VGP353 – Week 2

- Agenda:
  - Assignment #1 due
  - Introduce shadow maps
    - Differences / similarities with shadow textures
    - Added benefits
    - Potential problems

Shadow Textures

- Shadow textures have a number of faults:
  - Separate texture for each caster / light pair
  - No self-shadowing
  - Difficulty with casters / receivers that are nearly the same distance from the light
- What is the fundamental limitation at the root of all these problems?

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  - Separate texture for each caster / light pair
  - No self-shadowing
  - Difficulty with casters / receivers that are nearly the same distance from the light
- What is the fundamental limitation at the root of all these problems?
  - Each shadow texel is a simple on-or-off. The remaining information must be inferred.

Shadow Textures

- To determine whether a position in 3-space is in shadow, what information is needed?

Shadow Textures

- To determine whether a position in 3-space is in shadow, what information is needed?
  - Is there something *closer* to the light in the direct line-of-sight
    - The shadow texture only tells whether there is something in the line of sight, *not* whether that something is closer to the light

Shadow Maps

- Instead of boolean “shadow” / “not shadow”, store the distance from the light to the nearest occluder
  - This is a *shadow map*
  - Compare the distance read from the shadow map to the distance between the object and the light
    - If $d_{shadow} < d_{object}$, the fragment is in shadow
    - If $d_{shadow} \geq d_{object}$, the fragment is not in shadow

Shadow Maps

- Shadow map stores “distance to nearest shadow caster.”
  - *Remind* you of anything?

Shadow Maps

- Shadow map stores “distance to nearest shadow caster.”
  - *Remind* you of anything?
  - A depth buffer!
    - Depth buffer (typically) stores the per-pixel distance to the object nearest to the eye
    - When rendering from the light's PoV, the distance stored in the depth buffer is the distance to the object nearest to the light

Shadow Textures vs. Shadow Maps

- Shadow texture:
  - Draw either light color or shadow color to a color texture
  - Read light color directly from shadow texture
  - Color fragment based on light color
- Shadow map:
  - Draw distance to nearest object to a depth texture
  - Compare occluder distance to object distance
  - Color fragment based on result of comparison

Shadow Maps

- Advantages:

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  - Objects can self-shadow!
  - Near-by objects can shadow each other correctly

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- Disadvantages:
  - Separate texture for each caster / light pair
    - *Is this necessary? NO!*

Shadow Maps Revised

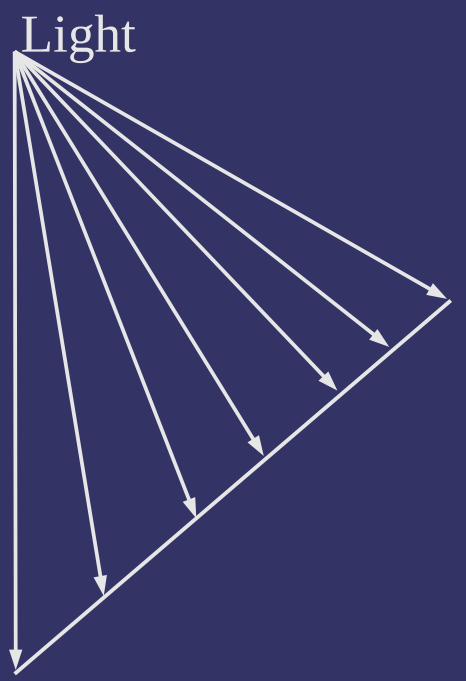
- Algorithm:
  - Group potential casters and receivers
  - Calculate frustum that encompasses all objects within a group
  - Render objects using calculated frustum.
    - Store depth buffer in a texture (shadow map)
  - Render objects from the camera's PoV with appropriate shadow map.
    - Use comparison previously described.

Shadow Map Problems

- Four big problems with shadow maps:
  - Sampling differences between shadow map rendering and reading...the dreaded “shadow acne”
  - Aliasing
  - Lack of depth precision
  - Omni-directional lights inside the view frustum

Shadow Acne

- Light and camera sample object at different positions
  - Drawing from the light's PoV samples one set of positions



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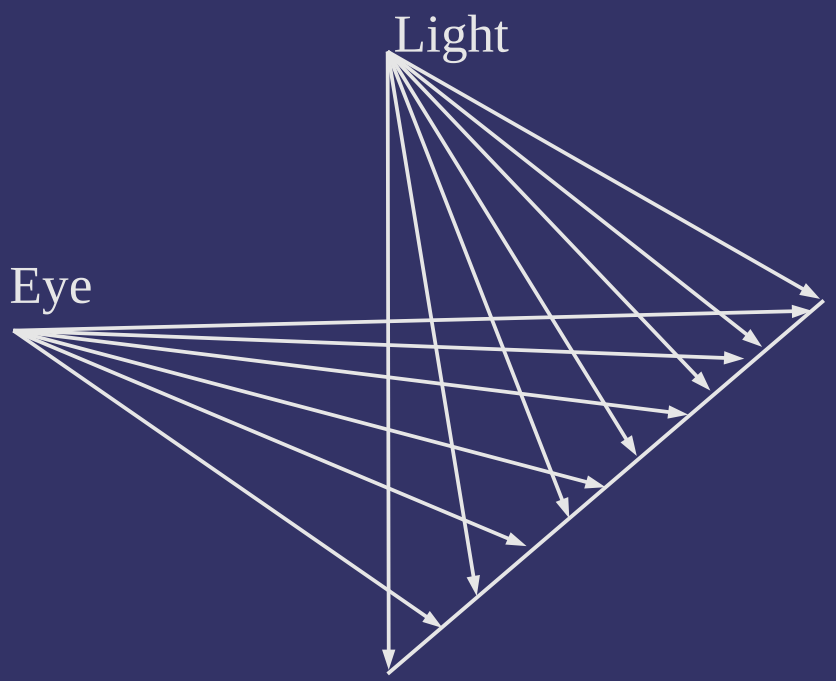
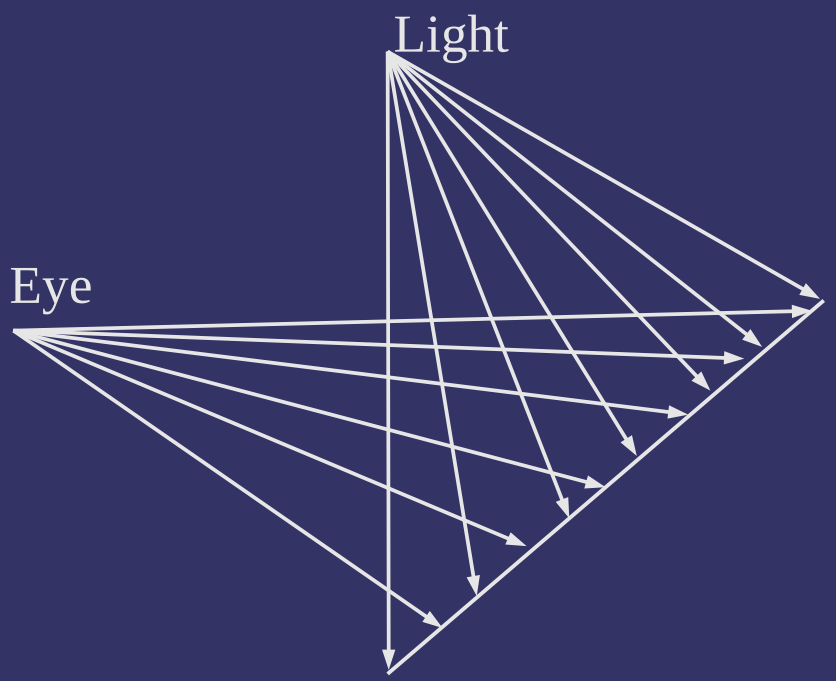


Shadow Acne

- Light and camera sample object at different positions
  - Drawing from the light's PoV samples one set of positions
  - Drawing from the camera's PoV samples a different set of positions
  - Result: incorrect values are used to determine if a surface shadows itself



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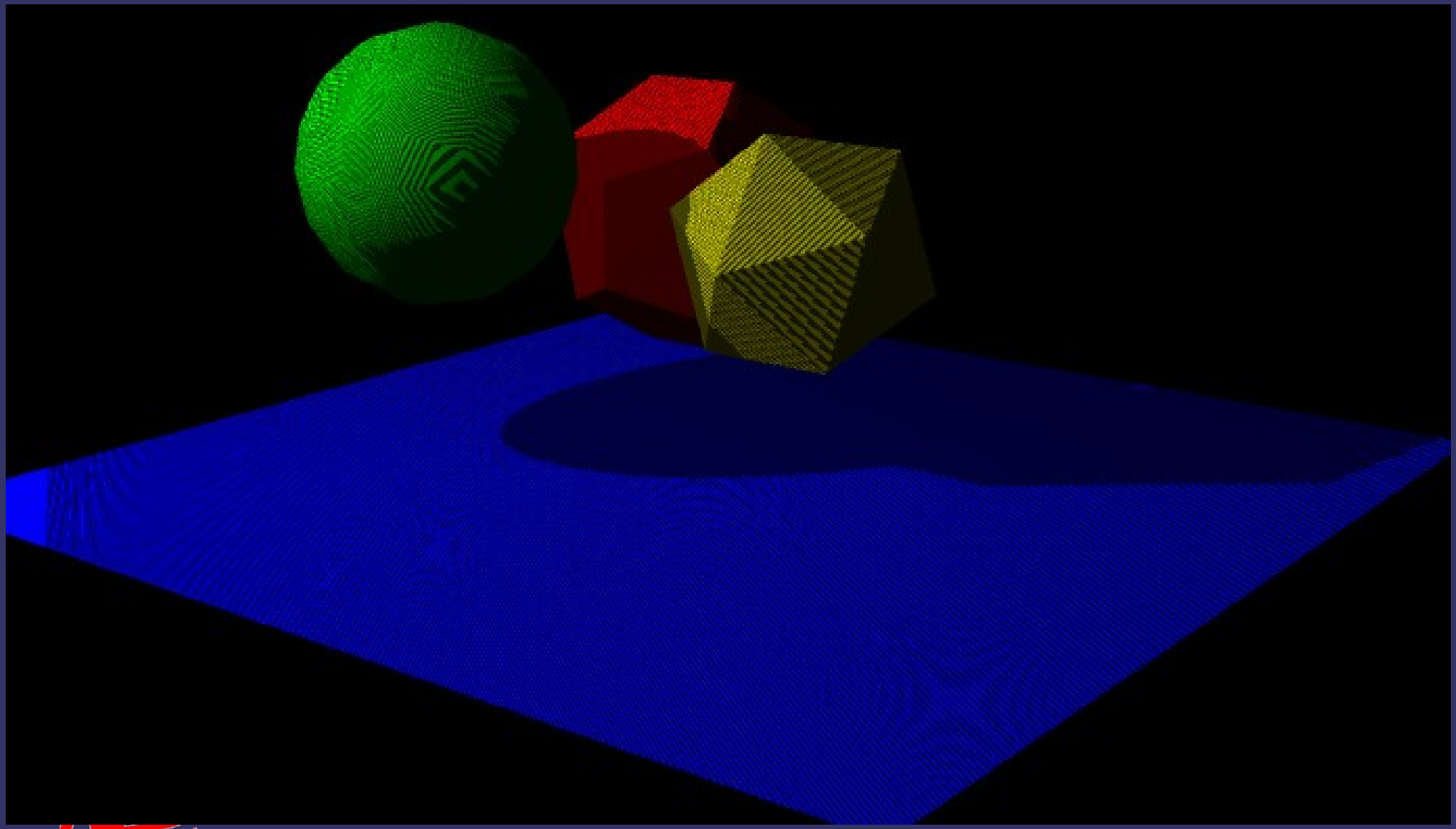

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  - Render back faces to shadow map
    - Front faces aren't drawn to shadow map, so they won't self-shadow
    - Back faces aren't lit: depth comparison result is irrelevant

Shadow Acne

- Two common solutions:
  - Render back faces to shadow map
    - Front faces aren't drawn to shadow map, so they won't self-shadow
    - Back faces aren't lit: depth comparison result is irrelevant
  - Use polygon offset
    - Bias fragment depth by small factor to ensure $d_{shadow} \geq d_{object}$

```
glPolygonOffset(1.1f, 1.0f);
```

    - Very tricky to get right! Movie fx companies spend *lots* of time tweaking every frame to eliminate artifacts[1]

[1] G. King, "Shadow Mapping Algorithms." NVIDIA. 2004. ftp://download.nvidia.com/developer/presentations/2004/GPU_Jackpot/Shadow_Mapping.pdf

Shadow Map Aliasing

- Several sources of aliasing in shadow maps
  - Must use nearest-neighbor sampling
    - Straightforward bi-linear or mipmap sampling would average depth values together for use in comparison
  - Depth maps are typically small, so fine details may get lost
    - Shadows from thin objects (telephone wires, chain link fence, etc.) may disappear
    - Small gaps between objects may fill-in
  - Objects distant from light may be too small in shadow map
    - If the object's shadow is near the camera, it will appear very blocky

Shadow Map Precision

- Every Z-buffer has potential precision problems

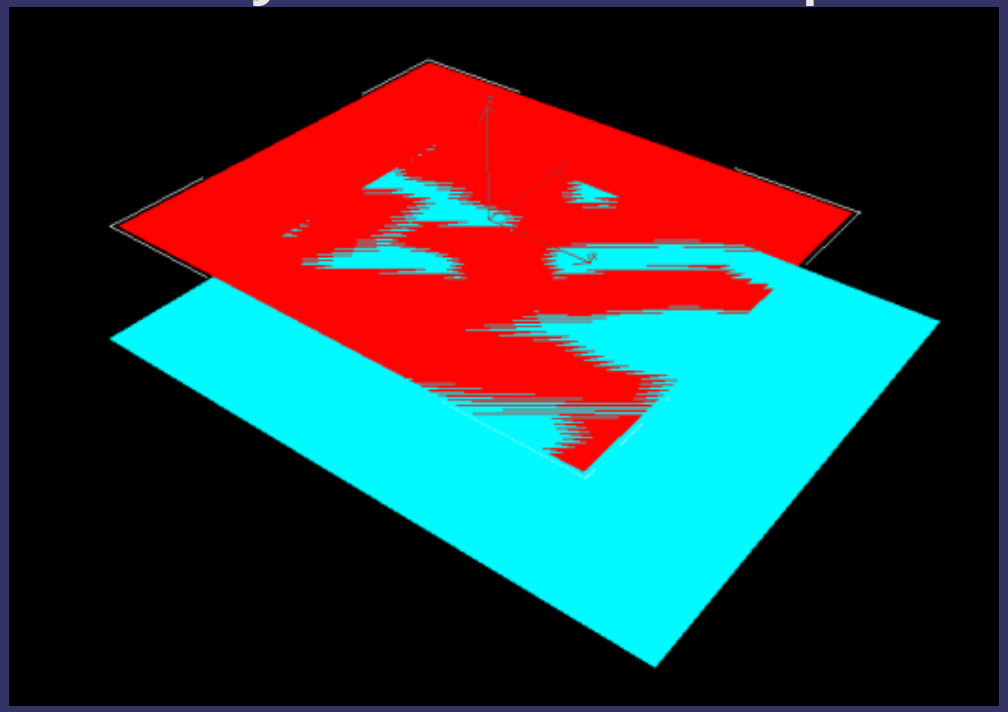
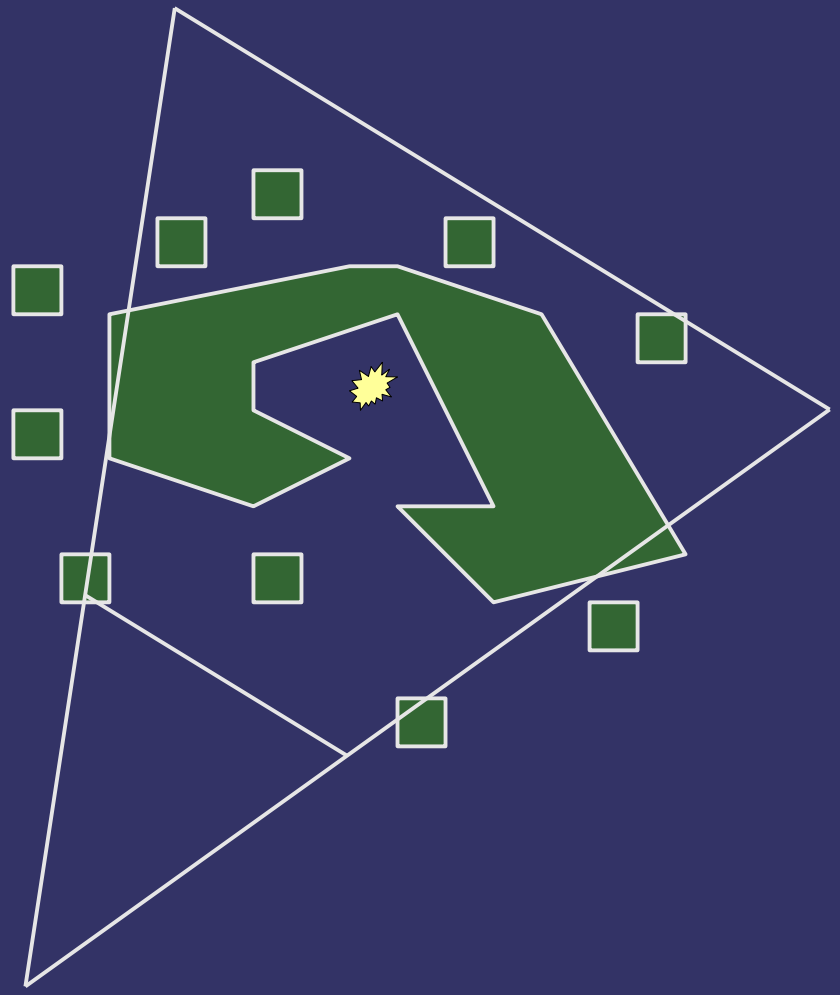


Image from http://en.wikipedia.org/wiki/Z-fighting

  - Objects distant from near-plane get fewer significant bits to store depth
    - May not be noticeable far from the near plane
  - Due to viewing differences, lack of Z precision far from *light's* near-plane may result in artifacts close to *camera's* near-plane

Omni-directional Lights

- Consider this scene...
  - What frustum do we pick for the light and the large object?
  - We'd need a 360˚ field-of-view!



Shadow Maps in GLSL

- New sampler types:
  - `sampler1DShadow`
  - `sampler2DShadow`
  - `sampler2DRectShadow`

Shadow Maps in GLSL

- New sampler functions:

```
vec4 shadow2D(sampler2DShadow, vec3)
vec4 shadow2DProj(sampler2DShadow, vec4)
```

  - 3rd component of texture coordinate is the distance used for comparison
  - There are also `1D` and `2DRect` versions
  - Value returned depends on comparison mode and `GL_DEPTH_TEXTURE_MODE` setting of texture unit
- As with projective textures, use shadow sampler types and functions instead of doing comparisons by hand

Shadow Maps in GLSL

- OpenGL 3.0 and GLSL 1.30 change things:
  - `GL_DEPTH_TEXTURE_MODE` is deprecated
    - You don't want it.
    - It's removed completely in 3.1
  - GLSL texture functions change name and return type:

```
float texture(sampler2DShadow, vec3)
float textureProj(sampler2DShadow, vec4)
```

    - `1D` and `2DRect` versions get similar changes

Shadow Maps in GLSL

- For GLSL 1.20 and earlier:
  - Leave `GL_DEPTH_TEXTURE_MODE` in the default state
    - `GL_LUMINANCE`
  - Wrap 1.20 API to look like 1.30 API:

```
float texture(sampler2DShadow s, vec3 c)
{
    return shadow2D(s, c).x;
}
```

Shadow Maps in GLSL

- Each texture has a depth comparison mode
  - Mode is set by calling `glTexParameteri` with *name* of `GL_TEXTURE_COMPARE_FUNC`
  - Sets mode used for comparison in `sampler[12]D` functions
  - Comparison mode is one of the “usual” `GL_LEQUAL`, etc. modes.
- Sampler function returns 1.0 if the test passes or 0.0 if the test fails

Depth Textures

- Store single component, normalized value used for depth (shadow) comparisons
  - Use one of three internal formats:
    - `GL_DEPTH_COMPONENT16`
    - `GL_DEPTH_COMPONENT24`
    - `GL_DEPTH_COMPONENT32`
  - Only format that can be used with GLSL shadow samplers
    - Can be also use with non-shadow samplers as a luminance, intensity, or alpha texture

Depth Textures

- Create just like any other texture:

```
glBindTexture(GL_TEXTURE_2D, my_shadow_tex);
glTexImage2D(GL_TEXTURE_2D, 0, GL_DEPTH_COMPONENT24,
             0, 0, width, height, GL_DEPTH_COMPONENT24,
             GL_UNSIGNED_INT, NULL);
```

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             GL_UNSIGNED_INT, NULL);
```

- To use as false-color texture:

```
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_COMPARE_MODE,
                GL_NONE);
```

  - Color returned is `vec4(d, d, d, 1)`

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```
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_COMPARE_MODE,
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```

  - Color returned is `vec4(d, d, d, 1)`

- To use as a shadow map:

```
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_COMPARE_MODE,
                GL_COMPARE_R_TO_TEXTURE);
```

Depth Textures

- Set comparison function similarly:

```
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_COMPARE_FUNC,
                GL_LESS);
```

  - In OpenGL 1.4 only `GL_LEQUAL` and `GL_GEQUAL` were available
  - In OpenGL $\geq$ 1.5 all 8 functions are available

Depth Textures and FBOs

- Attach the depth-component texture to the depth attachment:

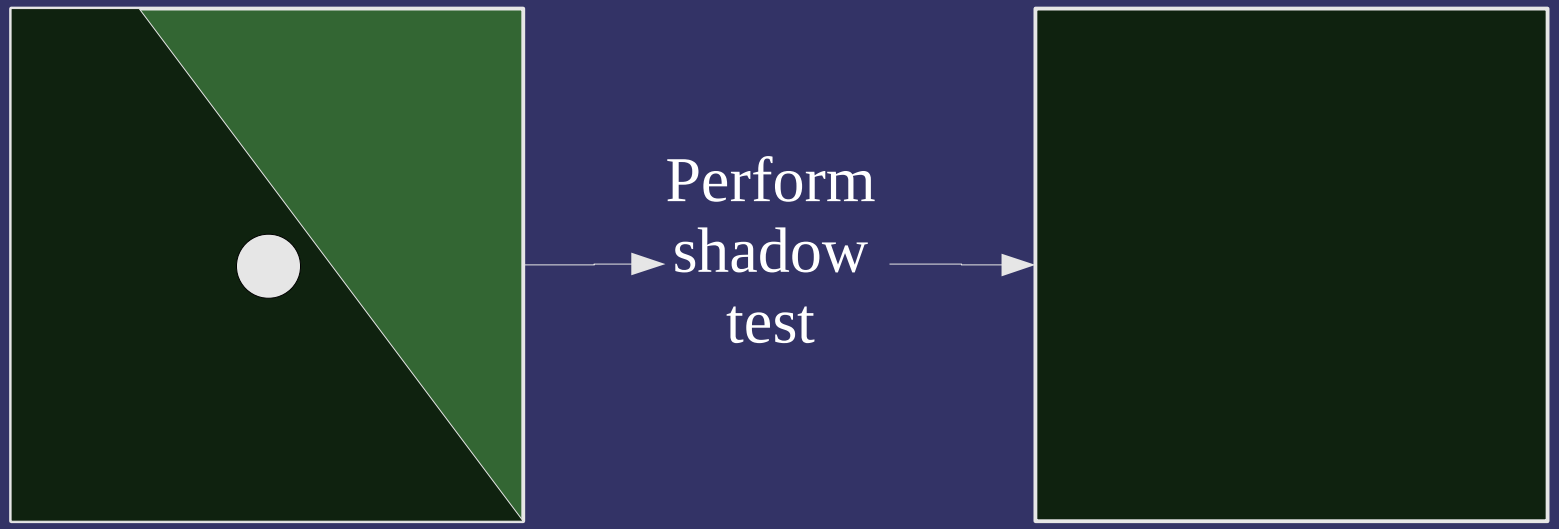
```
glFramebufferTexture2D(GL_FRAMEBUFFER,
                       GL_DEPTH_ATTACHMENT,
                       GL_TEXTURE_2D, tex, 0);
```

  - If there are no mipmaps (likely), as usual, be sure to set non-mipmap minification mode
  - If there is no color output (likely), be sure to disable all color buffer access:

```
glDrawBuffer(GL_NONE);
glReadBuffer(GL_NONE);
```

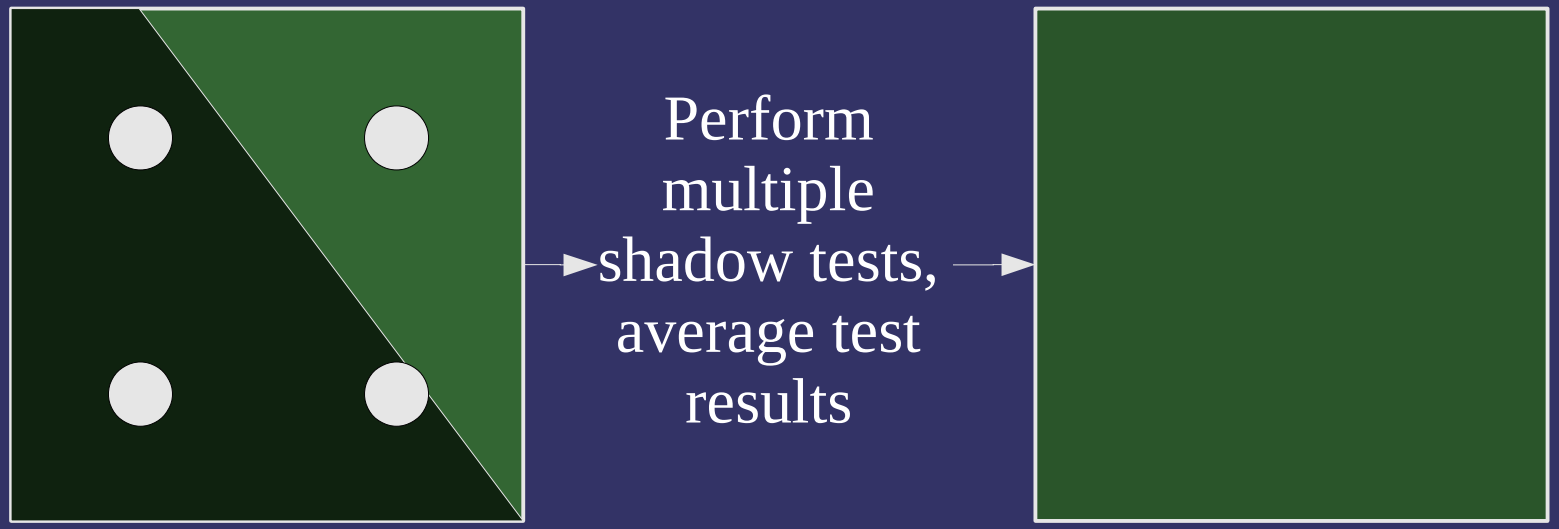
Shadow Map Texture Filtering

- Shadow test samples shadow map once per fragment
  - Results in two possible light levels: fully lit or fully shadowed



Shadow Map Texture Filtering

- Percentage closer filtering (PCF) reads multiple samples, performs one test per sample, averages test results
  - Results in n+1 possible light levels, where n is the number of samples



Shadow Map Texture Filtering

- Straight forward implementation in GLSL:

```
uniform vec2 bias;
uniform sampler2DShadow map;

void main()
{
    vec3 proj = coord.xyz / coord.w;
    vec3 p0 = proj – vec3((0.5 * bias.xy), 0.0);

    float s = texture(map, p0);
    s += texture(map, p0 + vec3(bias.x, 0.0, 0.0));
    s += texture(map, p0 + vec3(0.0, bias.y, 0.0));
    s += texture(map, p0 + vec3(bias.x, bias.y, 0.0));

    shadow /= 4.0;

    ...
}
```

Shadow Map Texture Filtering

- More concise in GLSL 1.30:

```
#version 130
uniform sampler2DShadow map;

void main()
{
    float s = textureProjOffset(map, coord, vec2(-1, -1));
    s += textureProjOffset(map, coord, vec2(-1,  1));
    s += textureProjOffset(map, coord, vec2( 1, -1));
    s += textureProjOffset(map, coord, vec2( 1,  1));

    shadow /= 4.0;

    ...
}
```

Shadow Map Texture Filtering

- Even better with GL_ARB_texture_gather
  - But you have to open-code the shadow comparison

```
#version 130
#extension GL_ARB_texture_gather: require

uniform sampler2D map;

void main()
{
    vec4 depth = textureGather(map, coord);
    vec4 s = vec4(lessThan(vec4(gl_FragDepth), depth);

    shadow = dot(s, vec4(0.25));

    ...
}
```

Percentage Closer Filtering

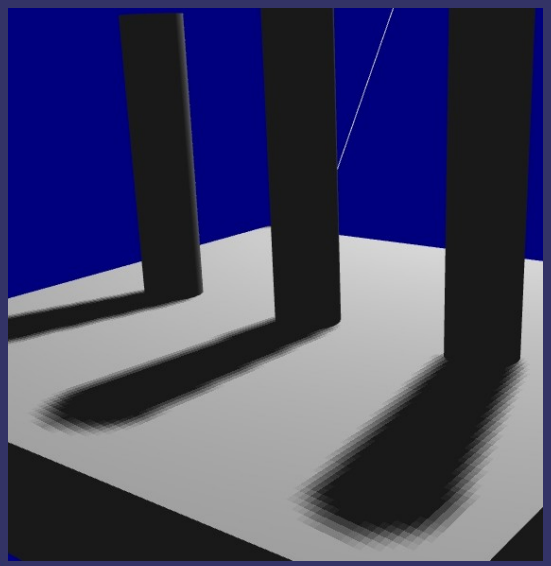
- The good news:
  - Improves quality
  - Larger filter kernels can be used to enable soft shadows
  - Some hardware can do 2x2 PCF nearly for free
    - Just enable `GL_LINEAR` filter on NVIDIA or Intel hardware

Percentage Closer Filtering

- The good news:
  - Improves quality
  - Larger filter kernels can be used to enable soft shadows
  - Some hardware can do 2x2 PCF nearly for free
    - Just enable `GL_LINEAR` filter on NVIDIA or Intel hardware
- The bad news:
  - Larger filter kernels are expensive
  - Grid-based sampling has artifacts

Grid-Based Sampling

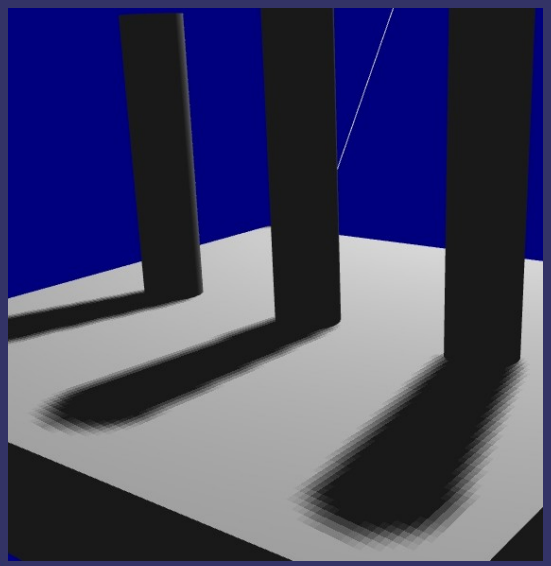
- Grid-based sampling artifacts have regular shape and are easily noticed by the eye

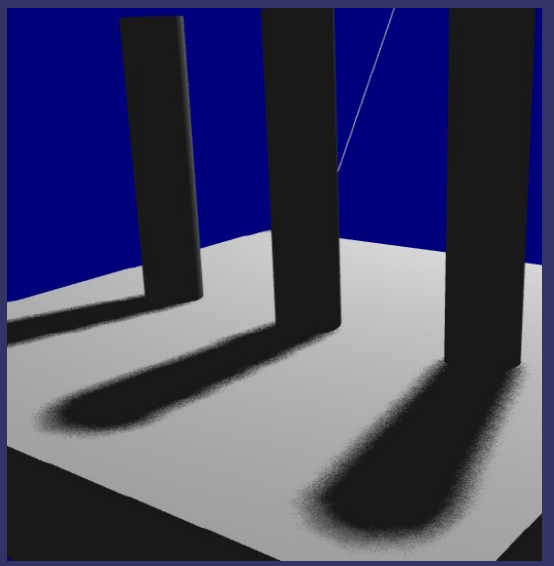


Images from http://ati.amd.com/developer/SIGGRAPH05/ShadingCourse_ATI.pdf

Grid-Based Sampling

- Grid-based sampling artifacts have regular shape and are easily noticed by the eye
- Irregular sample patterns are more easily accepted by the eye
  - Can even use fewer samples in the same size area





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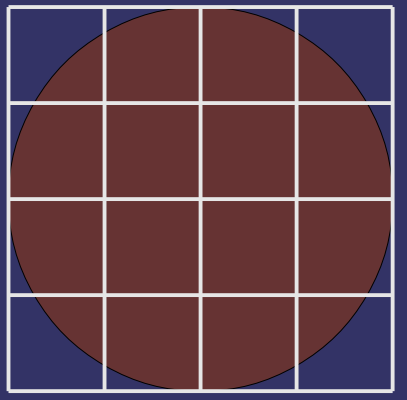
Irregular Sampling

- Select filter area



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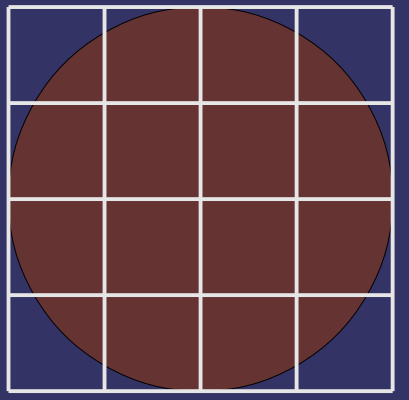
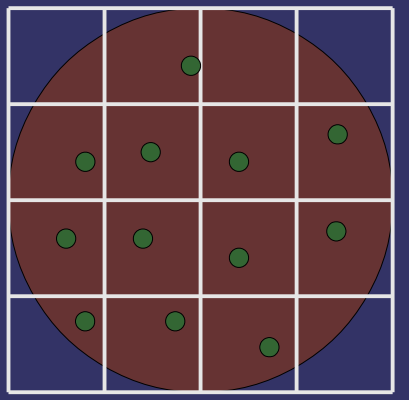


- Select random sample locations within area



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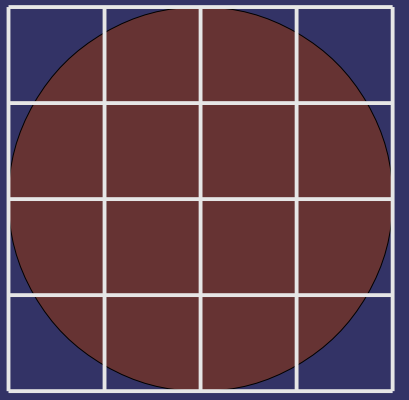

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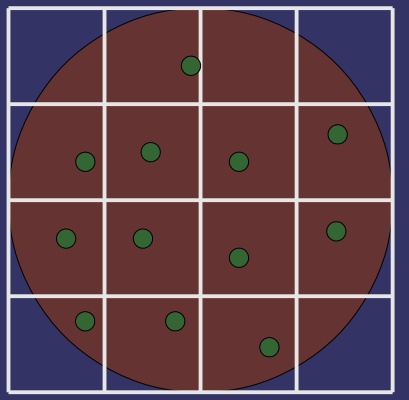
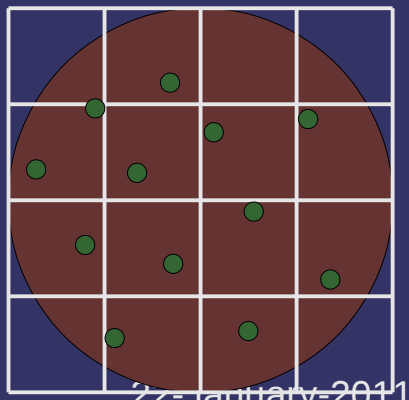


- Randomly rotate sample locations
  - Rotation based on screen location



Irregular Sampling

```
uniform vec2 sample_locations[12];
uniform mat2x2 sample_rotations[7];

float pcf_shadow_filter(sampler2DShadow map, vec4 coord)
{
    // Select rotation matrix based on pixel location
    int k = int(mod(gl_FragPosition.x + gl_FragPosition.y, 7.0));
    vec3 proj = coord.xyz / coord.w;
    float sum = 0.0;

    for (int i = 0; i < sample_locations.length(); i++) {
         vec2 offset = sample_rotations[k] * sample_locations[i]
         sum += texture(map, proj + vec3(offset, 0.0));
    }

    return sum / float(sample_locations.length());
}
```

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- 12 or 16 samples per fragment is expensive

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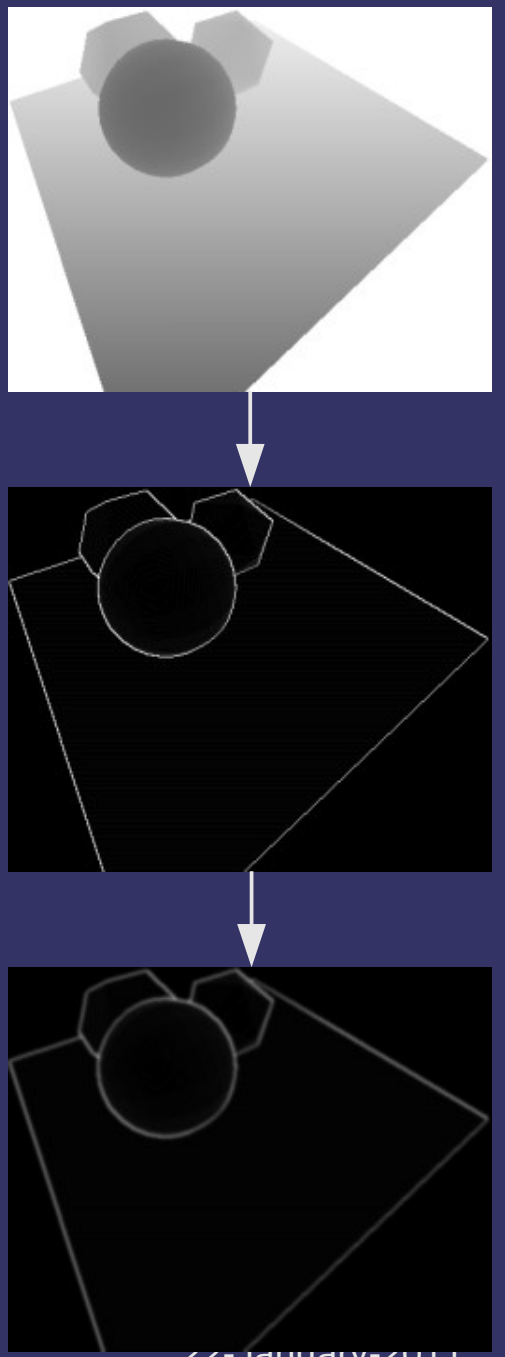
  - Nyquist–Shannon sampling theorem tells us that areas with only low-frequency information need fewer samples than areas with high-frequency information

Filter Cost

- 12 or 16 samples per fragment is expensive
  - In most of the final image, expensive sampling is unnecessary
  - Nyquist–Shannon sampling theorem tells us that areas with only low-frequency information need fewer samples than areas with high-frequency information
    - The only high-frequency information is near the shadow boundaries!

Shadow Boundary Map

- Find boundaries in shadow map using edge detection filter
  - The edges in the map are the regions where the expensive filter should be applied
- Blur edge map using a blur kernel equal in size to the shadow map sample filter
  - This increases the area where the expensive filter will be applied and ensures that it will be applied everywhere that it needs to be



Shadow Boundary Map

- Use the shadow boundary map to determine whether to use one or many shadow samples

```
if (texture2DProj(boundary_map, proj) > 0.0) {
    shadow = pcf_shadow_filter(shadow_map, proj);
} else {
    shadow = shadow2DProj(shadow_map, proj)
}
```

  - On hardware that support dynamic flow control, this can be a *big* win
    - DFC is a required part of DX 9.0c Shader Model 3.0
      - Geforce6 and later
      - Radeon X1xxx (R500) and later
      - Intel GMA X3000 (G965) and later

References

Sander, P. and Isidoro, J. *Explicit Early-Z Culling and Dynamic Flow Control on Graphics Hardware*. ATI Corporation, 2005, accessed 20 April 2008; available from http://ati.amd.com/developer/techpapers.html

Next week...

- Advanced shadow map techniques
  - Quiz #1
  - Assignment #1, part 2... due *next week*
  - Read:

W. Reeves, D. Salesin, and R. Cook, "Rendering Antialiased Shadows with Depth Maps." In Proceedings of SIGGRAPH '87. 1987. http://graphics.pixar.com/ShadowMaps/

R. Fernando, "Percentage-Closer Soft Shadows." In Proceedings of SIGGRAPH 2005. 2005. http://developer.nvidia.com/object/siggraph_2005_presentations.html

  - Reducing shadow map aliasing
  - Percentage closer soft shadows (PCSS)
  - Depth range optimizations

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