UCLA

CS174A : Introduction to Computer Graphics

Royce 190
TT 4-6pm

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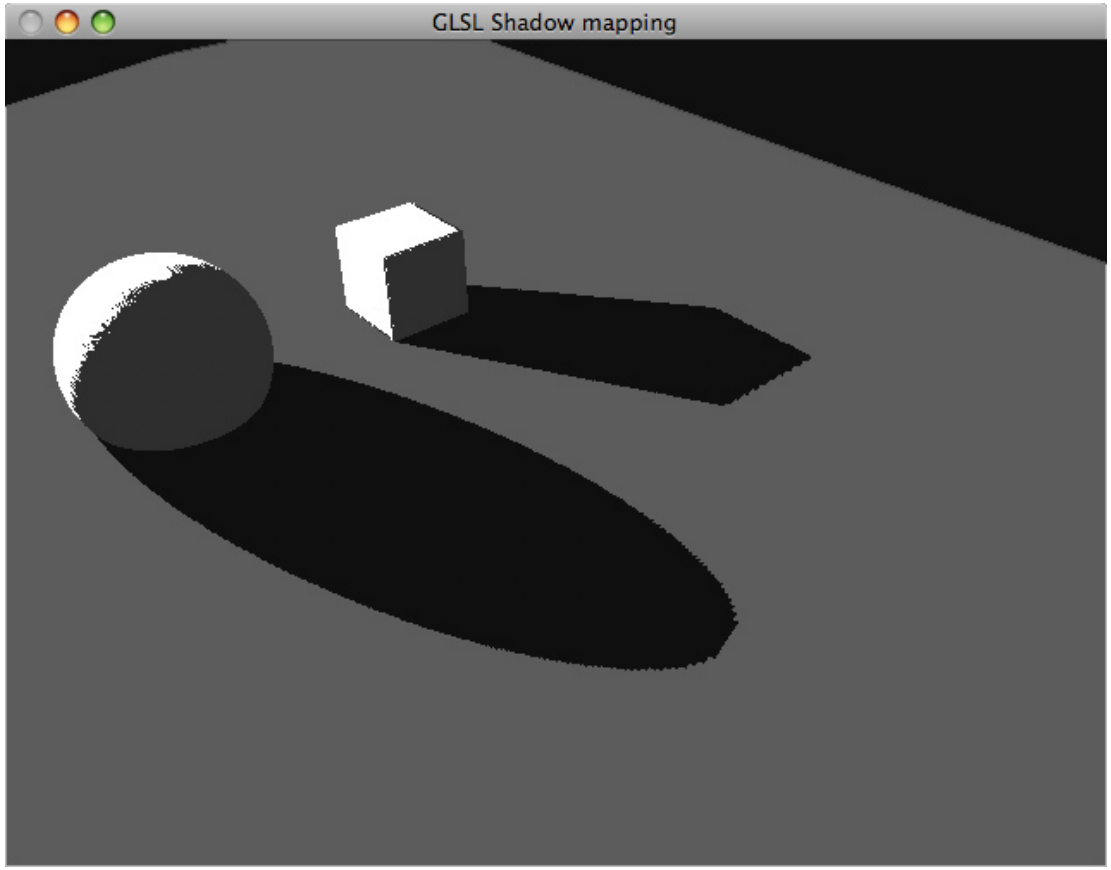
Shadows



Shadows

- Shadows are integral to light as experienced in the real world.
  - They help us understand the shape and spatial relationship between objects.
  - Particularly challenging in real-time graphics.
  - Conceptually simple algorithms are too slow to implement in real-time.
  - No single technique, even today, works effectively in all situations.
    - As we have seen before, the best approach really depends on the particular constraints of the situation.

Shadows

- What is a shadow?
  - Dictionary
    - *An area that is not or only partially illuminated because of the interception of light by an opaque object between the area and the light.*
  - More specifically, from a graphics perspective
    - *A shadow is the region of space for which at least one point of a light source is occluded.*
  - Assumptions
    - Only direct illumination is considered, bouncing light ignored
    - Occluders are assumed to be opaque

Shadows

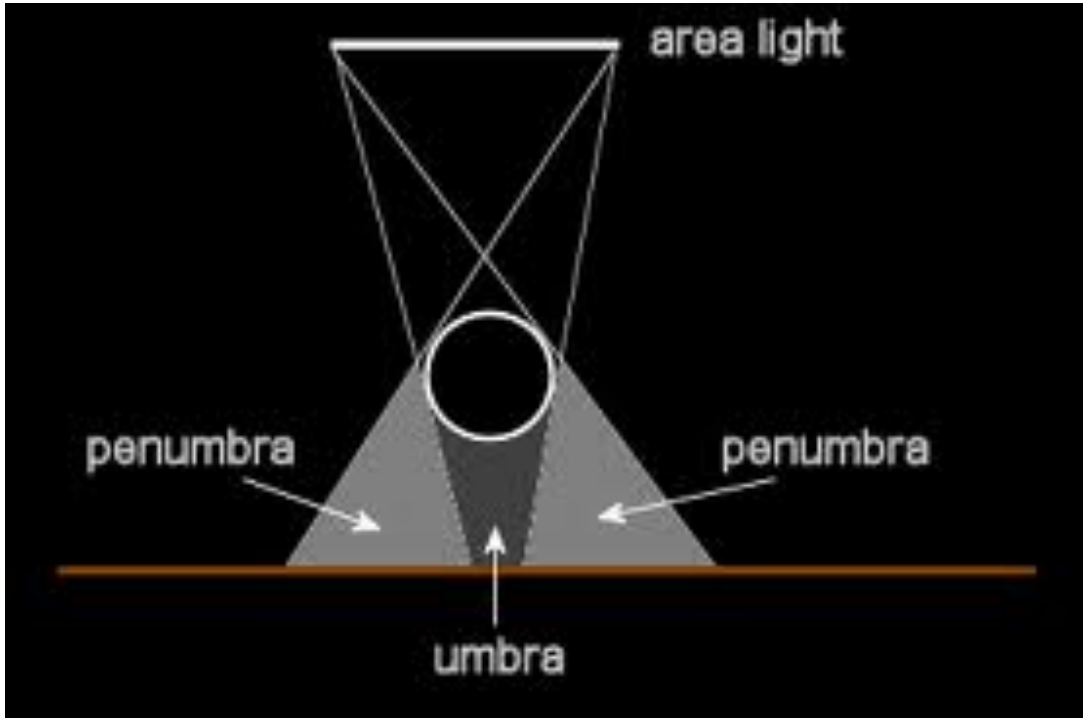
- What is a shadow?
  - Completely general algorithms that extend beyond opaque objects and direct illumination are still very much beyond current hardware capabilities for real-time rendering.
  - Accurate shadows have been on every list of most important unsolved problems in graphics.
  - Given that, we will stick to a simplified definition.

Shadows

- What is *in* shadow?
  - A point *p* on a surface can be one of the following with respect to an *area* light source (more than a point)
    - Entire light source is blocked by the scene
      - » *p* is within the umbra and in shadow
    - Light source partially blocked by the scene
      - » *p* is within the prenumbra and partially in shadow
    - Light source not blocked by the scene
      - » *p* is lit and not in shadow

Shadows

- What is *in* shadow?



Shadows

- What is *in* shadow?
  - Basically, we trace a ray from the light source l to a point p on a surface.
    - If there is an intersection inbetween l and p the point p is in shadow.
    - The object the ray intersects is called the ***occluder***.
      - » Also, sometimes, called the *blocker or shadow caster*.
    - The object the point p belongs to is called the ***receiver***.

Shadows

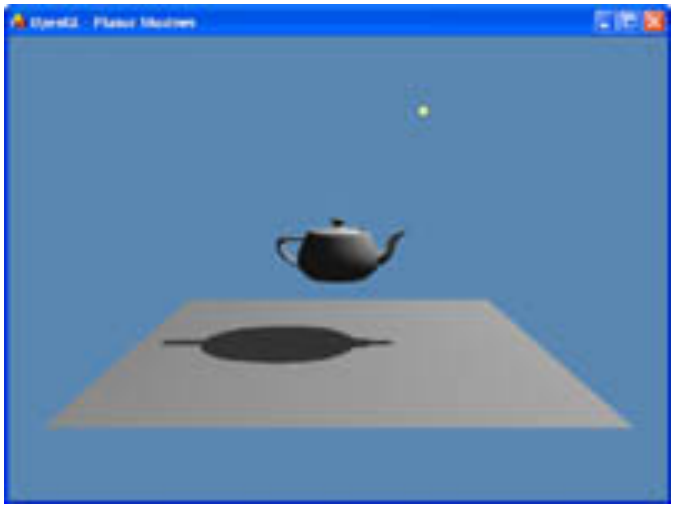
- Simplify even more.
  - To avoid the difficult integration needed for area light sources we will restrict ourselves to point lights.
  - Considering point light sources restricts the result to hard shadows only. *Why is that do you think?*
  - Soft shadows can be achieved using approximation techniques that give the appearance of sampling an area light source (e.g. percentage closer filtering)
  - We are not going to discuss soft shadows in this class.

Shadows

- Techniques for hard shadows
  - Shadow mapping (projective & depth)
  - Shadow volumes (not going to talk about)
  - All variations are a tradeoff of efficiency and accuracy
  - The term *hard* is used because the result is binary, either a point is lit or it is not (in shadow or not).
  - It is also useful to remember that there is no such thing as a point light source in the real world.
    - It is an approximation to simplify the computation in order to achieve interactive frame rates – that is all.
    - Even a light bulb is not a point light source!!

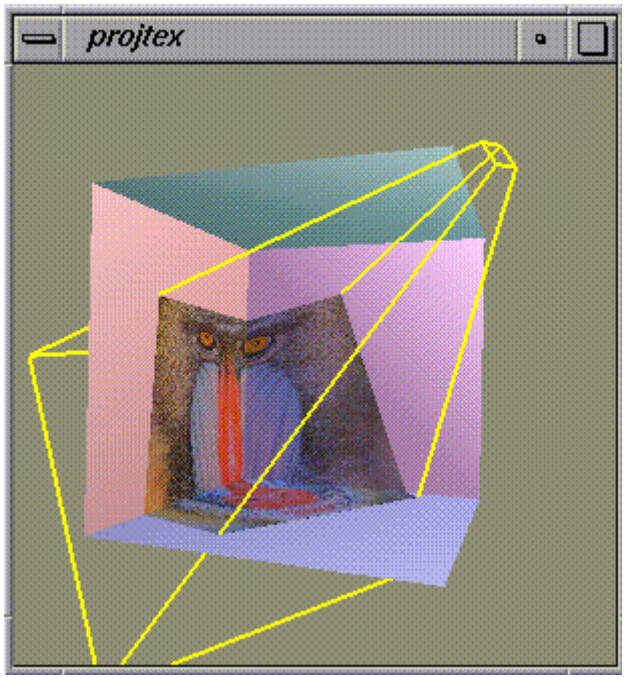
Shadows

- Planer projective shadows
  - Discussed briefly in the book
  - Projection of a shadow onto a planar (flat) surfaces only!
  - Has a lot of problems – not really used ever.



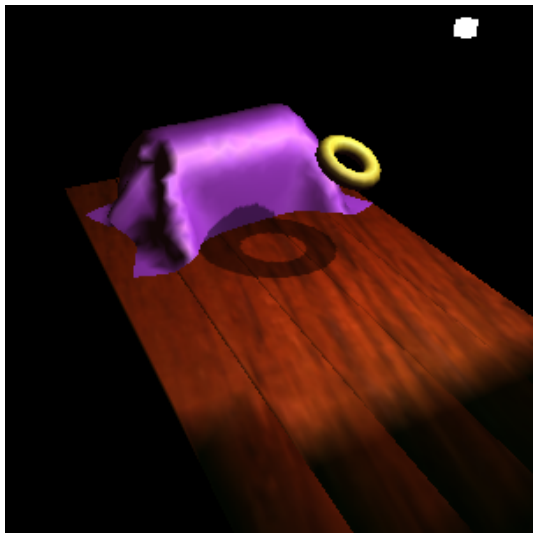
Shadows

- Projective shadow texture
  - A variation of projective textures



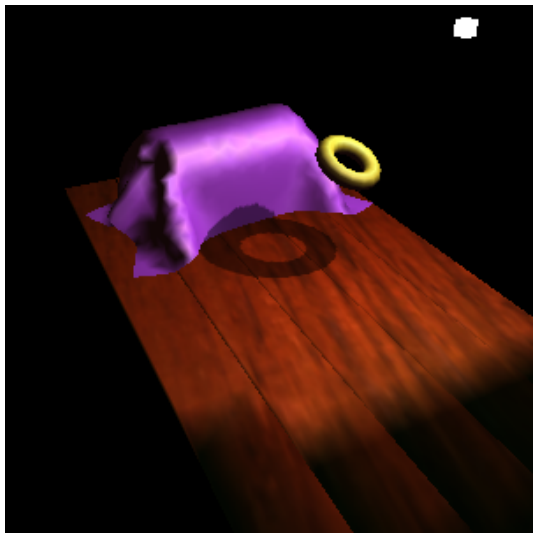
Shadows

- Projective shadow texture
  - Not limited to planar receiver surfaces.
  - Think of a projector at the light source casting an image of the shadow onto the receivers.



Shadows

- Projective shadow texture
  - A buffer (texture) is cleared to white.
  - Occluders are rendered in black into the buffer.
    - A single texture lookup can tell us if receiver in shadow or not.



Shadows

- Projective shadow texture
  - In order to render into the texture we have to setup our camera in *light space*, as opposed to *camera space*.
  - Conveniently, here is a good use of the LookAt() function to setup the appropriate projection matrix.
    - We position the 'camera' at the location of the light source.
    - The camera is pointed in the direction of the shadow (light).
  - The result is a transformation matrix that transforms a vertex from world space to light space.

Shadows

- Projective shadow texture
  - We next need a projection matrix that will transform our points into *light clip space*.
  - Orthographic or perspective transform can be used.
    - Common to use an orthographic projection for infinite light sources, like the sun.
    - A point light source would use a perspective transform.
    - d is the distance from the light source to the projection plane.

$$M_V^L = \begin{bmatrix} d & 0 & 0 & 0 \\ 0 & d & 0 & 0 \\ 0 & 0 & d & 0 \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

Shadows

- Projective shadow texture
  - However, since we are in clip space we want everything to map to [-1,1] so d is typically 1 which projects to z=-1
  - Keeping x and y in that same range requires a small change to our projection matrix adding the additional scaling values.
    - w and h are the size of our shadow texture buffer.

$$M_P^L = \begin{bmatrix} w & 0 & 0 & 0 \\ 0 & h & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

Shadows

- Projective shadow texture
  - Not useful for this technique but for others is to maintain the depth information rather than projecting everything to z=-1
  - this results in a very familiar perspective projection matrix and you can use the Perspective() function.
  - Similar to the results you get with a Kinect

$$M_P^L = \begin{bmatrix} \frac{1}{\alpha}\cot\frac{fovy}{2} & 0 & 0 & 0 \\ 0 & \cot\frac{fovy}{2} & 0 & 0 \\ 0 & 0 & -\frac{f+n}{f-n} & -\frac{2fn}{f-n} \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

Shadows

- Projective shadow texture
  - In the *vertex* shader when rendering the receivers, texture coordinates into the shadow texture are computed as v^s.
    - Furthermore, we need to adjust the light clip values from [-1,1] to conventional texture coordinate range of [0,1]

$$M_t = \begin{bmatrix} 0.5 & 0 & 0 & 0.5 \\ 0 & 0.5 & 0 & 0.5 \\ 0 & 0 & 0.5 & 0.5 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

    - The entire projection can be baked into M_s

$$M_S = M_t M_P^L M_V^L$$
$$v^S = M_S v$$

Shadows

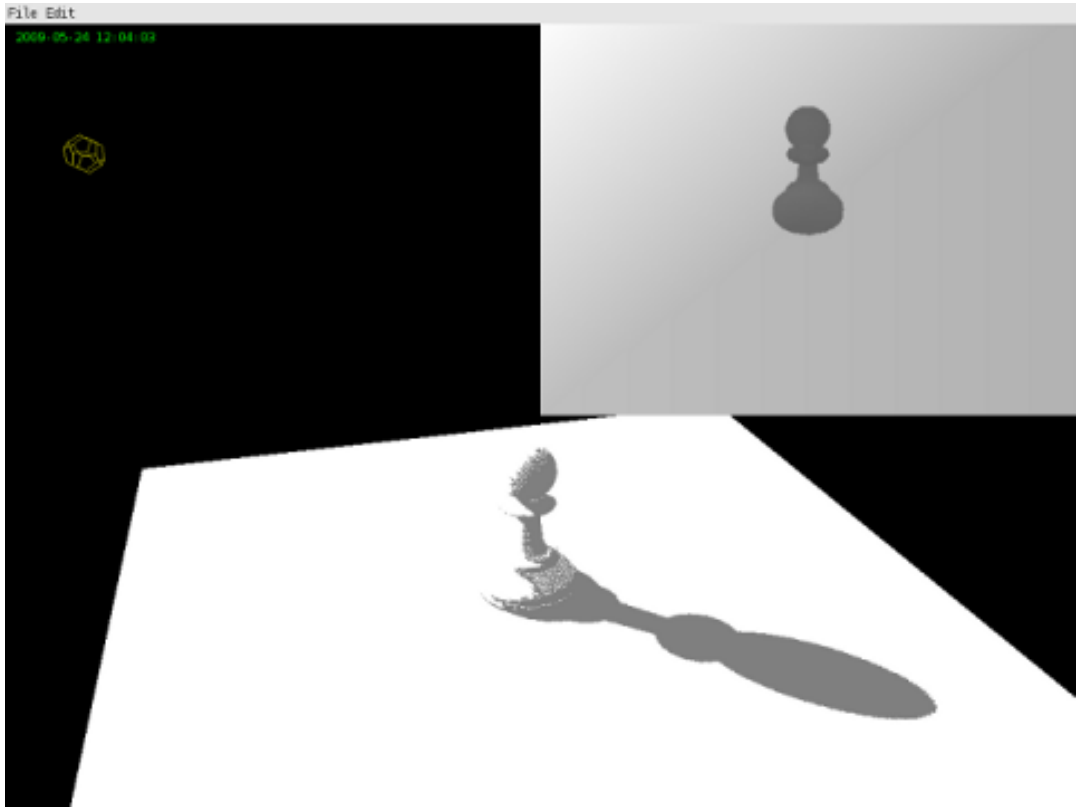
- Projective shadow texture
  - Values that fall outside of [0,1] are not shadowed.
    - This can be checked for in the fragment shader.
  - Many issues, bad and good
    - Occluders and receivers must be separated
    - Requires shadow texture per blocker
    - No self shadowing
    - Achieve a form of soft shadow by filtering the texture map.
    - Often called a *light attenuation map,* which is used to bake shadows of static lights, occluders and receivers into a scene.
  - Overall a simple technique

Shadows

- Shadow mapping
  - More general form of projective texture shadows
    - No need to separate occluders from receviers
    - Can handle self-shadowing
  - Here we, again, render from the position of the light source.
    - However, the entire scene is rendered.
    - Every point that is rendered is, implicitly, lit.
    - Anything else is in shadow.
    - Determining whether a 3d position is in shadow or not becomes a matter of checking whether it is lit in the shadow map or not.

Shadows

- Shadow mapping



Shadows

- Shadow mapping
  - Simple in theory, harder to do nicely in practice.
  - Image space based so artifacts are a fact of life.
    - Shadow map resolution can result is jagged shadow edges
  - We are really only interested in the depth map created by rendering from the light's position.
  - Here each fragment's position p is transformed into *light clip space* as before.
    - The x and y components index into the depth map.
    - The z value is the distance from the light source.

Shadows

- Shadow mapping
  - Recall that the actual x and y values need to be scaled like the projective texture was to [0,1], or p^S
  - In any case the z value is compared to the depth value of the point under consideration.
    - If the point in light clip space has a depth value greater than the point's value in the shadow map the fragment is hidden, or in shadow.
    - Otherwise it is lit and shaded normally.

Shadows

- Shadow mapping
  - The fact that we have been producing these maps via projection and rendering may make you wonder…
  - Does this work only for spot (directional) lights?
  - No, the typical solution involves rendering six frustums around the light source - similar to a cube map.
    - Again, spherical maps are more efficient in terms of pixels and rendering geometry but cube maps are simpler.
    - Others have suggested using tetrahedrons as a compromise.

Shadows

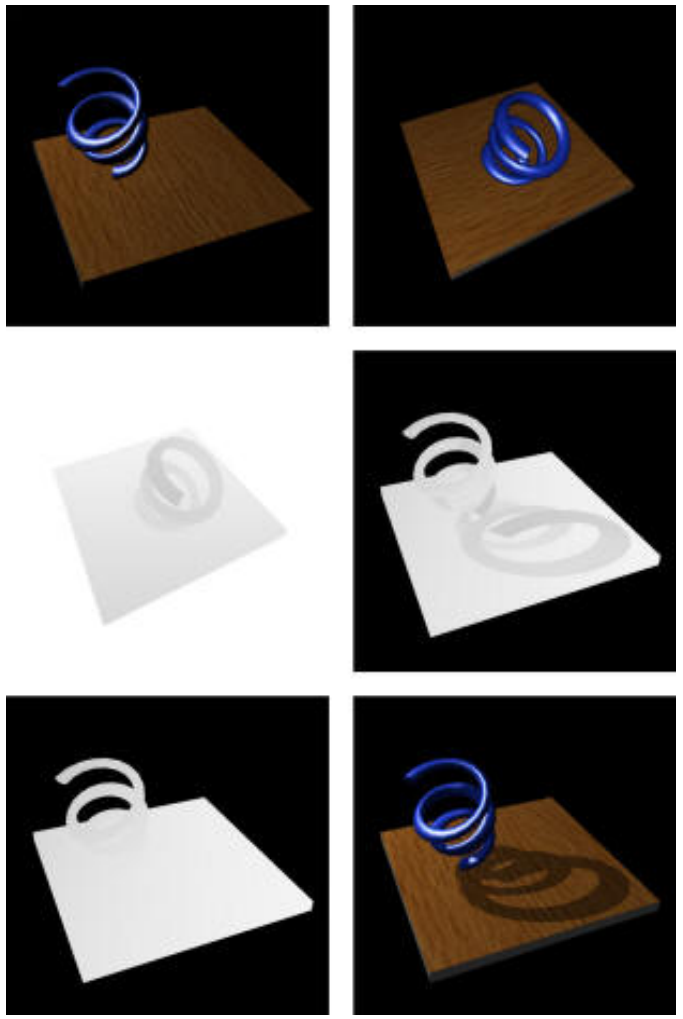
- Shadow mapping
  - Another more direct issue is related to sampling the shadow map buffer during depth comparison.
    - The shadow map has a limited precision to represent depth values.
    - The shadow map has sampled the scene at a different resolution than the camera, typically.
    - Rarely is the point in eye space that we have projected into light space correspond to an exact depth map sample.
    - This can lead to light "leaks" due to *z-fighting*.
    - This occurs, particularly, when the receiver is tilted and the discretization of the depth values result in an incorrect comparison.

Shadows

- Shadow mapping
  - The "solution" to this problem is to introduce a *bias*.
    - This bias value pushes the depth values away from the light source slightly.
    - The problem is that there is no rule of thumb for deciding what the bias value should be – experimentation is required.
    - There is, however, a built-in mechanism in OpenGL for applying this bias called glPolygonOffset()

Shadows

- Shadow mapping
  - View from camera (tl)
  - View from light (tr)
  - Shadow map from light (ml)
  - Shadow map from camera (mr)
  - Scene depth (bl)
  - Final image after compare (br)



Shadows

- Shadow mapping
  - You may have noticed that all this assumes we can render to a texture.
  - In the depth map case we are rendering depth values to a texture.
  - This is accomplished using an OpenGL frame buffer object, or FBO.

Shadows

- Shadow mapping
  - The setup starts with creating an appropriate texture.
  - Notice the compare parameters which control how the depth comparison will operate.

```
glGenTextures(1,&shadowMapTexture);
glBindTexture(GL_TEXTURE_2D,shadowMapTexture);
glTexImage2D(GL_TEXTURE_2D,0,GL_DEPTH_COMPONENT32,
    shadowMapResolutionX,shadowMapResolutionY,0,
    GL_DEPTH_COMPONENT,GL_FLOAT,0);
glTexParameteri(GL_TEXTURE_2D,GL_TEXTURE_MIN_FILTER,GL_LINEAR);
glTexParameteri(GL_TEXTURE_2D,GL_TEXTURE_MAG_FILTER,GL_LINEAR);
glTexParameteri(GL_TEXTURE_2D,GL_TEXTURE_WRAP_S,GL_CLAMP_TO_BORDER);
glTexParameteri(GL_TEXTURE_2D,GL_TEXTURE_WRAP_T,GL_CLAMP_TO_BORDER);
glTexParameteri(GL_TEXTURE_2D,GL_TEXTURE_COMPARE_MODE,GL_COMPARE_REF_TO_TEXTURE);
glTexParameteri(GL_TEXTURE_2D,GL_TEXTURE_TEXTURE_COMPARE_FUNC,GL_LEQUAL);
float ones[] = {1.0f,1.0f,1.0f,1.0f};
glTexParameteri(GL_TEXTURE_2D,GL_TEXTURE_BORDER_COLOR,&ones);
```

Shadows

- Shadow mapping
  - Next we create the FBO itself and associate it with the texture we just defined.

```
glGenFramebuffers(1,&shadowMapFBO);
glBindFramebuffer(GL_FRAMEBUFFER,shadowMapFBO);
glFramebufferTexture2D(GL_FRAMEBUFFER,GL_DEPTH_ATTACHMENT,GL_TEXTURE_2D,
    shadowMapTexture,0);
```

  - Finally, we can render to the FBO as follows

```
// Activate FBO shadowMapFBO
glBindFramebuffer(GL_FRAMEBUFFER,shadowMapFBO);
glPolygonOffset(2.5f,10.0f);
glEnable(GL_POLYGON_OFFSET_FILL);
// render the scene from the perspective of the light source
glDisable(GL_POLYGON_OFFSET_FILL);
// Active the default color framebuffer again
glBindFramebuffer(GL_FRAMEBUFFER,0);
```