Tesselation Shaders

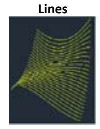
Thanks to Mike Bailey (OSU)

Why a tesselation shader

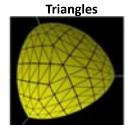
- You can perform adaptive subdivision based on a variety of criteria (size, curvature, etc.)
- Your application can provide coarser models (≈ geometric compression)
- You can apply detailed displacement maps without supplying equally detailed geometry
- You can adapt visual quality to the required level of detail
- You can create smoother silhouettes

What patterns can the Tessellation shaders produce?

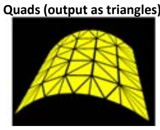
Lines

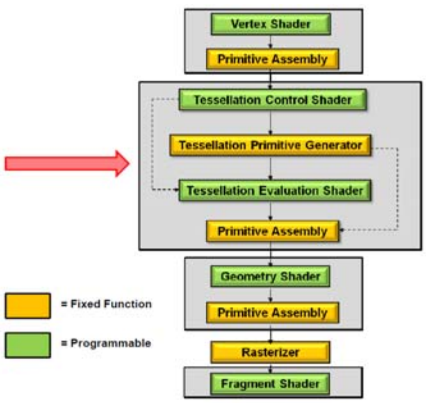


Triangles



Quads (output as triangles)





Another view of the Tess Shader

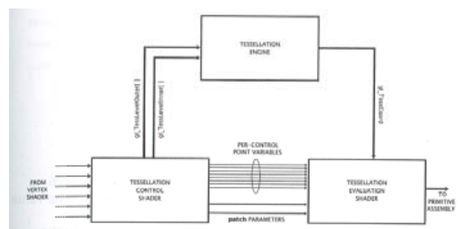
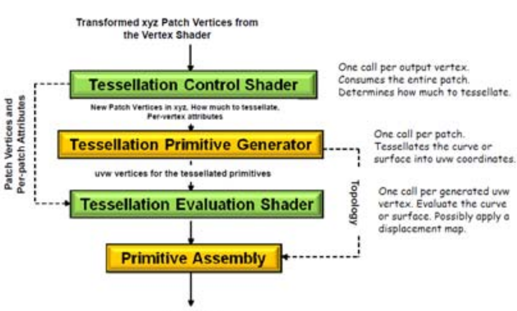
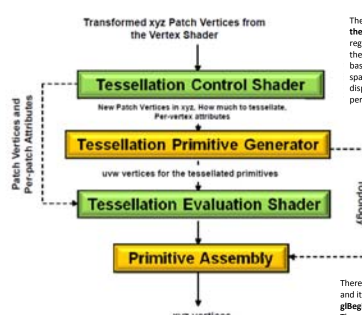


Figure 8.1: Schematic of OpenGL tessellation





The **Tessellation Control Shader (TCS) transforms the input coordinates to a** regular surface representation. It also computes the required tessellation level based on distance to the eye, screen space spanning, hull curvature, or displacement roughness. There is one invocation per output vertex.

The Fixed-Function **Tessellation Primitive Generator (TPG) generates semiregular** u-v-w coordinates.

The **Tessellation Evaluation Shader (TES) evaluates the surface in *uvw*** coordinates. It interpolates attributes and applies displacements. There is one invocation per generated vertex.

There is a new "Patch" primitive – it is the face and its neighborhood:
glBegin(GL_PATCHES)
There is no implied order – that is user-given.

In the OpenGL Program

```
glBegin( GL_PATCHES );
        glVertex3f( … );
        glVertex3f( … );
glEnd( );
```

These have no implied topology – it's up to how your shader interprets the order

```
GLuint tcs = glCreateShader( GL_TESS_CONTROL_SHADER );

GLuint tes = glCreateShader( GL_TESS_EVALUATION_SHADER );

glPatchParameteri( GL_PATCH_VERTICES, num );
        # vertices in each patch
```

If you have a TCS, you must also have a Vertex Shader

TCS Inputs

- **gl_in[ ]** is an array of structures containing:
  - gl_Position
  - gl_PointSize
  - gl_ClipDistance[ ]
- **gl_InvocationID** tells you which output vertex you are working on, This *must be the* index into the **gl_out[ ]** array.
- **gl_PatchVerticesIn** is the number of vertices in each patch and the dimension of **gl_in[ ]**
- **gl_PrimitiveID** is the number of primitives since last glBegin( ) (the first one is #0)
- **barrier( )** causes all instances of TCS's to wait here

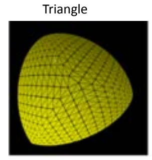
TCS Outputs

- **gl_out[ ]** is an array of structures containing:
  - gl_Position;
  - gl_PointSize;
  - gl_ClipDistance[ ];
- All invocations of the TCS have read-only access to all the output information. **barrier( )** causes all instances of TCS's to wait here
- **layout(vertices = n) out;** Used to specify the number of vertices output to the TPG
- Defining how many vertices this patch will output:
  layout(vertices = 16) out;
- **gl_TessLevelOuter[4]** is an array containing up to 4 edges of tessellation levels
- **gl_TessLevelInner[2]** is an array containing up to 2 edges of tessellation levels
- User-defined variables defined per-vertex are qualified as "out"
- User-defined variables defined per-patch are qualified as "patch out"

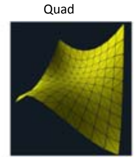
Tessellation Primitive Generator

- Is "fixed-function", i.e., you can't change its operation except by setting parameters
- Consumes all vertices from the TCS and emits tessellated **triangles, quads, or lines**
- Outputs positions as coordinates in barycentric (u,v,w)
- All three coordinates (u,v,w) are used for triangles
- Just (u,v) are used for quads and isolines

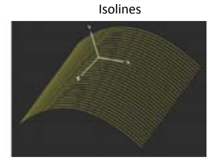
Triangle



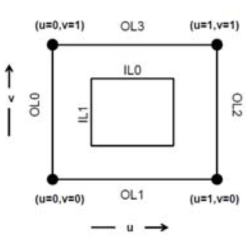
Quad

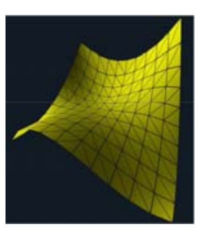


Isolines

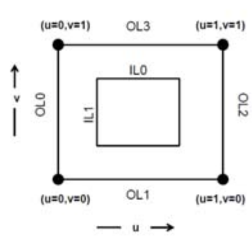


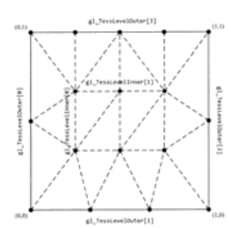
TES Output Topologies: the Quad Pattern



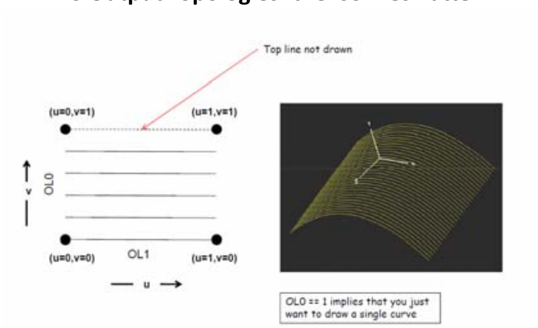


TES Output Topologies: the Quad Pattern

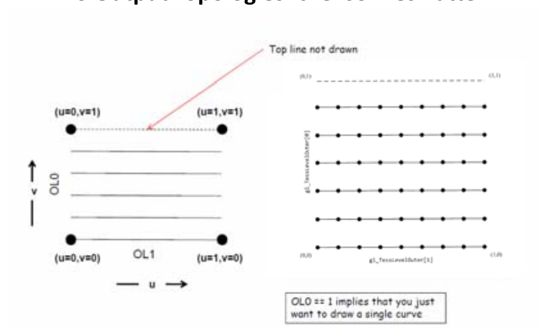




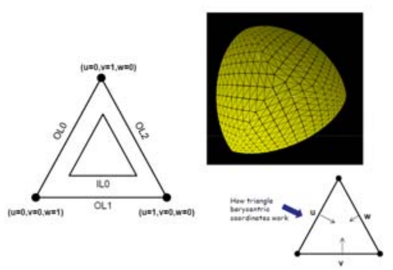
TES Output Topologies: the Isolines Pattern



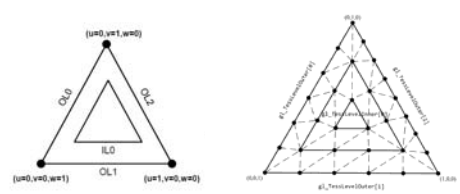
TES Output Topologies: the Isolines Pattern



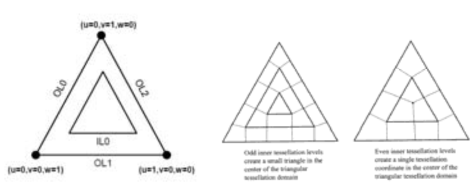
TES Output Topologies: the Triangle Pattern



TES Output Topologies: the Triangle Pattern



TES Output Topologies: the Triangle Pattern



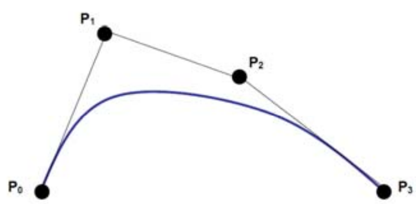
Demo tessmodes

TES subdivision

- layout(triangles, equal_spacing, ccw) in;
- ***equal_spacing*** means that the triangle edges will be subdivided into segments with equal lengths (according to the TLs).
- ***fractional_even_spacing*** means if there is a fractional portion based on TLs, it is evenly split between the ends.
- ***fractional_odd_spacing*** means if there is a fractional portion based on TLs, it is not evenly split between the ends.

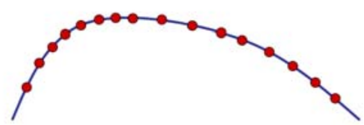
Demo tesssubdivisionmodes

Example: A Bézier Curve



$$P(u) = (1-u)^3 P_0 + 3u(1-u)^2 P_1 + 3u^2(1-u) P_2 + u^3 P_3$$

Example: A Bézier Curve



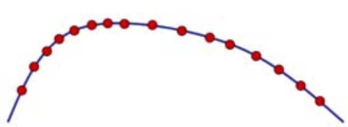
$$P(u) = (1-u)^3 P_0 + 3u(1-u)^2 P_1 + 3u^2(1-u) P_2 + u^3 P_3$$

1. The Tessellation Control Shader figures how much to tessellate the curve based on screen area, curvature, etc.

Can tessellate non-uniformly if desired

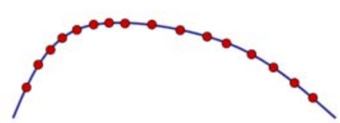
The OpenGL tessellation can also do 1D curves. Just set OL0 = 1.

Example: A Bézier Curve



2. The Tessellation Primitive Generator generates u[,v,w] values for as many subdivisions as the TCS asked for.

Example: A Bézier Curve



$$P(u) = (1-u)^3 P_0 + 3u(1-u)^2 P_1 + 3u^2(1-u) P_2 + u^3 P_3$$

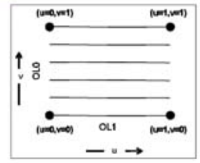
3. The Tessellation Evaluation Shader computes the x,y,z coordinates based on the TPG's u values

$$P(u) = u^3(-P_0 + 3P_1 - 3P_2 + P_3) + u^2(3P_0 - 6P_1 + 3P_2) + u(-3P_0 + 3P_1) + P_0$$

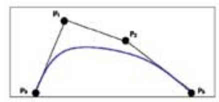
In the OpenGL Program

```
glPatchParameteri( GL_PATCH_VERTICES, 4 );

glBegin( GL_PATCHES );
            glVertex3f( x0, y0, z0 );
            glVertex3f( x1, y1, z1 );
            glVertex3f( x2, y2, z2 );
            glVertex3f( x3, y3, z3 );
glEnd( );
```

In the TCS Shader

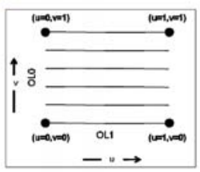


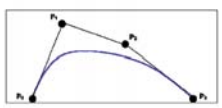

```
#version 400
#ension GL_ARB_tessellation_shader: enable

uniform int uOuter0, uOuter1;

layout( vertices = 4 )  out;

void main( )
{
      gl_out[ gl_InvocationID ].gl_Position = gl_in[ gl_InvocationID ].gl_Position;

      gl_TessLevelOuter[0] = float( uOuter0 );
      gl_TessLevelOuter[1] = float( uOuter1 );
}
```



In the TES Shader

```
#version 400
#ension GL_ARB_tessellation_shader: enable

layout( isolines, equal_spacing)  in;

void main( )
{
      vec4 p0 = gl_in[0].gl_Position;
      vec4 p1 = gl_in[1].gl_Position;
      vec4 p2 = gl_in[2].gl_Position;
      vec4 p3 = gl_in[3].gl_Position;

      float u = gl_TessCoord.x;

      // the basis functions:

      float b0 = (1.-u) * (1.-u) * (1.-u);
      float b1 = 3. * u * (1.-u) * (1.-u);
      float b2 = 3. * u * u * (1.-u);
      float b3 = u * u * u;

      gl_Position = b0*p0 + b1*p1 + b2*p2 + b3*p3;
}
```

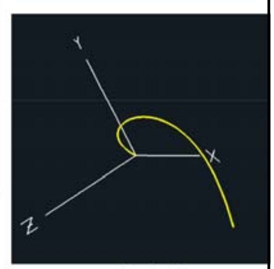




Assigning the intermediate pi's is here to make the code more readable. We assume that the compiler will optimize this away.

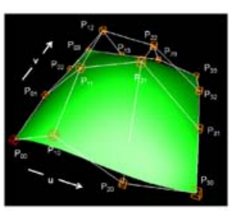
Example: A Bézier Curve

Outer1 = 5



Outer1 = 50

Bézier Surface Parametric Equations



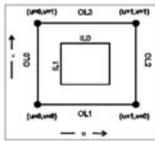
$$P(u,v)=\begin{bmatrix}(1-u)^3 & 3u(1-u)^2 & 3u^2(1-u) & u^3\end{bmatrix}\begin{bmatrix}P_{00} & P_{01} & P_{02} & P_{03}\\ P_{10} & P_{11} & P_{12} & P_{13}\\ P_{20} & P_{21} & P_{22} & P_{23}\\ P_{30} & P_{31} & P_{32} & P_{33}\end{bmatrix}\begin{Bmatrix}(1-v)^3\\ 3v(1-v)^2\\ 3v^2(1-v)\\ v^3\end{Bmatrix}$$

In the OpenGL Program

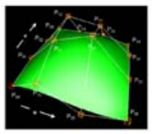
```
glPatchParameteri( GL_PATCH_VERTICES, 16 );

glBegin( GL_PATCHES );
            glVertex3f( x00, y00, z00 );
            glVertex3f( x10, y10, z10 );
            glVertex3f( x20, y20, z20 );
            glVertex3f( x30, y30, z30 );
            glVertex3f( x01, y01, z01 );
            glVertex3f( x11, y11, z11 );
            glVertex3f( x21, y21, z21 );
            glVertex3f( x31, y31, z31 );
            glVertex3f( x02, y02, z02 );
            glVertex3f( x12, y12, z12 );
            glVertex3f( x22, y22, z22 );
            glVertex3f( x32, y32, z32 );
            glVertex3f( x03, y03, z03 );
            glVertex3f( x13, y13, z13 );
            glVertex3f( x23, y23, z23 );
            glVertex3f( x33, y33, z33 );
glEnd( );
```

This order is unimportant. Pick a convention yourself and stick to it! GLSL doesn't care as long as you are consistent.

In the TCS Shader

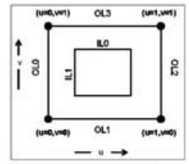


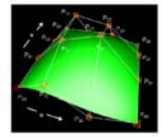

```
#version 400
#extension GL_ARB_tessellation_shader : enable

uniform float uOuter02, uOuter13, uInner0, uInner1;

layout( vertices = 16 )  out;

void main( )
{
        gl_out[ gl_InvocationID ].gl_Position = gl_in[ gl_InvocationID ].gl_Position;

        gl_TessLevelOuter[0] = gl_TessLevelOuter[2] = uOuter02;
        gl_TessLevelOuter[1] = gl_TesslevelOuter[3]  = uOuter13;
        gl_TessLevelInner[0]  = uInner0;
        gl_TessLevelInner[1]  = uInner1;
}
```



In the TES Shader

```
#version 400 compatibility
#extension GL_ARB_tessellation_shader : enable

layout( quads, equal_spacing, ccw)  in;

out vec3 teNormal;

void main(  )
{
        vec4 p00 = gl_in[ 0].gl_Position;
        vec4 p10 = gl_in[ 1].gl_Position;
        vec4 p20 = gl_in[ 2].gl_Position;
        vec4 p30 = gl_in[ 3].gl_Position;
        vec4 p01 = gl_in[ 4].gl_Position;
        vec4 p11 = gl_in[ 5].gl_Position;
        vec4 p21 = gl_in[ 6].gl_Position;
        vec4 p31 = gl_in[ 7].gl_Position;
        vec4 p02 = gl_in[ 8].gl_Position;
        vec4 p12 = gl_in[ 9].gl_Position;
        vec4 p22 = gl_in[10].gl_Position;
        vec4 p32 = gl_in[11].gl_Position;
        vec4 p03 = gl_in[12].gl_Position;
        vec4 p13 = gl_in[13].gl_Position;
        vec4 p23 = gl_in[14].gl_Position;
        vec4 p33 = gl_in[15].gl_Position;

        float u = gl_TessCoord.x;
        float v = gl_TessCoord.y;
```

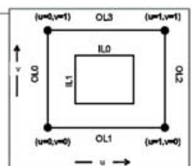




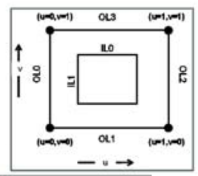
Assigning the intermediate pij's is here to make the code more readable. We assume that the compiler will optimize this away.

In the TES Shader – Computing the Position

```
// the basis functions:

float bu0 = (1.-u) * (1.-u) * (1.-u);
float bu1 = 3. * u * (1.-u) * (1.-u);
float bu2 = 3. * u * u * (1.-u);
float bu3 = u * u * u;

float dbu0 = -3. * (1.-u) * (1.-u);
float dbu1 =  3. * (1.-u) * (1.-3.*u);
float dbu2 =  3. * u *      (2.-3.*u);
float dbu3 =  3. * u *      u;

float bv0 = (1.-v) * (1.-v) * (1.-v);
float bv1 = 3. * v * (1.-v) * (1.-v);
float bv2 = 3. * v * v * (1.-v);
float bv3 = v * v * v;

float dbv0 = -3. * (1.-v) * (1.-v);
float dbv1 =  3. * (1.-v) * (1.-3.*v);
float dbv2 =  3. * v *      (2.-3.*v);
float dbv3 =  3. * v *      v;

// finally, we get to compute something:

gl_Position =          bu0 * ( bv0*p00 + bv1*p01 + bv2*p02 + bv3*p03 )
                     + bu1 * ( bv0*p10 + bv1*p11 + bv2*p12 + bv3*p13 )
                     + bu2 * ( bv0*p20 + bv1*p21 + bv2*p22 + bv3*p23 )
                     + bu3 * ( bv0*p30 + bv1*p31 + bv2*p32 + bv3*p33 );
```



In the TES Shader – Computing the Normal

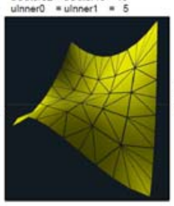



```
        vec4 dpdu =    dbu0 * ( bv0*p00 + bv1*p01 + bv2*p02 + bv3*p03 )
                     + dbu1 * ( bv0*p10 + bv1*p11 + bv2*p12 + bv3*p13 )
                     + dbu2 * ( bv0*p20 + bv1*p21 + bv2*p22 + bv3*p23 )
                     + dbu3 * ( bv0*p30 + bv1*p31 + bv2*p32 + bv3*p33 );

        vec4 dpdv =    bu0 * ( dbv0*p00 + dbv1*p01 + dbv2*p02 + dbv3*p03 )
                     + bu1 * ( dbv0*p10 + dbv1*p11 + dbv2*p12 + dbv3*p13 )
                     + bu2 * ( dbv0*p20 + dbv1*p21 + dbv2*p22 + dbv3*p23 )
                     + bu3 * ( dbv0*p30 + dbv1*p31 + dbv2*p32 + dbv3*p33 );

        teNormal = normalize( cross( dpdu.xyz, dpdv.xyz ) );
}
```

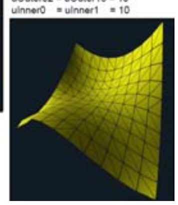
Example: A Bézier Surface

uOuter02 = uOuter13 = 5
uInner0 = uInner1 = 5

uOuter02 = uOuter13 = 10
uInner0 = uInner1 = 5

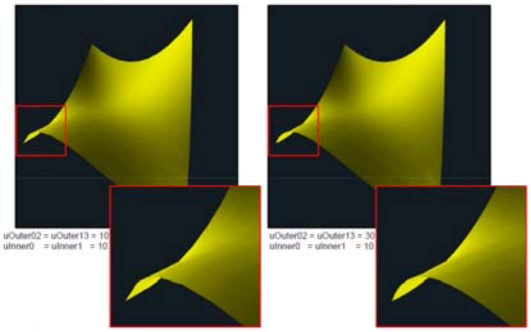


uOuter02 = uOuter13 = 10
uInner0 = uInner1 = 10



Bezier Patch

Tessellation Levels and Smooth Shading



Smoothing edge boundaries is one of the reasons that you can set Outer and Inner tessellation levels separately

Example: Whole-Sphere Subdivision

spheresubd.vert

```
#version 400 compatibility

out vec3  vCenter;
out float  vRadius;

void main( )
{
        vCenter = aVertex.xyz;
        vRadius = aVertex.w;

        gl_Position = vec4( 0., 0., 0., 1. );
}
```

Using the x, y, z, and w to specify the center and radius of the sphere

Example: Whole-Sphere Subdivision

spheresubd.tcs

```
#version 400 compatibility
#extension GL_ARB_tessellation_shader : enable

in float  vRadius[ ];
in vec3  vCenter[ ];

patch out float  tcRadius;
patch out vec3  tcCenter;

uniform float uDetail;
uniform float uScale;

layout( vertices = 1 ) out;

void main( )
{
        gl_out[ gl_InvocationID ].gl_Position = gl_in[ 0 ].gl_Position;    // (0,0,0,1)

        tcCenter = vCenter[ 0 ];
        tcRadius = vRadius[ 0 ];

        gl_TessLevelOuter[0] = 2.;
        gl_TessLevelOuter[1] = uScale * tcRadius * uDetail;
        gl_TessLevelOuter[2] = 2.;
        gl_TessLevelOuter[3] = uScale * tcRadius * uDetail;
        gl_TessLevelInner[0]  = uScale * tcRadius * uDetail;
        gl_TessLevelInner[1]  = uScale * tcRadius * uDetail;
}
```

Using the scale and the radius to help set the tessellation detail

Outer[0] and Outer[2] are the number of divisions at the poles. Outer[1] and Outer[3] are the number of divisions at the vertical seams. Inner[0] and Inner[1] are the inside sphere detail.

Example: Whole-Sphere Subdivision

spheresubd.tes

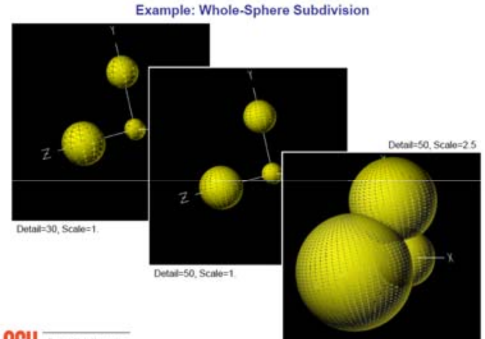
```
#version 400 compatibility
#extension GL_ARB_tessellation_shader : enable

uniform float  uScale;

layout( quads, equal_spacing, ccw) in;

patch in float  tcRadius;
patch in vec3  tcCenter;

out vec3        teNormal;

const float PI = 3.14159265;

void main( )
{
        vec3 p = gl_in[0].gl_Position.xyz;

        float u  = gl_TessCoord.x;
        float v  = gl_TessCoord.y;
        float w = gl_TessCoord.z;

        float phi   =       PI * ( u - .5 );
        float theta = 2. * PI * ( v - .5 );

        float cosphi = cos(phi);
        vec3 xyz = vec3( cosphi*cos(theta), sin(phi), cosphi*sin(theta) );
        teNormal = xyz;

        xyz *= ( uScale * tcRadius );
        xyz += tcCenter;

        gl_Position = uModelViewMatrix * vec4( xyz,1. );
}
```

$-\frac{\pi}{2} \le \theta \le +\frac{\pi}{2}$

$-\pi \le \theta \le +\pi$

Turning u and v into spherical coordinates

Example: Whole-Sphere Subdivision



Making the Whole-Sphere Subdivision Adapt to Screen Coverage

sphereadapt.tcs, I

```
#version 400 compatibility
#extension GL_ARB_tessellation_shader : enable

in float  vRadius[ ];
in vec3  vCenter[ ];

patch out float  tcRadius;
patch out vec3  tcCenter;

uniform float uDetail;

layout( vertices = 1 ) out;

void main( )
{
        gl_out[ gl_InvocationID ].gl_Position = gl_in[ 0 ].gl_Position;        // (0,0,0,1)

        tcCenter = vCenter[ 0 ];
        tcRadius = vRadius[ 0 ];

        vec4 mx = vec4( vCenter[0] - vec3( vRadius[0], 0., 0. ),  1. );
        vec4 px  = vec4( vCenter[0] + vec3( vRadius[0], 0., 0. ),  1. );
        vec4 my = vec4( vCenter[0] - vec3( 0., vRadius[0], 0. ),  1. );
        vec4 py  = vec4( vCenter[0] + vec3( 0., vRadius[0], 0. ),  1. );
        vec4 mz = vec4( vCenter[0] - vec3( 0., 0., vRadius[0] ),  1. );
        vec4 pz  = vec4( vCenter[0] + vec3( 0., 0., vRadius[0] ),  1. );
```

Extreme points of the sphere

Making the Whole-Sphere Subdivision Adapt to Screen Coverage

sphereadapt.tcs, II

```
        mx = uModelViewProjectionMatrix * mx;
        px  = uModelViewProjectionMatrix * px;
        my = uModelViewProjectionMatrix * my;
        py  = uModelViewProjectionMatrix * py;
        mz = uModelViewProjectionMatrix * mz;
        pz  = uModelViewProjectionMatrix * pz;

        mx.xy /= mx.w;
        px.xy  /= px.w;
        my.xy /= my.w;
        py.xy  /= py.w;
        mz.xy /= mz.w;
        pz.xy  /= pz.w;

        float dx = distance( mx.xy, px.xy );
        float dy = distance( my.xy, py.xy );
        float dz = distance( mz.xy, pz.xy );
        float dmax = sqrt( dx*dx + dy*dy + dz*dz );

        gl_TessLevelOuter[0] = 2.;
        gl_TessLevelOuter[1] = dmax * uDetail;
        gl_TessLevelOuter[2] = 2.;
        gl_TessLevelOuter[3] = dmax * uDetail;
        gl_TessLevelInner[0]  = dmax * uDetail;
        gl_TessLevelInner[1]  = dmax * uDetail;
}
```

Extreme points of the sphere in Clip space

Extreme points of the sphere in NDC space

How large are the lines between the extreme points?

We no longer use uScale or tcRadius. But, we do use uDetail to provide a way to convert from NDC to Screen Space or to indicate the quality you'd like

(I.e., uDetail depends on how good you want the spheres to look and on how large the window is in pixels.)

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Making the Whole-Sphere Subdivision Adapt to Screen Coverage

sphereadapt.tes

```
#version 400 compatibility
#extension GL_ARB_tessellation_shader : enable

layout( quads, equal_spacing, ccw) in;

patch in float  tcRadius;
patch in vec3  tcCenter;

out vec3        teNormal;

const float PI = 3.14159265;

void main( )
{
        vec3 p = gl_in[0].gl_Position.xyz;

        float u = gl_TessCoord.x;
        float v = gl_TessCoord.y;
        float w = gl_TessCoord.z;

        float phi    = PI *      ( u - .5 );
        float theta = 2. * PI * ( v - .5 );

        float cosphi = cos(phi);
        vec3 xyz = vec3( cosphi*cos(theta), sin(phi), cosphi*sin(theta) );
        teNormal = xyz;

        xyz *=  tcRadius;
        xyz += tcCenter;

        gl_Position = uModelViewMatrix * vec4( xyz,1. );
}
```

$-\frac{\pi}{2} \le \phi \le +\frac{\pi}{2}$

$-\pi \le \theta \le +\pi$

Spherical coordinates

No longer uses uScale

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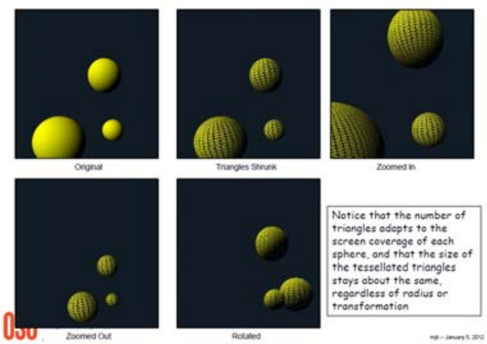
Making the Whole-Sphere Subdivision Adapt to Screen Coverage



Original · Triangles Shrunk · Zoomed In · Zoomed Out · Rotated

Notice that the number of triangles adapts to the screen coverage of each sphere, and that the size of the tessellated triangles stays about the same, regardless of radius or transformation

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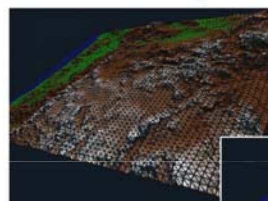
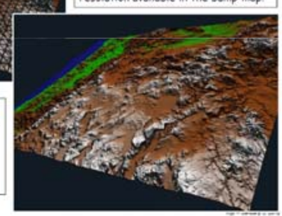
Demonstrating the Limits of Tessellation Shaders



The tessellation is using 64x64 (the maximum allowed).

The bump-map resolution is 4096x2276.

This is pretty good-looking, but doesn't come close to using the full resolution available in the bump-map.



Of course you could sub-tile the terrain so that each tile uses the full resolution of the bump-map in the tessellated terrain.

But, that would require 64x36, or 2304, tiles.

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Demo Displacement