Course overview

Digital Image Synthesis

Yung-Yu Chuang

with slides by Mario Costa Sousa, Pat Hanrahan and Revi Ramamoorthi

Logistics

- **Meeting time:** 2:20pm-5:20pm, Thursday
- **Classroom:** CSIE Room 111
- **Instructor:** Yung-Yu Chuang (cyy@csie.ntu.edu.tw)
- **TA:** 陳育聖
- **Webpage**:
  http://www.csie.ntu.edu.tw/~cyy/rendering
  id/password
- **Mailing list**: rendering@cmlab.csie.ntu.edu.tw
  Please subscribe via
  https://cmlmail.csie.ntu.edu.tw/mailman/listinfo/rendering/

Prerequisites

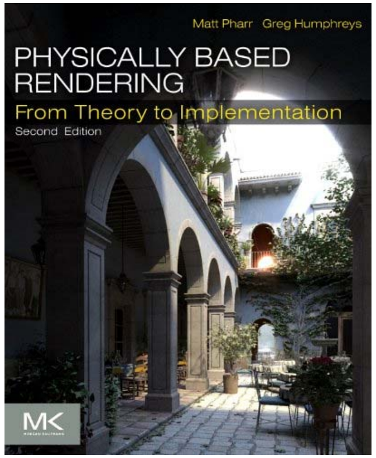
- **C++ programming experience is required**.
- Basic knowledge on algorithm and data structure is essential.
- Knowledge on linear algebra, probability, calculus and numerical methods is a plus.
- Though not required, it is recommended that you have background knowledge on computer graphics.

Requirements (subject to change)

- 3 programming assignments (60%)
- Class participation (5%)
- Final project (35%)

Textbook

[*Physically Based Rendering from Theory to Implementation*](#), 2nd ed, by Matt Pharr and Greg Humphreys



- Authors have a lot of experience on ray tracing
- **Complete (educational) code, more concrete**
- Has been used in many courses and papers
- Implement some advanced or difficult-to-implement methods: subdivision surfaces, Metropolis sampling, BSSRDF, PRT.
- 3rd edition is coming next year!

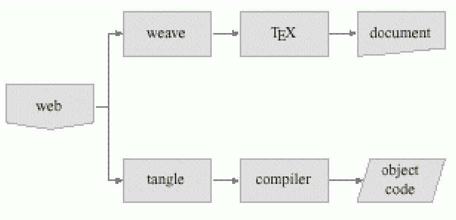
pbrt won Oscar 2014

- To **Matt Pharr, Greg Humphreys** and **Pat Hanrahan** for their formalization and reference implementation of the concepts behind physically based rendering, as shared in their book *Physically Based Rendering.*

Physically based rendering has transformed computer graphics lighting by more accurately simulating materials and lights, allowing digital artists to focus on cinematography rather than the intricacies of rendering. First published in 2004, Physically Based Rendering *is both a textbook and a complete source-code implementation that has provided a widely adopted practical roadmap for most physically based shading and lighting systems used in film production.*

Literate programming

- A programming paradigm proposed by Knuth when he was developing Tex.
- Programs should be written more for people's consumption than for computers' consumption.
- The whole book is a long literate program. That is, when you read the book, you also read the complete program.



Processing a WEB

Features

- Mix prose with source: description of the code is as important as the code itself
- Allow presenting the code to the reader in a different order than to the compiler
- Easy to make index
- Traditional text comments are usually not enough, especially for graphics
- This decomposition lets us present code a few lines at a time, making it easier to understand.
- It looks more like pseudo code.

LP example

```
@\section{Selection Sort: An Example for LP}

We use {\it selection sort} to illustrate the concept of
{it literate programming}.
Selection sort is one of the simplest sorting algorithms.
It first find the smallest element in the array and exchange
it with the element in the first position, then find the
second smallest element and exchange it the element in the
second position, and continue in this way until the entire
array is sorted.
The following code implement the procedure for selection sort
assuming an external array [[a]].

<<*>>=
<<external variables>>
void selection_sort(int n) {
    <<init local variables>>
    for (int i=0; i<n-1; i++) {
        <<find minimum after the ith element>>
        <<swap current and minimum>>
    }
}
```

LP example

```
<<find minimum after the ith element>>=
min=i;
for (int j=i+1; j<n; j++) {
    if (a[j]<a[min]) min=j;
}

<<init local variables>>=
int min;

@ To swap two variables, we need a temporary variable [[t]] which is declared
at the beginning of the procedure.
<<init local variables>>=
int t;

@ Thus, we can use [[t]] to preserve the value of [[a[min]] so that the
swap operation works correctly.
<<swap current and minimum>>=
t=a[min]; a[min]=a[i]; a[i]=t;

<<external variables>>=
int *a;
```

LP example (tangle)

```
int *a;

void selection_sort(int n) {
    int min;

    int t;

    for (int i=0; i<n-1; i++) {
        min=i;
        for (int j=i+1; j<n; j++) {
            if (a[j]<a[min]) min=j;
        }

        t=a[min]; a[min]=a[i]; a[i]=t;

    }
}
```

LP example (weave)

1 Selection Sort: An Example for LP

We use *selection sort* to illustrate the concept of it literate programming. Selection sort is one of the simplest sorting algorithms. It first find the smallest element in the array and exchange it with the element in the first position, then find the second smallest element and exchange it the element in the second position, and continue in this way until the entire array is sorted. The following code implement the procedure for seletion sort assuming an external array a.

1a ⟨* 1a⟩≡

```
⟨external variables 1f⟩
void selection_sort(int n) {
        ⟨init local variables 1c⟩
        for (int i=0; i<n-1; i++) {
                ⟨find minimum after the ith element 1b⟩
                ⟨swap current and minimum 1e⟩
        }
}
```

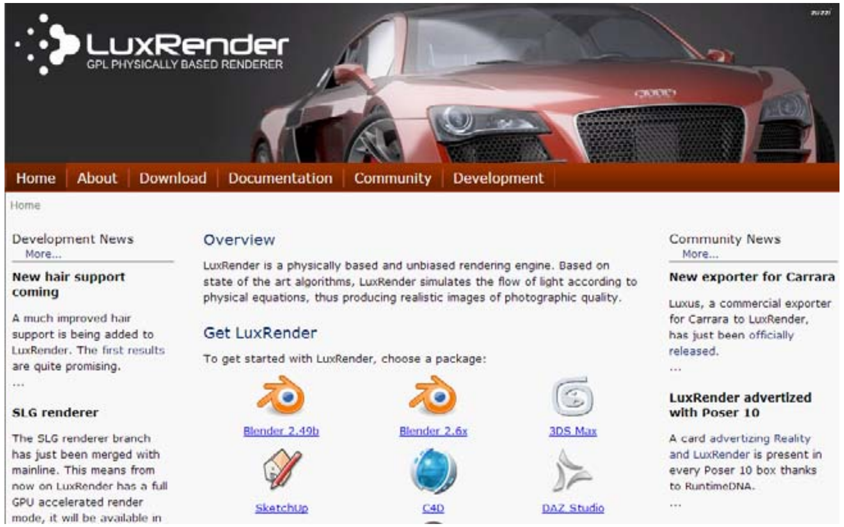
1b ⟨*find minimum after the ith element* 1b⟩≡ (1a)

```
min=i;
for (int j=i+1; j<n; j++) {
        if (a[j]<a[min]) min=j;
}
```

pbrt

- Pbrt is designed to be
  - Complete: includes features found in commercial high-quality renderers.
  - Illustrative: select and implement elegant methods.
  - Physically based
- Efficiency was given a lower priority (the unofficial fork luxrender could be more efficient)
- Source code browser

LuxRender (http://www.luxrender.net)



Mitsuba (http://www.mitsuba-renderer.org/)

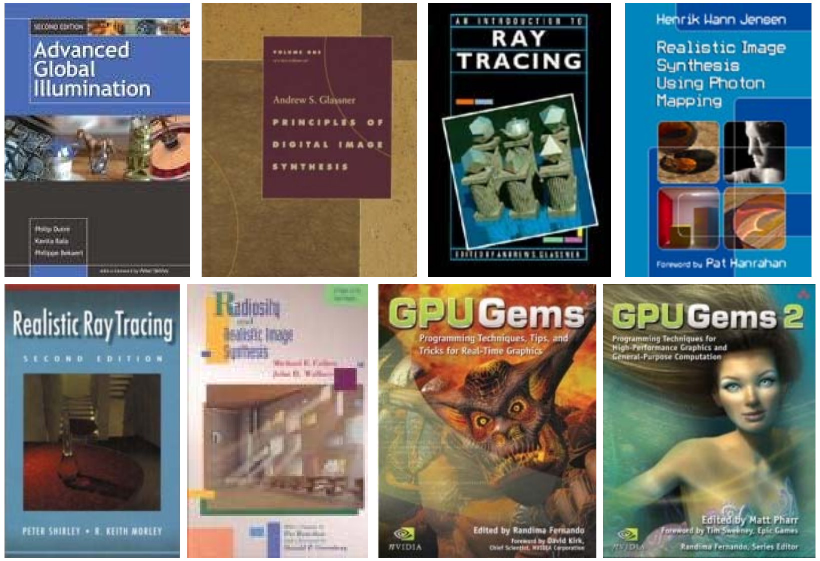
New features of pbrt2

- Remove plug-in architecture, but still an *extensible* architecture
- Add multi-thread support (automatic or --ncores)
- OpenEXR is recommended, not required
- HBV is added and becomes default
- Can be full spectral, do it at compile time
- Animation is supported
- Instant global illumination, extended photon map, extended infinite light source
- Improved irradiance cache

New features of pbrt2

- BSSRDF is added
- Metropolis light transport
- Precomputed radiance transfer
- Support measured BRDF

Reference books



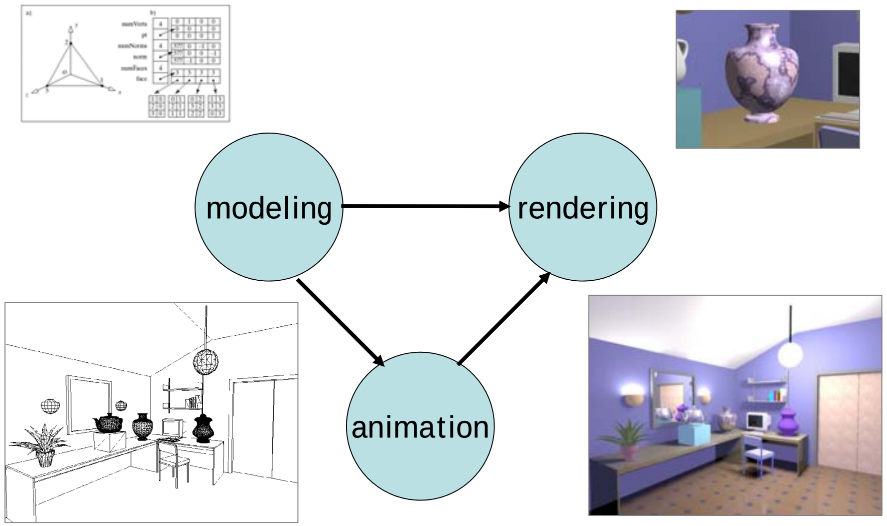
References

- SIGGRAPH proceedings
- SIGGRAPH Asia proceedings
- Proceedings of Eurographics Symposium on Rendering
- Eurographics proceedings
- Most can be found at this link.

Image synthesis (Rendering)

- Create a 2D picture of a 3D world

Computer graphics



Physically-based rendering

uses physics to simulate the interaction between matter and light, realism is the primary goal

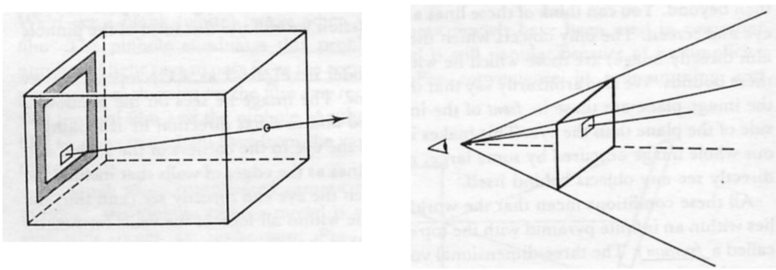
Realism

- Shadows
- Reflections (Mirrors)
- Transparency
- Interreflections
- Detail (Textures…)
- Complex Illumination
- Realistic Materials
- And many more

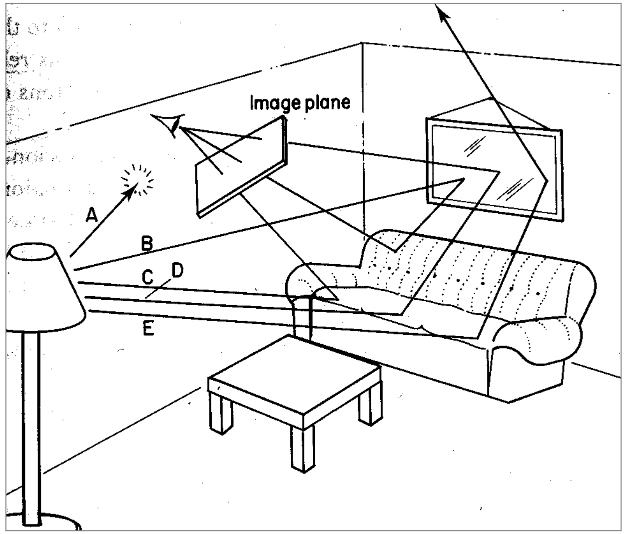
Other types of rendering

- Non-photorealistic rendering
- Image-based rendering
- Point-based rendering
- Volume rendering
- Perceptual-based rendering
- Artistic rendering

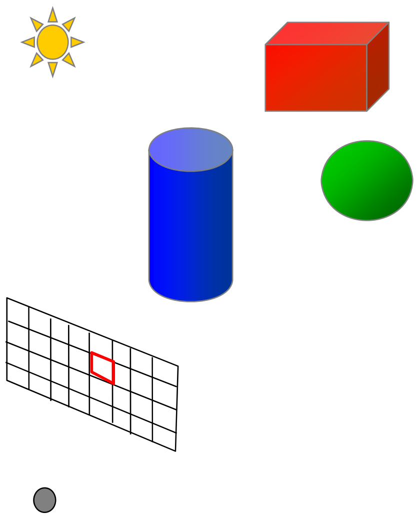
Pinhole camera



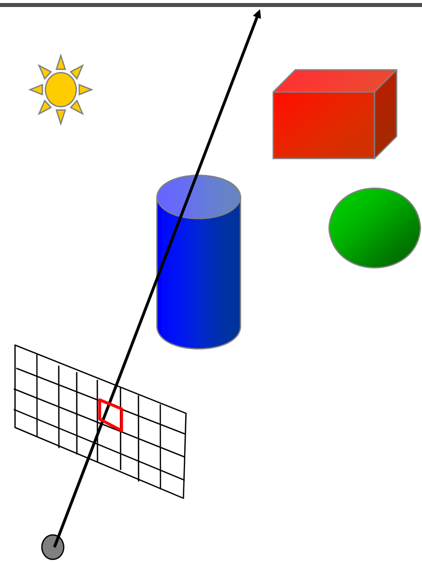
Introduction to ray tracing



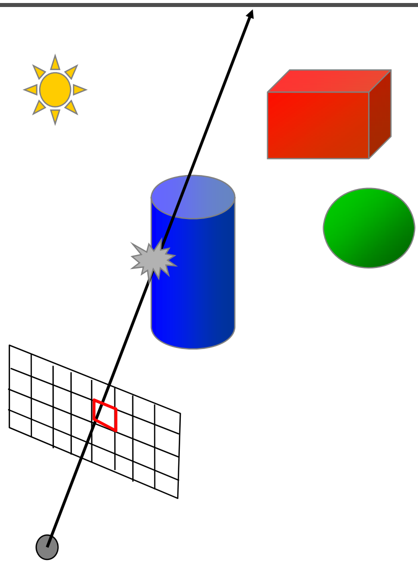
Ray Casting (Appel, 1968)



Ray Casting (Appel, 1968)

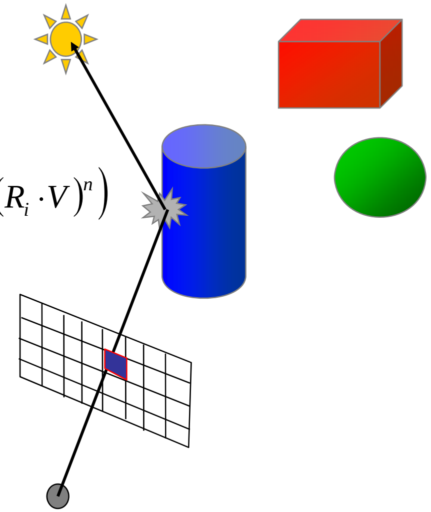


Ray Casting (Appel, 1968)

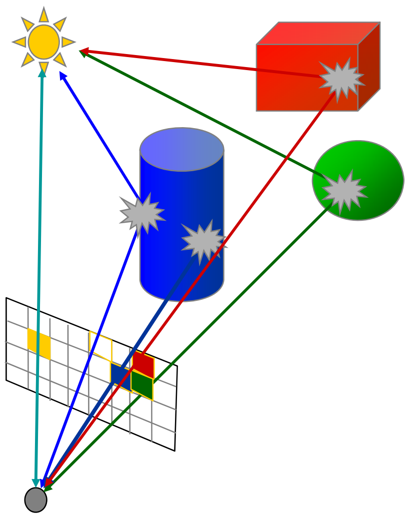


Ray Casting (Appel, 1968)

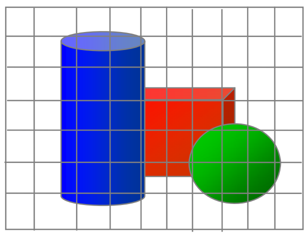
$$k_a I_a + \sum_{i=1}^{nls} I_i \left(k_d \left(L_i \cdot N \right) + k_s \left(R_i \cdot V \right)^n \right)$$



Ray Casting (Appel, 1968)

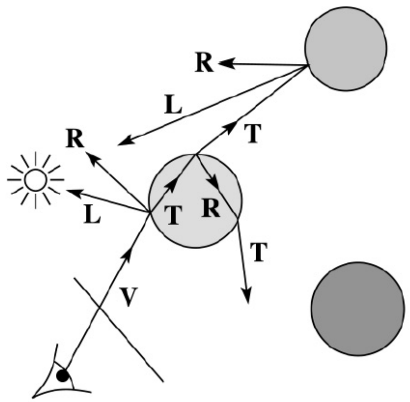


direct illumination



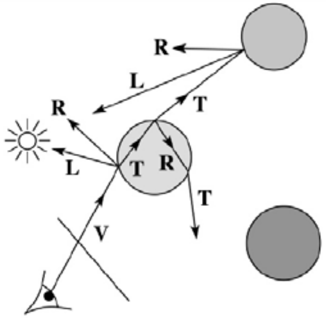
Whitted ray tracing algorithm

- Combines eye ray tracing + rays to light
- Recursively traces rays



Whitted ray tracing algorithm

1. For each pixel, trace a **primary ray** in direction **V** to the first visible surface.
2. For each intersection, trace **secondary rays**:
   - **Shadow rays** in directions $\mathbf{L}_i$ to light sources
   - **Reflected ray** in direction **R**.
   - **Refracted ray** or **transmitted ray** in direction **T**.



Shading

If $I(P_0, \mathbf{u})$ is the intensity seen from point P along direction **u**

$$I(P_0, \mathbf{u}) = I_{direct} + I_{reflected} + I_{transmitted}$$

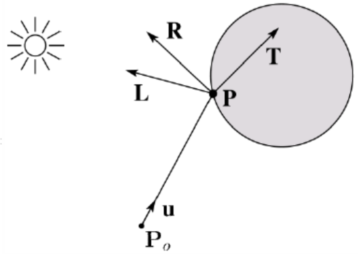
where

I_{direct} = Shade(**N**, **L**, **u**, **R**) (e.g. Phong shading model)

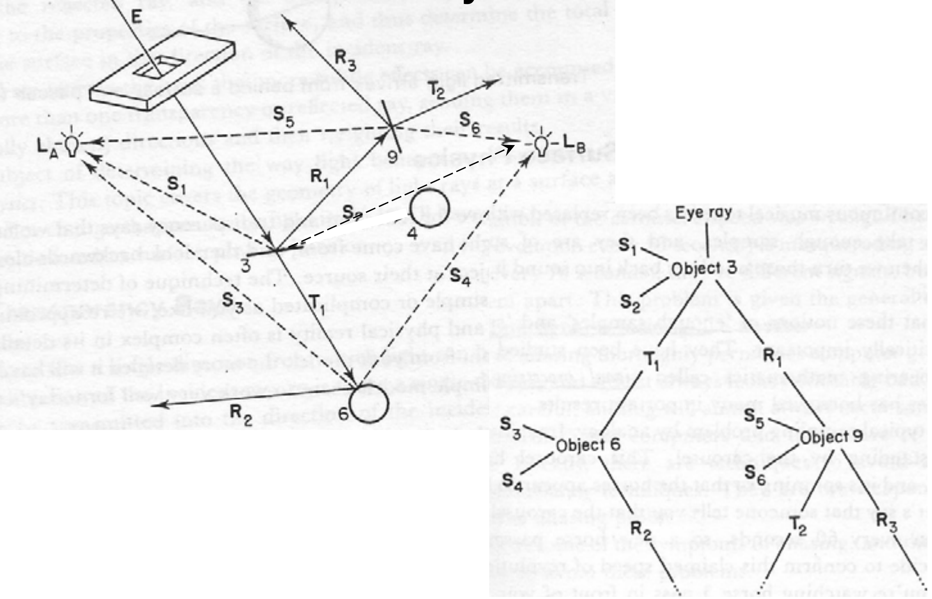
$$I_{reflected} = k_r I(P, \mathbf{R})$$

$$I_{transmitted} = k_t I(P, \mathbf{T})$$

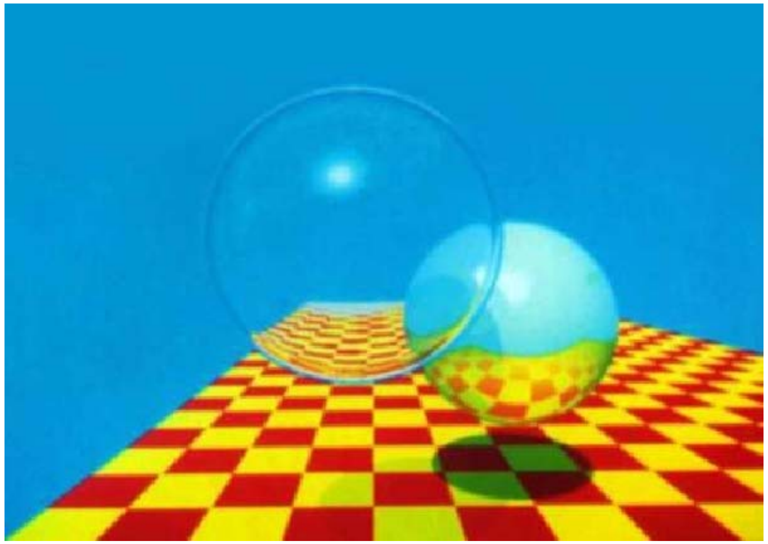
Typically, we set $k_r = k_s$ and k_t



Ray tree



Recursive ray tracing (Whitted, 1980)



Components of a ray tracer

- Cameras
- Films
- Lights
- Ray-object intersection
- Visibility
- Surface scattering
- Recursive ray tracing

Minimal ray tracer

- Minimal ray tracer contest on *comp.graphics*, 1987
- Write the shortest Whitted-style ray tracer in C with the minimum number of tokens. The scene is consisted of spheres. (specular reflection and refraction, shadows)
- Winner: 916 tokens
- Cheater: 66 tokens (hide source in a string)
- Almost all entries have six modules: main, trace, intersect-sphere, vector-normalize, vector-add, dot-product.

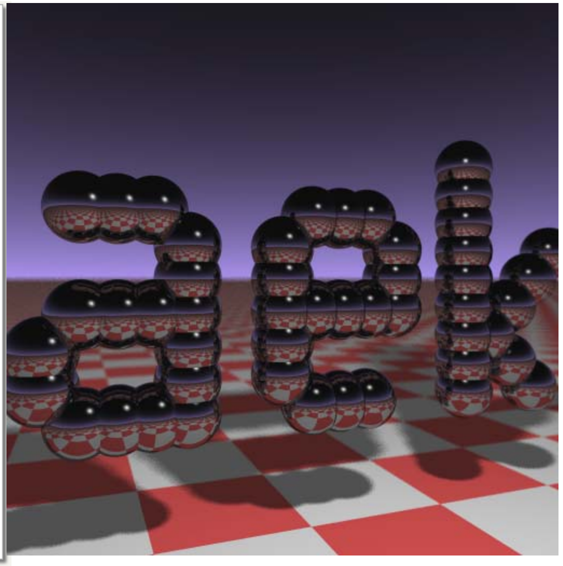
Minimal ray tracer (Heckbert 1994)

```
typedef struct{double x,y,z}vec;vec U,black,amb={.02,.02,.02};struct sphere{ vec cen,color;
double rad,kd,ks,kt,kl,ir}*s,*best,sph[]={0.,6.,.5,1.,1.,1.,.9, .05,.2,.85,0.,1.7,-1.,8.,-.5,1.,.5,.2,1.,
.7,.3,0.,.05,1.2,1.,8.,-.5,.1,.8,.8, 1.,.3,.7,0.,0.,1.2,3.,-6.,15.,1.,.8,1.,7.,0.,0.,0.,.6,1.5,-3.,-3.,12.,
.8,1., 1.,5.,0.,0.,0.,.5,1.5,};yx;double u,b,tmin,sqrt(),tan();double vdot(A,B)vec A ,B;{return A.x
*B.x+A.y*B.y+A.z*B.z;}vec vcomb(a,A,B)double a;vec A,B;{B.x+=a* A.x;B.y+=a*A.y;B.z+=a*A.z;
return B;}vec vunit(A)vec A;{return vcomb(1./sqrt( vdot(A,A)),A,black);}struct sphere*intersect
(P,D)vec P,D;{best=0;tmin=1e30;s= sph+5;while(s-->sph)b=vdot(D,U=vcomb(-1.,P,s->cen)),
u=b*b-vdot(U,U)+s->rad*s ->rad,u=u>0?sqrt(u):1e31,u=b-u>1e-7?b-u:b+u,tmin=u>=1e-7&&
u<tmin?best=s,u: tmin;return best;}vec trace(level,P,D)vec P,D;{double d,eta,e;vec N,color;
struct sphere*s,*l;if(!level--)return black;if(s=intersect(P,D));else return amb;color=amb;eta=
s->ir;d= -vdot(D,N=vunit(vcomb(-1.,P=vcomb(tmin,D,P),s->cen )));if(d<0)N=vcomb(-1.,N,black),
eta=1/eta,d= -d;l=sph+5;while(l-->sph)if((e=l ->kl*vdot(N,U=vunit(vcomb(-1.,P,l->cen))))>0&&
intersect(P,U)==l)color=vcomb(e ,l->color,color);U=s->color;color.x*=U.x;color.y*=U.y;color.z
*=U.z;e=1-eta* eta*(1-d*d);return vcomb(s->kt,e>0?trace(level,P,vcomb(eta,D,vcomb(eta*d-
sqrt (e),N,black))):black,vcomb(s->ks,trace(level,P,vcomb(2*d,N,D)),vcomb(s->kd, color,vcomb
(s->kl,U,black))));}main(){printf("%d %d\n",32,32);while(yx<32*32) U.x=yx%32-32/2,U.z=32/2-
yx++/32,U.y=32/2/tan(25/114.5915590261),U=vcomb(255., trace(3,black,vunit(U)),black),printf
("%.0f %.0f %.0f\n",U);}/*minray!*/
```

What it can do

Another business card raytracer

```
#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,
249748,18578,18577,231184,16,16};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);}}
```



That's it?

- In this course, we will study how state-of-art ray tracers work.

Issues

- Better Lighting + Forward Tracing
- Texture Mapping
- Sampling
- Modeling
- Materials
- Motion Blur, Depth of Field, Blurry Reflection/Refraction
  - *Distributed Ray-Tracing*
- Improving Image Quality
- Acceleration Techniques (better structure, faster convergence)

Disney's Practical Guide to Path Tracing

Really Practical Guide to Path Tracing

$$L_o(\mathrm{p},\omega_\mathrm{o}) = L_e(\mathrm{p},\omega_\mathrm{o}) + \int_{S^2} f(\mathrm{p},\omega_\mathrm{o},\omega_\mathrm{i}) L_i(\mathrm{p},\omega_\mathrm{i}) \left|\cos\theta_\mathrm{i}\right| \, d\omega_\mathrm{i}$$

Complex lighting

Complex lighting

Refraction/dispersion

Caustics

Realistic materials

Translucent objects

Texture and complex materials

Even more complex materials

Complex material (luxrender)

Depth of field (luxrender)

Motion blur (luxrender)

Refraction (Luxrender)

Applications

- Movies
- Interactive entertainment
- Industrial design
- Architecture
- Culture heritage

IKEA

- Today (2014), around 60-75% of all IKEA's product (single product) images are CG. About 35% of all IKEA Communication's non-product images are fully CG.

IKEA

- They use 3DStudio Max and V-Ray.

Animation production pipeline


story

text treatment


storyboard


voice


storyreal


look and feel

Animation production pipeline


modeling/articulation


layout

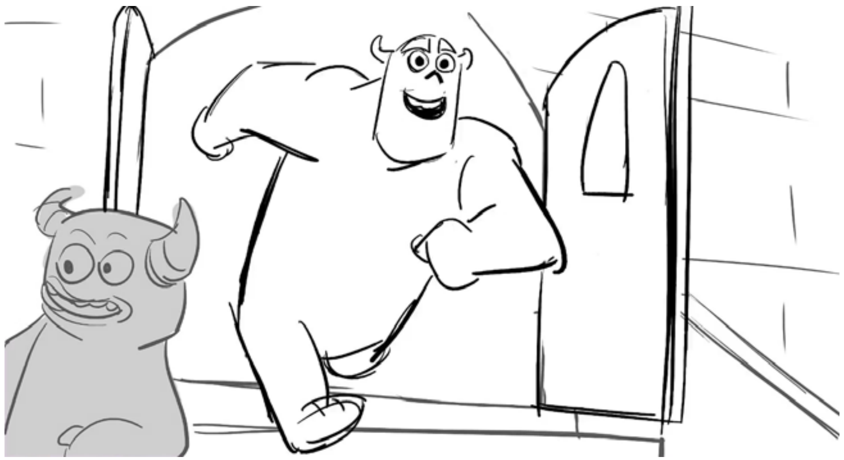

animation


shading/lighting


rendering


final touch

Monster University Progression



Pixar in a Box

Ray tracing finally catches up

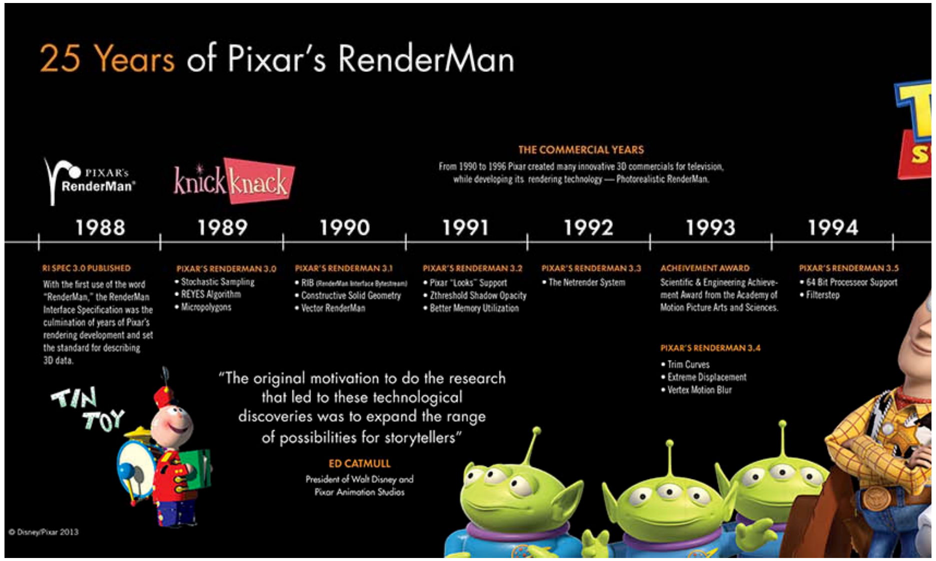
Arnold renderer

Manuka (Weta digital)

http://www.fxguide.com/featured/manuka-weta-digitals-new-renderer/

Hyperion (Disney)

Pixar Renderman Timeline



Monster University

The blue umbrella

Homework #0

- Download and install pbrt2.
- Run several examples
- Set it up in a debugger environment so that you can trace the code
- Optionally, create your own scene