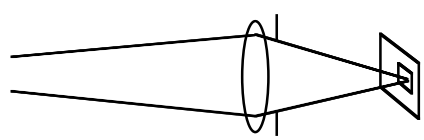
Camera Simulation

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, radiance

***Optics in Photography*. R. Kingslake**

***Photography*, Upton and London**

The Measurement Equation



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

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

Integrate!! Extension of pixel averaging

Paraxial Refraction

Snell's Law

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

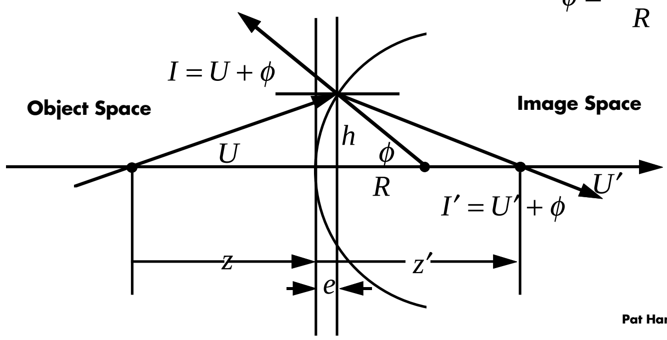
Paraxial approximation

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

$$u = \frac{h}{z}$$

$$u' = -\frac{h}{z'}$$

$$\phi = -\frac{h}{R}$$



Vergence and Power

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

Thin lense equation $V' = V + P$

Surface Power $P = \frac{n' - n}{R}$

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

Focal Points and Focal Lengths

Move lens relative to backplane

Power and focal length

$$P = \frac{n' - n}{R} = \frac{1}{f}$$

Perspective transform

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

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

Thick Lenses

Tessar

Telephoto

Eye

Gullstrand *Schematic Eye*

60 diopters: 43-cornea, 17-lens

Radii of curvature	
Cornea	+7.80mm
Lens	
Anterior	+10.00
Posterior	-6.00
Refractive indices	
Aqueous	1.336
Lens (cumulative)	1.413
Vitreous	1.336

Retinal illumination - Troland (1mm)

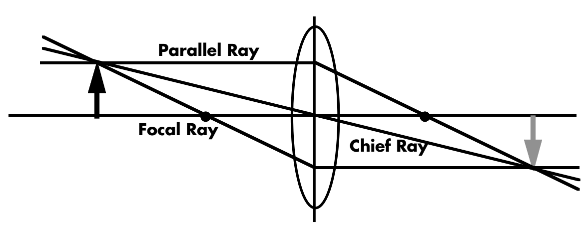
Accomodation/focusing - flatten lens

Refractive anomalies

***Myopia* (near-sighted) focus in front of retina**

***Hyperopia* (far-sighted)**

Ray Tracing



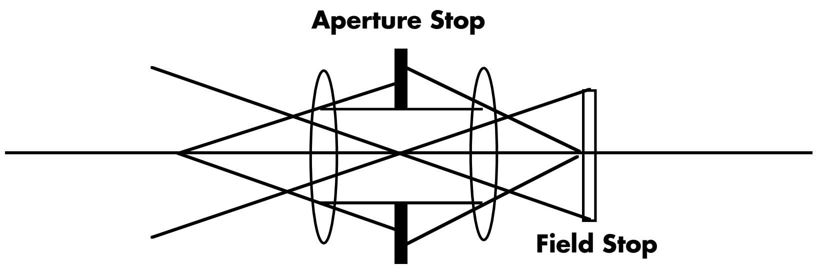
Meridional rays vs. skew rays

Paraxial approximation

Combinations of lenses

Spot diagrams

Stops and Pupils



In any optical system the light passing through is limited in cross-section, either by the finite diameter of the lense, or by diaphragms, called *stops*

Stops - physical limits

Pupils - logical limits

Effective pupils: entering and exiting

Field of View

Eye

- Concentrate 10º (half-angle)
- Resolve 26º
- Detect 60º

Lenses

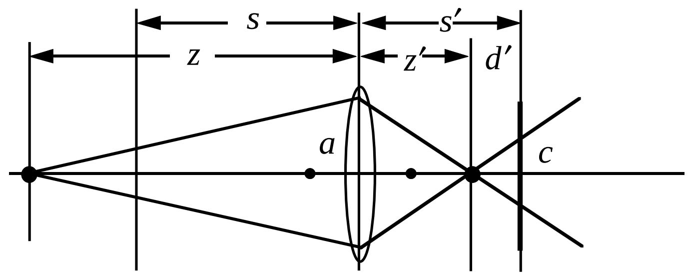
- Normal 26º
  Film diagonal = focal length
- Wide-angle 75-90º
- Narrow-angle 10º

Still vs. Motion

- Still designed for scanning, wider than eye
- Motion narrower (14º)
- Focal length of the projector greater than camera

Circle of Confusion

Image space view:



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

$$\begin{aligned} \frac{c}{a} &= \frac{d'}{z'} \\ &= \frac{s'-z'}{z'} \quad \textit{behind focal} - \textit{plane} \\ &= \frac{z'-s'}{z'} \quad \textit{before focal} - \textit{plane} \end{aligned}$$

Depth of Field

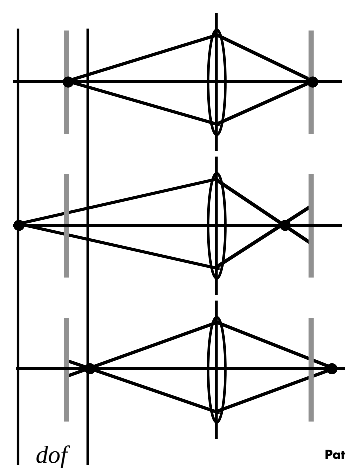
Object space view

- **Resolving power** $\frac{c}{s} \approx \frac{1}{1000}$
- **Depth of field series**

$$\begin{aligned} \frac{c}{a} &= \frac{d}{z} \\ &= \frac{d_f}{s+d_f} \Rightarrow d_f = \frac{s^2}{1000a - s} \\ &= \frac{d_n}{s-d_n} \Rightarrow d_f = \frac{s^2}{1000a + s} \end{aligned}$$

- **Hyperfocal distance**

Due to finite aperture



Camera Exposure

H = E x T

- **Reciprocity failure**
- **Automatic exposure**

Exposure overdetermined

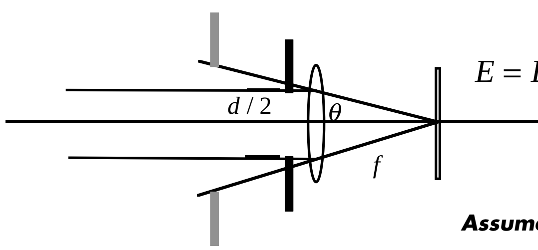
Aperture: f-stop - 1 stop doubles H

Interaction with depth of field

Shutter: Doubling the effective time doubles H

Interaction with motion blur

Image Irradiance



$$E = Lt\,\pi \sin^2\theta = Lt\frac{\pi}{4}\left(\frac{d}{f}\right)^2$$

$$= Lt\frac{\pi}{4}\frac{1}{N^2}$$

Assumes image plane at focal point

F-Stop/F-Number: $d = f / N$

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

1 stop doubles exposure

Shutters

Two types

- **At aperture (Between the lens)**
  - Iris
- **At film plane**
  - Sliding window

Effective vs. total exposure time

- **Opening and closing ramps**
- **Variation with aperture**

Photographic Exposure

Density vs. Transparency

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

Gamma

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

Film speed

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

Non-Ideal Behaviour

Vignetting

- **cos 4**
- **Lens barrel**

Aberations

- **Chromatic**
- **Spherical**
- **Coma, Astigmatism**
- **Distortion**

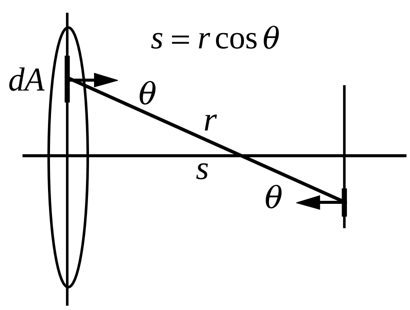
Diffraction

- **Rayleigh's Law**

Non-uniform Exposure

1.

$$E = L\cos\theta\, d\omega$$
$$= L\cos\theta \frac{\cos\theta\, dA}{r^2}$$
$$= \frac{L\, dA}{s^2}\cos^4\theta$$



2. Integrate over off-axis disk

3. Vignetting

Chromatic and Spherical Aberrations

Chromatic

Spherical (caustic)