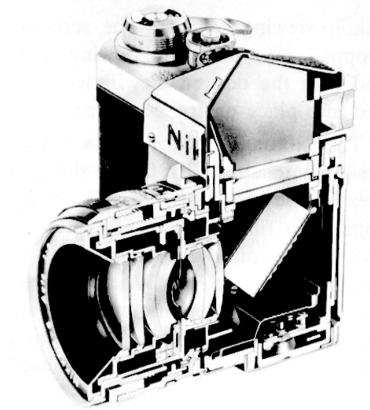
Camera Simulation



Effect	Cause
Field of view	Field stop and focal length of lenses
Depth of field	Aperture stop and focal length
Motion blur	Shutter
Exposure	Film, aperture, shutter

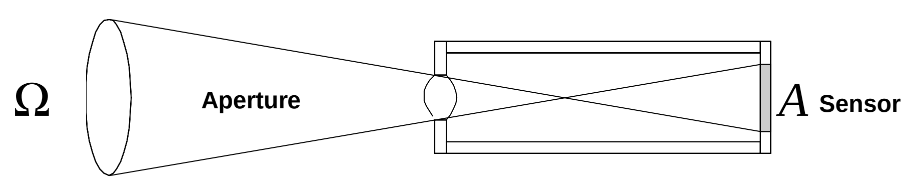
References

Photography, B. London and J. Upton

Optics in Photography, R. Kingslake

Sensor Response

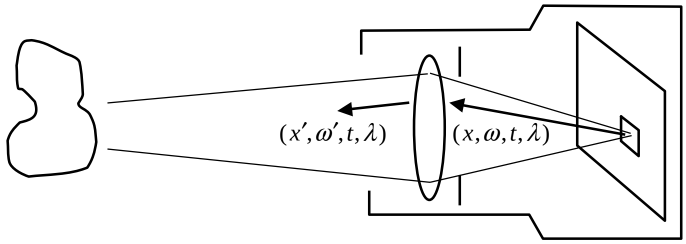
The response of a sensor is proportional to the radiance and the throughput



$$R = \int_A \int_\Omega L \cos\theta \, d\omega \, dA = L \int_A \int_\Omega \cos\theta \, d\omega \, dA = LT$$

Throughput $T = \int_A \int_\Omega \cos\theta \, d\omega \, dA$

The Measurement Equation



$$R = \iint \iint L(T(x,\omega,\lambda),t,\lambda) P(x,\lambda') S(x,\omega,t)\, d\vec{A} \bullet d\vec{\omega}\, dt\, d\lambda$$

Scene radiance	$L(x,\omega,t,\lambda)$
Imaging optics	$(x',\omega') = T(x,\omega,\lambda)$
Sensor/Pixel response	$P(x,\lambda)$
Shutter	$S(x,\omega,t)$

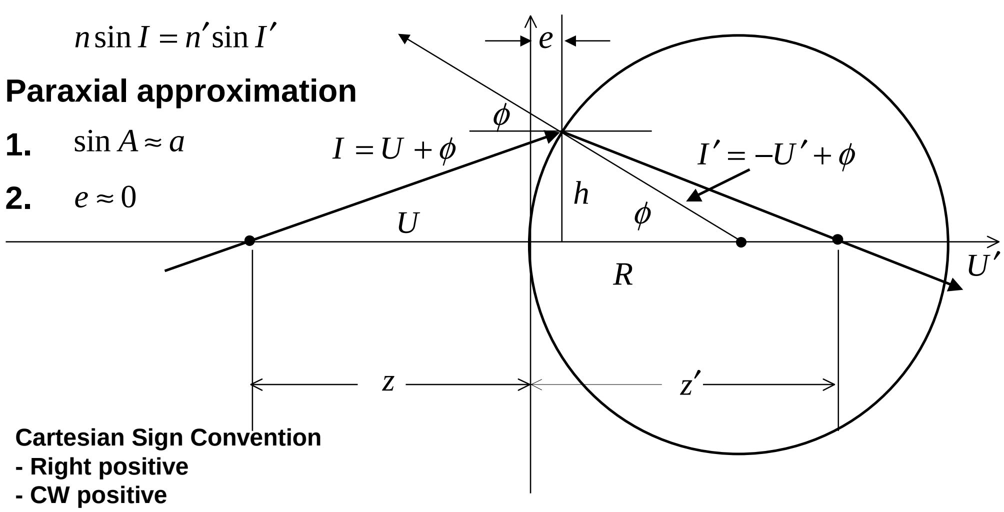
Paraxial Refraction

Snell's Law

$n \sin I = n' \sin I'$

Paraxial approximation

1. $\sin A \approx a$
2. $e \approx 0$



Cartesian Sign Convention
- Right positive
- CW positive

Derivation

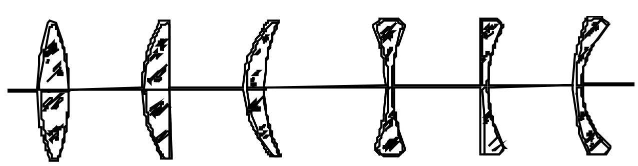
$$n' \sin I' = n \sin I$$
$$ni' = ni$$
$$n'(-u' + \phi) = n(u + \phi)$$
$$n'(\frac{h}{z'} - \frac{h}{R}) = n(\frac{h}{z} - \frac{h}{R})$$
$$\frac{n'}{z'} = \frac{n}{z} + \frac{(n'-n)}{R}$$

Cartesian sign convention

$$\sin U \approx u \approx \tan U = \frac{h}{z}$$
$$\sin U' \approx u' \approx \tan U' = -\frac{h}{z'}$$
$$\phi = -\frac{h}{R}$$

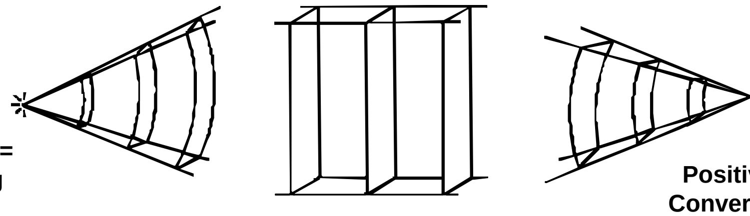
Lensmakers Formula

$$P = (n' - n)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) = \frac{1}{f}$$



Convex = Converging **Concave = Diverging**

Thin Lense Equation



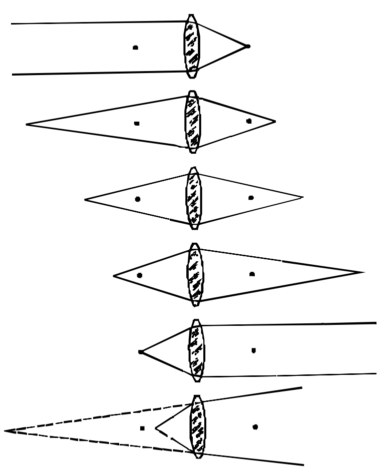
Vergence $V = \frac{n}{r} = \frac{n}{z}$

Thin lens equation $V' = V + P$

$$\frac{1}{z'} = \frac{1}{z} + \frac{1}{f}$$

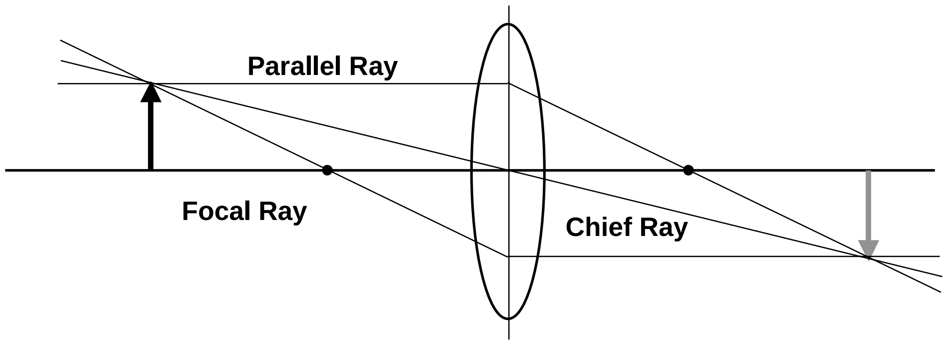
Focal Points and Focal Lengths

To focus: move lens relative to backplane



$$\frac{1}{z'} = \frac{1}{z} + \frac{1}{f}$$

Gauss' Ray Tracing Construction



Perspective Transformation

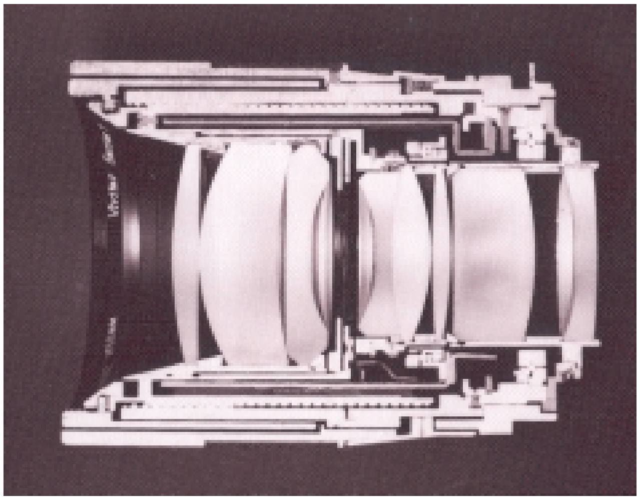
Thin lens equation

$$\frac{1}{z'} = \frac{1}{z} + \frac{1}{f} \Rightarrow z' = \frac{fz}{z+f}$$

$$\Rightarrow x' = \frac{fx}{z+f}$$

Represent transformation as a 4x4 matrix

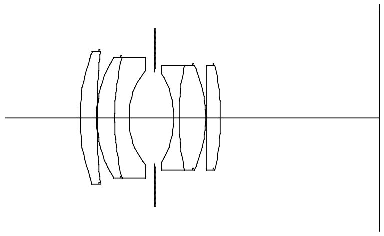
Real Lens



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

Double Gauss

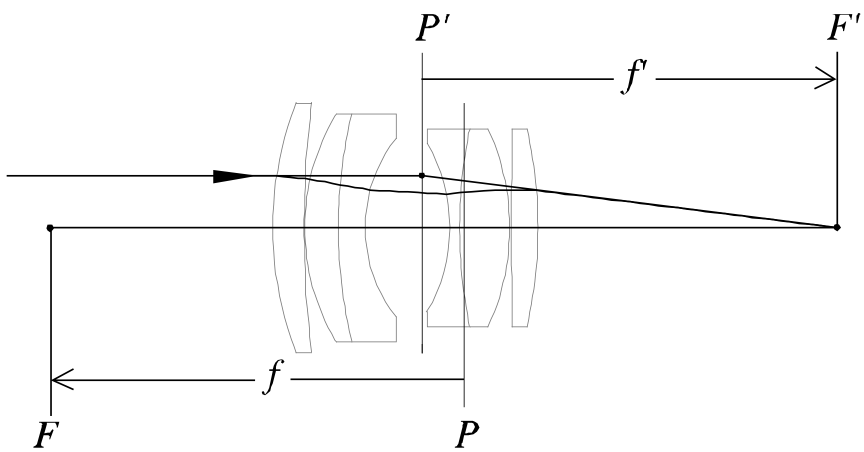
Radius (mm)	Thick (mm)	n_d	V-no	aperture
58.950	7.520	1.670	47.1	50.4
169.660	0.240			50.4
38.550	8.050	1.670	47.1	46.0
81.540	6.550	1.699	30.1	46.0
25.500	11.410			36.0
	9.000			34.2
-28.990	2.360	1.603	38.0	34.0
81.540	12.130	1.658	57.3	40.0
-40.770	0.380			40.0
874.130	6.440	1.717	48.0	40.0
-79.460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



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

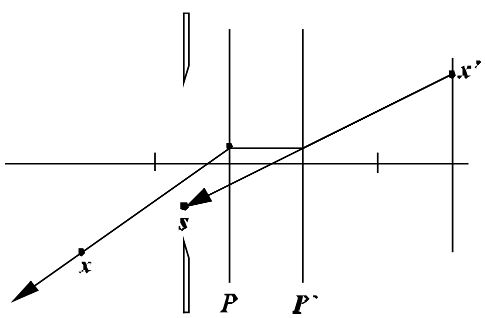
Positive radii, convex; negative radii, concave

Thick Lenses

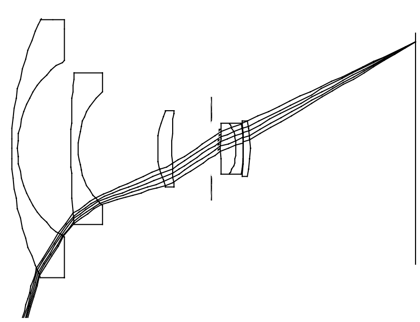


Measure distances from *principal planes*

Camera Simulation



Algorithm 1



Algorithm 2

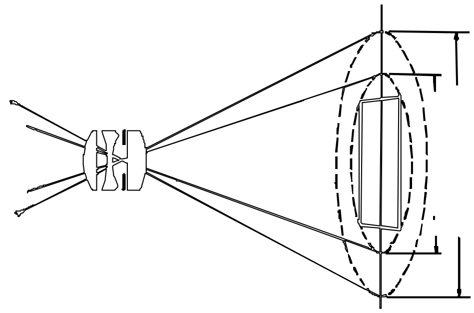
From Kolb, Mitchell and Hanrahan (1995)

Field of View

Lenses

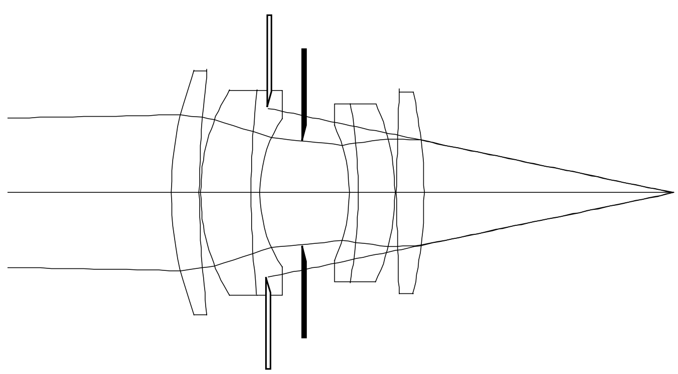
- **Normal** **26º**

  Film diagonal = focal length
- **Wide-angle** **75-90º**
- **Narrow-angle** **10º**



From Kingslake,
Optics in Photography

Stops and Pupils



Stops - physical limits

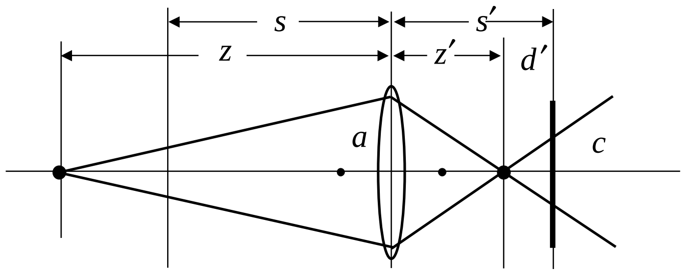
Pupils - logical limits

Exit and Entry pupil

Finite Aperture
1. **Depth of field**
2. **Collects light**

Circle of Confusion

Image space view



In-focus

$$\frac{1}{s'} = \frac{1}{s} + \frac{1}{f}$$

Out-of-focus

$$\frac{1}{z'} = \frac{1}{z} + \frac{1}{f}$$

Note: Circle of confusion proportional to the size of the aperture

$$\frac{c}{a} = \frac{d'}{z'} = \frac{s' - z'}{z'}$$

Depth of Field

Object space view

- **Resolving power: sets c**

$$\frac{c}{s} = \frac{1}{1000}$$

- **Depth of field: equal c**

$$\frac{c}{a} = \frac{d_f}{z_f} = \frac{d_n}{z_n}$$

- **Hyperfocal distance**

z_n

$z_f = \infty$

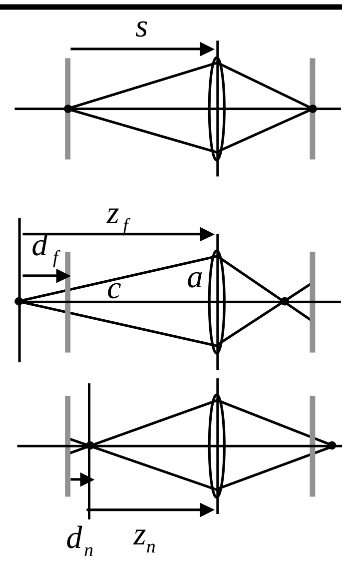
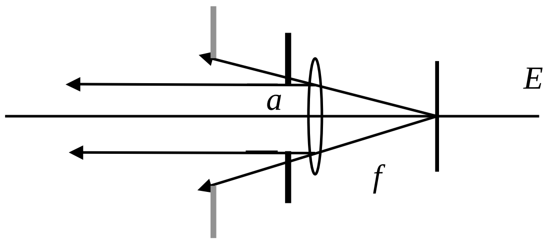


Image Irradiance



$$E = Lt\pi \sin^2\theta = Lt\frac{\pi}{4}\left(\frac{a}{f}\right)^2$$
$$= Lt\frac{\pi}{4}\frac{1}{N^2}$$

F-Stop/F-Number: $a = \frac{f}{N}$

Fstops: 1.4 2 2.8 4.0 5.6 8 11 16 22 32 45 64

- **1 stop doubles exposure**

Camera Exposure

Exposure $H = E \times T$

Exposure overdetermined

- **Aperture: f-stop - 1 stop doubles *H***
  - **Interaction with depth of field**
- **Shutter: Doubling the effective time doubles *H***
  - **Interaction with motion blur**

Automatic exposure

- **Shutter priority**
- **Aperture priority**
- **Programmed**

Photographic Exposure

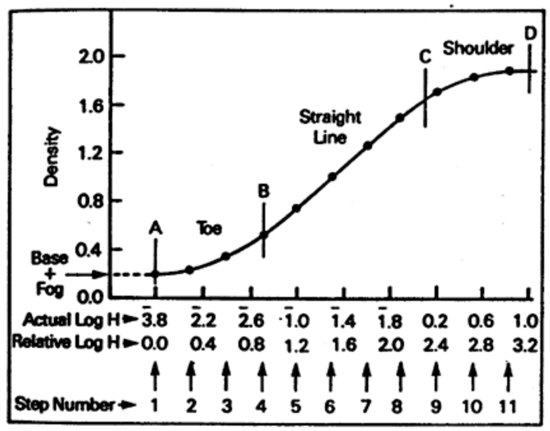
Density vs. Transparency

$$D = \log \frac{1}{T}$$

Gamma

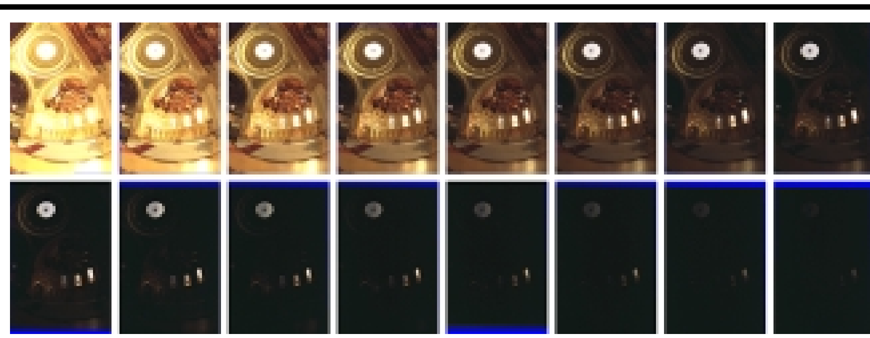
$$\gamma = \frac{\Delta D}{\Delta \log H}$$

Film speed



$$Speed = \frac{1}{H} \Rightarrow ISO(ASA) = 0.8 \frac{1}{H_m}$$

High Dynamic Range

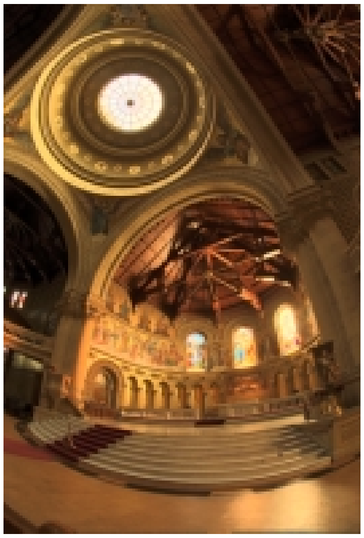


Sixteen photographs of the Stanford Memorial Church taken at 1-stop increments from 30s to 1/1000s.

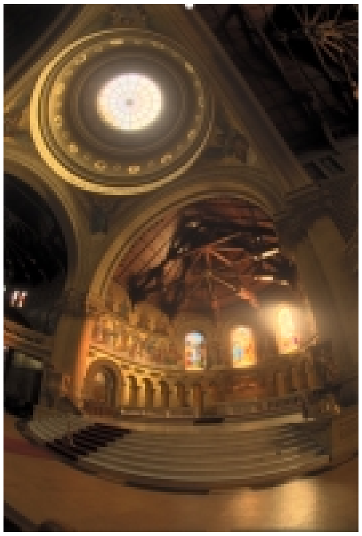
From Debevec and Malik, High dynamic range photographs.

Method: Each stop has a useful range of radiances …

Simulated Photograph



Adaptive histogram compression



Also with glare, contrast, blur

Derivation