Using Shaders to Enhance Scientific Visualizations

You Can Do Image Processing on Dynamic Scenes with a Two-pass Approach

Pass #1
- Lighting Shader
- Render a 3D dynamic scene
- Texture

Pass #2
- Render a quadrilateral
- Framebuffer
- Sharpening Shader
Surprisingly, the negative of a 3D object often reveals additional details.
Changing the emboss angle is interesting.
Toon Rendering for Non-Photorealistic Effects

Using the GPU to enhance scientific, engineering, and architectural illustration

A Vector Visualization Technique: Hedgehog Plots
Terrain Height Bump-mapping

No Exaggeration

Exaggerated

Terrain Height Bump-mapping

Portland
Salem
Corvallis
Eugene
Bump-Mapping for Terrain Visualization

Visualization by Nick Gebbie

3D Object Silhouettes
Visualization -- Polar Hyperbolic Space

\[ \Theta' = \Theta \]
\[ R' = \frac{R}{R + K} \]

Dome Projection for Immersive Visualization

Use the GPU to perform nonlinear vertex transformations
Image Manipulation Example – Where is it Likely to Snow?

if( have_clouds && have_a_low_temperature && have_water_vapor )
    color = green;
else
    color = from visible map

Writing 3D Point Cloud Data into a Floating-Point Texture for glman

fwrite( &nums, 4, 1, fp );
fwrite( &numt, 4, 1, fp );
fwrite( &nump, 4, 1, fp );
for( int p = 0; p < nump; p++ )
{
    for( int t = 0; t < numt; t++ )
    {
        for( int s = 0; s < nums; s++ )
        {
            float red, green, blue, alpha;
            << assign red, green blue, alpha >>
            fwrite( &red, 4, 1, fp );
            fwrite( &green, 4, 1, fp );
            fwrite( &blue, 4, 1, fp );
            fwrite( &alpha, 4, 1, fp );
        }
    }
}
Where to Place the Geometry?

I personally like thinking of the data as living in a cube that ranges from -1. to 1. in X, Y, and Z. It is straightforward to position geometry in this space and easy to view and transform it. This means that any 3D object in that space, not just a point cloud, can map itself to the 3D texture data space.

So, because the s texture coordinate goes from 0. to 1., then the linear mapping from the physical x coordinate to the texture s coordinate is:

\[-1. \leq x \leq 1. \quad \rightarrow \quad s = \frac{x + 1.}{2.} \quad \rightarrow \quad 0. \leq s \leq 1.\]

The same mapping applies to y and z to create the t and p texture coordinates.

In GLSL, this conversion can be done in one line of code using the vec3:

```glsl
vec3 xyz = ???

vec3 stp = (xyz + 1.) / 2.;
```

You can also go the other way:

```glsl
vec3 xyz = -1. + (2. * stp);
```
The Vertex Shader

```glsl
out vec3 vMC;

void main() {
    vMC = gl_Vertex.xyz;
    gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

The Fragment Shader

```glsl
uniform float uMin, uMax;
uniform sampler3D uTexUnit;
in vec3 vMC;
const float SMIN = 0.;
const float SMAX = 120.;

void main() {
    vec3 stp = ( vMC + 1. ) / 2.; // maps [-1.,1.] to [0.,1.]
    if( any( lessThan( stp, vec3(0.,0.,0.) ) ) )
        discard;
    if( any( greaterThan( stp, vec3(1.,1.,1.) ) ) )
        discard;
    float scalar = texture( uTexUnit, stp ).r; // data is hiding in the red component
    if( scalar < uMin || scalar > uMax )
        discard;
    float t = ( scalar - SMIN ) / ( SMAX - SMIN );
    vec3 rgb = Rainbow( t );
    gl_FragColor = vec4( rgb, 1. );
}
```
A Problem with Uniform Pointclouds:
Row-of-Corn and Moire Patterns

Uniform Points vs. Jittered Points

"Jittering" moves each point a small random amount in ±x, ±y, and ±z. Because our data value lookup comes from (s,t,p) which comes from (x,y,z), the lookup will be correct at the jittered points.
Enhanced Point Clouds

The shaders can potentially change:

- Color
- Alpha
- Pointsize

Color Cutting Planes

Now, change the Point Cloud geometry to a quadrilateral geometry. If we keep the coordinate range from -1. to 1., then the same shader code will work, except that we now want to base the color assignment on Eye Coordinates instead of Model Coordinates:

```cpp
in vec3 vEC;

void main( )
{
  vec3 stp = ( vEC + 1. ) / 2.;  // maps [-1.,1.] to [0.,1.]

  ...  
}
```

Eye (transformed) coordinates are being used here because the cutting plane is moving through the data.

Note that the plane can be oriented at any angle because the s-t-p data lookup comes from the transformed x-y-z coordinates of the cutting plane.
The cutting plane is actually just being used as a fragment-generator. Each fragment is then being asked “what data value lives at the same place you live”?

```cpp
in vec3 vEC;
void main( )
{
  vec3 stp = ( vEC + 1. ) / 2.;
  // maps [-1.,1.] to [0.,1.]
  
  This is very much like how we handled rendering a rainbow.
}
```

Let’s say that we want “contour gaps” at each 10 degrees of temperature. Then the main change to the shader will be that we need to find how close each fragment’s interpolated scalar data value is to an even multiple of 10. To do this, we add this discretization code to the fragment shader:

```cpp
float scalar10 = float( 10.*int( (scalar+5.)/10. ) );
if( abs( scalar - scalar10 )  <  uTol )
  discard;
```

Notice that this uses a uniform variable called uTol, which is read from a slider and has a range of 0. to 5. uTol is used to determine how close to an even multiple of 10 degrees we will accept, and thus how thick we want the contour gaps to be.
Note that when $uTol=5$, the $uTol$ if-statement

```c
float scalar10 = float( 10*int( (scalar+5.)/10. ) );
if( abs( scalar - scalar10 ) < uTol )
    discard;
```

always fails, and we end up with the same display as we had with the interpolated colors. Thus, we wouldn’t actually need a separate color cutting plane shader at all. Shaders that can do double duty are always appreciated!

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The cutting plane is actually being used as a fragment-generator. Each fragment is then being asked “what data value lives at the same place you live”? Some shapes make better probes than others do… ☺️
An Observation

Note that Point Clouds, Jitter Clouds, Colored Cutting Planes, Contour Cutting Planes, and 3D Data Probes are really all the same technique!

They just vary in what type of geometry the data is mapped to. They use the same shader code, possibly with a switch between model and eye coordinates.

How about something less obvious like a torus?

Visualization Transfer Function – Relating Display Attributes to the Scalar Value

Frequency Histogram
Colors
Opacity
Scalar Value
Visualization -- Don't Send Colored Data to the GPU, Send the Raw Data and a Separate Transfer Function to the Fragment Shader

Use the GPU to turn the data into colored graphics on-the-fly

A Visualization Scenario

A thermal analysis reveals that a bar has a temperature of 0º at one end and 100º at the other end:

You want to color it with a rainbow scale as follows:

You also want to use smooth shading, so that you can render the bar as a single quadrilateral.

Should you assign colors first then interpolate, or interpolate first then assign colors? Will it matter? If so, how?
A Visualization Scenario

Assign colors from temperatures, then interpolate:

WRONG!

Interpolate temperatures first, then assign colors:

RIGHT!

Conclusion: let the rasterizer interpolate your scalar values and let your fragment shader assign colors and alphas to those values

Point Clouds – Three Ways to Assign the Scalar Function

Without shaders:
Assigning colors first – problems with interpolation

```
glBegin( GL_POINTS );
< convert s0 to r0,g0,b0, a0 >
gIColor4f( r0, g0, b0, a0 );
gPointSize( p0 );
gVertex3f( x0, y0, z0 );
...  
gEnd( );
```

With shaders:
Put the data in attribute variables

```
Pattern.Use( );
gBegin( GL_POINTS );
    Pattern.SetAttributeVariable( "Temperature", s0 );
gVertex3f( x0, y0, z0 );
...  
gEnd( );
```
With shaders:
"Hiding" the scalar value in the w component

```cpp
Pattern.Use();
glBegin( GL_POINTS );
  glVertex4f( x0, y0, z0, s0 );
  . . .
glEnd( );
```

With shaders:
The hidden scalar value in the w component must be extracted and replaced with 1.0 in the vertex shader

```cpp
out float vScalar;

void main() {
  vScalar = gl_Vertex.w;
  gl_Position = gl_ModelViewProjectionMatrix * vec4(gl_Vertex.xyz, 1. );
}
```

Volume Rendering – a different way to think of visualizing 3D Scalar Data

Each voxel has a color and opacity depending on its scalar value

Visualization by Ankit Khare
Volume Rendering – Compositing via Ray Casting

Thinking about it back-to-front:

\[
\begin{align*}
\text{color}_{12} &= \alpha_2 \text{color}_2 + (1 - \alpha_2) \text{black}, \\
\text{color}_{01} &= \alpha_1 \text{color}_1 + (1 - \alpha_1) \text{color}_{12}, \\
\text{color}^* &= \alpha_0 \text{color}_0 + (1 - \alpha_0) \text{color}_{01}.
\end{align*}
\]

Gives the front-to-back equation:

\[
\text{color}^* = \alpha_4 \text{color}_5 + (1 - \alpha_4) \alpha_3 \text{color}_5 + (1 - \alpha_4) (1 - \alpha_3) \alpha_2 \text{color}_2 + (1 - \alpha_4)(1 - \alpha_3)(1 - \alpha_2) \text{black}.
\]

\begin{verbatim}
float astar = 1.;
vec3 cstar = vec3( 0., 0., 0. );
for( int i = 0; i < uNumSteps; i++, STP += uDirSTP )
{
    if( any( lessThan( STP, vec3(0.,0.,0.) ) ) )
        continue;
    if( any( greaterThan( STP, vec3(1.,1.,1.) ) ) )
        continue;
    float scalar = texture3D( uTexUnit, STP ).r;
    if( scalar < uMin )
        continue;
    if( scalar > uMax )
        continue.;
    float alpha = uAmax;
    float t = ( scalar - SMIN ) / ( SMAX - SMIN );
    vec3 rgb = Rainbow( t );
    cstar += astar * alpha * rgb;
    astar *= ( 1. - alpha );
    // break out if the rest of the tracing won't matter:
    if( astar == 0. )
        break;
}
gl_FragColor = vec4( cstar, 1. );
\end{verbatim}
Volume Rendering – Compositing via Ray Casting

Volume Filtering – Median Filter

Visualizations by Ankit Khare
Volume Filtering – High Pass Filter Followed by Median Filter

Visualizations by Ankit Khare

Volume Visualization for OSU’S College of Vet Medicine

Visualization by Chris Schultz
At each fragment:

1. Find the flow field velocity vector there
2. Follow that vector in both directions
3. Blend in the colors at the other fragments along that vector

Use a vector field equation, or "hide" the velocity field in another texture image: \((v_x, v_y, v_z) \equiv (r, g, b)\)

```
uniform int                     uLength;
uniform sampler2D       uImageUnit;
uniform sampler2D       uFlowUnit;
uniform float                  uTime;
in vec2                            vST;

void main(  )
{
    ivec2 res = textureSize( uImageUnit, 0 );

    // flow field direction:
    vec2 st = vST;
    vec2 v = texture( uFlowUnit, st ).xy;
    v *= 1./vec2(res);

    st = vST;
    vec3 color = texture( uImageUnit, st ).rgb;
    int count = 1;
}
```
Vector Visualization: 2D Line Integral Convolution

```
st = vST;
for( int i = 0; i < uLength; i++ ) {
    st += uTime*v;
    vec3 new = texture( ulmageUnit, st ).rgb;
    color += new;
    count++;
}
st = vST;
for( int i = 0; i < uLength; i++ ) {
    st -= uTime*v;
    vec3 new = texture( ulmageUnit, st ).rgb;
    color += new;
    count++;
}
```

Flow around a corner

Flow in a circle
Vector Visualization: 3D Line Integral Convolution

Visualizations by Vasu Lakshmanan