Computergrafik

Matthias Zwicker
Universität Bern
Herbst 2016

Today

More shading

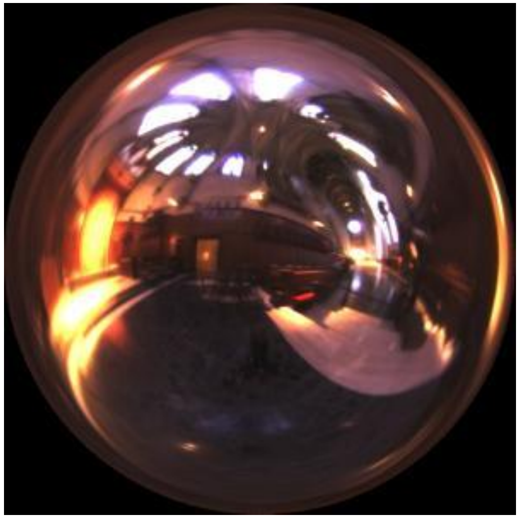
- Environment maps
- Reflection mapping
- Irradiance environment maps
- Ambient occlusion
- Reflection and refraction
- Toon shading

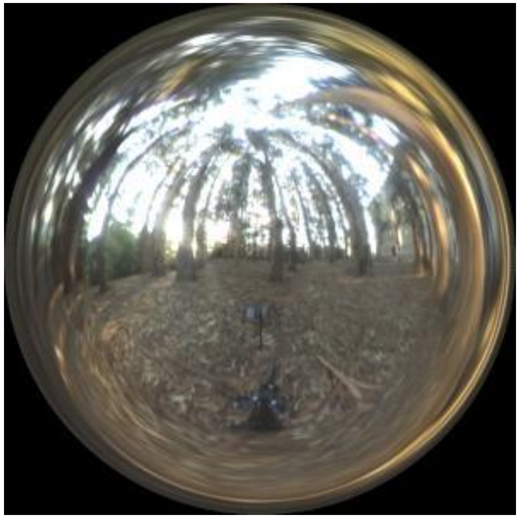
More realistic illumination

- In real world, at each point in scene light arrives from all directions
  - Not just from point light sources
- Environment maps
  - Store “omni-directional” illumination as images
  - Each pixel corresponds to light from a certain direction

Capturing environment maps

- "360 degrees" panoramic image
- Instead of 360 degrees panoramic image, take picture of mirror ball (light probe)





Light probes

[Paul Debevec, http://www.debevec.org/Probes/]

Environment maps as light sources

Simplifying assumption

- Assume light captured by environment map is emitted infinitely far away
- Environment map consists of directional light sources
  - Value of environment map is defined for each direction, independent of position in scene
- Use single environment map as light source at all locations in the scene
- Approximation!

Environment maps as light sources

- How do you compute shading of a diffuse surface using an environment map?
- What is more expensive to compute, shading a diffuse or a specular surface?

Environment maps applications

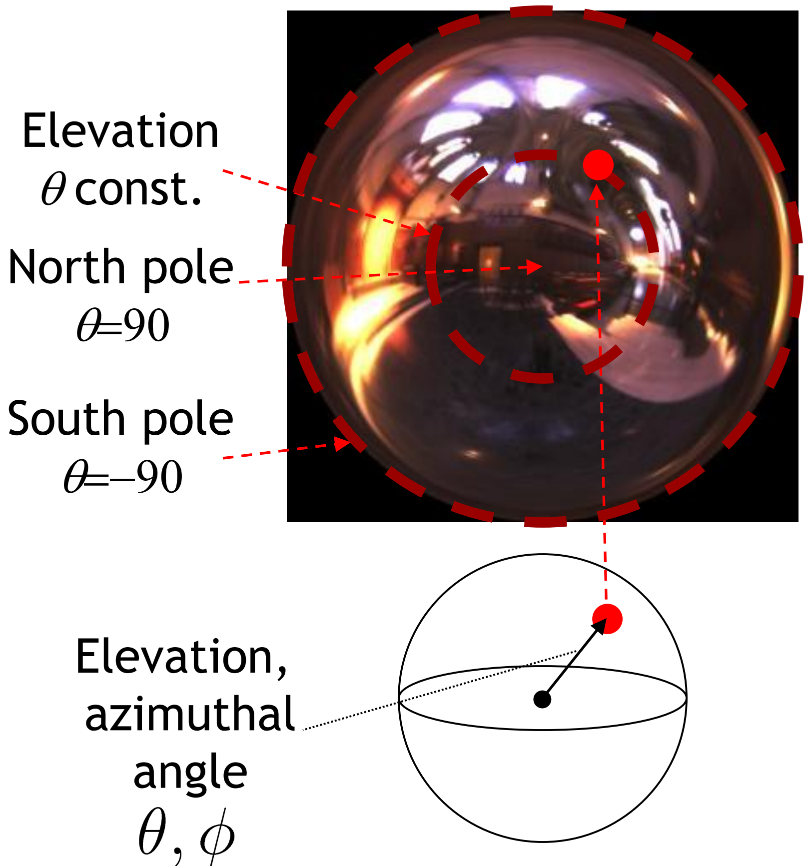
- Use environment map as "light source"

Global illumination
[Sloan et al.]

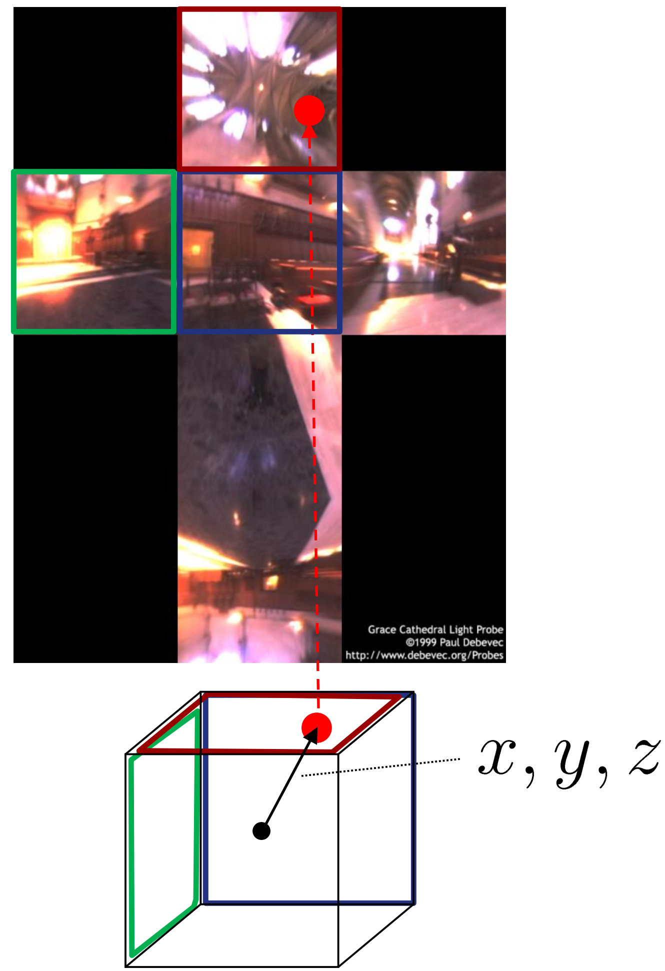
Reflection mapping

Sphere & cube maps

- Store incident light on sphere or on six faces of a cube



Spherical map



Cube map

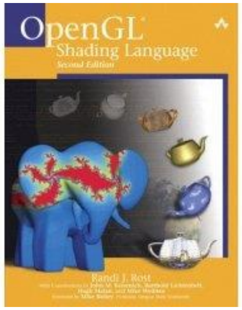
Cube maps in OpenGL

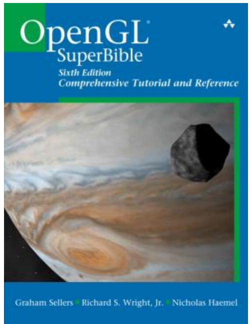
Application setup

- Load, bind a cube environment map

```
glBindTexture(GL_TEXTURE_CUBE_MAP, …);
// the six cube faces
glTexImage2D(GL_TEXTURE_CUBE_MAP_POSITIVE_X,…);
glTexImage2D(GL_TEXTURE_CUBE_MAP_NEGATIVE_X,…);
glTexImage2D(GL_TEXTURE_CUBE_MAP_POSITIVE_Y,…);
…
glEnable(GL_TEXTURE_CUBE_MAP);
```

- More details
  - "OpenGL Shading Language", Randi Rost
  - "OpenGL Superbible", Sellers et al.
  - Online tutorials





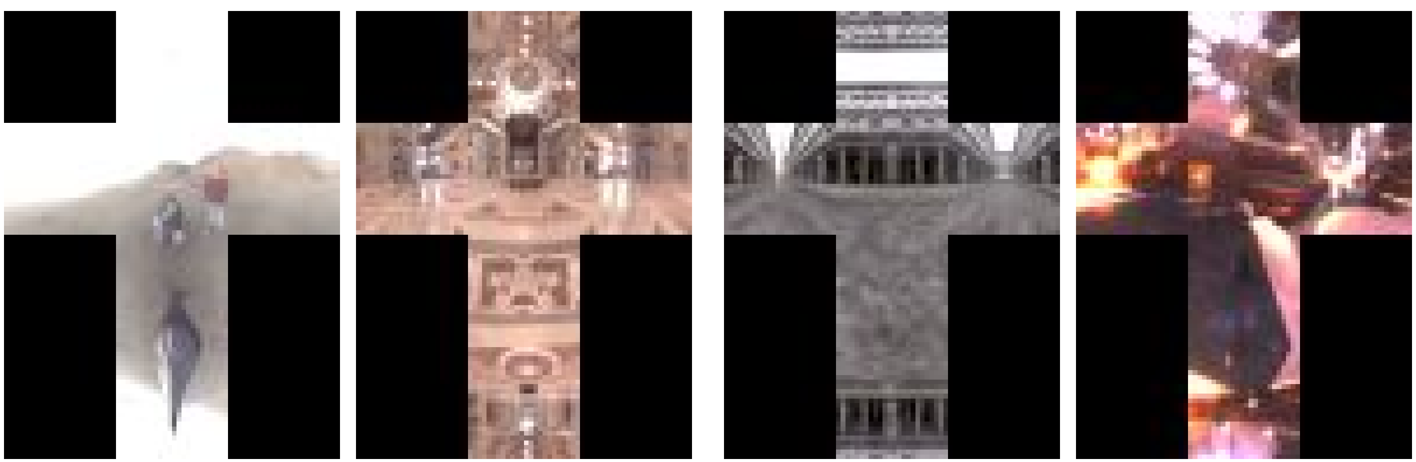
Cube maps in OpenGL

Look-up

- Given direction (x,y,z)
- Largest coordinate component determines cube map face
- Dividing by magnitude of largest component yields coordinates within face
- Look-up function built into GLSL
  - Use (x,y,z) direction as texture coordinates to `samplerCube`

Environment map data

- Also called „light probes“
  http://www.debevec.org/Probes/
- Tool for high dynamic range data (HDR)
  http://projects.ict.usc.edu/graphics/HDRShop/
- Pre-rendered light probes for games
  http://docs.unity3d.com/Manual/LightProbes.html



Light probes (http://www.debevec.org/Probes/)

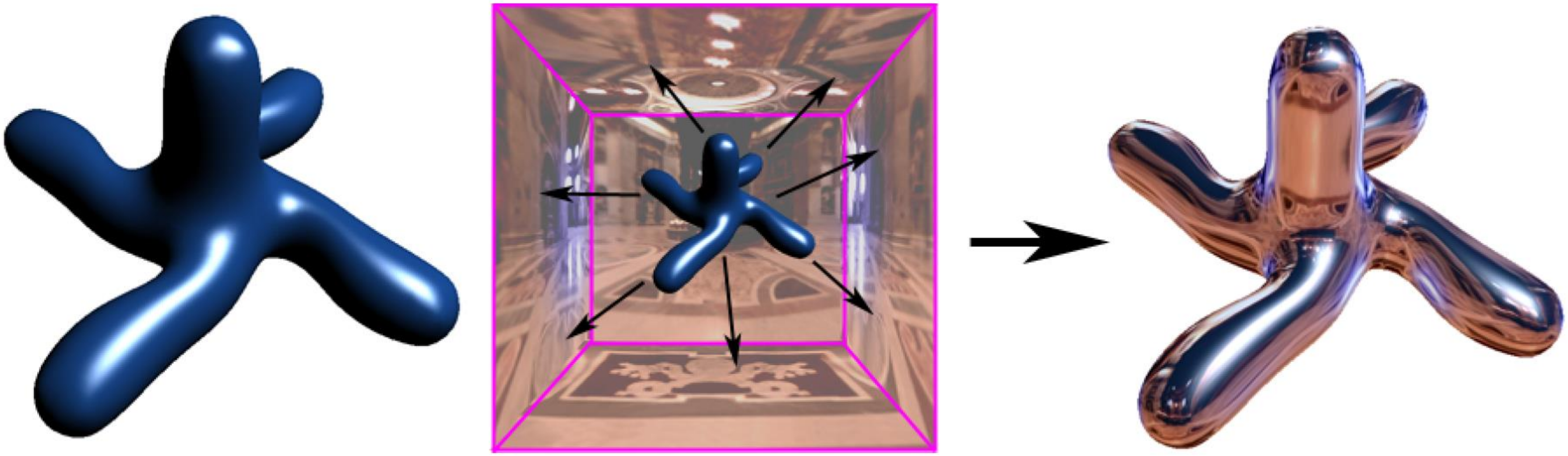
Today

More shading

- Environment maps
- Reflection mapping
- Irradiance environment maps
- Ambient occlusion
- Reflection and refraction
- Toon shading

Reflection mapping

- Simulate mirror reflection
- Compute reflection vector at each pixel using view direction and surface normal
- Use reflection vector to look up cube map
- Rendering cube map itself is optional



Reflection mapping

Reflection mapping in GLSL

Vertex shader

- Compute viewing direction for each vertex
- Reflection direction
  - Use GLSL built-in `reflect` function
- Pass reflection direction to fragment shader

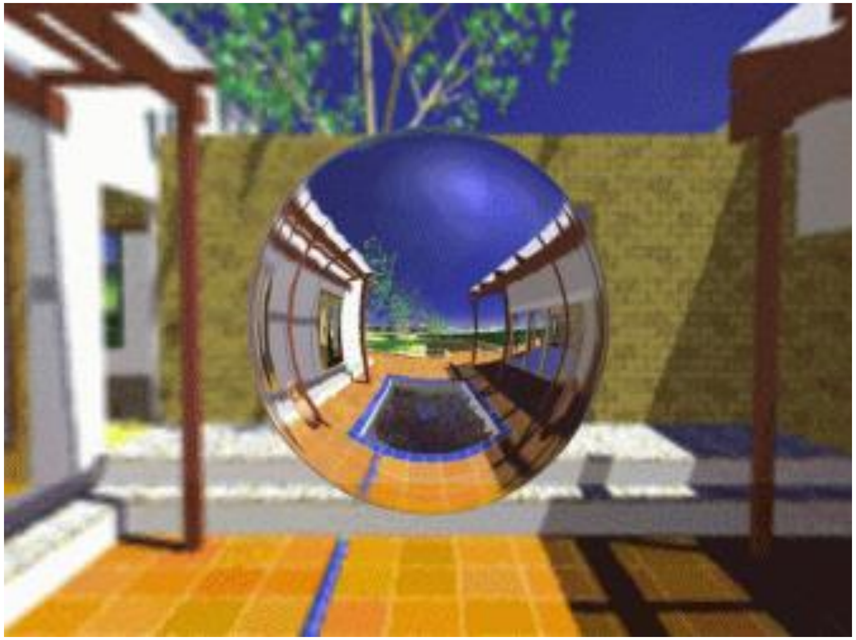
Fragment shader

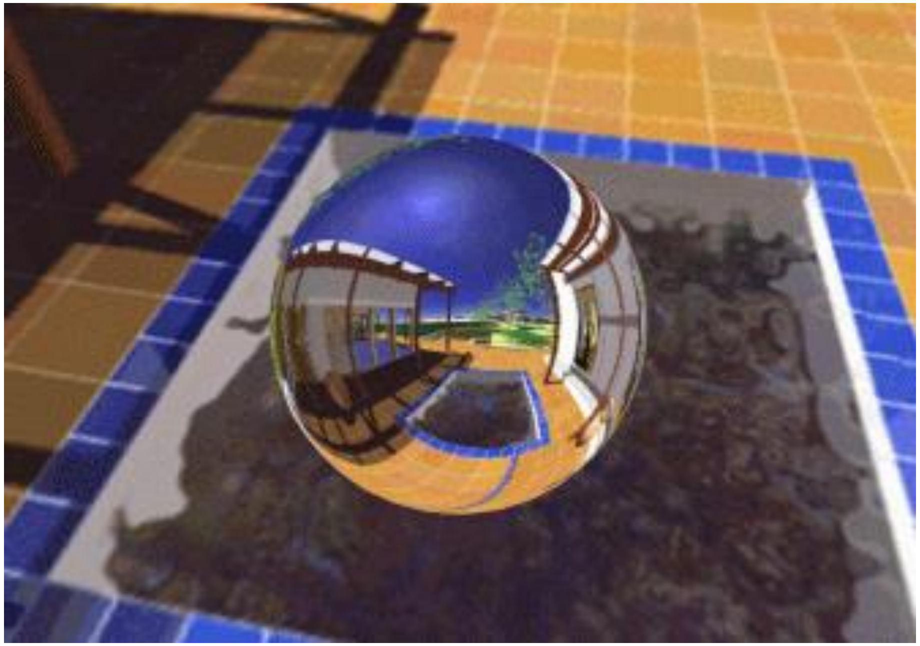
- Look-up cube map using interpolated reflection direction

```
in float3 refl;
uniform samplerCube envMap;
texture(envMap, refl);
```

Reflection mapping examples

- Approximation, reflections are not accurate





[NVidia]

Today

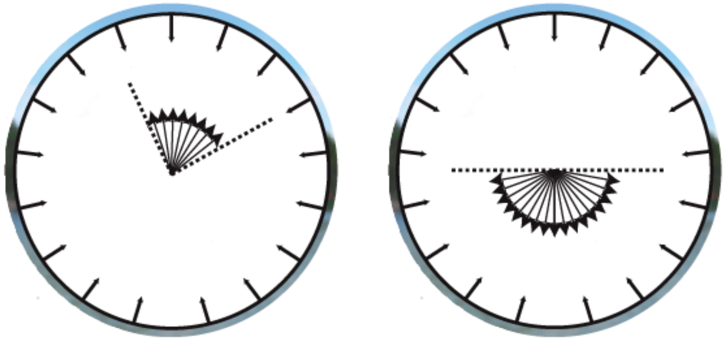
More shading

- Environment maps
- Reflection mapping
- Irradiance environment maps
- Ambient occlusion
- Reflection and refraction
- Toon shading

Shading using environment map

- Assumption: distant lighting
  - Incident light is a function of direction, but not position
- Realistic shading requires
  - Take into account light from all directions
  - Include occlusion

Illumination from environment



Same environment map for both points
“Illumination is a function of direction, but not position”

Mathematical model

- Assume Lambertian (diffuse) material, BRDF k_d
  - Ignore occlusion for now
- Illumination from point light sources

$$c = k_d \sum_i c_{l_i} (\mathbf{L}_i \cdot \mathbf{n})$$

- Illumination from environment map using hemispherical integral

$$c = k_d \int_\Omega c(\omega)(\omega \cdot \mathbf{n}) d\omega$$

  - Directions ω
  - Hemisphere of directions Ω
  - Environment map, radiance from each direction $c(\omega)$

Irradiance environment maps

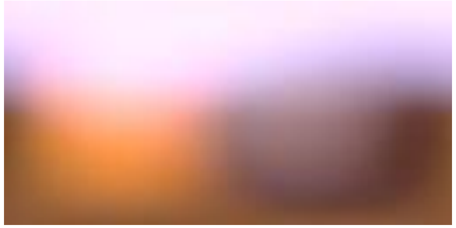
- Precompute irradiance as a function of normal

$$E(\mathbf{n}) = \int_\Omega c(\omega)(\omega \cdot \mathbf{n}) d\omega$$

  - Store as irradiance environment map
- Shading computation at render time
  - Depends only on normal, not position

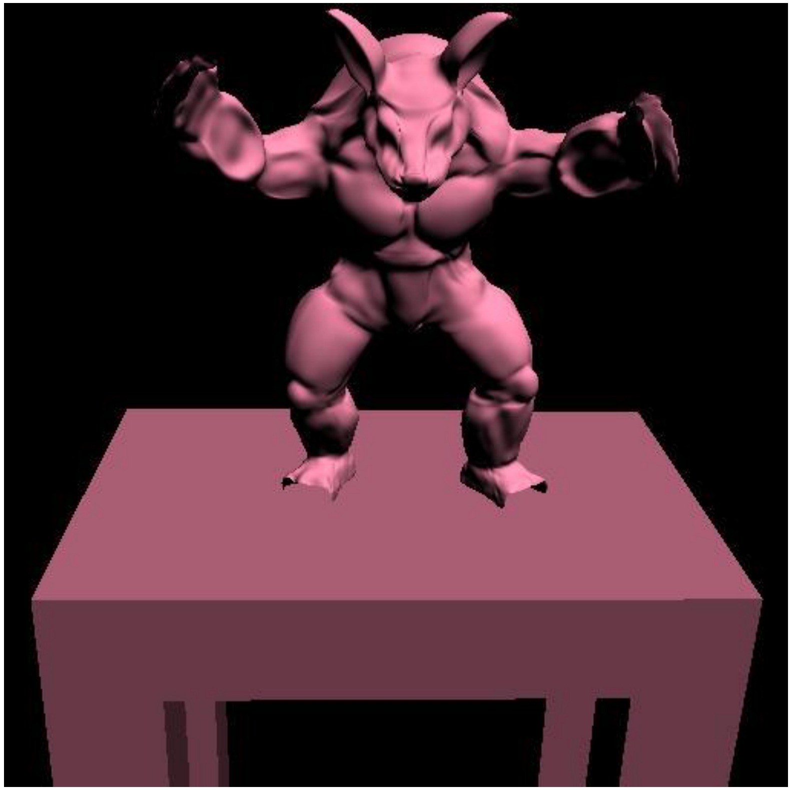
$$c = k_d E(\mathbf{n})$$

Environment map



Irradiance map

Irradiance environment maps



Directional light

Environment illumination

Images from http://www.cs.berkeley.edu/~ravir/papers/envmap/

Implementation

- Precompute irradiance map from environment
  - HDRShop tool, “diffuse convolution”
    http://projects.ict.usc.edu/graphics/HDRShop/
- At render time, look up irradiance map using surface normal
  - When object rotates, rotate normal accordingly
- Can also approximate glossy reflection
  - Blur environment map less heavily
  - Look up blurred environment map using reflection vector

Today

More shading

- Environment maps
- Reflection mapping
- Irradiance environment maps
- Ambient occlusion
- Reflection and refraction
- Toon shading

Including occlusion

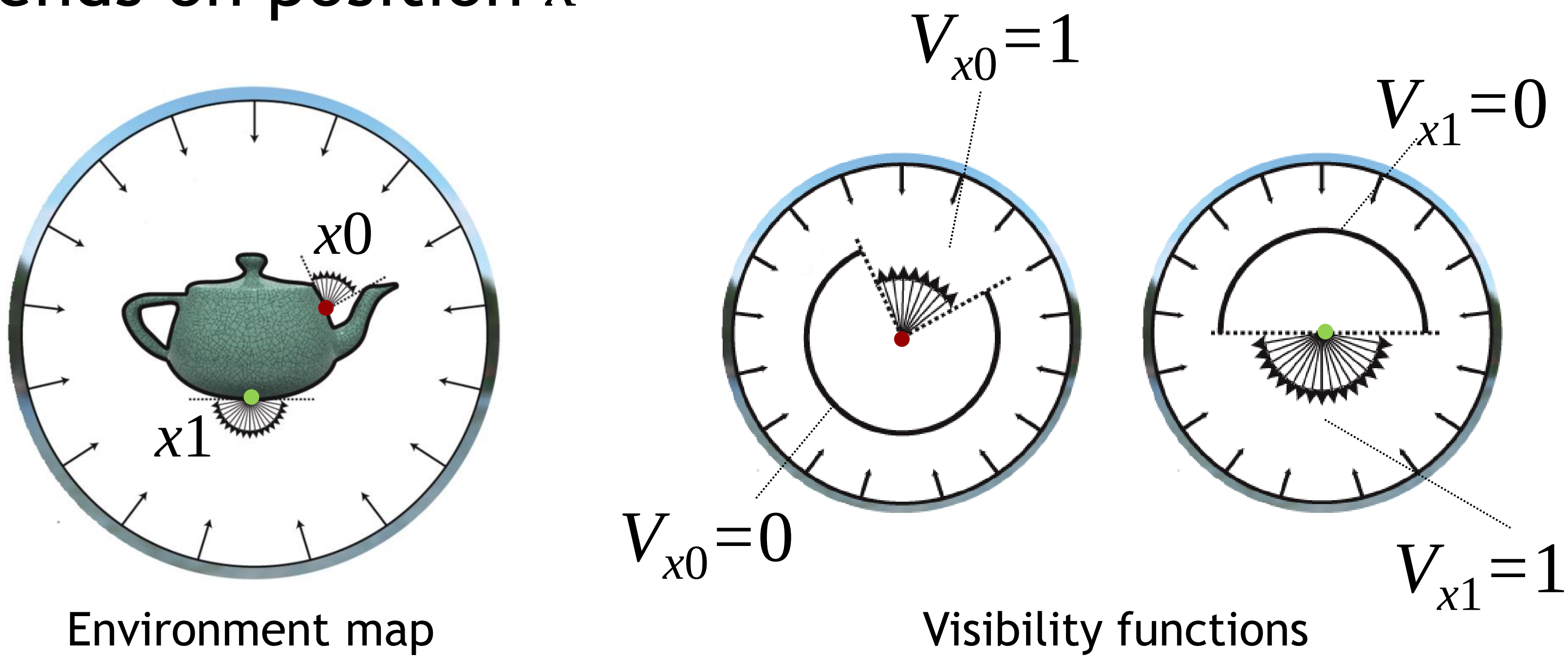
- At each point, environment is partially occluded by geometry
- Add light only from un-occluded directions

Visualization of un-occluded directions

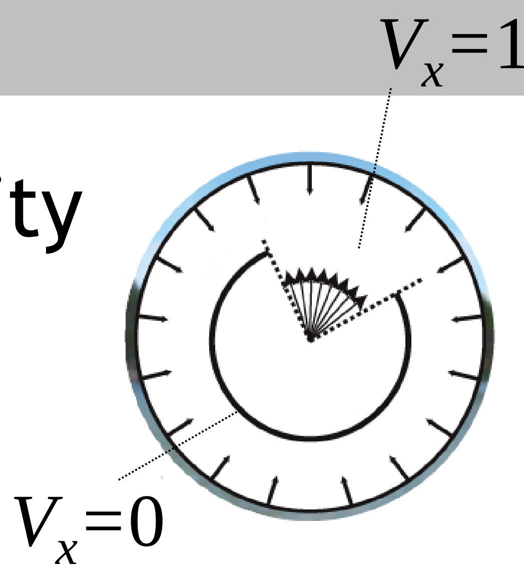
Including occlusion

Visibility function $V_x(\omega)$

- Binary function of direction ω
- Indicates if environment is occluded
- Depends on position x



Mathematical model



- Diffuse illumination with visibility

$$c = k_d \int_\Omega V_x(\omega) c(\omega)(\omega \cdot \mathbf{n}) d\omega$$

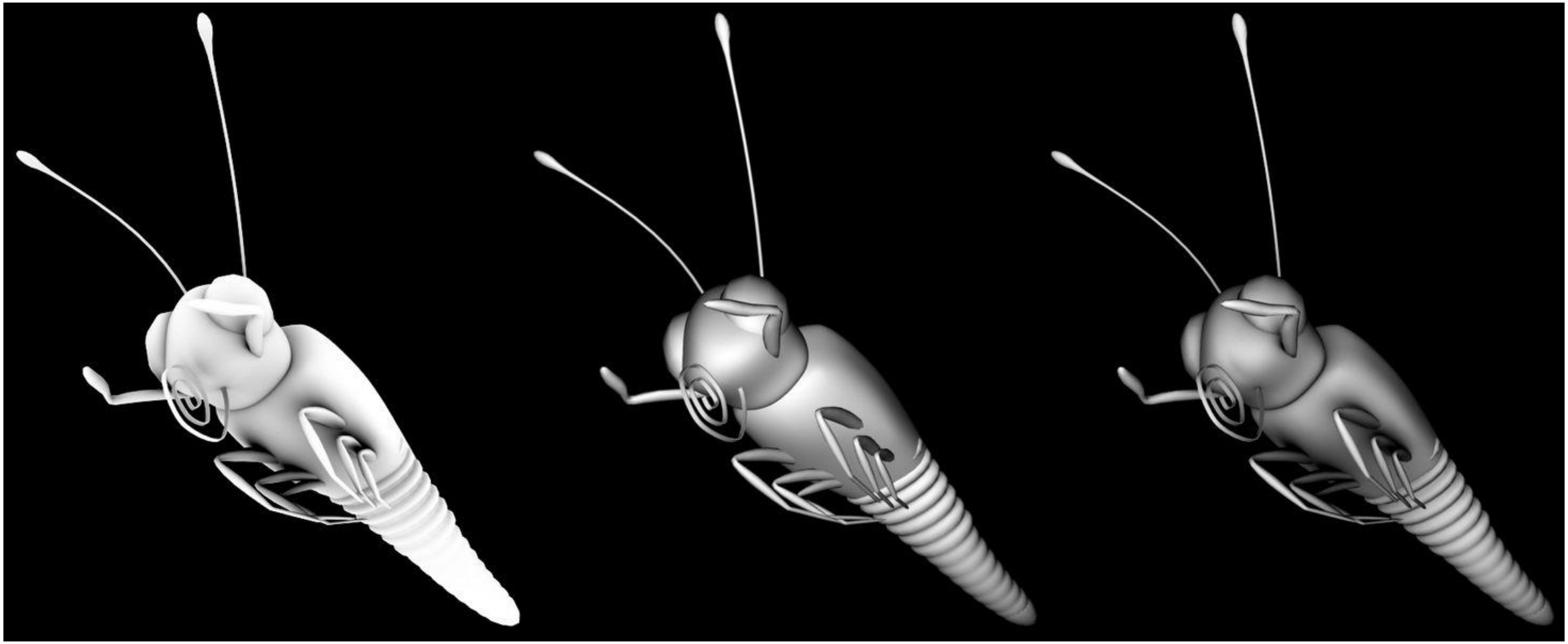
- Ambient occlusion
  - "Fraction" of environment that is not occluded from a point *x*
  - Scalar value

$$a_x = \int_\Omega V_x(\omega)(\omega \cdot \mathbf{n}) d\omega$$

- Approximation: diffuse shading given by irradiance weighted by ambient occlusion

$$c = k_d a_x E(\mathbf{n}) \qquad E(\mathbf{n}) = \int_\Omega c(\omega)(\omega \cdot \mathbf{n}) d\omega$$

Ambient occlusion



Ambient occlusion | Diffuse shading | Ambient occlusion combined (using multiplication) with diffuse shading

http://en.wikipedia.org/wiki/Ambient_occlusion

Implementation

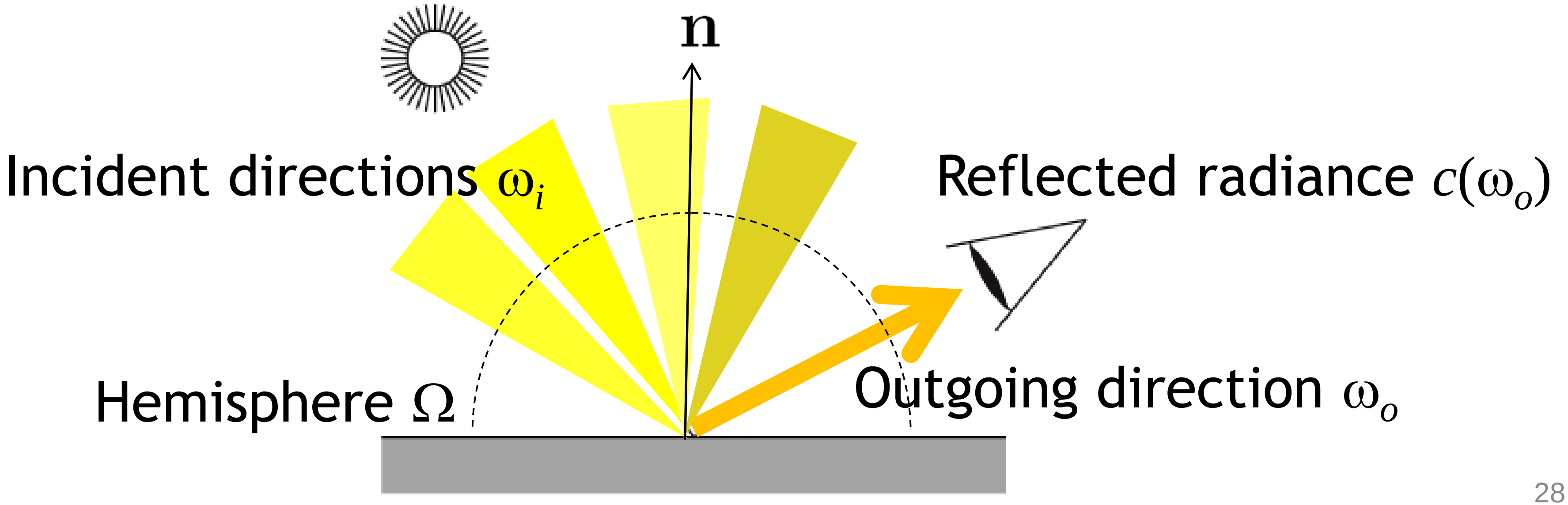
- Precomputation (off-line, before rendering)
  - Compute ambient occlusion on a per-vertex basis
  - Using ray tracing
  - Free tool that saves meshes with per-vertex ambient occlusion
    http://www.xnormal.net/
- Caution
  - Basic pre-computed ambient occlusion does not work for animated objects

Shading integral

- Ambient occlusion with irradiance environment maps is crude approximation to general shading integral

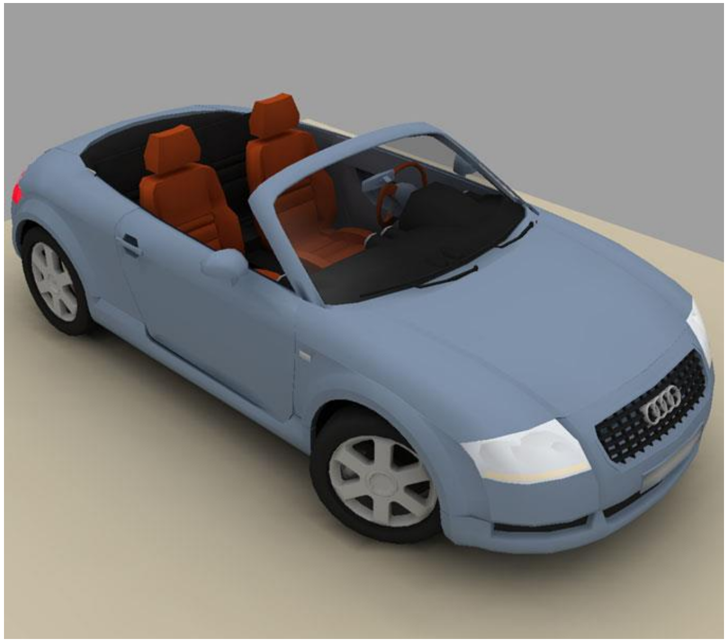
$$c(\omega_o) = \int_\Omega V_x(\omega_i) c(\omega_i) f(\omega_o, \omega_i)(\omega_i \cdot \mathbf{n}) d\omega_i$$

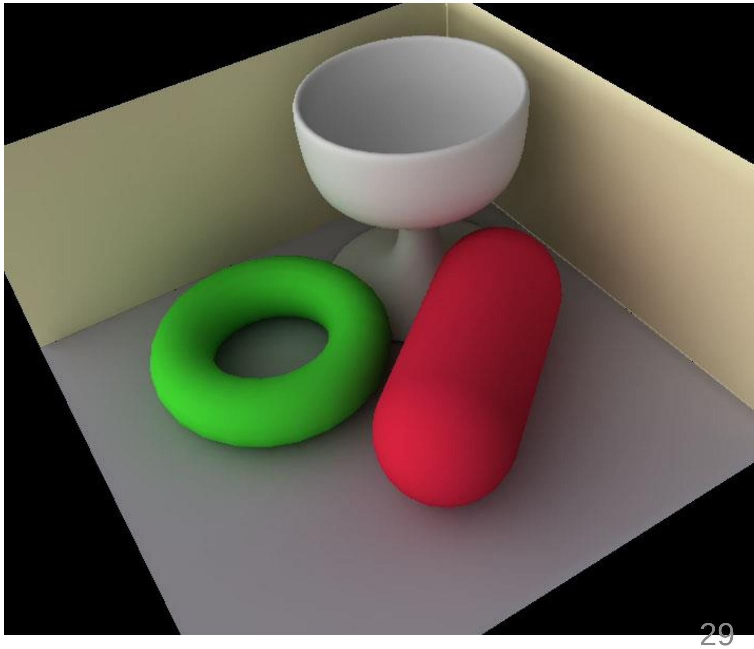
  - BRDF for (non-diffuse) material $f(\omega_o, \omega_i)$



Shading integral

- Accurate evaluation is expensive to compute
  - Requires numerical integration
- Many tricks for more accurate and general approximation than ambient occlusion and irradiance environment maps exist
  - Spherical harmonics shading
    http://www.research.scea.com/gdc2003/spherical-harmonic-lighting.pdf

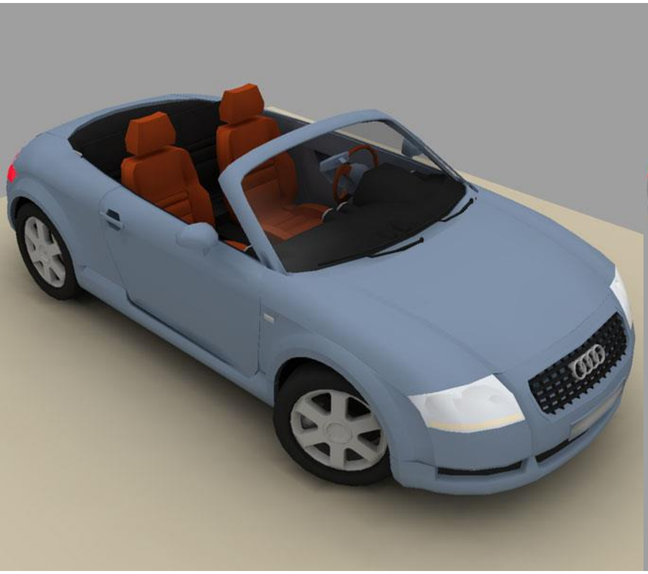




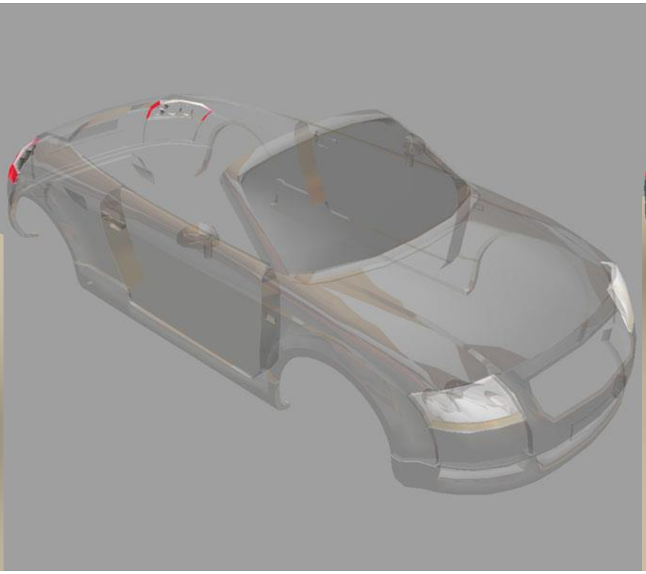
Note

- Visually interesting results using combination (sum) of diffuse shading with ambient occlusion and reflection mapping

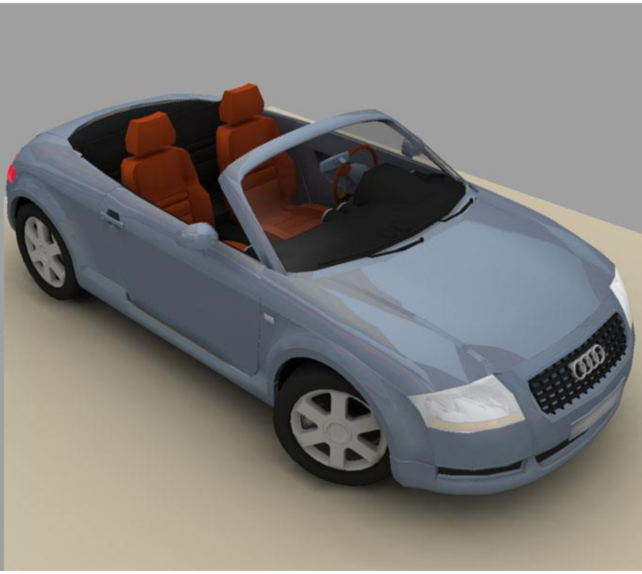
Diffuse shading with ambient occlusion



Reflection mapping



Combination (sum)



http://www.research.scea.com/gdc2003/spherical-harmonic-lighting.pdf

Today

More shading

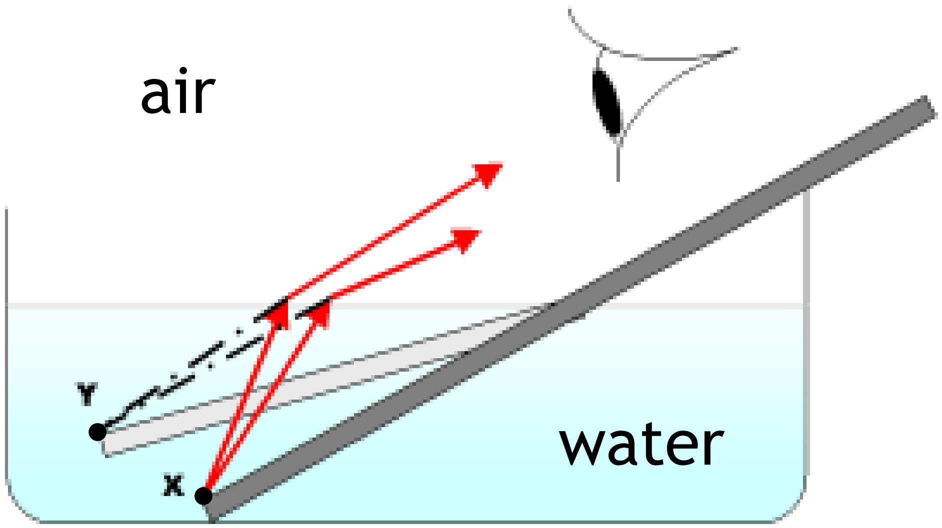
- Environment maps
- Reflection mapping
- Irradiance environment maps
- Ambient occlusion
- Reflection and refraction
- Toon shading

Reflection & refraction

Refraction

http://en.wikipedia.org/wiki/Refraction

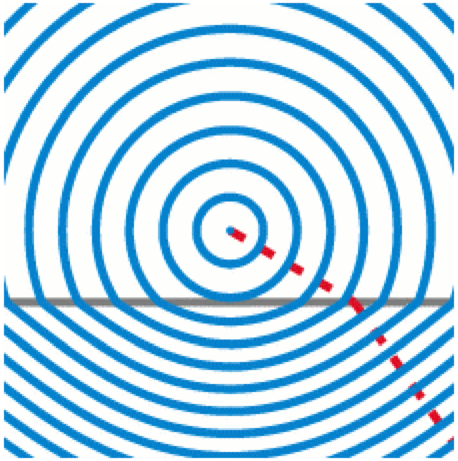
- Light rays that travel from one medium to an other are bent
- To the viewer, object at location x appears to be at location y



Index of refraction

http://en.wikipedia.org/wiki/Refractive_index

- Speed of light depends on medium
  - Speed of light in vacuum c
  - Speed of light in medium v
- Index of refraction $n=c/v$
  - Air 1.00029
  - Water 1.33
  - Acrylic glass 1.49
- "Change in phase velocity leads to bending of light rays"



Snell's law

http://en.wikipedia.org/wiki/Snell's_law

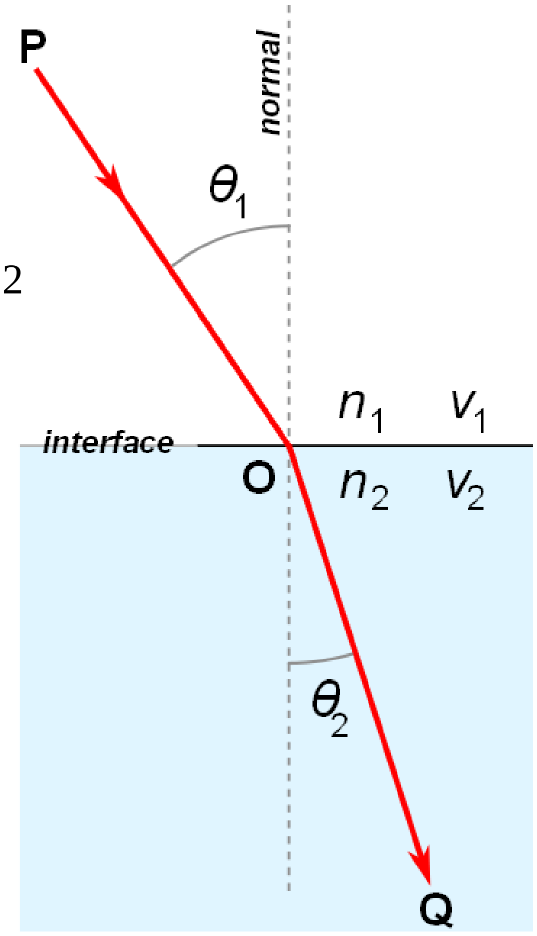
- Ratio of sines of angle of incidence θ_1 and refraction θ_2 is equal to opposite ratio of indices of refraction n_1, n_2

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

- Vector form in 3D

$$\mathbf{r} = \frac{n_1}{n_2}\mathbf{v} + \left(\frac{n_1}{n_2}\cos\theta_1 + \cos\theta_2\right)\mathbf{n}$$

  - Viewing, refracted direction $\mathbf{v}, \mathbf{r}$
  - Normal vector $\mathbf{n}$



Total internal reflection

http://en.wikipedia.org/wiki/Total_internal_reflection

- Angle of refracted ray

$$\theta_2 = \arcsin\left(\theta_1 \frac{n_1}{n_2}\right)$$

- Critical angle

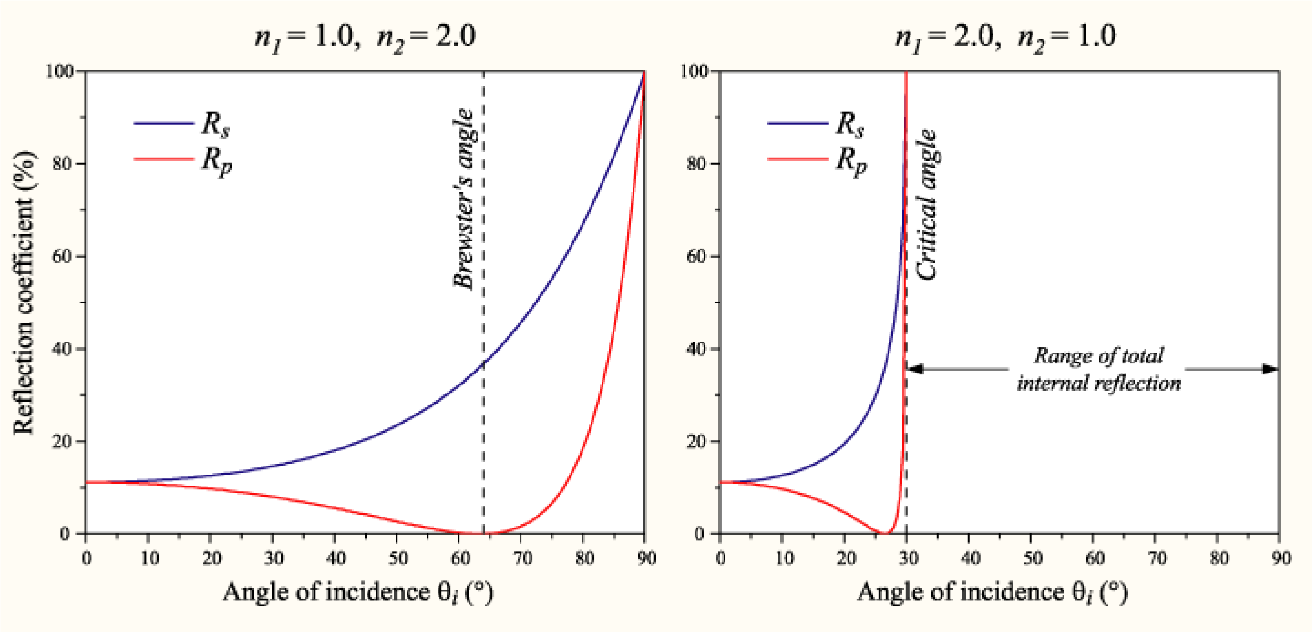
$$\theta_c = \frac{n_2}{n_1}$$

  - If $\theta_1 = \theta_c$ we get $\theta_2 = \pi/2$, refracted ray is parallel to interface
  - If $\theta_1 > \theta_c$ we have total internal reflection (light ray does not cross interface between media)

Fresnel equations

http://en.wikipedia.org/wiki/Fresnel_equations

- When light travels from one medium to an other, both reflection and refraction may occur
- Fresnel equations describe fraction of intensity of light that is reflected and refracted
  - Depend on polarization of light (R_s, R_p in plots)



Fresnel equations

- Fresnel equations are relatively complex to evaluate
- In graphics, often use Schlick's approximation
  https://en.wikipedia.org/wiki/Schlick%27s_approximation
  - Ratio F between reflected and refracted light
  - Indices of refraction n_1, n_2

$$F = f + (1 - f)(1 - \mathbf{v} \cdot \mathbf{n})^5 \qquad f = \frac{\left(1.0 - \frac{n_1}{n_2}\right)^2}{\left(1.0 + \frac{n_1}{n_2}\right)^2}$$

Implementation

- Accurate implementation requires ray tracing
- For interactive graphics, approximation using environment maps
  - Use reflected and refracted rays to look up environment map
  - Use Fresnel equations to determine fraction of reflected and refracted light
  - Does not take into account geometry after first bounce (i.e., surface intersection)
  - Assumes illumination is infinitely far away

Vertex shader

```
const float Eta = 0.67;         // Ratio of indices of refraction (air -> glass)
const float FresnelPower = 10.0; // Controls degree of reflectivity at grazing angles

const float F  = ((1.0 - Eta) * (1.0 - Eta)) / ((1.0 + Eta) * (1.0 + Eta));

varying vec3  Reflect;
varying vec3  Refract;
varying float Ratio;

void main(void)
{
    vec4 ecPosition  = gl_ModelViewMatrix * gl_Vertex;
    vec3 ecPosition3 = ecPosition.xyz / ecPosition.w;

    vec3 i = normalize(ecPosition3);
    vec3 n = normalize(gl_NormalMatrix * gl_Normal);

    Ratio = F + (1.0 - F) * pow((1.0 - dot(-i, n)), FresnelPower);

    Refract = refract(i, n, Eta);
    Refract = vec3(gl_TextureMatrix[0] * vec4(Refract, 1.0));

    Reflect = reflect(i, n);
    Reflect = vec3(gl_TextureMatrix[0] * vec4(Reflect, 1.0));

    gl_Position   = ftransform();
}
```

CAUTION: need to update this for OpenGL 3 compliance

Fragment shader

- Application needs to set up cube map

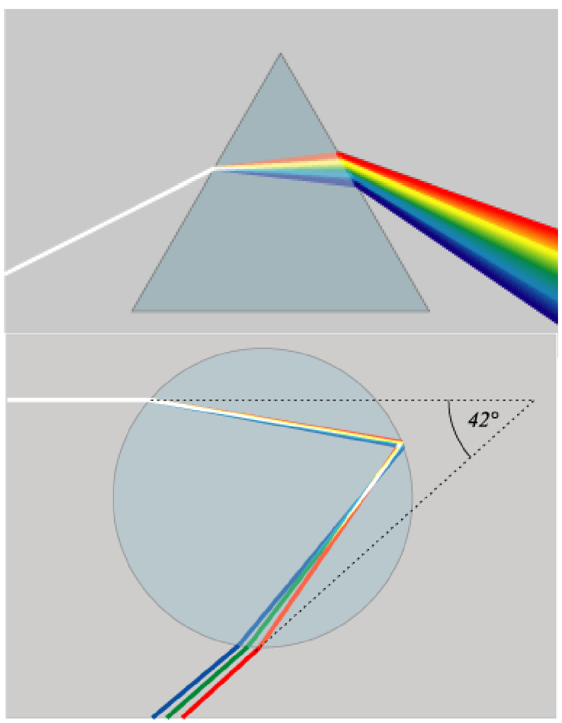
```
varying vec3  Reflect;
varying vec3  Refract;
varying float Ratio;

uniform samplerCube cubemap;

void main(void)
{
    vec3 refractColor = vec3 (textureCube(cubemap, Refract));
    vec3 reflectColor = vec3 (textureCube(cubemap, Reflect));

    vec3 color   = mix(refractColor, reflectColor, Ratio);

    gl_FragColor = vec4(color, 1.0);
}
```

CAUTION: need to update this for OpenGL 3 compliance

Chromatic dispersion

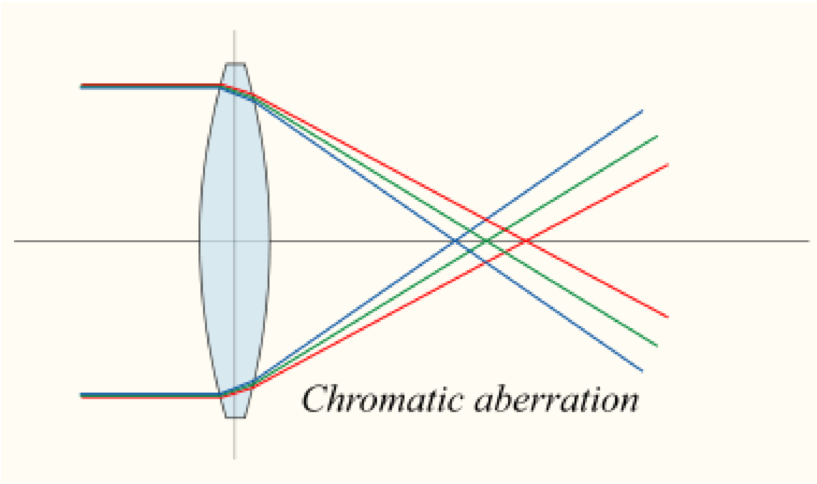
http://en.wikipedia.org/wiki/Dispersion_(optics)

- Phase velocity (i.e., index of refraction) in many media depends on wavelength/frequency
  - Dispersive media
- Different colors refract at different angles



Chromatic dispersion

- In the context of camera lenses, chromatic aberration
  - Try to use *achromatic* lenses



Implementation

- Approximate dispersion by using three different ratios of indices of refraction for R,G,B channels
  - Glass: 0.65, 0.67, 0.69
- Perform separate look-ups for R,G,B channels in environment map

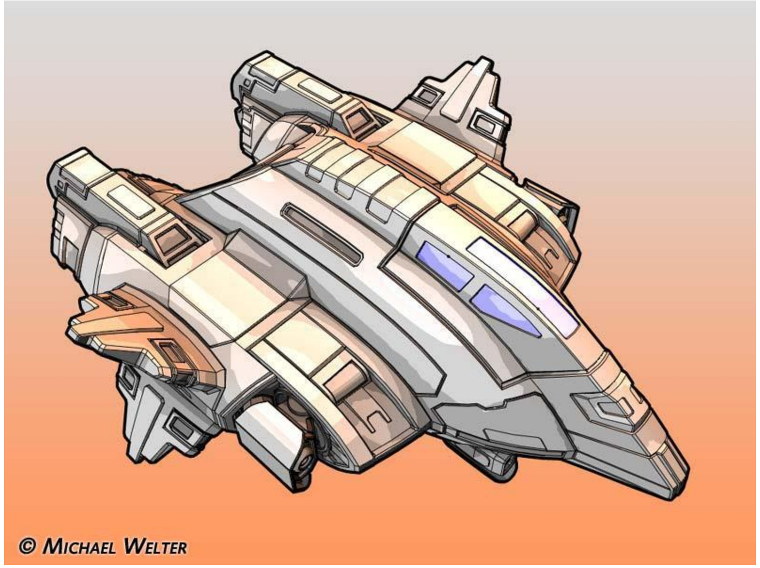
Today

More shading

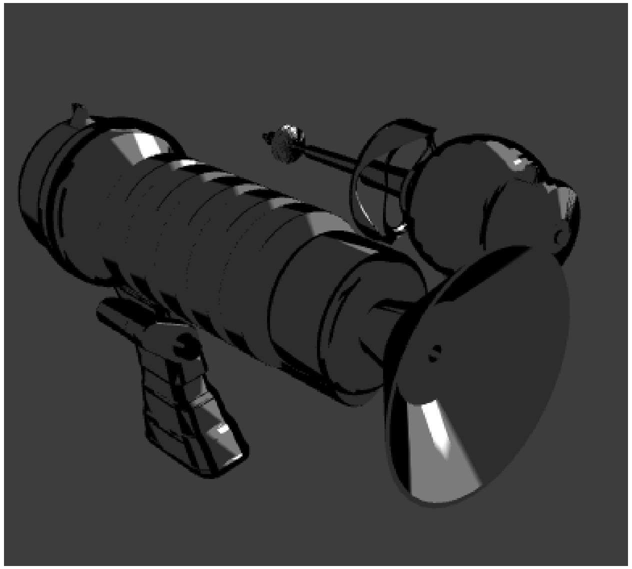
- Environment maps
- Reflection mapping
- Irradiance environment maps
- Ambient occlusion
- Reflection and refraction
- Toon shading

Toon shading

- Simple cartoon style shader
- Emphasize silhouettes
- Discrete steps for diffuse shading, highlights
- Sometimes called CEL shading
  http://en.wikipedia.org/wiki/Cel-shaded_animation



Off-line toon shader

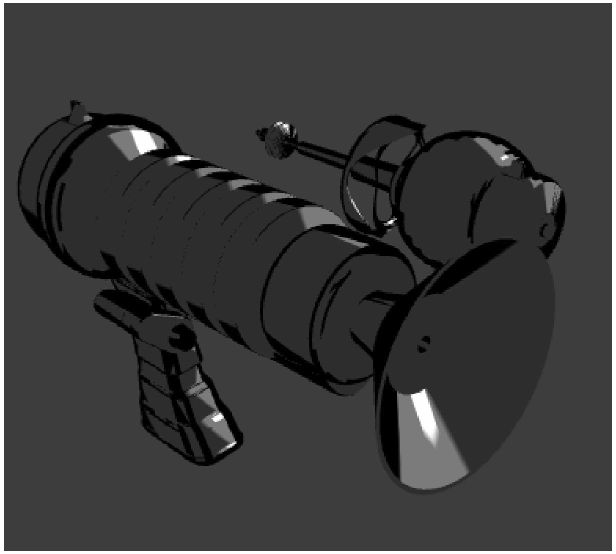


GLSL toon shader

Toon shading

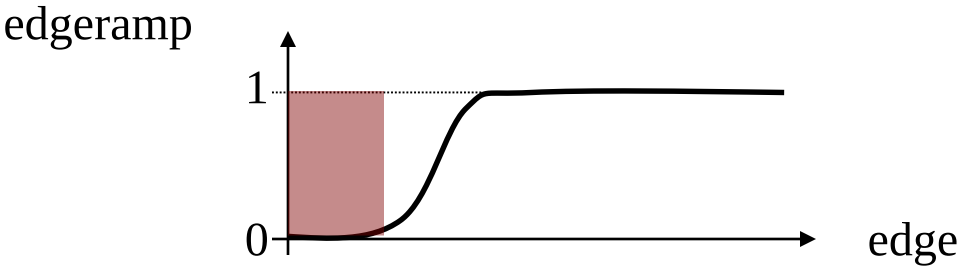
- Silhouette edge detection
  - Compute dot product of viewing direction $\mathbf{v}$ and normal $\mathbf{n}$

$$\text{edge} = \max(0, \mathbf{n} \cdot \mathbf{v})$$



  - Use 1D texture to define edge ramp

uniform sample1D edgeramp; e=texture1D(edgeramp,edge);



Toon shading

- Compute diffuse and specular shading

$$\text{diffuse} = \mathbf{n} \cdot \mathbf{L} \qquad \text{specular} = (\mathbf{n} \cdot \mathbf{h})^s$$

- Use 1D textures diffuseramp, specularramp to map diffuse and specular shading to colors
- Final color

```
uniform sampler1D diffuseramp;
uniform sampler1D specularramp;
c = e * (texture(diffuse,diffuseramp)+
         texture(specular,specularramp));
```

Tools

- Nvidia developer page
  http://developer.nvidia.com/page/home.html

Next time

- Bump mapping, shadows