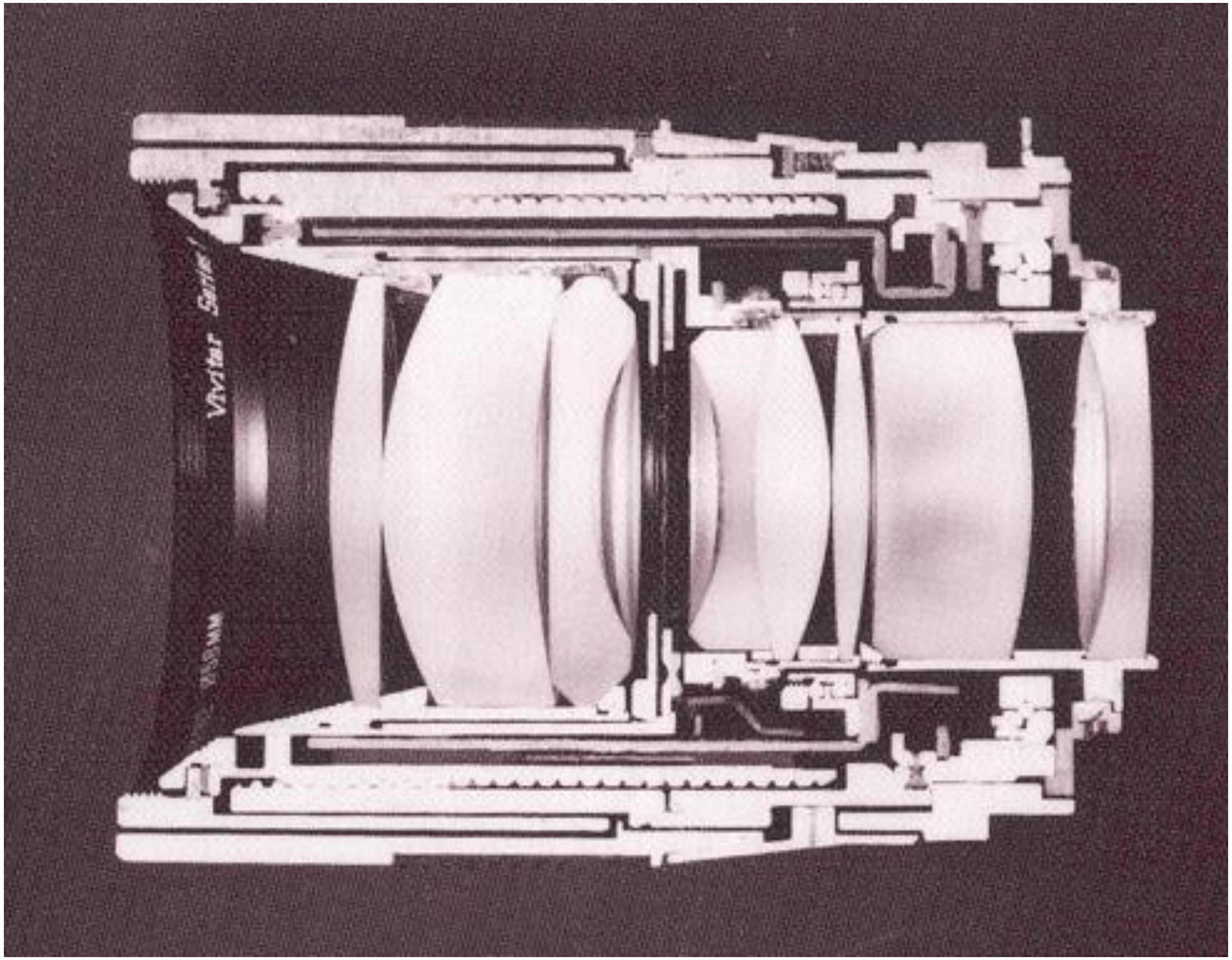
Optics

Computational Photography

Matthias Hullin

universitätbonn

Real lens



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

universitätbonn

Optics

- Physics of light
  - Light as rays, waves, and particles
  - Refraction and diffraction

- Image formation
  - Pinhole model
  - Thin lens model

- Modeling more complex optical systems
  - Matrix optics

- Optical parameters in photography

- Other effects and phenomena

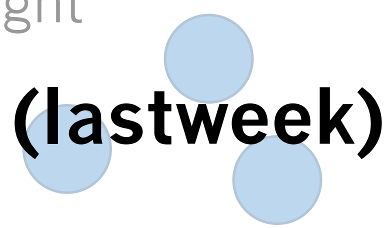
Light

Particle model

(Quantum optics)

Valid for interaction between light and electrons, and for very low light levels

Photon, massless light particle with energy $E = h\nu = \frac{hc}{\lambda}$ traveling at speed of light



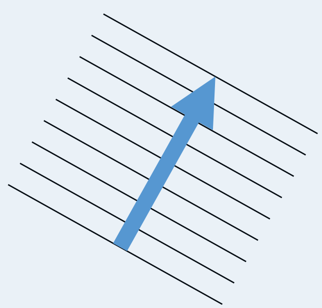
Explains photoel. effect; absorption; fluorescence; ...

Wave model

(Physical optics)

Valid for interaction with small-scale structures; coherent light (interference)

Wave, variation of electromagnetic field over space and time



Explains polarization; nonlin. optics (frequency mixing); ...

Ray model

(Geometric optics)

Valid in large-scale limit for incoherent light (like, 99% of computer graphics)

Ray, light energy travelling on a well-defined path (by default, along a straight line)

Explains many things like shadows, refraction

Geometric optics

- “Ray tracing”

Light in media

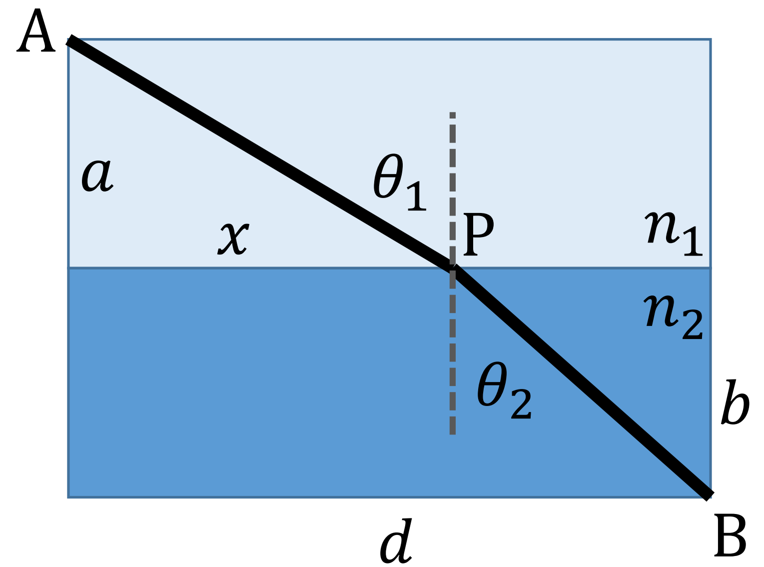
- Refractive index: slow-down factor for speed of light

Vacuum:	$n = 1$	$c = c_{\text{vac}} = 299\,792\,458\, m/s$
Glass:	$n \approx 1.5$	$c \approx c_{\text{vac}}/1.5$
Water:	$n \approx 1.3$	$\ldots$
Diamond:	$n \approx 2.4$	$\ldots$

Refraction in ray optics

- Fermat's Principle: Light travels between two points in the shortest possible time (in *stationary* time)

Travel time from A to B via P:



$$t(x) = \sqrt{a^2 + x^2}/c_1 + \sqrt{b^2 + (d - x)^2}/c_2$$

$$\mathbf{0} = \frac{\partial t}{\partial x} = \frac{1}{c_1}\frac{x}{\sqrt{a^2+x^2}} - \frac{1}{c_2}\frac{d-x}{\sqrt{(d-x)^2+b^2}}$$

With $x = \sin\theta_1 \sqrt{a^2 + x^2}$

and $d - x = \sin\theta_2 \sqrt{(d - x)^2 + b^2}$:

$$0 = \frac{\sin\theta_1}{c_1} - \frac{\sin\theta_2}{c_2} = \frac{n_1}{c_{\text{vac}}}\sin\theta_1 - \frac{n_2}{c_{\text{vac}}}\sin\theta_2$$

$$\Leftrightarrow \boxed{n_1 \sin\theta_1 = n_2 \sin\theta_2}$$ (Snell's Law!)

Continuous refraction

- Ray equation

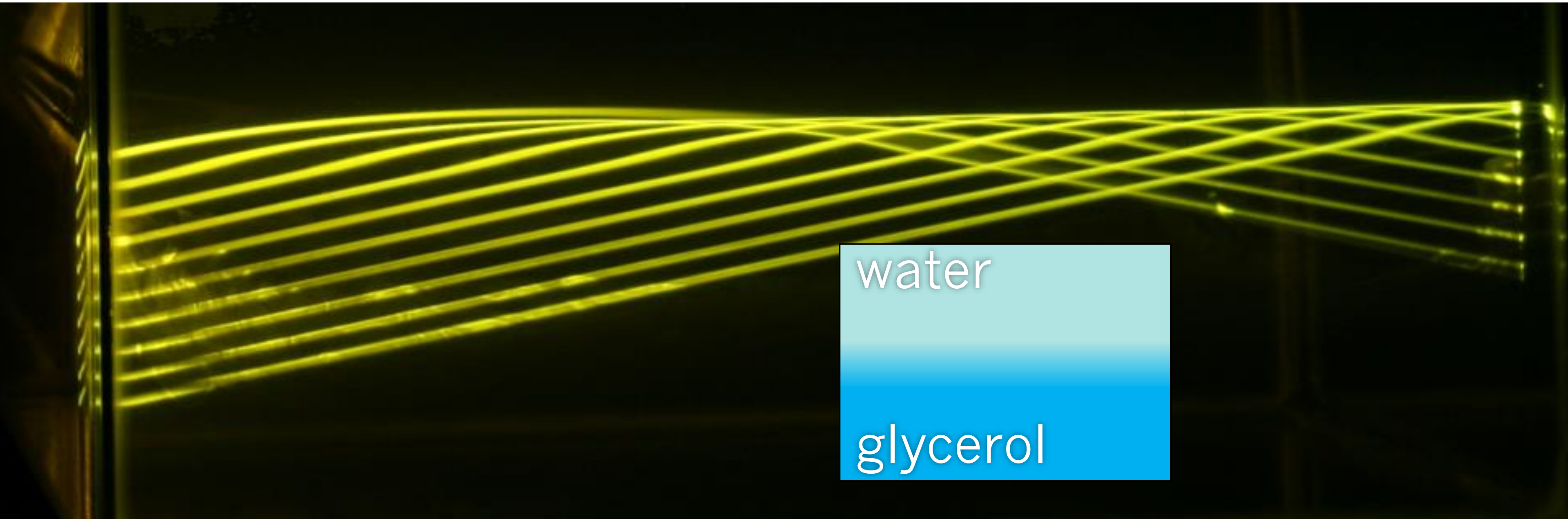
$$\frac{d^2\mathbf{x}}{da^2} = \nabla\left(\frac{1}{2}n^2\right)$$

with “stepping parameter”

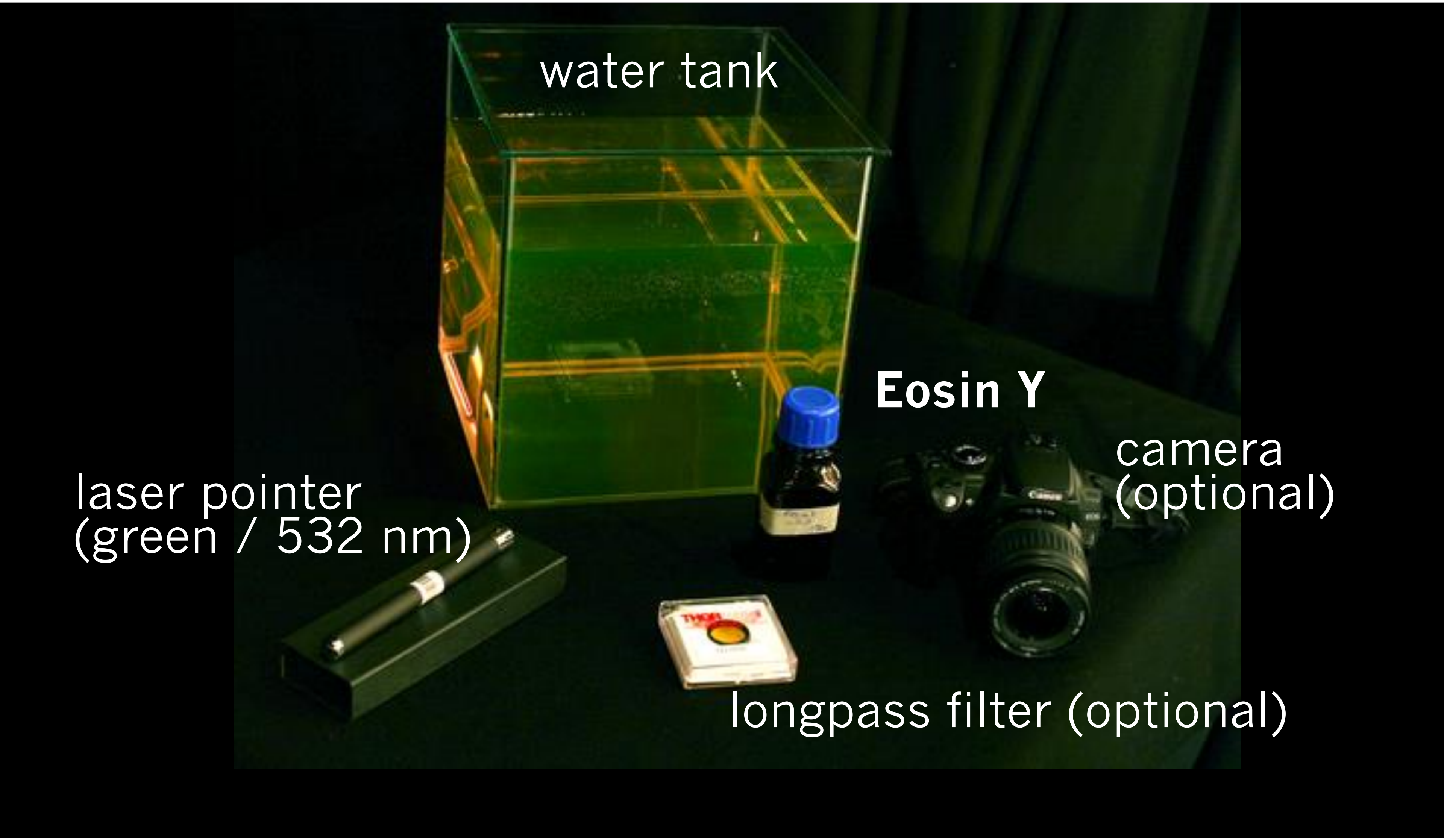
$$\left|\frac{dx}{da}\right| = n$$

Nabla operator (3D gradient):

$$\nabla = \begin{pmatrix} \partial/\partial x \\ \partial/\partial y \\ \partial/\partial z \end{pmatrix}$$



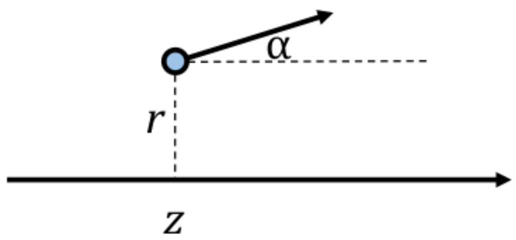
How these images were created



Paraxial approximation

Characterize 2D ray by its angle and distance to optical axis:

$$\mathbf{r}(z) = \begin{pmatrix} r(z) \\ \alpha(z) \end{pmatrix}$$



Paraxial approximation:

Assume $r,\ \alpha$ small; use 1st-order Taylor term

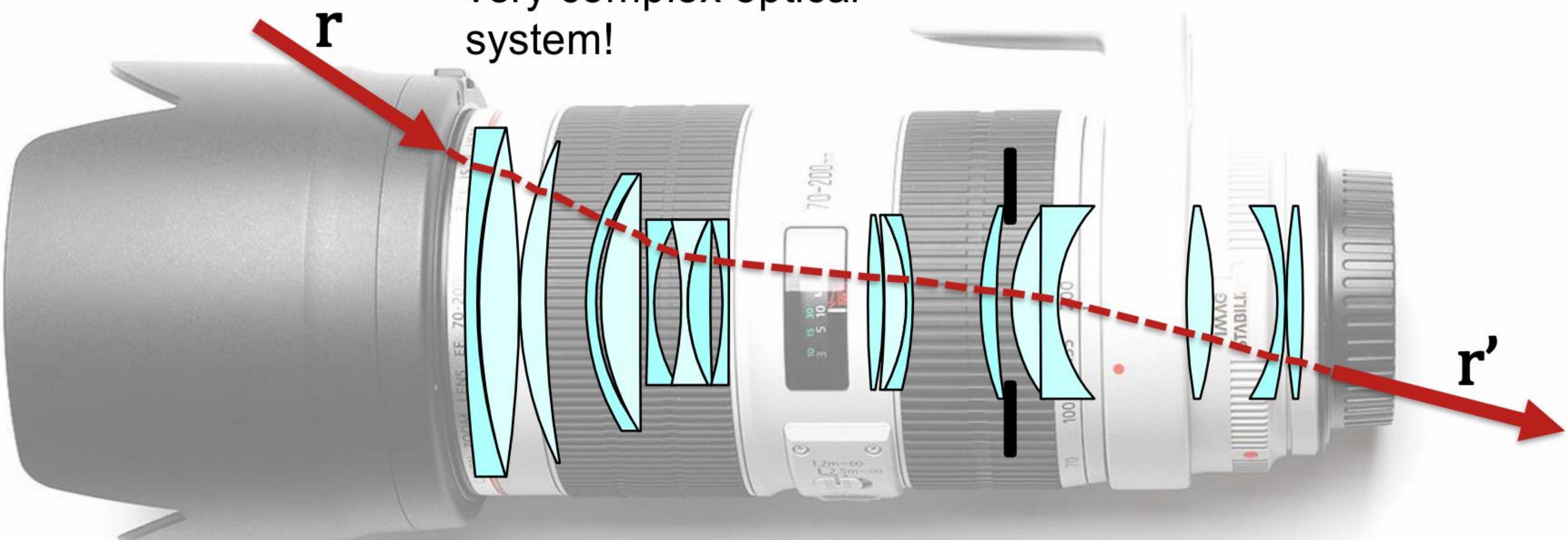
$$\sin\alpha \approx \tan\alpha \approx \cancel{\cot}\,\alpha \approx \alpha$$
$$\alpha^2 \approx 0$$
$$\cos\alpha \approx 1$$

Matrix optics

Ray transfer matrix

$$\text{Outgoing ray} \quad \begin{pmatrix} r' \\ \alpha' \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} r \\ \alpha \end{pmatrix} \quad \text{Incoming ray}$$

This could stand for a very complex optical system!



Example matrices

Element	Matrix	Remarks
Propagation in free space or in a medium of constant refractive index	$\begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix}$	d = distance
Refraction at a flat interface	$\begin{pmatrix} 1 & 0 \\ 0 & \frac{n_1}{n_2} \end{pmatrix}$	n_1 = initial refractive index n_2 = final refractive index.
Refraction at a curved interface	$\begin{pmatrix} 1 & 0 \\ \frac{n_1 - n_2}{R \cdot n_2} & \frac{n_1}{n_2} \end{pmatrix}$	R = radius of curvature, $R > 0$ for convex (centre of curvature after interface) n_1 = initial refractive index n_2 = final refractive index.
Reflection from a flat mirror	$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$	
Reflection from a curved mirror	$\begin{pmatrix} 1 & 0 \\ -\frac{2}{R} & 1 \end{pmatrix}$	R = radius of curvature, R > 0 for concave, valid in the paraxial approximation
Thin lens	$\begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix}$	f = focal length of lens where $f > 0$ for convex/positive (converging) lens. Only valid if the focal length is much greater than the thickness of the lens.

Wave optics

Wave optics

- Maxwell's Equations (don't learn!)

Electric field

Divergence $\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$ Charge density; Permittivity of free space

Magnetic field

$$\nabla \cdot \mathbf{B} = 0$$

Curl $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$

$$\nabla \times \mathbf{B} = \mu_0 \left(J + \epsilon_0 \frac{\partial E}{\partial t} \right)$$

Permeability of free space; Current density

Nabla operator (3D gradient):

$$\nabla = \begin{pmatrix} \partial/\partial x \\ \partial/\partial y \\ \partial/\partial z \end{pmatrix}$$

Wave equations

- Maxwell's Equations in vacuum (don't learn!)

$$\nabla \cdot \mathbf{E} = 0 \qquad \nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \nabla \times \mathbf{B} = \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$

- With "curl-of-curl identity" $\nabla \times (\nabla \times \mathbf{X}) = \nabla(\nabla \cdot \mathbf{X}) - \nabla^2 \mathbf{X}$, we obtain a pair of wave equations:

$$\frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} - \nabla^2 \mathbf{E} = 0 \qquad \frac{1}{c^2}\frac{\partial^2 \mathbf{B}}{\partial t^2} - \nabla^2 \mathbf{B} = 0$$

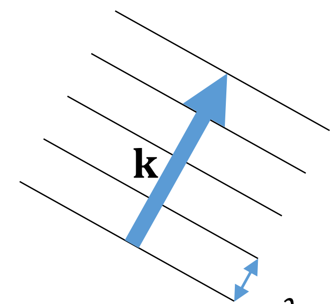
Good to know: Wave equations relate
2nd spatial to 2nd temporal derivative

Solutions to wave equation

- Functions that solve the wave equation are called "eigenfunctions" with corresponding "eigenfrequencies" (recall eigenvectors, eigenvalues)

- For $\mathbf{E}$-field: wave equation

$$\frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} - \nabla^2 \mathbf{E} = 0$$



$$\lambda = \frac{2\pi c}{\omega}$$

- Solution: planar wave

$$E(\mathbf{r}, t) = g(\omega t - \mathbf{k} \cdot \mathbf{r})$$

Angular frequency $\omega = 2\pi\nu$

with *wave vector*

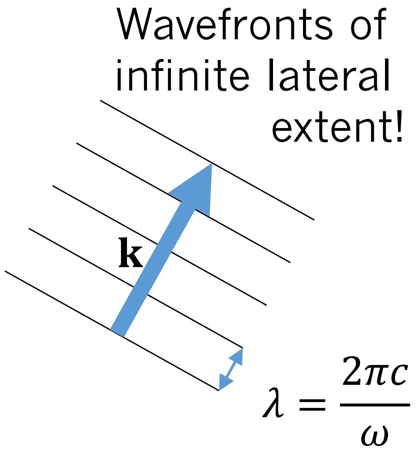
$$\mathbf{k} = \omega \hat{\mathbf{d}} / c$$

Monochromatic planar/spherical waves

- Particularly useful families of solutions:

1. Planar wave (corresponds to a “ray”)

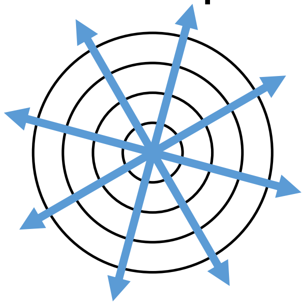
$$\mathbf{E}(\mathbf{r},t) = \mathbf{E}_0 \cos(\omega t - \mathbf{k}\cdot\mathbf{r} + \phi_0)$$



Perfect directionality, no localization

2. Spherical wave (corresponds to a “point source”)

$$\mathbf{E}(\mathbf{r},t) = \frac{\mathbf{E}_0}{r}\cos(\omega \mathrm{t} - k\cdot r + \phi_0), \qquad r = |\mathbf{r} - \mathbf{r}_0|$$

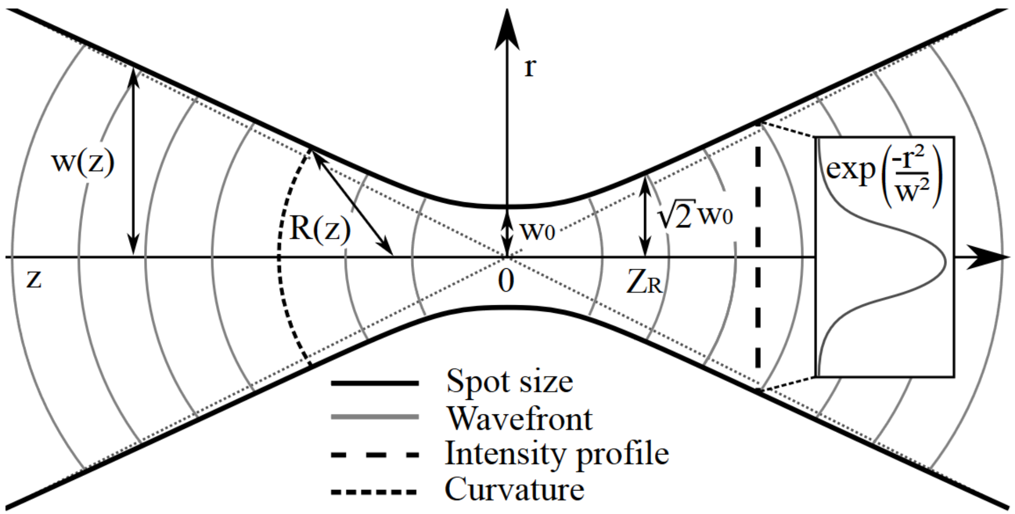


Perfect localization, no directionality

The closest thing to a "ray"

3. Gaussian beam: Compromise between directionality and spatial localization (don't memorize the equation, only that it exists)

$$E(r,z,t) = E_0 \frac{w_0}{w(z)} \exp\left(-\frac{r^2}{w(z)^2} - ikz - ik\,\frac{r^2}{2R(z)} + i\,\zeta(z)\right) e^{i\omega t}$$



Gaussian beams have a minimum diameter ("waist" w_0). The smaller the waist, the wider the angle of divergence!

E-field vs intensity

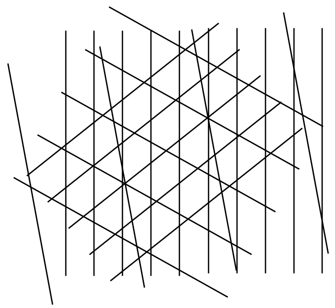
- Optical power (which our devices observe) is related to the squared absolute value of electrical field E:

$$\langle U \rangle = \frac{n^2 \epsilon_0}{2} |E|^2$$

($\langle U \rangle =$ time-averaged energy density)

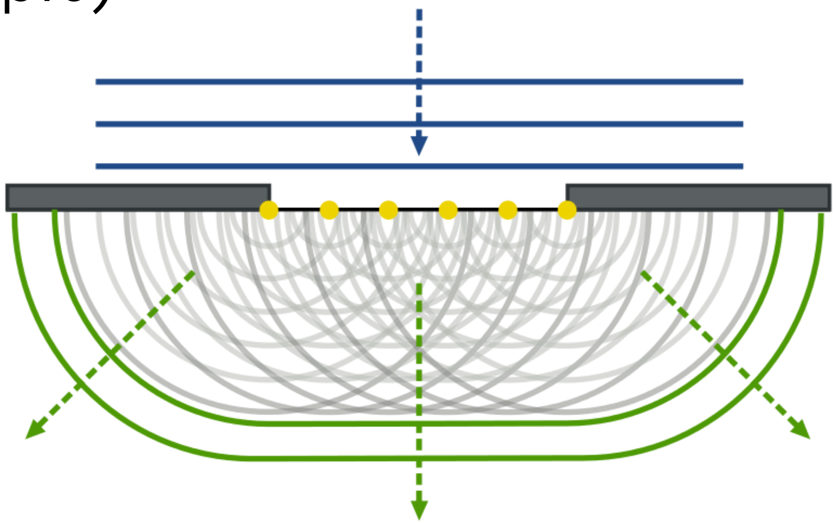
Arbitrary waves as superpositions

- “Everything is a sum of planar waves” (Fourier optics)



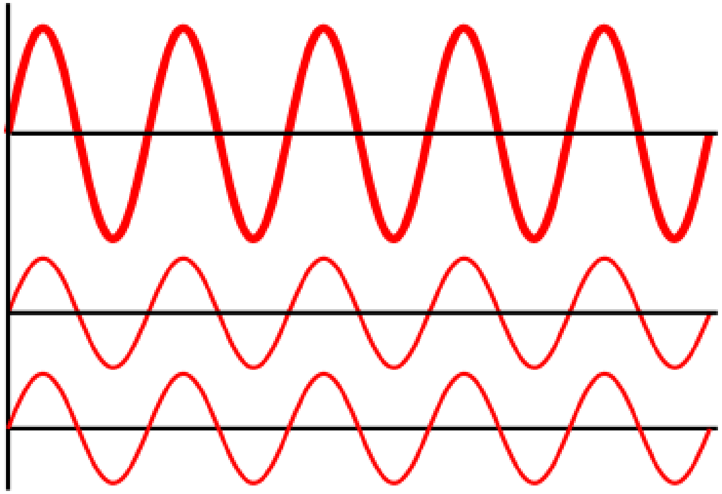
- “Everything is a sum of spherical waves” (Huygens-Fresnel principle)

Diffraction:
Waves protrude into geometrically shadowed regions



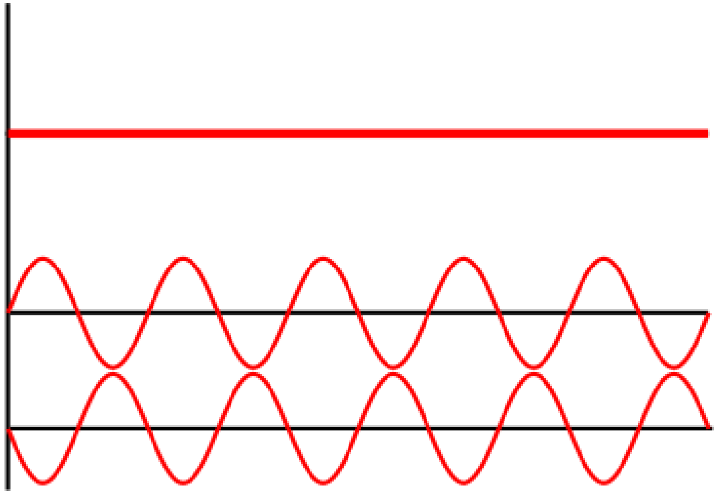
Superposition and interference

- Sums of solutions also solve the wave equation (linearity)
- For coherent light (only one value of ω), superposition of waves creates interference.



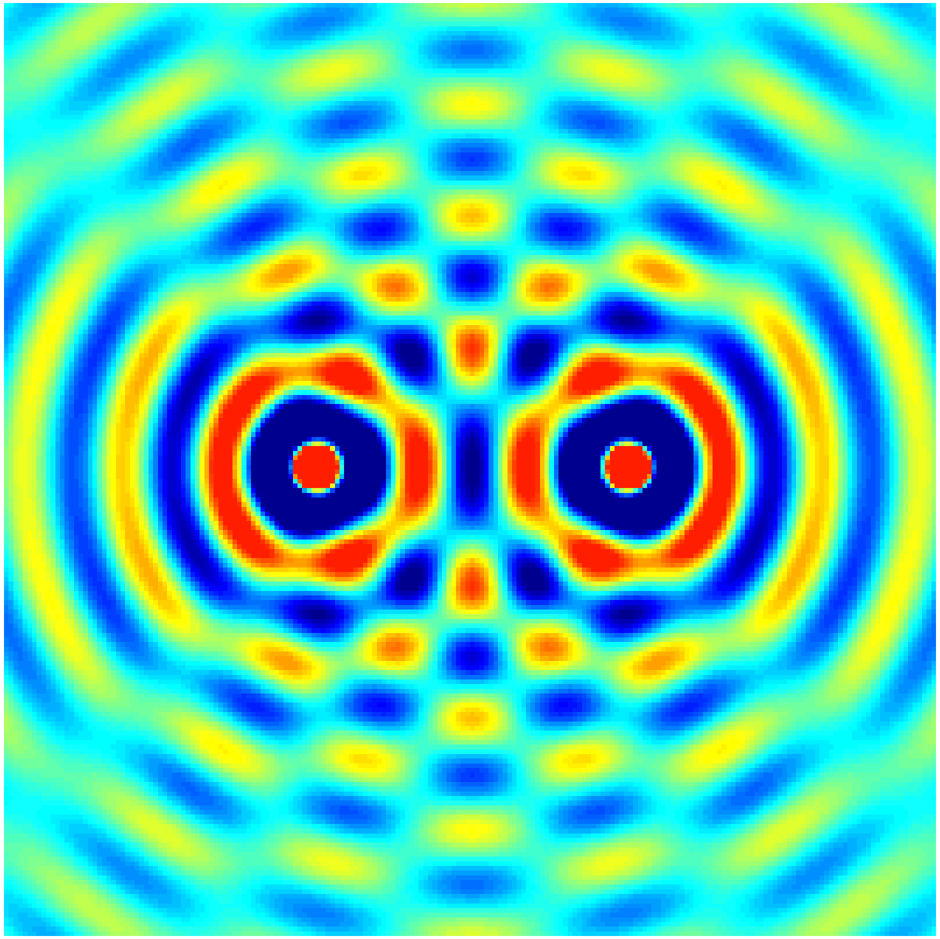
Constructive interference: waves add up

(up to 4-fold intensity!!)



Destructive interference: waves cancel out

Two spherical waves interfering



Waves in media

- Wave optics gets MUCH more complicated in non-vacuum and in particular inhomogeneous media or at boundaries.

- Let's ignore that and look at Snell's Law in wave optics

Refraction / Snell's Law

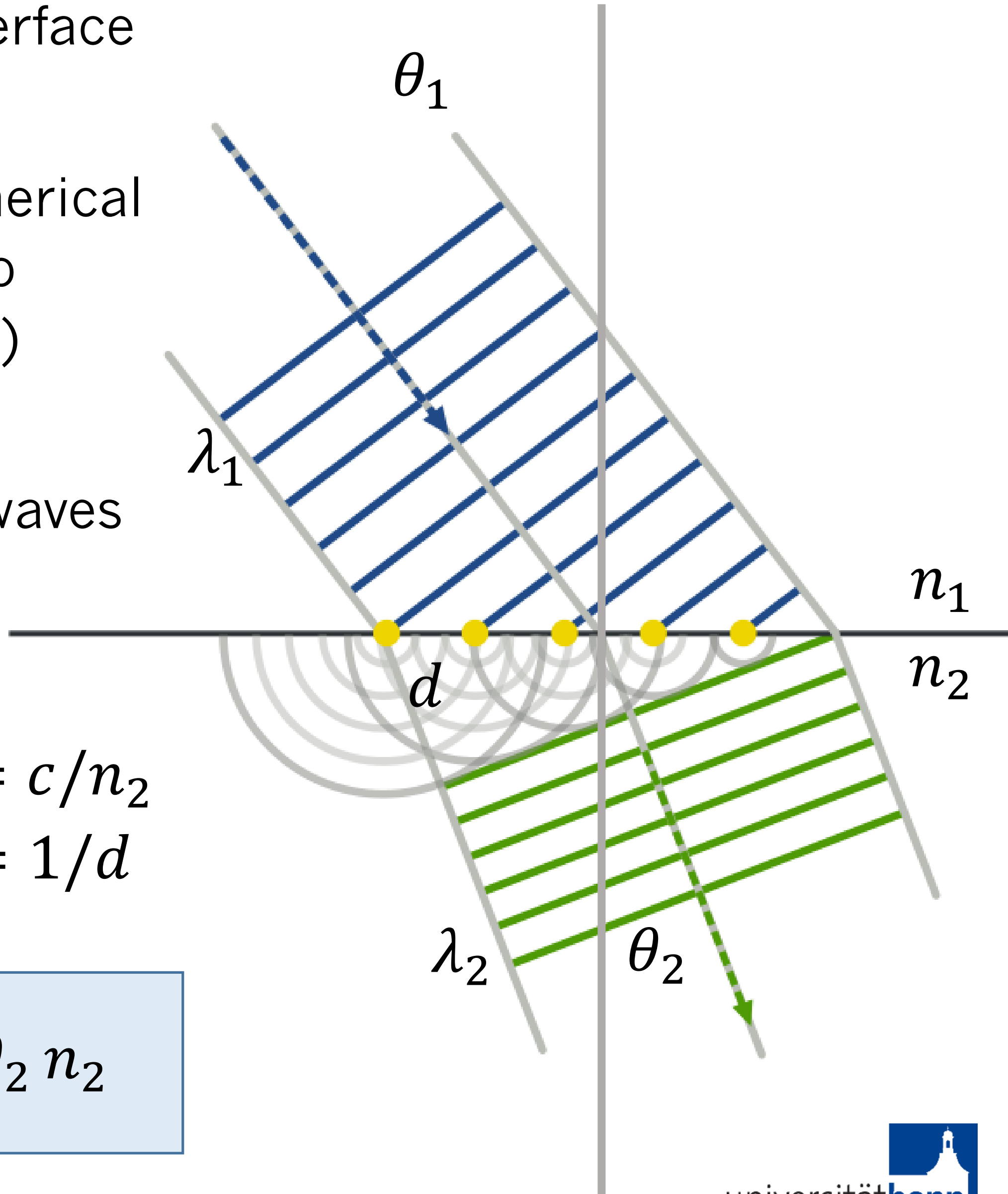
- Incoming wavefronts hit interface surface in medium 1
- Intersection points emit spherical waves of reduced speed into medium 2 (Huygens-Fresnel)
- New, tilted wavefronts from superposition of spherical waves
- Use trigonometry to obtain

  Snell's Law:

$$\lambda_1/\nu = c/n_1 \qquad \lambda_2/\nu = c/n_2$$

$$\sin\theta_1/\lambda_1 = \sin\theta_2/\lambda_2 = 1/d$$

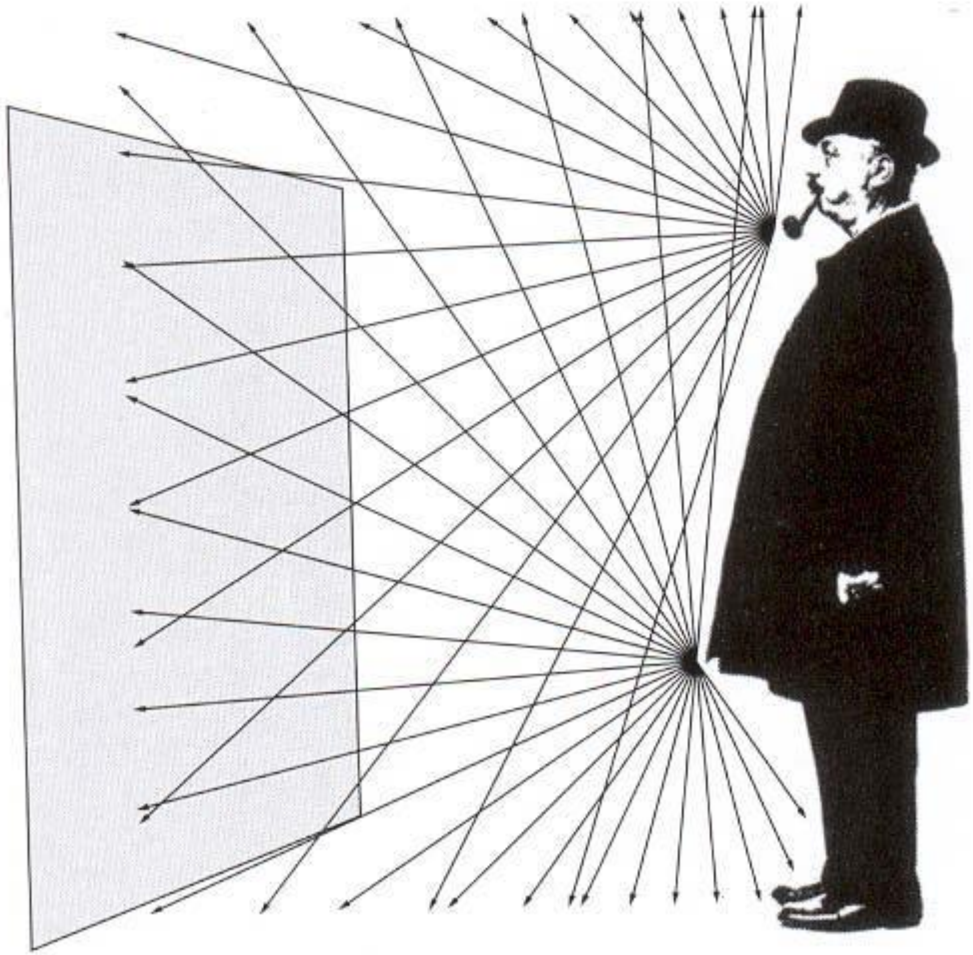
$$\rightarrow \quad \boxed{\sin\theta_1\, n_1 = \sin\theta_2\, n_2}$$



universitätbonn

Forming an image

Why not use sensors without optics?



(London)

The plenoptic function

- [Adelson and Bergen 1991]

"Function of everything visible"

What is the radiance carried by a ray passing through point (x, y, z) in direction (θ, ϕ) at time t, at wavelength λ ?

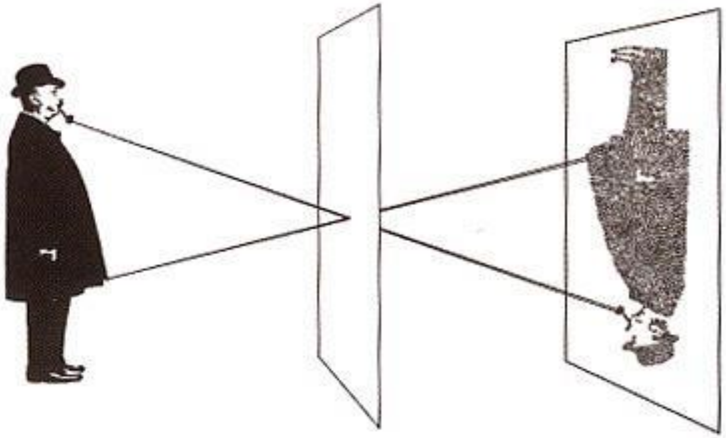
$$f(x, y, z, \theta, \phi, t, \lambda)$$

How do we turn this into a 2-dimensional image?

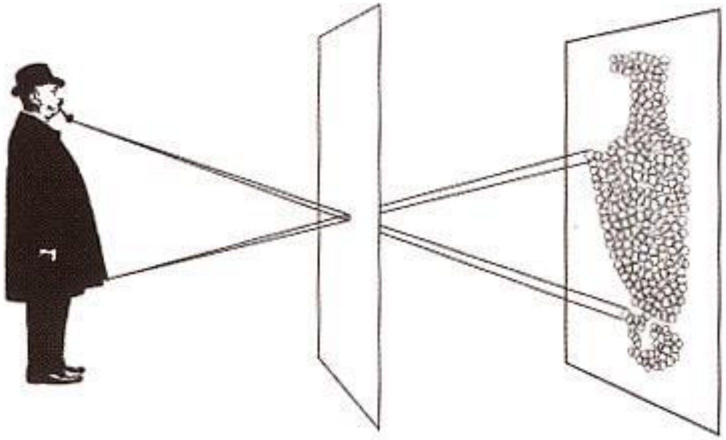
=> **Integration**, e.g. over t, λ, θ, ϕ

Pinhole camera

Photograph made with small pinhole



Photograph made with larger pinhole

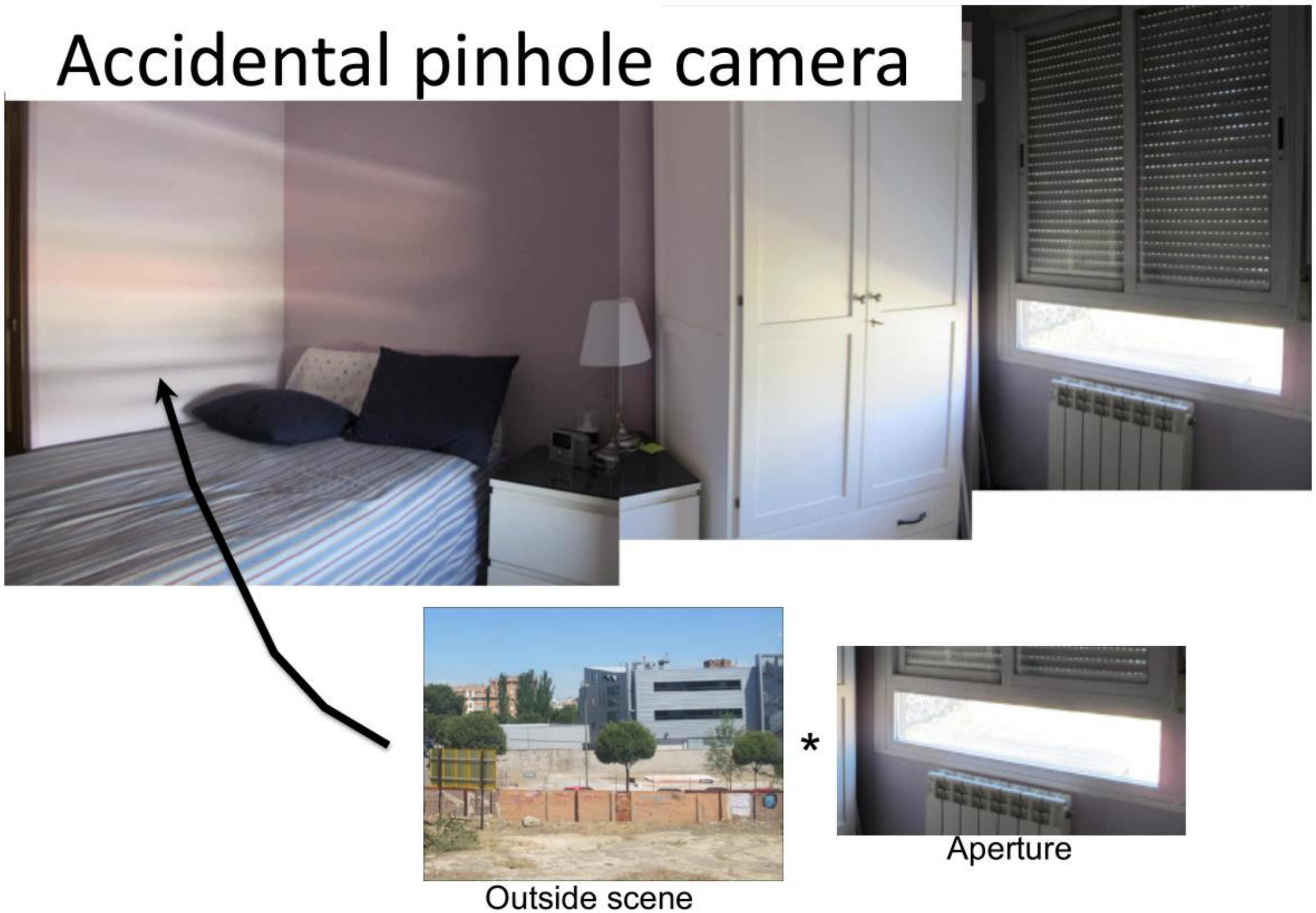


(London)

universitätbonn

Pinhole cameras are everywhere

- Torralba and Freeman, Accidental Pinpoint and Pinspeck Cameras (CVPR 2012)



See Zomet, A.; Nayar, S.K. CVPR 2006 for a detailed analysis.


Spring 2016, on our balcony...

Pinhole camera

- Large pinhole gives geometric blur
- Small pinhole gives diffraction blur
- Optimal pinhole gives very little light
  - for 35mm format, around f/200

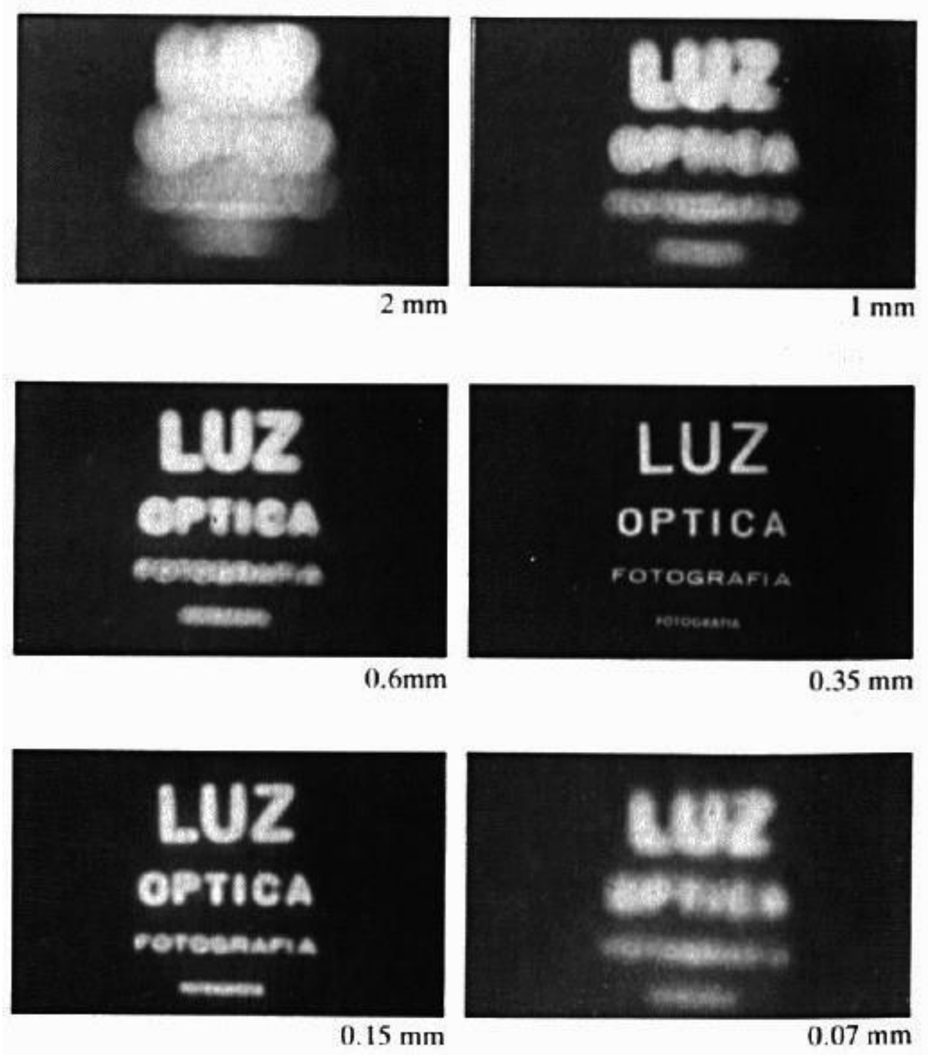
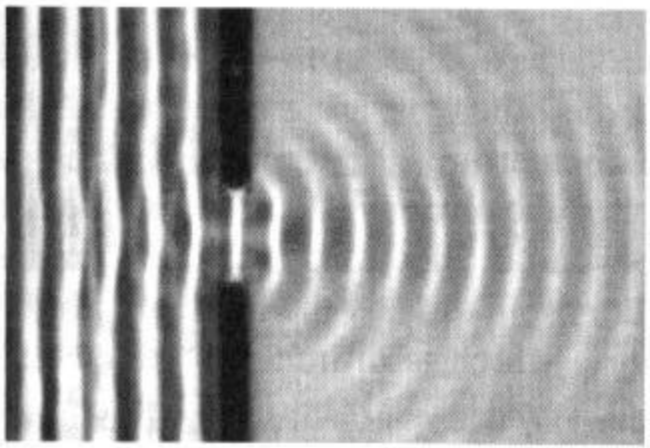
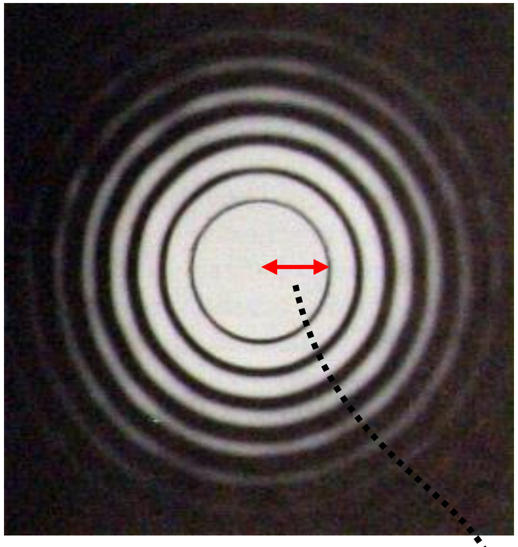


image: Hecht

Diffraction



- Huygens: every point on a wavefront can be considered as a source of spherical wavelets
- Fresnel: the amplitude of the optical field is the superposition of these waves, considering amplitude and phase
- Fraunhofer: resulting far-field diffraction pattern



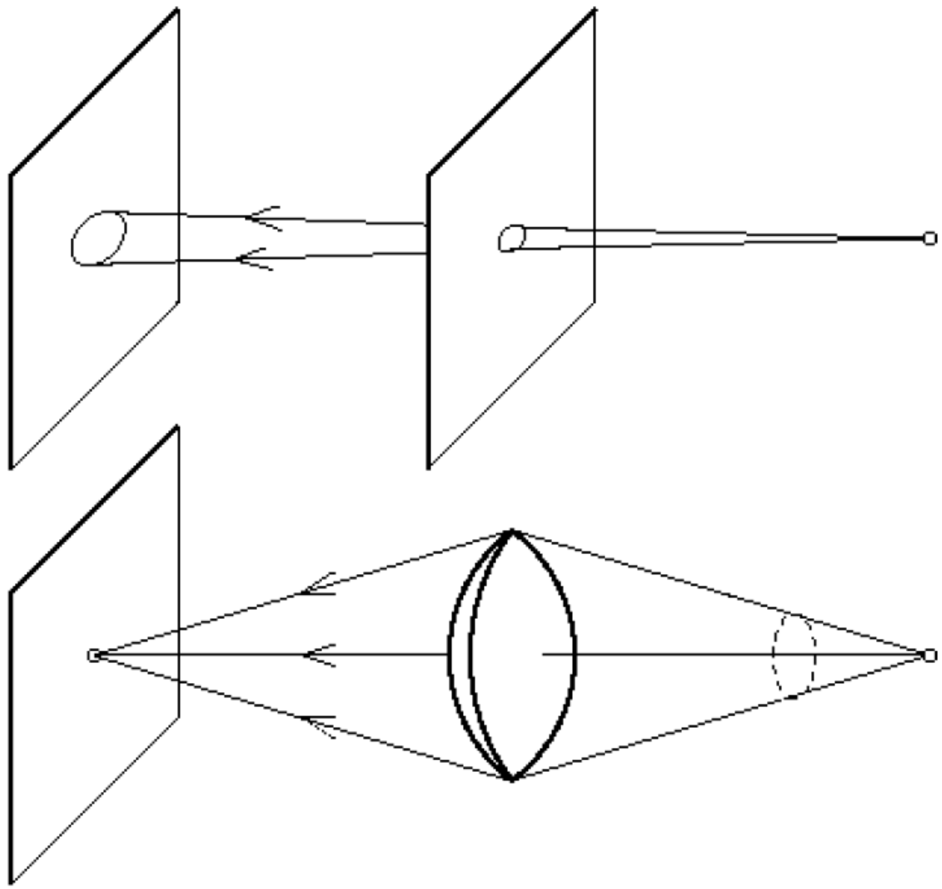
Diffraction from a circular aperture: Airy rings

Angular half-width of central maximum:

$$\sin\alpha \approx 1.22\,\lambda/d$$

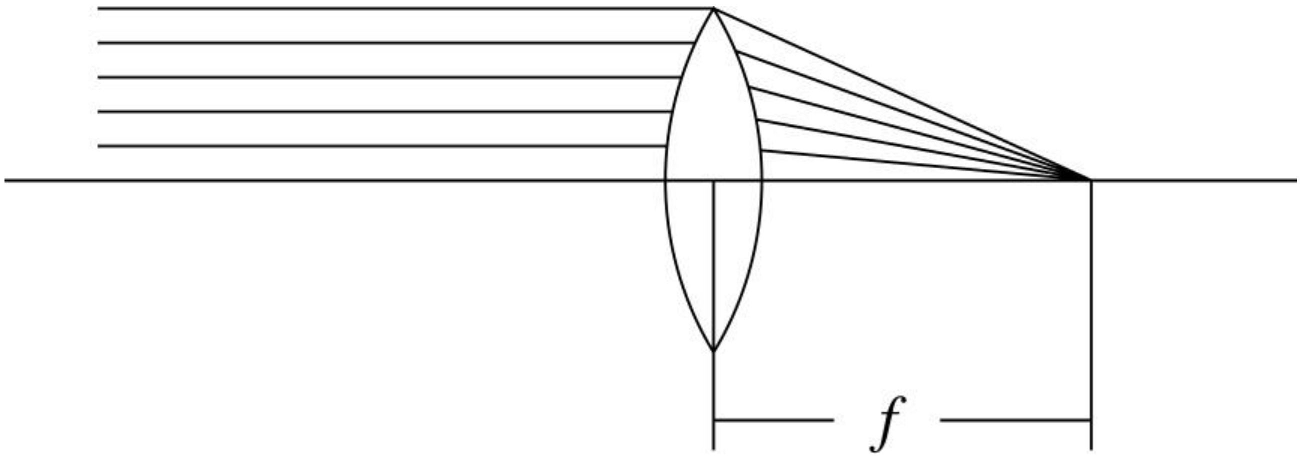
images: Hecht

The reason for lenses



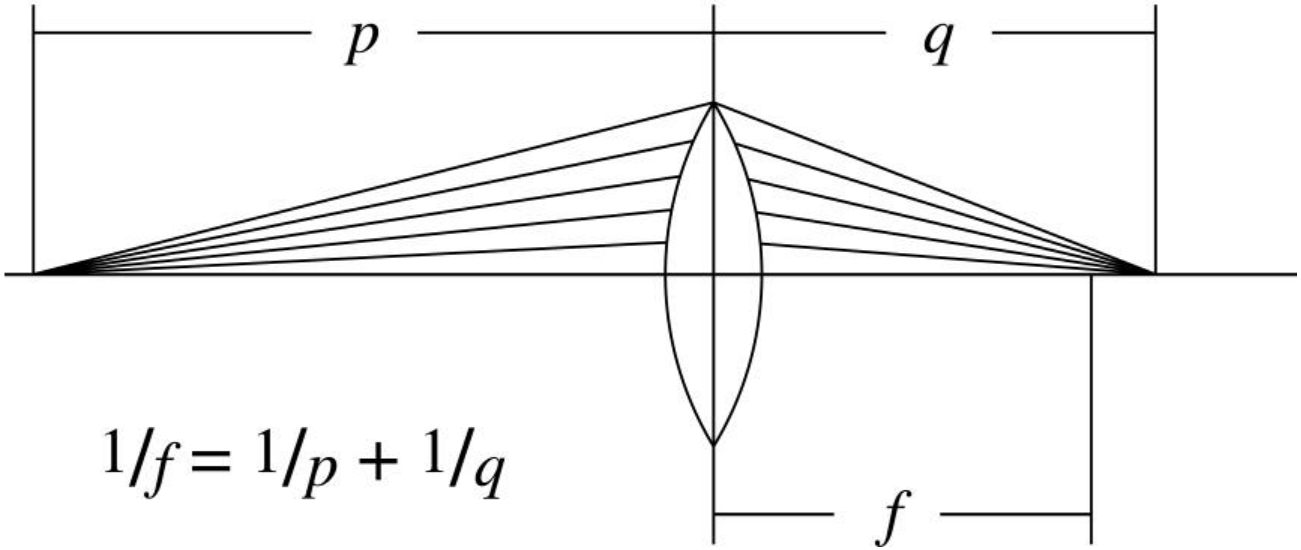
Purpose of lens

- Produce bright but still sharp image
- Focus rays emerging from a point to a point



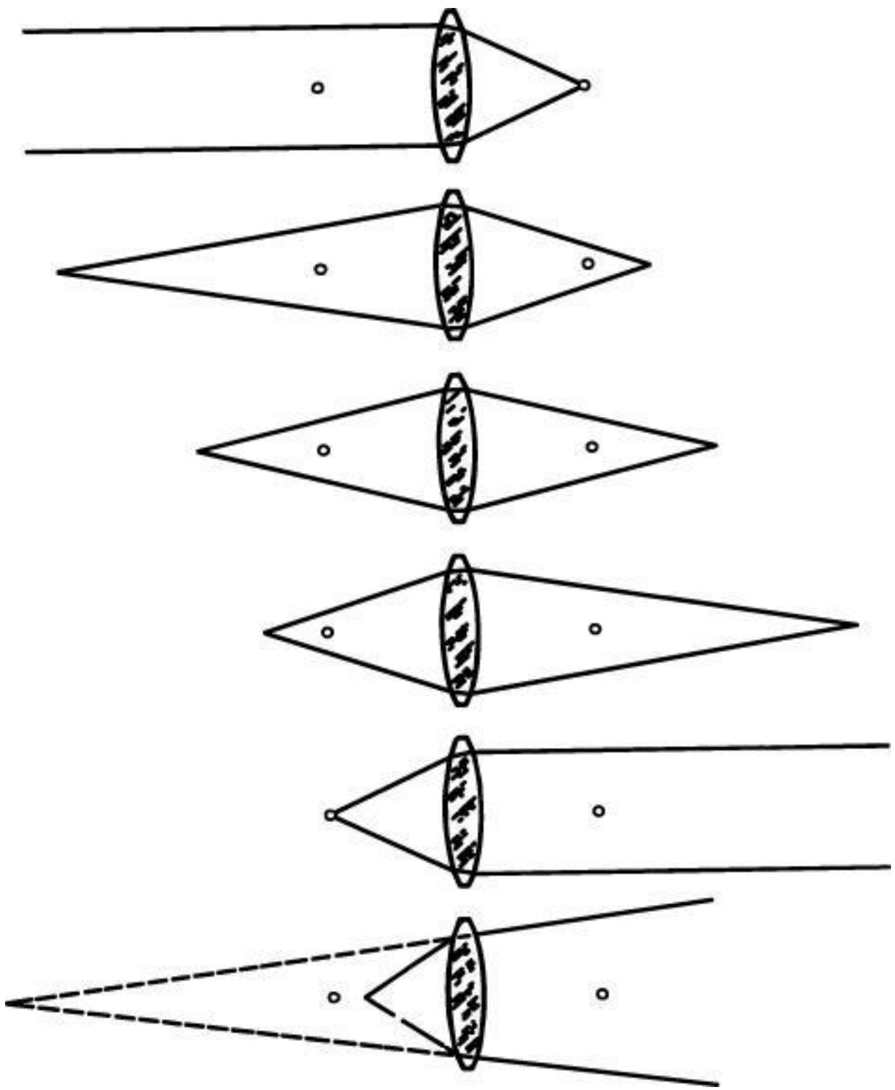
Purpose of lens

- Produce bright but still sharp image
- Focus rays emerging from a point to a point

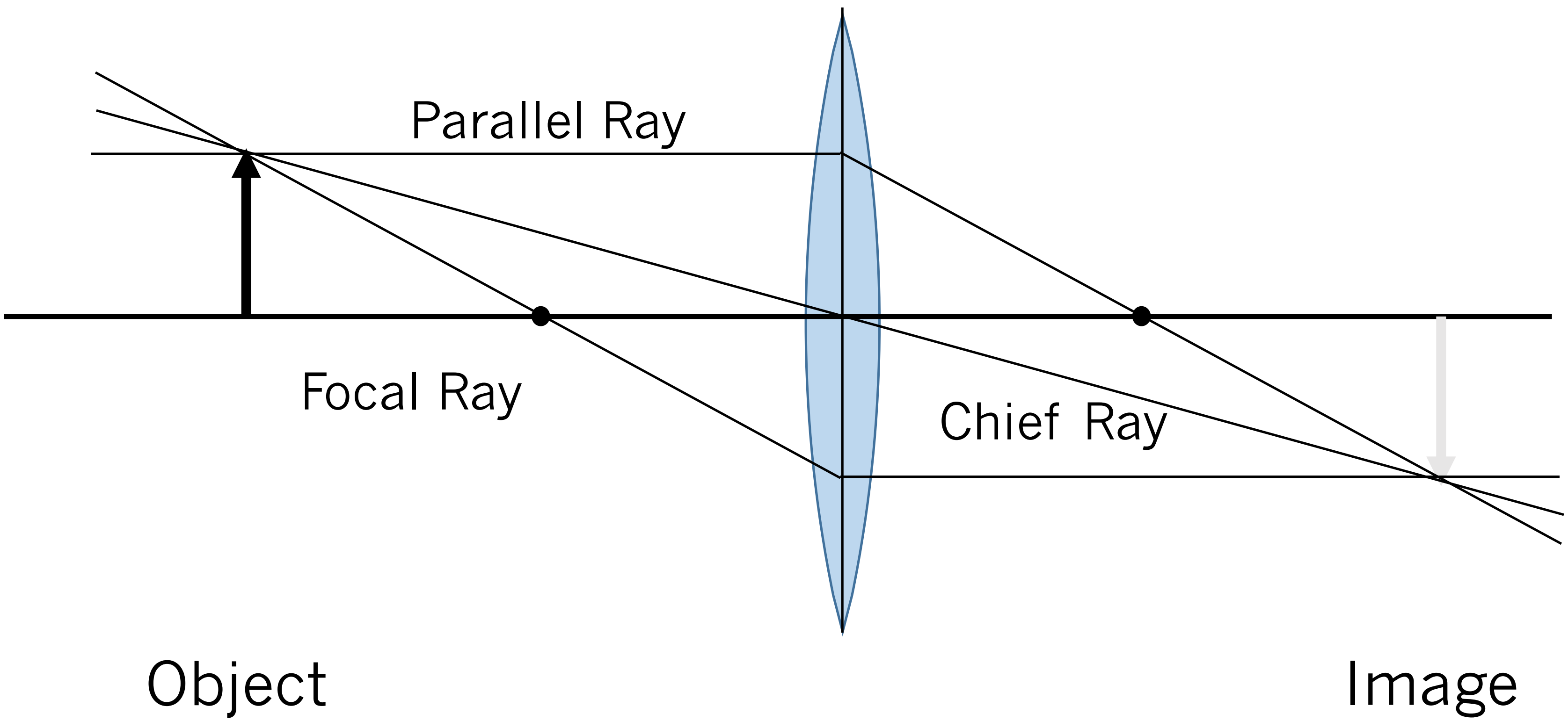


Focal points and focal lengths

- To focus: move lens relative to backplane



Gaussian ray tracing construction



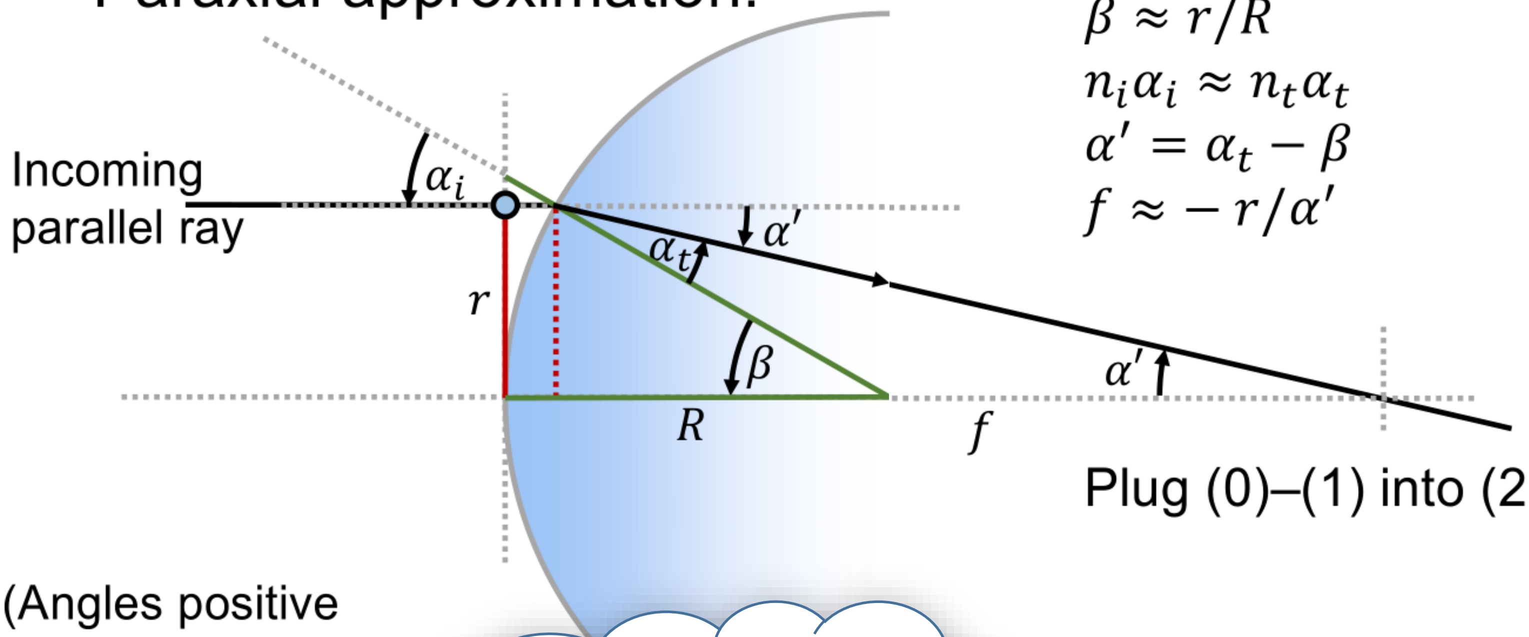
Refractive spherical interface

What is the focal length of a spherical interface $n_i \to n_t$?

Exact solution through ray tracing

Paraxial approximation:

$$\alpha := 0 \implies \alpha_i = \beta \qquad (0)$$
$$\beta \approx r/R \qquad (1)$$
$$n_i \alpha_i \approx n_t \alpha_t \qquad (2)$$
$$\alpha' = \alpha_t - \beta \qquad (3)$$
$$f \approx -r/\alpha' \qquad (4)$$



(Angles positive if arrow ccw; negative if cw)

Refraction at a curved interface	$\begin{pmatrix} 1 & 0 \\ \frac{n_1-n_2}{R \cdot n_2} & \frac{n_1}{n_2} \end{pmatrix}$
Thin lens	$\begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix}$

Plug (0)–(1) into (2):

$$\alpha_t = \frac{n_i r}{R n_t}$$

Further, with (3) into (4):

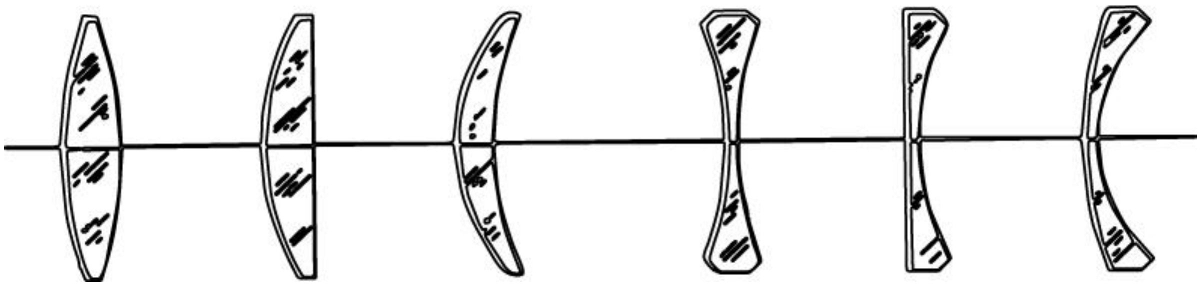
$$f = \frac{r}{\frac{r}{R} - \frac{n_i r}{R n_t}} = \frac{R n_t}{n_t - n_i}$$

universitätbonn

Lens-makers Formula

Refractive Power for lenses with two radii

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



Biconvex | Pos. Meniscus | Plano concave |

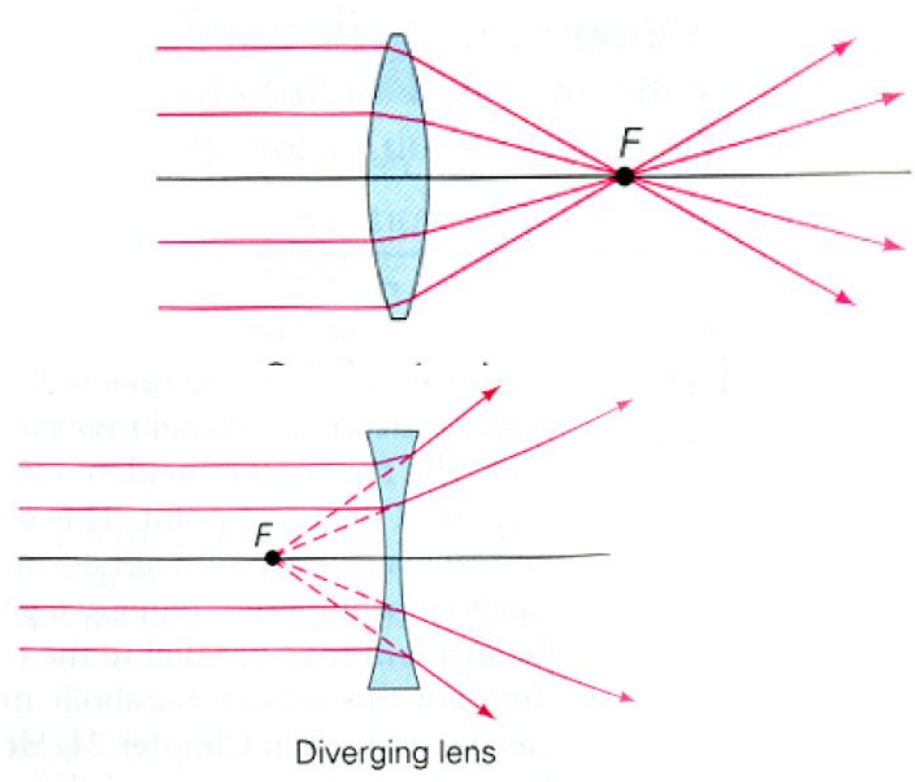
Plano-convex Biconcave Neg. meniscus

Convex = Converging Concave = Diverging

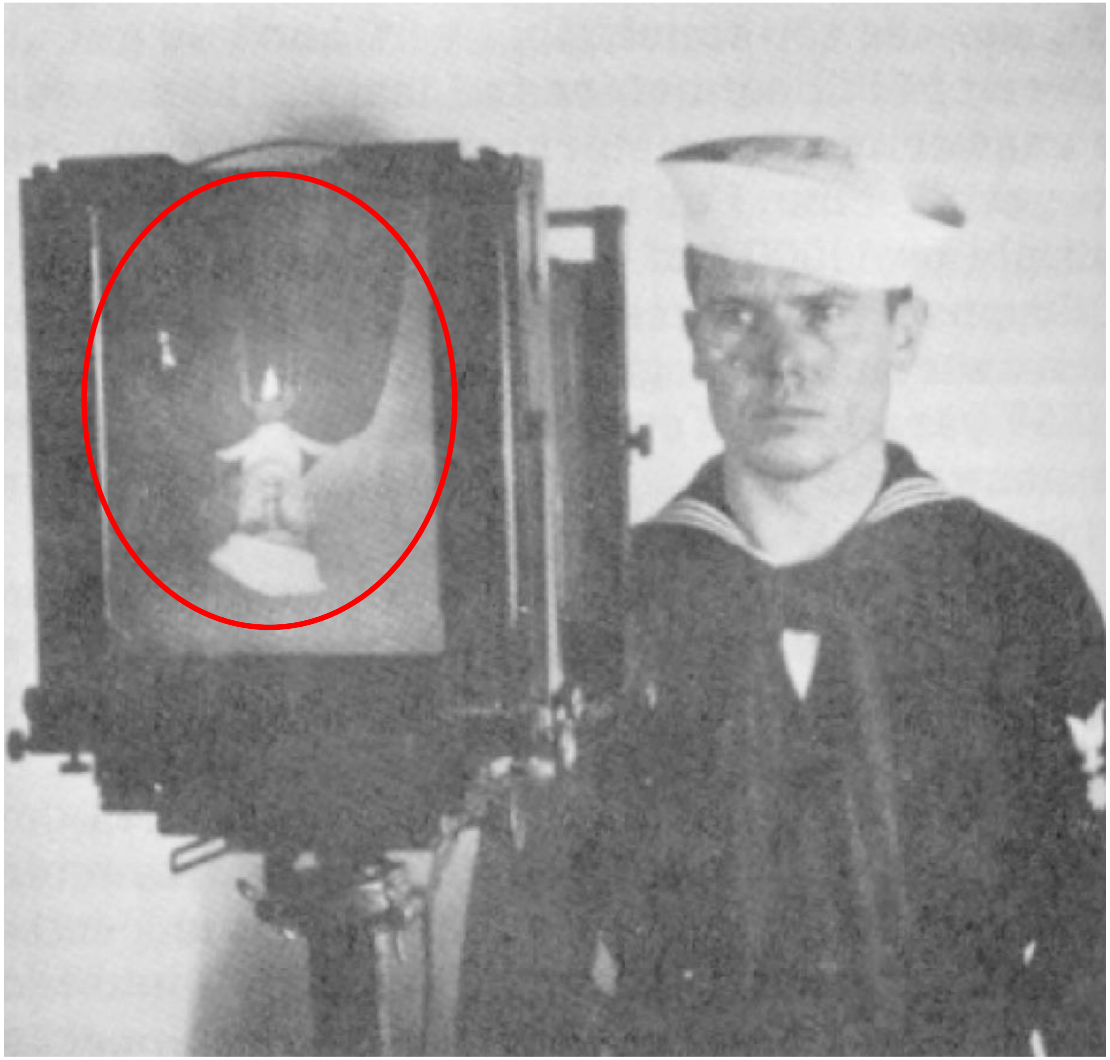
image: Smith 2000

Convex and Concave Lenses

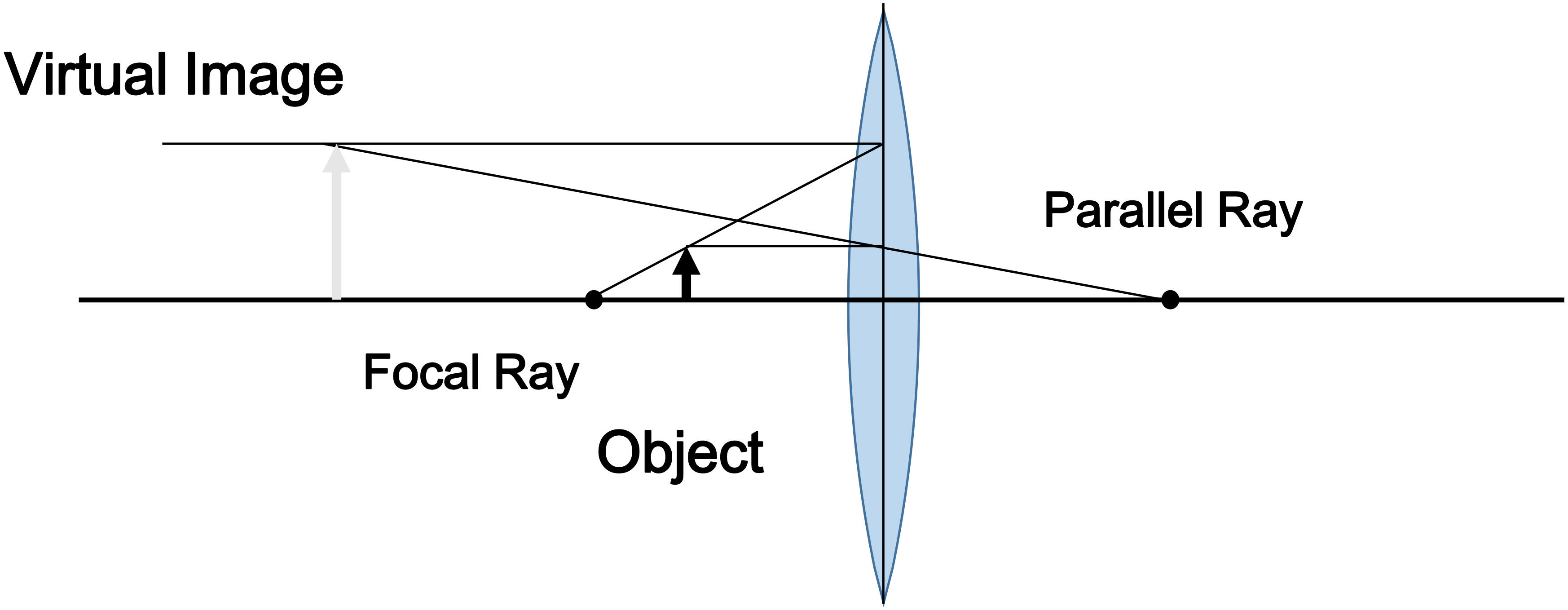
- positive vs. negative focal length



Real Image



Magnifying Glass



Thick lenses

- Complex optical system is characterized by a few numbers

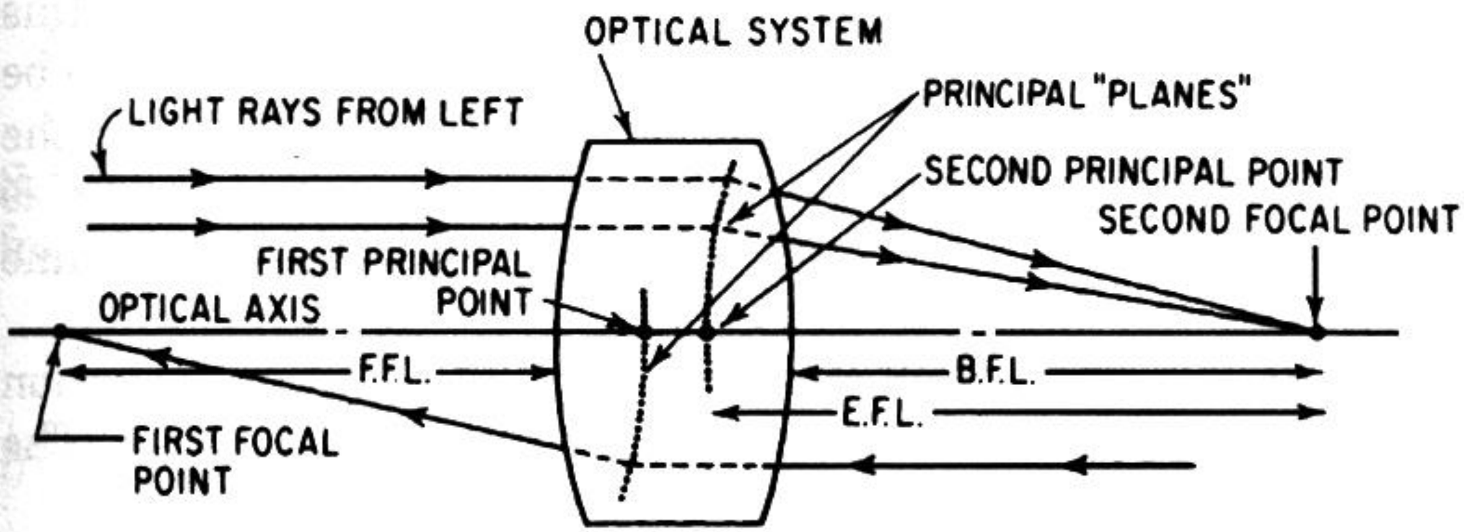


Figure 2.1 Illustrating the location of the focal points and principal points of a generalized optical system.

- Principal planes are the paraxial approximation of a spherical “equivalent refracting surface”

image: Smith 2000

The “center of perspective”

- In a thin lens, the *chief ray* traverses the lens (through its optical center) without changing direction
- In a thick lens, the intersections of this ray with the optical axis are called the *nodal points*
- For a lens in air, these coincide with the principal points
- The first nodal point is the center of perspective

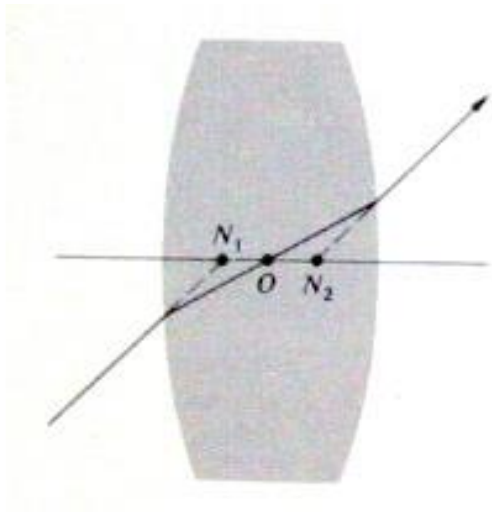


image: Hecht

When taking panorama photos by rotating camera, use N_1 as center of rotation

Optical parameters in photography

Focal length and magnification

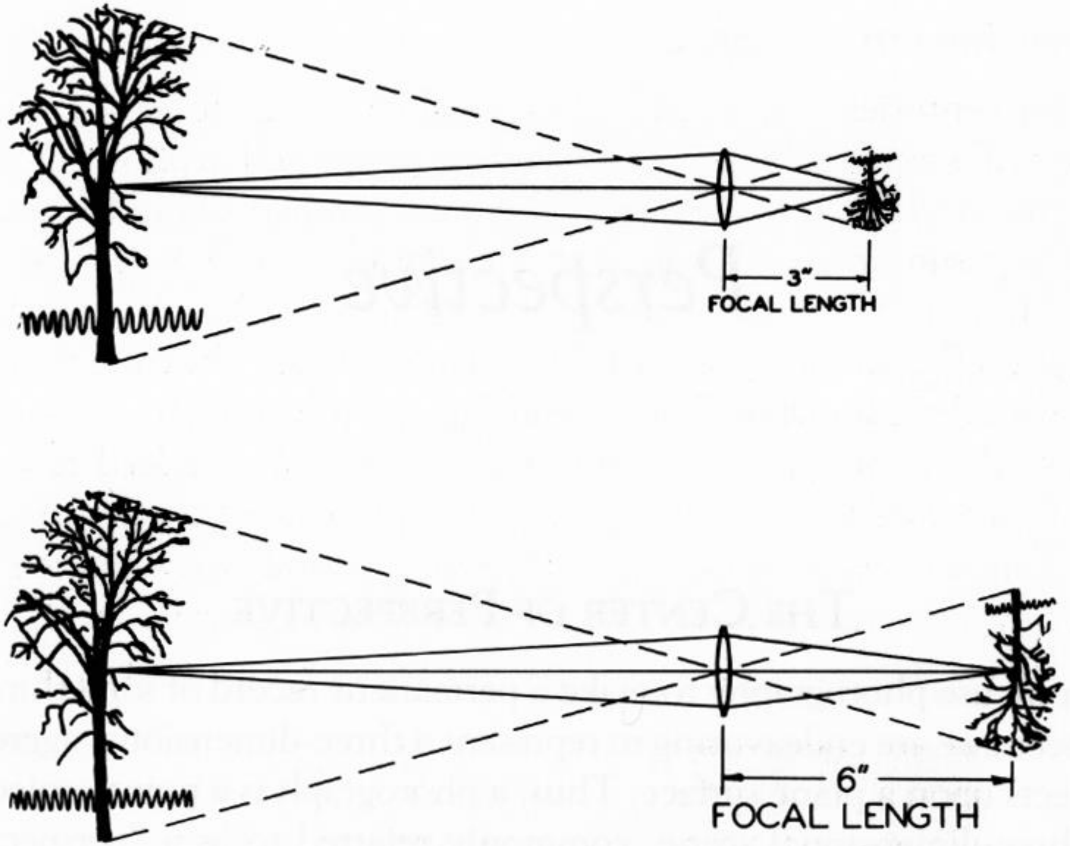


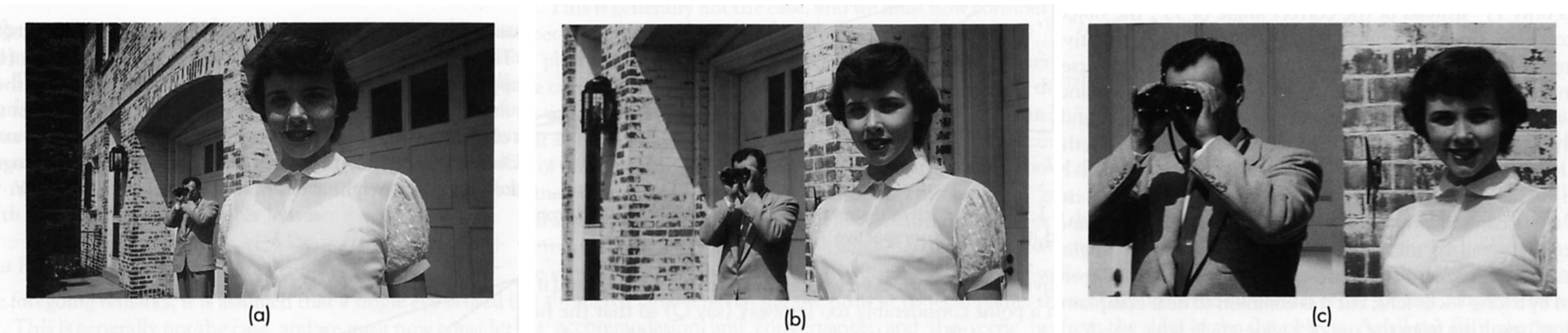
Figure 1.2. A lens of long focus produces a larger image than one of short focus.

image: Kingslake 1992

universitätbonn

Focal length and field of view

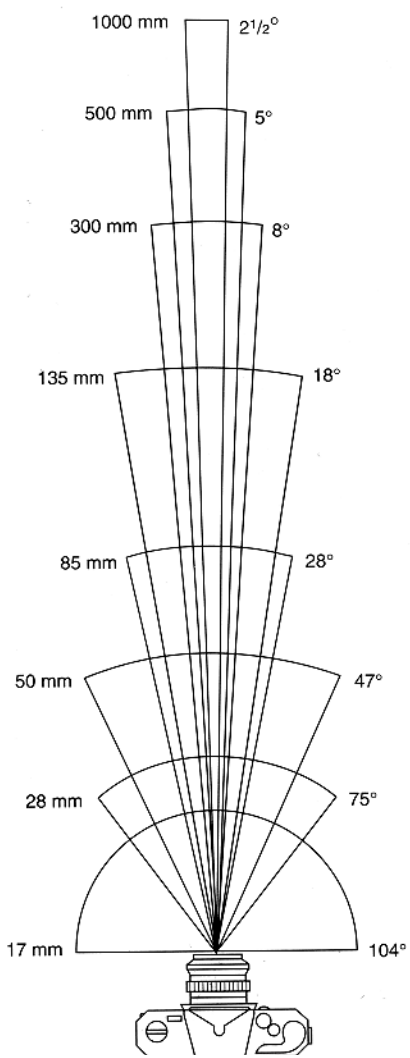
- Changing the magnification lets us move back from a subject, while maintaining its size on the image
- Moving back changes perspective relationships

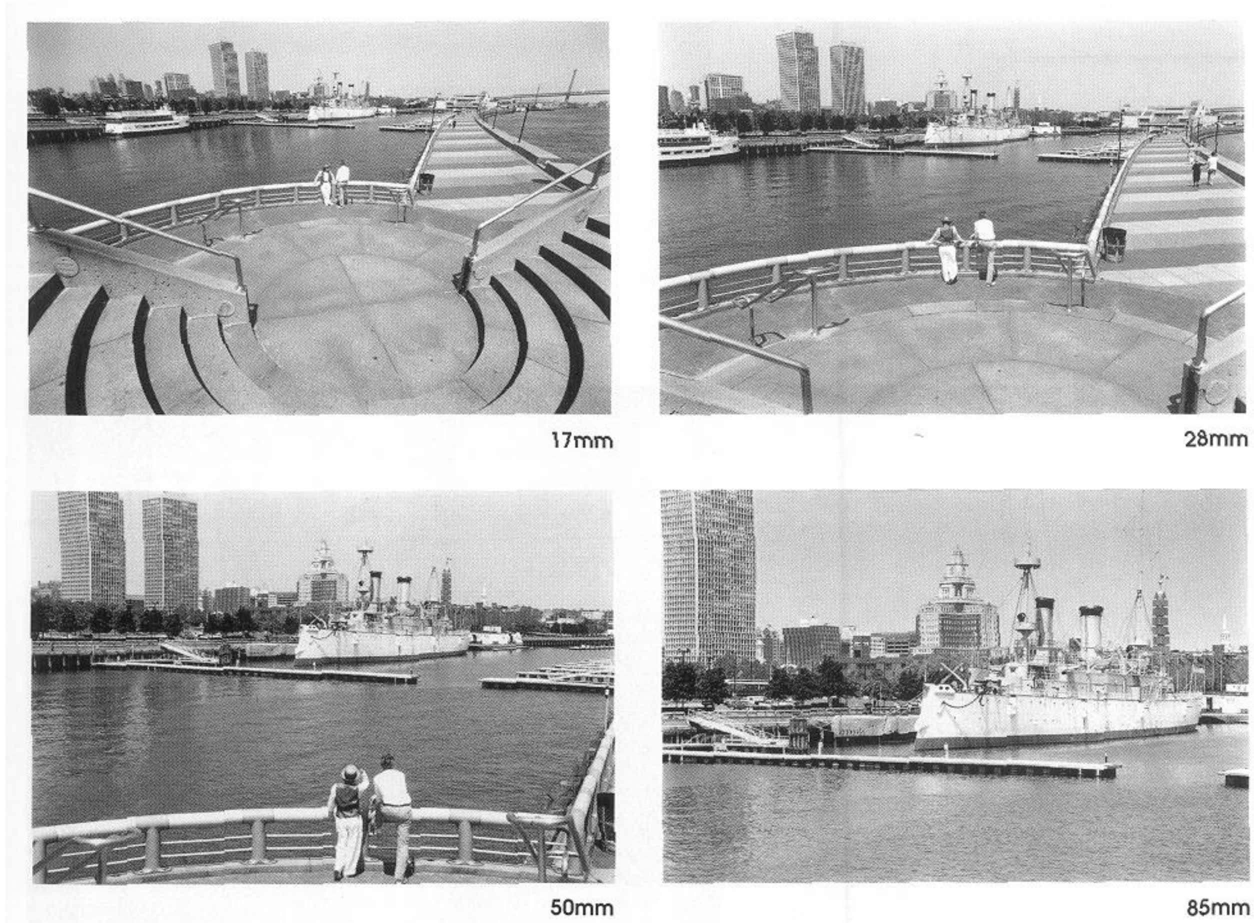


From (a) to (c), we've moved back from the subject and employed lenses with longer focal lengths

image: Kingslake 1992

Field of View

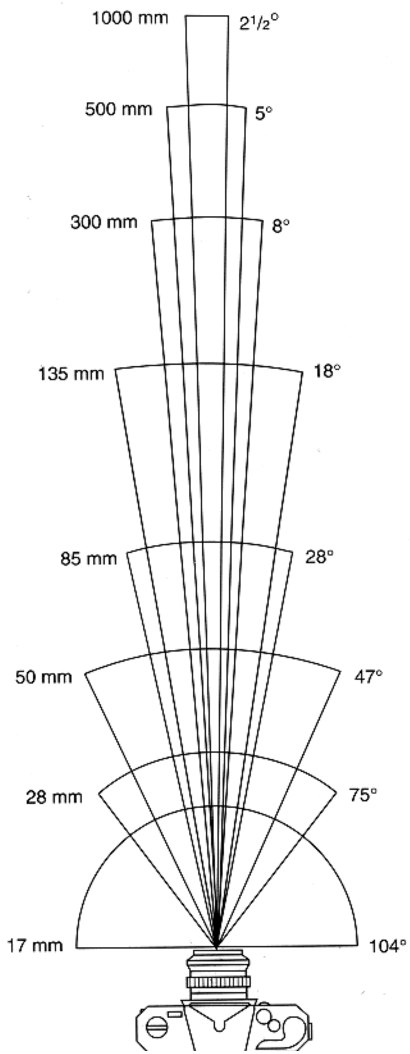


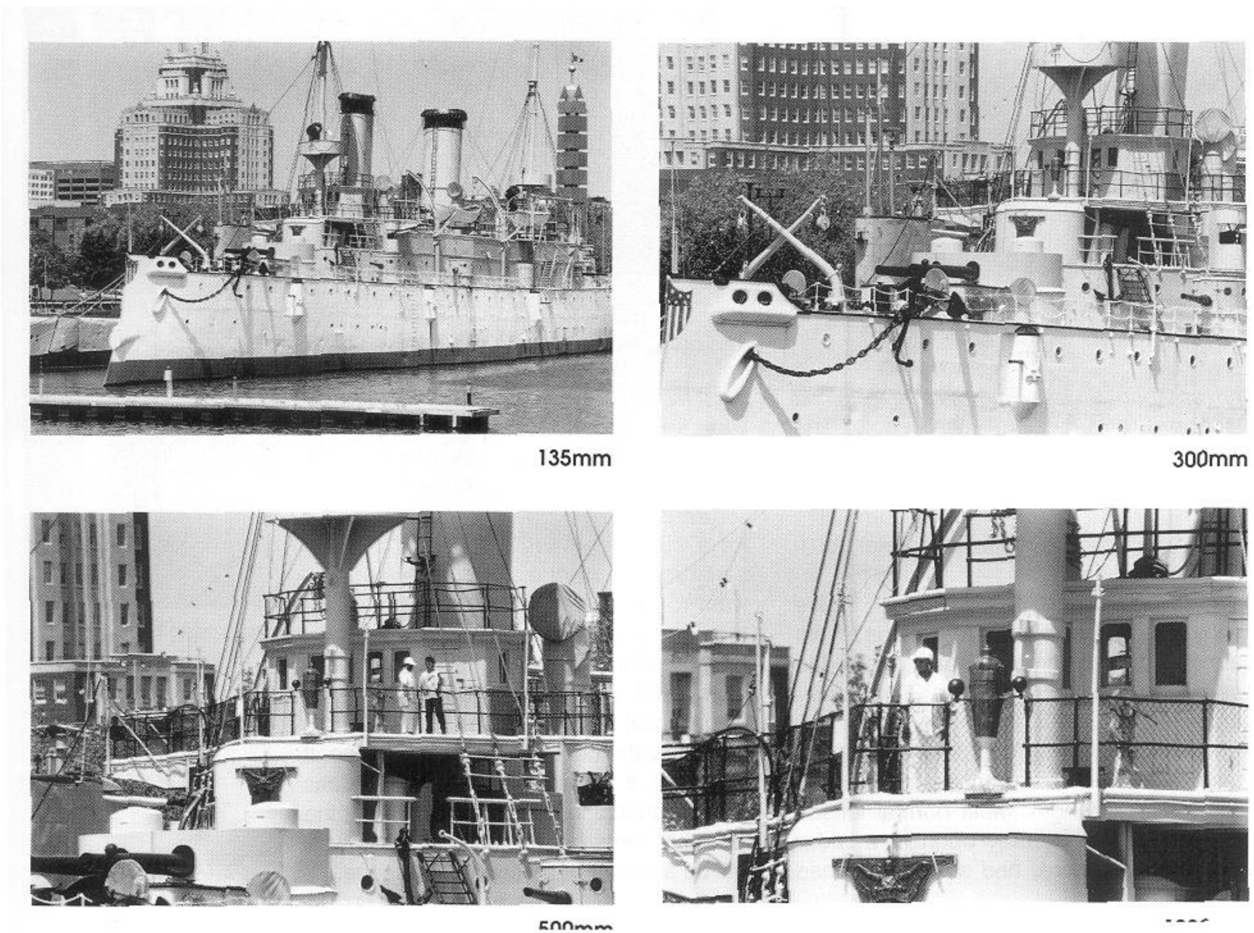


images: London and Upton

universitätbonn

Field of View



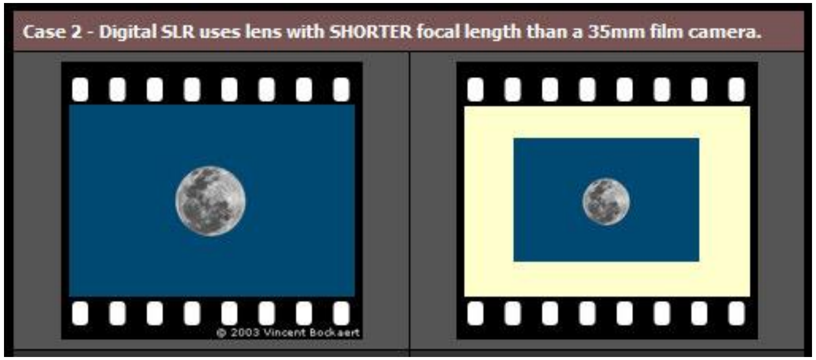


images: London and Upton

Effects of image format

- Field of view

$$\tan\left(\frac{\text{fov}}{2}\right) = \left(\frac{\text{filmsize}}{2f}\right)$$



- Types of lenses
  - Film camera
    - 36mm x 24mm filmsize
    - 50mm focal length = 40° field of view
  - Digital camera
    - field of view is 2/3 of film for given focal length

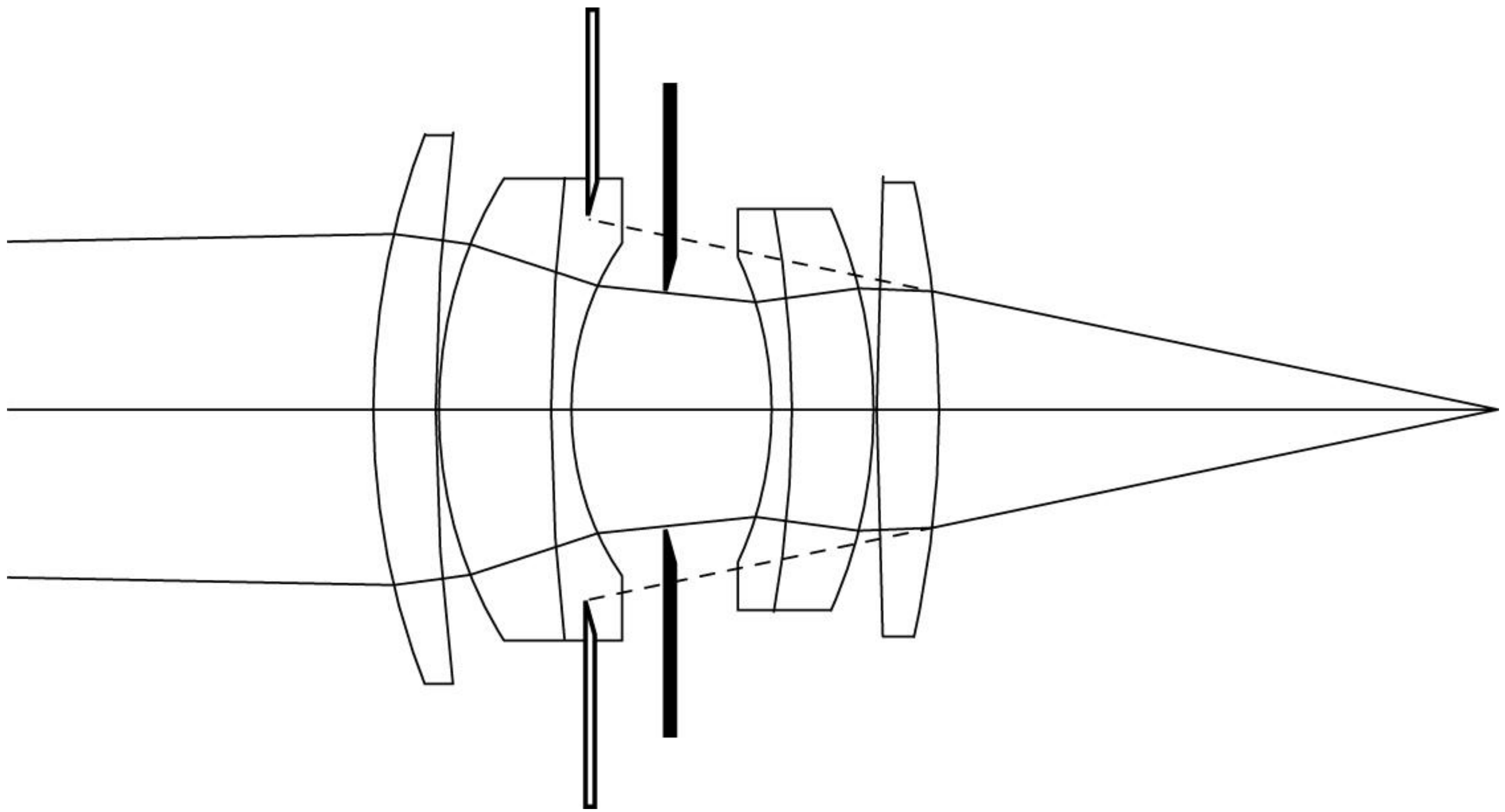
images: dpreview.com

universitätbonn

Effects of image format

- Smaller formats have…
  - shorter focal length for same field of view, as we've seen
  - smaller aperture size for same f-number
    - leads to larger depth of field
  - lighter, smaller lens for same design
    - enables use of bulkier designs
- Beware: diffraction does not scale down!
  - smaller apertures suffer more from diffraction

Aperture: Stops and Pupils



- Principal effect: changes exposure
- Side effect: depth of field

Aperture

- Irradiance on sensor is proportional to
  - square of aperture diameter A
  - inverse square of sensor distance (~ focal length)
- Aperture N therefore specified relative to focal length

$$N = f \,/\, A$$ **f-number**

  - numbers like "f/1.4" – for 50mm lens, aperture is ~35mm
  - exposure proportional to square of f-number, and independent of actual focal length of lens!
- Doubling series is traditional for exposure
  - therefore the familiar (rounded) $\sqrt{2}$ series
  - 1.4, 2.0, 2.8, 4.0, 5.6, 8.0, 11, 16, 22, 32, ...

How low can N be?

- Lowest N (in air) is f/0.5
- Lowest N in SLR lenses around f/1

$$N = \frac{1}{2\sin(\theta')}$$

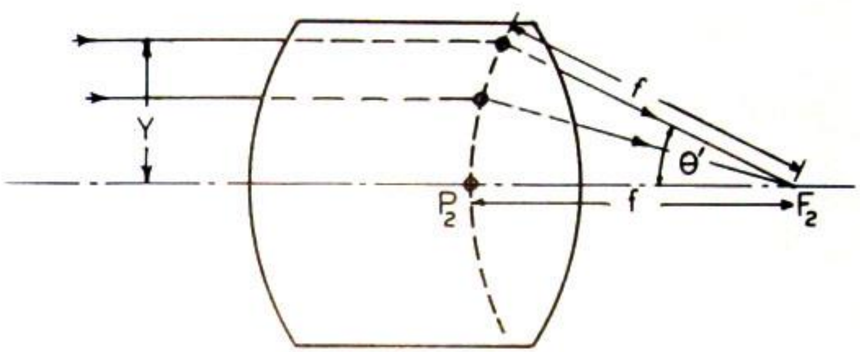
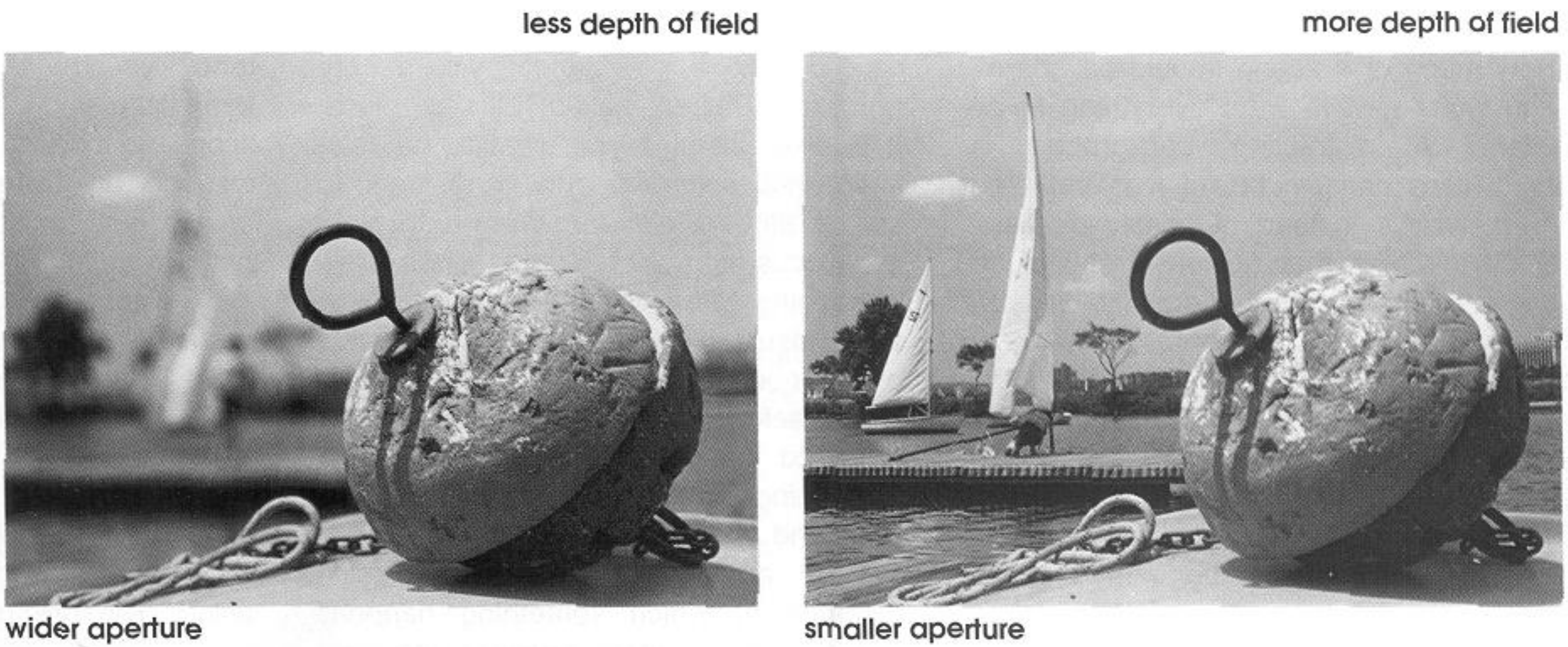


image: Kingslake 1992

Canon EOS 50mm f/1.0 (discontinued)

Canon 50mm f/0.95 (1961, discontinued)

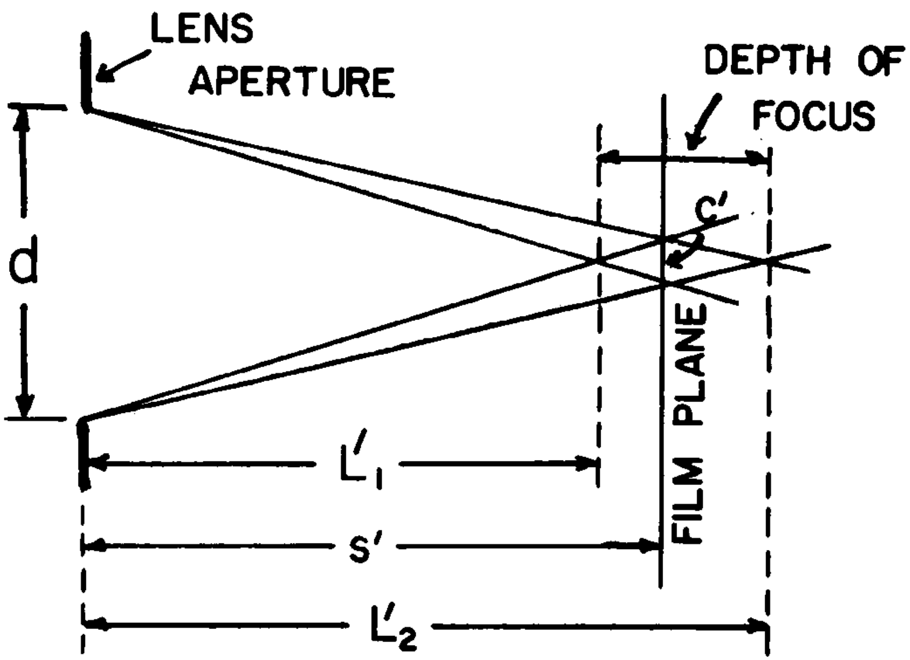
Depth of Field



images: London and Upton

Depth of focus (in image space)

- tolerance for placing the focus plane



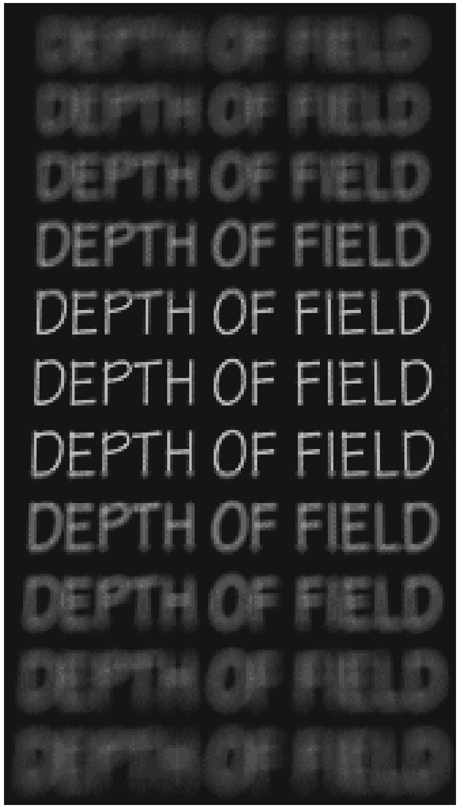
C' - circle of confusion

- Note that distance from (in-focus) film plane to front versus back of depth of focus differ

image: Kingslake 1992

Depth of field (in object space)

- the range of depths where the object will be in focus



www.cambridgeincolour.com

universitätbonn

Depth of field (in object space)

- Total depth of field (i.e. both sides of in-focus plane)

$$D_{tot} = \frac{2NCU^2}{f^2}$$

- where
  - N = f-number of lens
  - C = size of circle of confusion (on image)
  - U = distance to focused plane (in object space)
  - f = focal length of lens

(from Goldberg)

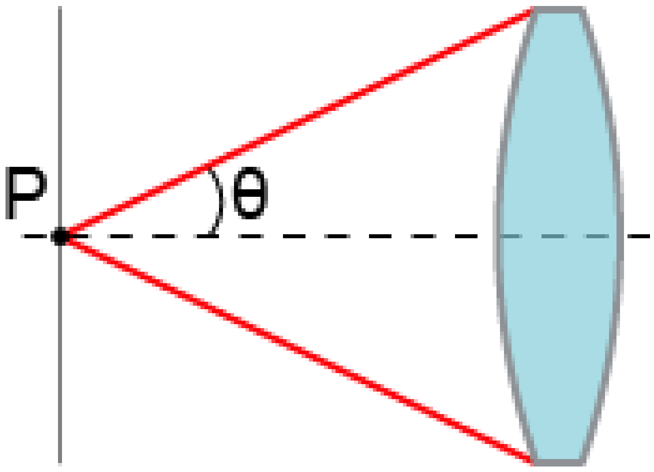
- Hyperfocal distance:

  Back focal depth becomes infinite when $\mathrm{U} = f^2/CN + f$

Applet – Depth of Field

- http://graphics.stanford.edu/courses/cs178-10/applets/dof.html

Numerical aperture



[Wikipedia]

$$NA = n \sin\theta$$

- The size of the finest detail that can be resolved is proportional to $\lambda/_{NA}$.
- larger numerical aperture ⇔ resolve finer detail

Numerical aperture vs. f-number

$$f/\# \approx \frac{1}{2NA}$$

$$f/\#_w = \frac{1}{2NA} \approx (1+m) f/\#$$

- Working f-number: $f/\#_w$
- Distance-related magnification: m

- relevant for systems with high magnification (microscopes or macro lenses)

Non-perfect imaging and noteworthy effects

Tilt and Shift Lens

- Lens shift simply moves the optical axis with regard to the film.
  - change of perspective (sheared perspective)
- Tilt allows for applying **Scheimpflug principle**
  - all points on a tilted plane in focus

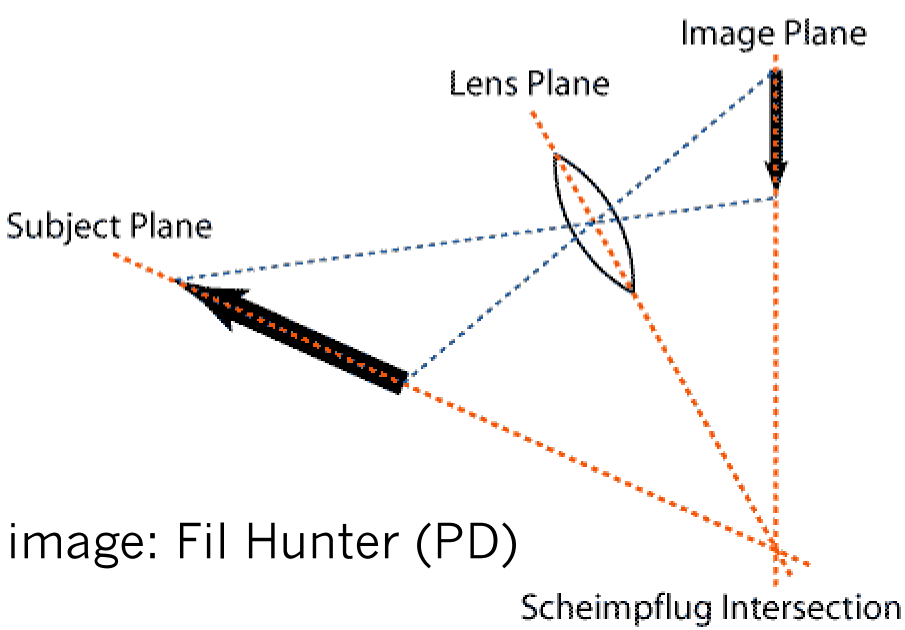


image: Fil Hunter (PD)

Pseudo-macro photography

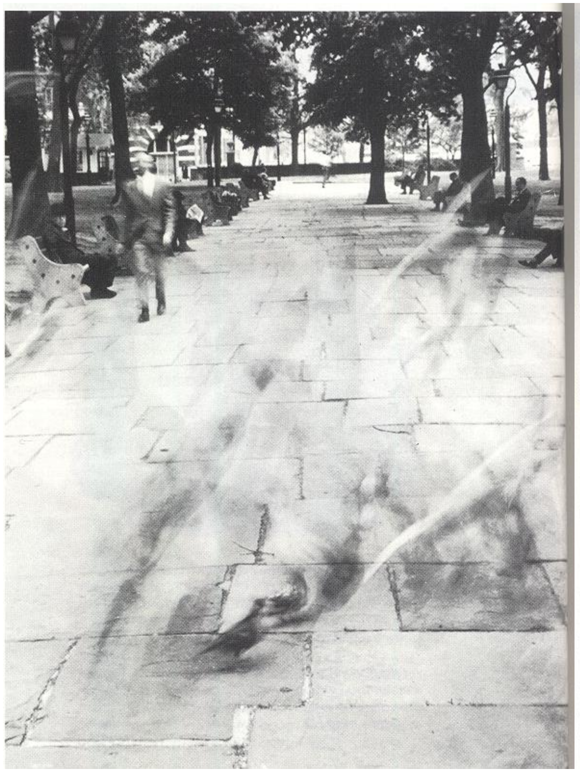
Perspective correction

Camera Exposure

$$H = ET$$

- 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

Aperture vs Shutter



f/16
1/8s

f/4
1/125s

f/2
1/500s

images: London and Upton

Describing Sharpness

- Point spread function (PSF)

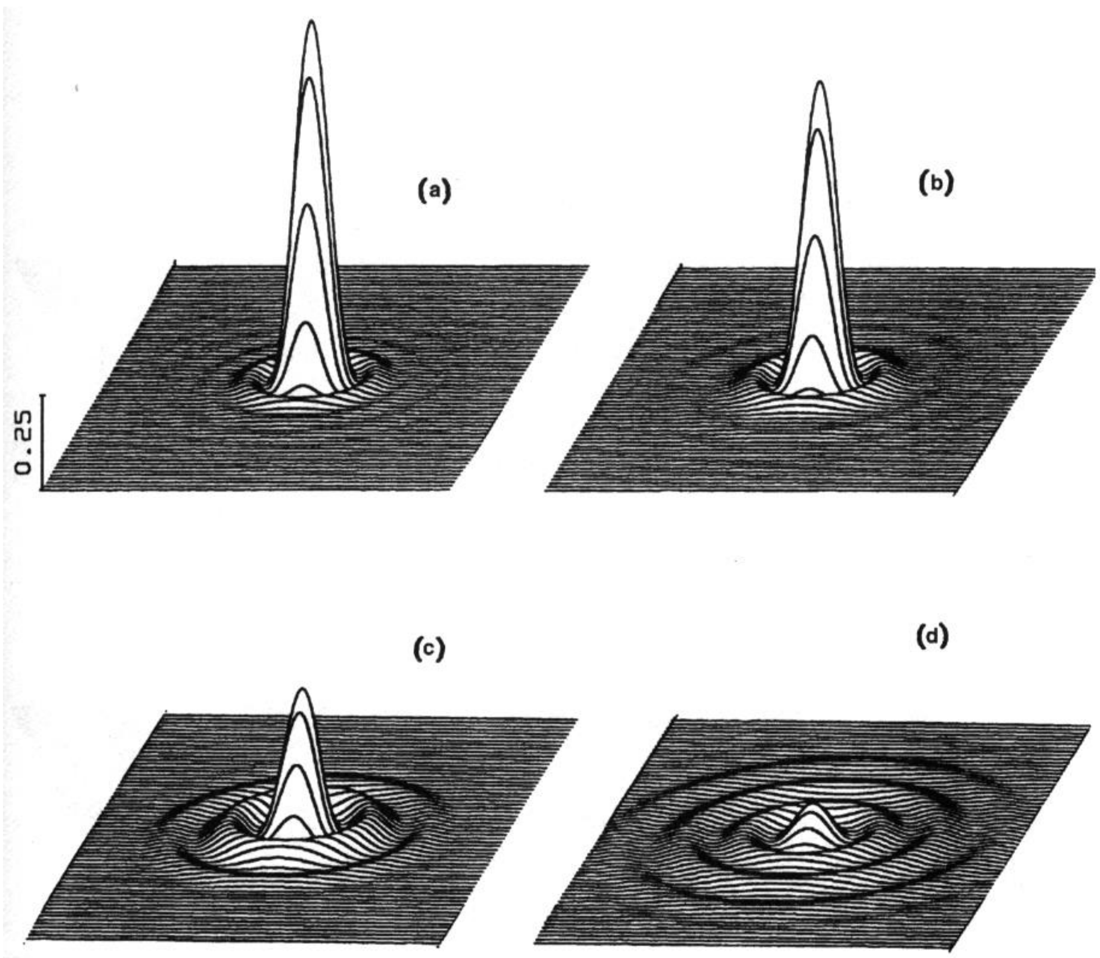
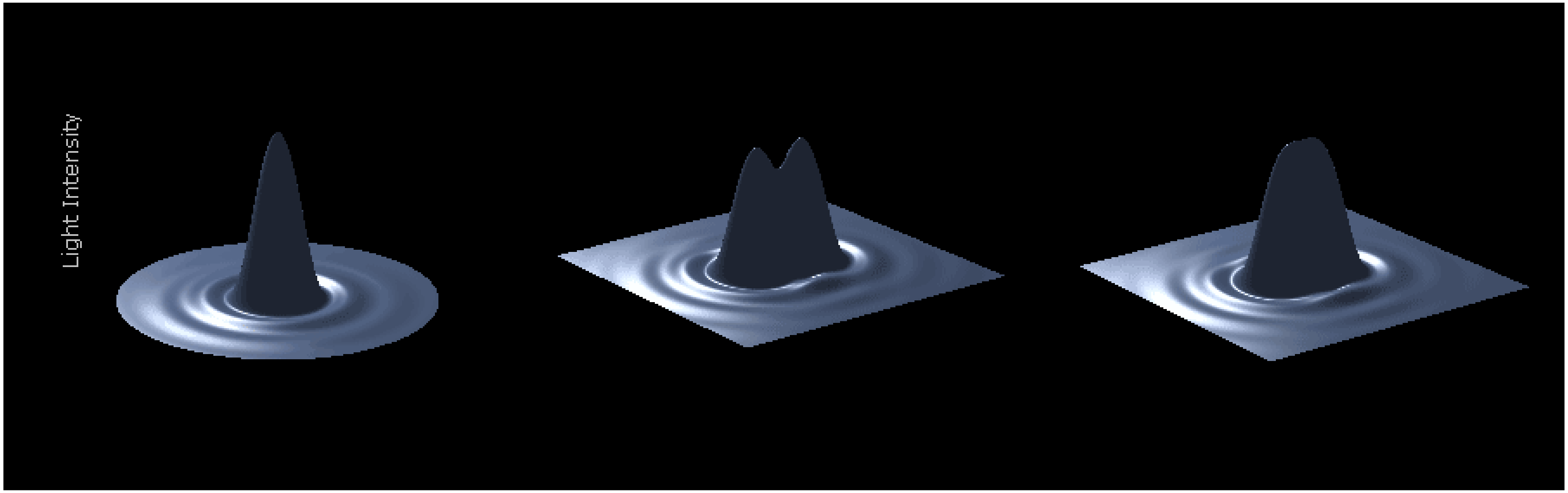


image: Smith 2000

Diffraction Limit

- Diameter d of 70% radius of the Airy disc

$$d = 1.22\lambda N = \frac{1.22\lambda f}{A}$$

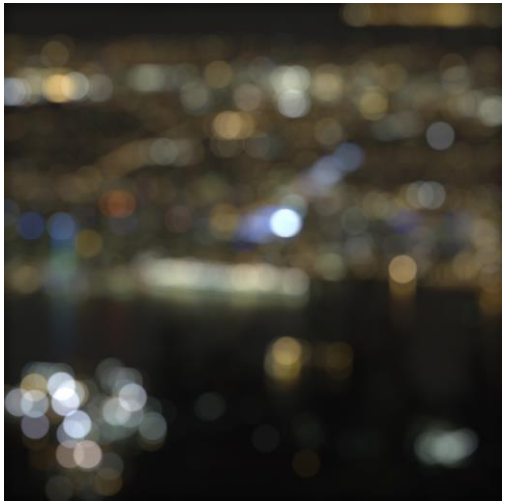


single spot barely resolved no longer resolved

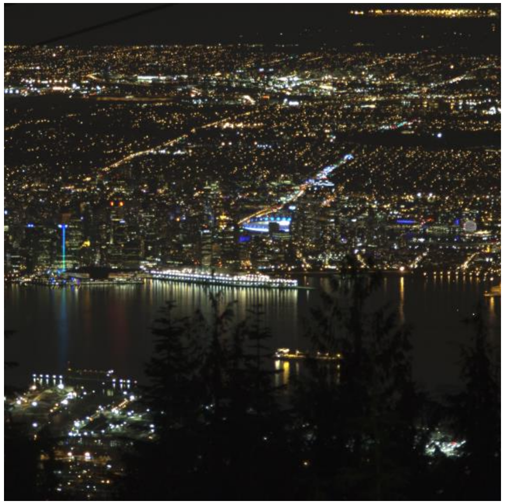
Point spread function

- Filter kernel applied by the imaging system
- Corresponds to the image of a single point feature
- Shape of the PSF $p(d)$ changes with object distance d (e.g. due to depth of field)
- Most often the $p(d)$ is assumed to be constant over the image

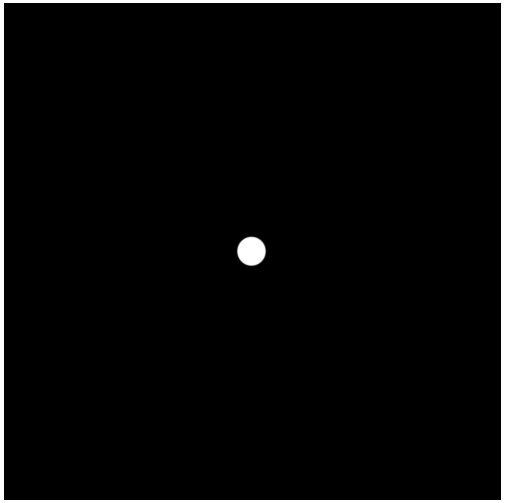
Convolution



$=$



$*$



Describing Sharpness

- Modulation transfer function (MTF)
  - Modulus of Fourier transform of PSF
  - “How well are the frequencies reproduced?

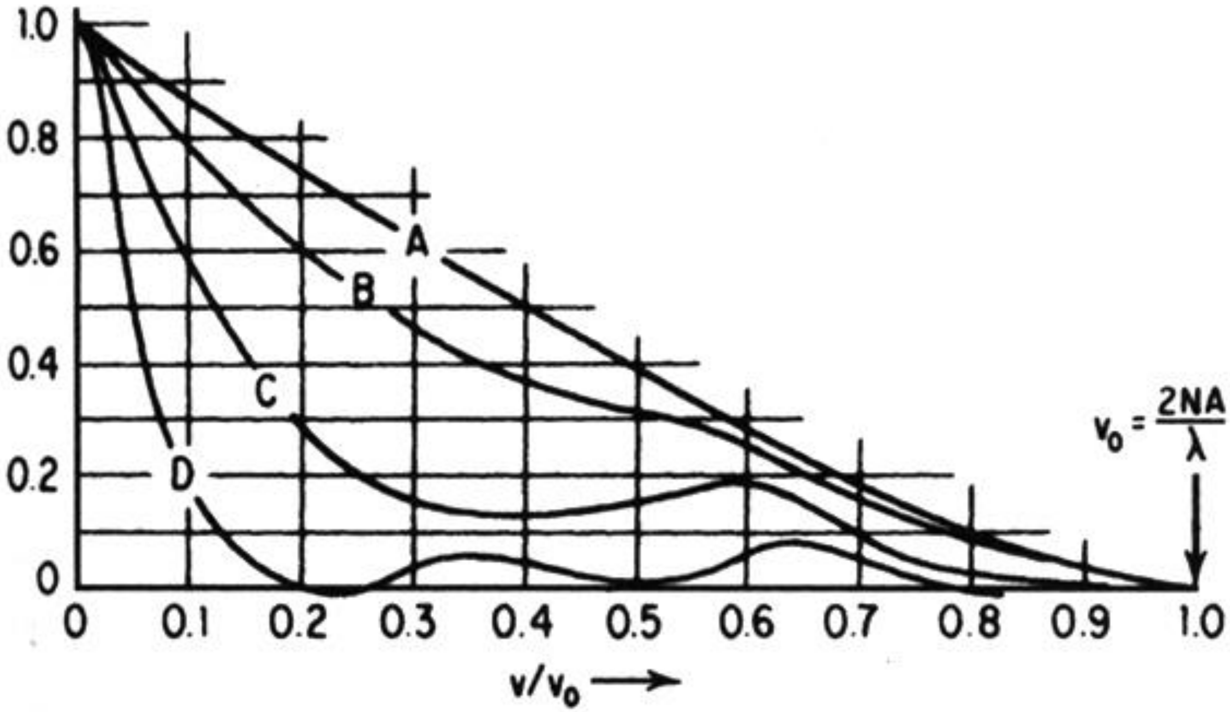


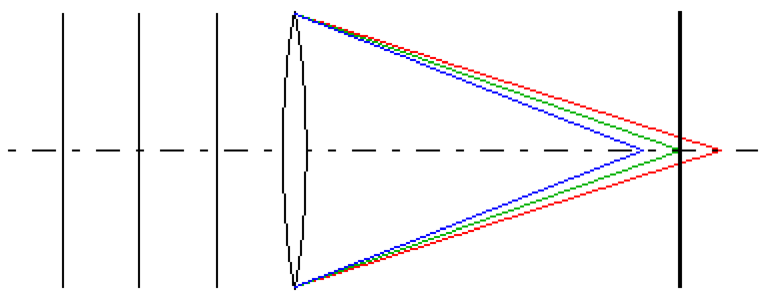
image: Smith 2000

Lens Aberrations

- Spherical aberration
- Coma
- Astigmatism
- Curvature of field
- Distortion

Chromatic Aberration

- Index of refraction varies with wavelength
- For convex lens, blue focal length is shorter
- Can correct using a two-element “achromatic doublet”, with a different glass (different n’) for the second lens



- Achromatic doublets only correct at two wavelengths…
- Why don’t humans see chromatic aberration?

Chromatic Aberrations

- Longitudinal chromatic aberration
  (change in focus with wavelength)

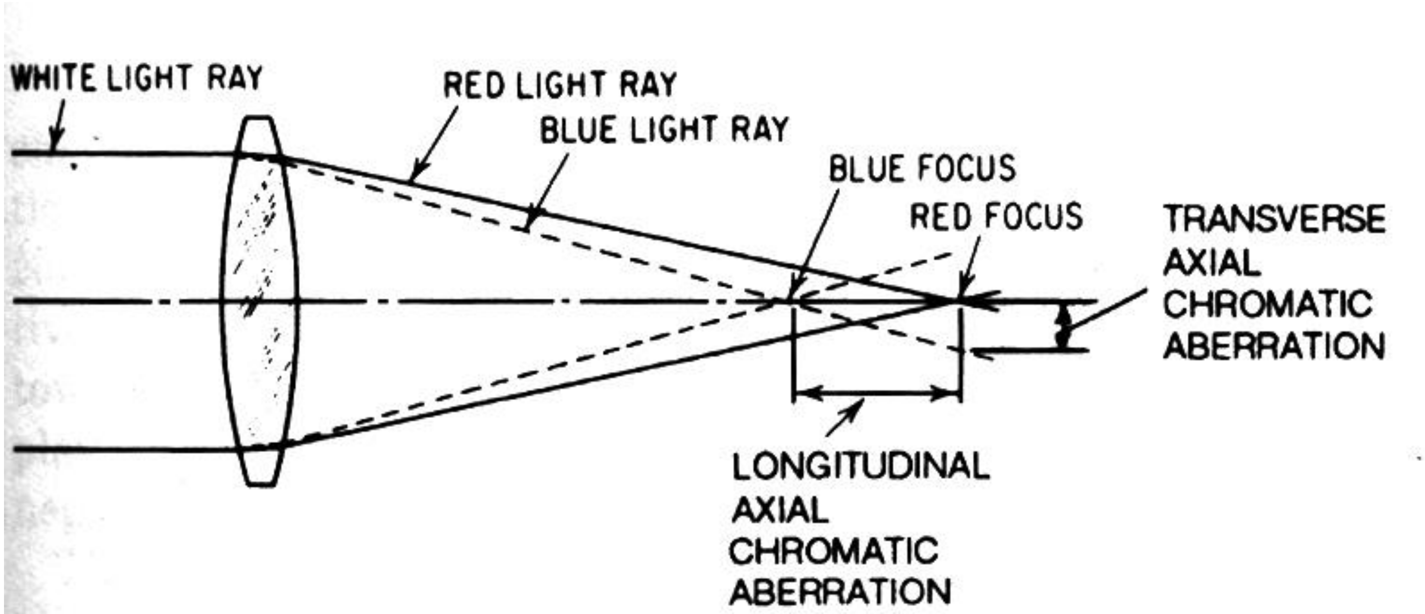


Figure 3.10 The undercorrected longitudinal chromatic aberration of a simple lens is due to the blue rays undergoing a greater refraction than the red rays.

image: Smith 2000

Chromatic Aberrations

- Lateral color (change in magnification with wavelength)

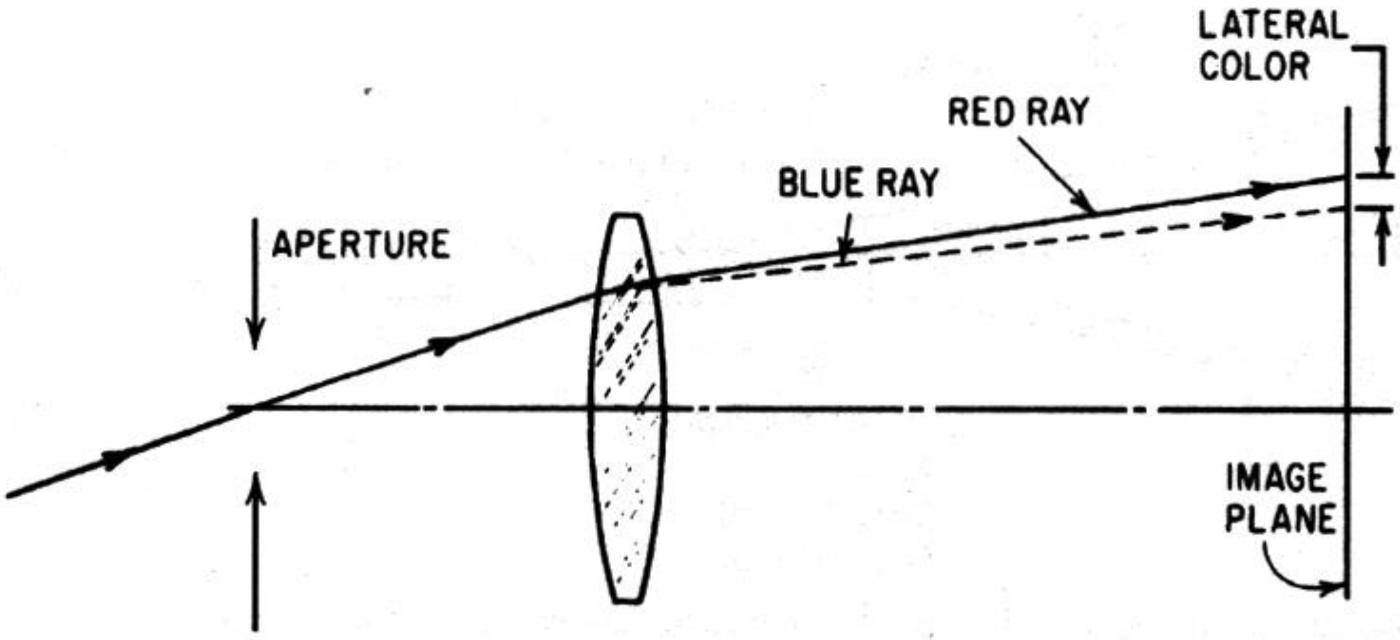
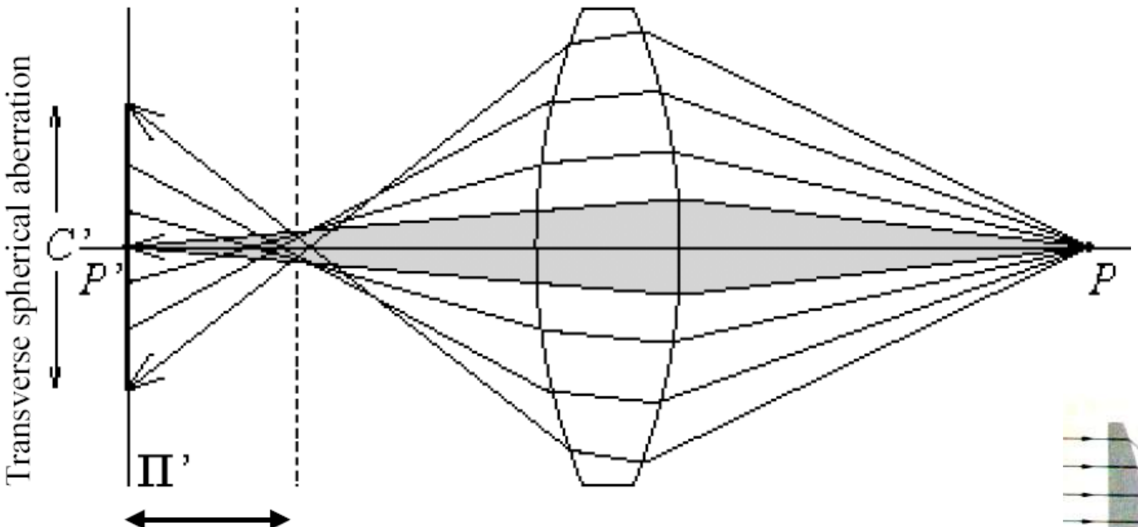


Figure 3.11 Lateral color, or chromatic difference of magnification, results in different-sized images for different wavelengths.

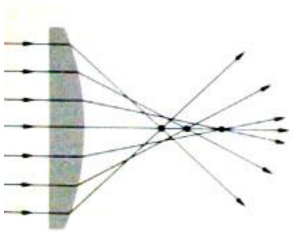
image: Smith 2000

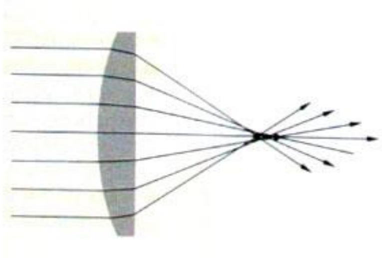
Spherical Aberration

- Focus varies with position on lens.



images: Forsyth&Ponce
and Hecht 1987





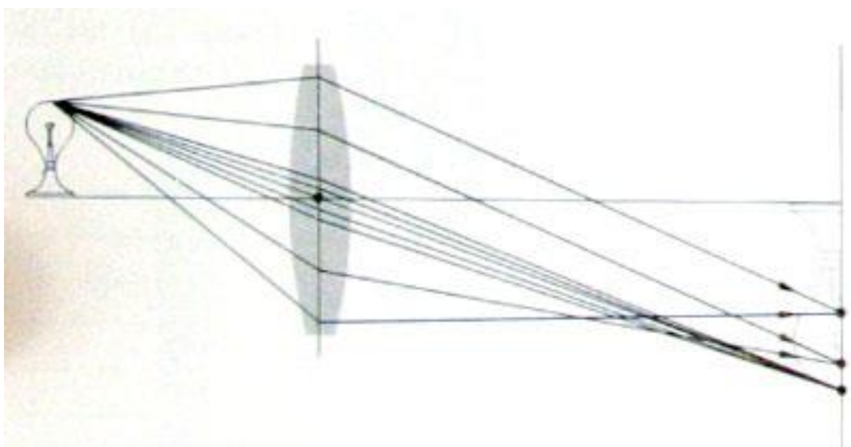
- Depends on shape of lens
- Can correct using an aspherical lens
- Can correct for this and chromatic aberration by combining with a concave lens of a different n'

Oblique Aberrations

- Spherical and chromatic aberrations occur on the lens axis. They appear everywhere on image.
- Oblique aberrations do not appear in center of field and get worse with increasing distance from axis.

Aberrations

- Coma
  - off-axis will focus to different locations depending on lens region
  - (magnification varies with ray height)



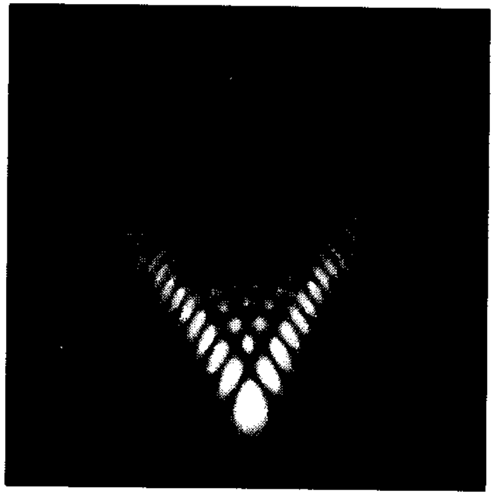
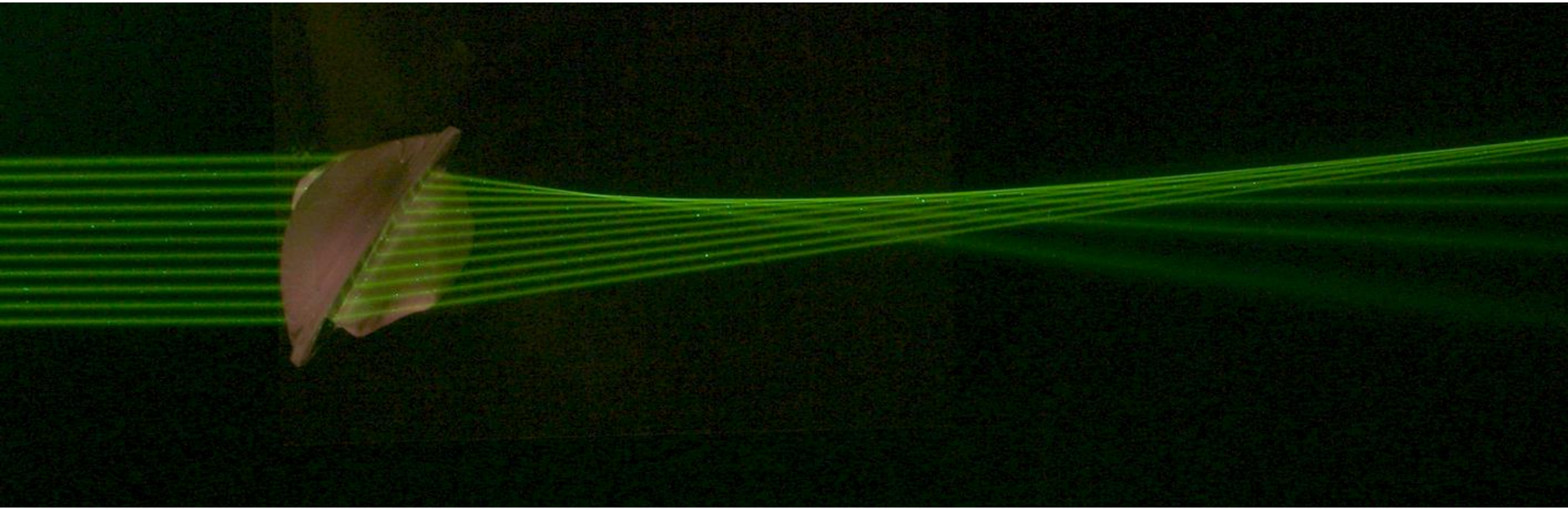


Figure 2.16. A typical comatic star image.

images: Smith 2000
and Hecht 1987

Coma



Astigmatism

- The shape of the lens for an of center point might look distorted, e.g. elliptical
  - different focus for tangential and sagittal rays

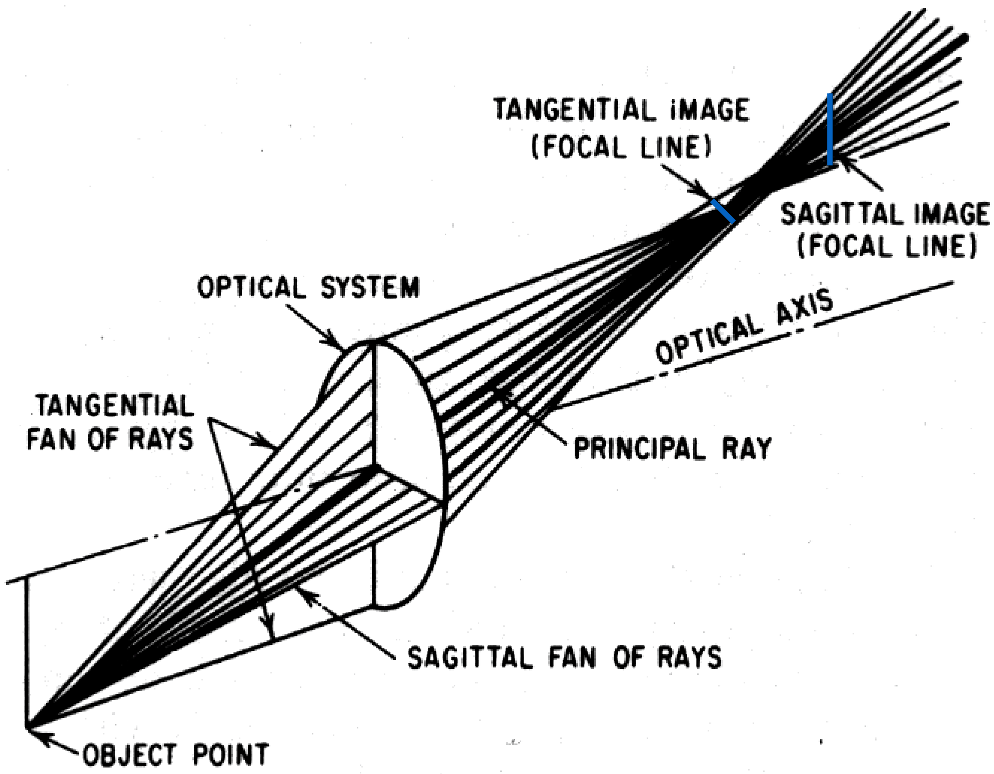


Figure 3.7 Astigmatism.

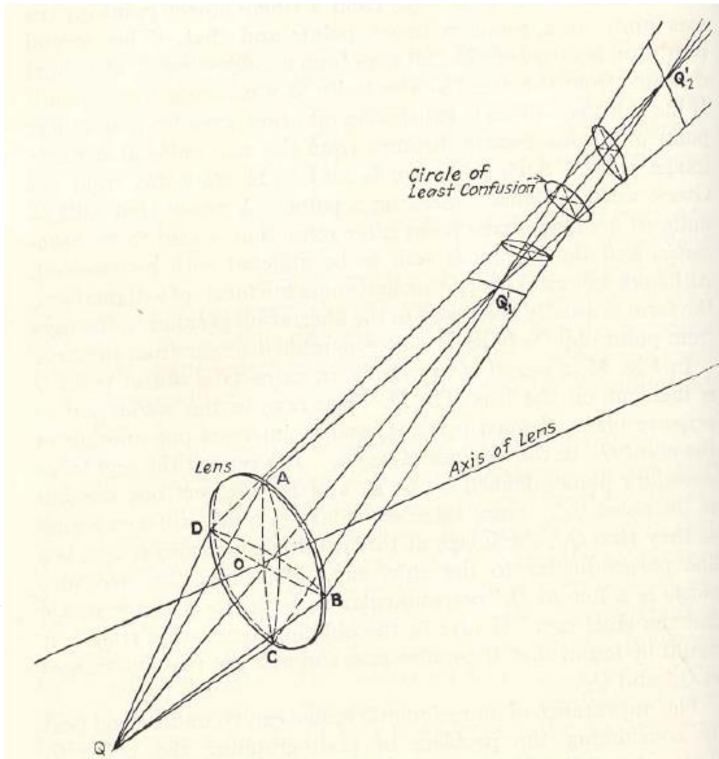


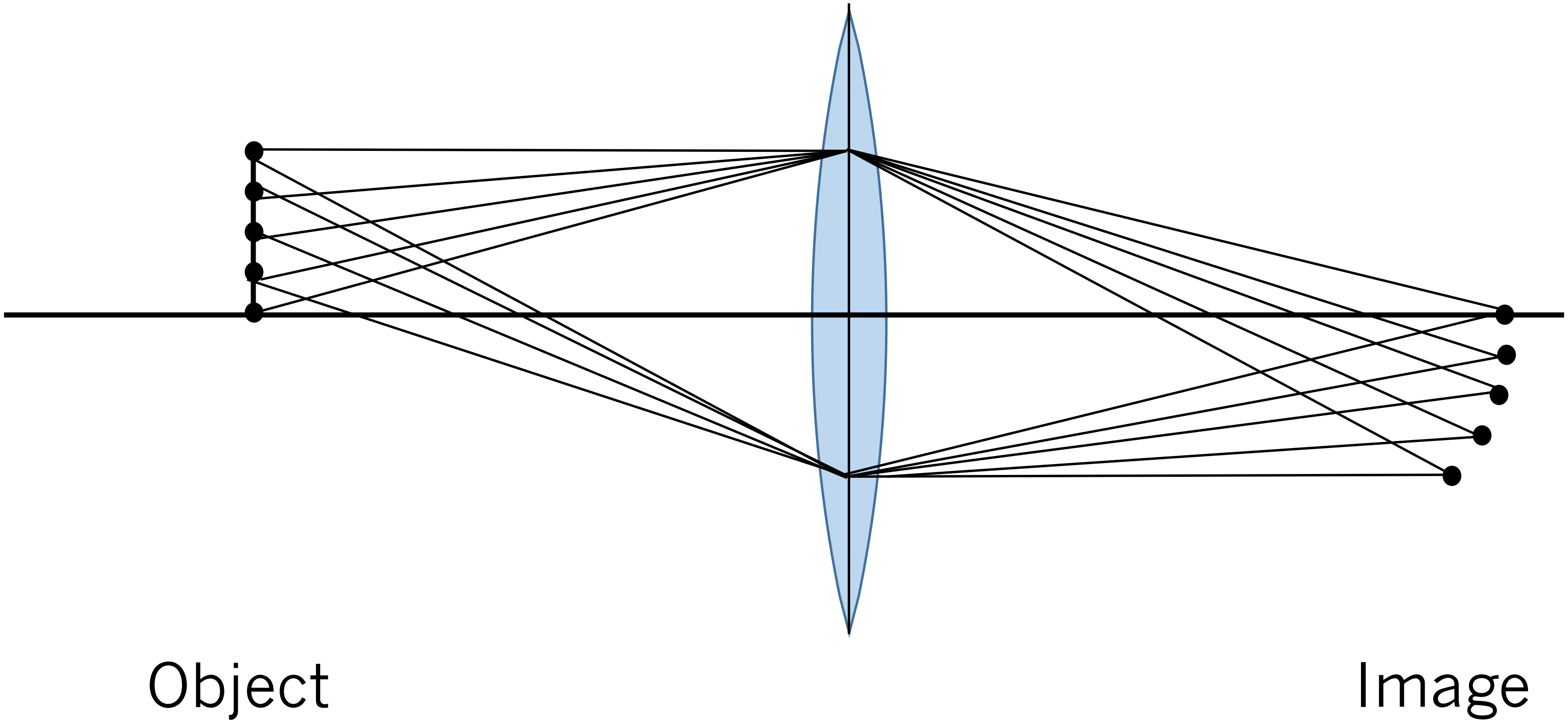
Fig. 45.—An illustration of the character of astigmatic images.

image: Smith 2000

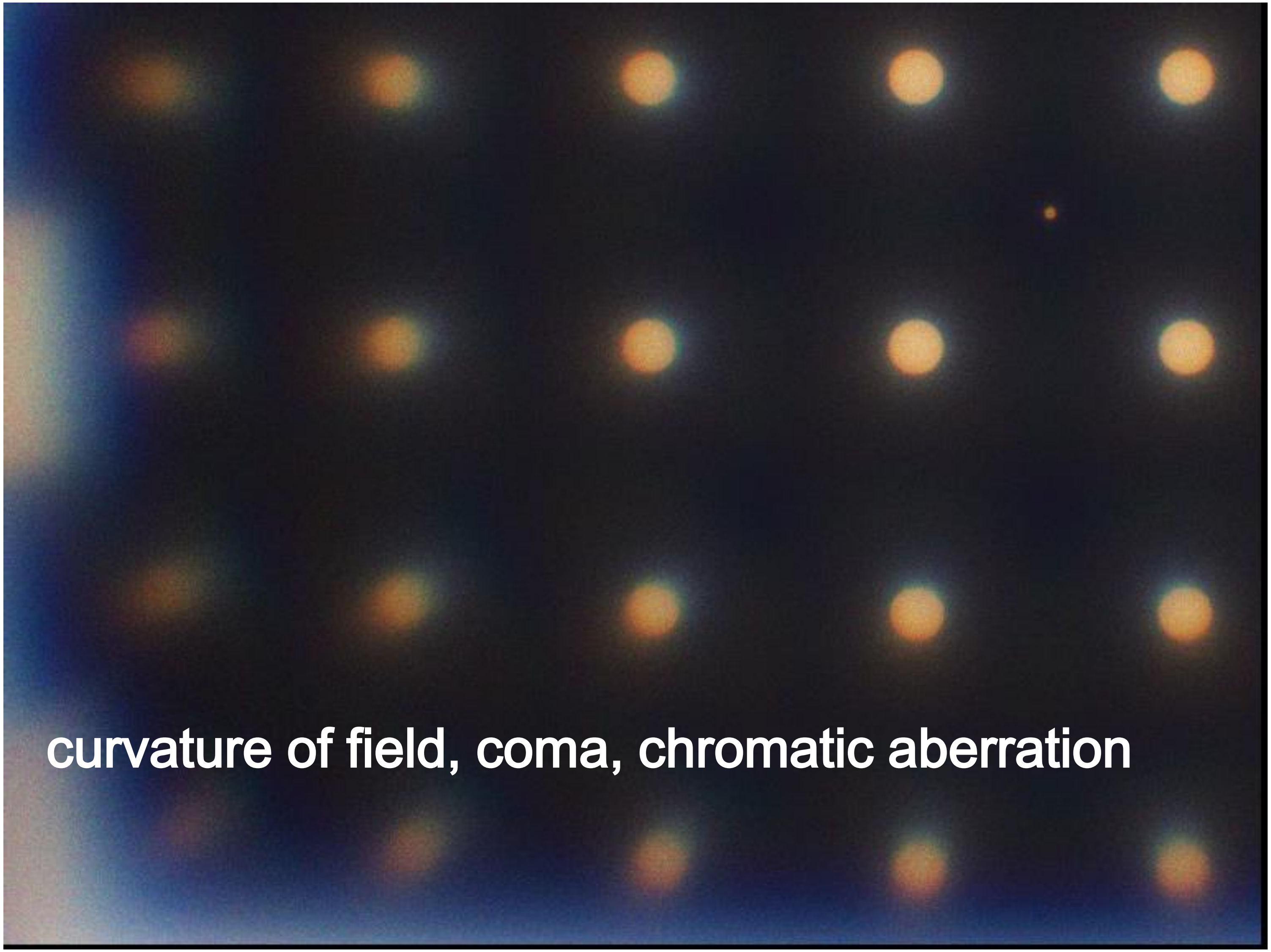
Hardy&Perrin

Curvature of Field

- focus “plane” is actually curved



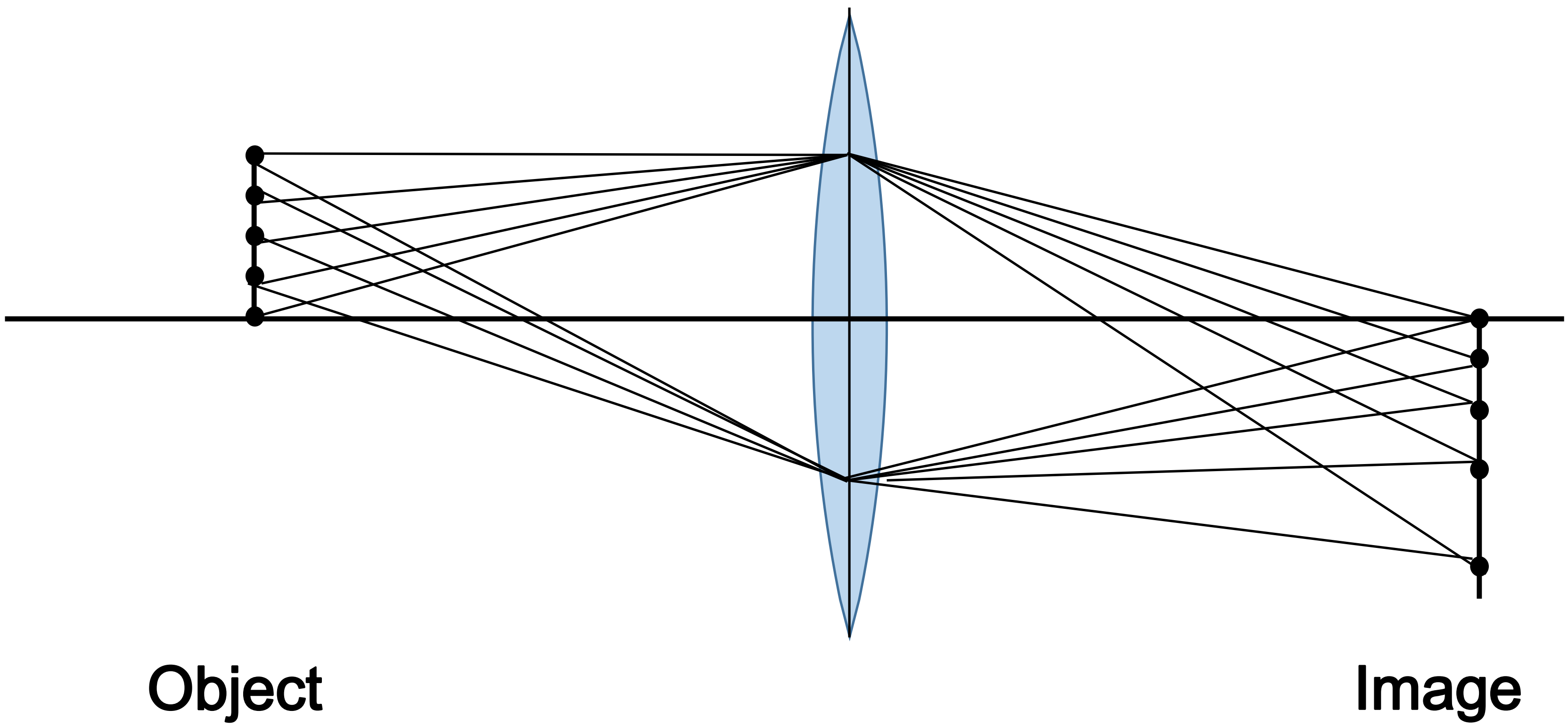
Bad Optics



universitätbonn

Distortion

- Ratios of lengths are no longer preserved.



Geometric distortion

- Change in magnification with image position

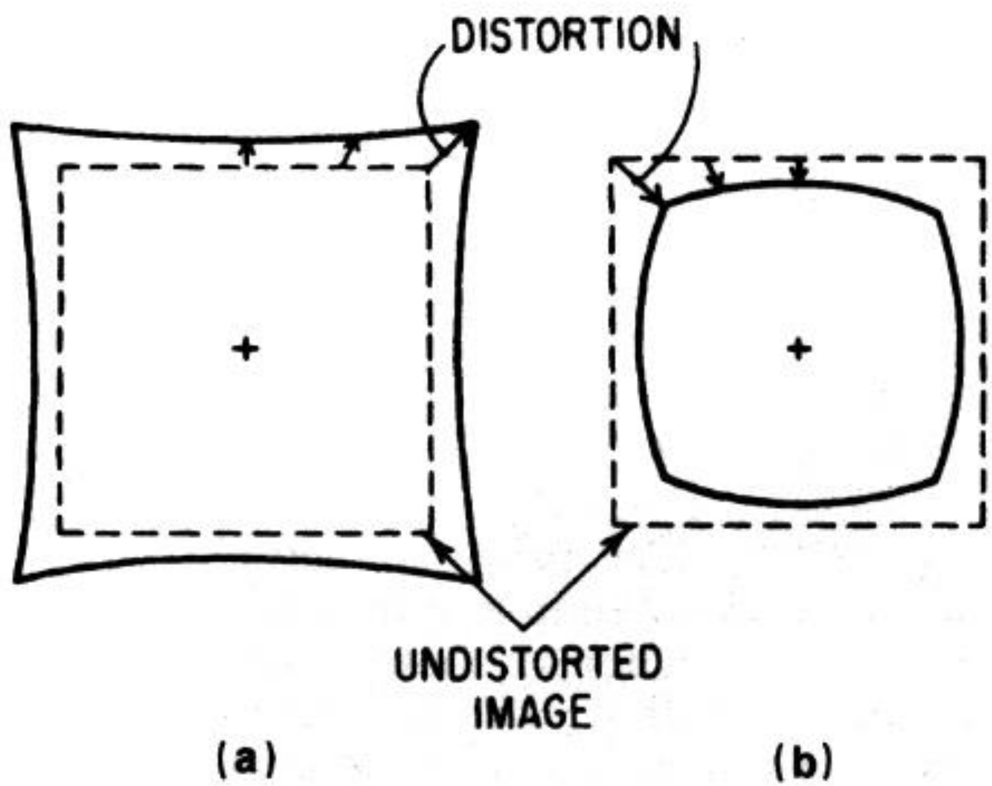


image: Smith 2000

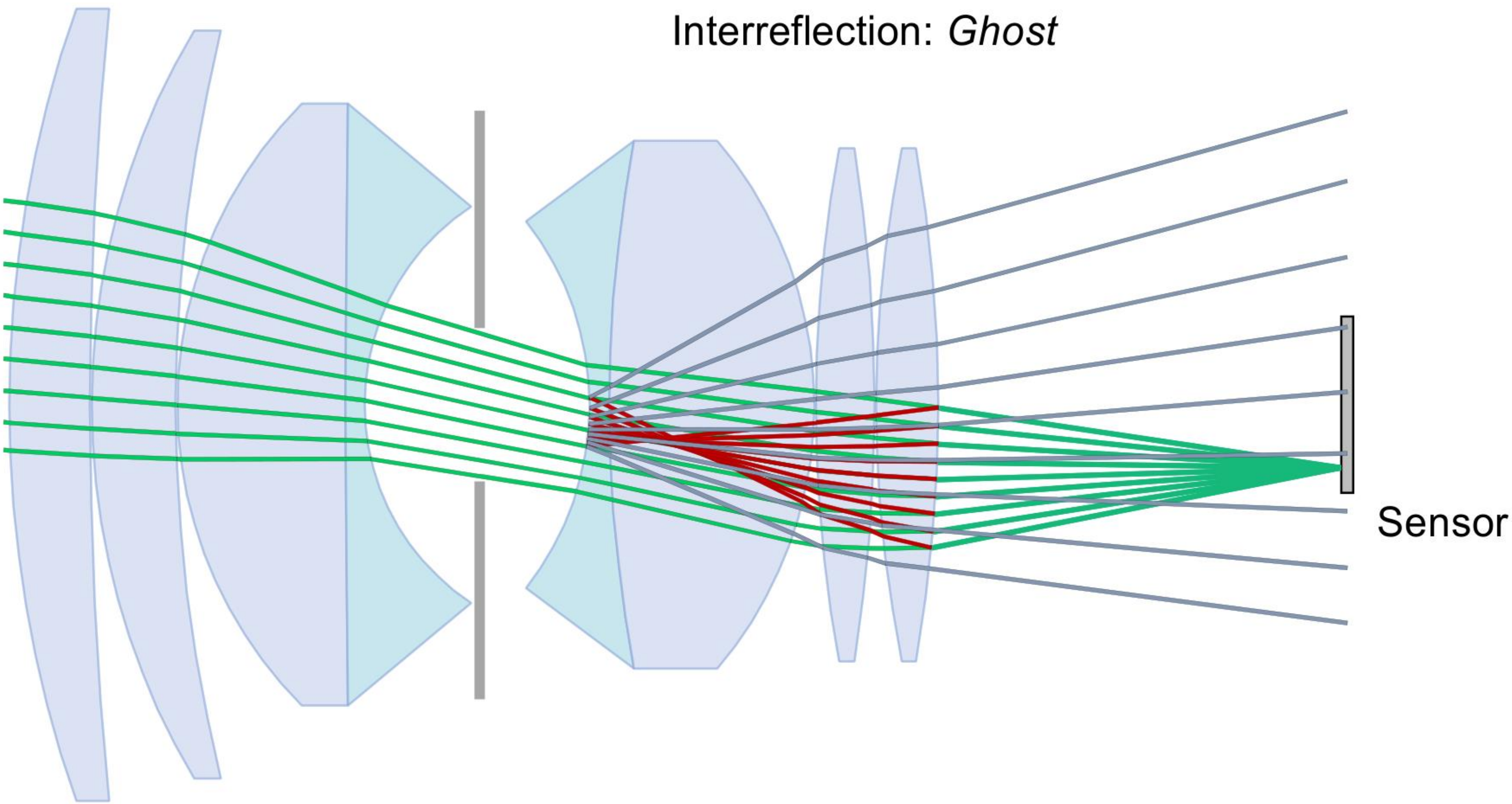
Radial Distortion

image: Kingslake

Flare

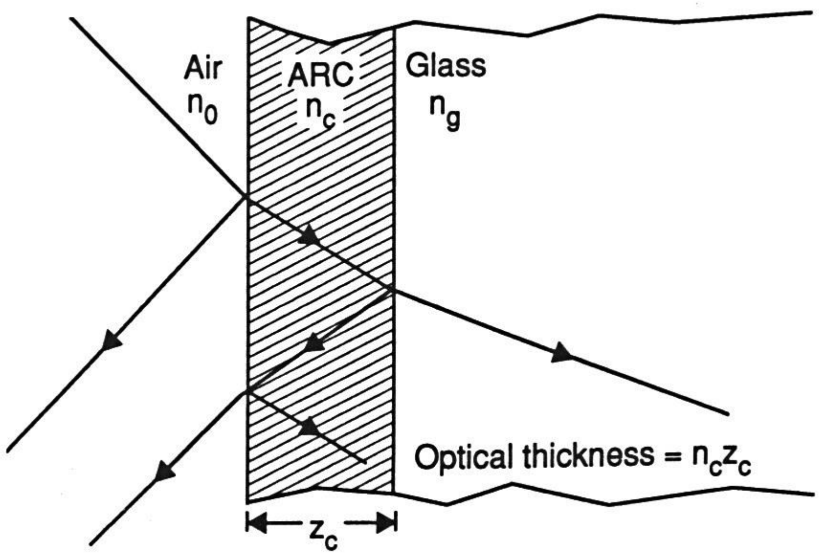
- Artifacts and contrast reduction caused by stray reflections

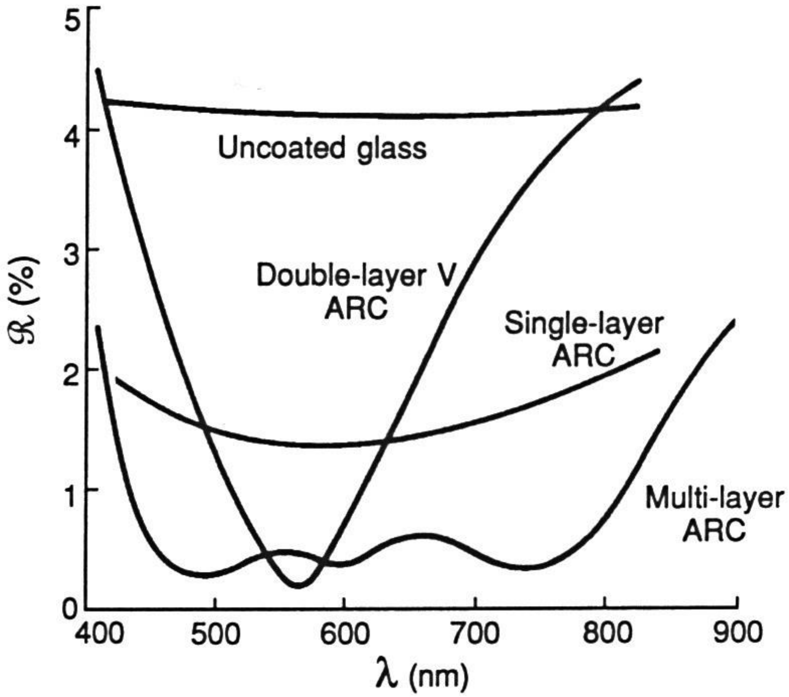
Flare



Flare

- Artifacts and contrast reduction caused by stray reflections
- Can be reduced by antireflection coating (now universal)



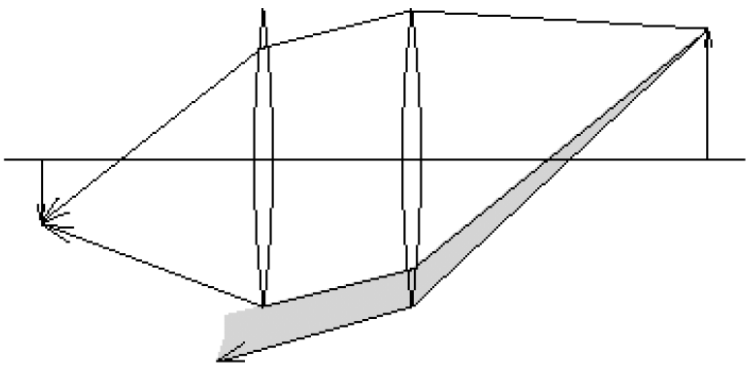


images: Curless notes

universitätbonn

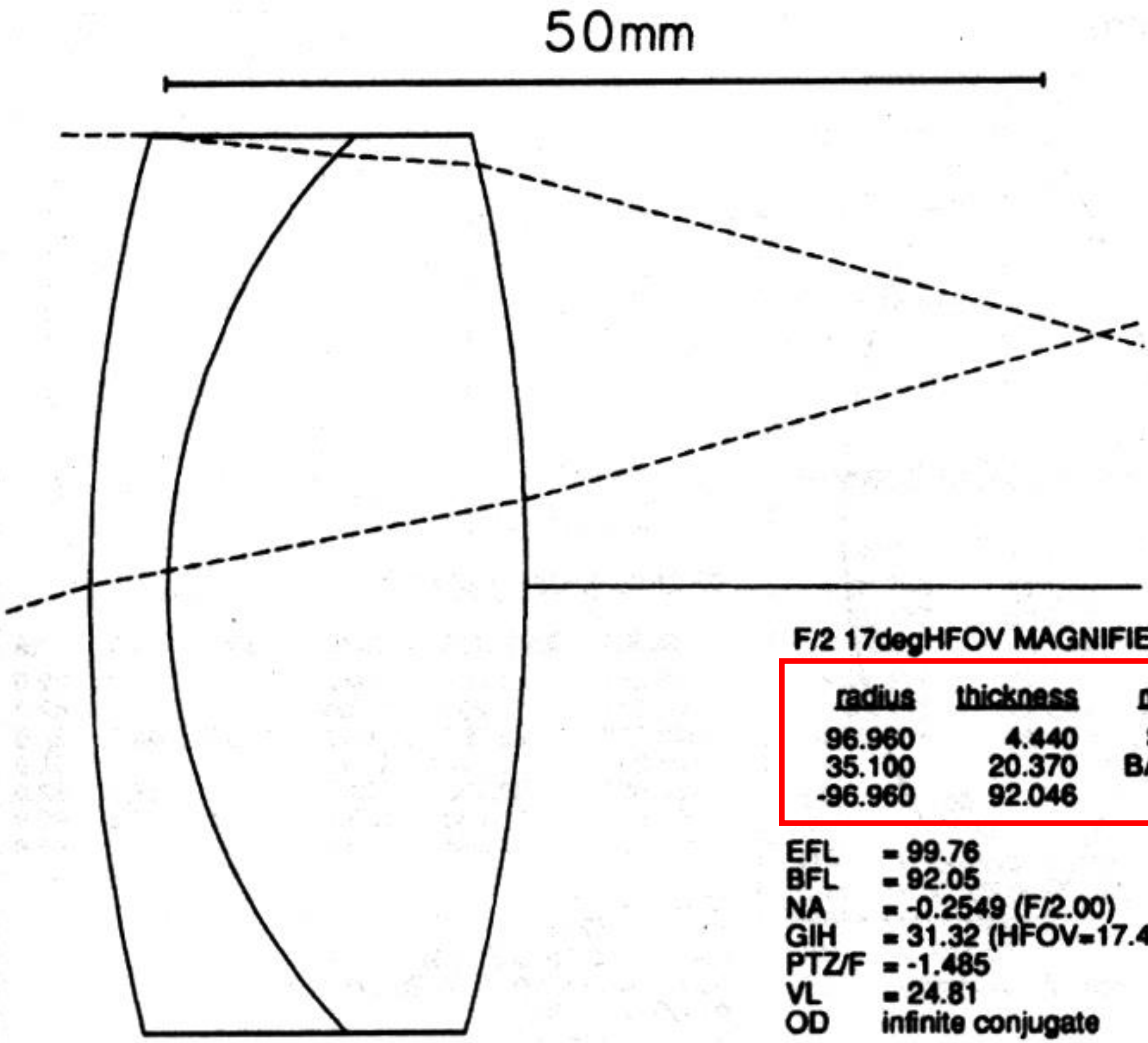
Radial Falloff

- Vignetting – your lens is basically a long tube.



- cos^4 falloff.
    - At an angle, area of aperture reduced by cos(a)
    - 1/r^2: Falls off as 1/cos(a)^2 (due to increased distance to lens)
    - Light falls on film plane at an angle, another cos(a) reduction.

Real lens designs



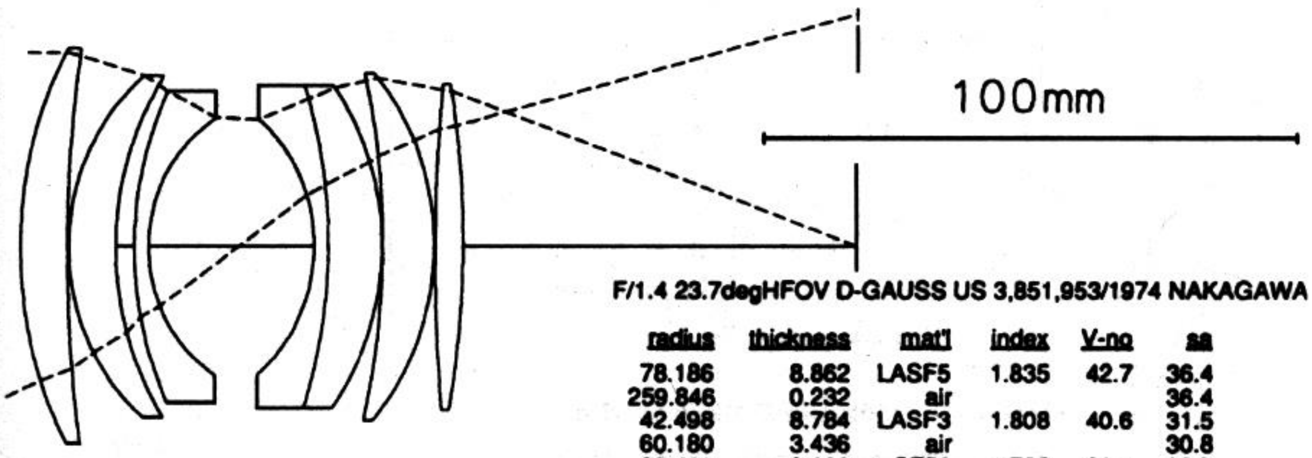
F/2 17degHFOV MAGNIFIER DOUBLET

radius	thickness	mat'l	index	V-no	sa
96.960	4.440	SF2	1.648	33.8	25.0
35.100	20.370	BAK1	1.572	57.5	25.0
-96.960	92.046	air			25.0

EFL = 99.76
BFL = 92.05
NA = -0.2549 (F/2.00)
GIH = 31.32 (HFOV=17.43)
PTZ/F = -1.485
VL = 24.81
OD infinite conjugate

image: Smith 2000

Real lens designs



F/1.4 23.7degHFOV D-GAUSS US 3,851,953/1974 NAKAGAWA

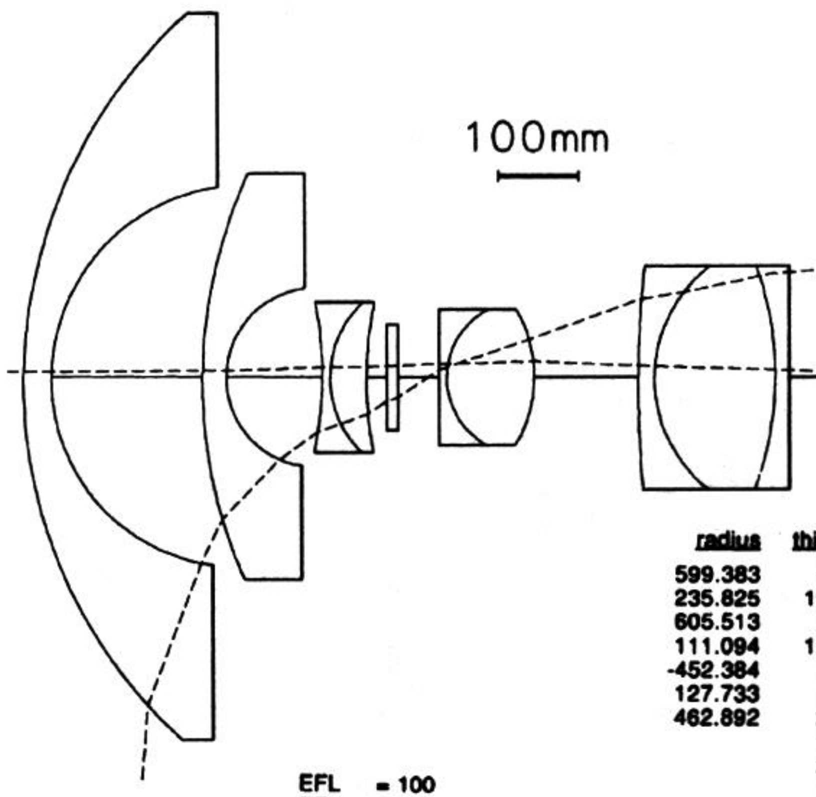
radius	thickness	mat'l	index	V-no	sa
78.186	8.862	LASF5	1.835	42.7	36.4
259.846	0.232	air			36.4
42.498	8.784	LASF3	1.808	40.6	31.5
60.180	3.436	air			30.8
69.416	2.606	SF56	1.785	26.1	28.7
28.654	16.888	air			23.7
	14.000	air			23.6
-31.582	2.646	SF56	1.785	26.1	23.5
-99.808	9.982	LASF3	1.808	40.6	29.7
-52.702	0.192	air			29.7
-150.994	9.692	LAK8	1.713	53.8	31.9
-50.290	0.232	air			31.9
338.224	5.174	LAK8	1.713	53.8	30.0
-186.406	73.796	air			30.0

EFL = 99.77
BFL = 73.8
NA = -0.3531 (F/1.40)
GIH = 43.90 (HFOV=23.75)
PTZ/F = -6.057
VL = 82.73
OD infinite conjugate

image: Smith 2000

Real lens designs

Mjposner (CC BY-SA 3.0)



FISHEYE F/8 90DEGHFOV
MIYAMOTO JOSA 1964

radius	thickness	mat'l	index	V-no	sa
599.383	35.030	BK7	1.517	64.2	448.4
235.825	190.161	air			234.0
605.513	30.025	FK5	1.487	70.4	251.8
111.094	120.102	air			110.1
-452.384	10.008	FK5	1.487	70.4	93.5
127.733	45.038	SF56	1.785	26.1	93.5
462.892	25.021	air			93.5
	15.013	K3	1.518	59.0	65.4
	36.281	air			65.5
	13.762	air			15.8
38507.649	10.008	SF56	1.785	26.1	84.1
95.081	110.093	LAF2	1.744	44.7	84.1
-162.638	130.110	air			84.1
1376.167	20.017	SF56	1.785	26.1	139.0
177.275	150.127	BSF52	1.702	41.0	139.0
-400.339	18.766	BASF6	1.668	41.9	139.0
-337.536	150.119	air			139.0

EFL = 100
BFL = 150.1
NA = -0.0626 (F/8.0)
GIH = 133.60 (HFOV=85.40)
PTZ/F = 49.15
VL = 959.56
OD infinite conjugate

image: Smith 2000

universitätbonn

Real lens designs

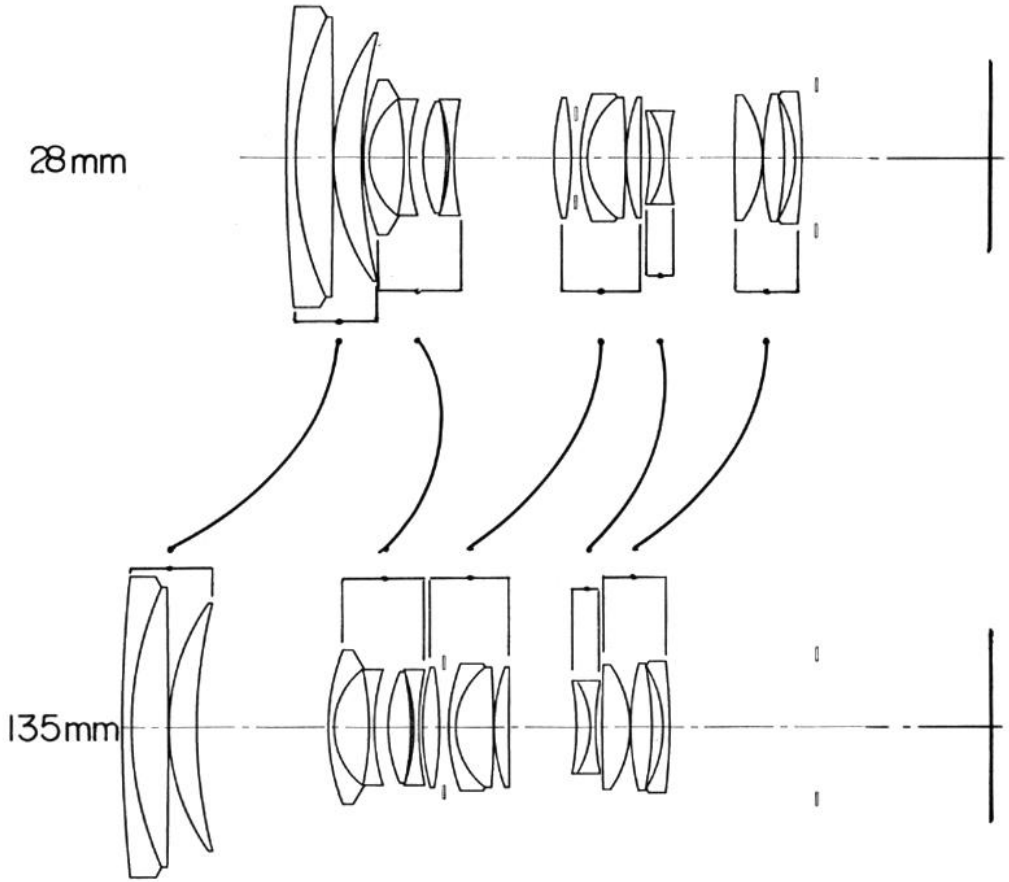


Figure 7.26 The Minolta zoom lens, 28–135 mm at *f*/4 to *f*/4.5.

image: Kingslake 1992

universitätbonn

Summary

- Physics of light
- Image formation
- Photographic parameters: focal length, aperture
- Aberrations and optical effects

Mini-exercises

1. Show that the planar wave $E(x,t) = g(\omega\mathrm{t} - kx)$ with wave number $k = \omega/c$ solves the 1D wave equation $\frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} - \frac{\partial^2 E}{\partial x^2} = 0$.
2. Using a tool of your choice, compute the 2D Fourier transform of a circular aperture function.
3. Calculate the magnification of a $f = 50\mathrm{mm}$ lens focused to $p = 3\mathrm{m}$ distance.

Bibliography

- Hecht, *Optics*. 2nd edition, Addison-Wesley, 1987.
- Smith, W. J. *Modern Optical Engineering*. McGraw-Hill, 2000.
- Kingslake, R. *A History of the Photographic Lens*. Academic Press, 1989.
- Kingslake, R. *Optics in Photography*. SPIE Press, 1992.
- London, B and Upton, J. *Photography*.Longman, 1998.