Cameras

Digital Image Synthesis

Yung-Yu Chuang

10/26/2006

with slides by Pat Hanrahan and Matt Pharr

Camera

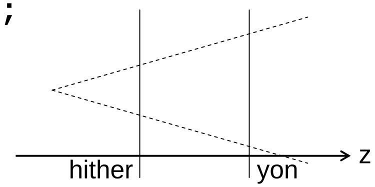
```
class Camera {
public:
  virtual float GenerateRay(const Sample
                  &sample, Ray *ray) const = 0;
  ...
  Film *film;
protected:
  Transform WorldToCamera, CameraToWorld;
  float ClipHither, ClipYon;
  float ShutterOpen, ShutterClose;
};
```

return a weight, useful for simulating real lens

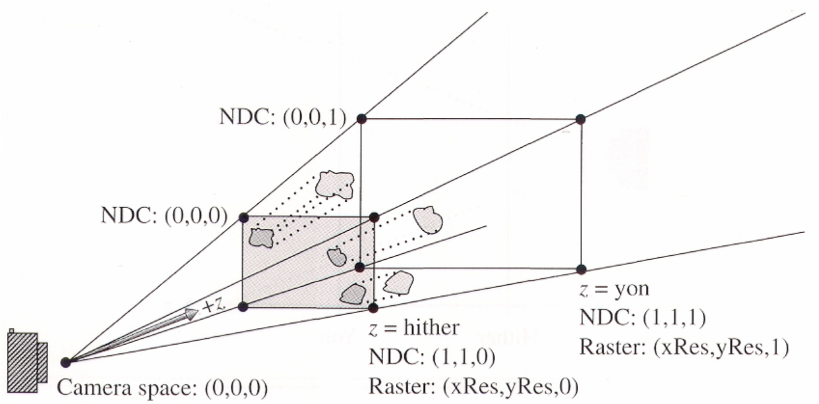
sample position at the image plane

corresponding normalized ray in the world space

for simulating motion blur, not Implemented yet



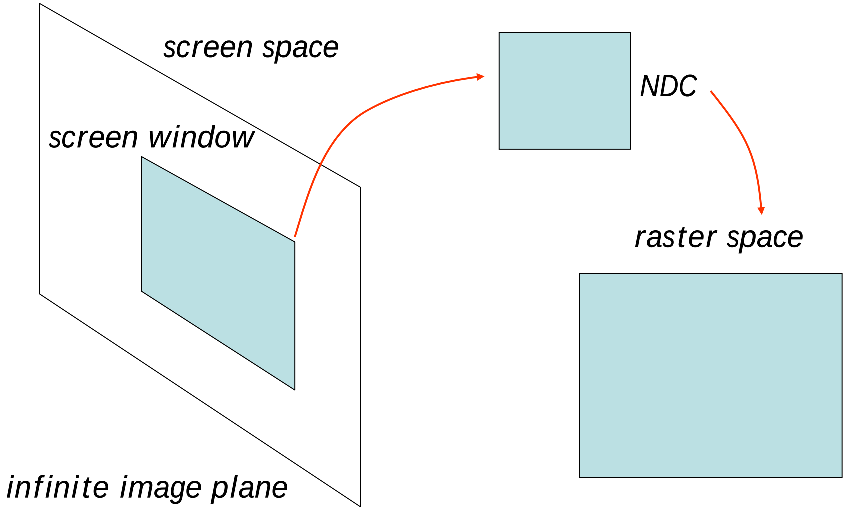
Camera space



Coordinate spaces

- world space
- object space
- camera space (origin: camera position, z: viewing direction, y: up direction)
- screen space: a 3D space defined on the image plane, z ranges from 0(near) to 1(far)
- normalized device space (NDC): (x, y) ranges from (0,0) to (1,1) for the rendered image, z is the same as the screen space
- raster space: similar to NDC, but the range of (x,y) is from (0,0) to (xRes, yRes)

Screen space



Projective camera models

- Transform a 3D scene coordinate to a 2D image coordinate by a 4x4 projective matrix

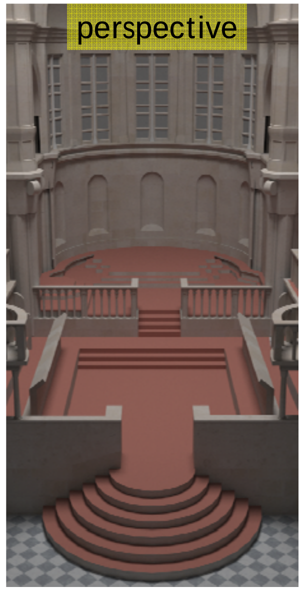
camera to screen projection

```
class ProjectiveCamera : public Camera {
public:
  ProjectiveCamera(Transform &world2cam,
    Transform &proj, float Screen[4],
    float hither, float yon, float sopen,
    float sclose, float lensr, float focald,
    Film *film);
protected:
  Transform CameraToScreen, WorldToScreen,
            RasterToCamera;
  Transform ScreenToRaster, RasterToScreen;
  float LensRadius, FocalDistance;
};
```

Projective camera models

```
ProjectiveCamera::ProjectiveCamera(...)
  :Camera(w2c, hither, yon, sopen, sclose, f) {
  ...
  CameraToScreen=proj;
  WorldToScreen=CameraToScreen*WorldToCamera;
  ScreenToRaster
   = Scale(float(film->xResolution),
           float(film->yResolution), 1.f)*
     Scale(1.f / (Screen[1] - Screen[0]),
           1.f / (Screen[2] - Screen[3]), 1.f)*
     Translate(Vector(-Screen[0],-Screen[3],0.f));
  RasterToScreen = ScreenToRaster.GetInverse();
  RasterToCamera =
      CameraToScreen.GetInverse() * RasterToScreen;
}
```

Projective camera models



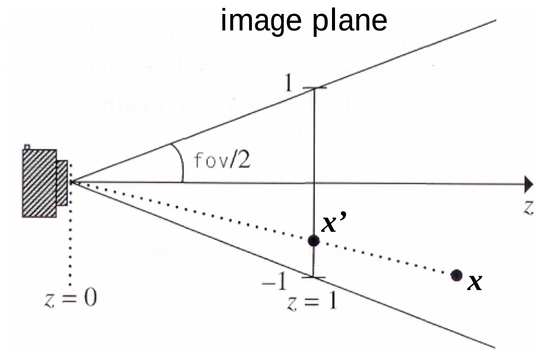
Orthographic camera

```
Transform Orthographic(float znear,
                       float zfar)
{
  return Scale(1.f, 1.f, 1.f/(zfar-znear))
    *Translate(Vector(0.f, 0.f, -znear));
}

OrthoCamera::OrthoCamera( ... )
  : ProjectiveCamera(world2cam,
      Orthographic(hither, yon),
      Screen, hither, yon, sopen, sclose,
      lensr, focald, f) {
}
```

OrthoCamera::GenerateRay

```
float OrthoCamera::GenerateRay
   (const Sample &sample, Ray *ray) const {
  Point Pras(sample.imageX,sample.imageY,0);
  Point Pcamera;
  RasterToCamera(Pras, &Pcamera);
  ray->o = Pcamera;
  ray->d = Vector(0,0,1);
  <Modify ray for depth of field>
  ray->mint = 0.;
  ray->maxt = ClipYon - ClipHither;
  ray->d = Normalize(ray->d);
  CameraToWorld(*ray, ray);
  return 1.f;
}
```

Perspective camera



$$x' = x / z$$

$$y' = y / z$$

$$z' = \frac{f(z-n)}{z(f-n)}$$

Perspective camera

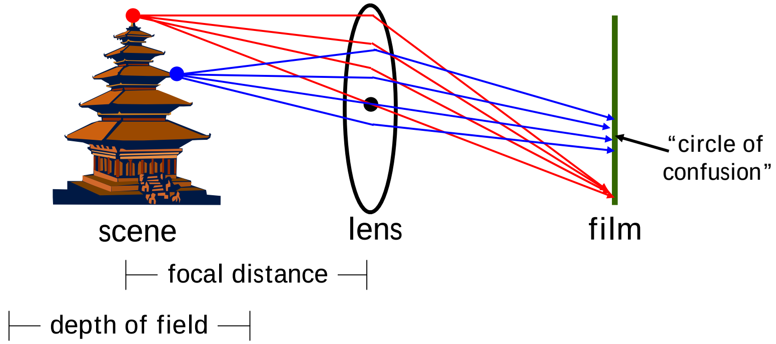
```
Transform Perspective(float fov,float n,float f)
{                                          near_z     far_z
  float inv_denom = 1.f/(f-n);
  Matrix4x4 *persp =
  new Matrix4x4(1, 0,       0,           0,
                0, 1,       0,           0,
                0, 0, f*inv_denom, -f*n*inv_denom,
                0, 0,       1,           0);

  float invTanAng= 1.f / tanf(Radians(fov)/2.f);
  return Scale(invTanAng, invTanAng, 1) *
         Transform(persp);
}
```

PerspectiveCamera::GenerateRay

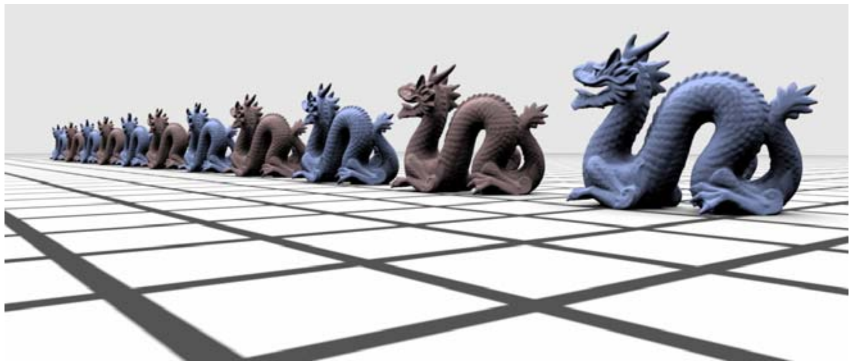
```
float PerspectiveCamera::GenerateRay
      (const Sample &sample, Ray *ray) const
{
  // Generate raster and camera samples
  Point Pras(sample.imageX, sample.imageY, 0);
  Point Pcamera;
  RasterToCamera(Pras, &Pcamera);
  ray->o = Pcamera;
  ray->d = Vector(Pcamera.x,Pcamera.y,Pcamera.z);
  <Modify ray for depth of field>
  ray->d = Normalize(ray->d);
  ray->mint = 0.;
  ray->maxt = (ClipYon-ClipHither)/ray->d.z;
  CameraToWorld(*ray, ray);
  return 1.f;
}
```

Depth of field

- Circle of confusion $\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$
- Depth of field: the range of distances from the lens at which objects appear in focus (circle of confusion roughly smaller than a pixel)

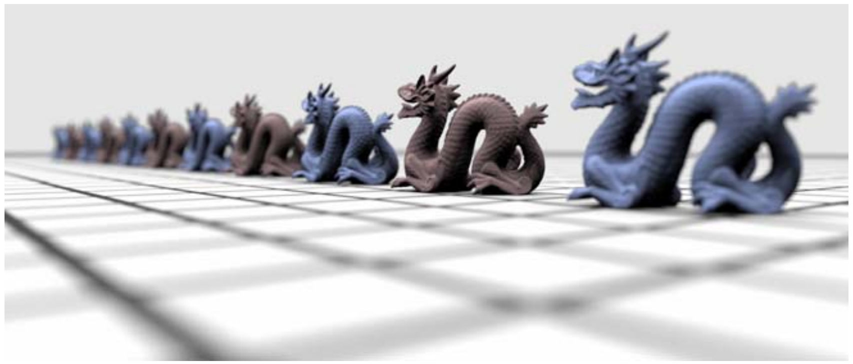


Depth of field



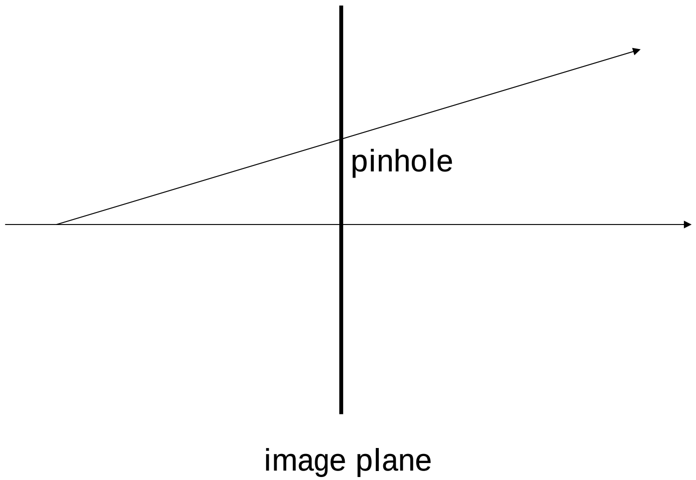
without depth of field

Depth of field

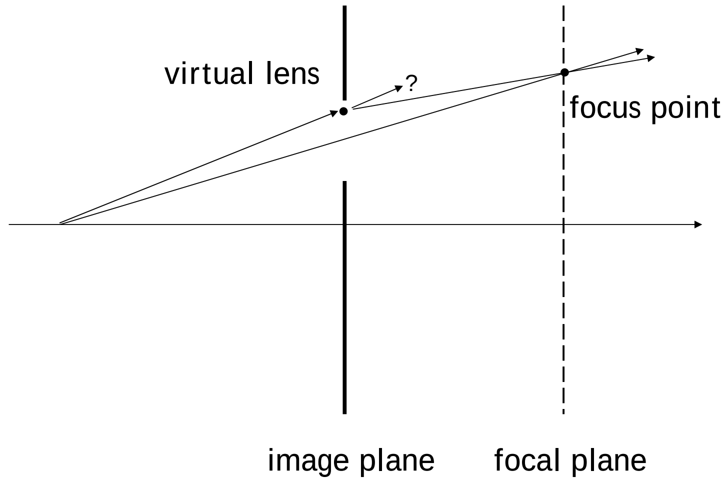


with depth of field

Sample the lens



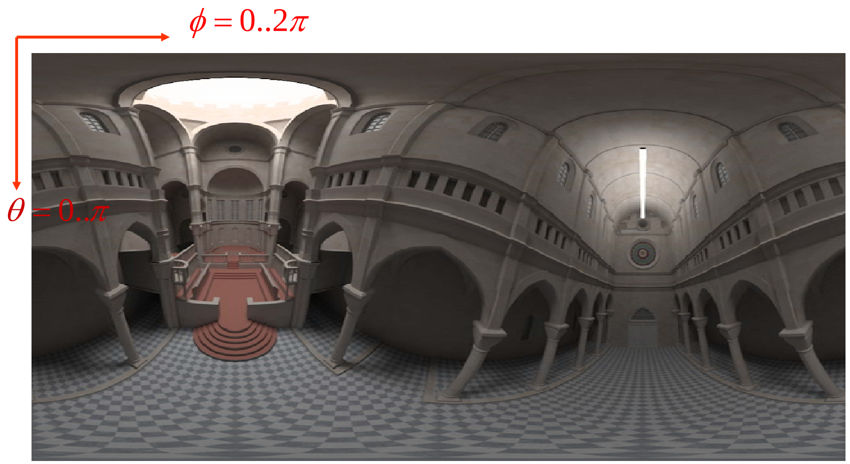
Sample the lens



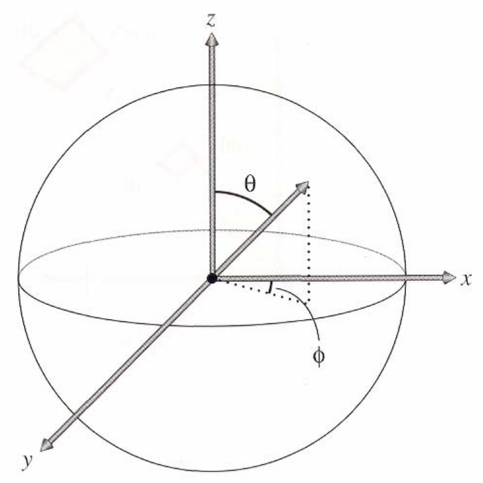
In `GenerateRay(…)`

```
if (LensRadius > 0.) {
  // Sample point on lens
  float lensU, lensV;
  ConcentricSampleDisk(sample.lensU, sample.lensV,
                       &lensU, &lensV);
  lensU *= LensRadius;
  lensV *= LensRadius;
  // Compute point on plane of focus
  float ft = (FocalDistance - ClipHither) / ray->d.z;
  Point Pfocus = (*ray)(ft);
  // Update ray for effect of lens
  ray->o.x += lensU;
  ray->o.y += lensV;
  ray->d = Pfocus - ray->o;
}
```

Environment camera



Environment camera



$x = \sin\theta \cos\phi$
$y = \sin\theta \sin\phi$
$z = \cos\theta$

EnvironmentCamera

```
EnvironmentCamera::
  EnvironmentCamera(const Transform &world2cam,
                    float hither, float yon,
                    float sopen, float sclose,
                    Film *film)
  : Camera(world2cam, hither, yon,
           sopen, sclose, film)
{
  rayOrigin = CameraToWorld(Point(0,0,0));
}
```

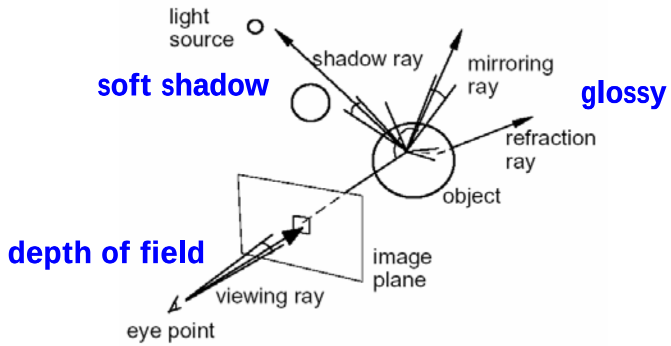
in world space

EnvironmentCamera::GenerateRay

```
float EnvironmentCamera::GenerateRay
      (const Sample &sample, Ray *ray) const
{
  ray->o = rayOrigin;
  float theta=M_PI*sample.imageY/film->yResolution;
  float phi=2*M_PI*sample.imageX/film->xResolution;
  Vector dir(sinf(theta)*cosf(phi), cosf(theta),
             sinf(theta)*sinf(phi));
  CameraToWorld(dir, &ray->d);
  ray->mint = ClipHither;
  ray->maxt = ClipYon;
  return 1.f;
}
```

Distributed ray tracing

- *SIGGRAPH 1984, by Robert L. Cook, Thomas Porter and Loren Carpenter from LucasFilm.*
- Apply distribution-based sampling to many parts of the ray-tracing algorithm.



Distributed ray tracing

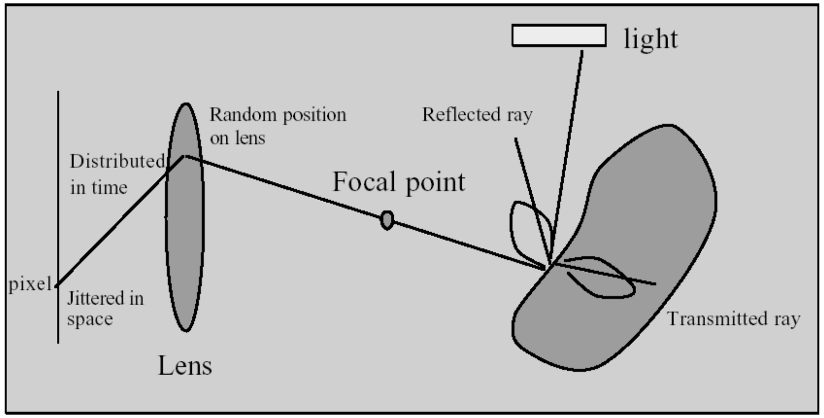
Gloss/Translucency
- Perturb directions reflection/transmission, with distribution based on angle from ideal ray

Depth of field
- Perturb eye position on lens

Soft shadow
- Perturb illumination rays across area light

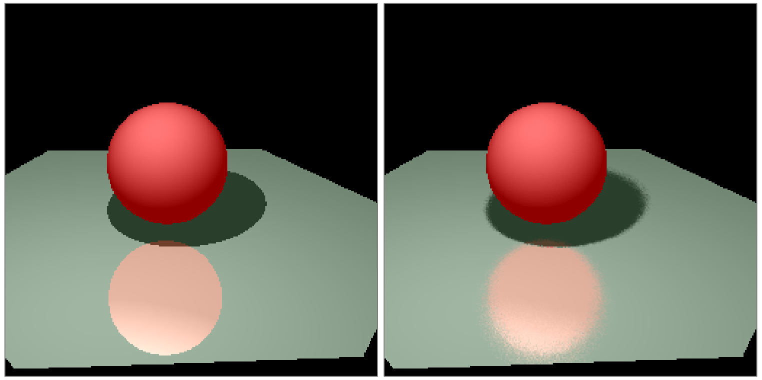
Motion blur
- Perturb eye ray samples in time

Distributed ray tracing



DRT: Gloss/Translucency

- Blurry reflections and refractions are produced by randomly perturbing the reflection and refraction rays from their "true" directions.

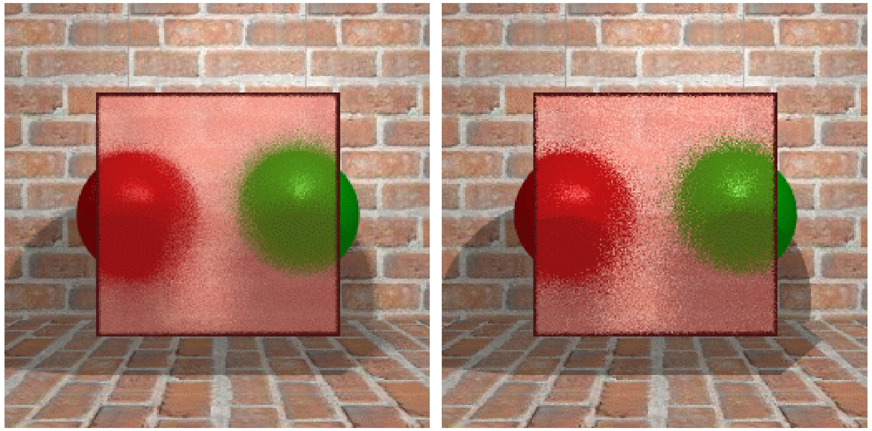


Glossy reflection

4 rays

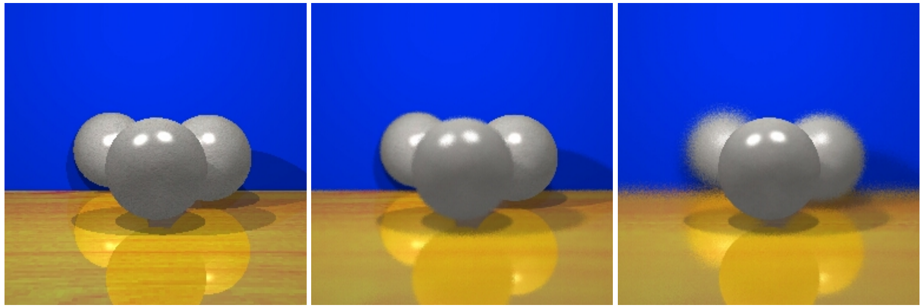
64 rays

Translucency

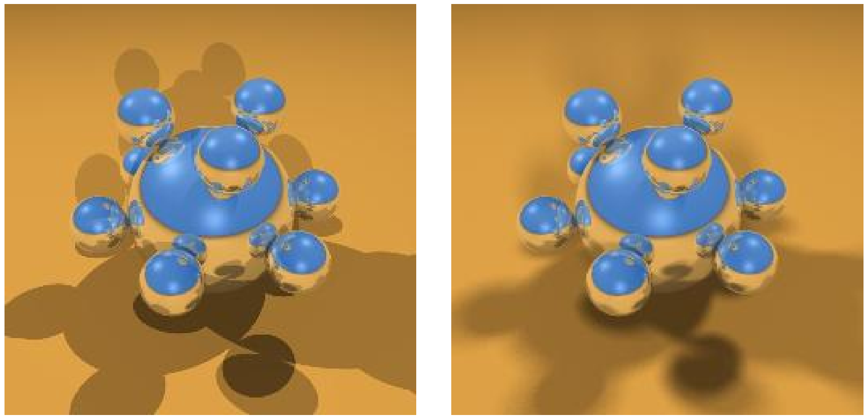


4 rays 16 rays

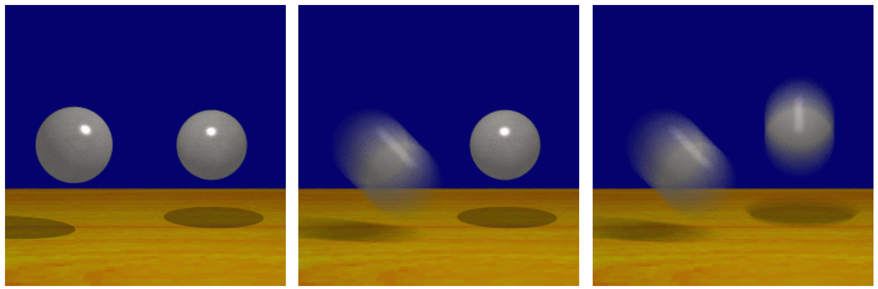
Depth of field



Soft shadows

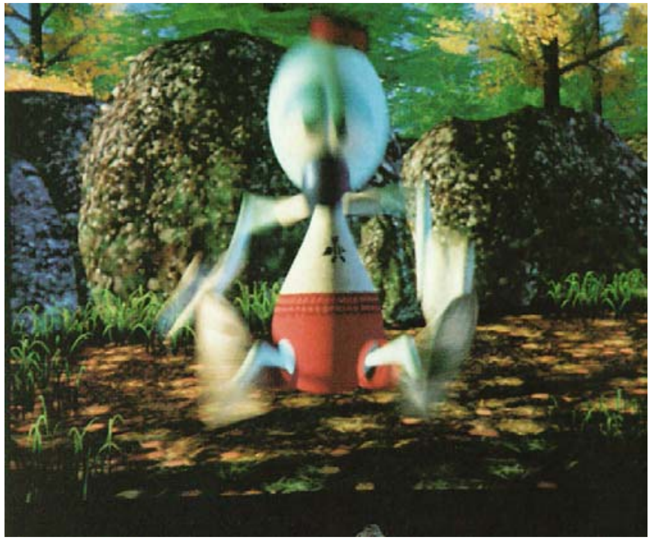


Motion blur



Results

Adventures of Andre & Wally B (1986)



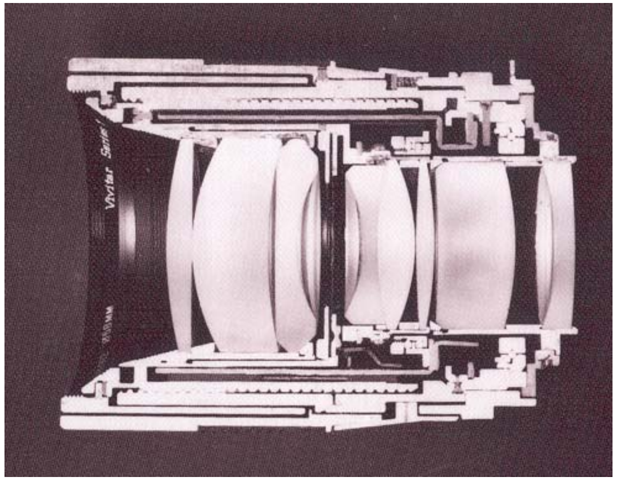
Realistic camera model

- Most camera models in graphics are not geometrically or radiometrically correct.
- Model a camera with a lens system and a film backplane. A lens system consists of a sequence of simple lens elements, stops and apertures.

Why a realistic camera model?

- Physically-based rendering. For more accurate comparison to empirical data.
- Seamlessly merge CGI and real scene, for example, VFX.
- For vision and scientific applications.
- The camera metaphor is familiar to most 3d graphics system users.

Real Lens

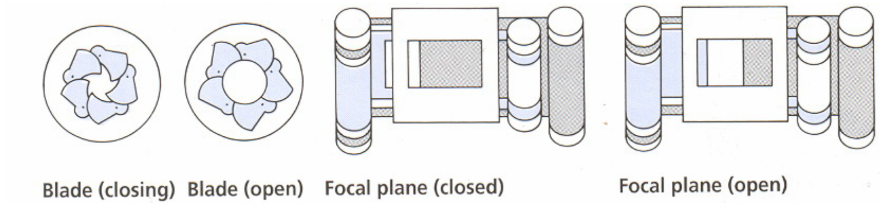


Cutaway section of a Vivitar Series 1 90mm f/2.5 lens
Cover photo, Kingslake, *Optics in Photography*

Exposure

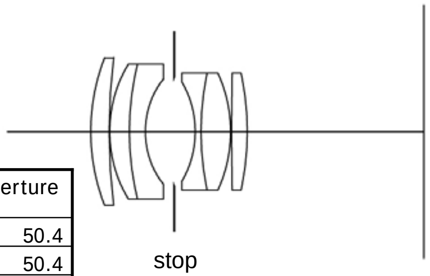
- Two main parameters:
  - Aperture (in f stop)

  - Shutter speed (in fraction of a second)



Double Gauss

Data from W. Smith,
Modern Lens Design, p 312

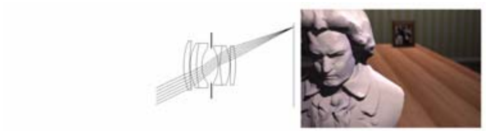


Radius (mm)	Thick (mm)	n_d	V-no	aperture
58.950	7.520	1.670	47.1	50.4
169.660	0.240			50.4
38.550	8.050	1.670	47.1	46.0
81.540	6.550	1.699	30.1	46.0
25.500	11.410			36.0
	9.000			34.2
-28.990	2.360	1.603	38.0	34.0
81.540	12.130	1.658	57.3	40.0
-40.770	0.380			40.0
874.130	6.440	1.717	48.0	40.0
-79.460	72.228			40.0

Ray Tracing Through Lenses

200 mm telephoto

35 mm wide-angle



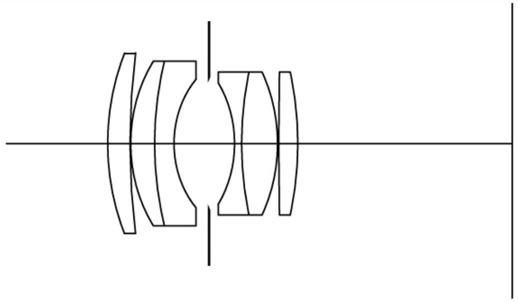
50 mm double-gauss

16 mm fisheye

From Kolb, Mitchell and Hanrahan (1995)

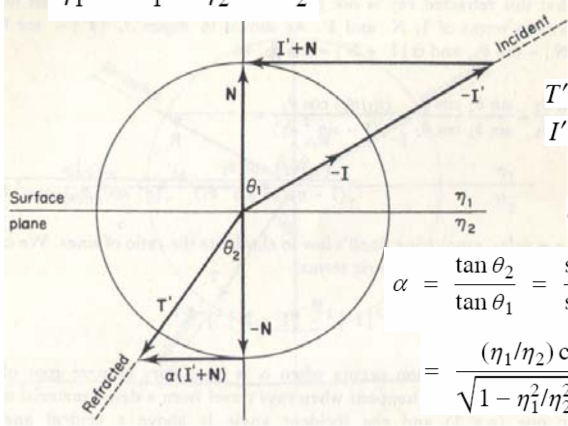
Tracing rays through lens systems

R = Ray(point on film plane, point on rear-most element)
For each lens element E_i, from rear to front,
  p = intersection of R and E_i
  If p is outside clear aperture of E_i
    ray is blocked
  Else if medium on far side of $E_i \neq$ medium on near side
    compute new direction for R using Snell's law



Whitted's method

$$\eta_1 \sin\theta_1 = \eta_2 \sin\theta_2$$



$$T' = \alpha(I' + N) - N \text{ for some } \alpha$$

$$I' = I/(-I \cdot N)$$

$$|I' + N| = \tan\theta_1$$

$$\alpha|I' + N| = \tan\theta_2$$

$$\alpha = \frac{\tan\theta_2}{\tan\theta_1} = \frac{\sin\theta_2}{\sin\theta_1}\frac{\cos\theta_1}{\cos\theta_2} = \frac{(\eta_1/\eta_2)\cos\theta_1}{\sqrt{1-\sin^2\theta_2}}$$

$$= \frac{(\eta_1/\eta_2)\cos\theta_1}{\sqrt{1-\eta_1^2/\eta_2^2\sin^2\theta_1}} = \frac{1}{\sqrt{n^2\sec^2\theta_1 - \tan^2\theta_1}}$$

$$|I'| = \sec\theta_1$$

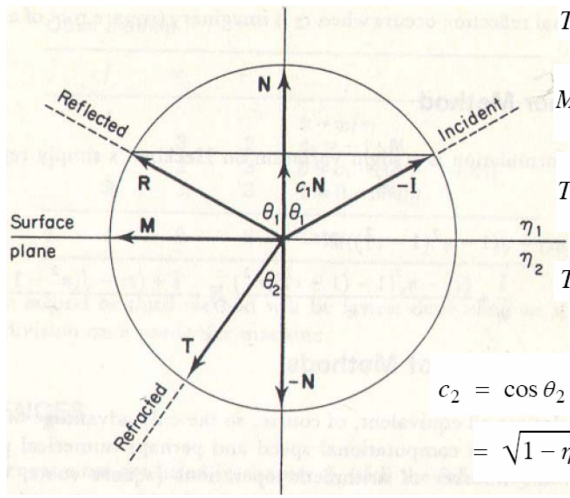
$$\alpha = (n^2|I'|^2 - |I' + N|^2)^{-1/2}$$

Whitted's method

Whitted's Method

$\sqrt{}$	/	×	+	
	1			$n = \eta_2/\eta_1$
	3	3	2	$I' = I/(-I \cdot N)$
			3	$J = I' + N$
1	1	8	5	$\alpha = 1/\sqrt{n^2(I' \cdot I') - (J \cdot J)}$
		3	3	$T' = \alpha J - N$
1	3	3	2	$T = T'/\lvert T'\rvert$
2	8	17	15	TOTAL

Heckber's method



$$T = \sin\theta_2 M - \cos\theta_2 N$$

$$M = \frac{I_{perp}}{|I_{perp}|} = \frac{I + c_1 N}{\sin\theta_1}$$

$$T = \frac{\sin\theta_2}{\sin\theta_1}(I + c_1 N) - \cos\theta_2 N$$

$$T = \eta I + (\eta c_1 - c_2)N$$

$$c_2 = \cos\theta_2 = \sqrt{1-\sin^2\theta_2}$$

$$= \sqrt{1-\eta^2\sin^2\theta_1} = \sqrt{1-\eta^2(1-c_1^2)}$$

Heckbert's method

Heckbert's Method

$\sqrt{}$	/	$\times$	+	
	1			$\eta = \eta_1/\eta_2$
		3	2	$c_1 = -I \cdot N$
1		3	2	$c_2 = \sqrt{1 - \eta^2(1 - c_1^2)}$
		7	4	$T = \eta I + (\eta c_1 - c_2)N$
1	1	13	8	TOTAL

Other method

$$
\begin{aligned}
T &= \eta I + (\eta c_1 - \sqrt{1 - \eta^2(1 - c_1^2)})N \\
&= \frac{I}{n} + \frac{c_1 - n\sqrt{1 - (1 - c_1^2)/n^2}}{n} N \\
&= \frac{I + (c_1 - \sqrt{n^2 - 1 + c_1^2})N}{n}
\end{aligned}
$$

Other Method

$\sqrt{}$	/	$\times$	+	
	1			$n = \eta_2/\eta_1$
		3	2	$c_1 = -I \cdot N$
1		2	3	$\beta = c_1 - \sqrt{n^2 - 1 + c_1^2}$
	3	3	3	$T = (I + \beta N)/n$
1	4	8	8	TOTAL

Comparisons

Whitted's Method

$\sqrt{}$	/	$\times$	+	
	1			$n = \eta_2/\eta_1$
	3	3	2	$I' = I/(-I \cdot N)$
			3	$J = I' + N$
1	1	8	5	$\alpha = 1/\sqrt{n^2(I' \cdot I') - (J \cdot J)}$
		3	3	$T' = \alpha J - N$
1	3	3	2	$T = T'/\lvert T' \rvert$
2	8	17	15	TOTAL

Heckbert's Method

$\sqrt{}$	/	$\times$	+	
	1			$\eta = \eta_1/\eta_2$
		3	2	$c_1 = -I \cdot N$
1		3	2	$c_2 = \sqrt{1 - \eta^2(1 - c_1^2)}$
		7	4	$T = \eta I + (\eta c_1 - c_2)N$
1	1	13	8	TOTAL

Other Method

$\sqrt{}$	/	$\times$	+	
	1			$n = \eta_2/\eta_1$
		3	2	$c_1 = -I \cdot N$
1		2	3	$\beta = c_1 - \sqrt{n^2 - 1 + c_1^2}$
	3	3	3	$T = (I + \beta N)/n$
1	4	8	8	TOTAL