OpenGL

- a quick guide

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Labs (= Tutorials)

- Some tutorials are on concepts treated on lectures at a later time.
  - When studying theory, it is beneficial to have some practice first…

  And

  - When doing tutorials, it is beneficial to have some theory first…

- Tradeoff
  - For practical reasons, we cannot have all theory in advance, so you get a bit of both worlds. The most important theory is often covered by lectures first.

Course strategy

- This course is more theory focused
  - Hardware acceleration evolves
    - Thus, implementation details change over time, while algorithms mostly stay the same.
  - Better to learn the algorithms, and look up hardware functionality at time of implementation
- Overview course
  - Less focus on details, which you can lookup yourself when you need them and if you are aware of the main concept.
- There will be half-time wrapup slides and full-time repetition slides
  - Covering **all** important topics for you on this course.

Repetition

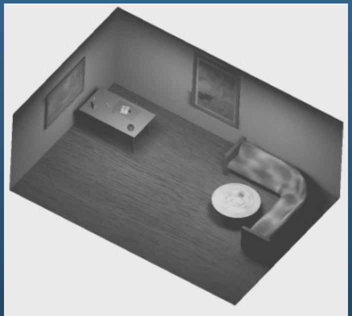
Rotation – here around z-axis

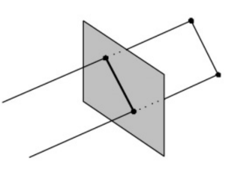
Translation

$$\mathbf{M} = \begin{pmatrix} \cos\alpha & -\sin\alpha & 0 & t_x \\ \sin\alpha & \cos\alpha & 0 & t_y \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\mathbf{M}_s = \begin{pmatrix} s_x & 0 & 0 & 0 \\ 0 & s_y & 0 & 0 \\ 0 & 0 & s_z & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\mathbf{M}_{ortho} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$





OpenGL vs Direct3D

Direct3D was messy to program version 3.0 – 6.0.

Today version 11 (12)

- Direct3D
  - Microsoft, Sept. ’95 on Windows95
  - Common for games
  - Historically: “Adapted to graphics hardware evolution”
    - Now: influences hardware features perhaps more than OpenGL
  - (Now after many upgrades very similar to OpenGL)
- OpenGL
  - SGI
  - Historically: “Precede the hardware evolution”
  - Operation system independent
  - Window system independent
  - Industry, games (Quake – thanks John Carmack)
  - January 1992
  - Extendable, stable API

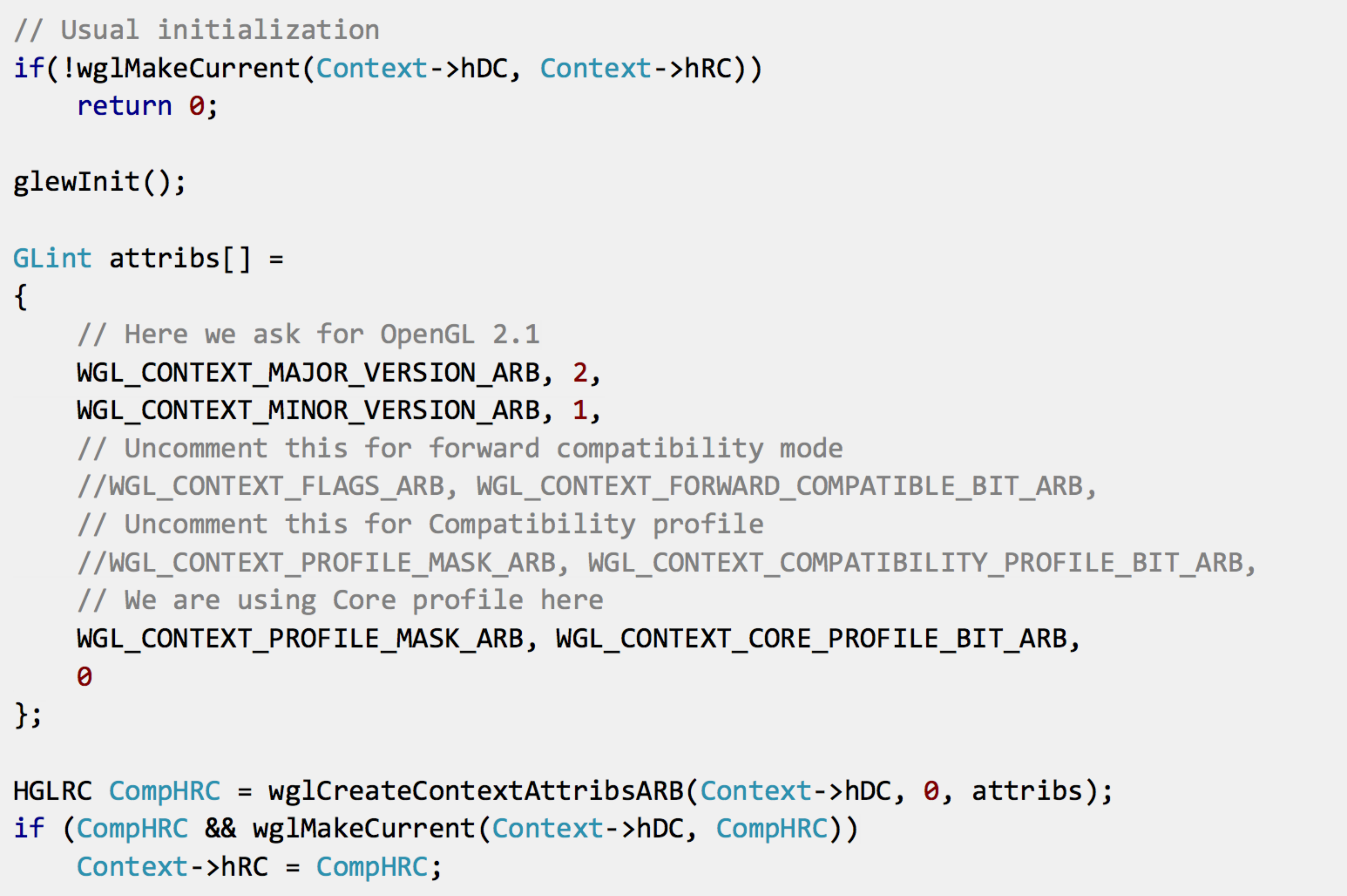
Perhaps why OpenGL still is largely used.

OpenGL – simplicity

- Single uniform interface to different 3D accelerators
- Hide different capabilities, requiring full support of the whole OpenGL feature set (using software emulation if necessary)

```
glMatrixMode( GL_PROJECTION );     /* Subsequent matrix commands will affect the projection matrix */
glLoadIdentity();                  /* Initialise the projection matrix to identity */
glFrustum( -1, 1, -1, 1, 1, 1000 ); /* Apply a perspective-projection matrix */

glMatrixMode( GL_MODELVIEW );      /* Subsequent matrix commands will affect the modelview matrix */
glLoadIdentity();                  /* Initialise the modelview to identity */
glTranslatef( 0, 0, -3 );          /* Translate the modelview 3 units along the Z axis */


glBegin( GL_POLYGON );   /* Begin issuing a polygon */
glColor3f( 0, 1, 0 );    /* Set the current color to green */
glVertex3f( -1, -1, 0 ); /* Issue a vertex */
glVertex3f( -1, 1, 0 );  /* Issue a vertex */
glVertex3f( 1, 1, 0 );   /* Issue a vertex */
glVertex3f( 1, -1, 0 );  /* Issue a vertex */
glEnd();                 /* Finish issuing the polygon */
```

E.g., setting OpenGL 2.1

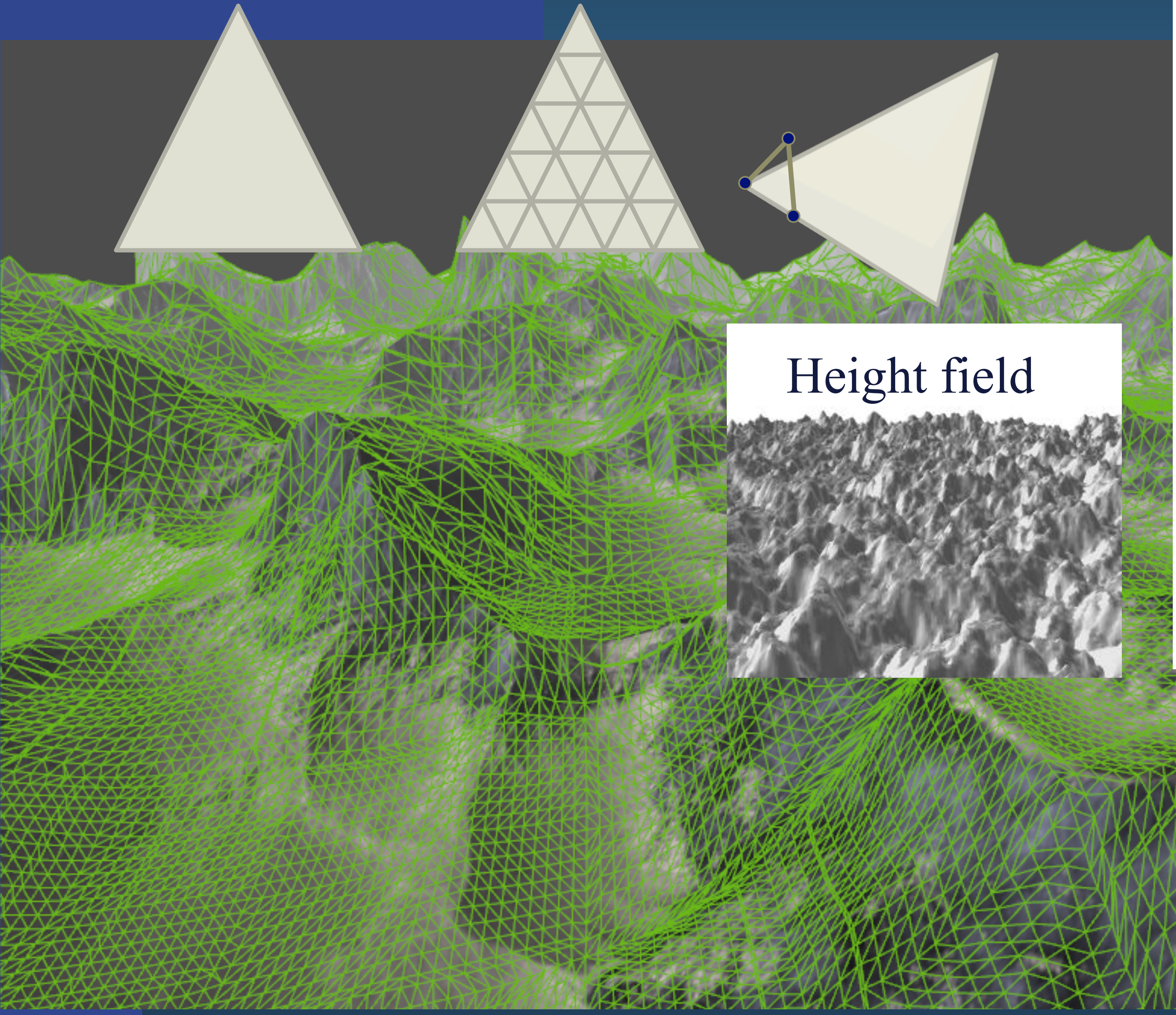


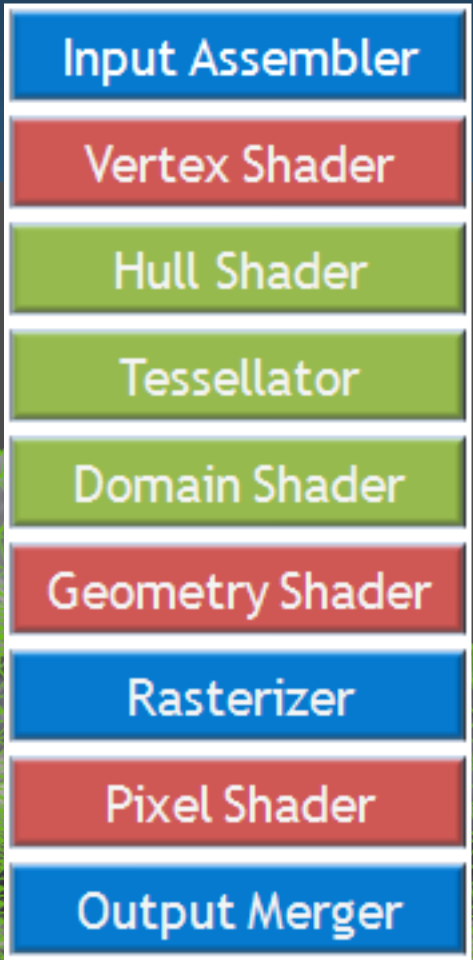
```
// Usual initialization
if(!wglMakeCurrent(Context->hDC, Context->hRC))
    return 0;

glewInit();

GLint attribs[] =
{
    // Here we ask for OpenGL 2.1
    WGL_CONTEXT_MAJOR_VERSION_ARB, 2,
    WGL_CONTEXT_MINOR_VERSION_ARB, 1,
    // Uncomment this for forward compatibility mode
    //WGL_CONTEXT_FLAGS_ARB, WGL_CONTEXT_FORWARD_COMPATIBLE_BIT_ARB,
    // Uncomment this for Compatibility profile
    //WGL_CONTEXT_PROFILE_MASK_ARB, WGL_CONTEXT_COMPATIBILITY_PROFILE_BIT_ARB,
    // We are using Core profile here
    WGL_CONTEXT_PROFILE_MASK_ARB, WGL_CONTEXT_CORE_PROFILE_BIT_ARB,
    0
};

HGLRC CompHRC = wglCreateContextAttribsARB(Context->hDC, 0, attribs);
if (CompHRC && wglMakeCurrent(Context->hDC, CompHRC))
    Context->hRC = CompHRC;
```

OpenGL Evolution

- Controlled by an Architecture Review Board (ARB)
  - Members include Apple, Intel, Nvidia, AMD, Samsung, Sony, ARM, Epic Games…….
  - Present version 4.5
    - Evolution reflects new hardware capabilities
      - **More functionality for vertex / fragment programs**
      - **Geometry shaders,**
      - **Tesselation units**
        - DX11: Hull shader = GL: Tesselation Control Shader
        - Domain shader = Tesselation Evaluation Shader
  - Allows for platform specific features through extensions

Tesselation – brief glance





Input Assembler

Vertex Shader

Hull Shader

Tessellator

Domain Shader

Geometry Shader

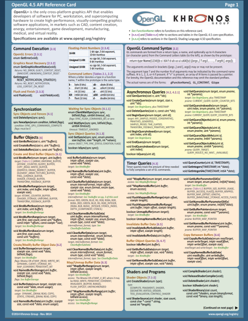
Rasterizer

Pixel Shader

Output Merger

Overview of today's OpenGL lecture

- OpenGL
  - Specifying vertices and polygons, Buffer Objects
  - Shaders
  - Framebuffer Objects
  - Texturing
  - Shadow Maps!
  - Blending
  - Buffers (frame b/f/l/r, depth, alpha-channel, stencil)
  - Misc: point/line width, clip planes
- GLU – The OpenGL Graphics System Utility Library
- GLUT – The OpenGL Utility Toolkit
  - Windows and menus
  - Callbacks for events
  - Text support
  - Predefined Objects

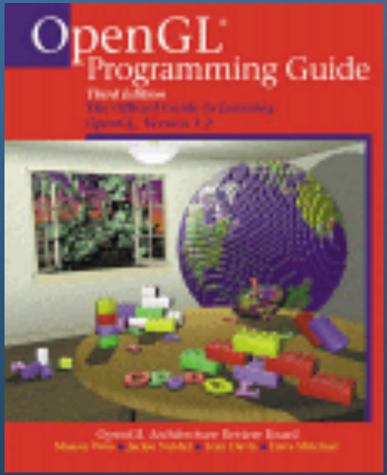


OpenGL – links

- https://www.khronos.org/files/opengl45-quick-reference-card.pdf
- Home page: www.opengl.org
- Sample code: http://www.opengl.org/wiki/Code_Resources/
- OpenGL 4.5 specification:
  - https://www.opengl.org/sdk/docs/man/
- GLU specification: http://www.cse.chalmers.se/~uffe/glu1.3.pdf
- GLUT specification: http://www.cse.chalmers.se/~uffe/glut-3.spec.pdf

ALSO ON COURSE HOME PAGE:

http://www.cse.chalmers.se/edu/course/TDA361/


OpenGL
Programming Guide
Third edition
The Official Guide to Learning OpenGL, Version 1.2
OpenGL Architecture Review Board
Mason Woo • Jackie Neider • Tom Davis • Dave Shreiner

- Programmers Manual and Reference Manual:
  - http://www.cse.chalmers.se/edu/course/TDA361/redbook.pdf
  - BUT IT IS HEAVILY OUTDATED BY NOW.
  - You can download the RedBook for OpenGL 4.3:
  - http://it-ebooks.info/book/2138/

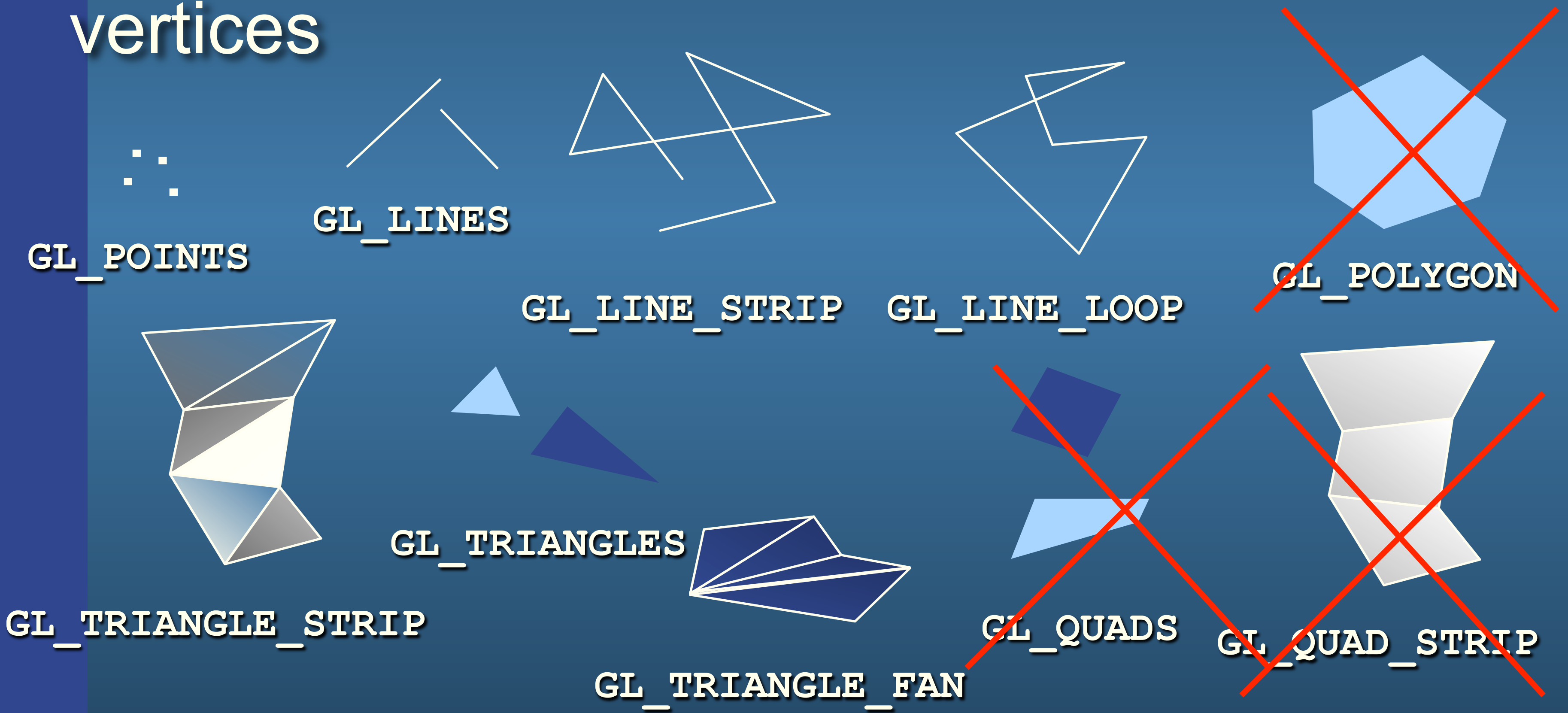
Include

- #include <GL/gl.h>
- Links with OpenGL32.lib (MS Windows)

- glew.h / glew32.lib / glew32.dll
- (GLee.h / GLee.cpp)

OpenGL Geometric Primitives

- All geometric primitives are specified by vertices



GL_POINTS

GL_LINES

GL_LINE_STRIP

GL_LINE_LOOP

GL_POLYGON

GL_TRIANGLE_STRIP

GL_TRIANGLES

GL_TRIANGLE_FAN

GL_QUADS

GL_QUAD_STRIP

Vertex order

glFrontFace(enum *dir)* *CCW, CW*
CullFace(enum *mode)* *-- mode: FRONT, BACK,*
FRONT_AND_BACK
glEnable/Disable(CULL_FACE)

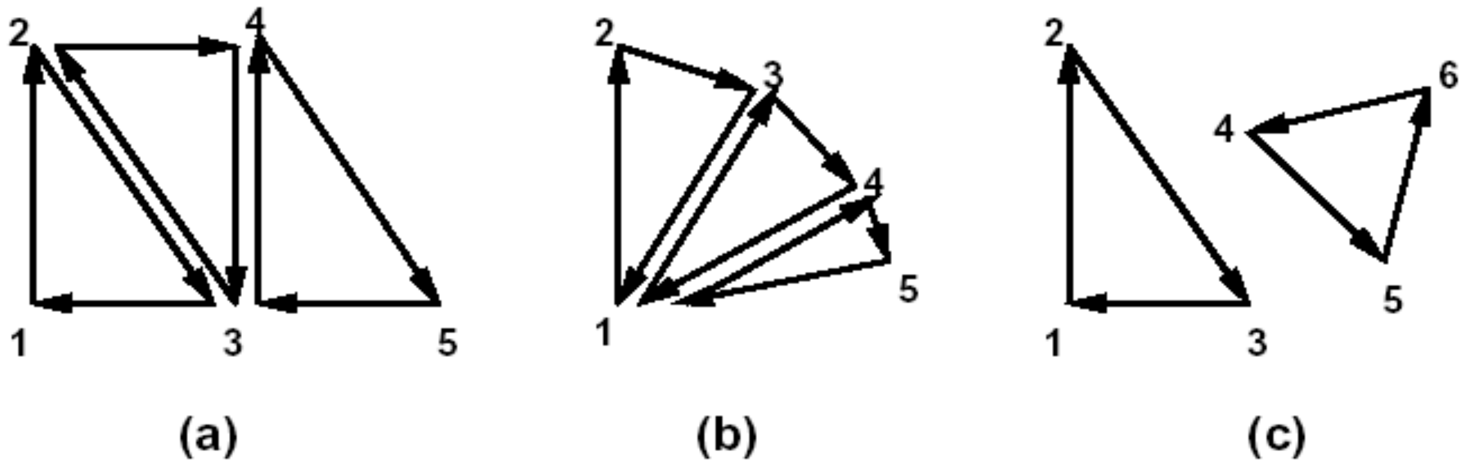


Figure 2.4. (a) A triangle strip. (b) A triangle fan. (c) Independent triangles. The numbers give the sequencing of the vertices between **Begin** and **End**. Note that in (a) and (b) triangle edge ordering is determined by the first triangle, while in (c) the order of each triangle's edges is independent of the other triangles.

Note: Vertex order indicates that all but the last triangle is backfacing with CCW-ordering (default for OpenGL).

Specifying vertices and polygons

- OpenGL is a state machine. Commands typically change the current state

Historical Commands:

- Multiple formats for the commands: `void` **glVertex{234}{sifd}**(`T` *coords*)**;**
- glBegin()/glEnd(). (Slow)

```
glBegin(GL_TRIANGLE)
        glVertex3f(0,0,0)
        glVertex3f(0,1,0);
        glVertex3f(1,1,0);
glEnd();
```

Optional: Can specify for instance glColor3f(r,g,b), glTexCoord2f(s,t), glNormal3f(x,y,z) - typically per vertex or per primitive.

TODAY, WE RATHER USE VERTEX ARRAYS

- Vertex Arrays (Fast):

void **DrawArrays(enum *mode, int first, sizei count);***

void **MultiDrawArrays(enum *mode, int *first, sizei *count,*** sizei *primcount);*

void **DrawElements(enum *mode, sizei count, enum type,*** void **indices);*

Using index list

other options exist - see the OpenGL Reference Manual online

```
MultiDrawArrays:
for (i = 0; i < primcount; i++)
    DrawArrays(mode, first[i], count[i]);
```

Example of using Vertex Arrays

1. // SEND THE VERTEX COORDINATES TO A BUFFER

```
glGenBuffers( 1, &coordBuffer );                          // Create a handle for the coordinate buffer
glBindBuffer( GL_ARRAY_BUFFER, coordBuffer );         // Set the newly created buffer as the current one
glBufferData( GL_ARRAY_BUFFER, sizeof(coords), coords, GL_STATIC_DRAW );     // Send the data

// Do the same thing for the color data
glGenBuffers( 1, &colorBuffer );
glBindBuffer( GL_ARRAY_BUFFER, colorBuffer );
glBufferData( GL_ARRAY_BUFFER, sizeof(colors), colors, GL_STATIC_DRAW );
```

```
Float coords[] = {
//   X     Y    Z
  0.0f,  0.5f, 1.0f,   // v0
 -0.5f, -0.5f, 1.0f,   // v1
  0.5f, -0.5f, 1.0f,   // v2
  0.0f, -1.0f, 1.0f    // v3
};

float colors[] = {
//  R     G     B
1.0f, 0.0f, 0.0f,  // Red
0.0f, 1.0f, 0.0f,  // Green
0.0f, 0.0f, 1.0f,  // Blue
1.0f, 1.0f, 0.0f   // Yellow
}
```

```
// Connect triangle data with a Vertex Array Object and the Vertex shader
glGenVertexArrays(1, &vertexArrayObject);
glBindVertexArray(vertexArrayObject);

// Connects coordBuffer to vertexArrayObject and activates coordBuffer for next command below.
glBindBuffer( GL_ARRAY_BUFFER_ARB, coordBuffer );
glVertexAttribPointer(0, 3, GL_FLOAT, false/*normalized*/, 0/*stride*/, 0/*offset*/ );

// Connects colorBuffer to vertexArrayObject and activates colorBuffer for command below.
glBindBufferARB( GL_ARRAY_BUFFER_ARB, colorBuffer );
glVertexAttribPointer(1, 3, GL_FLOAT, false/*normalized*/, 0/*stride*/, 0/*offset*/ );

glEnableVertexAttribArray(0);
glEnableVertexAttribArray(1);
```

VERTEX SHADER

```
in  vec3 vertex;
in  vec3 color;
out vec3 outColor;
uniform mat4 modelViewProjectionMtx;

void main() {
   gl_Position = modelViewProjectionMtx*
                        vec4(vertex,1);
   outColor = color;
}
```

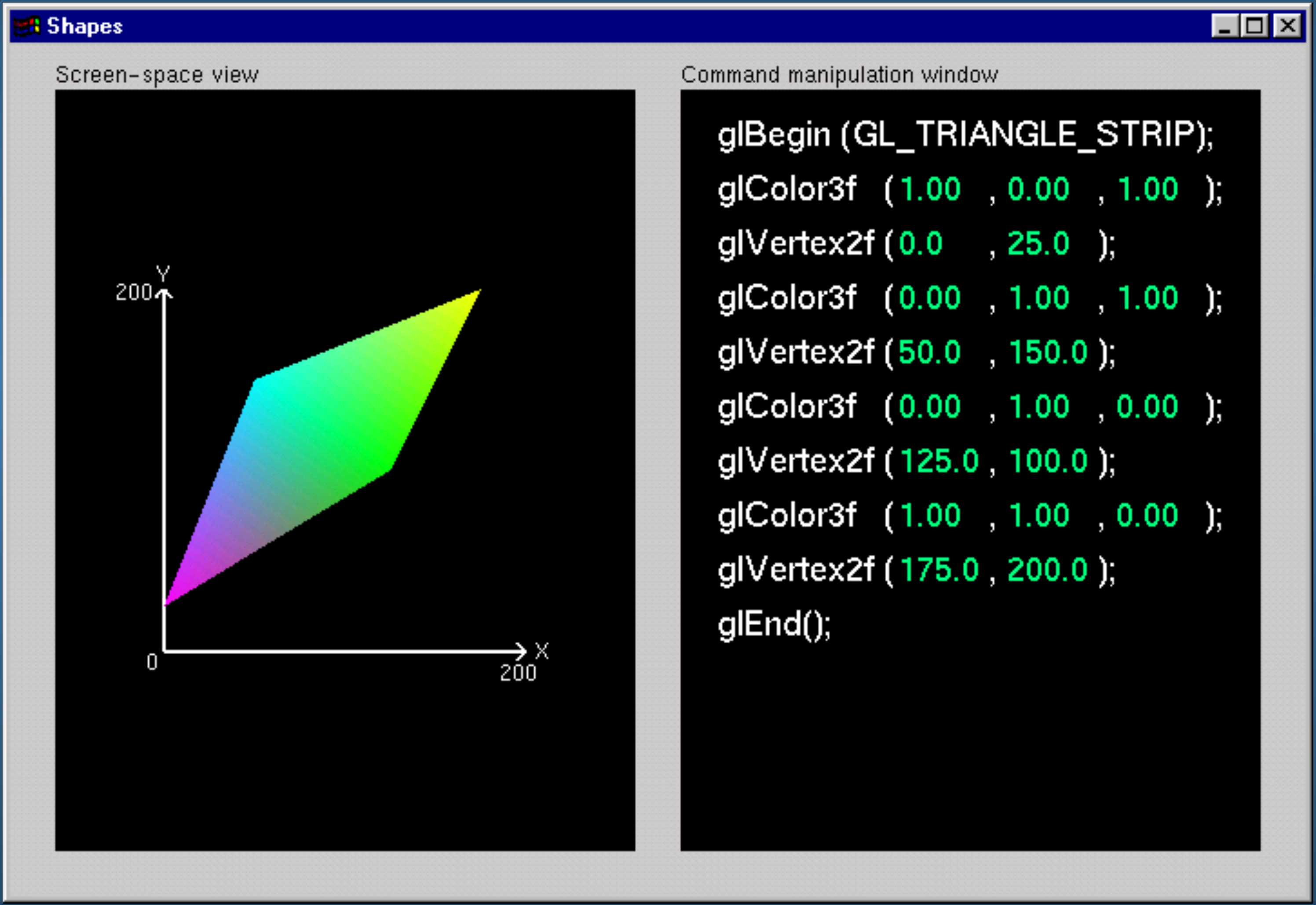
2. // Just before linking the shader program, you should specify:

```
glBindAttribLocation(shaderProgram, 0, "vertex");
glBindAttribLocation(shaderProgram, 1, "color");
```

3. COMMANDS TO DRAW

```
glUseProgram( shaderProgram );
glBindVertexArray(vertexArrayObject);
glDrawArrays( GL_TRIANGLE_STRIP, 0, 4 );
```

Example of historical slow way:



```
glBegin (GL_TRIANGLE_STRIP);
glColor3f  (1.00  , 0.00  , 1.00  );
glVertex2f (0.0   , 25.0  );
glColor3f  (0.00  , 1.00  , 1.00  );
glVertex2f (50.0  , 150.0 );
glColor3f  (0.00  , 1.00  , 0.00  );
glVertex2f (125.0 , 100.0 );
glColor3f  (1.00  , 1.00  , 0.00  );
glVertex2f (175.0 , 200.0 );
glEnd();
```

Example of a GfxObject Class

```
class GfxObject {
public:
        Object() {};
        ~Object() {};
        render(); E.g.:
        load(“filename”);
…
private:
        Matrix4x4               m_modelToWorldTransform;
        std::vector<vec3f>      m_vertices;
        std::vector<vec3f>      m_normals;
        std::vector<vec2f>      m_texCoords;
        std::vector<vec3f>      m_colors;
or just:
        GLhandle                m_shaderProgram;
        GLuint                  m_vertexArrayObject;
}
```

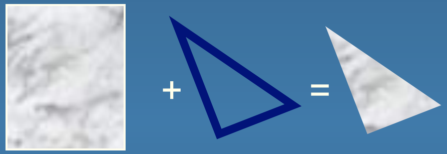
```
{
  glUseProgram(m_shaderProgram);
  int loc = glGetUniformLocation(shaderProgram,
                  "modelViewProjectionMatrix");
  glUniformMatrix4fv(loc, 1, false,
                  &modelViewProjectionMatrix);

  glBindVertexArray(m_vertexArrayObject);
  glDrawArrays( GL_TRIANGLES, 0, m_vertices.size());
}
```

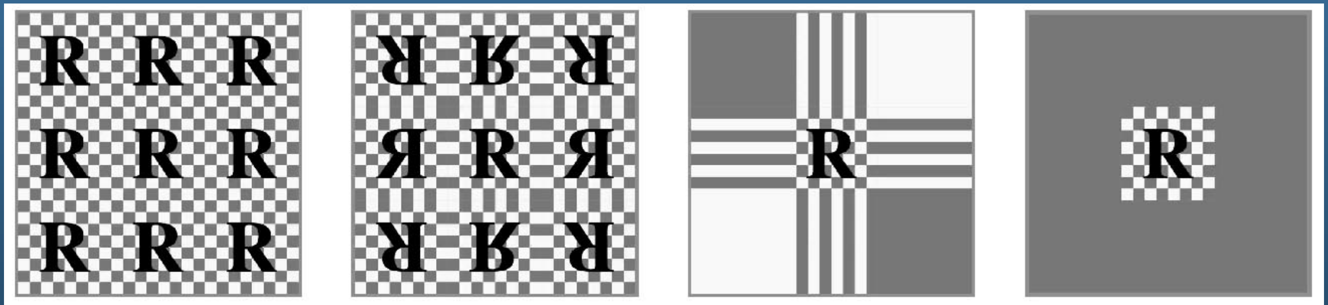
Triangle data is necessary for collision detection and updating of data.

Texture Mapping

You probably recognize from lab 2

- Three steps
  - ① specify texture
    - read or generate image
    - assign to texture – `glGenTextures(), glBindTexture(), glTexImage2D(), glGenerateMipMap()`
  - ② assign texture coordinates to vertices
  - ③ specify texture parameters
    - set texture filter – `glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER,… )`
    - set texture wrap mode – `glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S,…)`





Texture Mapping

Specifying Texture:

```
texID = ilutGLLoadImage("flake.ppm"); // Here, we use DevIL
glActiveTexture(enum texUnit) -- specify texture unit  (up to 32)
glBindTexture(texID), -- specify texture ID that this texture unit and data is identified with
glTexImage1/2/3D (), glCopyTexSubImage2D() -- set / affect ima
glGenerateMipMap() -- Create the mipmap hierarchy
glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_MAX_ANISOTROPY
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPE
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPE
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LI
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR
```

VERTEX SHADER

```
in  vec3 vertex;
in  vec3 texCoordIn;
out vec3 texCoord;
uniform mat4 modelViewProjectionMtx;
void main() {
   gl_Position = modelViewProjectionMtx*
                    vec4(vertex,1);
   texCoord = texCoordIn;
}
```

Specifying Texture Coordinates

```
1. // Send the TEXTURE COORDINATES to a buffer
glGenBuffers( 1, &texcoordBuffer );                 // Create a handle for the texcoord buffer
glBindBuffer( GL_ARRAY_BUFFER, texcoordBuffer );    // Set the newly created buffer as the current one
glBufferData( GL_ARRAY_BUFFER, sizeof(texcoords), texcoords, GL_STATIC_DRAW ); // Send the data
```

```
float texcoords[] = {
0.0f, 1.0f,
 0.0f, 0.0f,
 1.0f, 0.0f,
 1.0f, 1.0f
};
```

```
// Connect texcoord data with the Vertex Array Object and the Vertex shader
glBindVertexArray(vertexArrayObject);

// Connects texcoordBuffer to vertexArrayObject
glBindBuffer( GL_ARRAY_BUFFER_ARB, texcoordBuffer );
glVertexAttribPointer(1, 2, GL_FLOAT, false/*normalized*/, 0/*stride*/, 0/*offset*/ );

glEnableVertexAttribArray(2);
```

```
useProgram (shaderProgram) ....
int texLoc = glGetUniformLocationARB( shaderProgram, "tex0" );
glUniform1iARB( texLoc, 0 );
```

FRAGMENT SHADER

```
uniform sampler2D tex0;

in vec2 texCoord;

void main()
{
   gl_FragColor = texture2D(tex0,
                    texCoord.xy);
}
```

Example of Loading a Texture

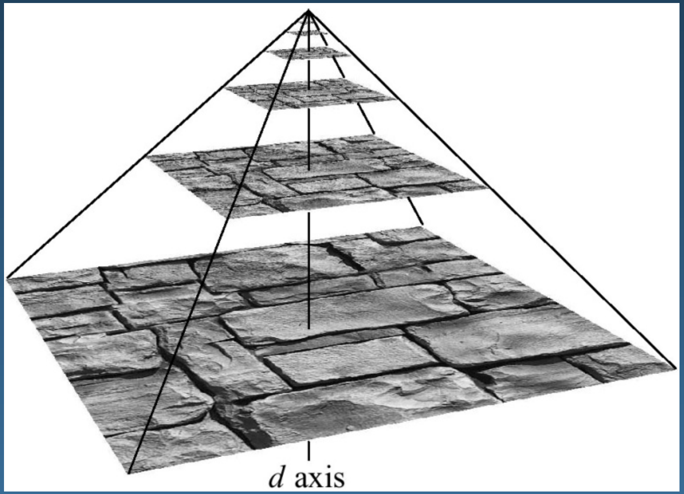
Do once when loading texture:

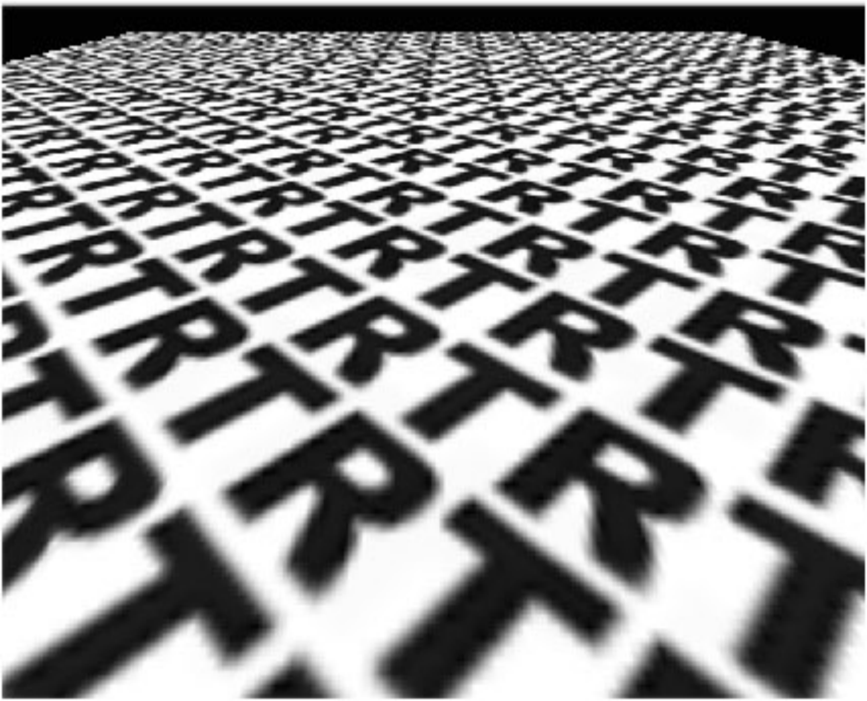
```
 texture = ilutGLLoadImage("flake.ppm");          // Here, we use DevIL
glActiveTexture(GL_TEXTURE0);
glBindTexture(GL_TEXTURE_2D, texture);
glGenerateMipmap(GL_TEXTURE_2D);

glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_MAX_ANISOTROPY_EXT, 16);

//Indicates that the active texture should be repeated over the surface
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT);
// Sets the type of mipmap interpolation to be used on magnifying and
// minifying the active texture. These are the nicest available options.
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER,
GL_LINEAR_MIPMAP_LINEAR);
```

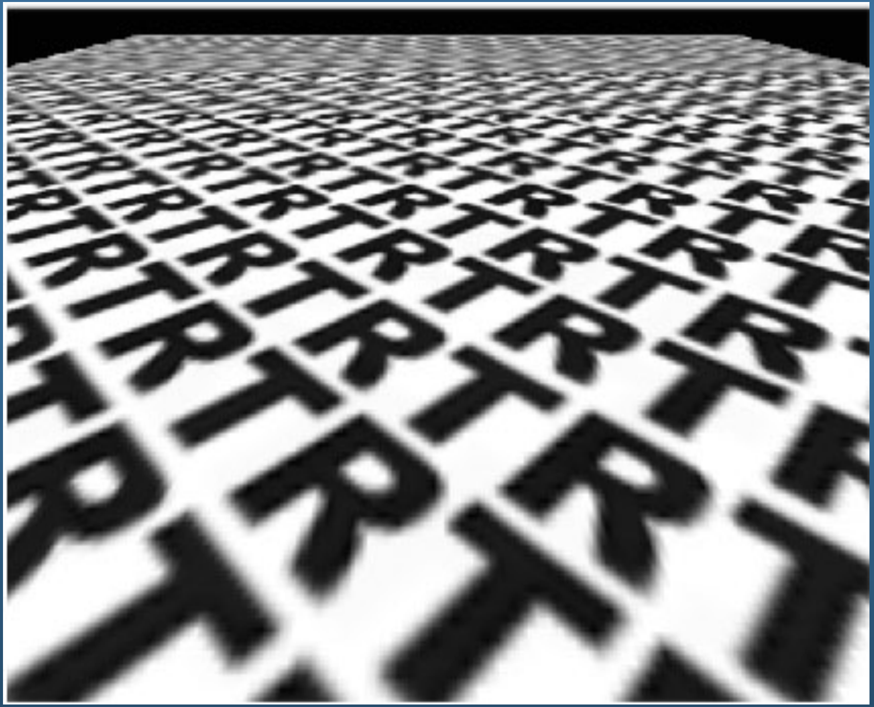
Do every time you want to use this texture when drawing:

```
 glActiveTexture(GL_TEXTURE0);
glBindTexture(GL_TEXTURE_2D, texture);
```

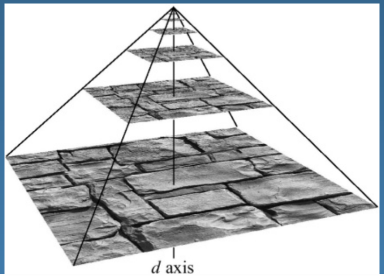
Mip Mapping

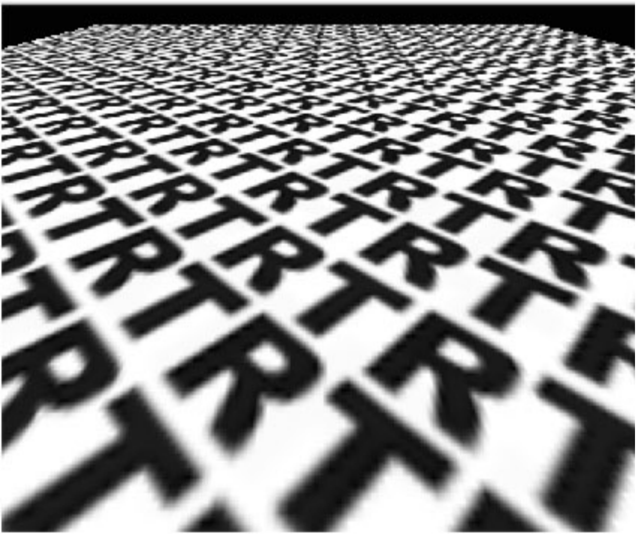




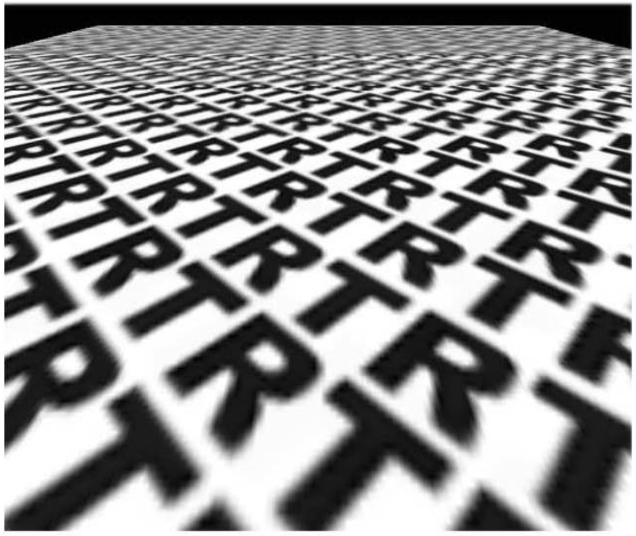


Anisotropic filtering

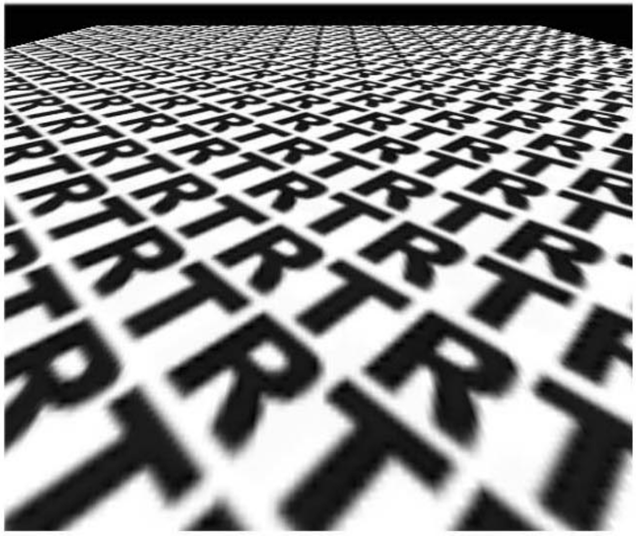




No filtering



Mipmapping



Anisotropic

Anisotropic filtering and auto-mipmap generation

Enabling anisotropic filtering:

- float MaxAnisotropy
- glGetFloatv(GL_MAX_TEXTURE_MAX_ANISOTROPY_EXT, &MaxAnisotropy);

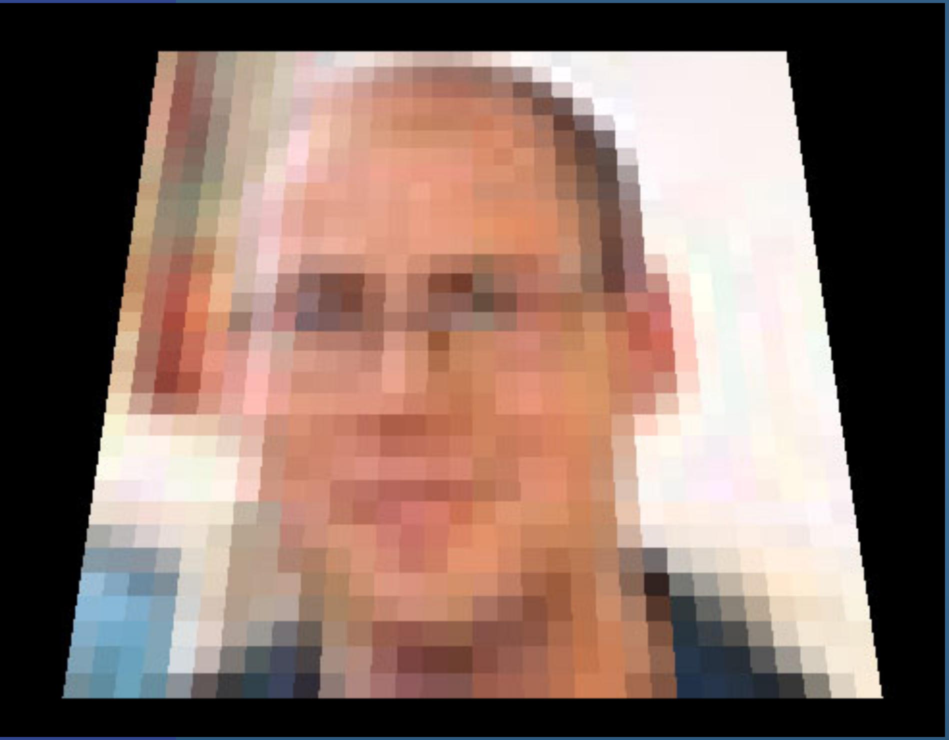
- glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_MAX_ANISOTROPY_EXT, MaxAnisotropy);

~~Enabling autogeneration of mipmaps (mipmaps are recomputed when the texture data changes) :~~

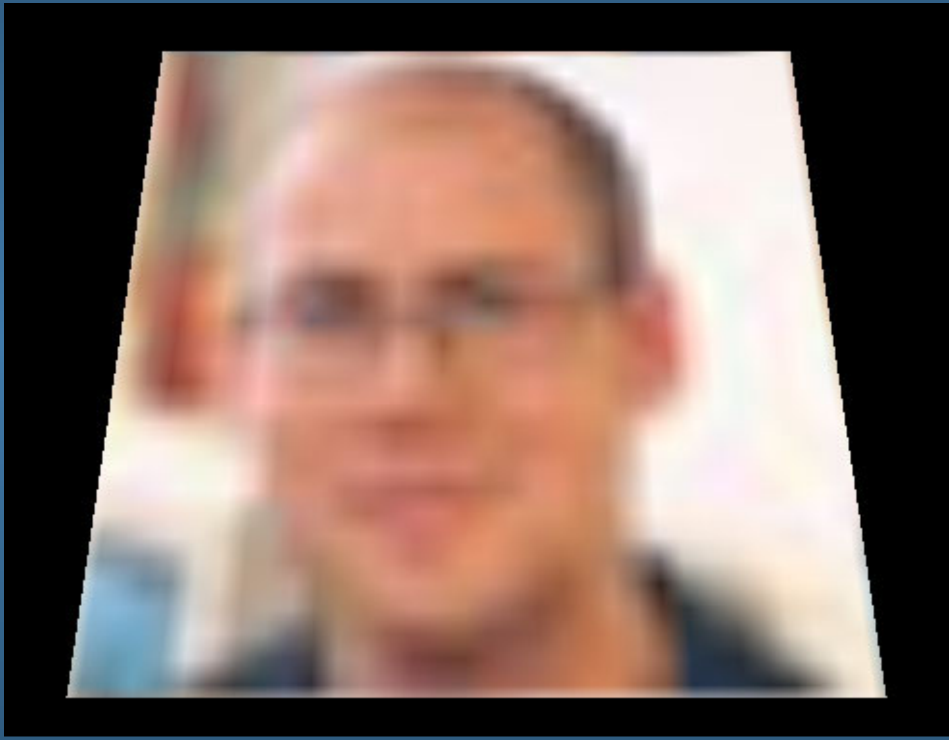
- ~~glTexParameteri(GL_TEXTURE_2D,~~

  ~~GL_GENERATE_MIPMAP_SGIS, GL_TRUE);~~

Examples of filtering



Nearest



Linear

Specifying a Texture: Other Methods

- Use frame buffer as source of texture image
  - uses current buffer as source image

```
glCopyTexImage1D(...)
glCopyTexImage2D(...)
```

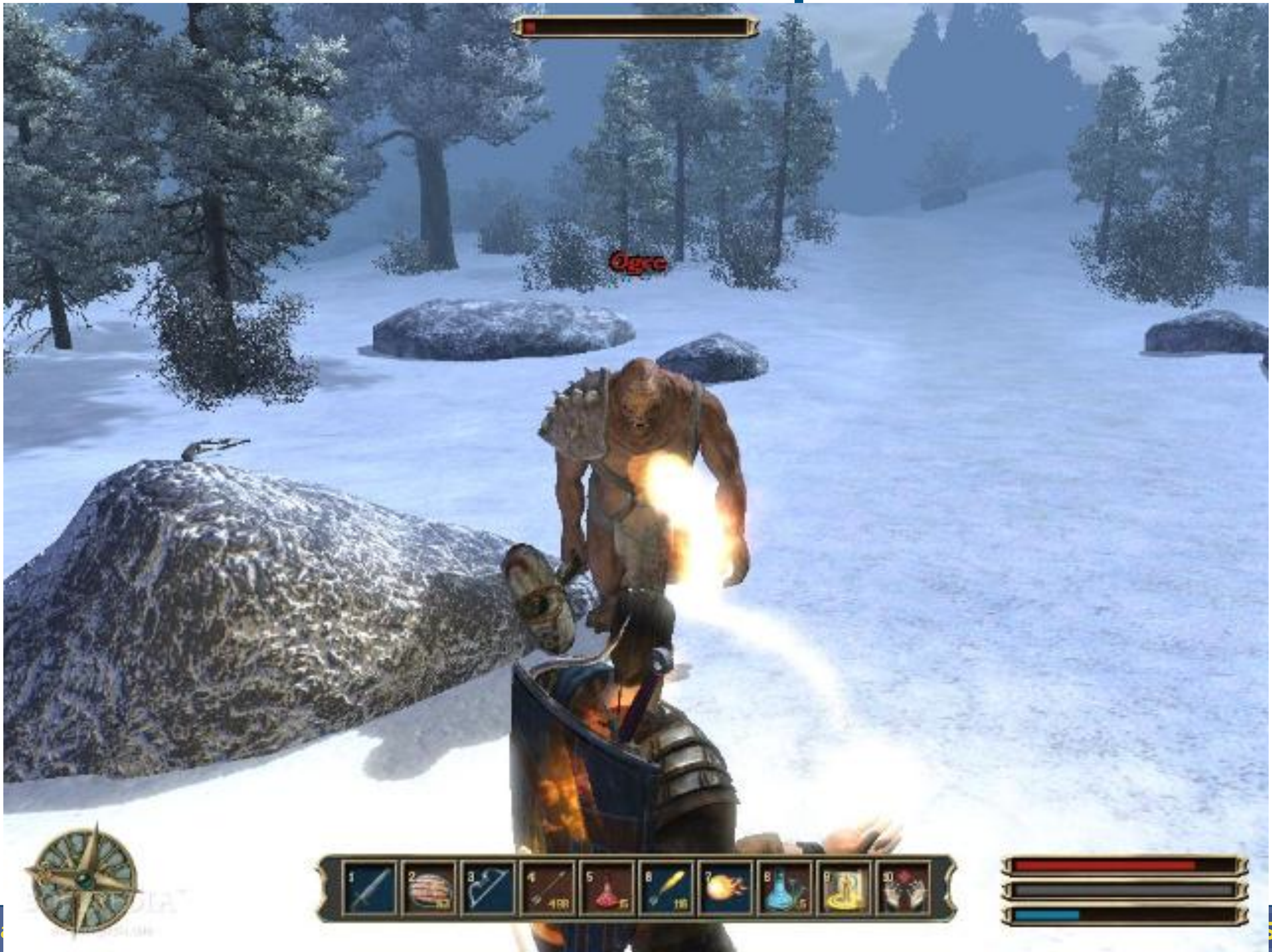
- Modify part of a defined texture

```
glTexSubImage1D(...)
glTexSubImage2D(...)
glTexSubImage3D(...)
```

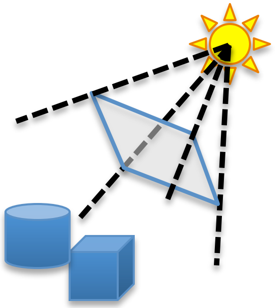
- Do both with ***`glCopyTexSubImage2D(...)`***, etc.

Shadow Maps

Shadow Maps



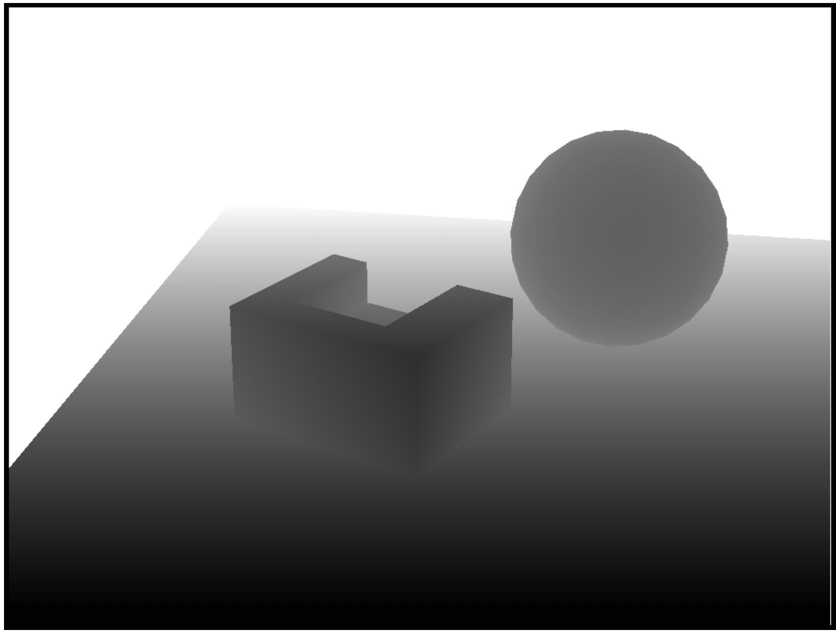
Shadow Maps



Basic Algorithm – the simple explanation:

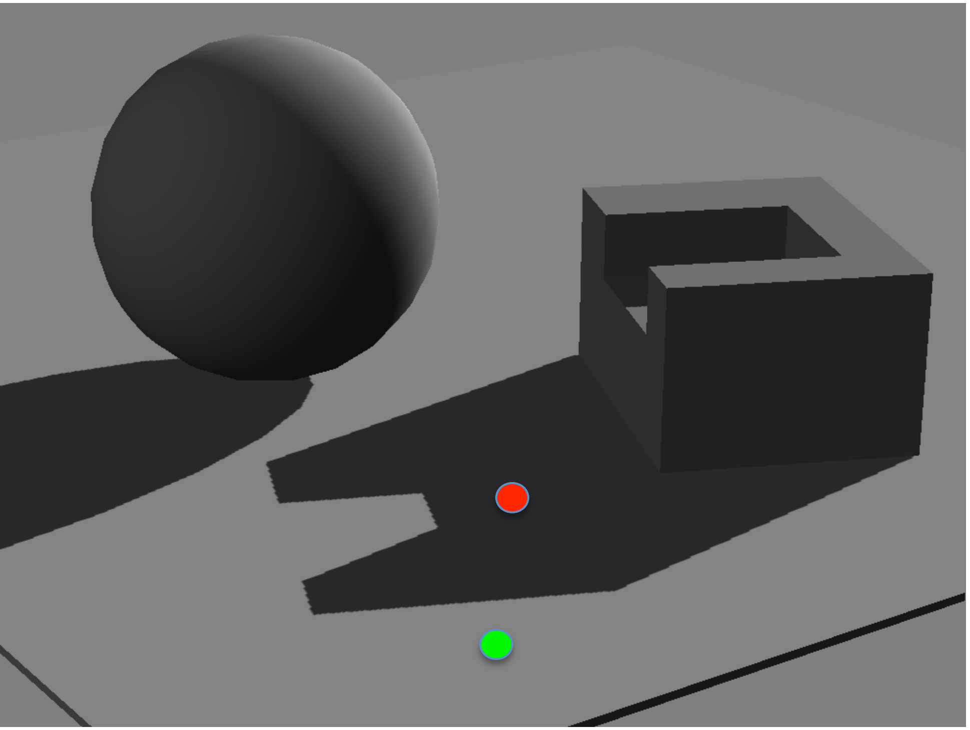
Idea:

- Render image from light source
  - Represents geometry in light
- Render from camera
  - Test if rendered point is visible in the light's view
    - If so -> point in light
    - Else -> point in shadow



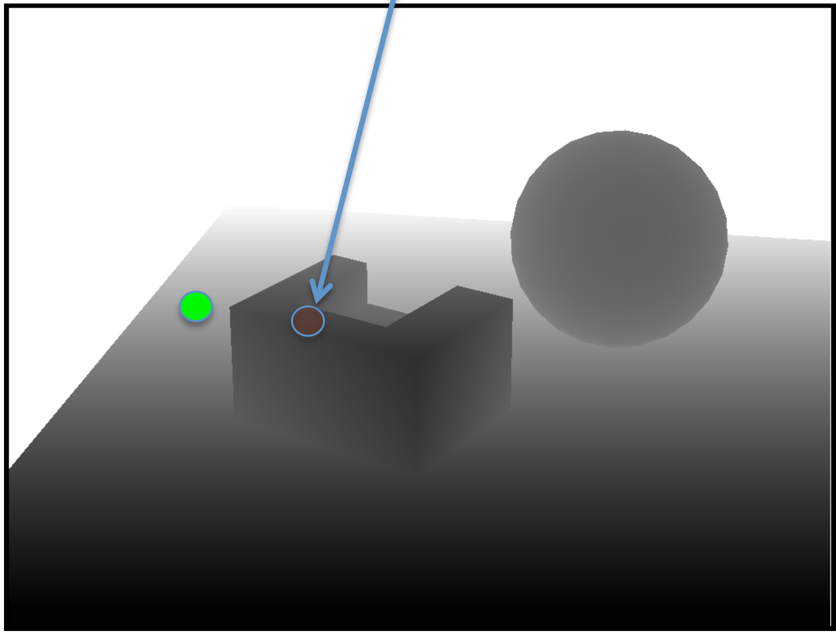
Shadow Map (light's view)

Shadow Maps



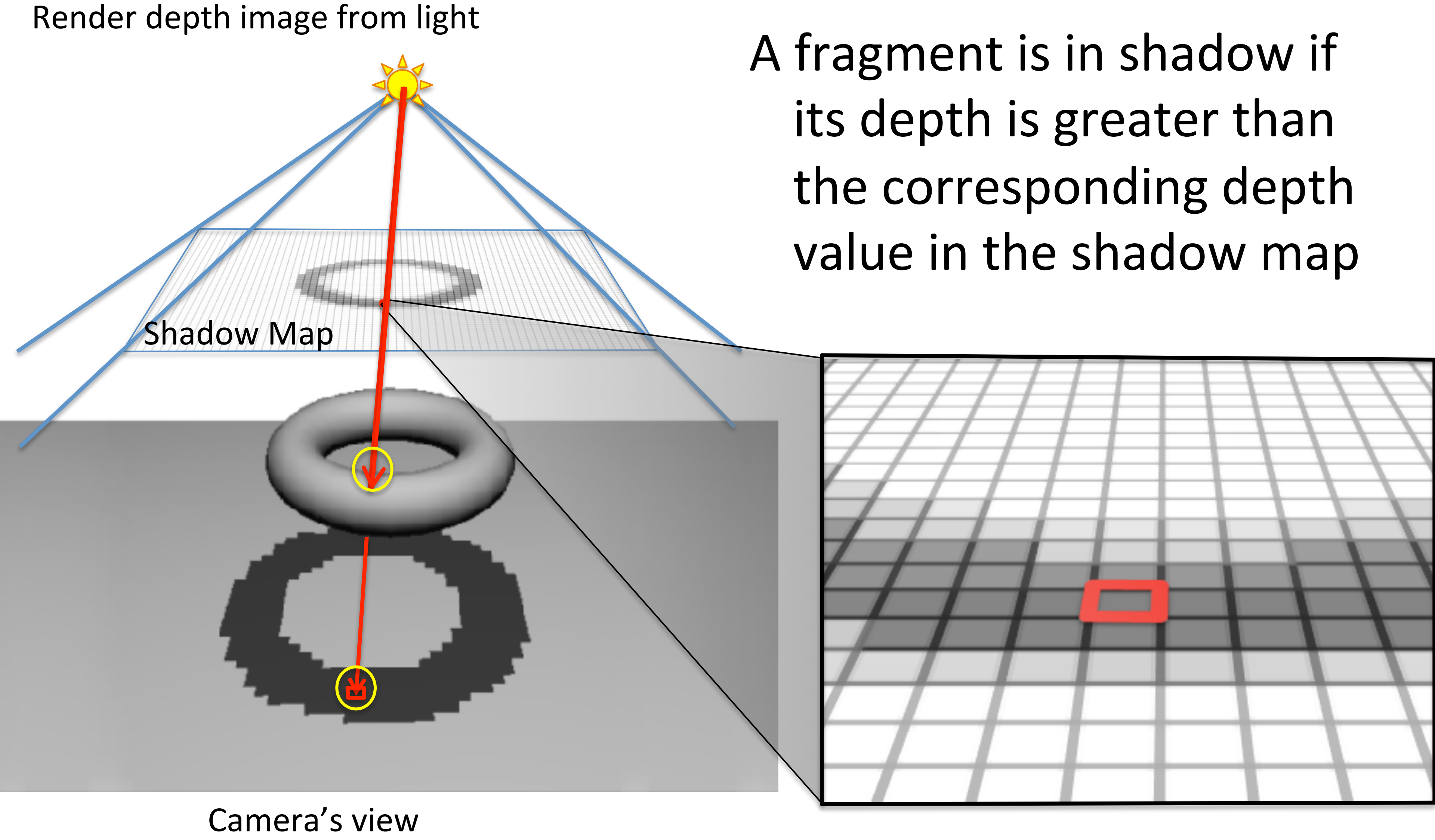
Camera's view

Point not represented in shadow map (point is behind box)



Light's view (Shadow Map)

Depth Comparison



Render depth image from light

Shadow Map

Camera's view

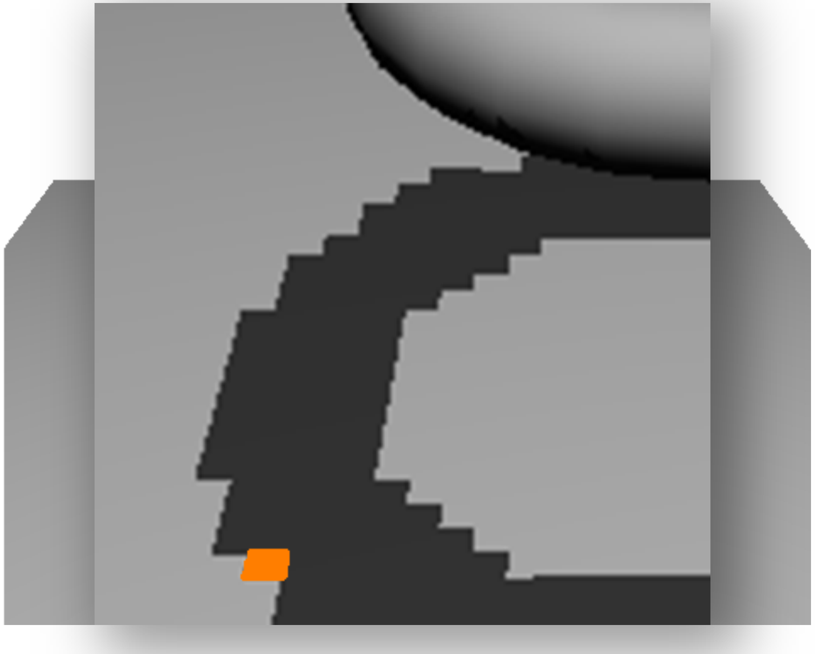
A fragment is in shadow if its depth is greater than the corresponding depth value in the shadow map

Shadow Maps

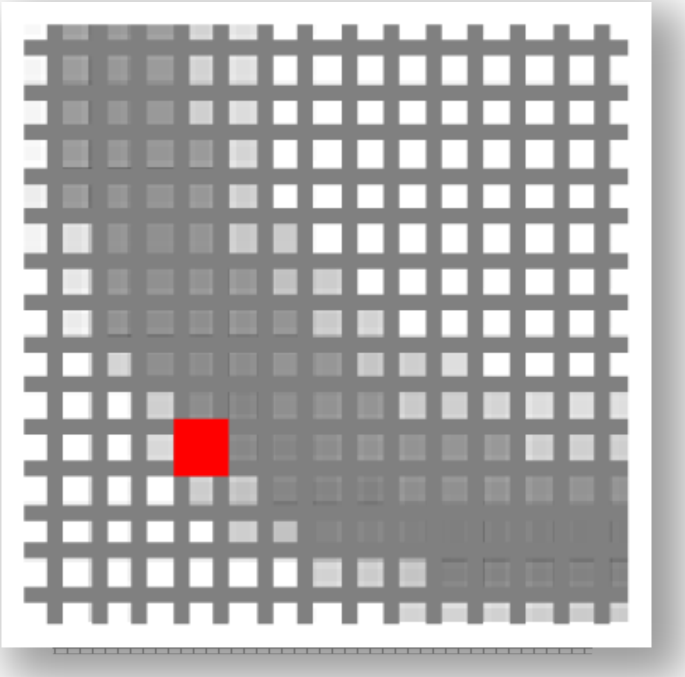
- Pros
  - Very efficient: “This is as fast as it gets”
- Cons…

Shadow Maps - Problems

- Low Shadow Map resolution results in jagged shadows



from viewpoint



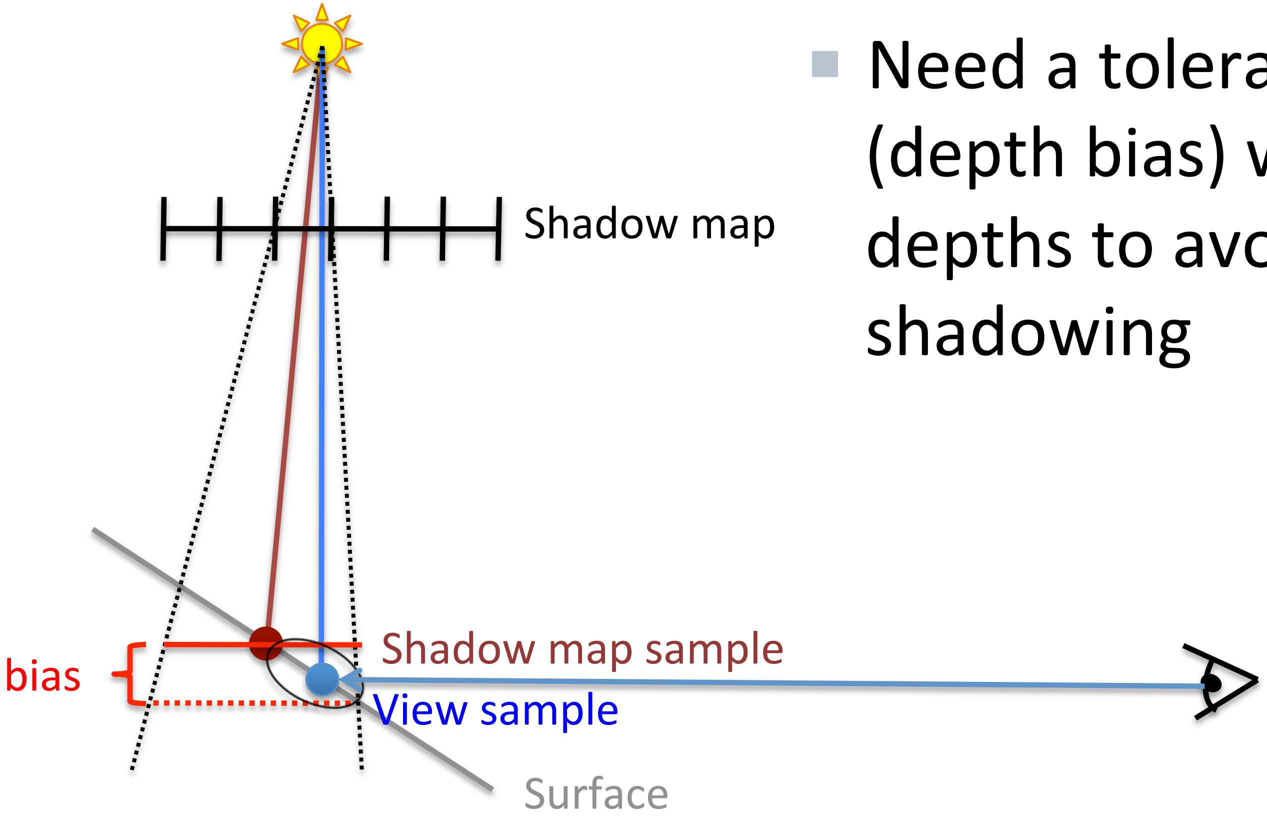
from light

Shadow Maps - Problems

In addition:

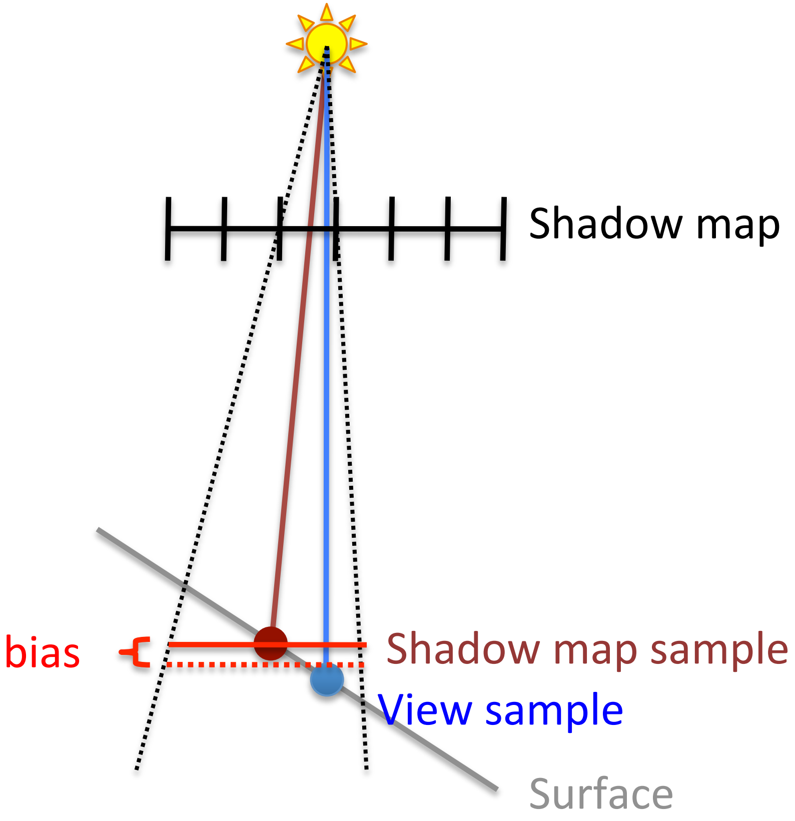
- A tolerance threshold (bias) needs to be tuned for each scene for the depth comparison

Bias

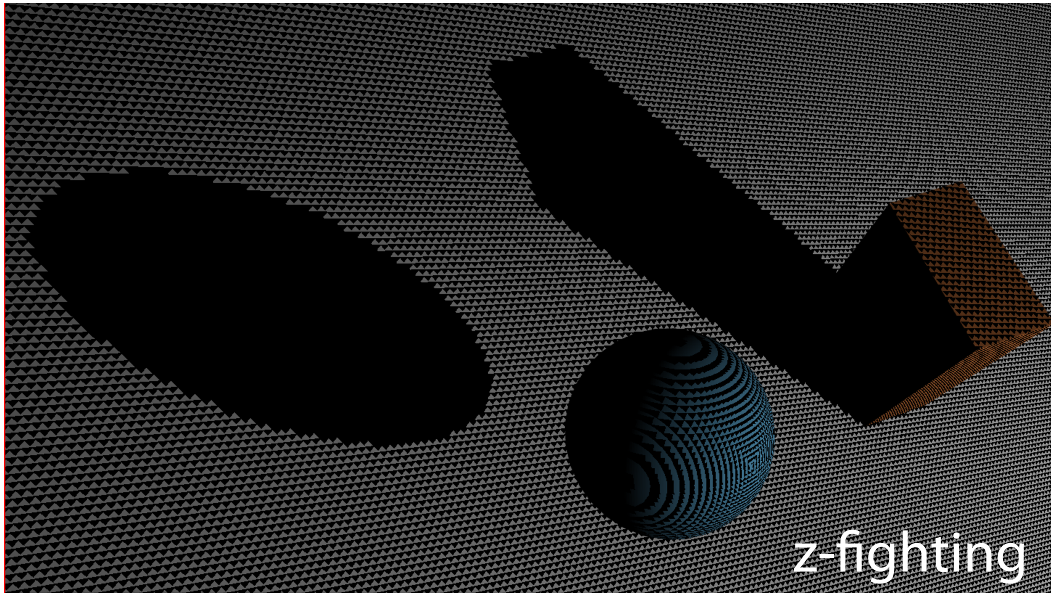


- Need a tolerance threshold (depth bias) when comparing depths to avoid surface self shadowing

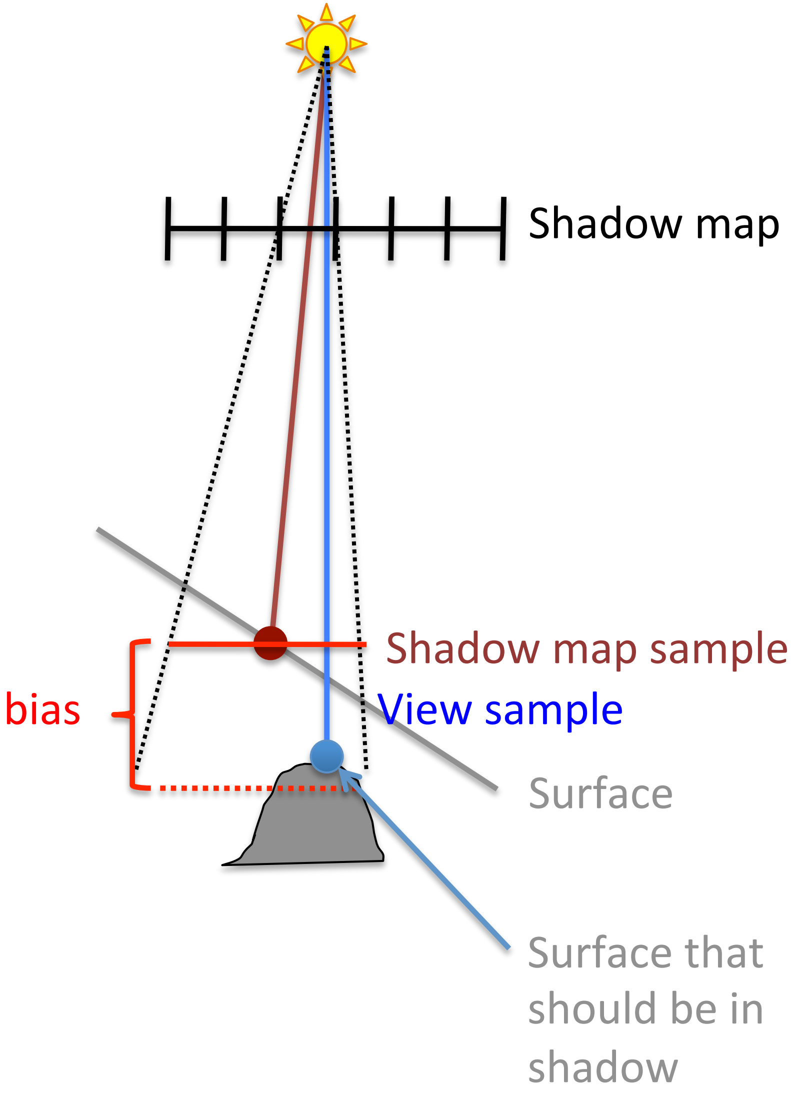
Bias



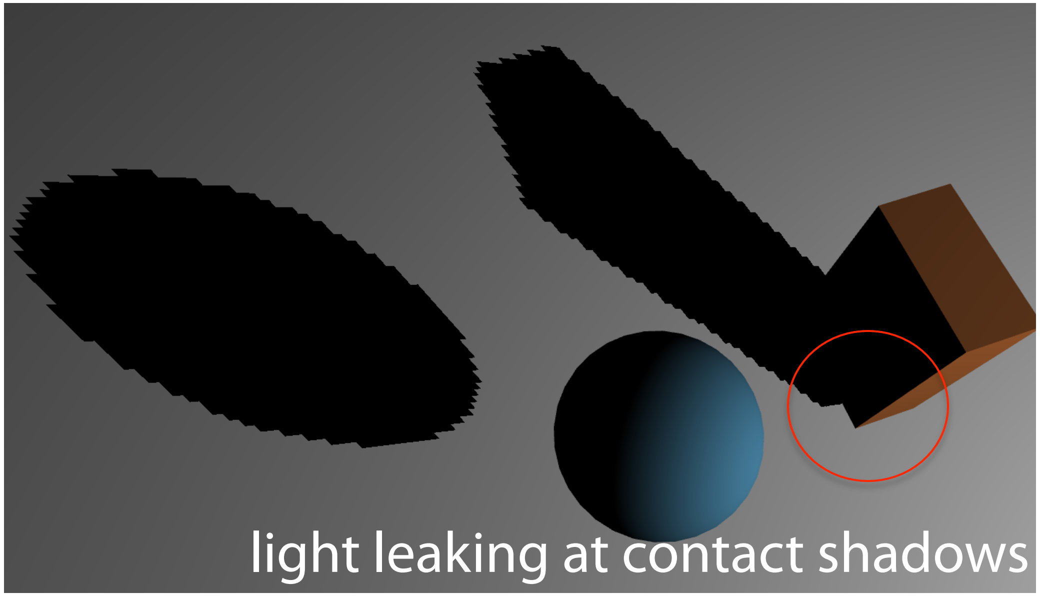
- Need a tolerance threshold (depth bias) when comparing depths to avoid surface self shadowing



Bias



- Need a tolerance threshold (depth bias) when comparing depths to avoid surface self shadowing

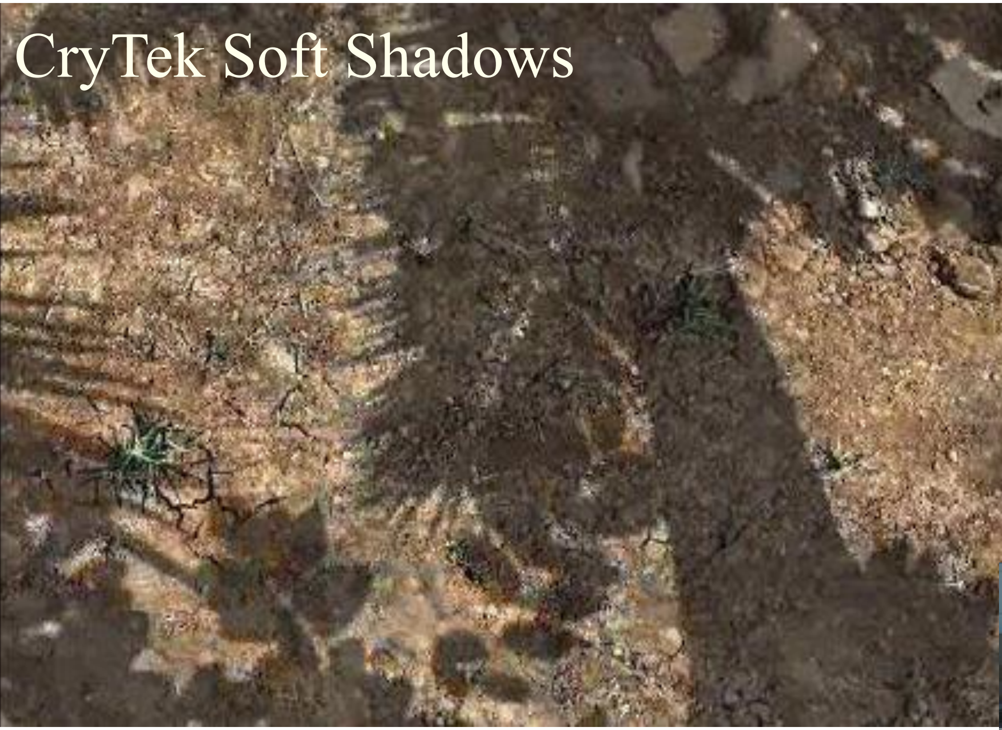


Implementing Shadow Maps

- See tutorial 6 on how to implement shadow maps in practice.
  - Changes every now and then, but algorithm stayed the same since 1978.

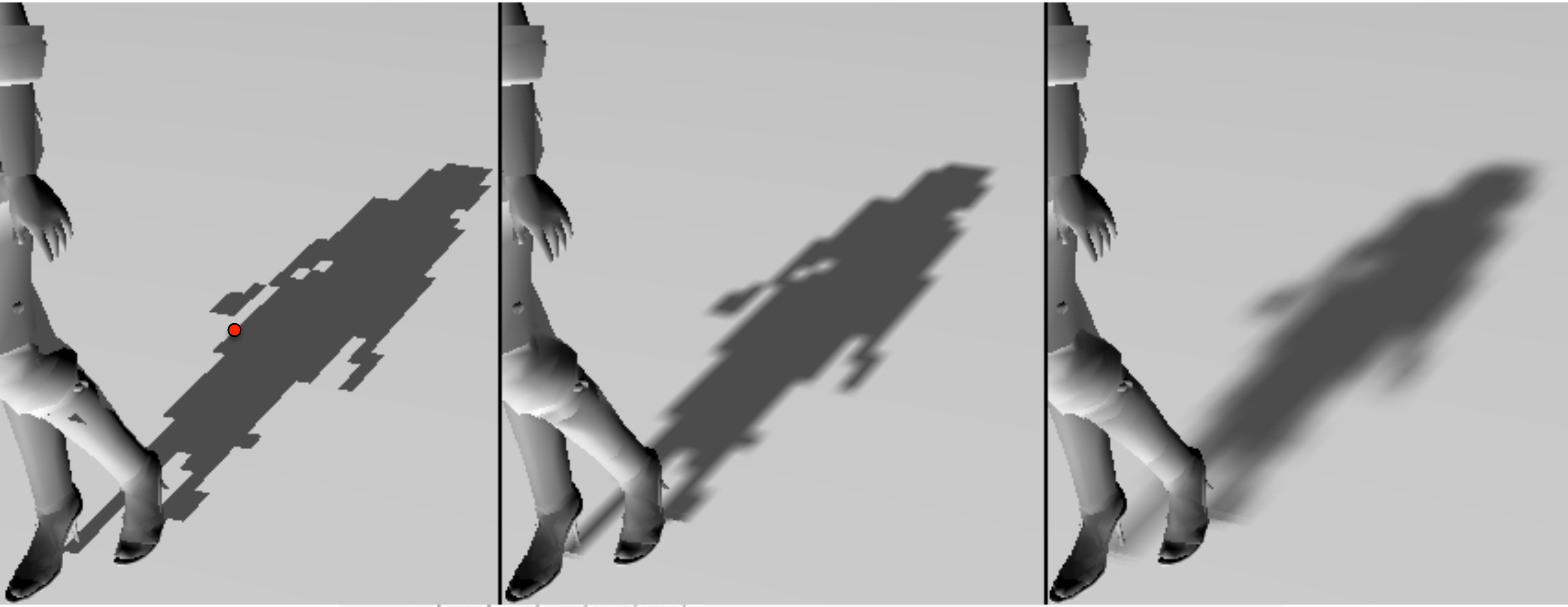
Percentage Closer Filtering

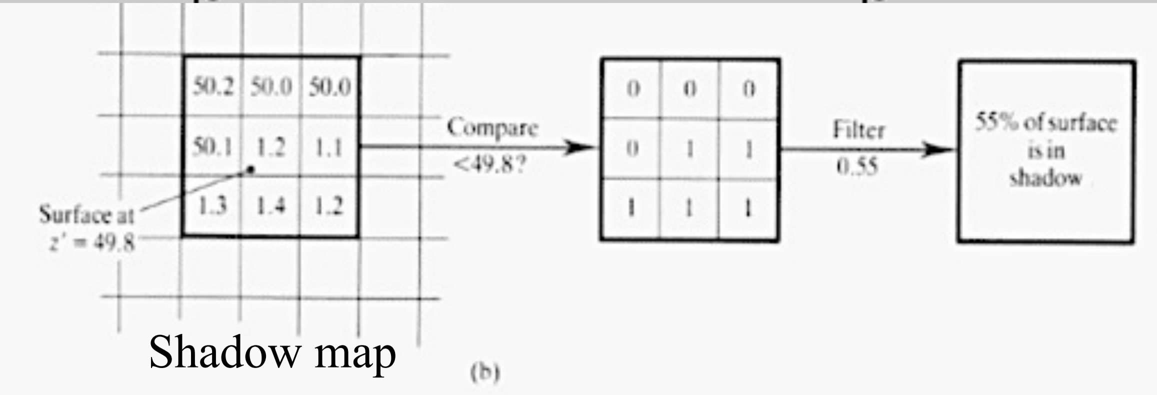
Percentage Closer Filtering



CryTek Soft Shadows

Percentage Closer Filtering





50.2	50.0	50.0
50.1	1.2	1.1
1.3	1.4	1.2

Surface at
z' = 49.8

Compare
<49.8?

0	0	0
0	1	1
1	1	1

Filter
0.55

55% of surface
is in
shadow

Shadow map

(b)

Blending

- Used for
  - Transparency
    - **glBlendFunc(GL_SRC_ALPHA, GL_ONE_MINUS_SRC_ALPHA)**
    - **glBlendEquation()**
    - **glBlendFuncSeparate() / glBlendEquationSeparate()**
  - Effects (shadows, reflections)
  - Complex materials
    - Quake3 uses up to 10 rendering passes, blending toghether contributions such as:
      - Diffuse lighting (for hard shadows)
      - Bump maps
      - Base texture
      - Specular and emissive lighting
      - Volumetric/atmospheric effects
  - Enable with **glEnable(GL_BLEND)**

Example of blending for Motion Blur

Possible with usage of e.g blending to floating point rgb buffer and averaging result before displaying

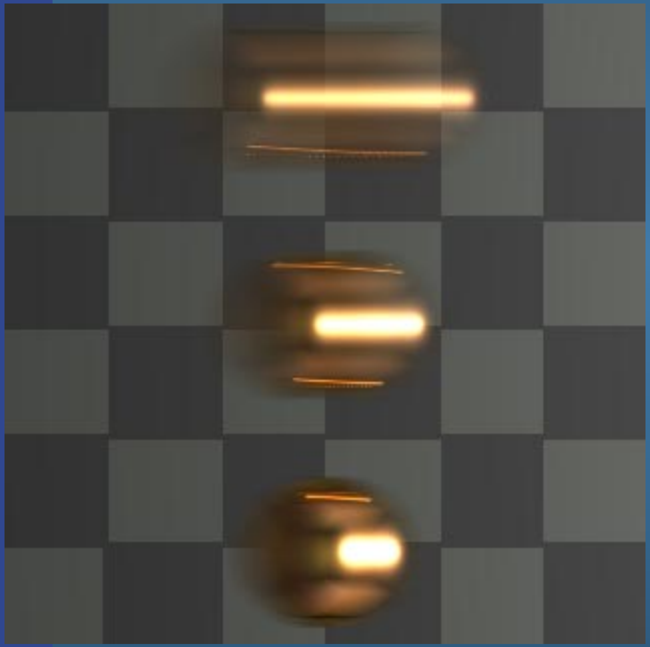


Image courtesy Brostow and Essa

Misc

Point / Line width

glPointSize(*float size*)

glEnable/Disable(VERTEX_PROGRAM_POINT_SIZE)

glLineWidth(*float width*)

glEnable/Disable(LINE_SMOOTH)

Polygon rendering

glPolygonMode(enum *face, enum mode***)**

– *face: FRONT, BACK, FRONT_AND_BACK*

– *mode: POINT, LINE, FILL*

glPolygonOffset(float *factor, float units***)**

glEnable/Disable(*target***)**

–*POLYGON_OFFSET_POINT, POLYGON_OFFSET_LINE,* POLYGON_OFFSET_FILL

Reading Frame Buffers

glReadPixels(*int x, int y, width, height, format, type, void *data);*

glReadBuffer(enum *src***);**

–*src: NONE, FRONT_LEFT, FRONT_RIGHT, BACK_LEFT, BACK_RIGHT,* FRONT, BACK, LEFT, RIGHT, FRONT_AND_BACK,

–AUX*i (where i is [0, AUX_BUFFERS - 1]), COLOR_ATTACHMENTi* (where *i is [0, MAX_COLOR_ATTACHMENTS - 1])*

glBlitFramebuffer(*srcX0, srcY0, srcX1, srcY1, dstX0, dstY0, dstX1, dstY1, bitfield mask, enum filter);*

–*mask: Bitwise OR of COLOR_BUFFER_BIT, DEPTH_BUFFER_BIT,*

–STENCIL_BUFFER_BIT

–*filter: LINEAR, NEAREST*

Buffers

Drawing to Frame Buffers

Selecting a Buffer for Writing :

glDrawBuffer(*enum buf***)**

- *buf: NONE, FRONT_LEFT, FRONT_RIGHT, BACK_LEFT,* BACK_RIGHT, FRONT, BACK, LEFT, RIGHT, FRONT_AND_BACK, COLOR_ATTACHMENT*i (where i is* [0, MAX_COLOR_ATTACHMENTS - 1]),
- AUX*i (where i is* [0, AUX_BUFFERS - 1])

DrawBuffers(*sizei n, const enum *bufs***);**

- *bufs: NONE, FRONT_LEFT, FRONT_RIGHT, BACK_LEFT, BACK_RIGHT,*
- COLOR_ATTACHMENT*i (where i is [0, MAX_COLOR_ATTACHMENTS - 1]),*
- AUX*i (where i is [0, AUX_BUFFERS - 1])*

```
FRAGMENT SHADER

void main()
{
   gl_FragData[0] =vec4(1,0,0,1);
   gl_FragData[1] =vec4(1,1,0,1);
}
```

Framebuffer Objects

Binding & Managing Framebuffer Objects (collection of renderbuffers, (<=8 colbuffs))

- **glBindFramebuffer(), glGenFramebuffers(), glDeleteFramebuffers()**

Renderbuffers:

- **BindRenderbuffer(), DeleteRenderBuffers(), glGenRenderBuffers(), glRenderBufferStorage() – w,h,depth/color/stencil**

Attaching renderbuffer to current framebuffer object

- **glFramebufferRenderbuffer()**

Attaching Texture Image to Framebuffer (i.e., render-to-texture)

- **glFrameBufferTexture1/2/3D()**

Buffers

- Frame buffer
  - Back/front/left/right – **glDrawBuffers()**
- Depth buffer (z-buffer)
  - For correct depth sorting
  - Instead of BSP-algorithm, painters algorithm…
  - **glDepthFunc(), glDepthMask(false)**
- Stencil buffer
  - Shadow volumes,
  - **glStencilFunc(), glStencilFuncSeparate, glStencilMask, glStencilOp**
- General commands:
  - **glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT | GL_STENCIL_BUFFER_BIT)**
  - Specify clearing value:, **glClearStencil(), glClearColor(), glClearDepth(default=1)**

Specials

- "Clip planes" (8):
  - Fragment shader: `glClipDistance[]`
  - `glEnable(GL_CLIP_DISTANCEi)`
- Scissors:
  - `glScissor(x,y,w,h), glEnable(GL_SCISSOR_TEST)`
- Finishes all draw calls before CPU-execution continues:
  - `glFinish()`

- ~~Fog: `glFog(), glEnable(GL_FOG);`~~

Fragment Operations

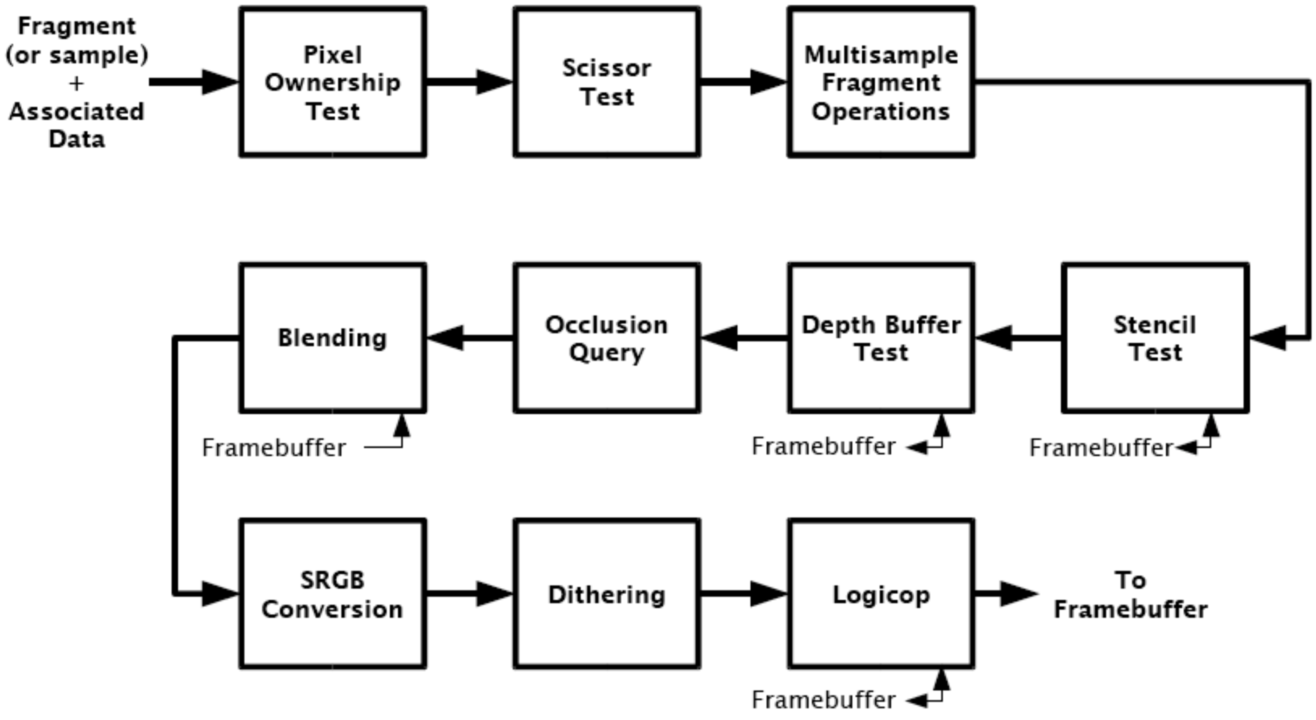


Figure 4.1. Per-fragment operations.

Errors:

- You might find the following code useful:

```
inline CheckGLError()
{
  GLenum errCode;
  const unsigned char* errString;
  if((errCode=glGetError()) != GL_NO_ERROR)
  {
        errString=gluErrorString(errCode);
        printf("OpenGL Error: %s\n", errString);
  }
}
```

Extensions

- glew.h + glew32.lib/dll   OR GLee.h + GLee.cpp
- Or get the extensions manually:
- Check if extension is supported:
  glutExtensionSupported("GL_EXT_framebuffer_sRGB")
  glutExtensionSupported("GL_EXT_texture_integer")
- Get address of extension function:
  - **gTexParameterIivEXT = wglGetProcAddress(”glTexParameterIivEXT");**
  - **glClearColorIiEXT = wglGetProcAddress(”glClearColorIiEXT");**

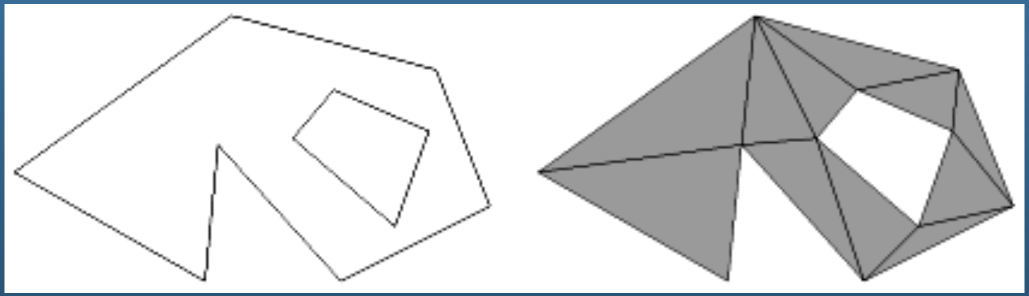
GLU – The OpenGL Graphics System Utility Library

- #include <GL/glu.h>. Loads: glu32.dll or link with glu32.lib
- ~~Support for creating Mip maps~~
- ~~Matrix manipulation functions (=camera helper functions)~~
- Polygon Tesselation
  - Creating arbitrary (non-convex) polygons
- Quadrics (2:nd order surfaces)
- NURBS

GLU - Polygon Tesselation

- The GLU Tesselation Functions

1. gluTessBeginPolygon() begins a new polygon.
2. gluTessBeginContour() begins a new contour.
3. gluTessVertex() is called repeatedly to pass the vertices to the tesselator.
4. gluTessEndContour() ends the contour. If there are more contours in the polygon, continue at Step 2.
5. gluTessEndPolygon()



A concave polygon with one hole (left) and the same polygon after tesselation (right)

GLU - Quadrics

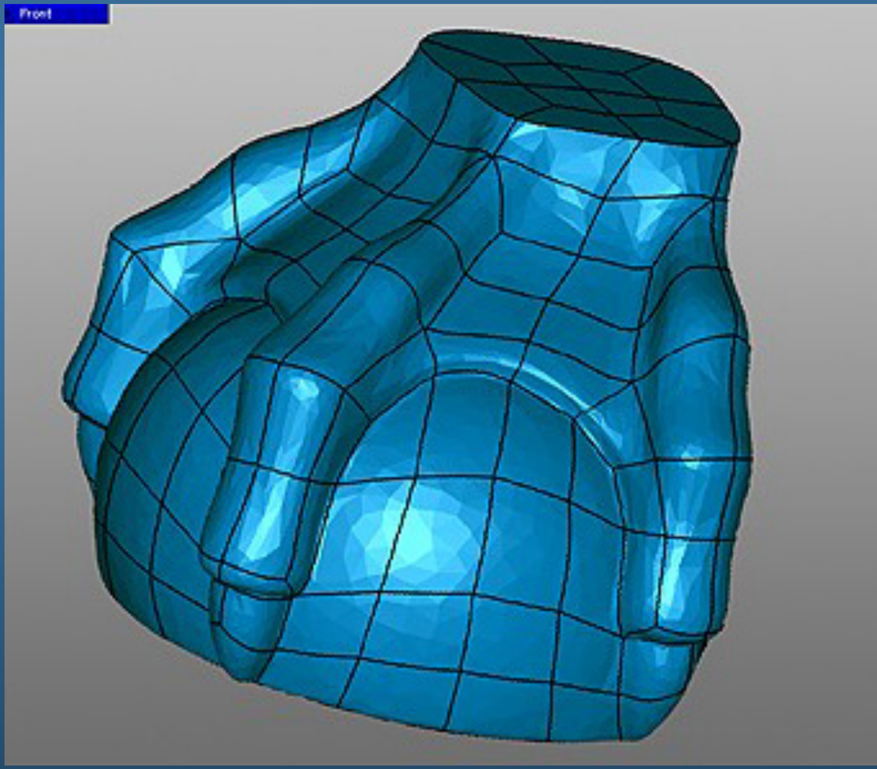
- To render spheres, cylinders and disks.
  - Example:

    ```
    GLUquadricObj *gQuad;
    gQuad=gluNewQuadric();
    gluQuadricDrawStyle(gQuad, GLU_FILL);
    gluSphere(gQuad,radius, 40,40); // slides, stacks – Draws the sphere
    ```

  - **gluQuadricNormals()** – **GLU_NONE, GLU_FLAT, GLU_SMOOTH**
  - **gluQuadricTexture()** – **GL_TRUE, GL_FALSE**
  - **gluQuadricOrientation()** – **GLU_OUTSIDE, GLU_INSIDE**
  - **gluQuadricDrawStyle()** – **GLU_FILL, GLU_LINE, GLU_POINT, GLU_SILHOUETTE**
- **gluSphere(), gluDisk(), gluCylinder()**

GLU - NURBS

- See chapter 7 in http://www.ce.chalmers.se/staff/uffe/glu1.3.pdf for more information.
- And chapter 24, page 34-38 in ”Introduktion till OpenGL” at course home-page



http://www.cse.chalmers.se/edu/course/TDA361/OPENGL_2006.pdf

GLUT – The OpenGL Utility Toolkit

- for creating an OpenGL application with platform independent code.
- #include <freeglut.h>
  - Links with freeglut32.lib or loads freeglut32.dll (MS Windows).
- Windows, menus, events, text, objects

- http://www.cse.chalmers.se/~uffe/glut-3.spec.pdf

GLUT – windows and menus

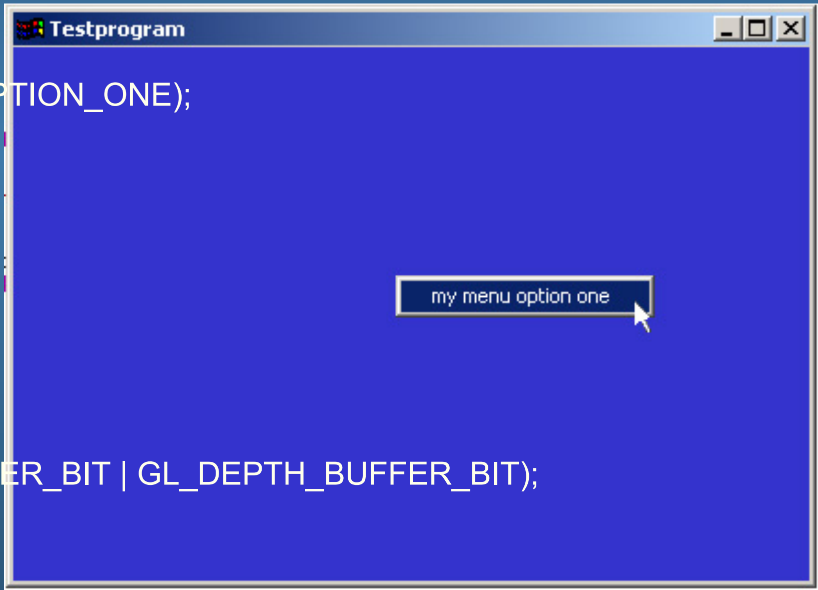
- Initialization:
  - glutInit(), glutInitDisplayMode(), glutInitWindowPosition(), glutInitWindowSize()
- Start main loop: glutMainLoop()
- Windows:
  - glutCreateWindow, glutCreateSubWindow, glutSetWindow, glutGetWindow, glutDestroyWindow, glutPositionWindow, glutReshapeWindow, glutFullScreen, glutPushWindow, glutPopWindow, glutShowWindow, glutHideWindow, glutIconifyWindow, glutSetWindowTitle, glutSetIconTitle,
  - glutPostRedisplay, glutSwapBuffers, glutSetCursor
- Overlays:
  - glutEstablishOverlay, glutUseLayer, glutRemoveOverlay, glutPostOverlayRedisplay, glutShowOverlay, glutHideOverlay
- Menus:
  - glutCreateMenu, glutSetMenu, glutGetMenu, glutDestroyMenu, glutAddMenuEntry, glutAddSubMenu, glutChangeToMenuEntry, glutChangeToSubMenu, glutRemoveMenuItem, glutAttachMenu, glutDetachMenu

Event Callbacks

- Most common:
  - glutDisplayFunc – the scene drawing should be done here
  - glutReshapeFunc – on resizing the window. Call **glViewport(0, 0, newWidth, newHeight);**
  - glutKeyboardFunc
  - glutMouseFunc – mouse buttons
  - glutMotionFunc – mouse movements when buttons are pressed
  - glutPassiveMotionFunc – when buttons are not pressed
  - glutSpecialFunc – for function or direction keys
  - glutIdleFunc
  - glutTimerFunc
- Not so common:
  - glutOverlayDisplayFunc, glutVisibilityFunc, glutEntryFunc, glutSpaceballMotionFunc, glutSpaceballRotateFunc, glutSpaceballButtonFunc, glutButtonBoxFunc, glutDialsFunc, glutTabletMotionFunc, glutTabletButtonFunc, glutMenuStatusFunc,

Program Example

```
#ifdef WIN32 #include <windows.h> #endif
#include <GL/glut.h>
enum {MY_MENU_OPTION_ONE};
int main(int argc, char *argv[]) {
        glutInit(&argc, argv);
        glutInitDisplayMode(GLUT_DOUBLE | GLUT_RGB | GLUT_DEPTH);
        glutInitWindowSize(800,600); glutCreateWindow(”Testprogram");
        glutKeyboardFunc(handleKeys); glutSpecialFunc(handleSpecialKeys); glutDisplayFunc(display);
        glutMouseFunc(mouse); glutMotionFunc(motion); glutReshapeFunc(reshape); glutIdleFunc( idle );

        glutCreateMenu(menus);
        glutAddMenuEntry(”my menu option one", MY_MENU_OPTION_ONE);
        glutAttachMenu(GLUT_RIGHT_BUTTON);
        glutMainLoop();
}
void idle() {
        … do animation computations …
        glutPostRedisplay();
}
void display() {
        glClearColor(0.2,0.2,0.8,1.0);  glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
        … draw the scene …
        glutSwapBuffers();  // swap front and back buffer
}
void menus(int value) {
        switch(value) {
        case MY_MENU_OPTION_ONE:
                … do some stuff …
        }
}
```



Obsolete for OpenGL 3
but you can still use it

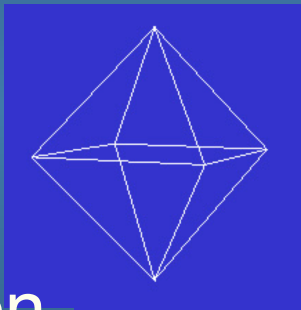
Text

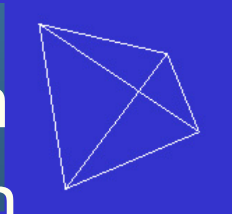
- Commands:
  - glutBitmapCharacter, glutStrokeCharacter,
- Example:

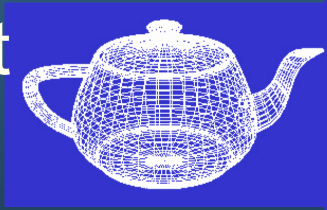
```
void print(char* str) {
    glMatrixMode(GL_PROJECTION); glPushMatrix();
    gluOrtho2D(0, mWinWidth, 0, mWinHeight);
    glMatrixMode(GL_MODELVIEW); glPushMatrix();
    glLoadIdentity();
    glColor3f(1,0,0); // set red text
    glRasterPos2f(10, 10); // origin is lower left window corner
    int len=strlen(str);
    for(int i=0; i<len; i++)
            glutBitmapCharacter(GLUT_BITMAP_8_BY_13, str[i]);
    glMatrixMode(GL_MODELVIEW); glPopMatrix();
    glMatrixMode(GL_PROJECTION); glPopMatrix();
}
```

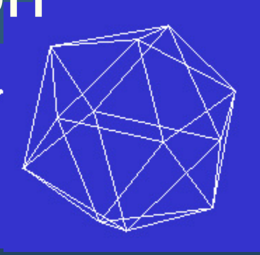
Predefined Objects

- glutSolidSphere, glutWireSphere
- glutSolidCone, glutWireCone
- glutSolidCube, glutWireCube
- glutSolidTorus, glutWireTorus
- glutSolidDodecahedron, glutWireDodecahedron
- glutSolidOctahedron, glutWireOctahedron
- glutSolidTetrahedron, glutWireTetrahedron
- glutSolidIcosahedron, glutWireIcosahedron
- glutSolidTeapot, glutWireTeapot









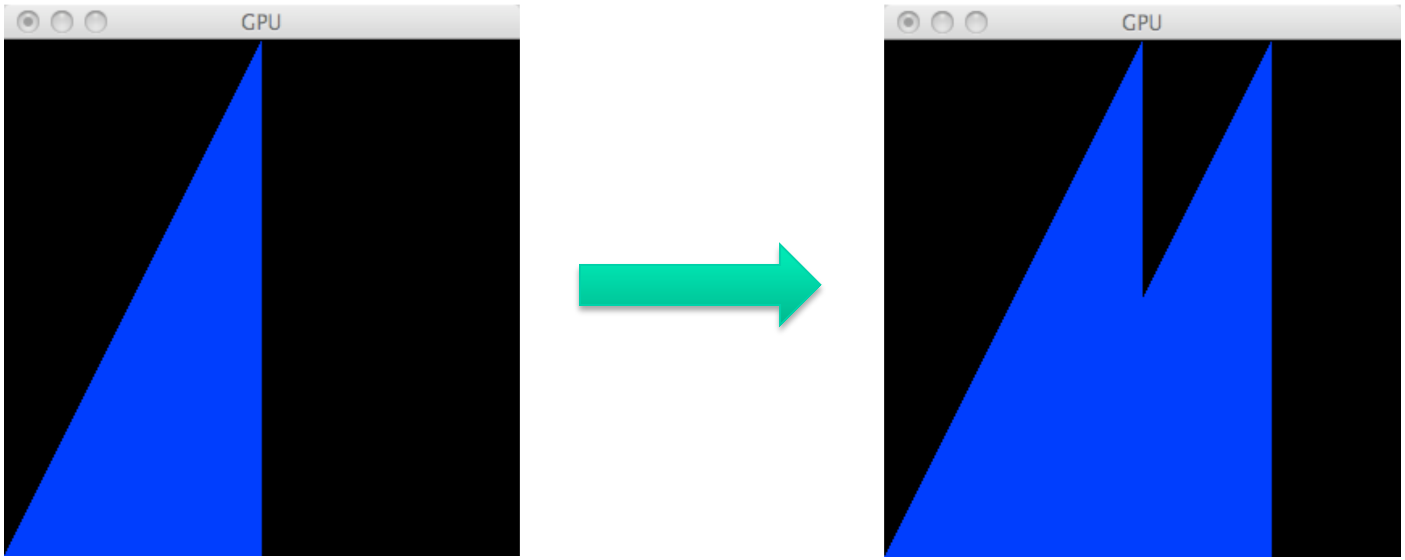
Exam Questions

- principles of a real-time rendering API like OpenGL
  - E.g. high level functionality
    - Shadow Maps
    - Types of buffers
    - How do you achieve transparency?
    - (Adding clip planes to the standard unit cube)
    - What defines what is the back and front side of a triangle?

```
Hunter ate Ranger's rocket
Wrote screenshots/shot0147.tga
```

END OF OPENGL, GLU AND GLUT LECTURE

Simple Geometry shader demo



Geometry shader

```
#version 120
#extension GL_EXT_geometry_shader4 : enable
void main(void){
    //Pass-thru vertices!
    for(i=0; i< gl_VerticesIn; i++){
        gl_Position = gl_PositionIn[i];
        EmitVertex();
    }
    EndPrimitive();

    //New piece of geometry!  Add translation
    for(i=0; i< gl_VerticesIn; i++){
        gl_Position = gl_PositionIn[i];
        gl_Position.xy += vec2(0.5,0);
        EmitVertex();
    }
    EndPrimitive();
}
```

Loading the shaders

```
void setShaders() {
	GLuint v = glCreateShader(GL_VERTEX_SHADER);
	GLuint f = glCreateShader(GL_FRAGMENT_SHADER);
	GLuint f = glCreateShader(GL_GEOMETRY_SHADER_EXT);

	char * vs = textFileRead("toon.vert");
	char * fs = textFileRead("toon.frag");
	char * gs = textFileRead("toon.geom");

	glShaderSource(v, 1, (const char **) &vs, NULL);
	glShaderSource(f, 1, (const char **)  &fs, NULL);
	glShaderSource(g, 1, (const char **)  &gs, NULL);
	free(vs);free(fs);free(gs);

	glCompileShader(v);  glCompileShader(f); glCompileShader(g);
	GLuint p = glCreateProgram();
	glAttachShader(p,f); glAttachShader(p,v); glAttachShader(p,g);

	glProgramParameteriEXT(p,GL_GEOMETRY_INPUT_TYPE_EXT,GL_TRIANGLES);
	glProgramParameteriEXT(p,GL_GEOMETRY_OUTPUT_TYPE_EXT,GL_TRIANGLES);
	GLint temp;
	glGetIntegerv(GL_MAX_GEOMETRY_OUTPUT_VERTICES_EXT,&temp);
	glProgramParameteriEXT(p,GL_GEOMETRY_VERTICES_OUT_EXT,temp);

	glLinkProgram(p);
	glUseProgram(p);					// 0 disables vertex/fragment shaders
}
```