Course overview

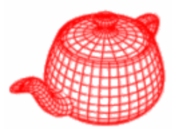
Digital Image Synthesis

Yung-Yu Chuang

9/21/2006

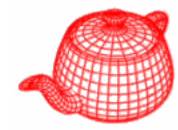
with slides by Mario Costa Sousa, Pat Hanrahan and Revi Ramamoorthi

Logistics



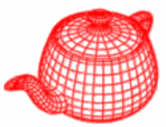
- **Meeting time**: 1:30pm-4:20pm, Thursday
- **Classroom**: CSIE Room 111
- **Instructor**: Yung-Yu Chuang (cyy@csie.ntu.edu.tw)
- **TA**: Shan-Yung Yang
- **Webpage**:
  http://www.csie.ntu.edu.tw/~cyy/rendering
  id/password
- **Forum**:
  http://www.cmlab.csie.ntu.edu.tw/~cyy/forum/viewforum.php?f=8
- **Mailing list**: rendering@cmlab.csie.ntu.edu.tw
  Please subscribe via
  https://cmlmail.csie.ntu.edu.tw/mailman/listinfo/rendering/

Prerequisites



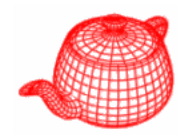
- C++ program experience is required.
- Basic knowledge on algorithm and data structure is essential.
- Knowledge on linear algebra, probability and compilers is a plus.
- Though not required, it is recommended that you have background knowledge on computer graphics.

Requirements (subject to change)



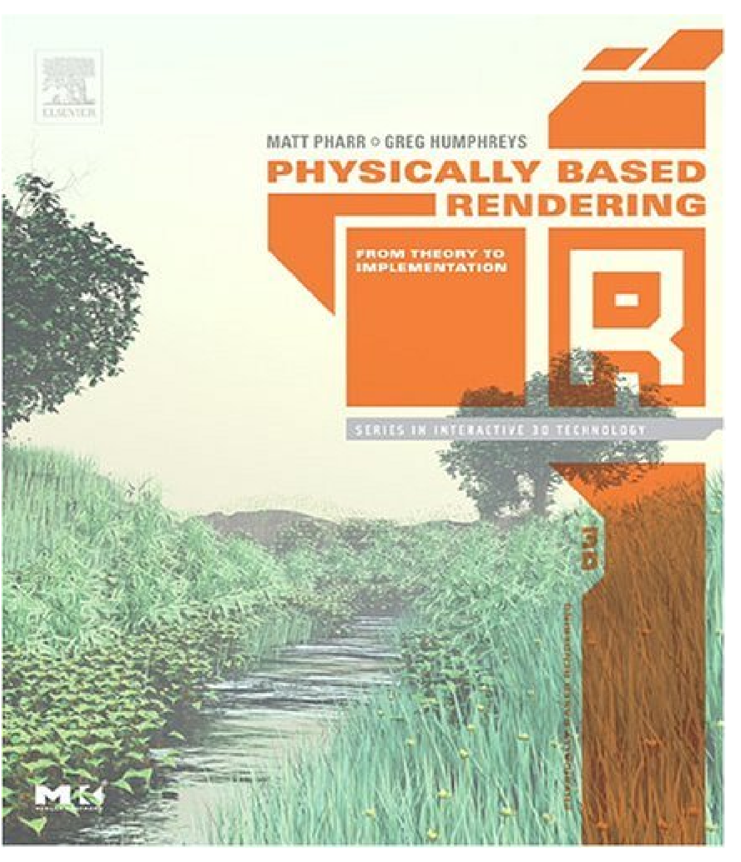
- 2 programming assignments (40%)
- Presentation (15%) (course will alternate between lectures and paper presentations)
- Class participation (5%)
- Final project (40%)

Textbook



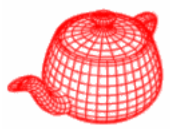
Physically Based Rendering from Theory to Implementation,

by Matt Pharr and Greg Humphreys

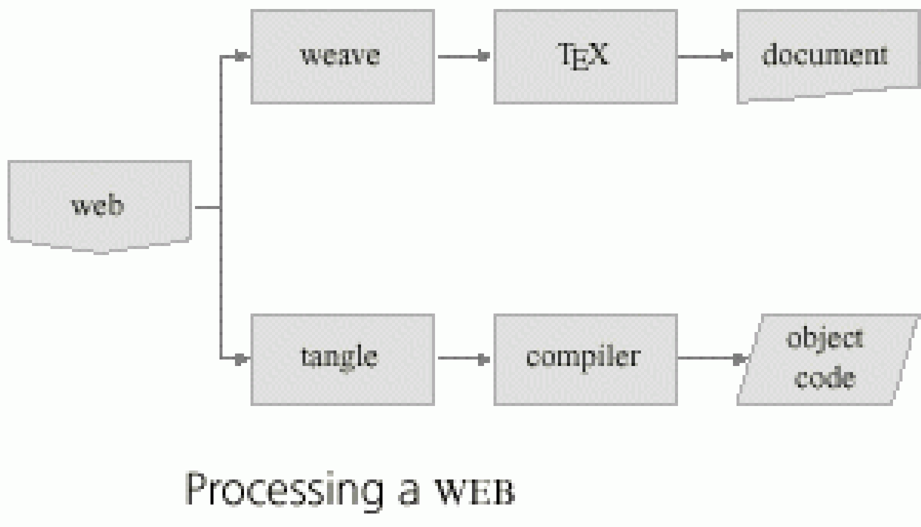


- Authors have a lot of experience on ray tracing
- Complete (educational) code, more concrete
- Plug-in architecture, easy for experiments and extension
- Has been used in some papers

Literate programming

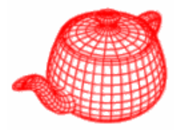


- A programming paradigm proposed by Knuth when he was developing Tex.
- Programs should be written more for people's consumption than for computers' consumption.
- The whole book is a long literate program. That is, when you read the book, you also read a complete program.



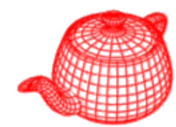
Processing a WEB

Features



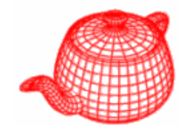
- Mix prose with source: description of the code is as important as the code itself
- Allow presenting the code to the reader in a different order than to the compiler
- Easy to make index
- Traditional text comments are usually not enough, especially for graphics
- This decomposition lets us present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

LP example



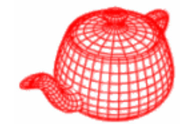
```
@\section{Selection Sort: An Example for LP}

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



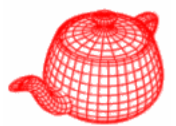
```
<<find minimum after the ith element>>=
min=i;
for (int j=i+1; j<n; j++) {
    if (a[j]<a[min]) min=j;
}

<<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 continute in this way until the entire array is sorted. The following code implement the procedure for seletion sort assuming an external array `a`.

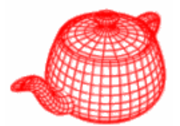
1a ⟨* 1a⟩≡

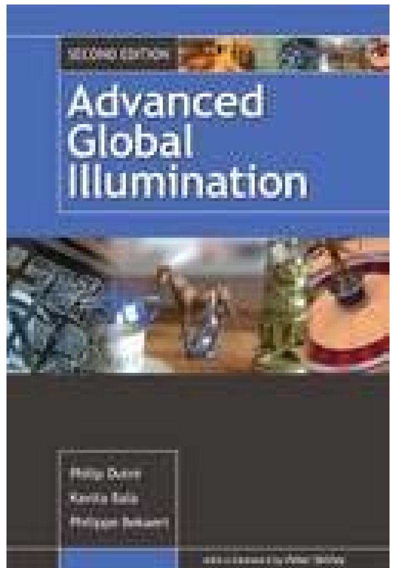
```
⟨external variables 1f⟩
void selection_sort(int n) {
        ⟨init local variables 1c⟩
        for (int i=0; i<n-1; i++) {
                ⟨find minimum after the ith element 1b⟩
                ⟨swap current and minimum 1e⟩
        }
}
```

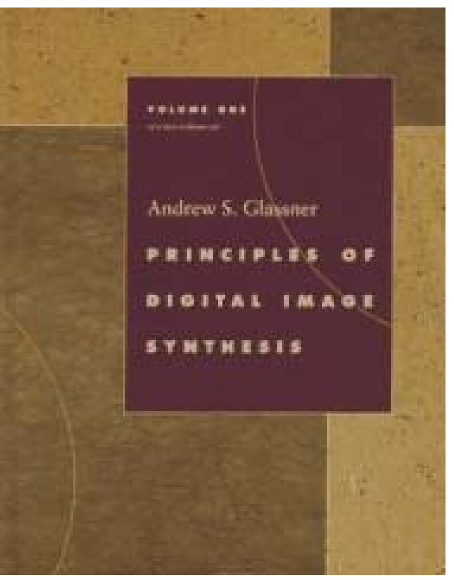
1b ⟨*find minimum after the ith element* 1b⟩≡ (1a)

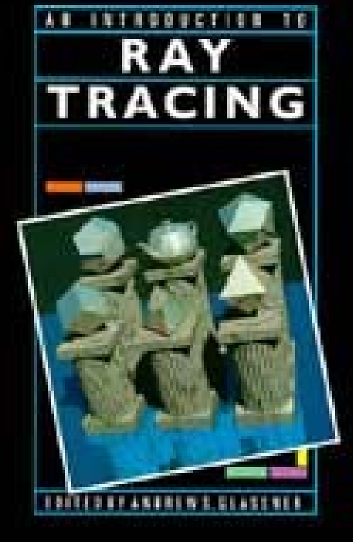
```
min=i;
for (int j=i+1; j<n; j++) {
        if (a[j]<a[min]) min=j;
}
```

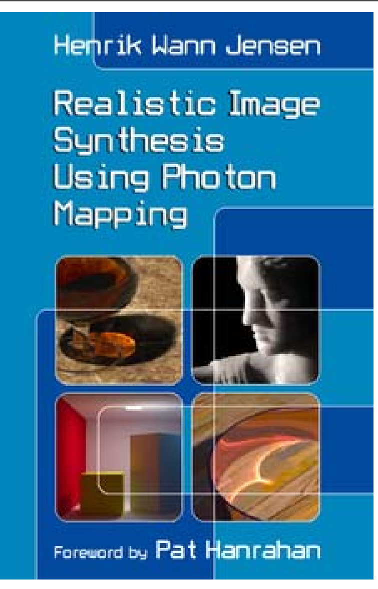
Reference books

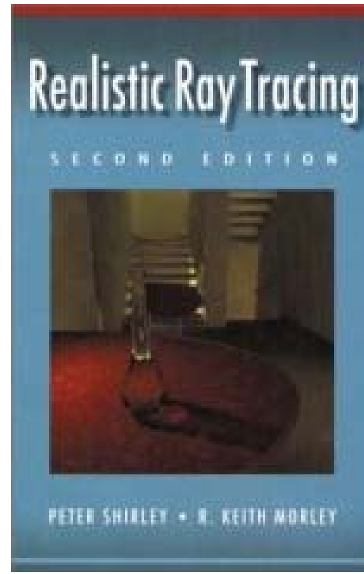


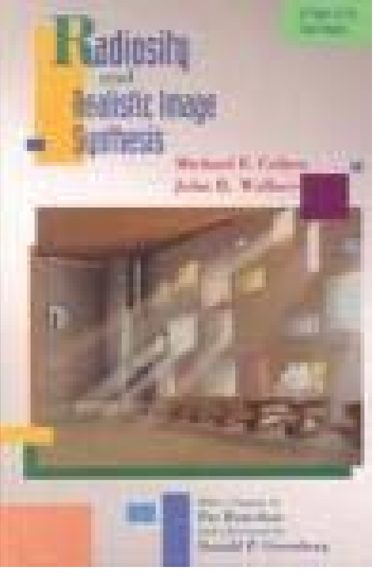


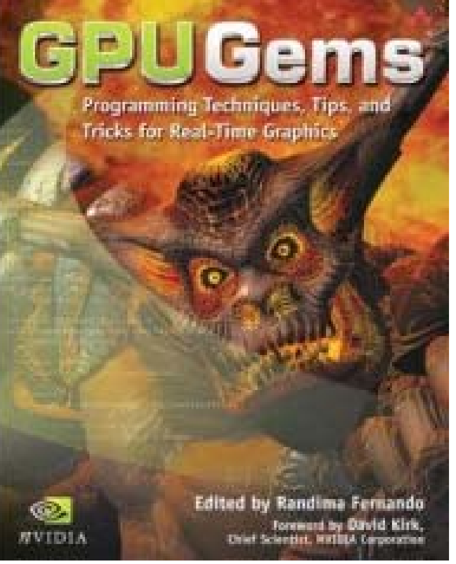


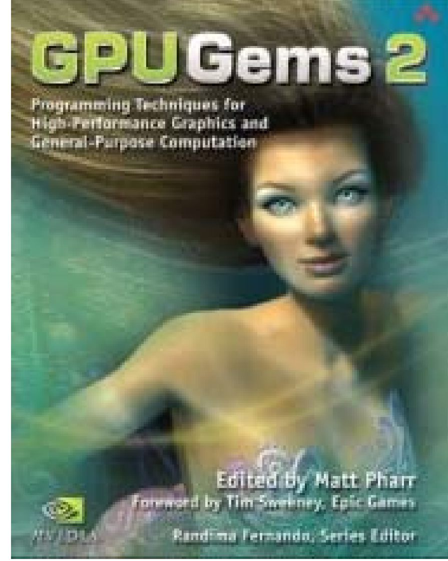




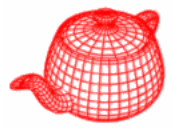






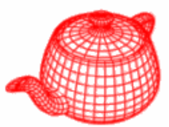


Reference



- SIGGRAPH proceedings
- Proceedings of Eurographics Symposium on Rendering
- Eurographics proceedings

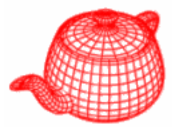
Image synthesis (Rendering)



- Create a 2D picture of a 3D world

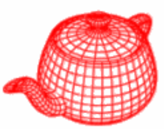
The Kitchen - Jaime Vives Piqueres - POVCOMP 2004

Applications



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

Animation production pipeline



story

text treatment

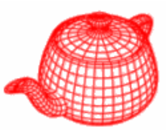
storyboard

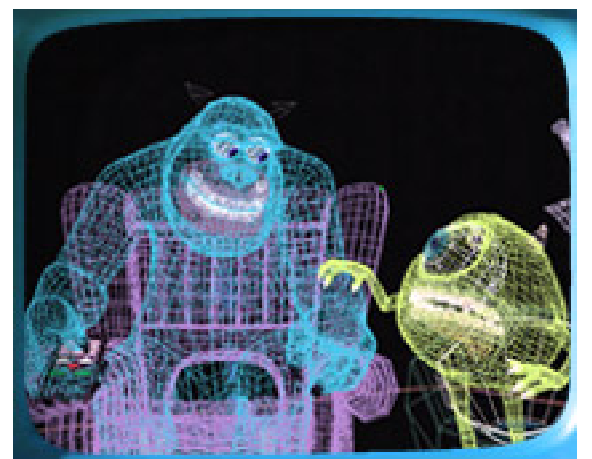
voice

storyreal

look and feel

Animation production pipeline





modeling/articulation

layout

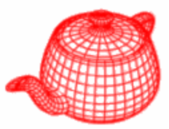
animation

shading/lighting

rendering

final touch

Computer graphics

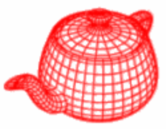


modeling

rendering

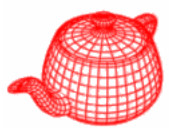
animation

The goal of this course



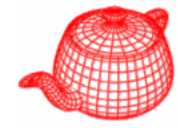
- Realistic rendering
- First part: physically based rendering
- Second part: real-time high quality rendering

Physically-based rendering

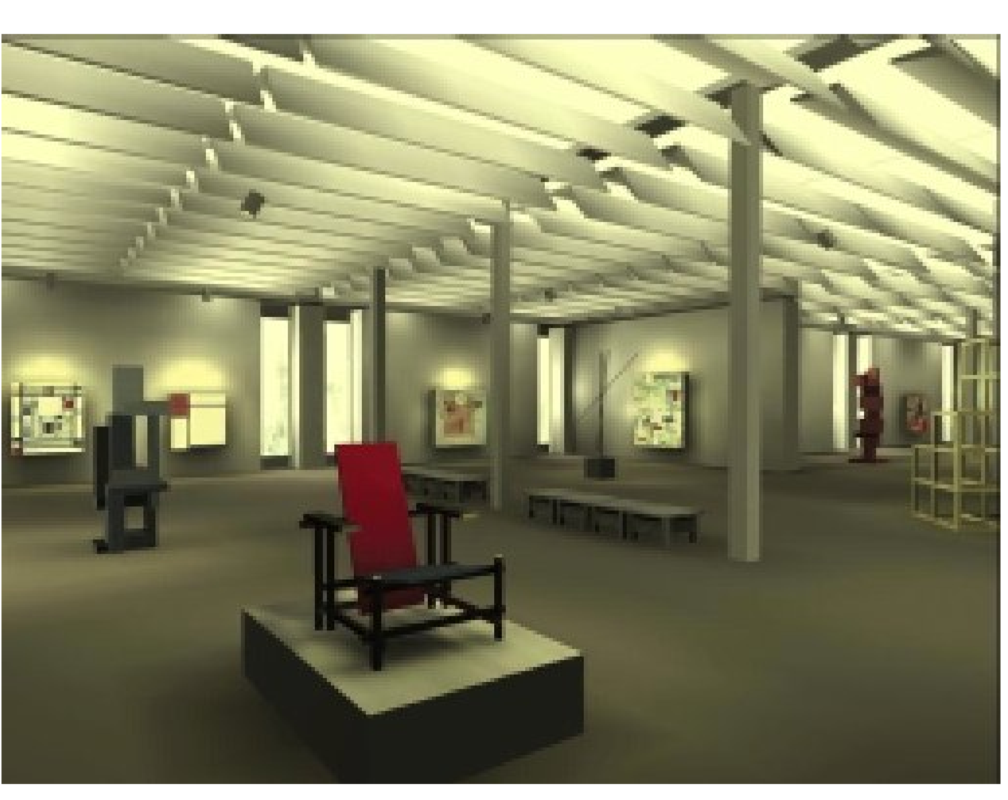


uses physics to simulate the interaction between matter and light, realism is the primary goal

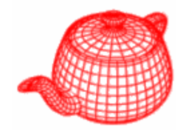
Realism



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

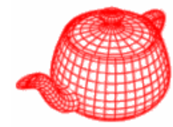


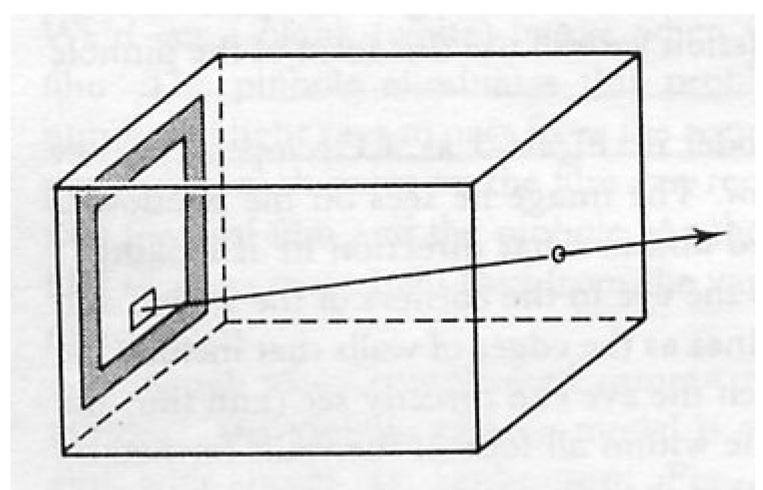
Other types of rendering

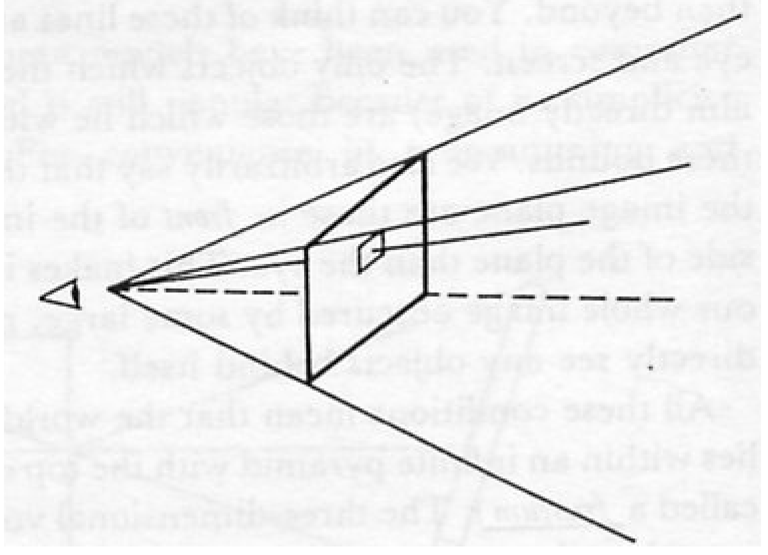


- Non-photorealistic rendering
- Image-based rendering
- Point-based rendering
- Volume rendering
- Perceptual-based rendering
- Artistic rendering

Pinhole camera







Introduction to ray tracing

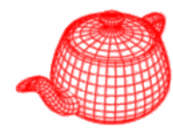


Image plane

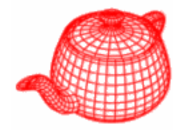
A

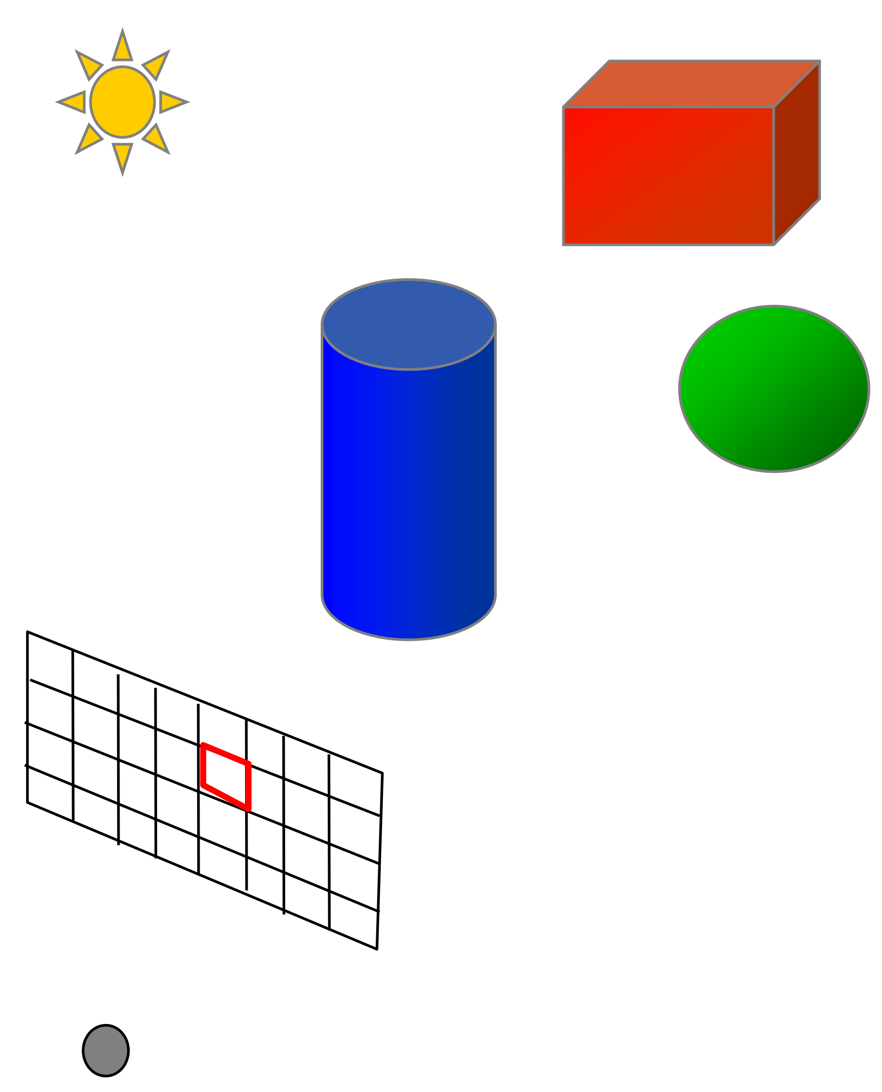
B

C D

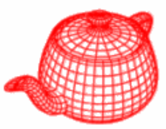
E

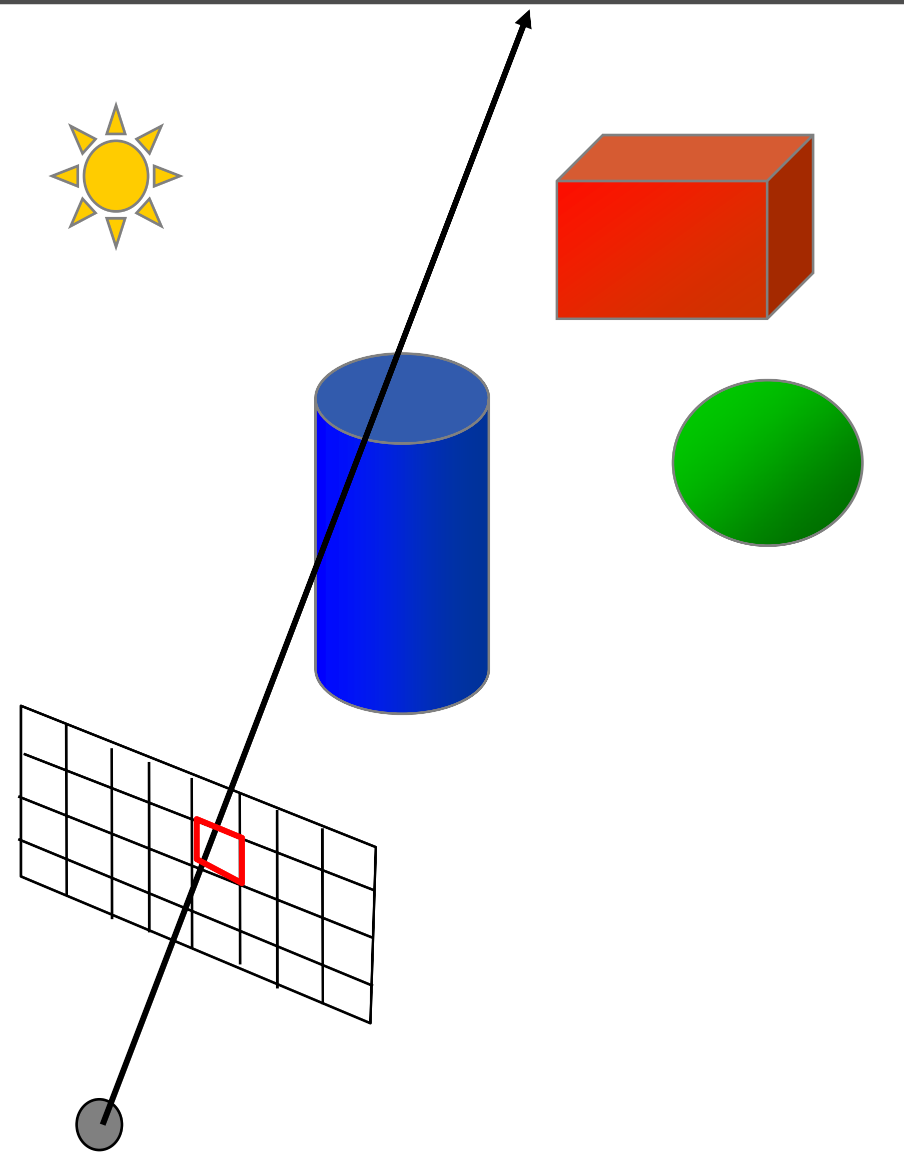
Ray Casting (Appel, 1968)



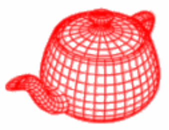


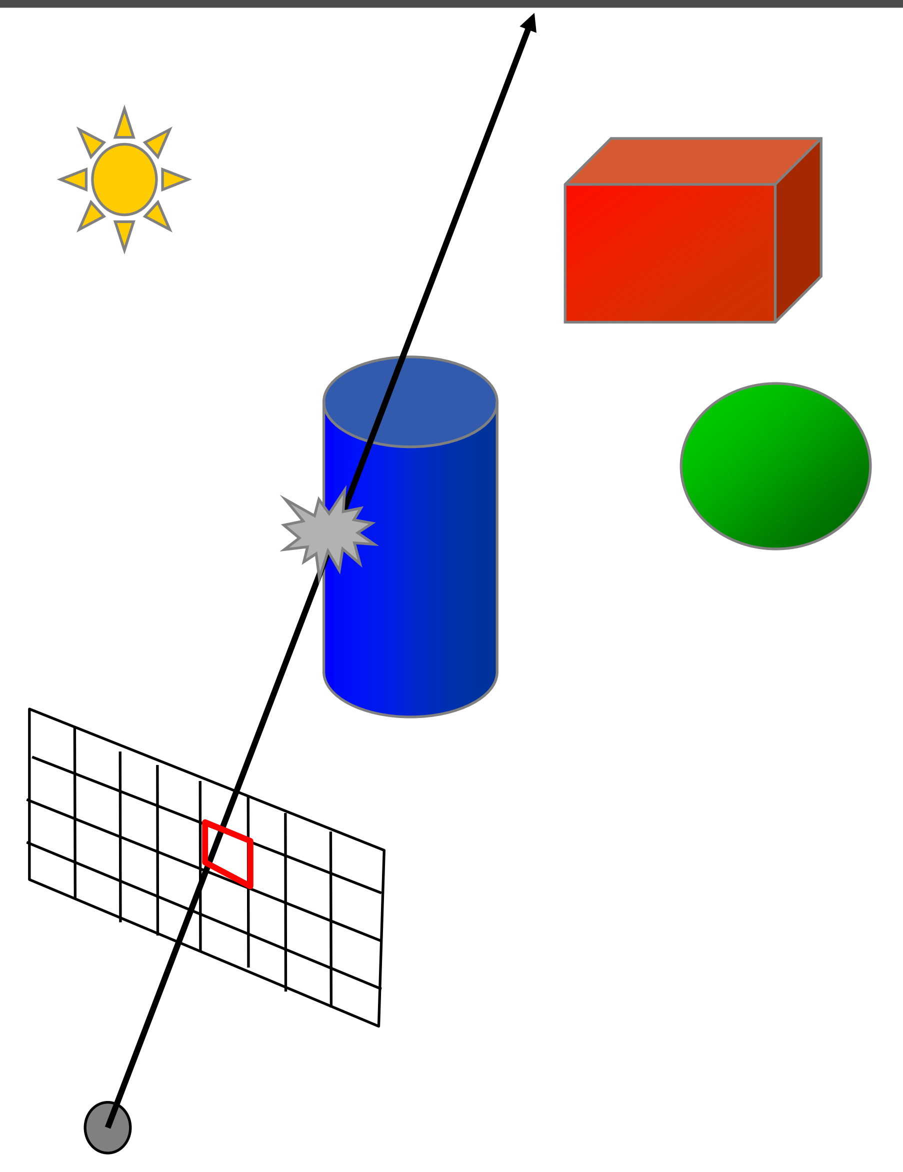
Ray Casting (Appel, 1968)



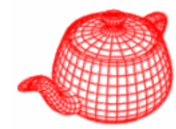


Ray Casting (Appel, 1968)



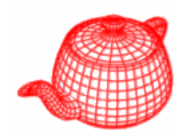


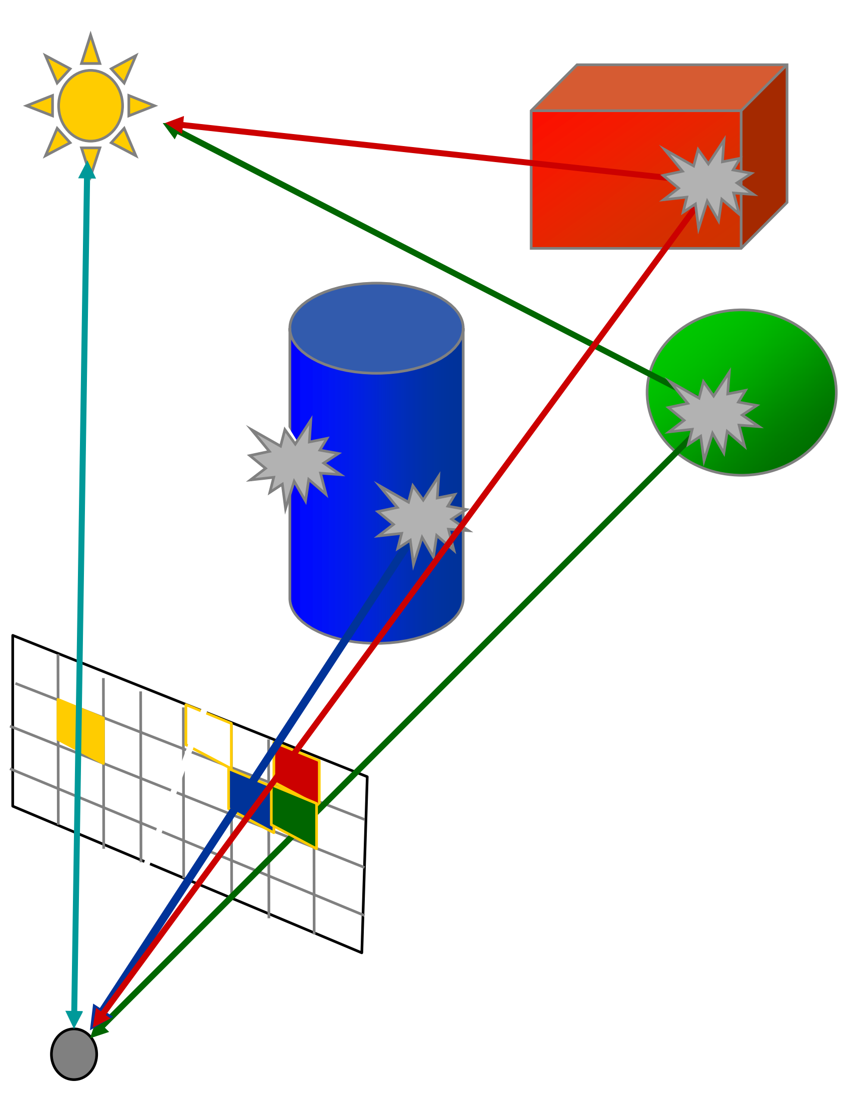
Ray Casting (Appel, 1968)



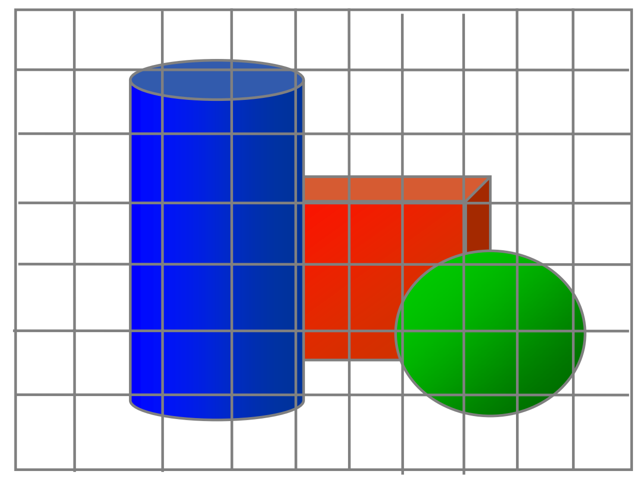
$$k_a I_a + \sum_{i=1}^{nls} I_i \left(k_d \left(L_i \cdot N \right) + k_s \left(R_i \cdot V \right)^n \right)$$

Ray Casting (Appel, 1968)

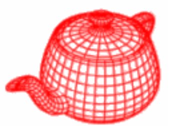




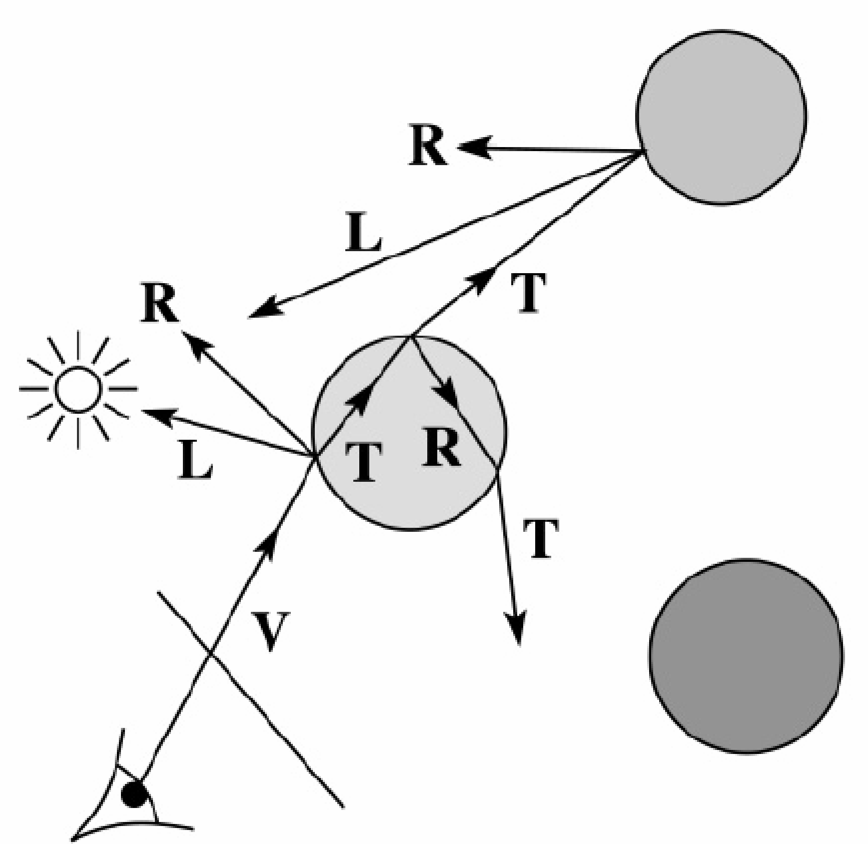
direct illumination



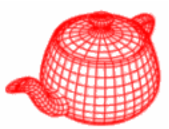
Whitted ray tracing algorithm



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

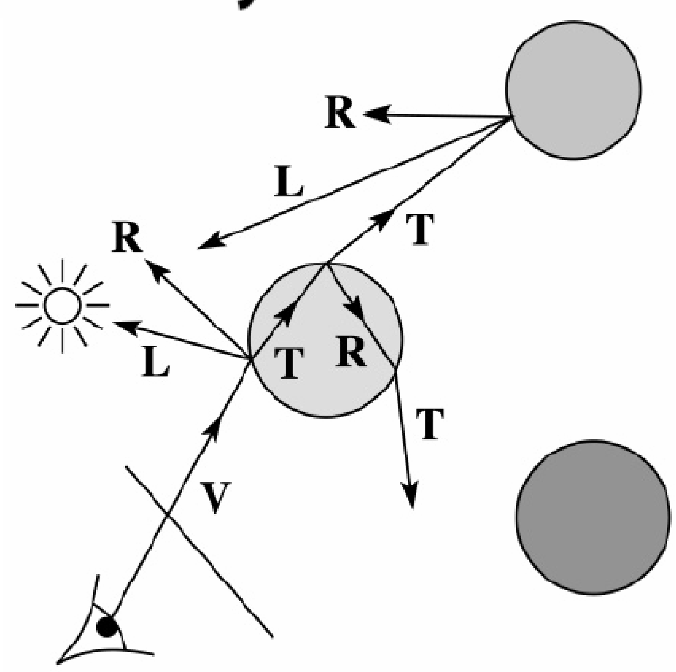


Whitted ray tracing algorithm

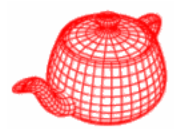


1. For each pixel, trace a **primary ray** in direction **V** to the first visible surface.

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 $\mathbf{u}$

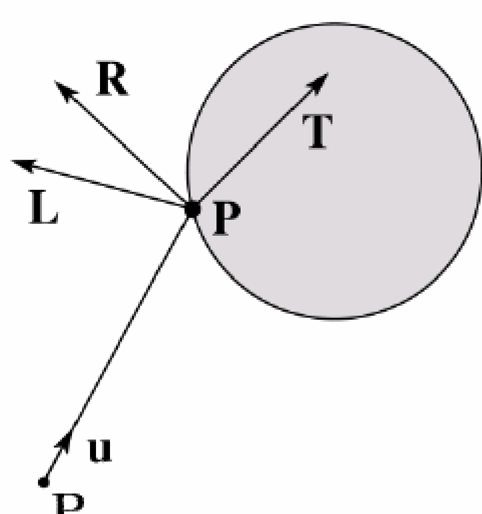
$$I(P_0, \mathbf{u}) = I_{direct} + I_{reflected} + I_{transmitted}$$

where

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

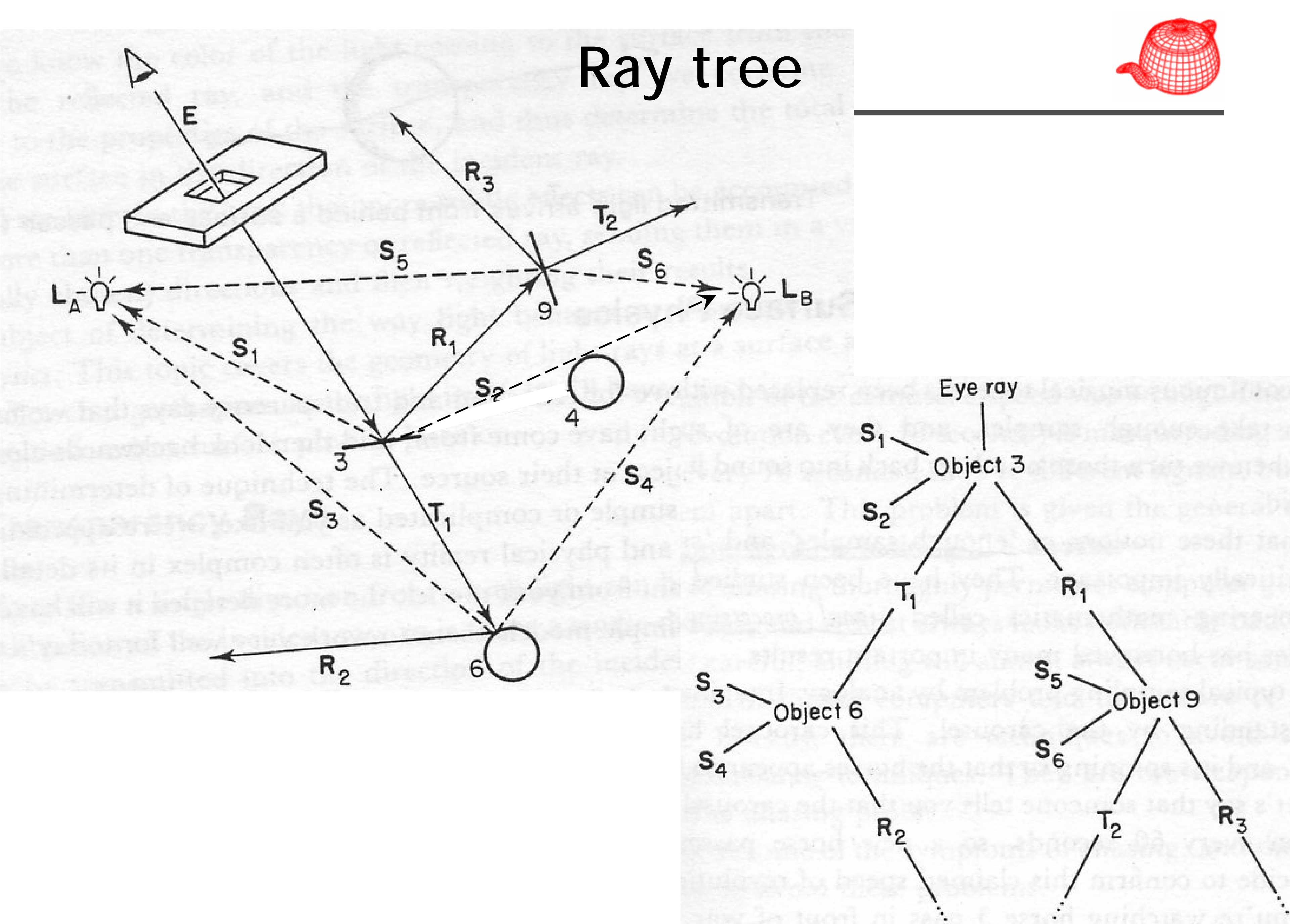
$$I_{reflected} = k_r I(P, \mathbf{R})$$

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

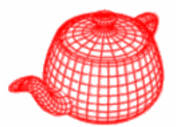


Typically, we set $k_r = k_s$ and k_t

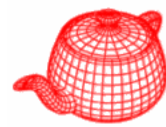
Ray tree



Recursive ray tracing (Whitted, 1980)

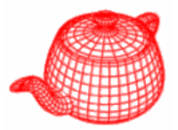


Components of a ray tracer



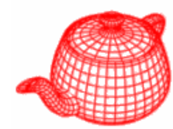
- Cameras
- Films
- Lights
- Ray-object intersection
- Visibility
- Surface scattering
- Recursive ray tracing

Minimal ray tracer



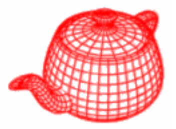
- Minimal ray tracer contest on *comp.graphics*, 1987
- Write the shortest Whitted-style ray tracer in C with the minimum number of tokens. The scene is consisted of spheres. (specular reflection and refraction, shadows)
- Winner: 916 tokens
- Cheater: 66 tokens (hide source in a string)
- Almost all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

Minimal ray tracer (Heckbert 1994)



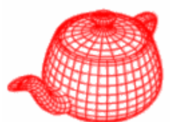
```
typedef struct{double x,y,z}vec;vec U,black,amb={.02,.02,.02};struct sphere{ vec cen,color;
double rad,kd,ks,kt,kl,ir}*s,*best,sph[]={0.,6.,.5,1.,1.,1.,.9, .05,.2,.85,0.,1.7,-1.,8.,-.5,1.,.5,.2,1.,
.7,.3,0.,.05,1.2,1.,8.,-.5,.1,.8,.8, 1.,.3,.7,0.,0.,1.2,3.,-6.,15.,1.,.8,1.,7.,0.,0.,0.,.6,1.5,-3.,-3.,12.,
.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!*/
```

Let’s trace code



- Pretty much the same as the format of the textbook, illustrating concepts by showing working source code
- Ray tracer usually contains tricks (for efficiency, here, for reducing tokens)
- The basic frameworks are the same

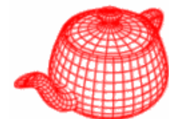
Minimal ray tracer (scene description)



- 888 tokens

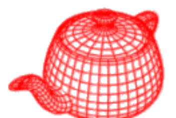
```
/* ray.h for test1, first test scene */
#define DEPTH 3          /* max ray tree depth */
#define SIZE 32          /* resolution of picture in x and y */
#define AOV 25           /* total angle of view in degrees */
#define NSPHERE 5        /* number of spheres */

AMBIENT = {.02, .02, .02};     /* ambient light color */
                              diffuse    refraction      index
/* sphere: x y z  r g b  rad    kd     ks     kt     kl      ir */
SPHERE = {                radius     reflection    emitting
     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,
};
```

Minimal ray tracer (geometry)



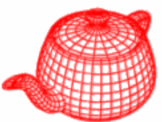
```
/* minimal ray tracer, hybrid version - 888 tokens
 * Paul Heckbert, ucbvax!pixar!ph, 13 Jun 87
 * Using tricks from Darwyn Peachey and Joe Cychosz.
*/

#define TOL 1e-7
#define AMBIENT vec U, black, amb
#define SPHERE struct sphere {vec cen, color; \
               double rad, kd, ks, kt, kl, ir} \
               *s, *best, sph[]
typedef struct {double x, y, z} vec;
#include "ray.h"
yx;
double u, b, tmin, sqrt(), tan();
```

Minimal ray tracer (geometry utilities)



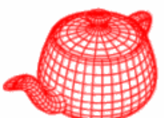
```
double vdot(A, B)
vec A, B;
{  return A.x*B.x + A.y*B.y + A.z*B.z; }

vec vcomb(a, A, B)        /* aA+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); }
```

Minimal ray tracer (cameras/films)



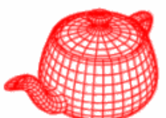
```
main()
{
 printf("%d %d\n", SIZE, SIZE);
 while (yx<SIZE*SIZE)
   U.x = yx%SIZE-SIZE/2,
   U.z = SIZE/2-yx++/SIZE,
                                    /* 360/PI~=114 */
   U.y = SIZE/2/tan(AOV/114.5915590261),
   U = vcomb(255.,trace(DEPTH,black,vunit(U)),black),
   /* yowsa!   non-portable! */
   printf("%.0f %.0f %.0f\n", U);
}
```

Minimal ray tracer (ray-object intersection)



```
struct sphere *intersect(P, D)
vec P, D;
{
  best = 0;
  tmin = 1e30;
  s = sph+NSPHERE;

  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>TOL ? b-u : b+u,
    tmin = u>=TOL && u<tmin ? best = s, u : tmin;
  return best;
}
```

Minimal ray tracer (ray-object intersection)



```
struct sphere *intersect(P, D)
vec P, D;
{
  best = 0;
  tmin = 1e30;
  s = sph+NSPHERE;

  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>TOL ? b-u : b+u,
    tmin = u>=TOL && u<tmin ? best = s, u : tmin;
  return best;
}
```

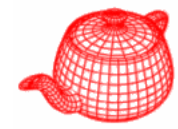
Minimal ray tracer (recursive ray tracing)

```
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) /* go into sphere */
    N = vcomb(-1., N, black),
    eta = 1/eta, d = -d;
```

Minimal ray tracer (recursive ray tracing)

```
 l = sph+NSPHERE;
 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);
 /* the following is non-portable: we assume right
    to left arg evaluation.
    (use U before call to trace, which modifies U)*/
 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))));
}
```

Reflection

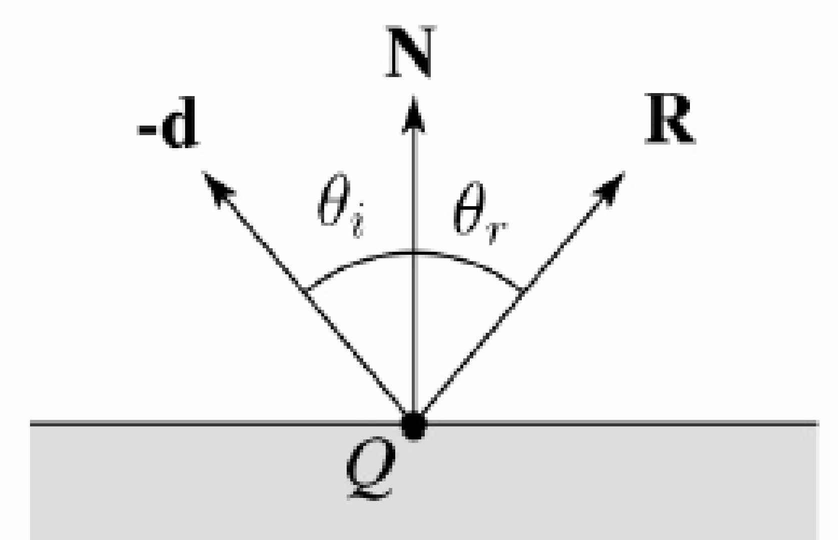


$$R = d - 2(N \cdot d)N$$

Law of reflection:

$$\theta_i = \theta_r$$

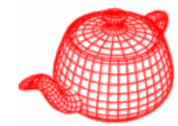
R is co-planar with **d** and **N**.



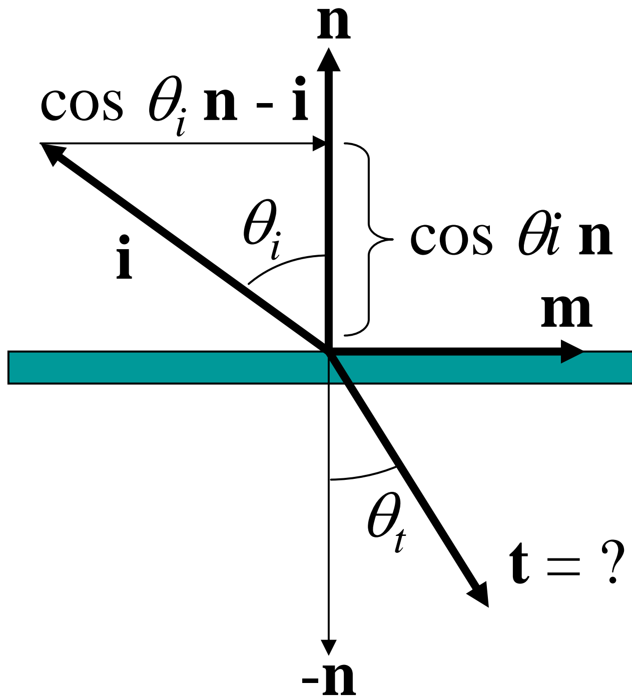
Minimal ray tracer (recursive ray tracing)

```
 l = sph+NSPHERE;
 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);
 /* the following is non-portable: we assume right
    to left arg evaluation.
    (use U before call to trace, which modifies U)*/
 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))));
}
```

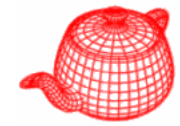
Refraction



$$\mathbf{t} = \left(\eta(\mathbf{n}\cdot\mathbf{i}) - \sqrt{1-\eta^2(1-(\mathbf{n}\cdot\mathbf{i})^2)}\right)\mathbf{n} - \eta\mathbf{i}$$

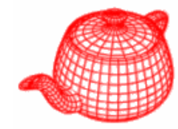


That's it?



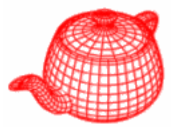
- In this course, we will study how state-of-art ray tracers work.

Issues

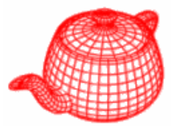


- Better Lighting + Forward Tracing
- Texture Mapping
- Sampling
- Modeling
- Materials
- Motion Blur, Depth of Field, Blurry Reflection/Refraction
  - *Distributed Ray-Tracing*
- Improving Image Quality
- Acceleration Techniques (better structure, faster convergence)

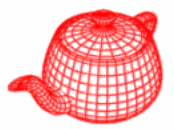
Complex lighting



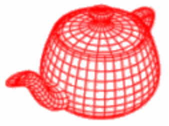
Complex lighting



Refraction/dispersion

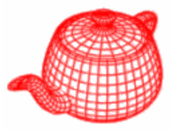


Caustics

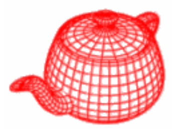


HENRIK WANN JENSEN 1995

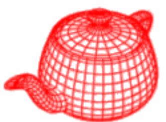
Realistic materials



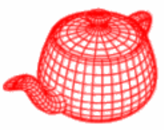
Translucent objects



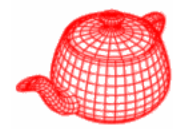
Texture and complex materials



Even more complex materials



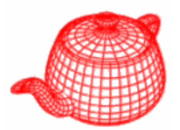
What else you can learn



- Literate programming
- Lex and yacc
- Object-oriented design
- Code optimization tricks
- Monte Carlo method
- Sampling and reconstruction
- Wavelet transform
- Spherical harmonics

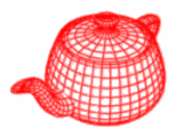
Carousel at Night *by Alex Kozlowski@UCSD*

Modeling



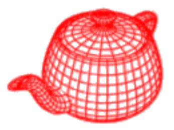
- Model this scene using blender
- Only one kind of horse due to lack of time
- 1.5M triangles (150K per horse, 200K for carousel)
- Render with his only render
- 6 minutes for BSP construction
- Export to obj format

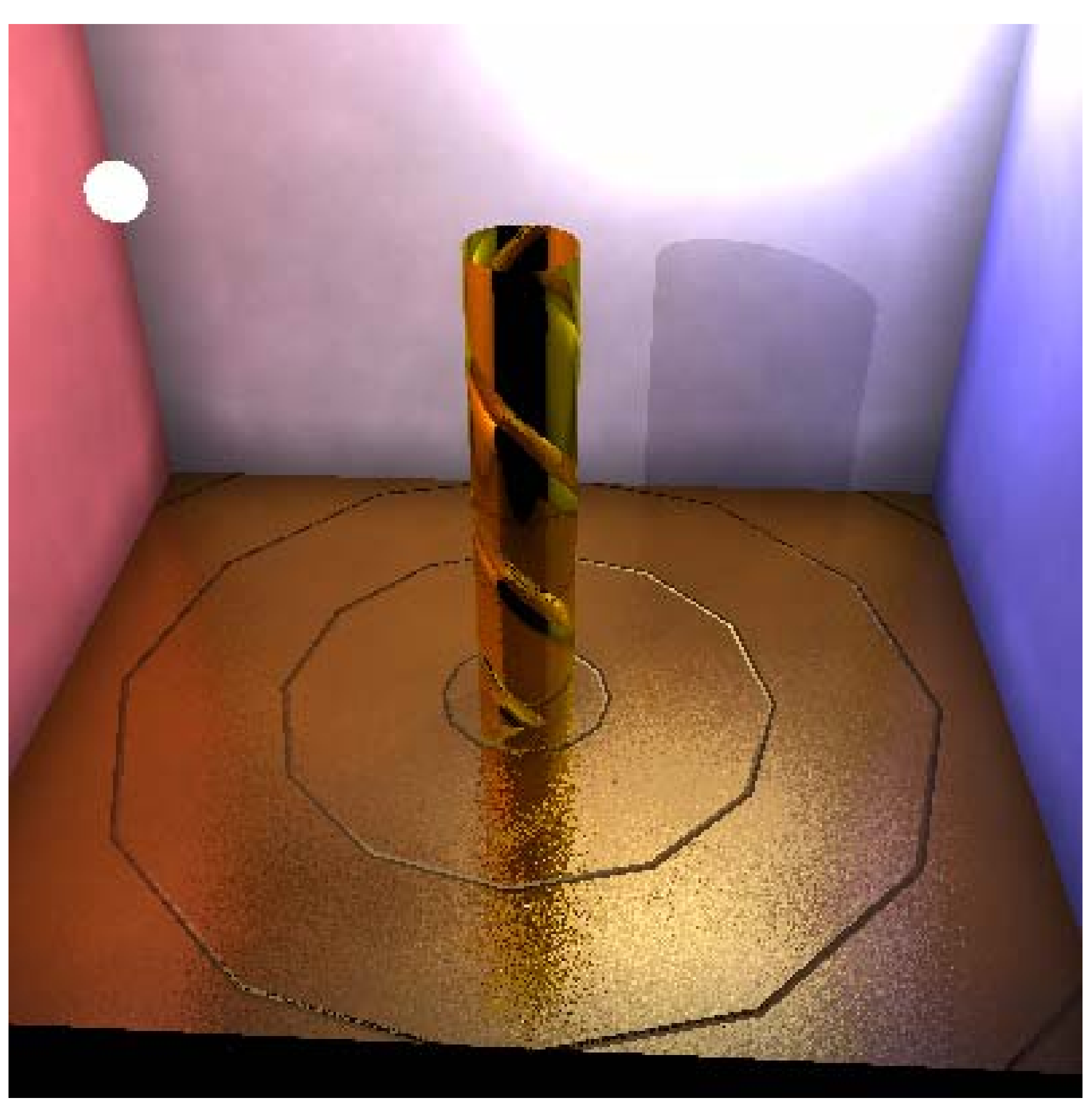
Soft shadows



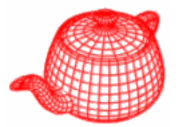
- stratified sampling of the spherical area lights

Bump mapping



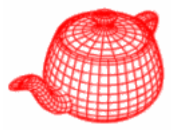


Glossy reflection

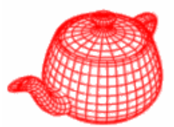


- Phong model

Perlin texture

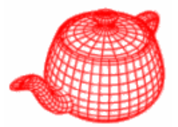


Depth of field/supersampling



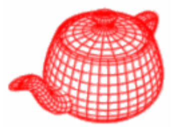
- circular lens with 16 samples per pixel, stratified sampling for both the pixel locations and the lens

Tone mapping



- 500 spherical lights, 3 Watts per light

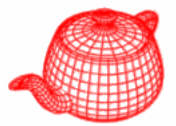
Tone mapping



- 500 spherical lights, 3 Watts per light

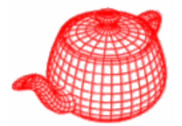
The Caterpillar *by T. Vaish & S. Budhiraja@Stanford*

Modeling



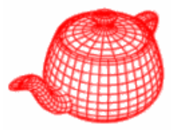
- Maya, NURB, Mayatopbrt

Modeling



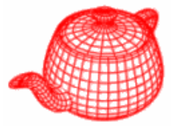
- Maya, NURB, Mayatopbrt

Rendering

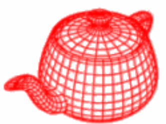


- Subsurface Scattering
- Non-uniform scattering within the body material
- Photon Mapping

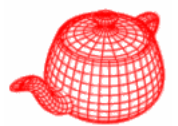
Final rendering



Lilypads *by T. Brow & R. Kumar@Stanford*

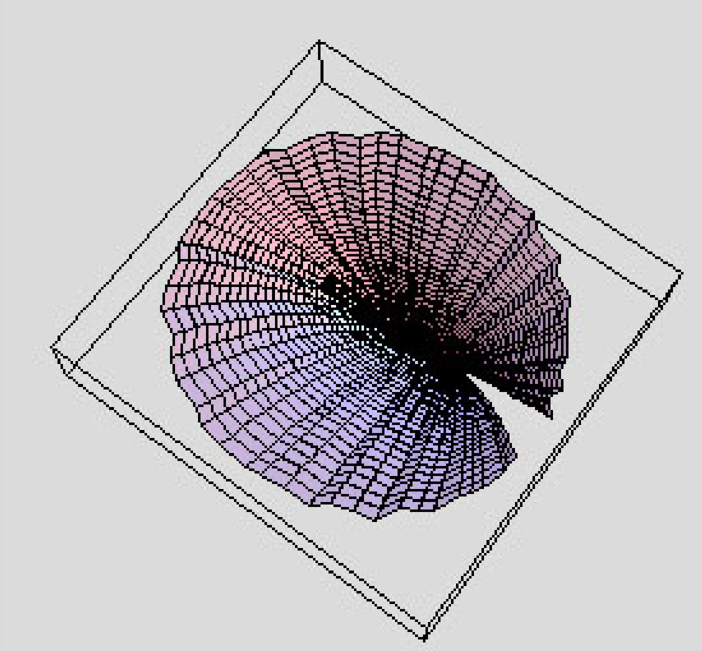


Modeling

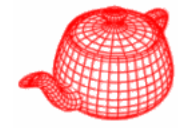


- Mathematica

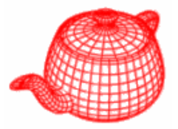
```
lilypad1 =
  ParametricPlot3D[
   {1.05*v^2*(1.1*Cos[u] - .1*Cos[u]*Sin[u] - .4*Cos[u]*Cos[u] +
        1/60*Cos[40*u] + 1/60*Cos[20*u]),
    v^4*(1.05*Sin[u] - .1*Sin[u]*Sin[u] - .4*Sin[u]*Cos[u] + 1/60*Sin[40*u] +
        1/60*Sin[20*u]), .5*Sin[v]}, {u, 0, 15*Pi/8}, {v, 0, 1},
   PlotPoints → 60];
```



Modeling

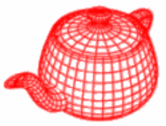


Rendering

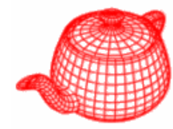


- Subsurface Scattering
- Photon Mapping

Final rendering



Homework #0



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