Optics I: lenses and apertures

CS 178, Spring 2012

Begun 4/10/12, finished 4/12

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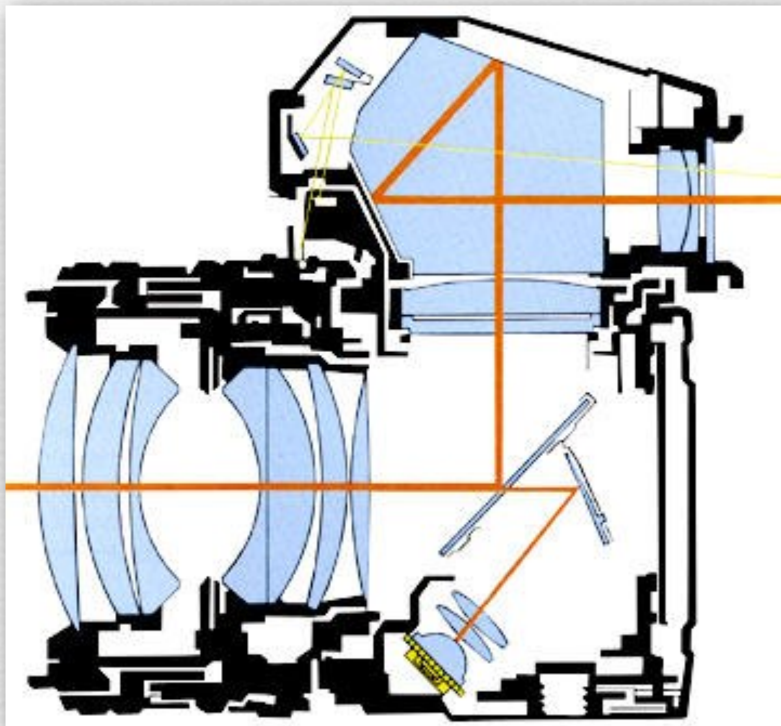
Outline

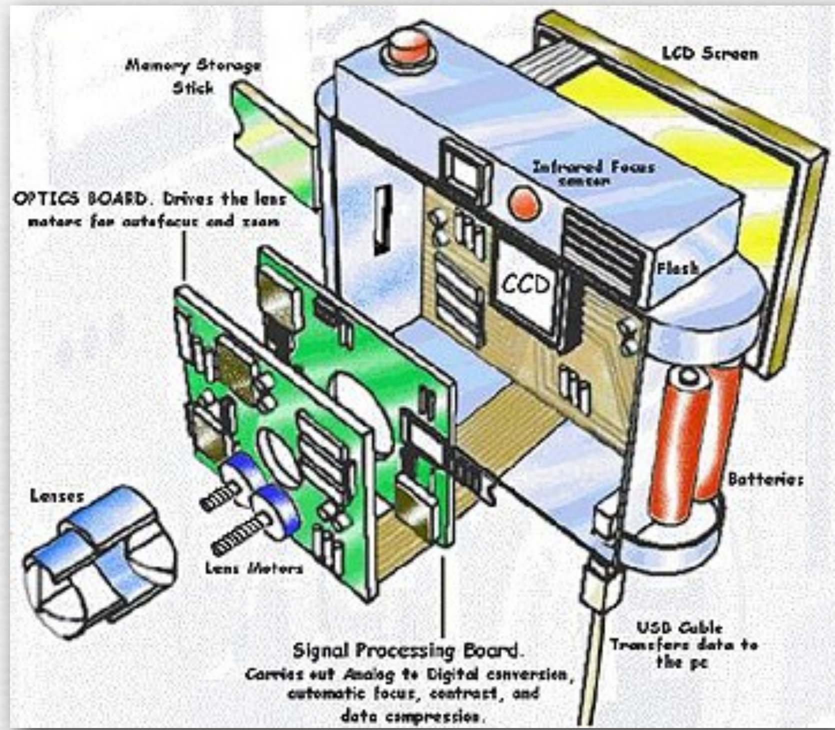
- why study lenses?
- thin lenses
  - graphical constructions, algebraic formulae
- thick lenses
  - center of perspective, lens as 3D $\rightarrow$ 3D transformation
- depth of field

- aberrations & distortion
- vignetting, glare, and other lens artifacts
- diffraction and lens quality
- special lenses
  - telephoto, zoom

Cameras and their lenses

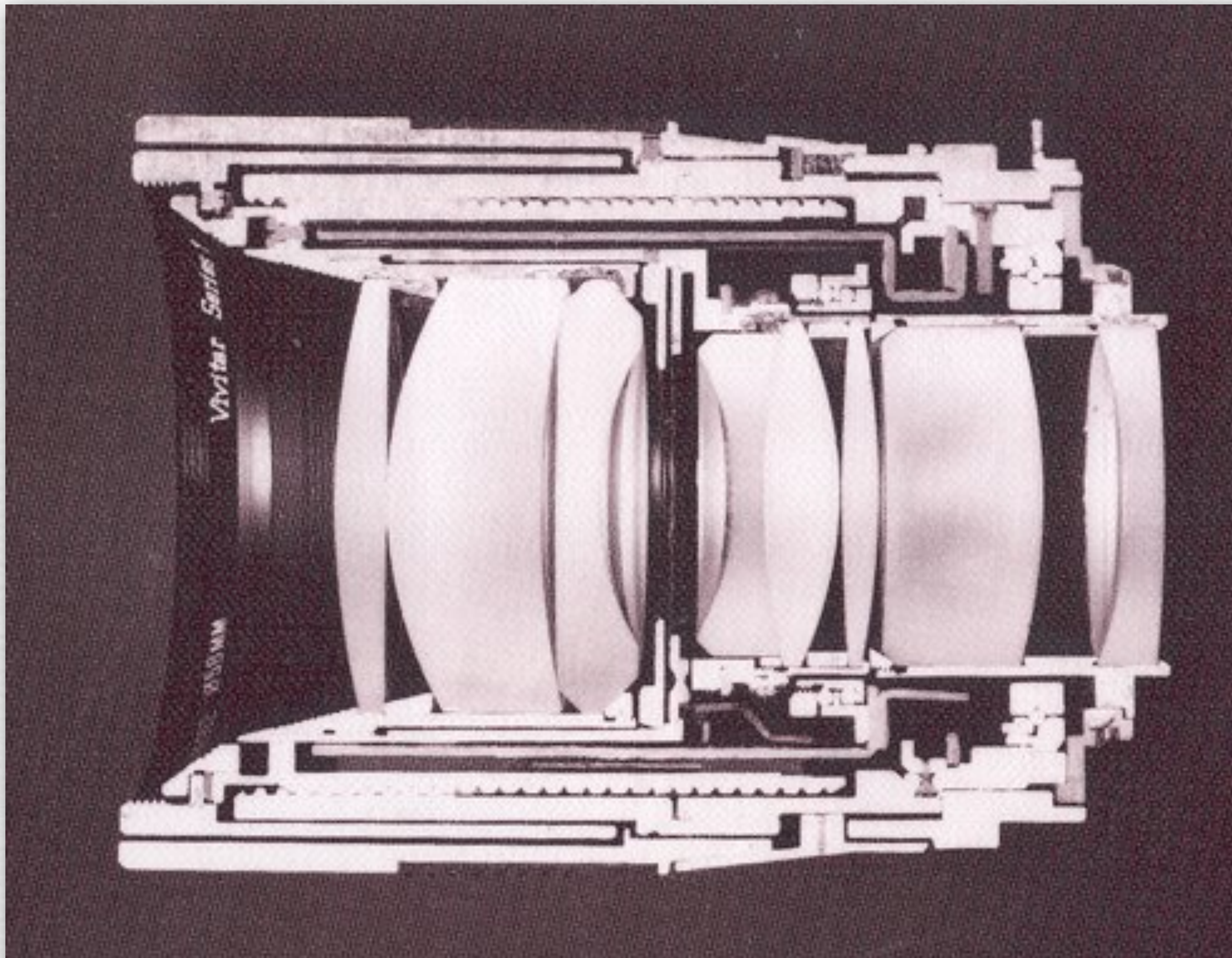


single lens reflex
(SLR) camera



digital still camera (DSC),
i.e. point-and-shoot

Cutaway view of a real lens



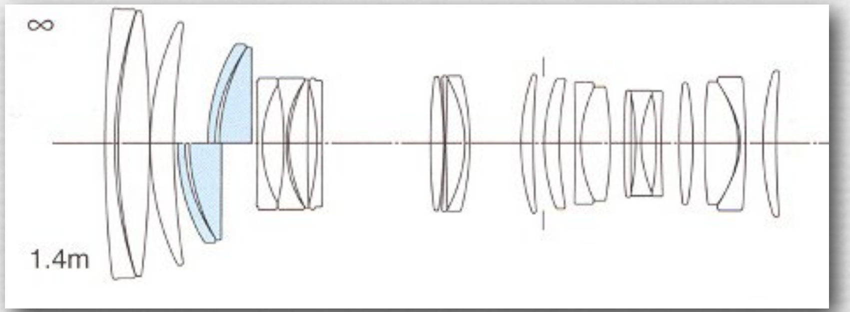
Vivitar Series 1 90mm f/2.5
Cover photo, Kingslake, *Optics in Photography*

Lens quality varies

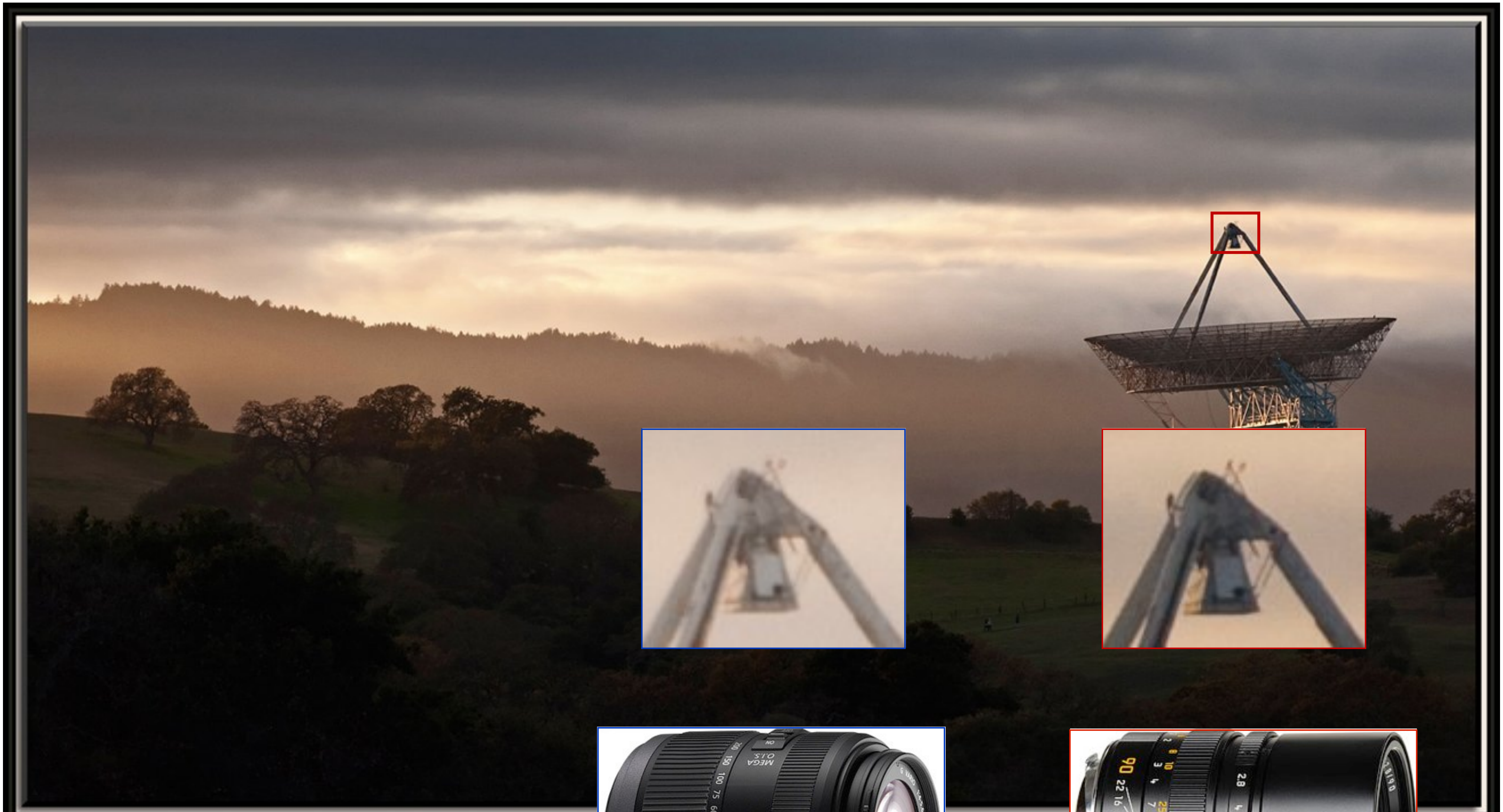
- Why is this toy so expensive?
  - EF 70-200mm f/2.8L IS USM
  - $1700

- Why is it better than this toy?
  - EF 70-300mm f/4-5.6 IS USM
  - $550

- And why is it so complicated?



(Canon)



Stanford Big Dish

Panasonic GF1

Panasonic 45-200/4-5.6 zoom, at 200mm f/4.6
$300

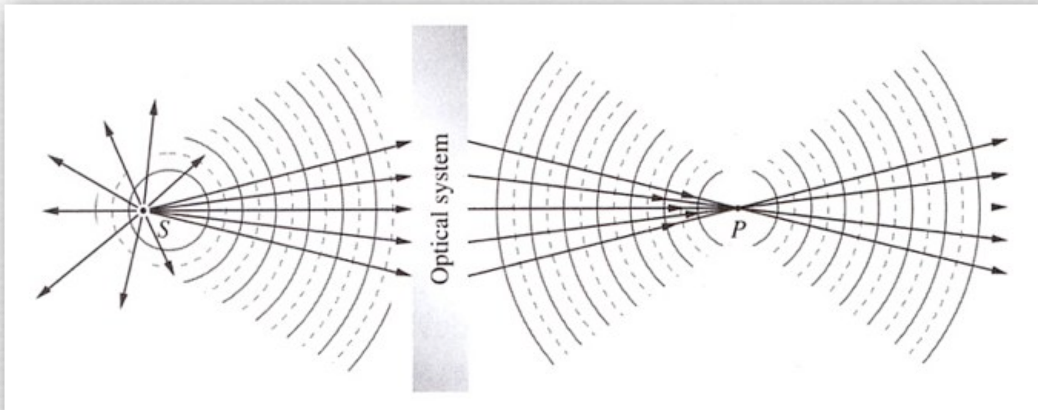
Leica 90mm/2.8 Elmarit-M prime, at f/4
$2000

Zoom lens versus prime lens

Canon 100-400mm/4.5-5.6
zoom, at 300mm and f/5.6
$1600

Canon 300mm/2.8
prime, at f/5.6
$4300

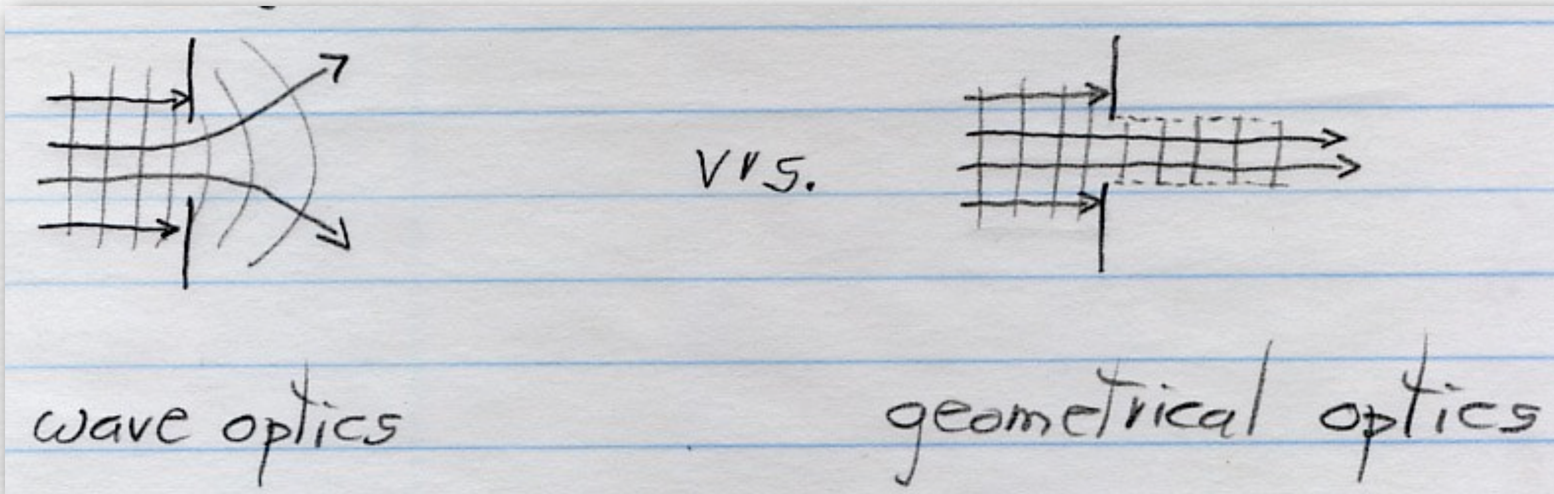
Physical versus geometrical optics



(Hecht)

- light can be modeled as traveling waves
- the perpendiculars to these waves can be drawn as rays
- diffraction causes these rays to bend, e.g. at a slit
- *geometrical optics* assumes
  - $\lambda \to 0$
  - no diffraction
  - in free space, rays are straight (a.k.a. rectilinear propagation)

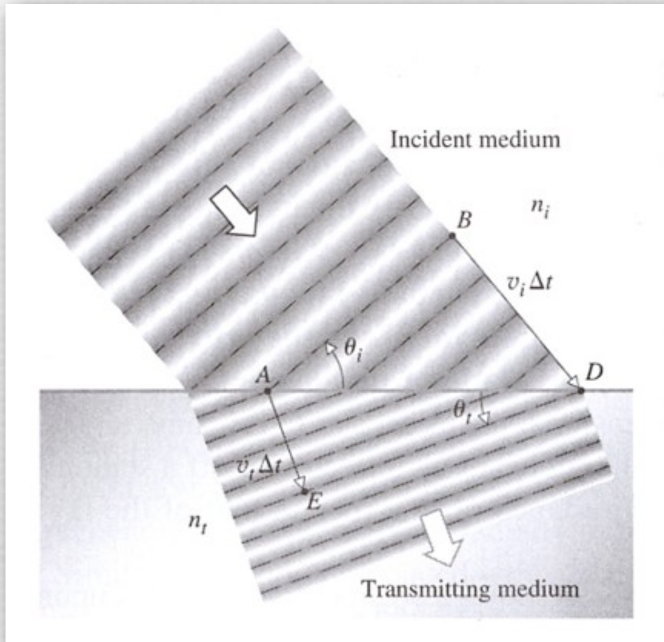
Physical versus geometrical optics (contents of whiteboard)

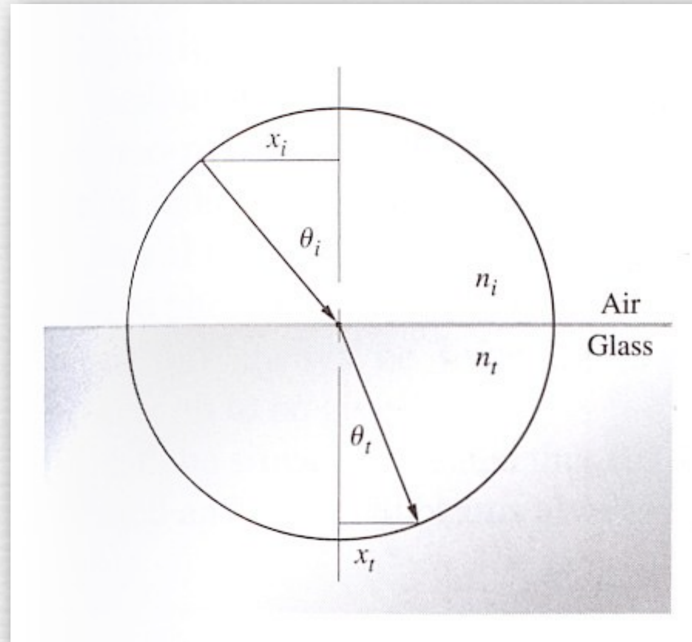


- in geometrical optics, we assume that rays do not bend as they pass through a narrow slit
- this assumption is valid if the slit is much larger than the wavelength, represented on the previous slide by the limit $\lambda \rightarrow 0$
- physical optics is a.k.a. wave optics

Snell's law of refraction

(Hecht)





$$\frac{x_i}{x_t} = \frac{\sin\theta_i}{\sin\theta_t} = \frac{n_t}{n_i}$$

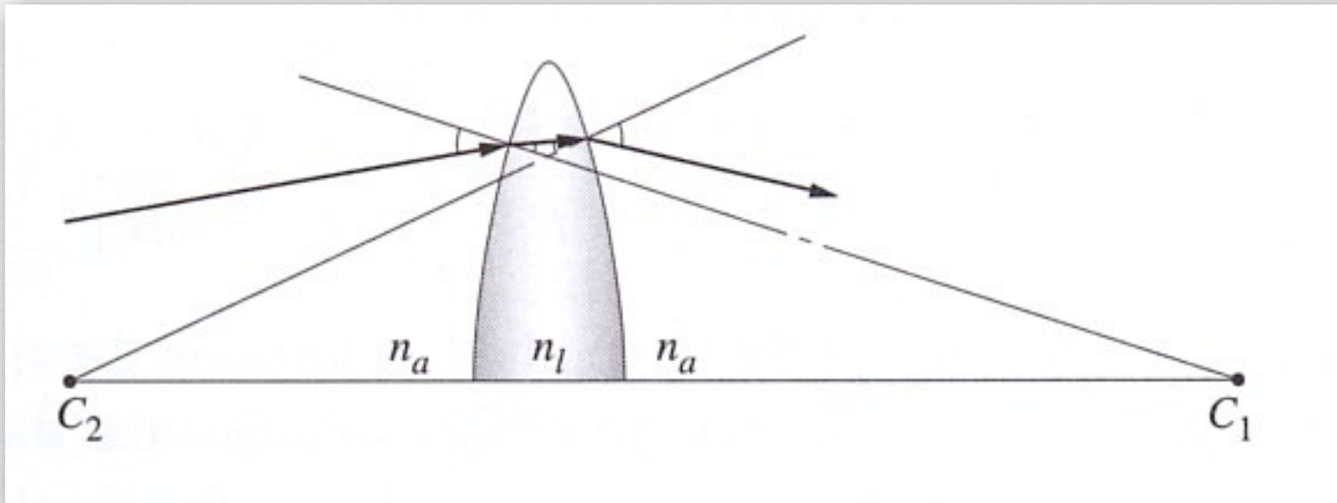
- as waves change speed at an interface, they also change direction
- index of refraction n_t is defined as $\dfrac{\text{speed of light in a vacuum}}{\text{speed of light in medium } t}$

Typical refractive indices (*n*)

- air = ~1.0
- water = 1.33
- glass = 1.5 - 1.8

mirage due to changes in the index of refraction of air with temperature

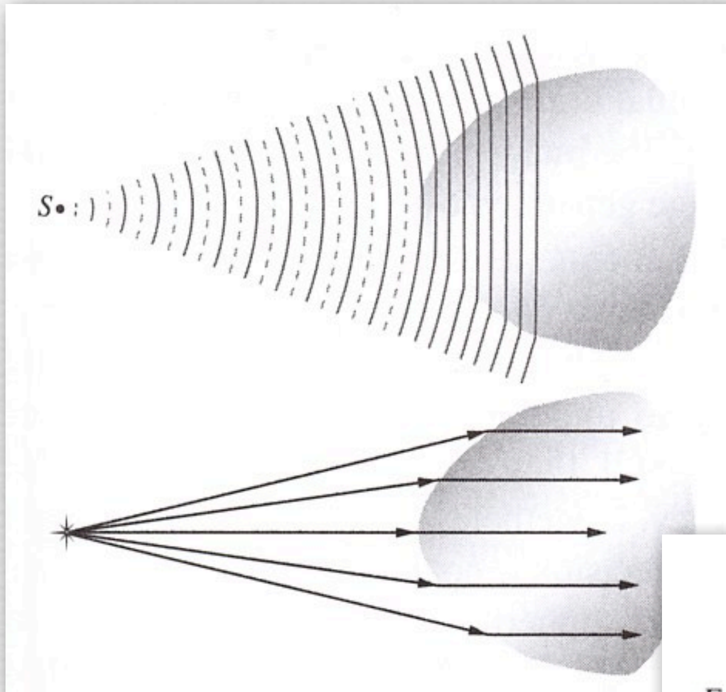
Refraction in glass lenses



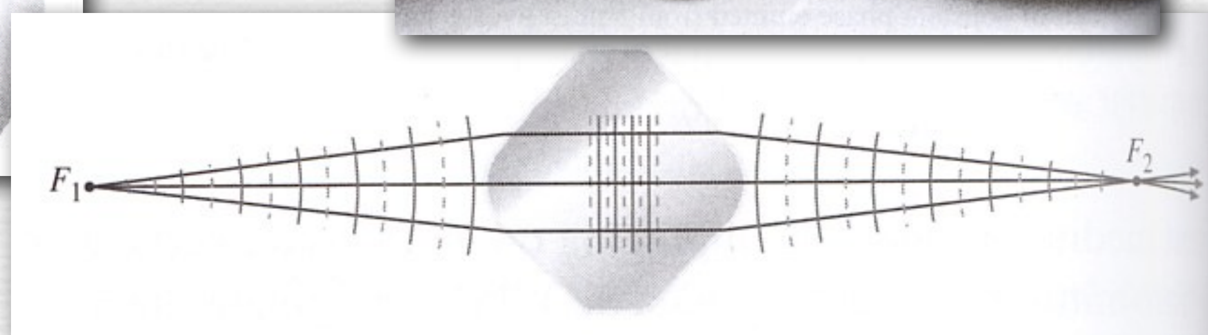
(Hecht)

- when transiting from air to glass, light bends towards the normal
- when transiting from glass to air, light bends away from the normal
- light striking a surface perpendicularly does not bend

Q. What shape should an interface be to make parallel rays converge to a point?



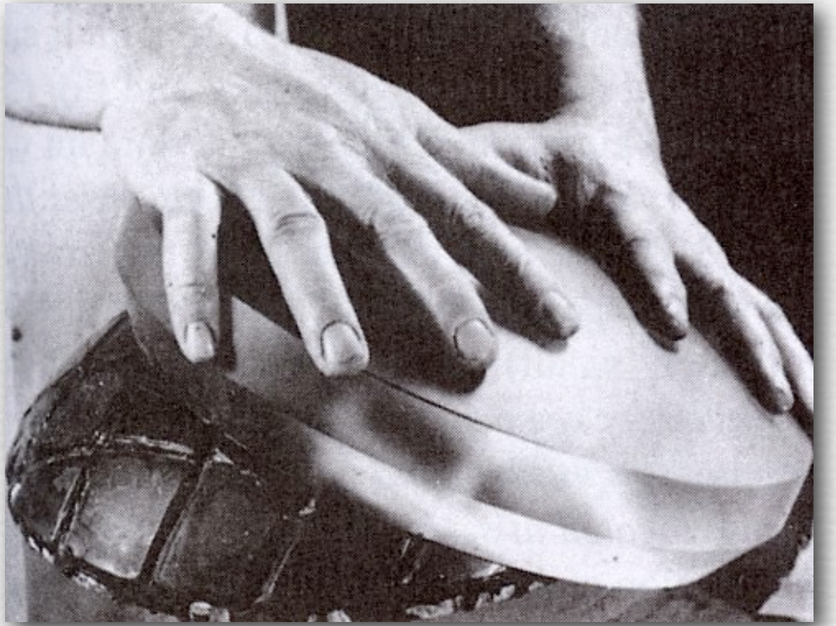
(Hecht)



A. a hyperbola

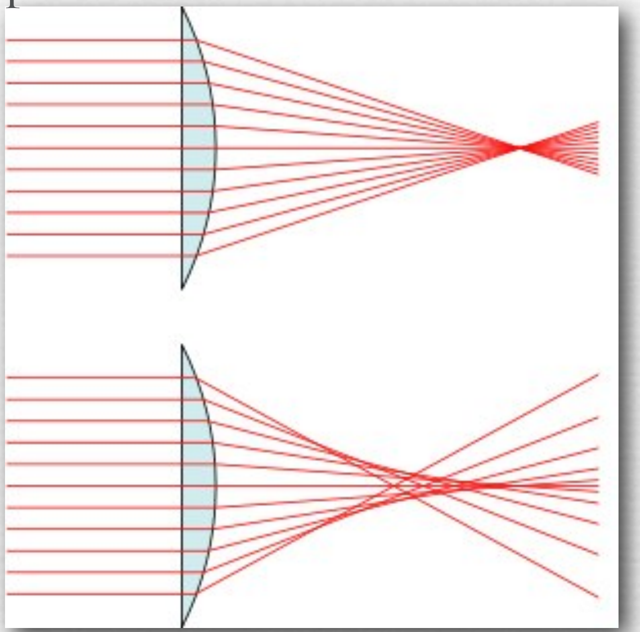
- so lenses should be hyperbolic!

Spherical lenses



(Hecht)

hyperbolic lens

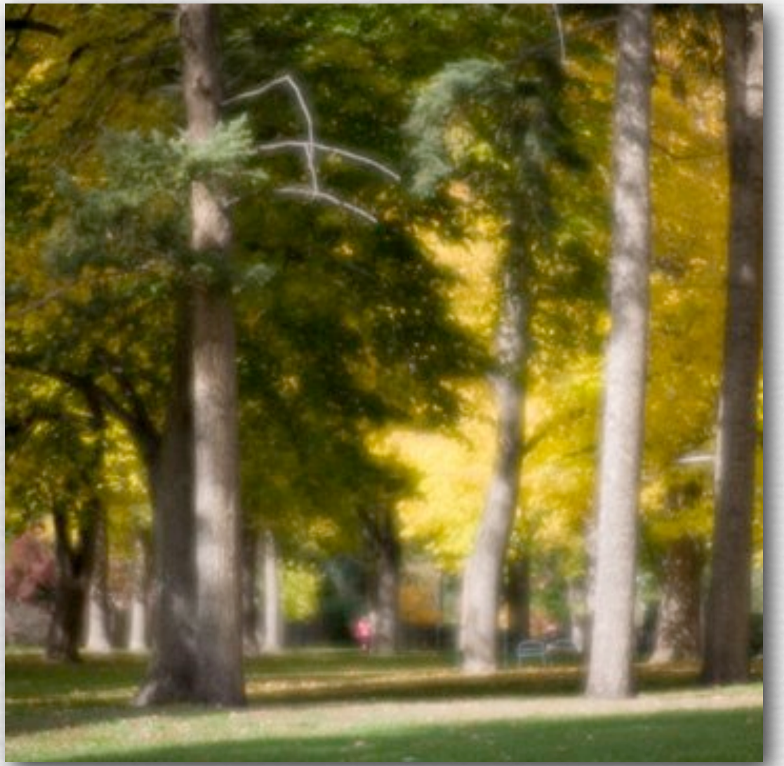


spherical lens

(wikipedia)

- two roughly fitting curved surfaces ground together will eventually become spherical
- spheres don't bring parallel rays to a point
  - this is called *spherical aberration*
  - nearly axial rays *(paraxial rays)* behave best

Examples of spherical aberration

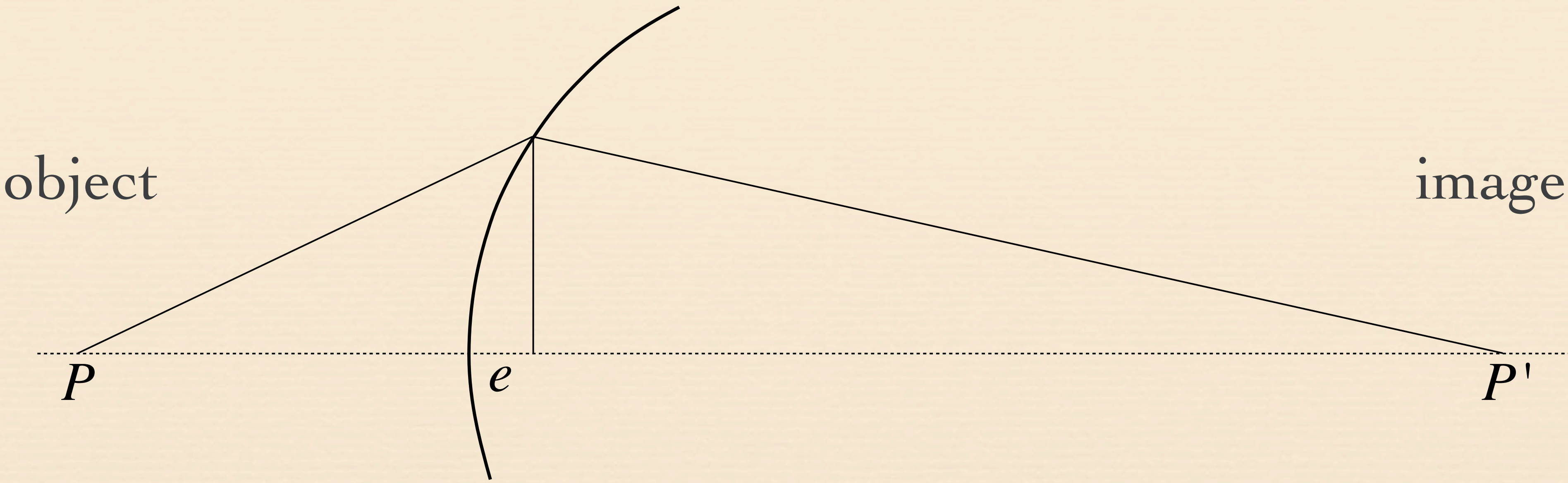


(gtmerideth)

(Canon)

Canon 135mm
soft focus lens

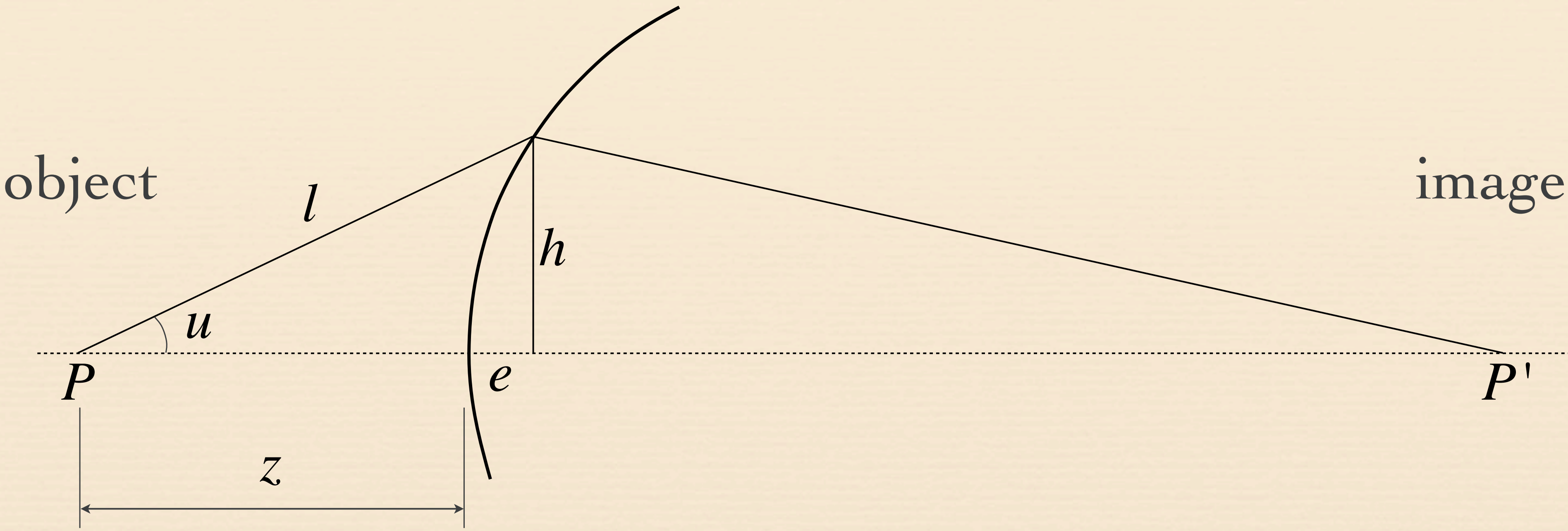
Paraxial approximation



- assume $e \approx 0$

Not responsible on exams for orange-tinted slides

Paraxial approximation

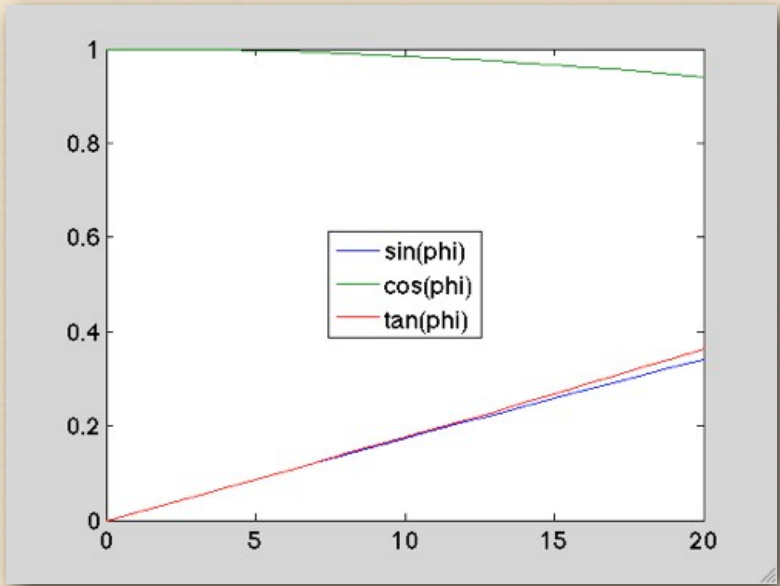


- assume $e \approx 0$
- assume $\sin u = h / l \approx u$ (for u in radians)
- assume $\cos u \approx z / l \approx 1$
- assume $\tan u \approx \sin u \approx u$

The paraxial approximation is a.k.a. first-order optics

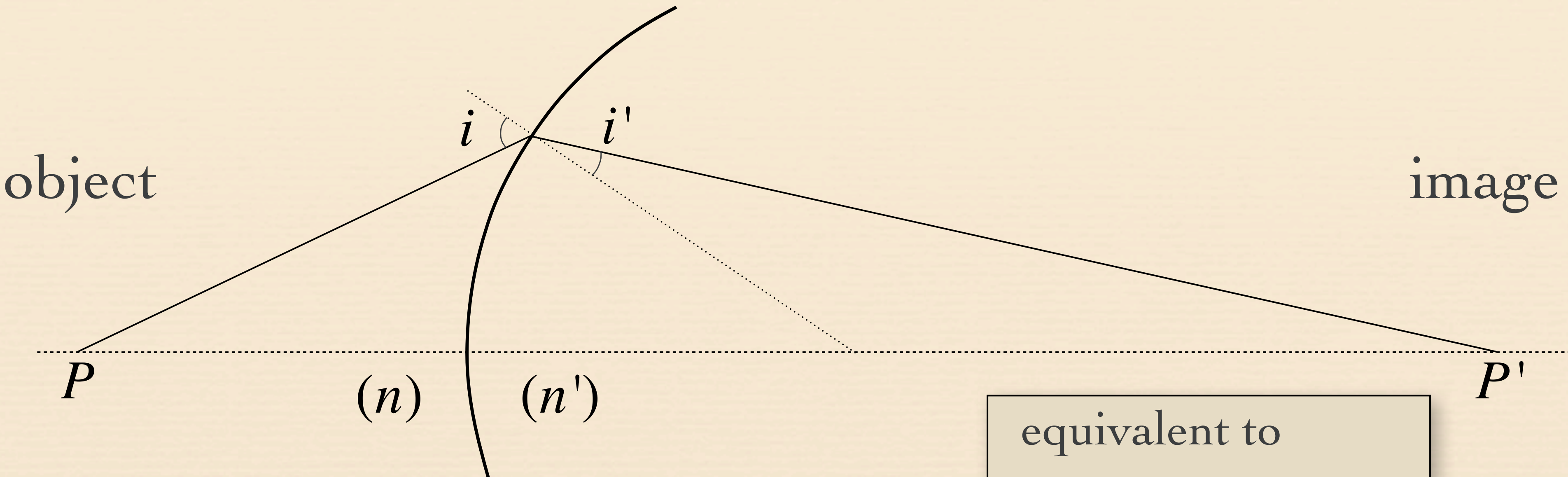
- assume first term of $\sin\phi \quad = \quad \phi - \frac{\phi^3}{3!} + \frac{\phi^5}{5!} - \frac{\phi^7}{7!} + \ldots$
  - i.e. $\sin\phi \approx \phi$
- assume first term of $\cos\phi \quad = \quad 1 - \frac{\phi^2}{2!} + \frac{\phi^4}{4!} - \frac{\phi^6}{6!} + \ldots$
  - i.e. $\cos\phi \approx 1$
  - so $\tan\phi \approx \sin\phi \approx \phi$

these are the Taylor series for $\sin\phi$ and $\cos\phi$



(phi in degrees)

Paraxial focusing



Snell's law:

$$n \sin i = n' \sin i'$$

paraxial approximation:

$$n\, i \approx n'\, i'$$

equivalent to

$$\frac{\sin\theta_i}{\sin\theta_t} = \frac{n_t}{n_i}$$

with

$n = n_i$ for air

$n' = n_t$ for glass

i, i' in radians

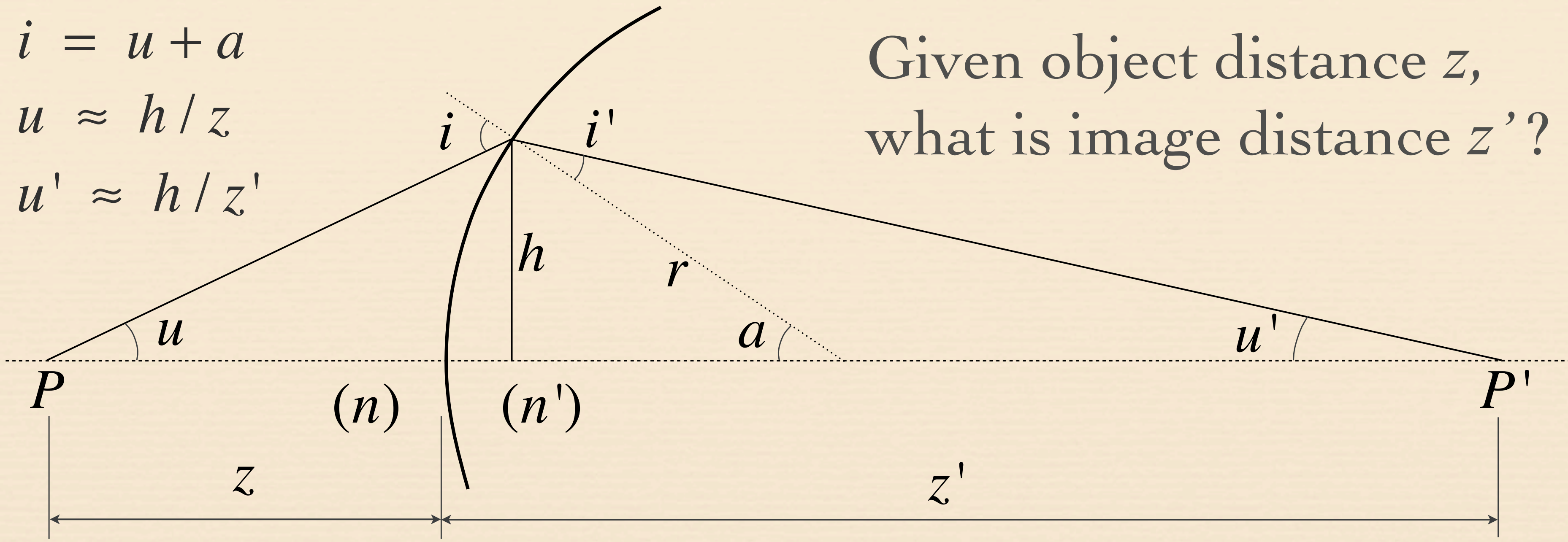
$\theta_i,\ \theta_t$ in degrees

Paraxial focusing

$i = u + a$

$u \approx h / z$

$u' \approx h / z'$



Given object distance *z*, what is image distance *z'*?

$n\, i \approx n'\, i'$

Paraxial focusing

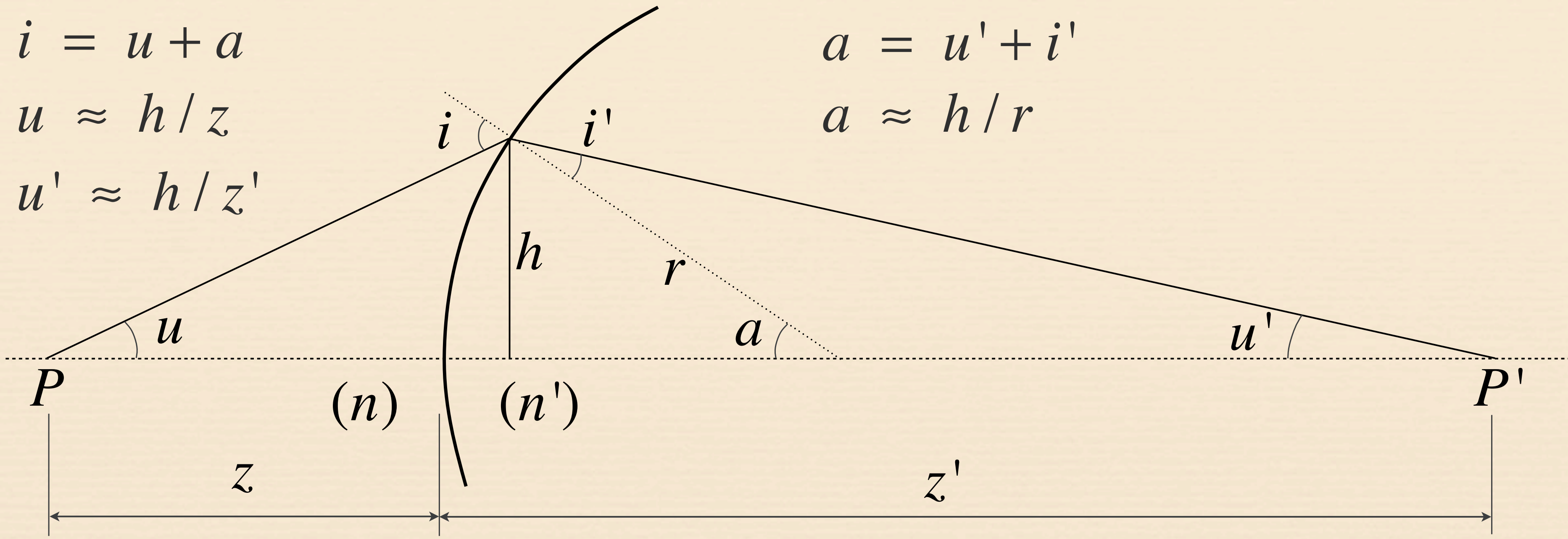
$$i = u + a$$

$$u \approx h / z$$

$$u' \approx h / z'$$

$$a = u' + i'$$

$$a \approx h / r$$



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

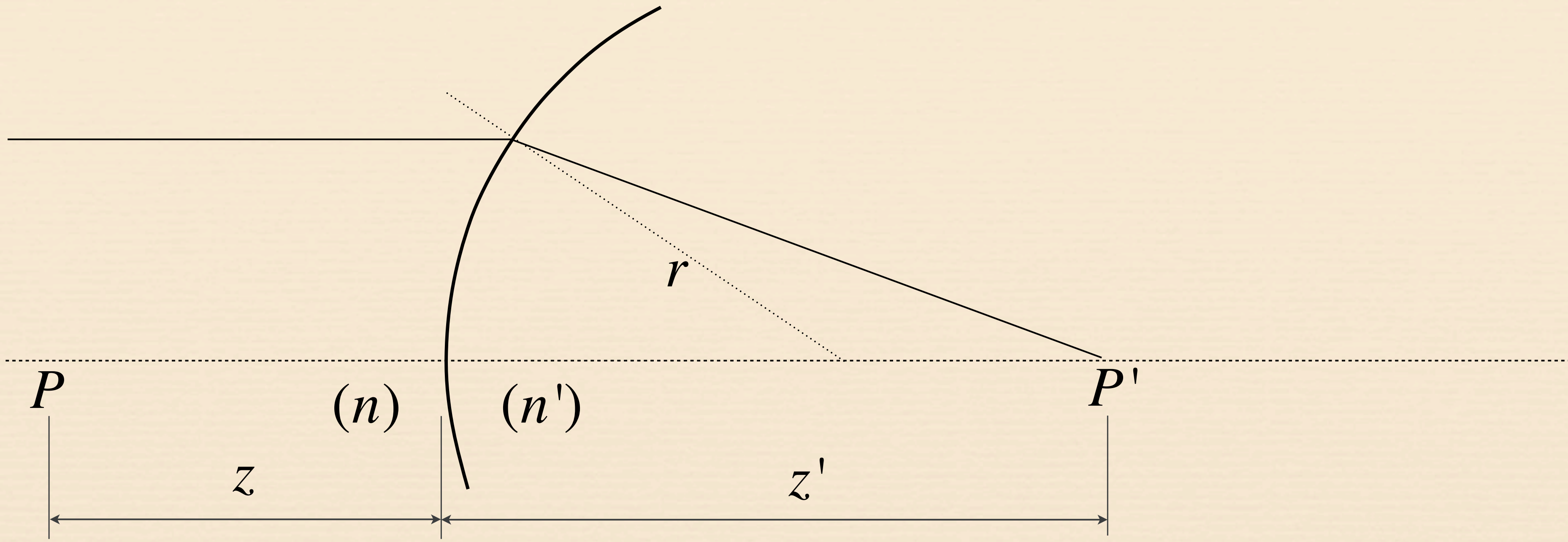
$$n\,(h/z + h/r) \approx n'\,(h/r - h/z')$$

$$n/z + n/r \approx n'/r - n'/z'$$

$$n\,i \approx n'\,i'$$

- *h* has canceled out, so any ray from *P* will focus to *P'*

Focal length



What happens if z is ∞ ?

$$n / z + n / r \approx n' / r - n' / z'$$

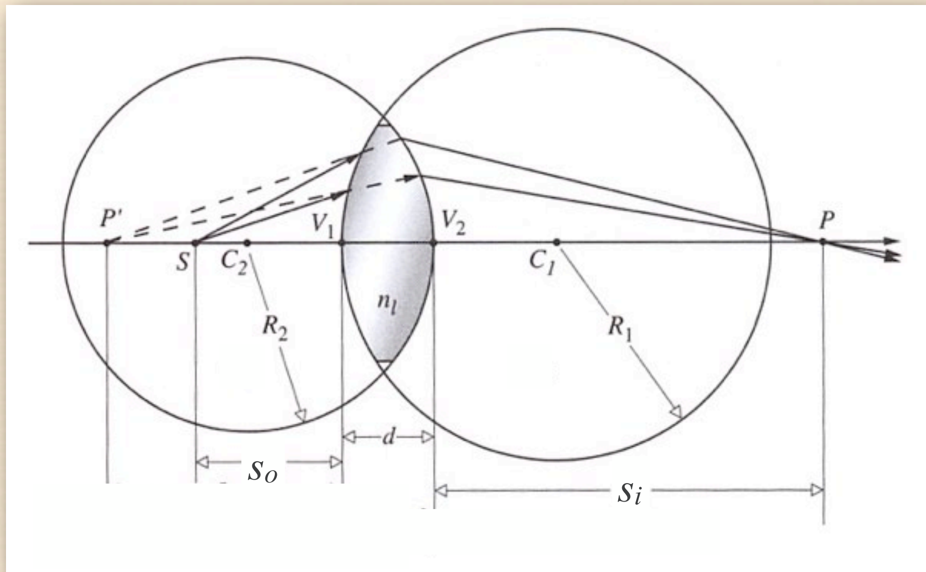
$$n / r \approx n' / r - n' / z'$$

$$z' \approx (r\, n') / (n' - n)$$

- $f \triangleq$ focal length = z'

Lensmaker's formula

- using similar derivations, one can extend these results to two spherical interfaces forming a lens in air



(Hecht, edited)

- as $d \rightarrow 0$ *(thin lens approximation)*, we obtain the lensmaker's formula

$$\frac{1}{s_o} + \frac{1}{s_i} = (n_l - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

Gaussian lens formula

- Starting from the lensmaker's formula

$$\frac{1}{s_o} + \frac{1}{s_i} = (n_l - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right),$$ (Hecht, eqn 5.15)

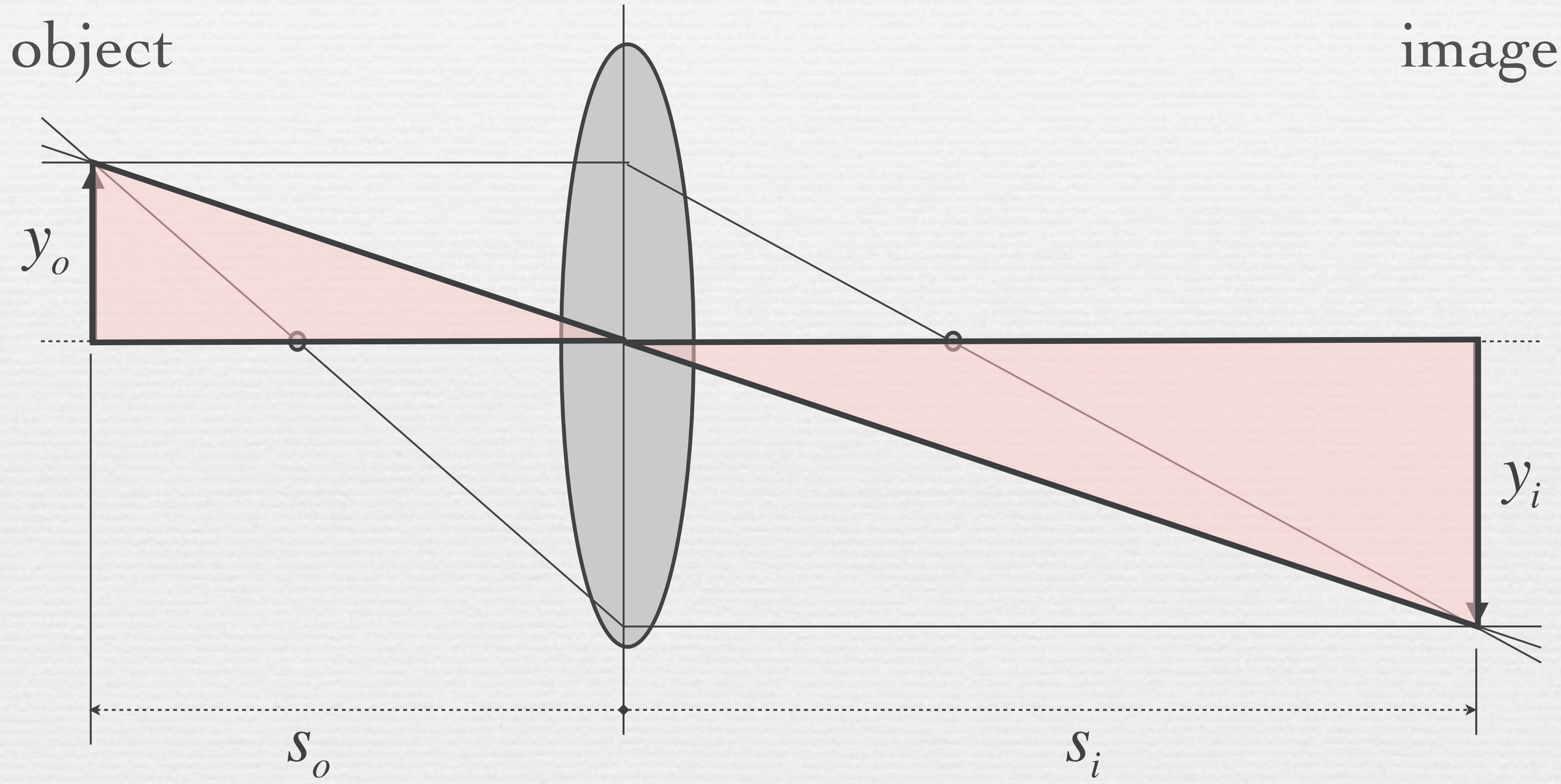
- and recalling that as object distance s_o is moved to infinity, image distance s_i becomes focal length f_i , we get

$$\frac{1}{f_i} = (n_l - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right).$$ (Hecht, eqn 5.16)

- Equating these two, we get the Gaussian lens formula

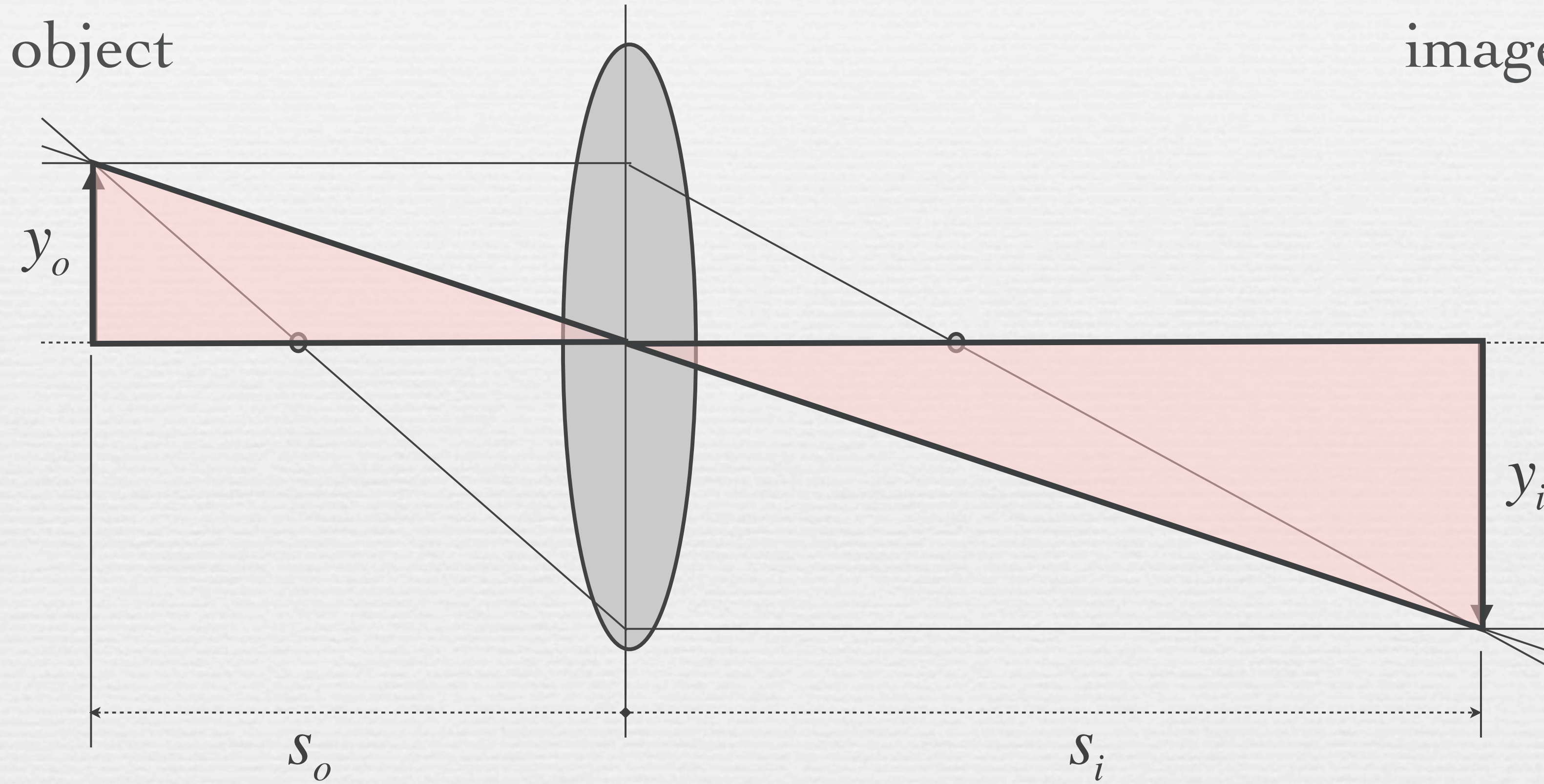
$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f_i}.$$ (Hecht, eqn 5.17)

From Gauss's ray construction to the Gaussian lens formula



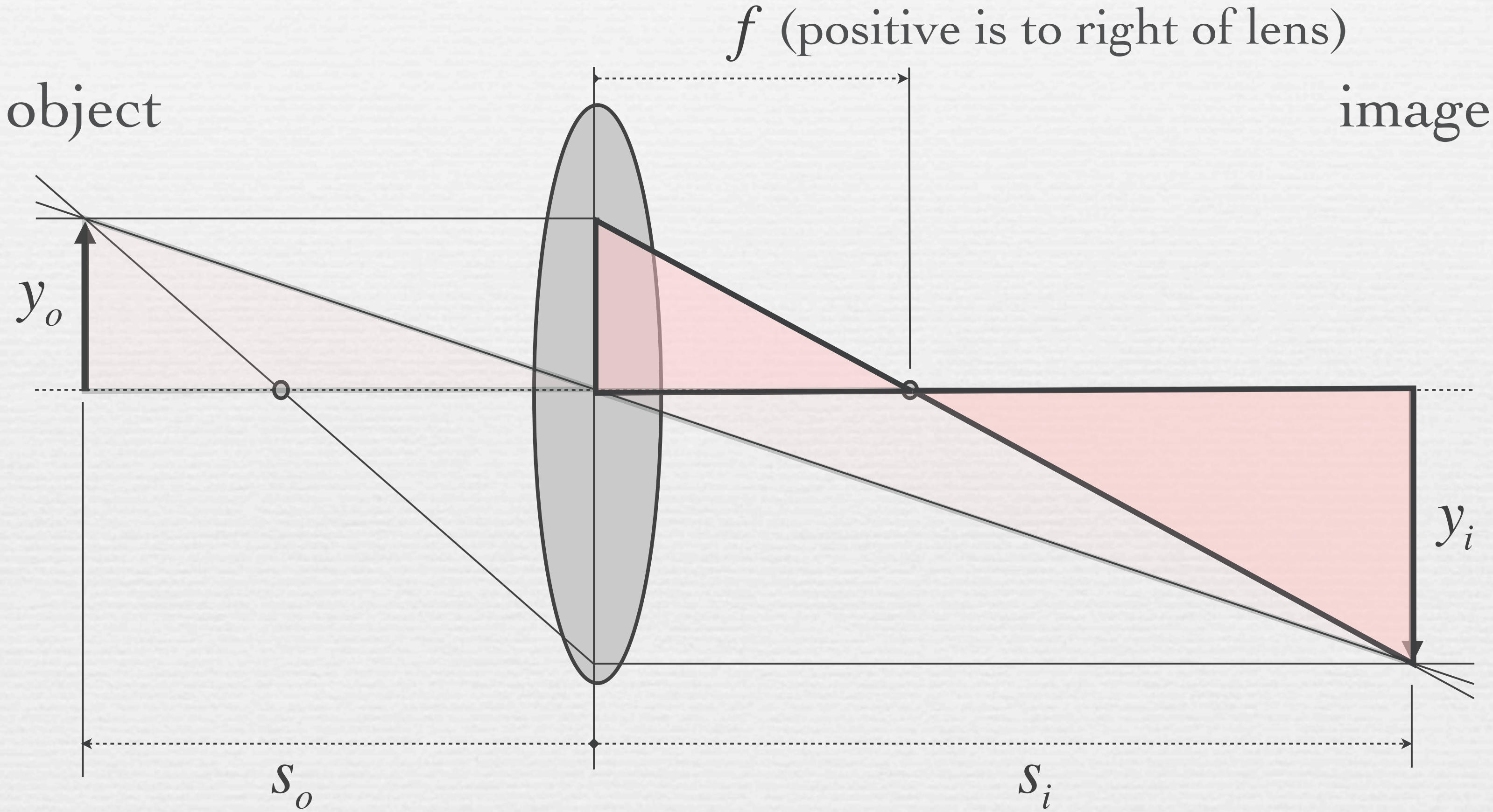
- positive s_i is rightward, positive s_o is leftward
- positive y is upward

From Gauss's ray construction to the Gaussian lens formula



$$\frac{|y_i|}{y_o} = \frac{s_i}{s_o}$$

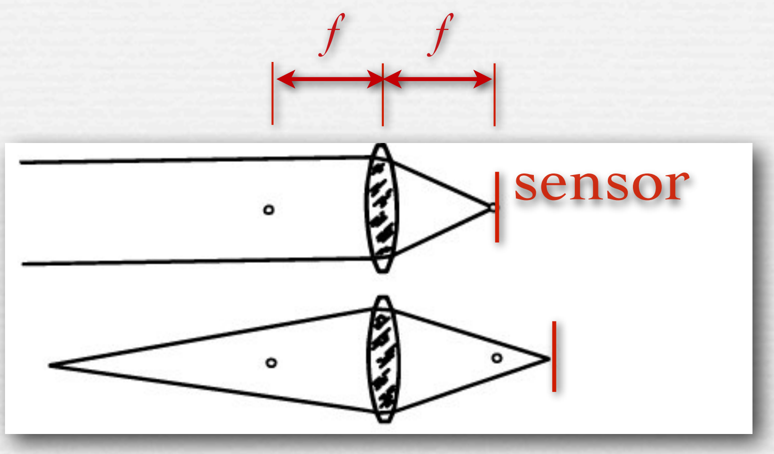
From Gauss's ray construction to the Gaussian lens formula



$$\frac{|y_i|}{y_o} = \frac{s_i}{s_o} \quad \text{and} \quad \frac{|y_i|}{y_o} = \frac{s_i - f}{f} \quad \ldots\ldots \quad \frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$$

Changing the focus distance

- to focus on objects at different distances, move sensor relative to lens



(FLASH DEMO)

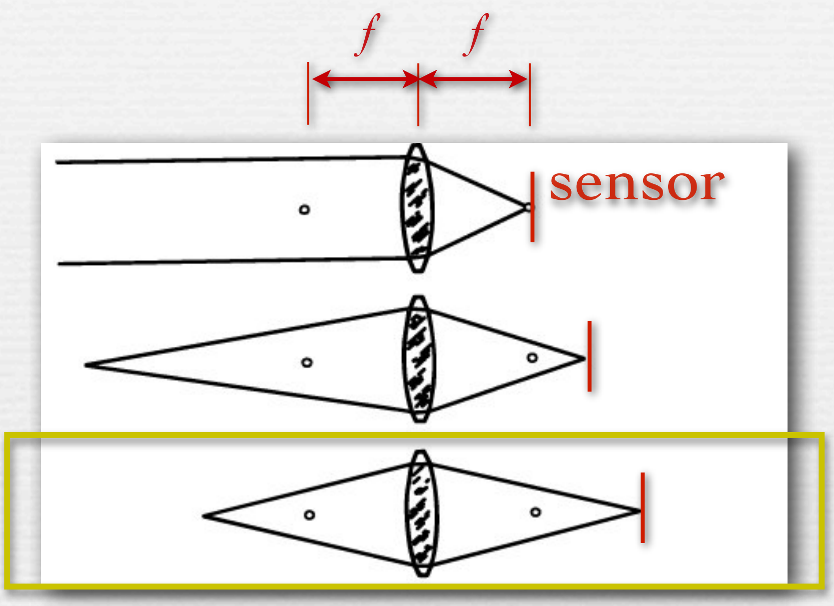
http://graphics.stanford.edu/courses/cs178/applets/gaussian.html

$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$$

Changing the focus distance

- to focus on objects at different distances, move sensor relative to lens
- at $s_o = s_i = 2f$ we have 1:1 imaging, because

$$\frac{1}{2f} + \frac{1}{2f} = \frac{1}{f}$$



In 1:1 imaging, if the sensor is 36mm wide, an object 36mm wide will fill the frame.

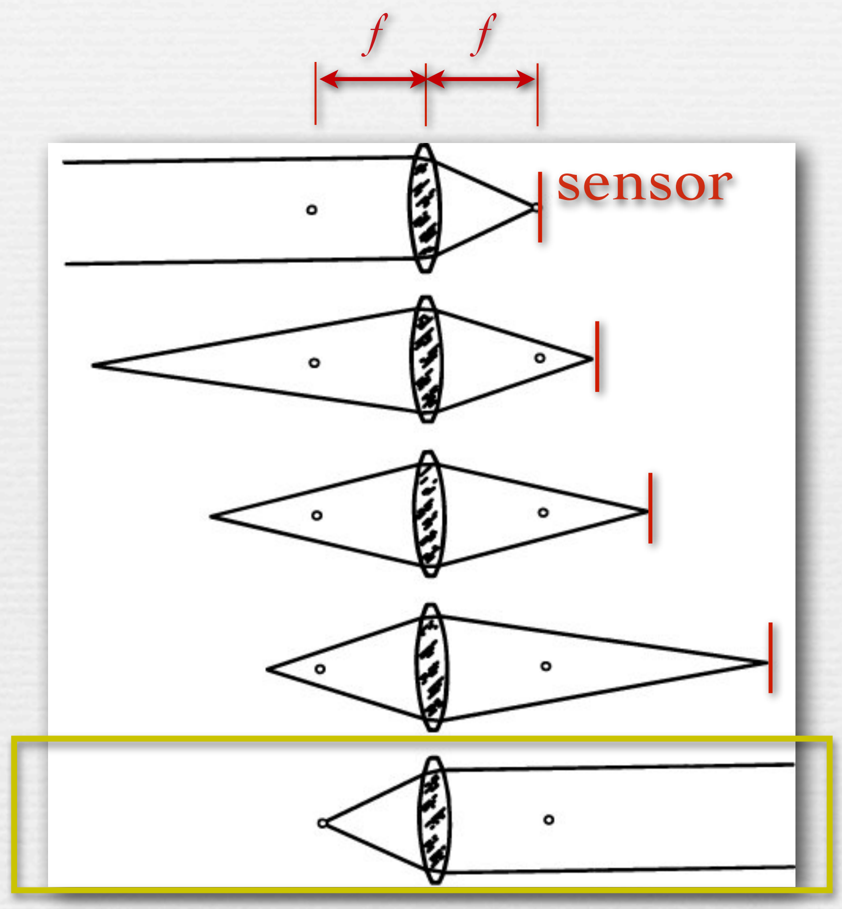
$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$$

Changing the focus distance

- to focus on objects at different distances, move sensor relative to lens
- at $s_o = s_i = 2f$ we have 1:1 imaging, because

$$\frac{1}{2f} + \frac{1}{2f} = \frac{1}{f}$$

- can't focus on objects closer to lens than its focal length f



$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$$

Recap

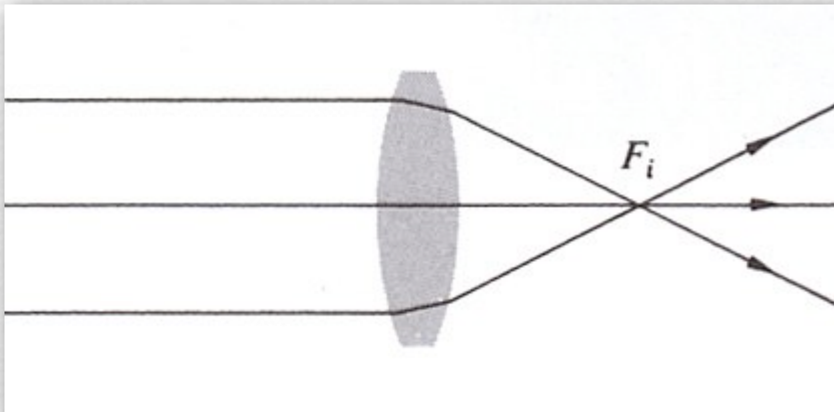
- approximations we sometimes make when analyzing lenses
  - geometrical optics instead of physical optics
  - spherical lenses instead of hyperbolic lenses
  - thin lens representation of thick optical systems
  - paraxial approximation of ray angles
- the Gaussian lens formula relates focal length f, object distance s_o, and image distance s_i
  - these settings, and sensor size, determine field of view
  - 1:1 imaging means $s_o = s_i$ and both are 2× focal length
  - $s_o = f$ is the minimum possible object distance for a lens

Que

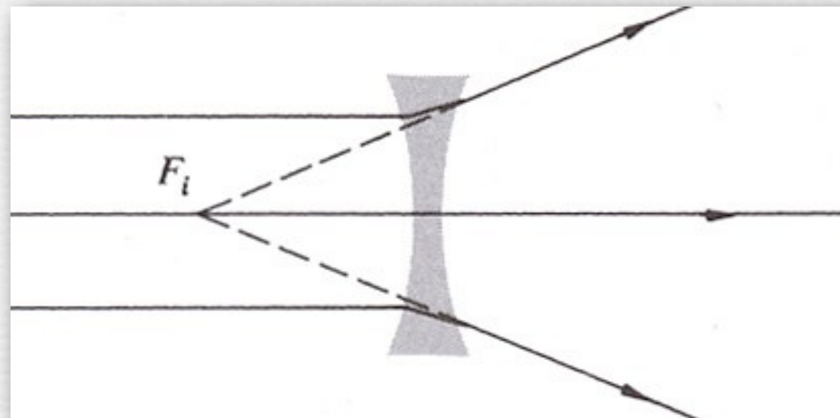
One must be careful applying this last rule in practice, because s_o may not be measured to the front of the barrel of a complex lens assembly, but to a plane you can't see inside the assembly. Also, many lenses can't crank out to the s_i that would enable the theoretically minimum s_o, because it is mechanically difficult or might produce poorly corrected (aberrant) images.

Convex versus concave lenses

(Hecht)



rays from a convex lens converge

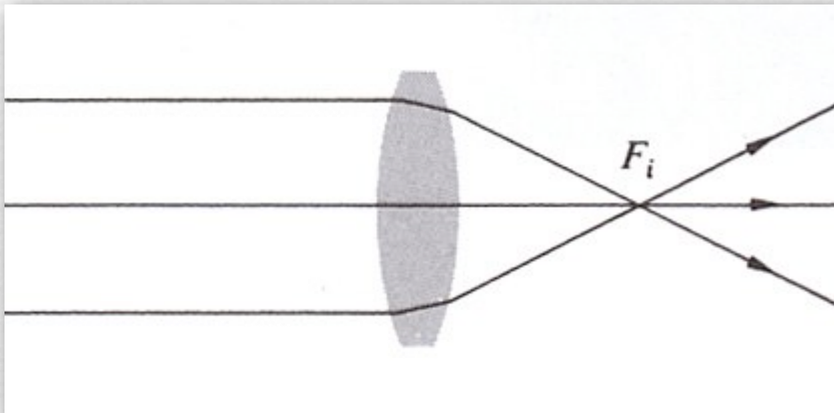


rays from a concave lens diverge

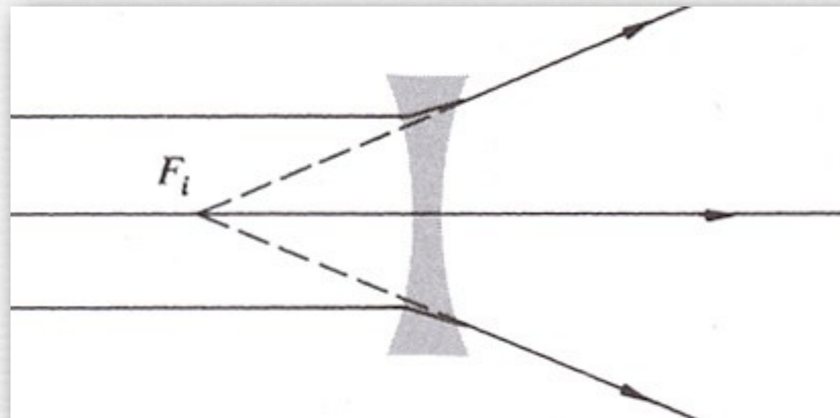
- positive focal length *f* means parallel rays from the left converge to a point on the right
- negative focal length *f* means parallel rays from the left converge to a point on the left (dashed lines above)

Convex versus concave lenses

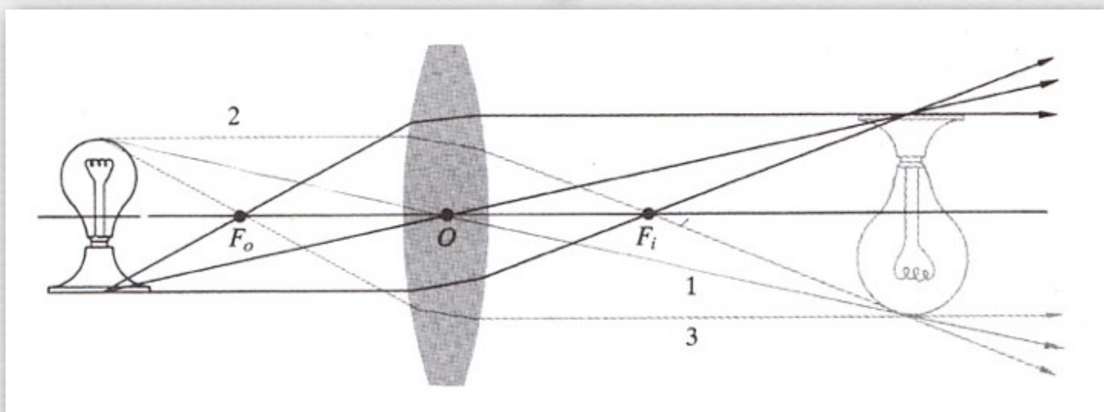
(Hecht)



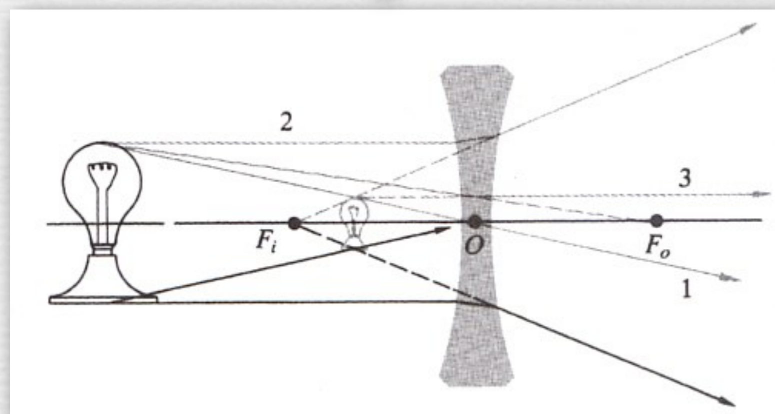
rays from a convex lens converge



rays from a concave lens diverge

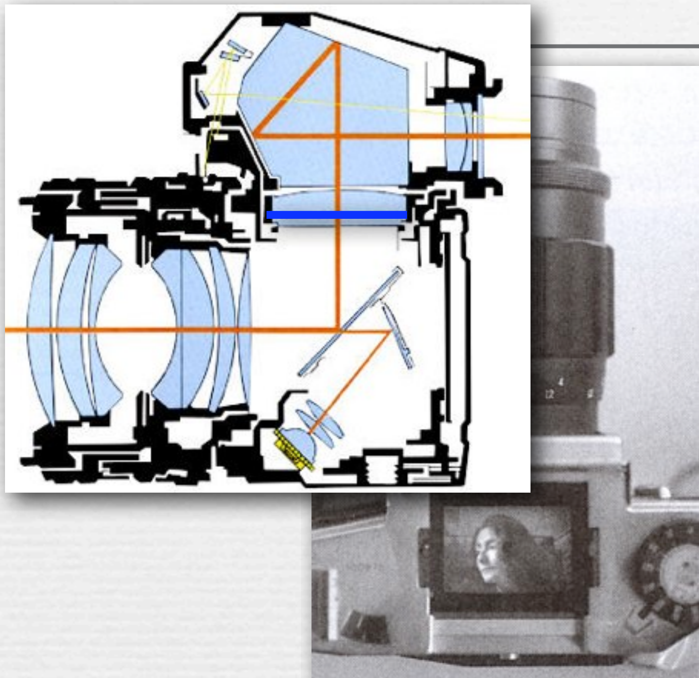


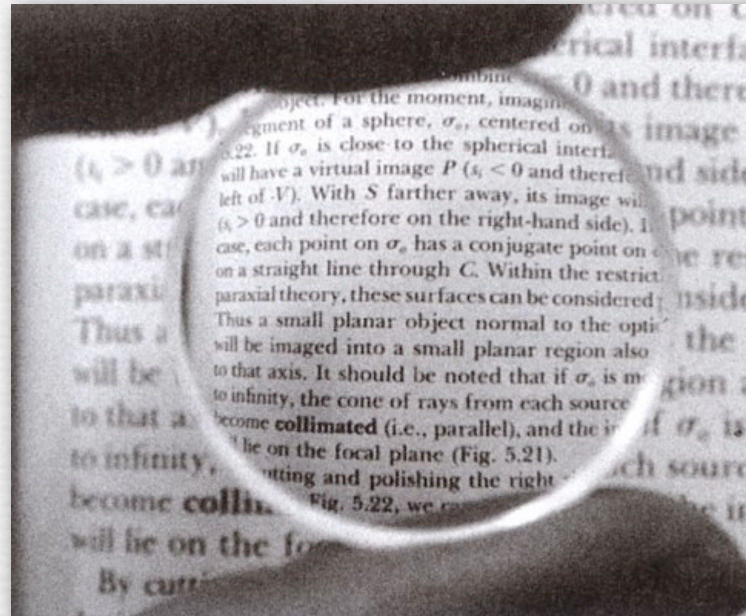
...producing a real image

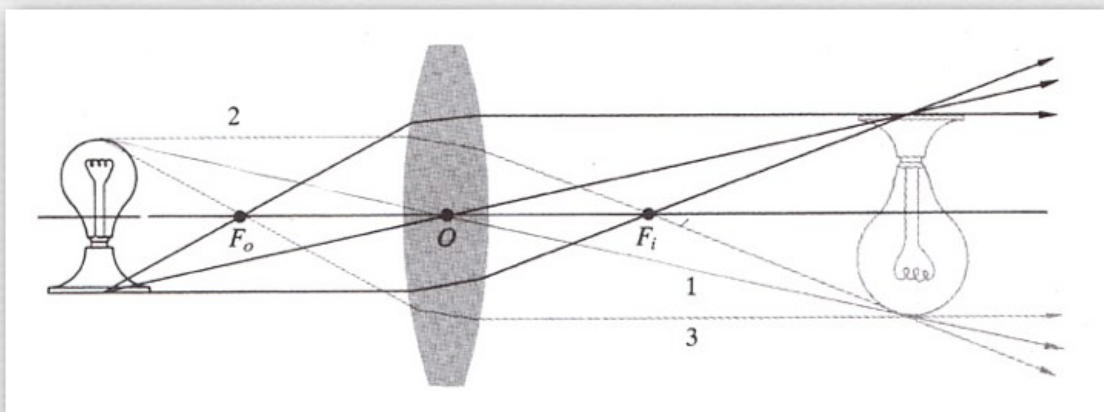


...producing a virtual image

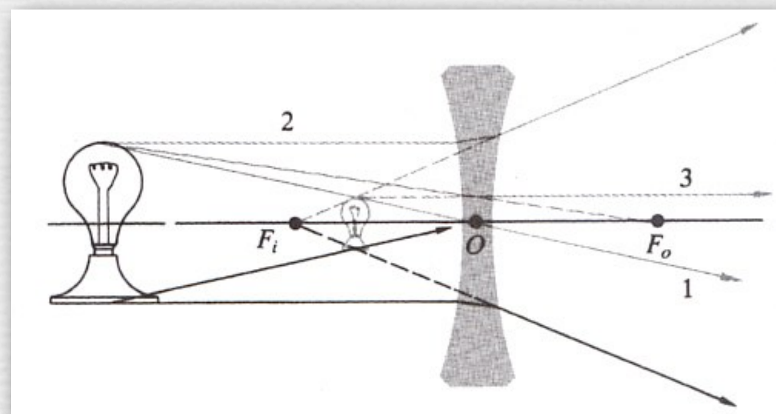
Convex versus concave lenses







...producing a real image



...producing a virtual image

The power of a lens

$$P = \frac{1}{f}$$

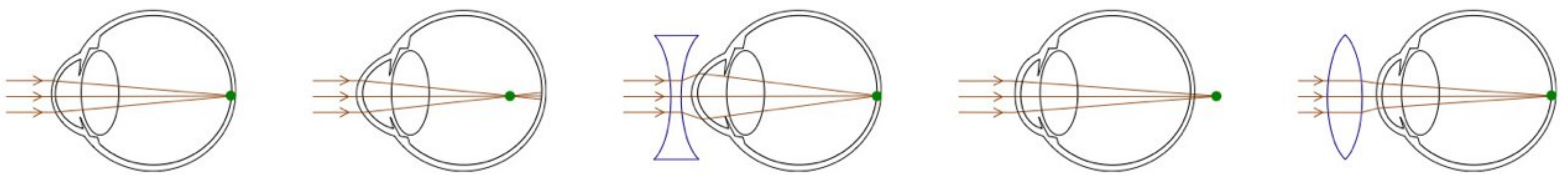
units are meters^{-1}

a.k.a. diopters

- my eyeglasses have the prescription
  - right eye: -0.75 diopters
  - left eye: -1.00 diopters

Q. What's wrong with me?
A. Myopia (nearsightedness)

(Pamplona)



(a) Perfect eye (b) Myopia (c) Corrected Myopia (d) Hyperopia (e) Corrected Hyperopia

Combining two lenses

- using focal lengths

$$\frac{1}{f_{tot}} = \frac{1}{f_1} + \frac{1}{f_2}$$

- using diopters

$$P_{tot} = P_1 + P_2$$

- example

The diopters version of this calculation was incorrect when shown in class. It has been corrected here. Thanks to Bryan Huh for finding the error.

$$\frac{1}{200mm} + \frac{1}{500mm} = \frac{1}{143mm}$$ -or- $$5.0 + 2.0 = 7.0 \text{ diopters}$$

Close-up filters

1/500mm = +2 diopters

(wikipedia)

- screw on to end of lens
- power is designated in diopters (usually)

Close-up filters

Panasonic 45-200

+

- changes longest focal length from 200mm to 143mm

$$\frac{1}{200mm} + \frac{1}{500mm} = \frac{1}{143mm}$$

Close-up filters

- for a fixed image distance, it reduces the object distance
  - at f=200mm, this len's minimum object distance s_o = 1000mm
  - at these settings, its effective image distance must be

$$s_i = \frac{1}{\frac{1}{f} - \frac{1}{s_o}} = \frac{1}{\frac{1}{200mm} - \frac{1}{1000mm}} = 250mm$$

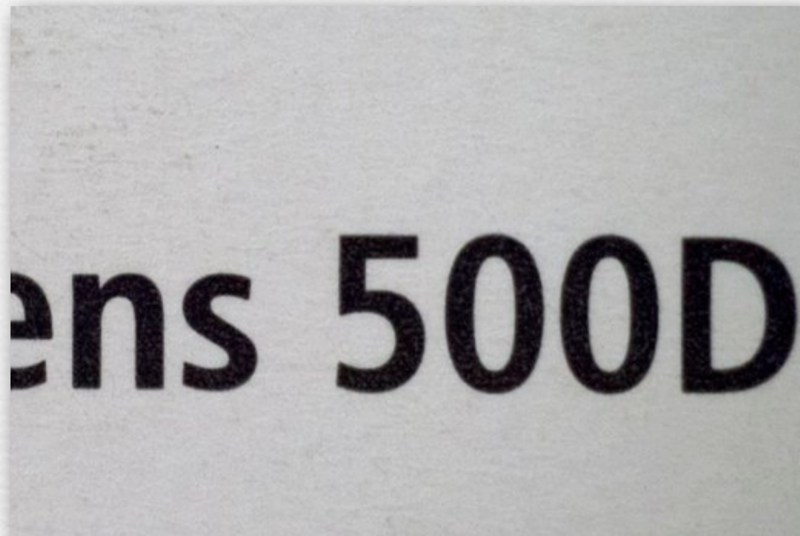
3× closer!

  - with the closeup filter and the same settings of focal length and image distance, the in-focus object distance becomes

$$s_o = \frac{1}{\frac{1}{f} - \frac{1}{s_i}} = \frac{1}{\frac{1}{143mm} - \frac{1}{250mm}} = 334mm$$

Close-up filters

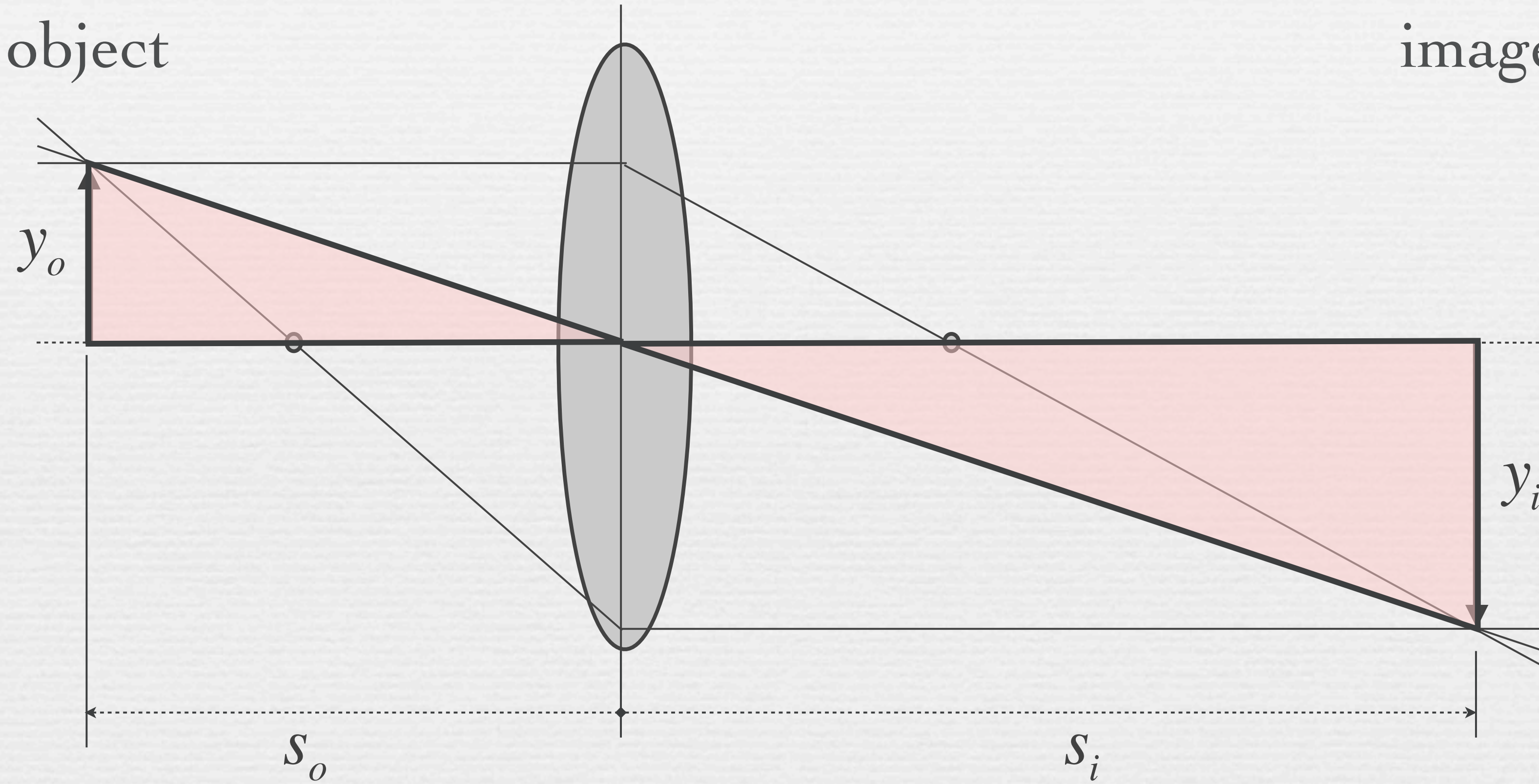
200mm lens
no closeup filter
s_o = 1000mm



200mm lens
500D closeup filter
s_o = 334mm

poor man's macro lens

Magnification

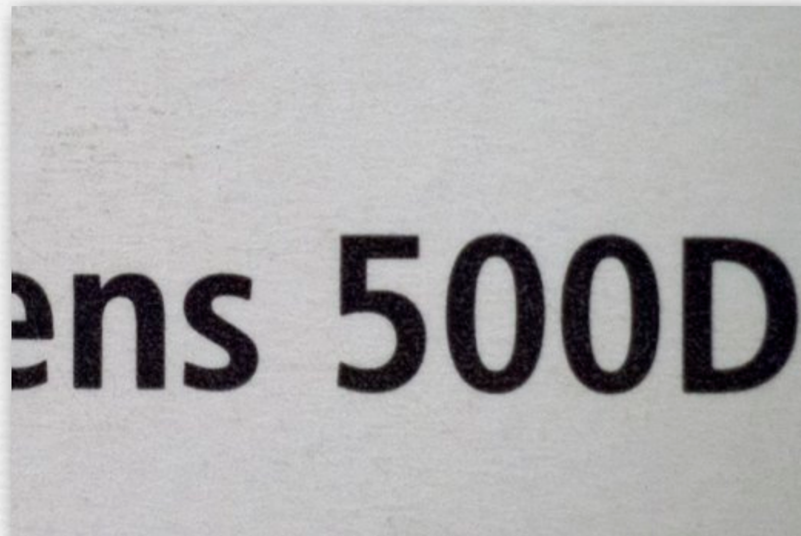


$$M_T \triangleq \frac{y_i}{y_o} = -\frac{s_i}{s_o}$$

Close-up filters

200mm lens
no closeup filter
s_o = 1000mm

$$M_T = -\frac{s_i}{s_o} = \frac{250}{1000} = -1:4$$

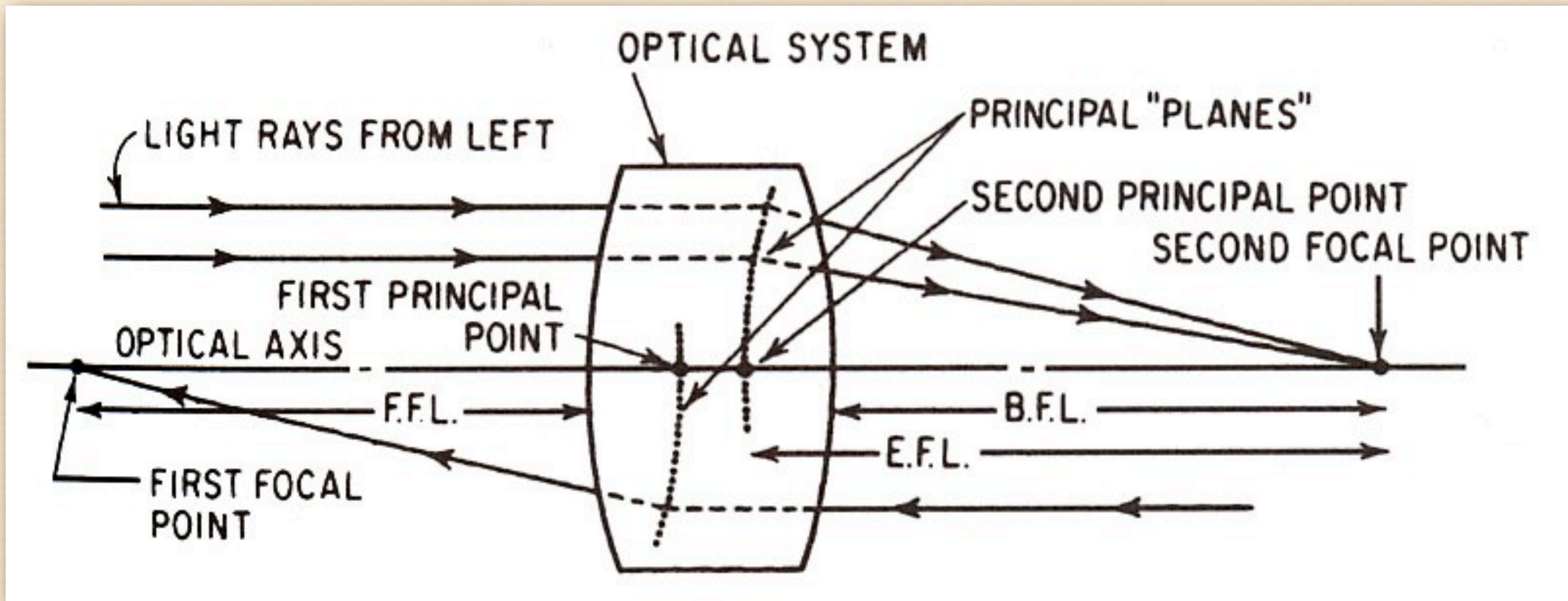


200mm lens
500D closeup filter
s_o = 334mm

$$M_T = -\frac{s_i}{s_o} = \frac{250}{334} = -3:4$$

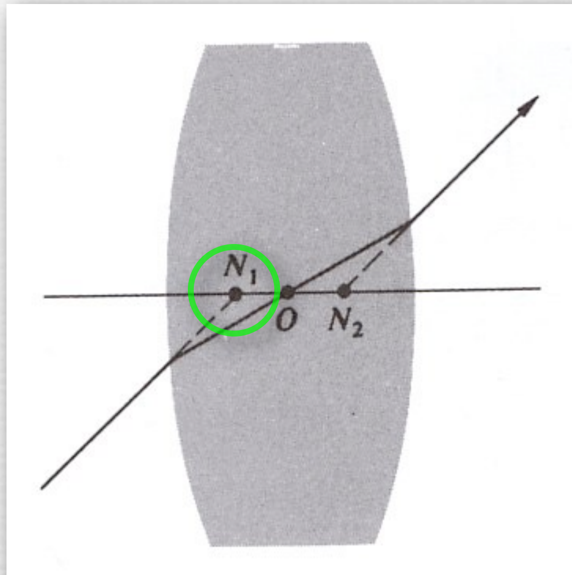
Thick lenses

- an optical system may contain many lenses, but can be characterized by a few numbers



(Smith)

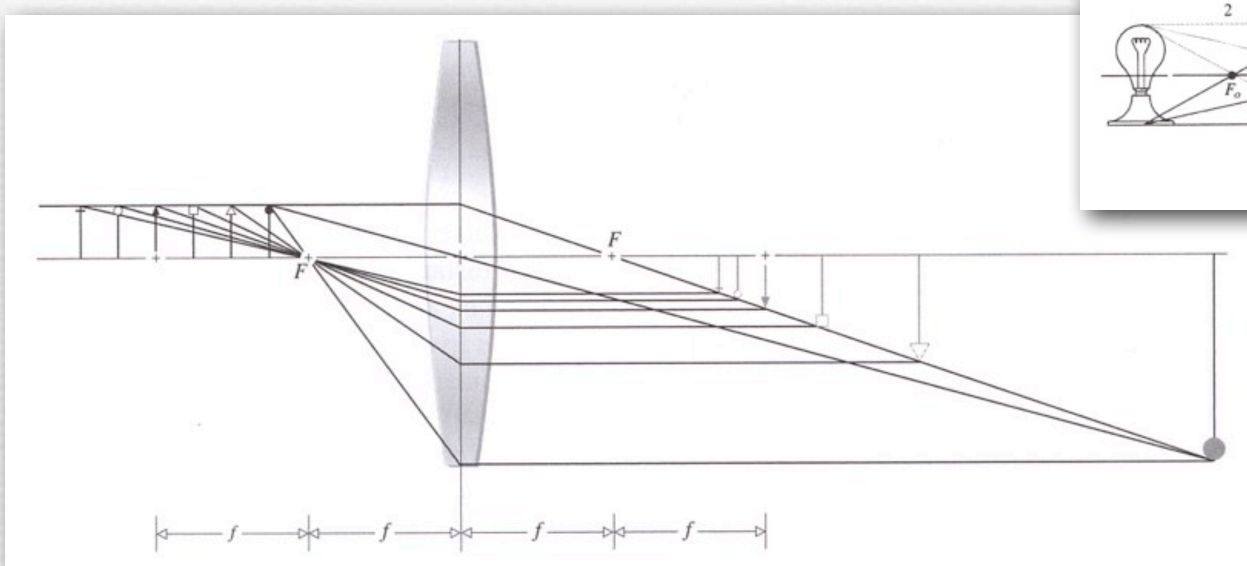
Center of perspective

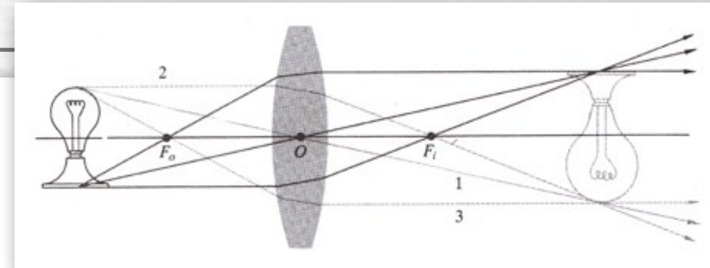


(Hecht)

- in a thin lens, the *chief ray* from a point 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*

Lenses perform a 3D perspective transform





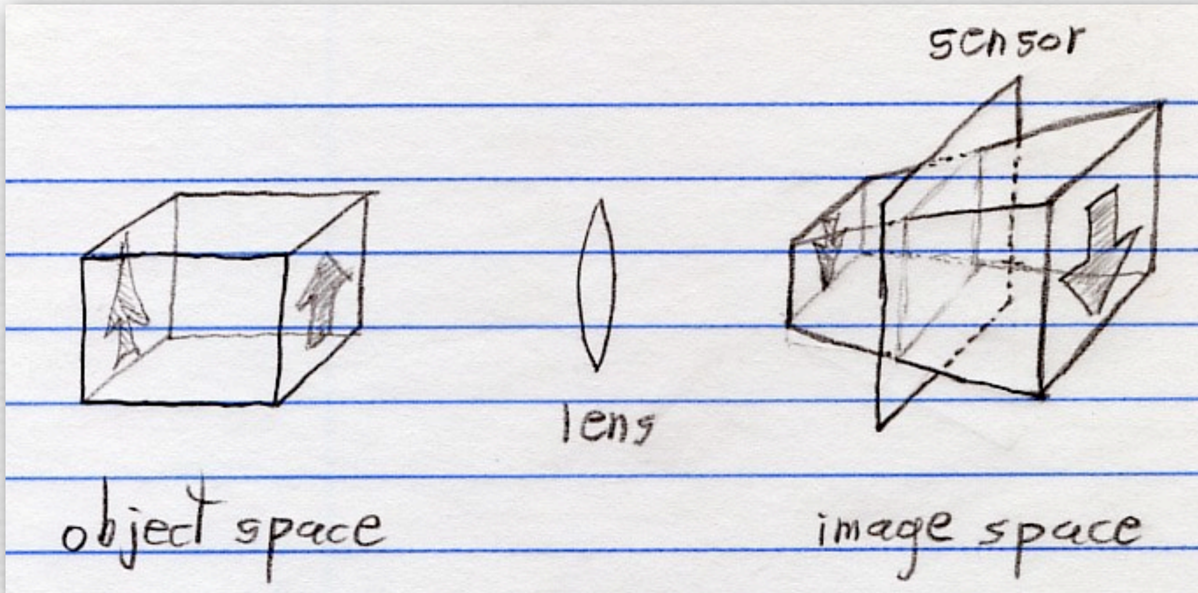
(FLASH DEMO)

http://graphics.stanford.edu/courses/cs178/applets/thinlens.html

(Hecht)

- lenses transform a 3D object to a 3D image; the sensor extracts a 2D slice from that image
- as an object moves linearly (in Z), its image moves non-proportionately (in Z)
- as you move a lens linearly relative to the sensor, the in-focus object plane moves non-proportionately
- as you refocus a camera, the image changes size !

Lenses perform a 3D perspective transform (contents of whiteboard)



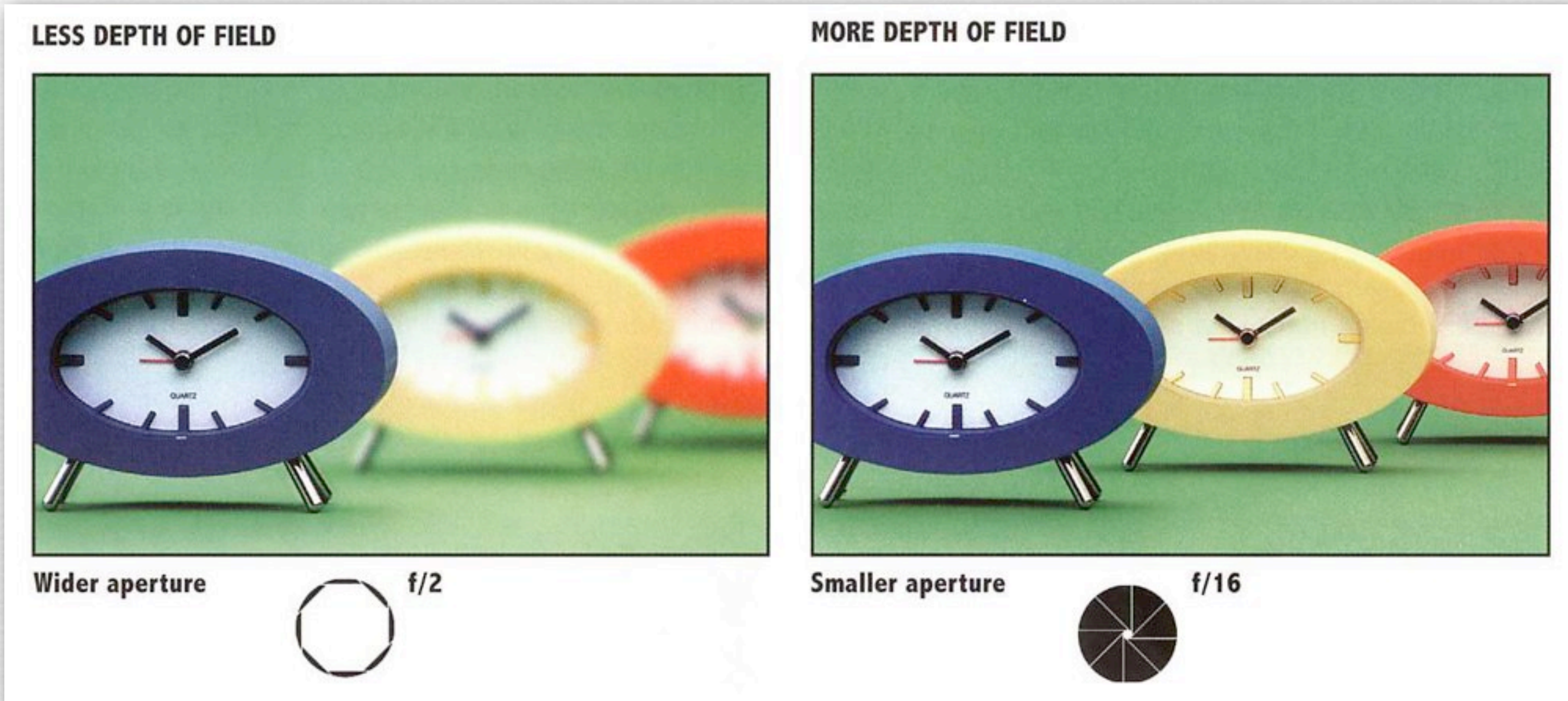
- a cube in object space is transformed by a lens into a 3D frustum in image space, with the orientations shown by the arrows
- in computer graphics this transformation is modeled as a 4×4 matrix multiplication of 3D points expressed in 4D homogenous coordinates
- in photography a sensor extracts a 2D slice from the 3D frustum; on this slice some objects will be sharply focused; others may be blurry

Recap

- more implications of the Gaussian lens formula
  - convex lenses make real images; concave make virtual images
  - the power of a lens (in diopters) is 1 over its focal length
  - when combining two lenses, add their powers
  - adding a closeup filter allows a smaller object distance
  - changing object and image distances changes magnification
- lenses perform a 3D perspective transform of object space
  - an object's apparent size is inversely proportional to its distance
  - linear lens motions move the in-focus plane non-linearly
  - focusing a lens changes the image size (slightly)

Questions?

Depth of field

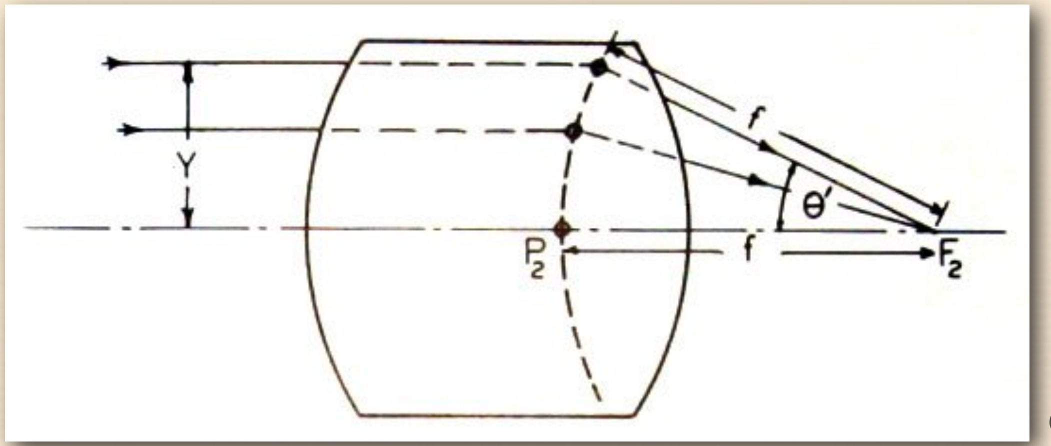


(London)

$$N = \frac{f}{A}$$

- lower N means a wider aperture and less depth of field

How low can N be?



(Kingslake)

- principal planes are the paraxial approximation of a spherical "equivalent refracting surface"

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

- lowest possible N in air is f/0.5
- lowest N I've seen in an SLR is f/1.0

Canon EOS 50mm f/1.0 (discontinued)

Cinematography by candlelight

Stanley Kubrick,
Barry Lyndon,
1975

- Zeiss 50mm f/0.7 Planar lens
  - originally developed for NASA's Apollo missions
  - very shallow depth of field in closeups (small object distance)

Cinematography by candlelight

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Barry Lyndon,
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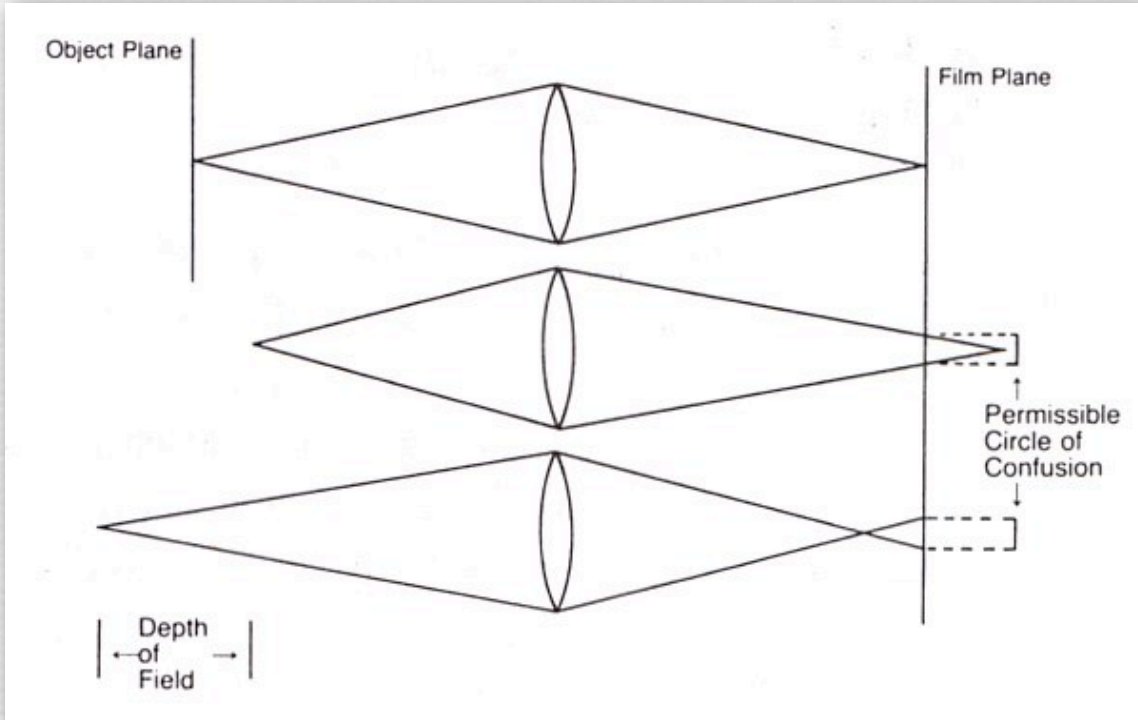
Circle of confusion (C)

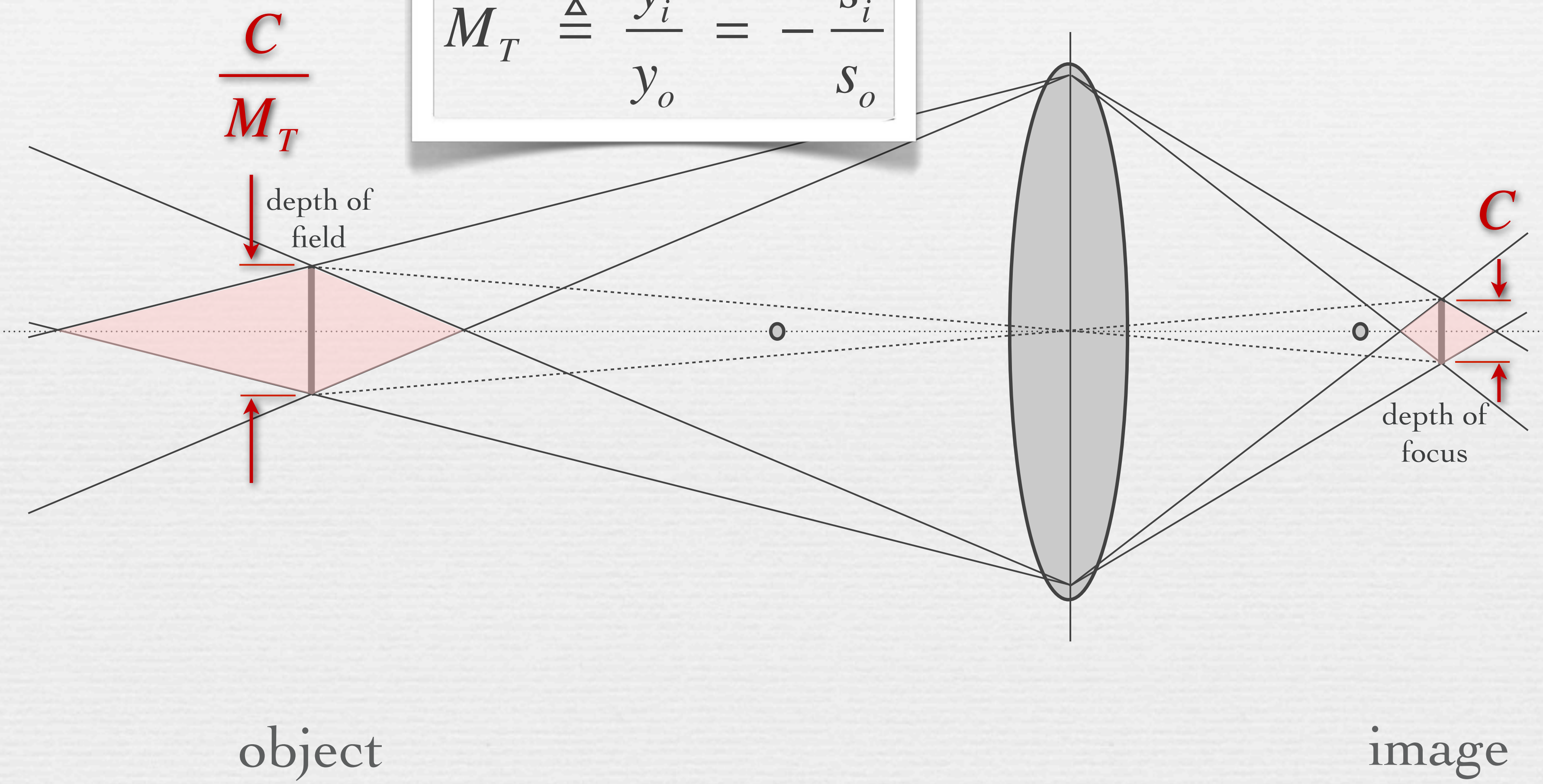


the right way to talk about C is in terms of angle subtended in the eye; we'll cover this later in the course

- C depends on sensing medium, reproduction medium, viewing distance, human vision,...
  - for print from 35mm film, 0.02mm (on negative) is typical
  - for high-end SLR, 6μ is typical (1 pixel)
  - larger if downsizing for web, or lens is poor

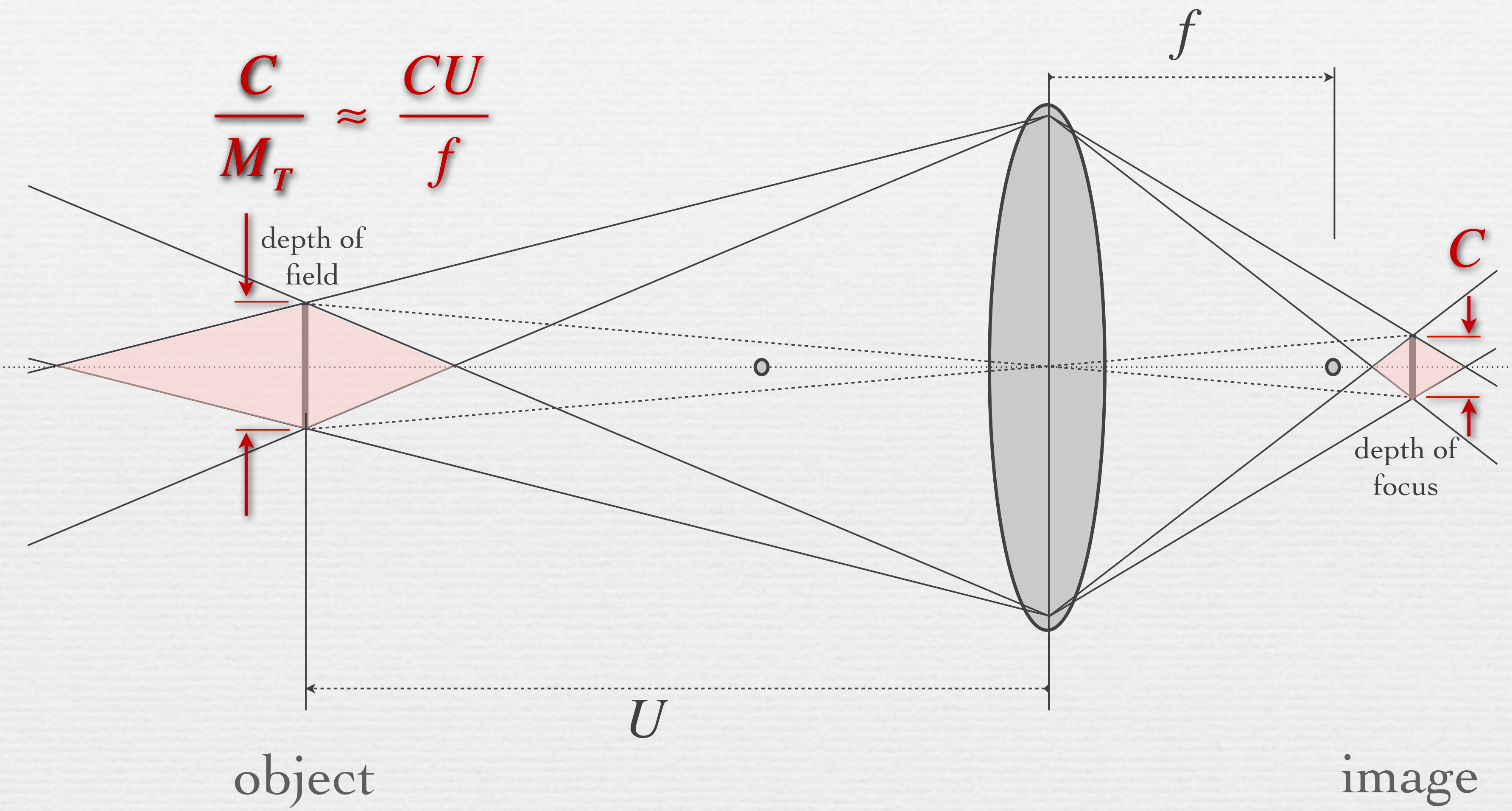
Depth of field formula

$$M_T \triangleq \frac{y_i}{y_o} = -\frac{s_i}{s_o}$$



- DoF is asymmetrical around the in-focus object plane
- conjugate in object space is typically bigger than C

Depth of field formula



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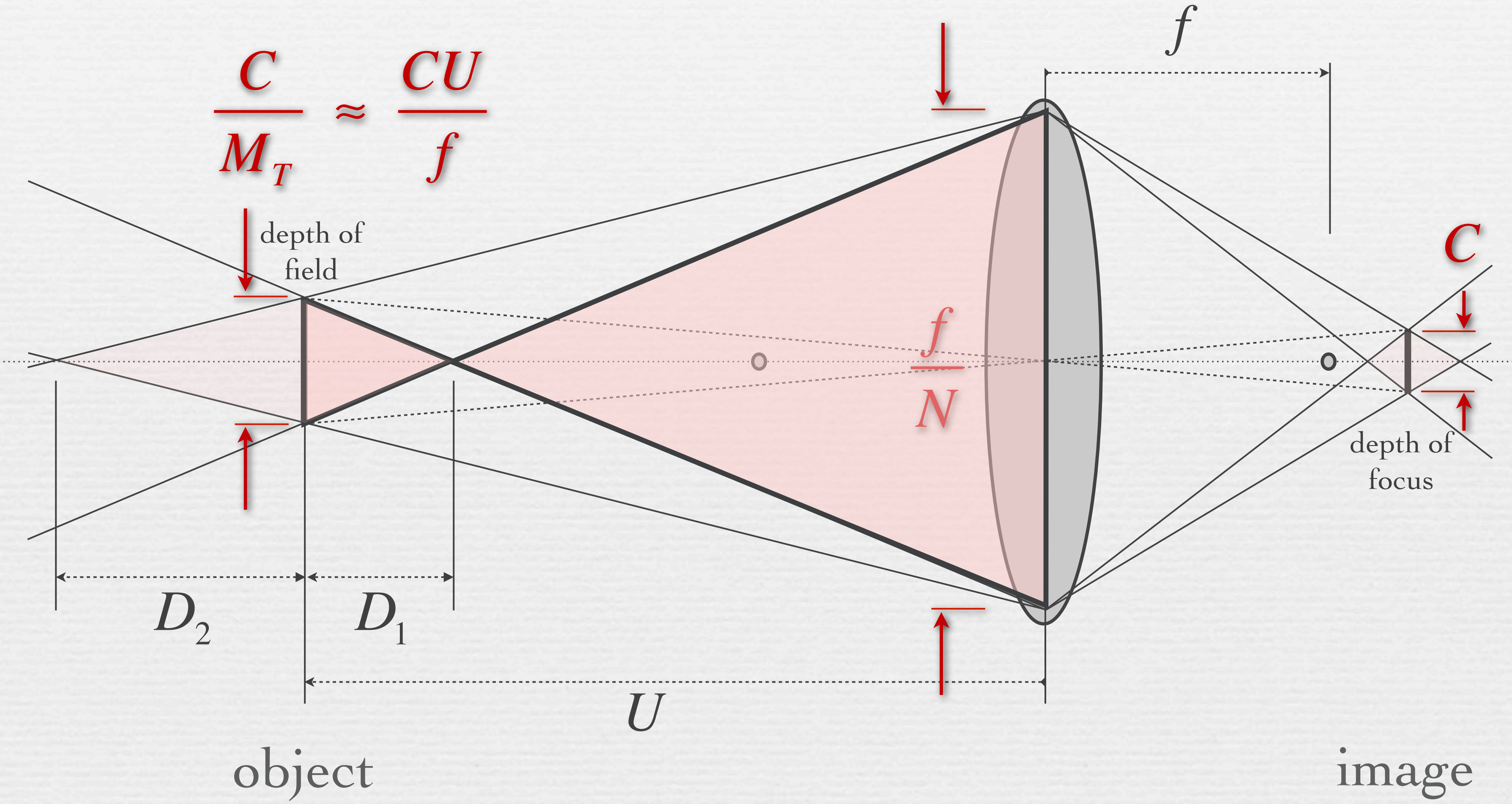
Depth of field formula



$$\frac{D_1}{CU / f} = \frac{U - D_1}{f / N} \quad ..... \quad D_1 = \frac{NCU^2}{f^2 + NCU} \qquad D_2 = \frac{NCU^2}{f^2 - NCU}$$

Depth of field formula

$$D_{TOT} = D_1 + D_2 = \frac{2NCU^2 f^2}{f^4 - N^2C^2U^2}$$

- $N^2C^2U^2$ can be ignored when conjugate of circle of confusion is small relative to the aperture

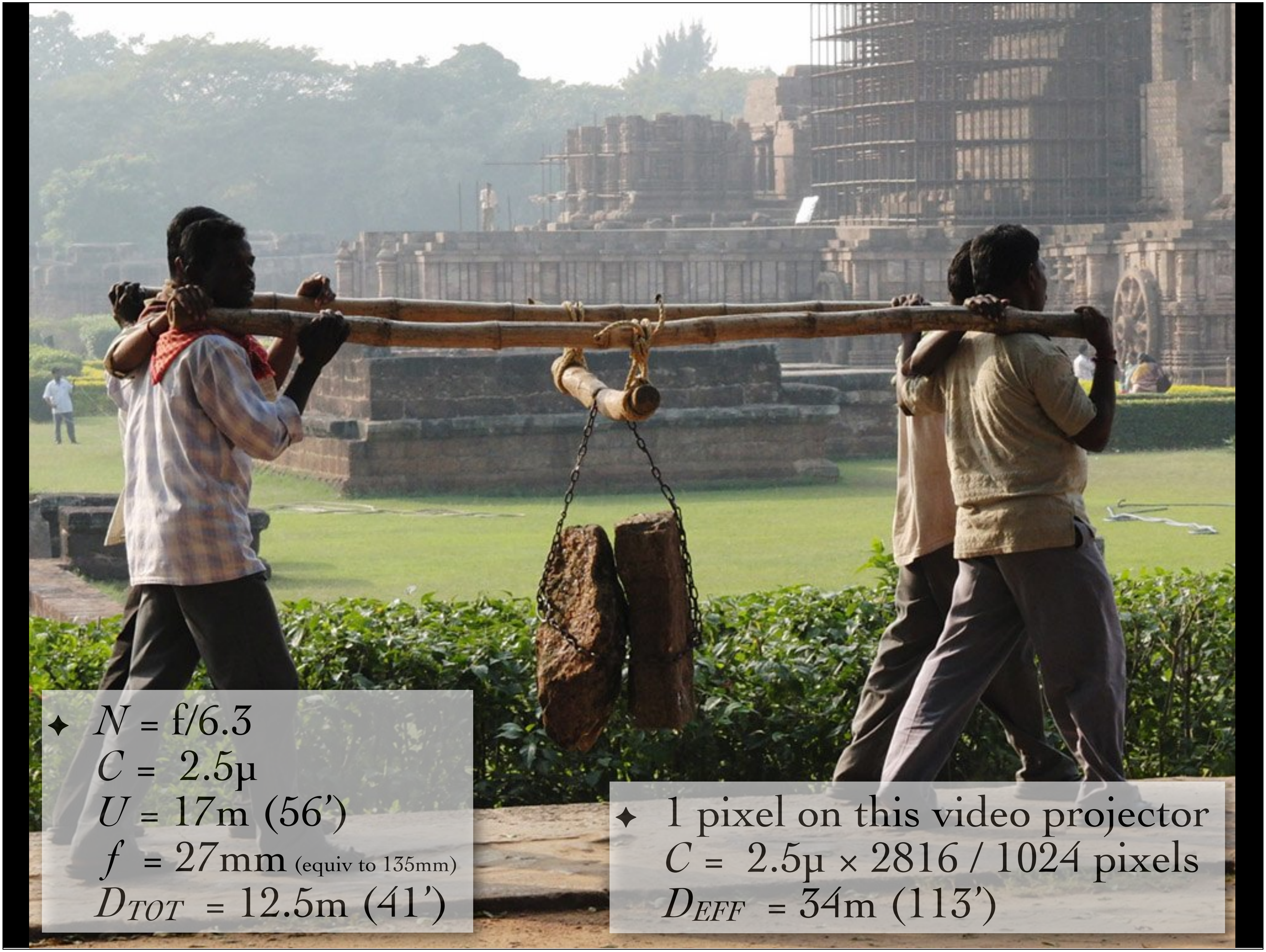
$$D_{TOT} \approx \frac{2NCU^2}{f^2}$$

- where
  - N is F-number of lens
  - C is circle of confusion (on image)
  - U is distance to in-focus plane (in object space)
  - f is focal length of lens

$$D_{TOT} \approx \frac{2NCU^2}{f^2}$$

- N = f/4.1
  C = 2.5μ
  U = 5.9m (19’)
  f = 73mm (equiv to 362mm)
  D_{TOT} = 132mm

- 1 pixel on this video projector
  C = 2.5μ × 2816 / 1024 pixels
  D_{EFF} = 363mm



✦ N = f/6.3
C = 2.5µ
U = 17m (56')
f = 27mm (equiv to 135mm)
DTOT = 12.5m (41')
✦ 1 pixel on this video projector
C = 2.5µ × 2816 / 1024 pixels
DEFF = 34m (113')

- N = f/5.6
  C = 6.4μ
  U = 0.7m
  f = 105mm
  D_{TOT} = 3.2mm

- 1 pixel on this video projector
  C = 6.4μ × 5616 / 1024 pixels
  D_{EFF} = 17.5mm

Canon MP-E
65mm 5:1 macro

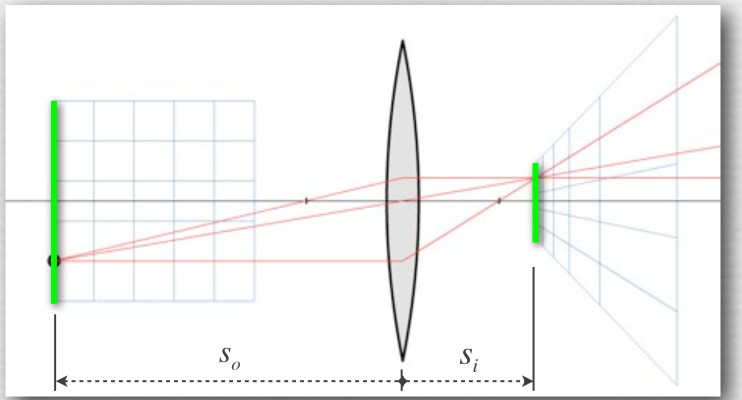
(Mikhail Shlemov)

- N = f/2.8
  C = 6.4μ
  U = 78mm
  f = 65mm
  (use $N' = (1+M_T)N$ at short conjugates (M_T=5 here)) = f/16
  D_{TOT} = 0.29mm!

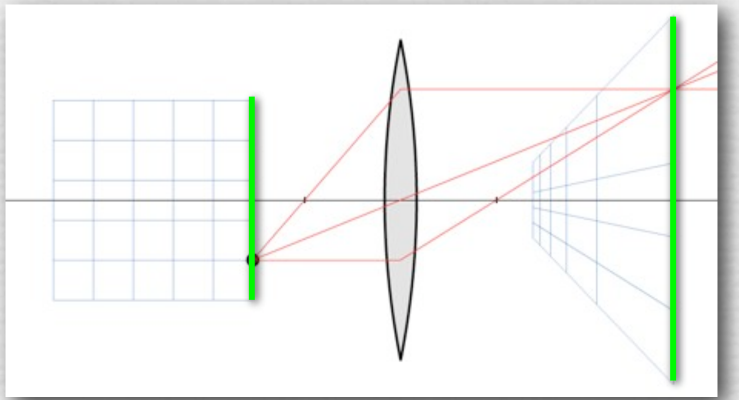
Sidelight: macro lenses

$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$$

Q. How can the Casio EX-F1 at 73mm and the Canon MP-E 65mm macro, which have similar *f* 's, have such different focusing distances?



normal



macro

- A. Because macro lenses are built to allow long s_i
  - this changes s_o, which changes magnification $M_T \triangleq -s_i / s_o$
  - macro lenses are also well corrected for aberrations at short s_o

Extension tube: fits between camera and lens, converts a normal lens to a macro lens

- toilet paper tube, black construction paper, masking tape
- camera hack by Katie Dektar (CS 178, 2009)

Extension tubes versus close-up filters

Canon 25mm

Canon f = 500mm

- both allow closer focusing, hence greater magnification
- both degrade image quality relative to a macro lens
- extension tubes work best with wide-angle lenses; close-up filters work best with telephoto lenses
- extension tubes raise F-number, reducing light
- need different close-up filter for each lens filter diameter

Extension tubes versus close-up filters versus teleconverters

Canon 25mm

Canon f = 500mm

Nikon 1.4×

- a teleconverter fits between the camera and lens, like an extension tube
- they increase *f*, narrowing FOV & increasing magnification, but they don't change the focusing range
- like extension tubes, they raise F-number, reducing light, and they are awkward to add or remove
- see http://www.cambridgeincolour.com/tutorials/macro-extension-tubes-closeup.htm

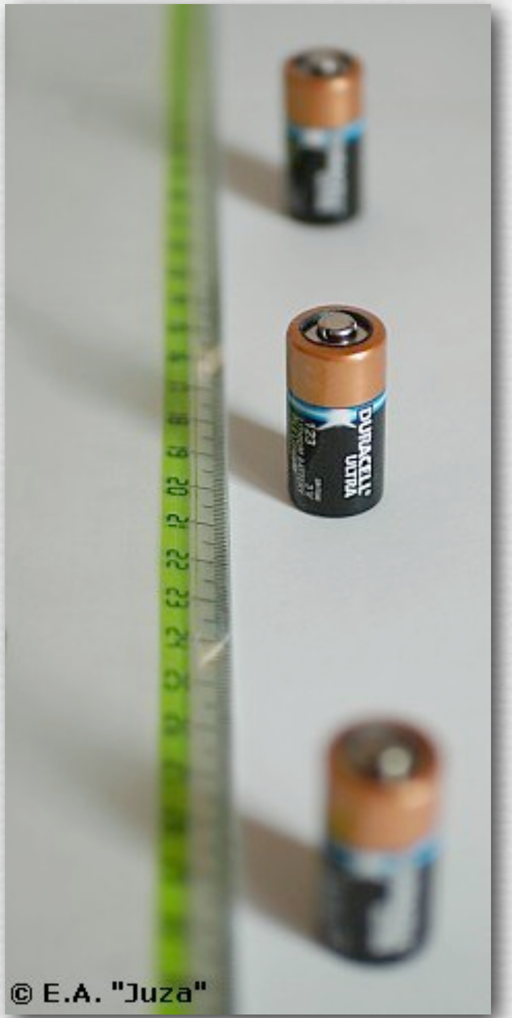
DoF is linear with F-number

(juzaphoto.com)

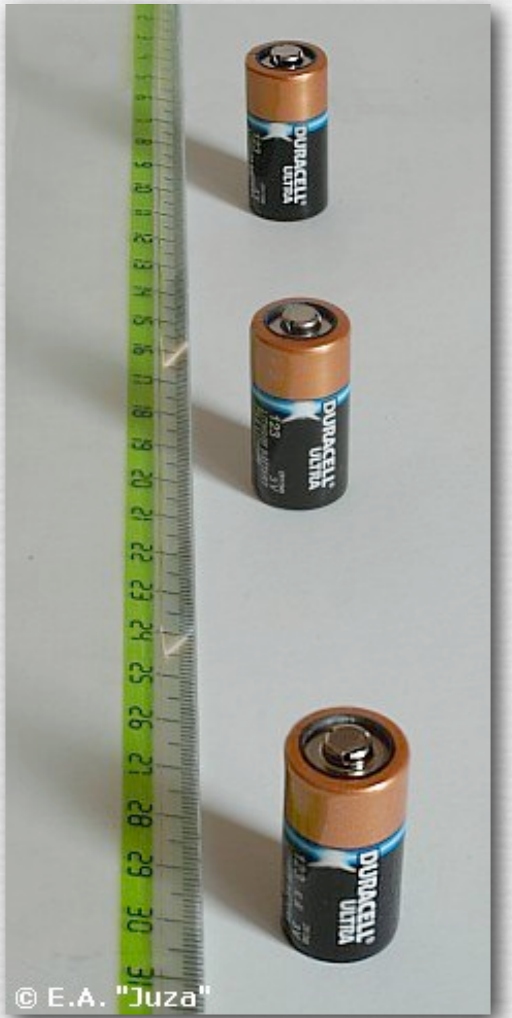
$$D_{TOT} \approx \frac{2NCU^2}{f^2}$$

(FLASH DEMO)

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



f/2.8



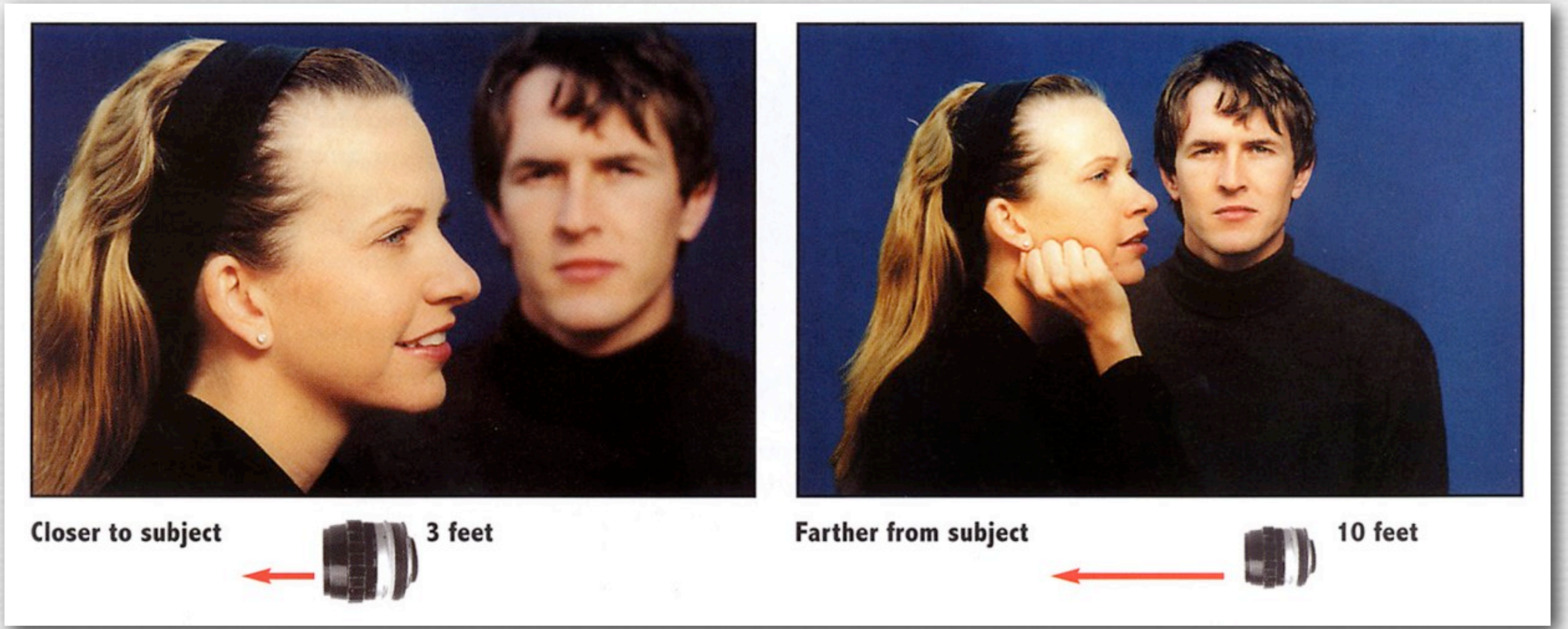
f/32

DoF is quadratic with subject distance

$$D_{TOT} \approx \frac{2NCU^2}{f^2}$$

(FLASH DEMO)

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



(London)

Hyperfocal distance

- the back depth of field

$$D_2 = \frac{NCU^2}{f^2 - NCU}$$

- becomes infinite if

$$U \geq \frac{f^2}{NC} \triangleq H$$

- N = f/6.3
  C = 2.5μ × 2816 / 1920 pixels
  U = 17m (56')
  f = 27mm (equiv to 135mm)
  D_{TOT} = 18.3m on HD projector
  H = 31.6m (104')

- In that case, the front depth of field becomes

$$D_1 = \frac{NCU^2}{f^2 + NCU} = \frac{H}{2}$$

(FLASH DEMO)

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

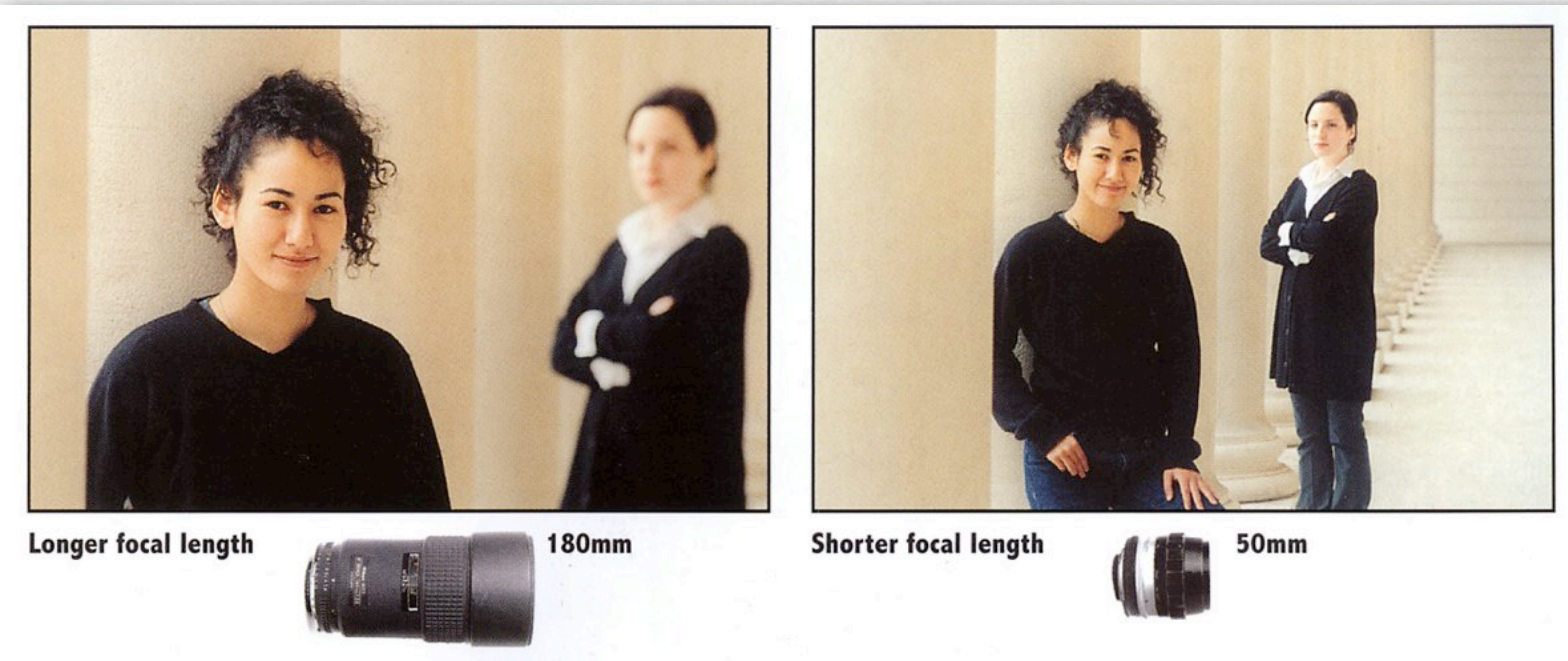
- so if I had focused at 32m, everything from 16m to infinity would be in focus on a video projector, including the men at 17m

DoF is inverse quadratic with focal length

$$D_{TOT} \approx \frac{2NCU^2}{f^2}$$

(FLASH DEMO)

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



(London)

Q. Does sensor size affect DoF?

$$D_{TOT} \approx \frac{2NCU^2}{f^2}$$

- as sensor shrinks, lens focal length f typically shrinks to maintain a comparable field of view
- as sensor shrinks, pixel size C typically shrinks to maintain a comparable number of pixels in the image
- thus, depth of field D_{TOT} increases linearly with decreasing sensor size on consumer cameras
- this is why amateur cinematographers are drawn to SLRs
  - their chips are larger than even pro-level video camera chips
  - so they provide unprecedented control over depth of field

Vincent Laforet, Nocturne (2009)
Canon 1D Mark IV

DoF and the dolly-zoom

- if we zoom in (increase f)
  and stand further back (decrease U) by the same factor

$$D_{TOT} \approx \frac{2NCU^2}{f^2}$$

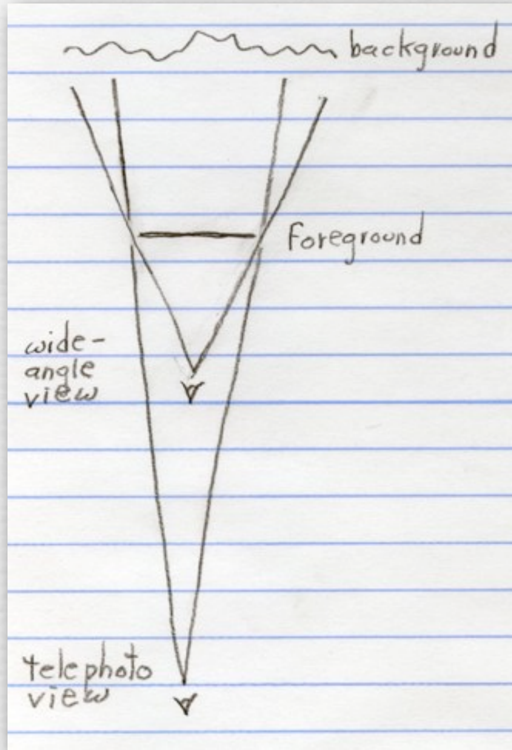
- depth of field stays the same, but background gets blurrier!
  - useful for macro when you can't get close enough

50mm f/4.8

(juzaphoto.com)

200mm f/4.8,
moved back 4× from subject

Macro photography using a telephoto lens (contents of whiteboard)



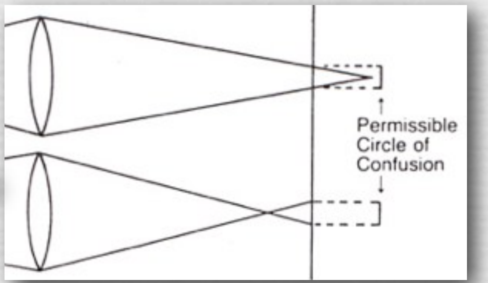
- changing from a wide-angle lens to a telephoto lens and stepping back, you can make a foreground object appear the same size in both lenses
- and both lenses will have the same depth of field on that object
- but the telephoto sees a smaller part of the background (which it blows up to fill the field of view), so the background will appear blurrier

(wikipedia.org)

Parting thoughts on DoF: the zen of *bokeh*

Canon 85mm prime f/1.8 lens

- the appearance of small out-of-focus features in a photograph with shallow depth of field
  - determined by the boundary of the aperture →
  - people get religious about it
  - but not every picture with shallow DoF has evident bokeh...



Natasha Gelfand (Canon 100mm f/2.8 prime macro lens)

Games with bokeh

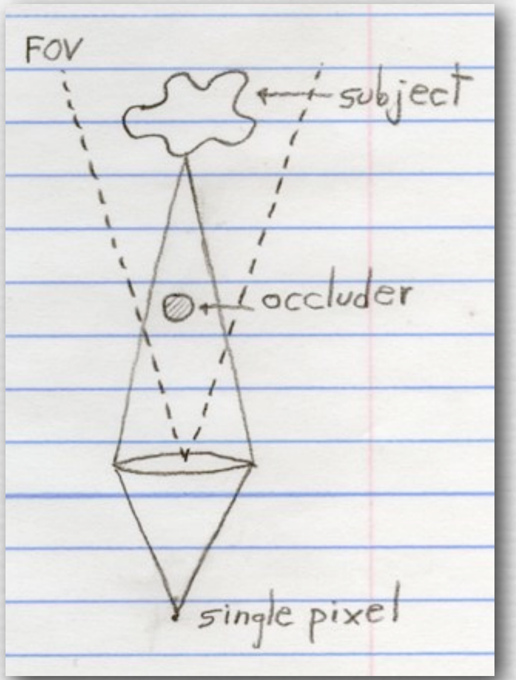
- picture by Alice Che (CS 178, 2010)
  - heart-shaped mask in front of lens
  - subject was Christmas lights
  - photograph was misfocused and under-exposed

Parting thoughts on DoF: seeing through occlusions

(Fredo Durand)

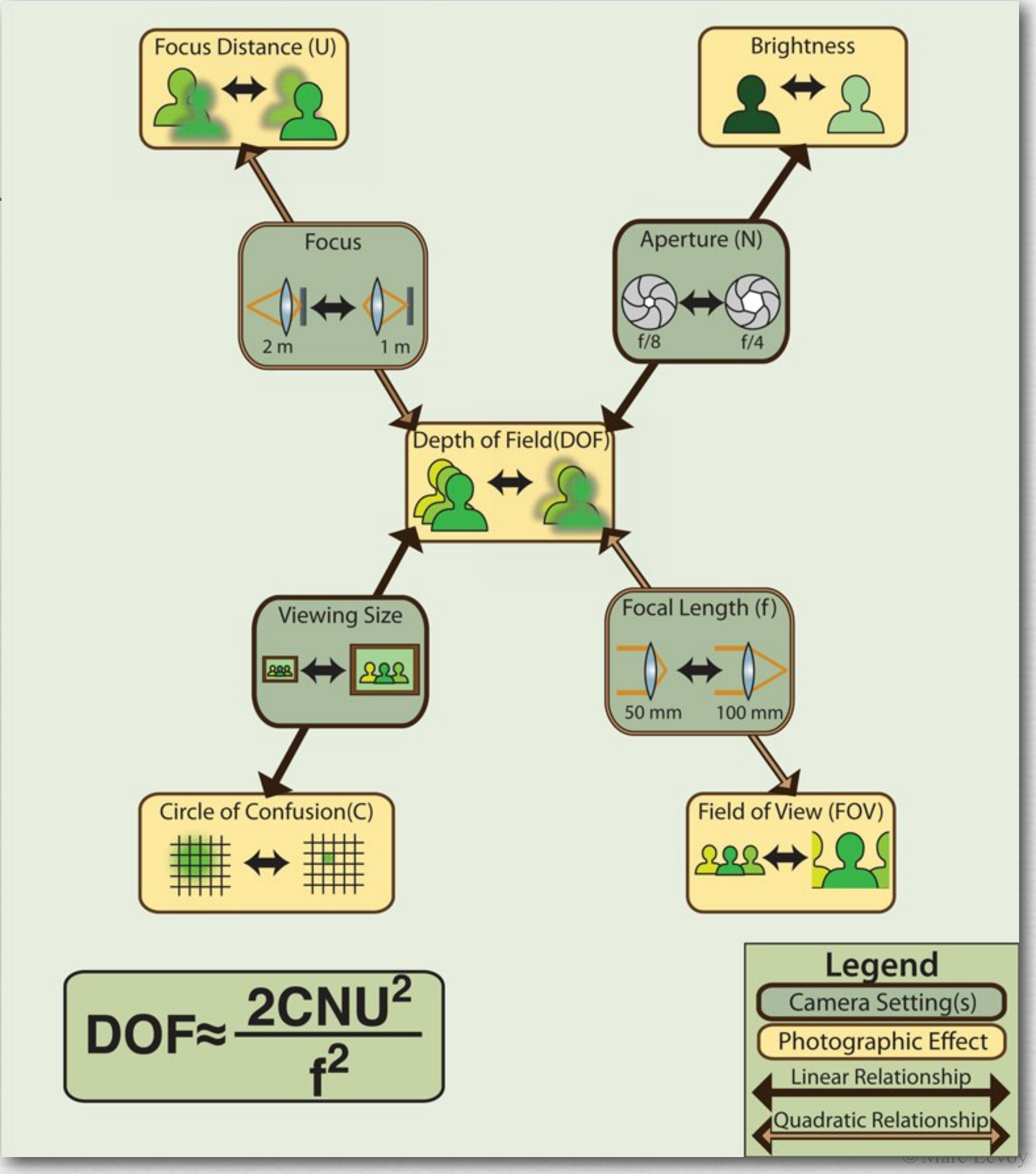
- depth of field is not a convolution of the image
  - i.e. not the same as blurring in Photoshop
  - DoF lets you eliminate occlusions, like a chain-link fence

Seeing through occlusions using a large aperture (contents of whiteboard)



- for a pixel focused on the subject, some of its rays will strike the occluder, but some will pass to the side of it, if the occluder is small enough
- the pixel will then be a mixture of the colors of the subject and occluder
- thus, the occluder reduces the contrast of your image of the subject, but it doesn't actually block your view of it

Tradeoffs affecting depth of field



$$DOF \approx \frac{2CNU^2}{f^2}$$

(Eddy Talvala)

Recap

- depth of field (D_{TOT}) is governed by circle of confusion (C), aperture size (N), subject distance (U), and focal length (f)

$$D_{TOT} \approx \frac{2NCU^2}{f^2}$$

  - depth of field is linear in some terms and quadratic in others
  - if you focus at the hyperfocal distance $H = f^2 / NC$, everything from $H / 2$ to infinity will be in focus
  - depth of field increases linearly with decreasing sensor size
- useful sidelights
  - bokeh refers to the appearance of small out-of-focus features
  - you can take macro photographs using a telephoto lens
  - depth of field blur is not the same as blurring an image

Questions?