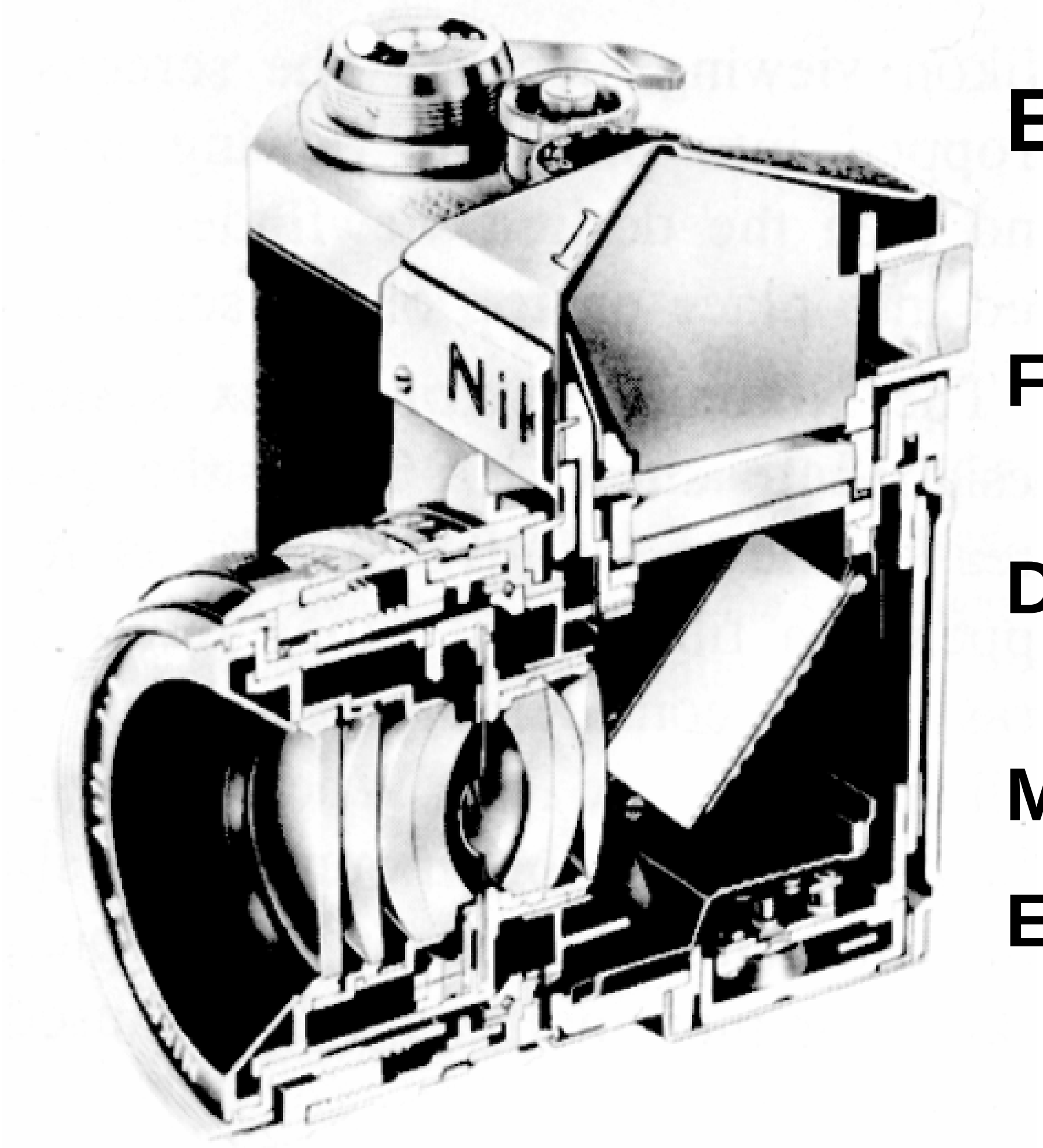
Cameras and Lenses

Ian Buck

CS 348b Spring 2003

(Many slides courtesy of Pat Hanrahan)

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

Interesting Cameras

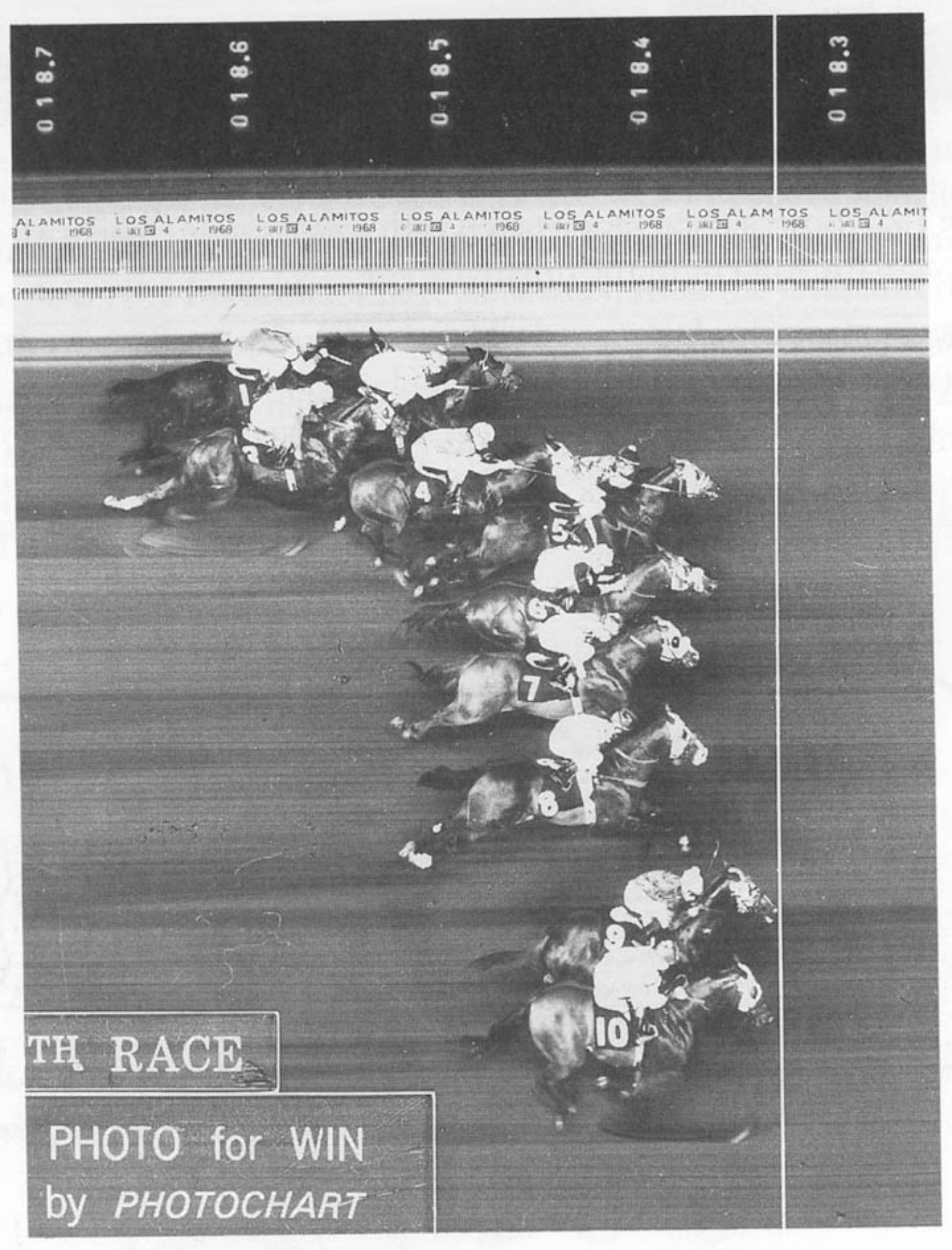


Figure 1.22. An actual photograph of a horse race in which ten quarterhorses were bunched together at the finish line. The time marker at the top was started when the starting gate opened, so that the winning horse's time was 18.33 seconds.

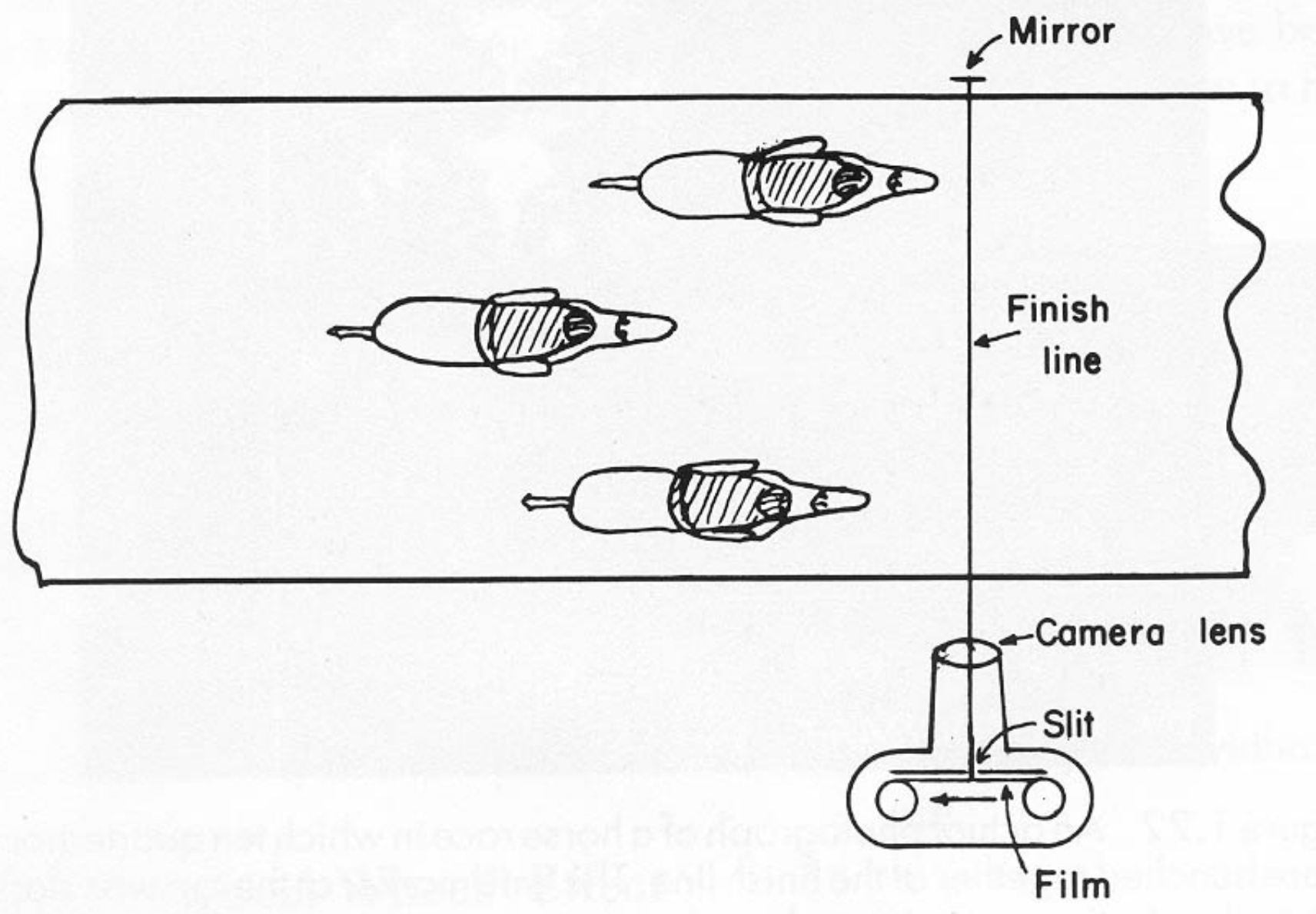


Figure 1.21. Schematic diagram of a race-track camera, with a narrow slit in front of the moving film to photograph only events along the finish line.

From *Optics in Photography*, Rudolf Kingslake

Interesting Cameras

First Prize of the A.C.F Dieppe
Jaques Henry Lartigue

From *Optics in Photography*, Rudolf Kingslake

Interesting Cameras

Interesting Cameras

Interesting Cameras

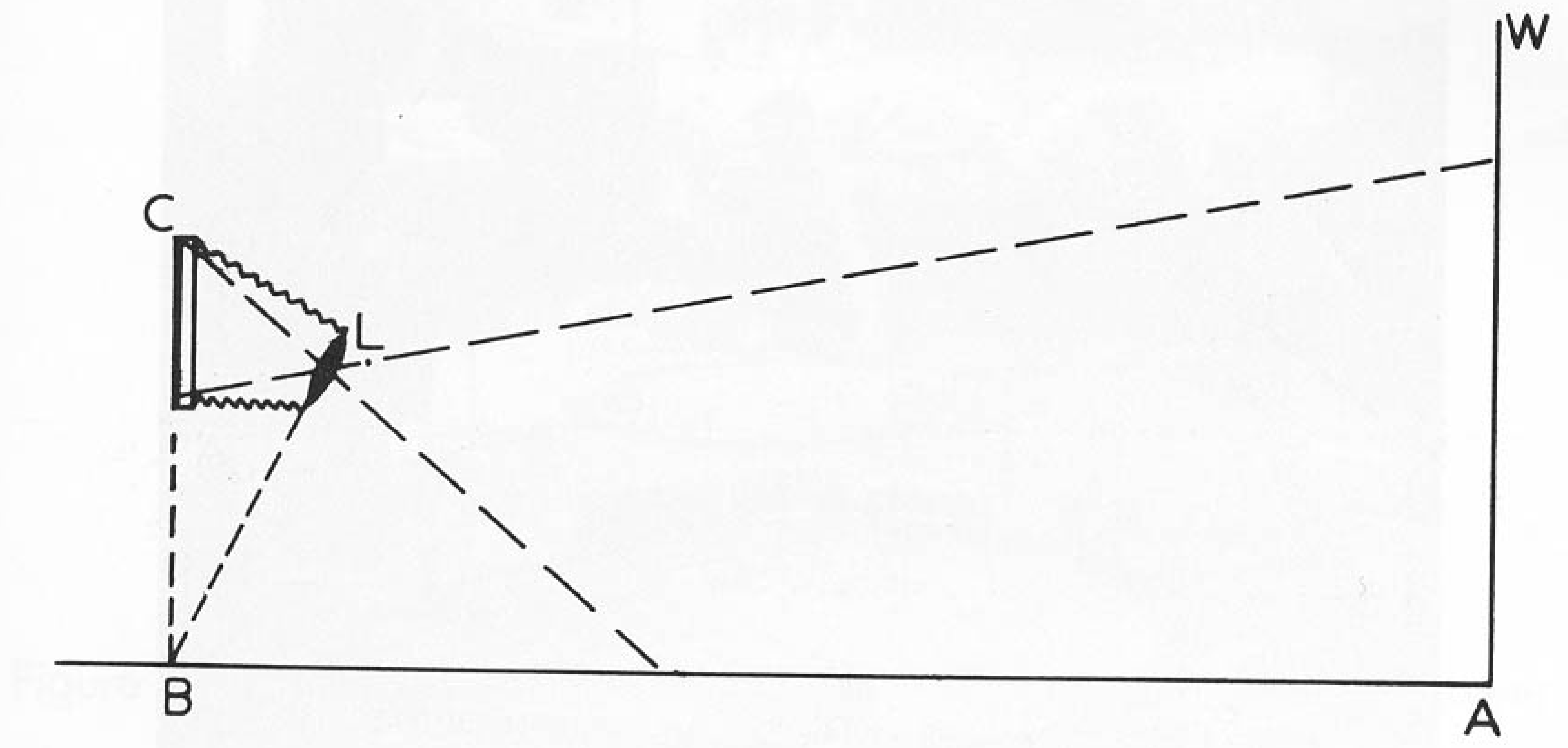
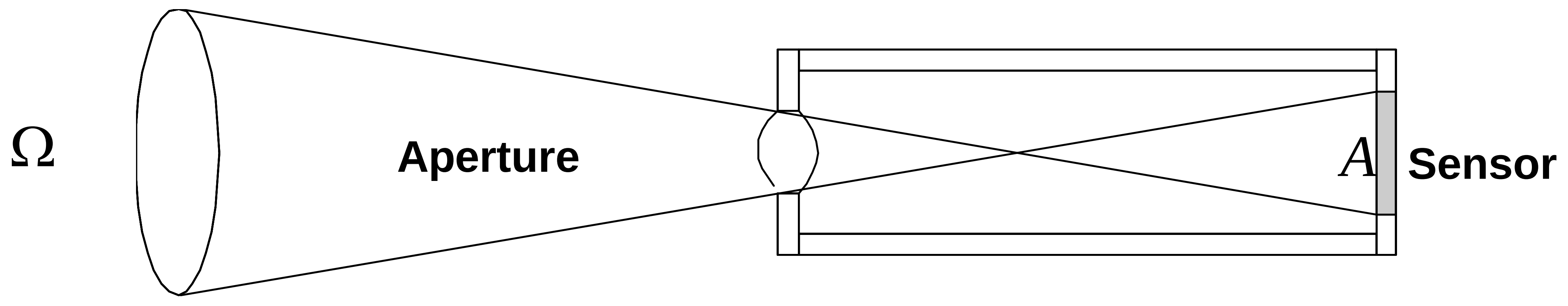


Figure 2.9. Arrangement for photographing a carpet, with vertical lines parallel.

From *Optics in Photography*, Rudolf Kingslake

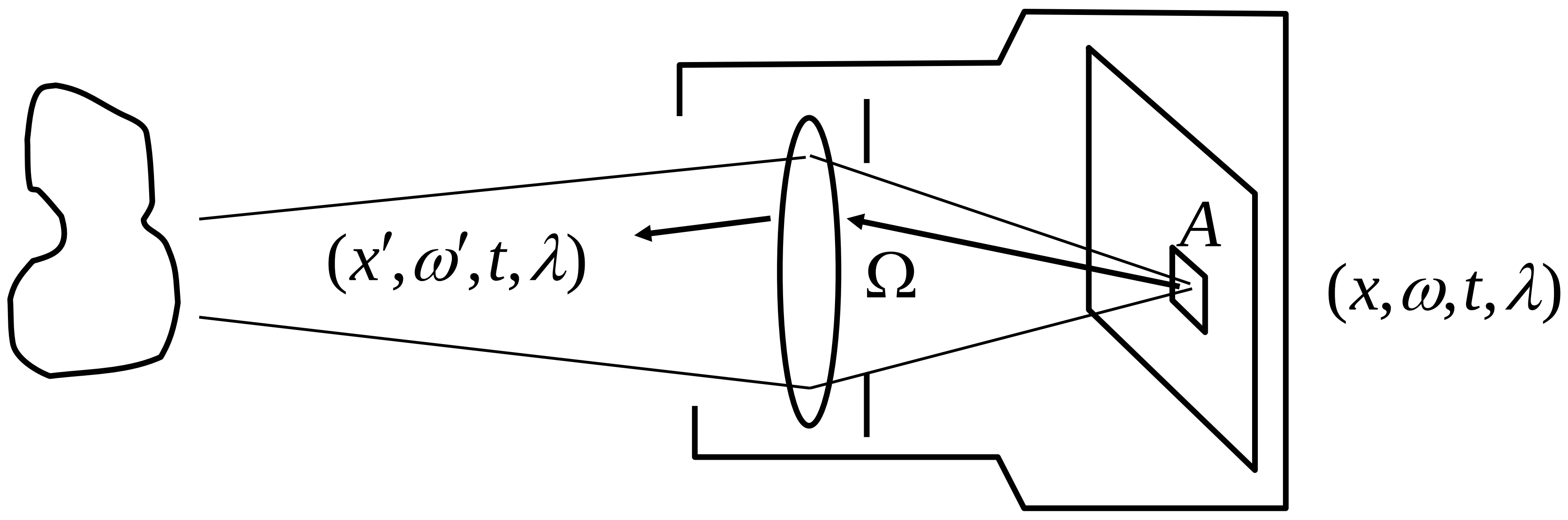
Sensor Response

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



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

The Measurement Equation



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

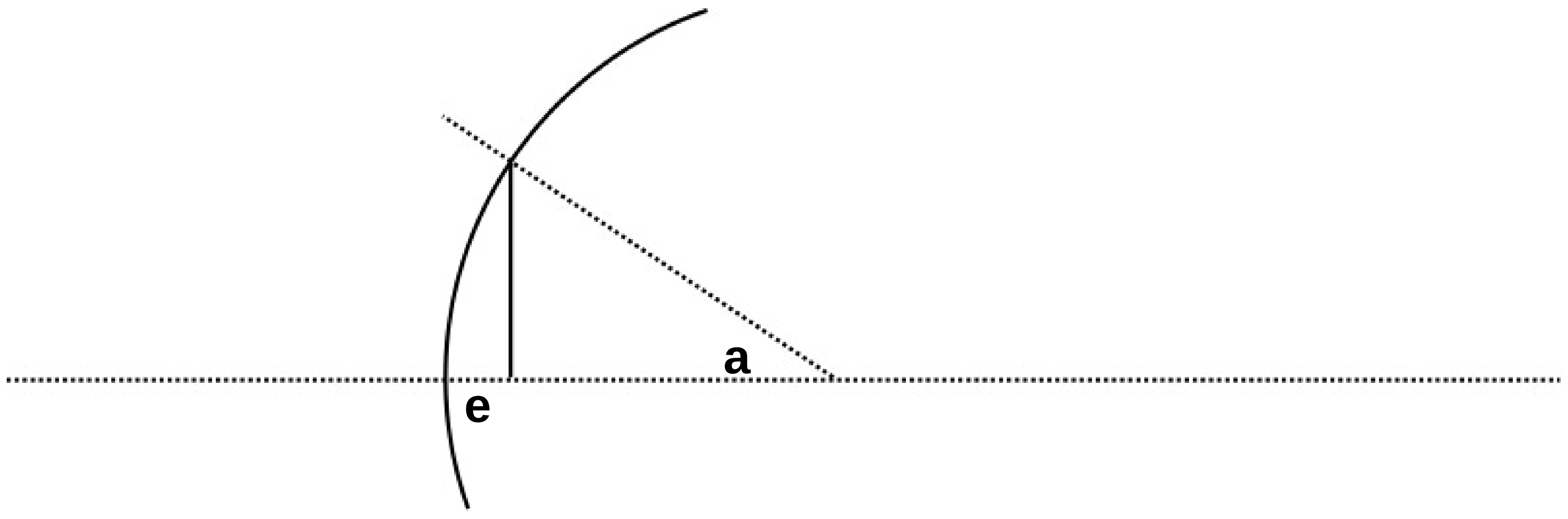
Pixel response	$P(x,\lambda)$
Lense optics	$(x',\omega')=T(x,\omega,\lambda)$
Shutter	$S(x,\omega,t)$
Scene radiance	$L(x,\omega,t,\lambda)$

Lenses

Paraxial Refraction

Paraxial approximation

1. **e = 0**
2. **sin a = a**

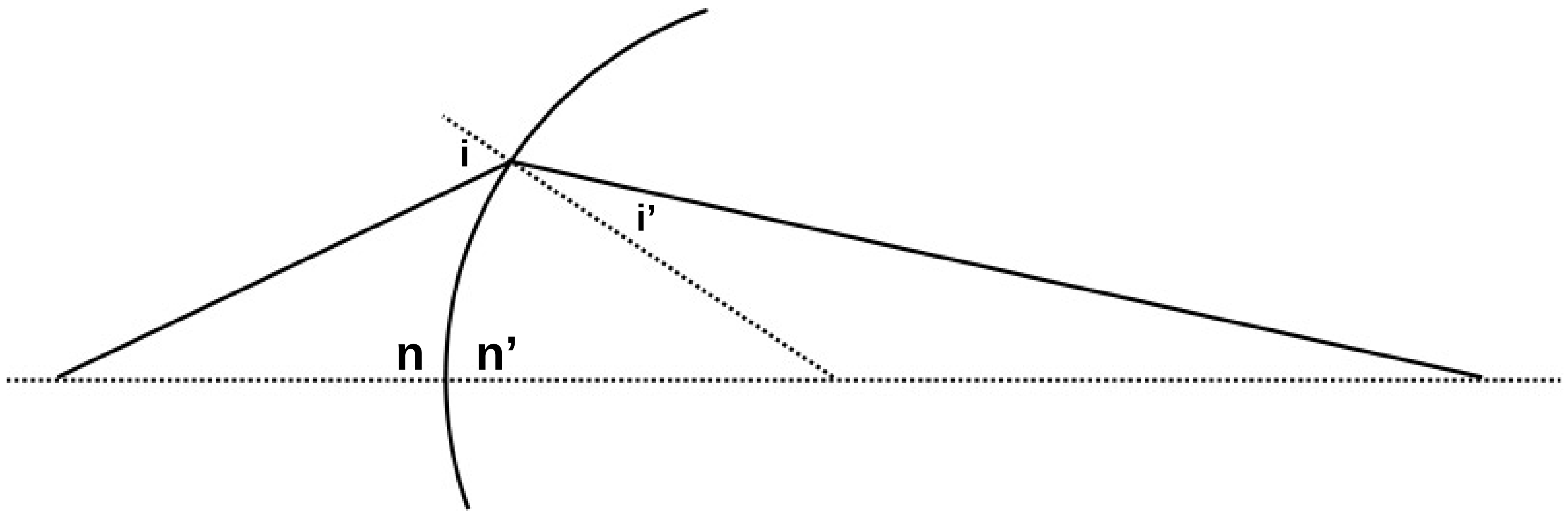


Paraxial Refraction

Snells Law

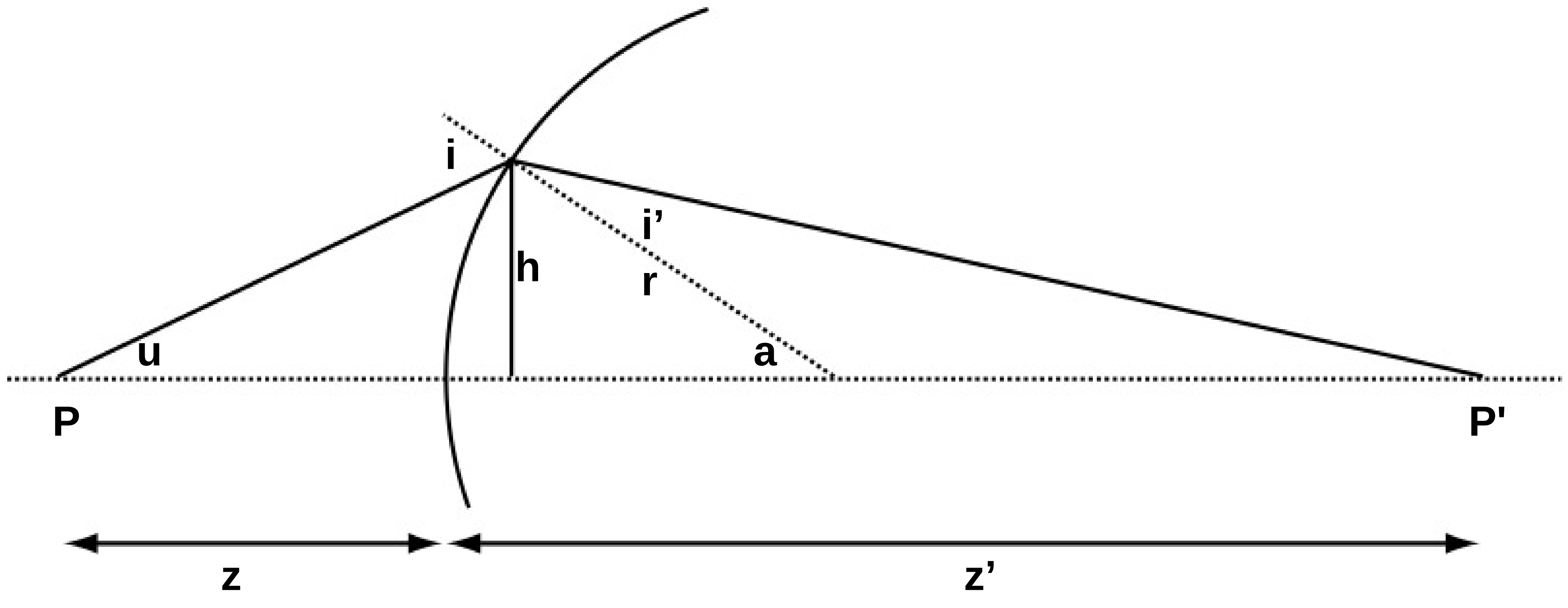
n sin i = n’ sin i’

n i = n’ i’

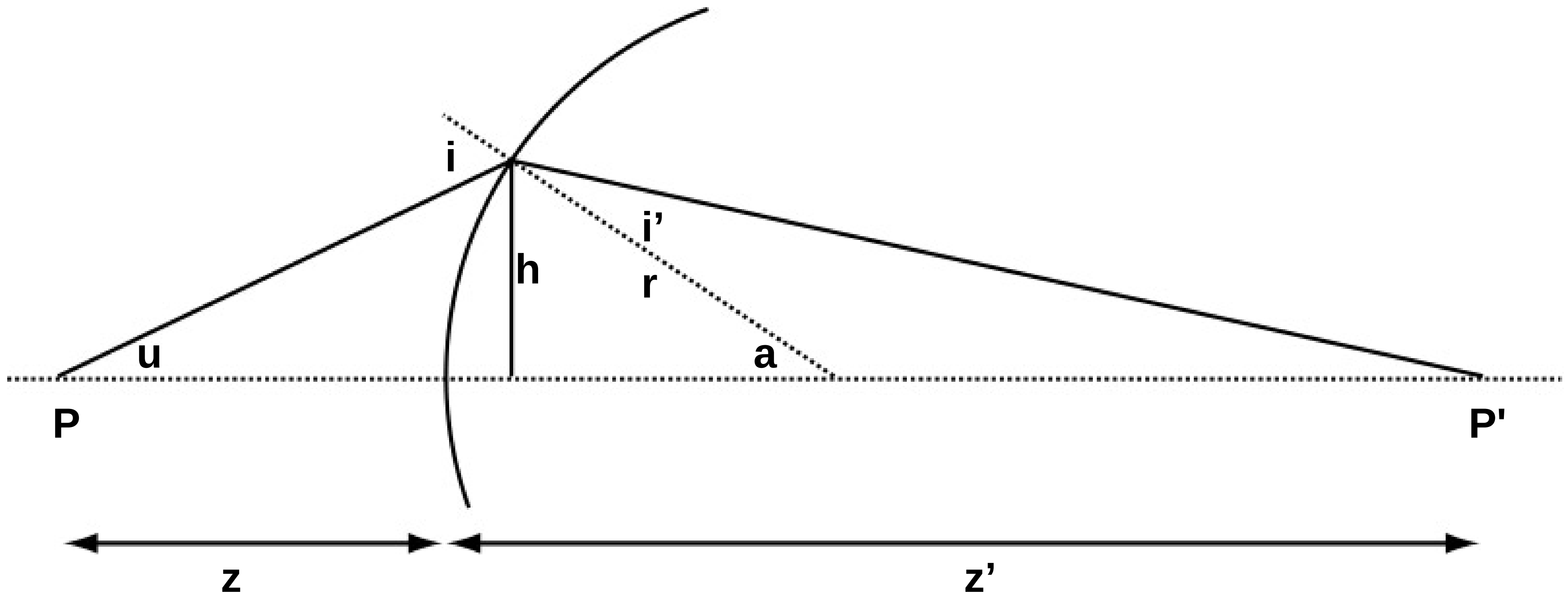


Paraxial Refraction

What is z’?



Paraxial Refraction



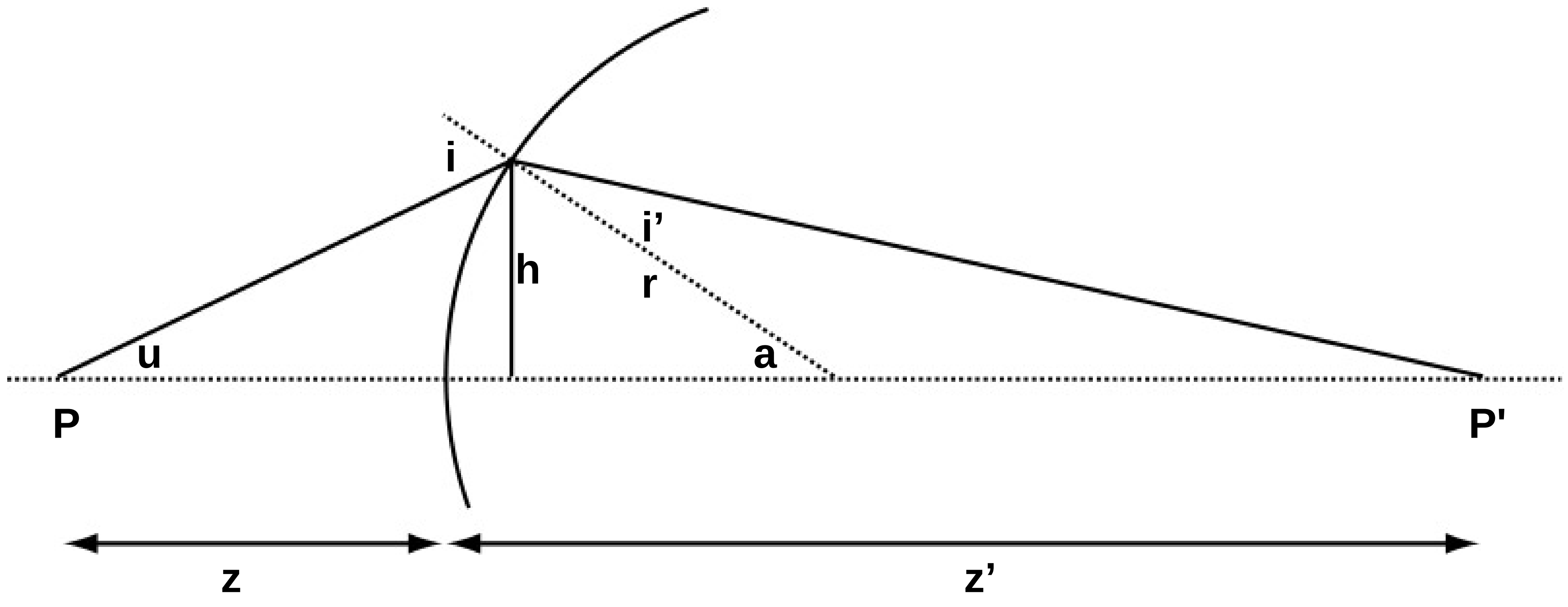
$i = u + a$ $a = u' + i'$

$u = h / z$ $u' = h / z'$

$a = h / r$

$n\, i = n'\, i'$

Paraxial Refraction



$i = u + a$ $\quad$ $a = u' + i'$

$u = h / z$ $\quad$ $u' = h / z'$

$a = h / r$

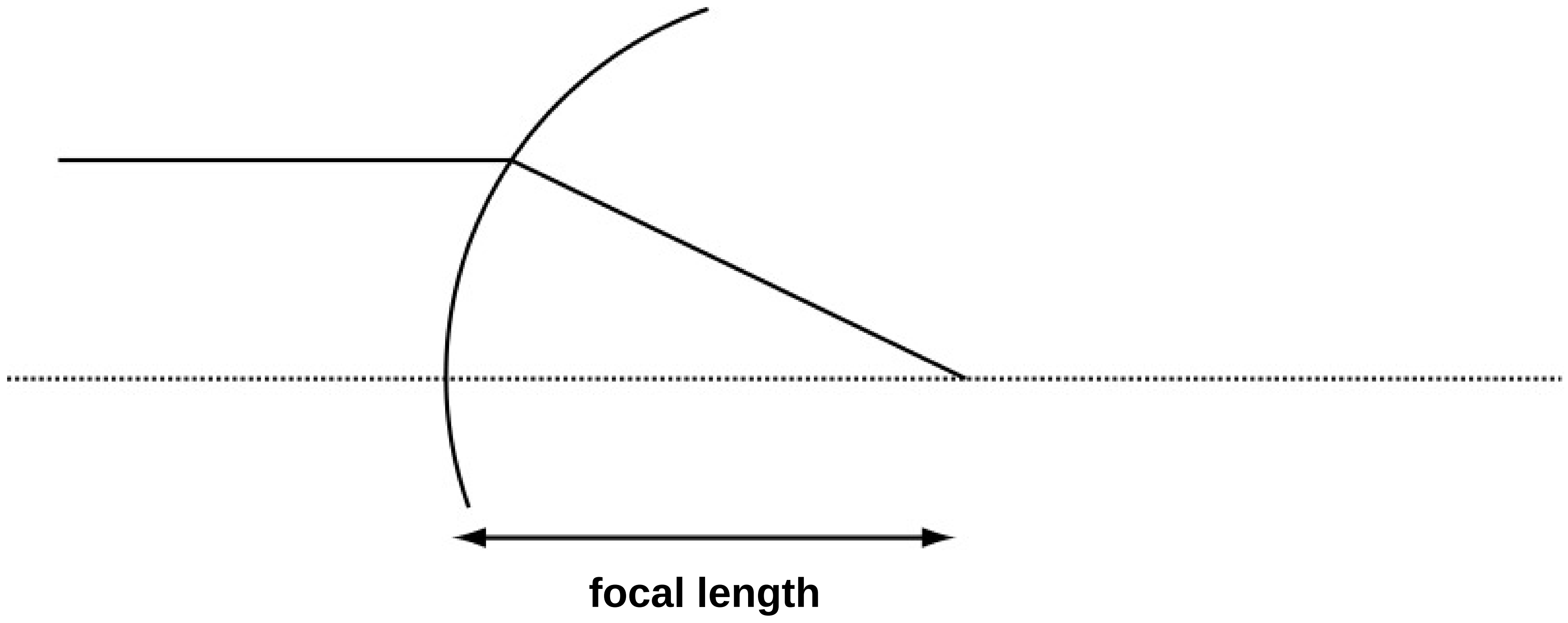
$n\, i = n'\, i'$

$n\,(u + a) = n'\,(u' - a)$

$n\,(h/z + h/r) = n'\,(h/z' - h/r)$

$$\boxed{n/z + n/r = n'/z' - n'/r}$$

Focal length



$z = \text{inf}$

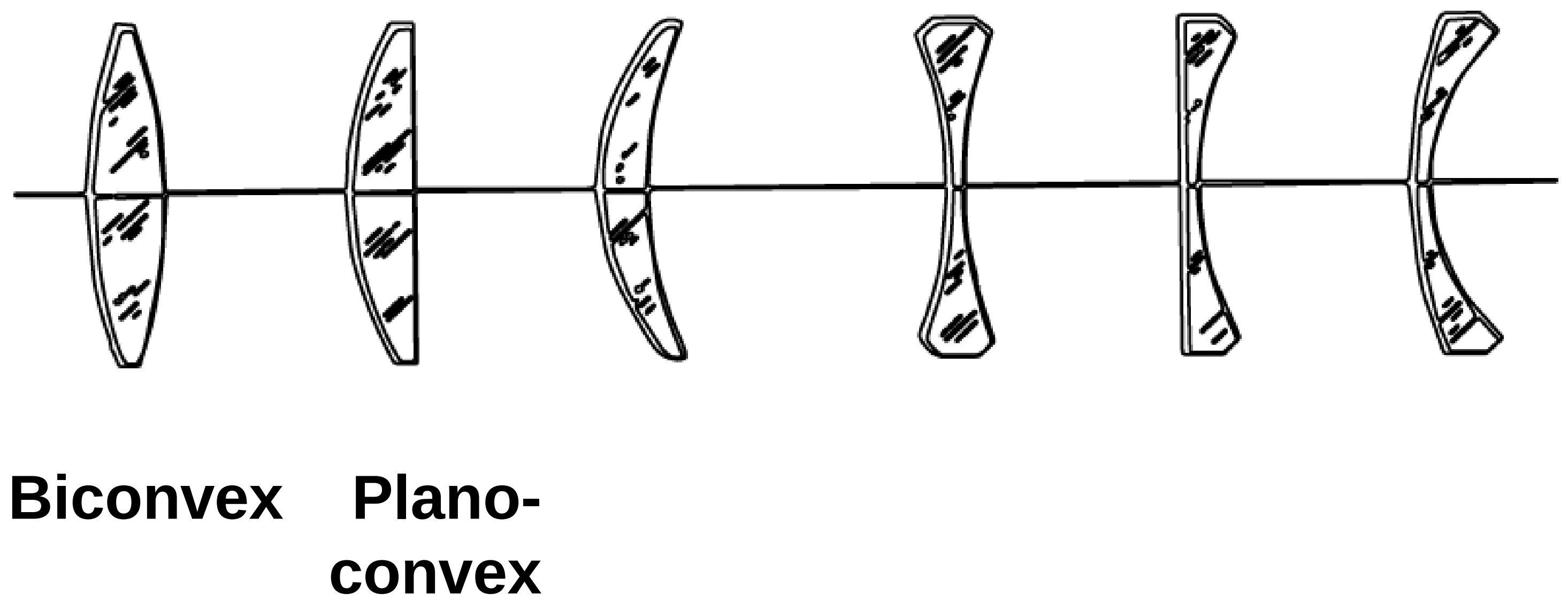
$n/r = n'/z' - n'/r$

$z' = f =$ focal length

Lens-makers Formula

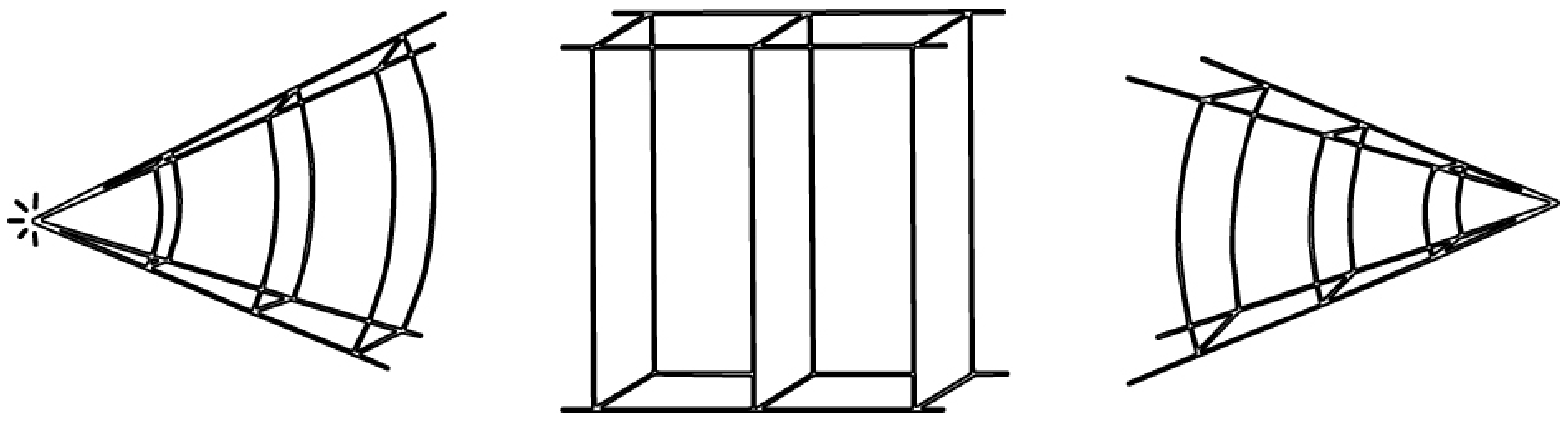
Refractive Power

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



Convex = Converging **Concave = Diverging**

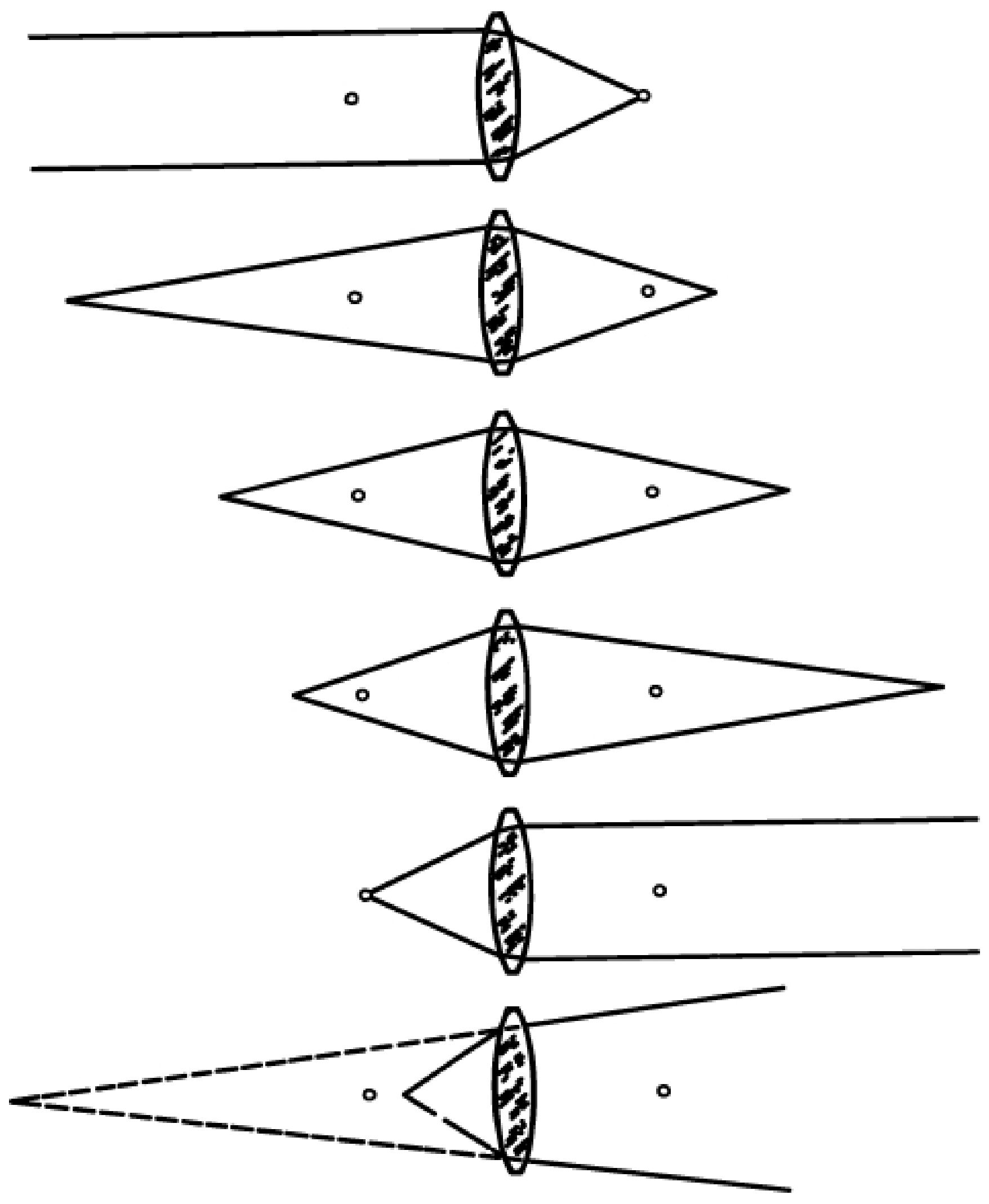
Thin Lens Equation



Thin lens equation $$\frac{1}{z'} = \frac{1}{z} + \frac{1}{f}$$

Focal Points and Focal Lengths

To focus: move lens relative to backplane



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

Perspective Transformation

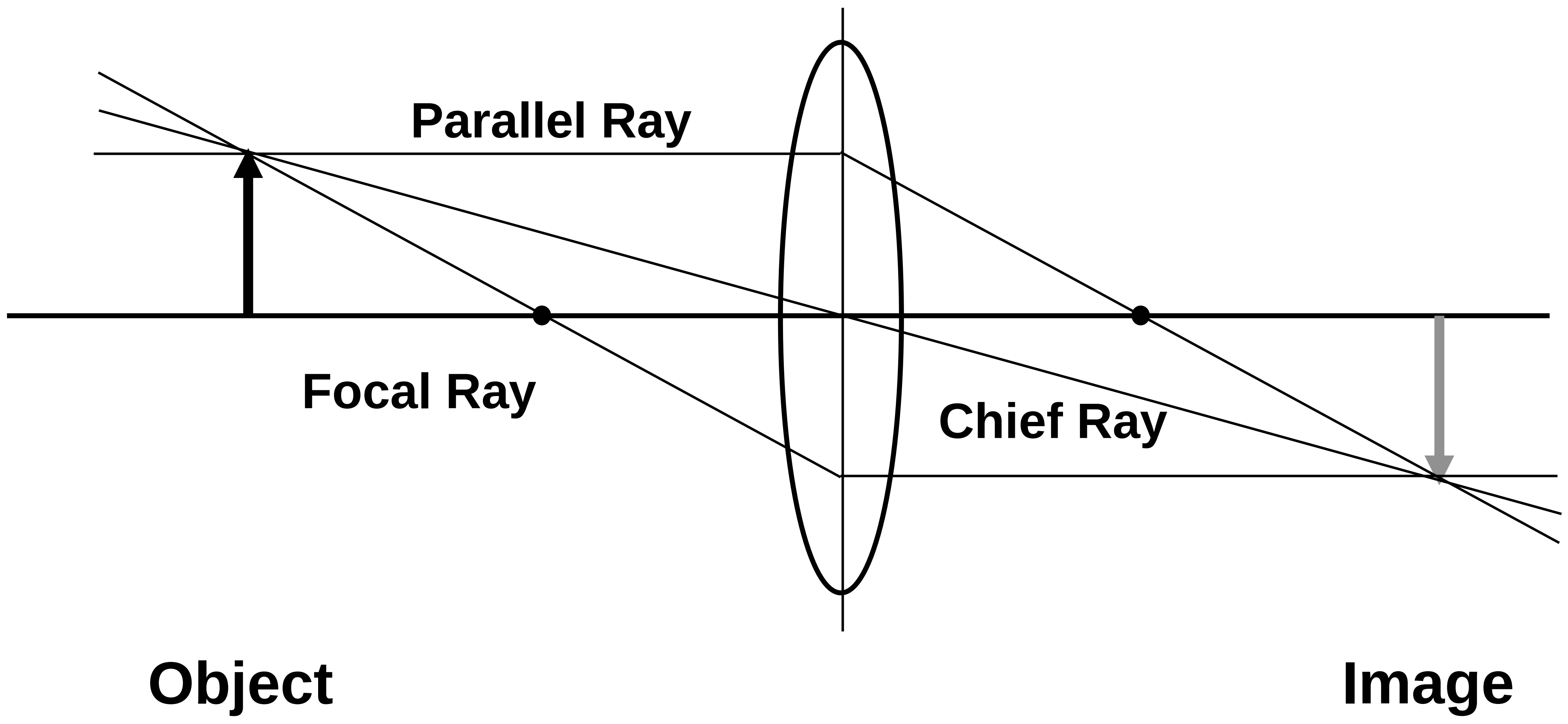
Thin lens equation

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

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

Represent transformation as a 4x4 matrix

Gauss' Ray Tracing Construction


Parallel Ray

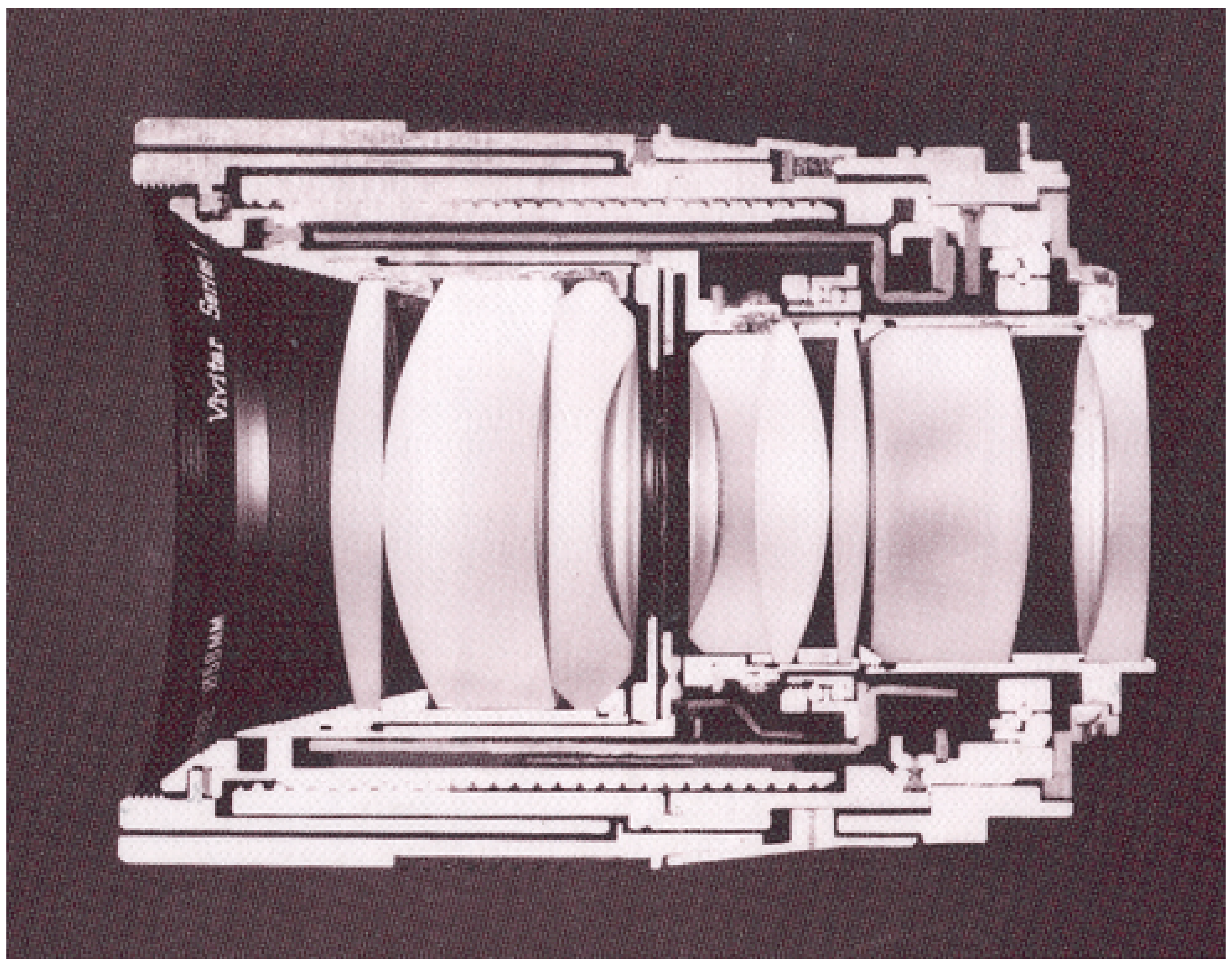
Focal Ray

Chief Ray

Object

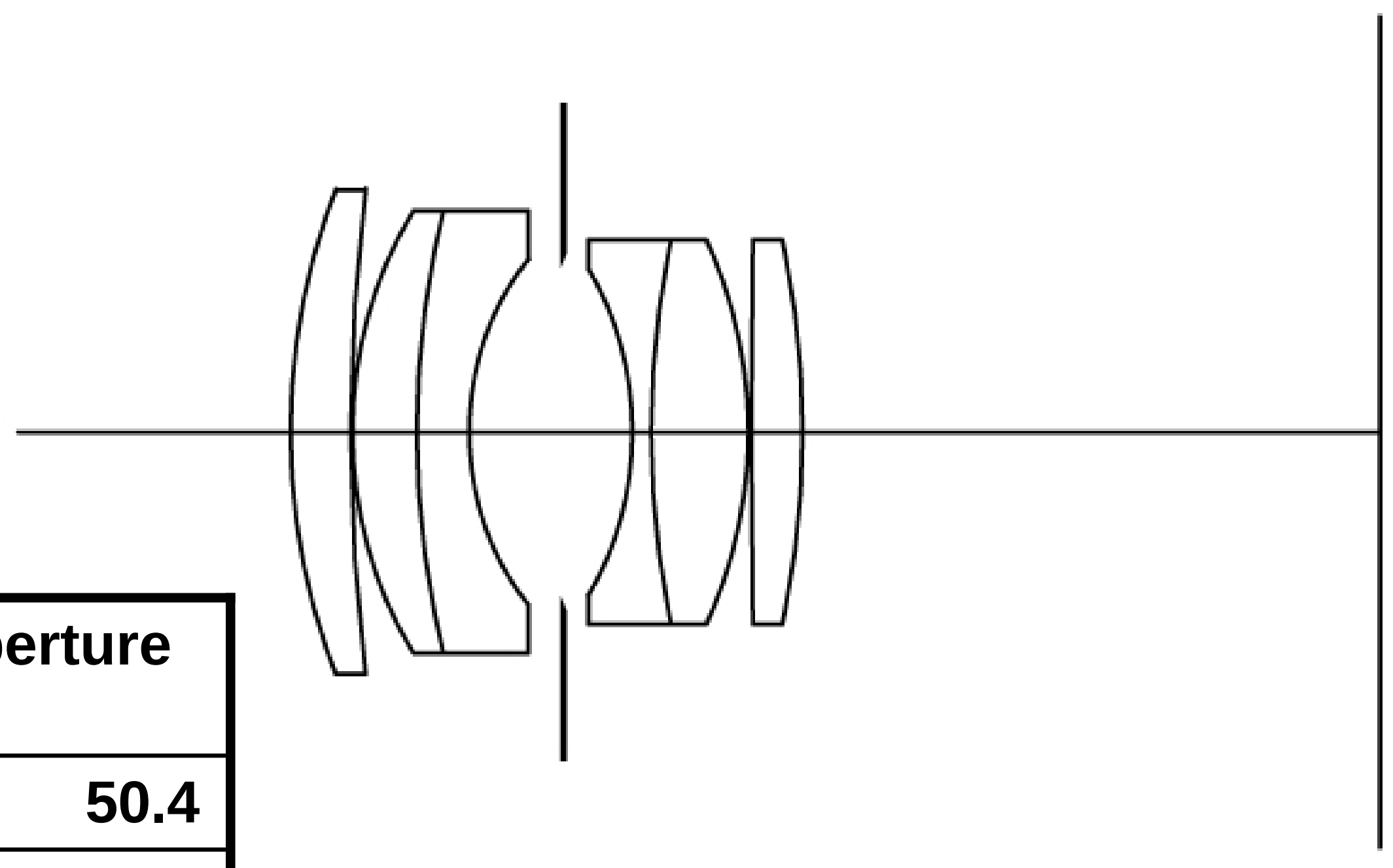
Image

Real Lens



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

Double Gauss



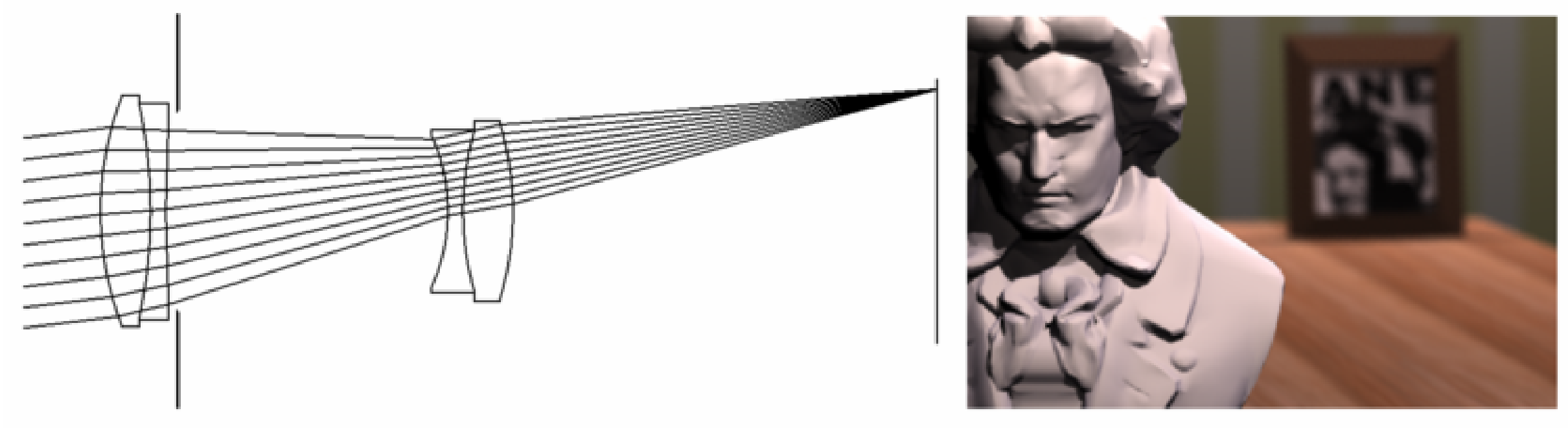
Data from W. Smith,
Modern Lens Design, p 312

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

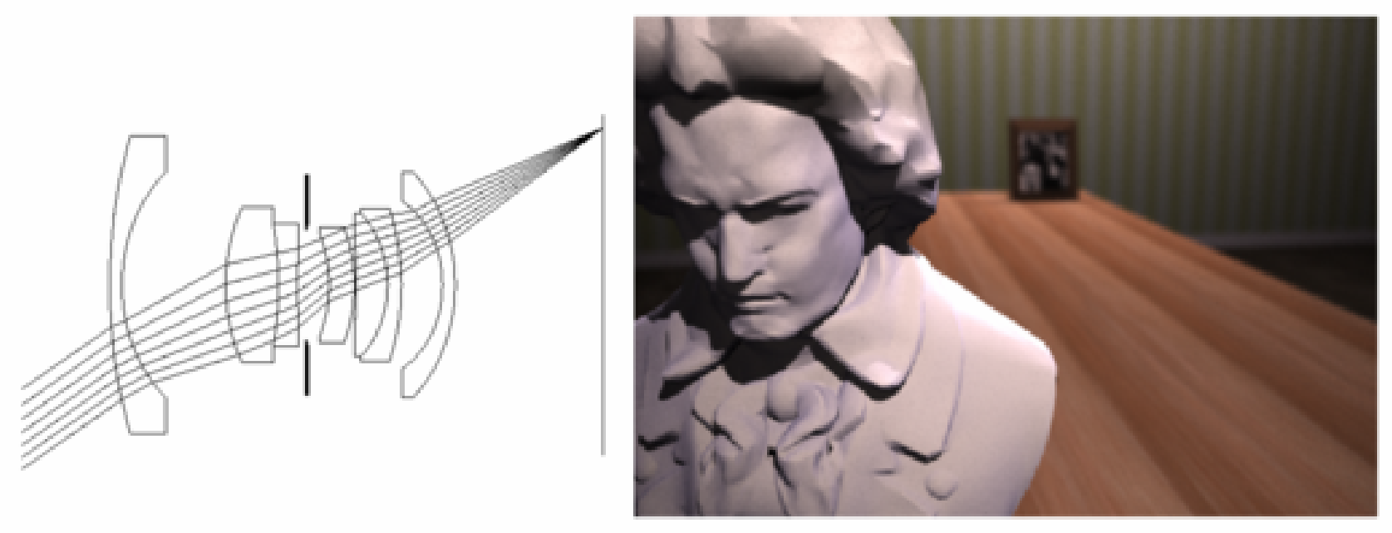
Positive radii = convex

Negative radii = concave

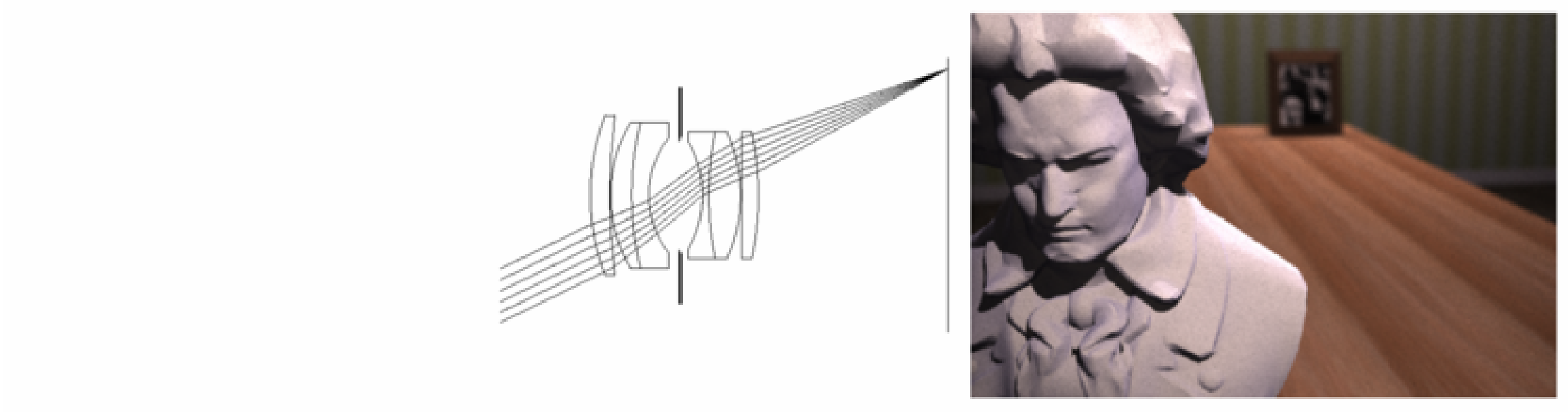
Ray Tracing Through Lenses



200 mm telephoto



35 mm wide-angle



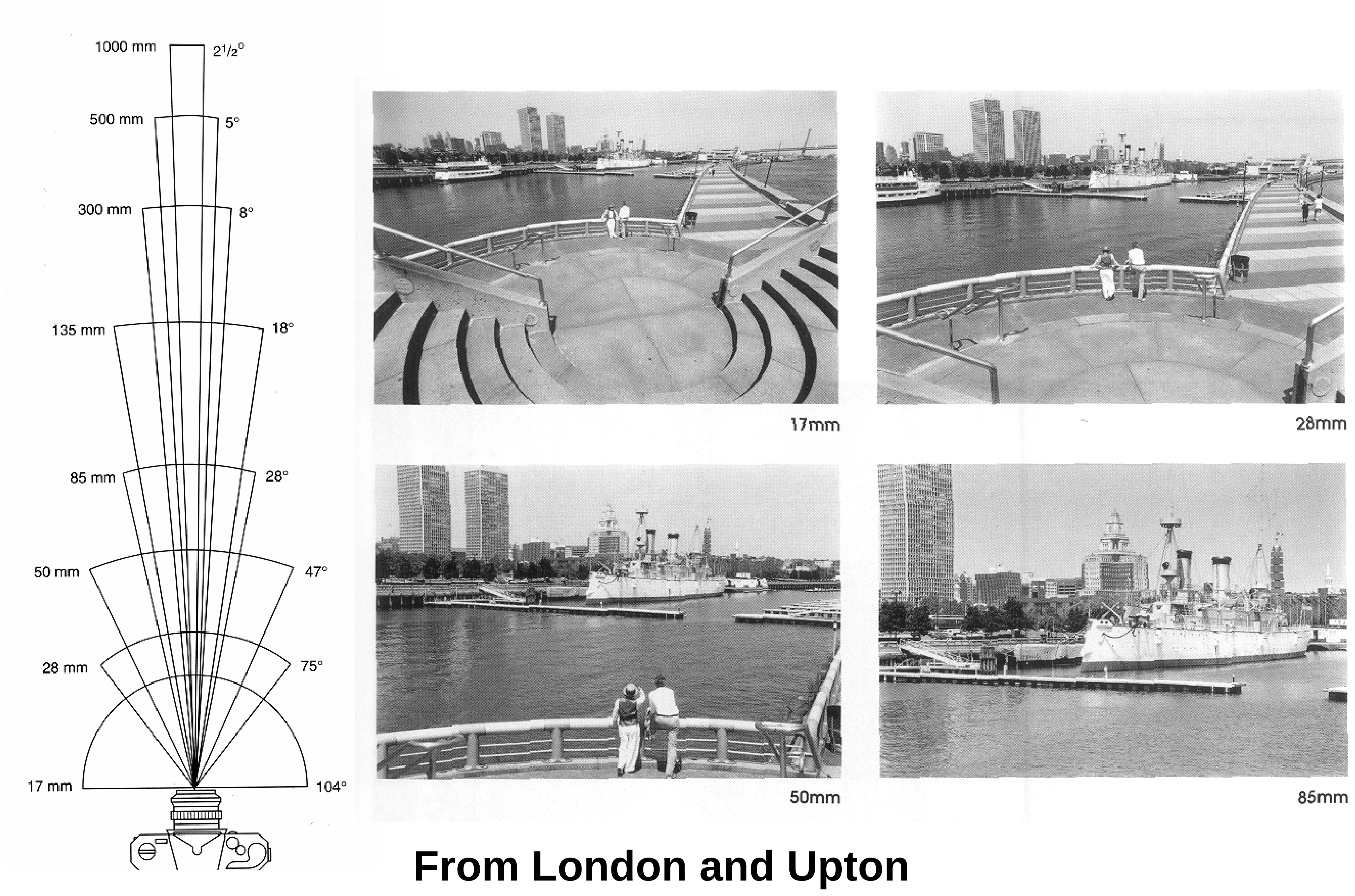
50 mm double-gauss

16 mm fisheye

From Kolb, Mitchell and Hanrahan (1995)

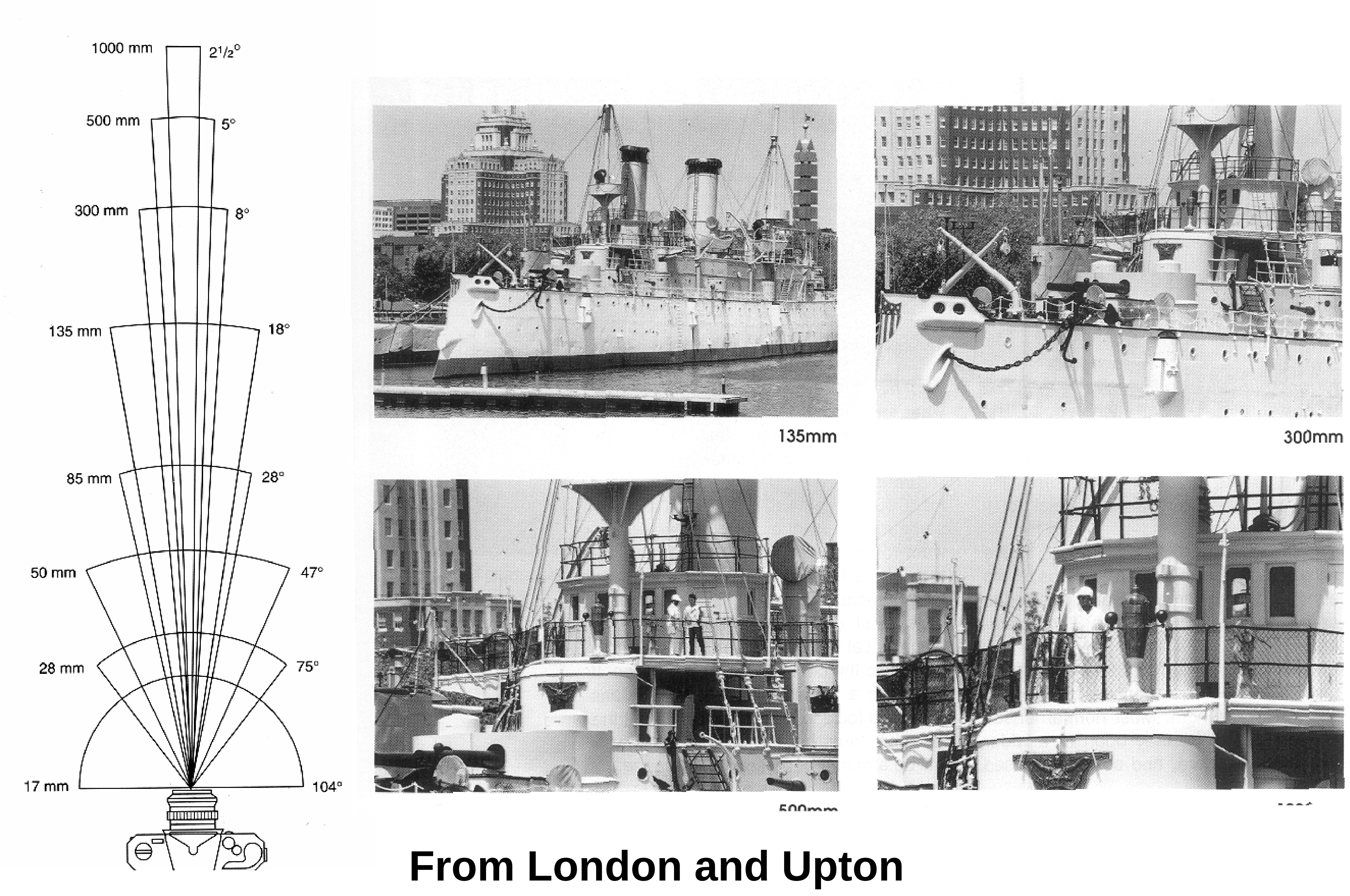
Field of View

Field of View



From London and Upton

Field of View



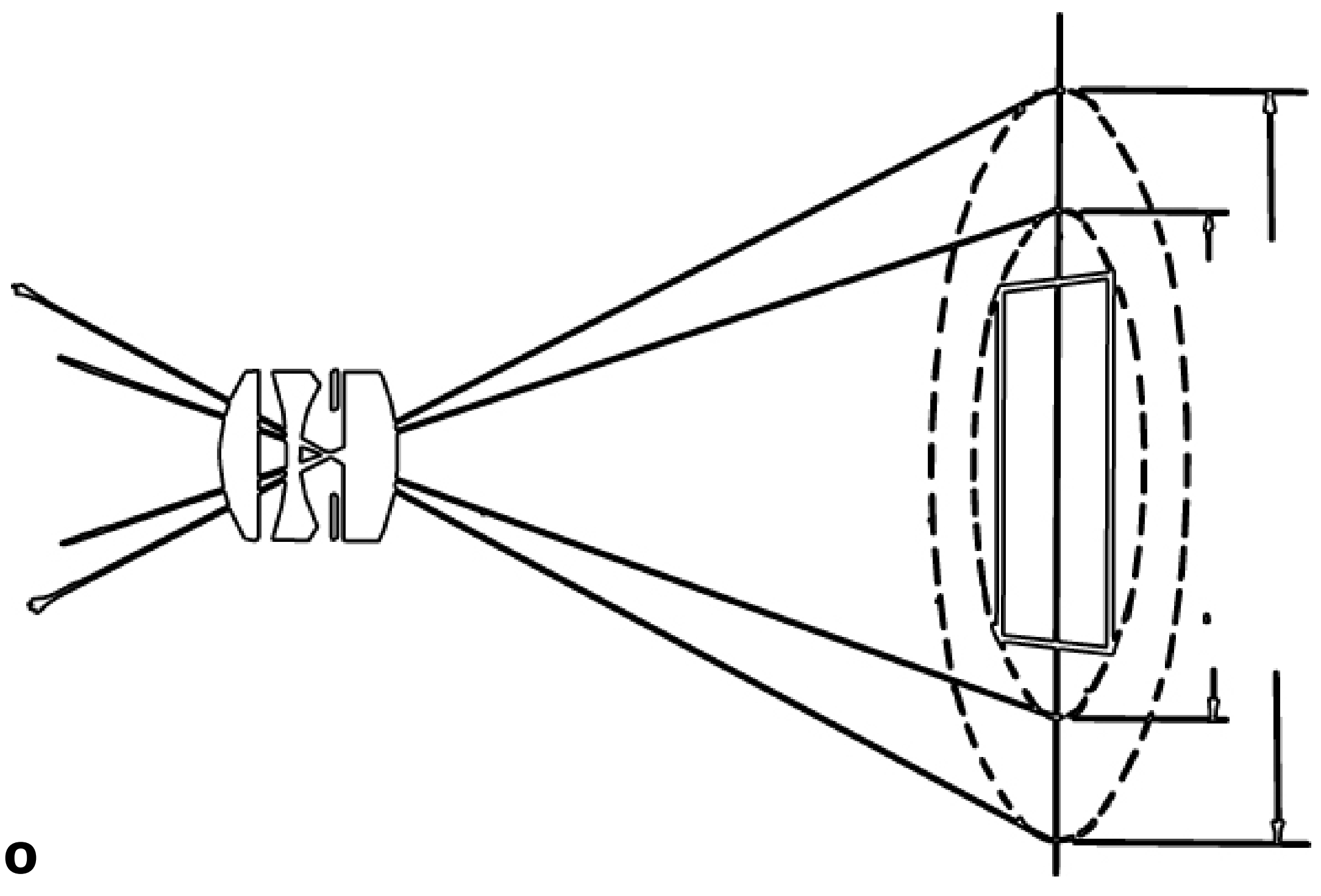
From London and Upton

Field of View

Field of view

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

Redrawn from Kingslake, *Optics in Photography*



Types of lenses

- **Normal** **26º**
  Film diagonal = focal length
- **Wide-angle** **45-90º**
- **Movie Camera** **14º**

Perspective Distortion

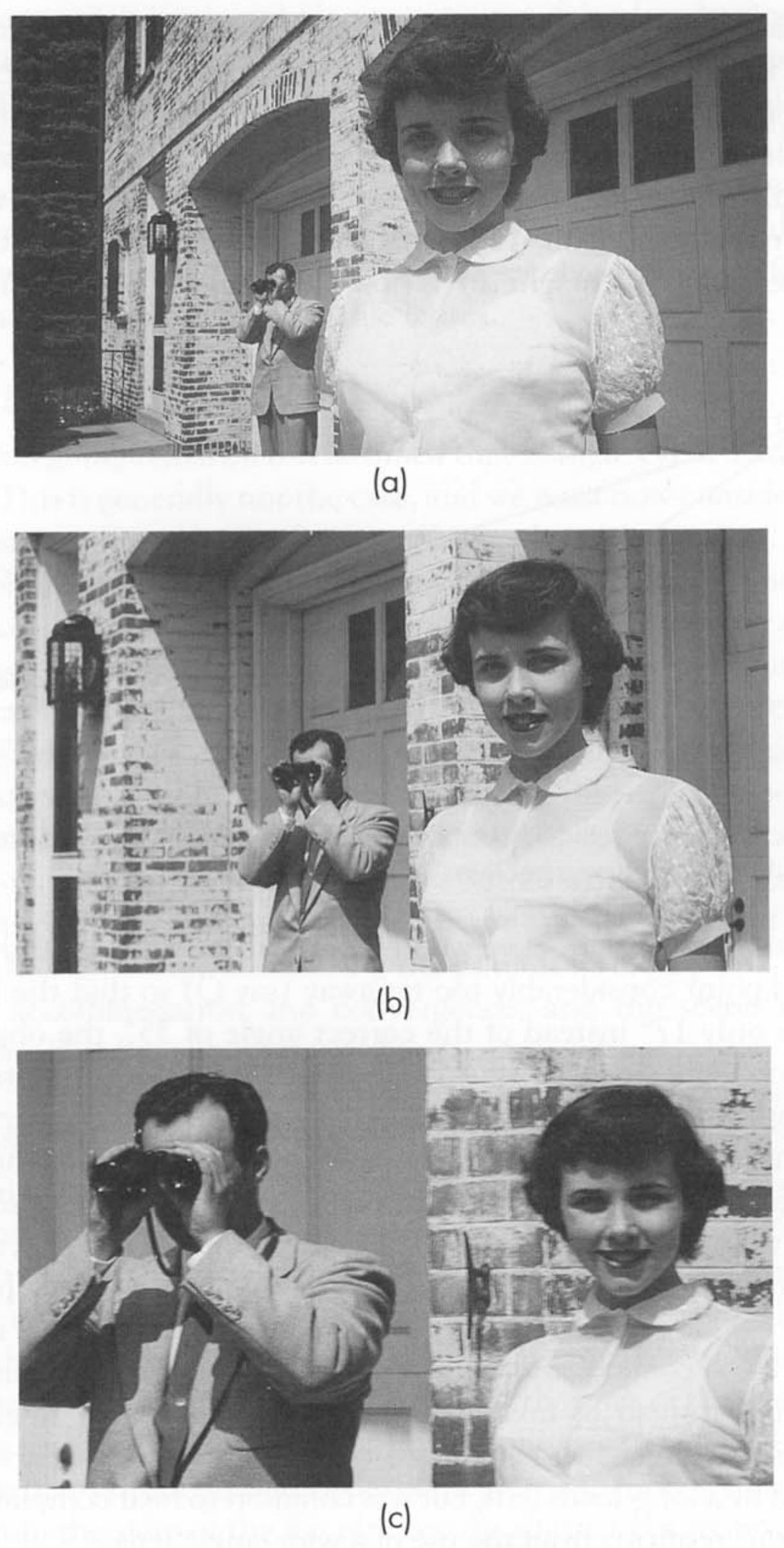
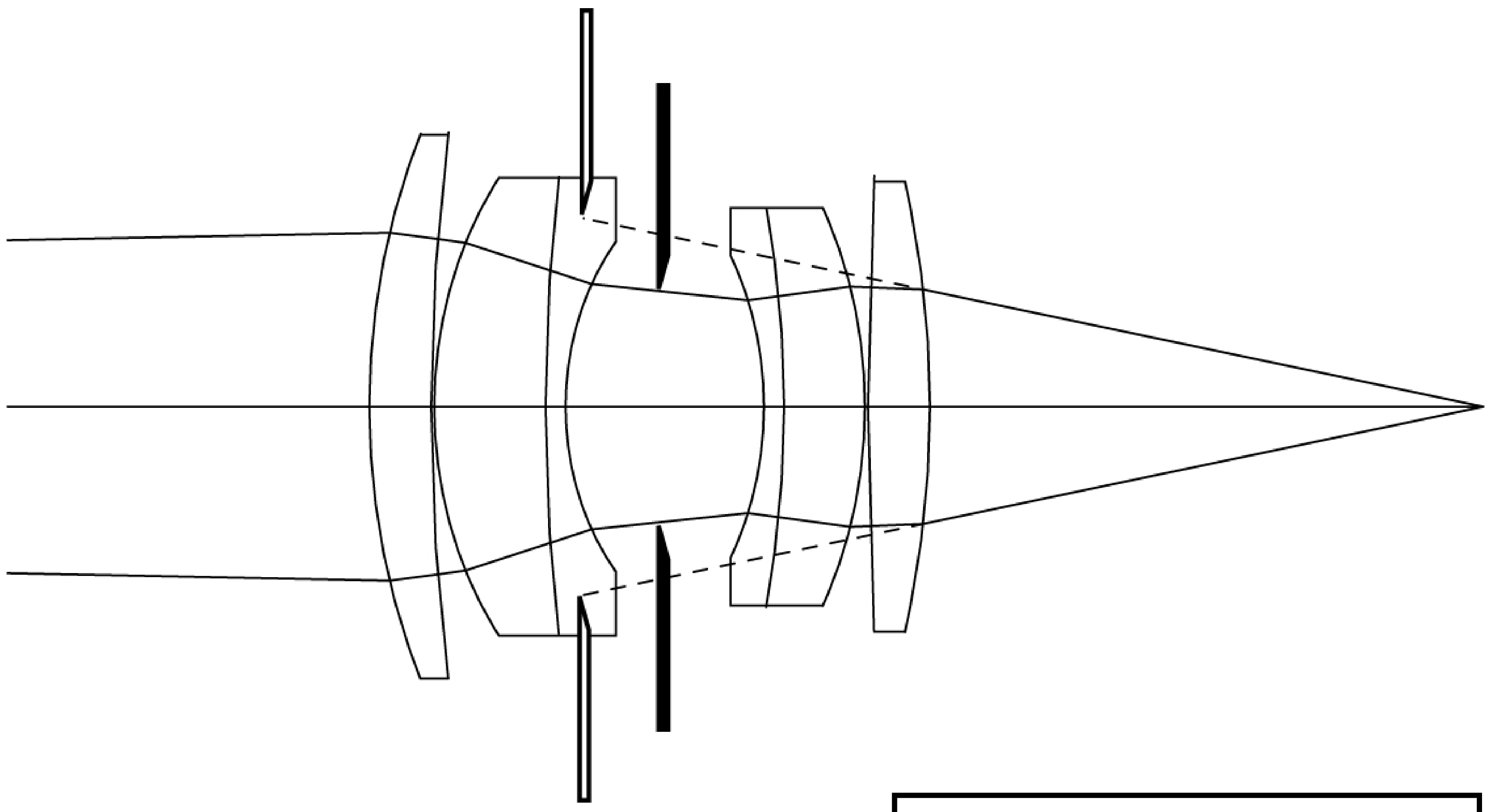


Figure 1.11. The effect of camera position in relation to a scene. For (a) the camera was placed at 2 feet from the girl; for (b) it was at 6 feet; and for (c) it was moved back to a point 38 feet from the girl. The negatives were enlarged in printing so as to make the girl appear at the same size in each print.

From *Optics in Photography*, Rudolf Kingslake

Stops and Pupils

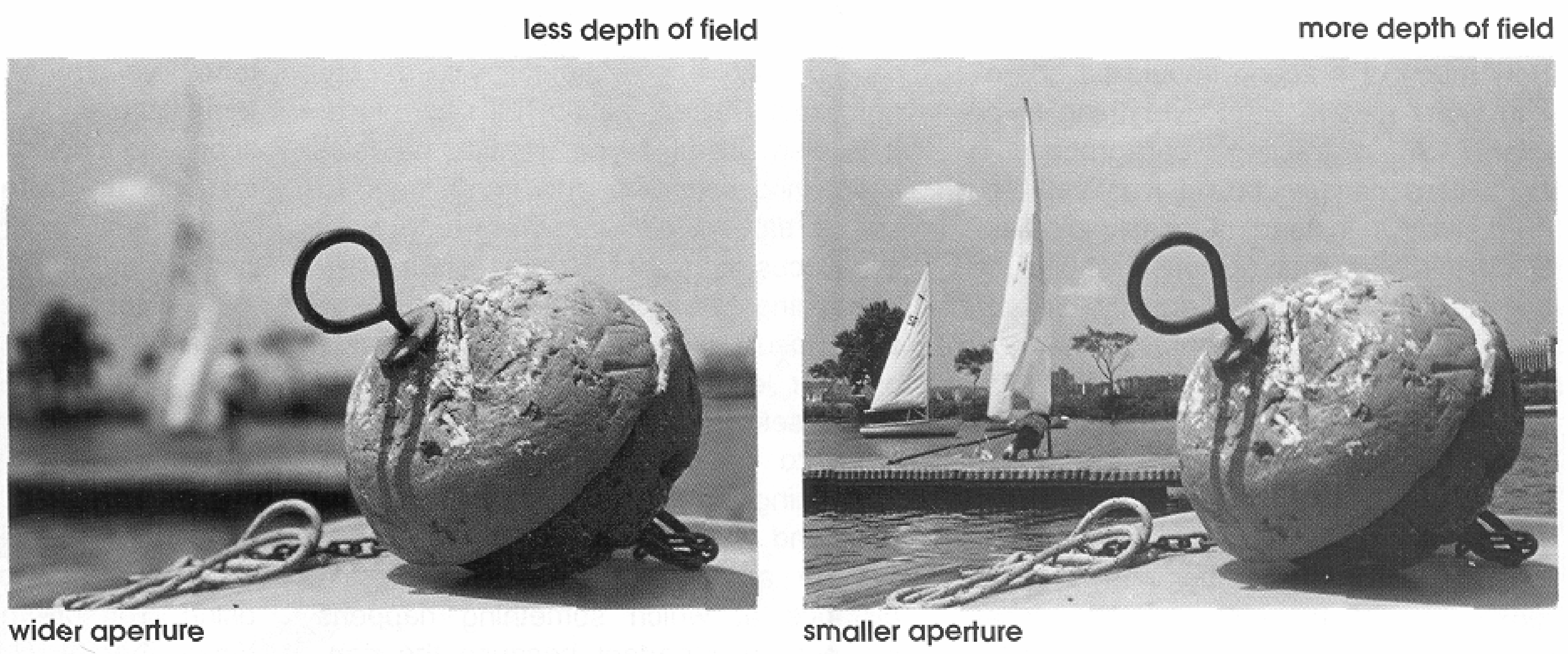


Finite Aperture

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

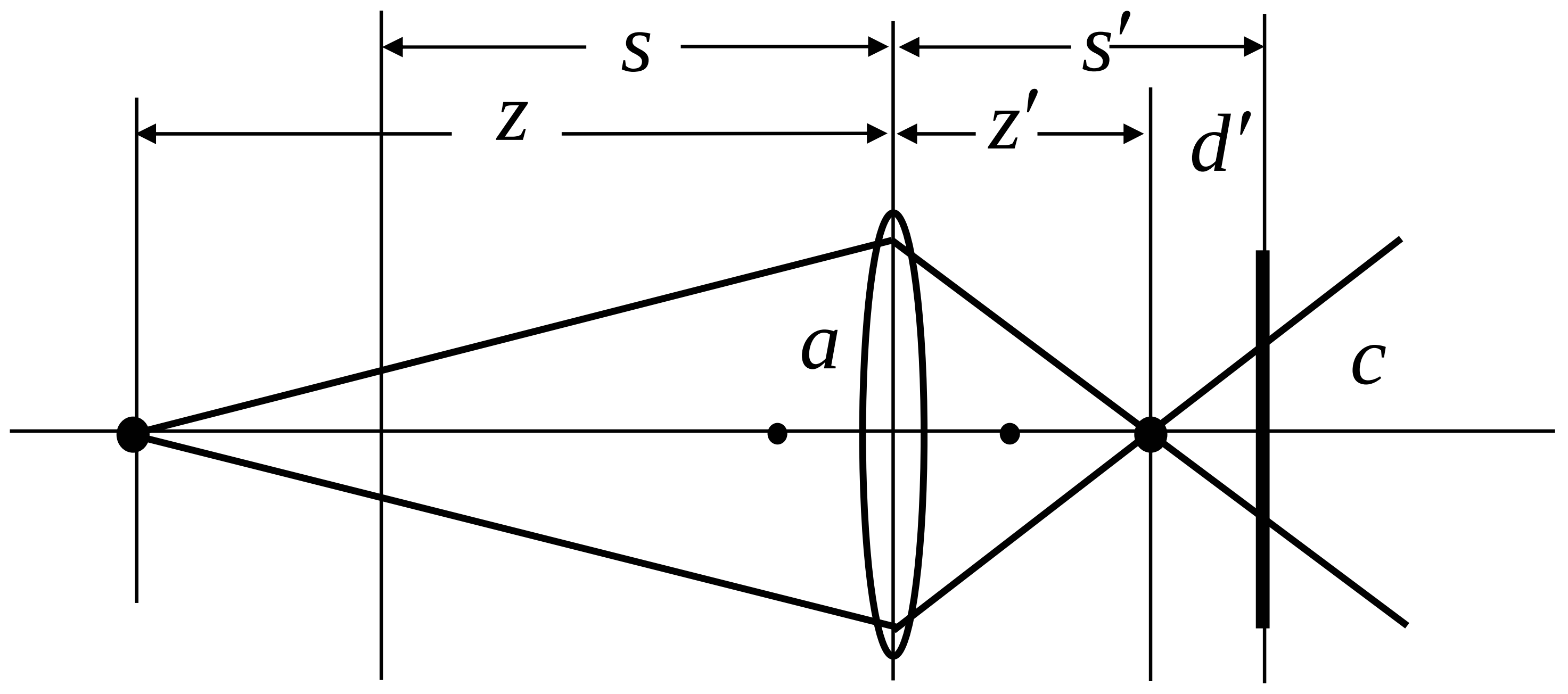
Depth of Field

Depth of Field



From London and Upton

Circle of Confusion



In-focus

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

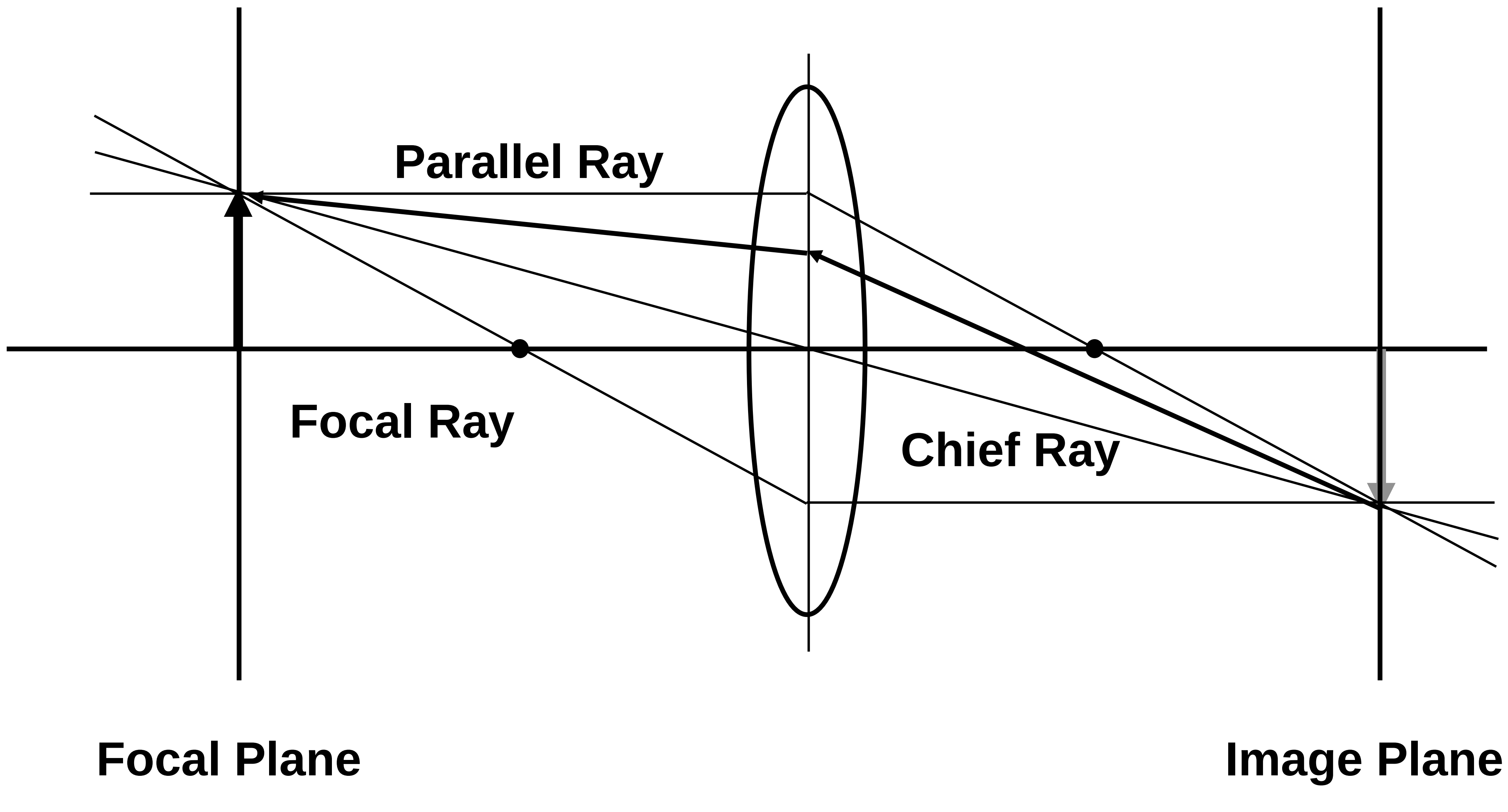
Out-of-focus

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

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

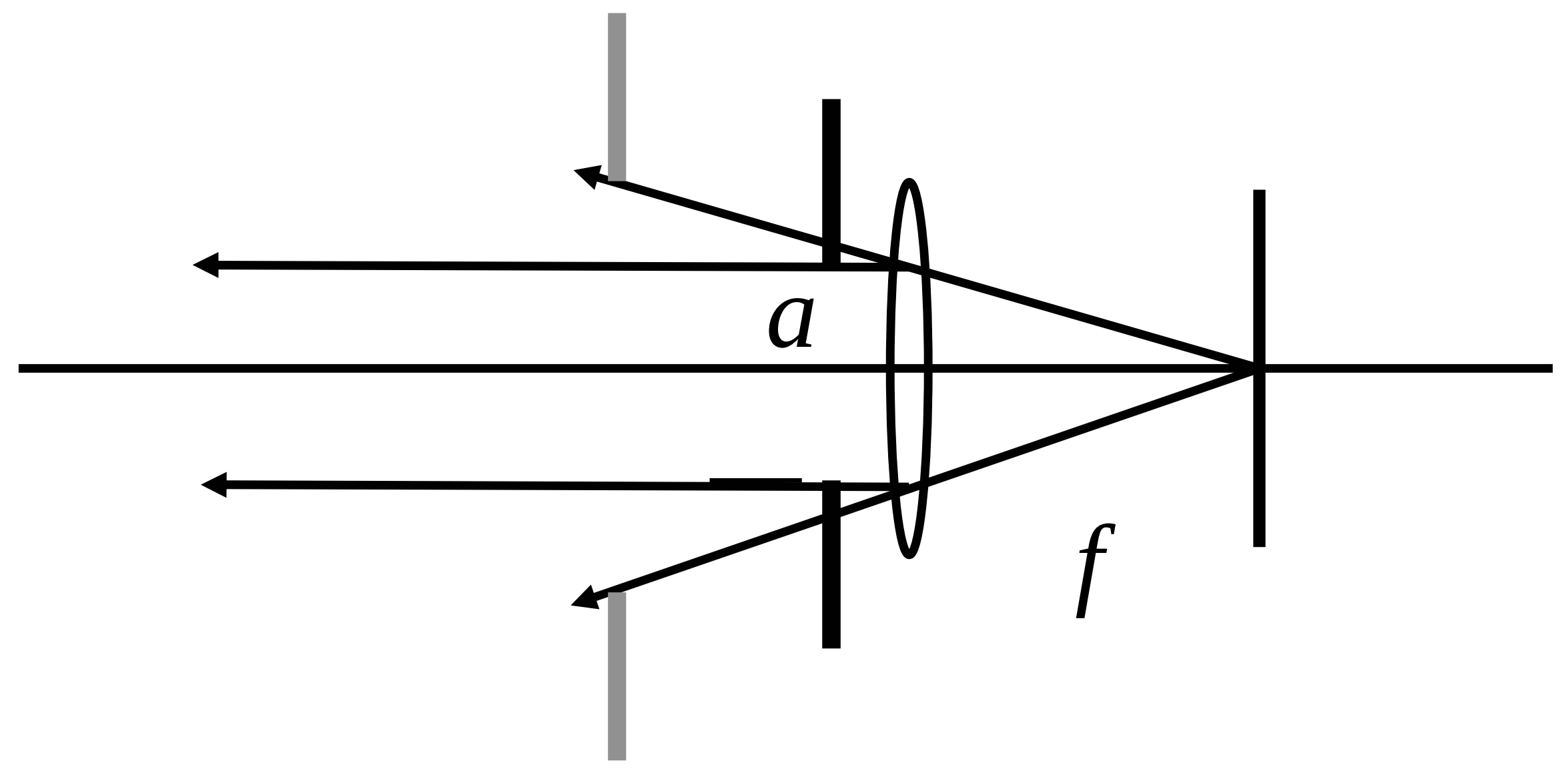
$$\frac{c}{a} = \frac{d'}{z'} = \frac{s' - z'}{z'}$$

Ray Tracing: Finite Aperture



Exposure

Image Irradiance



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

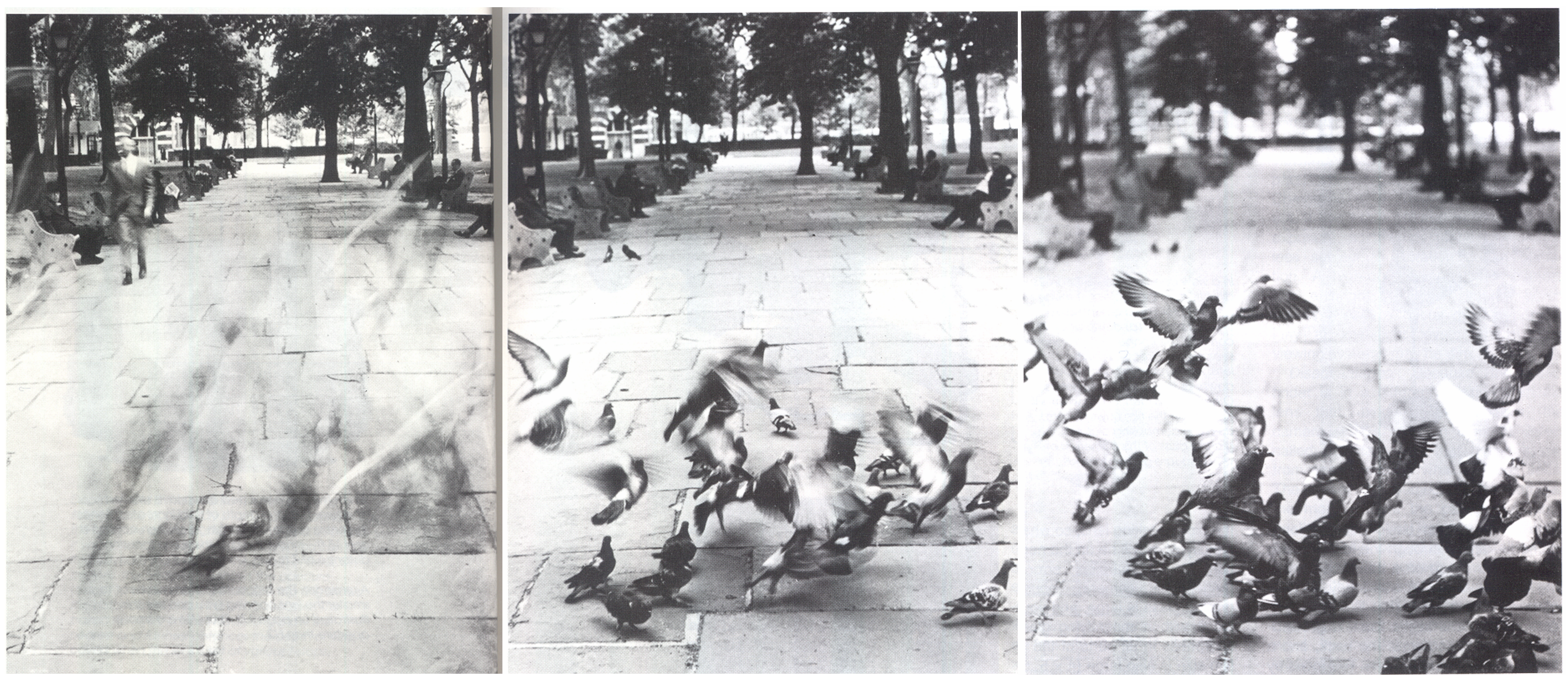
1 stop doubles exposure

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

Lens Design

Minimize artifacts, maximize flexibility

- **Artifacts**
  - **Spherical Aberration**

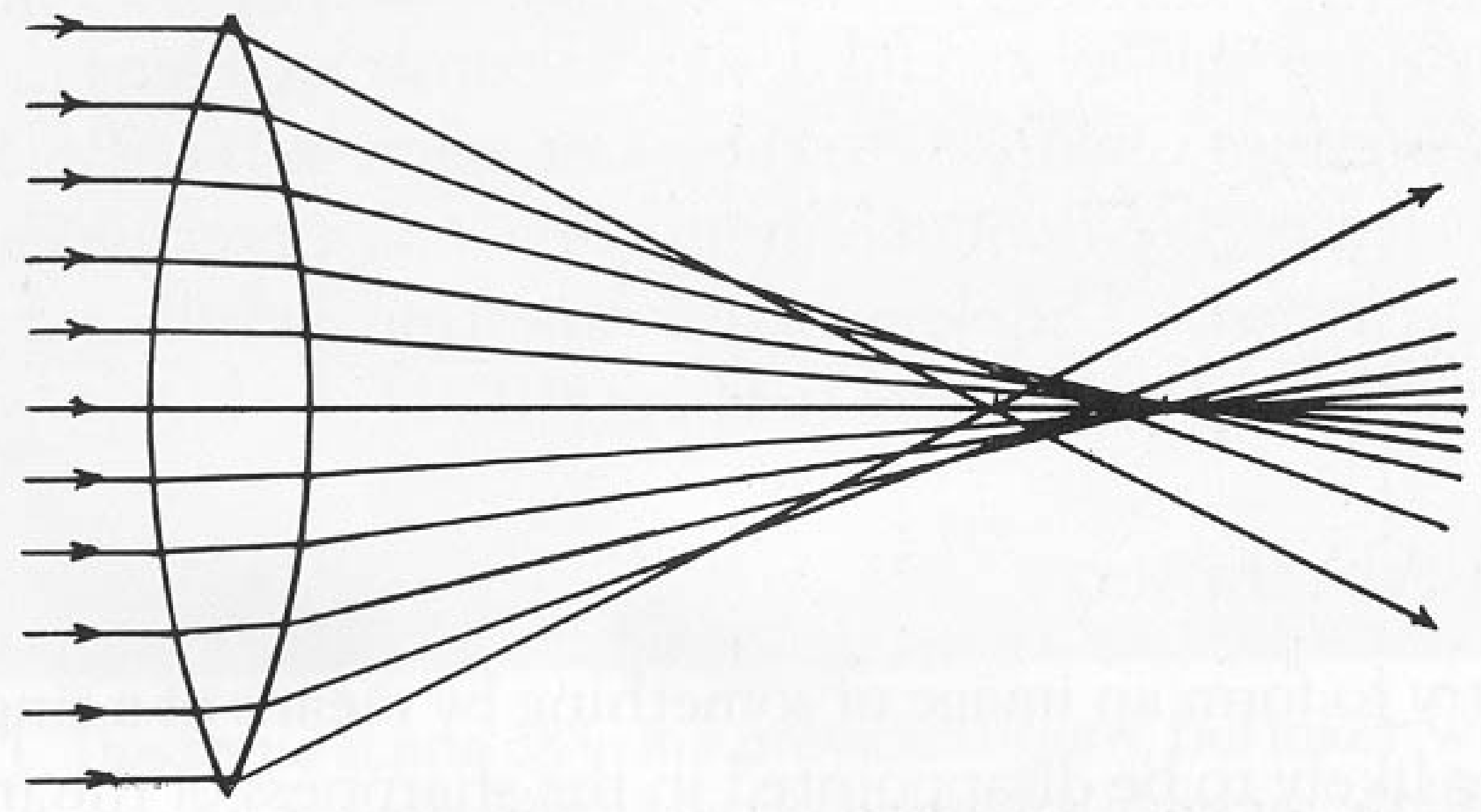
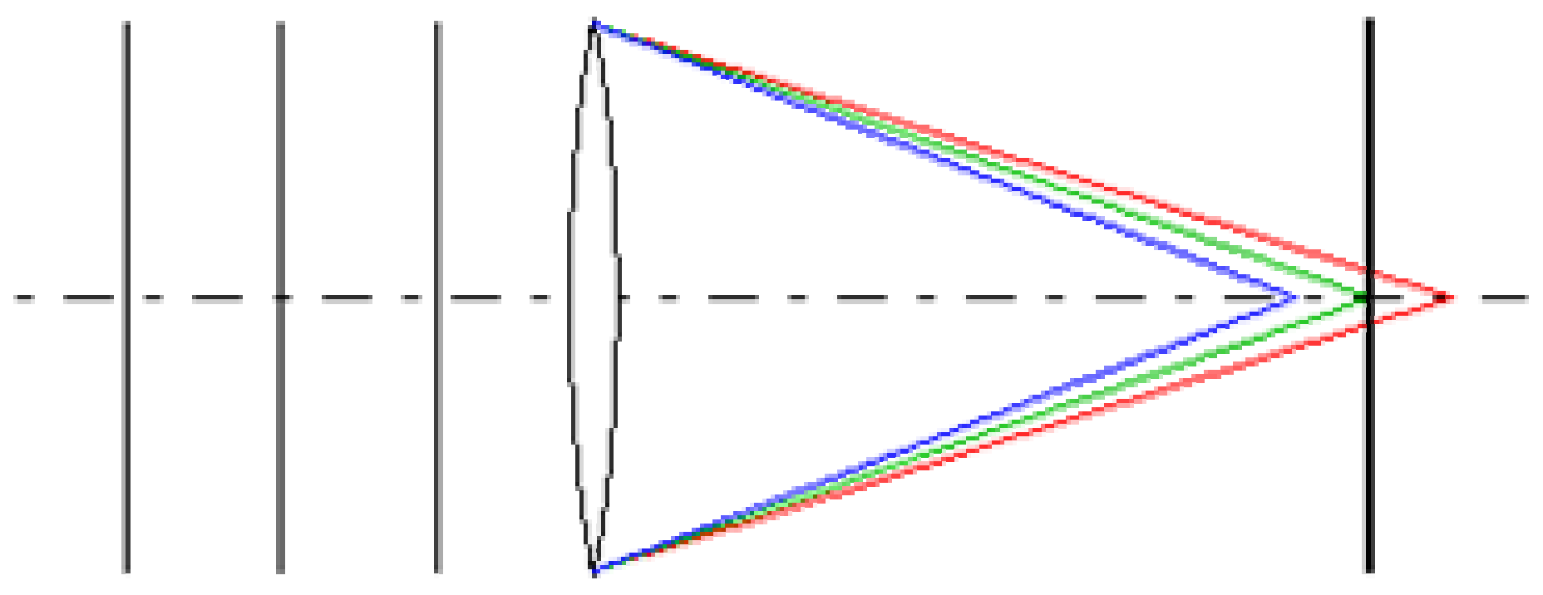


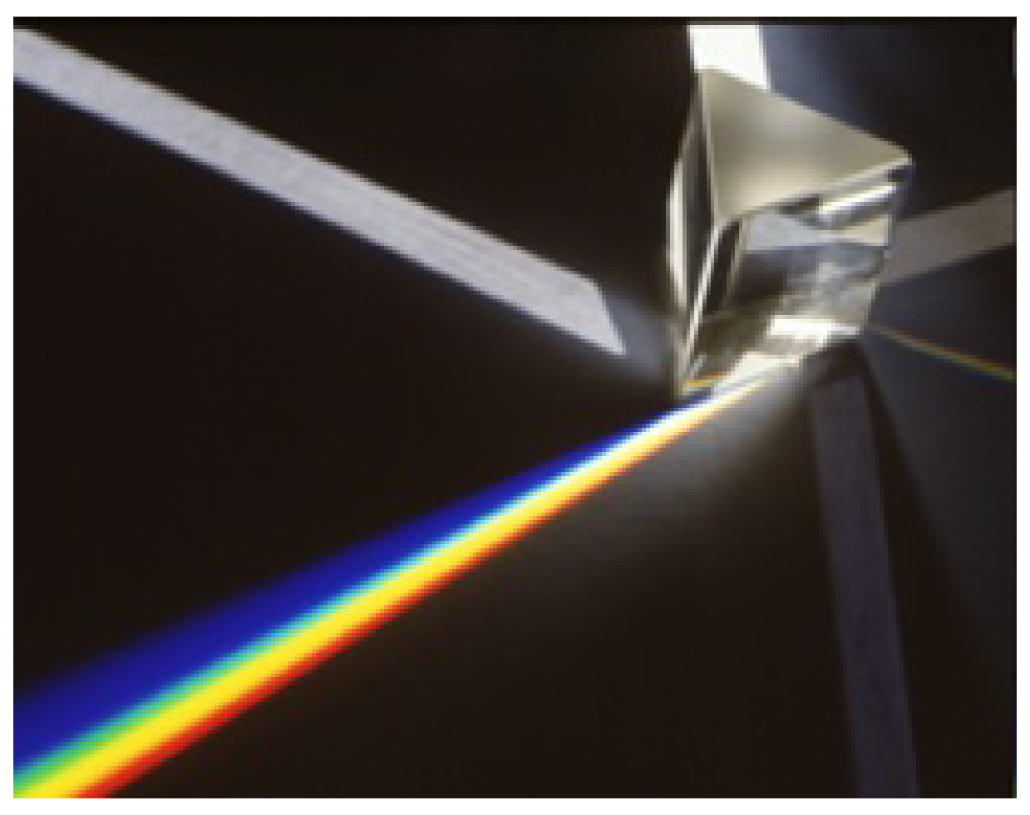
Figure 2.14. The typical ray distribution caused by spherical aberration.

Lens Design

Minimize artifacts, maximize flexibility

- **Artifacts**
  - **Spherical Aberration**
  - **Chromatic Aberration**





Lens Design

Minimize artifacts, maximize flexibility

- **Artifacts**
  - **Spherical Aberration**
  - **Chromatic Aberration**
  - **Distortions**

Lens Design

Minimize artifacts, maximize flexibility

- **Artifacts**
  - **Spherical Aberration**
  - **Chromatic Aberration**
  - **Distortions**
  - **Lens Flare**

Figure 6.13. A typical family of ghost images, formed by an uncoated high-aperture lens.

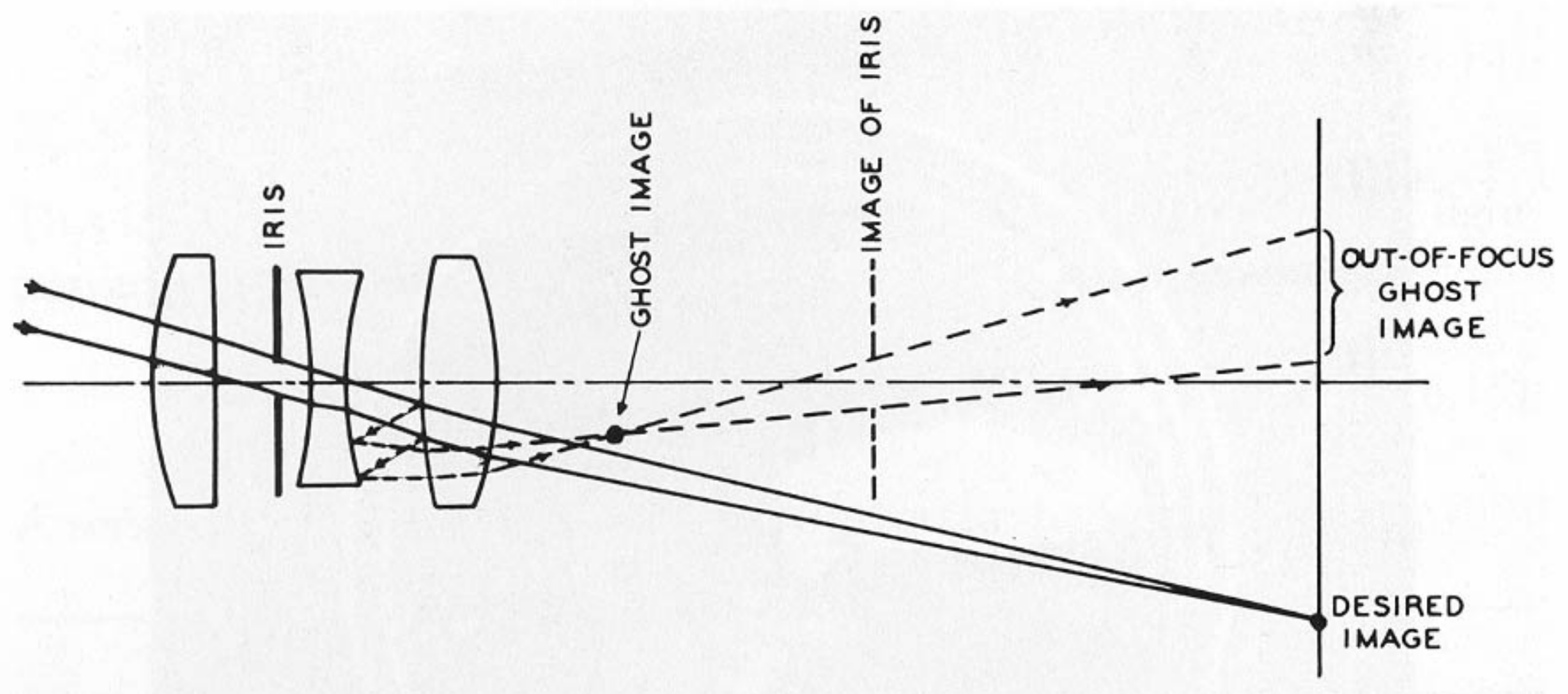


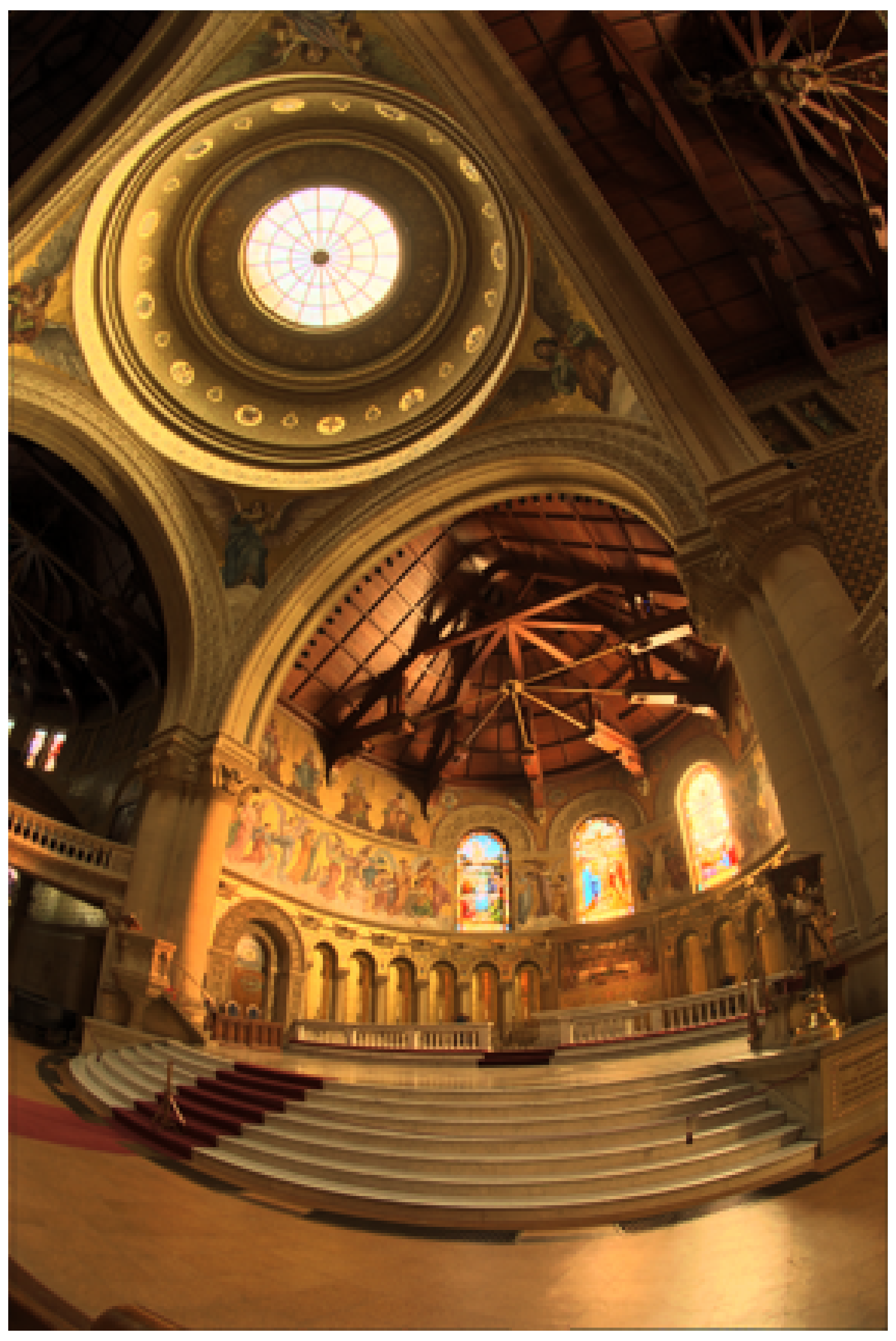
Figure 6.14. The formation of ghost images by light reflected from the internal surfaces in a lens.

High Dynamic Range

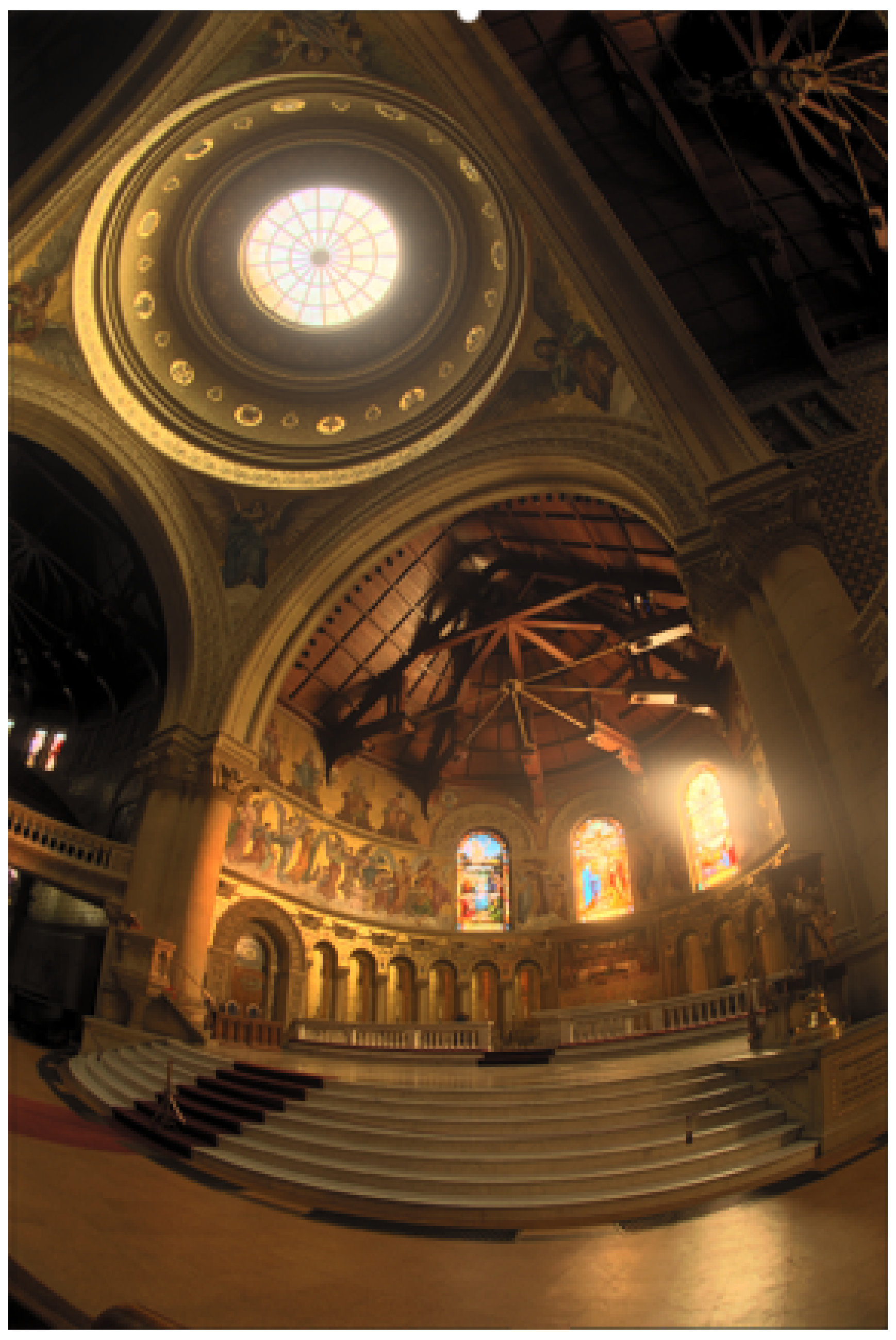
Sixteen photographs of the Stanford Memorial Church taken at 1-stop increments from 30s to 1/1000s.

From Debevec and Malik, High dynamic range photographs.

Simulated Photograph



Adaptive histogram



With glare, contrast, blur