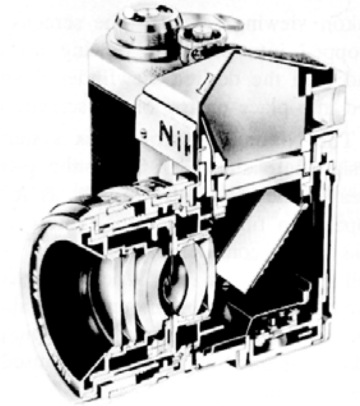
## Camera Simulation



| Effect | Cause |
|---|---|
| Field of view | Film size, stops and pupils |
| Depth of field | Aperture (f-stop), focal length |
| Motion blur | Shutter |
| Exposure | Film speed, aperture, shutter |

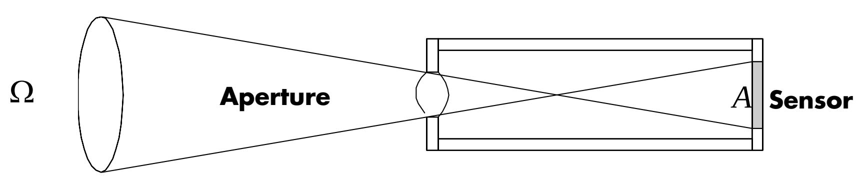
**References**

- Photography, B. London and J. Upton
- Optics in Photography, R. Kingslake



## Sensor Response

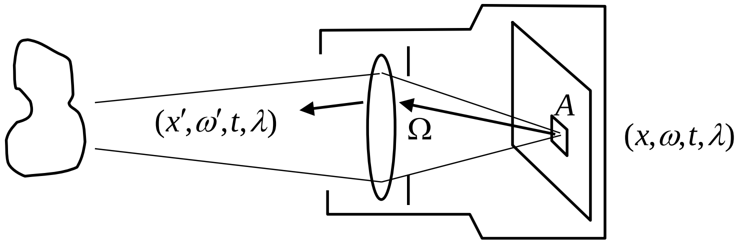
**The response of a sensor is proportional to the radiance of the surface visible to the sensor.**




$$R = \int_A \int_\Omega L \, d\omega \, dA = \overline{L} T$$

$$T = \int_A \int_\Omega d\omega \, dA$$

## The Measurement Equation




$$R = \int_A \int_\Omega \int_T \int_\Lambda P(x,\lambda') S(x,\omega,t) L(T(x,\omega,\lambda),t,\lambda)\, d\vec{A} \bullet d\vec{\omega}\, dt\, d\lambda$$

| | |
|---|---|
| **Pixel response** | $P(x,\lambda)$ |
| **Lense optics** | $(x',\omega') = T(x,\omega,\lambda)$ |
| **Shutter** | $S(x,\omega,t)$ |
| **Scene radiance** | $L(x,\omega,t,\lambda)$ |



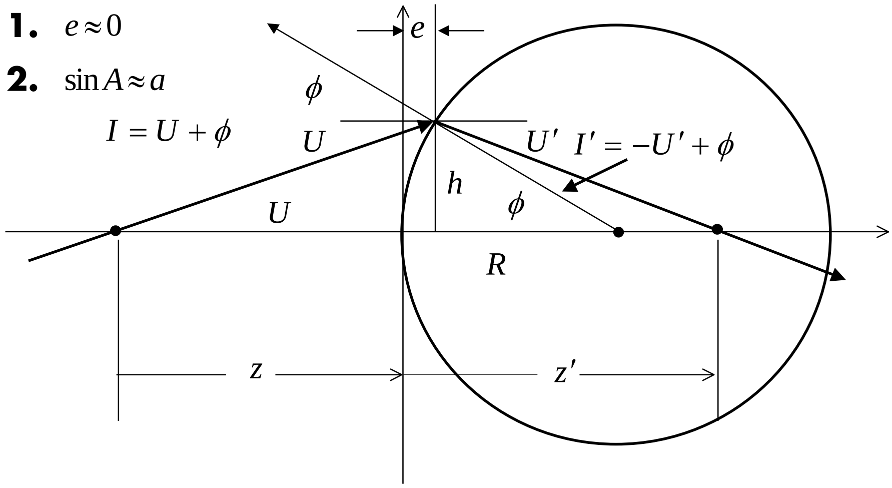
# Lenses

# Paraxial Refraction

## Paraxial approximation

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

$I = U + \phi$






# Derivation

$$I = U + \phi$$
$$I' = -U' + \phi$$

$$n' \sin I' = n \sin I$$
$$n' i' = n i$$
$$n'(-u' + \phi) = n(u + \phi)$$

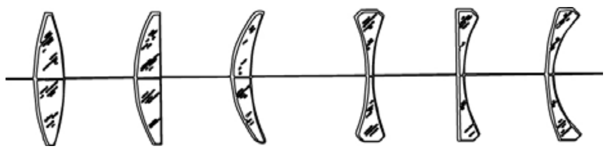
$$n'\left(\frac{h}{z'} - \frac{h}{R}\right) = n\left(\frac{h}{z} - \frac{h}{R}\right)$$
$$\frac{n'}{z'} = \frac{n}{z} + \frac{(n' - n)}{R}$$

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

## Lens-makers Formula

**Refractive Power**

$$P = (n' - n)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) = \frac{1}{f} \quad \left[\frac{1}{m} = diopters\right]$$

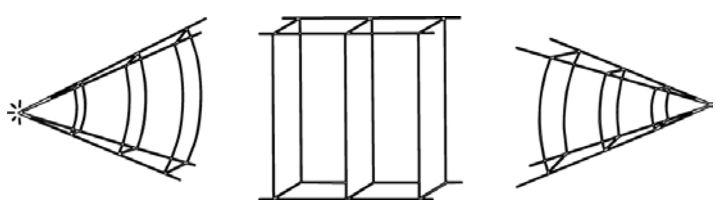


**Biconvex** **Plano-convex**

**Convex = Converging** **Concave = Diverging**



## Thin Lens Equation



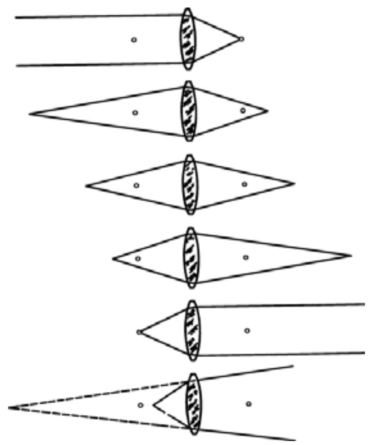
**Vergence** $$V = \frac{n}{r} = \frac{n}{z}$$

**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**



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



## Perspective Transformation

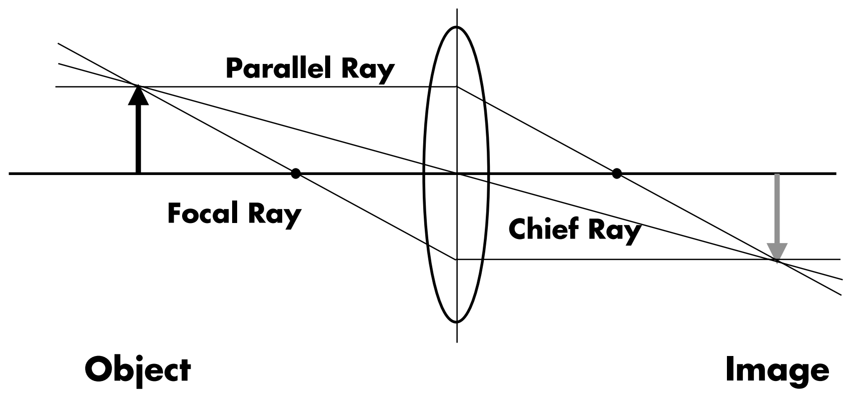
**Thin lens equation**

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

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

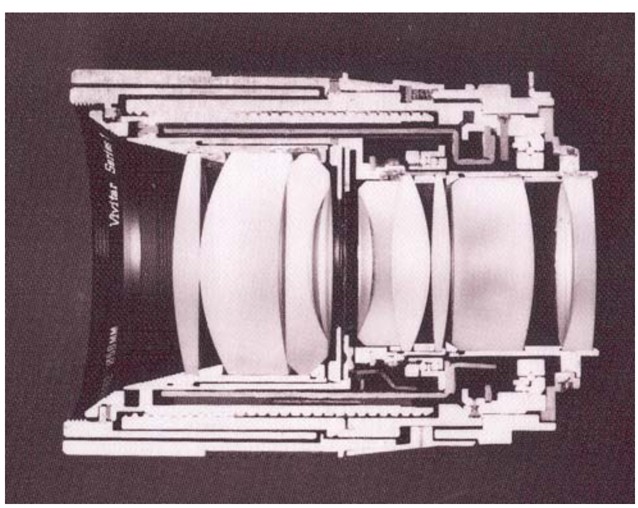
**Represent transformation as a 4x4 matrix**

## Gauss' Ray Tracing Construction



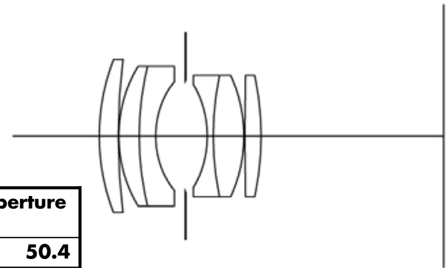



## Real Lens



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

## Double Gauss



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

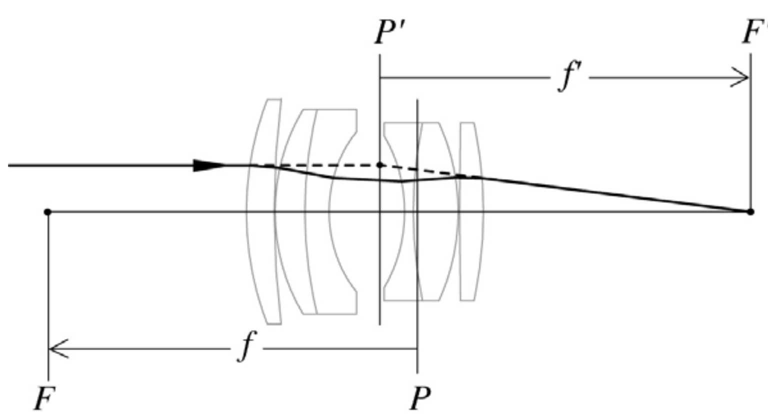
| Radius (mm) | Thick (mm) | $n_d$ | V-no | aperture |
|---|---|---|---|---|
| 58.950 | 7.520 | 1.670 | 47.1 | 50.4 |
| 169.660 | 0.240 | | | 50.4 |
| 38.550 | 8.050 | 1.670 | 47.1 | 46.0 |
| 81.540 | 6.550 | 1.699 | 30.1 | 46.0 |
| 25.500 | 11.410 | | | 36.0 |
| | 9.000 | | | 34.2 |
| -28.990 | 2.360 | 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 |

**Positive radii = convex**

**Negative radii = concave**



## Thick Lenses




***Measure distances from principal planes***

# Ray Tracing Through Lenses

200 mm telephoto

35 mm wide-angle

50 mm double-gauss

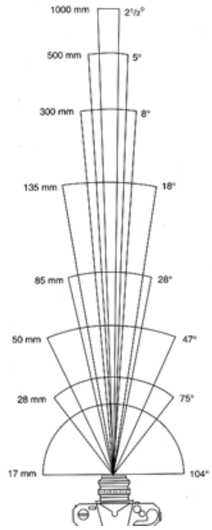
16 mm fisheye

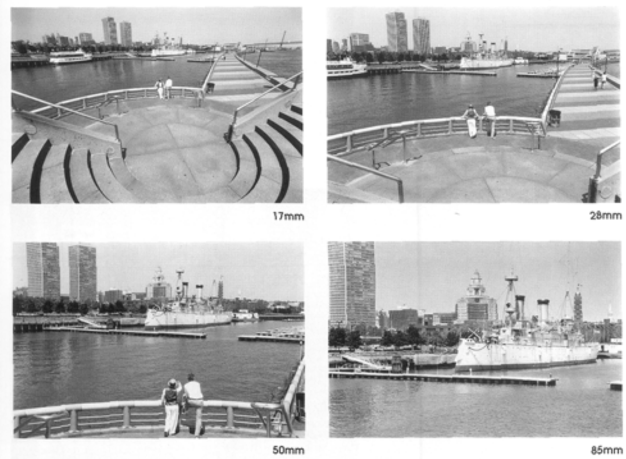
From Kolb, Mitchell and Hanrahan (1995)



# Field of View

# Field of View

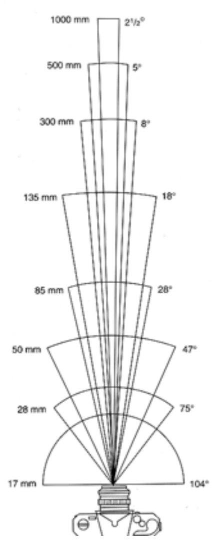


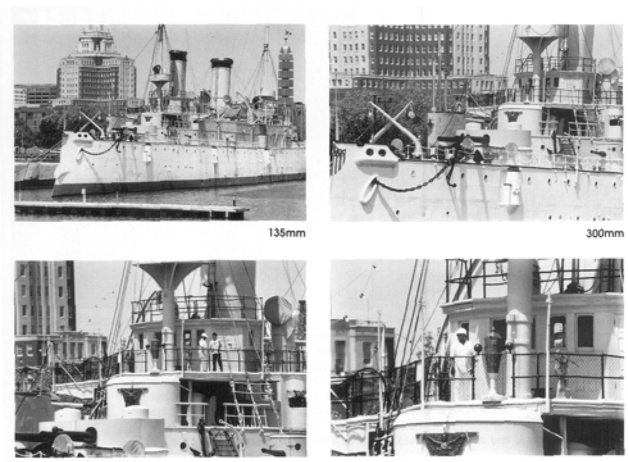




From London and Upton



# Field of View



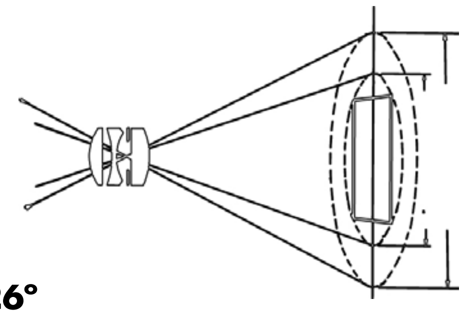

From London and Upton

# Field of View

**Field of view**

$$\tan\frac{fov}{2} = \frac{filmsize}{f}$$

**Redrawn from Kingslake, *Optics in Photography***

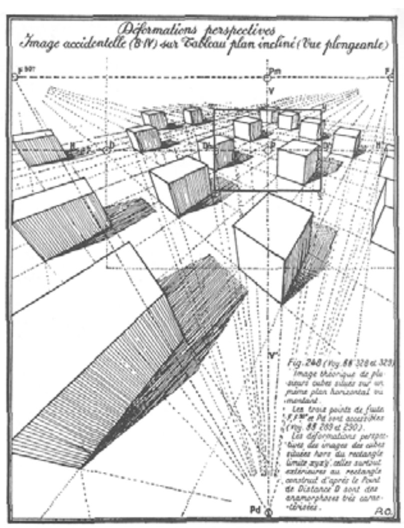


**Types of lenses**

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

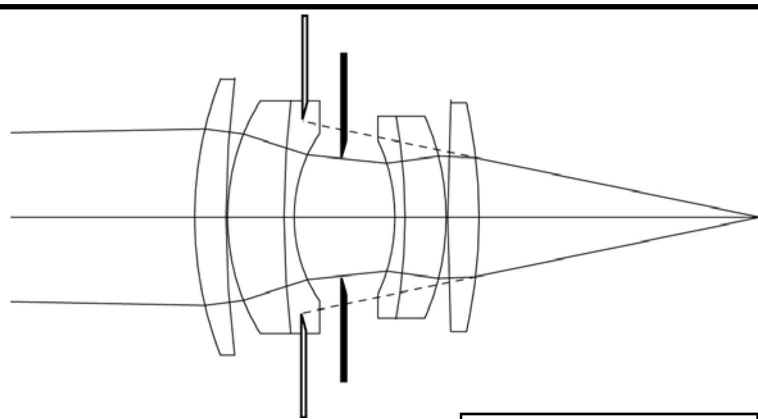


# Perspective Distortion




From Olmer, Perspective Artistique

## Stops and Pupils



Stops - physical limits

Pupils - logical limits

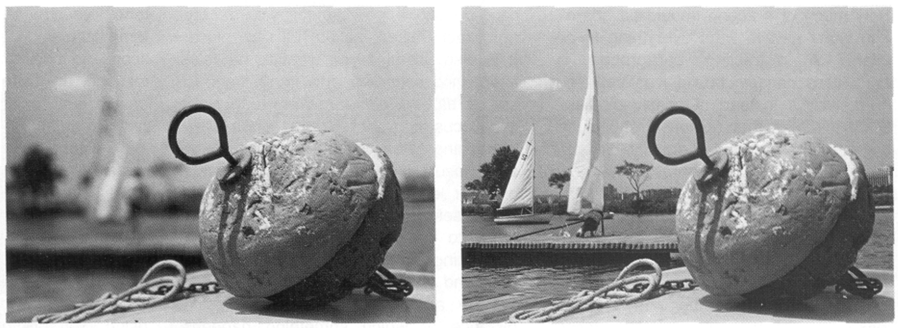
Exit and entry pupil

Finite Aperture
1. Depth of field
2. Collects light



## Depth of Field

## Depth of Field

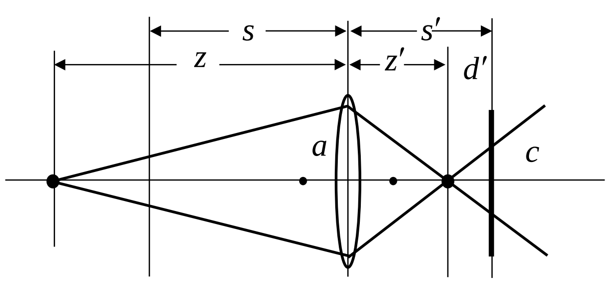



**From London and Upton**



## 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**

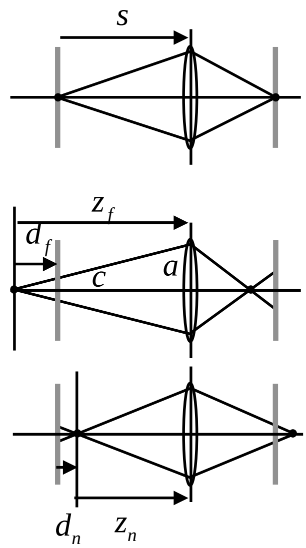
$$\frac{c}{s} = \frac{1}{1000}$$

- **Depth of field: equal c**

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

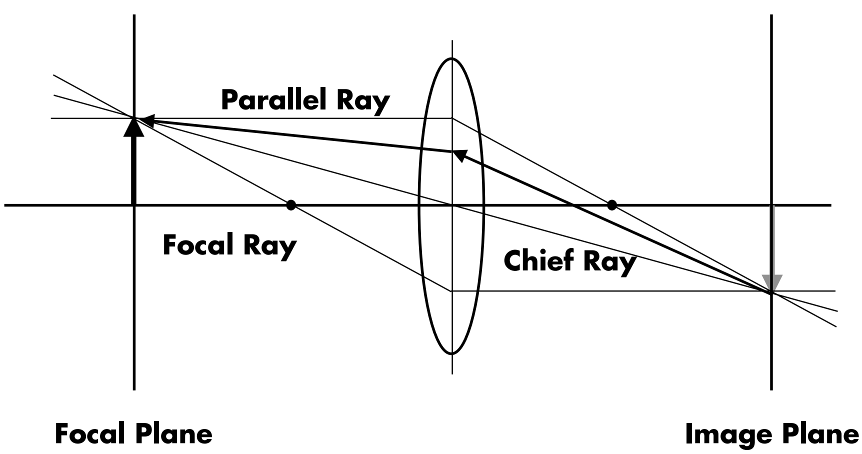
- **Hyperfocal distance**

$$z_n$$
$$z_f = \infty$$



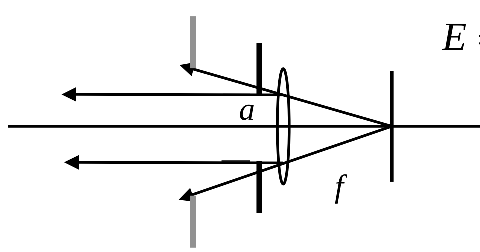



# Ray Tracing: Finite Aperture



# Exposure

## Image Irradiance




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

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

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

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

**1 stop doubles exposure**

## Camera Exposure

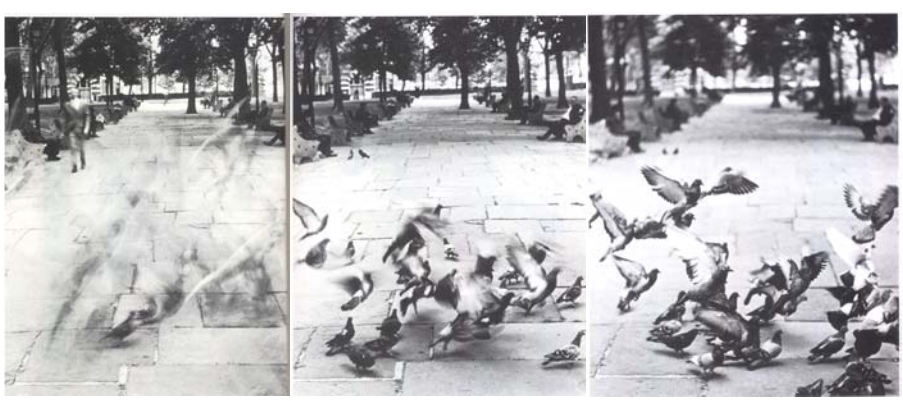
**Exposure** $H = E \times T$

**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**



## Aperture vs Shutter



**f/16 1/8s** **f/4 1/125s** **f/2 1/500s**

**From London and Upton**

# Photographic Exposure

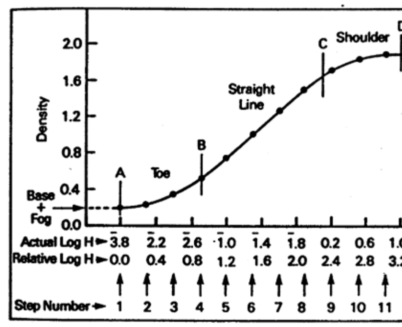
**Density vs. Transparency**

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

**Gamma**

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

**Film speed**




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



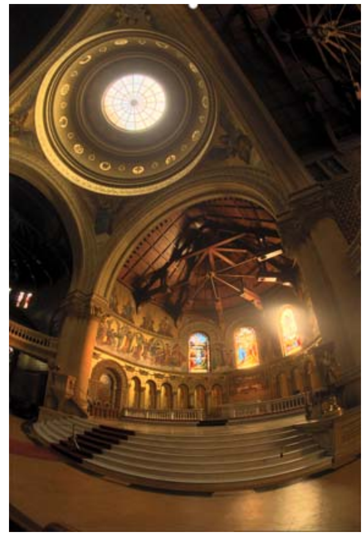
# High Dynamic Range

**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.**

# Simulated Photograph

Adaptive histogram



With glare, contrast, blur