

OpenGL

- a quick guide

Ulf Assarsson
Department of Computer Engineering
Chalmers University of Technology

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.

OpenGL vs Direct3D

- 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)

**Direct3D was
messy to program
version 3.0 – 6.0.**

Today version 12

- OpenGL

- SGI
- Historically:
 - “Precede the hardware evolution”
 - Operation system independent
 - Window system independent
 - Industry, games (Quake –John Carmack, Apple, Linux)
 - January 1992
 - Extendable, stable, better design,

**Today
version 4.7**

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., getting OpenGL 4.1

```
SDL_GL_LoadLibrary(nullptr); // Default OpenGL is fine.
```

```
// Request an OpenGL 4.1 context (should be Core for us)
```

```
// - Most Macs support 4.1 and requires Core 4.1 exactly
```

```
// - Some Intel graphics cards only support Core
```

```
// - NVIDIA's nsight (profiling tool) requires Core.
```

```
SDL_GL_SetAttribute(SDL_GL_ACCELERATED_VISUAL, 1);
```

```
SDL_GL_SetAttribute(SDL_GL_CONTEXT_PROFILE_MASK, SDL_GL_CONTEXT_PROFILE_CORE);
```

```
SDL_GL_SetAttribute(SDL_GL_CONTEXT_MAJOR_VERSION, 4);
```

```
SDL_GL_SetAttribute(SDL_GL_CONTEXT_MINOR_VERSION, 1);
```

```
SDL_GL_SetAttribute(SDL_GL_CONTEXT_FLAGS, SDL_GL_CONTEXT_DEBUG_FLAG);
```

```
// Also request a depth buffer
```

```
SDL_GL_SetAttribute(SDL_GL_DOUBLEBUFFER, 1);
```

```
SDL_GL_SetAttribute(SDL_GL_DEPTH_SIZE, 24);
```

```
// Create the window
```

```
SDL_Window* window = SDL_CreateWindow(caption.c_str(), SDL_WINDOWPOS_UNDEFINED,
```

```
SDL_WINDOWPOS_UNDEFINED, width, height, SDL_WINDOW_OPENGL | SDL_WINDOW_RESIZABLE);
```

```
static SDL_GLContext maincontext = SDL_GL_CreateContext(window);
```

SDL_GL_CONTEXT_PROFILE_CORE	OpenGL core profile - deprecated functions are disabled
SDL_GL_CONTEXT_PROFILE_COMPATIBILITY	OpenGL compatibility profile - deprecated functions are allowed

OpenGL Evolution

- Controlled by Khronos Group
 - Members include Intel, Nvidia, AMD, Samsung, Sony, ARM, EA, Google...
 - Present version 4.6
 - Evolution reflects new hardware capabilities
 - **More functionality for vertex / fragment programs**
 - **Geometry shaders,**
 - **Tessellation shaders**
 - DX11: Hull shader = GL: Tessellation Control Shader
 - Domain shader = Tessellation Evaluation Shader
 - **Compute shaders (similar to OpenCL, CUDA)**
 - **Mesh shaders**
 - Allows for platform specific features through extensions

Tessellation – brief glance

Input Assembler

Vertex Shader

Hull Shader

Tessellator

Domain Shader

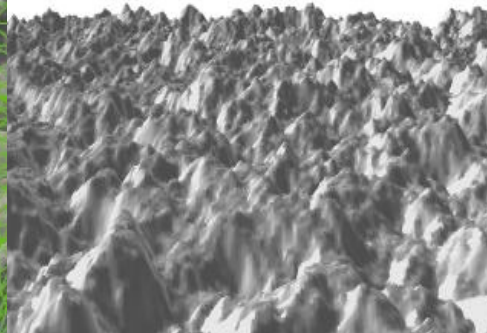
Geometry Shader

Rasterizer

Pixel Shader

Output Merger

Height field



GLSL Tessellation Control Shader

```

// thread ID
#define TID gl_InvocationID

out float sharable_len[];
in vec3 eye_space_pos[];
in vec2
    scaled_window_space_pos[];

out vec3 eye_space_pos2[];

void main(void)
{
    sharable_len[TID] =
        distance(scaled_window_space_pos[TID],
            scaled_window_space_pos[(TID+1)%3]);
    barrier();

    float len0 = sharable_len[0],
           len1 = sharable_len[1],
           len2 = sharable_len[2];
    eye_space_pos2[TID] = eye_space_pos[TID];

    // Limit level-of-detail output to thread 0
    if (TID == 0) {
        // Outer LOD
        gl_TessLevelOuter[0]=len1; //V1-to-V2 edge
        gl_TessLevelOuter[1]=len2; //V2-to-V0 edge
        gl_TessLevelOuter[2]=len0; //V0-to-V1 edge
        // Inner LOD
        gl_TessLevelInner[0] =
            max(len0, max(len1, len2));
    }
}

```

Overview of today's OpenGL lecture

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

Instead of GLUT:

- SDL, GLFW, QT, freeglut
(glut does not work for Mac)

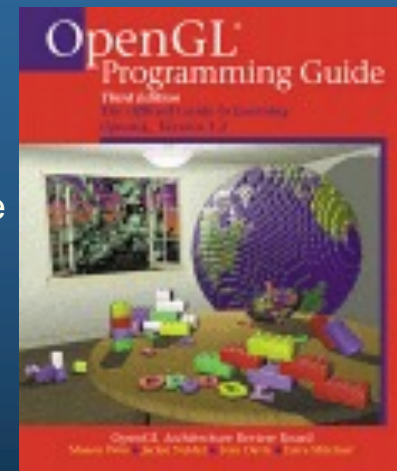
OpenGL – links



- <https://www.khronos.org/files/opengl46-quick-reference-card.pdf>
- Home page: www.opengl.org
- OpenGL 4.6 specification:
 - <https://www.khronos.org/registry/OpenGL/specs/gl/glspec46.core.pdf>
- GLU specification: <http://www.cse.chalmers.se/~uffe/glu1.3.pdf>

You can also find the links on the course home page:
<http://www.cse.chalmers.se/edu/course/TDA362/>

- Programmers Manual and Reference Manual:
 - <http://www.cse.chalmers.se/edu/course/TDA362/redbook.pdf>
 - BUT IT IS HEAVILY OUTDATED BY NOW.
 - Sometimes versions of the RedBook for OpenGL X.X are free online

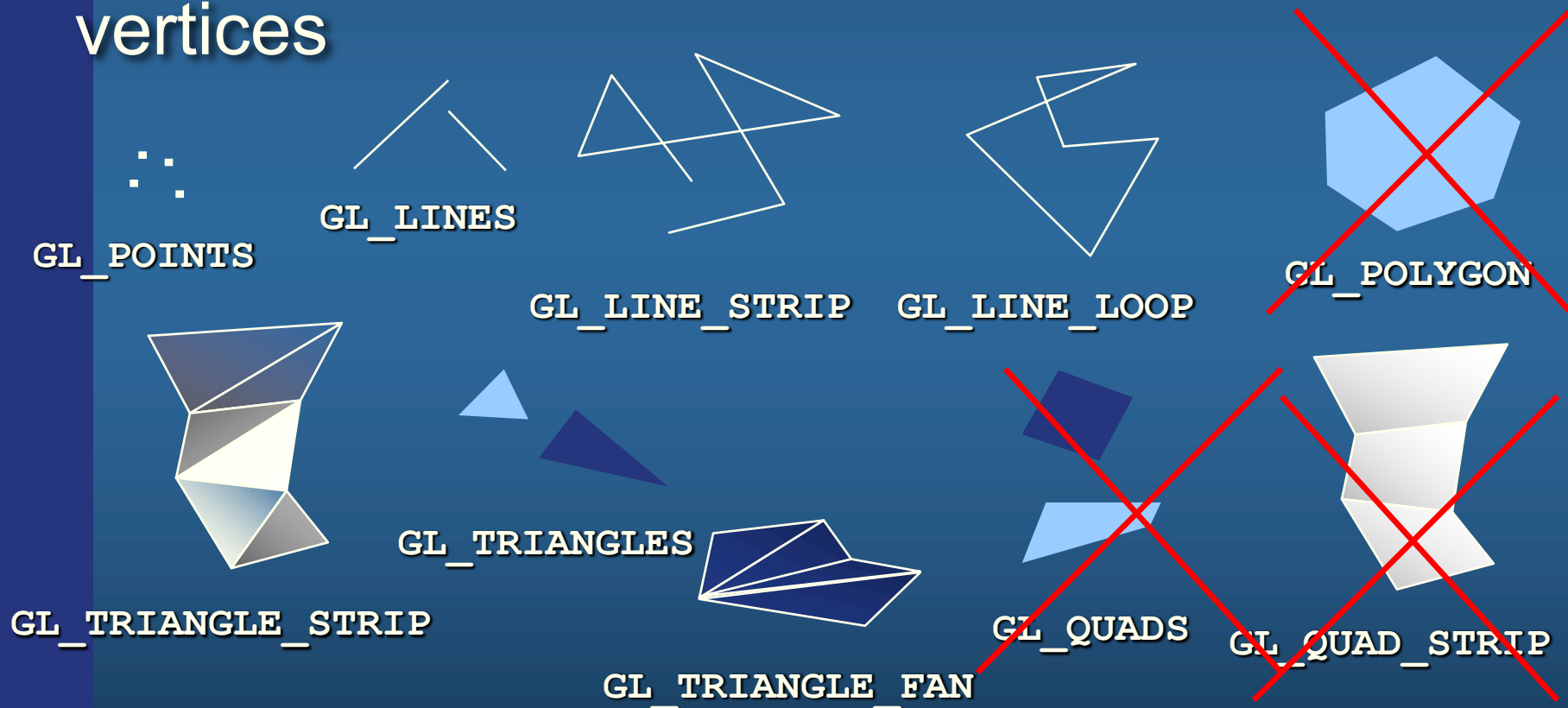


Include

- `#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

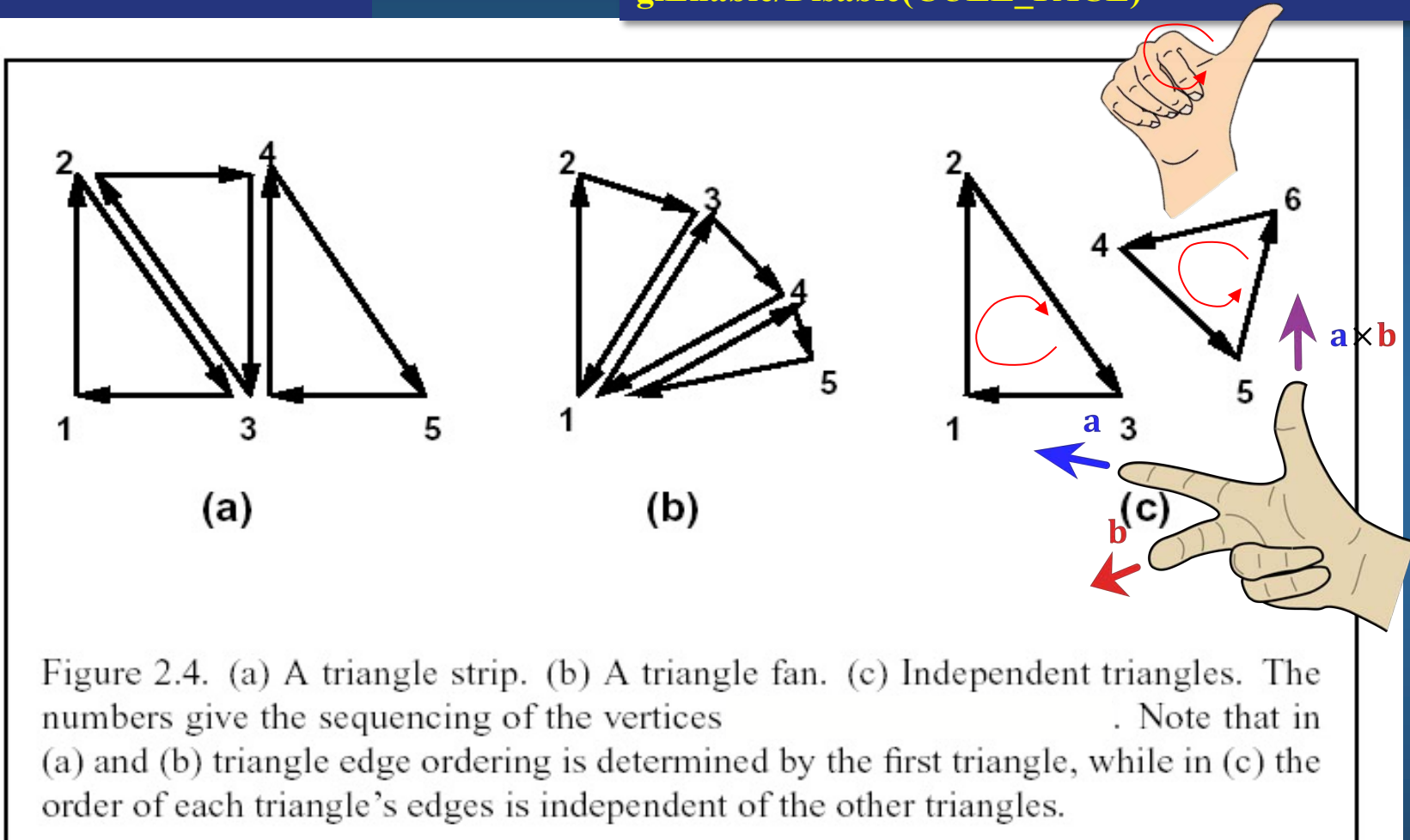


Vertex order

`glFrontFace(enum dir) CCW, CW`

`CullFace(enum mode) -- mode: FRONT, BACK, FRONT_AND_BACK`

`glEnable/Disable(CULL_FACE)`



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:

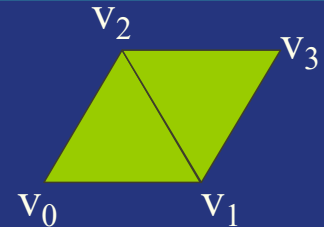
- Multiple formats for the commands: `void glVertex{234}{sifd}( T coords );`
- `glBegin()/glEnd().` (Slow)

```
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.

Index list:

```
vec3f pos[] = v0, v1, v2, v3;
uint indices[] = 0,1,2, 1,3,2;
```



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

```
layout(location = 0) in vec3 vertex;
layout(location = 1) in vec3 color;
out vec3 outColor;
uniform mat4 modelViewProjectionMtx;
```

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

2. COMMANDS TO DRAW

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

Example of a GfxObject Class

```
class GfxObject {  
public:
```

```
    Object() {};  
    ~Object() {};
```

E.g.:

```
{  
    glUseProgram(m_shaderProgram);  
    mat4 modelViewProjectionMatrix = projectionMatrix * viewMatrix *  
                                     m_modelMatrix;  
    int loc = glGetUniformLocation(shaderProgram,  
                                   "modelViewProjectionMatrix");  
    glUniformMatrix4fv(loc, 1, false, &modelViewProjectionMatrix);  
  
    glBindVertexArray(m_vertexArrayObject);  
    glDrawArrays( GL_TRIANGLES, 0, m_vertices.size());  
}
```

```
    render(mat4 projectionMatrix, mat4 viewMatrix);  
    load("filename");  
    ...
```

```
private:
```

```
    Matrix4x4  
    std::vector<vec3f>  
    std::vector<vec3f>  
    std::vector<vec2f>  
    std::vector<vec3f>
```

```
    m_modelMatrix; // Model-to-world matrix  
    m_vertices;  
    m_normals;  
    m_texCoords;  
    m_colors;
```

```
or just:
```

```
    GLhandle  
    GLuint
```

```
    m_shaderProgram;  
    m_vertexArrayObject;
```

```
}
```

The triangle data can be necessary for collision detection and updating of data.

Texture Mapping

You recognize from
lab 2

• Three steps

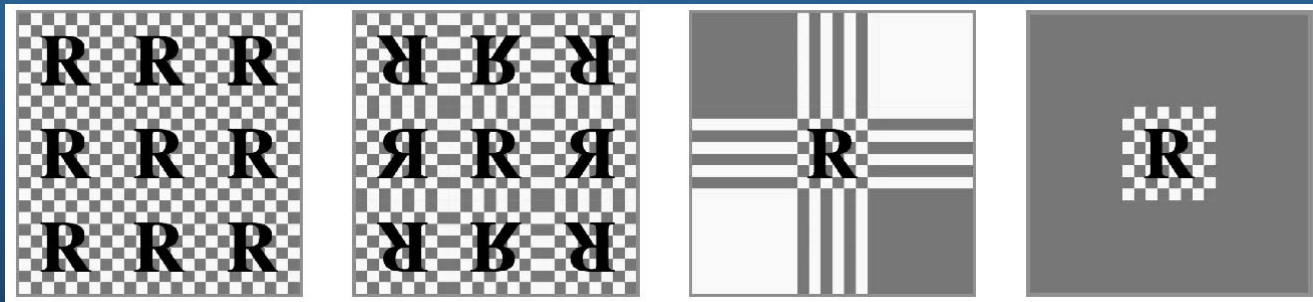
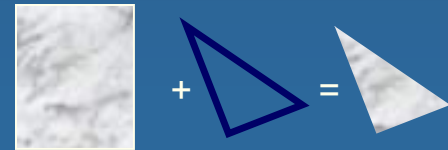
① specify texture

- generate image or read it from file
- 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:

glGenTextures(1, &texID) – generate a texture ID. (Is just an unsigned int.)

glActiveTexture(enum texUnit) -- specify texture unit (up to 32)

glBindTexture(texID), -- specify texture ID that this texture unit and

glTexImage1/2/3D(), **glCopyTexSubImage2D()** -- set / affect image

glGenerateMipmap() -- Create the mipmap hierarchy

glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_MAX_ANISOTROPY, ...)

glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT)

glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT)

glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR)

glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR)

VERTEX SHADER

```
layout(location = 0) in vec3 vertex;
layout(location = 2) in vec2 texCoordIn;
out vec2 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(2, 2, GL_FLOAT, false/*normalized*/, 0/*stride*/, 0/*offset*/);
```

```
glEnableVertexAttribArray(2);
```

FRAGMENT SHADER

```
layout(binding = 0) uniform sampler2D tex0;
in vec2 texCoord;

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

glActiveTexture(0); 2. COMMANDS TO DRAW

glBindTexture(texID);

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

Anisotropic filtering

Enabling anisotropic filtering:

- float MaxAnisotropy
- glGetFloatv(GL_MAX_TEXTURE_MAX_ANISOTROPY_EXT, &MaxAnisotropy);
- glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_MAX_ANISOTROPY_EXT, MaxAnisotropy);

Specifying a Texture: Other Methods

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

`glCopyTexImage1D(...)`

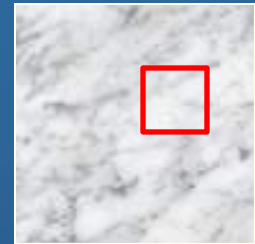
`glCopyTexImage2D(...)`

- Modify part of a defined texture

`glTexSubImage1D(...)`

`glTexSubImage2D(...)`

`glTexSubImage3D(...)`



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

Reflections with environment mapping

- Texture lookups from an environment map



VERTEX SHADER

```
in vec3      vertex;  
in vec3      normalIn;    // The normal  
out vec3     normal;  
out vec3     eyeVector;  
  
uniform mat4 normalMatrix; //transpose of inverse of modelViewMatrix  
uniform mat4 modelViewMatrix;  
uniform mat4 modelViewProjectionMatrix;
```

```
void main()
```

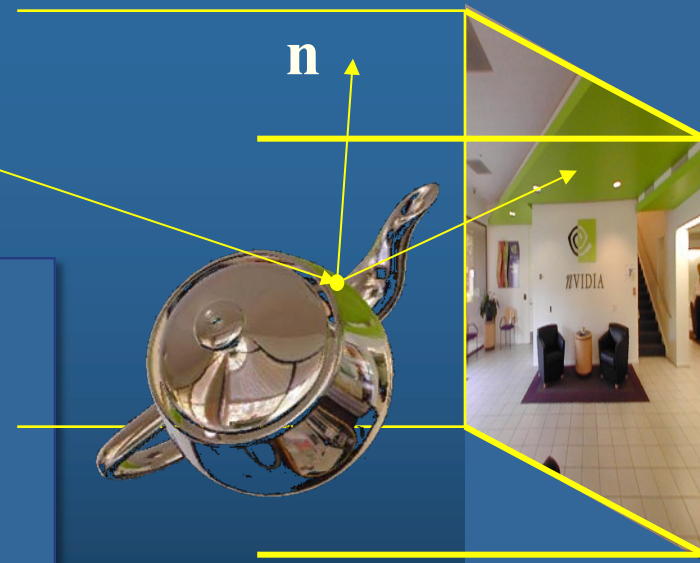
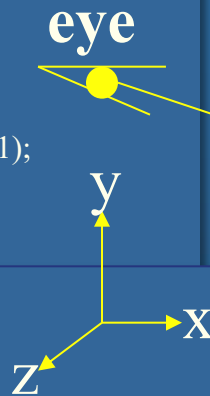
```
{  
    gl_Position = modelViewProjectionMatrix * vec4(vertex,1);  
    eyeVector = (modelViewMatrix * vec4(vertex, 1)).xyz;  
    normal = (normalMatrix * vec4(normalIn,0.0)).xyz;  
}
```

FRAGMENT SHADER

```
in vec3 normal;  
in vec3 eyeVector;  
uniform samplerCube tex0;  
out vec4 fragmentColor;
```

```
void main()
```

```
{  
    vec3 reflectionVector = normalize(reflect(normalize(eyeVector), normalize(normal)));  
    fragmentColor = texture(tex0, reflectionVector);  
}
```



Shadow Maps



Shadow Maps

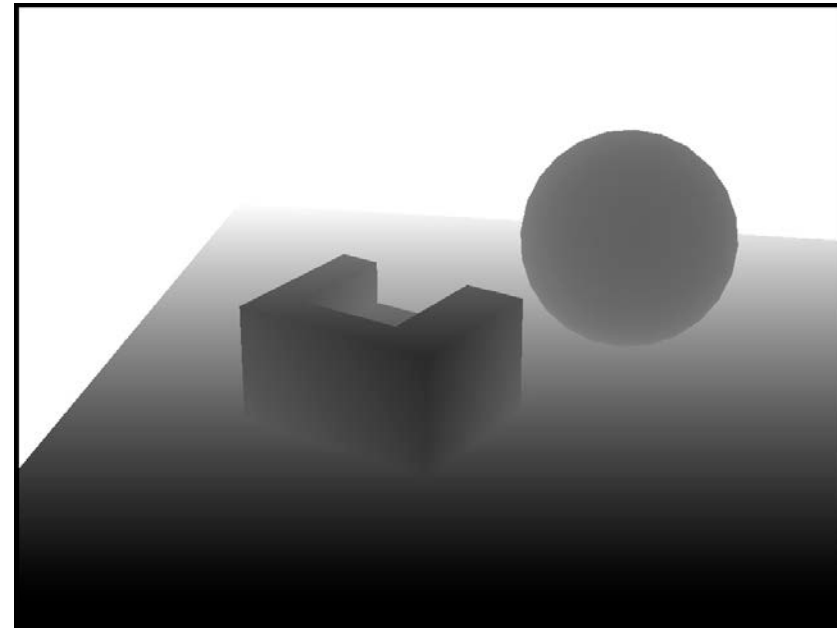
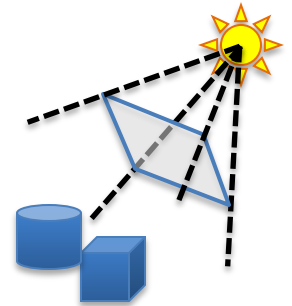


Shadow Maps

Basic Algorithm – the simple explanation:

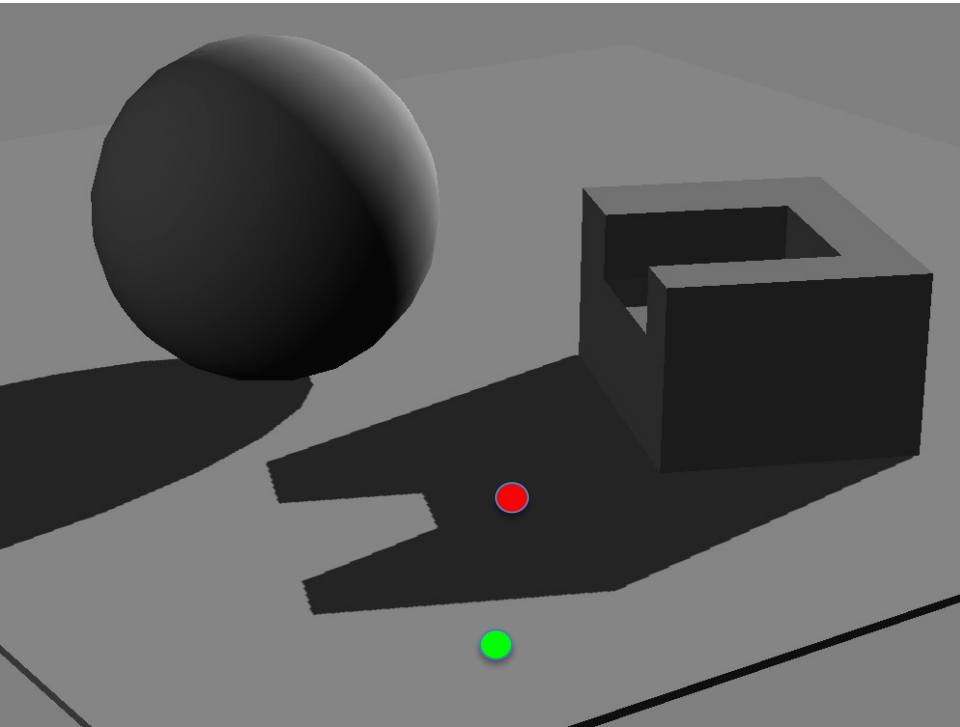
Idea:

- 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



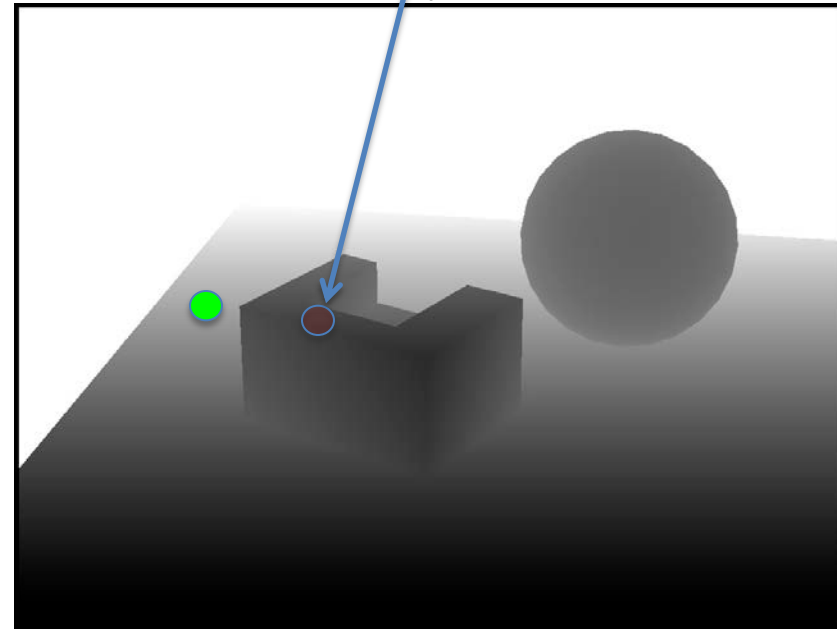
Shadow Map (light's view)

Shadow Maps



Camera's view

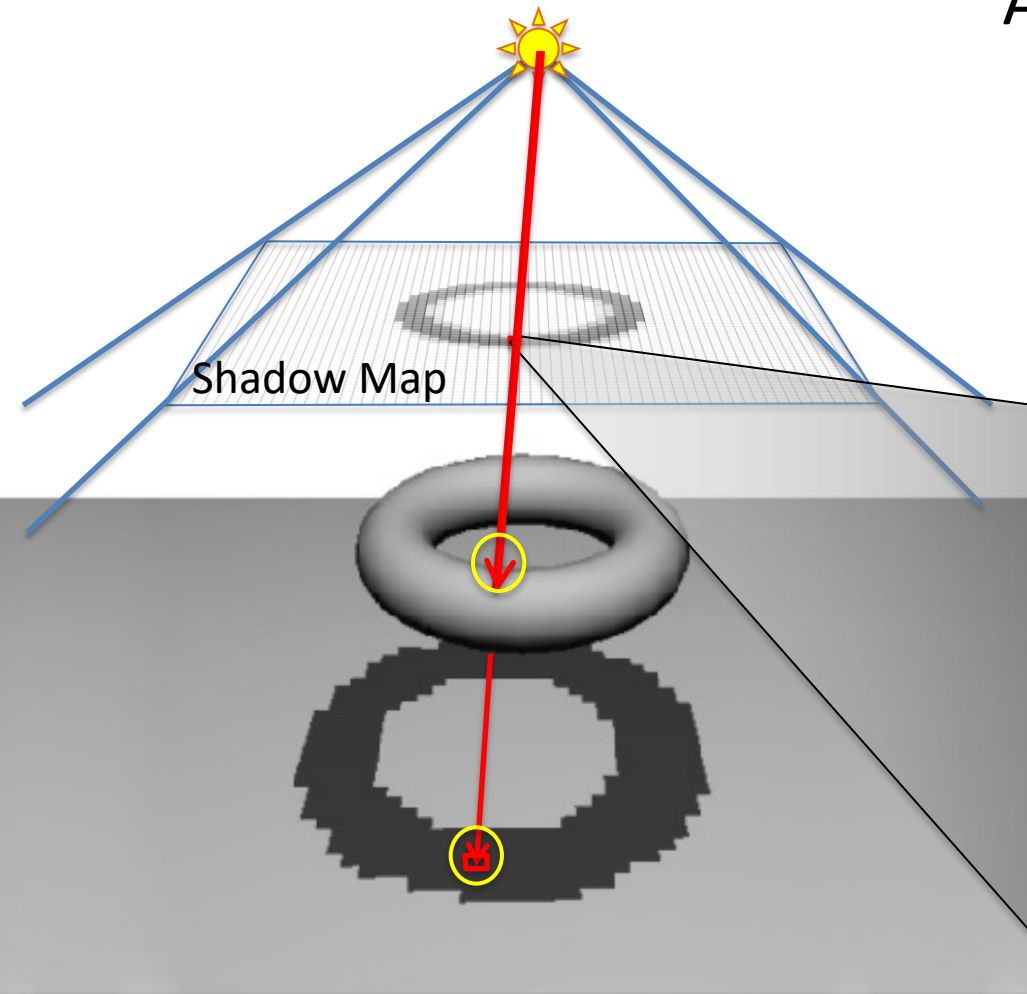
Point not
represented in
shadow map (point is
behind box)



Light's view
(Shadow Map)

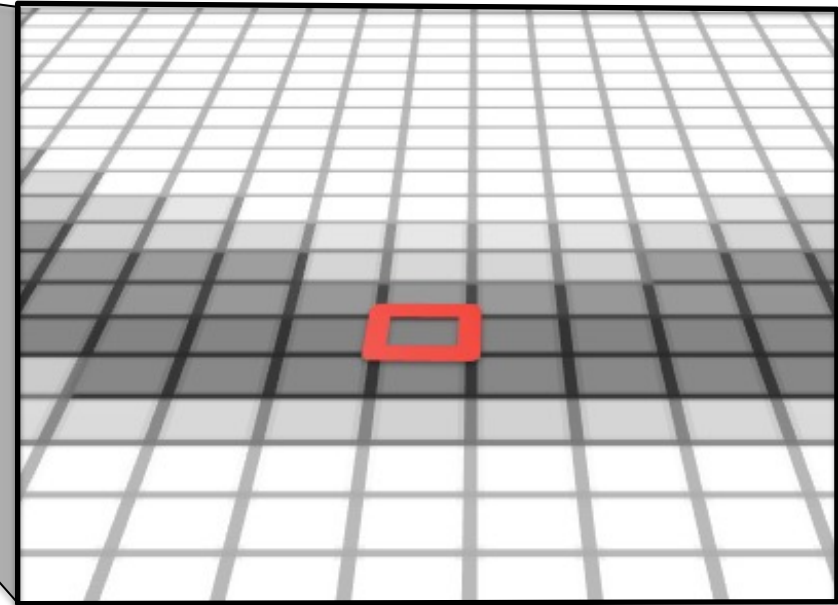
Depth Comparison

Render depth image from light



Camera's view

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



Shadow Maps

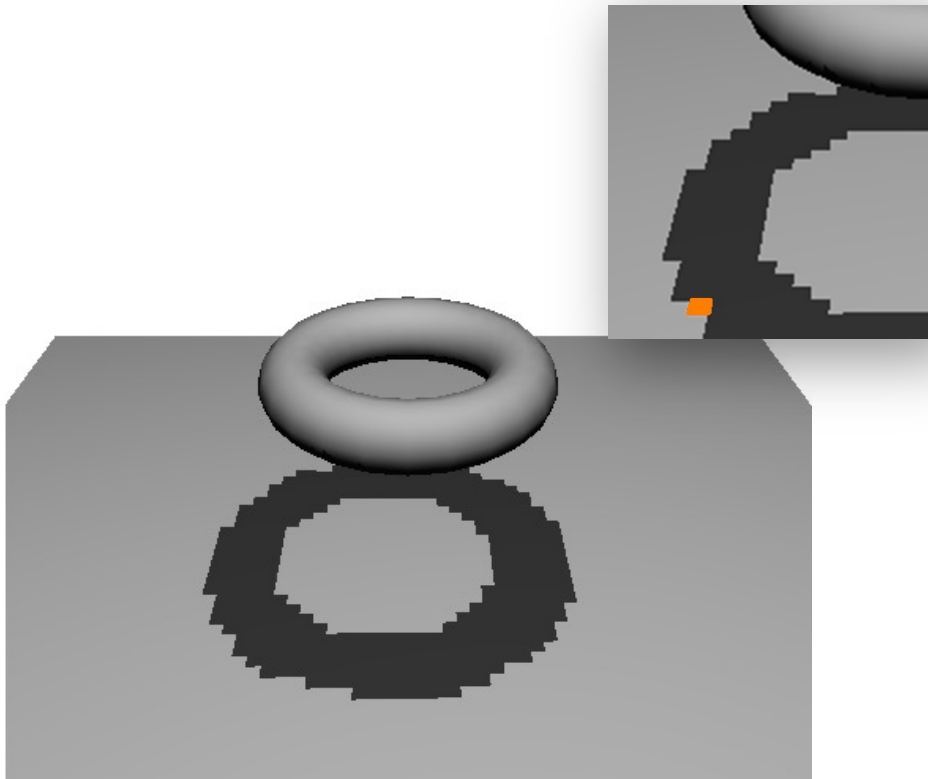
- Pros

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

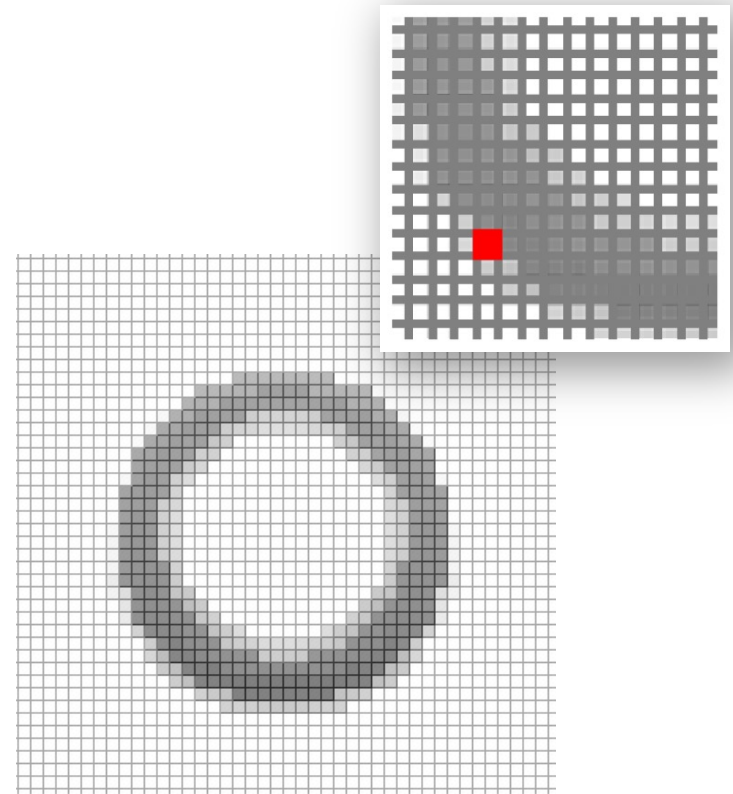
- Cons...

Shadow Maps - Problems

- Low Shadow Map resolution results in jagged shadows



from viewpoint



from light

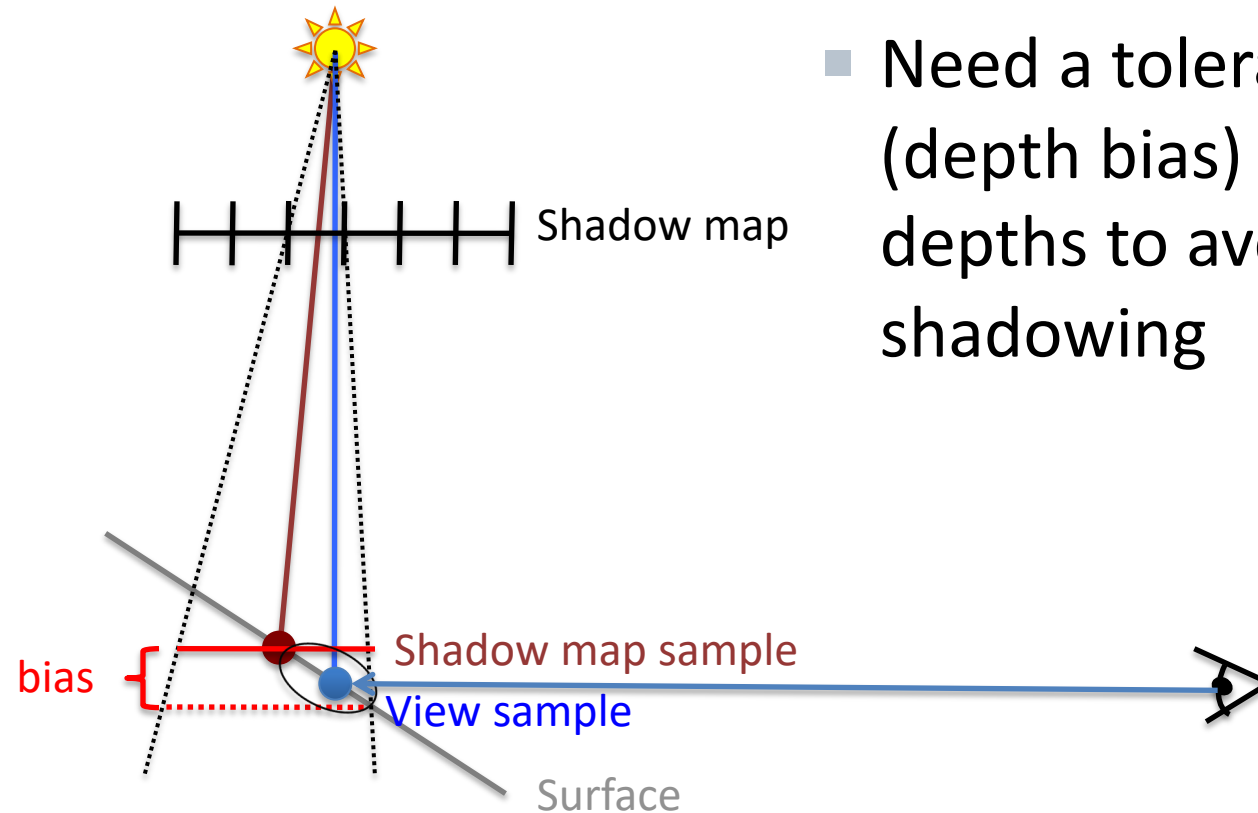
Shadow Maps - Problems

In addition:

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

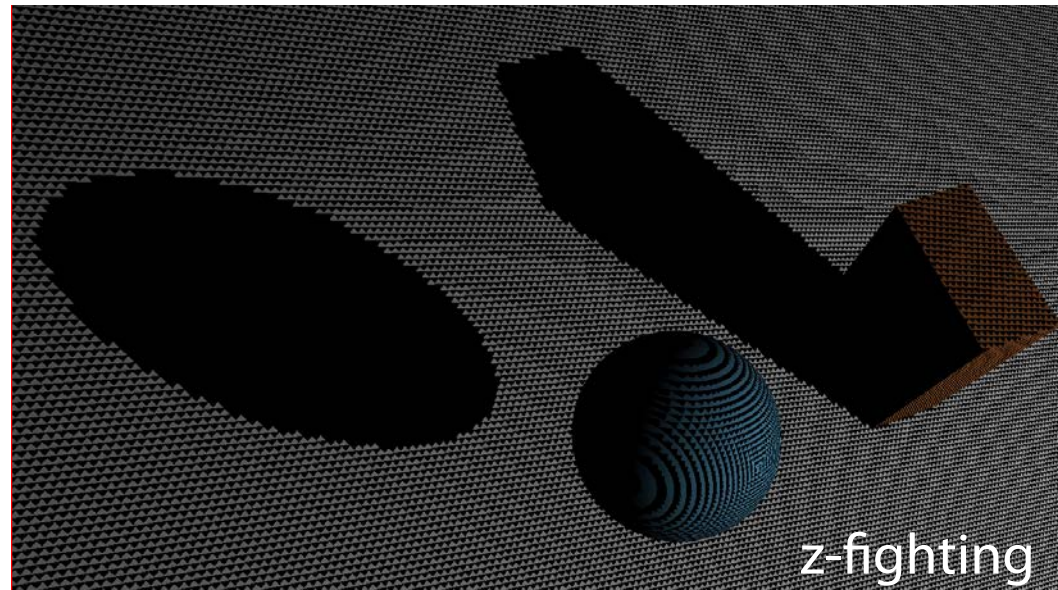
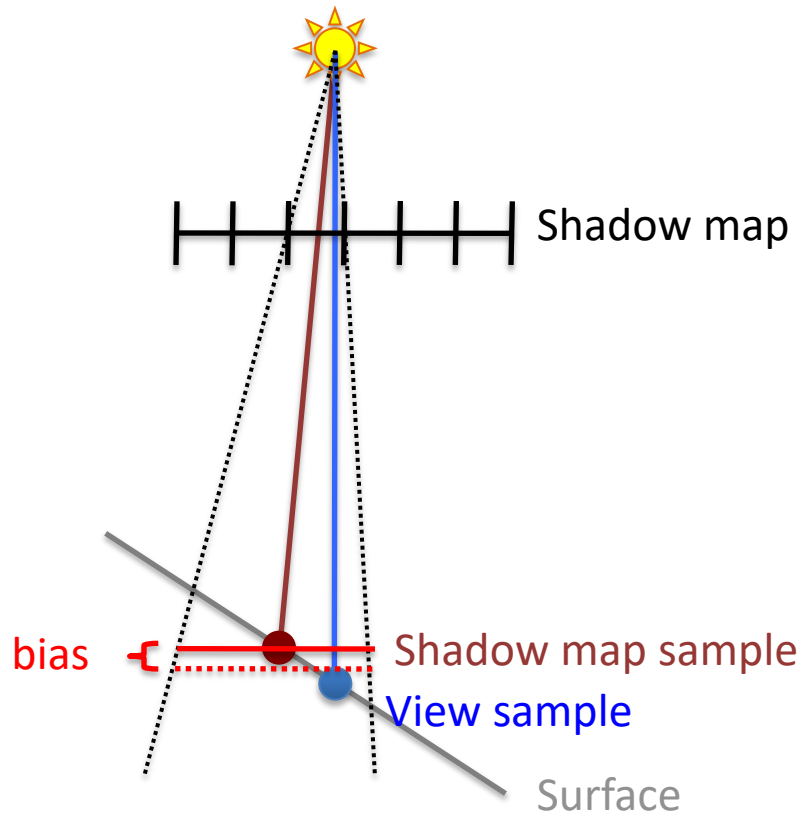
Bias

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



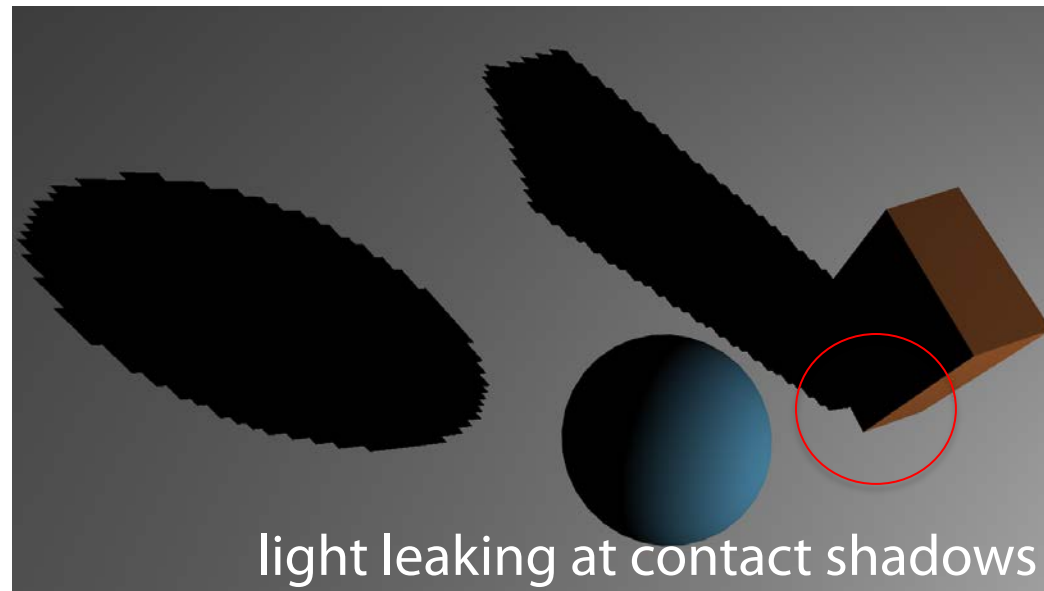
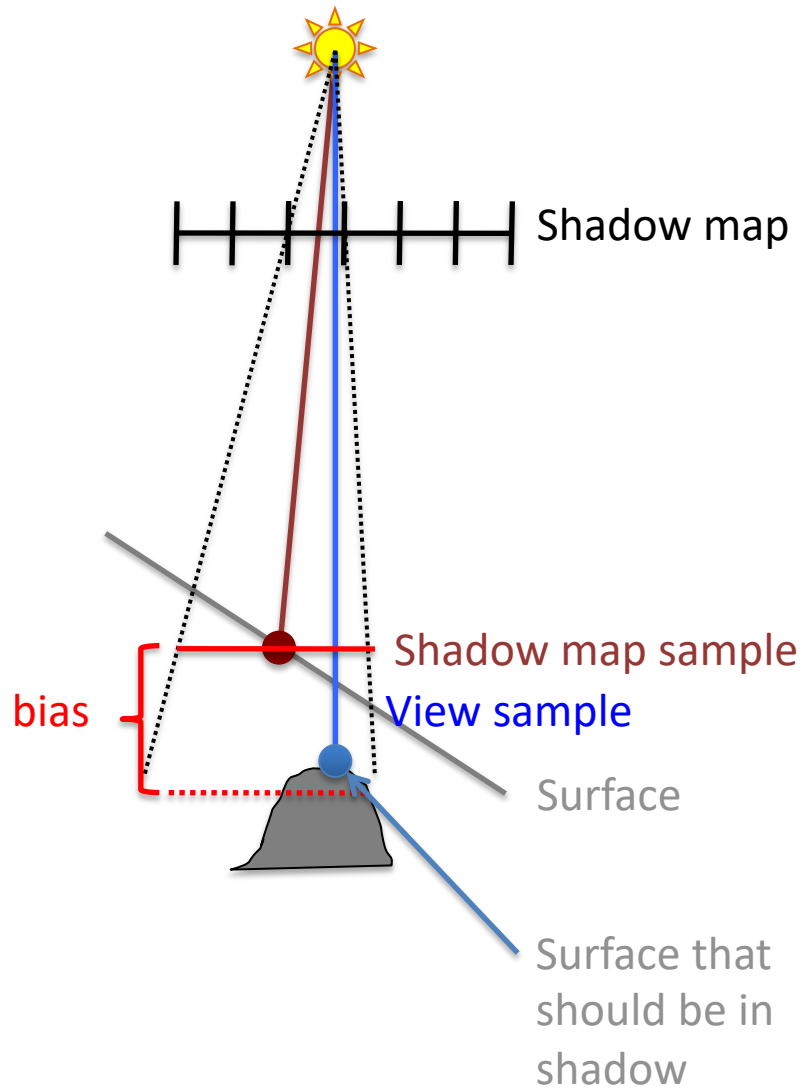
Bias

- 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, as since 2012 😊.
 - Changes every now and then, but algorithm stayed the same since 1978.

Percentage Closer Filtering

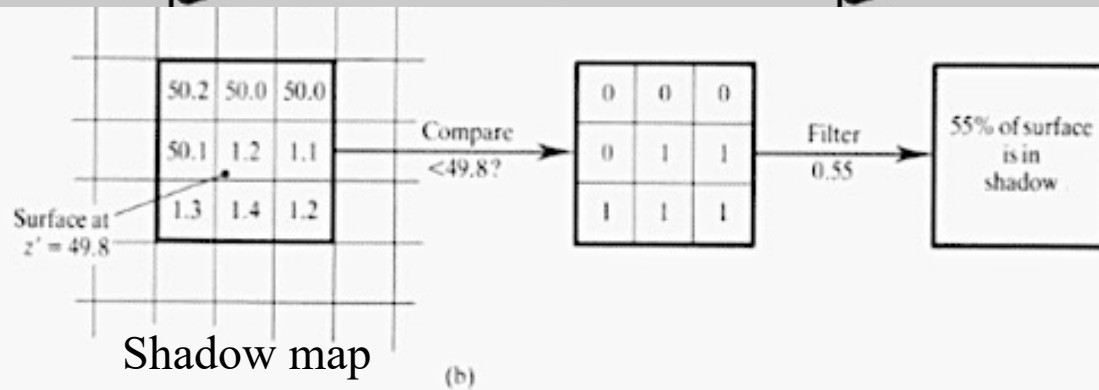
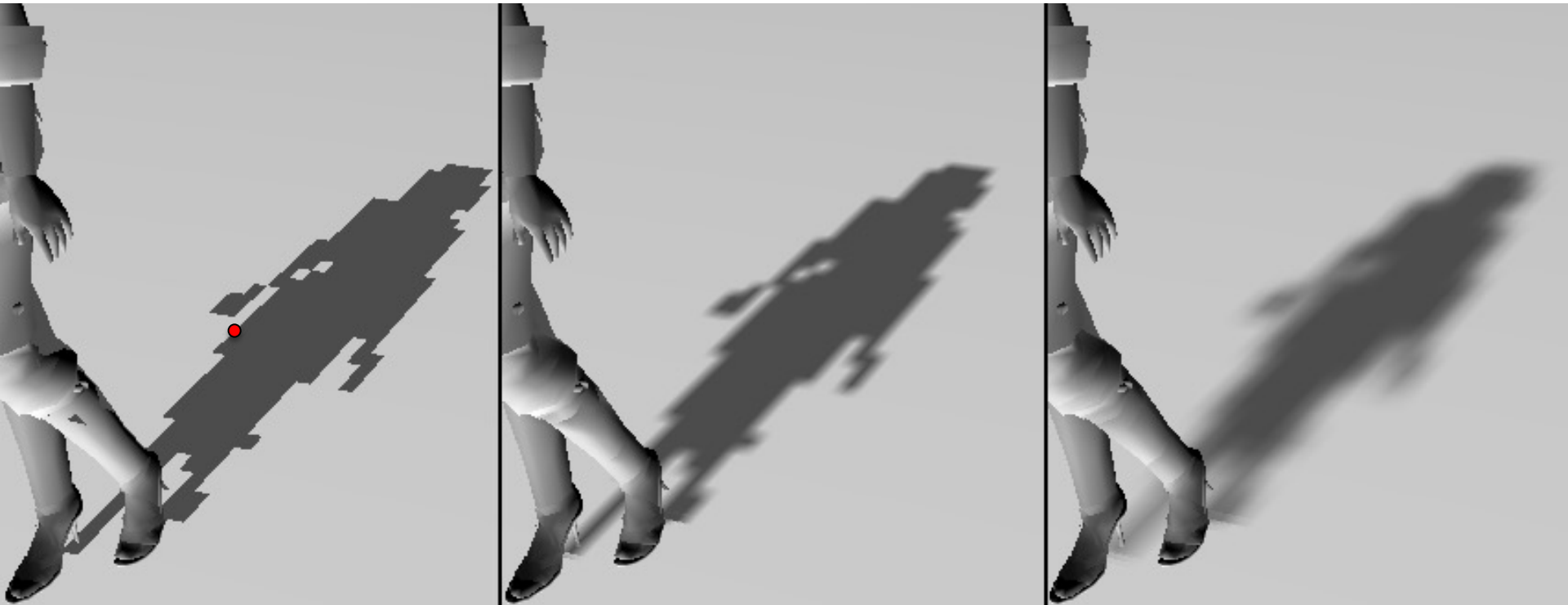


Percentage Closer Filtering

CryTek Soft Shadows



Percentage Closer Filtering



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 together 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

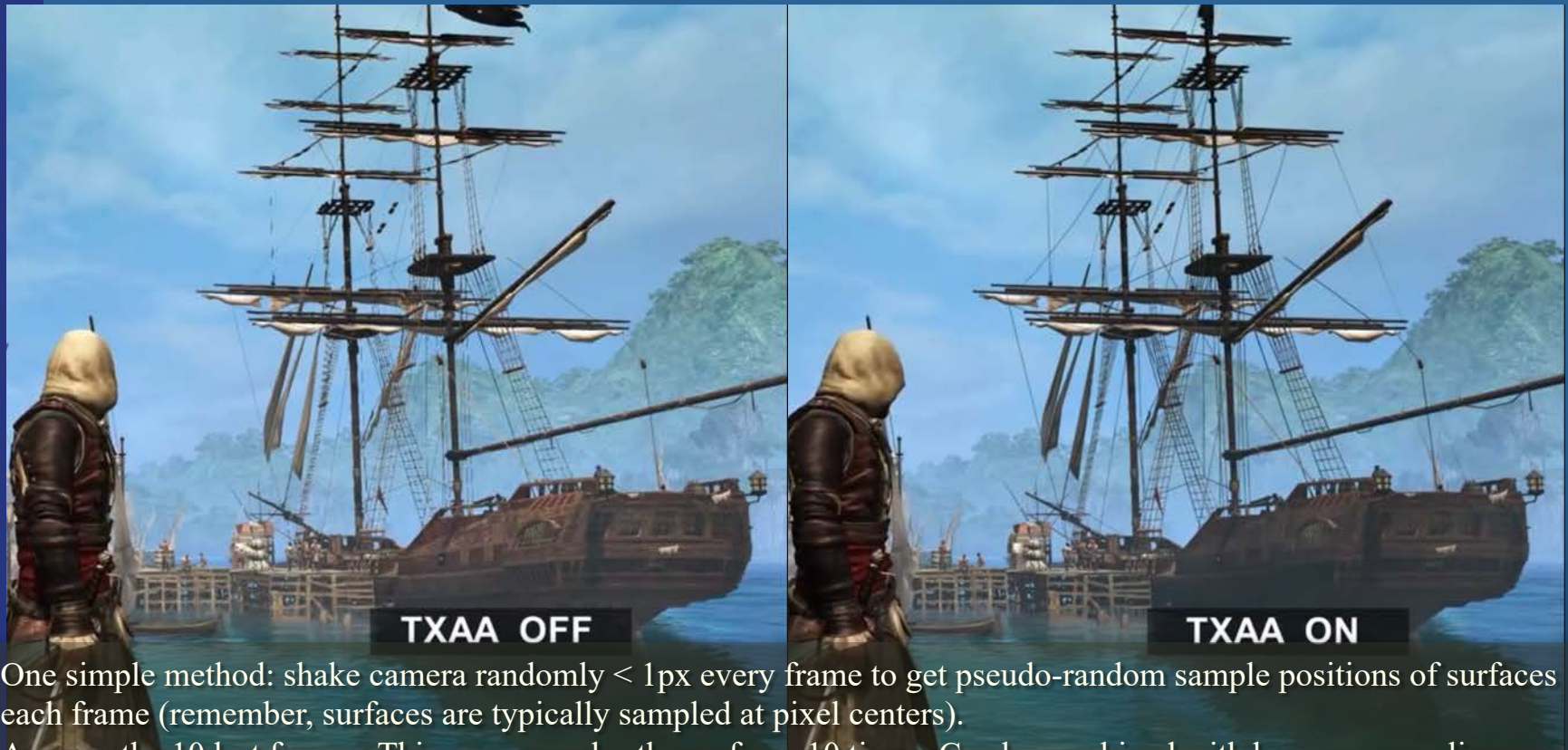


Image courtesy Brostow and Essa

Temporal Anti-aliasing (TXAA)

• Assassin's Creed IV Black Flag

Temporal Anti-aliasing seeks to reduce or remove the effects of **temporal aliasing**. (A common example of **temporal aliasing** in film is the appearance of vehicle wheels travelling backwards, the so-called wagon-wheel effect.) **Temporal anti-aliasing** can also help to reduce jaggies, making images appear softer:



- One simple method: shake camera randomly $< 1\text{px}$ every frame to get pseudo-random sample positions of surfaces each frame (remember, surfaces are typically sampled at pixel centers).
- Average the 10 last frames. This supersamples the surfaces 10 times. Can be combined with hw supersampling.
- For moving objects $\rightarrow$ utilize their motion vectors to fetch correct screen-space sample from frame $(n-i)$, $i \in [0,9]$

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`,

– `AUXi` (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

```
layout(location = 0) out vec4 fragColor0;
layout(location = 1) out vec4 fragColor1;
void main()
{
    fragColor0 =vec4(1,0,0,1);
    fragColor1 =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)** – disables writing of z-values into depth buffer
 - **glDisable(GL_DEPTH)** – disables depth testing
- Stencil buffer (e.g. used for Shadow volumes)
 - **glStencilFunc(GL_EQUAL, 0, 0xffffffff)**
 - enables and disables color-/depth-buffer drawing on a per-pixel basis – here only where stencilbuffer = 0.
 - less, lequal, greater, gequal, always
 - **glStencilFuncSeparate(...)** – settings for back-facing vs front-facing polygons
 - **glStencilOp** – how to update the stencil buffer: keep, replace, incr, decr
 - **(glStencilMask,)**
- 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[]`
 - which are sent as outputs from the vertex shader to the fragment shader.
 - `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

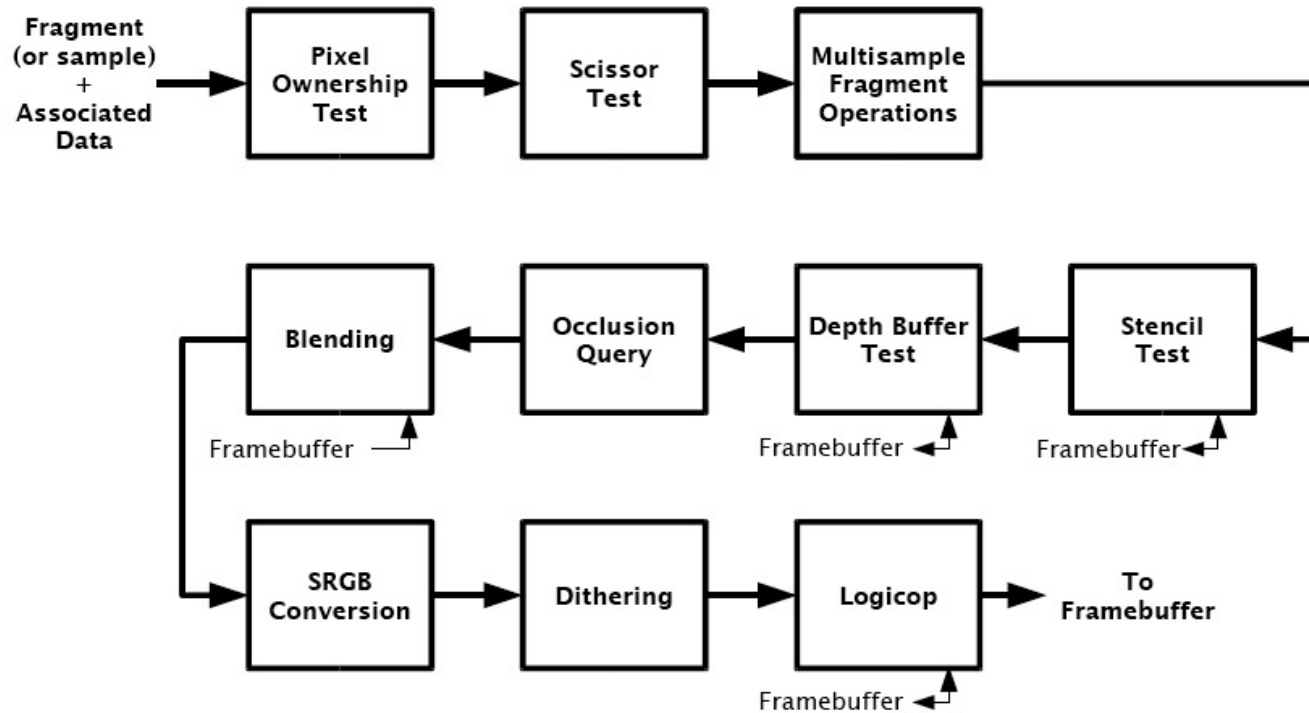


Figure 4.1. Per-fragment operations.

Other misc. newer functionality

- *Image* (“object/buffer/texture”) OpenGL 4.2

in Fragment shader to read/write to/from an *image* texture:

- **gvec4** imageLoad(**gimage** *image*, **vec2** pos);
- **void** imageStore(**gimage** *image*, **vec2** pos, **gvec4** *data*);
- https://www.khronos.org/opengl/wiki/Image_Load_Store

- *Transform feedback*

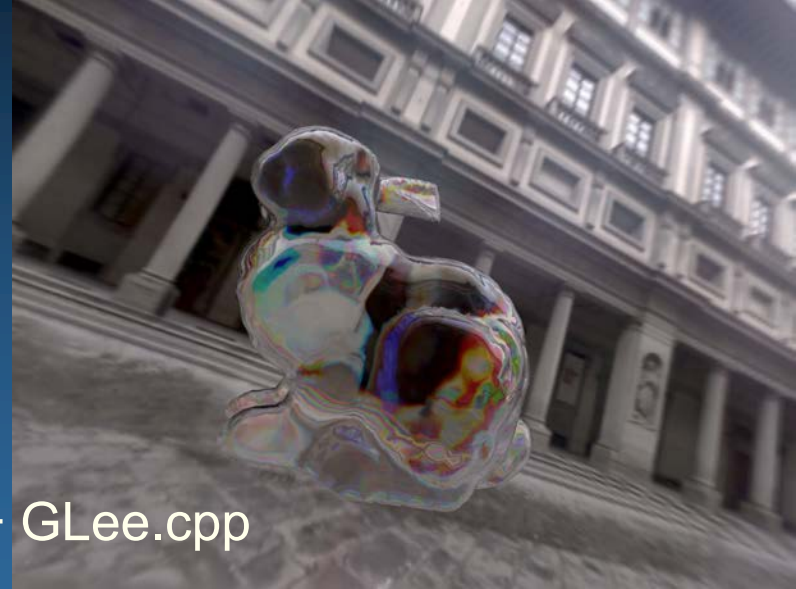
- Routing vertex-processing (vertex-, tessellation-, geometry shaders) results into a buffer object on the GPU instead of to the rasterization stage.
- **void** glBeginTransformFeedback(GLenum *primitiveMode*);
- **void** glEndTransformFeedback(*void*);

- *Occlusion queries*

to count #pixels drawn to in the frame buffer.

- glBeginQuery(GLenum *target*, GLuint *id*);
- glEndQuery(GLenum *target*);

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:
 - `glTexParameterIivEXT = wglGetProcAddress("glTexParameterIivEXT");`
 - `glClearColorIiEXT = wglGetProcAddress("glClearColorIiEXT");`

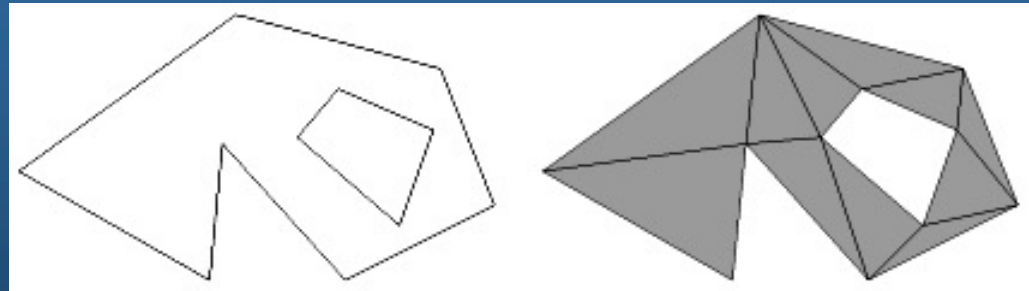
GLU – The OpenGL Graphics System Utility Library

- `#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 tessellator.
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)

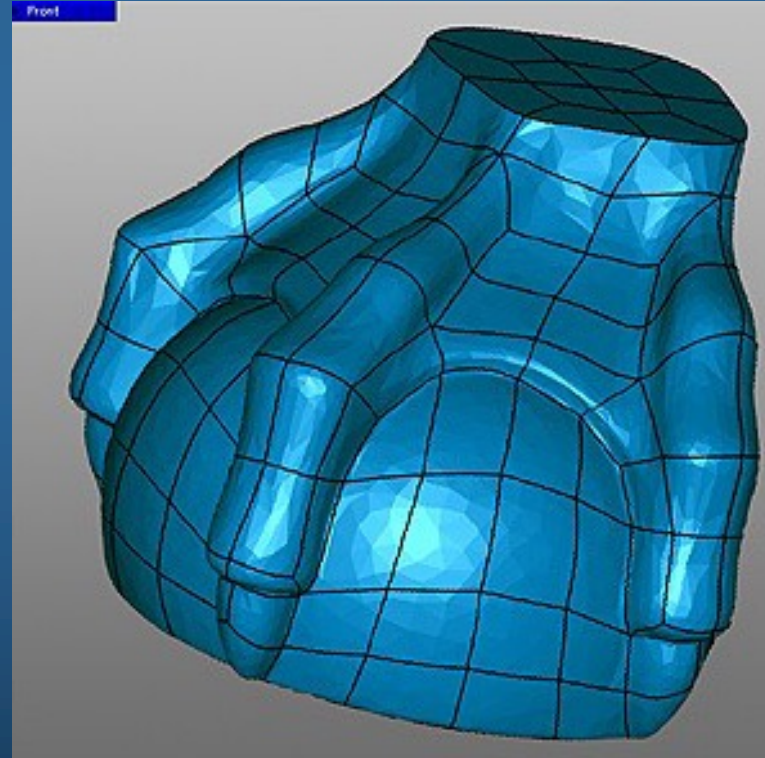
GLU - Quadrics

- 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 homepage



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

Types of 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?
 - 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