MIT 6.837 - Ray Tracing

Ray Tracing

MIT EECS 6.837

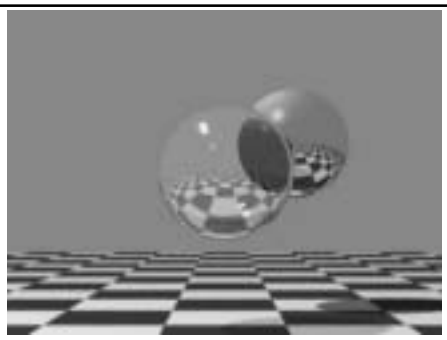
Most slides are taken from Frédo Durand and Barb Cutler

Some slides courtesy of Leonard McMillan

Ray Tracing

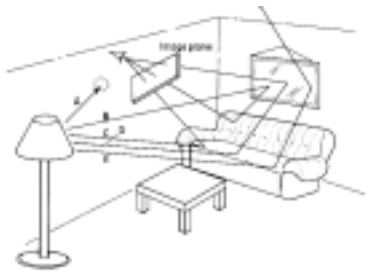
- Ray Tracing kills two birds with one stone:
  - Solves the Hidden Surface Removal problem
  - Evaluates an improved global illumination model
    - shadows
    - ideal specular reflections
    - ideal specular refractions
  - Enables direct rendering of a large variety of geometric primitives
- Book: A. Glassner, An Introduction to Ray Tracing
- Web: `http://www.cs.cf.ac.uk/Ray.Tracing`

Ray Tracing



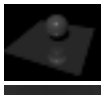
Recursive ray tracing: Turner Whitted, 1980

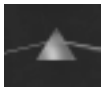
Backward Tracing

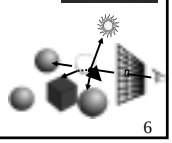


Overview of today

- Shadows
- Reflection
- Refraction
- Recursive Ray Tracing



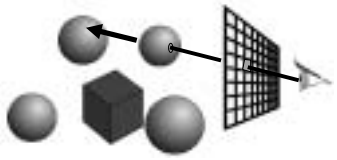




Ray Casting (a.k.a. Ray Shooting)

```
For every pixel (x,y)
  Construct a ray from the eye
  color[x,y]=castRay(ray)
```

- Complexity?
  - O(n * m)
  - n: number of objects, m: number of pixels



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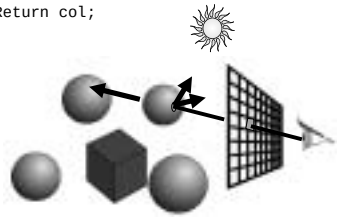
Ray Casting with diffuse shading

```
Color castRay(ray)
  Hit hit();
  For every object ob
      ob->intersect(ray, hit, tmin);
   Color col=ambient*hit->getColor();
   For every light L
      col=col+hit->getColorL()*L->getColor*
        L->getDir()->Dot3( hit->getNormal() );
   Return col;
```



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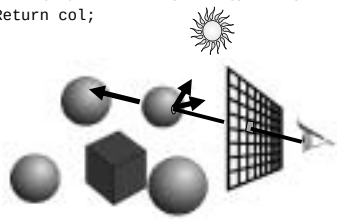
Encapsulating shading

```
Color castRay(ray)
  Hit hit();
  For every object ob
      ob->intersect(ray, hit, tmin);
   Color col=ambient*hit->getMaterial()->getDiffuse();
   For every light L
      col=col+hit->getMaterial()->shade
        (ray, hit, L->getDir(), L->getColor());
   Return col;
```



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Questions?

- Image computed using the RADIANCE system by Greg Ward

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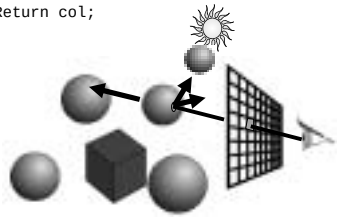
How can we add shadows?

```
Color castRay(ray)
  Hit hit();
  For every object ob
      ob->intersect(ray, hit, tmin);
   Color col=ambient*hit->getMaterial()->getDiffuse();
   For every light L
      col=col+hit->getMaterial()->shade
        (ray, hit, L->getDir(), L->getColor());
   Return col;
```



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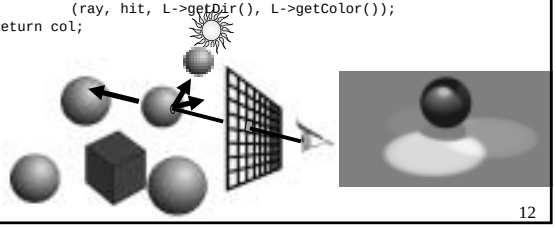
Shadows

```
Color castRay(ray)
    Hit hit();
    For every object ob
        ob->intersect(ray, hit, tmin);
     Color col=ambient*hit->getMaterial()->getDiffuse();
     For every light L
        Ray ray2(hitPoint, L->getDir()); Hit hit2(L->getDist(),,)
        For every object ob
            ob->intersect(ray2, hit2, 0);
        If (hit->getT> L->getDist())
            col=col+hit->getMaterial()->shade
              (ray, hit, L->getDir(), L->getColor());
     Return col;
```



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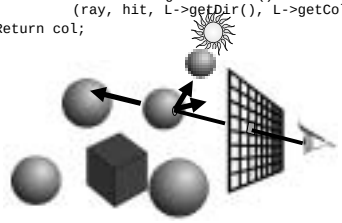
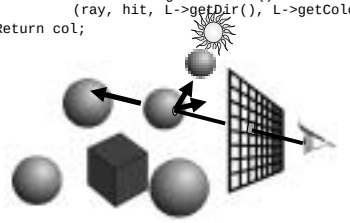
Shadows – problem?

```
Color castRay(ray)
     Hit hit();
     For every object ob
            ob->intersect(ray, hit, tmin);
       Color col=ambient*hit->getMaterial()->getDiffuse();
      For every light L
          Ray ray2(hitPoint, L->getDir()); Hit hit2(L->getDist(),,)
          For every object ob
              ob->intersect(ray2, hit2, 0);
          If (hit->getT> L->getDist())
              col=col+hit->getMaterial()->shade
                (ray, hit, L->getDir(), L->getColor());
      Return col;
```



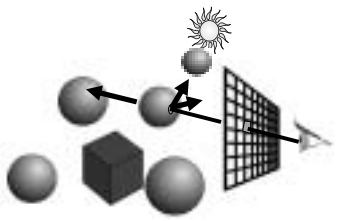
Avoiding self shadowing

```
Color castRay(ray)
     Hit hit();
     For every object ob
            ob->intersect(ray, hit, tmin);
       Color col=ambient*hit->getMaterial()->getDiffuse();
      For every light L
          Ray ray2(hitPoint, L->getDir()); Hit hit2(L->getDist(),,)
          For every object ob
              ob->intersect(ray2, hit2, epsilon);
          If (hit->getT> L->getDist())
              col=col+hit->getMaterial()->shade
                (ray, hit, L->getDir(), L->getColor());
      Return col;
```



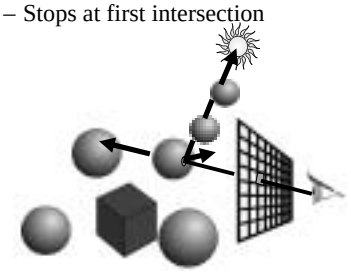
Shadow optimization

- Shadow rays are special
- How can we accelerate our code?



Shadow optimization

- We only want to know whether there is an intersection, not which one is closest
- Special routine `Object3D::intersectShadowRay()`
  - Stops at first intersection

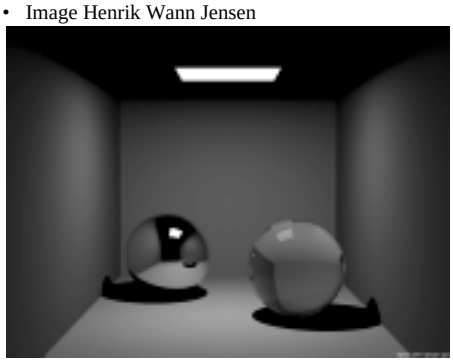


Shadow ray casting history

- Due to Appel [1968]
- First shadow method in graphics
- Not really used until the 80s

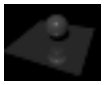
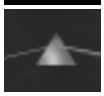
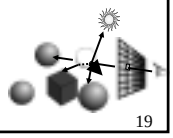
Questions?

- Image Henrik Wann Jensen



Overview of today

- Shadows
- Reflection
- Refraction
- Recursive Ray Tracing

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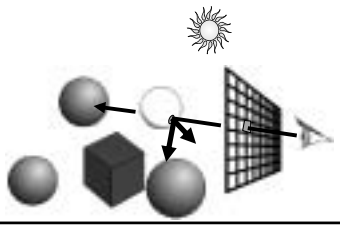
Mirror Reflection

- Compute mirror contribution
- Cast ray
  - In direction symmetric wrt normal
- Multiply by reflection coefficient (color)

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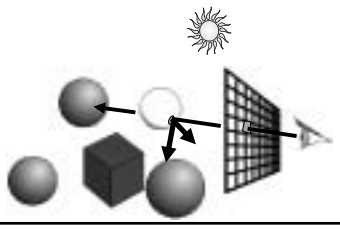
Mirror Reflection

- Cast ray
  - In direction symmetric wrt normal
- Don't forget to add epsilon to the ray

Without epsilon




With epsilon

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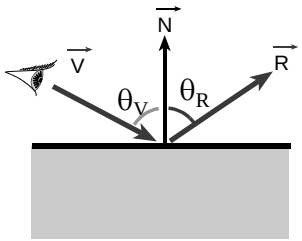
Reflection

- Reflection angle = view angle



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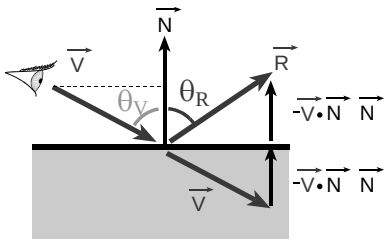
Reflection

- Reflection angle = view angle

$$\vec{R} = \vec{V} - 2\left(\vec{V} \bullet \vec{N}\right)\vec{N}$$



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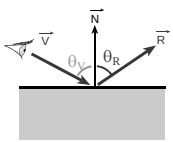
Amount of Reflection

- Traditional (hacky) ray tracing
  - Constant coefficient `reflectionColor`
  - Component per component multiplication



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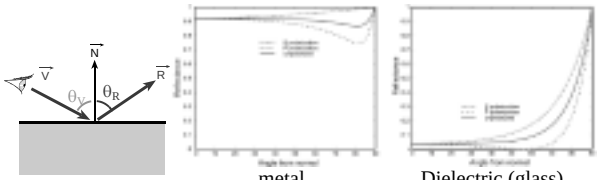
Amount of Reflection

- More realistic:
  - Fresnel reflection term
  - More reflection at grazing angle
  - Schlick's approximation: $R(\theta)=R_0+(1-R_0)(1-\cos\theta)^5$



metal Dielectric (glass)

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Fresnel reflectance demo

- Lafortune et al., Siggraph 1997

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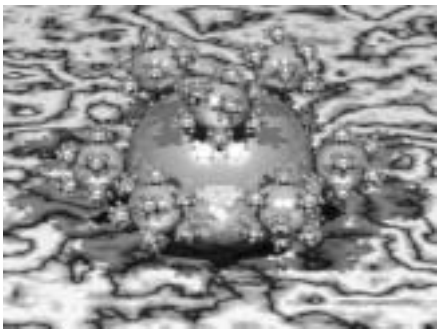
Questions?

- Image by Henrik Wann Jensen



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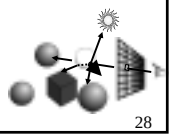
Overview of today

- Shadows
- Reflection
- Refraction
- Recursive Ray Tracing



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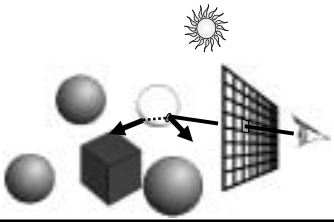
Transparency

- Compute transmitted contribution
- Cast ray
  - In refracted direction
- Multiply by transparency coefficient (color)



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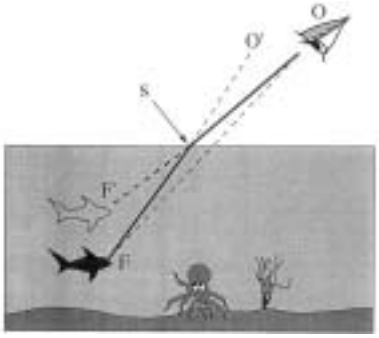
Qualitative refraction

- From "Color and Light in Nature" by Lynch and Livingston



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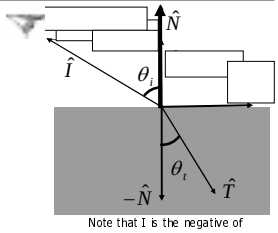
Refraction

Fig. 3. Refraction causes the ruler to appear bent in a glass of water.

Refraction

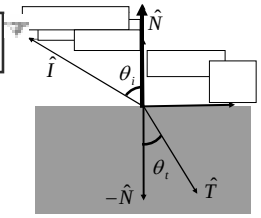
Snell-Descartes Law



Refraction

Snell-Descartes Law

$$\frac{\sin\theta_i}{\sin\theta_t} = \frac{\eta_t}{\eta_i} = \eta_r$$

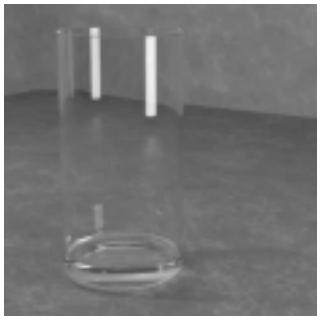


Total internal reflection

- From “Color and Light in Nature” by Lynch and Livingstone

Cool refraction demo

- Enright, D., Marschner, S. and Fedkiw, R.,



Cool refraction demo

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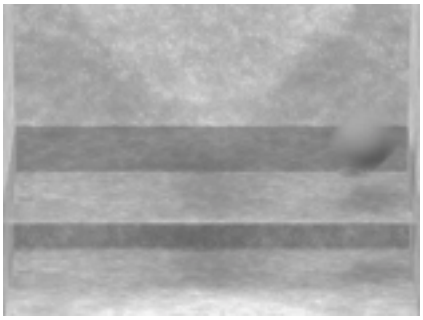
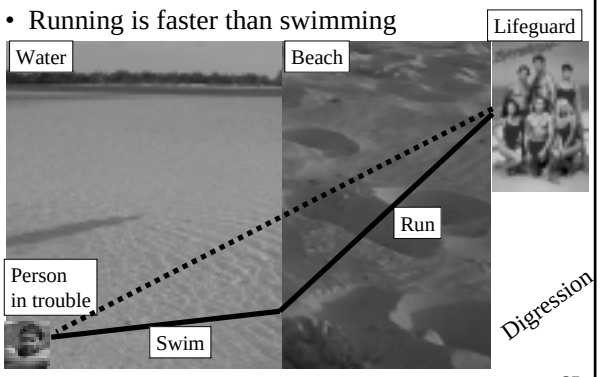


Refraction and the lifeguard problem

- Running is faster than swimming



Digression

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Wavelength

- Refraction is wavelength-dependent
- Newton's experiment
- Usually ignored in graphics

Pink Floyd, *The Dark Side of the Moon*

Pittoni, 1725, Allegory to Newton

Rainbow

- From "Color and Light in Nature" by Lynch and Livingstone

Digression

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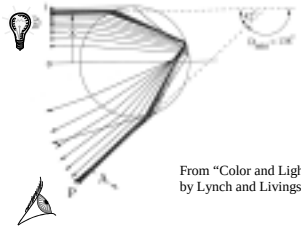
Rainbow

- Refraction depends on wavelength
- Rainbow is caused by refraction+internal reflection+refraction
- Maximum for angle around 42 degrees

Digression



From "Color and Light in Nature" by Lynch and Livingstone

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Questions?

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Overview of today

- Shadows
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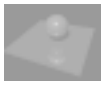
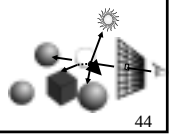
- Recursive Ray Tracing



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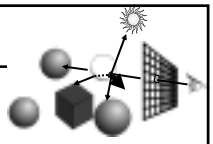
Recap: Ray Tracing



```
traceRay
   Intersect all objects
   Ambient shading
   For every light
      Shadow ray
      shading
   If mirror
      Trace reflected ray
   If transparent
      Trace transmitted ray
```

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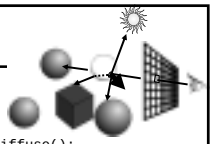
Recap: Ray Tracing



```
Color traceRay(ray)
   For every object ob
        ob->intersect(ray, hit, tmin);
    Color col=ambient*hit->getMaterial()->getDiffuse();
    For every light L
        If ( not castShadowRay( hit->getPoint(), L->getDir())
            col=col+hit->getMaterial()->shade
              (ray, hit, L->getDir(), L->getColor());
    If (hit->getMaterial()->isMirror())
        Ray rayMirror (hit->getPoint(),
          getMirrorDir(ray->getDirection(), hit->getNormal());
        Col=col+hit->getMaterial->getMirrorColor()
          *traceRay(rayMirror, hit2);
    If (hit->getMaterial()->isTransparent()
        Ray rayTransmitted(hit->getPoint(),
          getRefracDir(ray, hit->getNormal(), curentRefractionIndex,
          hit->Material->getRefractionIndex());
        Col=col+hit->getMaterial->getTransmittedColor()
          *traceRay(rayTransmitted, hit3);
    Return col;
```

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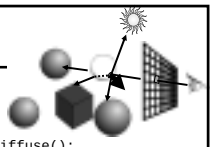
Does it end?



```
Color traceRay(ray)
   For every object ob
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              (ray, hit, L->getDir(), L->getColor());
    If (hit->getMaterial()->isMirror())
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          getMirrorDir(ray->getDirection(), hit->getNormal());
        Col=col+hit->getMaterial->getMirrorColor()
          *traceRay(rayMirror, hit2);
    If (hit->getMaterial()->isTransparent()
        Ray rayTransmitted(hit->getPoint(),
          getRefracDir(ray, hit->getNormal(), curentRefractionIndex,
          hit->Material->getRefractionIndex());
        Col=col+hit->getMaterial->getTransmittedColor()
          *traceRay(rayTransmitted, hit3);
    Return col;
```

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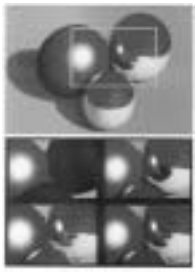
The depth of reflection



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Avoiding infinite recursion

Stopping criteria:

- Recursion depth
  - Stop after a number of bounces
- Ray contribution
  - Stop if transparency/transmitted attenuation becomes too small

Usually do both

```
Color traceRay(ray)
    For every object ob
            ob->intersect(ray, hit, tmin);
        Color col=ambient*hit->getMaterial()->getDiffuse();
        For every light L
                If ( not castShadowRay( hit->getPoint(), L->getDir())
                        col=col+hit->getMaterial()->shade
                                (ray, hit, L->getDir(), L->getColor());
        If (hit->getMaterial()->isMirror())
                Ray rayMirror (hit->getPoint(),
                        getMirrorDir(ray->getDirection(), hit->getNormal());
                Col=col+hit->getMaterial->getMirrorColor()
                        *traceRay(rayMirror);
        If (hit->getMaterial()->isTransparent()
                Ray rayTransmitted(hit->getPoint(),
                        getRefracDir(ray, hit->getNormal(),
                        CurentRefractionIndex, hit->Material-
                        >getRefractionIndex());
                Col=col+hit->getMaterial->getTransmittedColor()
                        *traceRay(rayTransmitted);
        Return col;
```


Recursion for reflection

0 recursion 1 recursion 2 recursions

Ray-Surface Intersection

- Implicit surfaces: $f(x, y, z) = 0$
  - Use a parametric representation for the ray:

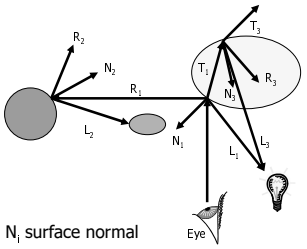
$$R(t) = O + tD$$
$$R_x(t) = O_x + tD_x$$
$$R_y(t) = O_y + tD_y$$
$$R_z(t) = O_z + tD_z$$

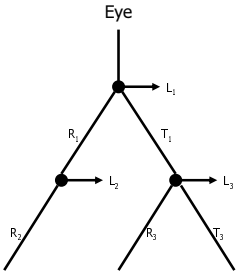
  - Substitute into the implicit equation:

$$f(O_x + tD_x, O_y + tD_y, O_z + tD_z) = 0$$

  - Solve the resulting equation
  - Examples: plane, sphere

The Ray Tree





N_i surface normal

R_i reflected ray

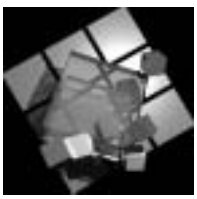
L_i shadow ray

T_i transmitted (refracted) ray

Kewl visualization

- Ben Garlick's SGI demo flyray
- On an Athena SGI O2:

```
add 6.837
cd /mit/6.837/demos/flyray/data
../flyray
```

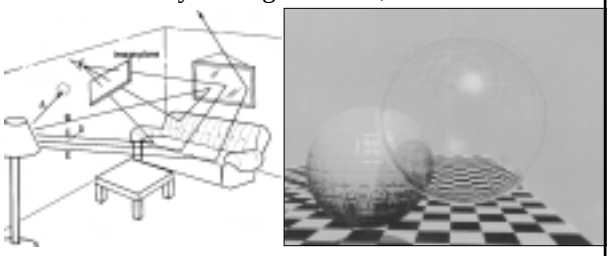


Real-time ray tracing

- Steve Parker et al. (U. of Utah)

Ray Tracing History

- Ray Casting: Appel, 1968
- CSG and quadrics: Goldstein & Nagel 1971
- Recursive ray tracing: Whitted, 1980



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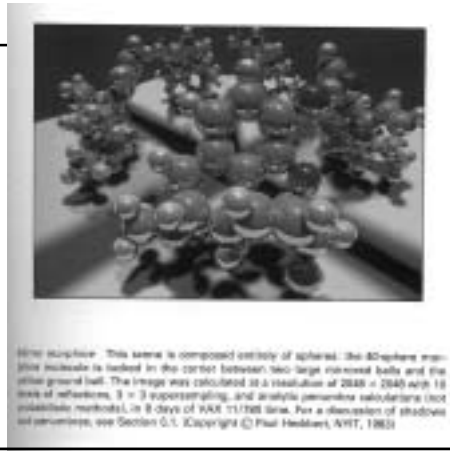

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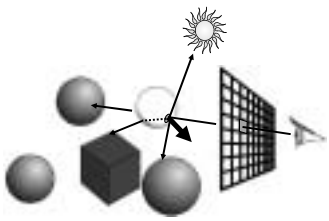
Does Ray Tracing simulate physics?

- Photons go from the light to the eye, not the other way
- What we do is backward ray tracing



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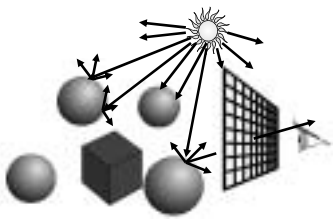
Forward ray tracing

- Start from the light source
- But low probability to reach the eye
  - What can we do about it?



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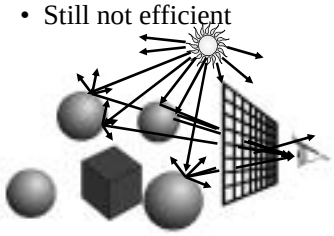
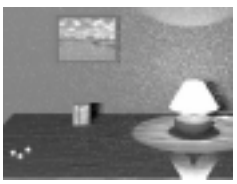
Forward ray tracing

- Start from the light source
- But low probability to reach the eye
  - What can we do about it?
  - Always send a ray to the eye
- Still not efficient





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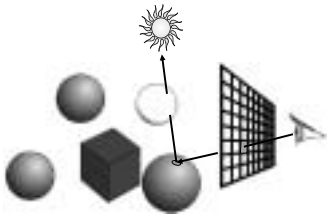
Does Ray Tracing simulate physics?

- Ray Tracing is full of dirty tricks
- e.g. shadows of transparent objects
  - Dirtiest: opaque
  - Still dirty: multiply by transparency color
    - But then no refraction



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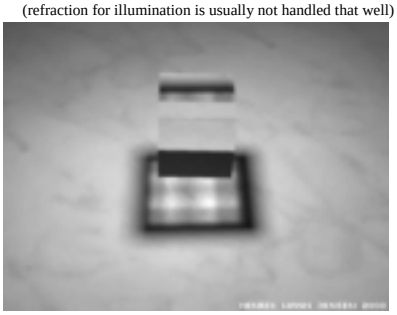
Correct transparent shadow

Animation by Henrik Wann Jensen

Using advanced refraction technique
(refraction for illumination is usually not handled that well)

Digression



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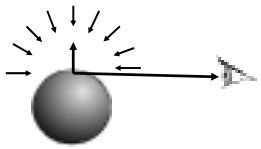
The Rendering equation

- Clean mathematical framework for light-transport simulation
- We'll see that in November
- At each point, outgoing light in one direction is the integral of incoming light in all directions multiplied by reflectance property



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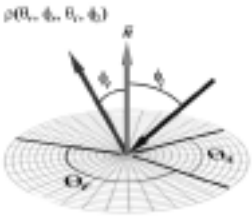
BRDF

- Reflectance properties, shading and BRDF
- Guest lecture by Wojciech Matusik



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