Overview of VTK

Hank Childs, University of Oregon
Announcements

• Quiz #2: Weds, Feb 21\textsuperscript{st}. On isolines
• Several types of trouble:
  – Bad edge indices
    • → my program says if isovalue within range
  – Missing triangle
    • → I can check how many triangles there should be
  – Other?
    • → I ran out of time to check these thoroughly
Project 7

• Due Thursday Feb 22\textsuperscript{nd}
• Conceptually easy at this point, but programming may be tough
  – Plan ahead. Be ready for OH early next week
  – Remember to try and minimize your code
    • Less cases
• I will live code in \~two weeks.
  – Aiming for 40 lines of code in “for” loop that generates triangles.
Project 7

- Extend your project 5 code to work in 3D
- In 6A, you used a module for setting up lines. I have created a new version for setting up triangles (see TriangleList.h).
Calendar

• Project 7, 8 coming

Calendar for March 2018 (United States)

<table>
<thead>
<tr>
<th>Sun</th>
<th>Mon</th>
<th>Tue</th>
<th>Wed</th>
<th>Thu</th>
<th>Fri</th>
<th>Sat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Dead Week

Faculty legislation controls the assignments that may be made during the last week of regular classes, commonly known as "Dead Week".

In the week preceding final examinations during Fall, Winter, and Spring terms:

- No examination worth more than 20% of the final grade will be given, with the exception of make-up examinations.
- No final examinations will be given under any guise.
- No projects will be due unless they have been clearly specified on the class syllabus within the first two weeks of the term.
- Take-home examinations will be due no earlier than the day of the formally assigned final examination for the class in question.

Questions about this policy should be addressed to the Senior Vice Provost for Academic Affairs, (541) 346-3081.
Final Project: Decision Tree

- This is volume rendering
410 Decision Tree

• Have a custom vis project you want to do?
  – Send me a proposal

• If not:
  – If you think it sounds fun to make a movie, then pay close attention next two weeks
  – Or do volume rendering
Have a custom vis project you want to do?
  – Send me a proposal
    • Even if volume rendering

If not:
  – If you think it sounds fun to make a movie, then pay close attention next two weeks

AND do volume rendering
Review
The Visualization ToolKit

• Open Source library for visualization and graphics
• Written in C++
  – Bindings in Tcl, Java, Python
• Object-oriented
  – Few base types
  – Many, many derived types that provide functionality
• Strengths:
  – Very powerful
  – Designed for extensibility
• Weaknesses:
  – Extensibility design choice comes with performance tradeoffs
VTK: a mature infrastructure

Textbook based on VTK, used for many college courses

Guide devoted to effective usage of VTK software

Nightly regression tests

Online documentation
Data Flow Overview

• VTK employs the data flow network paradigm

• Basic idea:
  – You have many modules
    • Hundreds!!
  – You compose modules together to perform some desired functionality

• Advantages:
  – Customizability
  – Design fosters interoperability between modules to the extent possible
Example of data flow (image processing)

• Sources:
  – FileReader: reader from file
  – Color: generate image with one color

• Filters:
  – Crop: crop image, leaving only a sub-portion
  – Transpose: view image as a 2D matrix and transpose it
  – Invert: invert colors
  – Concatenate: paste two images together

• Sinks:
  – FileWriter: write to file
Example of data flow (image processing)

FileReader

Crop

Transpose

Invert

Color

Concatenate

FileWriter

OREGON

OREGON

OREGON
Example of data flow (image processing)

- **Participants:**
  - **Source:** a module that produces data
    - It creates an output
  - **Sink:** a module that consumes data
    - It operates on an input
  - **Filter:** a module that transforms input data to create output data

- **Pipeline:** a collection of sources, filters, and sinks connected together
Key abstract types in VTK

- `vtkDataObject` / `vtkDataSet`
- `vtkAlgorithm`
- Graphics modules
Key abstract types in VTK

- `vtkDataObject / vtkDataSet`
- `vtkAlgorithm`
- Graphics modules
Example of data flow (image processing)

We are now talking about the data objects that flow between modules ... not just images.
While `vtkDataObject` allows VTK developers to add custom abstractions, almost all usage by new users of VTK is via `vtkDataSet`.

Key abstract type in VTK: vtkDataObject

I’ve gone 20 years using almost exclusively four concrete types of vtkDataObject.

Important derived types of vtkDataSet

- `vtkStructuredGrid`
- `vtkUnstructuredGrid`
- `vtkRectilinearGrid`
- `vtkPolyData`
Key abstract types in VTK

- vtkDataObject / vtkDataSet
- vtkAlgorithm
- Graphics modules
Key abstract type in vtk: vtkAlgorithm

• While data flow has clear concepts for “Source”, “Sink”, and “Filter”, VTK has a single class “vtkAlgorithm”
  – Previously had differentiated types

• vtkAlgorithm:
  – has zero, one, or more inputs
    • void SetInputConnection(vtkAlgorithmOutput *); // port 0
    • void SetInputData(int port, vtkAlgorithmOutput *);
  – has zero, one, or more outputs
    • vtkAlgorithmOutput *GetOutputPort(void); // port 0
    • vtkAlgorithmOutput *GetOutput(int);
First program

```c
#include <vtkDataSetReader.h>
#include <vtkContourFilter.h>
#include <vtkDataSetWriter.h>

int main()
{
    vtkDataSetReader *rdr = vtkDataSetReader::New();
    rdr->SetFileName("noise.vtk");

    // Contour the data.
    vtkContourFilter *cf = vtkContourFilter::New();
    cf->SetNumberOfContours(1);
    cf->SetValue(0.3);
    cf->SetInputConnection(rdr->GetOutputPort());

    vtkDataSetWriter *wrtr = vtkDataSetWriter::New();
    wrtr->SetFileName("contour.vtk");
    wrtr->SetInputConnection(cf->GetOutputPort());
    wrtr->Write();
}
```

```
fawcett@VTK_ex childs$ make
```
```shell
g++ -g -o contour_no_graphics -I/Users/childs/visit/vtk/6.0.0/i386-apple-darwin10_gcc-4.2/include/vtk-6.0 contour_no_graphics.C -L/Users/childs/visit/vtk/6.0.0/i386-apple-darwin10_gcc-4.2/lib -lvtkRenderingFreeTypeOpenGL-6.0 -lvtkRenderingFreeType-6.0 -lvtkInteractionStyle-6.0 -lvtkRenderingOpenGL-6.0 -lvtkImage-6.0 -lvtkIOLegacy-6.0 -lvtkIOCore-6.0 -lvtkRenderingCore-6.0 -lvtkFiltersCore-6.0 -lvtkCommonDataModel-6.0 -lvtkCommonMisc-6.0 -lvtkCommonExecutionModel-6.0 -lvtkCommonCore-6.0
```
```shell
fawcett@VTK_ex childs$ ./contour_no_graphics
```
```
fawcett@VTK_ex childs$ ls -l contour.vtk
```
```shell
-rw-r--r--  1 childs staff 1383911 Jul  6 15:47 contour.vtk
```
First program

```
fawcett:VTK_ex child$ cat contour_no_graphics.C
#include <vtkDataSetReader.h>
#include <vtkContourFilter.h>
#include <vtkDataSetWriter.h>

int main()
{
    vtkDataSetReader *rdr = vtkDataSetReader::New();
    rdr->SetFileName("noise.vtk");

    // Contour the data.
    vtkContourFilter *cf = vtkContourFilter::New();
    cf->SetNumberOfContours(1);
    cf->SetValue(0, 3.0);
    cf->SetInputConnection(rdr->GetOutputPort());

    vtkDataSetWriter *wrtr = vtkDataSetWriter::New();
    wrtr->SetFileName("contour.vtk");
    wrtr->SetInputConnection(cf->GetOutputPort());
    wrtr->Write();
}
```
First program

VTK forces all VTK objects to be allocated using dynamic memory (the heap).
VTK memory management

• VTK uses reference counting for all objects (vtkAlgorithm, vtkDataObject, etc)

• Rules:
  – All new objects have a reference count of 1
  – Register() increments the reference count
  – Delete() deletes the reference count
  – When reference count hits 0, the object is deleted

• VTK shares arrays between vtkDataObjects, to save on memory...
  – ... which means they can’t store arrays on stack, since the arrays could go out of scope (dangling pointer)

VTK has recently introduced a templated type, vtkSmartPointer, to assist with reference counting.
First program (leak free version)

```c
#include <vtkDataSetReader.h>
#include <vtkContourFilter.h>
#include <vtkDataSetWriter.h>

int main()
{
    vtkDataSetReader *rdr = vtkDataSetReader::New();
    rdr->SetFileName("noise.vtk");

    // Contour the data.
    vtkContourFilter *cf = vtkContourFilter::New();
    cf->SetNumberOfContours(1);
    cf->SetValue(0, 3.0);
    cf->SetInputConnection(rdr->GetOutputPort());

    vtkDataSetWriter *wrtr = vtkDataSetWriter::New();
    wrtr->SetFileName("contour.vtk");
    wrtr->SetInputConnection(cf->GetOutputPort());
    wrtr->Write();

    rdr->Delete();
    cf->Delete();
    wrtr->Delete();
}
First program

The pipeline is constructed via `SetInputConnection()` and `GetOutputPort()` calls.

```c
#include <vtkDataSetReader.h>
#include <vtkContourFilter.h>
#include <vtkDataSetWriter.h>

int main()
{
  vtkDataSetReader *rdr = vtkDataSetReader::New();
  rdr->SetFileName("noise.vtk");

  // Contour the data.
  vtkContourFilter *cf = vtkContourFilter::New();
  cf->SetNumberOfContours(1);
  cf->SetValue(0, 3, 0):
  cf->SetInputConnection(rdr->GetOutputPort());

  vtkDataSetWriter *wrtr = vtkDataSetWriter::New();
  wrtr->SetFileName("contour.vtk");
  wrtr->SetInputConnection(cf->GetOutputPort());
  wrtr->Write();
}
```

How does VTK control execution?
VTK’s Execution Model

• Key method: Update()
  – Update() requests a module to get its output “up-to-date”, i.e., to calculate it

• But what if that modules inputs are not up-to-date?
  – Part of an Update() is to call Update() on all the inputs to a module

• In the example program, “Write()” knows to request its input is up-to-date, which propagates up the pipeline
First program

```c
#include <vtkDataSetReader.h>
#include <vtkContourFilter.h>
#include <vtkDataSetWriter.h>

int main()
{
  vtkDataSetReader *rdr = vtkDataSetReader::New();
  rdr->SetFileName("noise.vtk");

  // Contour the data.
  vtkContourFilter *cf = vtkContourFilter::New();
  cf->SetNumberOfContours(1);
  cf->SetValue(0, 3.0);
  cf->SetInputConnection(rdr->GetOutputPort());

  vtkDataSetWriter *wrtr = vtkDataSetWriter::New();
  wrtr->SetFileName("contour.vtk");
  wrtr->SetInputConnection(cf->GetOutputPort());
  wrtr->Write();
}
```

1) wrtr asks cf to Update()
2) cf asks rdr to Update()
3) rdr reads from the file
4) cf calculates contour
5) wrtr writes file
VTK & Time Stamps

• VTK prevents unnecessarily re-calculation of the pipeline
  
  – It uses time stamps to keep track of when a module or its input was modified, and when the last time was it calculated its outputed.
#include <vtkDataSetReader.h>
#include <vtkContourFilter.h>
#include <vtkDataSetWriter.h>

int main()
{
    vtkDataSetReader *rdr = vtkDataSetReader::New();
rdr->SetFileName("noise.vtk");

    // Contour the data.
    vtkContourFilter *cf = vtkContourFilter::New();
    cf->SetNumberOfContours(1);
    cf->SetValue(0, 3.0);
    cf->SetInputConnection(rdr->GetOutputPort());

    vtkDataSetWriter *wrtr = vtkDataSetWriter::New();
    wrtr->SetFileName("contour.vtk");
    wrtr->SetInputConnection(cf->GetOutputPort());
    wrtr->Write();

    cf->SetValue(0, 3.5);
    wrtr->SetFileName("contour2.vtk");
    wrtr->Write();

    rdr->Delete();
cf->Delete();
wrtr->Delete();
}

1) wrtr asks cf to Update()
2) cf asks rdr to Update()
3) rdr doesn't read from the file
4) cf calculates contour
5) wrtr writes file
Topology of pipelines

- Each module can have multiple inputs, multiple outputs
- Multiple sinks are fine
  - Call Update() on each
- Cycles are technically OK, but can be problematic
Key abstract types in VTK

- vtkDataObject / vtkDataSet
- vtkAlgorithm
- Graphics modules
Graphics Modules

- 90+% of VTK source code is sources, sinks, and filters.
- <10% is graphics / windowing.
- ... but ~50% of most “getting started” programs involve graphics / windows
5 Abstractions for Graphics / Windowing

1. **RenderWindow**: a window
2. **Renderer**: the place inside a window where you can render
   – There can be multiple renderers within a window
3. **Actor**: something that can be placed into a renderer
4. **Mapper**: maps data to geometric primitives
   – One mapper can be associated with multiple actors
5. **RenderWindowInteractor**: defines what button clicks, mouse movements, etc. should do
int main()
{
  // The following lines create a sphere represented by polygons.
  vtkSmartPointer<vtkSphereSource> sphere =
    vtkSmartPointer<vtkSphereSource>::New();
sphere->SetThetaResolution(100);
sphere->SetPhiResolution(50);

  // The mapper is responsible for pushing the geometry into the graphics
  // library. It may also do color mapping, if scalars or other attributes
  // are defined.
  vtkSmartPointer<vtkPolyDataMapper> sphereMapper =
    vtkSmartPointer<vtkPolyDataMapper>::New();
sphereMapper->SetInputConnection(sphere->GetOutputPort());

  vtkSmartPointer<vtkActor> sphere1 =
    vtkSmartPointer<vtkActor>::New();
sphere1->SetMapper(sphereMapper);
sphere1->GetProperty()->SetColor(1,0,0);

  vtkSmartPointer<vtkActor> sphere2 =
    vtkSmartPointer<vtkActor>::New();
sphere2->SetMapper(sphereMapper);
sphere2->GetProperty()->SetColor(0,1,0);
sphere2->AddPosition(1.25,0,0);

  // Adapted from SpecularSpheres.cxx in VTK source code.
Example with graphics / windowing (pt 2)

```c++
// Create the graphics structure. The renderer renders into the
// render window. The render window interactor captures mouse events
// and will perform appropriate camera or actor manipulation
// depending on the nature of the events.
//
vtkSmartPointer<vtkRenderer> ren1 =
    vtkSmartPointer<vtkRenderer>::New();
vtkSmartPointer<vtkRenderWindow> renWin =
    vtkSmartPointer<vtkRenderWindow>::New();
renWin->AddRenderer(ren1);
vtkSmartPointer<vtkRenderWindowInteractor> iren =
    vtkSmartPointer<vtkRenderWindowInteractor>::New();
iren->SetRenderWindow(renWin);

// Add the actors to the renderer, set the background and size.
//
ren1->AddActor(sphere1);
ren1->AddActor(sphere2);
ren1->SetBackground(0.1, 0.2, 0.4);
renWin->SetSize(400, 200);

ren1->GetActiveCamera()->SetFocalPoint(0,0,0);
ren1->GetActiveCamera()->SetPosition(0,0,1);
ren1->GetActiveCamera()->SetViewUp(0,1,0);
ren1->GetActiveCamera()->ParallelProjectionOn();
ren1->ResetCamera();
ren1->GetActiveCamera()->SetParallelScale(1.5);

// This starts the event loop and invokes an initial render.
//
iren->Initialize();
iren->Start();

return EXIT_SUCCESS;
```
More Example Programs

• Many example programs in VTK download
• Some C++, some Python
• Challenge is typically figuring out how to map what you want to do to VTK modules
  – How to find the right module?
  – How to set up the module’s options?
  – Good reference for these questions:
Summary

• VTK is open source, written in C++, and is supported by a large community
• It employs the data flow paradigm
• It has many modules (readers, filters, mappers), which makes it very powerful
• It is well-suited to for many tasks including:
  – foundation for visualization tools
  – one-off visual explorations of data
  – custom visualization tools, especially when considering the effort to incorporate it
Additional Visualization Algorithms
Slicing

• Assume rectilinear mesh with
  – $X = \{0,1,2,3,4,5,6,7,8,9\}$
  – $Y = \{0,1,2,3,4,5,6,7,8,9\}$
  – $Z = \{0,1,2,3,4,5,6,7,8,9\}$

How do we generate slice at $Y=5$?
Slice at Y=5

- Output mesh:
  - $X=\{0,1,2,3,4,5,6,7,8,9\}$
  - $Y=\{5\}$
  - $Z=\{0,1,2,3,4,5,6,7,8,9\}$

```c
for (int z = 0 ; z < 10 ; z++)
    for (int x = 0 ; x < 10 ; x++)
        outF[z*10+x] = F[z*100+5*10+x];
```
Slicing

• Assume rectilinear mesh with
  – $X=\{0,1,2,3,4,5,6,7,8,9\}$
  – $Y=\{0,1,2,3,4,5,6,7,8,9\}$
  – $Z=\{0,1,2,3,4,5,6,7,8,9\}$

How do we generate slice at $Y=5.3$?
Slice at $Y=5.3$

- **Output mesh:**
  - $X\{0,1,2,3,4,5,6,7,8,9\}$
  - $Y\{5.3\}$
  - $Z\{0,1,2,3,4,5,6,7,8,9\}$

```cpp
for (int z = 0 ; z < 10 ; z++)
  for (int x = 0 ; x < 10 ; x++)
    outF[z*10+x] =
      (0.3)*(F[z*100+6*10+x]-F[z*100+5*10+x])
    + F[z*100+5*10+x];
```
Slicing

• Assume rectilinear mesh with
  – $X=\{0,1,2,3,4,5,6,7,8,9\}$
  – $Y=\{0,1,2,3,4,5,6,7,8,9\}$
  – $Z=\{0,1,2,3,4,5,6,7,8,9\}$

How do we generate slice at plane $X+Y+Z=0$?

Answer: we will need “distance functions”
Distance Functions

• Distance function: measures how far a point is from surface

• Example: how far are you from the plane $X+Y+Z=0$?

• How far is the point $(3,0,0)$ from this plane?

  Answer: 3 units
Distance Functions

• Distance function: measures how far a point is from surface
• Example: how far are you from the plane X+Y+Z=0?
• How far is the point (1,1,0) from this plane?

Answer: \( \sqrt{2} \) units
How to use distance functions to slice?

• Step #1: create distance function
• Step #2: isosurface with iso-value = 0
Revisiting $Y=5.3$

- Some cells straddle $Y=5.3$
- When classifying, all $Y=5$ get 0, all $Y=6$ get 1
Distance Functions: approximate version

• Distance function: measures how far a point is from surface
• Example: how far are you from the plane \( X+Y+Z=0 \)?
• How far is the point \((x,y,z)\) from this plane?

Approx. answer: \( x+y+z \) units

Why? Approximate answer: the overestimates (on both sides) cancel each other out.
Analogy

- UCD Math 127A: Introduction to Mathematical Analysis
- 10 week course
- First 8 weeks:
  - Intermediate Value Theorem
- Last two weeks:
  - All of derivatives and integrals
Threshold

- Keep cell if it meets some criteria, else discard
- Criteria:
  - Pressure > 2
  - 10 < temperature < 20

Cells that meet criteria
How to implement threshold

• Iterate over cells
• If a cell meets the criteria, then place that cell in the output
• Output is an unstructured mesh
Interval Volumes

Isolates portion of volume between two values, $V_{\text{low}}$ and $V_{\text{hi}}$. 
Interval volumes vs isosurfaces

Interval volume between 2.5 and 2.7.

Isosurfaces at 2.5 and 2.7.
How to implement interval volumes

• Iterate over cells
• Like marching cubes, but making topologically 3D output (tetrahedrons, not triangles)
• Now 3 states: below, within interval, above
• Many, many cases to determine
• Isolate portion of volume within a box

-8 < x < 8
-9 < y < 5.7
-3.2 < z < 6.4
How to implement box

• Iterate over cells
• Three cases:
  – Retain cell
  – Discard cell
  – Split cell (i.e., straddles box boundary)
• How to split cell?
  – Box:Interval Volume as Slicing:Isosurfacing
    • (set up 6 distance fields and use interval volumes)
    • (why not 1 distance field?)
Clip by arbitrary functions
How to implement Clip

• Same as Box, but different spatial function
• Iterate over cells
• Three cases:
  – Retain cell
  – Discard cell
  – Split cell (i.e., straddles clip boundary)
• How to split cell?
  – Clip: Interval Volume as Slicing: Isosurfacing
    • (possibly multiple clips)
Slicing by non-planes
How to non-planar slicing

• Set up distance function for spatial function (cone, sphere)
• Apply Marching Cubes
Isosurface by one variable, color by another

Isosurface by var1, color by var1

Isosurface by var1, color by var2
How to implement isosurface by var1, color by var2

• Marching Cubes based on var1.
• Need operation:
  – As Marching Cubes calculates each triangle, evaluate var2 for each vertex of that triangle
  – Create variable var2 on output triangle mesh