EECS 487: Interactive Computer Graphics

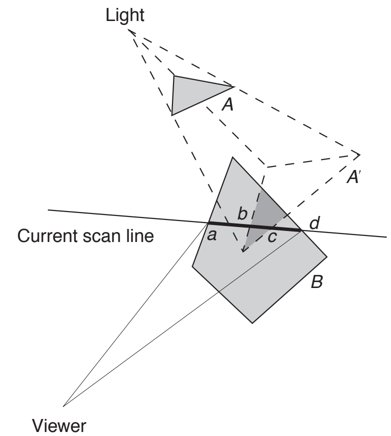
Lecture 31: Interactive Visual Effects

- Stencil Buffer
- Framebuffer Object (see sample code: http://web.eecs.umich.edu/~sugih/courses/eecs487/common/notes/gl3+webgl.tgz)

Clipped Projected Shadows

Once the projection matrix is determined:

- draw receiving planar polygon
- disable z-buffering
- draw projected occluder
  - in some dark color
  - but only where receiver is drawn
    - using stencil buffer

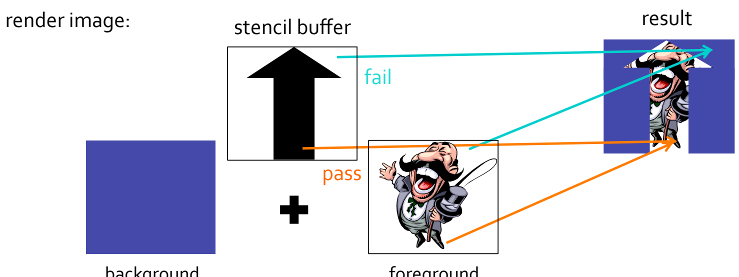


Foley et al.

Stencil Buffer

Restrict drawing to certain portion of the screen

- stencil test: for each fragment, check the corresponding stencil buffer content before rendering
- main idea: fragment rendering depends on contents of the stencil buffer passing the test
  - (not on "content of the fragment passing the test")



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Stencil Buffer

Stencil buffer usually 8 bits/pixel

Not all stencil buffer bits are tested, only those corresponding to the fragment bits

Several actions are possible depending on outcome of stencil test

- including modifying the stencil buffer contents themselves

Stencil Buffer

First specify:

- criterion for passing
- the reference value to test against the stencil buffer content

```
void
glStencilFunc(GLenum func, GLint ref, GLuint mask);
```

- `mask`: which bits of `ref` and stencil buffer content to perform the test on
- `func`:
  - `GL_NEVER`
  - `GL_LESS`: passes if `(ref & mask) < (stencil & mask)`
  - `GL_EQUAL`: passes if `(ref & mask) == (stencil & mask)`
  - ...
  - `GL_ALWAYS`

Stencil Buffer

`glStencilFunc()` and `glStencilOp()` can be used together to initialize stencil buffer content

Next specify what to do to stencil buffer content if:

- `fail`: the test fails stencil test, or
- `zfail`: passes stencil test but fails depth test, or
- `zpass`: passes both stencil and depth tests

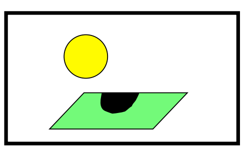
```
void
glStencilOp(GLenum fail, GLenum zfail, GLenum zpass);
```

- actions:
  - `GL_KEEP` keep the current value of stencil buffer
  - `GL_ZERO` set the stencil buffer value to zero
  - `GL_REPLACE` set the stencil buffer value to `ref`, as specified with `glStencilFunc()`
  - `GL_INCR` increment the current stencil buffer value (clamped to max)
  - `GL_DECR` decrement the current stencil buffer value (clamped to 0)
  - `GL_INVERT` bitwise invert the current stencil buffer value

Stencil Test Example

```
void glStencilFunc(GLenum func, GLint ref, GLuint mask);
void glStencilOp(GLenum fail, GLenum zfail, GLenum zpass);
```

Want:

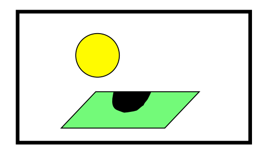


`GL_REPLACE`: set the stencil buffer value to `ref`

both color and stencil buffers

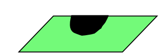
```
// draw lit receiver on both color and stencil buffers
glStencilFunc(GL_ALWAYS, 1, 1);
glStencilOp(GL_ZERO, GL_ZERO, GL_REPLACE);

glCallList(receiver);   // set stencil to 1 everywhere receiver is drawn
```

Stencil Test Example

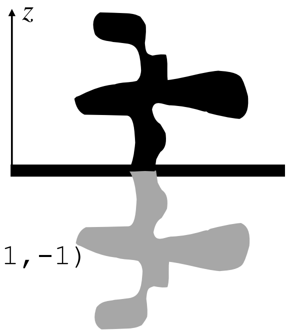


```
void glStencilFunc(GLenum func, GLint ref, GLuint mask);
void glStencilOp(GLenum fail, GLenum zfail, GLenum zpass);
```

```
// draw unlit receiver in shadowed area, onto color buffer only
glDepthFunc(GL_LEQUAL);
glDisable(GL_LIGHTING);
glStencilFunc(GL_EQUAL, 1, 1);  // draw if corresponding stencil
                                // pixel is 1, else don't draw
glColor3f(0.0f, 0.0f, 0.0f);    // color it black
glPushMatrix();
glMultMatrixf((GLfloat*)shadowM); // shadow projection matrix
glCallList(occluder);  // transform+draw onto color buffer in black
                       // where stencil buffer is 1
glPopMatrix();
glDepthFunc(GL_LESS);
```



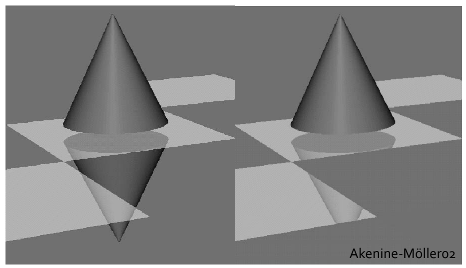
Planar Reflections



Reflections also influence visual perception of spatial relationships and help increase realism

For plane at $z = 0$, apply `glScalef(1,1,-1)`
- back facing polygons become front facing!
- lights must be reflected as well

When reflection surface is smaller than reflected image, reflected image need to be clipped (how?)



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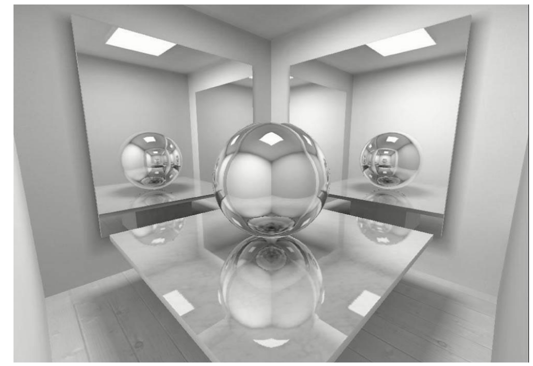
Rendering Planar Reflections

Render:
1. the mirror plane into the stencil buffer
2. the scaled $(1,1,-1)$ model, but masked with the stencil buffer
3. the mirror plane (semi-transparent)
4. the unscaled model

Alternate method: instead of scaling,
1. reflect the camera position and direction in the plane
2. render reflection image from there



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Framebuffer Object

The accumulation buffer has been deprecated since OpenGL 3.1

Instead, use framebuffer object with floating-point pixel format (for the increased resolution)

OpenGL Default Framebuffer

Framebuffer: a collection of images that store information representing the image OpenGL eventually displays

OpenGL default framebuffer consists of:
- color buffer(s): contains info about the color of each pixel, there could be up to 4 color buffers: two for double buffering, which, together with the other 2, enable stereoscopic rendering
- depth (or z-) buffer: stores depth info of each pixel, allowing closer pixels to be drawn over those farther away
- stencil buffer: for masked rendering
- multisample buffer: for anti-aliasing
- accumulation buffer: for GFX
- auxiliary color buffer(s): for off-screen rendering

subsumed by FBO since OpenGL 3

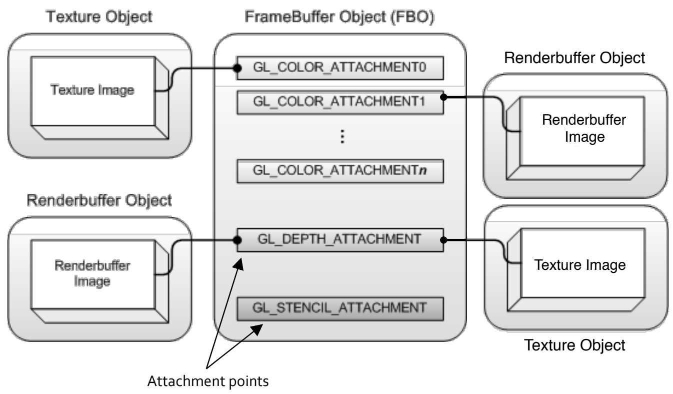
Framebuffer Object (FBO)

A mechanism for rendering to other than the default framebuffer, e.g., render-to-texture, as accumulation buffer, or other intermediate buffers for GFX

Each FBO can have texture object or renderbuffer object attached to it

Attachment is different from binding:
- binding binds an object to a context, the states of the context are mapped to the states of the object (changing one changes the other)
- attachment simply connects two objects together

FBO Graphicallly



[Ahn]

Texture vs. Renderbuffer Object

A texture object (we're familiar with from texturing):
- contains one or more images
- the images must all have the same format
- but could be of different sizes (for mipmapping, e.g.)
- used for render-to-texture
  - can be used to render from/with
  - can be bound to shader variables

A renderbuffer object:
- contains a single 2D image, no mipmaps, cubemap faces, etc.
- optimized to be used as render target
- can only be attached to an FBO and be rendered to
- mostly used as depth and stencil buffers
- also for offscreen-rendering and for pixel transfer (see PBO)
  - cannot be used to render from/with
  - cannot be bound to shader variables

Framebuffer Object (FBO)

Similar to the default framebuffer, an FBO have attachment points for:
- n (≥ 1) color-buffers (`GL_COLOR_ATTACHMENT`i)
  - `glGetFramebufferAttachmentParameter(…, GL_MAX_COLOR_ATTACHMENTS, …)` for value of n
- 1 depth-buffer (`GL_DEPTH_ATTACHMENT`)
- 1 stencil-buffer (`GL_STENCIL_ATTACHMENT`)
- also `GL_DEPTH_STENCIL_ATTACHMENT`
- (all may be multisampled)
- (no accumulation buffer)

Different attachment points impose different limitations on the format of attachable image

Framebuffer Object Setup

As with other OpenGL objects, first call `glGen*()`:

```
glGenFramebuffers(GLsizei n, GLuint *fbods);
```

Next bind FBO descriptor to a type of framebuffer

```
glBindFramebuffer(target, fbod);
// target is GL_FRAMEBUFFER (for read/write),
// GL_DRAW_FRAMEBUFFER, or
// GL_READ_FRAMEBUFFER, allowing for
// glReadPixels() and glDraw*() to operate
// on separate framebuffers
// fbod=0 is reserved for the default framebuffer, use fbod=0
// to unbind current framebuffer and revert to the default framebuffer
```

Subsequently, all rendering goes to the bound framebuffer

- `glViewport(0, 0, width, height)` render to the whole buffer

Renderbuffer Object Setup

To set up a renderbuffer object as the render target:

```
int rbod;
glGenRenderbuffers(1, &rbod);
glBindRenderbuffer(GL_RENDERBUFFER, rbod);
```

allocate storage for the renderbuffer:

```
glRenderbufferStorage(GL_RENDERBUFFER,
   internalformat, width, height);
// internalformat: depending on attachment: GL_RGBA, GL_RGB32F, etc.
// or GL_DEPTH_COMPONENT, GL_STENCIL_INDEX, GL_DEPTH_STENCIL
// see http://www.opengl.org/wiki/Image_Format#Required_formats
// width, height: must be < GL_MAX_RENDERBUFFER_SIZE
//    use glGet(GL_MAX_RENDERBUFFER_SIZE, …)
```

and attach it to the framebuffer

```
glFramebufferRenderbuffer(target, attachment_point,
                          GL_RENDERBUFFER, rbod);
```

Texture Object Setup

To set up a texture object as the render target:

```
int tod;
glGenTextures(1, &tod);
glBindTexture(GL_TEXTURE_2D, tod);
glTexImage2D(GL_TEXTURE_2D, level, internalformat,
   width, height, border, format, GL_UNSIGNED_BYTE, 0);
// the last argument is 0, no texture needs be copied
// level: can render to different levels of a mipmap, but no auto mipmap
//     with TexParam GL_GENERATE_MIPMAP b/c no texture is copied,
//     instead use glGenerateMipmap() after base image is modified
```

and attach it to the framebuffer:

```
glFramebufferTexture2D(target, attachment_point,
                       GL_TEXTURE_2D, tod, level);
// target: GL_FRAMEBUFFER (== GL_DRAW_FRAMEBUFFER, not read & write)
//         or GL_READ_FRAMEBUFFER
// tod==0 detaches texture object
```

Framebuffer Check

Before using the framebuffer target, check that it is set up properly and all objects are correctly attached:

```
GLenum glCheckFramebufferStatus(GL_FRAMEBUFFER);
```

you want to see `GL_FRAMEBUFFER_COMPLETE` returned

If the framebuffer is not complete, any reading/writing command will fail

See the wiki page for completeness rules and corresponding error messages: http://www.opengl.org/wiki/Framebuffer_Object

Render-to-Texture

Used to generate dynamic texture, e.g., for reflection effect, dynamic environment maps, shadow maps

Remember to:

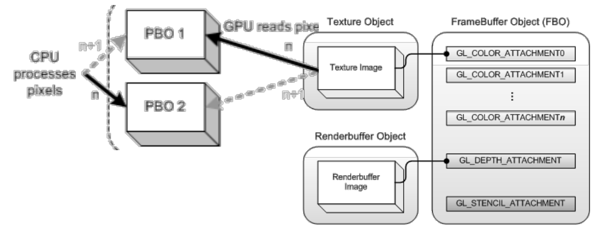
- `glEnable(GL_TEXTURE_2D)` before applying the texture (use `glPushAttrib(GL_ENABLE_BIT)` and `glPopAttrib()`)
- set the texture parameters for minification (and magnification and texture coordinate wrap around behavior, as necessary)
- and set the texture application mode: `GL_REPLACE`, `GL_BLEND`, etc.

Render-to-Texture

Even if you only need the color buffer, you may have to provide depth and stencil buffers if the rendering process needs them

- unless you want to store a shadow map, the depth buffer is usually a renderbuffer (faster)

Can be combined with PBO for post-processing FX such as image-based motion blur and depth-of-field



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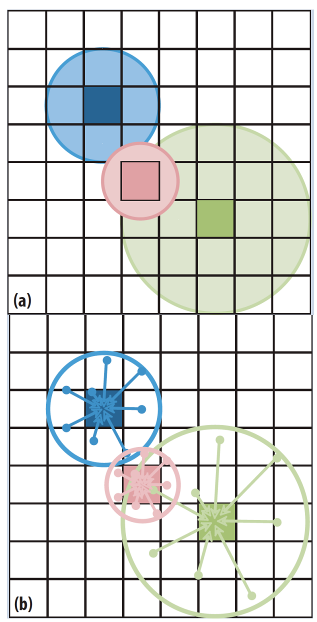
Post-processing FX

Creating multiple images takes time

Instead, simulate depth of field and motion blur as image post-processing

Depth of field, for depths away from focal distance:

a. forward mapping: color of a pixel is spread out to its circle of confusion as a function of depth
b. reverse mapping: color of a pixel is averaged from neighboring pixels, neighborhood size a function of depth



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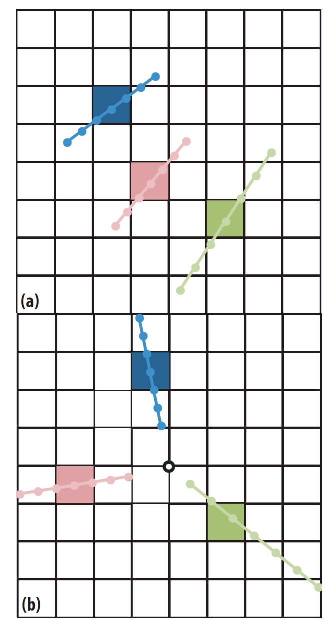
Post-processing FX

Motion blur:

- during rendering, render to a velocity buffer the screen-space velocity of object at each pixel
- during post-processing, each pixel is blurred by averaging pixels in a line segment with equally spaced sampling point
- the direction and length of the line segment is a function of the velocity

- can also be simulated in object space by stretching vertices over time



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Read and Render Targets

In the app, you can specify which buffer to draw to or read from per bound framebuffer using:

```
glDrawBuffer(GL_COLOR_ATTACHMENTi);
glReadBuffer(GL_COLOR_ATTACHMENTi);
```

or specify more than one draw buffers:

```
glDrawBuffers(#buffers, buffers[]);
```

For example, to use buffer 0 as texture to render to buffer 1:

```
glReadBuffer(GL_COLOR_ATTACHMENT0);
glDrawBuffer(GL_COLOR_ATTACHMENT1);
glDrawArrays(…);
```

Render Target in Shader

If you attach a texture object `tod` at mipmap level 0 to color attachment 1:

```
glFramebufferTexture(GL_FRAMEBUFFER,
      GL_COLOR_ATTACHMENT1, tod, 0);
```

your fragment shader specifies this render target with:

```
layout(location = 1) out vec3 color;
```

To render to multiple targets, attach multiple color attachments and specify a different location for each fragment shader variable, e.g., temperature, stress level, etc. rendered as false color into different targets

Framebuffer Blitting

Blitting ::= copying a rectangular area of pixels from one framebuffer to another

- can blit between FBOs
- can also blit between an FBO and the default framebuffer, in either direction
- blitting is more limited than pixel transfer in format conversion (see http://www.opengl.org/wiki/Framebuffer_Object)

Framebuffer Blitting Example

To copy from buffer 1 of your fbo to the default framebuffer, for example:

```
glBindFramebuffer(GL_DRAW_FRAMEBUFFER, 0);
glBindFramebuffer(GL_READ_FRAMEBUFFER, fbod);
glReadBuffer(GL_COLOR_ATTACHMENT1);
glBlitFramebuffer(srcX0, srcY0, srcX1, srcY1, dstX0,
dstY0, dstX1, dstY1, GLbitfield mask, GLenum filter);
// mask: GL_COLOR_BUFFER_BIT, GL_DEPTH_BUFFER_BIT, or
// GL_STENCIL_BUFFER_BIT
// filter: if the image needs to be stretched, interpolate by
// GL_NEAREST or GL_LINEAR
```

For color buffer, only `GL_READ_FRAMEBUFFER` is copied to `GL_DRAW_FRAMEBUFFER`

Multi renders if more than one `GL_DRAW_FRAMEBUFFER` is specified

Using FBO as Accumulation Buffer

What we need: a framebuffer object with:

- a texture object with `GL_RGBA` *`internalformat`* to be our per-frame color buffer (attachment 0)
- a renderbuffer object with `GL_RGB32F` *`internalformat`* to be our accumulation buffer (attachment 1)
- a renderbuffer object to serve as our depth (and stencil) buffer

Init: clear our "accumulation buffer" (to 0):

```
glDrawBuffer(GL_COLOR_ATTACHMENT1);
glClearColor(0.0, 0.0, 0.0, 0.0);
glClear(GL_COLOR_BUFFER_BIT);
glDrawBuffer(GL_COLOR_ATTACHMENT0);
          // for per-frame rendering
```

Using FBO as Accumulation Buffer

After each frame is rendered to color buffer 0:

- draw a quad that fills the screen (modify model-view and projection matrices) onto the accumulation buffer, textured with color buffer 0 already bound to `GL_TEXTURE_2D`:

```
glPushAttrib(GL_ENABLE_BIT);
glDisable(GL_DEPTH_TEST); glDisable(GL_LIGHTING);
// enable blending as per below
glDrawBuffer(GL_COLOR_ATTACHMENT1);
glEnable(GL_TEXTURE_2D);
glDrawArrays(…);
glDrawBuffer(GL_COLOR_ATTACHMENT0);
glPopAtrib();
```

- blend color buffer 0 with content of "accumulation buffer":

```
glEnable(GL_BLEND);
glBlendColor(0.0, 0.0, 0.0, weight);
      // same weight used with glAccum()
glBlendFunc(GL_CONSTANT_ALPHA, GL_ONE);
glBlendEquation(GL_FUNC_ADD);
```

Using FBO as Accumulation Buffer

To display the accumulation buffer:

- bind our FBO to `GL_READ_FRAMEBUFFER`, set color attachment 1 as the read buffer
- bind the default FBO (0) to `GL_DRAW_FRAMEBUFFER`
- call `glBlitFramebuffer()`
- bind the default FBO (0) to `GL_FRAMEBUFFER` and display

See `fbo.cpp` for example