. But, appearances can be deceiving, and even two objects that share all the same characteristics may still have different identities. Two automobiles may have the same manufacturer, model, options and colors, but remain two different cars. The real world distinguishes the two cars by a vehicle identification number. Likewise, programming systems that deal with multiple entities need an identity mechanism. A pointer to allocated memory or a variable name in a system-managed symbol table are often used to distinguish objects in a system. In a database system, a set of identifier keys (called an *n*-tuple) identifies an entity in a system.

But, how do object-oriented systems differ from conventional, procedural programming systems? The major difference is in the way the two approaches treat data abstraction. Conventional systems limit abstraction to data typing, while object-oriented systems create abstractions for both

the data and the operations that can be applied to the data. In fact, an object-oriented system keeps the data and operations together in one programming construct called an object. Together, the data and operations comprise an object's *properties*. When an operation is applied to an object, the programming language's dynamic-binding mechanism executes the procedure that is appropriate for that object. This is not the case in procedure-oriented systems. The programmer must supply logic to decide which procedure to call. Systems that handle multiple types are often littered with case statements to select the appropriate procedure for an operation. As new types are added to these systems, the code that dispatches operations based on data type must be extended to handle the new type. For example, in a program to display different types of primitives, the following pseudo code shows how a procedure-oriented system differs from an object-oriented system.

Procedure oriented (in C++):

Listing 2.1: Procedure oriented.

```

1 Primitive *aPrim;
2 ...
3 DrawPrimitive (aPrim)
4 ...
5 procedure DrawPrimitive (aPrim)
6 {
7     if (aPrim->type == TRIANGLE) then DrawTriangle (aPrim)
8     else if (aPrim->type == SQUARE) then DrawSquare (aPrim)
9     else if (aPrim->type == CIRCLE) then DrawCircle (aPrim)
10 ...
11 }
```

Object-oriented (in C++):

Listing 2.2: Object-oriented.

```

1 ...
2 aPrim->Draw ();
3 ...
```

Later in this project's existence, someone may want to add a new primitive, let's say a quadratic. The person assigned with such a formidable task must search the existing system for all occurrences of the if statements in the first example and add a test for the new quadratic type. Of course, a good programmer will have isolated the code in one location, as we have done here, so the task is easier. Nevertheless, that programmer must first realize that the original programmer was skilled enough to modularize the drawing code, then find the code (without necessarily knowing the procedure name) and modify the code. To complicate matters, a system built by more than one programmer will undoubtedly be under a configuration management system, requiring a check-out, edit, and check-in cycle.

The object-oriented programmer has an easier task. Consulting the design document that defines the object properties for a primitive, this programmer adds a draw operation to the quadratic object. The new primitive is available to the system without changing any existing code! Of course, this is an oversimplified example. But think about past programs you have written and remember how hard it was to add a new data type. Were your changes isolated to the new code you added? Did you have to edit code that you did not write and maybe did not understand? Keep this example in mind as you read our object-oriented implementation of a data visualization library.

Before describing object-oriented design and programming in more detail, we provide an observation and prediction. Over the several years that we have designed and implemented software

using an object-oriented methodology, we have observed that newcomers to the technique will say, "But this is how I already write programs. My systems are modular; they're robust; I can easily add to them." If you still feel that way after reading this book, do not fault the object-oriented approach. Rather, we have failed as authors. However, such a negative response is unlikely. In our experience, users become comfortable with this approach in a short time. Especially when they are introduced to objects through an existing, well-designed object-oriented system. You will reach the "aha" stage, after which it will be difficult to begin a software project without looking for the objects in the problem.

2.4 Object-Oriented Terminology

As with any software engineering design methodology, object-oriented design has its own terminology. Unfortunately, not everyone agrees on what that is. We adopt much of our terminology from Rumbaugh [12] and, since the *Visualization Toolkit* is written in C++, from Stroustrup [20]. For the most part, Rumbaugh's terminology is independent of programming language, while Stroustrup is specific to implementation in C++. The transition from design to programming will be painless though, and the mappings between the two terminologies are mostly obvious. Where we think there might be confusion, we will point out the correspondences.

2.4.1 What Is an Object?

An *object* is an abstraction that models the state and behavior of entities in a system. Abstraction is a mental process that extracts the essential aspects of a situation for a particular purpose. Entities are things in the system that have identity. Chairs, airplanes, and cameras are objects that correspond to physical entities in the real world. Binary trees, symbol tables, and ordered collections are objects that exist only within the world of computer science.

Figure 2.1 is an example of the abstraction that occurs when we map the state and behavior of a system component to an object. Here, the object is a particular type of tree: a pin oak. In this application we desire to simulate the growth of various types of trees over the course of a season. For our purpose we have decided that the important state variables are the tree's age, trunk diameter, height, and habit (i.e., growing form). To capture the behavior of the pin oak we have methods to simulate growth and seasonal effects corresponding to spring, summer, fall, and winter. There are also methods (not shown) for setting and getting current state variables.

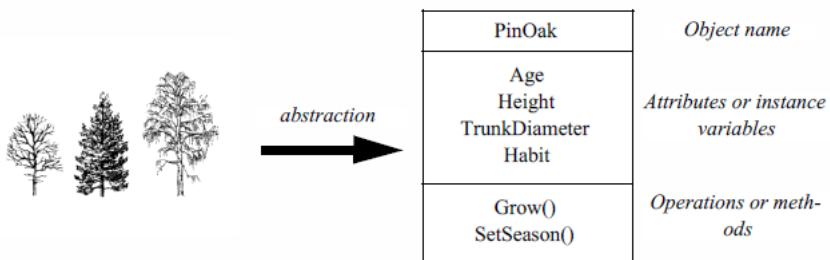


Figure 2.1: Mapping a real-world object into an object abstraction. The real-world objects are various types of trees. One of these objects (a pin oak tree) is mapped into the computer object we call PinOak.

We call the state of an object its *attributes* (also called *instance variables*) and define its behavior by the *operations* that can be applied to it. Attributes have a name, a data type, and a data

value. The data type of an attribute may be a primitive type in the programming language (such as a char or float in C++), or another object. For example, the vtkTransform object in our visualization system has an attribute of type vtkMatrix4x4 , another object. vtkMatrix4x4 in turn has attributes that are an array of primitive values declared as float values in C++.

Operations are functions or transformations that can be applied to an object. Operations define the behavior of the object. The operations for a particular object are implemented in procedures we call *methods*.

Together, the attributes and operations of an object comprise its *properties*. A two-dimensional line graph could have attributes that include an *x* and *y* axis, a legend, and a connected set of points. This graph has methods that draw the graph in a window. It also has methods that let a user specify the axes, data to draw, and legend to use.

Objects that share the same properties can be grouped using the process of *classification*. An object class, usually just called a class, specifies the properties that all objects in the class have. The class only specifies the names of the properties, not their specific values. Different classes can (and usually do) have properties with names that exist in other classes. Many classes in our visualization system have an attribute named Position. Although both a camera and actor in our visualization system have this attribute, the effect on each is different because they are different classes. Attribute names are shared by all objects in a given class, but separate storage is allocated for each object's attribute values.

When an operation with the same name is applied to objects of different classes we call the operation *polymorphic*. For example, our visualization system has an operation named Render() that can be applied to many different objects. The implementation of an operation for a particular class is called a method. The print operation for a vtkMatrix4x4 object is implemented in its print method. That is, there exists code that knows how to print objects of class vtkMatrix4x4 and not objects of other classes. Objects know which method to use because they are kept within each object's data structure. In most systems the code for the methods is shared by all objects in the same class. Some programming languages, including C++, define a method by combining an operation name with its argument types. This process is called overloading an operation and is a powerful technique that permits the same name to be used for logically similar operations. For example, the class definition below defines three methods for calculating the square of a number. Even though these methods have the same operation name, they are unique because C++ uses both the operation name and the operations argument types.

Listing 2.3: math class.

```

1 class math
2 {
3     float square(float x);
4     int square(int x);
5     double square(double x);
6 }
```

To use a member of a class for some purpose, we create an instance of the class (the process of *instantiation*). Instance creation establishes the identity of the instance including specifying its initial state. The instance's class serves as a template for the instance during creation, defining the names of each of its attributes and operations. Creation establishes the similarities and differences between this instance and other instances of the same class. The similarities are the names and type of its attributes and the methods that implement its operations. The differences are the specific values of the attributes. The details of how one creates an instance of a class vary from programming language to programming language. In C++, a program creates an instance using a declarative form such as

```
vtkActor aBall;
```

which creates an object from the program stack, or by applying the new operation

```
vtkActor *aBall = new vtkActor;
```

which creates the object from the program heap.

2.4.2 Inheritance

Inheritance is a programming mechanism that simplifies adding new classes to a system when they differ in small ways from currently existing classes. The notion of inheritance is adopted from the observation that most systems can be specified using a hierarchical classification system. A fine example of a classification system is the phyla of life on earth.

Earlier we created an object corresponding to a pin oak tree. The properties of the tree can be more thoroughly described using inheritance (Figure 2.2). The classification shown here is based on the five kingdom system of Margulis and Schwartz [[Margulis88]]. In this system, biota is classified as belonging to one of the five kingdoms Prokaryotae (bacteria), Protocista (algae, protozoans and slime molds), Fungi (mushrooms, molds, lichens), Plantae (mosses, ferns, cone-bearing, and flowering plants), and Animalia (animals with and without backbones). Below this level we have the classifications division, class, order, family, genus, and species. The figure shows the kingdom, division, class, genus, and species of the pin oak.

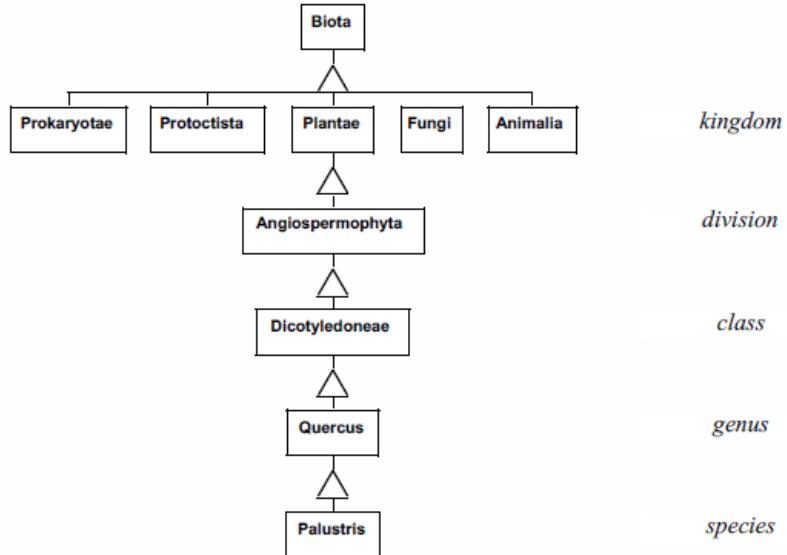


Figure 2.2: Inheritance hierarchy for pin oak tree.

Organizing objects into an inheritance hierarchy provides many benefits. Properties of a general classification are also properties of its subclassification. For example, we know that all species of genus *Quercus* form acorns. From the software point of view this means any instance variables and methods of a *superclass* are automatically inherited by its *subclass*. This allows us to make changes to a number of objects simultaneously by modifying their superclass. Furthermore, if we desire to add a new class (say a red oak tree) to the hierarchy we can do so without duplicating

existing functionality. We need only differentiate the new class from the others by adding new instance variables or overloading existing methods.

The ability to quickly add new classes that are slightly different from currently existing classes promotes the extensibility of a system. Inheritance can be derived top-down using a process called *specialization*, or it can be created bottom-up, combining similar classes during a process called *generalization*. The use of inheritance implies a class hierarchy with one or more classes being the superclasses of one or more subclasses. A subclass inherits the operations and attributes of its superclasses. In C++, subclasses are called *derived* classes and superclasses are called *base* classes. A subclass can add additional operations and attributes that modify the properties it inherited from its superclasses. Through this inheritance, an object can exhibit its superclass's behavior plus any additional behavior it wishes. It can also restrict, or override, operations implemented by its superclass.

Classes that exist only to act as superclasses for their subclasses are called *abstract* classes. Instance creation of an abstract class is generally prohibited. Abstract classes are useful for gathering attributes and methods that all subclasses will use. They can also define protocols for behavior for their subclasses. This is a powerful use of inheritance that will show up in the design of our visualization system. Abstract classes can enforce complex sequence, control protocols, and ensure uniform behavior. They remove the responsibility of complex protocols from the individual sub-classes and isolate the protocol in the superclass.

An example of a simple plotting package illustrates the power of abstract classes. Consider a data presentation application that allows for a variety of two-dimensional plotting. This application must support line charts and horizontal and vertical bar charts. The design process identifies properties common to all plots including title, axes, and legend. We then create an abstract class called TwoDPlot to contain these common attributes. Common behavior can also be captured in TwoDPlot within its plot method:

Listing 2.4: TwoDPlot.

```

1 Method Plot
2 {
3     Draw the border
4     Scale the data
5     Draw the axes
6     Draw the data
7     Draw the title
8     Draw the legend
9 }
```

An abstract class may or may not provide default behavior for each operation. In this example, default behavior for border and title drawing might be provided. Then subclasses of TwoDPlot would define their own functions for the other methods. The protocol specification explicitly spells out what methods a subclass of TwoDPlot should respond to. In the above example, subclasses will need to define their own methods for drawing the axis, data, and legend. Some subclasses might use TwoDPlot's methods for drawing the border, others might require their own version of this method. The abstract interface defined in TwoDPlot makes it easier to add new classes of 2D plots and the resulting subclasses tend to be more uniform and consistent.

Another mechanism, *delegation*, is useful for isolating and reusing behavior. Using delegation, an object applies operations to one of its attributes that is an object. As an example, in the *Visualization Toolkit* the vtkTransform object delegates its Identity() operation to its vtkMatrix4x4 attribute. This instance of vtkMatrix4x4 then performs the operation. There are many more useful object-oriented concepts, but for the time being we have enough information to describe how we

can use objects to design a system.

2.5 Object-Oriented Modelling and Design

The design of any large software system is a formidable task and the first steps in system design are often the most challenging. No matter what design technique we choose, we must have a thorough understanding of the system's application domain. It would be difficult to see how one could design a fly-by-wire airplane control system without a detailed knowledge of the underlying hardware control systems. Of course, all flight system software is not designed by aeronautical engineers, so some form of system specification must exist. The depth of information in the specifications varies from application to application.

Object-oriented system design begins with a modelling step that extracts objects and their relationships with other objects from a problem statement or software requirement specification. First, the designer must completely understand the problem being solved. This often requires an in-depth knowledge of the problem domain or access to detailed specifications of the problem being solved. Then, major abstractions must be identified within the system. The abstractions will become, at this high level of design, the first set of objects. For example, a system that keeps track of an investment portfolio will need objects such as stocks, bonds, and mutual funds. In a computer animation system we might need actors, cameras, and lights. A medical computed tomography system will have a table, X-ray source, detectors, and gantry. Our visualization system will have models, isosurfaces, streamlines, and cut planes. During this modelling step, we search the problem domain for objects, properties, and relationships. Later, during multiple passes through the design, the model will be expanded.

Modelling is a step in most design processes regardless of whether we are designing a ship, house, electronics system, or software. Each discipline follows a methodology that uses techniques specifically created to make the design process efficient and worthwhile. These techniques are so-called "tools of the trade." An electrical engineer uses schematics and logic diagrams, an architect uses drawings and mock-ups, and a ship builder uses scale models. Likewise, software designers need tools that can help create a model of the system. The software tools should have enough expressive power to help the software designer evaluate a design against a specification and help communicate that design to others on the software team.

We use the Object Modeling Technique (OMT) developed at GE by Jim Rumbaugh and his colleagues [12]. OMT uses three models to specify an object-oriented design: an object model, a dynamic model, and a functional model. Each model describes a different aspect of the system and each has a corresponding diagramming technique that helps us analyze, design, and implement software systems.

2.5.1 The Object Model

The object model identifies each object in the system, its properties, and its relationships to other objects in the system. For most software systems, the object model dominates the design. The OMT graphical technique uses rectangles to depict object classes, and a variety of connectors to depict inheritance and other object-object relations. Object classes are represented as solid rectangles. Instances are represented as dotted rectangles. The name of the class or instance occupies the top of the rectangle. A line separates the class name from the next section that contains the attributes; a third section describes the methods. Relationships between objects are shown with line segments connecting the two related objects. In OMT, relationships are called associations and they can have various cardinalities: one-to-one, one-to-many, and many-to-many. Special associations that represent containers of other objects are called aggregations. Associations can be labeled with

roles. (Roles are names given to associations and are used to further describe the nature of the association.) OMT represents inheritance with a triangle, with the superclass attached to the apex, and sub-classes attached to the base of the triangle. Figure 2.3 shows an object model for locator devices in a virtual reality system.

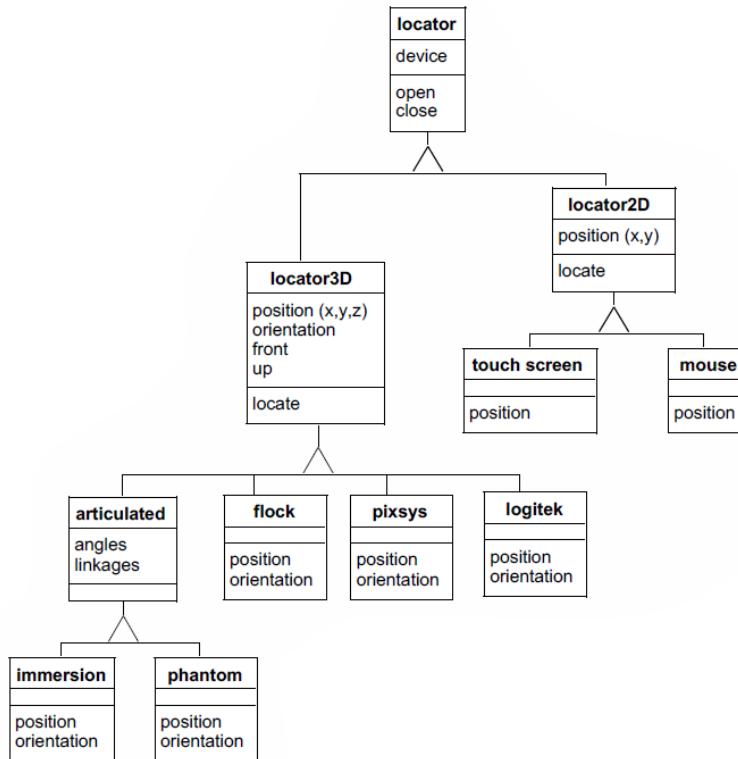


Figure 2.3: Object model for locator devices.

The first object in the class hierarchy is **locator**. This abstract class specifies common attributes and methods for all locators. The subclasses of **locator** are **locator2D** and **locator3D**. In the current rendition of this object model, the **locator** only has one attribute, a device and two methods, **open()** and **close()**. The two subclasses of **locator**, **locator2D** and **locator3D** are also abstract classes, containing attributes and methods that distinguish them from each other based on their spatial dimensionality. For example, **locator3D** has an *x*, *y*, *z* position while **locator2D** has an *x*, *y* position. Both locators have a **locate()** method that updates the current position. In the 3D locator class, **locate()** also updates the orientation. The subclasses of **locator3D** include hardware from three different manufacturers: **flock**, **pixsys**, and **logitek**, as well as an articulated positioner abstract class. The three object classes for the hardware contain methods specific to each device. Each method knows how to convert the hardware specific codes returned by the device. They know that to be considered a **locator3D** subclass, they must implement a position and orientation operation that will provide *x*, *y*, *z* coordinates and three angular rotations that can be composed into a transformation matrix. The object model also shows us that the articulated locator has angles and linkages. Two specific articulated locators are **immersion** and **phantom**. An object model diagrammed in this fashion serves as a starting point for design and discussion. It reveals common methods and attributes as well as the distinguishing characteristics of each class.

Later, during implementation, we will convert these object models into software objects. The particular computer language we choose for implementation will dictate the details of the conversion.

2.5.2 The Dynamic Model

The object model describes the static portion of a system while the dynamic model details the sequences of events and time dependencies of the system. OMT uses state diagrams to model system dynamics. Dynamic models are frequently used to design control systems and user interfaces. Our visualization system has limited sequence and control aspects, so we will not dwell on state diagrams. But, if we were designing a user-friendly interface for a digital wristwatch, the state diagram in Figure 2.4 would be useful.

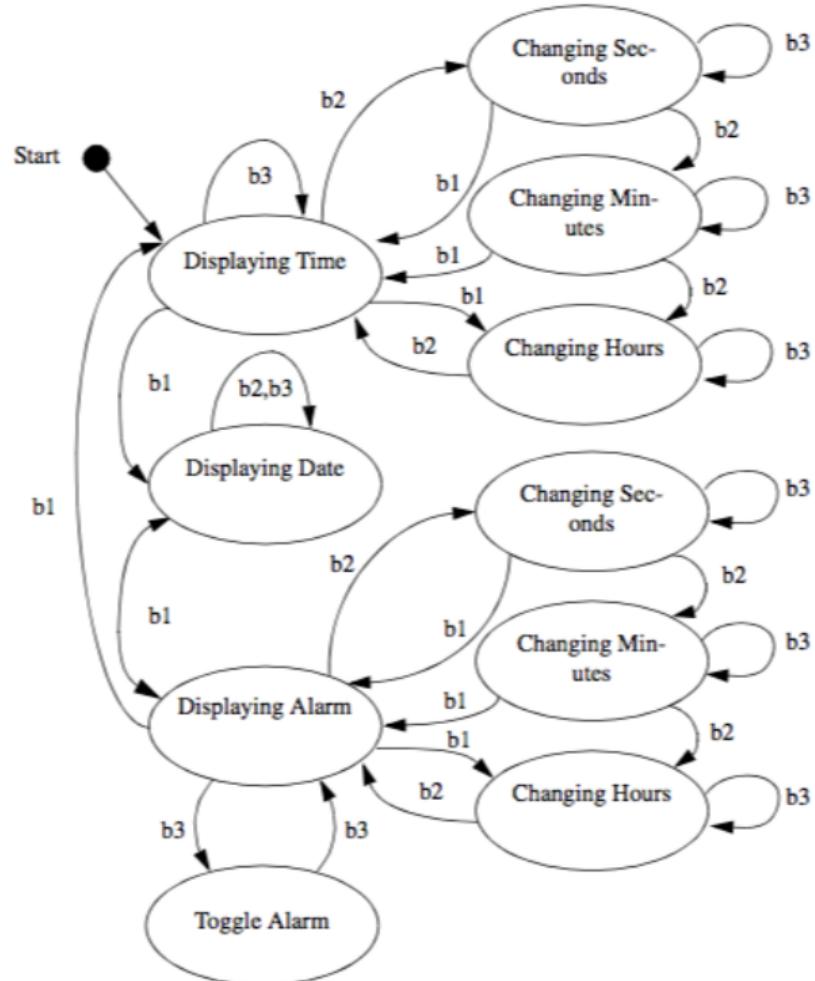


Figure 2.4: State diagram for a wristwatch.

The ovals in the diagram show a state; the arrows show a transition from one state to another; and the labels on the arrows show an event that causes the state transition. This example shows three

display states and multiple setting states. The event b1 means button one is pressed. This watch has three buttons. The diagram shows what happens in each state when any of the three buttons is pressed. The diagram clearly shows that b1 is used to move between display modes for time, date, and alarm. B2 changes from display mode into setting mode or selects the field to change in a given mode. B3 increments the selected field by one unit. The state diagram also shows what happens when illegal buttons are pressed. If the watch is displaying time and button 3 is pressed, nothing happens. If button 3 is pressed when the watch is displaying the alarm, the alarm on/off is toggled.

2.5.3 The Functional Model

The functional model shows how data flows through the system and how processes and algorithms transform the data. It also shows functional dependencies between processes. Exposing these relationships will affect the associations in the object model. The major components of a data flow diagram (DFD) are data sources, data sinks, and processes. Data sources and sinks are represented as rectangles. Ellipses show processes. Data stores are shown within two horizontal lines. DFDs are useful to describe the overall flow in the system. They can also be used to describe any process that transforms one data representation into another. Processes identified in the DFD during function modelling may turn up as operations or objects in the object model.

Figure 2.5 shows a data flow diagram for a 3D medical imaging system. The diagram shows the data acquisition on the computed tomography (CT) or magnetic resonance imaging (MRI) scanner. The series of cross-sectional slices provided by the scanner is first processed by image processing filters to enhance features in the gray scale slices. A segment process identifies tissues and produces labels for the various tissues present in the slices. These labeled slices are then passed through a surface extraction process to create triangles that lie on the surface of each tissue. The render process transforms the geometry into an image. Alternatively, the write process stores the triangles in a file. Later, the triangles can be read and rendered into an image. We defer the decision whether to make the processes objects or operations until later. Chapter [The Visualization Pipeline](#) uses DFDs to model the visualization pipeline.

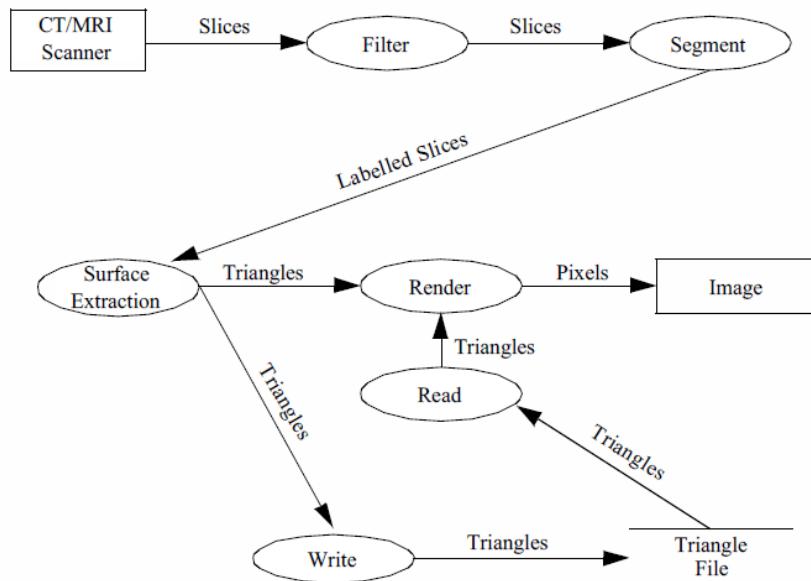


Figure 2.5: Data flow diagram.

2.6 Object-Oriented Programming Languages

The choice of computer programming language is a religious issue. Every computer language has its evangelists and followers. Most of our experience in object-oriented languages is with C and C++. C itself does not have object-oriented facilities, but an object-oriented methodology and strict coding guidelines permit the development of object-oriented code. We chose C++ for the *Visualization Toolkit* because it has built-in support for the notion of classes, dynamic binding of methods to objects, and inheritance. C++ is also widely available on many UNIX platforms and personal computers.

Simula [10] is usually acknowledged as the first object-oriented language, but Smalltalk [4] is probably the best-known language. Smalltalk was developed at the Xerox Palo Alto Research Center (PARC) in the seventies and eighties. Well before its time, Smalltalk provided not just a language, but also an operating system and programming environment built with objects. When you use Smalltalk, you live and breathe objects. For the object-oriented purist, there is no substitute. Smalltalk spin-offs include window systems, workstations, and the desktop paradigm. Both Apple Computer and Microsoft acknowledge the influence that Smalltalk and Xerox PARC had on the Macintosh and Windows. Smalltalk was probably conceived 10 years too early for widespread commercial acceptance. During Smalltalk's infancy and adolescence, the complexity of software was much lower than today's systems. FORTRAN served the scientific and engineering community, COBOL was the choice for business applications and the computer science community embraced C. The use of abstractions was limited to mathematicians and other abstract thinkers. Programming was considered an art form and programmers concentrated on clever implementations of algorithms. Each new task often required a new program. Technical programmers did use numerical libraries for common mathematical operations, but any notions of common abstractions at a higher level were relatively few.

2.7 Object-Oriented Visualization

Don't underestimate the investment required to design a system. Although object-oriented technologies have tremendous potential to produce good software designs, these techniques do not guarantee a good design. The visualization system we present in this text has its roots in an animation [23] and visualization system [24] that we developed over a 10-year period. The initial design, which identified 25 classes for computer animation of industrial applications, took four software professionals 10 months (almost 3.5 person years) to complete. During this design stage the developers produced zero (!) lines of code. The subsequent implementation took one month, or ten percent of the effort. This system still serves our visualization group even after 20 other software developers have added over 500 classes to the system. The original 25 classes still exist in the system today.

As a reader, we hope that you can benefit from our experience in visualization system design. We have tried to assist you by describing the properties (attributes and methods) of many of the *Visualization Toolkit* classes in each chapter's "Putting It All Together" section. There are also included a series of object diagrams generated by the Doxygen documentation system that will give you a quick overview of object relationships such as superclass and subclass. This documentation can be found on the CD-ROM or on-line at [VTK Documentation](#). In the next chapter we will also explain the decisions we made to design the VTK object-oriented toolkit.

2.8 Chapter Summary

This chapter introduced object-oriented concepts and terminology. The emphasis was on dealing with complexity and how object-oriented technology provides mechanisms to reduce the complexity of software.

Model building is an important part of any design methodology. We introduced three models and notations. The object model describes the objects in a system and their static relationships, attributes, and methods. Object diagrams succinctly present this static information. The dynamic model focuses on the time dependent aspects of the system. State transition diagrams are used to model the sequence and control portions of the system. The functional model shows how objects in the system transform data or other objects. The data flow diagram is a convenient notation for showing functional dependencies.

There are several choices available today for object-oriented implementations. Although it is possible to implement an object-oriented system in a non-object-oriented language such as C, the methodology is best served by an object-oriented language. We have chosen C++ to implement the *Visualization Toolkit*.

The emphasis in this book is on architecture, data structure design, and algorithms. The object-oriented aspects of the system are important, but what the system does is far more important.

2.9 Bibliographic Notes

There are several excellent textbooks on object-oriented design. Both [12] and [10] present language-independent design methodologies. Both books emphasize modelling and diagramming as key aspects of design. [15] also describes the OO design process in the context of Eiffel, an OO language. Another popular book has been authored by Booch [6].

Anyone who wants to be a serious user of object-oriented design and implementation should read the books on Smalltalk [4] [11] by the developers of Smalltalk at Xerox Parc. In another early object-oriented programming book, [7] describes OO techniques and the programming language Objective-C. Objective-C is a mix of C and Smalltalk and was used by Next Computer in the implementation of their operating system and user interface.

There are many texts on object-oriented languages. CLOS [14] describes the Common List Object System. Eiffel, a strongly typed OO language is described by [15]. Objective-C [7] is a weakly typed language.

Since C++ has become a popular programming language, there now many class libraries available for use in applications. [13] describes an extensive class library for collections and arrays modeled after the Smalltalk classes described in [4]. [18] and [16] describe the Standard Template Library, a framework of data structures and algorithms that is now a part of the ANSI C++ standard. Open Inventor [1] is a C++ library supporting interactive 3D computer graphics. The Insight Segmentation and Registration Toolkit (ITK) is a relatively newclass library often used in combination with VTK [21] for medical data processing. VXL is a C++library for computer vision research and implementation [22]. Several mathematical libraries such as VNL (a part of VXL) and Blitz++ [2] are also available. A wide variety of other C++ toolkits are available, Google searches [3] are the best way to find them.

C++ texts abound. The original description by the author of C++ [20] is a must for any serious C++ programmer. Another book [8] describes standard extensions to the language. These days the UML book seriesof which [9] and [19] are quite popularare highly recommended resources. Several books on generic programming [5] and STL [17] are also useful. Check with your colleagues for their favourite C++ book. To keep in touch with new developments there are conferences, journals, and Web sites. The strongest technical conference on object-oriented topics

is the annual Object-Oriented Programming Systems, Languages, and Applications (OOPSLA) conference. This is where researchers in the field describe, teach and debate the latest techniques in object-oriented technology. The bimonthly Journal of Object-Oriented Programming (JOOP) published by SIGS Publications, NY, presents technical papers, columns, and tutorials on the field. Resources on the World Wide Web include the Usenet newsgroups comp.object and comp.lang.c++.

Bibliography

- [1] URL: <http://oss.sgi.com/projects/inventor/>.
- [2] URL: <http://www.oonumerics.org/blitz/>.
- [3] URL: <https://www.google.com/>.
- [4] A. Goldberg, D. Robson. *Smalltalk-80: The Language and Its Implementation*. Addison-Wesley, Reading, MA, 1983.
- [5] M. H. Austern. *Generic Programming and the STL*. Addison-Wesley, 1999.
- [6] G. Booch. *Object-Oriented Design with Applications*. Benjamin/Cummings Publishing Co., Redwood City, CA, 1991.
- [7] B. J. Cox. *Object-Oriented Programming: An Evolutionary Approach*. Addison-Wesley, Reading, MA, 1986.
- [8] M. Ellis and B. Stroustrup. *The Annotated C++ Reference Manual*. Addison-Wesley, Reading, MA, 1990.
- [9] J. Rumbaugh G. Booch I. Jacobson. *The Unified Modeling Language User Guide (Addison-Wesley Object Technology Series)*. Addison-Wesley Professional, 1998. ISBN: 0201571684.
URL: <https://www.amazon.com/Unified-Modeling-Language-Addison-Wesley-Technology/dp/0201571684?SubscriptionId=0JYN1NVW651KCA56C102&tag=techkie-20&linkCode=xm2&camp=2025&creative=165953&creativeASIN=0201571684>.
- [10] G. M. Birtwistle, O. Dahl, B. Myhrhaug, and K. Nygaard. *Simula Begin*. Chartwell-Bratt Ltd, England. 1979.
- [11] A. Goldberg. *Smalltalk-80: The Interactive Programming Environment*. Addison-Wesley, Reading, MA, 1984.
- [12] J. Rumbaugh, M. Blaha, W. Premerlani, F. Eddy, and W. Lorensen. *Object-Oriented Modeling and Design*. Prentice Hall, Englewood Cliffs, NJ, 1991.
- [13] K. Gorlen, S. Orlow, and P. Plexico. *Data Abstraction and Object-Oriented Programming*. John Wiley & Sons, Ltd., Chichester, England, 1990.
- [14] S. Keene. *Object-Oriented Programming in Common Lisp: A Programmers Guide to CLOS*. Addison-Wesley, Reading, MA, 1989.
- [15] B. Meyer. *Object-Oriented Software Construction*. Prentice Hall International, Hertfordshire, England, 1988.
- [16] D. Musser and A. Stepanov. “Algorithm-Oriented Generic Libraries”. In: *Software Practice and Experience* 24.7 (July 1994), pp. 623–642.

- [17] David R. Musser and Atul Saini. *Stl Tutorial & Reference Guide: C++ Programming With the Standard Template Library* (Addison-Wesley Professional Computing Series). Addison-Wesley, 1996. ISBN: 0201633981. URL: <https://www.amazon.com/Stl-Tutorial-Reference-Guide-Addison-Wesley/dp/0201633981?SubscriptionId=0JYN1NVW651KCA56C102&tag=techkie-20&linkCode=xm2&camp=2025&creative=165953&creativeASIN=0201633981>.
- [18] P.J. Plauger et al. *The C++ Standard Template Library*. Prentice Hall, 2000. ISBN: 978-0134376332. URL: <https://www.amazon.com/C-Standard-Template-Library/dp/0134376331?SubscriptionId=0JYN1NVW651KCA56C102&tag=techkie-20&linkCode=xm2&camp=2025&creative=165953&creativeASIN=0134376331>.
- [19] James Rumbaugh, Ivar Jacobson, and Grady Booch. *The Unified Modeling Language Reference Manual*. Addison-Wesley Professional. ISBN: 020130998X. URL: <https://www.amazon.com/Unified-Modeling-Language-Reference-Manual/dp/020130998X?SubscriptionId=0JYN1NVW651KCA56C102&tag=techkie-20&linkCode=xm2&camp=2025&creative=165953&creativeASIN=020130998X>.
- [20] Bjarne Stroustrup. *The C++ Programming Language: Special Edition (3rd Edition)*. Addison-Wesley Professional, 2000. ISBN: 0-201-70073-5. URL: <https://www.amazon.com/Programming-Language-Special-3rd/dp/0201700735?SubscriptionId=0JYN1NVW651KCA56C102&tag=techkie-20&linkCode=xm2&camp=2025&creative=165953&creativeASIN=0201700735>.
- [21] *The Insight Software Consortium*. URL: <https://www.itk.org>.
- [22] *VXL*. URL: <http://vxl.sourceforge.net/>.
- [23] B. Yamrom W. E. Lorensen. “Object-Oriented Computer Animation”. In: *Proceedings of IEEE NAECON, Dayton, Ohio*. Vol. 2. 1989, pp. 588–595.
- [24] W. J. Schroeder, W. E. Lorensen, G. Montanaro, and C. Volpe. “Visage: An Object-Oriented Scientific Visualization System”. In: *Proceedings of Visualization ’92*. IEEE Computer Society Press, Los Alamitos, CA, Oct. 1992, pp. 219–226.

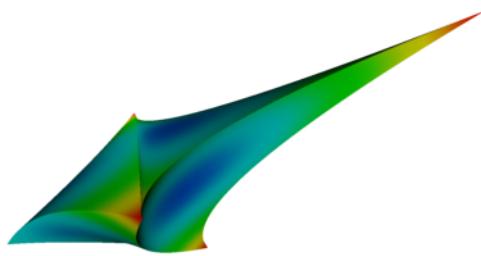
2.10 Exercises

1. Answer the following questions about a program you have written.
 - (a) How much time did you spend on design and implementation?
 - (b) What methodology, if any, did you use?
 - (c) Could you easily extend the system?
 - (d) Could anyone extend the system?
2. Identify the major objects and operations for the following applications.
 - (a) An airline reservation system.
 - (b) An adventure game.
 - (c) A 2D plotting package.
 - (d) An automatic teller machine.
3. Draw an object diagram for each example in Exercise 2.

4. Computer animation uses concepts from graphics and movie making. Identify the major objects and operations in a computer animation system.
5. For the animation system in Exercise 4, design control and looping objects that will allow flexible control of the properties of the actors in the system. If we call these control and looping objects scenes and cues, how would you expect them to look?
6. Draw a state diagram for your wristwatch using Figure 2.4 as an example.
7. Draw a data flow diagram for calculating the surface area and volume of a sphere and cylinder.

3.0

Computer Graphics Primer



Rendering quadratic tetrahedra.

Computer graphics is the foundation of data visualization. Practically speaking, visualization is the process that transforms data into a set of graphics primitives. The methods of computer graphics are then used to convert these primitives into pictures or animations. This chapter discusses basic computer graphics principles. We begin by describing how lights and physical objects interact to form what we see. Next we examine how to simulate these interactions using computer graphics techniques. Hardware issues play an important role here since modern computers have built-in hardware support for graphics. The chapter concludes with a series of examples that illustrate our object-oriented model for 3D computer graphics.

3.1 Introduction

Computer graphics is the process of generating images using computers. We call this process *rendering*. There are many types of rendering processes, ranging from 2D paint programs to sophisticated 3D techniques. In this chapter we focus on basic 3D techniques for visualization.

We can view rendering as the process of converting graphical data into an image. In data visualization our goal is to transform data into graphical data, or *graphics primitives*, that are then rendered. The goal of our rendering is not so much photo realism as it is information content. We also strive for interactive graphical displays with which it is possible to directly manipulate the underlying data. This chapter explains the process of rendering an image from graphical data. We begin by looking at the way lights, cameras, and objects (or actors) interact in the world around us. From this foundation we explain how to simulate this process on a computer.

3.2 A Physical Description of Rendering

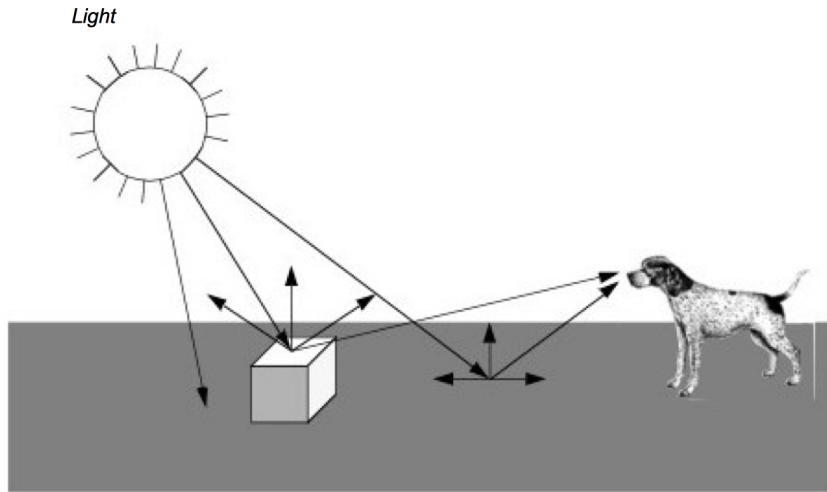


Figure 3.1: Physical generation of an image.

Figure 3.1 presents a simplified view of what happens when we look at an object, in this case a cube. Rays of light are emitted from a light source in all directions. (In this example we assume that the light source is the sun.) Some of these rays happen to strike the cube whose surface absorbs some of the incident light and reflects the rest of it. Some of this reflected light may head towards us and enter our eyes. If this happens, then we "see" the object. Likewise, some of the light from the sun will strike the ground and some small percentage of it will be reflected into our eyes.

As you can imagine, the chances of a ray of light travelling from the sun through space to hit a small object on a relatively small planet are low. This is compounded by the slim odds that the ray of light will reflect off the object and into our eyes. The only reason we can see is that the sun produces such an enormous amount of light that it overwhelms the odds. While this may work in real life, trying to simulate it with a computer can be difficult. Fortunately, there are other ways to look at this problem.

A common and effective technique for 3D computer graphics is called *ray-tracing* or *ray-casting*. Ray-tracing simulates the interaction of light with objects by following the path of each light ray. Typically, we follow the ray backwards from the viewer's eyes and into the world to determine what the ray strikes. The direction of the ray is in the direction we are looking (i.e., the view direction) including effects of perspective (if desired). When a ray intersects an object, we can determine if that point is being lit by our light source. This is done by tracing a ray from the point of intersection towards the light. If the ray intersects the light, then the point is being lit. If the ray intersects something else before it gets to the light, then that light will not contribute to illuminating the point. For multiple light sources we just repeat this process for each light source. The total contributions from all the light sources, plus any ambient scattered light, will determine the total lighting or shadow for that point. By following the light's path backwards, ray tracing only looks at rays that end up entering the viewer's eyes. This dramatically reduces the number of rays that must be computed by a simulation program.

Having described ray tracing as a rendering process, it may be surprising that many members of the graphics community do not use it. This is because ray tracing is a relatively slow image generation method since it is typically implemented in software. Other graphics techniques have

been developed that generate images using dedicated computer hardware. To understand why this situation has emerged, it is instructive to briefly examine the taxonomy and history of computer graphics.

3.2.1 Image-Order and Object-Order Methods

Rendering processes can be broken into two categories: *image-order* and *object-order*. Ray tracing is an image-order process. It works by determining what happens to each ray of light, one at a time. An object-order process works by rendering each object, one at a time. In the above example, an object-order technique would proceed by first rendering the ground and then the cube.

To look at it another way consider painting a picture of a barn. Using an image-order algorithm you would start at the upper left corner of the canvas and put down a drop of the correct color paint. (Each paint drop is called a picture element or *pixel*.) Then you would move a little to the right and put down another drop of paint. You would continue until you reached the right edge of the canvas, then you would move down a little and start on the next row. Each time you put down a drop of paint you make certain it is the correct color for each pixel on the canvas. When you are done you will have a painting of a barn.

An alternative approach is based on the more natural (at least for many people) object-order process. We work by painting the different objects in our scene, independent of where the objects actually are located on the scene. We may paint from back to front, front-to-back, or in arbitrary order. For example, we could start by painting the sky and then add in the ground. After these two objects were painted we would then add in the barn. In the image-order process we worked on the canvas in a very orderly fashion; left to right, top to bottom. With an object-order process we tend to jump from one part of the canvas to another, depending on what object we are drawing.

The field of computer graphics started out using object-order processes. Much of the early work was closely tied to the hardware display device, initially a vector display. This was little more than an oscilloscope, but it encouraged graphical data to be drawn as a series of line segments. As the original vector displays gave way to the currently ubiquitous raster displays, the notion of representing graphical data as a series of objects to be drawn was preserved. Much of the early work pioneered by Bresenham [1] at IBM focused on how to properly convert line segments into a form that would be suitable for line plotters. The same work was applied to the task of rendering lines onto the raster displays that replaced the oscilloscope. Since then the hardware has become more powerful and capable of displaying much more complex primitives than lines.

It wasn't until the early 1980s that a paper by Turner Whitted [7] prompted many people to look at rendering from a more physical perspective. Eventually ray tracing became a serious competitor to the traditional object-order rendering techniques, due in part to the highly realistic images it can produce. Object-order rendering has maintained its popularity because there is a wealth of graphics hardware designed to quickly render objects. Ray tracing tends to be done without any specialized hardware and therefore is a time-consuming process.

3.2.2 Surface versus Volume Rendering

The discussion to this point in the text has tacitly assumed that when we render an object, we are viewing the surfaces of objects and their interactions with light. However, common objects such as clouds, water, and fog, are translucent, or scatter light that passes through them. Such objects cannot be rendered using a model based exclusively on surface interactions. Instead, we need to consider the changing properties inside the object to properly render them. We refer to these two rendering models as *surface rendering* (i.e., render the surfaces of an object) and *volume rendering* (i.e., render the surface and interior of an object).

Generally speaking, when we render an object using surface rendering techniques, we mathematically model the object with a surface description such as points, lines, triangles, polygons, or 2D and 3D splines. The interior of the object is not described, or only implicitly represented from the surface representation (i.e., surface is the boundary of the volume). Although techniques do exist that allow us to make the surface transparent or translucent, there are still many phenomena that cannot be simulated using surface rendering techniques alone (e.g., scattering or light emission). This is particularly true if we are trying to render data interior to an object, such as X-ray intensity from a CT scan.

Volume rendering techniques allow us to see the inhomogeneity inside objects. In the prior CT example, we can realistically reproduce X-ray images by considering the intensity values from both the surface and interior of the data. Although it is premature to describe this process at this point in the text, you can imagine extending our ray tracing example from the previous section. Thus rays not only interact with the surface of an object, they also interact with the interior.

In this chapter we focus on surface rendering techniques. While not as powerful as volume rendering, surface rendering is widely used because it is relatively fast compared to volumetric techniques, and allows us to create images for a wide variety of data and objects. Chapter 7 describes volume rendering in more detail.

3.2.3 Visualization Not Graphics

Although the authors would enjoy providing a thorough treatise on computer graphics, such a discourse is beyond the scope of this text. Instead we make the distinction between visualization (exploring, transforming, and mapping data) and computer graphics (mapping and rendering). The focus will be on the principles and practice of visualization, and not on 3D computer graphics. In this chapter and Chapter 7 we introduce basic concepts and provide a working knowledge of 3D computer graphics. For those more interested in this field, we refer you to the texts recommended in the "Bibliographic Notes" on page 87 at the end of this chapter.

One of the regrets we have regarding this posture is that certain rendering techniques are essentially visualization techniques. We see this hinted at in the previous paragraph, where we use the term "mapping" to describe both visualization and computer graphics. There is not currently and will likely never be a firm distinction between visualization and graphics. For example, many researchers consider volume rendering to be squarely in the field of visualization because it addresses one of the most important forms of visualization data. Our distinction is mostly for our own convenience, and offers us the opportunity to finish this text. We recommend that a serious student of visualization supplement the material presented here with deeper books on computer graphics and volume rendering.

In the next few pages we describe the rendering process in more detail. We start by describing several color models. Next we examine the primary components of the rendering process. There are sources of light such as the sun, objects we wish to render such as a cube or sphere (we refer to these objects as actors), and there is a camera that looks out into the world. These terms are taken from the movie industry and tend to be familiar to most people. Actors represent graphical data or objects, lights illuminate the actors, and the camera constructs a picture by projecting the actors onto a view plane. We call the combination of lights, camera, and actors the scene, and refer to the rendering process as rendering the scene.

3.3 Color

The electromagnetic spectrum visible to humans contains wavelengths ranging from about 400 to 700 nanometers. The light that enters our eyes consists of different *intensities* of these

wavelengths, an example of which is shown in Figure 3.2. This intensity plot defines the color of the light, therefore a different plot results in a different color. Unfortunately, we may not notice the difference since the human eye throws out most of this information. There are three types of color receptors in the human eye called *cones*. Each type responds to a subset of the 400 to 700 nanometer wave-length range as shown in Figure 3.3. Any color we see is encoded by our eyes into these three overlapping responses. This is a great reduction from the amount of information that actually comes into our eyes. As a result, the human eye is incapable of recognizing differences in any colors whose intensity curves, when applied to the human eye's response curves, result in the same triplet of responses. This also implies that we can store and represent colors in a computer using a simplified form without the human eye being able to recognize the difference.

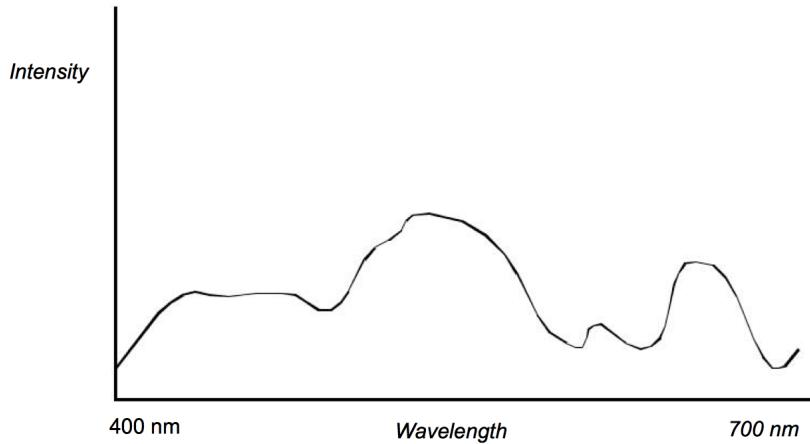


Figure 3.2: Wavelength versus Intensity plot.

The two simplified component systems that we use to describe colors are RGB and HSV color systems. The RGB system represents colors based on their red, green, and blue intensities. This can be thought of as a three dimensional space with the axes being red, green, and blue. Some common colors and their RGB components are shown in Table 3.1.

The HSV system represents colors based on their hue, saturation, and value. The value component is also known as the brightness or intensity component, and represents how much light is in the color. A value of 0.0 will always give you black and a value of 1.0 will give you something bright. The hue represents the dominant wavelength of the color and is often illustrated using a circle as in Figure 3.4. Each location on the circumference of this circle represents a different hue and can be specified using an angle. When we specify a hue we use the range from zero to one, where zero corresponds to zero degrees on the hue circle and one corresponds to 360 degrees. The saturation indicates how much of the hue is mixed into the color. For example, we can set the value to one, which gives us a bright color, and the hue to 0.66, to give us a dominant wavelength of blue. Now if we set the saturation to one, the color will be a bright primary blue. If we set the saturation to 0.5, the color will be sky blue, a blue with more white mixed in. If we set the saturation to zero, this indicates that there is no more of the dominant wavelength (hue) in the color than any other wavelength. As a result, the final color will be white (regardless of hue value). Table 3.1 lists HSV values for some common colors.

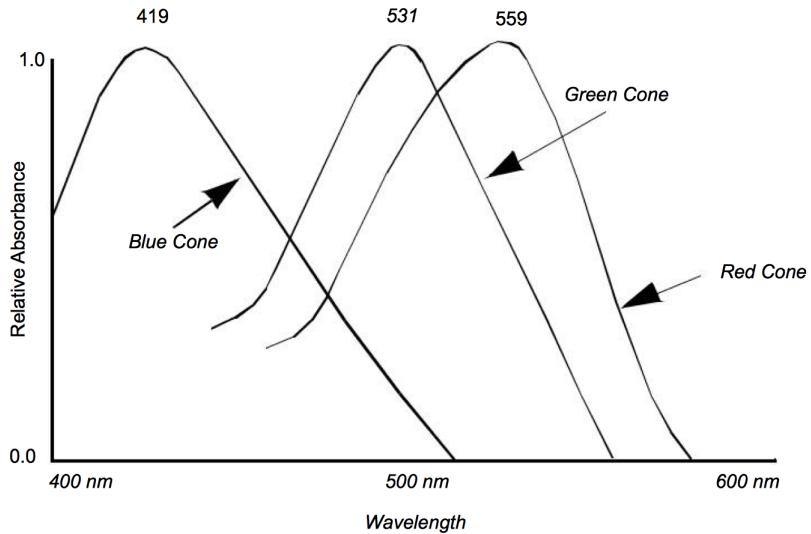


Figure 3.3: Relative absorbance of light by the three types of cones in the human retina.

Color	RGB	HSV
Black	0, 0, 0	*, *, 0
White	1, 1, 1	*, 0, 1
Red	1, 0, 0	0, 1, 1
Green	0, 1, 0	1/3, 1, 1
Blue	0, 0, 1	2/3, 1, 1
Cyan	0, 1, 1	1/2, 1, 1
Magenta	1, 0, 1	5/6, 1, 1
Yellow	1, 1, 0	1/6, 1, 1
Sky Blue	1/2, 1/2, 1	2/3, 1/2, 1

Table 3.1: Common colors in RGB and HSV space

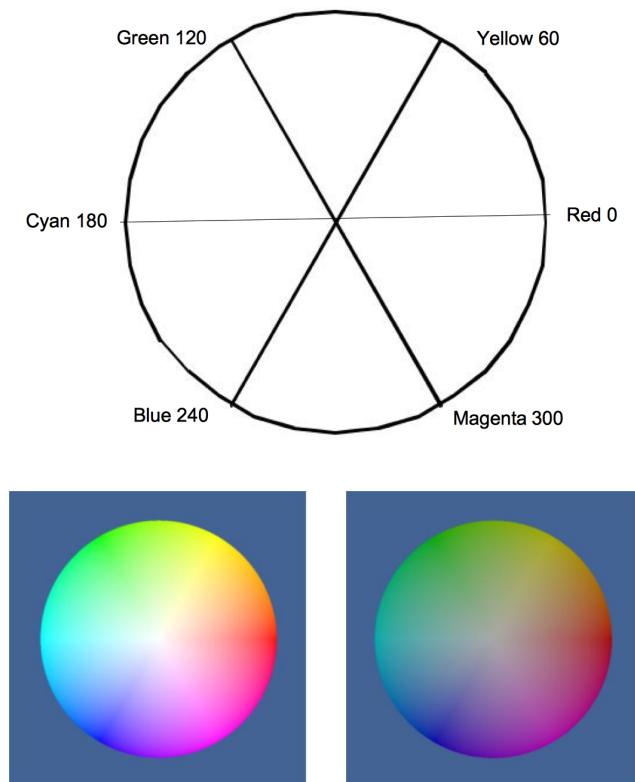


Figure 3.4: On the top, circular representation of hue. The other two images on the bottom are slices through the HSV color space. The first slice has a value of 1.0, the other has a value of 0.5.

3.4 Lights

One of the major factors controlling the rendering process is the interaction of light with the actors in the scene. If there are no lights, the resulting image will be black and rather uninformative. To a great extent it is the interaction between the emitted light and the surface (and in some cases the interior) of the actors in the scene that defines what we see. Once rays of light interact with the actors in a scene, we have something for our camera to view.

Of the many different types of lights used in computer graphics, we will discuss the simplest, the infinitely distant, point light source. This is a simplified model compared to the lights we use at home and work. The light sources that we are accustomed to typically radiate from a region in space (a filament in an incandescent bulb, or a light-emitting gas in a fluorescent light). The point source lighting model assumes that the light is emitted in all directions from a single point in space. For an infinite light source, we assume that it is positioned infinitely far away from what it is illuminating. This is significant because it implies that the incoming rays from such a source will be parallel to each other. Figure 3.5 illustrates the differences between a local light source with a finite volume, versus an infinite point light source. The intensity of the light emitted by our infinite light sources also remains constant as it travels, in contrast to the actual $1/distance^2$ relationship physical lights obey. As you can see this is a great simplification, which later will allow us to use less complex lighting equations.

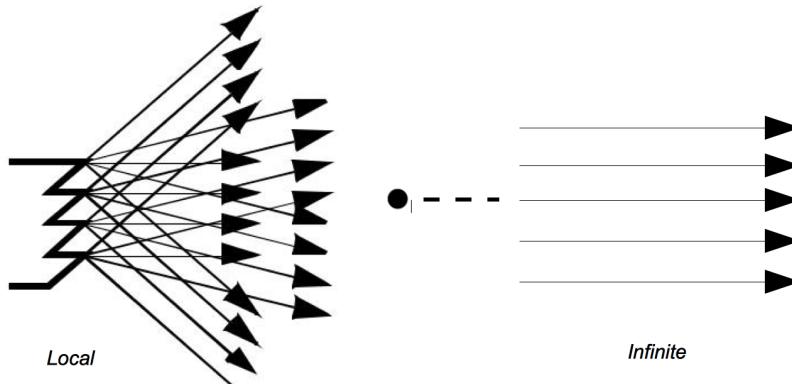


Figure 3.5: Local light source with a finite volume versus an infinite point light source.

3.5 Surface Properties

As rays of light travel through space, some of them intersect our actors. When this happens, the rays of light interact with the surface of the actor to produce a color. Part of this resulting color is actually not due to direct light, but rather from *ambient* light that is being reflected or scattered from other objects. An ambient lighting model accounts for this and is a simple approximation of the complex scattering of light that occurs in the real world. It applies the intensity curve of the light source to the color of the object, also expressed as an intensity curve. The result is the color of the light we see when we look at that object. With such a model, it is important to realize that a white light shining on a blue ball is indistinguishable from a blue light shining on a white ball. The ambient lighting equation is

$$R_a = L_c \cdot O_a \quad (3.1)$$

where R_a is the resulting intensity curve due to ambient lighting, L_c is the intensity curve of the ambient light, and O_a is the color curve of the object. To help keep the equations simple we assume that all of the direction vectors are normalized (i.e., have a magnitude of one).

Two components of the resulting color depend on direct lighting. *Diffuse lighting*, which is also known as Lambertian reflection, takes into account the angle of incidence of the light onto an object. Figure 3.6 shows the image of a cylinder that becomes darker as you move laterally from its center. The cylinder's color is constant; the amount of light hitting the surface of the cylinder changes. At the center, where the incoming light is nearly perpendicular to the surface of the cylinder, it receives more rays of light per surface area. As we move towards the side, this drops until finally the incoming light is parallel to the side of the cylinder and the resulting intensity is zero.

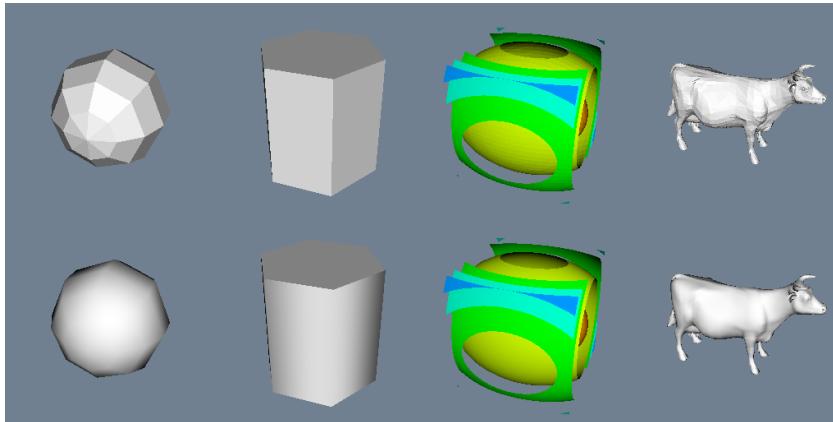


Figure 3.6: Flat and Gouraud shading. Different shading methods can dramatically improve the look of an object represented with polygons. On the top, flat shading uses a constant surface normal across each polygon. On the bottom, Gouraud shading interpolates normals from polygon vertices to give a smoother look.

The contribution from diffuse lighting is expressed in Equation 3.2 and illustrated in Figure 3.7.

$$R_d = L_c O_d [\vec{O}_n \cdot (-\vec{L}_n)] \quad (3.2)$$

where R_d is the resulting intensity curve due to diffuse lighting, L_c is the intensity curve for the light, and O_d is the color curve for the object. Notice that the diffuse light is a function of the relative angle between incident light vector and \vec{L}_n and the surface normal of the object \vec{O}_n . As a result diffuse lighting is independent of viewer position.

Specular lighting represents direct reflections of a light source off a shiny object. Figure 3.9 shows a diffusely lit ball with varying specular reflection. The specular intensity (which varies between the top and bottom rows) controls the intensity of the specular lighting. The specular power, $O_s p$, indicates how shiny an object is, more specifically it indicates how quickly specular reflections diminish as the reflection angles deviate from a perfect reflection. Higher values indicate

a faster drop off, and therefore a shinier surface. Referring to Figure 3.8, the equation for specular lighting is

$$R_s = L_c O_s [\vec{S} \cdot (-\vec{C}_n)]^{O_{sp}} \vec{S} = 2[\vec{O}_n \cdot (-\vec{L}_n)] \vec{O}_n + \vec{L}_n \quad (3.3)$$

where \vec{C}_n is the direction of projection for the camera and \vec{S} is the direction of specular reflection.

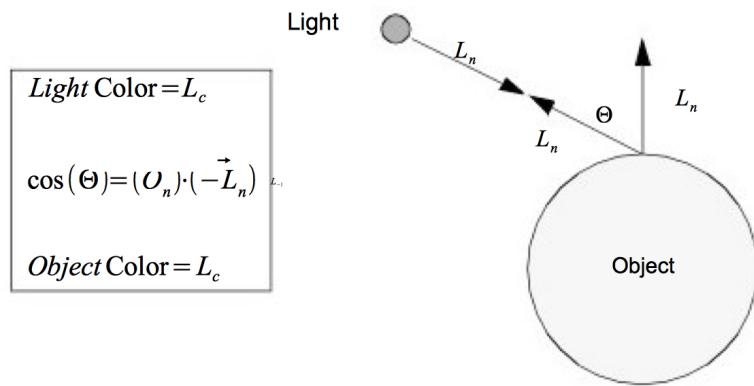


Figure 3.7: Diffuse lighting

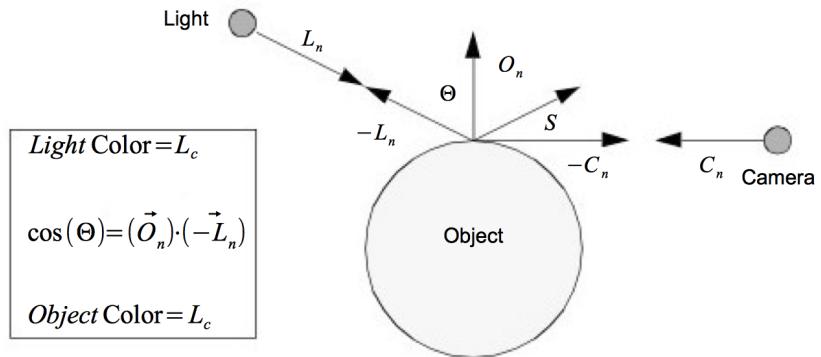


Figure 3.8: Specular lighting.

We have presented the equations for the different lighting models independently. We can apply all lighting models simultaneously or in combination. Equation 3.4 combines ambient, diffuse and specular lighting into one equation.

$$R_c = O_{ai} O_{ac} L_c - O_{di} O_{dc} L_c (\vec{O}_n \cdot \vec{L}_n) + O_{si} O_{sc} L_c [\vec{S} \cdot (-\vec{C}_n)]^{O_{sp}} \quad (3.4)$$

The result is a color at a point on the surface of the object. The constants O_{ai} , O_{di} , and O_{si} control the relative amounts of ambient, diffuse and specular lighting for an object. The constants

O_{ac} , O_{dc} and O_{sc} specify the colors to be used for each type of lighting. These six constants along with the specular power are part of the surface material properties. (Other properties such as transparency will be covered in later sections of the text.) Different combinations of these property values can simulate dull plastic and polished metal. The equation assumes an infinite point light source as described in Lights on 3.4. However the equation can be easily modified to incorporate other types of directional lighting.

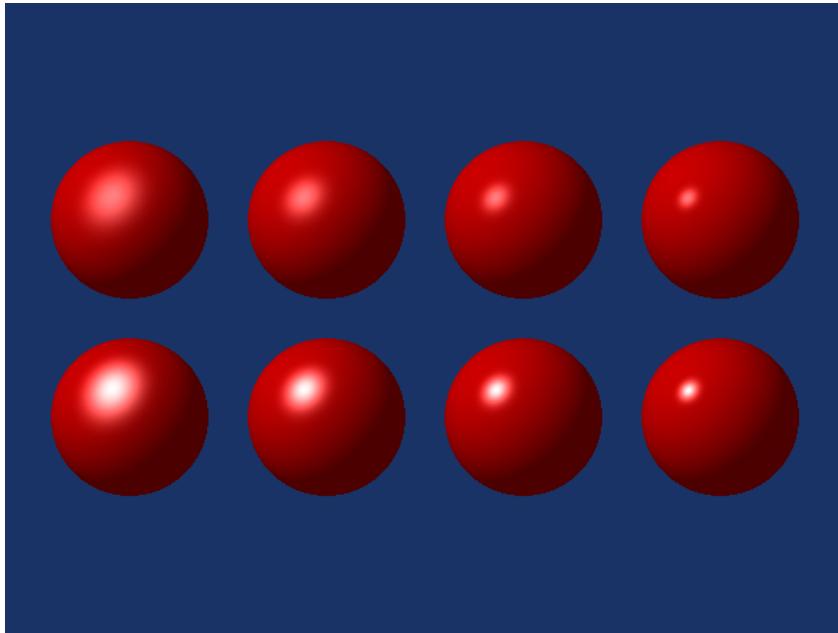


Figure 3.9: Effects of specular coefficients. Specular coefficients control the apparent "shininess" of objects. The top row has a specular intensity value of 0.5; the bottom row 1.0. Along the horizontal direction the specular power changes. The values (from left to right) are 5, 10, 20, and 40.

3.6 Cameras

We have light sources that are emitting rays of light and actors with surface properties. At every point on the surface of our actors this interaction results in some composite color (i.e., combined color from light, object surface, specular, and ambient effects). All we need now to render the scene is a camera. There are a number of important factors that determine how a 3D scene gets projected onto a plane to form a 2D image (see Figure 3.10). These are the position, orientation, and focal point of the camera, the method of camera projection , and the location of the camera clipping planes.

The position and focal point of the camera define the location of the camera and where it points. The vector defined from the camera position to the focal point is called the direction of projection . The camera image plane is located at the focal point and is typically perpendicular to the projection vector. The camera orientation is controlled by the position and focal point plus the camera view-up vector. Together these completely define the camera view.

The method of projection controls how the actors are mapped to the image plane. *Orthographic projection* is a parallel mapping process. In orthographic projection (or parallel projection) all rays of light entering the camera are parallel to the projection vector. *Perspective projection*

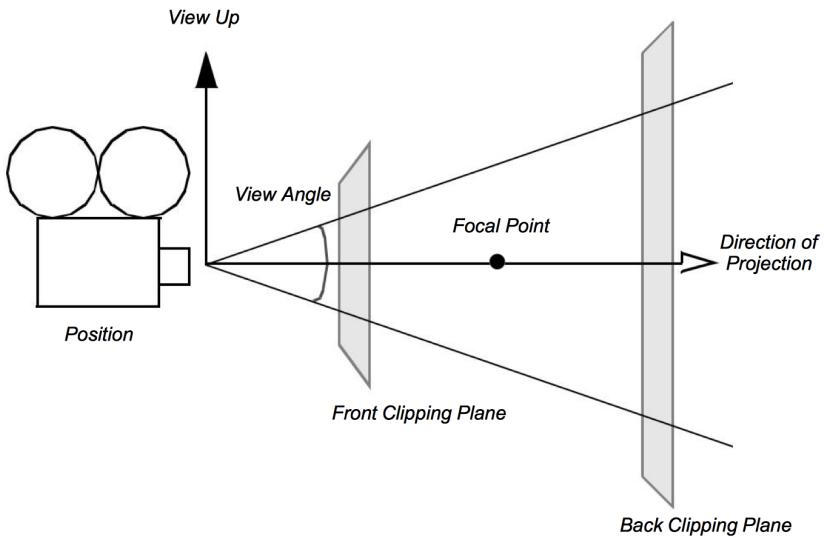


Figure 3.10: Camera attributes.

occurs when all light rays go through a common point (i.e., the viewpoint or center of projection). To apply perspective projection we must specify a perspective angle or camera view angle.

The front and back clipping planes intersect the projection vector, and are usually perpendicular to it. The clipping planes are used to eliminate data either too close to the camera or too far away. As a result only actors or portions of actors within the clipping planes are (potentially) visible. Clipping planes are typically perpendicular to the direction of projection. Their locations can be set using the cameras clipping range. The location of the planes are measured from the cameras position along the direction of projection. The front clipping plane is at the minimum range value, and the back clipping plane is at the maximum range value. Later on in Chapter 7 , when we discuss stereo rendering, we will see examples of clipping planes that are not perpendicular to the direction of projection.

Taken together these camera parameters define a rectangular pyramid, with its apex at the cameras position and extending along the direction of projection. The pyramid is truncated at the top with the front clipping plane and at the bottom by the back clipping plane. The resulting view frustum defines the region of 3D space visible to the camera.

While a camera can be manipulated by directly setting the attributes mentioned above, there are some common operations that make the job easier. Figure 3.11 and Figure 3.12 will help illustrate these operations. Changing the azimuth of a camera rotates its position around its view up vector, centered at the focal point . Think of this as moving the camera to the left or right while always keeping the distance to the focal point constant. Changing a cameras elevation rotates its position around the cross product of its direction of projection and view up centered at the focal point. This corresponds to moving the camera up and down. To roll the camera, we rotate the view up vector about the view plane normal. Roll is sometimes called twist.

The next two motions keep the cameras position constant and instead modify the focal point. Changing the yaw rotates the focal point about the view up centered at the cameras position. This is like an azimuth, except that the focal point moves instead of the position. Changes in pitch rotate the focal point about the cross product of the direction of projection and view up centered at the cameras position. Dollying in and out moves the cameras position along the direction of projection, either closer or farther from the focal point. This operation is specified as the ratio of its current

distance to its new distance. A value greater than one will dolly in, while a value less than one will dolly out. Finally, zooming changes the cameras view angle, so that more or less of the scene falls within the view frustum.

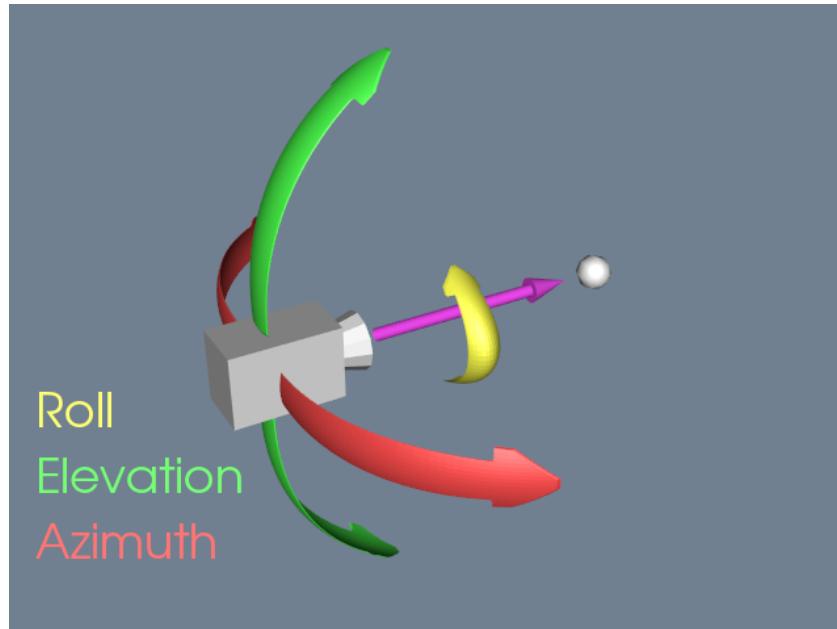


Figure 3.11: Camera movements around the focal point.

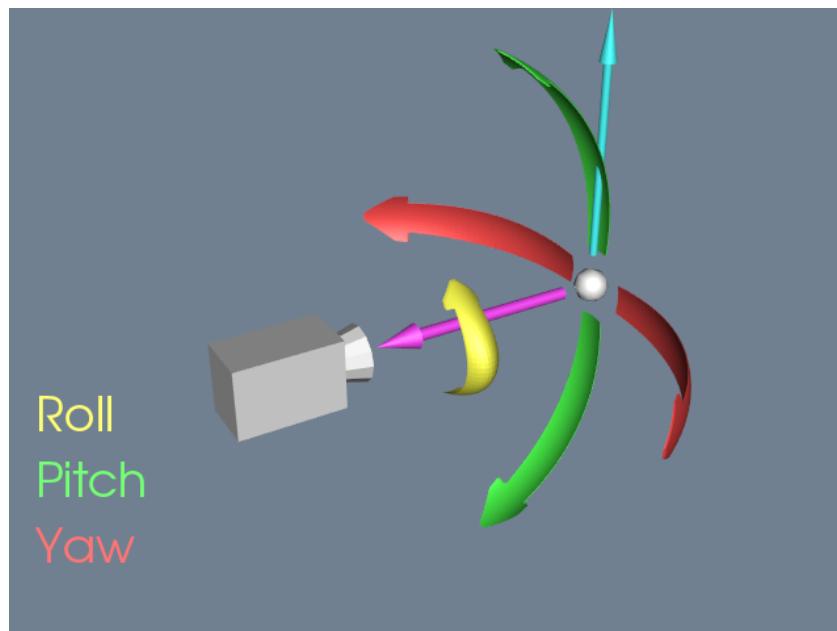


Figure 3.12: Camera movements around the camera position.

Once we have the camera situated, we can generate our 2D image. Some of the rays of light traveling through our 3D space will pass through the lens on the camera. These rays then strike a flat surface to produce an image. This effectively projects our 3D scene into a 2D image. The cameras position and other properties determine which rays of light get captured and projected. More specifically, only rays of light that intersect the cameras position, and are within its viewing frustum, will affect the resulting 2D image.

This concludes our brief rendering overview. The light has traveled from its sources to the actors, where it is reflected and scattered. Some of this light gets captured by the camera and produces a 2D image. Now we will look at some of the details of this process.

3.7 Coordinate Systems

There are four coordinate systems commonly used in computer graphics and two different ways of representing points within them (Figure 3.13). While this may seem excessive, each one serves a purpose. The four coordinate systems we use are: *model*, *world*, *view*, and *display*.

The model coordinate system is the coordinate system in which the model is defined, typically a local Cartesian coordinate system. If one of our actors represents a football, it will be based on a coordinate system natural to the football geometry (e.g., a cylindrical system). This model has an inherent coordinate system determined by the decisions of whoever generated it. They may have used inches or meters as their units, and the football may have been modelled with any arbitrary axis as its major axis.

The world coordinate system is the 3D space in which the actors are positioned. One of the actors responsibilities is to convert from the models coordinates into world coordinates. Each model may have its own coordinate system but there is only one world coordinate system. Each actor must scale, rotate, and translate its model into the world coordinate system. (It may also be necessary for the modeller to transform from its natural coordinate system into a local Cartesian system.) The world coordinate system is also the system in which the position and orientation of cameras and lights are specified.

The view coordinate system represents what is visible to the camera. This consists of a pair of x and y values, ranging between (-1,1), and a z depth coordinate. The x, y values specify location in the image plane, while the z coordinate represents the distance, or range, from the camera. The cameras properties are represented by a four by four transformation matrix (to be described shortly), which is used to convert from world coordinates into view coordinates. This is where the perspective effects of a camera are introduced.

The display coordinate system uses the same basis as the view coordinate system, but instead of using negative one to one as the range, the coordinates are actual x, y pixel locations on the image plane. Factors such as the windows size on the display determine how the view coordinate range of (-1,1) is mapped into pixel locations. This is also where the viewport comes into effect.

You may want to render two different scenes, but display them in the same window. This can be done by dividing the window into rectangular viewports. Then, each renderer can be told what portion of the window it should use for rendering. The viewport ranges from (0,1) in both the x and y axis. Similar to the view coordinate system, the z-value in the display coordinate system also represents depth into the window. The meaning of this z-value will be further described in the section titled Z-Buffer on page 67.

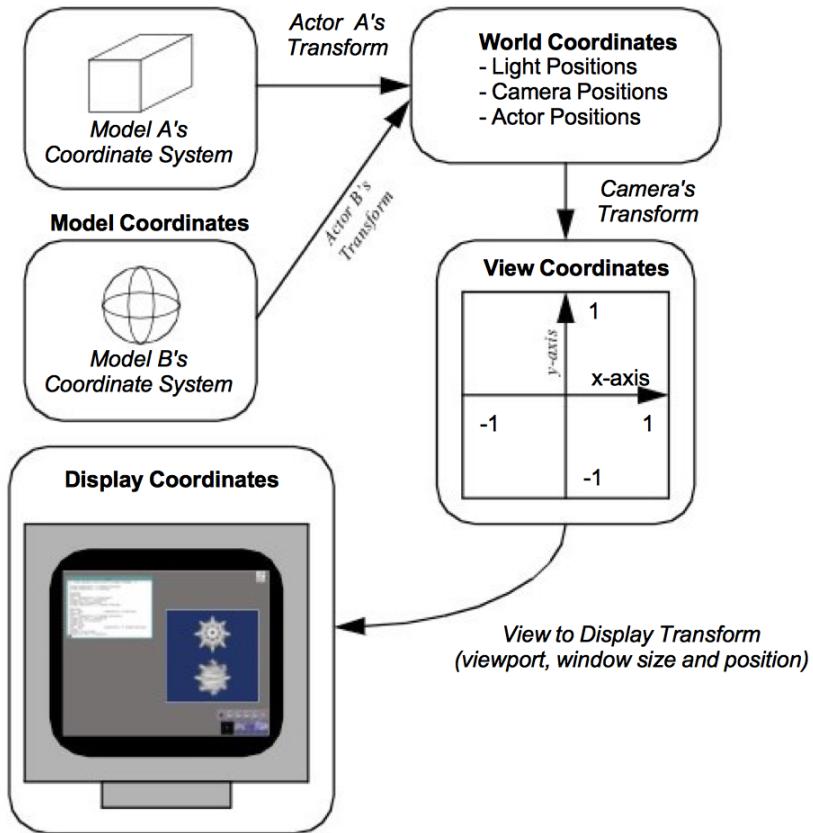


Figure 3.13: Modelling, world, view and display coordinate system.

3.8 Coordinate Transformation

When we create images with computer graphics, we project objects defined in three dimensions onto a two-dimensional image plane. As we saw earlier, this projection naturally includes perspective. To include projection effects such as vanishing points we use a special coordinate system called homogeneous coordinates.

The usual way of representing a point in 3D is the three element Cartesian vector (x, y, z) . Homogeneous coordinates are represented by a four element vector (x_h, y_h, z_h, w_h) . The conversion between Cartesian coordinates and homogeneous coordinates is given by:

$$x = \frac{x_h}{w_h} \quad x = \frac{y_h}{w_h} \quad x = \frac{z_h}{w_h} \quad (3.5)$$

Using homogeneous coordinates we can represent an infinite point by setting w_h to zero. This capability is used by the camera for perspective transformations. The transformations are applied by using a 4×4 transformation matrix. Transformation matrices are widely used in computer graphics because they allow us to perform translation, scaling, and rotation of objects by repeated matrix multiplication. Not all of these operations can be performed using a 3×3 matrix.

For example, suppose we wanted to create a transformation matrix that translates a point

(x, y, z) in Cartesian space by the vector (t_x, t_y, t_z) . We need only construct the translation matrix given by

$$T_T = \begin{bmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.6)$$

and then postmultiply it with the homogeneous coordinate (x_h, y_h, z_h, w_h) . To carry this example through, we construct the homogeneous coordinate from the Cartesian coordinate (x, y, z) by setting $w_h = 1$ to yield $(x, y, z, 1)$. Then to determine the translated point (x', y', z') we premultiply current position by the transformation matrix T_T to yield the translated coordinate. Substituting into Equation 3.6 we have the result

$$\begin{bmatrix} x' \\ y' \\ z' \\ w' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \quad (3.7)$$

Converting back to Cartesian coordinates via Equation 3.5 we have the expected solution

$$x' = x + t_x y' = y + t_y z' = z + t_z \quad (3.8)$$

The same procedure is used to scale or rotate an object. To scale an object we use the transformation matrix

$$T_s = \begin{bmatrix} s_x & 0 & 0 & 0 \\ 0 & s_y & 0 & 0 \\ 0 & 0 & s_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.9)$$

where the parameters s_x , s_y , and s_z are scale factors along the x , y , z axes. Similarly we can rotate an object around the x axes by angle θ using the matrix

$$T_{R_x} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta & 0 \\ 0 & \sin \theta & \cos \theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.10)$$

Around the y axis we use

$$TT_{R_y} = \begin{bmatrix} \cos \theta & 0 & \sin \theta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin \theta & 0 & \cos \theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.11)$$

and around the z axis we use

$$T_{R_z} = \begin{bmatrix} \cos \theta & -\sin \theta & 0 & 0 \\ \sin \theta & \cos \theta & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.12)$$

Another useful rotation matrix is used to transform one coordinate axes $x - y - z$ to another coordinate axes $x' - y' - z'$. To derive the transformation matrix we assume that the unit x' . To derive the transformation matrix we assume that the unit x' axis make the angles $(\theta_{x'x}, \theta_{x'y}, \theta_{x'z})$ around the $x-y-z$ axes (these are called direction cosines). Similarly, the unit y' axis makes the angles $(\theta_{y'x}, \theta_{y'y}, \theta_{y'z})$ and the unit z' axis makes the angles $(\theta_{z'x}, \theta_{z'y}, \theta_{z'z})$. The resulting rotation matrix is formed by placing the direction cosines along the rows of the transformation matrix as follows

$$T_R = \begin{bmatrix} \cos \theta_{x'x} & \cos \theta_{x'y} & \cos \theta_{x'z} & 0 \\ \cos \theta_{y'x} & \cos \theta_{y'y} & \cos \theta_{y'z} & 0 \\ \cos \theta_{z'x} & \cos \theta_{z'y} & \cos \theta_{z'z} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.13)$$

Rotations occur about the coordinate origin. It is often more convenient to rotate around the center of the object (or a user-specified point). Assume that we call this point the objects center . To rotate around we Oc must first translate the object to the Oorigin, apply rotations, and then translate the object back.

Transformation matrices can be combined by matrix multiplication to achieve combinations of translation, rotation, and scaling. It is possible for a single transformation matrix to represent all types of transformation simultaneously. This matrix is the result of repeated matrix multiplications. A word of warning: The order of the multiplication is important. For example, multiplying a translation matrix by a rotation matrix will not yield the same result as multiplying the rotation matrix by the translation matrix.

3.9 Actor Geometry

We have seen how lighting properties control the appearance of an actor, and how the camera in combination with transformation matrices is used to project an actor to the image plane. What is left to define is the geometry of the actor, and how we position it in the world coordinate system.

3.9.1 Modelling

A major topic in the study of computer graphics is modelling or representing the geometry of physical objects. Various mathematical techniques have been applied including combinations of points, lines, polygons, curves, and splines of various forms, and even implicit mathematical functions.

This topic is beyond the scope of the text. The important point here is that there is an underlying geometric model that specifies what the object's shape is and where it is located in the model coordinate system.

In data visualization, modelling takes a different role. Instead of directly creating geometry to represent an object, visualization algorithms *compute* these forms. Often the geometry is abstract (like a contour line) and has little relationship to real world geometry. We will see how these models are computed when we describe visualization algorithms in Chapter 6 and Chapter 9.

The representation of geometry for data visualization tends to be simple, even though computing the representations is not. These forms are most often primitives like points, lines, and polygons, or visualization data such as volume data. We use simple forms because we desire high performance and interactive systems. Thus we take advantage of computer hardware (to be covered in “Graphics Hardware” on 3.10) or special rendering techniques like volume rendering (see “Volume Rendering” on 7.3).

3.9.2 Actor Location and Orientation

Every actor has a transformation matrix that controls its location and scaling in world space. The actor's geometry is defined by a model in model coordinates. We specify the actor's location using orientation, position, and scale factors along the coordinate axes. In addition, we can define an origin around which the actor rotates. This feature is useful because we can rotate the actor around its center or some other meaningful point.

The orientation of an actor is determined by rotations stored in an orientation vector (O_x, O_y, O_z). This vector defines a series of rotational transformation matrices. As we saw in the previous section on transformation matrices, the order of application of the transformations is not arbitrary. We have chosen a fixed order based on what we think is natural to users. The order of transformation is a rotation by O_y around the y axis, then by O_x around the x axis, and finally by O_z around the z axis. This ordering is arbitrary and is based on the standard camera operations. These operations (in order) are a camera azimuth, followed by an elevation, and then a roll (Figure 3.14).

All of these rotations take place around the origin of the actor. Typically this is set to the center of its bounding box, but it can be set to any convenient point. There are many different methods for changing an actor's orientation. `RotateX()`, `RotateY()`, and `RotateZ()` are common methods that rotate about their respective axes. Many systems also include a method to rotate about a user-defined axis. In the Visualization Toolkit the `RotateXYZ()` method is used to rotate around an arbitrary vector passing through the origin.

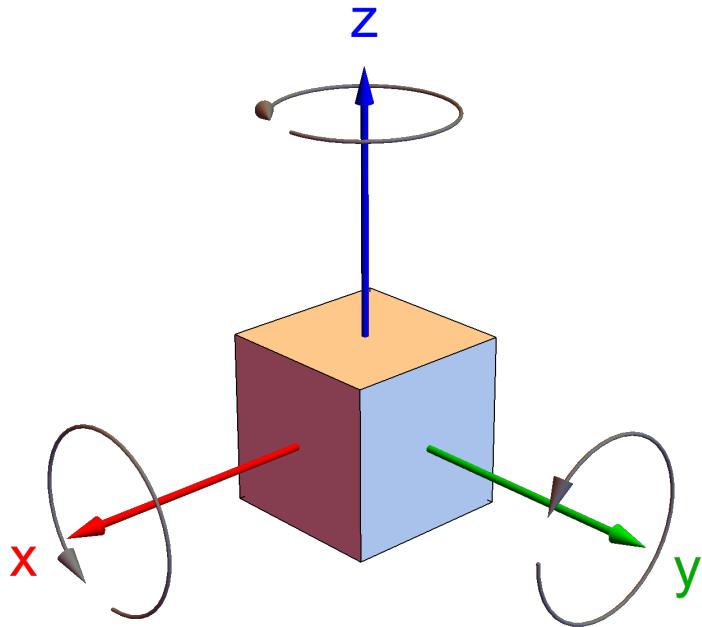


Figure 3.14: Actor coordinate system.

3.10 Graphics Hardware

Earlier we mentioned that advances in graphics hardware have had a large impact on how rendering is performed. Now that we have covered the fundamentals of rendering a scene, we look at some of the hardware issues. First, we discuss raster devices that have replaced vector displays as the primary output device. Then, we look at how our programs communicate to the graphics hardware. We also examine the different coordinate systems used in computer graphics, hidden line/surface removal, and z -buffering.

3.10.1 Raster Devices

The results of computer graphics is pervasive in today's world—digital images (generated with computer graphics) may be found on cell phones, displayed on computer monitors, broadcast on TV, shown at the movie theatre and presented on electronic billboards. All of these, and many more, display mediums are raster devices. A raster device represents an image using a two dimensional array of picture elements called pixels. For example, the word "hello" can be represented as an array of pixels, as shown in Figure 3.15. Here the word "hello" is written within a pixel array that is twenty-five pixels wide and ten pixels high. Each pixel stores one bit of information, whether it is black or white. This is how a black and white laser printer works, for each point on the paper it either prints a black dot or leaves it the color of the paper. Due to hardware limitations, raster devices such as laser printers and computer monitors do not actually draw accurate square pixels like those in Figure 3.15. Instead, they tend to be slightly blurred and overlapping. Another hardware limitation of raster devices is their resolution. This is what causes a 300 dpi (dots per inch) laser printer to produce more detailed output than a nine pin dot matrix printer. A 300 dpi laser printer has a resolution of 300 pixels per inch compared to roughly 50 dpi for the dot matrix printer.

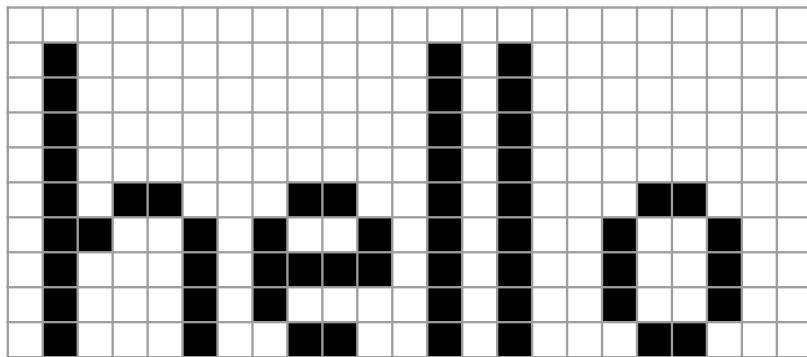


Figure 3.15: A pixel array for the word "hello".

Color computer monitors typically have a resolution of about 80 pixels per inch, making the screen a pixel array roughly one thousand pixels in width and height. This results in over one million pixels, each with a value that indicates what color it should be. Since the hardware in color monitors uses the RGB system, it makes sense to use that to describe the colors in the pixels. Unfortunately, having over one million pixels, each with a red, green, and blue component, can take up a lot of memory. This is part of what differentiates the variety of graphics hardware on the market. Some companies use 24 bits of storage per pixel, others use eight, some advanced systems use more than 100 bits of storage per pixel. Typically, the more bits per pixel the more accurate the colors will be.

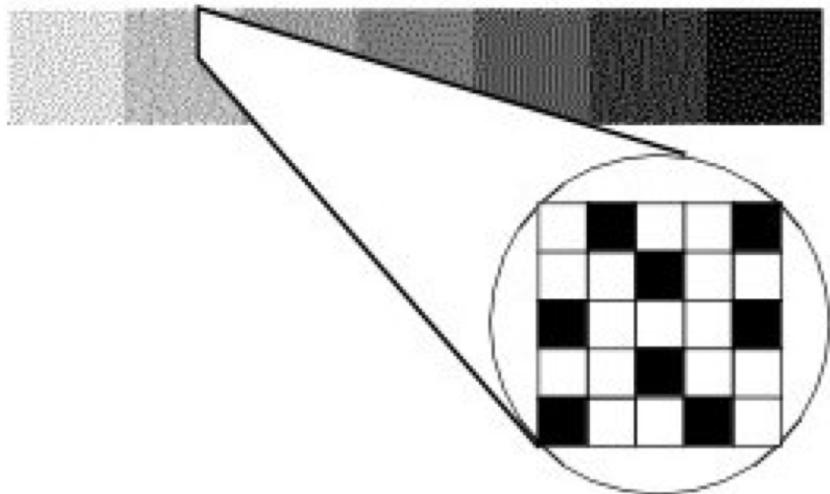


Figure 3.16: Black and white dithering.

One way to work around color limitations in the graphics hardware is by using a technique called *dithering*. Say, for example, that you want to use some different shades of gray, but your graphics hardware only supports black and white. Dithering lets you approximate shades of gray by using a mixture of both black and white pixels. In Figure 3.16, seven gray squares are drawn using a mixture of black and white pixels. From a distance the seven squares look like different shades of gray even though up close, it's clear that they are just different mixtures of black and white pixels. This same technique works just as well for other colors. For example, if your graphics hardware supports primary blue, primary green, and white but not a pastel sea green, you can approximate this color by dithering the green, blue, and white that the hardware does support.

3.10.2 Interfacing to the Hardware

Now that we have covered the basics of display hardware, the good news is that you rarely need to worry about them. Most graphics programming is done using higher-level primitives than individual pixels. Figure 3.17 shows a typical arrangement for a visualization program. At the bottom of the hierarchy is the display hardware that we already discussed; chances are your programs will not interact directly with it. The top three layers above the hardware are the layers you may need to be concerned with.

Many programs take advantage of application libraries as a high-level interface to the graphics capabilities of a system. The *Visualization Toolkit* accompanying this book is a prime example of this. It allows you to display a complex object or graph using just a few commands. It is also possible to interface to a number of different graphics libraries, since different libraries may be supported on different hardware platforms.

The graphics library and graphics hardware layers both perform similar functions. They are responsible for taking high-level commands from an application library or program, and executing them. This makes programming much easier by providing more complex primitives to work with. Instead of drawing pixels one at a time, we can draw primitives like polygons, triangles, and lines, without worrying about the details of which pixels are being set to which colors. Figure 3.18 illustrates some high-level primitives that all mainstream graphics libraries support.

This functionality is broken into two different layers because different machines may have

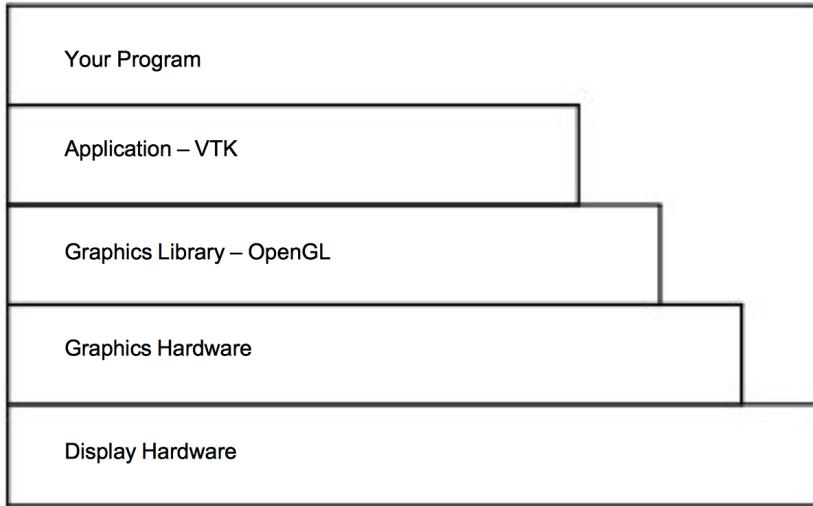


Figure 3.17: Typical graphics interface hierarchy.

vastly different graphics hardware. If you write a program that draws a red polygon, either the graphics library or the graphics hardware must be able to execute that command. On high-end systems, this may be done in the graphics hardware, on others it will be done by the graphics library in software. So the same commands can be used with a wide variety of machines, without worrying about the underlying graphics hardware.

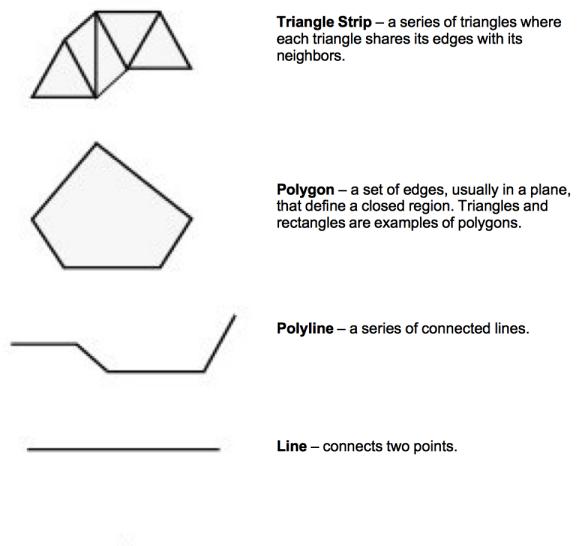


Figure 3.18: Graphics primitives.

The fundamental building block of the primitives in Figure 3.18 is a point (or vertex). A

vertex has a position, normal, and color, each of which is a three element vector. The position specifies where the vertex is located, its normal specifies which direction the vertex is facing, and its color specifies the vertex's red, green, and blue components.

A polygon is built by connecting a series of points or vertices as shown in Figure 3.19. You may be wondering why each vertex has a normal, instead of having just one normal for the entire polygon. A planar polygon can only be facing one direction regardless of what the normals of its vertices indicate. The reason is that sometimes a polygon is used as an approximation of something else, like a curve. Figure 3.20 shows a top-down view of a cylinder. As you can see, it's not really a cylinder but rather a polygonal approximation of the cylinder drawn in gray. Each vertex is shared by two polygons and the correct normal for the vertex is not the same as the normal for the polygon. Similar logic explains why each vertex has a color instead of just having one color for an entire polygon.

When you limit yourself to the types of primitives described above, there are some additional properties that many graphics systems support. Edge color and edge visibility can be used to highlight the polygon primitives that make up an actor. Another way to do this is by adjusting the representation from *surface* to *wireframe* or *points*. This replaces surfaces such as polygons with either their boundary edges or points respectively. While this may not make much sense from a physical perspective, it can help in some illustrations. Using edge visibility when rendering a CAD model can help to show the different pieces that comprise the model.

3.10.3 Rasterization

At this point in the text we have described how to represent graphics data using rendering primitives, and we have described how to represent images using raster display devices. The question remains, how do we convert graphics primitives into a raster image? This is the topic we address in this section. Although a thorough treatise on this topic is beyond the scope of this text, we will do our best to provide a high-level overview.

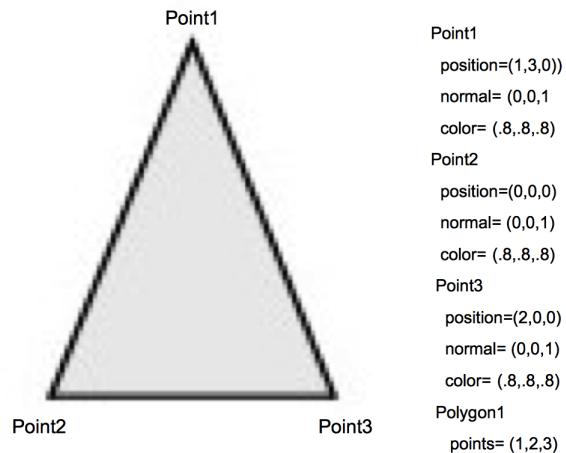


Figure 3.19: An example polygon.

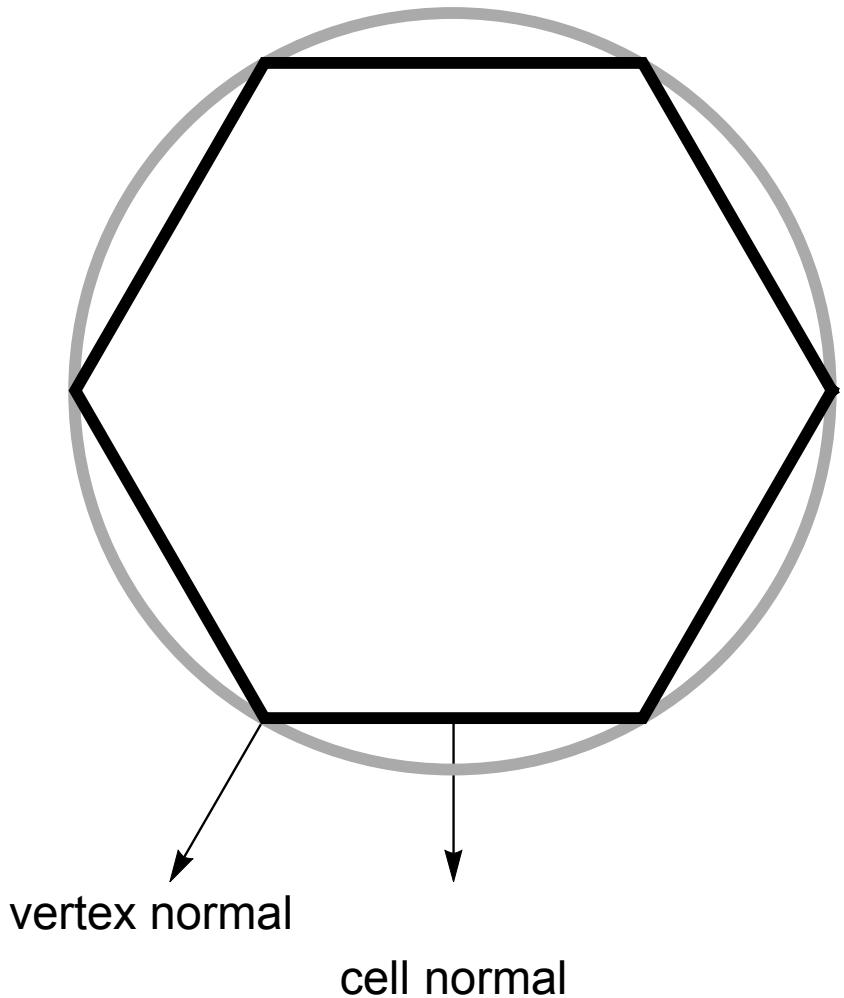


Figure 3.20: Vertex and polygon normals.

The process of converting a geometric representation into a raster image is called *rasterization* or *scan conversion*. In the description that follows we assume that the graphics primitives are triangle polygons. This is not as limiting as you might think, because any general polygon can be tessellated into a set of triangles. Moreover, other surface representations such as splines are usually tessellated by the graphics system into triangles or polygons. (The method described here is actually applicable to convex polygons.)

Most of today's hardware is based on object-order rasterization techniques. As we saw earlier in this chapter, this means processing our actors in order. And since our actors are represented by polygon primitives, we process polygons one at a time. So although we describe the processing of one polygon, bear in mind that many polygons and possibly many actors are processed.

The first step is to transform the polygon using the appropriate transformation matrix. We also project the polygon to the image plane using either parallel or orthographic projection. Part of this process involves clipping the polygons. Not only do we use the front and back clipping planes to clip polygons too close or too far, but we must also clip polygons crossing the boundaries of the image plane. Clipping polygons that cross the boundary of the view frustum means we have to

generate new polygonal boundaries.

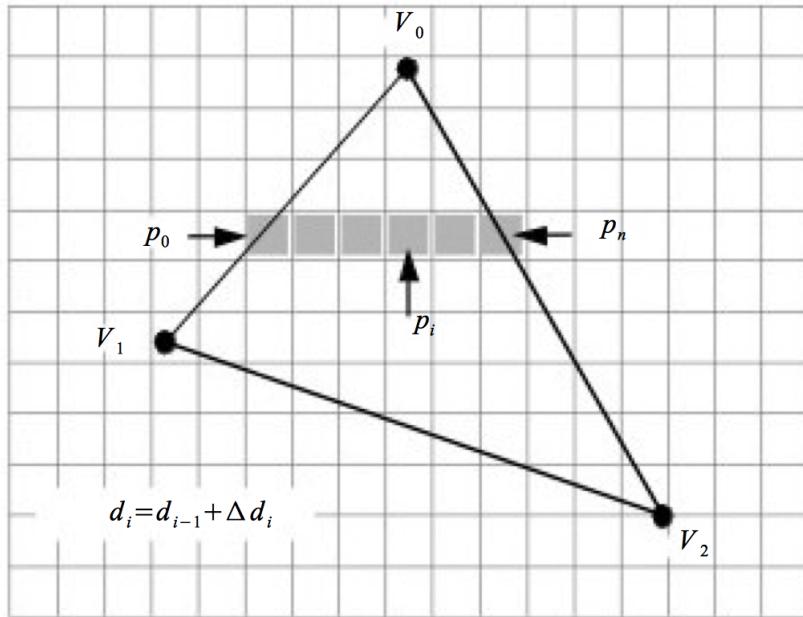


Figure 3.21: Rasterizing a convex polygon. Pixels are processed in horizontal spans (or scan-lines) in the image plane. Data values d_i at point p_i are interpolated along the edges and then along the scan-line using delta data values. Typical data values are RGB components of color.

With the polygon clipped and projected to the image plane, we can begin scan-line processing (Figure 3.21). The first step identifies the initial scan-line intersected by the projected polygon. This is found by sorting the vertices' y values. We then find the two edges joining the vertex on the left and right sides. Using the slopes of the edges along with the data values we compute delta data values. These data are typically the R , G , and B color components. Other data values include transparency values and z depth values. (The z values are necessary if we are using a z -buffer, described in the next section.) The row of pixels within the polygon (i.e., starting at the left and right edges) is called a *span*. Data values are interpolated from the edges on either side of the span to compute the internal pixel values. This process continues span-by-span, until the entire polygon is filled. Note that as new vertices are encountered, it is necessary to recompute the delta data values.

The shading of the polygon (i.e., color interpolation across the polygon) varies depending on the actor's interpolation attribute. There are three possibilities: *flat*, *Gouraud*, or *Phong shading*. Figure 3.6 illustrates the difference between flat and Gouraud interpolation. Flat shading calculates the color of a polygon by applying the lighting equations to just one normal (typically the surface normal) of the polygon. Gouraud shading calculates the color of a polygon at all of its vertices using the vertices' normals and the standard lighting equations. The interior and edges of the polygon are then filled in by applying the scan-line interpolation process. Phong shading is the most realistic of the three. It calculates a normal at every location on the polygon by interpolating the vertex normals. These are then used in the lighting equations to determine the resulting pixel colors. Both flat and Gouraud shading are commonly used methods. The complexity of Phong shading has prevented it from being widely supported in hardware.

3.10.4 Z-Buffer

In our earlier description of the rendering process, we followed rays of light from our eye through a pixel in the image plane to the actors and back to the light source. A nice side effect of ray tracing is that viewing rays strike the first actor they encounter and ignore any actors that are hidden behind it. When rendering actors using the polygonal methods described above, we have no such method of computing which polygons are hidden and which are not. We cannot generally count on the polygons being ordered correctly. Instead, we can use a number of hidden-surface methods for polygon rendering.

One method is to sort all of our polygons from back to front (along the cameras view vector) and then render them in that order. This is called the painters algorithm or painters sort, and has one major weakness illustrated in Figure 3.22. Regardless of the order in which we draw these three triangles, we cannot obtain the desired result, since each triangle is both in front of, and behind, another triangle. There are algorithms that sort and split polygons as necessary to treat such a situation [Carlson85]. This requires more initial processing to perform the sorting and splitting. If the geometric primitives change between images or the camera view changes, then this processing must be performed before each render.

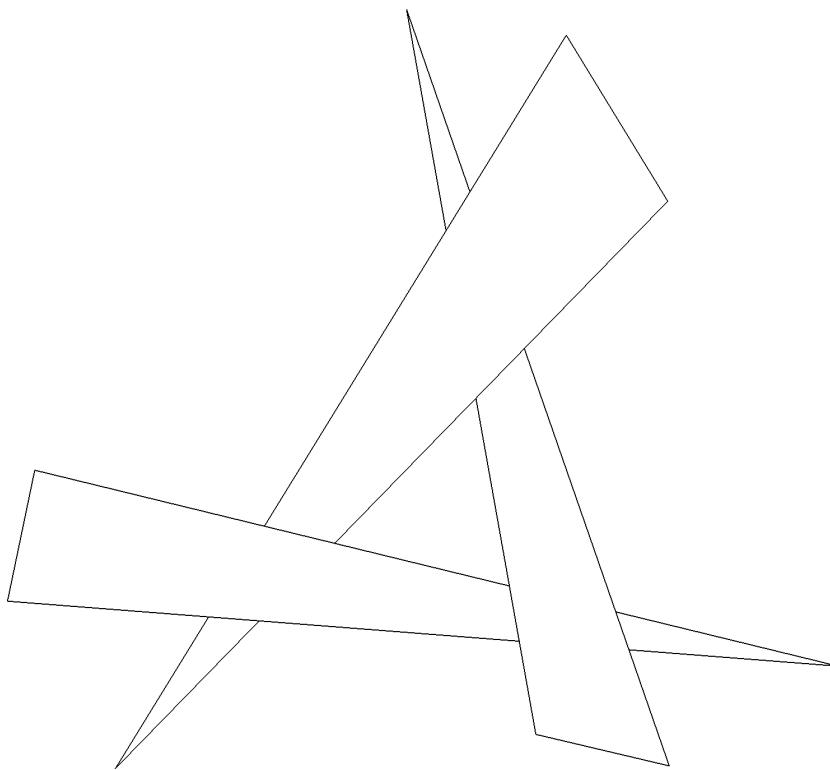


Figure 3.22: Problem with Painter’s algorithm.

Another hidden surface algorithm, z-buffering, takes care of this problem and does not require sorting. Z-buffering takes advantage of the z-value (i.e., depth value along direction of projection) in the view coordinate system. Before a new pixel is drawn, its z-value is compared against the

current z-value for that pixel location. If the new pixel would be in front of the current pixel, then it is drawn and the z-value for that pixel location is updated. Otherwise the current pixel remains and the new pixel is ignored. Z-buffering has been widely implemented in hardware because of its simplicity and robustness. The downside to z-buffering is that it requires a large amount of memory, called a z-buffer, to store a z-value of every pixel. Most systems use a z-buffer with a depth of 24 or 32 bits. For a 1000 by 1000 display that translates into three to four megabytes just for the z-buffer. Another problem with z-buffering is that its accuracy is limited depending on its depth. A 24-bit z-buffer yields a precision of one part in 16,777,216 over the height of the viewing frustum. This resolution is often insufficient if objects are close together. If you do run into situations with z-buffering accuracy, make sure that the front and back clipping planes are as close to the visible geometry as possible.

3.11 Putting It All Together

This section provides an overview of the graphics objects and how to use them in VTK.

3.11.1 The Graphics Model

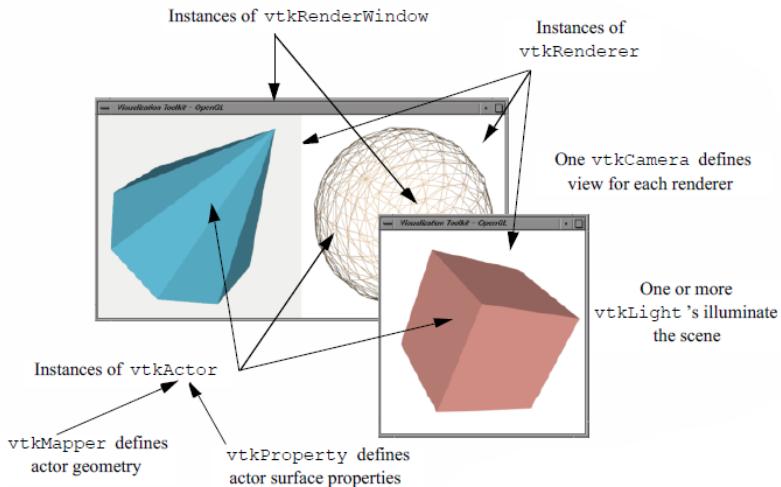


Figure 3.23: Illustrative diagram of graphics objects ([Model.cxx](#)) and ([Model.py](#)).

We have discussed many of the objects that play a part in the rendering of a scene. Now it's time to put them together into a comprehensive object model for graphics and visualization.

In the *Visualization Toolkit* there are seven basic objects that we use to render a scene. There are many more objects behind the scenes, but these seven are the ones we use most frequently. The objects are listed in the following and illustrated in Figure 3.23.

- **vtkRenderWindow** — manages a window on the display device; one or more renderers draw into an instance of vtkRenderWindow.
- **vtkRenderer** — coordinates the rendering process involving lights, cameras, and actors.
- **vtkLight** — a source of light to illuminate the scene.

- `vtkCamera` — defines the view position, focal point, and other viewing properties of the scene.
- `vtkActor` — represents an object rendered in the scene, including its properties and position in the world coordinate system. (*Note:* `vtkActor` is a subclass of `vtkProp`. `vtkProp` is a more general form of actor that includes annotation and 2D drawing classes. See “Assemblies and Other Types of `vtkProp`” on page 74 for more information.)
- `vtkProperty` — defines the appearance properties of an actor including color, transparency, and lighting properties such as specular and diffuse. Also representational properties like wireframe and solid surface.
- `vtkMapper` — the geometric representation for an actor. More than one actor may refer to the same mapper.

The class `vtkRenderWindow` ties the rendering process together. It is responsible for managing a window on the display device. For PCs running Windows, this will be a Microsoft display window, for Linux and UNIX systems this will be an X window, and on the Mac (OSX) a Quartz window. In VTK, instances of `vtkRenderWindow` are device independent. This means that you do not need to be concerned about what underlying graphics hardware or software is being used, the software automatically adapts to your computer as instances of `vtkRenderWindow` are created. (See “Achieving Device Independence” on page 70 for more information.)

In addition to window management, `vtkRenderWindow` objects are used to manage renderers and store graphics specific characteristics of the display window such as size, position, window title, *window depth*, and the *double buffering* flag. The depth of a window indicates how many bits are allocated per pixel. Double buffering is a technique where a window is logically divided into two buffers. At any given time one buffer is currently visible to the user. Meanwhile, the second buffer can be used to draw the next image in an animation. Once the rendering is complete, the two buffers can be swapped so that the new image is visible. This common technique allows animations to be displayed without the user seeing the actual rendering of the primitives. High-end graphics systems perform double buffering in hardware. A typical system would have a rendering window with a depth of 72 bits. The first 24 bits are used to store the red, green, and blue (RGB) pixel components for the front buffer. The next 24 bits store the RGB values for the back buffer. The last 24 bits are used as a *z*-buffer.

The class `vtkRenderer` is responsible for coordinating its lights, camera, and actors to produce an image. Each instance maintains a list of the actors, lights, and an active camera in a particular scene. At least one actor must be defined, but if lights and a camera are not defined, they will be created automatically by the renderer. In such a case the actors are centered in the image and the default camera view is down the *z*-axis. Instances of the class `vtkRenderer` also provide methods to specify the background and ambient lighting colors. Methods are also available to convert to and from world, view, and display coordinate systems.

One important aspect of a renderer is that it must be associated with an instance of the `vtkRenderWindow` class into which it is to draw, and the area in the render window into which it draws must be defined by a rectangular *viewport*. The viewport is defined by normalized coordinates (0,1) in both the *x* and *y* image coordinate axes. By default, the renderer draws into the full extent of the rendering window (viewport coordinates (0,0,1,1)). It is possible to specify a smaller viewport, and to have more than one renderer draw into the same rendering window.

Instances of the class `vtkLight` illuminate the scene. Various instance variables for orienting and positioning the light are available. It is also possible to turn on/off lights as well as setting their color. Normally at least one light is “on” to illuminate the scene. If no lights are defined and turned on, the renderer constructs a light automatically. Lights in VTK can be either positional or infinite.

Positional lights have an associated cone angle and attenuation factors. Infinite lights project light rays parallel to one another.

Cameras are constructed by the class `vtkCamera`. Important parameters include camera position, focal point, location of front and back clipping planes, view up vector, and field of view. Cameras also have special methods to simplify manipulation as described previously in this chapter.

These include elevation, azimuth, zoom, and roll. Similar to `vtkLight`, an instance of `vtkCamera` will be created automatically by the renderer if none is defined.

Instances of the class `vtkActor` represent objects in the scene. In particular, `vtkActor` combines object properties (color, shading type, etc.), geometric definition, and orientation in the world coordinate system. This is implemented behind the scenes by maintaining instance variables that refer to instances of `vtkProperty`, `vtkMapper`, and `vtkTransform`. Normally you need not create properties or transformations explicitly, since these are automatically created and manipulated using `vtkActor`'s methods. You do need to create an instance of `vtkMapper` (or one of its subclasses). The mapper ties the data visualization pipeline to the graphics device. (We will say more about the pipeline in the next chapter.)

In VTK, actors are actually subclasses of `vtkProp` (arbitrary props) and `vtkProp3D` (those that can be transformed in 3D space. (The word prop is derived from the stage, where a prop is an object in the scene.) There are other subclasses of props and actors with specialized behavior (see “Assemblies and Other Types of `vtkProp`” on page 74 for more information). One example is `vtkFollower`. Instances of this class always face the active camera. This is useful when designing signs or text that must be readable from any camera position in the scene.

Instances of the class `vtkProperty` affect the rendered appearance of an actor. When actors are created, a property instance is automatically created with them. It is also possible to create property objects directly and then associate the property object with one or more actors. In this way actors can share common properties.

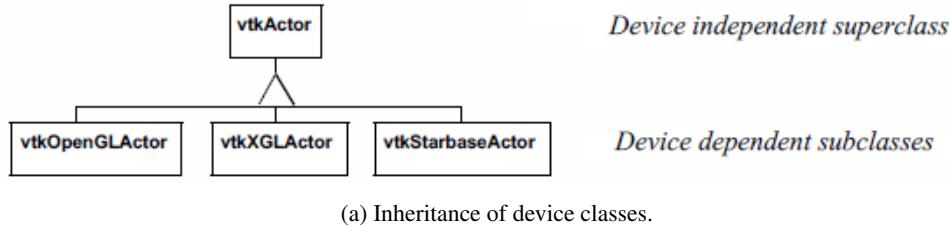
Finally, `vtkMapper` (and its subclasses) defines object geometry and, optionally, vertex colors. In addition, `vtkMapper` refers to a table of colors (i.e., `vtkLookupTable`) that are used to color the geometry. (We discuss mapping of data to colors in “Color Mapping” on page 163.) We will examine the mapping process in more detail in “Mapper Design” on page 195. For now assume that `vtkMapper` is an object that represents geometry and other types of visualization data.

There is another important object, `vtkRenderWindowInteractor`, that captures events (such as mouse clicks and mouse motion) for a renderer in the rendering window. `vtkRenderWindowInteractor` captures these events and then triggers certain operations like camera dolly, pan, and rotate, actor picking, into/out of stereo mode, and so on. Instances of this class are associated with a rendering window using the `SetRenderWindow()` method.

3.11.2 Achieving Device Independence

A desirable property of applications built with VTK is that they are device independent. This means that computer code that runs on one operating system with a particular software/hardware configuration runs unchanged on a different operating system and software/hardware configuration. The advantage of this is that the programmer does not need to expend effort porting an application between different computer systems. Also, existing applications do not need to be rewritten to take advantage of new developments in hardware or software technology. Instead, VTK handles this transparently by a combination of inheritance and a technique known as *object factories*.

Figure 3.24 (a) illustrates the use of inheritance to achieve device independence. Certain classes like `vtkActor` are broken into two parts: a device independent superclass and a device dependent subclass.



(a) Inheritance of device classes.

```

1  vtkActor *vtkActor::New()
2  {
3      vtkObject* ret = vtkGraphicsFactory::CreateInstance("vtkActor");
4      return (vtkActor*)ret;
5  }
  
```

(b) Code fragment from vtkActor::New().

```

1  if (!strcmp("OpenGL",r1) || !strcmp("Win32OpenGL",r1) ||
2      !strcmp("CarbonOpenGL",r1) || !strcmp("CocoaOpenGL",r1))
3  {
4      if(strcmp(vtkclassname, "vtkActor") == 0)
5      {
6          return vtkOpenGLActor::New();
7      }
  
```

(c) Code fragment from vtkGraphicsFactory::CreateInstance(vtkclassname).

Figure 3.24: Achieving device independence using (a) inheritance and object factories (b) and (c)..

The trick here is that the user creates a device dependent subclass by invoking the special constructor New() in the device independent superclass. For example we would use (in C++)

```
1  vtkActor *anActor = vtkActor::New()
```

to create a device dependent instance of vtkActor. The user sees no device dependent code, but in actuality anActor is a pointer to a device dependent subclass of vtkActor. Figure 3.24 (b) is a code fragment of the constructor method New() which uses VTK's object factory mechanism. In turn, the vtkGraphicsFactory (used to instantiate graphical classes) produces the appropriate concrete subclass when requested to instantiate an actor as shown in Figure 3.24.

The use of object factories as implemented using the New() method allows us to create device independent code that can move from computer to computer and adapt to changing technology. For example, if a new graphics library became available, we would only have to create a new device dependent subclass, and then modify the graphics factory to instantiate the appropriate sub-class based on environment variables or other system information. This extension would be localized and only done once, and all applications based on these object factories would be automatically ported without change.

This section works through some simple applications implemented with VTK graphics objects. The focus is on the basics: how to create renderers, lights, cameras, and actors. Later chapters tie together these basic principles to create applications for data visualization.

3.11.3 Examples

Render a Cone.

The following C++ code uses most of the objects introduced in this section to create an image of a cone. The vtkConeSource generates a polygonal representation of a cone and vtkPolyDataMapper maps the geometry (in conjunction with the actor) to the underlying graphics library. (The source code to this example can be found in [Cone.cxx](#) or [Cone.py](#). The source code contains additional documentation as well.)

Listing 3.1: Cone.cxx

```

1 #include "vtkConeSource.h"
2 #include "vtkPolyDataMapper.h"
3 #include "vtkRenderWindow.h"
4 #include "vtkCamera.h"
5 #include "vtkActor.h"
6 #include "vtkRenderer.h"
7
8 int main( int argc, char *argv[] )
9 {
10    vtkConeSource *cone = vtkConeSource::New();
11    cone->SetHeight( 3.0 );
12    cone->SetRadius( 1.0 );
13    cone->SetResolution( 10 );
14
15    vtkPolyDataMapper *coneMapper = vtkPolyDataMapper::New();
16    coneMapper->SetInputConnection( cone->GetOutputPort() );
17    vtkActor *coneActor = vtkActor::New();
18    coneActor->SetMapper( coneMapper );
19
20    vtkRenderer *ren1= vtkRenderer::New();
21    ren1->AddActor( coneActor );
22    ren1->SetBackground( 0.1, 0.2, 0.4 );
23
24    vtkRenderWindow *renWin = vtkRenderWindow::New();
25    renWin->AddRenderer( ren1 ); renWin->SetSize( 300, 300 );
26
27    int i;
28    for (i = 0; i < 360; ++i)
29    {
30        // render the image
31        renWin->Render();
32        // rotate the active camera by one degree
33        ren1->GetActiveCamera()->Azimuth( 1 );
34    }
35    cone->Delete();
36    coneMapper->Delete();
37    coneActor->Delete();
38    // cleanup
39    ren1->Delete();

```

```

40     renWin->Delete();
41
42     return 0;
43 }
```

Some comments about this example. The include files vtk*.h include class definitions for the objects in VTK necessary to compile this example. We use the constructor New() to create the objects in this example, and the method Delete() to destroy the objects. In VTK the use of New() and Delete() is mandatory to insure device independence and properly manage reference counting. (See VTK Users Guide for details.) In this example the use of Delete() is really not necessary because the objects are automatically deleted upon program termination. But generally speaking, you should always use a Delete() for every invocation of New(). (Future examples will not show the Delete() methods in the scope of the main() program to conserve space, nor show the required #include statements.)

The data representing the cone (a set of polygons) in this example is created by linking together a series of objects into a pipeline (which is the topic of the next chapter). First a polygonal representation of the cone is created with a vtkConeSource and serves as input to the data mapper as specified with the SetInput() method. The SetMapper() method associates the mapper's data with the coneActor. The next line adds coneActor to the renderer's list of actors. The cone is rendered in a loop running over 360°. Since there are no cameras or lights defined in the above example, VTK automatically generates a default light and camera as a convenience to the user. The camera is accessed through the GetActiveCamera() method, and a one degree azimuth is applied as shown. Each time a change is made to any objects a Render() method is invoked to produce the corresponding image. Once the loop is complete all allocated objects are destroyed and the program exits.

There are many different types of source objects in VTK similar to vtkConeSource as shown in Figure 3.25. In the next chapter we will learn more about source and other types of filters.

Events and Observers.

A visualization toolkit like VTK is frequently used in interactive applications or may be required to provide status during operation. In addition, integration with other packages such as GUI toolkits is a common task. Supporting such features requires a mechanism for inserting user functionality into the software. In VTK, the *command/observer* design pattern [4] is used for this purpose.

Fundamental to this design pattern as implemented in VTK is the concept of *events*. An event signals that an important operation has occurred in the software. For example, if the user presses the left mouse button in the render window, VTK will invoke the LeftButtonPressEvent. Observers are objects that register their interest in a particular event or events. When one of these events is invoked, the observer receives notification and may perform any valid operation at that point; that is, execute the command associated with the observer. The benefit of the command/observer design pattern is that is simple in concept and implementation, yet provides significant power to the user. However it does require the software implementation to invoke events as it operates.

In the next example, an observer watches for the StartEvent invoked by the renderer just as it begins the rendering process. The observer in turn executes its associated command which simply prints out the camera's current position.

```

1 #include "vtkCommand.h"
2 // Callback for the interaction
3 class vtkMyCallback : public vtkCommand
4 {
5 public:
```

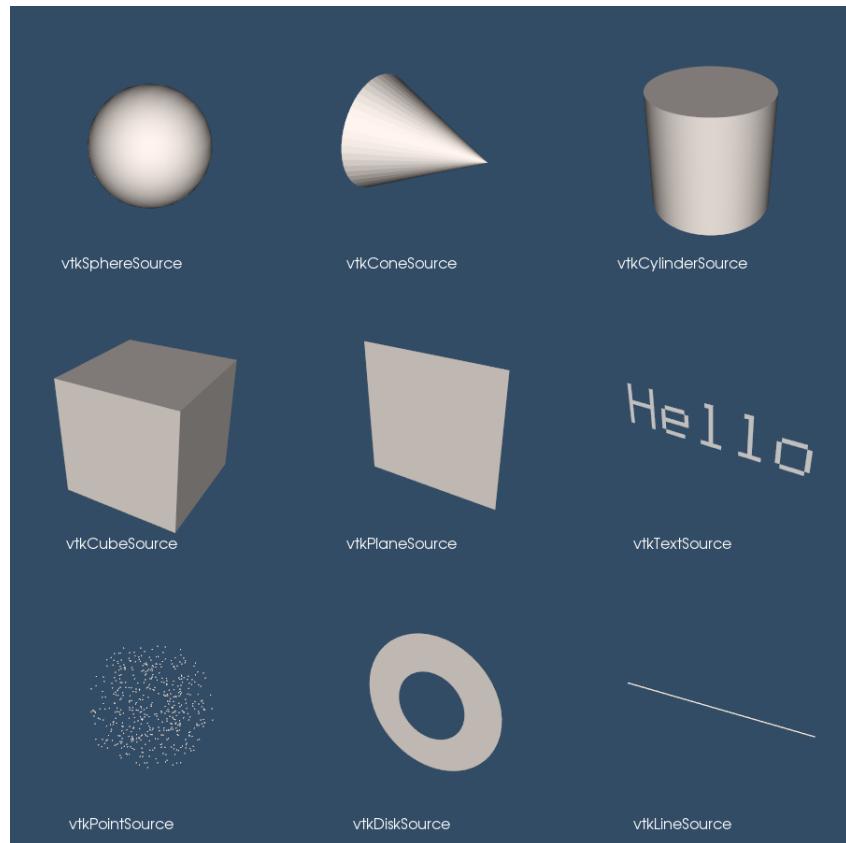


Figure 3.25: Examples of source objects that procedurally generate polygonal models. These nine images represent just some of the capability of VTK. From upper left in reading order: sphere, cone, cylinder, cube, plane, text, random point cloud, disk (with or without hole), and line source. Other polygonal source objects are available; check the subclasses of `vtkPolyDataAlgorithm`. See [SourceObjectsDemo.cxx](#) or [SourceObjectsDemo.py](#)

```

6   static vtkMyCallback *New()
7   { return new vtkMyCallback; }
8   virtual void Execute(vtkObject *caller, unsigned long, void*)
9   {
10     vtkRenderer *ren =
11       reinterpret_cast<vtkRenderer*>(caller);
12     cout << ren->GetActiveCamera()->GetPosition()[0] << " "
13     ren->GetActiveCamera()->GetPosition()[1] << " "
14     ren->GetActiveCamera()->GetPosition()[2] << "n";
15   }
16 };
17
18 int main( int argc, char *argv[] )
19 {
20   vtkConeSource *cone = vtkConeSource::New();
21   cone->SetHeight( 3.0 );

```

```

22     cone->SetRadius( 1.0 );
23     cone->SetResolution( 10 );
24
25     vtkPolyDataMapper *coneMapper = vtkPolyDataMapper::New();
26     coneMapper->SetInputConnection(cone->GetOutputPort());
27     vtkActor *coneActor = vtkActor::New();
28     coneActor->SetMapper( coneMapper );
29
30     vtkRenderer *ren1= vtkRenderer::New();
31     ren1->AddActor( coneActor );
32     ren1->SetBackground( 0.1, 0.2, 0.4 );
33
34     vtkRenderWindow *renWin = vtkRenderWindow::New();
35     renWin->AddRenderer( ren1 ); renWin->SetSize( 300, 300 );
36
37     vtkMyCallback *mo1 = vtkMyCallback::New();
38     ren1->AddObserver(vtkCommand::StartEvent,mo1); mo1->Delete();
39
40     int i;
41     for (i = 0; i < 360; ++i)
42     {
43         // render the image
44         renWin->Render();
45         // rotate the active camera by one degree
46         ren1->GetActiveCamera()->Azimuth( 1 );
47     }
48
49     cone->Delete();
50     coneMapper->Delete();
51     coneActor->Delete();
52     ren1->Delete();
53     renWin->Delete();
54     return 0;
55 }
```

The observer is created by deriving from the class `vtkCommand`. The `Execute()` method is required to be implemented by any concrete subclass of `vtkCommand` (i.e., the method is pure virtual). The resulting subclass, `vtkMyCommand`, is instantiated and registered with the renderer instance `ren1` using the `AddObserver()` method. In this case the `StartEvent` is the observed event.

This simple example does not demonstrate the true power of the command/observer design pattern. Later in this chapter (“Interpreted Code” on page 79) we will see how this functionality is used to integrate a simple GUI into VTK. In Chapter 7 three-dimensional interaction widgets will be introduced (“3D Widgets and User Interaction” on page 150).

Creating Multiple Renderers.

The next example is a bit more complex and uses multiple renderers that share a single rendering window. We use viewports to define where the renderers should draw in the render window. (This C++ code can be found in `Cone3.cxx`.)

Listing 3.2: Cone3.cxx

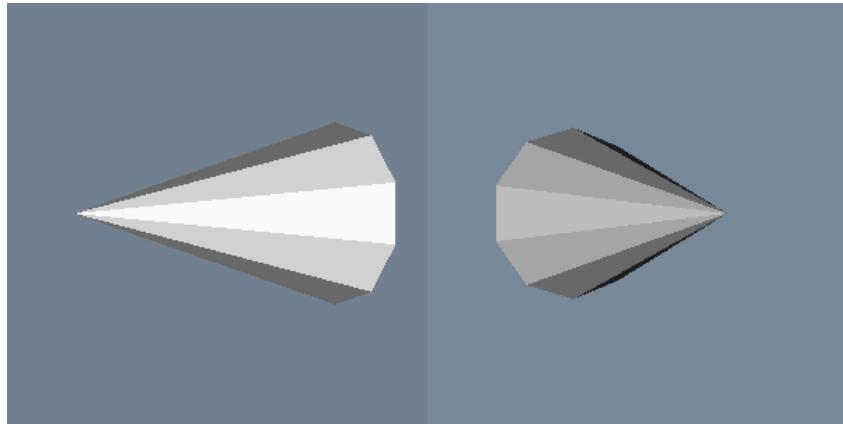


Figure 3.26: Two frames of output from Cone3.cxx. See [Cone3.cxx](#) or [Cone3.py](#)

```

1  vtkRenderer *ren1= vtkRenderer::New();
2  ren1->AddActor( coneActor );
3  ren1->SetBackground( 0.1, 0.2, 0.4 );
4  ren1->SetViewport(0.0, 0.0, 0.5, 1.0);
5
6  vtkRenderer *ren2= vtkRenderer::New();
7  ren2->AddActor( coneActor );
8  ren2->SetBackground( 0.2, 0.3, 0.5 );
9  ren2->SetViewport(0.5, 0.0, 1.0, 1.0);
10
11 vtkRenderWindow *renWin = vtkRenderWindow::New();
12  renWin->AddRenderer( ren1 );
13  renWin->AddRenderer( ren2 );
14  renWin->SetSize( 600, 300 );
15
16 ren1->GetActiveCamera()->Azimuth(90);
17
18 int i;
19 for (i = 0; i < 360; ++i)
20 {
21   // render the image renWin->Render();
22   // rotate the active camera by one degree
23   ren1->GetActiveCamera()->Azimuth( 1 );
24   ren2->GetActiveCamera()->Azimuth( 1 );
25 }
```

As you can see, much of the code is the same as the previous example. The first difference is that we create two renderers instead of one. We assign the same actor to both renderers, but set each renderer's background to a different color. We set the viewport of the two renderers so that one is on the left half of the rendering window and the other is on the right. The rendering window's size is specified as 600 by 300 pixels, which results in each renderer drawing into a viewport of 300 by 300 pixels.

A good application of multiple renderers is to display different views of the same world as demonstrated in this example. Here we adjust the first renderer's camera with a 90 degree azimuth. We then start a loop that rotates the two cameras around the cone. Figure 3.26 shows two frames from this animation.

Properties and Transformations.

The previous examples did not explicitly create property or transformation objects or apply actor methods that affect these objects. Instead, we accepted default instance variable values. This procedure is typical of VTK applications. Most instance variables have been preset to generate acceptable results, but methods are always available for you to override the default values.

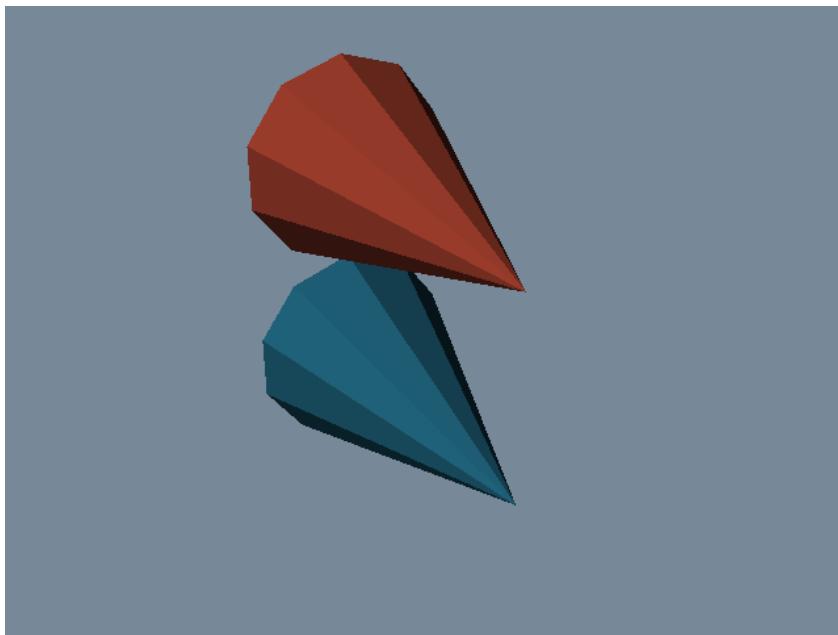


Figure 3.27: Modifying properties and transformation matrix. See [Cone4.cxx](#) or [Cone4.py](#)

This example creates an image of two cones of different colors and specular properties. In addition, we transform one of the objects to lay next to the other. The C++ source code for this example can be found in [Cone4.cxx](#).

Listing 3.3: Cone4.cxx

```

1 vtkActor *coneActor = vtkActor::New();
2   coneActor->SetMapper(coneMapper);
3   coneActor->GetProperty()->SetColor(0.2, 0.63, 0.79);
4   coneActor->GetProperty()->SetDiffuse(0.7);
5   coneActor->GetProperty()->SetSpecular(0.4);
6   coneActor->GetProperty()->SetSpecularPower(20);
7
8 vtkProperty *property = vtkProperty::New();
9   property->SetColor(1.0, 0.3882, 0.2784);
10  property->SetDiffuse(0.7);
11  property->SetSpecular(0.4);

```

```

12   property->SetSpecularPower(20);
13
14 vtkActor *coneActor2 = vtkActor::New();
15   coneActor2->SetMapper(coneMapper);
16   coneActor2->GetProperty()->SetColor(0.2, 0.63, 0.79);
17   coneActor2->SetProperty(property);
18   coneActor2->SetPosition(0, 2, 0);
19
20 vtkRenderer *ren1= vtkRenderer::New();
21   ren1->AddActor( coneActor );
22   ren1->AddActor( coneActor2 );
23   ren1->SetBackground( 0.1, 0.2, 0.4 );

```

We set the actor coneActor properties by modifying the property object automatically created by the actor. This differs from actor coneActor2, where we create a property directly and then assign it to the actor. ConeActor2 is moved from its default position by applying the SetPosition() method. This method affects the transformation matrix that is an instance variable of the actor. The resulting image is shown in Figure 3.27.

Introducing vtkRenderWindowInteractor.

The previous examples are not interactive. That is, it is not possible to directly interact with the data without modifying and recompiling the C++ code. One common type of interaction is to change camera position so that we can view our scene from different vantage points. In the *Visualization Toolkit* we have provided a suite of convenient objects to do this: vtkRenderWindowInteractor, vtkInteractorStyle and their derived classes.

Instances of the class vtkRenderWindowInteractor capture windowing system specific mouse and keyboard events in the rendering window, and then translate these events into VTK events. For example, mouse motion in an X11 or Windows application (occurring in a render window) would be translated by vtkRenderWindowInteractor into VTK's MouseMoveEvent. Any observers registered for this event would be notified (see “Events and Observers” on 73). Typically an instance of vtkInteractorStyle is used in combination with vtkRenderWindowInteractor to define a behavior associated with particular events. For example, we can perform camera dolly, pan, and rotation by using different mouse button and motion combinations. The following code fragment shows how to instantiate and use these objects. This example is the same as our first example with the addition of the interactor and interactor style. The complete example C++ code is in Cone5.cxx.

Listing 3.4: Cone5.cxx

```

1 vtkRenderWindowInteractor *iren =
2   vtkRenderWindowInteractor::New();
3
4   iren->SetRenderWindow(renWin);
5
6 vtkInteractorStyleTrackballCamera *style =
7   vtkInteractorStyleTrackballCamera::New();
8
9   iren->SetInteractorStyle(style);
10  iren->Initialize();
11  iren->Start();

```

After the interactor is created using its New() method, we must tell it what render window to capture events in using the SetRenderWindow() method. In order to use the interactor we have to initialize and start the event loop using the Initialize() and Start() methods, which works with the event loop of the windowing system to begin to catch events. Some of the more useful events include the “w” key, which draws all actors in wireframe; the “s” key, which draws the actors in surface form; the “3” key, which toggles in and out of 3D stereo for those systems that support this; the “r” key, which resets camera view; and the “e” key, which exits the application. In addition, the mouse buttons rotate, pan, and dolly about the camera’s focal point. Two advanced features are the “u” key, which executes a user-defined function; and the “p” key, which picks the actor under the mouse pointer.

Interpreted Code.

In the previous example we saw how to create an interactor style object in conjunction with vtkRenderWindowInteractor to enable us to manipulate the camera by mousing in the render window. Although this provides flexibility and interactivity for a large number of applications, there are examples throughout this text where we want to modify other parameters. These parameters range from actor properties, such as color, to the name of an input file. Of course we can always write or modify C++ code to do this, but in many cases the turn-around time between making the change and seeing the result is too long. One way to improve the overall interactivity of the system is to use an interpreted interface. Interpreted systems allow us to modify objects and immediately see the result, without the need to recompile and relink source code. Interpreted languages also provide many tools, such as GUI (Graphical User Interface) tools, that simplify the creation of applications.

The Visualization Toolkit has built into its compilation process the ability to automatically generate language bindings to the [Ousterhout94]. This so-called wrapping process automatically creates a layer between the C++ VTK library and the interpreter as illustrated in Figure 3.28. There is a one-to-one mapping between C++ methods and Tcl C++ functions for most objects and methods in the system. To demonstrate this, the following example repeats the previous C++ example except that it is implemented with a Tcl script. (The script can be found in Cone5.tcl).

Listing 3.5: Cone5.tcl

```

1 package require vtk
2 package require vtkinteraction
3 vtkConeSource cone
4   cone SetHeight 3.0
5   cone SetRadius 1.0
6   cone SetResolution 10
7
8 vtkPolyDataMapper coneMapper
9   coneMapper SetInputConnection [cone GetOutputPort]
10
11 vtkActor coneActor
12   coneActor SetMapper coneMapper
13
14 vtkRenderer ren1
15   ren1 AddActor coneActor
16   ren1 SetBackground 0.1 0.2 0.4
17
18 vtkRenderWindow renWin
19   renWin AddRenderer ren1

```



Figure 3.28: In VTK the C++ library is automatically wrapped with the interpreted languages Tcl, Python, and Java.

```

20    renWin SetSize 300 300
21
22  vtkRenderWindowInteractor iren
23    iren SetRenderWindow renWin
24
25  vtkInteractorStyleTrackballCamera style
26    iren SetInteractorStyle style
27    iren AddObserver UserEvent {wm deiconify .vtkInteract}
28    iren Initialize
29
30  wm withdraw .

```

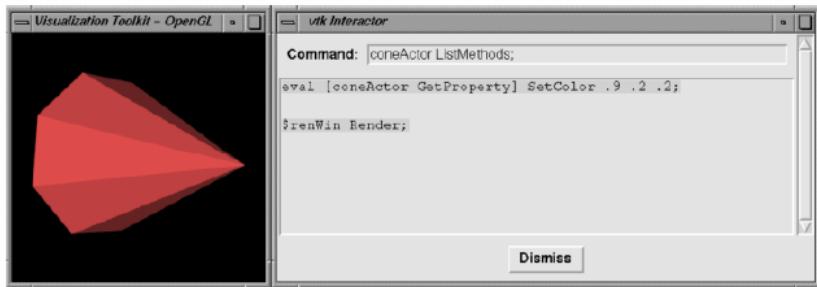


Figure 3.29: Using Tcl and Tk to build an interpreted application (Cone5.tcl).

The example begins by loading some shared libraries defining various VTK classes. Next the standard visualization pipeline is created from the `vtkConeSource` and `vtkPolyDataMapper`. The rendering classes are created exactly the same as with the C++ example. One major addition is an observer to watch for a `UserEvent` in the rendering window (by default a “keypress-u”). The observer triggers the invocation of a Tcl script to raise a Tk interactor GUI widget called `.vtkInteract`. This GUI, which allows the direct typing of Tcl statements, is shown in Figure 3.29 and is defined by the Tcl command package `require vtkinteraction` which was executed earlier in the script. (Note: Tk is a popular GUI toolkit for interpreted languages and is distributed as part of Tcl.)

As we can see from this example, the number of lines of code is less for the Tcl example than for equivalent C++ code. Also, many of the complexities of C++ are hidden using the interpreted language. Using this user-interface GUI we can create, modify, and delete objects, and modify their instance variables. The resulting changes appear as soon as a `Render()` method is applied or mouse events in the rendering window cause a render to occur. We encourage you to use Tcl (or one of the other interpreters) for rapid creation of graphics and visualization examples. C++ is best used when you desire higher performing applications.

Transform Matrices

Transformation matrices are used throughout the Visualization Toolkit. Actors (subclasses of `vtkProp3D` — see “Assemblies and Other Types of `vtkProp`” on page 83) use them to position and orient themselves. Various filters, including `vtkGlyph3D` and `vtkTransformFilter`, use transformation matrices to implement their own functionality. As a user you may never use transformation matrices directly, but understanding them is important to successful use of many VTK classes.

The most important aspect to applying transformation matrices is to understand the order in which the transformations are applied. If you break down a complex series of transformations into

simple combinations of translation, scaling, and rotation, and keep careful track of the order of application, you will have gone a long way to mastering their use.

A good demonstration example of transformation matrices is to examine how vtkActor uses its internal matrix. vtkActor has an internal instance variable Transform to which it delegates many of its methods or uses the matrix to implement its methods. For example, the RotateX(), RotateY(), and RotateZ() methods are all delegated to Transform. The method SetOrientation() uses Transform to orient the actor. The vtkActor class applies transformations in an order that we feel is natural to most users.

The vtkActor class applies transformations in an order that we feel is natural to most users. As a convenience, we have created instance variables that abstract the transformation matrices. The he Origin (o_x, o_y, o_z) specifies the point that is the center of rotation and scaling. The Position (p_x, p_y, p_z) specifies a final translation of the object. Orientation (r_x, r_y, r_z) defines the rotation about the x, y and z axes. Scale (s_x, s_y, s_z) defines scale factors for the x, y , and z axes. Internally, the actor uses these instance variables to create the following sequence of transformations (see Equation (3.6), Equation (3.9), Equation (3.13)).

$$T = T_T(p_x + o_x p_y + o_y p_z + o_z) T_{R_z} T_{R_x} T_{R_z} T_S T_T(-o_x, -o_y, -o_z) \quad (3.14)$$

The term $T_T(x, y, z)$ denotes the translations in the x, y and z direction. Recall that we premultiply the transformation matrix times the position vector. This means the transformations are read from right to left. In other words, Equation (3.14) proceeds as follows:

1. Translate the actor to its origin. Scaling and rotation will occur about this point. The initial translation will be countered by a translation in the opposite direction after scaling and rotations are applied.
2. Scale the geometry.
3. Rotate the actor about the *y*, then *x*, and then *z* axes.
4. Undo the translation of step 1 and move the actor to its final location.

The order of the transformations is important. In VTK the rotations are ordered to what is natural in most cases. We recommend that you spend some time with the software to learn how these transformations work with your own data.

Probably the most confusing aspect of transformations are rotations and their effect on the Orientation instance variable. Generally orientations are not set directly by the user, and most users will prefer to specify rotations with the RotateX(), RotateY(), and RotateZ() methods. These methods perform rotations about the x, y , and z axes in an order specified by the user. New rotations are applied to the right of the rotation transformation. If you need to rotate your actor about a single axis, the actor will rotate exactly as you expect it will, and the resulting orientation vector will be as expected. For example, the operation RotateY(20) will produce an orientation of (0,20,0) and a RotateZ(20) will produce (0,0,20). However, a RotateY(20) followed by a RotateZ(20) will not produce (0,20,20) but produce an orientation of (6.71771, 18.8817, 18.8817)! This is because the rotation portion of Equation (3.14) is built from the rotation order z, then x, and then y. To verify this, a RotateZ(20) followed by a RotateY(20) does produce an orientation of (0,20,20). Adding a third rotation can be even more confusing.

A good rule of thumb is to only use the SetOrientation() method to either reset the orientation to (0,0,0) or to set just one of the rotations. The RotateX(), RotateY(), and RotateZ() methods are preferred to SetOrientation() when multiple angles are needed. Remember that these rotations are applied in reverse order. Figure 3.30 illustrates the use of the rotation methods. We turn off the

erase between frames using the render windows EraseOff() method so we can see the effects of the rotations. Note that in the fourth image the cow still rotates about her own y axis even though an x axis rotation preceded the y rotation.

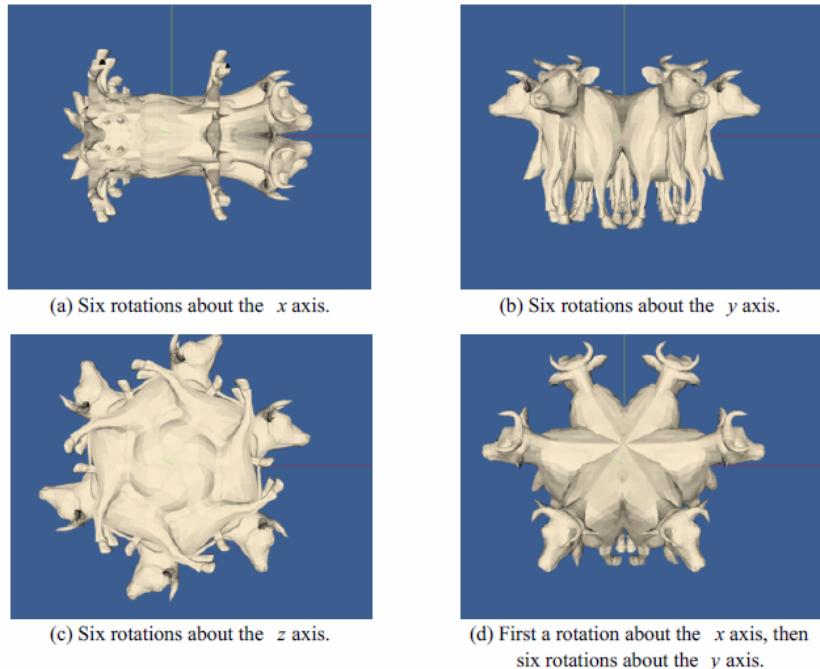


Figure 3.30: Rotations of a cow about her axes. In this model, the *x* axis is from the left to right; the *y* axis is from bottom to top; and the *z* axis emerges from the image. The camera location is the same in all four images.

We have seen that VTK hides some of the complexities of matrix transformations by using instance variables that are more natural than a transformation matrix. But there will be times when the predefined order of transformations performed by the actor will not be sufficient. `vtkActor` has an instance variable `UserMatrix` that contains a 4×4 transformation matrix. This matrix is applied before the transformation composed by the actor. As you become more comfortable with 4×4 transformation matrices you may want to build your own matrix. The object `vtkTransform` creates and manipulates these matrices. Unlike an actor, an instance of `vtkTransform` does not have an instance variable for position, scale, origin, etc. You control the composition of the matrix directly.

The following statements create an identical 4×4 matrix that the actor creates:

```

1  vtkTransform *myTrans = vtkTransform::New();
2  myTrans->Translate(position[0],position[1],position[2]);
3  myTrans->Translate(origin[0],origin[1],origin[2]);
4  myTrans->RotateZ(orientation[2]);
5  myTrans->RotateX(orientation[0]);
6  myTrans->RotateZ(orientation[1]);
7  myTrans->Scale (scale[0],scale[1],scale[2]);
8  myTrans->Translate (-origin[0],-origin[1],-origin[2]);

```

Compare this sequence of transform operations with the transformation in Equation (3.14).

Our final example shows how the transform built with `vtkTransform` compares with a transform built by `vtkActor`. In this example, we will transform our cow so that she rotates about the world coordinate origin (0, 0, 0). She will appear to be walking around the origin. We accomplish this in two ways: one using `vtkTransform` and the actor's `UserMatrix`, then using the actor's instance variables.

First, we will move the cow five feet along the z axis then rotate her about the origin. We always specify transformations in the reverse order of their application:

```

1  vtkTransform *walk = vtkTransform::New(); walk->RotateY(0, 20, 0);
2  walk->Translate(0, 0, 5);
3
4  vtkActor *cow=vtkActor::New();
5  cow->SetUserMatrix(walk->GetMatrix());

```

These operations produce the transformation sequence:

$$T = T_T(0, 0, 5 - (-5))T_{R_y}T_S T_T(0, 0, -(-5)) \quad (3.15)$$

Now we do the same using the cow's instance variables:

```

1  vtkActor *cow=vtkActor::New();
2  cow->SetOrigin(0, 0, -5);
3  cow->RotateY(20);
4  cow->SetPosition(0, 0, 5);

```

These operations produce the transformation sequence:

$$T = T_T(0, 0, 5 - (-5))T_{R_y}T_S T_T(0, 0, -(-5)) \quad (3.16)$$

Cancelling the minus signs in the right-most translation matrix and combining the position and origin translation produce the equivalent transform that we built with `vtkTransform`. Figure 3.30 shows the cow rotating with the specified transformation order. Your preference is a matter of taste and how comfortable you are with matrix transformations. As you become more skilled (and your demands are greater) you may prefer to always build your transformations. VTK gives you the choice.

There is one final and powerful operation that affects an actor's orientation. You can rotate an actor about an arbitrary vector positioned at the actor's origin. This is done with the actor's (and transform's) `RotateWXYZ()` method. The first argument of the operation specifies the number of degrees to rotate about the vector specified by the next three arguments. Figure 3.31 shows how to rotate the cow about a vector passing through her nose. At first, we leave the origin at (0, 0, 0). This is obviously not what we wanted. The second figure shows the rotation when we change the cow's rotation origin to the tip of her nose.

Assemblies and Other Types of `vtkProp`

Often it is desirable to collect actors into a hierarchy of transform-dependent groups. For example, a robot arm may be represented by rigid links connected at joints such as the shoulder joint, upper arm, elbow, lower arm, wrist joint, and hand. In such a configuration, when the shoulder joint rotates, the expected behavior is that the entire arm rotates since the links are connected together. This is an example of what is referred to as an *assembly* in VTK. `vtkAssembly` is just one of many actor-like classes in VTK. As Figure 3.33 shows, these classes are arranged into a hierarchy of `vtkProps`. (In stage and film terminology, a prop is something that appears or is used on stage.)

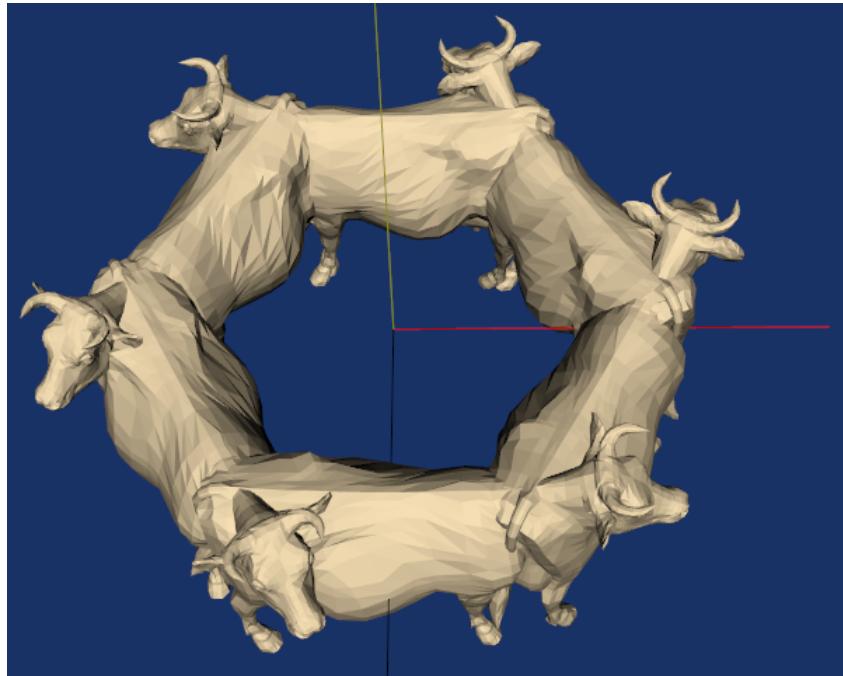


Figure 3.31: Modifying properties and transformation matrix. See [WalkCow.cxx](#) or [WalkCow.py](#)

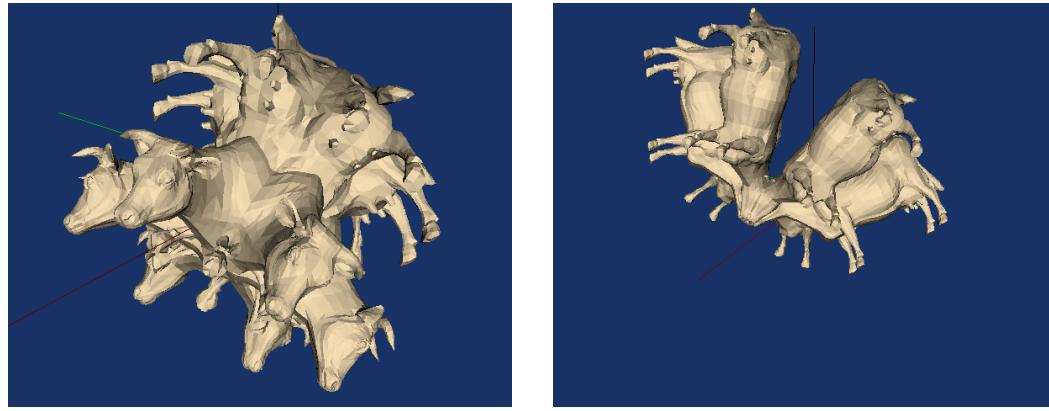
Assemblies are formed in VTK by instantiating a `vtkAssembly` and then adding *parts* to it. A part is any instance of `vtkProp3D` —including other assemblies. This means that assemblies can be formed into hierarchies (as long as they do not contain self-referencing loops). Assemblies obey the rules of transformation concatenation illustrated in the previous section (see “Transformation Matrices” on page 80). Here is an example of how to create a simple assembly hierarchy (from `assembly.tcl`).

Listing 3.6: Part of assembly.tcl

```

1  vtkSphereSource sphere
2  vtkPolyDataMapper sphereMapper
3    sphereMapper SetInputConnection [sphere GetOutputPort] vtkActor
4  sphereActor
5    sphereActor SetMapper sphereMapper
6    sphereActor SetOrigin 2 1 3
7    sphereActor RotateY 6
8    sphereActor SetPosition 2.25 0 0
9    [sphereActor GetProperty] SetColor 1 0 1
10
11 vtkCubeSource cube
12 vtkPolyDataMapper cubeMapper
13  cubeMapper SetInputConnection [cube GetOutputPort] vtkActor
14 cubeActor
15  cubeActor SetMapper cubeMapper
16  cubeActor SetPosition 0.0 .25 0
17  [cubeActor GetProperty] SetColor 0 0 1

```



(a) With origin $(0, 0, 0)$.([WalkCowA.cxx](#) or [WalkCowA.py](#))

(b) With origin at $(6.1, 1.3, .02)$.([WalkCowB.cxx](#) or [WalkCowB.py](#))

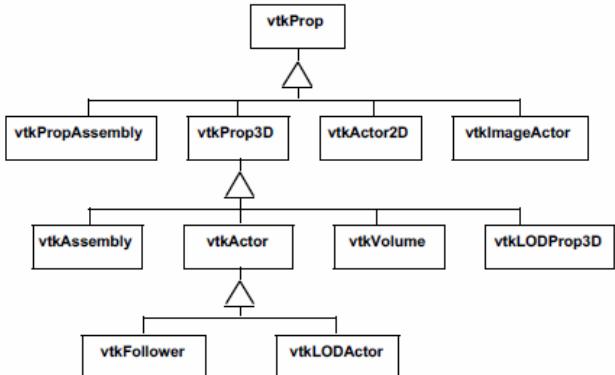
Figure 3.32: The cow rotating about a vector passing through her nose.

```

18 vtkConeSource cone
19 vtkPolyDataMapper coneMapper
20   coneMapper SetInputConnection [cone GetOutputPort] vtkActor
21 coneActor
22   coneActor SetMapper coneMapper
23   coneActor SetPosition 0 0 .25
24   [coneActor GetProperty] SetColor 0 1 0
25 vtkCylinderSource cylinder
26 vtkPolyDataMapper cylinderMapper
27   cylinderMapper SetInputConnection [cylinder GetOutputPort]
28   cylinderMapper SetResolveCoincidentTopologyToPolygonOffset
29
30 vtkActor cylinderActor
31   cylinderActor SetMapper cylinderMapper
32   [cylinderActor GetProperty] SetColor 1 0 0
33
34 vtkAssembly assembly
35   assembly AddPart cylinderActor
36   assembly AddPart sphereActor
37   assembly AddPart cubeActor
38   assembly AddPart coneActor
39   assembly SetOrigin 5 10 15
40
41 // allows faces a specified camera and is used for billboards.
42   assembly AddPosition 5 0 0
43   assembly RotateX 15
44   ren1 AddActor assembly
45   ren1 AddActor coneActor
46 }
```

Note that in this example various actors are added to the assembly with the `AddPart()` method.

Figure 3.33: The vtkProp hierarchy. Props that can be transformed in 3D space are a subclass of vtkProp3D. Images can be drawn effectively with vtkImageActor. Overlay text and graphics use vtkActor2D. Hierarchical groups of vtkProps are gathered into a vtkPropAssembly. Volume rendering uses vtkVolume. Collections of transformable props create a vtkAssembly. Level-of-detail rendering uses vtkLODProp3D and vtkLODActor. A vtkFollower allows faces a specified camera and is used for billboards.



The top-level element of the assembly is the only prop in the hierarchy added to the renderer (with `AddActor()`). Note also that the coneActor appears twice: once as a part of the assembly, and once as a separate actor added to the renderer with `AddActor()`. As you might imagine, this means that the rendering of assemblies requires concatenation of transformation matrices to insure the correct positioning of each vtkProp3D. Furthermore, hierarchical assemblies require special treatment during picking (i.e., graphically selecting props) since a vtkProp can appear more than once in different assembly hierarchies. Picking issues are discussed in more detail in “Picking” on page 152.

As Figure 3.33 indicates, there are other types of vtkProp as well. Most of these will be informally described in the many examples found in this book. In particular, extensive coverage is given to vtkVolume when we describe volume rendering (see “Volume Rendering” on page 150).

3.12 Chapter Summary

Rendering is the process of generating an image using a computer. Computer graphics is the field of study that encompasses rendering techniques, and forms the foundation of data visualization.

Three-dimensional rendering techniques simulate the interaction of lights and cameras with objects, or actors, to generate images. A scene consists of a combination of lights, cameras, and actors. Object-order rendering techniques generate images by rendering actors in a scene in order. Image-order techniques render the image one pixel at a time. Polygon based graphics hardware is based on object-order techniques. Ray tracing or ray-casting is an image-order technique.

Lighting models require a specification of color. We saw both the RGB (red-green-blue) and HSV (hue-saturation-value) color models. The HSV model is a more natural model than the RGB model for most users. Lighting models also include effects due to ambient, diffuse, and specular lighting.

There are four important coordinate systems in computer graphics. The model system is the 3D coordinate system where our geometry is defined. The world system is the global Cartesian system. All modelled data is eventually transformed into the world system. The view coordinate system represents what is visible to the camera. It is a 2D system scaled from $(-1, 1)$. The display coordinate system uses actual pixel locations on the computer display.

Homogeneous coordinates are a 4D coordinate system in which we can include the effects of perspective transformation. Transformation matrices are 4×4 matrices that operate on homogeneous coordinates. Transformation matrices can represent the effects of translation, scaling, and rotation

of an actor. These matrices can be multiplied together to give combined transformations.

Graphics programming is usually implemented using higher-level graphics libraries and specialized hardware systems. These dedicated systems offer better performance and easier implementation of graphics applications. Common techniques implemented in these systems include dithering and z-buffering. Dithering is a technique to simulate colors by mixing combinations of available colors. Z-buffering is a technique to perform hidden-line and hidden-surface removal.

3.13 Bibliographic Notes

This chapter provides the reader with enough information to understand the basic issues and terms used in computer graphics. There are a number of good text books that cover computer graphics in more detail and are recommended to readers who would like a more thorough understanding. The bible of computer graphics is [5]. For those wishing for less intimidating books [2] and [6] are also useful references. You also may wish to peruse proceedings of the ACM SIGGRAPH conferences. These include papers and references to other papers for some of the most important work in computer graphics. [3] provides a good introduction for those who wish to learn more about the human vision system.

Bibliography

- [1] J. E. Bresenham. “Algorithm for Computer Control of a Digital Plotter”. In: *IBM Systems Journal* 4.1 (Jan. 1965), pp. 25–30.
- [2] P. Burger and D. Gillies. *Interactive Computer Graphics Functional, Procedural and Device-Level Methods*. Addison-Wesley Publishing Company, Reading, MA, 1989.
- [3] N. R. Carlson. *Physiology of Behaviour (3d Edition)*. Allyn and Bacon Inc., Newton, MA, 1985.
- [4] E. Gamma, R. Helm, R. Johnson, J. Vlissides. *Design Patterns: Elements of Reusable Object-Oriented Software*. Addison-Wesley Professional, 1994. ISBN: 0-201-63361-2. URL: <https://www.amazon.com/Design-Patterns-Elements-Reusable-Object-Oriented/dp/0201633612?SubscriptionId=0JYN1NVW651KCA56C102&tag=techkie-20&linkCode=xm2&camp=2025&creative=165953&creativeASIN=0201633612>.
- [5] J. D. Foley, A. van Dam, S. K. Feiner, and J. F. Hughes. *Computer Graphics Principles and Practice (2d Ed)*. Addison-Wesley, Reading, MA, 1990.
- [6] A. Watt. *3D Computer Graphics (2d Edition)*. Addison-Wesley, Reading, MA, 1993.
- [7] T. Whitted. “An Improved Illumination Model for Shaded Display”. In: *Communications of the ACM* 23.6 (1980), pp. 343–349.

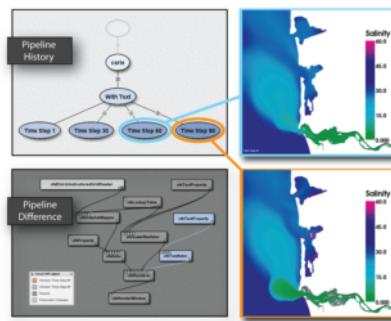
3.14 Exercises

1. Estimate the odds of a ray of light being emitted from the sun, traveling to earth and hitting a one meter square picnic blanket. You can assume that the sun is a point light source that emits light uniformly in all directions. The approximate distance from the sun to the earth is 150,000,000km.
 - (a) What are the odds when the sun is directly overhead?
 - (b) What are the odds when the sun is inclined 45 degrees relative to the surface normal of the picnic blanket?
 - (c) What assumptions or approximations did you make?
2. Proceeding from your result of Exercise 3.1, what are the difficulties in determining the odds of a ray of light traveling from the sun to hit the picnic blanket and then entering a viewer’s eye?
3. The color cyan can be represented in both the HSV and RGB color spaces as shown in Table 3.1. These two representations for cyan do not yield the same wavelength intensity plots. How do they differ?

4. The vtkSphereSource class generates a polygonal model of a sphere. Using the examples at the end of this chapter as starting points, create a program to display a white sphere. Set the ambient and diffuse intensities to 0.5. Then add a for-loop to this program that adjusts the ambient and diffuse color of this sphere so that as the loop progresses, the diffuse color goes from red to blue, and the ambient color goes from blue to green. You might also try adjusting other lighting parameters such as specular color, ambient, diffuse, and specular intensity.
5. Using the vtkSphereSource as described in Exercise 3.4, create a program to display the sphere with a light source positioned at (1, 1, 1). Then extend this program by adding a for loop that will adjust the active cameras clipping range so that increasing portions of the interior of the sphere can be seen. By increasing the first value of the clipping range, you will be adjusting the position of the front clipping plane. Once the front clipping plane starts intersecting the sphere, you should be able to see inside of it. The default radius of the vtkSphereSource is 0.5, so make sure that you adjust the clipping range in increments less than 1.0.
6. Modify the program presented in “Render a Cone” on page 72 so that the user can enter in a world coordinate in homogenous coordinates and the program will print out the resulting display coordinate. Refer to the reference page for vtkRenderer for some useful methods.
 - (a) Are there any world coordinates that you would expect to be undefined in display coordinates?
 - (b) What happens when the world coordinates are behind the camera?
7. Consider rasterizing a ten by ten pixel square. Contrast the approximate difference in the number of arithmetic operations that would need to be done for the cases where it is flat, Gouraud, or Phong shaded.
8. When using a z-buffer, we must also interpolate the z-values (or depth) when rasterizing a primitive. Working from Exercise 3.7, what is the additional burden of computing z-buffer values while rasterizing our square?
9. vtkTransform has a method GetOrientation() that looks at the resulting transformation matrix built from a series of rotations and provides the single x, y, and z rotations that will reproduce the matrix. Specify a series of rotations in a variety of orders and request the orientation with GetOrientation(). Then apply the rotations in the same order that vtkActor does and verify that the resulting 4 x 4 transformation matrix is the same.
10. vtkTransform, by default, applies new transformations at the right of the current transformation. The method PostMultiply() changes the behavior so that the transformations are applied to the left.
 - (a) Use vtkTransform to create a transform using a variety of transformation operators including Scale(), RotateXYZ(), and Translate(). Then create the same matrix with PostMultiplyOn().
 - (b) Applying rotations at the right of a series of transformations in effect rotates the object about its own coordinate system. Use the rotations.tcl script to verify this. Can you explain this?
 - (c) Applying rotations at the left of a series of transformations in effect rotates the object about the world coordinate system. Modify the rotations.tcl script to illustrate this. (Hint: you will have to create an explicit transform with vtkTransform and set the actor’s transform with SetUserMatrix().)

4.0

The Visualization Pipeline



The VisTrails multi-view visualization system. VisTrails enables interactive creation of visualization pipelines, maintaining the history of their evolution, optimizing their execution and allowing multiple pipelines to be compared in a spreadsheet-style layout. Image courtesy of SCI Institute University of Utah.

In the previous chapter we created graphical images using simple mathematical models for lighting, viewing, and geometry. The lighting model included ambient, diffuse, and specular effects. Viewing included the effects of perspective and projection. Geometry was defined as a static collection of graphics primitives such as points and polygons. In order to describe the process of visualization we need to extend our understanding of geometry to include more complex forms. We will see that the visualization process transforms data into graphics primitives. This chapter examines the process of data transformation and develops a model of data flow for visualization systems.

4.1 Overview

Visualization transforms data into images that efficiently and accurately convey information about the data. Thus, visualization addresses the issues of *transformation* and *representation*.

Transformation is the process of converting data from its original form into graphics primitives, and eventually into computer images. This is our working definition of the visualization process. An example of such a transformation is the process of extracting stock prices and creating an *x-y* plot depicting stock price as a function of time.

Representation includes both the internal data structures used to depict the data and the graphics primitives used to display the data. For example, an array of stock prices and an array of times

are the computational representation of the data, while the x - y plot is the graphical representation. Visualization transforms a computational form into a graphical form.

From an object-oriented viewpoint, transformations are processes in the functional model, while representations are the objects in the object model. Therefore, we characterize the visualization model with both functional models and object models.

4.1.1 A Data Visualization Example

A simple mathematical function for a quadric will clarify these concepts. The function

$$F(x, y, z) = a_0x^2 + a_1y^2 + a_2z^2 + a_3xy + a_4yz + a_5xz + a_6x + a_7y + a_8z + a_9 \quad (4.1)$$

is the mathematical representation of a quadric. Figure 4.1a shows a visualization of Equation 4.1 in the region $-1 \leq x, y, z \leq 1$. The visualization process is as follows. We sample the data on a regular grid at a resolution of 50x50x50. Three different visualization techniques are then used. On the left, we generate 3D surfaces corresponding to the function $F(x, y, z) = c$ where c is an arbitrary constant (i.e., the isosurface value). In the center, we show three different planes that cut through the data and are colored by function value. On the right we show the same three planes that have been contoured with constant valued lines. Around each we place a wireframe outline.

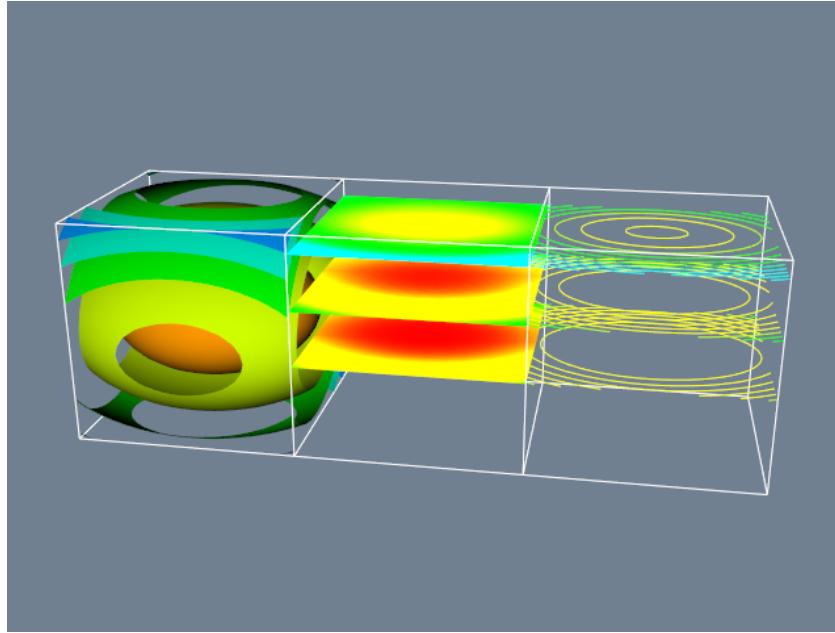
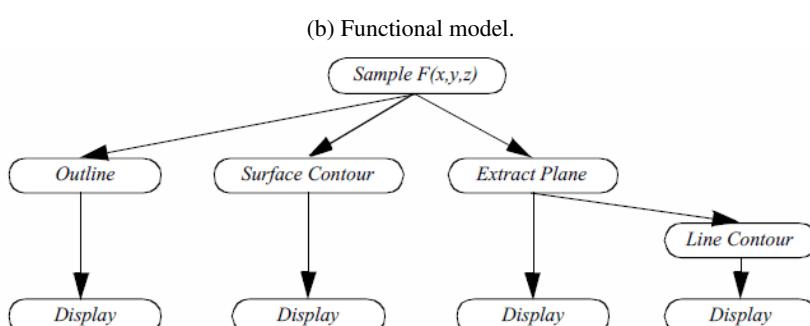
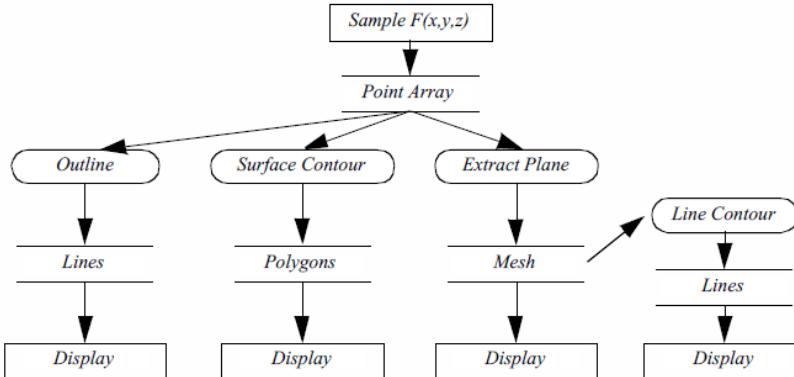
4.1.2 The Functional Model

The functional model in Figure 4.1b illustrates the steps to create the visualization. The oval blocks indicate operations (processes) we performed on the data, and the rectangular blocks represent data stores (objects) that represent and provide access to data. Arrows indicate the direction of data movement. Arrows that point into a block are inputs; data flowing out of a block indicate outputs. The blocks also may have local parameters that serve as additional input. Processes that create data with no input are called data *source* objects, or simply sources. Processes that consume data with no output are called *sinks* (they are also called *mappers* because these processes map data to a final image or output). Processes with both an input and an output are called *filters*.

The functional model shows how data flows through the system. It also describes the dependency of the various parts upon one another. For any given process to execute correctly, all the inputs must be up to date. This suggests that functional models require a synchronization mechanism to insure that the correct output will be generated.

4.1.3 The Visualization Model

In the examples that follow we will frequently use a simplified representation of the functional model to describe visualization processes (Figure 4.1c). We will not explicitly distinguish between sources, sinks, data stores, and process objects. Sources and sinks are implied based on the number of inputs or outputs. Sources will be process objects with no input. Sinks will be process objects with no output. Filters will be process objects with at least one input and one output. Intermediate data stores will not be represented. Instead we will assume that they exist as necessary to support the data flow. Thus, as Figure 4.1c shows, the *Lines* data store that the *Outline* object generates (Figure 4.1b) are combined into the single object *Outline*. We use oval shapes to represent objects in the visualization model.

(a) Quadric visualization. ([QuadricVisualization.cxx](#) or [QuadricVisualization.py](#))

(c) Visualization network.

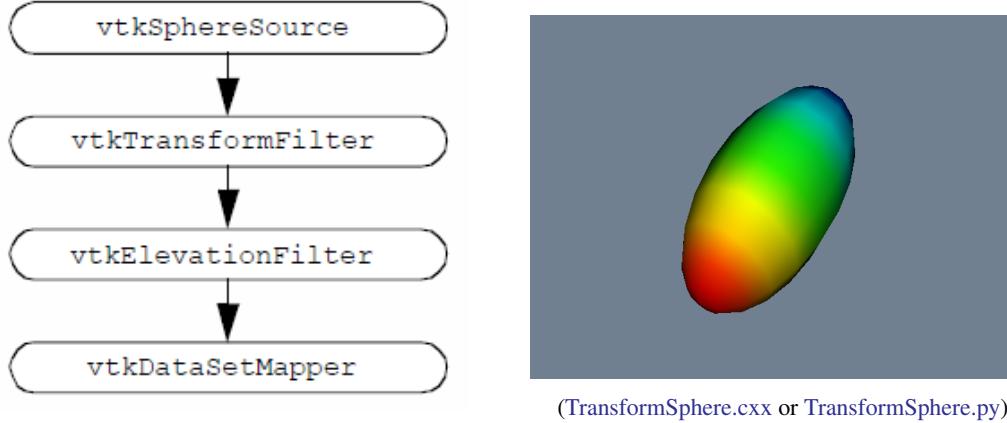
Figure 4.1: Visualizing a quadric function $F(x,y,z) = c$.

4.2 The Visualization Pipeline

4.2.1 Pipeline Design and Implementation

4.3 Putting it All Together

4.3.1 Warped Sphere



Listing (4.1) Warped Sphere.

```

1  vtkSphereSource *sphere = vtkSphereSource::New();
2      sphere->SetThetaResolution(12);
3      sphere->SetPhiResolution(12);
4
5  vtkTransform *aTransform = vtkTransform::New();
6      aTransform->Scale(1,1.5,2);
7
8  vtkTransformFilter *transFilter = vtkTransformFilter::New();
9      transFilter->SetInputConnection(sphere->GetOutputPort());
10     transFilter->SetTransform(aTransform);
11
12 vtkElevationFilter *colorIt = vtkElevationFilter::New();
13     colorIt->SetInputConnection(transFilter->GetOutputPort());
14     colorIt->SetLowPoint(0,0,-1);
15     colorIt->SetHighPoint(0,0,1);
16
17 vtkLookupTable *lut = vtkLookupTable::New();
18     lut->SetHueRange(0.667,0.0); lut->SetSaturationRange(1,1);
19     lut->SetValueRange(1,1);
20
21 vtkDataSetMapper *mapper = vtkDataSetMapper::New();
22     mapper->SetLookupTable(lut);
23     mapper->SetInputConnection(colorIt->GetOutputPort());
24
25 vtkActor *actor = vtkActor::New();
26     actor->SetMapper(mapper);

```

Figure 4.2: The addition of a transform filter to the previous example.

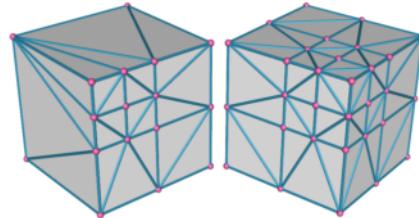
4.4 Executing the Pipeline

4.4.1 Explicit Execution

4.4.2 Implicit Execution

5.0

Basic Data Representation



Compatible tessellations.

In Chapter 4 we developed a pragmatic definition of the visualization process: mapping information into graphics primitives. We saw how this mapping proceeds through one or more steps, each step transforming data from one form, or data representation, into another. In this chapter we examine common data forms for visualization. The goal is to familiarize you with these forms, so that you can visualize your own data using the tools and techniques provided in this text.

5.1 Introduction

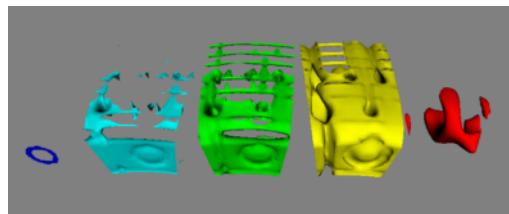
To design representational schemes for data we need to know something about the data we might encounter. We also need to keep in mind design goals, so that we can design efficient data structures and access methods. The next two sections address these issues.

5.1.1 Characterizing Visualization Data

Since our aim is to visualize data, clearly we need to know something about the character of the data. This knowledge will help us create useful data models and powerful visualization systems.

6.0

Fundamental Algorithms



Isosurfaces of a combustor dataset computed at multiple values..

We have seen how to represent basic types of visualization data such as image data, structured grids, unstructured grids, and polygonal data. This chapter explores methods to transform this data to and from these various representations, eventually generating graphics primitives that we can render. These methods are called algorithms, and are of special interest to those working in the field of visualization. Algorithms are the verbs that allow us to express our data in visual form. By combining these verbs appropriately, we can reduce complex data into simple, readily comprehensible sentences that are the power of data visualization.

6.1 Introduction

The algorithms that transform data are the heart of data visualization. To describe the various transformations available, we need to categorize algorithms according to the structure and type of transformation. By structure we mean the effects that transformation has on the topology and geometry of the dataset. By type we mean the type of dataset that the algorithm operates on.

Structural transformations can be classified in four ways, depending on how they affect the geometry, topology, and attributes of a dataset.

- *Geometric transformations* alter input geometry but do not change the topology of the dataset. For example, if we translate, rotate, and/or scale the points of a polygonal dataset, the topology does not change, but the point coordinates, and therefore the geometry, does.
- *Topological transformations* alter input topology but do not change geometry and attribute data. Converting a dataset type from polygonal data to unstructured grid data, or from image data to unstructured grid, changes the topology but not the geometry. More often, however, the geometry changes whenever the topology does, so topological transformation is uncommon.

- *Attribute transformations* convert data attributes from one form to another, or create new attributes from the input data. The structure of the dataset remains unaffected. Computing vector magnitude or creating scalars based on elevation are data attribute transformations.
- *Combined transformations* change both dataset structure and attribute data. For example, computing contour lines or surfaces is a combined transformation.

We also may classify algorithms according to the type of data they operate on, or the type of data they generate. By type, we most often mean the type of attribute data, such as scalars or vectors. Typical categories include:

- *Scalar algorithms* operate on scalar data. For example, the generation of contour lines of temperature on a weather map.
- *Vector algorithms* operate on vector data. Showing oriented arrows of airflow (direction and magnitude) is an example of vector visualization.
- *Tensor algorithms* operate on tensor matrices. An example of a tensor algorithm is to show the components of stress or strain in a material using oriented icons.
- *Modelling algorithms* generate dataset topology or geometry, or surface normals or texture data. Modelling algorithms tend to be the catch-all category for many algorithms, since some do not fit neatly into any single category mentioned above. For example, generating glyphs oriented according to the vector direction and then scaled according to the scalar value, is a combined scalar/vector algorithm. For convenience we classify such an algorithm as a modelling algorithm, because it does not fit squarely into any other category.

Algorithms also can be classified according to the type of data they process. This is the most common scheme found in the visualization literature. However, this scheme is not without its problems. Often the categories overlap, resulting in confusion. For example, a category (not mentioned above) is *volume visualization*, which refers to the visualization of volume data (or in our terminology, image data). This category was initially created to describe the visualization of scalar data arranged on a volume, but more recently, vector (and even tensor) data has been visualized on a volume. Hence, we have to qualify our techniques to *volume vector visualization*, or other potentially confusing combinations.

In the text that follows, we will use the attribute type classification scheme: scalar, vector, tensor, and modelling. In cases where the algorithms operate on a particular dataset type, we place them in the appropriate category according to our best judgment. Be forewarned, though, that alternative classification schemes do exist, and may be better suited to describing the true nature of the algorithm.

6.1.1 Generality Versus Efficiency

Most algorithms can be written specifically for a particular dataset type, or more generally, treating any dataset type. The advantage of a specific algorithm is that it is usually faster than a comparable general algorithm. (See "Other Data Abstractions" on page 138 where we discussed the tradeoff between abstract and concrete forms.) An implementation of a specific algorithm also may be more memory efficient and its implementation may better reflect the relationship between the algorithm and the dataset type it operates on.

One example of this is contour surface creation. Algorithms for extracting contour surfaces were originally developed for volume data, mainly for medical applications. The regularity of volumes lends itself to efficient algorithms. However, the specialization of volume-based algorithms

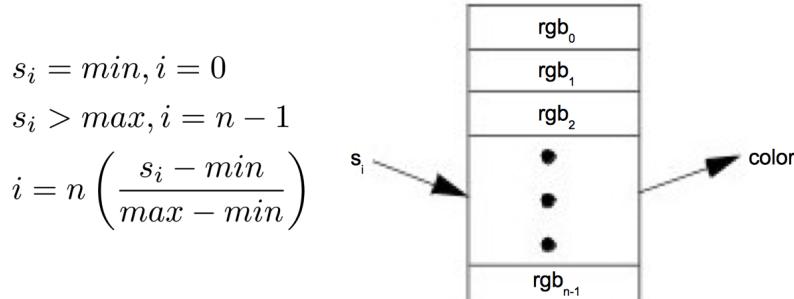


Figure 6.1: Mapping scalars to colors via a lookup table.

precludes their use for more general datasets such as structured or unstructured grids. Although the contour algorithms can be adapted to these other dataset types, they are less efficient than those for volume datasets.

Our presentation of algorithms favors the more general implementations. In some special cases we will describe performance improving techniques for particular dataset types. Refer to the bibliography at the end of each chapter for detailed descriptions of specialized algorithms.

6.2 Scalar Algorithms

Scalars are single data values associated with each point and/or cell of a dataset. (Recall that in the *Visualization Toolkit* we associate data with points.) Because scalar data is commonly found in real-world applications, and because scalar data is so easy to work with, there are many different algorithms to visualize it.

6.2.1 Color Mapping

Color mapping is a common scalar visualization technique that maps scalar data to colors, and displays the colors on the computer system. The scalar mapping is implemented by indexing into a *color lookup table*. Scalar values serve as indices into the lookup table.

The mapping proceeds as follows. The lookup table holds an array of colors (e.g., red, green, blue components or other comparable representations). Associated with the table is a minimum and maximum *scalar range* (\min, \max) into which the scalar values are mapped. Scalar values greater than the maximum range are clamped to the maximum color, scalar values less than the minimum range are clamped to the minimum color value. Then, for each scalar value x_i , the index i into the color table with n entries (and 0-offset) is given by Figure 6.1.

A more general form of the lookup table is called a transfer function. A transfer function is any expression that maps scalar values into a color specification. For example, Figure 6.2 maps scalar values into separate intensity values for the red, green, and blue color components. We can also use transfer functions to map scalar data into other information such as local transparency. (Transfer functions are discussed in more detail in “Transparency and Alpha Values” on page 149 and “Volume Rendering” on page 150). A lookup table is a discrete sampling of a transfer function. We can create a lookup table from any transfer function by sampling the transfer function at a set of discrete points.

Color mapping is a one-dimensional visualization technique. It maps one piece of information (i.e., a scalar value) into a color specification. However, the display of color information is not limited to one-dimensional displays. Often we use color information mapped onto 1D, 2D, or 3D objects. This is a simple way to increase the information content of our visualizations.

The key to color mapping for scalar visualization is to choose the lookup table entries carefully. Figure 6.3 shows four different lookup tables used to visualize gas density as fluid flows through a combustion chamber. The first lookup table is gray-scale. Grayscale tables often provide better structural detail to the eye. The other three images in Figure 6.3 uses different colored lookup tables. The second uses rainbow hues from blue to red. The third uses rainbow hues arranged from red to blue. The last table uses a table designed to enhance contrast. Careful use of colors can often enhance important features of a dataset. However, any type of lookup table can exaggerate unimportant details or create visual artifacts because of unforeseen interactions between data, color choice, and human physiology.

Designing lookup tables is as much art as it is science. From a practical point of view, tables should accentuate important features, while minimizing less important or extraneous details. It is also desirable to use palettes that inherently contain scaling information. For example, a color rainbow scale from blue to red is often used to represent temperature scale, since many people associate "blue" with cold temperatures, and "red" with hot temperatures. However, even this scale is problematic: a physicist would say that blue is hotter than red, since hotter objects emit more blue light (i.e., shorter wavelength) than red. Also, there is no need to limit ourselves to "linear" lookup tables. Even though the mapping of scalars into colors has been presented as a linear operation (Figure 6.1, the table itself need not be linear. That is, tables can be designed to enhance small variations in scalar value using logarithmic or other schemes, improving the comfort level and engaging the human observer more deeply in the presentation of data improves the effectiveness of communication.

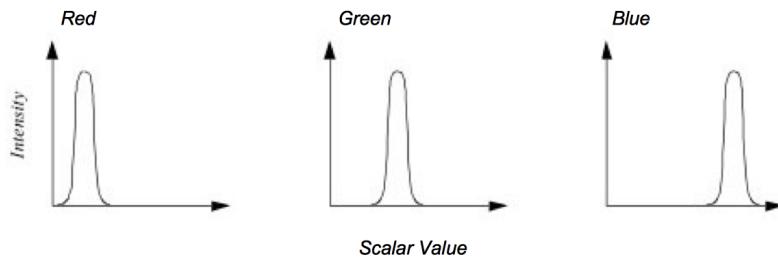


Figure 6.2: Transfer function for color components red, green and blue as a function of scalar value.

6.2.2 Contouring

A natural extension to color mapping is *contouring*. When we see a surface colored with data values, the eye often separates similarly colored areas into distinct regions. When we contour data, we are effectively constructing the boundary between these regions. These boundaries correspond to contour lines (2D) or surfaces (3D) of constant scalar value.

Examples of 2D contour displays include weather maps annotated with lines of constant temperature (isotherms), or topological maps drawn with lines of constant elevation. Three-dimensional contours are called *isosurfaces*, and can be approximated by many polygonal primitives. Examples of isosurfaces include constant medical image intensity corresponding to body tissues such as skin,

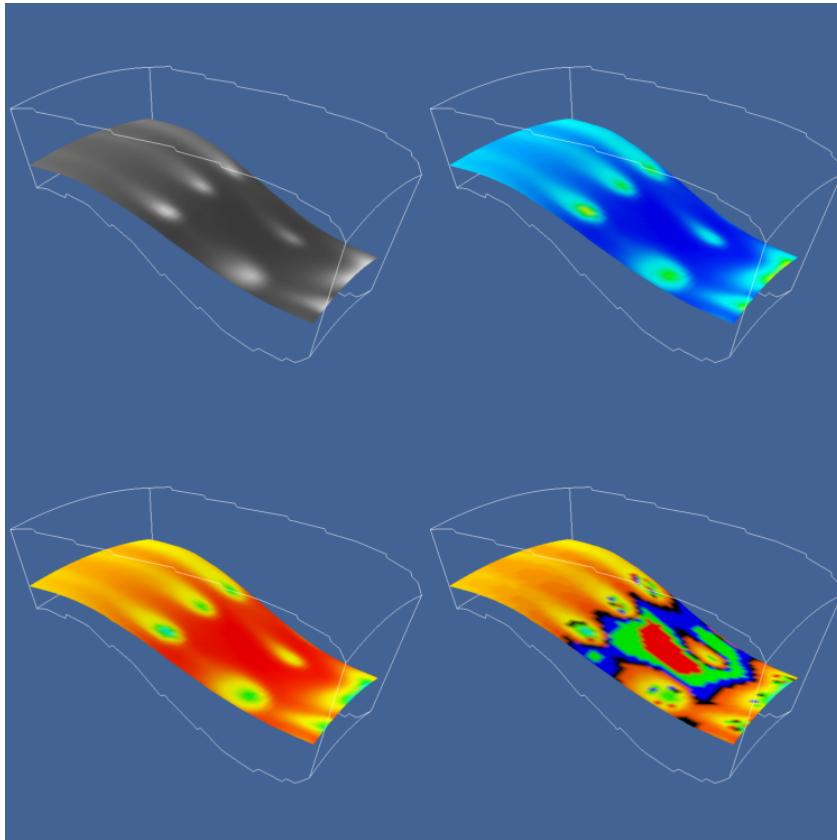


Figure 6.3: Flow density colored with different lookup tables. Top-left: grayscale; Top-right rainbow (blue to red); lower-left rainbow (red to blue); lower-right large contrast. ([Rainbow.cxx](#)) and ([Rainbow.py](#))

bone, or other organs. Other abstract isosurfaces such as surfaces of constant pressure or temperature in fluid flow also may be created.

Consider the 2D structured grid shown in Figure 6.4. Scalar values are shown next to the points that define the grid. Contouring always begins by selecting a scalar value, or contour value, that corresponds to the contour lines or surfaces generated. To generate the contours, some form of interpolation must be used. This is because we have scalar values at a finite set of points in the dataset, and our contour value may lie between the point values. Since the most common interpolation technique is linear, we generate points on the contour surface by linear interpolation along the edges. If an edge has scalar values 10 and 0 at its two endpoints, and if we are trying to generate a contour line of value 5, then edge interpolation computes that the contour passes through the midpoint of the edge.

Once the points on cell edges are generated, we can connect these points into contours using a few different approaches. One approach detects an edge intersection (i.e., the contour passes through an edge) and then "tracks" this contour as it moves across cell boundaries. We know that if a contour edge enters a cell, it must exit a cell as well. The contour is tracked until it closes back on itself, or exits a dataset boundary. If it is known that only a single contour exists, then the process stops. Otherwise, every edge in the dataset must be checked to see whether other contour lines exist. Another approach uses a divide and conquer technique, treating cells independently. This is

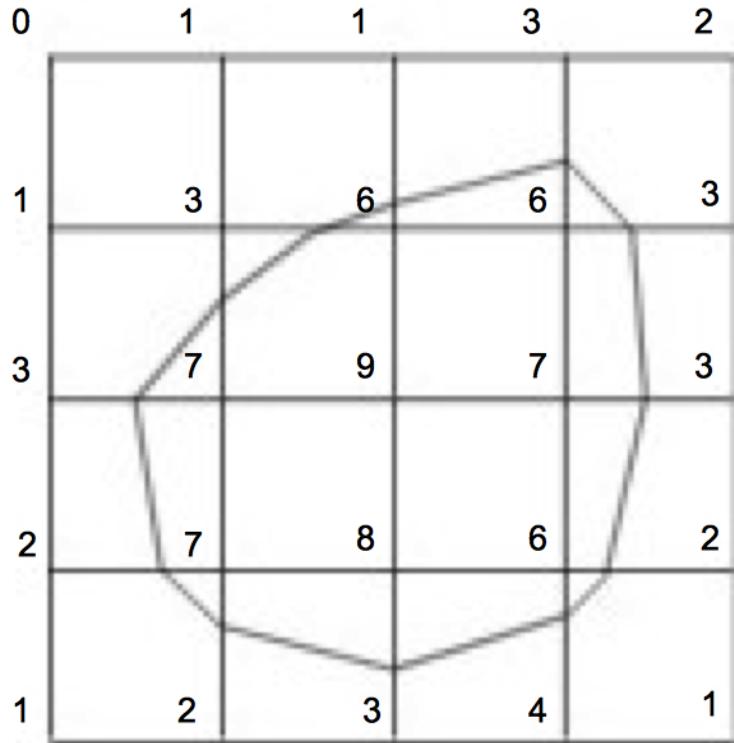


Figure 6.4: Contouring a 2D stuctured grid with contour line value = 5.

the *marching squares* algorithm in 2D, and *marching cubes* [16] in 3D. The basic assumption of these techniques is that a contour can only pass through a cell in a finite number of ways. A case table is constructed that enumerates all possible topological *states* of a cell, given combinations of scalar values at the cell points. The number of topological states depends on the number of cell vertices, and the number of inside / outside relationships a vertex can have with respect to the contour value. A vertex is considered inside a contour if its scalar value is larger than the scalar value of the contour line. Vertices with scalar values less than the contour value are said to be outside the contour. For example, if a cell has four vertices and each vertex can be either inside or outside the contour, there are $2^4 = 16$ possible ways that the contour passes through the cell. In the case table we are not interested in where the contour passes through the cell (e.g., geometric intersection), just how it passes through the cell (i.e., topology of the contour in the cell).

Figure 6.5 shows the sixteen combinations for a square cell. An index into the case table can be computed by encoding the state of each vertex as a binary digit. For 2D data represented on a rectangular grid, we can represent the 16 cases with 4 bit index. Once the proper case is selected, the location of the contour line / cell edge intersection can be calculated using interpolation. The algorithm processes a cell and then moves, or *marches* to the next cell. After all cells are visited, the contour will be completed. In summary, the marching algorithms proceed as follows:

1. Select a cell.
2. Calculate the inside / outside state of each vertex of the cell.
3. Create an index by storing the binary state of each vertex in a separate bit.

4. Use the index to look up the topological state of the cell in a case table.
5. Calculate the contour location (via interpolation) for each edge in the case table.

This procedure will construct independent geometric primitives in each cell. At the cell boundaries duplicate vertices and edges may be created. These duplicates can be eliminated by using a special coincident point merging operation. Note that interpolation along each edge should be done in the same direction. If not, numerical roundoff will likely cause points to be generated that are not precisely coincident, and will not merge properly.

There are advantages and disadvantages to both the edge-tracking and marching cubes approaches. The marching squares algorithm is easy to implement. This is particularly important when we extend the technique into three dimensions, where isosurface tracking becomes much more difficult. On the other hand, the algorithm creates disconnected line segments and points, and the required merging operation requires extra computation resources. The tracking algorithm can be implemented to generate a single polyline per contour line, avoiding the need to merge coincident points.

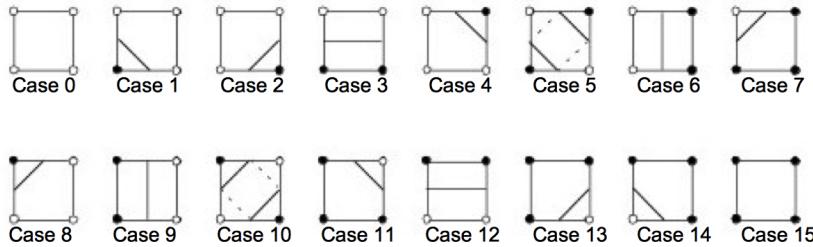


Figure 6.5: Sixteen different marching squares cases. Dark vertices indicate scalar value is above contour value. Cases 5 and 10 are ambiguous.

As mentioned previously, the 3D analogy of marching squares is marching cubes. Here, there are 256 different combinations of scalar value, given that there are eight points in a cubical cell (i.e., 2^8 combinations). Figure 6.6 shows these combinations reduced to 15 cases by using arguments of symmetry. We use combinations of rotation and mirroring to produce topologically equivalent cases.

In two dimensions, contour ambiguity is simple to treat: for each ambiguous case we implement one of the two possible cases. The choice for a particular case is independent of all other choices. Depending on the choice, the contour may either extend or break the current contour as illustrated in Figure 6.9. Either choice is acceptable since the resulting contour lines will be continuous and closed (or will end at the dataset boundary).

In three dimensions the problem is more complex. We cannot simply choose an ambiguous case independent of all other ambiguous cases. For example Figure 6.9 shows what happens if we carelessly implement two cases independent of one another. In this figure we have used the usual case 3 but replaced case 6 with its *complementary* case. Complementary cases are formed by exchanging the “dark” vertices with “light” vertices. (This is equivalent to swapping vertex scalar value from above the isosurface value to below the isosurface value, and vice versa.) The result of pairing these two cases is that a hole is left in the isosurface.

Several different approaches have been taken to remedy this problem. One approach tessellates the cubes with tetrahedron, and uses a *marching tetrahedra* technique. This works because the marching tetrahedra exhibit no ambiguous cases. Unfortunately, the marching tetrahedra algorithm generates isosurfaces consisting of more triangles, and the tessellation of a cube with tetrahedra

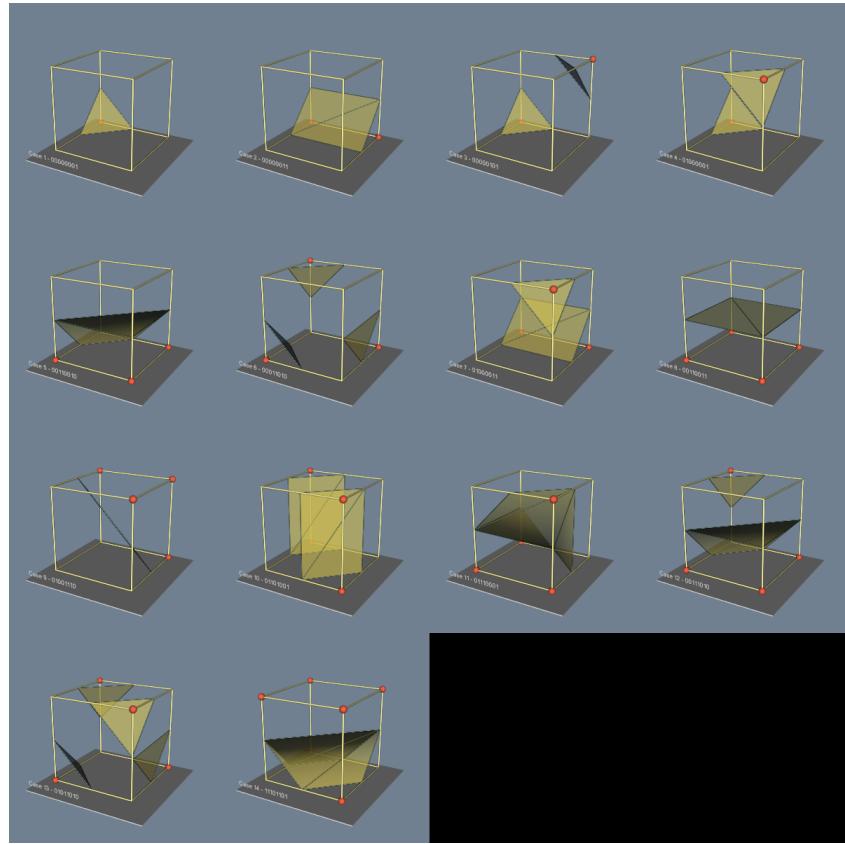


Figure 6.6: Marching Cubes cases for 3D isosurface generation. The 256 possible cases have been reduced to 15 cases using symmetry. Red vertices are greater than the selected isosurface value. ([MarchingCasesA.cxx](#)) and ([MarchingCasesA.py](#))

requires making a choice regarding the orientation of the tetrahedra. This choice may result in artificial “bumps” in the isosurface because of interpolation along the face diagonals as shown in Figure 6.7. Another approach evaluates the asymptotic behavior of the surface, and then chooses the cases to either join or break the contour. Nielson and Hamann [19] have developed a technique based on this approach they call the *asymptotic decider*. It is based on an analysis of the variation of the scalar variable across an ambiguous face. The analysis determines how the edges of isosurface polygons should be connected.

A simple and effective solution extends the original 15 marching cubes cases by adding additional complementary cases. These cases are designed to be compatible with neighboring cases and prevent the creation of holes in the isosurface. There are six complementary cases required, corresponding to the marching cubes cases 3, 6, 7, 10, 12, and 13. The complementary marching cubes cases are shown in Figure 6.10.

We can extend the general approach of marching squares and marching cubes to other topological types. In VTK we use marching lines, triangles, and tetrahedra to contour cells of these types (or composite cells that are composed of these types). In addition, although we speak of regular types such as squares and cubes, marching cubes can be applied to any cell type topologically equivalent to a cube (e.g., hexahedron or non-cubical voxel).

Figure 6.11 shows four applications of contouring. In Figure 6.11a we see 2D contour lines of

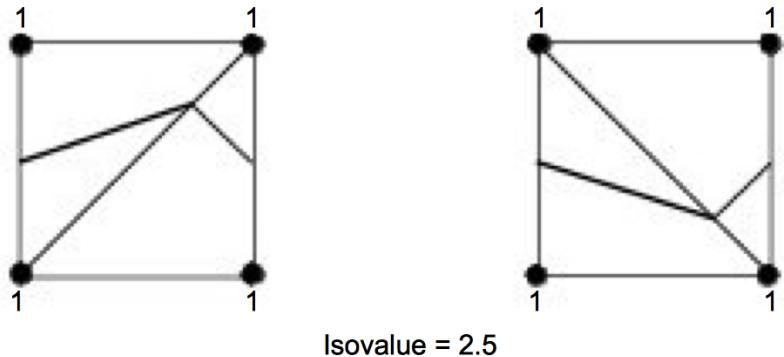


Figure 6.7: Using marching triangles or marching tetrahedra to resolve ambiguous cases on rectangular lattice (only face of cube is shown). Choice of diagonal orientation may result in “bumps” in contour surface. In 2D, diagonal orientation can be chosen arbitrarily, but in 3D diagonal is constrained by neighbor.

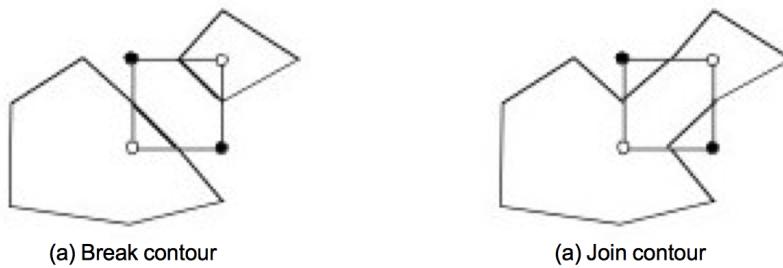
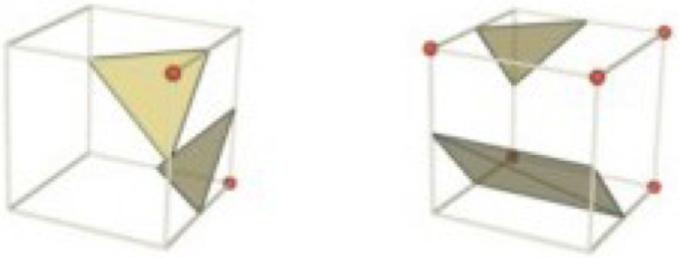


Figure 6.8: Choosing a particular contour case will break (a) or join (b) the current contour. Case shown is marching squares case 10.

CT density value corresponding to different tissue types. These lines were generated using marching squares. Figure 6.11b through Figure 6.11d are isosurfaces created by marching cubes. Figure 6.11b is a surface of constant image intensity from a computed tomography (CT) X-ray imaging system. (Figure 6.11a is a 2D subset of this data.) The intensity level corresponds to human bone. Figure 6.11c is an isosurface of constant flow density. Figure 6.11d is an isosurface of electron potential of an iron protein molecule. The image shown in Figure 6.11b is immediately recognizable because of our familiarity with human anatomy. However, for those practitioners in the fields of computational fluid dynamics and molecular biology, Figure 6.11c and Figure 6.11d are equally familiar. As these examples show, methods for contouring are powerful yet general techniques for visualizing data from a variety of fields.

6.2.3 Scalar Generation

The two visualization techniques presented thus far, color mapping and contouring, are simple, effective methods to display scalar information. It is natural to turn to these techniques first when visualizing data. However, often our data is not in a form convenient to these techniques. The data may not be single-valued (i.e., a scalar), or it may be a mathematical or other complex rela-



Case 3 Case 6c

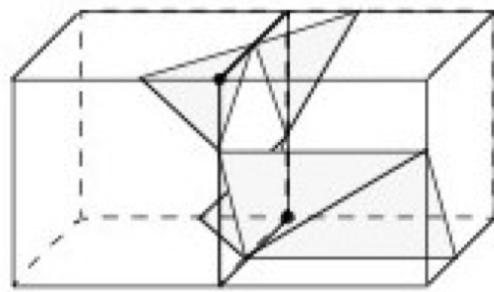
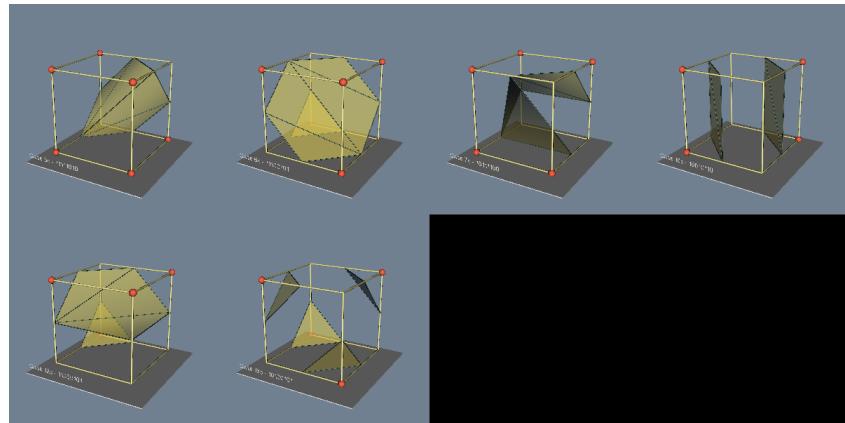


Figure 6.9: Arbitrarily choosing marching cubes cases leads to holes in the isosurface.

Figure 6.10: Marching cubes complementary cases.([MarchingCasesB.cxx](#)) and ([MarchingCasesB.py](#))

tionship. That is part of the fun and creative challenge of visualization: We must tap our creative resources to convert data into a form we can visualize.

For example, consider terrain data. We assume that the data is xyz coordinates, where x and y represent the coordinates in the plane, and z represents the elevation above sea level. Our desired visualization is to color the terrain according to elevation. This requires creating a color map — possibly using white for high altitudes, blue for sea level and below, and various shades of green

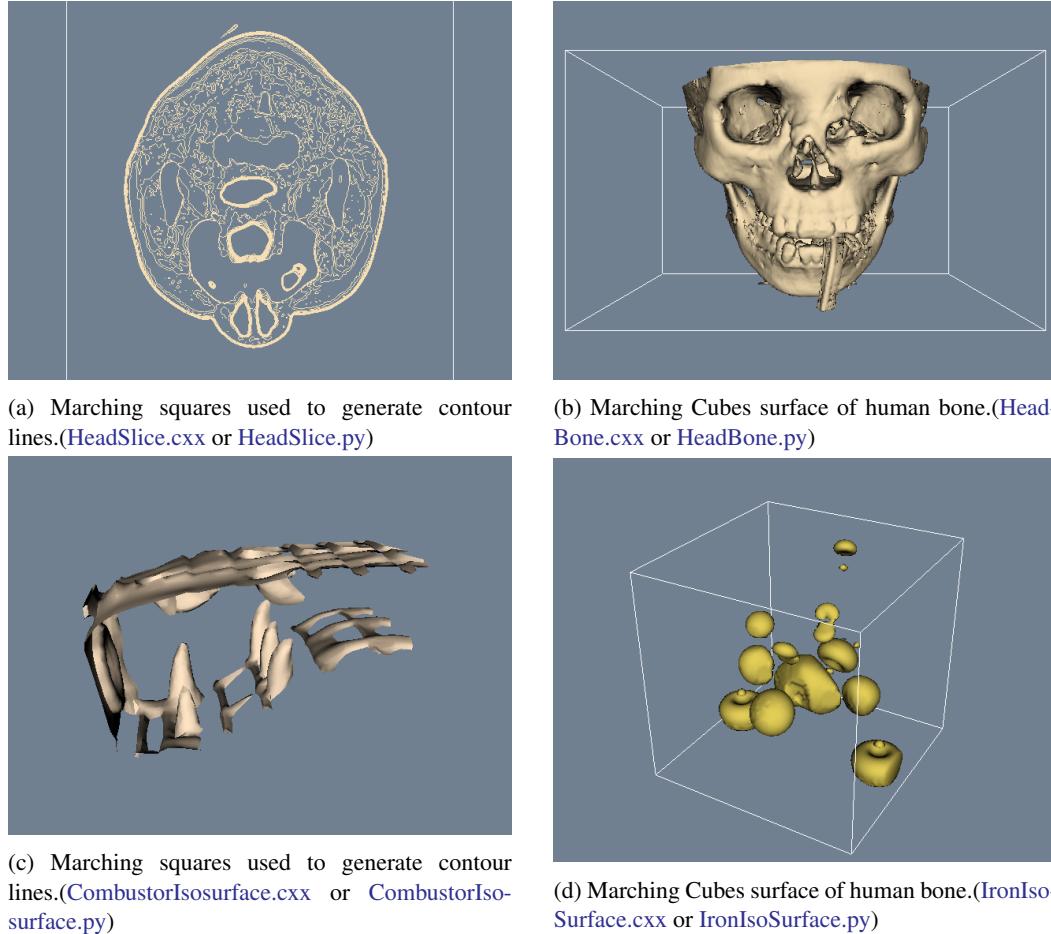
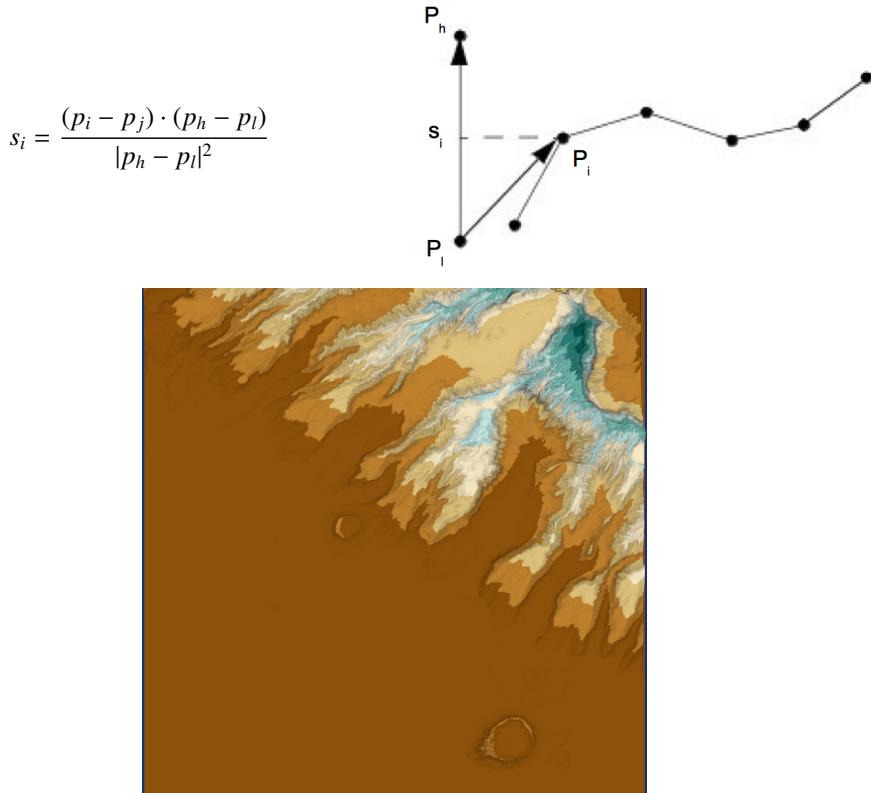


Figure 6.11: Contouring examples.

and brown corresponding to elevation between sea level and high altitude. We also need scalars to index into the color map. The obvious choice here is to extract the z coordinate. That is, scalars are simply the z -coordinate value.

This example can be made more interesting by generalizing the problem. Although we could easily create a filter to extract the z -coordinate, we can create a filter that produces elevation scalar values where the elevation is measured along any axis. Given an oriented line starting at the (low) point p_l (e.g., sea level) and ending at the (high) point p_h (e.g., mountain top), we compute the elevation scalar s_i at point $p_i = (x_i, y_i, z_i)$ using the dot product as shown in Figure 6.12. The scalar is normalized using the magnitude of the oriented line, and may be clamped between minimum and maximum scalar values (if necessary). The bottom half of this figure shows the results of applying this technique to a terrain model of Honolulu, Hawaii. A lookup table of 256 colors ranging from deep brown (water) to dark turquoise (mountain top) is used to color map this figure.

Part of the creative practice of visualization is selecting the best technique for given data from the palette of available techniques. Often this requires creative mapping by the user of the visualization system. In particular, to use scalar visualization techniques we need only to create a relationship to generate a unique scalar value. Other examples of scalar mapping include an index value into a list of data, computing vector magnitude or matrix determinate, evaluating surface



Applying the technique to terrain data from Honolulu, Hawaii. ([Hawaii.cxx](#) or [Hawaii.py](#))

Figure 6.12: Computing scalars using normalized dot product.

curvature, or determining distance between points. Scalar generation, when coupled with color mapping or contouring, is a simple, yet effective, technique for visualizing many types of data.

6.3 Vector Algorithms

Vector data is a three-dimensional representation of direction and magnitude. Vector data often results from the study of fluid flow, or when examining derivatives (i.e., rate of change) of some quantity.

6.3.1 Hedgehogs and Oriented Glyphs

A natural vector visualization technique is to draw an oriented, scaled line for each vector (Figure 6.13a). The line begins at the point with which the vector is associated and is oriented in the direction of the vector components (v_x, v_y, v_z). Typically, the resulting line must be scaled up or down to control the size of its visual representation. This technique is often referred to as a *hedgehog* because of the bristly result.

There are many variations of this technique (Figure 6.13b). Arrows may be added to indicate the direction of the line. The lines may be colored according to vector magnitude, or some other

scalar quantity (e.g., pressure or temperature). Also, instead of using a line, oriented “glyphs” can be used. By glyph we mean any 2D or 3D geometric representation such as an oriented triangle or cone.

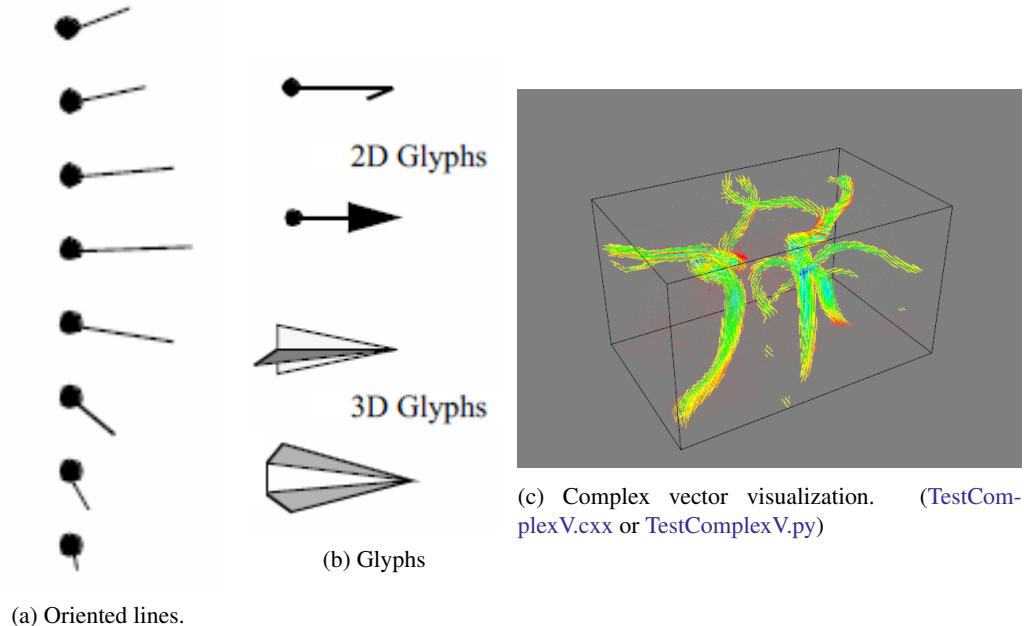


Figure 6.13: Vector visualization techniques.

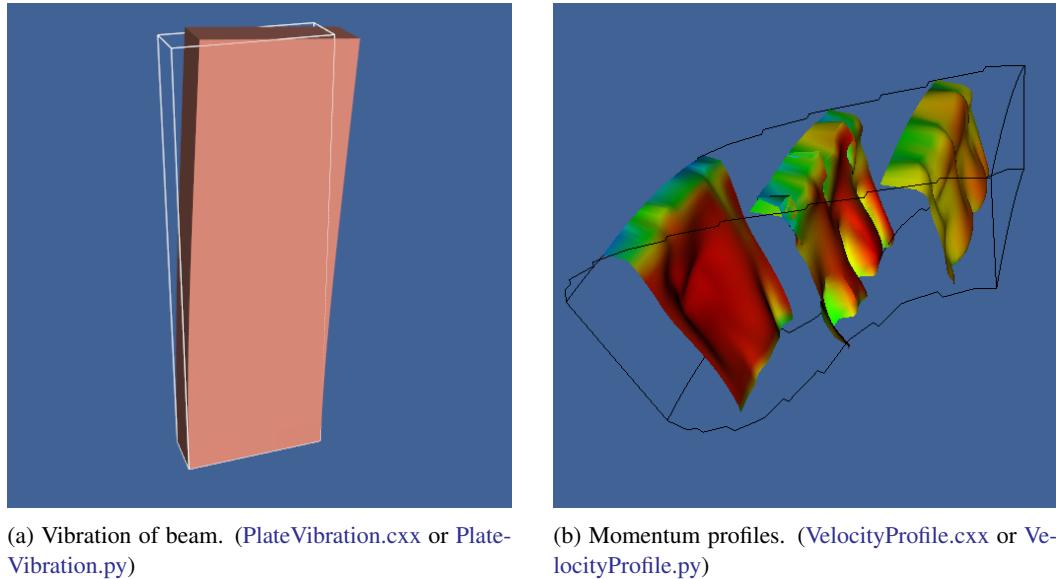
Care should be used in applying these techniques. In 3D it is often difficult to understand the position and orientation of a vector because of its projection into a 2D image. Also, using large numbers of vectors can clutter the display to the point where the visualization becomes meaningless. Figure 6.13c shows 167,000 3D vectors (using oriented and scaled lines) in the region of the human carotid artery. The larger vectors lie inside the arteries, the smaller vectors lie outside the arteries and are randomly oriented (measurement error) but small in magnitude. Clearly the details of the vector field are not discernible from this image.

Scaling glyphs also poses interesting problems. In what Tufte has termed a “visualization lie”, [24] scaling a 2D or 3D glyph results in nonlinear differences in appearance. The surface area of an object increases with the square of its scale factor, so two vectors differing by a factor of two in magnitude may appear up to four times different based on surface area. Such scaling issues are common in data visualization, and great care must be taken to avoiding misleading viewers.

6.3.2 Warping

Vector data is often associated with “motion”. The motion is in the form of velocity or displacement. An effective technique for displaying such vector data is to “warp” or deform geometry according to the vector field. For example, imagine representing the displacement of a structure under load by deforming the structure. Or if we are visualizing the flow of fluid, we can create a flow profile by distorting a straight line inserted perpendicular to the flow.

Figure 6.14 shows two examples of vector warping. In the first example the motion of a vibrating beam is shown. The original undeformed outline is shown in wireframe. The second example shows warped planes in a structured grid dataset. The planes are warped according to flow



(a) Vibration of beam. ([PlateVibration.cxx](#) or [PlateVibration.py](#))
 (b) Momentum profiles. ([VelocityProfile.cxx](#) or [VelocityProfile.py](#))

Figure 6.14: Warping geometry to show vector field.

momentum. The relative back and forward flow are clearly visible in the deformation of the planes.

Typically, we must scale the vector field to control geometric distortion. Too small a distortion may not be visible, while too large a distortion can cause the structure to turn inside out or self-intersect. In such a case the viewer of the visualization is likely to lose context, and the visualization will become ineffective.

6.3.3 Displacement Plots

Vector displacement on the surface of an object can be visualized with displacement plots. A displacement plot shows the motion of an object in the direction perpendicular to its surface. The object motion is caused by an applied vector field. In a typical application the vector field is a displacement or strain field.

Vector displacement plots draw on the ideas in “Scalar Generation” on page 107. Vectors are converted to scalars by computing the dot product between the surface normal and vector at each point (Figure 6.15a). If positive values result, the motion at the point is in the direction of the surface normal (i.e., positive displacement). Negative values indicate that the motion is opposite the surface normal (i.e., negative displacement).

A useful application of this technique is the study of vibration. In vibration analysis, we are interested in the eigenvalues (i.e., natural resonant frequencies) and eigenvectors (i.e., mode shapes) of a structure. To understand mode shapes we can use displacement plots to indicate regions of motion. There are special regions in the structure where positive displacement changes to negative displacement. These are regions of zero displacement. When plotted on the surface of the structure, these regions appear as the so-called *modal* lines of vibration. The study of modal lines has long been an important visualization tool for understanding mode shapes.

Figure 6.15b shows modal lines for a vibrating rectangular beam. The vibration mode in this figure is the second torsional mode, clearly indicated by the crossing modal lines. (The aliasing in the figure is because of the coarseness of the analysis mesh.) To create the figure we combined the procedure of Figure 6.15a with a special lookup table. The lookup table was arranged with white

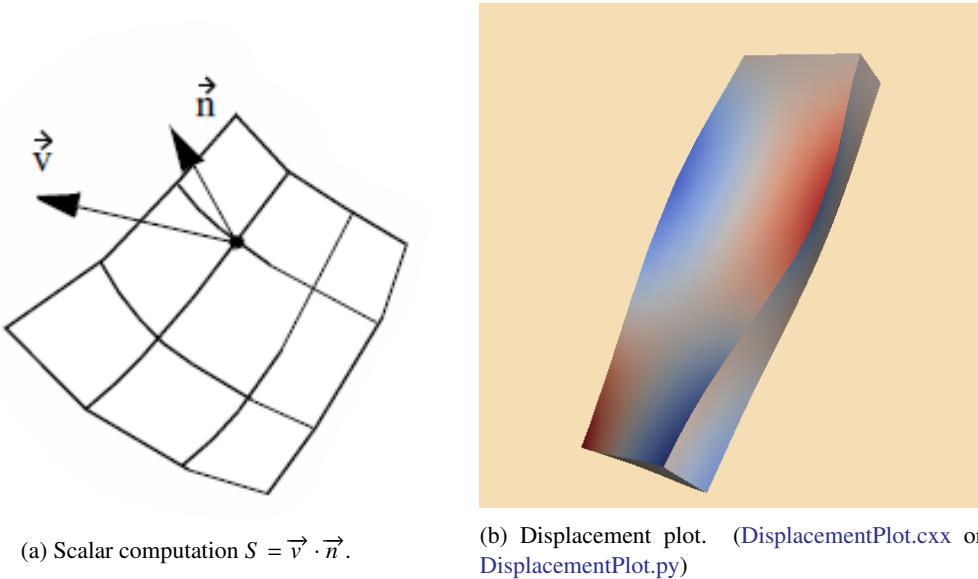


Figure 6.15: Vector displacement plots. (a) Vector converted to scalar via dot product computation; (b) Surface plot of vibrating plate. Dark areas show nodal lines. Bright areas show maximum motion.

areas in the center (i.e., corresponds to zero dot product) and dark areas at the beginning and end of the table (corresponds to 1 or -1 dot product). As a result, regions of large normal displacement are dark and regions near the modal lines are light.

6.3.4 Time Animation

Some of the techniques described so far can be thought of as moving a point or object over a small time step. The hedgehog line is an approximation of a point's motion over a time period whose duration is given by the scale factor. In other words, if velocity $\vec{V} = dx/dt$, then displacement of a point is

$$dx = \vec{V} dt \quad (6.1)$$

This suggests an extension to our previous techniques: repeatedly displace points over many time steps. Figure 6.16 shows such an approach. Beginning with a sphere S centered about some point C , we move S repeatedly to generate the bubbles shown. The eye tends to trace out a path by connecting the bubbles, giving the observer a qualitative understanding of the fluid flow in that area. The bubbles may be displayed as an animation over time (giving the illusion of motion) or as a multiple exposure sequence (giving the appearance of a path).

Such an approach can be misused. For one thing, the velocity at a point is instantaneous.

Once we move away from the point the velocity is likely to change. Using Equation 6.1 assumes that the velocity is constant over the entire step. By taking large steps we are likely to jump over changes in the velocity. Using smaller steps we will end in a different position. Thus the choice of step size is a critical parameter in constructing accurate visualization of particle paths in a vector field.

To evaluate Equation 6.1 we can express it as an integral:

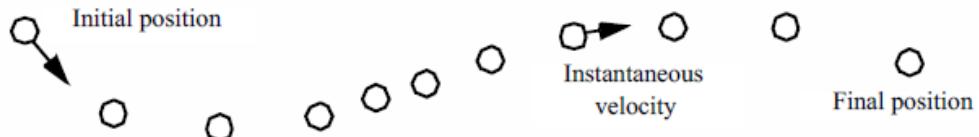


Figure 6.16: Time animation of a point C . Although the spacing between points varies, the time increment between each point is constant.

$$\vec{x}(t) = \int_t \vec{V} dt \quad (6.2)$$

Although this form cannot be solved analytically for most real world data, its solution can be approximated using numerical integration techniques. Accurate numerical integration is a topic beyond the scope of this book, but it is known that the accuracy of the integration is a function of the step size dt . Since the path is an integration throughout the dataset, the accuracy of the cell interpolation functions, as well as the accuracy of the original vector data, plays an important role in realizing accurate solutions. No definitive study is yet available that relates cell size or interpolation function characteristics to visualization error. But the lesson is clear: the result of numerical integration must be examined carefully, especially in regions of large vector field gradient. However, as with many other visualization algorithms, the insight gained by using vector integration techniques is qualitatively beneficial, despite the unavoidable numerical errors.

The simplest form of numerical integration is Euler's method,

$$\vec{x}_{i+1} = \vec{x}_i + \vec{V}_i \Delta t \quad (6.3)$$

where the position at time is the \vec{x}_{i+1} vector sum of the previous position plus the instantaneous velocity times the incremental time step Δt .

Euler's method has error on the order of $O(\Delta t^2)$, which is not accurate enough for some applications. One such example is shown in Figure 6.17. The velocity field describes perfect rotation about a central point. Using Euler's method we find that we will always diverge and, instead of generating circles, will generate spirals instead.

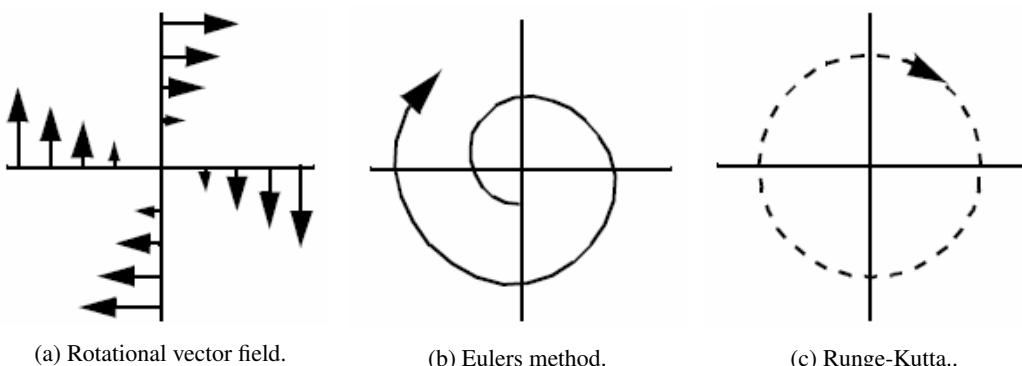


Figure 6.17: Eulers integration (b) and Runge-Kutta integration of order 2 (c) applied to uniform rotational vector field (a). Eulers method will always diverge.

In this text we will use the Runge-Kutta technique of order 2 [7]. This is given by the expression

$$\vec{x}_{i+1} = \vec{x}_i + \frac{\Delta t}{2}(\vec{V}_i + \vec{V}_{i+1}) \quad (6.4)$$

One final note about accuracy concerns. The errors involved in either perception or computation of visualizations is an open research area. The discussion in the preceding paragraph is a good example of this. There we characterized the error in streamline integration using conventional numerical integration arguments. But there is a problem with this argument. In visualization applications, we are integrating across cells whose function values are continuous, but whose derivatives are not. As the streamline crosses the cell boundary, subtle effects may occur that are not treated by the standard numerical analysis. Thus the standard arguments need to be extended for visualization applications.

Integration formulas require repeated transformation from global to local coordinates. Consider moving a point through a dataset under the influence of a vector field. The first step is to identify the cell that contains the point. This operation is a search (see “Searching” on page 152), plus a conversion to local coordinates. Once the cell is found, then the next step is to compute the velocity at that point by interpolating the velocity from the cell points. The point is then incrementally repositioned (using the integration formula Equation 6.4). The process is then repeated until the point exits the dataset or the distance or time traversed exceeds some specified value.

This process can be computationally demanding. There are two important steps we can take to improve performance.

1. *Improving search procedures.* There are two distinct types of searches. Initially, the starting location of the particle must be determined by a global search procedure. Once the initial location of the point is determined in the dataset, an incremental search procedure can then be used. Incremental searching is efficient because the motion of the point is limited within a single cell, or at most across a cell boundary. Thus, the search space is greatly limited, and the incremental search is faster relative to the global search.
2. *Coordinate transformation.* The cost of a coordinate transformation from global to local coordinates can be reduced if either of the following conditions are true: the local and global coordinate systems are identical with one another (or vary by xyz translation), or if the vector field is transformed from global space to local coordinate space. The image data coordinate system is an example of a local coordinates which are parallel to global coordinates, hence global to local coordinate transformation can be greatly accelerated. If the vector field is transformed into local coordinates (either as a preprocessing step or on a cell by cell basis), then the integration can proceed completely in local space. Once the integration path is computed, selected points along the path can be transformed into global space for the sake of visualization.

6.3.5 Streamlines

A natural extension of the previous time animation techniques is to connect the point position over many time steps. The result is a numerical approximation to a particle trace represented as a line.

Borrowing terminology from the study of fluid flow, we can define three related line representation schemes for vector fields.

- *Particle traces* are trajectories traced by fluid particles over time.

- *Streaklines* are the set of particle traces at a particular time t_i through a specified point x_i .
- *Streamlines* are integral curves along a curve s satisfying the equation

$$s = \int_t \vec{V} ds, \text{ with } s = (x, t) \quad (6.5)$$

for a particular time t .

Streamlines, streaklines, and particle traces are equivalent to one another if the flow is steady. In time-varying flow, a given streamline exists only at one moment in time. Visualization systems generally provide facilities to compute particle traces. However, if time is fixed, the same facility can be used to compute streamlines. In general, we will use the term streamline to refer to the method of tracing trajectories in a vector field. Please bear in mind the differences in these representations if the flow is time-varying.

Figure 6.18 shows forty streamlines in a small kitchen. The room has two windows, a door (with air leakage), and a cooking area with a hot stove. The air leakage and temperature variation combine to produce air convection currents throughout the kitchen. The starting positions of the streamlines were defined by creating a *rake*, or curve (and its associated points). Here the rake was a straight line. These streamlines clearly show features of the flow field. By releasing many streamlines simultaneously we obtain even more information, as the eye tends to assemble nearby streamlines into a “global” understanding of flow field features.

Many enhancements of streamline visualization exist. Lines can be colored according to velocity magnitude to indicate speed of flow. Other scalar quantities such as temperature or pressure also may be used to color the lines. We also may create constant time dashed lines. Each dash represents a constant time increment. Thus, in areas of high velocity, the length of the dash will be greater relative to regions of lower velocity. These techniques are illustrated in Figure 6.19 for airflow around a blunt fin. This example consists of a wall with half a rounded fin projecting into the fluid flow. (Using arguments of symmetry, only half of the domain was modeled.) Twenty five streamlines are released upstream of the fin. The boundary layer effects near the junction of the fin and wall are clearly evident from the streamlines. In this area, flow recirculation is apparent, as well as the reduced flow speed.

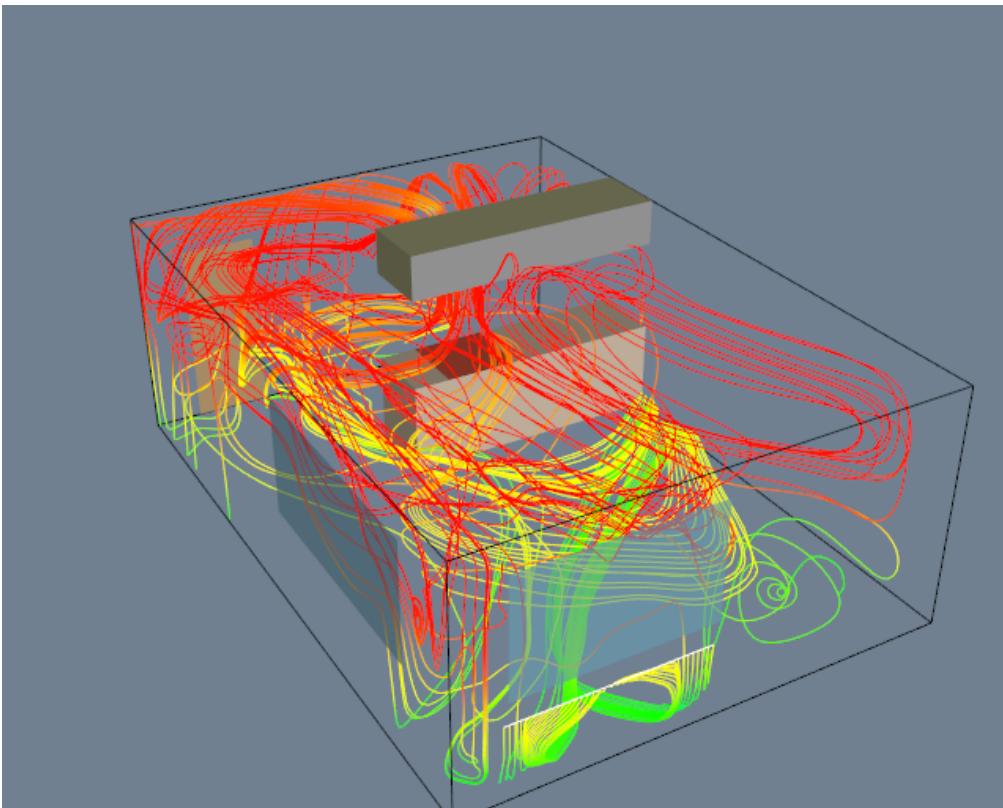


Figure 6.18: Flow velocity computed for a small kitchen. Forty streamlines start along the rake positioned under the window. Some eventually travel over the hot stove and are convected upwards. ([Kitchen.cxx](#) or [Kitchen.py](#))

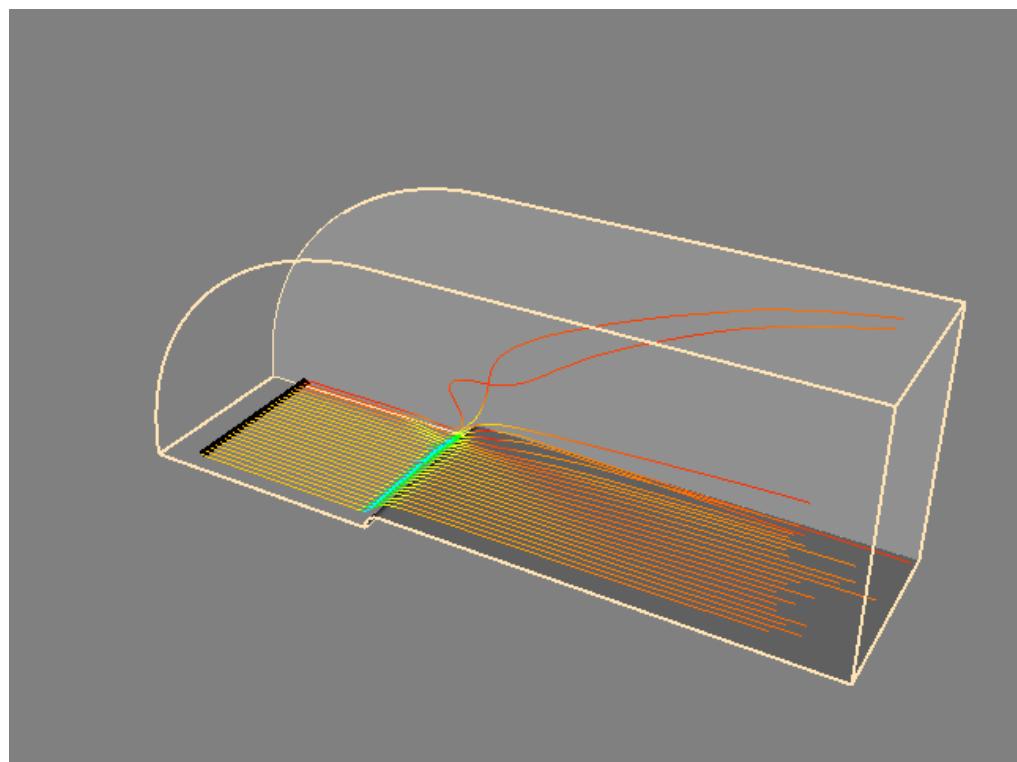


Figure 6.19: airflow around a blunt fin. ([BluntStreamlines.cxx](#) or [BluntStreamlines.py](#))

6.4 Tensor Algorithms

As we mentioned earlier, tensor visualization is an active area of research. However there are a few simple techniques that we can use to visualize real 3×3 symmetric tensors. Such tensors are used to describe the state of displacement or stress in a 3D material. The stress and strain tensors for an elastic material are shown in Figure 6.20*.

In these tensors the diagonal coefficients are the so-called normal stresses and strains, and the off-diagonal terms are the shear stresses and strains. Normal stresses and strains act perpendicular to a specified surface, while shear stresses and strains act tangentially to the surface. Normal stress is either compression or tension, depending on the sign of the coefficient.

A 3×3 real symmetric matrix can be characterized by three vectors in 3D called the eigenvectors, and three numbers called the eigenvalues of the matrix. The eigenvectors form a 3D coordinate system whose axes are mutually perpendicular. In some applications, particularly the study of materials, these axes also are referred to as the principle axes of the tensor and are physically significant. For example, if the tensor is a stress tensor, then the principle axes are the directions of normal stress and no shear stress. Associated with each eigenvector is an eigenvalue. The eigenvalues are often physically significant as well. In the study of vibration, eigenvalues correspond to the resonant frequencies of a structure, and the eigenvectors are the associated mode shapes.

Mathematically we can represent eigenvalues and eigenvectors as follows. Given a matrix A the eigenvector \vec{x} and eigenvalue λ must satisfy the relation

$$A \cdot x = \lambda \vec{x} \quad (6.6)$$

For Equation 6.6 to hold, the matrix determinant must satisfy

$$\det|A - \lambda I| = 0 \quad (6.7)$$

Expanding this equation yields a n^{th} degree polynomial in λ whose roots are the eigenvalues. Thus, there are always n eigenvalues, although they may not be distinct. In general, Equation 6.7 is not solved using polynomial root searching because of poor computational performance. (For matrices of order 3 root searching is acceptable because we can solve for the eigenvalues analytically.) Once we determine the eigenvalues, we can substitute each into Equation 6.7 to solve for the associated eigenvectors.

We can express the eigenvectors of the 3×3 system as

$$\vec{v}_i = \lambda_i \vec{e}_i \text{ with } i = 1, 2, 3 \quad (6.8)$$

with \vec{e}_i a unit vector in the direction of the eigenvalue, and λ_i the eigenvalues of the system. If we order eigenvalues such that

$$\lambda_1 \geq \lambda_2 \geq \lambda_3 \quad (6.9)$$

then we refer to the corresponding eigenvectors \vec{v}_1 , \vec{v}_2 and \vec{v}_3 as the *major*, *medium* and *minor* eigenvectors.

$$\begin{aligned}
 \text{(a) Stress tensor.} & \quad \left[\begin{array}{ccc} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{array} \right] \\
 \text{(b) Strain tensor} & \quad \left[\begin{array}{ccc} \frac{\partial u}{\partial x} & \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial z} \right) & \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \\ \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial z} \right) & \frac{\partial v}{\partial y} & \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right) \\ \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) & \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right) & \frac{\partial w}{\partial z} \end{array} \right]
 \end{aligned}$$

Figure 6.20: Stress and strain tensors. Normal stresses in the $x - y - z$ coordinate directions indicated as $(\sigma_x, \sigma_y, \sigma_z)$, shear stresses indicated as τ_{ij} . Material displacement represented by (u, v, w) components.

6.4.1 Tensor Ellipsoids

This leads us to the tensor ellipsoid technique for the visualization of real, symmetric 3×3 matrices. The first step is to extract eigenvalues and eigenvectors as described in the previous section. Since eigenvectors are known to be orthogonal, the eigenvectors form a local coordinate system. These axes can be taken as the *minor*, *medium* and *major* axes of an ellipsoid. Thus, the shape and orientation of the ellipsoid represents the relative size of the eigenvalues and the orientation of the eigenvectors.

To form the ellipsoid we begin by positioning a sphere at the tensor location. The sphere is then rotated around its origin using the eigenvectors, which in the form of Equation 6.8 are direction cosines. The eigenvalues are used to scale the sphere. Using 4×4 transformation matrices and referring to Equation 3.6, Equation 3.9 and Equation 3.13, we form the ellipsoid by transforming the sphere centered at the origin using the matrix T

$$T = T_T \cdot T_R \cdot T_S \quad (6.10)$$

(remember to read right to left). The eigenvectors can be directly plugged in to create the rotation matrix, while the point coordinates $x - y - z$ and eigenvalues $\lambda_1 \geq \lambda_2 \geq \lambda_3$ are inserted into the translation and scaling matrices. A concatenation of these matrices forms the final transformation matrix T .

Figure 6.21a depicts the tensor ellipsoid technique. In Figure 6.21b) we show this technique to visualize material stress near a point load on the surface of a semiinfinite domain. (This is the so-called Boussinesq's problem.) From Saada [22] we have the analytic expression for the stress components in Cartesian coordinates shown in Figure 6.21c. Note that the z -direction is defined as the axis originating at the point of application of the force P . The variable ρ is the distance from the point of load application to a point $x - y - z$. The orientation of the x and y axes are in the plane perpendicular to the z axis. (The rotation in the plane of these axes is unimportant since the solution is symmetric around the z axis.) (The parameter ν is Poisson's ratio which is a property of the material. Poisson's ratio relates the lateral contraction of a material to axial elongation under a uniaxial stress condition. See [22] or [23] for more information.)

In Figure 6.21a we visualize the analytical results of Boussinesq's problem from Saada. The

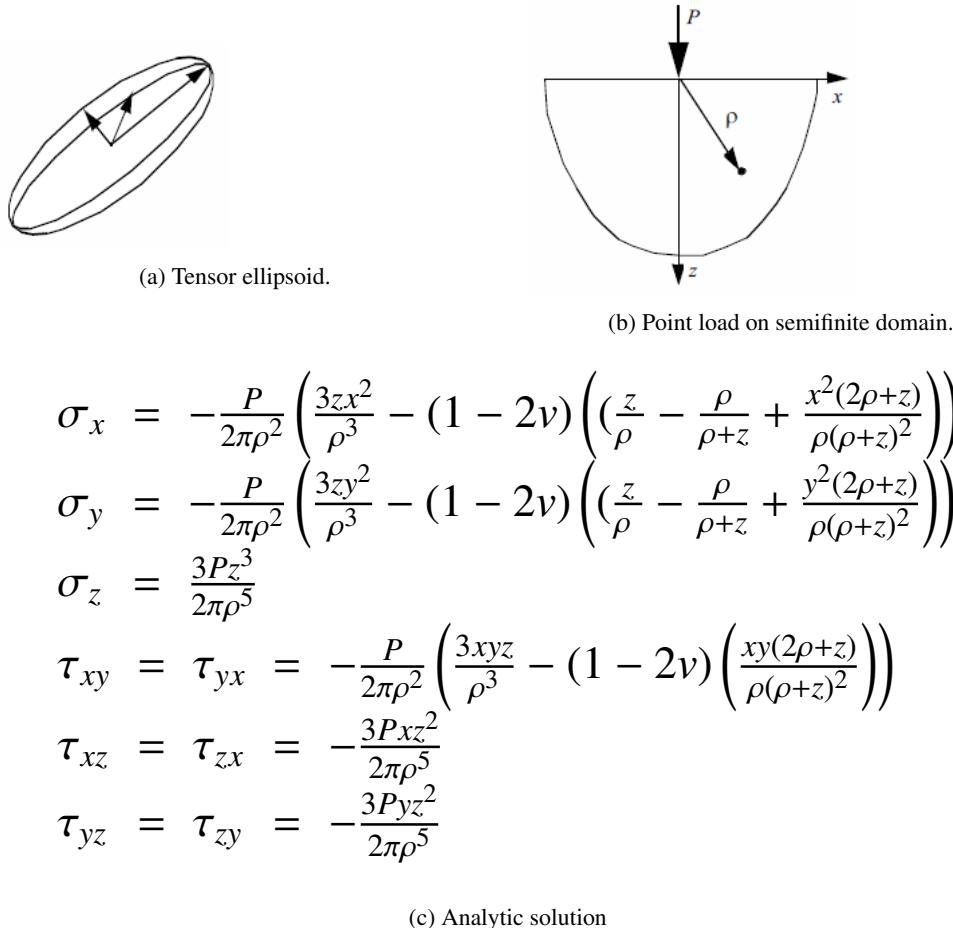


Figure 6.21: Stress and strain tensors. Normal stresses in the $x - y - z$ coordinate directions indicated as $(\sigma_x, \sigma_y, \sigma_z)$, shear stresses indicated as τ_{ij} . Material displacement represented by (u, v, w) components.

top portion of the figure shows the results by displaying the scaled and oriented principal axes of the stress tensor. (These are called *tensor axes*.) In the bottom portion we use tensor ellipsoids to show the same result. Tensor ellipsoids and tensor axes are a form of *glyph* (see "Glyphs" on page 127) specialized to tensor visualization.

A certain amount of care must be taken to visualize this result since there is a stress singularity at the point of contact of the load. In a real application loads are applied over a small area and not at a single point. Also, plastic behavior prevents stress levels from exceeding a certain point. The results of the visualization, as with any computer process, are only as good as the underlying model.

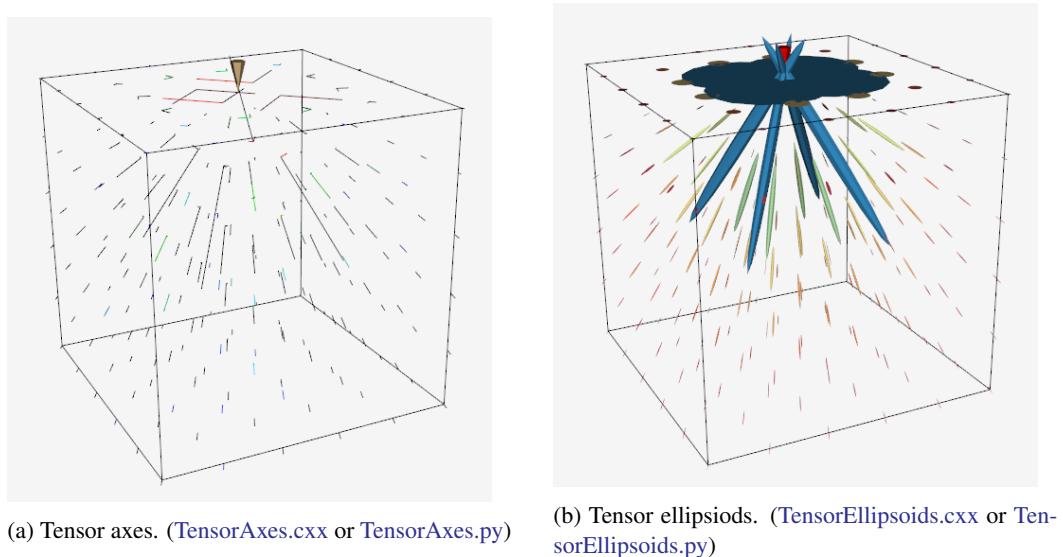


Figure 6.22: Tensor visualization techniques; (a) Tensor axes, (b) Tensor ellipsoids.

6.5 Modelling Algorithms

Modelling algorithms are the catchall category for our taxonomy of visualization techniques. Modelling algorithms have one thing in common: They create or change dataset geometry or topology.

6.5.1 Source Objects

As we have seen in previous examples, source objects begin the visualization pipeline. Source objects are used to create geometry such as spheres, cones, or cubes to support visualization context or are used to read in data files. Source objects also may be used to create dataset attributes. Some examples of source objects and their use are as follows.

Modelling Simple Geometry. Spheres, cones, cubes, and other simple geometric objects can be used alone or in combination to model geometry. Often we visualize real-world applications such as air flow in a room and need to show real-world objects such as furniture, windows, or doors. Real-world objects often can be represented using these simple geometric representations. These source objects generate their data procedurally. Alternatively, we may use reader objects to access geometric data defined in data files. These data files may contain more complex geometry such as that produced by a 3D CAD (ComputerAided Design) system.

Supporting Geometry. During the visualization process we may use source objects to create supporting geometry. This may be as simple as three lines to represent a coordinate axis or as complex as tubes wrapped around line segments to thicken and enhance their appearance. Another common use is as supplemental input to objects such as streamlines or probe filters. These filters take a second input that defines a set of points. For streamlines, the points determine the initial positions for generating the streamlines. The probe filter uses the points as the position to compute attribute values such as scalars, vectors, or tensors.

Data Attribute Creation. Source objects can be used as procedures to create data attributes. For example, we can procedurally create textures and texture coordinates. Another use is to create scalar values over a uniform grid. If the scalar values are generated from a mathematical function, then we can use the visualization techniques described here to visualize the function. In fact, this leads us to a very important class of source objects: implicit functions.

6.5.2 Implicit Functions

Implicit functions are functions of the form

$$F(x, y, z) = c \quad (6.11)$$

where c is an arbitrary constant. Implicit functions have three important properties.

- *Simple geometric description.* Implicit functions are convenient tools to describe common geometric shapes. This includes planes, spheres, cylinders, cones, ellipsoids, and quadrics.
- *Region separation.* Implicit functions separate 3D Euclidean space into three distinct regions. These regions are inside, on, and outside the implicit function. These regions are defined as $F(x, y, z) < 0$, $F(x, y, z) = 0$ and $F(x, y, z) > 0$, respectively.
- *Scalar generation.* Implicit functions convert a position in space into a scalar value. That is, given an implicit function we can sample it at a point (x_i, y_i, z_i) to generate a scalar value c_i .

An example of an implicit function is the equation for a sphere of radius R .

$$F(x, y, z) = x^2 + y^2 + z^2 - R^2 \quad (6.12)$$

This simple relationship defines the three regions (on $F(x, y, z) = 0$ on the sphere), $F(x, y, z) < 0$ (inside the sphere), and $F(x, y, z) > 0$ (outside the sphere). Any point maybe be classified as inside, on, or outside the sphere simply by evaluating Equation 6.12.

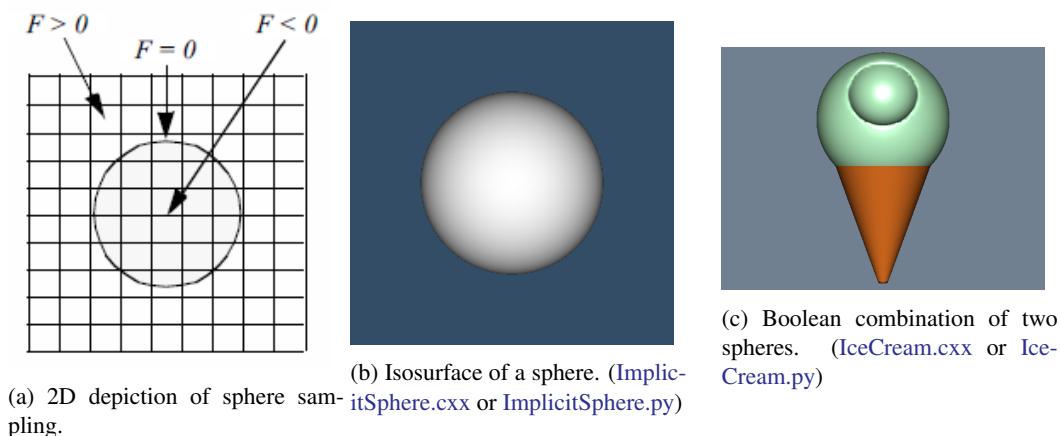


Figure 6.23: Sampling functions: (a) 2D depiction of sphere sampling] (b) Isosurface of sampled sphere; (c) Boolean combination of two spheres, a cone, and two planes. (One sphere intersects the other, the planes clip the cone).

Implicit functions have a variety of uses. This includes geometric modelling, selecting data, and visualizing complex mathematical descriptions.

6.5.3 Modelling Objects.

Implicit functions can be used alone or in combination to model geometric objects. For example, to model a surface described by an implicit function, we sample F on a dataset and generate an isosurface at a contour value c_i . The result is a polygonal representation of the function. Figure 6.23b shows an isosurface for a sphere of radius=1 sampled on a volume. Note that we can choose nonzero contour values to generate a family of offset surfaces. This is useful for creating blending functions and other special effects.

Implicit functions can be combined to create complex objects using the boolean operators union, intersection, and difference. The union operation between $F \cup G$ between two functions $F(x, y, z)$ and $G(x, y, z)$ is the minimum value

$$F \cup G = \{\max(F(\vec{x}), G(\vec{x})) \mid \vec{x} \in \mathbb{R}^n\} \quad (6.13)$$

The intersection between two implicit functions is given by

$$F \cap G = \{\min(F(\vec{x}), G(\vec{x})) \mid \vec{x} \in \mathbb{R}^n\} \quad (6.14)$$

The difference of two implicit functions is given by

$$F - G = \{\min(F(\vec{x}), -G(\vec{x})) \mid \vec{x} \in \mathbb{R}^n\} \quad (6.15)$$

Figure 6.23c shows a combination of simple implicit functions to create an ice-cream cone. The cone is created by clipping the (infinite) cone function with two planes. The ice cream is constructed by performing a difference operation on a larger sphere with a smaller offset sphere to create the “bite.” The resulting surface was extracted using surface contouring with isosurface value 0.0.

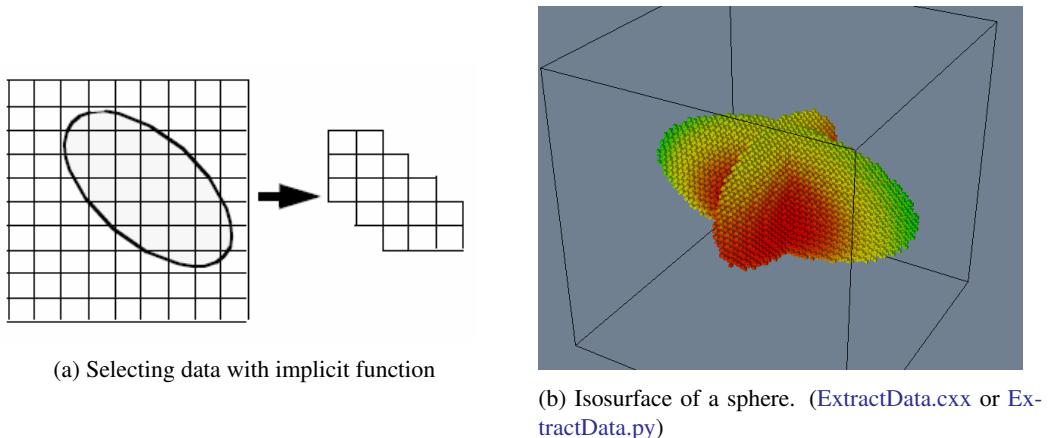


Figure 6.24: Implicit functions used to select data: (a) 2D cells lying in ellipse are selected; (b) Two ellipsoids combined using the union operation used to select voxels from a volume. Voxels shrunk 50 percent.

6.5.4 Selecting Data

We can take advantage of the properties of implicit functions to select and cut data. In particular we will use the region separation property to select data. (We defer the discussion on cutting to "Cutting" on page 129.)

Selecting or extracting data with an implicit function means choosing cells and points (and associated attribute data) that lie within a particular region of the function. To determine whether a point xyz lies within a region, we simply evaluate the point and examine the sign of the result. A cell lies in a region if all its points lie in the region.

Figure 6.24a shows a 2D implicit function, here an ellipse, used to select the data (i.e., points, cells, and data attributes) contained within it. Boolean combinations also can be used to create complex selection regions as illustrated in Figure 6.24b. Here, two ellipses are used in combination to select voxels within a volume dataset. Note that extracting data often changes the structure of the dataset. In Figure 6.24 the input type is a image data dataset, while the output type is an unstructured grid dataset.

6.5.5 Visualizing Mathematical Descriptions

Some functions, often discrete or probabilistic in nature, cannot be cast into the form of Equation 6.11. However, by applying some creative thinking we can often generate scalar values that can be visualized. An interesting example of this is the so-called *strange attractor*.

Strange attractors arise in the study of nonlinear dynamics and chaotic systems. In these systems, the usual types of dynamic motion — equilibrium, periodic motion, or quasiperiodic motion — are not present. Instead, the system exhibits chaotic motion. The resulting behavior of the system can change radically as a result of small perturbations in its initial conditions.

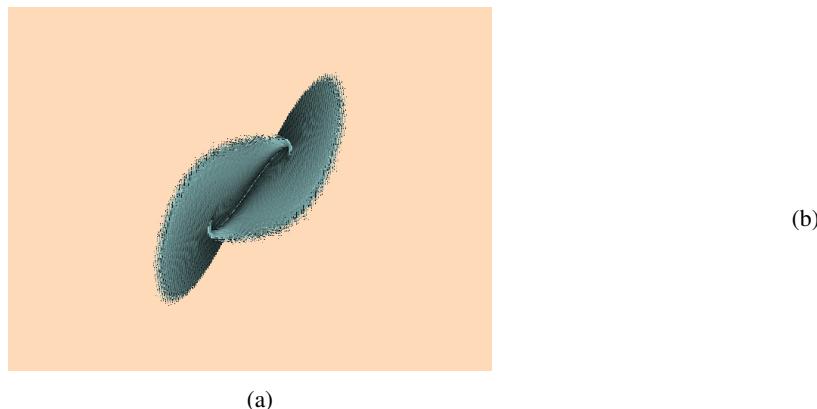


Figure 6.25: Visualizing a Lorenz strange attractor by integrating the Lorenz equations in a volume. The number of visits in each voxel is recorded as a scalar function. The surface is extracted via marching cubes using a visit value of 50. The number of integration steps is 10 million, in a volume of dimensions 200^3 . The surface roughness is caused by the discrete nature of the evaluation function. ([Lorenz.cxx](#) or [Lorenz.py](#))

A classical strange attractor was developed by Lorenz in 1963 [17]. Lorenz developed a simple model for thermally induced fluid convection in the atmosphere. Convection causes rings of rotating fluid and can be developed from the general Navier Stokes partial differential equations for fluid flow. The Lorenz equations can be expressed in nondimensional form as

$$\begin{aligned}
 \frac{dx}{dt} &= \sigma(y - z) \\
 \frac{dy}{dt} &= \rho x - y - xz \\
 \frac{dz}{dt} &= xy - \beta z
 \end{aligned} \tag{6.16}$$

where x is proportional to the fluid velocity in the fluid ring, y and z measure the fluid temperature in the plane of the ring, the parameters σ and ρ are related to the Prandtl number and Raleigh number, respectively, and β is a geometric factor.

Certainly these equations are not in the implicit form of Equation 6.11, so how do we visualize them? Our solution is to treat the variables x , y , and z as the coordinates of a three-dimensional space, and integrate Equation 6.16 to generate the system “trajectory”, that is, the state of the system through time. The integration is carried out within a volume and scalars are created by counting the number of times each voxel is visited. By integrating long enough, we can create a volume representing the “surface” of the strange attractor, Figure 6.25. The surface of the strange attractor is extracted by using marching cubes and a scalar value specifying the number of visits in a voxel.

6.5.6 Implicit Modelling

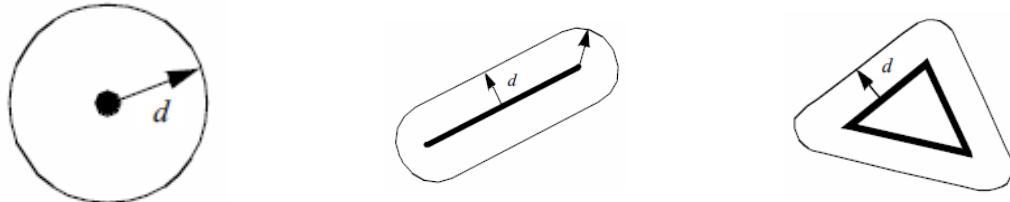


Figure 6.26: Distance functions to a point, line and triangle.

In the previous section we saw how implicit functions, or boolean combinations of implicit functions, could be used to model geometric objects. The basic approach is to evaluate these functions on a regular array of points, or volume, and then to generate scalar values at each point in the volume. Then either volume rendering (see “Volume Rendering” on page 150), or isosurface generation in combination with surface rendering, is used to display the model.

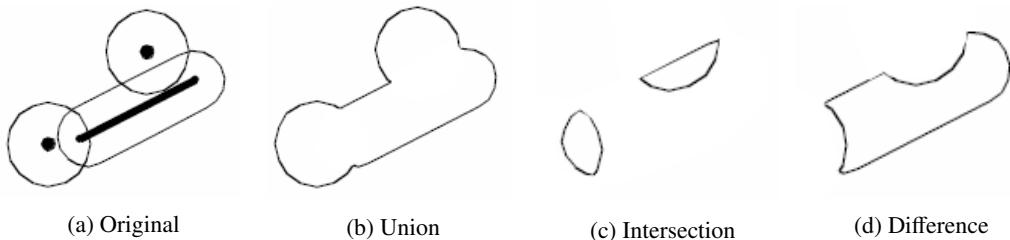


Figure 6.27: Distance functions to a point, line and triangle.

An extension of this approach, called implicit modeling, is similar to modeling with implicit functions. The difference lies in the fact that scalars are generated using a distance function instead of the usual implicit function. The distance function is computed as a Euclidean distance to a set of generating primitives such as points, lines, or polygons. For example, Figure 6.26 shows the distance functions to a point, line, and triangle. Because distance functions are wellbehaved monotonic functions, we can define a series of offset surfaces by specifying different isosurface values, where the value is the distance to the generating primitive. The isosurfaces form approximations to the true offset surfaces, but using high volume resolution we can achieve satisfactory results.

Used alone the generating primitives are limited in their ability to model complex geometry. By using boolean combinations of the primitives, however, complex geometry can be easily modeled. The boolean operations union, intersection, and difference (Equation 6.13, Equation 6.14, and Equation 6.15, respectively) are illustrated in Figure 6.27. Figure 6.28 shows the application of implicit modeling to "thicken" the line segments in the text symbol "HELLO". The isosurface is generated on a volume $110 \times 40 \times 20$ at a distance offset of 0.25 units. The generating primitives were combined using the boolean union operator. Although Euclidean distance is always a nonnegative value, it is possible to use a signed distance function for objects that have an outside and an inside. A negative distance is the negated distance of a point inside the object to the surface of the object. Using a signed distance function allows us to create offset surfaces that are contained within the actual surface.

Figure 6.28: Implicit modelling used to thicken a stroked font. Original lines can be seen within the translucent implicit surface.(Hello.cxx or Hello.py)



Another interesting feature of implicit modeling is that when isosurfaces are generated, more than one connected surface can result. These situations occur when the generating primitives form concave features. Figure 6.29 illustrates this situation. If desired, multiple surfaces can be separated by using the connectivity algorithm described in “Connectivity” on page 154.

6.5.7 Glyphs

Glyphs, sometimes referred to as icons, are a versatile technique to visualize data of every type. A glyph is an “object” that is affected by its input data. This object may be geometry, a dataset, or a graphical image. The glyph may orient, scale, translate, deform, or somehow alter the appearance of the object in response to data. We have already seen a simple form of glyph: hedgehogs are lines that are oriented, translated and scaled according to the position and vector value of a point. A variation of this is to use oriented cones or arrows. (See “Hedgehogs and Oriented Glyphs” on page 110 for more information.)

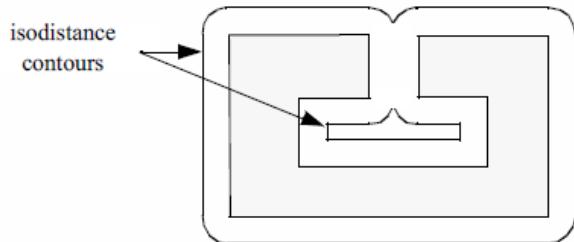


Figure 6.29: Concave features can result in multiple contour lines/surfaces.

More elaborate glyphs are possible. In one creative visualization technique Chernoff [6] tied data values to an iconic representation of the human face. Eyebrows, nose, mouth, and other features were modified according to financial data values. This interesting technique built on the human capability to recognize facial expression. By tying appropriate data values to facial characteristics, rapid identification of important data points is possible.

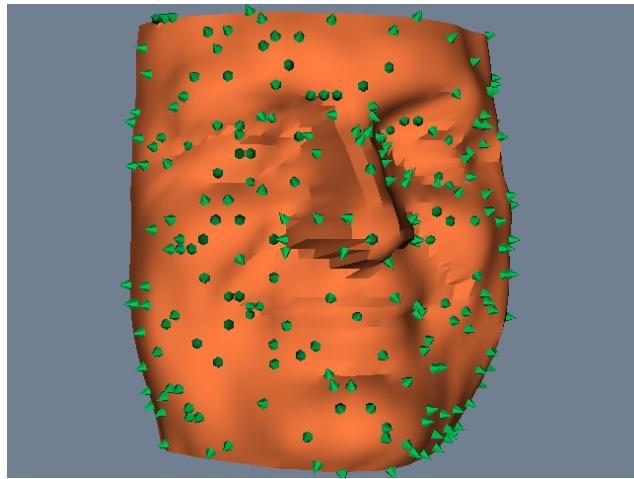


Figure 6.30: Glyphs indicate surface normals on model of human face. Glyph positions are randomly selected. ([SpikeFran.cxx](#) or [SpikeFran.py](#))

In a sense, glyphs represent the fundamental result of the visualization process. Moreover, all the visualization techniques we present can be treated as concrete representations of an abstract glyph class. For example, while hedgehogs are an obvious manifestation of a vector glyph, isosurfaces can be considered a topologically twodimensional glyph for scalar data. Delmarcelle and Hesselink [8] have developed a unified framework for flow visualization based on types of glyphs. They classify glyphs according to one of three categories.

- *Elementary icons** represent their data across the extent of their spatial domain. For example, an oriented arrow can be used to represent surface normal.
- *Local icons* represent elementary information plus a local distribution of the values around the spatial domain. A surface normal vector colored by local curvature is one example of a local icon, since local data beyond the elementary information is encoded.
- *Global icons* show the structure of the complete dataset. An isosurface is an example of a global icon.

This classification scheme can be extended to other visualization techniques such as vector and tensor data, or even to nonvisual forms such as sound or tactile feedback. We have found this

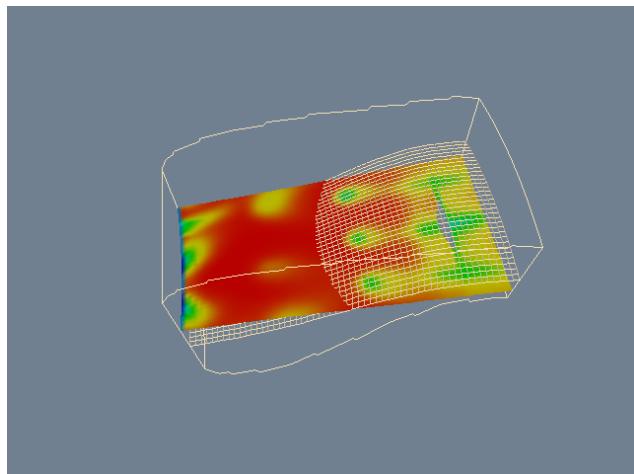
classification scheme to be helpful when designing visualizations or creating visualization techniques. Often it gives insight into ways of representing data that can be overlooked.

Figure 6.30 is an example of glyphing. Small 3D cones are oriented on a surface to indicate the direction of the surface normal. A similar approach could be used to show other surface properties such as curvature or anatomical keypoints.

6.5.8 Cutting

Often we want to cut through a dataset with a surface and then display the interpolated data values on the surface. We refer to this technique as *data cutting* or simply *cutting*. The data cutting operation requires two pieces of information: a definition for the surface and a dataset to cut. We will assume that the cutting surface is defined by an implicit function. A typical application of cutting is to slice through a dataset with a plane, and color map the scalar data and/or warp the plane according to vector value.

Figure 6.31: Cut through structured grid with plane. The cut plane is shown solid shaded. A computational plane of constant value is shown in wireframe for comparison. The colors correspond to flow density. Cutting surfaces are not necessarily planes: implicit functions such as spheres, cylinders, and quadrics can also be used. ([CutStructuredGrid.cxx](#) or [CutStructuredGrid.py](#))



A property of implicit functions is to convert a position into a scalar value (see “Implicit Functions” on page 123). We can use this property in combination with a contouring algorithm (e.g., marching cubes) to generate cut surfaces. The basic idea is to generate scalars for each point of each cell of a dataset (using the implicit cut function), and then contour the surface value $F(x, y, z) = 0$.

The cutting algorithm proceeds as follows. For each cell, function values are generated by evaluating $F(x, y, z)$ for each cell point. If all the points evaluate positive or negative, then the surface does not cut the cell. However, if the points evaluate positive and negative, then the surface passes through the cell. We can use the cell contouring operation to generate the isosurface $F(x, y, z) = 0$. Data attribute values can then be computed by interpolating along cut edges.

Figure 6.31 illustrates a plane cut through a structured grid dataset. The plane passes through the center of the dataset with normal $(-0.287, 0, 0.9579)$. For comparison purposes a portion of the grid geometry is also shown. The grid geometry is the grid surface $k = 9$ (shown in wireframe). A benefit of cut surfaces is that we can view data on (nearly) arbitrary surfaces. Thus, the structure of the dataset does not constrain how we view the data.

We can easily make multiple planar cuts through a structured grid dataset by specifying multiple isovalue for the cutting algorithm. Figure 6.32 shows 100 cut planes generated perpendicular to the camera’s view plane normal. Rendering the planes from back to front with an opacity of 0.05 produces a simulation of volume rendering (see “Volume Rendering” on page 150).

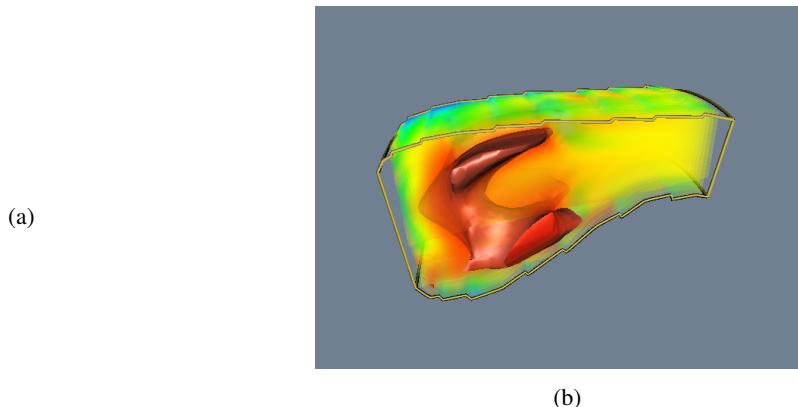


Figure 6.32: 100 cut planes with opacity of 0.05. Rendered back-to-front to simulate volume rendering. ([PseudoVolumeRendering.cxx](#) or [PseudoVolumeRendering.py](#))

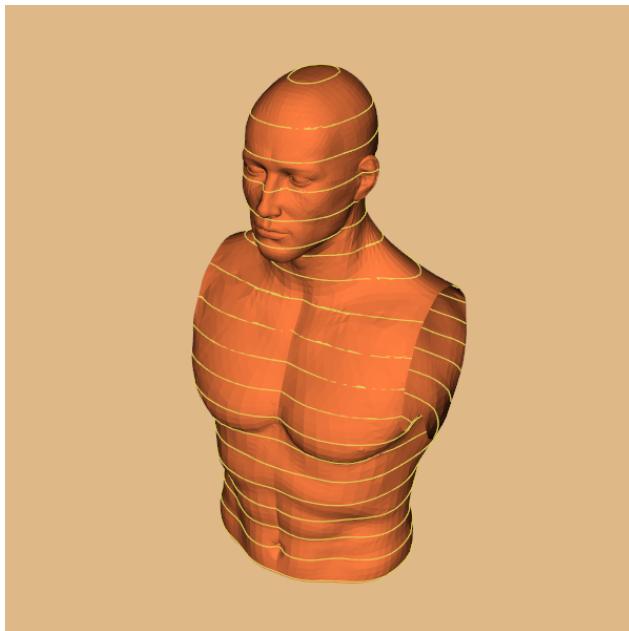


Figure 6.33: Cutting a surface model of the skin with a series of planes produces contour lines. Lines are wrapped with tubes for clarity. ([CutWithScalars.cxx](#) or [CutWithScalars.py](#))

This example illustrates that cutting the volumetric data in a structured grid dataset produced polygonal cells. Similarly, cutting polygonal data produces lines. Using a single plane equation, we can extract “contour lines” from a surface model defined with polygons. Figure 6.33 shows contours extracted from a surface model of the skin. At each vertex in the surface model we evaluate the equation of the plane and $F(x,y,z) = c$ and store the valuec of the function as a scalar value. Cutting the data with 46 isovaluec from 1.5 to 136.5 produces contour lines that are 3 units apart.

6.6 Putting It All Together

Algorithms are implemented in the *Visualization Toolkit* as process objects. These objects may be either sources, filters, or mappers (see “The Visualization Pipeline” on page 94). In this

section we will describe how these objects are implemented.

6.6.1 Process Object Design

Source Design

Source objects have no visualization data for input and one or more outputs, Figure 6.34. To create a source object, inheritance is used to specify the type of dataset that the process object creates for output. `vtkSphereSource`. This class inherits from `vtkPolyDataAlgorithm`, indicating that it creates polygonal data on output.

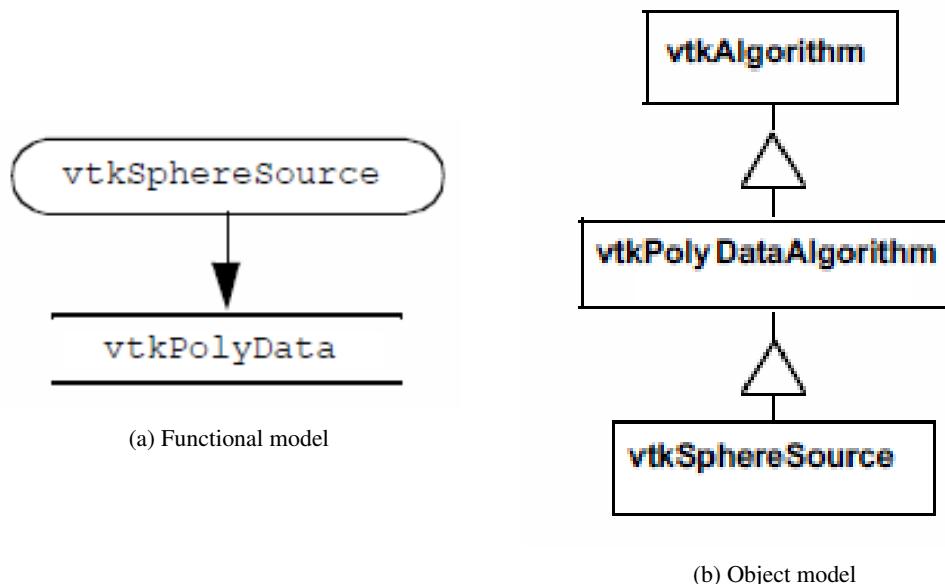


Figure 6.34: Source object design. Example shown is a source object that creates a polygonal representation of a sphere.

Filter Design

Filter objects have one or more inputs and one or more outputs as shown in Figure 6.34. (You may also refer to “Pipeline Design and Implementation” on page 94.) To create Figure 6.35 a filter object, inheritance is used to specify the type of input and output data objects. illustrates this for the concrete source object `vtkContourFilter` (which implements marching cubes and other contouring techniques). It is worth examining this object diagram in detail since it is the basis for the architecture of the visualization pipeline.

The superclasses of `vtkContourFilter` are `vtkAlgorithm` and `vtkPolyDataAlgorithm`. The class `vtkPolyDataAlgorithm` specifies the type of data `vtkContourFilter` produces on output (i.e., a `vtkPolyData`). Because this filter should take any subclass of `vtkDataSet` as input, it must override its superclasses implementation of the `FillInputPortInformation()` method to specify this. Note that inheritance from `vtkPolyDataAlgorithm` is optional — this functionality could be implemented directly in `vtkContourFilter`. This optional superclass is simply a convenience object to make class derivation a little easier.

What is left for vtkContourFilter to implement is its RequestData() method (as well as constructor, print method, and any other methods special to this class). Thus the primary difference between classes with equivalent inheritance hierarchies is the implementation of the RequestData() method.

Subclasses of vtkAlgorithm enforce filter input and output type by use of the FillInputPortInformation() and FillOutputPortInformation() methods. By default, its subclass vtkDataSetAlgorithm accepts input type vtkDataSet (or subclasses) and produces a vtkDataSet on output. (The type of the output is determined by the type of the input.) Since vtkDataSet is a base class for all data types, subclasses of vtkDataSetAlgorithm will accept any type as input. Specialized filters are derived from other classes. For example, filters that accept polygonal data might be derived from vtkPolyDataAlgorithm, and filters that accept unstructured grid datasets might be derived from vtkUnstructuredGridAlgorithm.

We encourage you to examine the source code carefully for a few filter and source objects.

The architecture is simple enough that you can grasp it quickly.

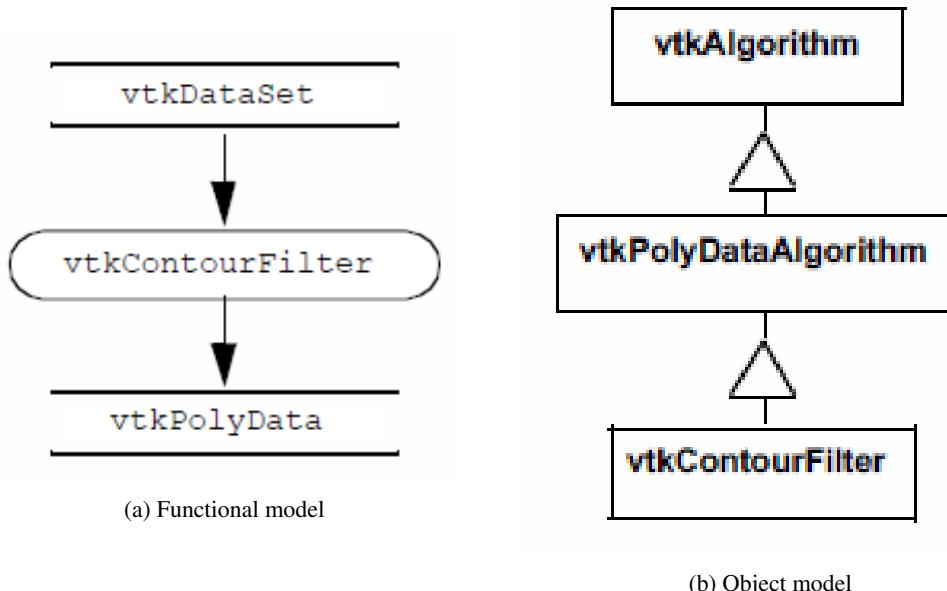


Figure 6.35: Filter object design. The example shown is for an object that receives a general dataset as input and creates polygonal data on output.

Mapper Design

Mapper objects have one or more inputs and no visualization data output, Figure 6.36. Two different types of mappers are available in the *Visualization Toolkit*: graphics mappers and writers. Graphics mappers interface geometric structure and data attributes to the graphics library; writers write datasets to disk or other I/O devices.

Since mappers take datasets as input, type enforcement is required. Each mapper implements this functionality directly. For example, both classes vtkPolyDataMapper and vtkSTLWriter implement a SetInput() method to enforce the input to be of type vtkPolyData. Other mappers and writers enforce input type as appropriate.

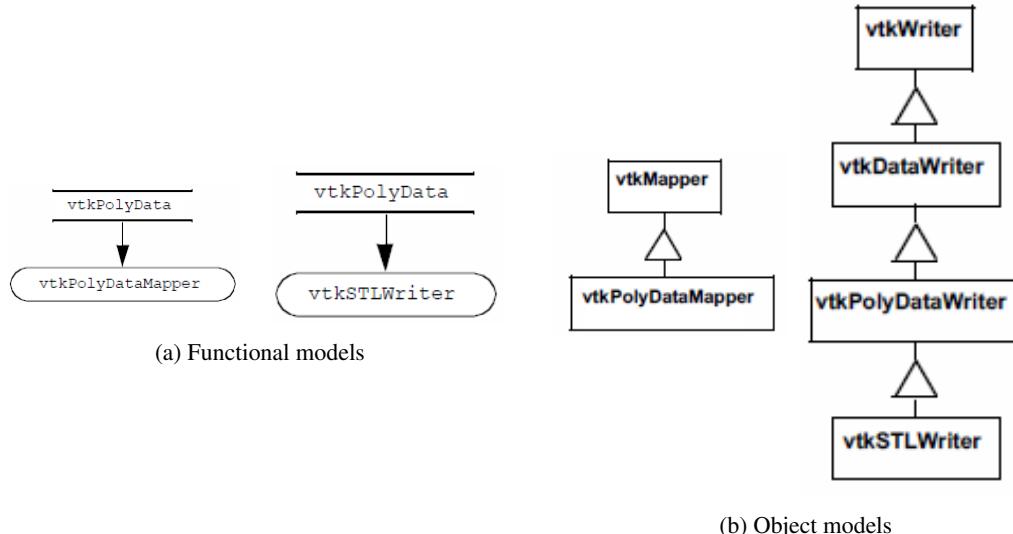


Figure 6.36: Mapper object design. Graphics mapper shown (e.g., vtkPolyDataMapper) maps polygonal data through graphics library primitives. Writer shown (e.g., vtkSTLWriter) writes polygonal data to stereo lithography format.

Although writers and mappers do not create visualization data, they both have methods similar to the RequestData() method of the sources and filters. Each subclass of vtkMapper must implement the Render() method. This method is exchanged by the graphics system actors and its associated mappers during the rendering process. The effect of the method is to map its input dataset to the appropriate rendering library/system. Subclasses of the class vtkWriter must implement the WriteData() method. This method causes the writer to write its input dataset to disk (or other I/O device).

Color Maps

Color maps are created in the Visualization Toolkit using instances of the class vtkLookupTable. This class allows you to create a lookup table using HSVA (e.g., hue, saturation, value, and alpha opacity) specification. Although we discussed the HSV color system in Chapter 3: [Computer Graphics Primer](#), we havent yet defined alpha opacity. We shall do so in Chapter 7: [Advanced Computer Graphics](#), but until then consider the alpha value to be the opacity of an object. Alpha values of one indicate that the object is opaque, while alpha values of zero indicate that the object is transparent.

The procedure for generating lookup table entries is to define pairs of values for HSVA. These pairs define a linear ramp for hue, saturation, value, and opacity. When the Build() method is invoked, these linear ramps are used to generate a table with the number of table entries requested. Alternatively, vtkLookupTable also enables you to load colors directly into the table. Thus, you build custom tables that cannot be simply expressed as linear ramps of HSVA values. To demonstrate this procedure, we specify a starting and ending value for each of the components of HSVA, then we will create a rainbow lookup table from blue to red by using the following C++ code.

Listing 6.1: Create a rainbow lookup table.

```
1 vtkLookupTable *lut = vtkLookupTable::New();
```

```

2   lut->SetHueRange(0.6667, 0.0);
3   lut->SetSaturationRange(1.0, 1.0);
4   lut->SetValueRange(1.0, 1.0);
5   lut->SetAlphaRange(1.0, 1.0);
6   lut->SetNumberOfColors(256);
7   lut->Build();

```

Since the default values for SaturationRange, ValueRange, AlphaRange, and the number of lookup table colors are (1, 1), (1, 1), (1, 1), and 256, respectively, we can simplify this process to the following

Listing 6.2: Create a rainbow lookup table (simplified).

```

1 vtkLookupTable *lut = vtkLookupTable::New();
2   lut->SetHueRange(0.6667, 0.0);
3   lut->Build();

```

(The default values for HueRange are (0.0, 0.6667) — a red to blue color table.)

To build a black and white lookup table of 256 entries we use

Listing 6.3: Create a black and white lookup table.

```

1 vtkLookupTable *lut = vtkLookupTable::New();
2   lut->SetHueRange(0.0, 0.0);
3   lut->SetSaturationRange(0.0, 0.0);
4   lut->SetValueRange(0.0, 1.0)

```

In some cases you may want to specify colors directly. You can do this by specifying the number of colors, building the table, and then inserting new colors. When you insert colors, the RGBA color description system is used. For example, to create a lookup table of the three colors red, green, and blue, use the following C++ code.

Listing 6.4: Directly specifying colors.

```

1 vtkLookupTable *lut = vtkLookupTable::New();
2   lut->SetNumberOfColors(3);
3   lut->Build();
4   lut->SetTableValue(0, 1.0, 0.0, 0.0, 1.0);
5   lut->SetTableValue(0, 0.0, 1.0, 0.0, 1.0);
6   lut->SetTableValue(0, 0.0, 0.0, 1.0, 1.0);

```

Lookup tables in the *Visualization Toolkit* are associated with the graphics mappers. Mappers will automatically create a red to blue lookup table if no table is specified, but if you want to create your own, use the mapper->SetLookupTable(lut) operation where mapper is an instance of vtkMapper or its subclasses.

A few final notes on using lookup tables.

- Mappers use their lookup table to map scalar values to colors. If no scalars are present, the mappers and their lookup tables do not control the color of the object. Instead the vtkProperty object associated with the vtkActor class does. Use vtkProperty's method **actor->GetProperty()->SetColor(r,g,b)** where r, g, and b are floating point values specifying color.

- If you want to prevent scalars from coloring your object, use `vtkMapper`'s method `mapper->ScalarVisibilityOff()` to turn off color mapping. Then the actor's color will control the color of the object.
- The scalar range (i.e., the range into which the colors are mapped) is specified with the mapper. Use the method `mapper->SetScalarRange(min, max)`.

You can also derive your own lookup table types. Look at `vtkLogLookupTable` for an example. This particular lookup table inherits from `vtkLookupTable`. It performs logarithmic mapping of scalar value to table entry, a useful capability when scalar values span many orders of magnitude.

Implicit Functions

As we have seen, implicit functions can be used for visualizing functions, creating geometry, and cutting or selecting datasets. VTK includes several implicit functions including a single plane (`vtkPlane`), multiple convex planes (`vtkPlanes`), spheres (`vtkSphere`), cones (`vtkCone`), cylinders (`vtkCylinder`), and the general quadric (`vtkQuadric`). The class `vtkImplicitBoolean` allows you to create boolean combinations of these implicit function primitives. Other implicit functions can be added to VTK by deriving from the abstract base class `vtkImplicitFunction`.

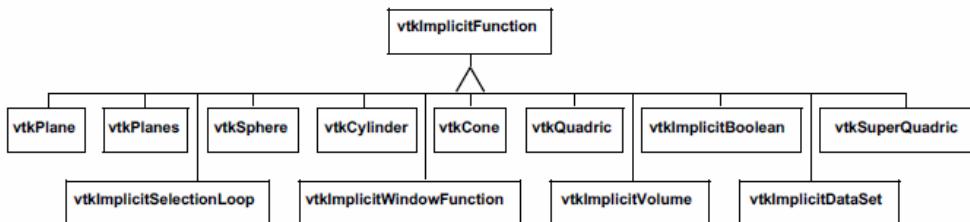


Figure 6.37: Inheritance hierarchy of `vtkImplicitFunction` and subclasses.

The existing inheritance hierarchy for implicit functions is shown in Figure 6.37. Subclasses of `vtkImplicitFunction` must implement the two methods `Evaluate()` and `Gradient(x)`. The method `Evaluate()` returns the value of the function at point (x, y, z) , while the method `Gradient()` returns the gradient vector to the function at point (x, y, z) .

Contouring

Scalar contouring is implemented in the Visualization Toolkit with `vtkContourFilter`. This filter object accepts as input any dataset type. Thus, `vtkContourFilter` treats every cell type and each cell type must provide a method for contouring itself.

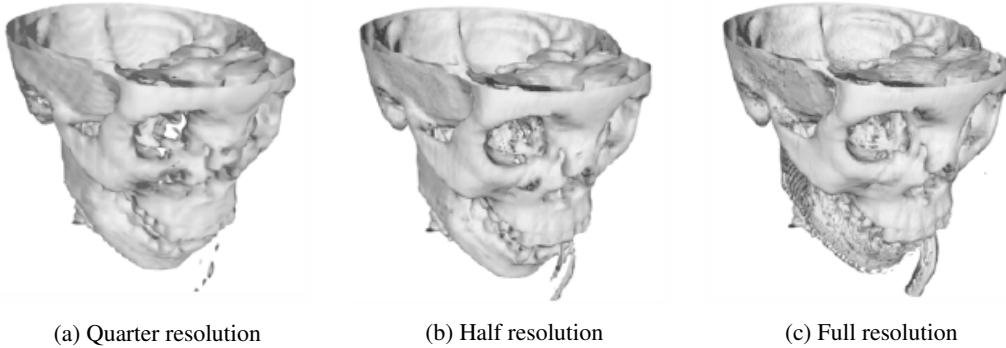
Contouring in VTK is implemented using variations of the marching cubes algorithm presented earlier. That is, a contour case table is associated with each cell type, so each cell will generate contouring primitives as appropriate. For example, the tetrahedron cell type implements “marching tetrahedron” and creates triangle primitives, while the triangle cell type implements “marching triangles” and generates line segments.

The implication of this arrangement is that `vtkContourFilter` will generate point, line, and surface contouring primitives depending on the combination of input cell types. Thus `vtkContourFilter` is completely general. We have created another contour filter, `vtkMarchingCubes`, that is specific to the dataset type image data (in particular, 3D volumes). These two filters allow us to compare (at least for this one algorithm) the cost of generality.

Recall from “Generality Versus Efficiency” on page 100 the issues regarding the trade-offs between general and specific algorithms. Figure 6.38 shows a comparison of CPU times for a volume dataset at $64 \times 64 \times 93$, $128 \times 128 \times 93$ and $256 \times 256 \times 93$. The volume is a CT dataset of a human head. Three cases were run. In the first case the `vtkMarchingCubes` object was used. The output of this filter is triangles plus point normals. In the second case, `vtkContourFilter` was run. The output of this filter is just triangles. In the last case, `vtkContourFilter` was combined with `vtkPolyDataNormals` (to generate point normals). The output of the combined filters is also triangles plus point normals.

The execution times are normalized to the smallest dataset using the `vtkMarchingCubes` object. The results are clear: The specific object outperforms the general object by a factor of 1.4 to 7, depending on data size and whether normals are computed. The larger differences occur on the smaller datasets. This is because the ratio of voxel cells containing the isosurface to the total number of voxels is larger for smaller datasets. (Generally the total number of voxels increases as the resolution cubed, while the voxels containing the isosurface increase as the resolution squared.) As a result, more voxels are processed in the smaller datasets relative to the total number of voxels than in the larger datasets. When the datasets become larger, more voxels are empty and are not processed.

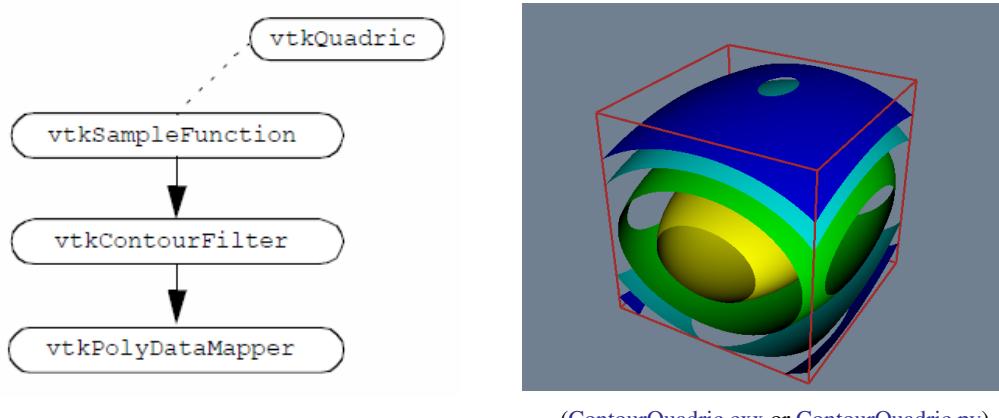
Although these results do not represent all implementations or the behavior of other algorithms, they do point to the cost of generality. Of course, there is a cost to specialization as well. This cost is typically in programmer time, since the programmer must rewrite code to adapt to new circumstances and data. Like all trade-offs, resolution of this issue requires knowledge of the application.



Resolution	Specific (w/ normals)	General (no normals)	Factor Factor	General (w normals)	Factor
$64 \times 64 \times 93$	1.000	2.889	2.889	7.131	7.131
$128 \times 128 \times 93$	5.058	11.810	2.330	23.360	4.600
$256 \times 256 \times 93$	37.169	51.160	1.390	87.230	2.350

Figure 6.38: The cost of generality. Isosurface generation of three volumes of different sizes are compared. The results show normalized execution times for two different implementations of the marching-cubes isosurface algorithm. The specialized filter is `vtkMarchingCubes`. The general algorithms are first `vtkContourFilter` and then in combination with `vtkPolyDataNormals`.

An example use of `vtkContourFilter` is shown in Figure 6.39. This example is taken from Figure 4.1, which is a visualization of a quadric function. The class `vtkSampleFunction` samples the



```

1 // Define implicit function
2 vtkQuadric *quadric = vtkQuadric::New();
3     quadric->SetCoefficients(.5,1,.2,0,.1,0,0,.2,0,0);
4 vtkSampleFunction *sample = vtkSampleFunction::New();
5     sample->SetSampleDimensions(50,50,50);
6     sample->SetImplicitFunction(quadric);
7 vtkContourFilter *contour = vtkContourFilter::New();
8     contour->SetInputConnection(sample->GetOutputPort());
9     contour->GenerateValues(5,0,1.2);
10    vtkPolyDataMapper *contourMapper = vtkPolyDataMapper::New();
11        contourMapper->SetInputConnection( contour->GetOutputPort());
12        contourMapper->SetScalarRange(0,1.2);
13    vtkActor *contourActor = vtkActor::New();
14        contourActor->SetMapper(contourMapper);
15 // Create outline
16 vtkOutlineFilter *outline = vtkOutlineFilter::New();
17     outline->SetInputConnection(sample->GetOutputPort());
18 vtkPolyDataMapper *outlineMapper = vtkPolyDataMapper::New();
19     outlineMapper->SetInputConnection(outline->GetOutputPort());
20    vtkActor *outlineActor = vtkActor::New();
21        outlineActor->SetMapper(outlineMapper);
22        outlineActor->GetProperty()->SetColor(0,0,0);

```

Figure 6.39: Contouring quadric function. Pipeline topology, C++ code, and resulting image are shown.

implicit quadric function using the `vtkQuadric` class. Although `vtkQuadric` does not participate in the pipeline in terms of data flow, it is used to define and evaluate the quadric function. It is possible to generate one or more isolines/isosurfaces simultaneously using `vtkContourFilter`. As Figure 6.39 shows, we use the `GenerateValues()` method to specify a scalar range, and the number of contours within this range (including the initial and final scalar values). `vtkContourFilter` generates duplicate

vertices, so we can use `vtkCleanPolyData` to remove them. To improve the rendered appearance of the isosurface, we use `vtkPolyDataNormals` to create surface normals. (We describe normal generation in Chapter 9: [Advanced Algorithms](#).)

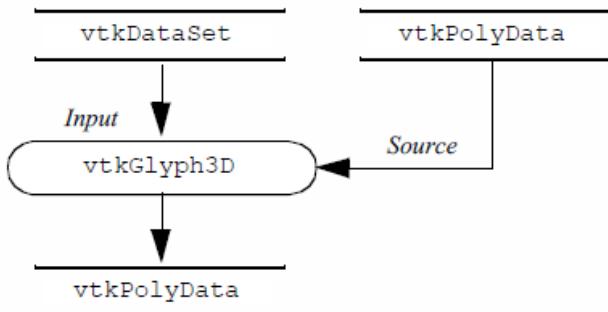


Figure 6.40: Data flow into and out of the `vtkGlyph3D` class.

6.6.2 Cutting

The `vtkCutter` class performs cutting of all VTK cell types. The `SetValue()` and `GenerateValues()` methods permit the user to specify which multiple scalar values to use for the cutting. `vtkCutter` requires an implicit function that will be evaluated at each point in the dataset. Then each cell is cut using the cell's `Contour` method. Any point attributes are interpolated to the resulting cut vertices. The sorting order for the generated polygonal data can be controlled with the `SortBy` method. The default sorting order, `SortByValue()`, processes cells in the inner loop for each contour value. `SortByCell()` processes the cutting value in the inner loop and produces polygonal data that is suitable for backtofront rendering (see Figure 6.32). (The sorting order is useful when rendering with opacity as discussed in Chapter 7: [Advanced Computer Graphics](#).) Notice the similarity of this filter to the `vtkContourFilter`. Both of these objects contour datasets with multiple isovalue. `vtkCutter` uses an implicit function to calculate scalar values while `vtkContourFilter` uses the scalar data associated with the dataset's point data.

6.6.3 Glyphs

The `vtkGlyph3D` class provides a simple, yet powerful glyph capability in the *Visualization Toolkit*. `vtkGlyph3D` is an example of an object that takes multiple inputs (Figure 6.40). One input, specified with the `SetInputConnection()` method, defines a set of points and possible attribute data at those points. The second input, specified with the `SetSourceConnection()` method, defines a geometry to be copied to every point in the input dataset. The source is of type `vtkPolyData`. Hence, any filter, sequence of filters creating polygonal data, or a polygonal dataset may be used to describe the glyph's geometry.

The behavior of an instance of `vtkGlyph3D` depends on the nature of the input data and the value of its instance variables. Generally, the input Source geometry will be copied to each point of the Input dataset. The geometry will be aligned along the input vector data and scaled according to the magnitude of the vector or the scalar value. In some cases, the point normal is used rather than the vector. Also, scaling can be turned on or off.

We saw how to use `vtkGlyph3D` in the example given in Figure 4.2. Cones were used as the glyph and were located at each point on the sphere, oriented along the sphere's surface normal.

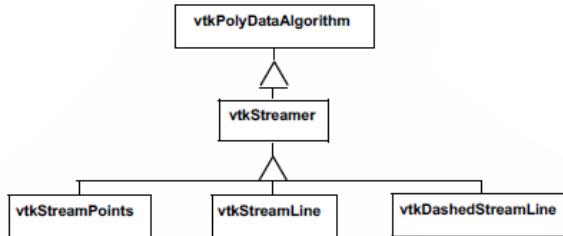


Figure 6.41: Inheritance hierarchy for `vtkStreamer` and subclasses.

6.6.4 Streamlines

Streamlines and particle motion require numerical integration to guide a point through the vector field. Vector visualization algorithms that we will see in later chapters also require numerical integration. As a result, we designed an object hierarchy that isolates the numerical integration process into a single base class. The base class is `vtkStreamer` and it is responsible for generating a particle path through a vector field of specified length (expressed as elapsed time). Each derived class of `vtkStreamer` takes advantage of this capability to move through the vector field but implements its own particular representational technique to depict particle motion. Streamlines (`vtkStreamLine`) draw connected lines while particle motion is shown by combining the output of `vtkStreamPoints` with the `vtkGlyph3D` object. Using `vtkGlyph3D` we can place spheres or oriented objects such as cones or arrows at points on the particle path created by `vtkStreamPoints`. The inheritance hierarchy for `vtkStreamer` and subclasses is shown in Figure 4.2.

The integration method in `vtkStreamer` is implemented as a virtual function. Thus it can be overloaded as necessary. Possible reasons for overloading include implementing an integration technique of higher or lower accuracy, or creating a technique specialized to a particular dataset type. For example, the search process in a volume is much faster than it is for other dataset types, therefore, highly efficient vector integration techniques can be constructed.

The vector integration technique in VTK will accommodate any cell type. Thus, integration through cells of any topological dimension is possible. If the cells are of topological dimension 2 or less, the integration process constrains particle motion to the surface (2D) or line (1D). The particle may only leave a cell by passing through the cell boundary, and traveling to a neighboring cell, or exiting the dataset.

6.6.5 Abstract Filters

Attribute transformations create or modify data attributes without changing the topology or geometry of a dataset. Hence filters that implement attribute transformation (e.g., `vtkElevationFilter`) can accept any dataset type as input, and may generate any dataset type on output. Unfortunately, because filters must specialize the particular type of data they output, at first glance it appears that filters that create general dataset types on output are not feasible. This is because the type `vtkDataSet` is an abstract type and must be specialized to allow instantiation.

Fortunately, there is a solution to this dilemma. The solution is to use the “virtual constructor” `NewInstance()`. Although C++ does not allow virtual constructors, we can simulate it by creating a special virtual function that constructs a copy of the object that it is invoked on. For example, if this function is applied to a dataset instance of type `vtkPolyData`, the result will be a copy of that instance (Figure 6.42). (Note that we use reference counting to make copies and avoid duplicating memory.) The virtual constructor function `NewInstance()` is implemented in a number of VTK

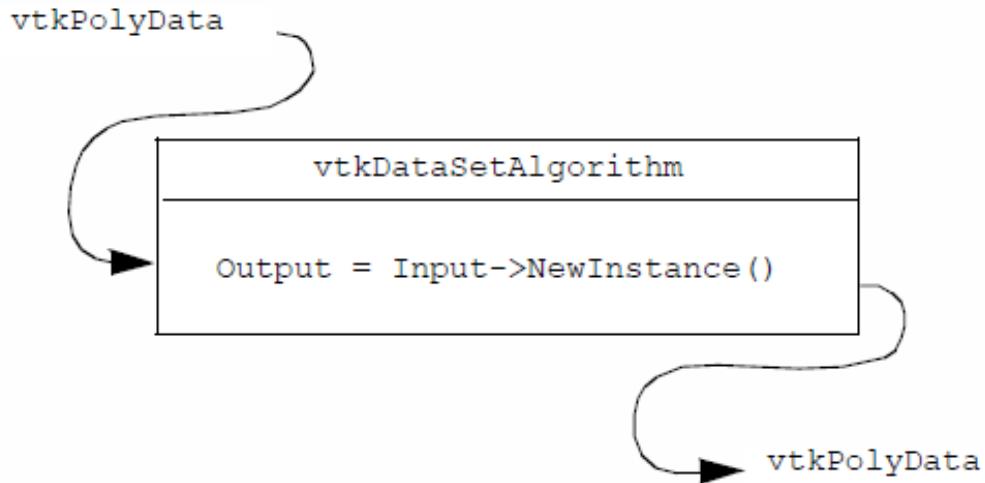


Figure 6.42: Depiction of data flow for abstract filter output. The output object type is the same as the input type.

classes including datasets and cells.

Using the virtual constructor we can construct filters that output abstract data types like `vtkDataSet`. We simply apply `NewInstance()` to the input of the filter. This will then return a pointer to a concrete object that is the output of the filter. The result is a general filter object that can accept any dataset type for input and creates the general `vtkDataSet` type as output. In VTK, this functionality has been implemented in the abstract class `vtkDataSetAlgorithm`.

There are other filters that implement variations of this delegation technique. The class `vtkPointSetAlgorithm` is similar to `vtkDataSetAlgorithm`. This class takes as input any dataset whose geometry is explicitly defined via an instance of `vtkPoints` (or subclass), and generates on output an object of the same type (i.e., `vtkPointSet`). The class `vtkMergeFilter` combines dataset structure and point attributes from one or more input datasets. For example, you can read multiple files and combine the geometry/topology from one file with different scalars, vectors, and normals from other files.

One difficulty using abstract filter types is that the output type may not match with the input type of a downstream filter. For example, the output of `vtkElevationFilter` is specified as `vtkDataSet` even though the input may be of type `vtkPolyData`, and we know from the previous discussion that the actual output type will be `vtkPolyData`. This difficulty is removed by using the filter `vtkCastToConcrete`, which allows you to runtime cast to the appropriate output type. In this case we would use the `GetPolyDataOutput()` from `vtkCastToConcrete`. After checking the validity of the cast, this method returns a dataset cast to `vtkPolyData`. Of course, this process requires that the input to `vtkCastToConcrete` be set before the output is requested.

6.6.6 Visualizing Blood Flow

In this example we'll combine a few different techniques to visualize blood flow in the human carotid arteries. Our data contains both vectors that represent the velocity of blood and scalars that are proportional to the magnitude of the velocity (i.e., speed).

We can provide context for the visualization by creating an isosurface of speed. This isosurface shows regions of fastest blood flow, and is similar to, but not the same as, the actual surface

of the arteries. However, it provides us with a visual cue to the structure of the arteries. The first vector visualization technique we'll use is to generate vector glyphs (Unfortunately, we cannot just create glyphs at each point because of the number of points (over 167,000 points). To do so would result in a confusing mess, and the interactive speed would be poor. Instead, we'll use two filters to select a subset of the available points. These filters are `vtkThresholdPoints` and `vtkMaskPoints`.

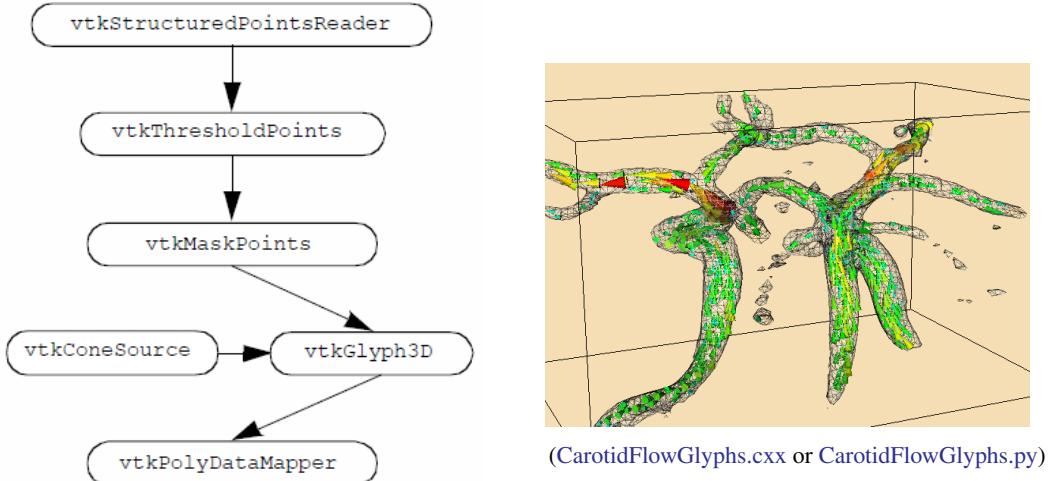
`vtkThresholdPoints` allows us to extract points that satisfy a certain threshold criterion. In our example, we choose points whose speed is greater than a specified value. This eliminates a large number of points, since most points lie outside the arteries and have a small speed value.

The filter `vtkMaskPoints` allows us to select a subset of the available points. We specify the subset with the `OnRatio` instance variable. This instance variable indicates that every `OnRatio` point is to be selected. Thus, if the `OnRatio` is equal to one, all points will be selected, and if the `OnRatio` is equal to ten, every tenth point will be selected. This selection can be either uniform or random. Random point selection is set using the `RandomModeOn()` and `RandomModeOff()` methods.

After selecting a subset of the original points, we can use the `vtkGlyph3D` filter in the usual way. A cone's orientation indicates blood flow direction, and its size and color correspond to the velocity magnitude. Figure 6.43 shows the pipeline, sample code, and a resulting image from this visualization. Note that we've implemented the example using the interpreted language `Tcl`. See Chapter 11: [Visualization on the Web](#) if you want more information about `Tcl`.

In the next part of this example we'll generate streamtubes of blood velocity. Again we use an isosurface of speed to provide us with context. The starting positions for the streamtubes were determined by experimenting with the data. Because of the way the data was measured and the resolution of the velocity field, many streamers travel outside the artery. This is because the boundary layer of the blood flow is not captured due to limitations in data resolution. Consequently, as the blood flows around curves, there is a component of the velocity field that directs the streamtube outside the artery. As a result it is hard to find starting positions for the streamtubes that yield interesting results. We use the source object `vtkPointSource` in combination with `vtkThresholdPoints` to work around this problem. `vtkPointSource` generates random points centered around a sphere of a specified radius. We need only find an approximate position for the starting points of the streamtubes and then generate a cloud of random seed points. `vtkThresholdPoints` is used to cull points that may be generated outside the regions of high flow velocity.

Figure 6.44 shows the pipeline, sample `Tcl` code, and a resulting image from the visualization. Notice that the isosurface is shown in wireframe. This provides context, yet allows us to see the streamtubes within the isosurface.

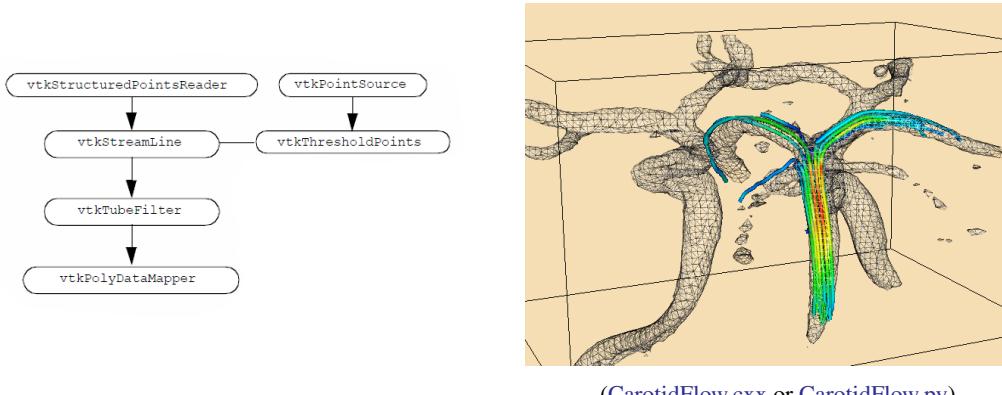


```

1  vtkStructuredPointsReader reader
2      reader SetFileName "$env(VTK_TEXTBOOK_DATA)/carotid.vtk"
3  vtkThresholdPoints threshold
4      threshold SetInputConnection [reader GetOutputPort]
5      threshold ThresholdByUpper 200
6  vtkMaskPoints mask
7      mask SetInputConnection [Threshold GetOutputPort]
8      mask SetOnRatio 10
9  vtkConeSource cone
10     cone SetResolution 3
11     cone SetHeight 1
12     cone SetRadius 0.25
13  vtkGlyph3D cones
14      cones SetInputConnection [mask GetOutputPort]
15      cones SetSourceConnection [cone GetOutputPort]
16      cones SetScaleFactor 0.5
17      cones SetScaleModeToScaleByVector
18  vtkLookupTable lut
19      lut SetHueRange .667 0.0
20      lut Build
21  vtkPolyDataMapper vecMapper
22      vecMapper SetInputConnection [cones GetOutputPort]
23      vecMapper SetScalarRange 2 10
24      vecMapper SetLookupTable lut

```

Figure 6.43: Visualizing blood flow in human carotid arteries. Cone glyphs indicate flow direction and magnitude.



(CarotidFlow.cxx or CarotidFlow.py)

```

1   vtkStructuredPointsReader reader
2     reader SetFileName "$env(VTK_TEXTBOOK_DATA)/carotid.vtk"
3   vtkPointSource source
4     source SetNumberOfPoints 25
5     source SetCenter 133.1 116.3 5.0
6     source SetRadius 2.0
7   vtkThresholdPoints threshold
8     threshold SetInputConnection [reader GetOutputPort]
9     threshold ThresholdByUpper 275
10  vtkStreamTracer streamers
11    streamers SetInputConnection [reader GetOutputPort]
12    streamers SetSourceConnection [source GetOutputPort]
13    streamers SetMaximumPropagationUnitToTimeUnit
14    streamers SetMaximumPropagation 100.0
15    streamers SetInitialIntegrationStepUnitToCellLengthUnit
16    streamers SetInitialIntegrationStep 0.2
17    streamers SetTerminalSpeed .1
18  vtkTubeFilter tubes
19    tubes SetInputConnection [streamers GetOutputPort]
20    tubes SetRadius 0.3
21    tubes SetNumberOfSides 6
22    tubes SetVaryRadiusToVaryRadiusOff
23  vtkPolyDataMapper streamerMapper
24    streamerMapper SetInputConnection [tubes GetOutputPort]
25    streamerMapper SetScalarRange 2 10
  
```

Figure 6.44: Visualizing blood flow in the human carotid arteries. Streamtubes of flow vectors.

6.7 Chapter Summary

Visualization algorithms transform data from one form to another. These transformations can change or create new structure and/or attributes of a dataset. Structural transformations change

either the topology or geometry of a dataset. Attribute transformations change dataset attributes such as scalars, vectors, normals, or texture coordinates.

Algorithms are classified according to the type of data they operate on. Scalar, vector, and tensor algorithms operate on scalar, vector, and tensor data, respectively. Modelling algorithms operate on dataset geometry or topology, texture coordinates, or normals. Modelling algorithms also may include complex techniques that may represent combinations of different data types.

Algorithms can be designed and implemented for general types of data or specialized for a specific type. General algorithms are typically less efficient than their specialized counterparts. Conversely, general algorithms are more flexible and do not require rewriting as new dataset types are introduced.

Important scalar algorithms include color mapping and contouring. Color maps are used to map scalar values to color values. Contouring algorithms create isosurfaces or isolines to indicate areas of constant scalar value.

Glyphs such as hedgehogs are useful for visualizing vector data. These techniques are limited by the number of glyphs that can be displayed at one time. Particle traces or streamlines are another important algorithm for vector field visualization. Collections of particle traces can convey something of the structure of a vector field.

Real, symmetric tensors 3×3 can be characterized by their eigenvalues and eigenvectors.

Tensors can be visualized using tensor ellipsoids or oriented axes.

Implicit functions and sampling techniques can be used to make geometry, cut data, and visualize complex mathematical descriptions. Glyphs are objects whose appearance is associated with a particular data value. Glyphs are flexible and can be created to visualize a variety of data.

6.8 Bibliographic Notes

Color mapping is a widely studied topic in imaging, computer graphics, visualization, and human factors. References [9] [26] [21] provide samples of the available literature. You also may want to learn about the physiological and psychological effects of color on perception. The text by Wyszecki and Stiles [28] serves as an introductory reference.

Contouring is a widely studied technique in visualization because of its importance and popularity. Early techniques were developed for 2D data [27]. Three-dimensional techniques were developed initially as contour connecting methods [12] — that is, given a series of 2D contours on evenly spaced planes, connect the contours to create a closed surface. Since the introduction of marching cubes [16], many other techniques have been implemented. (A few of these include [19] [5] and [10]). A particularly interesting reference is given by Livnat et al. [29]. They show a contouring method with the addition of a preprocessing step that generates isocontours in near optimal time.

Although we barely touched the topic, the study of chaos and chaotic vibrations is a delightfully interesting topic. Besides the original paper by Lorenz [17], the book by Moon [18] is a good place to start.

Two- and three-dimensional vector plots have been used by computer analysts for many years [1]. Streamlines and streamribbons also have been applied to the visualization of complex flows [25]. Good general references on vector visualization techniques are given in [14] and [20].

Tensor visualization techniques are relatively few in number. Most techniques are glyph oriented [13] [15]. We will see a few more techniques in Chapter 9.

Blinn [2], Bloomenthal [4] [3] and Wyvill [11] have been important contributors to implicit modeling. Implicit modeling is currently popular in computer graphics for modeling “soft” or “blobby” objects. These techniques are simple, powerful, and are becoming widely used for advanced computer graphics modeling.

Bibliography

- [1] A.J Fuller Baden and M.L.X dos Santos. “Computer Generated Display of 3D Vector Fields”. In: *Computer Aided Design* 12.2 (1980), pp. 61–66.
- [2] J. F. Blinn. “A Generalization of Algebraic Surface Drawing”. In: *ACM Transactions on Graphics* 1.3 (July 1982), pp. 235–256.
- [3] J. Bloomenthal, ed. *Introduction to Implicit Surfaces*. Morgan Kaufmann Publishers, Inc., San Francisco, CA., 1997.
- [4] J. Bloomenthal. “Polygonization of Implicit Surfaces”. In: *Computer Aided Geometric Design* 5.4 (Nov. 1982), pp. 341–355.
- [5] R. Scateni C. Montani and R. Scopigno. “A Modified LookUp Table for Implicit Disambiguation of Marching Cubes”. In: *Visual Computer* 10 (1994), pp. 353–355.
- [6] H. Chernoff. “Using Faces to Represent Points in K-Dimensional Space Graphically”. In: *J. American Statistical Association* 68 (1973), pp. 361–368.
- [7] S. D. Conte and C. de Boor. *Elementary Numerical Analysis*. McGrawHill Book Company, 1972.
- [8] T. Delmarcelle and L. Hessellink. *A Unified Framework for Flow Visualization*. Ed. by R. S. Gallagher. CRC Press, Boca Raton, FL, 1995.
- [9] H. J. Durrett, ed. *Color and the Computer*. Academic Press, Boston, MA, 1987.
- [10] M. J. Durst. “Additional Reference to Marching Cubes”. In: *Computer Graphics* 22.2 (1988), pp. 72–73.
- [11] G. Wyvill, C. McPheevers, B. Wyvill. “Data Structure for Soft Objects”. In: *Visual Computer* 2.4 (1986), pp. 227–234.
- [12] H. Fuchs, Z. M. Kedem, and S. P. Uselton. “Optimal Surface Reconstruction from Planar Contours”. In: *Communications of the ACM* 20.10 (1977), pp. 693–702.
- [13] R. B. Haber and D. A. McNabb. “Visualization Idioms: A Conceptual Model to Scientific Visualization Systems”. In: *Visualization in Scientific Computing*. Ed. by L. J. Rosenblum G. M. Nielson B. Shriver. IEEE Computer Society Press, 1990, pp. 61–73.
- [14] J. Helman and L. Hessellink. “Representation and Display of Vector Field Topology in Fluid Flow Data Sets”. In: *Visualization in Scientific Computing*. Ed. by L. J. Rosenblum G. M. Nielson B. Shriver. IEEE Computer Society Press, 1990, pp. 61–73.
- [15] W. C. de Leeuw and J. J. van Wijk. “A Probe for Local Flow Field Visualization”. In: *Proceedings of Visualization '93*. IEEE Computer Society Press, Los Alamitos, CA, 1993, pp. 39–45.
- [16] W. E. Lorensen and H. E. Cline. “Marching Cubes: A High Resolution 3D Surface Construction Algorithm”. In: *Computer Graphics* 21.3 (July 1987), pp. 163–169.
- [17] E. N. Lorenz. “Deterministic NonPeriodic Flow”. In: *Journal of Atmospheric Science* 20 (1963), pp. 130–141.

- [18] F. C. Moon. *Chaotic Vibrations*. WileyInterscience, New York, NY, 1987.
- [19] G. M. Nielson and B. Hamann. “he Asymptotic Decider: Resolving the Ambiguity in Marching Cube”. In: *Proceedings of Visualization '91*. IEEE Computer Society Press, Los Alamitos, CA, 1991, pp. 83–91.
- [20] R. Richter, J. B. Vos, A. Bottaro, and S. Gavrilakis. “Scientific Visualization and Graphics Simulation”. In: ed. by D. Thalmann. John Wiley and Sons, 1990. Chap. Visualization of Flow Simulations, pp. 161–171.
- [21] P. Rheingans. “Color, Change, and Control for Quantitative Data Display”. In: *Proceedings of Visualization '92*. IEEE Computer Society Press, Los Alamitos, CA, 1992, pp. 252–259.
- [22] A. S. Saada. *Elasticity Theory and Applications*. Pergamon Press, Inc., New York, NY, 1974.
- [23] S. P. Timoshenko and J. N. Goodier. *Theory of Elasticity, 3d Edition*. McGrawHill Book Company, New York, NY, 1970.
- [24] E. R. Tufte. *The Visual Display of Quantitative Information*. Graphics Press, Cheshire, CT, 1990.
- [25] G. Volpe. “Technical Report AIAA-89-0140”. In: *27th Aerospace Sciences Meeting*. 1989.
- [26] C. Ware. “Color Sequences for Univariate Maps: Theory, Experiments and Principles”. In: *IEEE Computer Graphics and Applications* 8.5 (1988), pp. 41–49.
- [27] D. F. Watson. *Contouring: A Guide to the Analysis and Display of Spatial Data*. Pergamon Press, 1992.
- [28] G. Wyszecki and W. Stiles. *Color Science: Concepts and Methods, Quantitative Data and Formulae*. John Wiley and Sons, 1982.
- [29] C. R. Johnson Y. Livnat H. W. Shen. “A Near Optimal Isosurface Extraction Algorithm for Structured and Unstructured Grids”. In: *IEEE Transactions on Visualization and Computer Graphics* 2.1 (Mar. 1996).

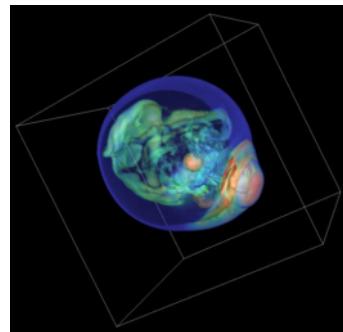
6.9 Exercises

1. Sketch contour cases for marching triangles. How many cases are there?
2. Sketch contour cases for marching tetrahedron. How many cases are there?
3. A common visualization technique is to animate isosurface value. The procedure is to smoothly vary isosurface value over a specified range.
 - (a) Create an animation sequence for the quadric example (Figure 4.1a)
 - (b) Create an animation sequence for the head sequence (Figure 6.11b)
4. Marching Cubes visits each cell during algorithm execution. Many of these cells do not contain the isosurface. Describe a technique to improve the performance of isosurface extraction by eliminating visits to cells not containing isosurface. (*Hint:* use a preprocessing step to analyze data. Assume that many isosurfaces will be extracted and that the preprocessing step will not count against execution time.)
5. Scanline rasterization proceeds along horizontal spans in graphics hardware (see “Rasterization” on page 61. Interpolation of color occurs along horizontal spans as well.
 - (a) Show how the orientation of a polygon affects interpolated color.

- (b) Discuss potential problems caused by orientation dependent viewing of visualizations.
6. Write a program to simulate beam vibration. Use the code associated with Figure 6.14a as your starting point.
 7. Using the filters vtkStreamLine, vtkMaskPoints, and vtkGlyph3D, create a visualization consisting of oriented glyphs along a streamline.
 8. Visualize the following functions.
 - (a) Scalar $S(x, y, z) = \sin(xy)$ for x, y , between 0 and π .
 - (b) The effective stress field (a scalar field) from **Figure621**.
 - (c) The vector field described in the combustor data (i.e., combq.bin and combxyz.bin).
 9. Tensor ellipsoids are based on an ellipsoidal glyph. Describe two other glyphs that you might use.
 10. Write a source object to generate a polygonal representation of a torus.
 11. Design a glyph to convey airplane heading, speed, and altitude, and proximity (i.e., distance) to other planes.
 12. Morphing is a process to smoothly blend images (2D) or geometry (3D) between two known images or geometry. Using an implicit modeling approach, how would you morph a torus into a cube?
 13. Describe a technique to visualize vector information by animating a color map. (emphHint: By choosing a map carefully, you can give the illusion of motion across a surface.)
 14. Isoline contours of different values are typically shown together in one image.
 - (a) Describe the advantages and disadvantages of displaying isosurfaces simultaneously.
 - (b) What two graphics properties might you adjust to improve the display of multiple isosurfaces?
 15. Describe a parallel algorithm for marching cubes. Use a parallel architecture of your choice.
 16. Decomposition can greatly increase the speed of an operation.
 - (a) Prove that 3D Gaussian smoothing can be decomposed into three 1D operations.
 - (b) Give the complexity of the decomposed filter and the same filter implemented as a 3D convolution.
 - (c) Under what conditions can constant smoothing be decomposed into 1D operations.

7.0

Advanced Computer Graphics



Volume rendering of a supernova dataset.

Chapter 3 introduced fundamental concepts of computer graphics. A major topic in that chapter was how to represent and render geometry using surface primitives such as points, lines, and polygons. In this chapter our primary focus is on volume graphics. Compared to surface graphics, volume graphics has a greater expressive range in its ability to render inhomogeneous materials, and is a dominant technique for visualizing 3D image (volume) datasets.

We begin the chapter by describing two techniques that are important to both surface and volume graphics. These are simulating object transparency using simple blending functions, and using texture maps to add realism without excessive computational cost. We also describe various problems and challenges inherent to these techniques. We then follow with a focused discussion on volume graphics, including both object-order and image-order techniques, illumination models, approaches to mixing surface and volume graphics, and methods to improve performance. Finally, the chapter concludes with an assortment of important techniques for creating more realistic visualizations. These techniques include stereo viewing, antialiasing, and advanced camera techniques such as motion blur, focal blur, and camera motion.

7.1 Transparency and Alpha Values

Up to this point in the text we have focused on rendering opaque objects that is, we have assumed that objects reflect, scatter, or absorb light at their surface, and no light is transmitted through to their interior. Although rendering opaque objects is certainly useful, there are many applications that can benefit from the ability to render objects that transmit light. One important application of transparency is volume rendering, which we will explore in greater detail later in the chapter.

7.2 Texture Mapping

Texture mapping is a technique to add detail to an image without requiring modelling detail. Texture mapping can be thought of as pasting a picture to the surface of an object. The use of texture mapping requires two pieces of information: a *texture map* and *texture coordinates*. The texture map is the picture we paste, and the texture coordinates specify the location where the picture is pasted. More generally, texture mapping is a table lookup for color, intensity, and/or transparency that is applied to an object as it is rendered. Textures maps and coordinates are most often two-dimensional, but three-dimensional texture maps and coordinates are supported by most new graphics hardware.

7.3 Volume Rendering

Until now we have concentrated on the visualization of data through the use of geometric primitives such as points, lines, and polygons. For many applications such as architectural walkthroughs or terrain visualization, this is obviously the most efficient and effective representation for the data. In contrast, some applications require us to visualize data that is inherently volumetric (which we refer to as 3D image or volume datasets). For example, in biomedical imaging we may need to visualize data obtained from an MR or CT scanner, a confocal microscope, or an ultrasound study. Weather analysis and other simulations also produce large quantities of volumetric data in three or more dimensions that require effective visualization techniques. As a result of the popularity and usefulness of volume data over the last several decades, a broad class of rendering techniques known as volume rendering has emerged. The purpose of volume rendering is to effectively convey information within volumetric data.

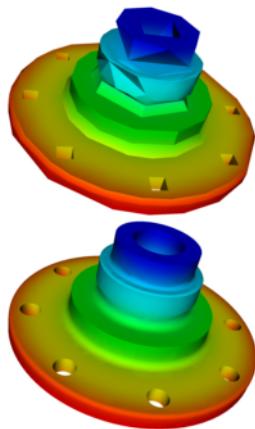
7.4 3D Widgets and User Interaction

Chapter 3 provided an introduction to interaction techniques for graphics (see “Introducing `vtkRenderWindowInteractor`” on page [78](#)). In the context of visualization, interaction is an essential feature of systems that provide methods for data exploration and query. The classes `vtkRenderWindowInteractor` and `vtkInteractorStyle` are core constructs used in VTK to capture windowing-system specific events in the render window, translate them into VTK events, and then take action as appropriate to that event invocation. In Chapter 3 we saw how these classes could be used to manipulate the camera and actors to interactively produce a desired view. This functionality, however, is relatively limited in its ability to interact with data. For example, users often wish to interactively control the positioning of streamline starting points, control the orientation of a clipping plane, or transform an actor. While using interpreted languages (see “Interpreted Code” on page [78](#)) can go a long way to provide this interaction, in some situations the ability to see what you are doing when placing objects is essential. Therefore, it is apparent that a variety of user interaction techniques is required by the visualization system if it is to successfully support real-world applications.

7.5 Exercises

8.0

Advanced Data Representation



Adaptive tessellation of higher-order cells.

This chapter examines advanced topics in data representation. Topics include topological and geometric relationships and computational methods for cells and datasets.

8.1 Coordinate Systems

We will examine three different coordinate systems: the global, dataset, and structured coordinate systems. Figure 8.1 shows the relationship between the global and dataset coordinate systems, and depicts the structured coordinate system.

8.1.1 Global Coordinate System

The global coordinate system is a Cartesian, three-dimensional space. Each point is expressed as a triplet of values (x, y, z) along the x , y , and z axes. This is the same system that was described in Chapter 3 (see 3.7). The global coordinate system is always used to specify dataset geometry (i.e., the point coordinates), and data attributes such as normals and vectors. We will use the word “position” to indicate that we are using global coordinates.

8.2 Searching

Searching is an operation to find the cell containing a specified point p , or to locate cells or points in a region surrounding p . Algorithms requiring this operation include streamline generation, where we need to find the starting location within a cell; probing, where the data values at a point are interpolated from the containing cell; or collision detection, where cells in a certain region must be evaluated for intersection. Sometimes (e.g., image datasets), searching is a simple operation because of the regularity of data. However, in less structured data, the searching operation is more complex.

To find the cell containing p , we can use the following naive search procedure. Traverse all cells in the dataset, finding the one (if any) that contains p . To determine whether a cell contains a point, the cell interpolation functions are evaluated for the parametric coordinates (r, s, t) . If these coordinates lie within the cell, then p lies in the cell. The basic assumption here is that cells do not overlap, so that at most a single cell contains the given point p . To determine cells or points lying in the region surrounding p , we can traverse cells or points to see whether they lie within the region around p . For example, we can choose to define the region as a sphere centered at p . Then, if a point or the points composing a cell lie in the sphere, the point or cell is considered to be in the region surrounding p .

8.3 Putting It All Together

In this section we will finish our earlier description of an implementation for unstructured data. We also define a high-level, abstract interface for cells and datasets. This interface allows us to implement the general (i.e., dataset specific) algorithms in the *Visualization Toolkit*. We also describe implementations for color scalars, searching and picking, and conclude with a series of examples to demonstrate some of these concepts.

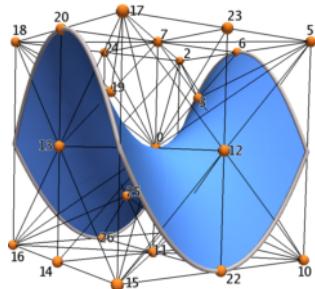
8.3.1 Picking

The Visualization Toolkit provides a variety of classes to perform actor (or `vtkProp`), point, cell, and world point picking (Figure 8.38).

8.3.2 Point Probe

9.0

Advanced Algorithms



An isocontour of a tri-quadratic Lagrange-interpolant. Image courtesy D. Thompson and P. Pébay Sandia National Labs.

We return again to visualization algorithms. This chapter describes algorithms that are either more complex to implement, or less widely used for 3D visualization applications. We retain the classification of algorithms as either scalar, vector, tensor, or modelling algorithms.

9.1 Scalar Algorithms

As we have seen, scalar algorithms often involve mapping scalar values through a lookup table, or creating contour lines or surfaces. In this section, we examine another contouring algorithm, dividing cubes, which generates contour surfaces using dense point clouds. We also describe carpet plots. Carpet plots are not true 3D visualization techniques, but are widely used to visualize many types of scalar data. Finally, clipping is another important algorithm related to contouring, where cells are cut into pieces as a function of scalar value.

9.1.1 Dividing Cubes

9.2 Vector Algorithms

9.2.1 Vector Field Topology

$$H_d = \vec{v} \cdot \vec{w} = |\vec{v}| |\vec{w}| \cos(\phi) \quad (9.1)$$

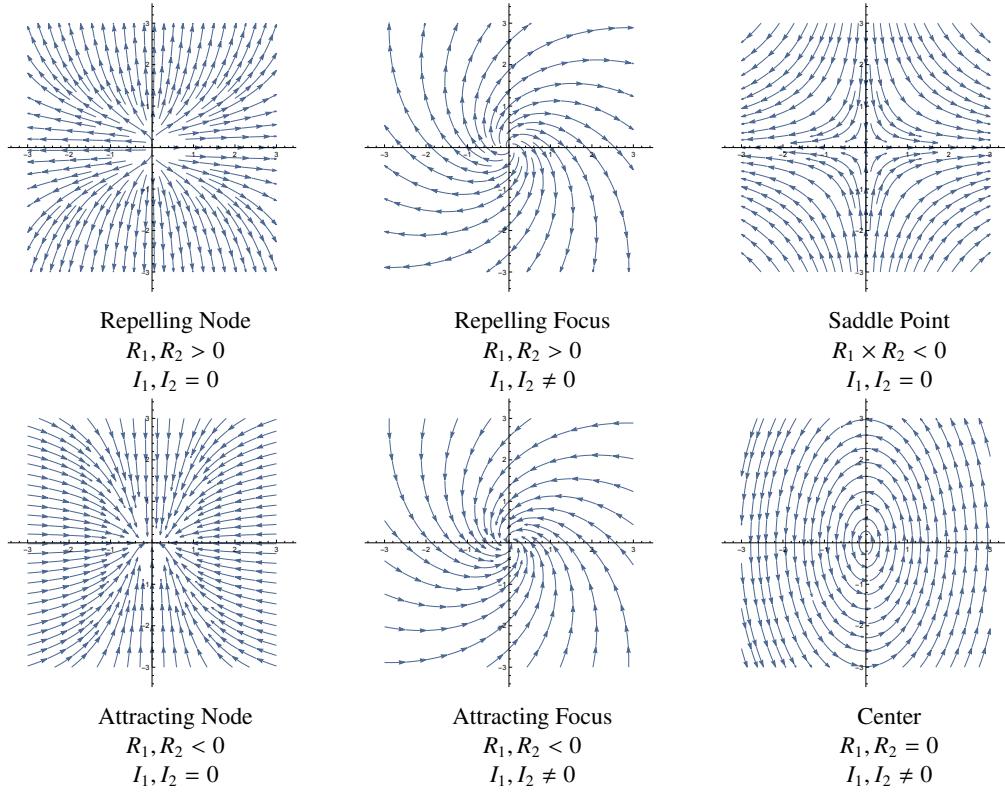


Figure 9.1: Critical points in two dimensions. The real part of the eigenvalues (R_1, R_2) of the matrix of first derivatives control the attraction or repulsion of the vector field. The imaginary part of the eigenvalues (I_1, I_2) controls the rotation.

9.3 Tensor Algorithms

9.4 Modelling Algorithms

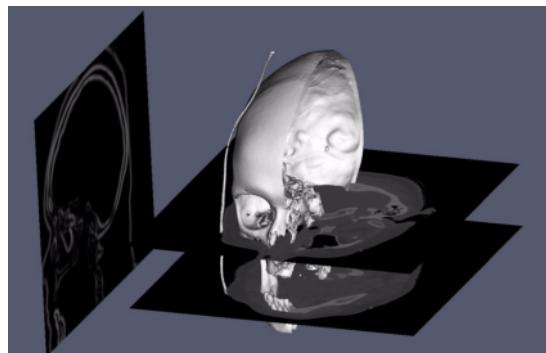
9.4.1 Mesh Smoothing

9.5 Putting It All Together

9.5.1 Connectivity

10.0

Image Processing



Gradient magnitude of a slice (vertical) of the Visible Woman CT dataset shown with an isosurface and two slices (horizontal) of the dataset.

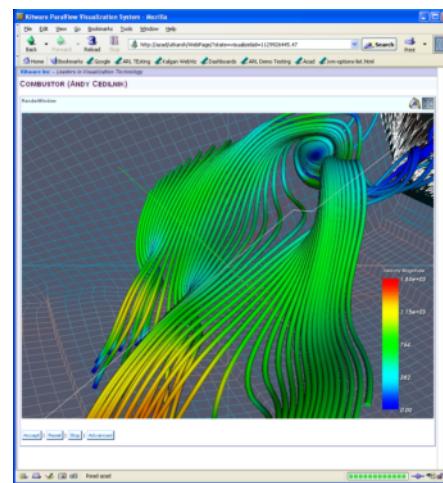
In this chapter we describe the image processing components of the Visualization Toolkit. The focus is on key representational ideas, pipeline issues such as data streaming, and useful algorithms for improving the appearance and effectiveness of image data visualizations.

10.1 Introduction

Image processing has been a mainstay of computing since the advent of the digital computer. Early efforts focused on improving image content for human interpretation.

11.0

Visualization on the Web



Streamline visualization with ParaView Enterprise Edition.

The early 1990s established the widespread use and accessibility of the World Wide Web. Once a network used primarily by researchers and universities, the Web has become something that is used by people throughout the world. The effects of this transformation have been significant, ranging from personal home pages with static images and text, to professional Web pages embedding animation and virtual reality. This chapter discusses some of those changes and describes how the World Wide Web can be used to make visualization more accessible, interactive, and powerful. Topics covered include the advantages and disadvantages of client-side versus server-side visualization, VRML, and Java3D, interwoven with demonstration examples.

11.1 Motivation

Before describing in detail how to perform visualization over the Web, it is important to understand what we expect to gain. Clearly people have been visualizing data prior to the invention of the Web, but what the Web adds is the ability for people throughout the world to share information quickly and efficiently. Like all successful communication systems, the Web enables people to interact and share information more efficiently compared to other methods. In many ways the Web shares the characteristic of computer visualization in its ability to communicate large amounts of data. For that reason, computer graphics and visualization are now vital parts of the Web, and are becoming widespread in their application.

12.0

Applications



Streamline visualization with ParaView Enterprise Edition.

We have described the design and implementation of an extensive toolkit of visualization techniques. In this chapter we examine several case studies to show how to use these tools to gain insight into important application areas. These areas are medical imaging, financial visualization, modeling, computational fluid dynamics, finite element analysis, and algorithm visualization. For each case, we briefly describe the problem domain and what information we expect to obtain through visualization. Then we craft an approach to show the results. Many times we will extend the functionality of the Visualization Toolkit with application specific tools. Finally, we present a sample program and show resulting images.

The visualization design process we go through is similar in each case. First, we read or generate application-specific data and transform it into one of the data representation types in the Visualization Toolkit. Often this first step is the most difficult one because we have to write custom computer code, and decide what form of visualization data to use. In the next step, we choose visualizations for the relevant data within the application. Sometimes this means choosing or creating models corresponding to the physical structure. Examples include spheres for atoms, polygonal surfaces to model physical objects, or computational surfaces to model flow boundaries. Other times we generate more abstract models, such as isosurfaces or glyphs, corresponding to important application data. In the last step we combine the physical components with the abstract components to create a visualization that aids the user in understanding the data.

12.1 3D Medical Imaging

Radiology is a medical discipline that deals with images of human anatomy. These images come from a variety of medical imaging devices, including X-ray, X-ray Computed Tomography

(CT), Magnetic Resonance Imaging (MRI), and ultrasound. Each imaging technique, called an imaging modality, has particular diagnostic strengths.

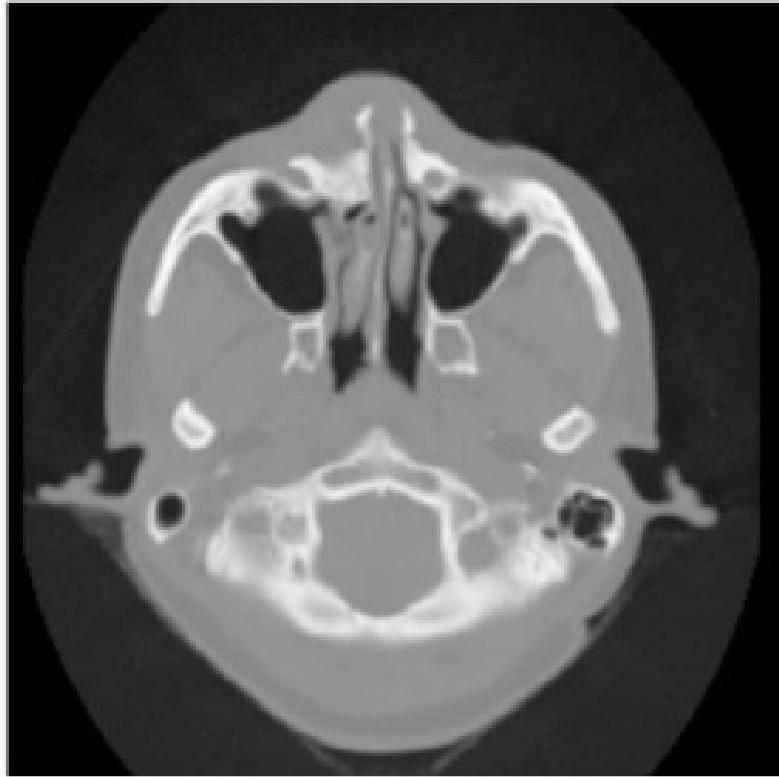


Figure 12.1: A CT slice through a human head.

This case study deals with CT data. Computed tomography measures the attenuation of X-rays as they pass through the body. A CT image consists of levels of gray that vary from black (for air), to gray (for soft tissue), to white (for bone). Figure 12.1 shows a CT cross section through a head. This slice is taken perpendicular to the spine approximately through the middle of the ears. The gray boundary around the head clearly shows the ears and bridge of the nose. The dark regions on the interior of the slice are the nasal passages and ear canals. The bright areas are bone. This study contains 93 such slices, spaced 1.5 mm apart. Each slice has 256^2 pixels spaced 0.8 mm apart with 12 bits of gray level.

Our challenge is to take this gray scale data (over 12 megabytes) and convert it into information that will aid the surgeon. Fortunately, our visualization toolkit has just the right techniques. We will use isocontouring techniques to extract the skin and bone surfaces and display orthogonal cross-sections to put the isosurface in context. From experience we know that a density value of 500 will define the air/skin boundary, and a value of 1150 will define the soft tissue/bone boundary. In VTK terminology, medical imaging slice data is image data. Recall from Chapter 5: [Basic Data Representation](#) that for image data, the topology and geometry of the data is implicitly known, requiring only dimensions, an origin, and the data spacing.

The steps we follow in this case study are common to many three-dimensional medical stud-

ies.

1. Read the input.
2. For each anatomical feature of interest, create an isosurface.
3. Transform the models from patient space to world space.
4. Render the models.

This case study describes in detail how to read input data and extract anatomical features using iso-contouring. Orthogonal planes will be shown using a texture-based technique. Along the way we will also show you how to render the data. We finish with a brief discussion of medical data transformations. This complete source code for the examples shown in this section are available from [MedicalDemo1.cxx](#) or [MedicalDemo1.py](#), [MedicalDemo2.cxx](#) or [MedicalDemo2.py](#), and [MedicalDemo3.cxx](#) or [MedicalDemo3.py](#).

12.1.1 Read the Input

Medical images come in many flavors of file formats. This study is stored as flat files without header information. Each 16-bit pixel is stored with little-endian byte order. Also, as is often the case, each slice is stored in a separate file with the file suffix being the slice number of the form `prefix.1`, `prefix.2`, and so on. Medical imaging files often have a header of a certain size before the image data starts. The size of the header varies from file format to file format. Finally, another complication is that sometimes one or more bits in each 16-bit pixel is used to mark connectivity between voxels. It is important to be able to mask out bits as they are read.

VTK provides several image readers including one that can read raw formats of the type described above — `vtkVolume16Reader`. To read this data we instantiate the class and set the appropriate instance variables as follows.

Listing 12.1: Reading raw formatted files.

```

1 vtkVolume16Reader *v16 = vtkVolume16Reader::New();
2   v16->SetDataDimensions (64,64); v16->SetImageRange (1,93);
3   v16->SetDataByteOrderToLittleEndian();
4   v16->SetFilePrefix ("headsq/quarter");
5   v16->SetDataSpacing (3.2, 3.2, 1.5);

```

The `FilePrefix` and `FilePattern` instance variable work together to produce the name of files in a series of slices. The `FilePattern` — which by default is `%s.%d` — generates the filename to read by performing a C-language `sprintf()` of the `FilePrefix` and the current file number into the `FilePattern` format specifier.

12.1.2 Create an Isosurface

We can choose from three techniques for isosurface visualization: volume rendering, marching cubes, and dividing cubes. We assume that we want to interact with our data at the highest possible speed, so we will not use volume rendering. We prefer marching cubes if we have polygonal rendering hardware available, or if we need to move up close to or inside the extracted surfaces. Even with hardware assisted rendering, we may have to reduce the polygon count to get reasonable rendering speeds. Dividing cubes is appropriate for software rendering. For this application we'll use marching cubes.

For medical volumes, marching cubes generates a large number of triangles. To be practical, we'll do this case study with a reduced resolution dataset. We took the original 256^2 data and reduced it to 64^2 slices by averaging neighboring pixels twice in the slice plane. We call the resulting dataset *quarter* since it has 1/4 the resolution of the original data. We adjust the DataSpacing for the reduced resolution dataset to 3.2 mm per pixel. Our first program will generate an isosurface for the skin.

The flow in the program is similar to most VTK applications.

- Generate some data.
- Process it with filters.
- Create a mapper to generate rendering primitives.
- Create actors for all mappers.
- Create actors for all mappers.

The filter we have chosen to use is `vtkMarchingCubes`. We could also use `vtkContourFilter` since it will automatically create an instance of `vtkMarchingCubes` as it delegates to the fastest subclass for a particular dataset type. The class `vtkPolyDataNormals` is used to generate nice surface normals for the data. `vtkMarchingCubes` can also generate normals, but sometimes better results are achieved when the normals are directly from the surface (`vtkPolyDataNormals`) versus from the data (`vtkMarchingCubes`). To complete this example, we take the output from the isosurface generator `vtkMarchingCubes` and connect it to a mapper and actor via `vtkPolyDataMapper` and `vtkActor`. The C++ code follows.

Listing 12.2: Creating an isosurface.

```

1  vtkContourFilter *skinExtractor = vtkContourFilter::New();
2  skinExtractor->SetInputConnection(v16->GetOutputPort());
3  skinExtractor->SetValue(0, 500);
4
5  vtkPolyDataNormals *skinNormals = vtkPolyDataNormals::New();
6  skinNormals->SetInputConnection(skinExtractor->GetOutputPort());
7  skinNormals->SetFeatureAngle(60.0);
8
9  vtkPolyDataMapper *skinMapper = vtkPolyDataMapper::New();
10  skinMapper->SetInputConnection(skinNormals->GetOutputPort());
11  skinMapper->ScalarVisibilityOff();
12
13  vtkActor *skin = vtkActor::New();
14  skin->SetMapper(skinMapper);
15
16  vtkOutlineFilter *outlineData = vtkOutlineFilter::New();
17  outlineData->SetInputConnection(v16->GetOutputPort());
18  vtkPolyDataMapper *mapOutline = vtkPolyDataMapper::New();
19  mapOutline->SetInputConnection(outlineData->GetOutputPort());
20
21  vtkActor *outline = vtkActor::New();
22  outline->SetMapper(mapOutline);
23  outline->GetProperty()->SetColor(0,0,0);
24

```

```
25 vtkCamera *aCamera = vtkCamera::New();
26 aCamera->SetViewUp (0, 0, -1);
27 aCamera->SetPosition (0, 1, 0);
28 aCamera->SetFocalPoint (0, 0, 0);
29 aCamera->ComputeViewPlaneNormal();
30
31 aRenderer->AddActor(outline);
32 aRenderer->AddActor(skin);
33 aRenderer->SetActiveCamera(aCamera);
34 aRenderer->ResetCamera ();
35
36 aCamera->Dolly(1.5);
37
38 aRenderer->SetBackground(1,1,1);
39
40 renWin->SetSize(640, 480);
41
42 aRenderer->ResetCameraClippingRange ();
43
44 // Initialize the event loop and then start it.
45 iren->Initialize();
46 iren->Start();
```

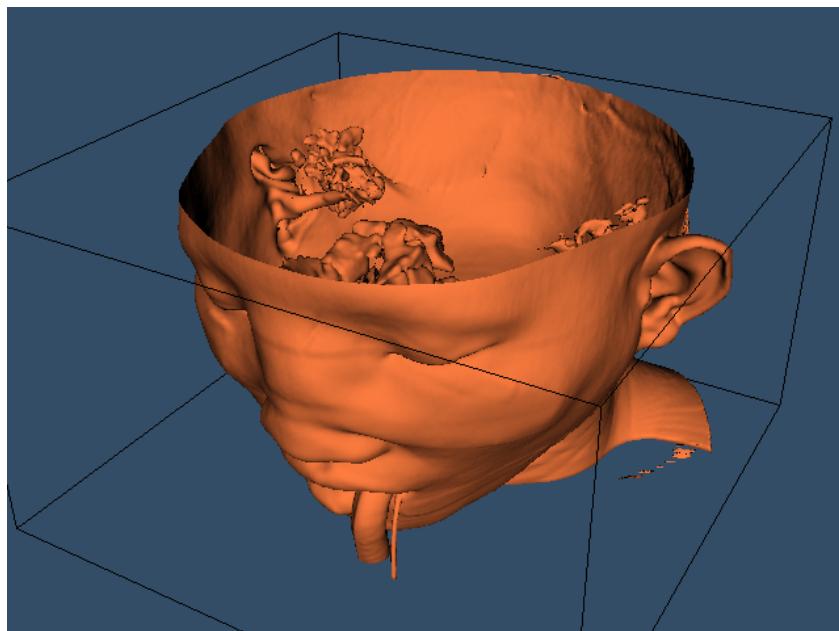


Figure 12.2: The skin extracted from a CT dataset of the head.([MedicalDemo1.cxx](#)) and ([MedicalDemo1.py](#))

To provide context for the isosurface an outline is created around the data. An initial view is set up in a window size of 640×480 pixels. Since the dolly command moves the camera towards

the data, the clipping planes are reset to insure that the isosurface is completely visible. Figure 12.2 shows the resulting image of the patient’s skin.

We can improve this visualization in a number of ways. First, we can choose a more appropriate color (and other surface properties) for the skin. We use the `vtkProperty` method `SetDiffuseColor()` to set the skin color to a fleshy tone. We also add a specular component to the skin surface. Next, we can add additional isosurfaces corresponding to various anatomical features. Here we choose to extract the bone surface by adding an additional pipeline segment. This consists of the filters `vtkMarchingCubes`, `vtkPolyDataMapper`, and `vtkActor`, just as we did with the skin. Finally, to improve rendering performance on our system, we create triangle strips from the output of the contouring process. This requires adding `vtkStripper`.

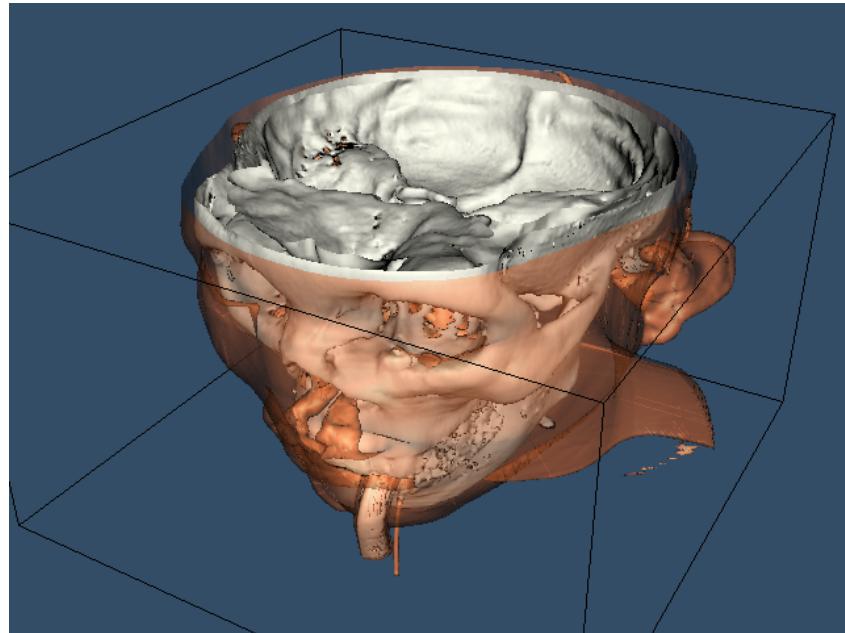


Figure 12.3: Skin and bone isosurfaces.([MedicalDemo2.cxx](#)) and ([MedicalDemo2.py](#))

Figure 12.3 shows the resulting image, and the following is the C++ code for the pipeline.

Listing 12.3: Improving the visualizarion of the isosurface.

```

1  vtkActor *skin = vtkActor::New();
2  skin->SetMapper(skinMapper);
3  skin->GetProperty()->SetDiffuseColor(1, .49, .25);
4  skin->GetProperty()->SetSpecular(.3);
5  skin->GetProperty()->SetSpecularPower(20);
6  skin->GetProperty()->SetOpacity(1.0);
7
8  vtkContourFilter *boneExtractor = vtkContourFilter::New();
9  boneExtractor->SetInputConnection(v16->GetOutputPort());
10  boneExtractor->SetValue(0, 1150);
11
12  vtkPolyDataNormals *boneNormals = vtkPolyDataNormals::New();
13  boneNormals->SetInputConnection(boneExtractor->GetOutputPort());
```

```

14 boneNormals->SetFeatureAngle(60.0);
15
16 vtkStripper *boneStripper = vtkStripper::New();
17 boneStripper->SetInputConnection(boneNormals->GetOutputPort());
18
19 vtkPolyDataMapper *boneMapper = vtkPolyDataMapper::New();
20 boneMapper->SetInputConnection(boneStripper->GetOutputPort());
21 boneMapper->ScalarVisibilityOff();
22
23 vtkActor *bone = vtkActor::New(); bone->SetMapper(boneMapper);
24 bone->GetProperty()->SetDiffuseColor(1, 1, .9412);

```

The *Visualization Toolkit* provides other useful techniques besides isocontouring for exploring volume data. One popular technique used in medical imaging is to view orthogonal slices, or planes, through the data. Because computer graphics hardware supports texture mapping, an approach using texture mapping gives the best result in terms of interactive performance.

We will extract three orthogonal planes corresponding to the axial, sagittal, and coronal cross sections that are familiar to radiologists. The axial plane is perpendicular to the patient's neck, sagittal passes from left to right, and coronal passes from front to back. For illustrative purposes, we render each of these planes with a different color lookup table. For the sagittal plane, we use a gray scale. The coronal and axial planes vary the saturation and hue table, respectively. We combine this with a translucent rendering of the skin (we turn off the bone with the C++ statement `bone->VisibilityOff()`). The following VTK code creates the three lookup tables that are used in the texture mapping process.

Listing 12.4: Lookup tables for the sectioning planes.

```

1 vtkLookupTable *bwLut = vtkLookupTable::New();
2   bwLut->SetTableRange (0, 2000);
3   bwLut->SetSaturationRange (0, 0);
4   bwLut->SetHueRange (0, 0);
5   bwLut->SetValueRange (0, 1);
6
7 vtkLookupTable *hueLut = vtkLookupTable::New();
8   hueLut->SetTableRange (0, 2000);
9   hueLut->SetHueRange (0, 1);
10  hueLut->SetSaturationRange (1, 1);
11  hueLut->SetValueRange (1, 1);
12
13 vtkLookupTable *satLut = vtkLookupTable::New();
14   satLut->SetTableRange (0, 2000);
15   satLut->SetHueRange (.6, .6);
16   satLut->SetSaturationRange (0, 1);
17   satLut->SetValueRange (1, 1);

```

The image data is mapped to colors using the filter `vtkImageMapToColors` in combination with the lookup tables created above. The actual display of the slice is performed with `vtkImageActor` (see “Assemblies and Other Types of `vtkProp`” on page 83 for more information). This class conveniently combines a quadrilateral, polygon plane with a texture map. `vtkImageActor` requires image data of type `unsigned char`, which the class `vtkImageMapToColors` conveniently provides. To avoid copying the data and to specify the 2D texture to use, the `DisplayExtent` of each `vtkIm-`

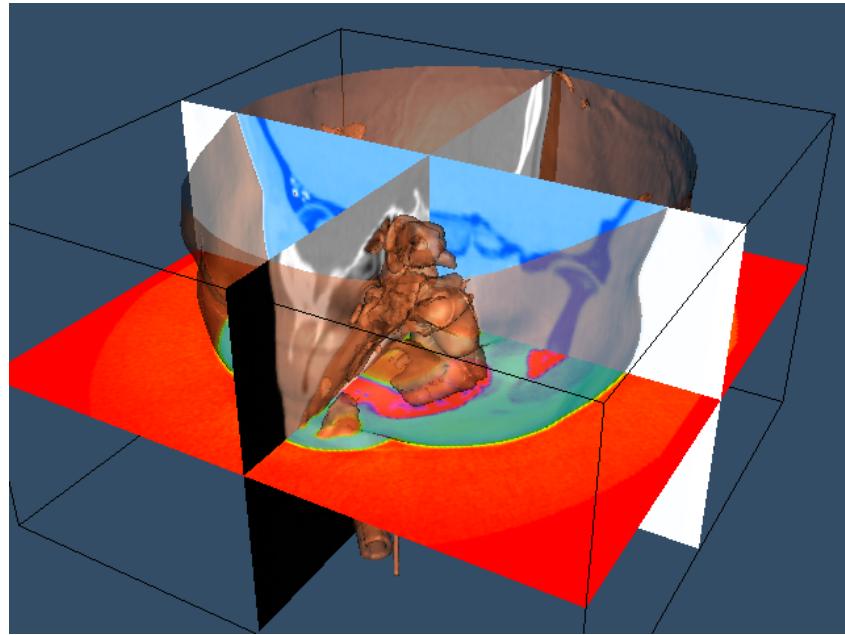


Figure 12.4: Composite image of three planes and translucent skin.([MedicalDemo3.cxx](#)) and ([MedicalDemo3.py](#))

ageActor is set appropriately. The C++ code is as follows:

Listing 12.5: Mapping the image data and displaying the image slices.

```

1 // saggital
2
3 vtkImageMapToColors *saggitalColors = vtkImageMapToColors::New();
4   saggitalColors->SetInputConnection(v16->GetOutputPort());
5   saggitalColors->SetLookupTable(bwLut);
6
7 vtkImageActor *saggital = vtkImageActor::New();
8   saggital->SetInputConnection(saggitalColors->GetOutputPort());
9   saggital->SetDisplayExtent(32,32, 0,63, 0,92);
10
11 // axial
12
13 vtkImageMapToColors *axialColors = vtkImageMapToColors::New();
14   axialColors->SetInputConnection(v16->GetOutputPort());
15   axialColors->SetLookupTable(hueLut);
16
17 vtkImageActor *axial = vtkImageActor::New();
18   axial->SetInputConnection(axialColors->GetOutputPort());
19   axial->SetDisplayExtent(0,63, 0,63, 46,46);
20
21 // coronal
22

```

```

23 vtkImageMapToColors *coronalColors = vtkImageMapToColors::New();
24 coronalColors->SetInputConnection(v16->GetOutputPort());
25 coronalColors->SetLookupTable(satLut);
26
27 vtkImageActor *coronal = vtkImageActor::New();
28 coronal->SetInputConnection(coronalColors->GetOutputPort());
29 coronal->SetDisplayExtent(0,63, 32,32, 0,92);
30
31 aRenderer->AddActor(outline);
32 aRenderer->AddActor(saggital);
33 aRenderer->AddActor(axial);
34 aRenderer->AddActor(coronal);
35 aRenderer->AddActor(bone);
36 aRenderer->AddActor(skin);

```

Figure 12.4 shows the resulting composite image.

In this example, the actor named skin is rendered last because we are using a translucent surface. Recall from "Transparency and Alpha Values" on page 213 that we must order the polygons composing transparent surfaces for proper results. We render the skin last by adding it to aRenderer's actor list last.

We need to make one last point about processing medical imaging data. Medical images can be acquired in a variety of orders that refer to the relationship of consecutive slices to the patient. Radiologists view an image as though they were looking at the patient's feet. This means that on the display, the patient's left appears on the right. For CT there are two standard orders: top to bottom or bottom to top. In a top to bottom acquisition, slice i is farther from the patient's feet than slice $\text{emphi} - 1$. Why do we worry about this order? It is imperative in medical applications that we retain the left / right relationship. Ignoring the slice acquisition order can result in a flipping of left and right. To correct this, we need to transform either the original dataset or the geometry we have extracted. (See "Exercises" on page 205 for more information.) Also, you may wish to examine the implementation of the classes vtkVolume16Reader and vtkVolumeReader (the superclass of vtkVolume16Reader). These classes have special methods that deal with transforming image data.

12.2 Creating Models from Segmented Volume Data

The previous example described how to create models from gray-scale medical imaging data. The techniques for extracting bone and skin models is straightforward compared to the task of generating models of other soft tissue. The reason is that magnetic resonance and, to some extent, computed tomography, generates similar gray-scale values for different tissue types. For example, the liver and kidney in a medical computed tomography volume often have overlapping intensities. Likewise, many different tissues in the brain have overlapping intensities when viewed with magnetic resonance imaging. To deal with these problems researchers apply a process called *segmentation* to identify different tissues. These processes vary in sophistication from almost completely automatic methods to manual tracing of images. Segmentation continues to be a hot research area. Although the segmentation process itself is beyond the scope of this text, in this case study we show how to process segmented medical data.

For our purposes we assume that someone (or many graduate students) have laboriously labeled each pixel in each slice of a volume of data with a tissue identifier. This identifier is an integer number that describes which tissue class each pixel belongs to. For example, we may be given a series of MRI slices of the knee with tissue numbers defining the meniscus, femur, muscles, and

so forth. Figure 12.5 shows two representations of a slice from a volume acquired from a patient's knee. The image on the left is the original MRI slice; the image on the right contains tissue labels for a number of important organs. The bottom image is a composite of the two images.

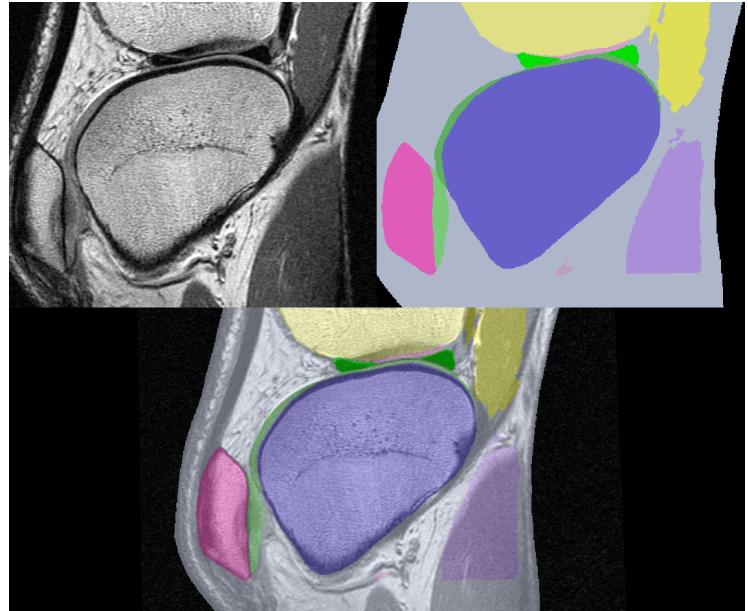


Figure 12.5: Magnetic Resonance Image of a knee(left); segmented tissue(right); composite (bottom).(Data and segmentation courtesy of Brigham and Women's Hospital Surgical Planning Lab.

Notice the difference in the information presented by each representation. The original slice shows gradual changes at organ borders, while the segmented slice has abrupt changes. The images we processed in the previous CT example used marching cubes isocontouring algorithm and an intensity threshold to extract the isosurfaces. The segmented study we present has integer labels that have a somewhat arbitrary numeric value. Our goal in this example is to somehow take the tissue labels and create grayscale slices that we can process with the same techniques we used previously. Another goal is to show how image processing and visualization can work together in an application.

12.2.1 The Virtual Frog

To demonstrate the processing of segmented data we will use a dataset derived from a frog. This data was prepared at Lawrence Berkeley National Laboratories and is included with their permission on the CD-ROM accompanying this book. The data was acquired by physically slicing the frog and photographing the slices. The original segmented data is in the form of tissue masks with one file per tissue. There are 136 slices per tissue and 15 different tissues. Each slice is 470×500 pixels. (To accommodate the volume readers we have in VTK, we processed the mask files and combined them all in one file for each slice.) We used integer numbers 1 – 15 to represent the 15 tissues. Figure 12.6 shows an original slice, a labeled slice, and a composite of the two representations.

Before we describe the process to go from binary labeled tissues to gray-scale data suitable for isosurface extraction, compare the two images of the frog's brain shown in Figure 12.7. On the left is a surface extracted using a binary labeling of the brain. The right image was created using the visualization pipeline that we will develop in this example.

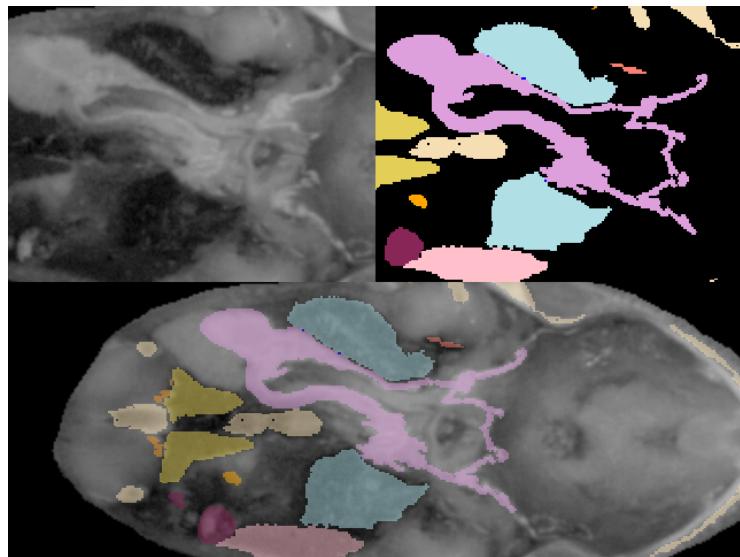


Figure 12.6: Photographic slice of frog (upper left), segmented frog (upper right) and composite of photo and segmentation (bottom). The purple color represents the stomach and the kidneys are yellow.[\(TestFrogSlice.cxx\)](#) and [\(TestFrogSlice.py\)](#)

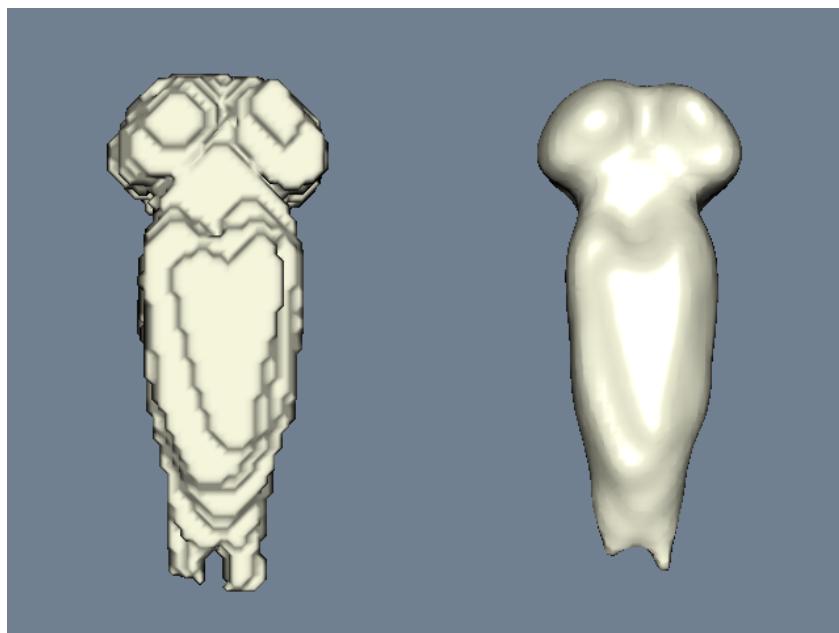


Figure 12.7: The frog's brain. Model extracted without smoothing (left) and with smoothing (right).[\(ViewFrogBoth.cxx\)](#) and [\(ViewFrogBoth.py\)](#)

12.2.2 Developing a Strategy

In the last example, we used C++ and created a program that was tailored to extract two surfaces: one of the skin and one of the bone. All the parameters for the surface extraction were hardcoded in the source. Since our frog has 15 different tissues; we seek a more general solution to this problem. We may have to experiment with a number of different parameters for a number of visualization and imaging filters. Our goal is to develop a general pipeline that will work not only

our 15 tissues but on other medical datasets as well. We'll design the program to work with a set of user-specified parameters to control the elements of the pipeline. A reasonable description might look like:

Listing 12.6: User specified parameters to control the elements of the pipeline.

```

1 SLICE_ORDER hfsi
2 ROWS 470
3 COLUMNS 500
4 STUDY ../frogMasks/frogTissue
5 PIXEL_SIZE 1
6 SPACING 1.5

```

plus possibly many more parameters to control decimation, smoothing, and so forth. Working in C++, we would have to design the format of the file and write code to interpret the statements. We make the job easier here by using Tcl interpreter. Another decision is to separate the modelling from the rendering. Our script will generate models in a “batch” mode. We will run one VTK Tcl script for each tissue. That script will create a .vtk output file containing the polygonal representation of each tissue. Later, we can render the models with a separate script.

12.2.3 Overview of the Pipeline

Figure 12.8 shows the design of the pipeline. This generic pipeline has been developed over the years in our laboratory and in the Brigham and Women's Hospital Surgical Planning Lab. We find that it produces reasonable models from segmented datasets. Do not be intimidated by the number of filters (twelve in all). Before we developed VTK, we did similar processing with a hodgepodge of programs all written with different interfaces. We used intermediate files to pass data from one filter to the next. The new pipeline, implemented in VTK, is more efficient in time and computing resources.

12.2.4 Read the Segmented Volume Data

We assume here that all the data to be processed was acquired with a constant center landmark. In VTK, the origin of the data applies to the lower left of an image volume. In this pipeline, we calculate the origin such that the x,y center of the volume will be $(0, 0)$. The DataSpacing describes the size of each pixel and the distance between slices. DataVOI selects a volume of interest (VOI). A VOI lets us select areas of interest, sometimes eliminating extraneous structures like the CT table bed. For the frog, we have written a small C program that reads the tissue label file and finds the volume of interest for each tissue.

The SetTransform() method defines how to arrange the data in memory. Medical images can be acquired in a variety of orders. For example, in CT, the data can be gathered from top to bottom (superior to inferior), or bottom to top (inferior to superior). In addition, MRI data can be acquired from left to right, right to left, front-to-back (anterior to posterior) or back-to-front. This filter transforms triangle vertices such that the resulting models will all “face” the viewer with a view up of $(0, -1, 0)$, looking down the positive z axis. Also, proper left-right correspondence will be maintained. That means the patient's left will always be left on the generated models. Look in SliceOrder.tcl to see the permutations and rotations for each order.

All the other parameters are self-explanatory except for the last. In this script, we know that the pipeline will only be executed once. To conserve memory, we invoke the ReleaseDataFlagOn() method. This allows the VTK pipeline to release data once it has been processed by a filter. For large medical datasets, this can mean the difference between being able to process a dataset or not.

Listing 12.7: Read the Segmented Volume Data.

```

1 set originx [expr ( $COLUMNS / 2.0 ) * $PIXEL_SIZE * -1.0]
2 set originy [expr ( $ROWS / 2.0 ) * $PIXEL_SIZE * -1.0]
3 vtkPNMReader reader
4   reader SetFilePrefix $STUDY
5   reader SetDataSpacing $PIXEL_SIZE $PIXEL_SIZE $SPACING
6   reader SetDataOrigin $originx $originy
7 [expr $START_SLICE * $SPACING]
8   reader SetDataVOI $VOI
9   reader SetTransform $SLICE_ORDER
10  [reader GetOutput] ReleaseDataFlagOn

```

12.2.5 Remove Islands

Some segmentation techniques, especially those that are automatic, may generate islands of misclassified voxels. This filter looks for connected pixels with the ISLAND_REPLACE label, and if the number of connected pixels is less than ISLAND_AREA, it replaces them with the label TISSUE. Note that this filter is only executed if ISLAND_REPLACE is positive.

Listing 12.8: Remove Islands.

```

1 set lastConnection reader
2 if {$ISLAND_REPLACE = 0} {
3   vtkImageIslandRemoval2D islandRemover
4   islandRemover SetAreaThreshold $ISLAND_AREA
5   islandRemover SetIslandValue $ISLAND_REPLACE
6   islandRemover SetReplaceValue $TISSUE
7   islandRemover SetInputConnection [$lastConnection GetOutputPort]
8   set lastConnection islandRemover
9 }

```

12.2.6 Select a Tissue

The rest of the pipeline requires gray-scale data. To convert the volume that now contains integer tissue labels to a gray-scale volume containing only one tissue, we use the threshold filter to set all pixels with the value TISSUE (the tissue of choice for this pipeline) to 255 and all other pixels to 0. The choice of 255 is somewhat arbitrary.

Listing 12.9: Select a Tissue.

```

1 vtkImageThreshold selectTissue
2   selectTissue ThresholdBetween $TISSUE $TISSUE
3   selectTissue SetInValue 255
4   selectTissue SetOutValue 0
5   selectTissue SetInputConnection [$lastConnection GetOutputPort]

```

12.2.7 Resample the Volume

Lower resolution volumes produce fewer polygons. For experimentation we often reduce the resolution of the data with this filter. However, details can be lost during this process. Averaging

creates new pixels in the resampled volume by averaging neighboring pixels. If averaging is turned off, every SAMPLE_RATE pixel will be passed through to the output.

Listing 12.10: Resample the Volume.

```

1  vtkImageShrink3D shrinker
2    shrinker SetInputConnection [selectTissue GetOutputPort] eval
3    shrinker SetShrinkFactors $SAMPLE_RATE
4    shrinker AveragingOn

```

12.2.8 Smooth the Volume Data

To this point, unless we have resampled the data, the volume is labeled with a value of 255 in pixels of the selected tissue and 0 elsewhere. This “binary” volume would produce stepped surfaces if we did not blur it. The Gaussian kernel specified in this filter accomplishes the smoothing we require to extract surfaces. The amount of smoothing is controlled by GAUSSIAN_STANDARD_DEVIATION that can be independently specified for each axis of the volume data. We only run this filter if some smoothing is requested,

Listing 12.11: Smooth the Volume Data.

```

1  set lastConnection shrinker
2  if {$GAUSSIAN_STANDARD_DEVIATION != "0 0 0"} {
3    vtkImageGaussianSmooth gaussian
4    gaussian SetDimensionality 3
5    gaussian SetStandardDeviation $GAUSSIAN_STANDARD_DEVIATION gaussian
6    SetRadiusFactor 1
7    gaussian SetInputConnection [shrinker GetOutputPort]
8    set lastConnection gaussian
9  }

```

12.2.9 Generate Triangles

Now we can process the volume with marching cubes just as though we had obtained gray-scale data from a scanner. We added a few more bells and whistles to the pipeline. The filter runs faster if we turn off gradient and normal calculations. Marching cubes normally calculates vertex normals from the gradient of the volume data. In our pipeline, we have concocted a gray-scale representation and will subsequently decimate the triangle mesh and smooth the resulting vertices. This processing invalidates the normals that are calculated by marching cubes.

Listing 12.12: Generate Triangles.

```

1  vtkMarchingCubes mcubes
2    mcubes SetInputConnection [toStructuredPoints GetOutputPort]
3    mcubes ComputeScalarsOff
4    mcubes ComputeGradientsOff
5    mcubes ComputeNormalsOff
6    eval mcubes SetValue 0 $VALUE
7    [mcubes GetOutput] ReleaseDataFlagOn

```

12.2.10 Reduce the Number of Triangles

There are often many more triangles generated by the isosurfacing algorithm than we need for rendering. Here we reduce the triangle count by eliminating triangle vertices that lie within a user-specified distance to the plane formed by neighboring vertices. We preserve any edges of triangles that are considered “features”.

Listing 12.13: Reduce the Number of Triangles.

```

1 vtkDecimatePro decimator
2   decimator SetInputConnection [mcubes GetOutputPort]
3   eval decimator SetFeatureAngle $DECIMATE_ANGLE
4   decimator PreserveTopologyOn
5   decimator SetTargetReduction $DECIMATE_REDUCTION
6   [decimator GetOutput] ReleaseDataFlagOn

```

12.2.11 Smooth the Triangle Vertices

This filter uses Laplacian smoothing described in “Mesh Smoothing” on page 154 to adjust triangle vertices as an “average” of neighboring vertices. Typically, the movement will be less than a voxel.

Of course we have already smoothed the image data with a Gaussian kernel so this step may not give much improvement; however, models that are heavily decimated can sometimes be improved with additional polygonal smoothing.

Listing 12.14: Smooth the Triangle Vertices.

```

1 vtkSmoothPolyDataFilter smoother
2   smoother SetInputConnection [decimator GetOutputPort]
3   eval smoother SetNumberOfIterations $SMOOTH_ITERATIONS
4   eval smoother SetRelaxationFactor $SMOOTH_FACTOR
5   eval smoother SetFeatureAngle $SMOOTH_ANGLE
6   smoother FeatureEdgeSmoothingOff
7   smoother BoundarySmoothingOff
8   smoother SetConvergence 0
9   [smoother GetOutput] ReleaseDataFlagOn

```

12.2.12 Generate Normals

To generate smooth shaded models during rendering, we need normals at each vertex. As in decimation, sharp edges can be retained by setting the feature angle.

Listing 12.15: Generate Normals.

```

1 vtkPolyDataNormals normals
2   normals SetInputConnection
3   [smoother GetOutputPort] eval normals
4   SetFeatureAngle $FEATURE_ANGLE
5   [normals GetOutput] ReleaseDataFlagOn

```

12.2.13 Generate Triangle Strips

Triangle strips are a compact representation of large numbers of triangles. This filter processes our independent triangles before we write them to a file.

Listing 12.16: Generate Triangle Strips.

```

1  vtkStripper stripper
2    stripper SetInputConnection [normals GetOutputPort]
3    [stripper GetOutput] ReleaseDataFlagOn

```

12.2.14 Write the Triangles to a File

Finally, the last component of the pipeline writes the triangles strips to a file.

Listing 12.17: Write the Triangles to a File.

```

1  vtkPolyDataWriter writer
2    writer SetInputConnection [stripper GetOutputPort]
3    eval writer SetFileName $NAME.vtk

```

12.2.15 Execute the Pipeline

If you have gotten this far in the book, you know that the *Visualization Toolkit* uses a demand-driven pipeline architecture and so far we have not demanded anything. We have just specified the pipeline topology and the parameters for each pipeline element.

`writer Update`

causes the pipeline to execute. In practice we do a bit more than just Update the last element of the pipeline. We explicitly Update each element so that we can time the individual steps. The script `frogSegmentation.tcl` contains the more sophisticated approach.

12.2.16 Specifying Parameters for the Pipeline

All of the variables mentioned above must be defined for each tissue to be processed. The parameters fall into two general categories. Some are specific to the particular study while some are specific to each tissue. For the frog, we collected the study-specific parameters in a file `frog.tcl` that contains:

Listing 12.18: Specifying Parameters for the Pipeline.

```

1  set SLICE_ORDER hfsi
2  set ROWS 470
3  set COLUMNS 500
4  set STUDY ../frogMasks/frogTissue
5  set PIXEL_SIZE 1
6  set SPACING 1.5
7  set VALUE 511.5
8  set SAMPLE_RATE "1 1 1"
9  set DECIMATE_REDUCTION .95
10 set DECIMATE_ITERATIONS 5
11 set DECIMATE_ERROR .0002

```

```

12 set DECIMATE_ERROR_INCREMENT .0002
13 set SMOOTH_ITERATIONS 0
14 set SMOOTH_FACTOR .01
15 set FEATURE_ANGLE 60

```

There is a specific file for each tissue type. This tissue-specific file reads in the frog-specific parameters, sets tissue-specific parameters, and then reads the pipeline script (we call it `frogSegmentation.tcl`). For example, `liver.tcl` contains:

Listing 12.19: Tissue specific file.

```

1 source frog.tcl
2 set NAME liver
3 set TISSUE 10
4 set START_SLICE 25
5 set END_SLICE 126
6 set VOI "167 297 154 304 $START_SLICE $END_SLICE"
7 source frogSegmentation.tcl

```

Parameters in `frog.tcl` can also be overridden. For example, `skeleton.tcl` overrides the standard deviation for the Gaussian filter.

Listing 12.20: Overriding parameters.

```

1 source frog.tcl
2 set NAME skeleton
3 set TISSUE 13
4 set VALUE 368.5
5 set START_SLICE 1
6 set END_SLICE 136
7 set ZMAX [expr $END_SLICE - $START_SLICE]
8 set VOI "23 479 8 473 0 $ZMAX"
9 set GAUSSIAN_STANDARD_DEVIATION "1.5 1.5 1"
10 source frogSegmentation.tcl

```

Note that both of these examples specify a volume of interest. This improves performance of the imaging and visualization algorithms by eliminating empty space.

Another script, `marchingFrog.tcl`, uses similar parameters but processes the original gray-scale volume rather than the segmented volume. This script is used in `skin.tcl` to extract the skin. The file `marchingFrog.tcl` does not have the island removal or threshold pipeline elements since the data is already has gray-scale information.

Once the models are generated with the process just outlined, they can be rendered using the following tcl script called `ViewFrog.tcl`. First we create a Tcl procedure to automate the creation of actors from the model files. All the pipeline elements are named consistently with the name of the part followed by the name of the pipeline element. This makes it easy for the user to identify each object in more sophisticated user interfaces.

Listing 12.21: Automating the creation of actors.

```

1 proc mkname {a b} {return $a$b}
2
3 # proc to make actors and create pipeline
4 proc MakeActor { name r g b}

```

```

5  {
6  set filename [eval mknname $name .vtk]
7  set reader [eval mknname $name PolyDataReader]
8  vtkPolyDataReader $reader
9    $reader SetFileName $filename
10 set mapper [eval mknname $name PolyDataMapper]
11 vtkPolyDataMapper $mapper
12   $mapper SetInputConnection [$reader GetOutputPort]
13   $mapper ScalarVisibilityOff
14 set actor [ eval mknname $name Actor]
15 vtkLODActor $actor
16   $actor SetMapper $mapper
17   eval [$actor GetProperty] SetDiffuseColor $r $g $b eval
18   [$actor GetProperty] SetSpecularPower 50
19   eval [$actor GetProperty] SetSpecular .5
20   eval [$actor GetProperty] SetDiffuse .8
21   return $actor
22 }

```

After the usual code to create required rendering objects, a single statement for each part creates an actor we can add to the renderer:

Listing 12.22: Create the actors.

```

1 # Now create the RenderWindow, Renderer and Interactor
2 vtkRenderer ren1
3 vtkRenderWindow renWin
4 renWin AddRenderer ren1
5 vtkRenderWindowInteractor iren
6 iren SetRenderWindow renWin
7
8 # Add the actors to the renderer using the MakeActor proc
9 ren1 AddActor [eval MakeActor lung $powder_blue]
10 ren1 AddActor [eval MakeActor heart $tomato]
11 ren1 AddActor [eval MakeActor liver $pink]
12 ren1 AddActor [eval MakeActor duodenum $orange]
13 ren1 AddActor [eval MakeActor blood $salmon]
14 ren1 AddActor [eval MakeActor brain $beige]
15 ren1 AddActor [eval MakeActor eye_retina $misty_rose]
16 ren1 AddActor [eval MakeActor eye_white $white]
17 ren1 AddActor [eval MakeActor ileum $raspberry]
18 ren1 AddActor [eval MakeActor kidney $banana]
19 ren1 AddActor [eval MakeActor l_intestine $peru]
20 ren1 AddActor [eval MakeActor nerve $carrot]
21 ren1 AddActor [eval MakeActor spleen $violet]
22 ren1 AddActor [eval MakeActor stomach $plum] ren1
23 AddActor [eval MakeActor skeleton $wheat]

```

The rest of the script defines a standard view.

Listing 12.23: Create the view.

```
1 ren1 SetBackground 0.2 0.3 0.4
2 renWin SetSize 450 450
3 [ren1 GetActiveCamera] SetViewUp 0 -1 0
4 [ren1 GetActiveCamera] Azimuth 30
5 [ren1 GetActiveCamera] Elevation 30
6 [ren1 GetActiveCamera] Dolly 1.75
7 iren Initialize
8 iren SetUserMethod {wm deiconify .vtkInteract}
9 # prevent the tk window from showing up
10 wm withdraw .
```

Figure 12.9 shows three views of the frog.

This lengthy example shows the power of a comprehensive visualization system like VTK.

- We mixed image processing and computer graphics algorithms to process data created by an external segmentation process.
- We developed a generic approach that allows users to control the elements of the pipeline with a familiar scripting language, tcl.
- We separated the task into a “batch” portion and an “interactive” portion.

12.2.17 Other Frog-Related Information

The folks at Lawrence Berkeley National Laboratory have an impressive Web site that features the frog used in this example. The site describes how the frog data was obtained and also permits users to create mpeg movies of the frog. There are also other datasets available. Further details on “The Whole Frog Project” can be found at [Frog](#). Also, the Stanford University Medical Media and Information Technologies (SUMMIT) group has on-going work using the Berkeley frog. They are early VTK users. Enjoy their *Virtual Creatures* project at: [creatures](#).

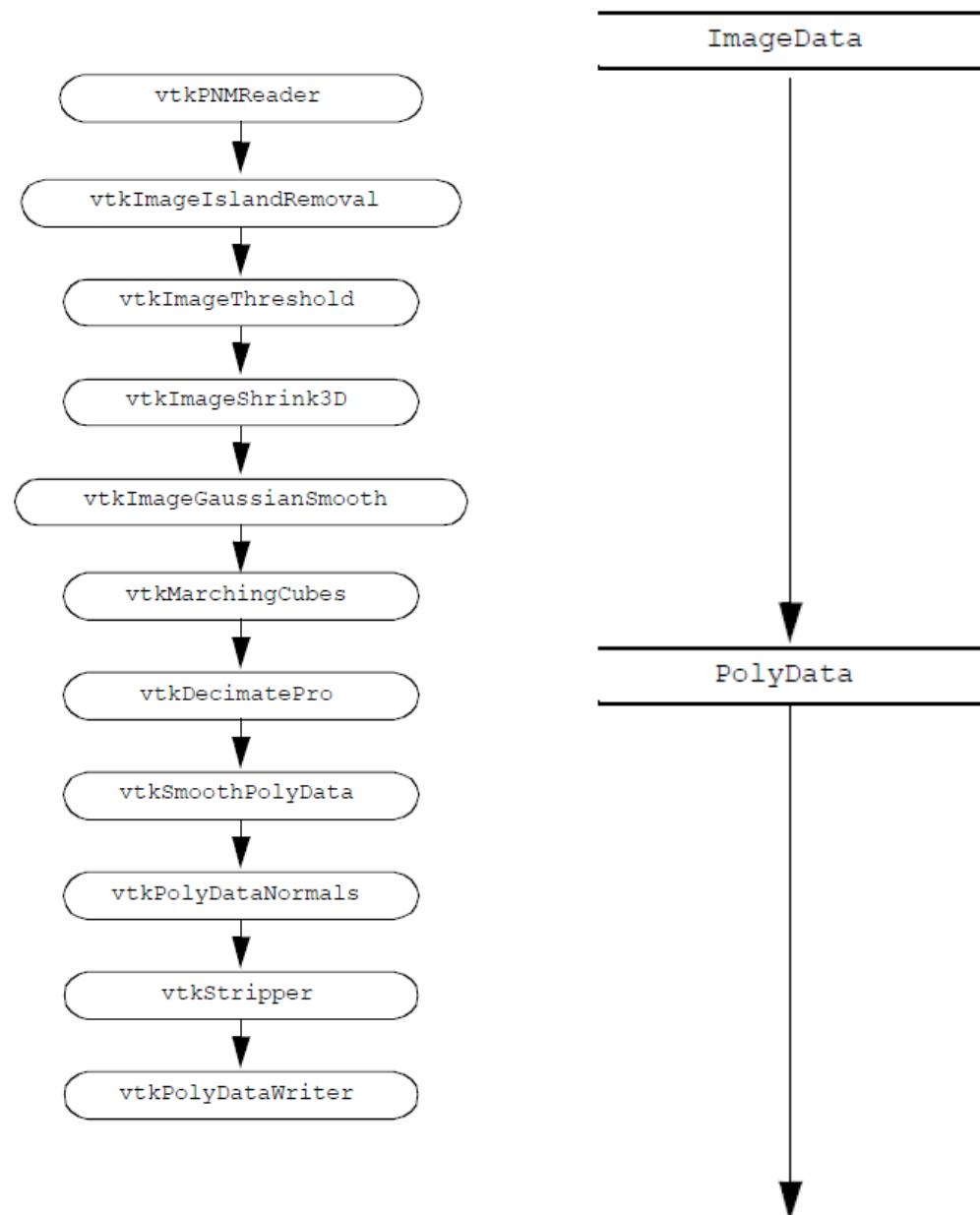


Figure 12.8: The segmented volume to triangle pipeline. Volume passes through image pipeline before isosurface extraction.

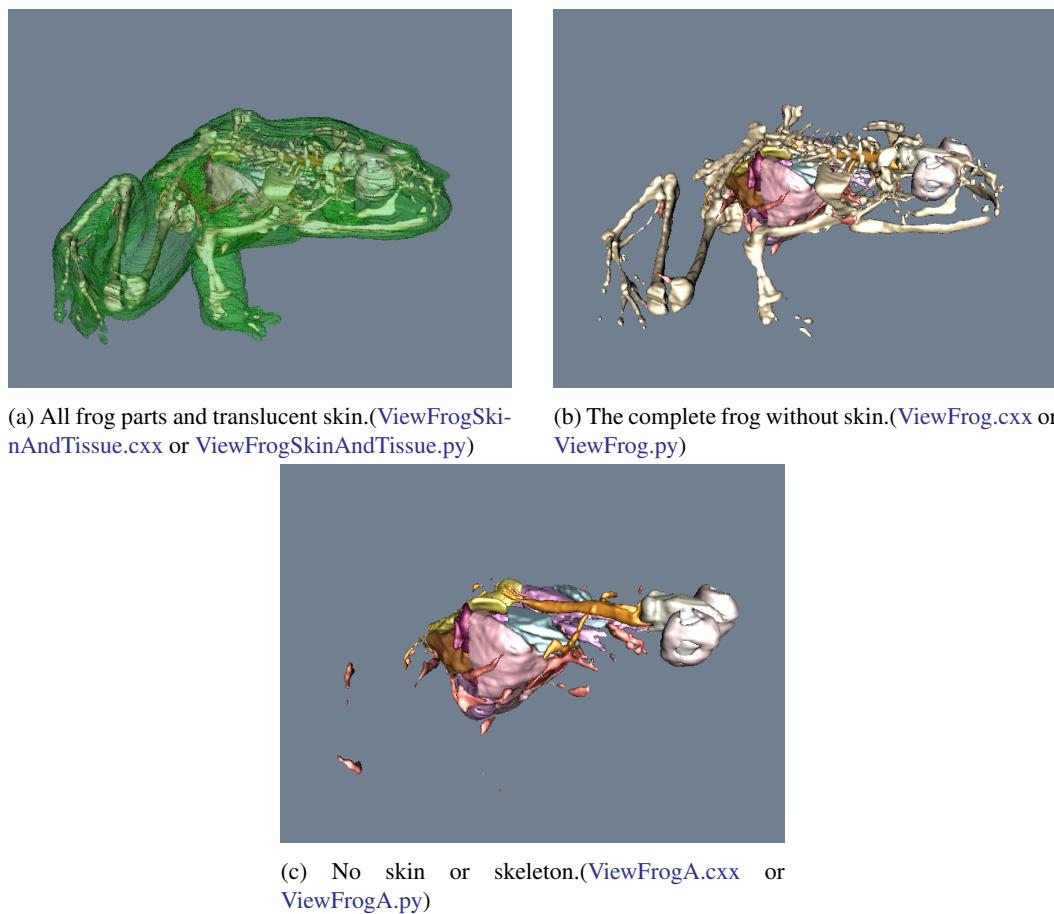


Figure 12.9: Various frog images.

12.3 Financial Visualization

The application of 3D visualization techniques to financial data is relatively new. Historically, financial data has been represented using 2D plotting techniques such as line, scatter plots, bar charts, and pie charts. These techniques are especially well suited for the display of price and volume information for stocks, bonds, and mutual funds. Three-dimensional techniques are becoming more important due to the increased volume of information in recent years, and 3D graphics and visualization techniques are becoming interactive. Interactive rates mean that visualization can be applied to the day-to-day processing of data. Our belief is that this will allow deeper understanding of today's complex financial data and other more timely decisions.

In this example we go through the process of obtaining data, converting it to a form that we can use, and then using visualization techniques to view it. Some of the external software tools used in this example may be unfamiliar to you. This should not be a large concern. We have simply chosen the tools with which we are familiar. Where we have used an Awk script, you might choose to write a small C program to do the same thing. The value of the example lies in illustrating the high-level process of solving a visualization problem.

The first step is to obtain the data. We obtained our data from a public site on the World Wide Web (WWW) that archives stock prices and volumes for many publicly traded stocks. (This Web site has closed down since publication of the first edition. The data for this example are available on the CD-ROM.)

Once we have obtained the data, we convert it to a format that can be read into VTK. While VTK can read in a variety of data formats, frequently your data will not be in one of those. The data files we obtained are stored in the following format:

```
930830 49.375 48.812 49.250 1139.2 56.1056
930831 49.375 48.938 49.125 1360.4 66.8297
930902 49.188 48.688 48.750 1247.2 60.801
...

```

Each line stores the data for one day of trading. The first number is the date, stored as the last two digits of the year, followed by a two-digit month and finally the day of the month. The next three values represent the high, low, and closing price of the stock for that day. The next value is the volume of trading in thousands of shares. The final value is the volume of trading in millions of dollars.

We used an Awk script to convert the original data format into a VTK data file. (See the *VTK User's Guide* for information on VTK file formats; or refer to the Web page [VTKFileFormats](#)). This conversion could be done using many other approaches, such as writing a C program or a Tcl script.

Listing 12.24: Awk: converting data file to VTK.

```
1 BEGIN {print "# vtk DataFile Version 2.0\n"
2 Data values for stock\nASCII\nDATASET POLYDATA"}
3 {count += 1}
4 { d = $1%100}
5 { m = int(($1%10000)/100)}
6 { if (m == 2) d += 31}
7 { if (m == 3) d += 59}
8 { if (m == 4) d += 90}
9 { if (m == 5) d += 120}
10 { if (m == 6) d += 151}
```

```

11 { if (m == 7) d += 181}
12 { if (m == 8) d += 212}
13 { if (m == 9) d += 243}
14 { if (m == 10) d += 273}
15 { if (m == 11) d += 304}
16 { if (m == 12) d += 334}
17 { d = d + (int($1/10000) - 93)*365}
18 {dates[count] = d; prices[count] = $4; volumes[count] = $5}
19 END {
20   print "POINTS " count " float";
21   for (i = 1; i <= count; i++) print dates[i] " " prices[i] " 0 ";
22   print "\nLINES 1 " (count + 1) " " count;
23   for (i = 0; i < count; i++) print i;
24   print "\nPOINT\_DATA " count "\nSCALARS volume float";
25   print "LOOKUP\_TABLE default";
26   for (i = 1; i <= count; i++) print volumes[i];
27 }
```

The above Awk script performs the conversion. Its first line outputs the required header information indicating that the file is a VTK data file containing polygonal data. It also includes a comment indicating that the data represents stock values. There are a few different VTK data formats that we could have selected. It is up to you to decide which format best suits the data you are visualizing. We have judged the polygonal format (`vtkPolyData`) as best suited for this particular stock visualization.

The next line of the Awk script creates a variable named `count` that keeps track of how many days worth of information is in the file. This is equivalent to the number of lines in the original data file.

The next fourteen lines convert the six digit date into a more useful format, since the original format has a number of problems. If we were to blindly use the original format and plot the data using the date as the independent variable, there would be large gaps in our plot. For example, 931231 is the last day of 1993 and 940101 is the first day of 1994. Chronologically, these two dates are sequential, but mathematically there are $(940101 - 931231) = 8870$ values between them. A simple solution would be to use the line number as our independent variable. This would work as long as we knew that every trading day was recorded in the data file. It would not properly handle the situation where the market was open, but for some reason data was not recorded. A better solution is to convert the dates into numerically ordered days. The preceding Awk script sets January 1, 1993, as day number one, and then numbers all the following days from there. At the end of these 14 lines the variable, `d`, will contain the resulting value.

The next line in our Awk script stores the converted date, closing price, and dollar volume into arrays indexed by the line number stored in the variable `count`. Once all the lines have been read and stored into the arrays, we write out the rest of the VTK data file. We have selected the date as our independent variable and x coordinate. The closing price we store as the y coordinate, and the z coordinate we set to zero. After indicating the number and type of points to be stored, the Awk script loops through all the points and writes them out to the VTK data file. It then writes out the line connectivity list. In this case we just connect one point to the next to form a polyline for each stock. Finally, we write out the volume information as scalar data associated with the points. Portions of the resulting VTK data file are shown below.

```
# vtk DataFile Version 2.0 Data values for stock
ASCII
```

```

DATASET POLYDATA
POINTS 348 float
242 49.250 0
243 49.125 0
245 48.750 0
246 48.625 0
...
LINES 1 349 348
0
1
2
3
...
POINT_DATA 348
SCALARS volume float
LOOKUP_TABLE default
1139.2
1360.4
1247.2
1745.4
...

```

Now that we have generated the VTK data file, we can start the process of creating a visualization for the stock data. To do this, we wrote a Tcl script to be used with the Tcl-based VTK executable. At a high level the script reads in the stock data, sends it through a tube filter, creates a label for it, and then creates an outline around the resulting dataset. Ideally, we would like to display multiple stocks in the same window. To facilitate this, we designed the Tcl script to use a procedure to perform operations on a per stock basis. The resulting script is listed below.

Listing 12.25: Tcl script for stock case study.

```

1 package require vtk
2 # this is a tcl script for the stock case study
3 # Create the RenderWindow, Renderer and both Actors
4 vtkRenderWindow renWin
5 renWin AddRenderer ren1
6 vtkRenderWindowInteractor iren
7 iren SetRenderWindow renWin
8
9 # create the outline
10 vtkAppendPolyData apf
11 vtkOutlineFilter olf
12 olf SetInputConnection [apf GetOutputPort]
13 vtkPolyDataMapper outlineMapper
14 outlineMapper SetInputConnection [olf GetOutputPort]
15 vtkActor outlineActor
16 outlineActor SetMapper outlineMapper
17
18 set zpos 0
19 # create the stocks
20 proc AddStock {prefix name x y z} {

```

```

21 global zpos
22
23 # create labels
24 vtkTextSource $prefix.TextSrc
25   $prefix.TextSrc SetText "$name"
26   $prefix.TextSrc SetBacking 0
27 vtkPolyDataMapper $prefix.LabelMapper
28   $prefix.LabelMapper SetInput [$prefix.TextSrc GetOutput]
29 vtkFollower $prefix.LabelActor
30   $prefix.LabelActor SetMapper $prefix.LabelMapper
31   $prefix.LabelActor SetPosition $x $y $z
32   $prefix.LabelActor SetScale 0.25 0.25 0.25
33 eval $prefix.LabelActor SetOrigin
34   [ $prefix.LabelMapper GetCenter]
35 # create a sphere source and actor
36 vtkPolyDataReader $prefix.PolyDataRead
37   $prefix.PolyDataRead SetFileName
38   "../../../vtkdata/$prefix.vtk"
39 vtkTubeFilter $prefix.TubeFilter
40   $prefix.TubeFilter
41   SetInputConnection \
42     [$prefix.PolyDataRead GetOutputPort]
43 $prefix.TubeFilter SetNumberOfSides 8
44 $prefix.TubeFilter SetRadius 0.5
45 $prefix.TubeFilter SetRadiusFactor 10000
46 vtkTransform $prefix.Transform
47 $prefix.Transform Translate 0 0 $zpos
48 $prefix.Transform Scale 0.15 1 1
49 vtkTransformPolyDataFilter $prefix.TransformFilter
50   $prefix.TransformFilter SetInputConnection
51     [$prefix.TubeFilter GetOutputPort]
52   $prefix.TransformFilter SetTransform
53   $prefix.Transform
54 # increment zpos
55 set zpos [expr $zpos + 10]
56 vtkPolyDataMapper $prefix.StockMapper
57   $prefix.StockMapper SetInputConnection
58     [$prefix.TransformFilter GetOutputPort]
59 vtkActor $prefix.StockActor
60   $prefix.StockActor SetMapper $prefix.StockMapper
61   $prefix.StockMapper SetScalarRange 0 8000
62   [$prefix.StockActorGetProperty] SetAmbient 0.5
63   [$prefix.StockActorGetProperty] SetDiffuse 0.5
64
65 apf AddInput [$prefix.TransformFilter GetOutput]
66
67 ren1 AddActor $prefix.StockActor
68 ren1 AddActor $prefix.LabelActor
69 $prefix.LabelActor SetCamera [ren1 GetActiveCamera]
70 }
```

```

71
72 # set up the stocks
73 ddStock GE "GE" 94 46 4
74 AddStock GM "GM" 107 39 14
75 AddStock IBM "IBM" 92 70 16
76 AddStock DEC "DEC" 70 19 26
77
78 # Add the actors to the renderer, set the background and size
79 #
80 ren1 AddActor outlineActor
81 ren1 SetBackground 0.1 0.2 0.4
82 renWin SetSize 1200 600
83
84 # render the image
85 [ren1 GetActiveCamera] SetViewAngle 10
86 ren1 ResetCamera
87 [ren1 GetActiveCamera] Zoom 2.8
88 [ren1 GetActiveCamera] Elevation 90
89 [ren1 GetActiveCamera] SetViewUp 0 0 -1
90 iren Initialize
91
92 # prevent the tk window from showing up then start the event loop
93 wm withdraw .

```

The first part of this script consists of the standard procedure for renderer and interactor creation that can be found in almost all of the VTK Tcl scripts. The next section creates the objects necessary for drawing an outline around all of the stock data. A vtkAppendPolyData filter is used to append all of the stock data together. This is then sent through a vtkOutlineFilter to create a bounding box around the data. A mapper and actor are created to display the result.

In the next part of this script, we define the procedure to add stock data to this visualization. The procedure takes five arguments: the name of the stock, the label we want displayed, and the x, y, z coordinates defining where to position the label. The first line of the procedure indicates that the variable ren1 should be visible to this procedure. By default the procedure can only access its own local variables. Next, we create the label using a vtkTextSource, vtkPolyDataMapper, and vtkFollower. The names of these objects are all prepended with the variable "\$prefix." so that the instance names will be unique. An instance of vtkFollower is used instead of the usual vtkActor, because we always want the text to be right-side up and facing the camera. The vtkFollower class provides this functionality. The remaining lines position and scale the label appropriately. We set the origin of the label to the center of its data. This insures that the follower will rotate about its center point.

The next group of lines creates the required objects to read in the data, pass it through a tube filter and a transform filter, and finally display the result. The tube filter uses the scalar data (stock volume in this example) to determine the radius of the tube. The mapper also uses the scalar data to determine the coloring of the tube. The transform filter uses a transform object to set the stocks position based on the value of the variable zpos. For each stock, we will increment zpos by 10, effectively shifting the next stock over 10 units from the current stock. This prevents the stocks from being stacked on top of each other. We also use the transform to compress the x-axis to make the data easier to view. Next, we add this stock as an input to the append filter and add the actors and followers to the renderer. The last line of the procedure sets the followers camera to be the active camera of the renderer.

Back in the main body of the Tcl script, we invoke the AddStock procedure four times with four different stocks. Finally, we add the outline actor and customize the renderer and camera to four different stocks. Finally, we add the outline actor and customize the renderer and camera to produce a nice initial view.

Two different views of the result are displayed in Figure 12.10. The top image shows a history of stock closing prices for our four stocks. The color and width of these lines correspond to the volume of the stock on that day. The lower image more clearly illustrates the changes in stock volume by looking at the data from above.



Figure 12.10: Two views from the stock visualization script. The top shows closing price over time; the bottom shows volume over time (`stocks.tcl`).

A legitimate complaint with Figure 12.10 is that the changing width of the tube makes it more difficult to see the true shape of the price versus the time curve. We can solve this problem by using a ribbon filter followed by a linear extrusion filter, instead of the tube filter. The ribbon filter will

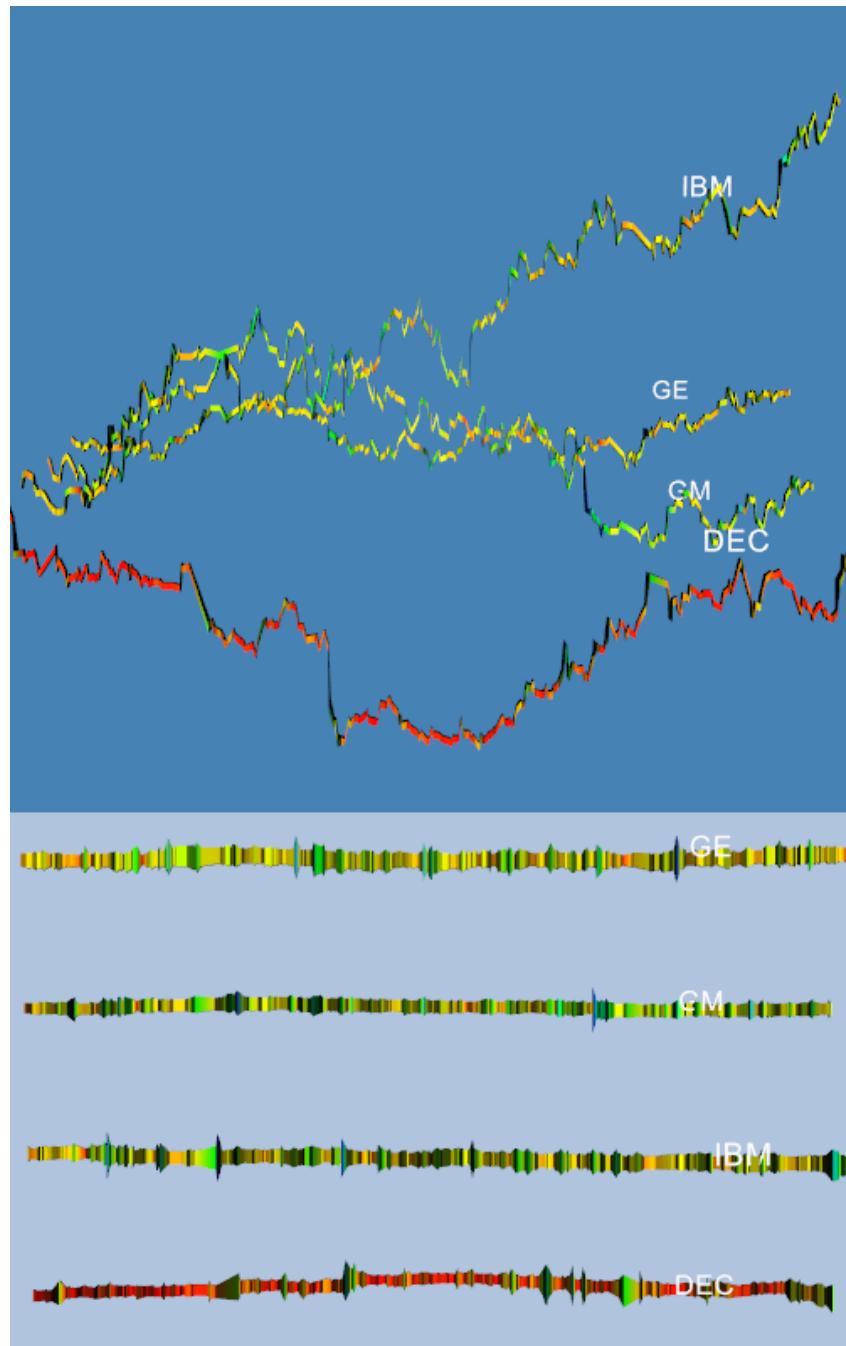


Figure 12.11: Two more views of the stock case study. Here the tube filter has been replaced by a ribbon filter followed with a linear extrusion filter.(Stocks.cxx) or ([Stocks.py](#))

create a ribbon whose width will vary in proportion to the scalar value of the data. We then use the linear extrusion filter to extrude this ribbon along the y-axis so that it has a constant thickness.

The resulting views are shown in Figure 12.11.

12.4 Implicit Modelling

The *Visualization Toolkit* has some useful geometric modelling capabilities. One of the most powerful features is implicit modelling. In this example we show how to use polygonal descriptions of objects and create ‘blobby’ models of them using the implicit modelling objects in VTK. This example generates a logo for the *Visualization Toolkit* from polygonal representations of the letters *v*, *t*, and *k*.

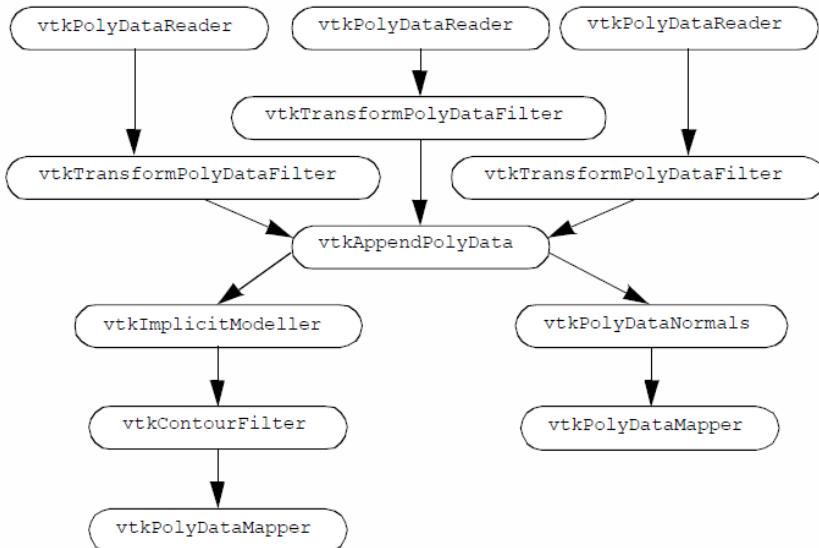


Figure 12.12: The visualization pipeline for the VTK blobby logo.

We create three separate visualization pipelines, one for each letter. Figure 12.12 shows the visualization pipeline. As is common in VTK applications, we design a pipeline and fill in the details of the instance variables just before we render. We pass the letters through a *vtkTransformPolyDataFilter* to position them relative to each other. Then we combine all of the polygons from the transformed letters into one polygon dataset using the *vtkAppendPolyData* filter. The *vtkImplicitModeller* creates a volume dataset of dimension 64^3 with each voxel containing a scalar value that is the distance to the nearest polygon. Recall from “Implicit Modelling” on page 126 that the implicit modelling algorithm lets us specify the region of influence of each polygon. Here we specify this using the *SetMaximumDistance()* method of the *vtkImplicitModeller*. By restricting the region of influence, we can significantly improve performance of the implicit modelling algorithm. Then we use *vtkContourFilter* to extract an isosurface that approximates a distance of 1.0 from each polygon. We create two actors: one for the blobby logo and one for the original polygon letters. Notice that both actors share the polygon data created by *vtkAppendPolyData*. Because of the nature of the VTK visualization pipeline (see “Implicit Execution” on page 96), the appended data will only be created once by the portion of the pipeline that is executed first. As a final touch, we move the polygonal logo in front of the blobby logo. Now we will go through the example in detail.

First, we read the geometry files that contain polygonal models of each letter in the logo. The data is in VTK polygonal format, so we use *vtkPolyDataReader*.

Listing 12.26: Reading the polygonal models of each letter.

```

1  vtkPolyDataReader *letterV = vtkPolyDataReader::New();
2    letterV->SetFileName ("v.vtk");
3
4  vtkPolyDataReader *letterT = vtkPolyDataReader::New();
5    letterT->SetFileName ("t.vtk");
6
7  vtkPolyDataReader *letterK = vtkPolyDataReader::New();
8    letterK->SetFileName ("k.vtk");

```

We want to transform each letter into its appropriate location and orientation within the logo. We create the transform filters here, but defer specifying the location and orientation until later in the program.

Listing 12.27: Transform each letter into its appropriate location.

```

1  vtkTransform *VTransform = vtkTransform::New();
2  vtkTransformPolyDataFilter *VTransformFilter =
3    vtkTransformPolyDataFilter::New();
4
5  VTransformFilter->SetInputConnection (letterV->GetOutputPort());
6  VTransformFilter->SetTransform (VTransform);
7
8  vtkTransform *TTransform = vtkTransform::New();
9  vtkTransformPolyDataFilter *TTransformFilter =
10   vtkTransformPolyDataFilter::New();
11
12 TTransformFilter->SetInputConnection (letterT->GetOutputPort());
13 TTransformFilter->SetTransform (TTransform);
14
15 vtkTransform *KTransform = vtkTransform::New();
16 vtkTransformPolyDataFilter *KTransformFilter =
17 vtkTransformPolyDataFilter::New();
18
19 KTransformFilter->SetInputConnection (letterK->GetOutputPort());
20 KTransformFilter->SetTransform (KTransform);

```

We collect all of the transformed letters into one set of polygons by using an instance of the class `vtkAppendPolyData`.

Listing 12.28: Collect the transformed letters into one set of polygons.

```

1  vtkAppendPolyData *appendAll = vtkAppendPolyData::New();
2  appendAll->AddInputConnection (VTransformFilter->GetOutputPort());
3  appendAll->AddInputConnection (TTransformFilter->GetOutputPort());
4  appendAll->AddInputConnection (KTransformFilter->GetOutputPort());

```

Since the geometry for each letter did not have surface normals, we add them here. We use `vtkPolyDataNormals`. Then we complete this portion of the pipeline by creating a mapper and an actor.

Listing 12.29: Add surface normals and create mapper and actor.

```

1 // create normals
2 vtkPolyDataNormals *logoNormals = vtkPolyDataNormals::New();
3 logoNormals->SetInputConnection (appendAll->GetOutputPort());
4 logoNormals->SetFeatureAngle (60);
5
6 // map to rendering primitives
7 vtkPolyDataMapper *logoMapper = vtkPolyDataMapper::New();
8 logoMapper->SetInputConnection (logoNormals->GetOutputPort());
9
10 // now an actor
11 vtkActor *logo = vtkActor::New();
12 logo->SetMapper (logoMapper);

```

We create the blobby logo with the implicit modeller, and then extract the logo with vtkContourFilter. The pipeline is completed by creating a mapper and an actor.

Listing 12.30: Create an implicit model of the letters and extract the logo.

```

1 // now create an implicit model of the letters
2 vtkImplicitModeller *blobbyLogoImp = vtkImplicitModeller::New();
3 blobbyLogoImp->SetInputConnection (appendAll->GetOutputPort());
4 blobbyLogoImp->SetMaximumDistance (.075);
5 blobbyLogoImp->SetSampleDimensions (64,64,64);
6 blobbyLogoImp->SetAdjustDistance (0.05);
7
8 // extract an iso surface
9 vtkContourFilter *blobbyLogoIso = vtkContourFilter::New();
10 blobbyLogoIso->SetInputConnection (blobbyLogoImp->GetOutputPort());
11 blobbyLogoIso->SetValue (1, 1.5);
12
13 // map to rendering primitives
14 vtkPolyDataMapper *blobbyLogoMapper = vtkPolyDataMapper::New();
15 blobbyLogoMapper->SetInputConnection (blobbyLogoIso->GetOutputPort());
16 blobbyLogoMapper->ScalarVisibilityOff ();
17
18 // now an actor
19 vtkActor *blobbyLogo = vtkActor::New();
20 blobbyLogo->SetMapper(blobbyLogoMapper);
21 blobbyLogo->SetProperty(banana);

```

To improve the look of our resulting visualization, we define a couple of organic colors. Softer colors show up better on some electronic media (e.g., VHS video tape) and are pleasing to the eye.

Listing 12.31: Define colors.

```

1 vtkProperty *tomato = vtkProperty::New();
2 tomato->SetDiffuseColor(1, 0.3882, 0.2784);
3 tomato->SetSpecular(0.3);
4 tomato->SetSpecularPower(20);
5 vtkProperty *banana = vtkProperty::New();
6 banana->SetDiffuseColor(0.89, 0.81, 0.34);
7 banana->SetDiffuse (0.7);

```

```

8   banana->SetSpecular(0.4);
9   banana->SetSpecularPower(20);

```

These colors are then assigned to the appropriate actors.

Listing 12.32: Assign colors to the appropriate actors.

```

1  logo->GetProperty(tomato);
2  blobbyLogo->GetProperty(banana);

```

And finally, we position the letters in the logo and move the polygonal logo out in front of the blobby logo by modifying the actor's position.

Listing 12.33: Position the letters and move the polygonal logo.

```

1  VTransform->Translate (-16,0,12.5);
2  VTransform->RotateY (40);
3  KTransform->Translate (14, 0, 0);
4  KTransform->RotateY (-40);
5
6 // move the polygonal letters to the front
7 logo->SetPosition(0,0,6);

```

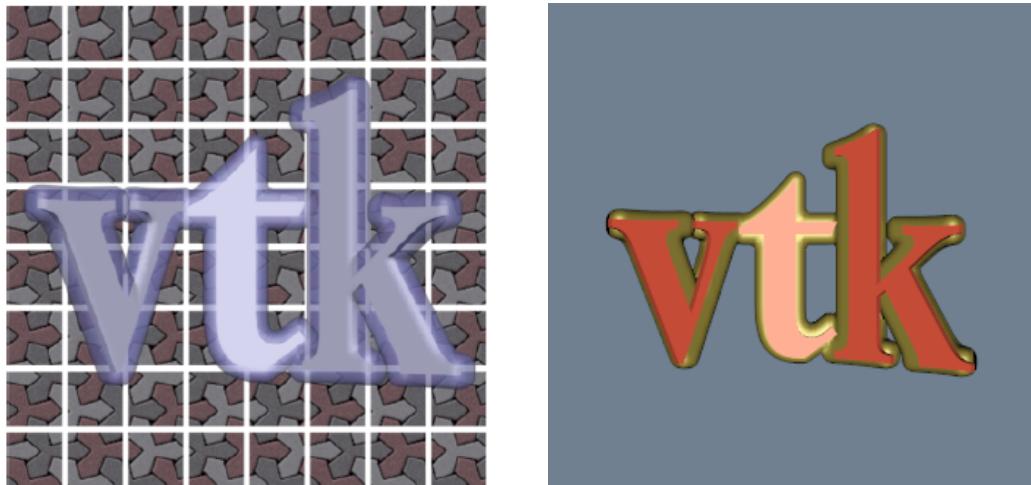


Figure 12.13: A logo created with vtkImplicitModeller.([BlobbyLogo.cxx](#)) or ([BlobbyLogo.py](#))

An image made from the techniques described in this section is shown in Figure 12.13 Note that the image on the left has been augmented with a texture map.

12.4.1 Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) visualization poses a challenge to any visualization toolkit. CFD studies the flow of fluids in and around complex structures. Often, large amounts of super-computer time is used to derive scalar and vector data in the flow field. Since CFD computations produce multiple scalar and vector data types, we will apply many of the tools described in

this book. The challenge is to combine multiple representations into meaningful visualizations that extract information without overwhelming the user.

CFD analysts often employ finite difference grids. A finite difference grid represents the discretization of the problem domain into small computational cells. The grid allows the analyst to create a large system of equations that can then be solved on a computer. The grid is topologically uniform in i - j - k space, but the corresponding physical coordinates need not be uniformly distributed. This is what we call a structured grid dataset in VTK.

There are a number of techniques we can use when we first look at the complex data presented by CFD applications. Since we need to apply several algorithms to the data, and since there will be many parameter changes for these algorithms, we suggest using the Tcl interpreter rather than C++ code. Our strategy for visualizing this CFD data includes the following:

- Display the computational grid. The analyst carefully constructed the finite difference grid to have a higher density in regions where rapid changes occur in the flow variables. We will display the grid in wireframe so we can see the computational cells.
- Display the scalar fields on the computational grid. This will give us an overview of where the scalar data is changing. We will experiment with the extents of the grid extraction to focus on interesting areas.
- Explore the vector field by seeding streamlines with a spherical cloud of points. Move the sphere through areas of rapidly changing velocity.
- Try using the computational grid itself as seeds for the streamlines. Of course we will have to restrict the extent of the grid you use for this purpose. Using the grid, we will be able to place more seeds in regions where the analyst expected more action.

For this case study, we use a dataset from NASA called the Lox Post. It simulates the flow of liquid oxygen across a flat plate with a cylindrical post perpendicular to the flow [10]. This analysis models the flow in a rocket engine. The post promotes mixing of the liquid oxygen.

We start by exploring the scalar and vector fields in the data. By calculating the magnitude of the velocity vectors, we derive a scalar field. This study has a particularly interesting vector field around the post. We seed the field with multiple starting points (using points arranged along a curve, referred to as a *rake*) and experiment with parameters for the streamlines. Stremppolygons are particularly appropriate here and do a nice job of showing the flow downstream from the post. We animate the streamline creation by moving the seeding line or rake back and forth behind the post.

Following our own advice, we first display the computational grid. The following Tcl code produced the left image of Figure 12.14.

Listing 12.34: Display the computational grid.

```

1 # read data
2 vtkPLOT3DReader pl3d
3   pl3d SetXYZFileName "$env(VTK_TEXTBOOK_DATA)/postxyz.bin"
4   pl3d SetQFileName "$env(VTK_TEXTBOOK_DATA)/postq.bin"
5   pl3d IBlankingOn
6   pl3d Update
7 # computational planes: the floor
8 vtkStructuredGridGeometryFilter floorComp
9   floorComp SetExtent 0 37 0 75 0 0
10  floorComp SetInputConnection [pl3d GetOutputPort]
```

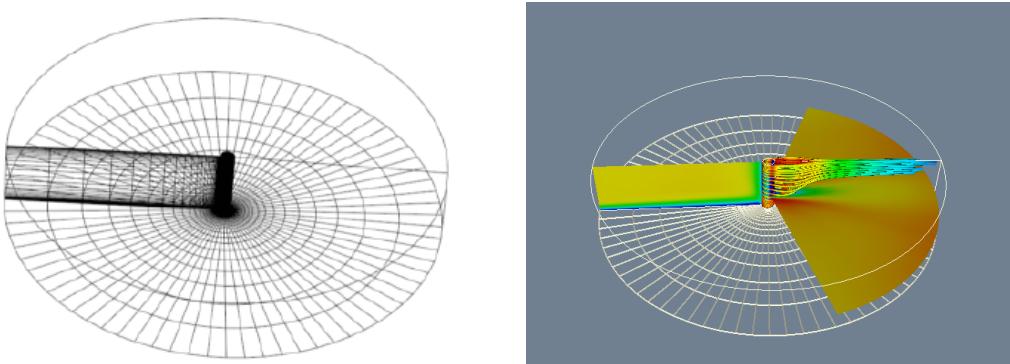


Figure 12.14: Portion of computational grid for the LOx post.(LOxGrid.cxx) or (LOxGrid.py)

```

11 vtkPolyDataMapper floorMapper
12   floorMapper SetInputConnection [floorComp GetOutputPort]
13   floorMapper ScalarVisibilityOff
14 vtkActor floorActor
15   floorActor SetMapper floorMapper
16   [floorActor GetProperty]SetColor 0 0 0
17   [floorActor GetProperty]SetRepresentationToWireframe
18 # the post
19 vtkStructuredGridGeometryFilter postComp
20   postComp SetExtent 10 10 0 75 0 37
21   postComp SetInputConnection [pl3d GetOutputPort]
22 vtkPolyDataMapper postMapper
23   postMapper SetInputConnection [postComp GetOutputPort]
24   postMapper ScalarVisibilityOff
25 vtkActor postActor
26   postActor SetMapper postMapper
27   [postActor GetProperty]SetColor 0 0 0
28   [postActor GetProperty]SetRepresentationToWireframe
29 # plane upstream of the flow
30 vtkStructuredGridGeometryFilter fanComp
31   fanComp SetExtent 0 37 38 38 0 37
32   fanComp SetInputConnection [pl3d GetOutputPort]
33 vtkPolyDataMapper fanMapper
34   fanMapper SetInputConnection [fanComp GetOutputPort]
35   fanMapper ScalarVisibilityOff
36 vtkActor fanActor
37   fanActor SetMapper fanMapper
38   [fanActor GetProperty]SetColor 0 0 0
39   [fanActor GetProperty]SetRepresentationToWireframe
40 # outline
41 vtkStructuredGridOutlineFilter outline

```

```

42     outline SetInputConnection [pl3d GetOutputPort]
43 vtkPolyDataMapper outlineMapper
44     outlineMapper SetInputConnection [outline GetOutputPort]
45 vtkActor outlineActor
46     outlineActor SetMapper outlineMapper
47     [outlineActor GetProperty] SetColor 0 0 0
48 # Create graphics stuff
49 vtkRenderer ren1
50 vtkRenderWindow renWin
51     renWin AddRenderer ren1
52 vtkRenderWindowInteractor iren
53     iren SetRenderWindow renWin
54 # Add the actors to the renderer, set the background and size
55 #
56     ren1 AddActor outlineActor
57     ren1 AddActor floorActor
58     ren1 AddActor postActor
59     ren1 AddActor fanAct

```

To display the scalar field using color mapping, we must change the actor's representation from wireframe to surface, turn on scalar visibility for each vtkPolyDataMapper, set each mapper's scalar range, and render again, producing the right image of Figure 12.14.

Listing 12.35: Display the scalar field.

```

1 postActor SetRepresentationToSurface
2 fanActor SetRepresentationToSurface
3 floorActor SetRepresentationToSurface
4 postMapper ScalarVisibilityOn
5 postMapper SetScalarRange [[pl3d GetOutput] GetScalarRange]
6 fanMapper ScalarVisibilityOn
7 fanMapper SetScalarRange [[pl3d GetOutput] GetScalarRange]
8 floorMapper ScalarVisibilityOn
9 floorMapper SetScalarRange [[pl3d GetOutput] GetScalarRange]

```

Now, we explore the vector field using vtkPointSource. Recall that this object generates a random cloud of points around a spherical center point. We will use this cloud of points to generate stream-lines. We place the center of the cloud near the post since this is where the velocity seems to be changing most rapidly. During this exploration, we use streamlines rather than streamtubes for reasons of efficiency. The Tcl code is as follows.

Listing 12.36: Explore the vector field using a point source.

```

1 # spherical seed points
2 vtkPointSource rake
3     rake SetCenter -0.74 0 0.3
4     rake SetNumberOfPoints 10
5 vtkStreamLine streamers
6     streamers SetInputConnection [pl3d GetOutputPort]
7     streamers SetSourceConnection [rake GetOutputPort]
8     streamers SetMaximumPropagationTime 250
9     streamers SpeedScalarsOn

```

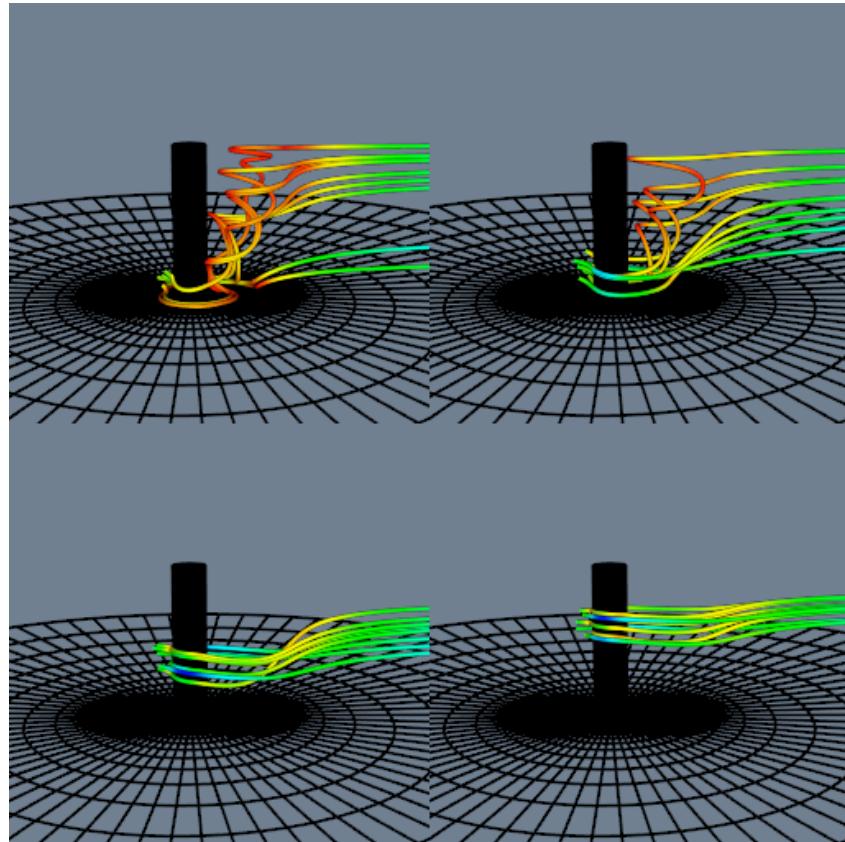


Figure 12.15: Streamlines seeded with spherical cloud of points. Four separate cloud positions are shown.([LOxSeeds.cxx](#)) or ([LOxSeeds.py](#))

```

10    streamers SetIntegrationStepLength 0.2
11    streamers SetStepLength 0.25
12  vtkPolyDataMapper mapTubes
13    mapTubes SetInputConnection [streamers GetOutputPort]
14    eval mapTubes SetScalarRange [[p13d GetOutput] GetScalarRange]
15  vtkActor tubesActor
16    tubesActor SetMapper mapTubes

```

Figure 12.15 shows streamlines seeded from four locations along the post. Notice how the structure of the flow begins to emerge as the starting positions for the streamlines are moved up and down in front of the post. This is particularly true if we do this interactively; the mind assembles the behavior of the streamlines into a global understanding of the flow field.

For a final example, we use the computational grid to seed streamlines and then generate streamtubes as is shown in Figure 12.16. A nice feature of this approach is that we generate more streamlines in regions where the analyst constructed a denser grid. The only change we need to make is to replace the rake from the sphere source with a portion of the grid geometry.

Listing 12.37: Use the computational grid to seed streamlines and then generate streamtubes.

```
1  vtkStructuredGridGeometryFilter seedsComp
```

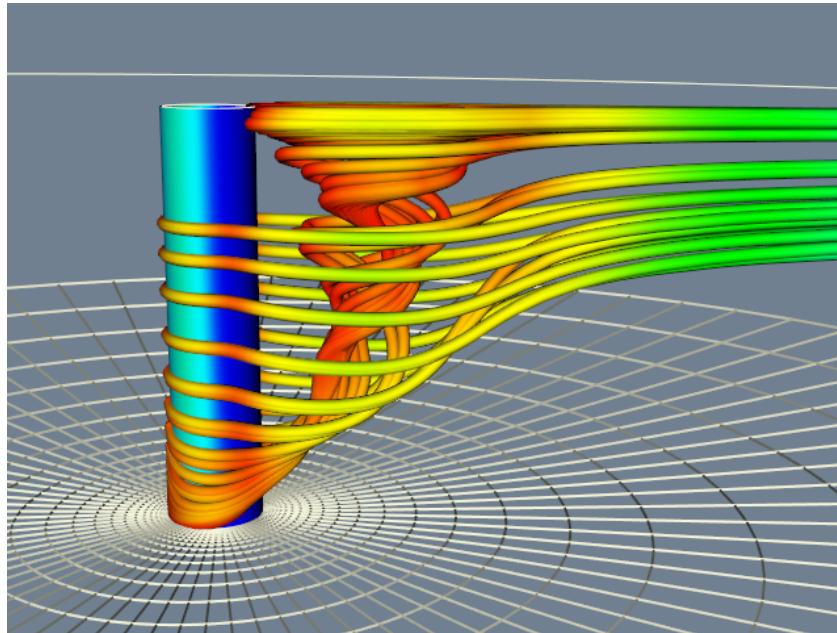


Figure 12.16: Streamlines seeded with spherical cloud of points. Four separate cloud positions are shown.[\(LOx.cxx\)](#) or [\(LOx.py\)](#)

```

2   seedsComp SetExtent 10 10 37 39 1 35
3   seedsComp SetInput [pl3d GetOutput]
4   streamers SetSourceConnection [seedsComp GetOutputPort]
5 # create tubes
6 vtkTubeFilter tubes
7 tubes SetInputConnection [streamers GetOutputPort]
8 tubes SetNumberOfSides 8
9 tubes SetRadius 0.08
10 tubes SetVaryRadiusOff
11 # change input to streamtubes
12 mapTubes SetInputConnection [tubes GetOutputPort]
```

There are a number of other methods we could use to visualize this data. A 3D widget such as the `vtkLineWidget` could be used to seed the streamlines interactively (see “3D Widgets and User Interaction” on page 150). As we saw in “Point Probe” on page 152, probing the data for numerical values is a valuable technique. In particular, if the probe is a line we can use it in combination with `vtkXYPlotActor` to graph the variation of data value along the line. Another useful visualization would be to identify regions of vorticity. We could use Equation 9.1 in conjunction with an isocontouring algorithm (e.g., `vtkContourFilter`) to creates isosurfaces of large helical-density.

12.5 Finite Element Analysis

Finite element analysis is a widely used numerical technique for finding solutions of partial differential equations. Applications of finite element analysis include linear and nonlinear structural, thermal, dynamic, electromagnetic, and flow analysis. In this application we will visualize

the results of a blow molding process.

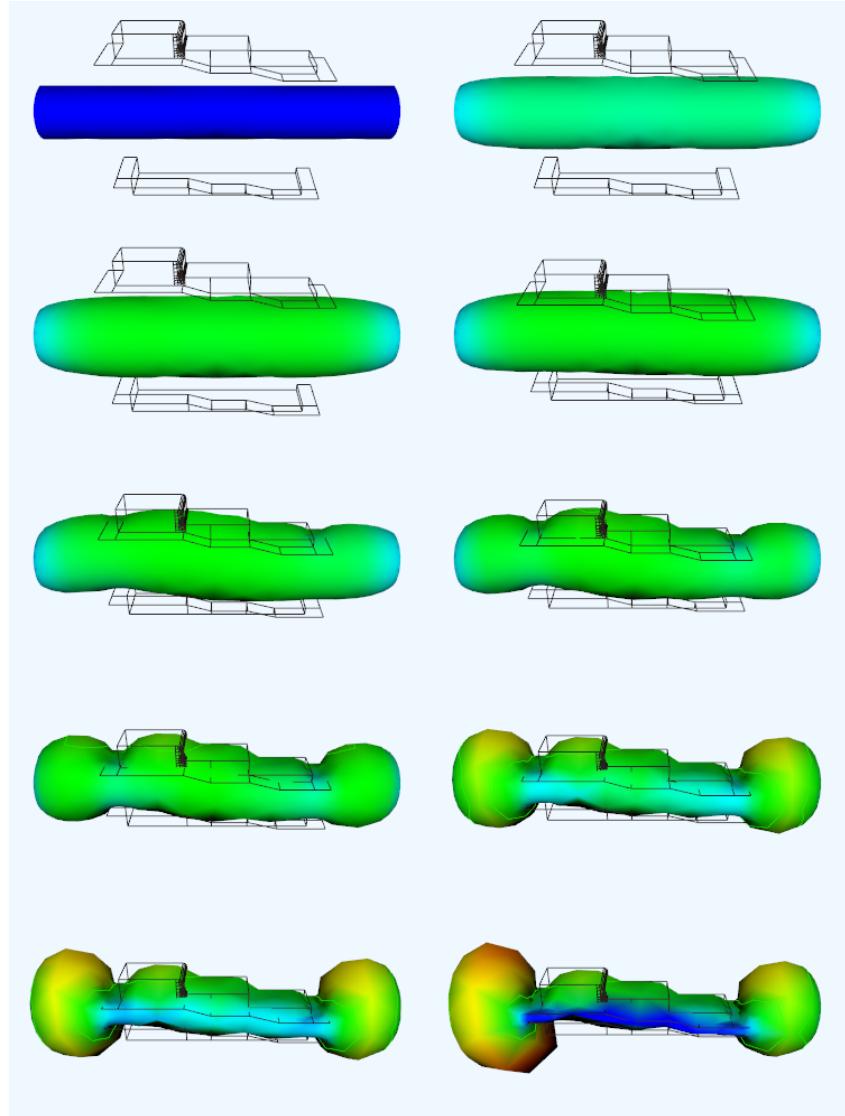


Figure 12.17: Ten frames from a blow molding finite element analysis. Mold halves (shown in wireframe) are closed around a parison as the parison is inflated. Coloring indicates thickness; red areas are thinner than blue. ([Blow.cxx](#)) or ([Blow.py](#))

In the extrusion blow molding process, a material is extruded through an annular die to form a hollow cylinder. This cylinder is called a *parison*. Two mold halves are then closed on the parison, while at the same time the parison is inflated with air. Some of the parison material remains within the mold while some becomes waste material. The material is typically a polymer plastic softened with heat, but blow molding has been used to form metal parts. Plastic bottles are often manufactured using a blow molding process.

Designing the parison die and molds is not easy. Improper design results in large variations in the wall thickness. In some cases the part may fail in thin-walled regions. As a result, analysis

tools based on finite element techniques have been developed to assist in the design of molds and dies.

The results of one such analysis are shown in Figure 12.17. The polymer was molded using an isothermal, nonlinear-elastic, incompressible (rubber-like) material. Triangular membrane finite elements were used to model the parison, while a combination of triangular and quadrilateral finite elements were used to model the mold. The mold surface is assumed to be rigid, and the parison is assumed to attach to the mold upon contact. Thus the thinning of the parison is controlled by its stretching during inflation and the sequence in which it contacts the mold.

Figure 12.17 illustrates 10 steps of one analysis. The color of the parison indicates its thickness. Using a rainbow scale, red areas are thinnest while blue regions are thickest. Our visualization shows clearly one problem with the analysis technique we are using. Note that while the nodes (i.e., points) of the finite element mesh are prevented from passing through the mold, the interior of the triangular elements are not. This is apparent from the occlusion of the mold wireframe by the parison mesh.

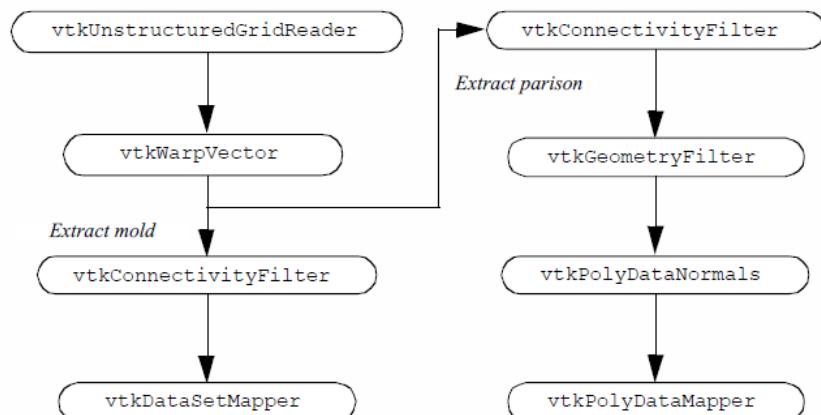


Figure 12.18: The network topology for the generation of the blow molding image.

The network topology used to generate these images is shown in Figure 12.18 with the corresponding Tcl script shown below

Listing 12.38: Script to generate the blow molding image.

```

1 # Create blow molding image (datapoint 5)
2 package require vtk
3 package require vtkinteraction
4
5 # Create graphics stuff
6 vtkRenderer ren1
7 vtkRenderWindow renWin
8 renWin AddRenderer ren1
9 vtkRenderWindowInteractor iren
10 iren SetRenderWindow renWin
11
12 # create reader and warp data with vectors
13 vtkUnstructuredGridReader reader
14 reader SetFileName "$VTK_DATA_ROOT/Data/blow.vtk"
15 reader SetScalarsName "thickness9"
  
```

```

16   reader SetVectorsName "displacement9"
17   vtkWarpVector warp
18     warp SetInputConnection [reader GetOutputPort]
19
20 # extract mold from mesh using connectivity
21 vtkConnectivityFilter connect
22   connect SetInputConnection [warp GetOutputPort]
23   connect SetExtractionModeToSpecifiedRegions
24   connect AddSpecifiedRegion 0
25   connect AddSpecifiedRegion 1
26 vtkDataSetMapper moldMapper
27   moldMapper SetInputConnection [connect GetOutputPort]
28   moldMapper ScalarVisibilityOff
29 vtkActor moldActor
30   moldActor SetMapper moldMapper
31   [moldActor GetProperty] SetColor .2 .2 .2
32   [moldActor GetProperty] SetRepresentationToWireframe
33
34 # extract parison from mesh using connectivity
35 vtkConnectivityFilter connect2
36   connect2 SetInputConnection [warp GetOutputPort]
37   connect2 SetExtractionModeToSpecifiedRegions
38   connect2 AddSpecifiedRegion 2
39 vtkGeometryFilter parison
40   parison SetInputConnection [connect2 GetOutputPort]
41 vtkPolyDataNormals normals2
42   normals2 SetInputConnection [parison GetOutputPort]
43   normals2 SetFeatureAngle 60
44 vtkLookupTable lut
45   lut SetHueRange 0.0 0.66667
46 vtkPolyDataMapper parisonMapper
47   parisonMapper SetInputConnection [normals2 GetOutputPort]
48   parisonMapper SetLookupTable lut
49   parisonMapper SetScalarRange 0.12 1.0
50 vtkActor parisonActor
51   parisonActor SetMapper parisonMapper
52
53 # Add the actors to the renderer, set the background and size
54 ren1 AddActor moldActor
55 ren1 AddActor parisonActor
56 ren1 SetBackground 1 1 1
57 renWin SetSize 750 400
58 iren Initialize
59 iren AddObserver UserEvent {wm deiconify .vtkInteract}
60
61 # prevent the tk window from showing up then start the event loop
62 wm withdraw .

```

The input data is in VTK format, so a vtkUnstructuredGridReader was used as a source object. The mesh displacement is accomplished using an instance of vtkWarpVector. At this point the

pipeline splits. We wish to treat the mold and parison differently (different properties such as wireframe versus surface), but the data for both mold and parison is combined. Fortunately, we can easily separate the data using two instances of class `vtkConnectivityFilter`. One filter extracts the parison, while the other extracts both parts of the mold. Finally, to achieve a smooth surface appearance on the parison, we use a `vtkPolyDataNormals` filter. In order to use this filter, we have to convert the data type from `vtkUnstructuredGrid` (output of `vtkConnectivityFilter`) to type `vtkPolyData`. The filter `vtkGeometryFilter` does this nicely.

12.6 Algorithm Visualization

Visualization can be used to display algorithms and data structures. Representing this information often requires creative work on the part of the application programmer. For example, Robertson et. al. [6] have shown 3D techniques for visualizing directory structures and navigating through them. Their approach involves building three dimensional models (the so-called "cone trees") to represent files, directories, and associations between files and directories. Similar approaches can be used to visualize stacks, queues, linked lists, trees, and other data structures.

In this example we will visualize the operation of the recursive Towers of Hanoi puzzle. In this puzzle there are three pegs (Figure 12.19). In the initial position there are one or more disks (or pucks) of varying diameter on the pegs. The disks are sorted according to disk diameter, so that the largest disk is on the bottom, followed by the next largest, and so on. The goal of the puzzle is to move the disks from one peg to another, moving the disks one at a time, and never placing a larger disk on top of a smaller disk.

The classical solution to this puzzle is based on a divide-and-conquer approach [2]. The problem of moving n disks from the initial peg to the second peg can be thought of as solving two subproblems of size $n - 1$. First move $n - 1$ disks from the initial peg to the third peg. Then move the n th disk to the second peg. Finally, move the $n - 1$ disks on the third peg back to the second peg.

The solution to this problem can be elegantly implemented using recursion. We have shown portions of the C++ code below. In the first part of the solution (which is not shown in the following) the table top, pegs, and disks are created using the two classes `vtkPlaneSource` and `vtkCylinderSource`. The function `Hanoi()` is then called to begin the recursion.

Listing 12.39: Recursive solution for the Towers of Hanoi.

```

1 // Recursive solution of Towers of Hanoi. Parameters are number
2 // of disks, originating peg, final peg, and intermediate peg.
3 static void Hanoi(int n, int peg1, int peg2, int peg3)
4 {
5     if (n != 1)
6     {
7         Hanoi(n-1, peg1, peg3, peg2);
8         Hanoi(1, peg1, peg2, peg3);
9         Hanoi(n-1, peg3, peg2, peg1);
10    }
11    else
12    {
13        MovePuck(peg1, peg2);
14    }
15 }
```

The routine MovePuck() is responsible for moving a disk from one peg to another. It has been jazzed up to move the disk in small, user-specified increments, and to flip the disc over as it moves from one peg to the next. This gives a pleasing visual effect and adds the element of fun to the visualization.

Listing 12.40: Moving the puck.

```

1 // Routine is responsible for moving disks from one peg to the next.
2 voidMovePuck(intpeg1,intpeg2)
3 {
4     doubledistance, flipAngle;
5     vtkActor*movingActor;
6     int i;
7
8     NumberofMoves++;
9     //get the actor t omove
10    movingActor=(vtkActor*)pegStack[peg1].Pop();
11    //get th edistance to move up
12    distance=(H-(L*(pegStack[peg1].GetNumberofItems()-1)) + rMax) /
13        NumberofSteps;
14    for(i=0;i<NumberofSteps;i++)
15    {
16        movingActor->AddPosition(0,distance,0);
17        Renwin->Render();
18    }
19
20    //get the distance to move across
21    distance=(peg2-peg1)*D/NumberofSteps;
22    flipAngle=180.0/NumberofSteps;
23    for(i=0;i<NumberofSteps;i++)
24    {
25        movingActor->AddPosition(distance,0,0);
26        movingActor->RotateX(flipAngle);
27        Renwin->Render();
28    }
29
30    //get the distance to move down
31    distance=((L*(pegStack[peg2].GetNumberofItems()-1))-HrMax) /
32        NumberofSteps;
33    for(i=0;i<NumberofSteps;i++)
34    {
35        movingActor->AddPosition(0,distance,0);
36        Renwin->Render();
37    }
38    pegStack[peg2].Push(movingActor);
39 }
```

Because of the clear relationship between algorithm and physical reality, the Towers of Hanoi puzzle is relatively easy to visualize. A major challenge facing visualization researchers is to visualize more abstract information, such as information on the Internet, the structure of documents, or the effectiveness of advertising/entertainment in large market segments. This type of visualiza-

tion, known as information visualization, is likely to emerge in the future as an important research challenge.

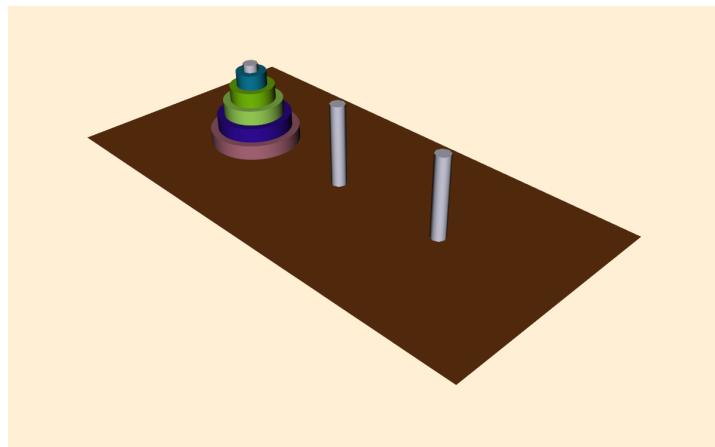
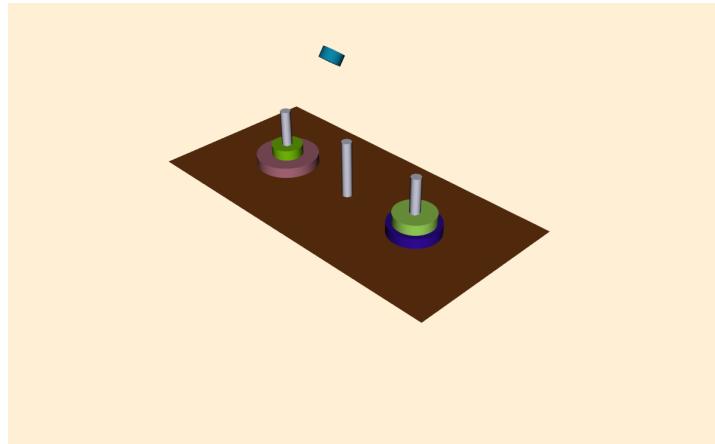
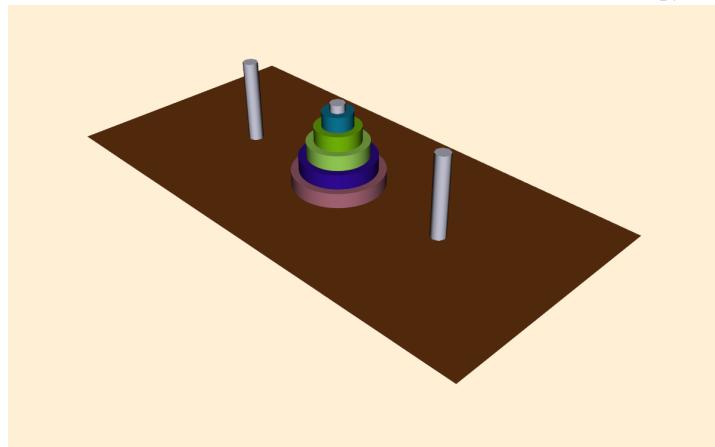
(a) Initial ([HanoiInitial.cxx](#)) or ([HanoiInitial.py](#))(b) Intermediate ([HanoiIntermediate.cxx](#)) or ([HanoiIntermediate.py](#))(c) Final ([Hanoi.cxx](#)) or ([Hanoi.py](#))

Figure 12.19: Towers of Hanoi. (a) Initial configuration. (b) Intermediate configuration. (c) Final configuration.

12.7 Chapter Summary

This chapter presented several case studies covering a variety of visualization techniques. The examples used different data representations including polygonal data, volumes, structured grids, and unstructured grids. Both C++ and Tcl code was used to implement the case studies.

Medical imaging is a demanding application area due to the size of the input data. Three-dimensional visualization of anatomy is generally regarded by radiologists as a communication tool

for referring physicians and surgeons. Medical datasets are typically image data—volumes or layered stacks of 2D images that form volumes. Common visualization tools for medical imaging include isosurfaces, cut planes, and image display on volume slices.

Next, we presented an example that applied 3D visualization techniques to financial data. In this case study, we began by showing how to import data from an external source. We applied tube filters to the data and varied the width of the tube to show the volume of stock trading. We saw how different views can be used to present different pieces of information. In this case, we saw that by viewing the visualization from the front, we saw a conventional price display. Then, by viewing the visualization from above, we saw trade volume.

In the modelling case study we showed how to use polygonal models and the implicit modelling facilities in VTK to create a stylistic logo. The final model was created by extracting an isosurface at a user-selected offset.

Computational fluid dynamics analysts frequently employ structured grid data. We examined some strategies for exploring the scalar and vector fields. The computational grid created by the analyst serves as a starting point for analyzing the data. We displayed geometry extracted from the finite difference grid, scalar color mapping, and streamlines and streamtubes to investigate the data.

In the finite element case study, we looked at unstructured grids used in a simulation of a blow molding process. We displayed the deformation of the geometry using displacement plots, and represented the material thickness using color mapping. We saw how we can create simple animations by generating a sequence of images.

We concluded the case studies by visualizing the Towers of Hanoi algorithm. Here we showed how to combine the procedural power of C++ with the visualization capabilities in VTK. We saw how visualization often requires our creative resources to cast data structures and information into visual form.

12.8 Bibliographic Notes

The case studies presented in the chapter rely on having interesting data to visualize. Sometimes the hardest part of practicing visualizing is finding relevant data. The Internet is a tremendous resource for this task. Paul Gilste [7] has written an excellent introduction to many of the tools for accessing information on the Internet. There are many more books available on this subject in the local bookstore.

In the stock case study we used a programming tool called AWK to convert our data into a form suitable for VTK. More information on AWK can be found in *The AWK Programming Language* [1]. Another popular text processing languages is Perl [11].

If you would like to know more about information visualization you can start with the references listed here [9] [3] [4] [5] [8] [6]. This is a relatively new field but will certainly grow in the near future.

Bibliography

- [1] A. V. Aho, B. W. Kernighan, and P. J. Weinberger. *The AWK Programming Language*. Addison Wesley, Reading, MA, 1988.
- [2] A. V. Aho, J. E. Hopcroft, and J. D. Ullman. *Data Structures and Algorithms*. Addison Wesley, Reading, MA, 1983.
- [3] C. Ding and P. Mateti. “A Framework for the Automated Drawing of Data Structure Diagrams”. In: *IEEE Transactions on Software Engineering* 16.5 (1990), pp. 543–557.
- [4] S. G. Eick and G. J. Wills. “Navigating Large Networks with Hierarchies”. In: *Proceedings of Visualization '93*. IEEE Computer Society Press, Los Alamitos, CA, Oct. 1993, pp. 204–210.
- [5] S. Feiner. “Seeing the Forest for the Trees: Hierarchical Displays of Hypertext Structures”. In: *Conference on Office Information Systems*. Palo Alto, CA, 1988.
- [6] G. G. Robertson, J. D. Mackinlay, and S. K. Card. “Cone Trees: Animated 3D Visualizations of Hierarchical Information”. In: *Proceedings of ACM CHI '91 Conference on Human Factors in Computing Systems*. 1991, pp. 189–194.
- [7] P. Gilster. *Finding It on the Internet: The Essential Guide to Archie, Veronica, Gopher, WAIS, WWW (including Mosaic), and Other Search and Browsing Tools*. John Wiley & Sons, Inc.
- [8] B. Johnson and B. Schneiderman. “Tree–Maps: A Space-Filling Approach to the Visualization of Hierarchical Information Structures”. In: *In Proceedings of Visualization '91* (Oct. 1991), pp. 284–291.
- [9] R. A. Becker, S. G. Eick, and A. R. Wilks. “Visualizing Network Data”. In: *IEEE Transactions on Visualization and Graphics* 1.1 (1995), pp. 16–28.
- [10] S. E. Rogers, D. Kwak, and U. K. Kaul. “A Numerical Study of Three–Dimensional Incompressible Flow Around Multiple Post”. In: *Proceedings of AIAA Aerospace Sciences Conference*. vol. AIAA Paper 86-0353. Reno, Nevada, 1986.
- [11] D. Till. *Teach Yourself Perl in 21 Days*. Sams Publishing, Indianapolis, Indiana, 1995.

12.9 Exercises

1. The medical example did nothing to transform the original data into a standard coordinate system. Many medical systems use RAS coordinates. R is right/left, A is anterior/posterior and S is Superior/Inferior. This is the patient coordinate system. Discuss and compare the following alternatives for transforming volume data into RAS coordinates. See ([AnatomicalOrientation.cxx](#)) and ([AnatomicalOrientation.py](#)).
 - (a) vtkActor transformation methods.
 - (b) vtkTransformFilter.

- (c) Reader transformations.
2. Modify the last example found in the medical application ([MedicalDemo3.cxx](#)) or ([MedicalDemo3.py](#)) to use `vtkImageDataGeometryFilter` instead of `vtkImageActor`. Compare the performance of using geometry with using texture. How does the performance change as the resolution of the volume data changes?
3. Modify the last medical example ([MedicalDemo3.cxx](#)) or ([MedicalDemo3.py](#)) to use `vtkTexture` and `vtkPlaneSource` instead of `vtkImageActor`.
4. Change the medical case study to use dividing cubes for the skin surface.
5. Combine the two scripts `frogSegmentation.tcl` and `marchingFrog.tcl` into one script that will handle either segmented or grayscale files. What other parameters and pipeline components might be useful in general for this application?
6. Create polygonal / line stroked models of your initials and build your own logo. Experiment with different transformations.
7. Enhance the appearance of Towers of Hanoi visualization.
 - (a) Texture map the disks, base plane, and pegs.
 - (b) Create disks with central holes.
8. Use the blow molding example as a starting point for the following.
 - (a) Create an animation of the blow molding sequence. Is it possible to interpolate between time steps? How would you do this?
 - (b) Create the second half of the parison using symmetry. What transformation matrix do you need to use?
9. Start with the stock visualization example presented in this chapter.
 - (a) Modify the example code to use a ribbon filter and linear extrusion filter as described in the text. Be careful of the width of the generated ribbons.
 - (b) Can you think of a way to present high/low trade values for each day?

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