EDAN30 Photorealistic Computer Graphics

Ray tracing

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Outline

- Recursive ray tracing
  - Whitted ray tracing,
    - "An improved illumination model for shaded display", Turner Whitted, CACM June 1980

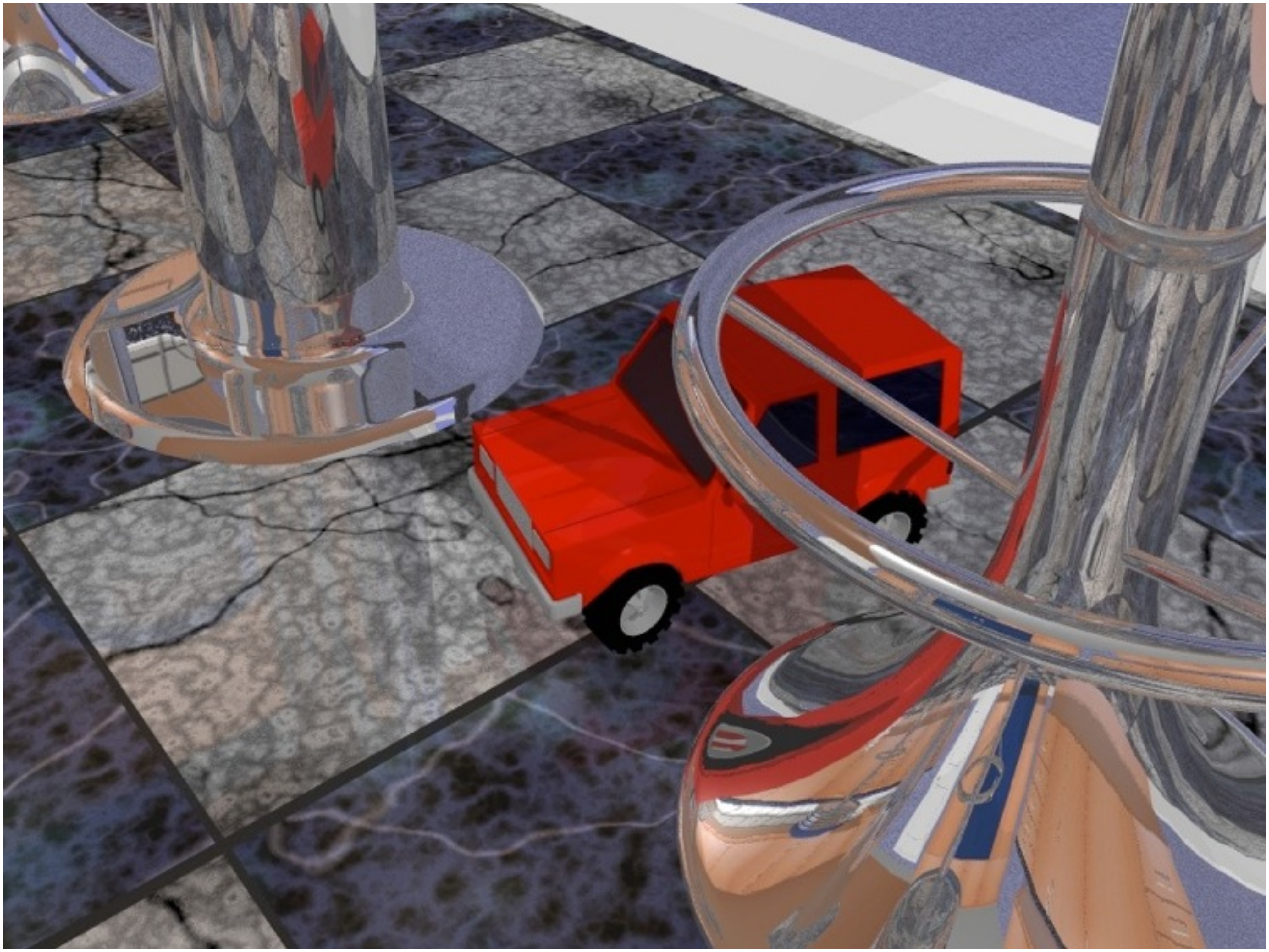
What is ray tracing?

- Another rendering algorithm
  - Fundamentally different from polygon rendering
- Rasterization (OpenGL, DirectX)
  - Renders one **triangle** at a time
  - Z-buffer stores nearest pixels
  - Local lighting (per-vertex or per-pixel)
- **Ray tracing**
  - Renders one **pixel** at a time
  - [Kind of] Sorts the geometry per pixel
  - Global lighting equation (reflections, shadows)

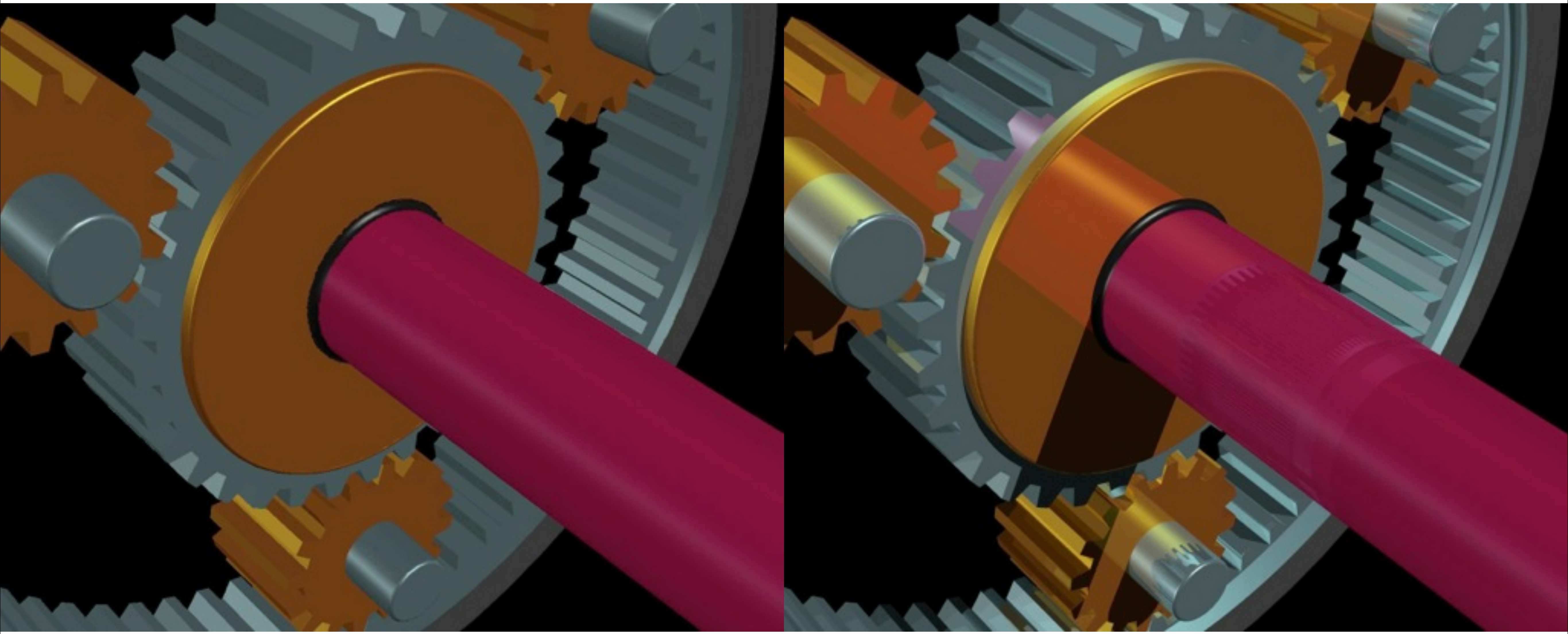
Why ray tracing?

- Simple concept
- Higher quality rendering
  - Global lighting equation
    - Accurate shadows, reflections, refraction, etc
    - Soft shadows, more realistic materials and lighting
  - All computations done per pixel
    - No interpolation
- Base for many advanced algorithms
  - Global illumination, e.g., path tracing, photon mapping
- A disadvantage: **can** take longer to render images!

Original goal: Add reflections



Side by side comparison (1980's)

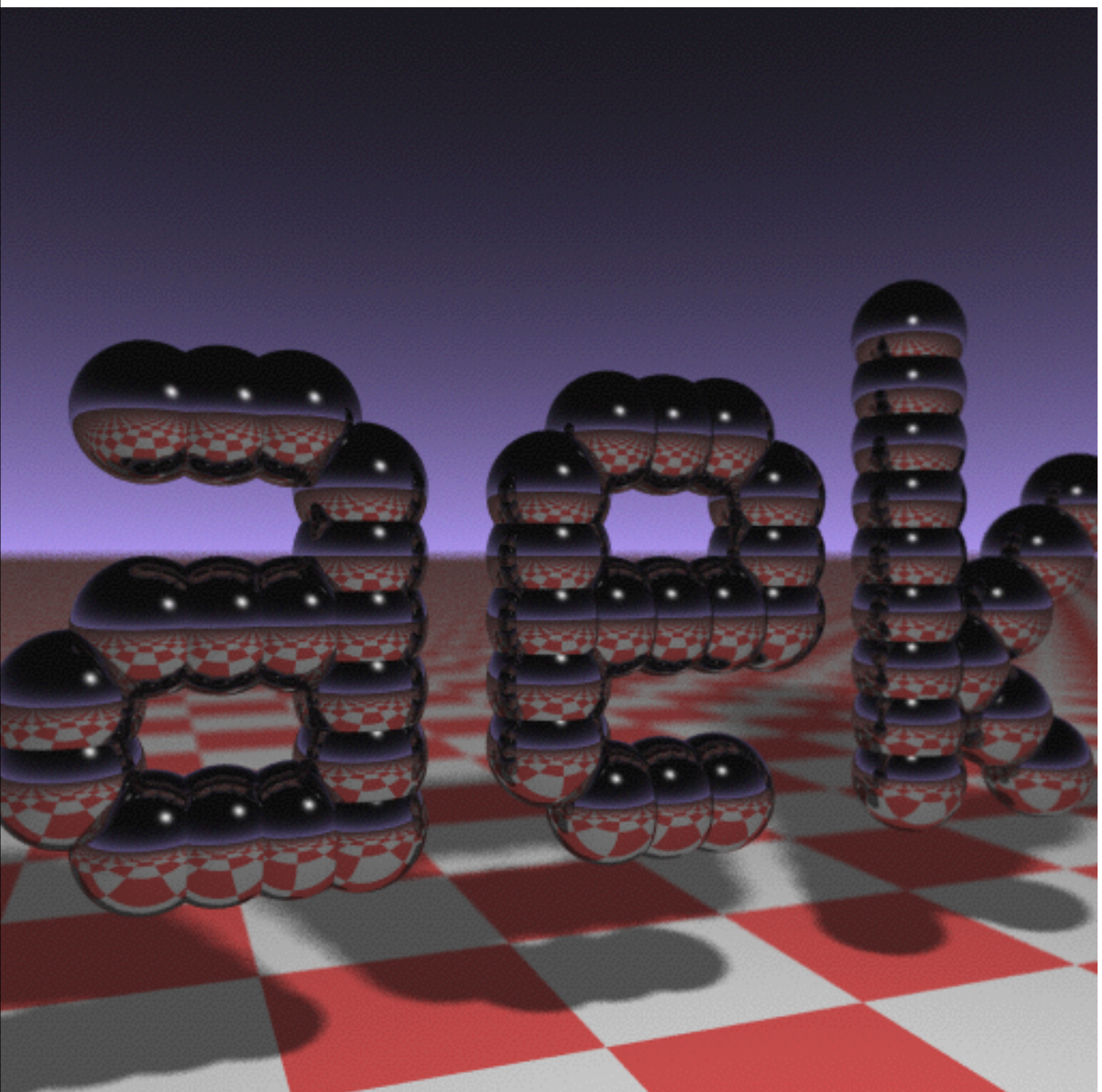


Images courtesy of Eric Haines

Newer example

[Image courtesy of ARTVPS www.artvps.com]

Card Ray Tracer

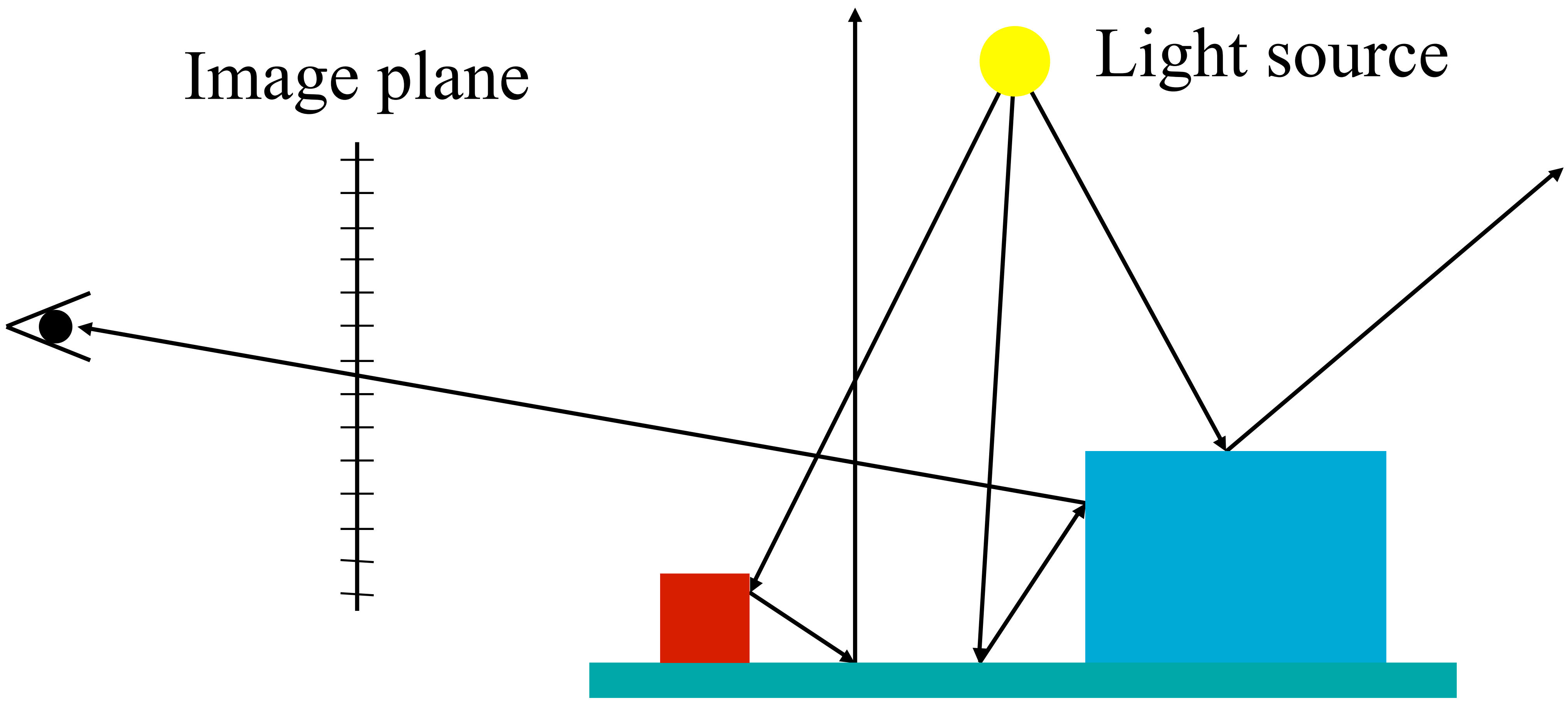


```
#include <stdlib.h>   // card > aek.ppm
#include <stdio.h>
#include <math.h>
typedef int i;typedef float f;struct v{f x,y,z;v
operator+(v r){return v(x+r.x,y+r.y,z+r.z);}v
operator*(f r){return v(x*r,y*r,z*r);}f operator%
(v r){return x*r.x+y*r.y+z*r.z;}v(){}v operator^(v
r){return v(y*r.z-z*r.y,z*r.x-x*r.z,x*r.y-y*r.x);}
v(f a,f b,f c){x=a;y=b;z=c;}v operator!()
{return*this*(1/sqrt(*this%*this));}};i
G[]={247570,280596,280600,249748,18578,18577,23118
4,16,16};f R(){return(f)rand()/RAND_MAX;}i T(v o,v
d,f&t,v&n){t=1e9;i m=0;f p=-o.z/d.z;if(.
01<p)t=p,n=v(0,0,1),m=1;for(i k=19;k--;)for(i
j=9;j--;)if(G[j]&1<<k){v p=o+v(-k,0,-j-4);f b=p
%d,c=p%p-1,q=b*b-c;if(q>0){f s=-b-
sqrt(q);if(s<t&&s>.01)t=s,n=!(p+d*t),m=2;}}return
m;}v S(v o,v d){f t;v n;i m=T(o,d,t,n);if(!
m)return v(.7,.6,1)*pow(1-d.z,4);v h=o+d*t,l=!
(v(9+R(),9+R(),16)+h*-1),r=d+n*(n%d*-2);f b=l
%n;if(b<0||T(h,l,t,n))b=0;f p=pow(l%r*(b>0),
99);if(m&1){h=h*.2;return((i)(ceil(h.x)
+ceil(h.y))&1?v(3,1,1):v(3,3,3))*(b*.2+.1);}return
v(p,p,p)+S(h,r)*.5;}i main(){printf("P6 512 512
255 ");v g=!v(-6,-16,0),a=!(v(0,0,1)^g)*.002,b=!
(g^a)*.002,c=(a+b)*-256+g;for(i y=512;y--;)for(i
x=512;x--;){v p(13,13,13);for(i r=64;r--;){v
t=a*(R()-.5)*99+b*(R()-.5)*99;p=S(v(17,16,8)+t,!
(t*-1+(a*(R()+x)+b*(y+R())+c)*16))*3.5+p;}
printf("%c%c%c",(i)p.x,(i)p.y,(i)p.z);}}
```

courtesy Andrew Kensler from http://www.cs.utah.edu/%7Eaek/code/

To be physically correct, follow photons from light source

- Not what we do for a simple ray tracer
  - Though this is almost what we do for more advanced techniques (photon mapping)

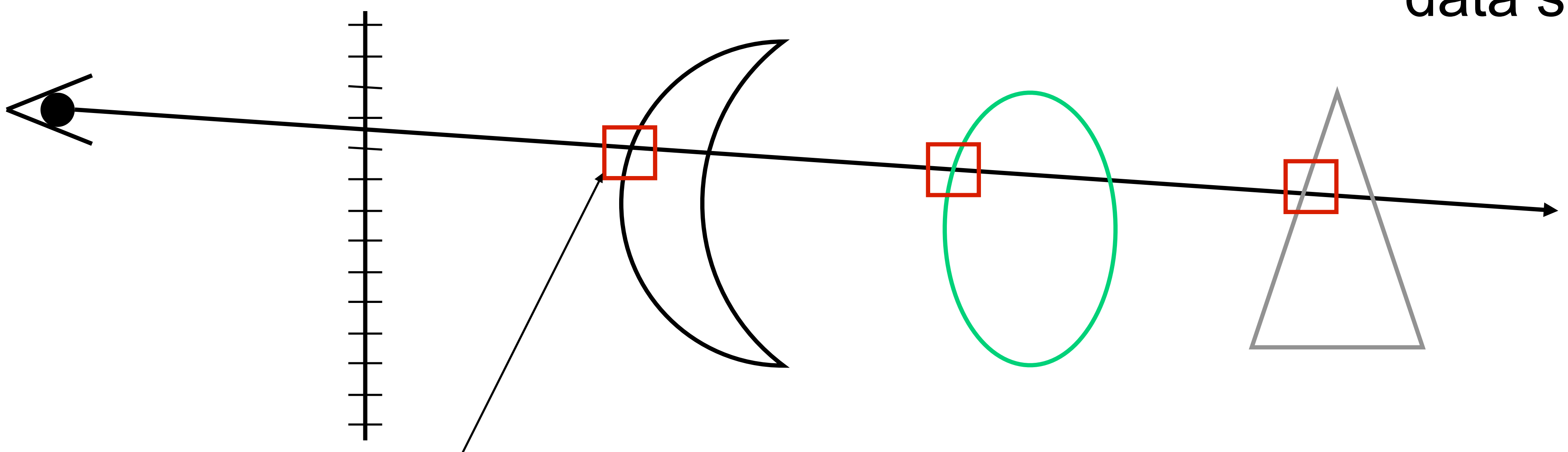


- Not effective, **not** many rays will arrive at the eye

Instead: follow "photons" backwards from the eye

- Rationale: find photons that arrive through each pixel
- How does one find the visible object at a pixel?
- With intersection testing
  - Ray, $\mathbf{r}(t)=\mathbf{o}+t\mathbf{d}$, against geometrical objects
    - r - ray, o - origin, d - direction, t - parameter
  - Use object that is closest to camera!
  - Valid intersections have $t > 0$
  - t is a signed distance

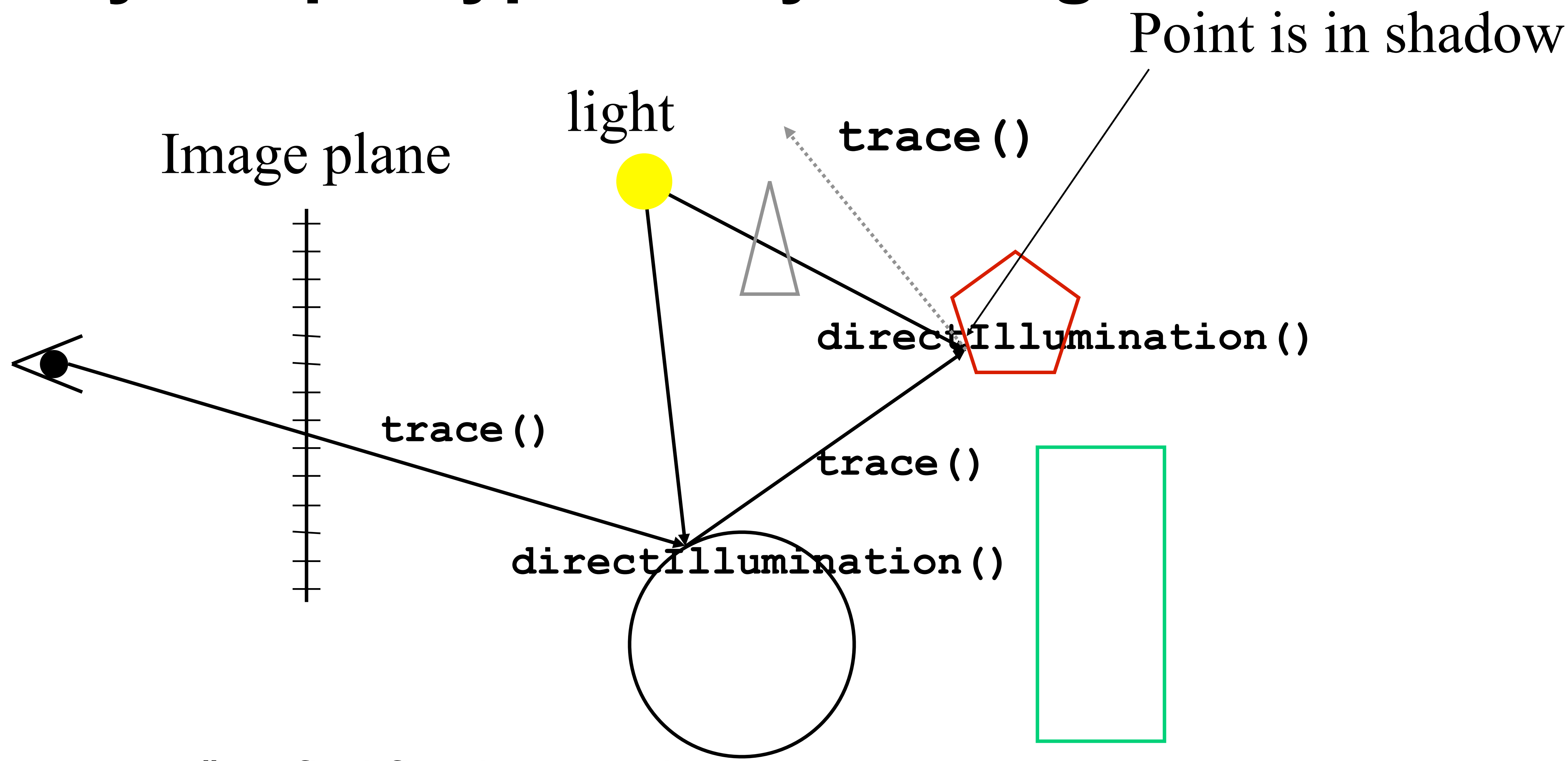
For fast intersection testing, use a spatial data structure!



trace() and directIllumination()

- We now know how to find the visible object at a pixel
- How about finding the color of the pixel?
- Basic ray tracing is essentially only two functions with recursive calls
  - **trace()** and **directIllumination()**
- **trace()**: finds the first intersection with an object
  - Calls **directIllumination()**, and then **trace()**
- **directionIllumination()**: computes the direct lighting at that intersection point

Whitted-style ray tracer: A very simple type of ray tracing



- First call **trace()** to find first intersection
- **directIllumination()** computes direct illumination from light sources
- **trace()** then calls **trace()** for reflection and refraction directions
- **directIllumination()** applies the BRDF of the surface, and so on...

`trace()` in detail

```
Color trace(Ray R)
{
        bool hit;
        Intersection is;
        Color col,col_tmp;
        hit=intersectScene(R,is);
        if(hit)
        {
                col=directIllumination(is);
                if(is indicates reflective object)
                {
                        col_tmp=trace(Reflected ray);
                        col = weightTogether(col,col_tmp);
                }
                if(is indicates transmissive object)
                {
                        col_tmp=trace(Refracted ray);
                        col = weightTogether(col,col_tmp);
                }
        }
        else col=background_color;
        return col;
}
```

[recursion should also be terminated.. could be done after fixed depth]

`directIllumination()` computes direct lighting

- For now, we will use the simple standard lighting equation that we used so far
  - Diffuse + Specular
- Could use other models for the BRDF (Bi-directional Reflection Distribution Function)
  - More realistic materials

directIllumination() in detail

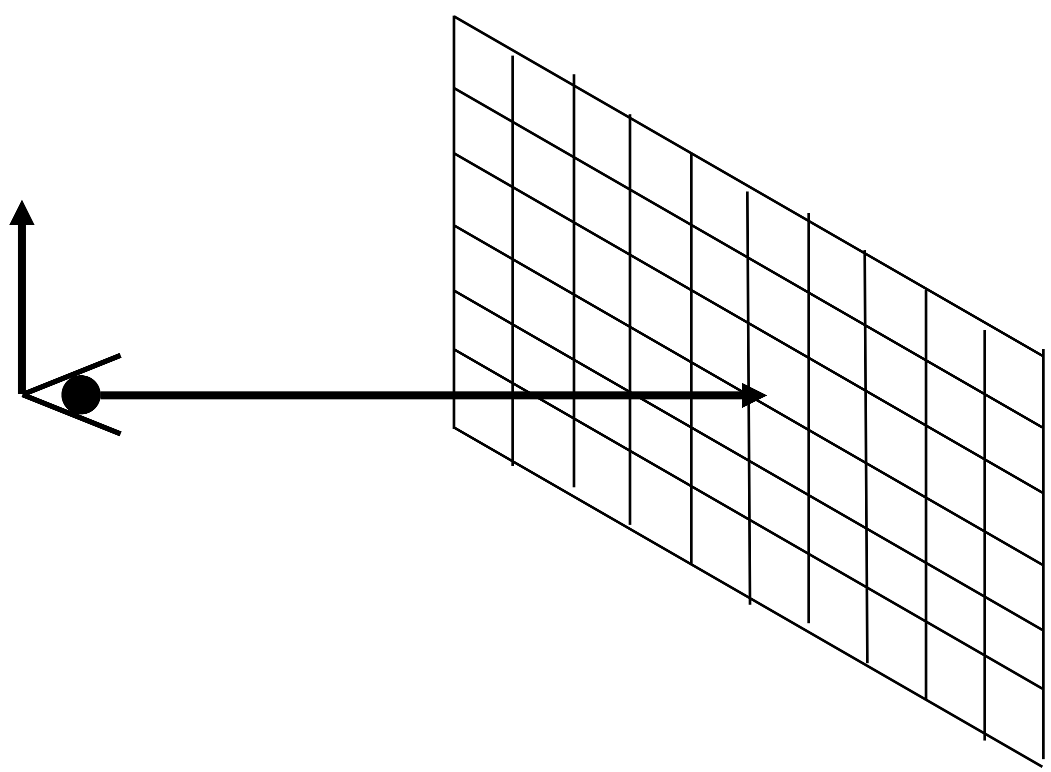
```
Color directIllumination(const Intersection &is)
{
      Color col(0,0,0);
      for each light L
      {
            // create shadow ray; is ”is” in shadow
            // use intersectScene for this...
            if(not inShadow(L,is))
            {
                  col+=DiffuseAndSpecular(L,is);
            }
      }
      return col;
}
```

In `directIllumination()`, we need a function `inShadow()`

- Compute distance from intersection point, $\mathbf{p}$, to light source: t_{max}
- Then use intersection testing:
  - Point is in shadow if $0 < t < t_{max}$ is true for **at least one** object

Who calls trace() to begin with?

- Someone need to spawn rays
  - One or more per pixel
  - A simple routine, **computeImage()**, computes rays, and calls **trace()** for each ray.

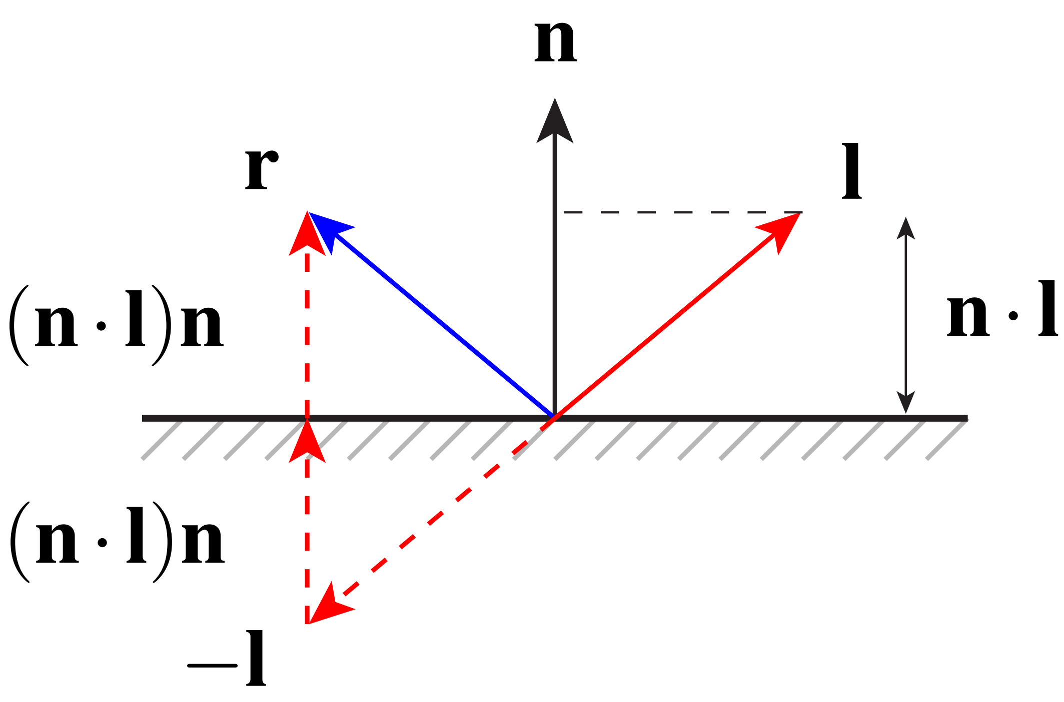


- Use camera parameters to compute rays
  - Resolution, FOV, camera direction & position & up

When does recursion stop?

- Recurse until ray does not hit anything?
  - Does not work for closed models
- One solution is to allow for max N levels of recursion
  - N=3 is often sufficient (sometimes 10 is sufficient)
- Another is to look at material parameters
  - E.g., if specular material color is (0,0,0), then the object is not reflective, and we don’t need to spawn a reflection ray
  - More systematic: send a weight, w, with recursion
  - Initially w=1, and after each bounce, w*=O.specular_color(); and so on.
  - Will give faster rendering, if we terminate recursion when weight is too small (say <0.01)
- We will return to this issue in future lectures ...

Quick recap: Reflection



$$\mathbf{r} = 2(\mathbf{n}\cdot\mathbf{l})\mathbf{n} - \mathbf{l}$$

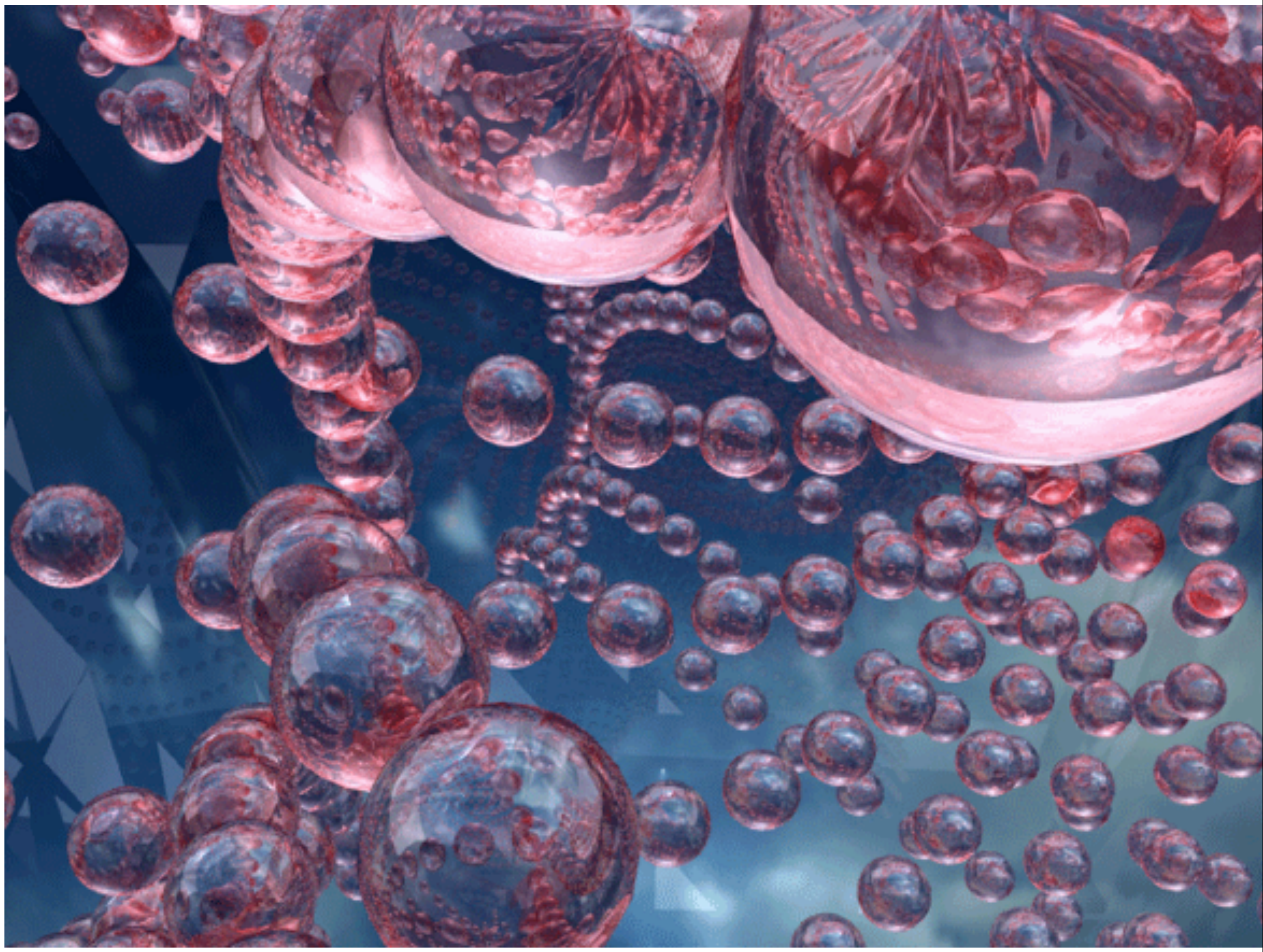
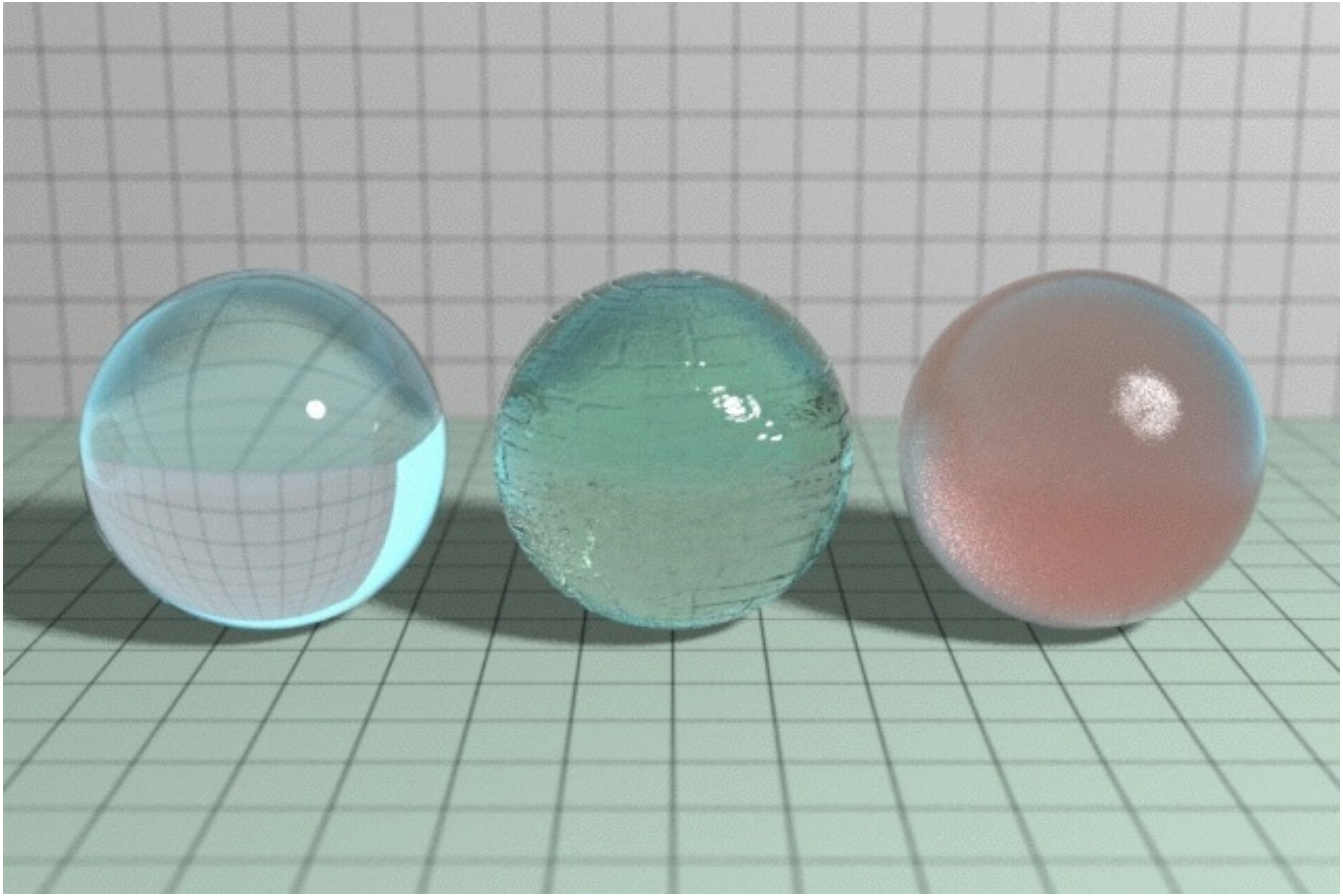


Image courtesy of Illuminate Labs

Refraction

[Image courtesy of *slartybartfast* at ompf.org]

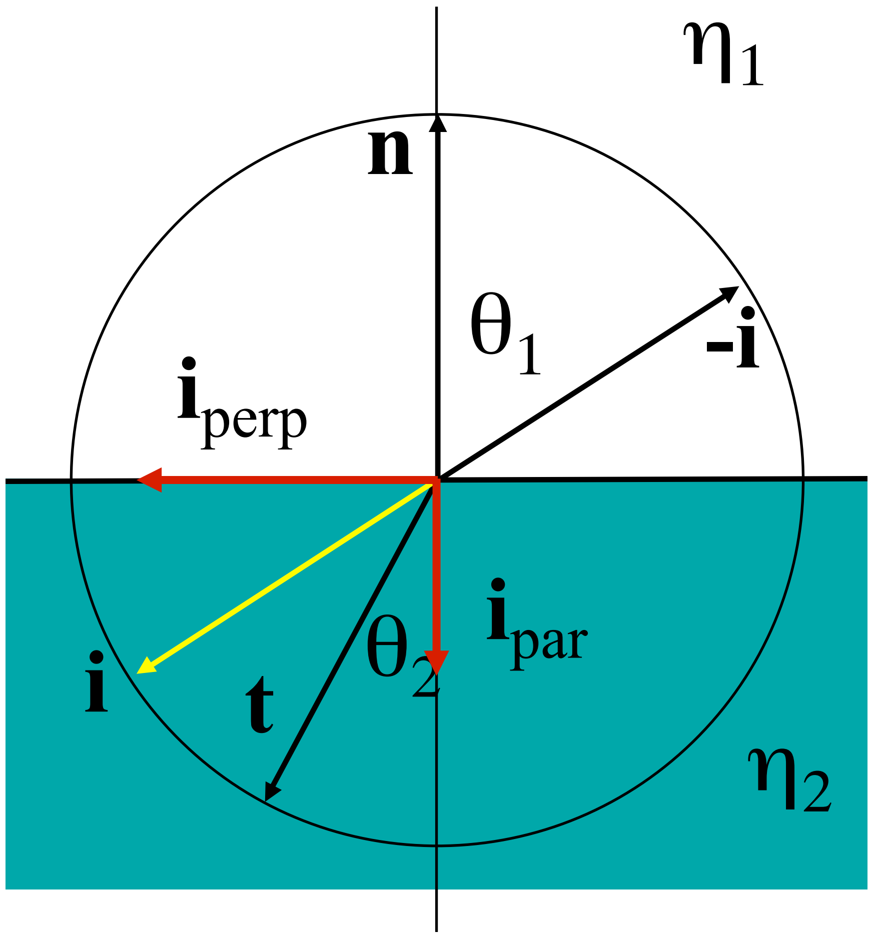


Refraction

[“Glasses” by Gilles Tran 2006]

Refraction: need a transmission vector, t

- **n**, **i**, **t** are unit vectors
- η_1 & η_2 are refraction indices
- $c_1=\cos(\theta_1)=-\mathbf{n}\cdot\mathbf{i}$
- Decompose **i** into:
- $\mathbf{i}_{par}=-c_1\mathbf{n}$, $\mathbf{i}_{perp}=\mathbf{i}+c_1\mathbf{n}$
- $\mathbf{t}=\sin(\theta_2)\mathbf{m} - \cos(\theta_2)\mathbf{n}$, where
- $\mathbf{m}=\mathbf{i}_{perp}/||\mathbf{i}_{perp}||=(\mathbf{i}+c_1\mathbf{n})/\sin(\theta_1)$
- Use Snell's law: $\sin(\theta_2)/\sin(\theta_1)=\eta_1/\eta_2 = \eta$
- $\mathbf{t} = \eta\mathbf{i} + (\eta c_1 - c_2)\,\mathbf{n}$, where $c_2=\cos(\theta_2)$
- Simplify: $c_2=\mathbf{sqrt}[\,1-\eta^2(1-c_1^2)\,]$

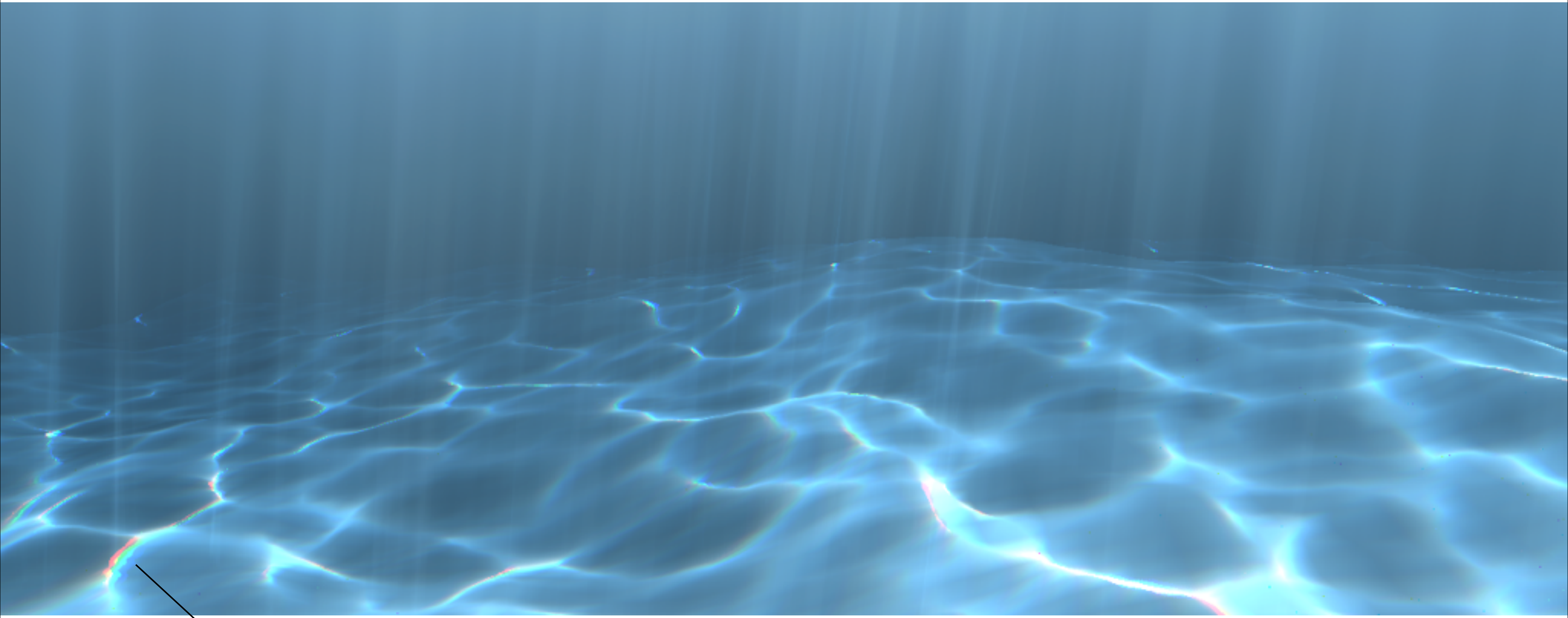


Known as Heckbert's method
see http://www.cs.cmu.edu/~ph/refr.ps.gz

Some refraction indices, η

- Measured with respect to vacuum
  - Air: 1.0003
  - Water: 1.33
  - Glass: around 1.45 – 1.65
  - Diamond: 2.42
  - Salt: 1.54
- Note 1: the refraction index varies with wavelength, but we often only use one index for all three color channels, RGB
  - Or use 3 slightly different → diffraction!
- Note 2: can get Total Internal Reflection (TIR)
  - Means no transmission, only reflection
  - Occurs when c_2 is imaginary (see previous slide)

Diffraction



Diffraction

Next Lecture

- Tomorrow - Sampling and Object intersection
- Reading
  - Textbook : Chapter 1: Getting started, Chapter 3.1 & 3.3 : A Simple Ray Tracer
  - Paper : "An improved illumination model for shaded display", Turner Whitted, CACM June 1980