Provenance for Visualizations: Reproducibility and Beyond

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May 11, 2009

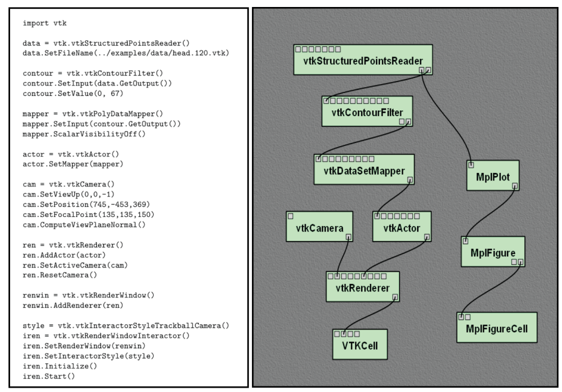
Abstract

The demand for the construction of complex visualizations is growing in many disciplines of science, as users are faced with ever increasing volumes of data to analyze. The authors present VisTrails, an open-source provenance management system that provides infrastructure for data exploration and visualization.

1 Introduction

Computing has been an enormous accelerator for science, leading to an information explosion in many different fields. Future scientific advances depend on our ability to comprehend the vast amounts of data currently being produced and acquired. To analyze and understand this data, though, we must assemble complex computational processes and generate insightful visualizations, which often require combining loosely coupled resources, specialized libraries, and grid and Web services. Such processes could generate yet more data, adding to the information overflow scientists currently deal with.

Today, the scientific community uses ad hoc approaches to data exploration, but such approaches have serious limitations. In particular, scientists and engineers must expend substantial effort managing data (such as scripts that encode computational tasks, raw data, data products, images, and notes) and recording provenance information (that is, all the information necessary for reproducing a certain piece of data or assertion) so that they can answer basic questions: Who created a data product and when? When was it modified, and who modified it? What process was used to create the data product? Were



(a) (b)

Figure 1: Dataflow programming for visualization. (a) We commonly use a script to describe a pipeline from existing libraries such as the Visualization Toolkit (VTK). (b) Visual programming interfaces, such as the one VisTrails provides, facilitate the creation and maintenance of these dataflow pipelines. The green rectangles represent modules, and the black lines represent connections.

two data products derived from the same raw data? Not only is this process time-consuming, its also error-prone.

Without provenance, its difficult (and sometimes impossible) to reproduce and share results, solve problems collaboratively, validate results with different input data, understand the process used to solve a particular problem, and reuse the knowledge involved in data analysis. In addition, data products longevity becomes limitedwithout precise and sufficient information about how the data product was generated, its value diminishes significantly.

The lack of adequate provenance support in visualization systems motivated us to build VisTrails, an open source provenance-management system that provides infrastructure for data exploration and visualization through workflows. VisTrails transparently records detailed provenance of exploratory computational tasks and leverages this information beyond just the ability to reproduce and share results. In particular, it uses this information to simplify the process of exploring data through visualization.

2 Visualization Systems

Visualization systems such as MayaVi (`http://mayavi.sourceforge.net`) and ParaView (`www.paraview.org`)which are built on top of Kitware's Visualization Toolkit (VTK) [2] as well as SCIRun (`http://software.sci.utah.edu/scirun.html`) enable users to interactively create and manipulate complex visualizations. Such systems are based on the notion of data flows [1], and they provide visual interfaces for producing visualizations by assembling pipelines out of modules (or functions) connected in a network. SCIRun supports an interface that lets users directly edit data flows, giving them complete control. MayaVi and ParaView have a different interaction paradigm that implicitly builds data flows as the user makes task-oriented choices (such as selecting an isosurface value).

Although these systems let users create complex visualizations, they lack the ability to support data exploration at a large scale. Notably, they dont adequately support collaborative creation and exploration of multiple visualizations. Because these systems dont distinguish between the definition of a data flow and its instances, to execute a given data flow with different parameters (for example, different input files), users must manually set these parameters through a GUI. Clearly, this process doesnt scale to more than a few visualizations at a time. Additionally, modifications to parameters or to a data flows definition are destructivethe systems dont maintain any change history. This requires the user to first construct the visualization and then remember the input data sets, parameter values, and the exact dataflow configuration that led to a particular image.

Finally, before constructing a visualization, users must often acquire, generate, or transform a given data setfor example, to calibrate a simulation, they must obtain data from sensors, generate data from a simulation, and finally construct and compare the visualization for both data sets. Most visualization systems, however, dont give users adequate support for creating the complex pipelines that use multiple libraries and services.

3 VisTrails: Provenance for Visualization

VisTrails (`www.vistrails.org`) is a new visualization system we developed at the University of Utah that provides a comprehensive provenance-management infrastructure and can be easily combined with existing visualization libraries. Unlike previous systems, VisTrails uses an action-based provenance model that uniformly captures changes to both parameter values and pipeline definitions by unobtrusively tracking all changes that users make to pipelines in an exploration task. We refer to this detailed provenance of the pipeline evolution as a visualization trail, or vistrail.

The stored provenance ensures that users will be able to reproduce the visualizations and lets them easily navigate through the space of pipelines created for a given exploration task. The VisTrails interface lets users query, interact with, and understand the visualization processs history. In particular, they can return to previous versions of a pipeline and change the specification or parameters to generate a new visualization without losing previous changes.

Another important feature of the action-based provenance model is that it enables a series of operations that greatly simplify the exploration process and could reduce the time to insight. In particular, it allows the flexible reuse of pipelines and provides a scalable mechanism for creating and comparing numerous visualizations as well as their corresponding pipelines. Although we originally built VisTrails to support exploratory visualization tasks, its extensi-

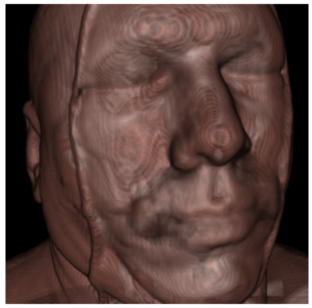


Figure 2: The end result of the script or VisTrails pipeline (see Figure 1) is a set of interactive visualizations.

ble infrastructure lets users integrate a wide range of libraries. This makes the system suitable for other exploratory tasks, including data mining and integration.

4 Creating an Interactive Visualization with VisTrails

To illustrate the issues involved in creating visualizations and how provenance can aid in this process, we present the following scenario, common in medical data visualization.

Starting from a volumetric computed tomography (CT) data set, we generate different visualizations by exploring the data through volume rendering, isosurfacing (extracting a contour), and slicing. Note that with proper modifications, this example also works for visualizing other types of data (for example, tetrahedral meshes).

4.1 Dataflow Processing Networks and Visual Programming

A useful paradigm for building visualization applications is the *dataflow model*. A data flow is a directed graph in which nodes represent computations, and edges represent data streams: each node or module corresponds to a procedure thats applied on the input data and generates some output data as a result. The data flow in the graph determines the order in which a dataflow system executes the processing nodes. In visualization, we commonly refer to a dataflow network as a visualization pipeline. (For this article, we use the terms workflow, data flow, and pipeline interchangeably.) Figure 1b shows an example of the data flow used to derive the images shown in Figure 2. The green rectangles represent modules, and the black lines represent connections. Most of the modules in Figure 1 are from VTK, and labels on each module indicate the corresponding VTK class. In this figure, we naturally think of data flowing from top to bottom, eventually being rendered and presented for display.

References

[1] E. A. Lee and T. M. Parks. Dataflow Process Networks. *Proceedings of the IEEE*, 83(5):773–801, 1995.

[2] W. Schroeder, K. Martin, and B. Lorensen. *The Visualization Toolkit An Object-Oriented Approach To 3D Graphics*. Kitware, 2003.