CS6640 Computational Photography

3. Camera basics

Practical items

- **Add yourselves to Piazza!**

  link on course home page, at top

- **Cameras in Randy's office**

  several Canon SLRs of 2 types, various lenses

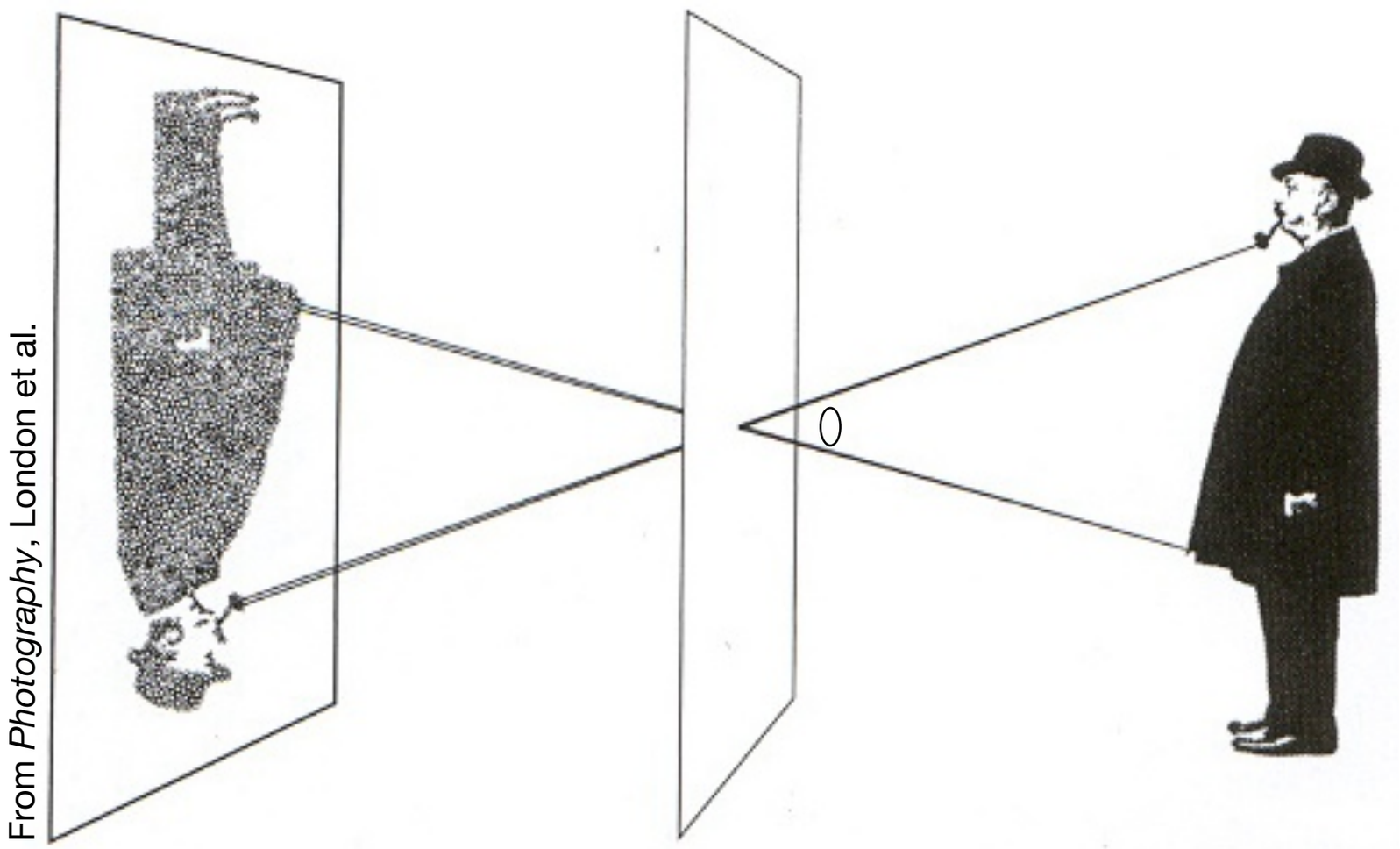
  sign them out from Randy in 5147 Upson

- **SLR boot camp**

  come to office hours today or Friday (2–3pm)

Pinhole camera

- **Simplest possible camera**
  1. light tight box with hole
  2. film
- **Rays are selected simply by occlusion**

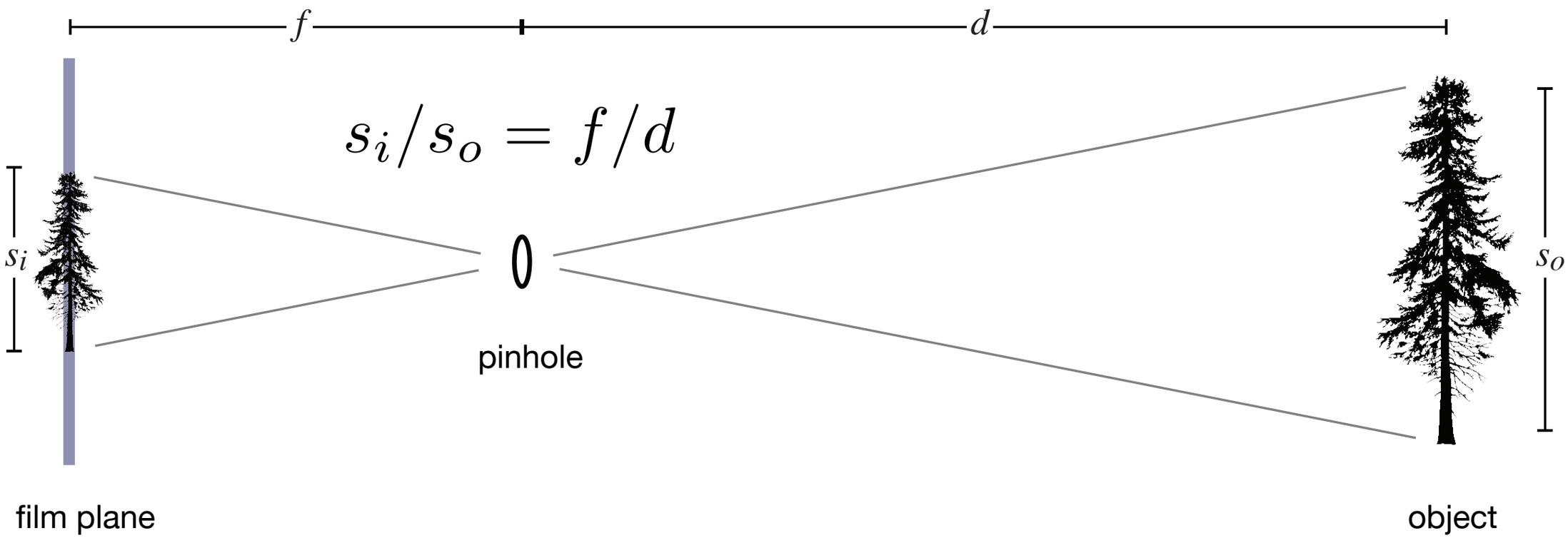


From *Photography*, London et al.

Worth a look

www.kodak.com/ek/US/en/Pinhole_Camera.htm

“Focal” length



- **Double “focal length” leads to**

  image twice as large

  one fourth as much illumination at image plane

tree image: NRC Canada

Field of view

- **Determines how much of scene is in frame**
- **Traditionally specified by focal length**

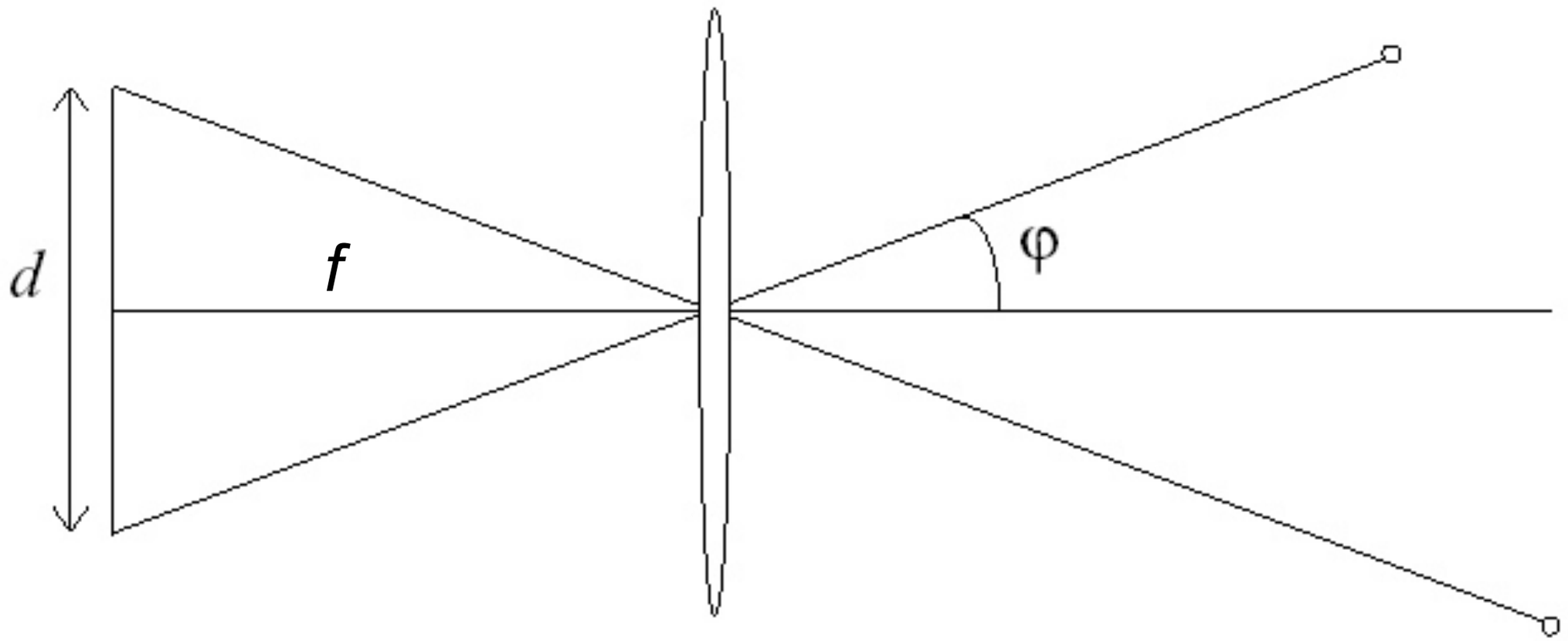
  but interpreting this number requires considering the "format," or size of the film or sensor
- **After decades of 35mm, that format is stuck in our heads**

  fields of view are usually discussed using the numbers that would be written on a lens for the 35mm format
- **Changing FOV while keeping the camera fixed**

  strictly "crops" the image: relationships between objects are fixed

  corresponds to turning the zoom control on a modern camera

FOV depends of Focal Length

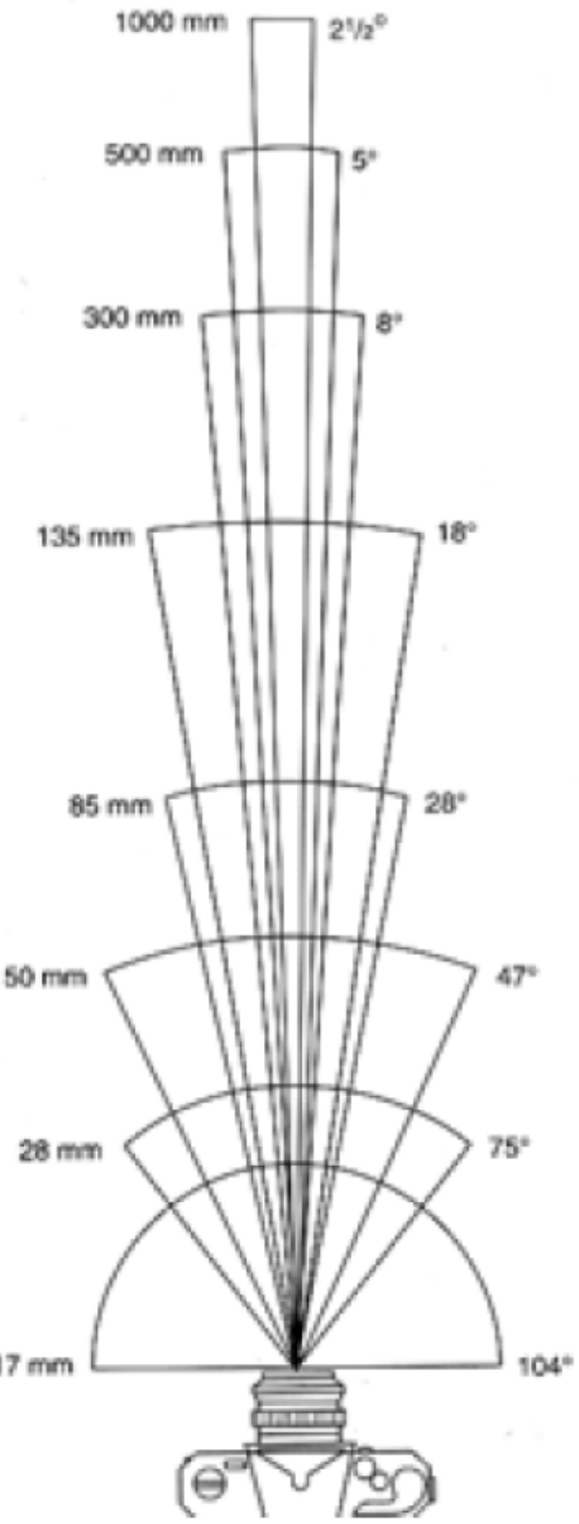


Size of field of view governed by size of the camera retina:

$$\varphi = \tan^{-1}\left(\frac{d}{2f}\right)$$

Smaller FOV = larger Focal Length

Changing FOV—viewpoint constant



17mm

28mm

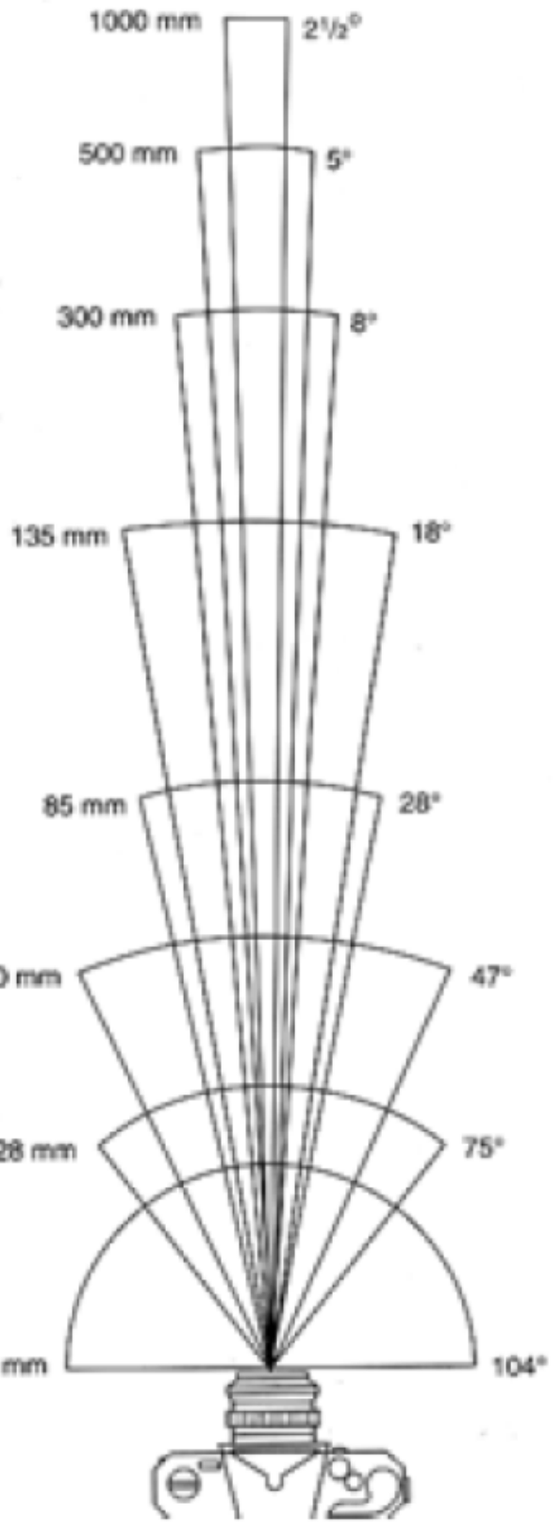
50mm

85mm

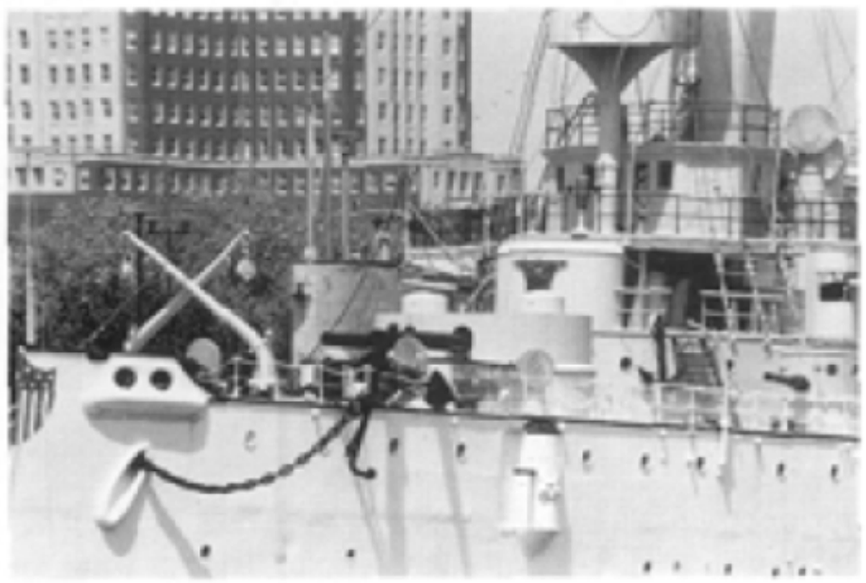
From London and Upton

slide by Alyosha Efros, CMU

Changing FOV—viewpoint constant



135mm



300mm

From London and Upton

Changing FOV—magnification constant

- **“Hitchcock zoom”**

Photos: Micaël Reynaud

see: http://www.petapixel.com/2012/05/03/trippy-example-of-hitchcock-zoom-shot-on-a-beach/

Perspective vs. viewpoint

- **Portrait: distortion with wide angle**
- **Why?**

Wide angle

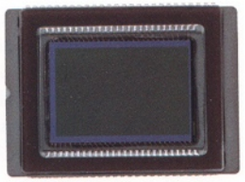
Standard

Telephoto

Focal length & sensor


EOS-1Ds : 35.8 x 23.8mm

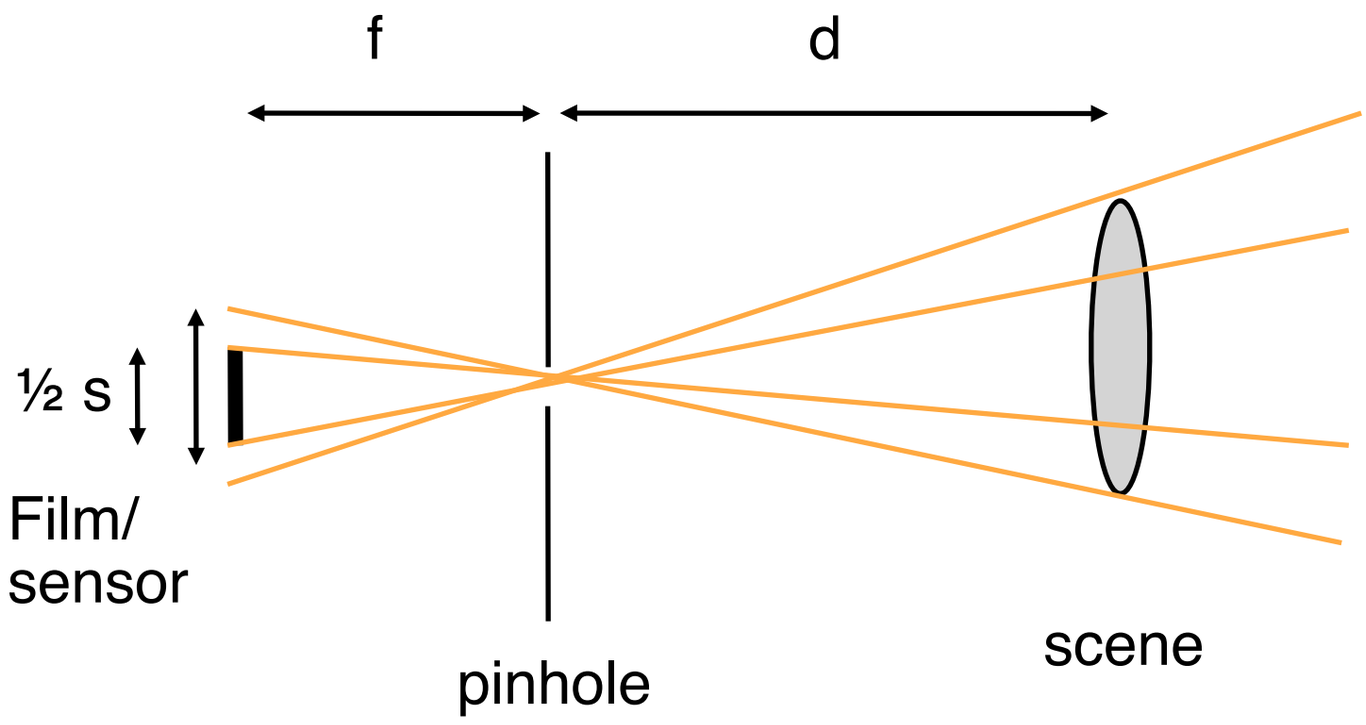

EOS-1D : 28.7 x 19.1mm

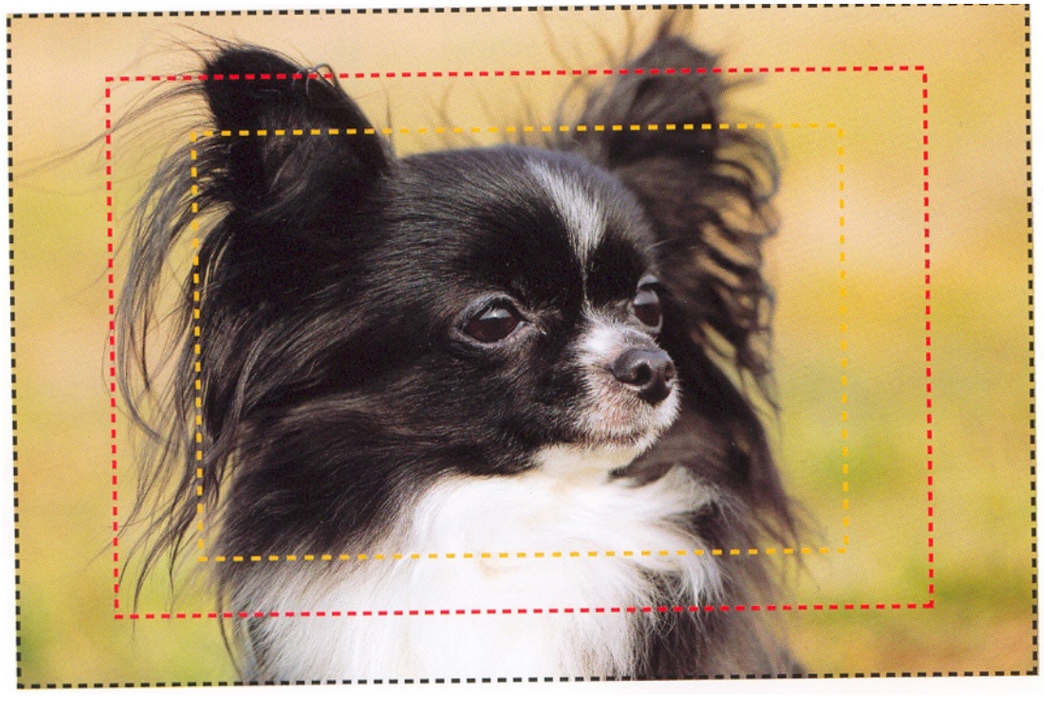

EOS 10D : 22.7 x 15.1mm

- **What happens when the film is half the size?**
- **Application:**
  - Real film is 36x24mm
  - On the 10D, the sensor is 22.5 x 15.0 mm
  - Conversion factor on the 20D?
  - On the SD500, it is 1/1.8 " (7.18 x 5.32 mm)
  - What is the 7.7-23.1mm zoom on the SD500?


EOS-1D

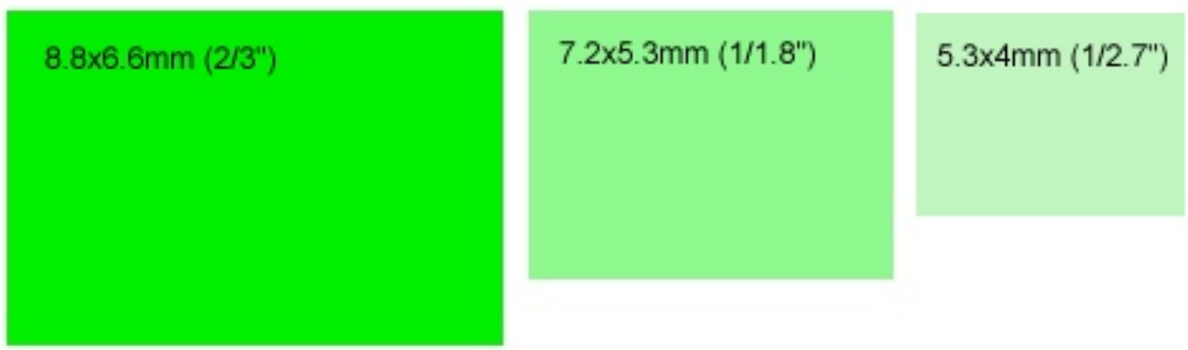
EOS 10D





slide by Frédo Durand, MIT

Dimensions of various sensors

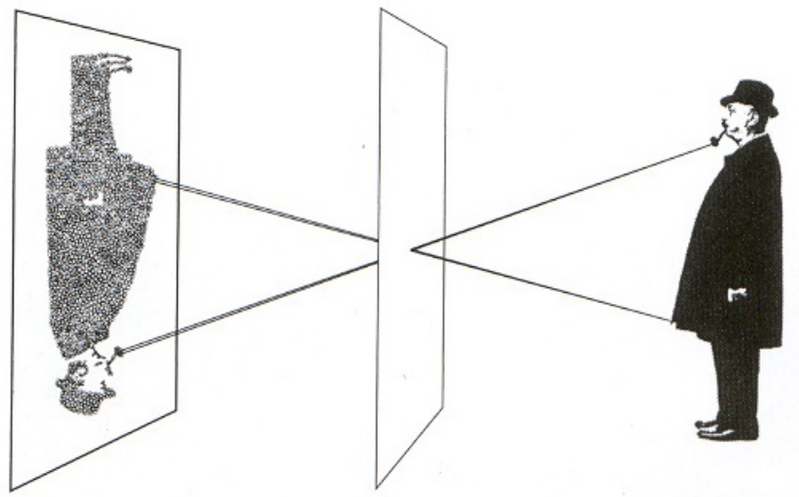


For more info
http://www.photozone.de/sensor-dimensions

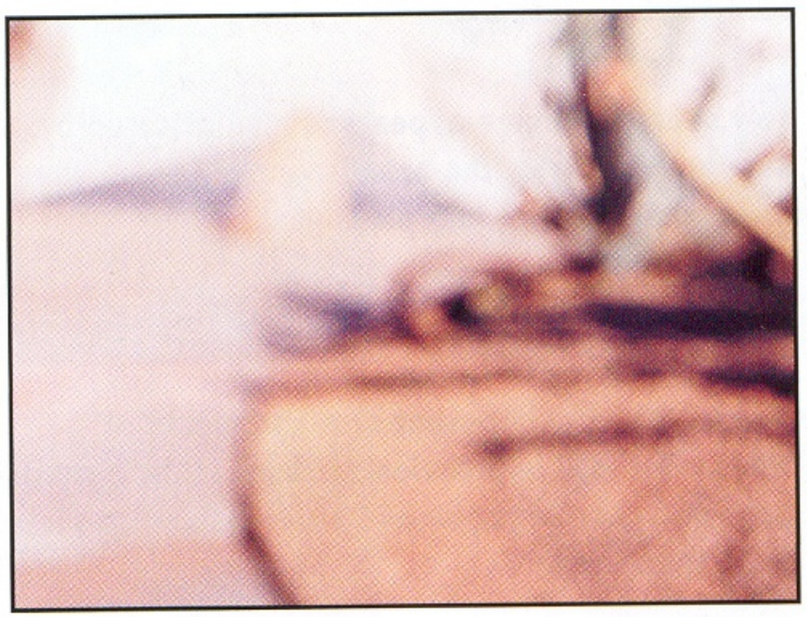
Questions?

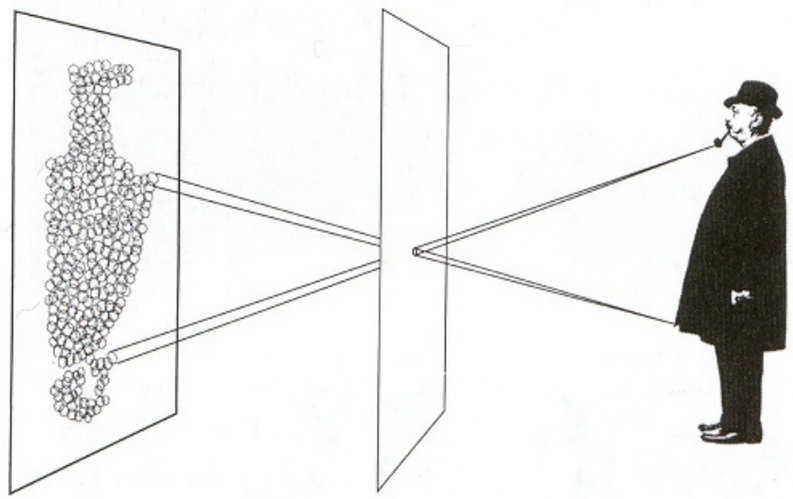
Effect of pinhole size

Photograph made with small pinhole



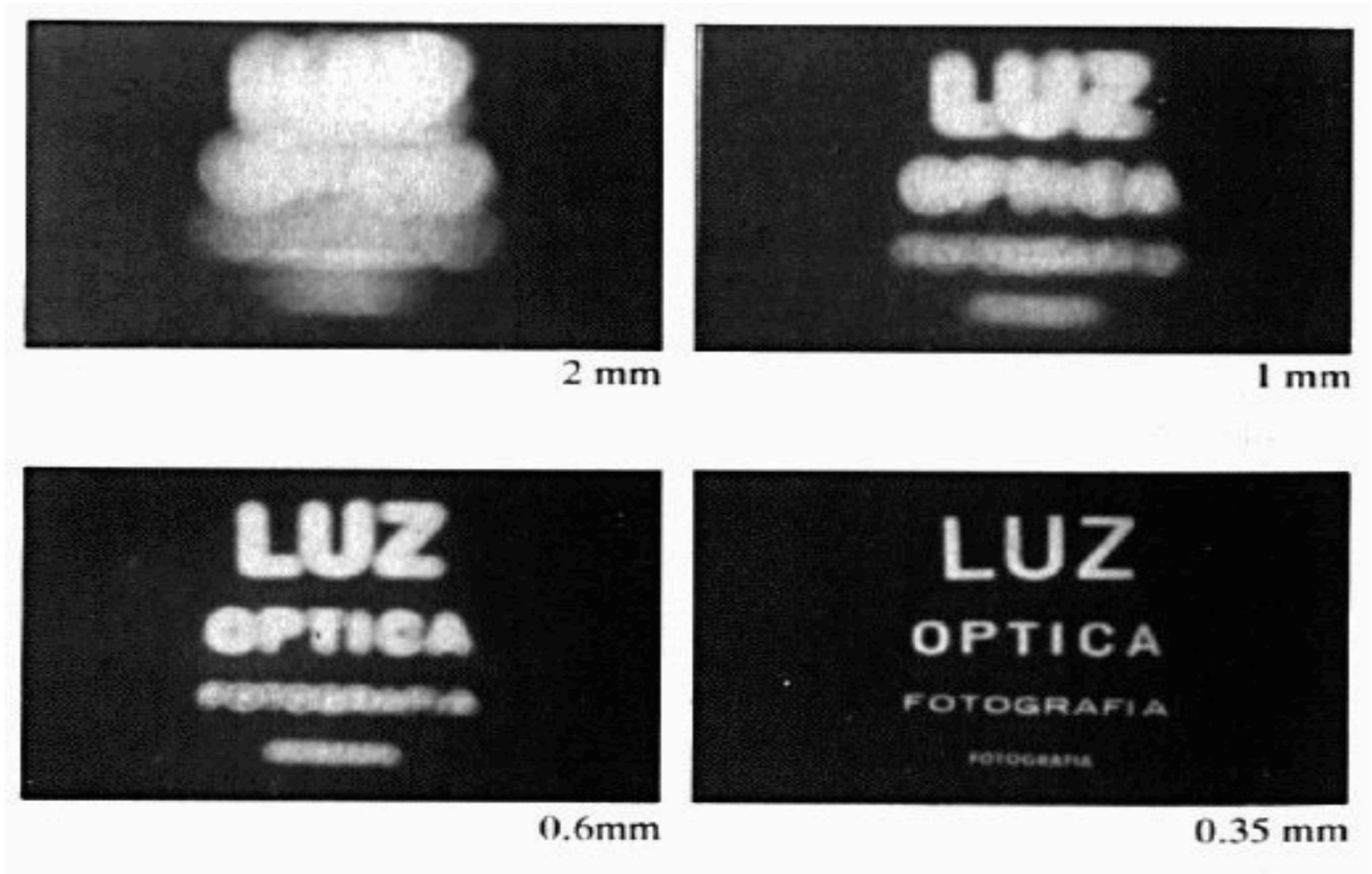
Photograph made with larger pinhole





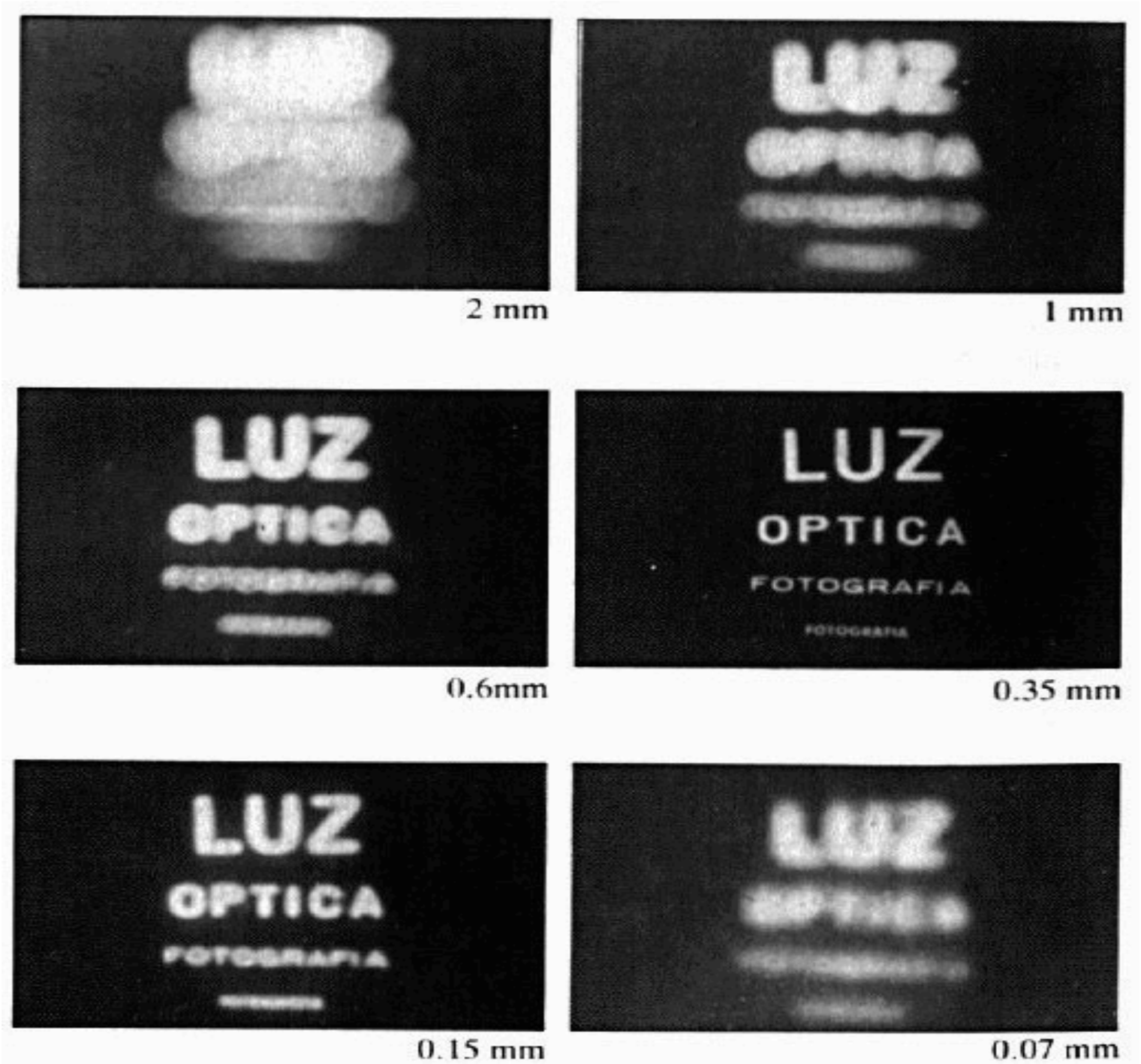
From *Photography*, London et al.

Smaller pinhole is sharper



Slide after Steve Seitz, U. Washington

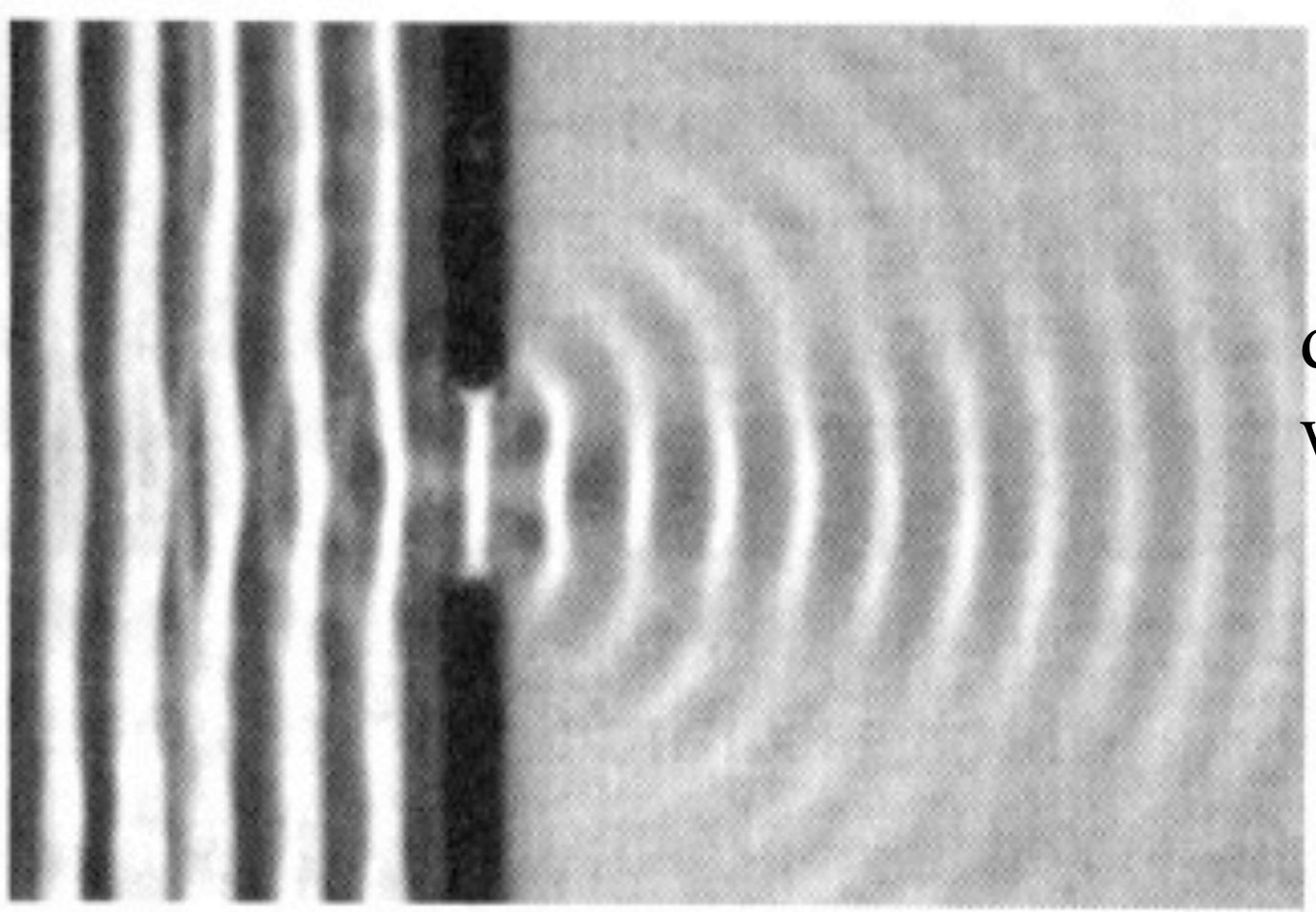
Smaller pinhole is sharper …to a point



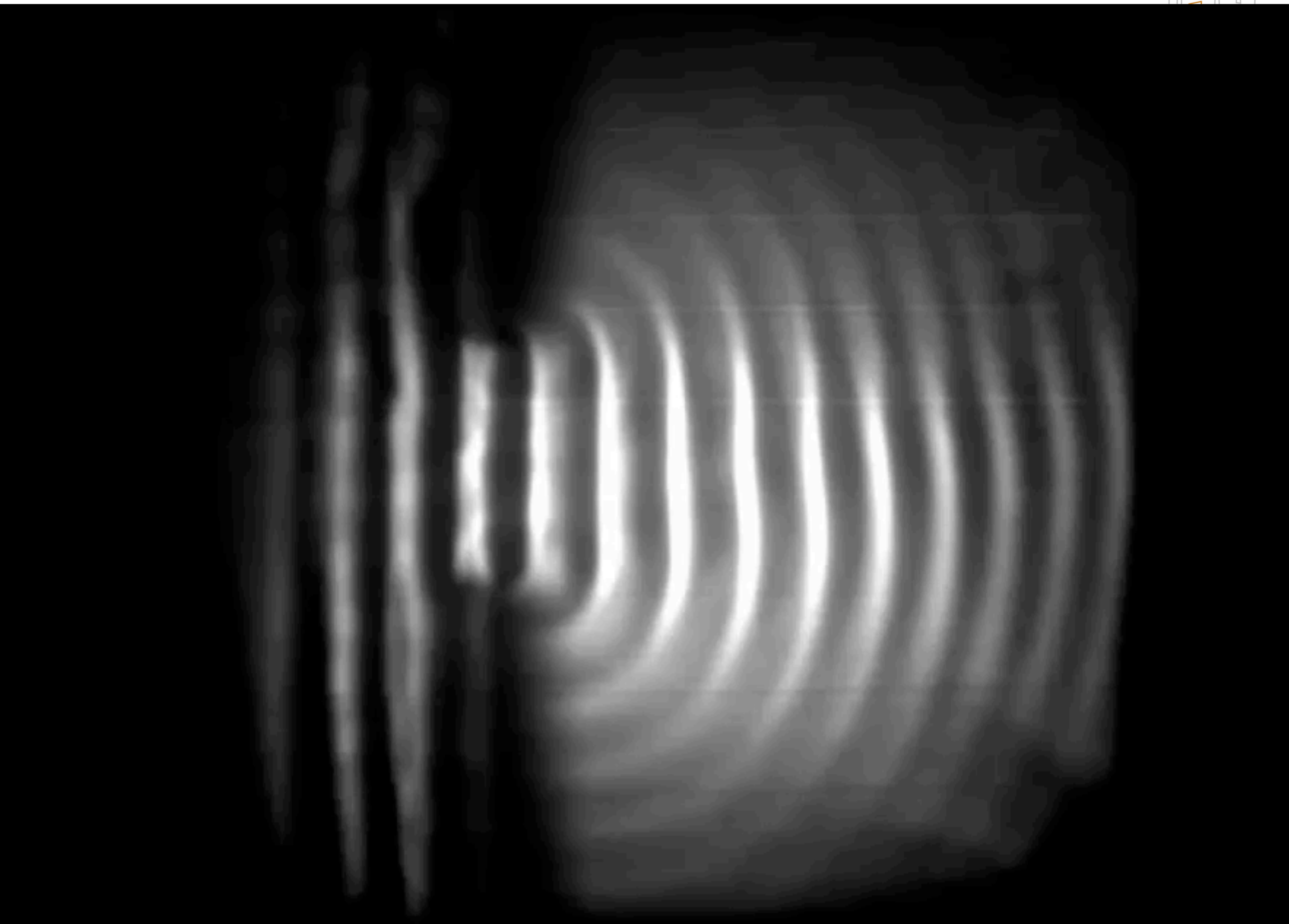
Slide after Steve Seitz, U. Washington

Diffraction

- **Wave nature of light**
- **Smaller aperture means more diffraction**
- **For Fourier fans:**
  - diffraction pattern = Fourier transform of the aperture. Smaller aperture means bigger Fourier spectrum.



diffraction of water waves



Youtube demos

- http://www.youtube.com/watch?v=kH57Di7Sj0c
- http://www.youtube.com/watch?v=lIn-BLJNXpY
- http://www.brightstorm.com/science/physics/vibration-and-waves/diffraction/
- http://www.youtube.com/watch?v=KSIg_EaIFrw
- http://www.youtube.com/watch?v=sjmBcm84iA4

Camera, version 0: box with hole

- **Simple, distortion-free, charmingly analog, but:**

  Large pinholes produce blurry images

  Small pinholes produce dim images

  Diffraction limits sharpness for very small pinholes

Francesco Capponi
Blown egg transformed into a wide-angle pinhole camera

http://www.petapixel.com/2011/04/25/eggs-transformed-into-pinhole-cameras/

Questions?

Replacing pinholes with lenses

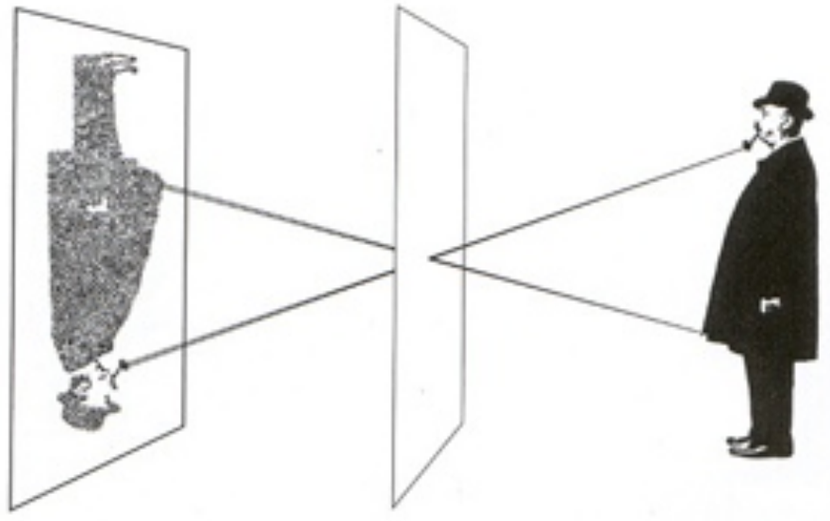
From *Photography*, London et al.

Lenses

- **Gather more light!**
- **But need to be focused**

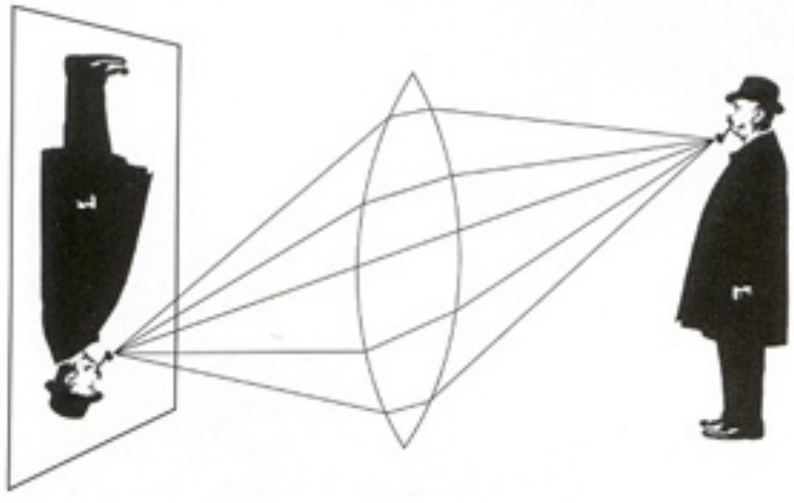
Photograph made with small pinhole

To make this picture, the lens of a camera was replaced with a thin metal disk pierced by a tiny pinhole, *equivalent in size to an aperture of f/182. Only a few rays of light from each point on the subject got through the tiny opening, producing a soft but acceptably clear photograph. Because of the small size of the pinhole, the exposure had to be 6 sec long.*



Photograph made with lens

This time, using a simple convex lens with an f/16 aperture, *the scene appeared sharper than the one taken with the smaller pinhole, and the exposure time was much shorter, only 1/100 sec.*



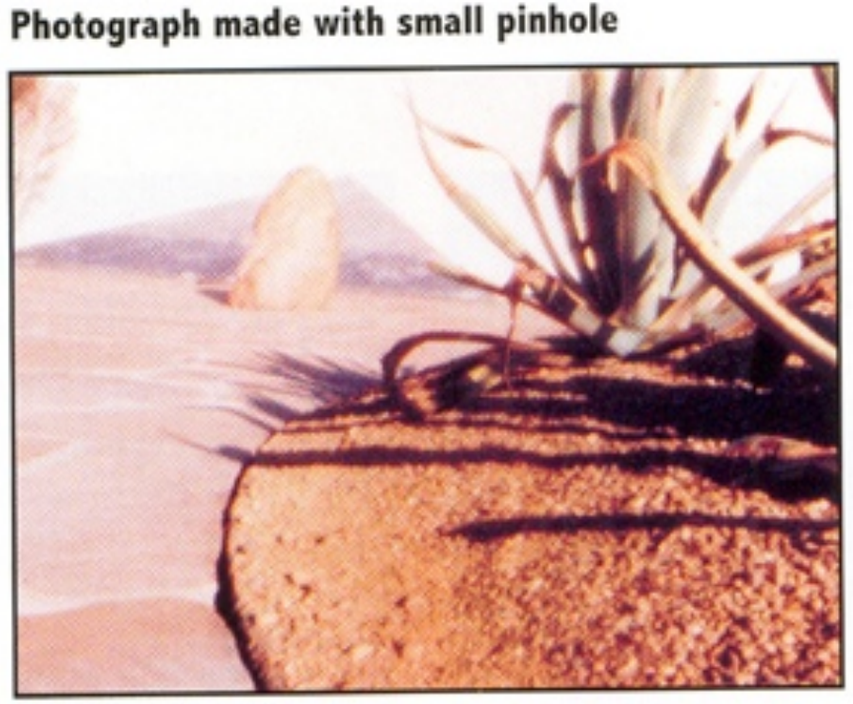
The lens opening was much bigger than the pinhole, letting in far more light, but it focused the rays from each point on the subject precisely so that they were sharp on the film.

From Photography, London et al.

slide by Frédo Durand, MIT

Lenses

- **Essentially add multiple pinhole images**
- **~ shift them to align (refraction)**
- **Alignment works only for one distance**



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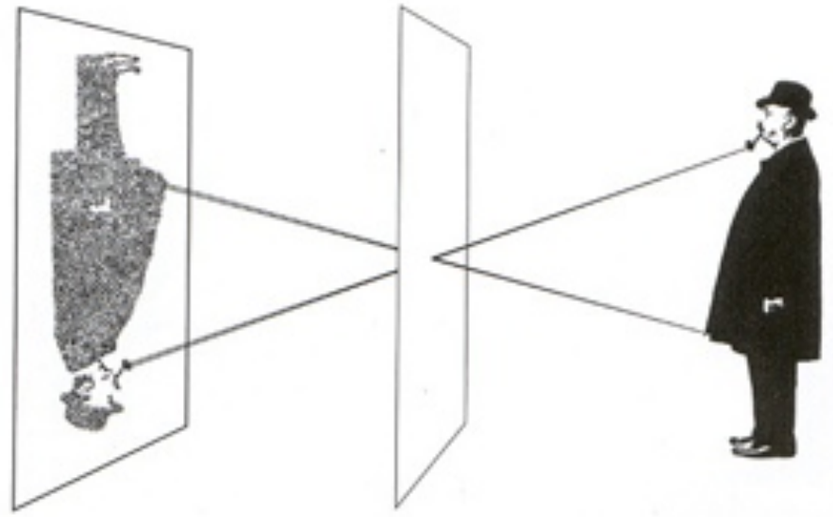

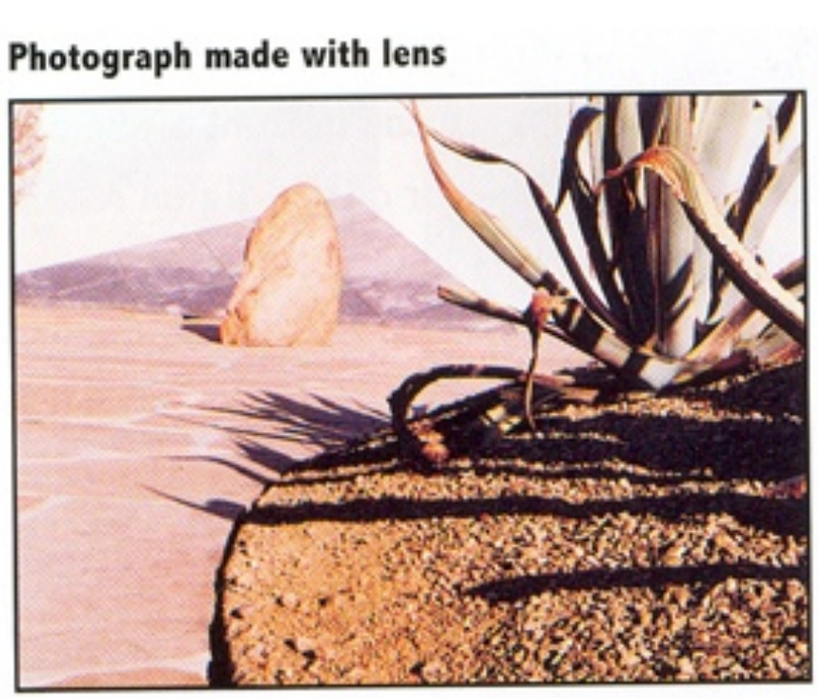

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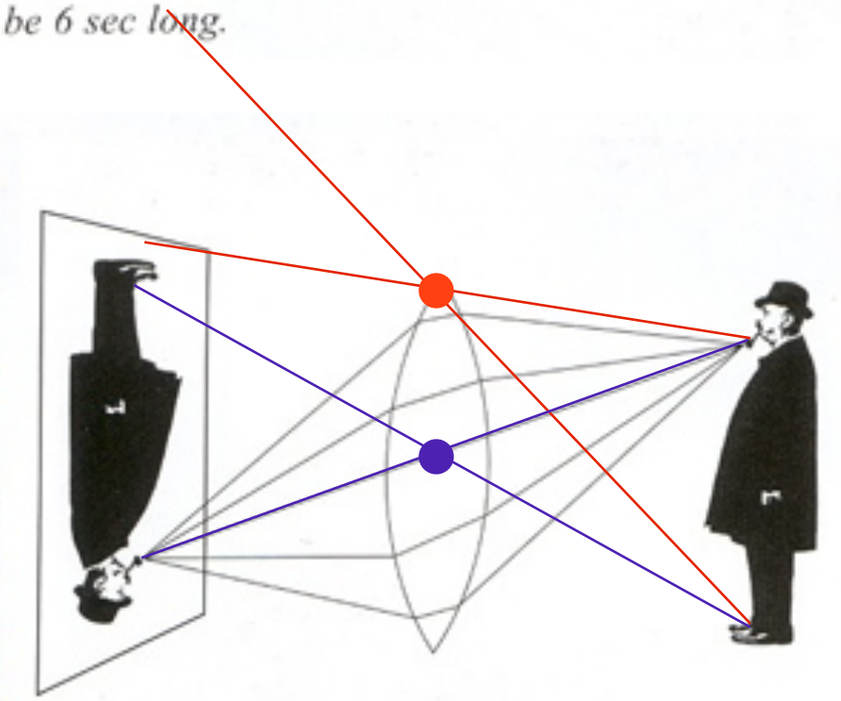

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From Photography, London et al.

slide by Frédo Durand, MIT

Camera, v. 1: Box with lens & shutter

- **First practical cameras had**

  film (roll film or glass plate)

  lens (small aperture)

  mechanism for winding film

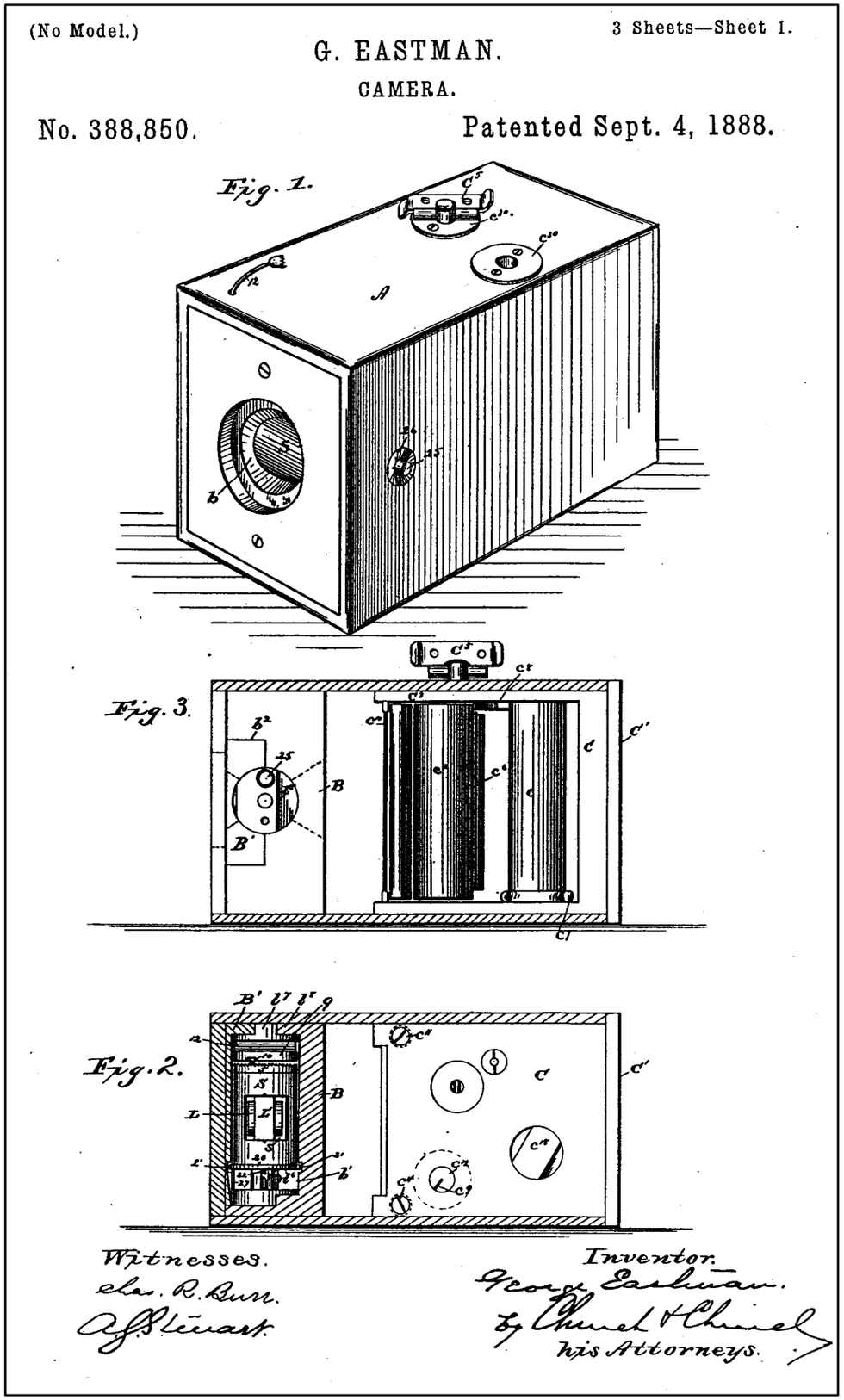
  mechanism for triggering shutter

- **Limitations**

  cannot control exposure

  focus is fixed (like an inexpensive cell phone camera today)

  want to be outdoors in strong light



George Eastman
Kodak Camera
1888

More ingredients

- **Timed shutter**

  with a UI for setting the duration of the exposure (“**exposure time**”)

- **Variable aperture**

  effective size of the hole through which light enters can be changed
  with a UI for setting the size (“**aperture**”)

- **Viewfinder**

some way better than guessing
to tell what you are photographing

photo: Ken Rockwell

Camera, v. 2: 3 variables, 5 controls

photo: Ken Rockwell

Basic camera controls

- **Adjustments that must be set for each image**

  by you or by the camera's software

  modern cameras for consumers hide these but they are still there

- **Shutter speed**

  interacts with aperture to determine expsoure

  interacts with subject/camera motion to affect sharpness

- **Aperture size**

  interacts with shutter speed to determine exposure

  interacts with focus and diffraction to affect sharpness

- **Focus**

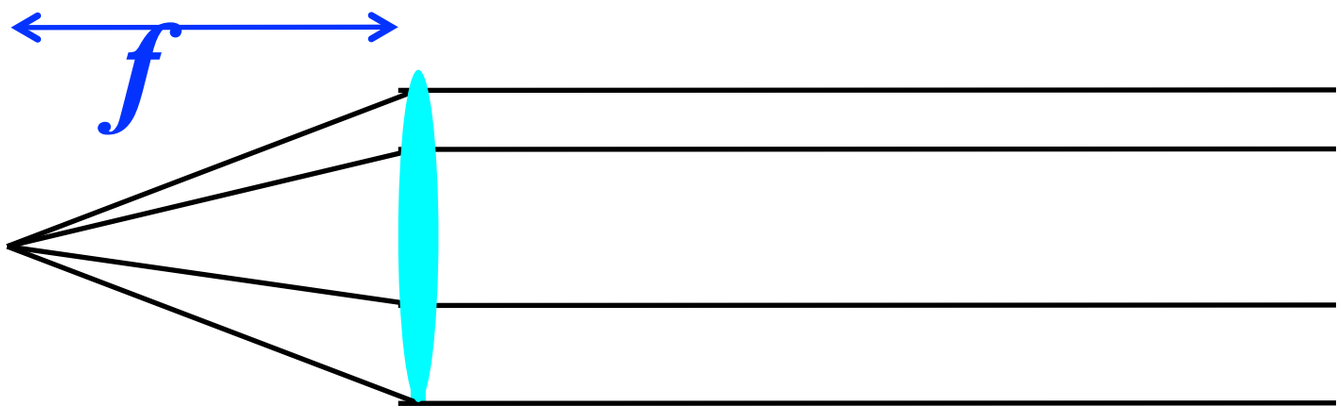
  determines what is sharp and what is not

  depth of focus related to aperture size and subject distance

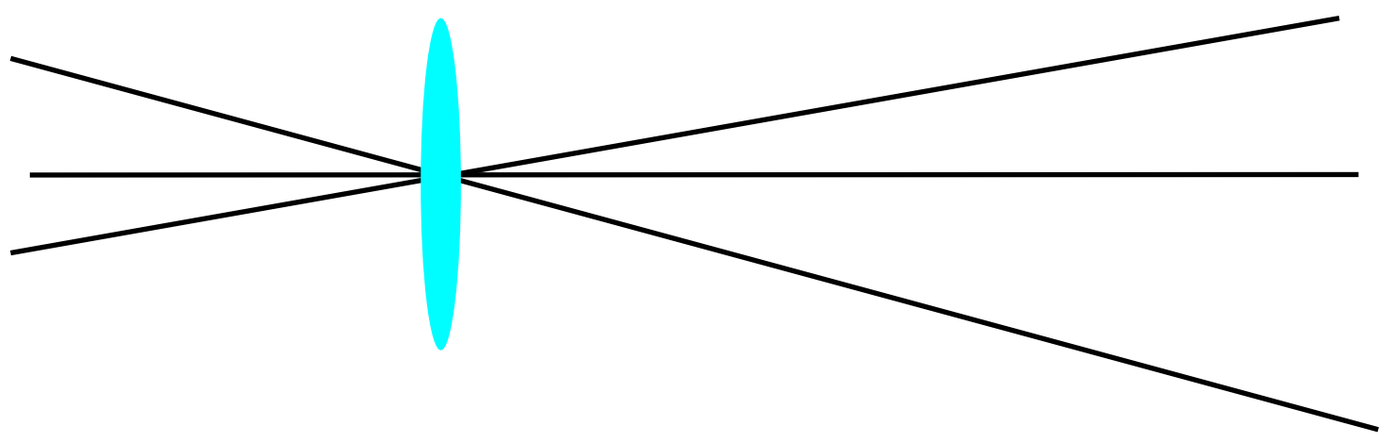
Questions?

Thin lens optics

- **Simplification of geometrical optics for well-behaved lenses**
- **All parallel rays converge to one point on a plane located at the focal length *f***

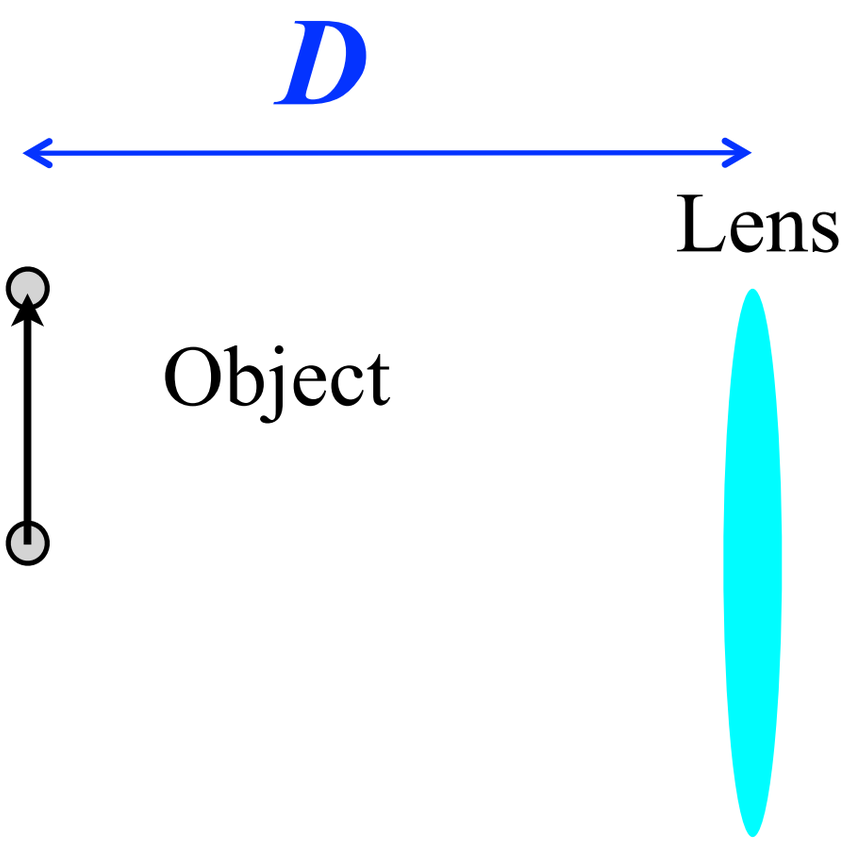


- **All rays going through the center are not deviated**
  - Hence same perspective as pinhole



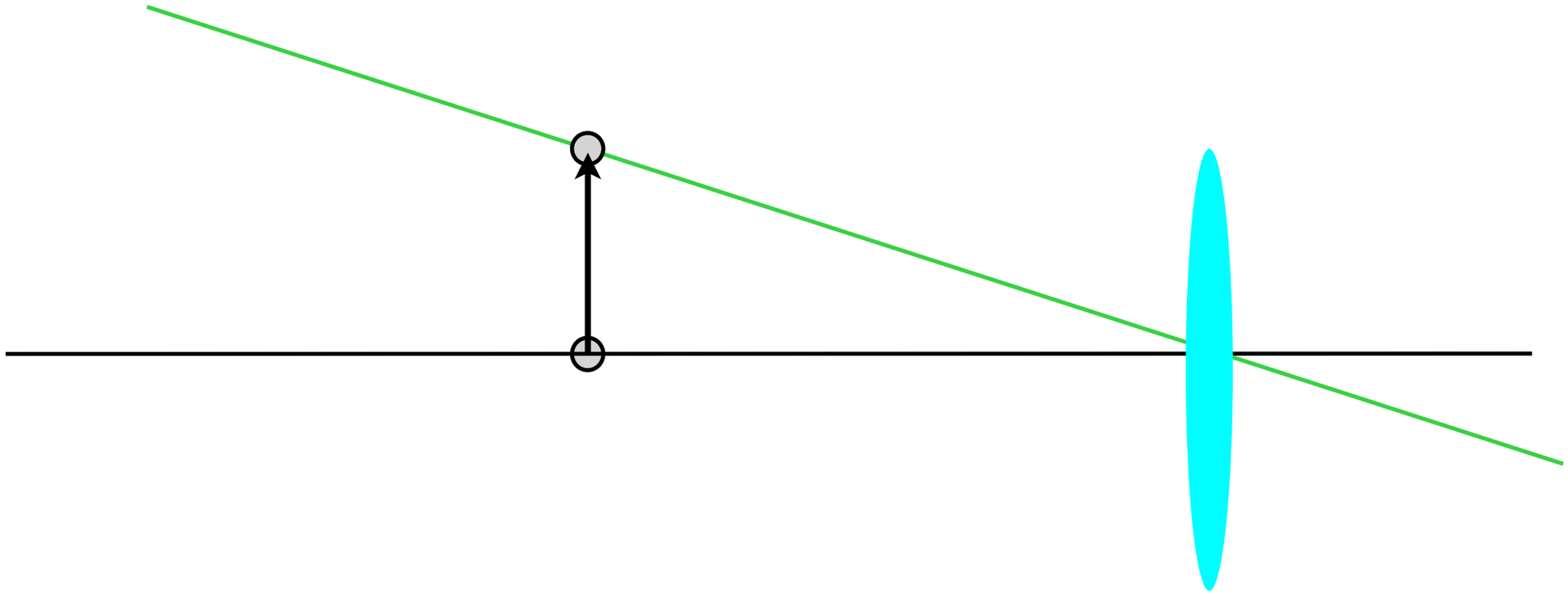
How lenses focus

- **Let's look at an object at distance D**



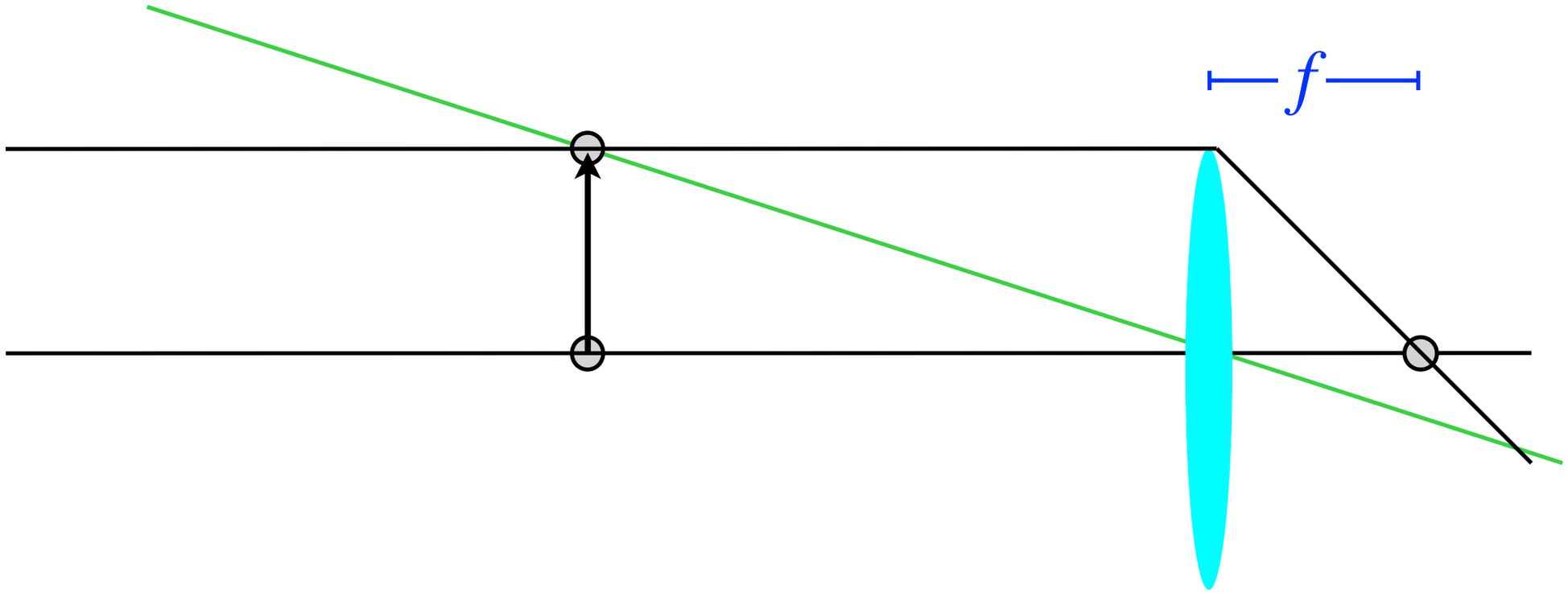
How to trace rays

- **Start by rays through the center**



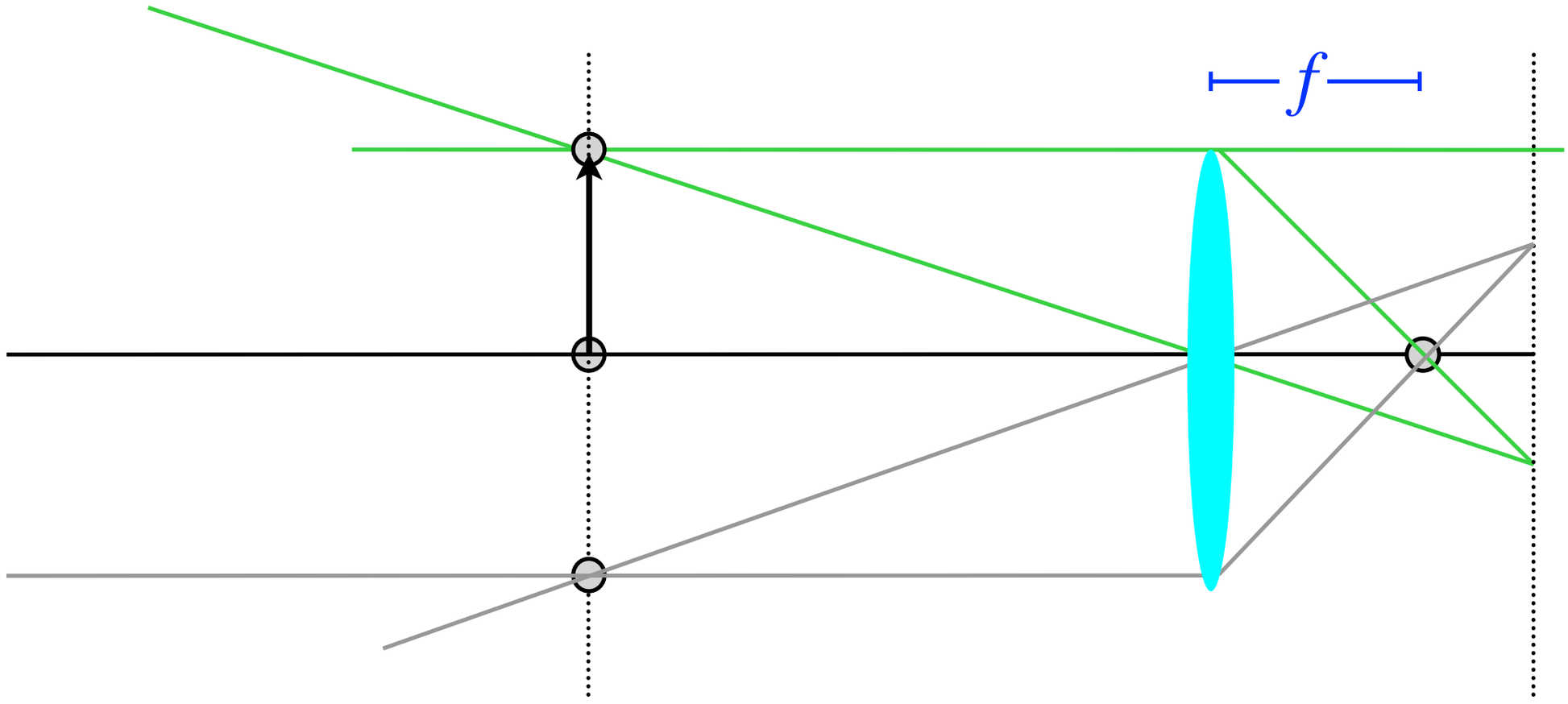
How to trace rays

- **Start by rays through the center**
- **Choose focal length, trace parallels**



How to trace rays

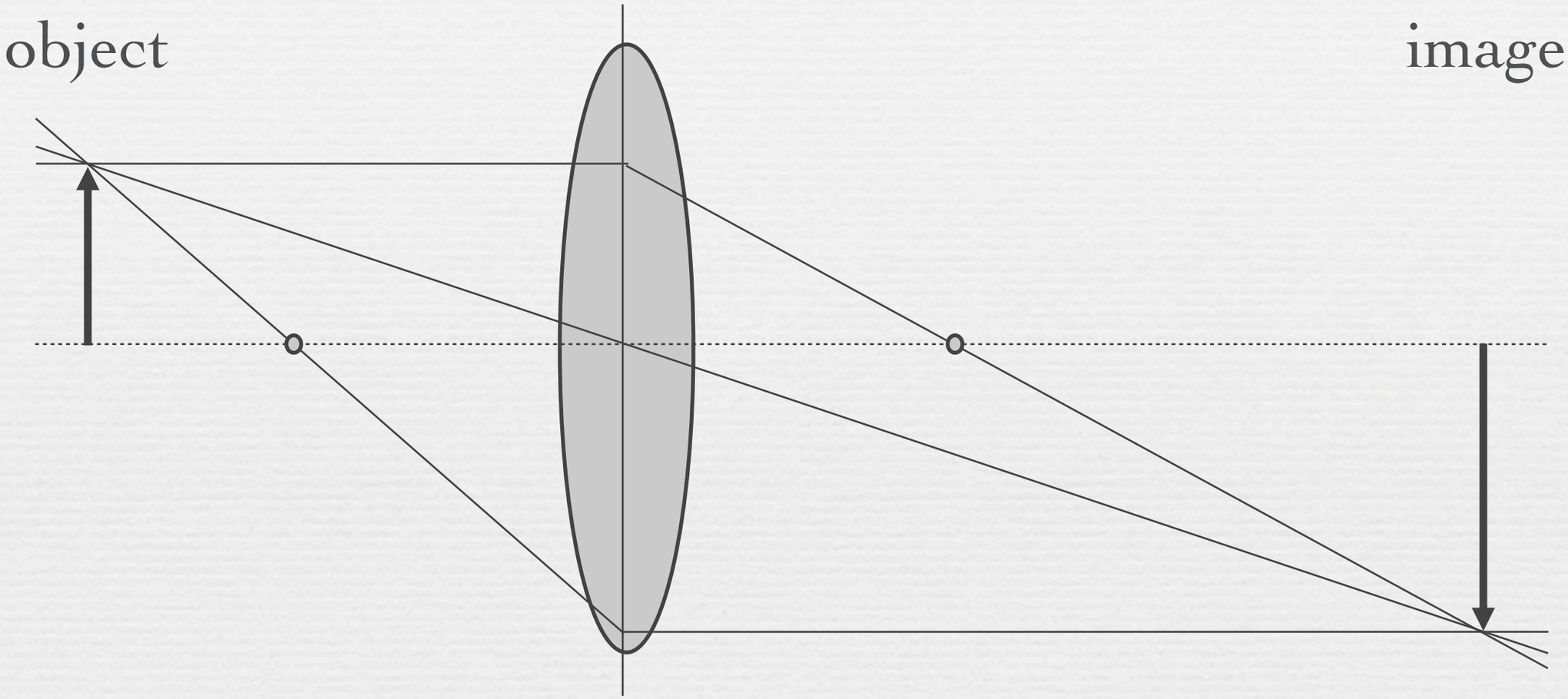
- **Start by rays through the center**
- **Choose focal length, trace parallels**
- **You get the focus plane for a given scene plane**
  - All rays coming from points on a plane parallel to the lens are focused on another plane parallel to the lens



Demo!

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

From Gauss's ray construction to the Gaussian lens formula



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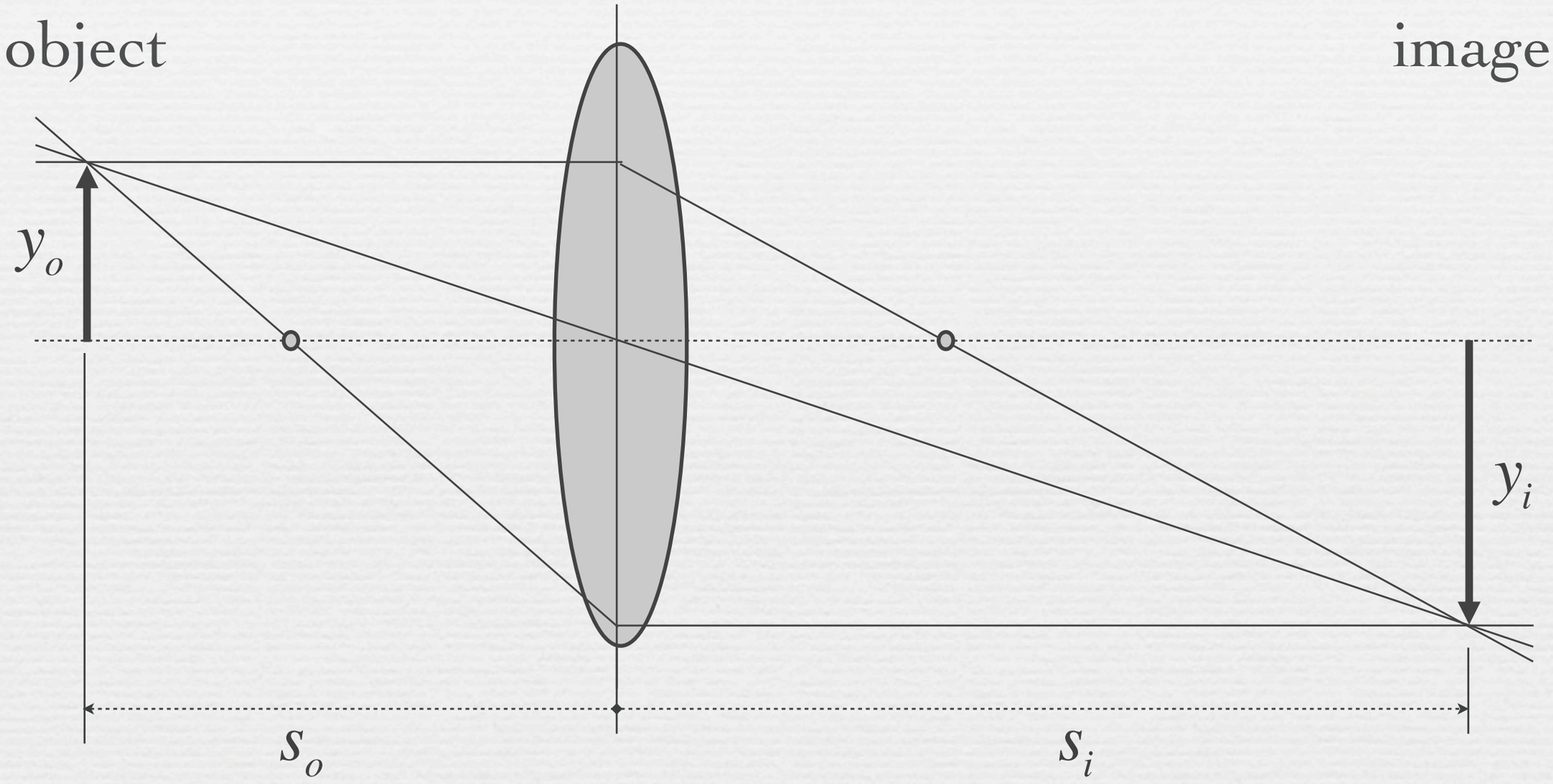
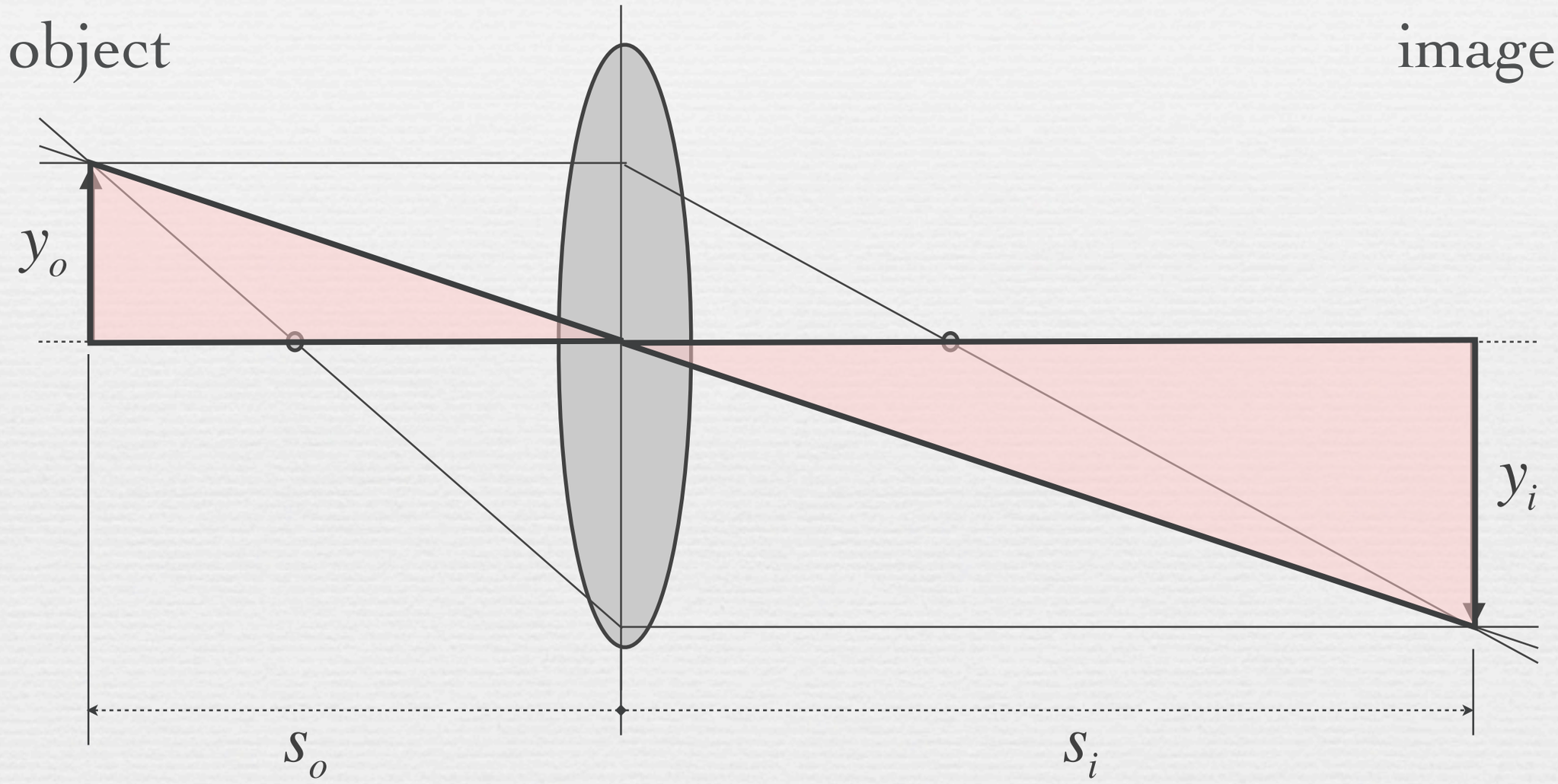


- positive s_i is rightward, positive s_o is leftward
- positive y is upward

From Gauss's ray construction to the Gaussian lens formula



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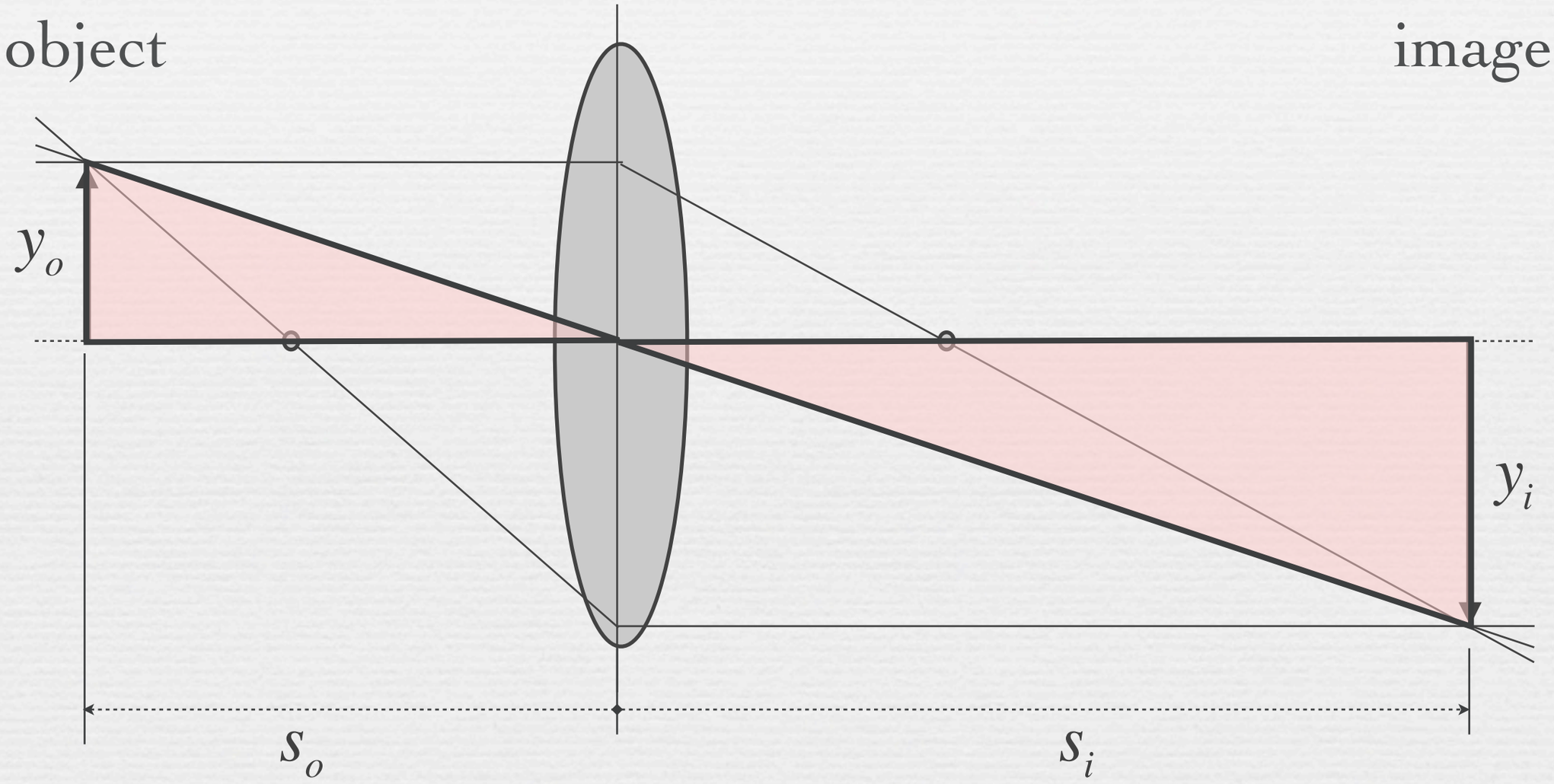
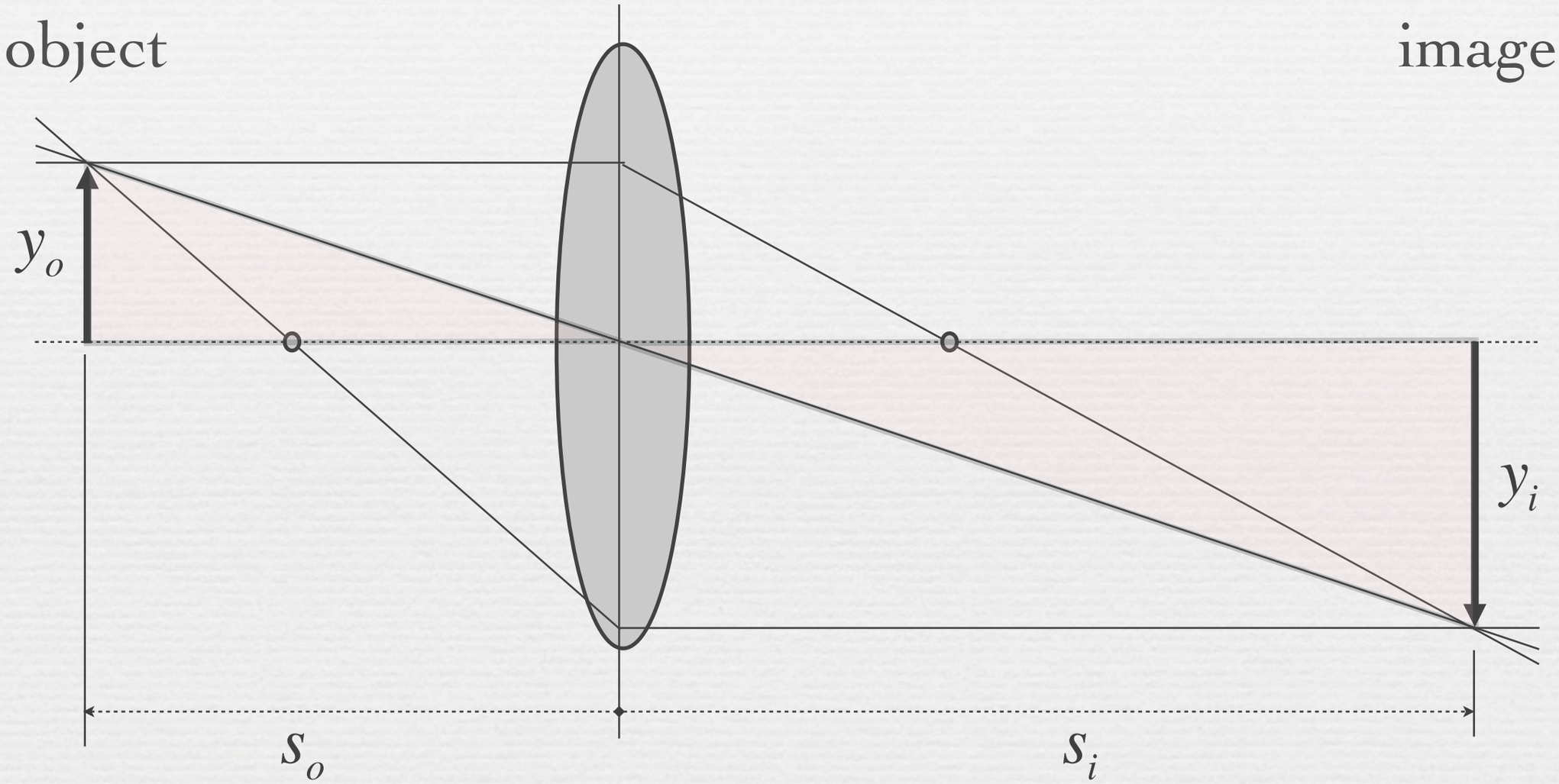


$$\frac{|y_i|}{y_o} = \frac{s_i}{s_o}$$

slide by Marc Levoy, Stanford

From Gauss's ray construction to the Gaussian lens formula



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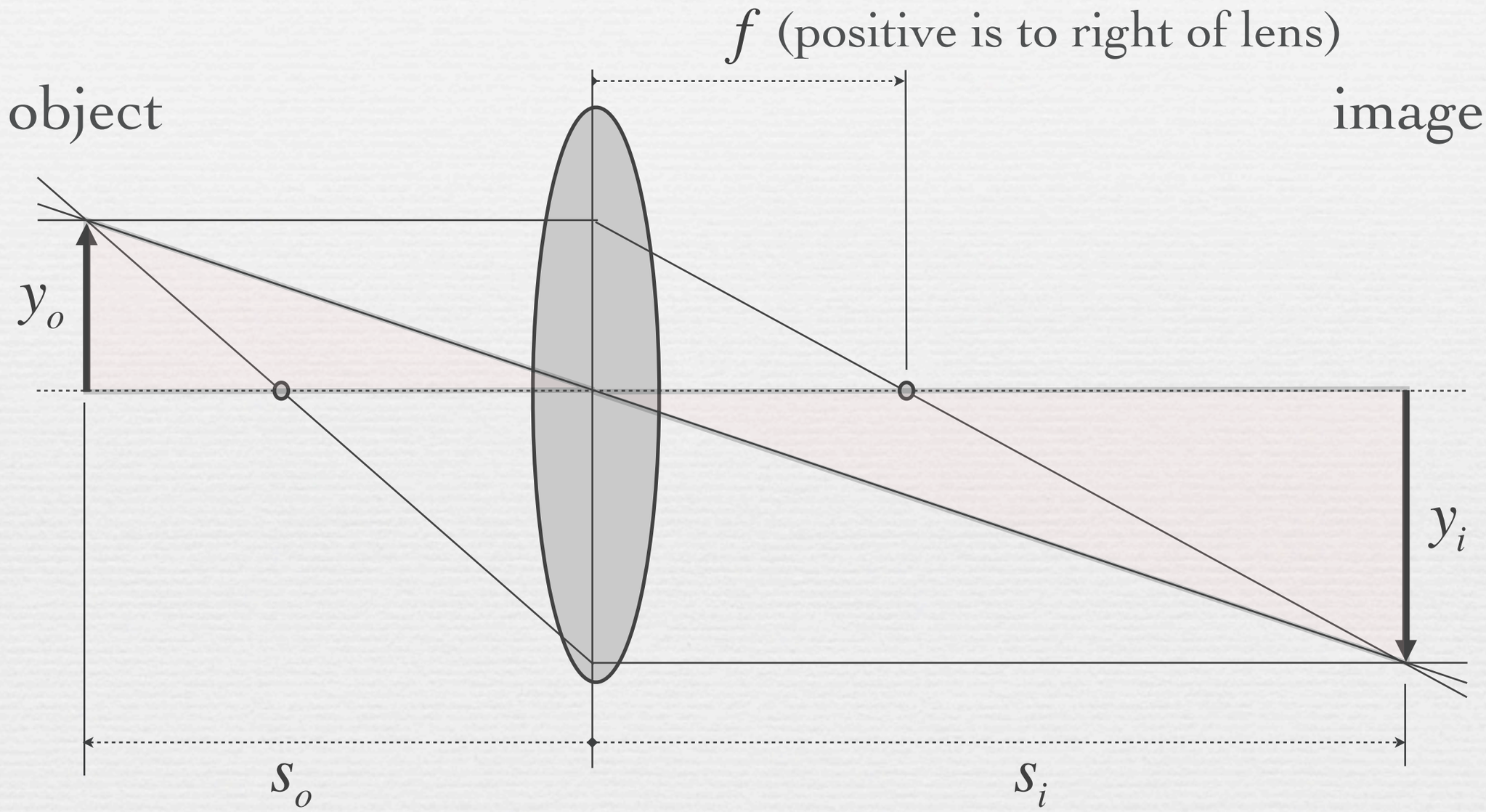

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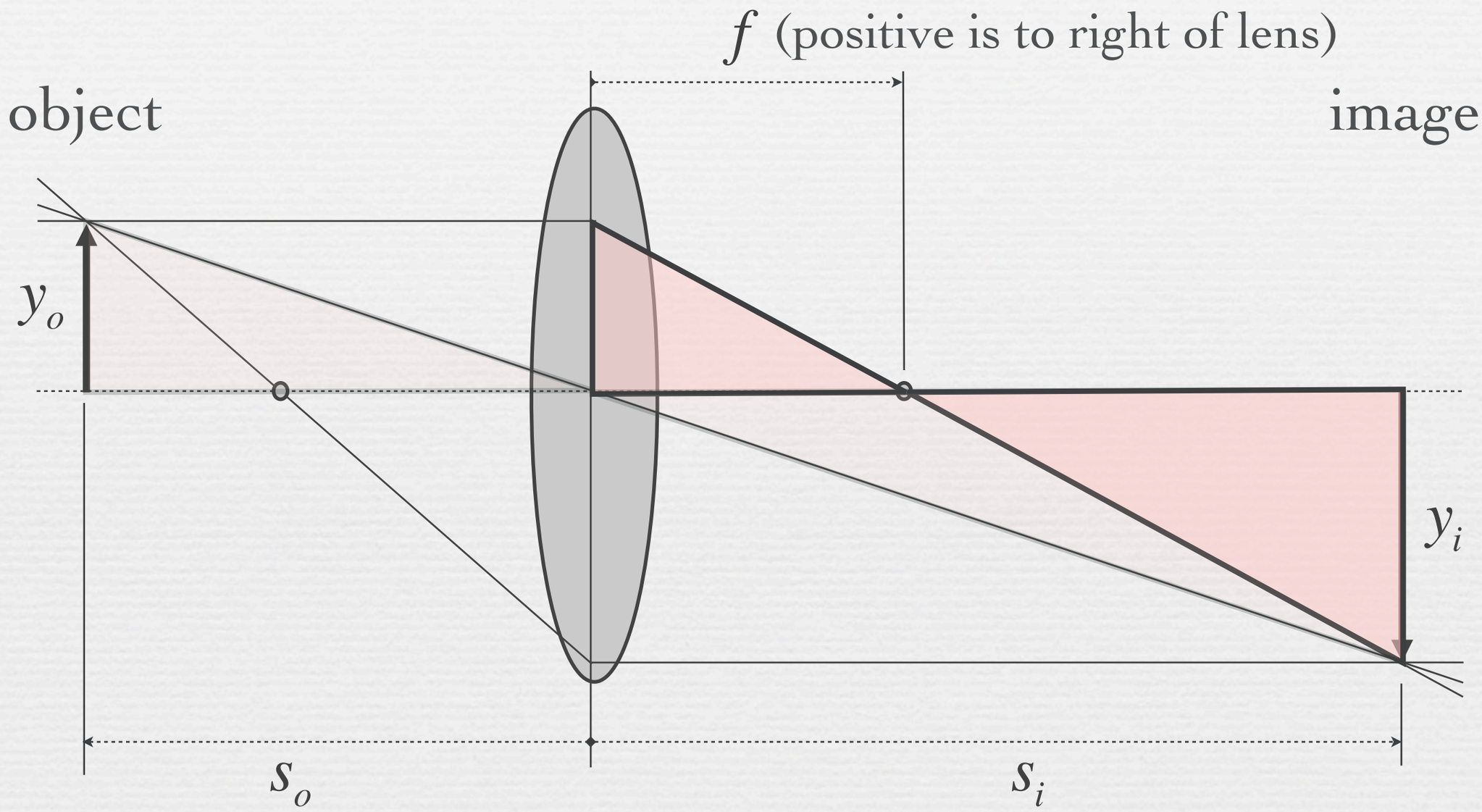

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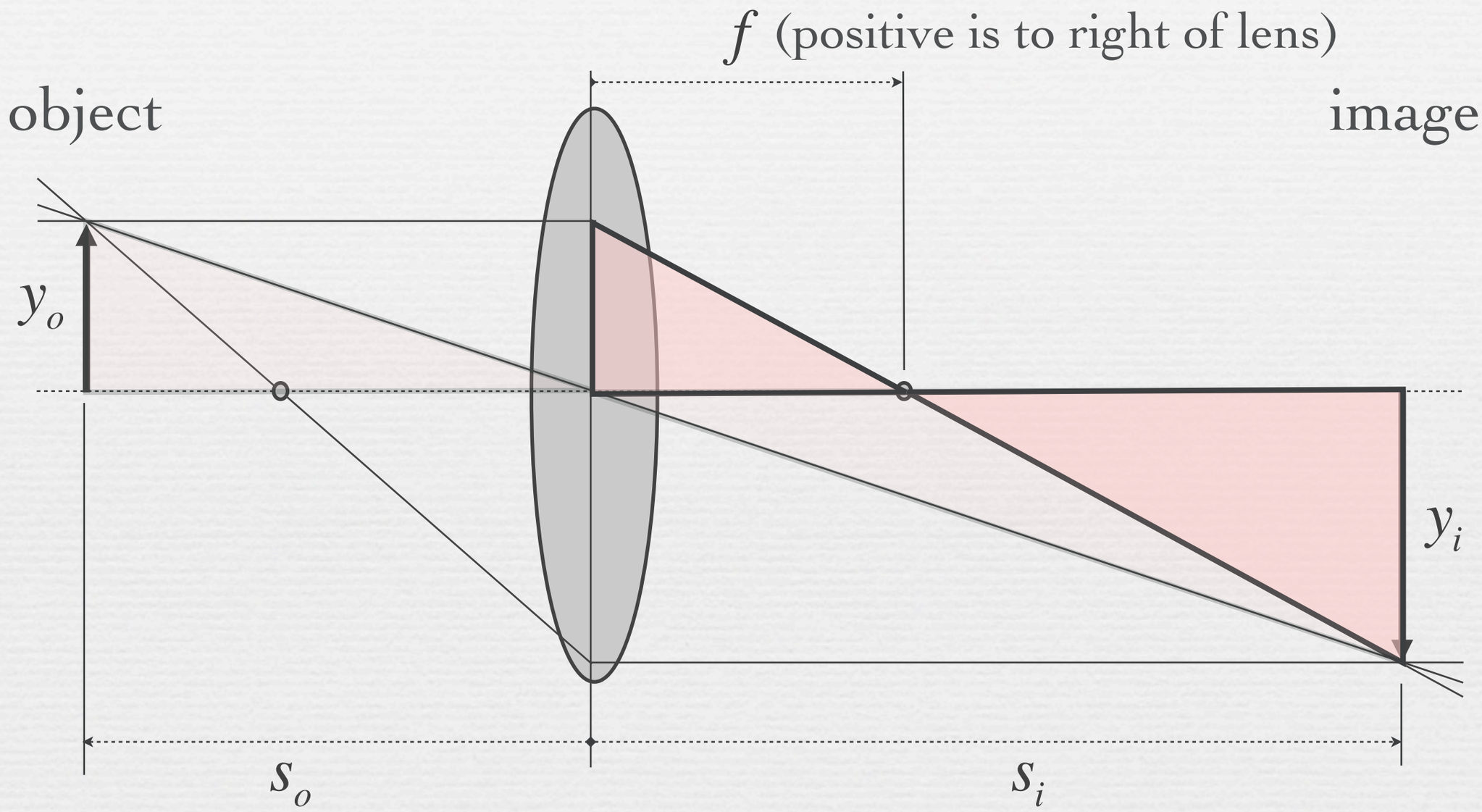
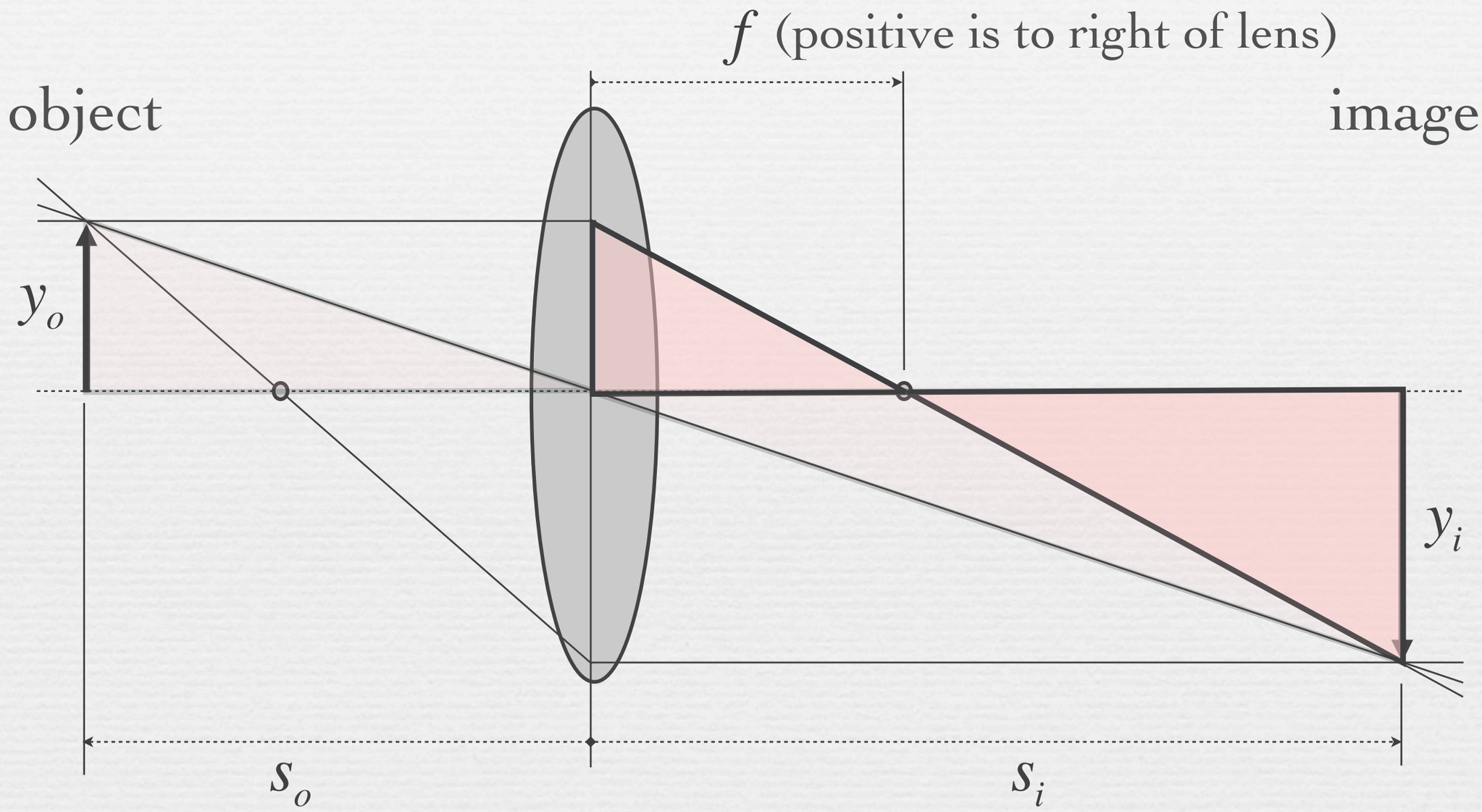


$$\frac{|y_i|}{y_o} = \frac{s_i}{s_o} \quad \text{and} \quad \frac{|y_i|}{y_o} = \frac{s_i - f}{f}$$

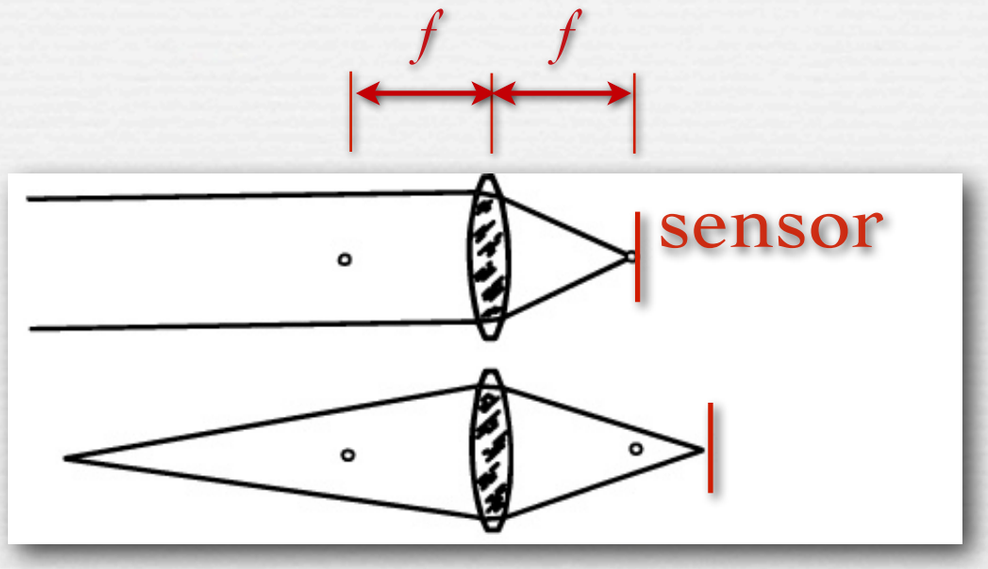
From Gauss's ray construction to the Gaussian lens formula



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

slide by Marc Levoy, Stanford

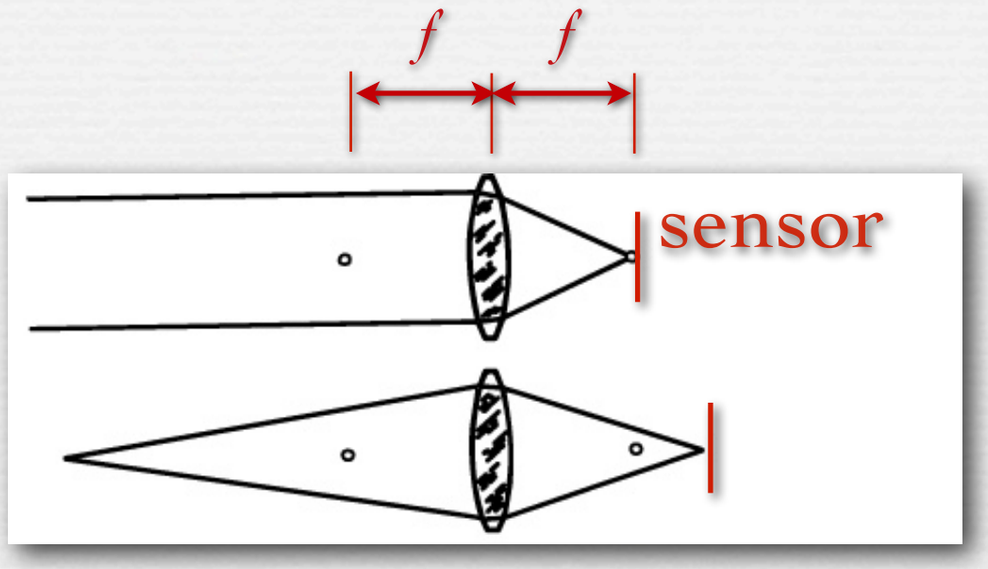
Changing the focus distance



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

Changing the focus distance

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



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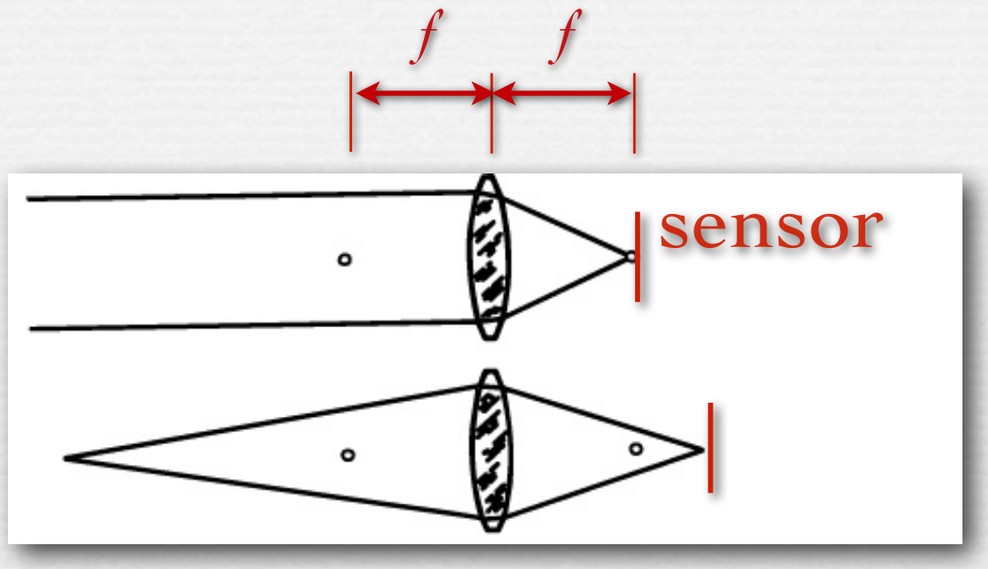
Changing the focus distance

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



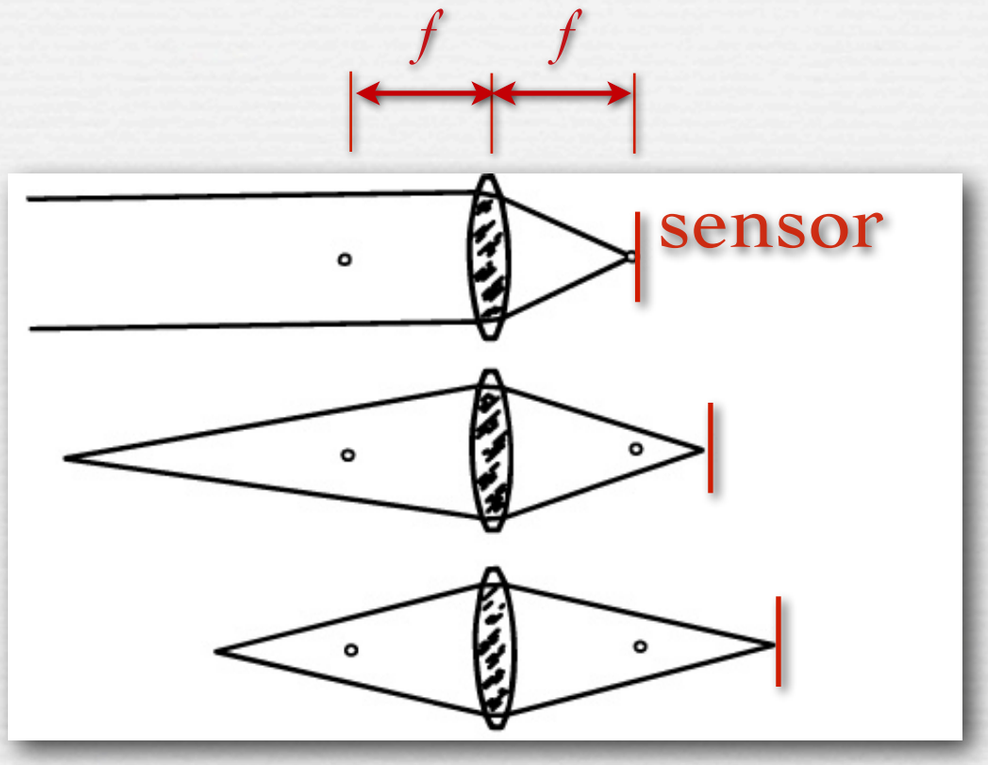
(FLASH DEMO)

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



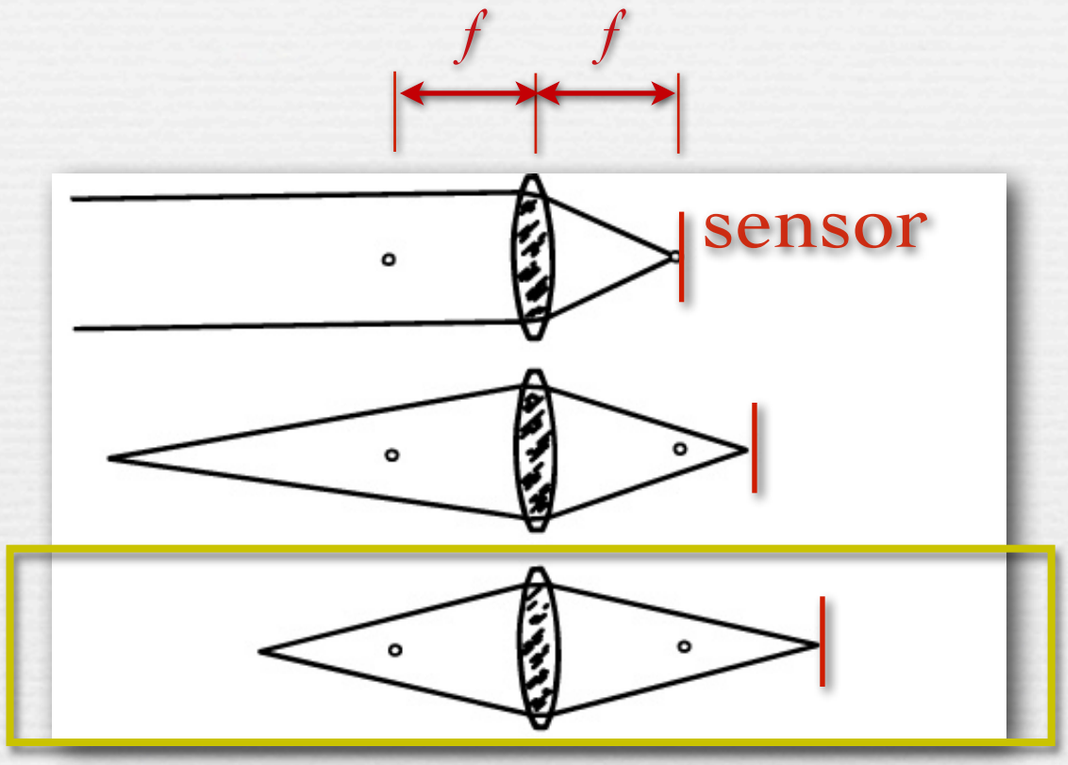
- at $s_o = s_i = 2f$ we have 1:1 imaging, because

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

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

Changing the focus distance

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



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

Changing the focus distance

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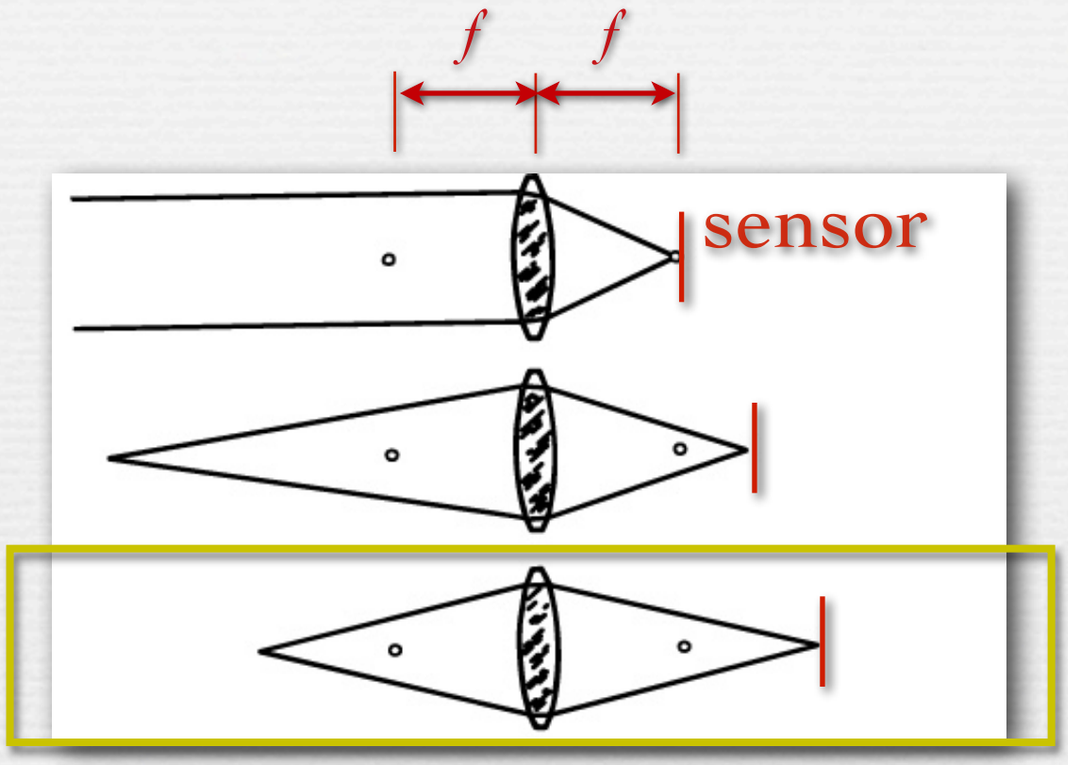


- at $s_o = s_i = 2f$ we have 1:1 imaging, because

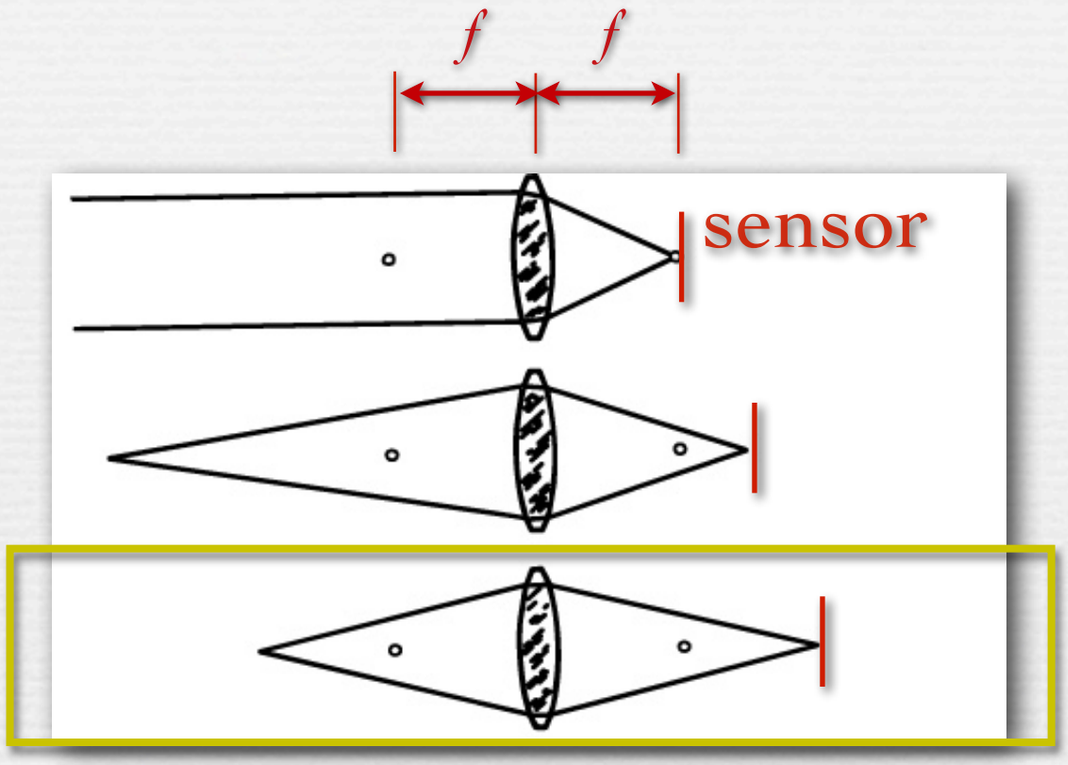
$$\frac{1}{2f} + \frac{1}{2f} = \frac{1}{f}$$

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



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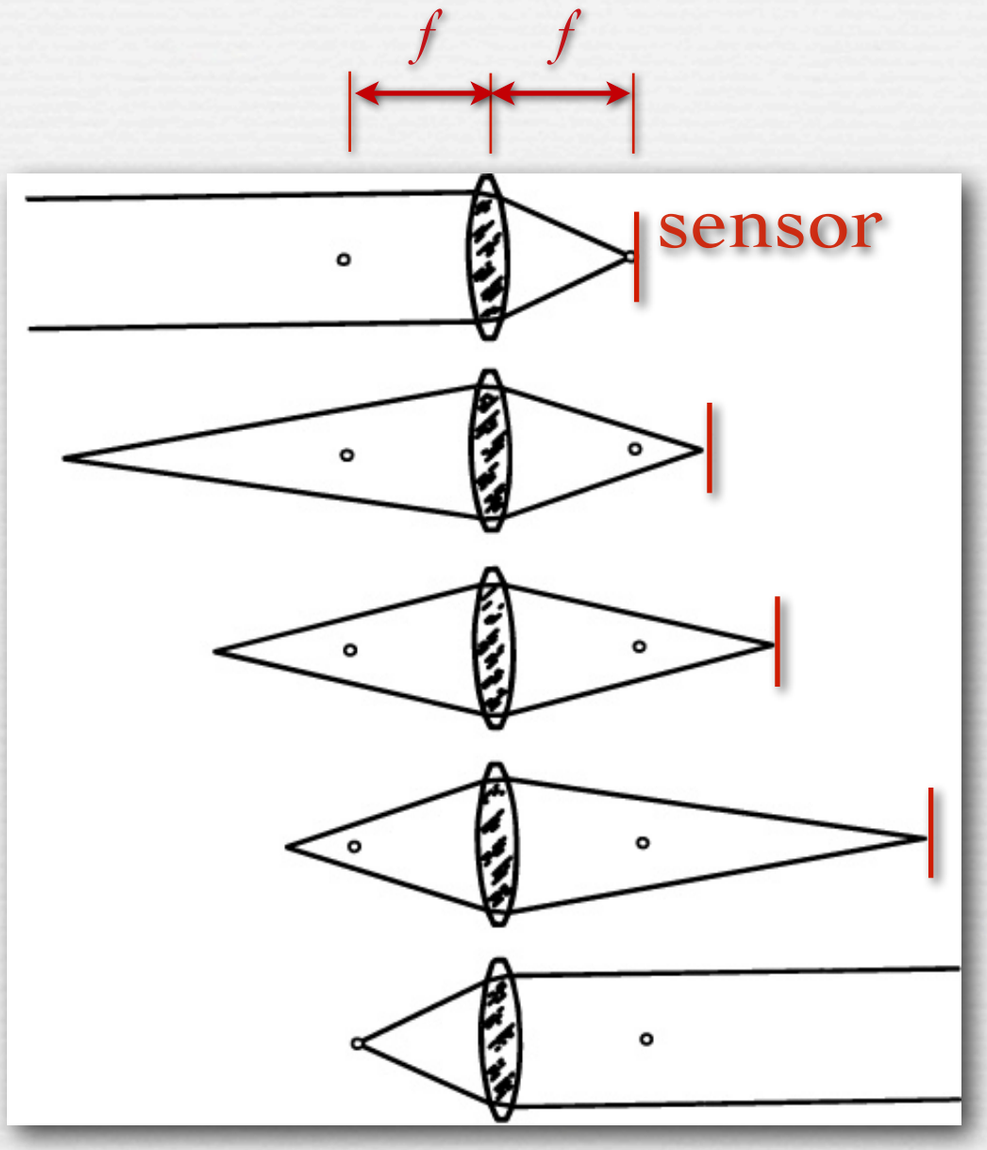
Changing the focus distance

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



- at $s_o = s_i = 2f$ we have 1:1 imaging, because

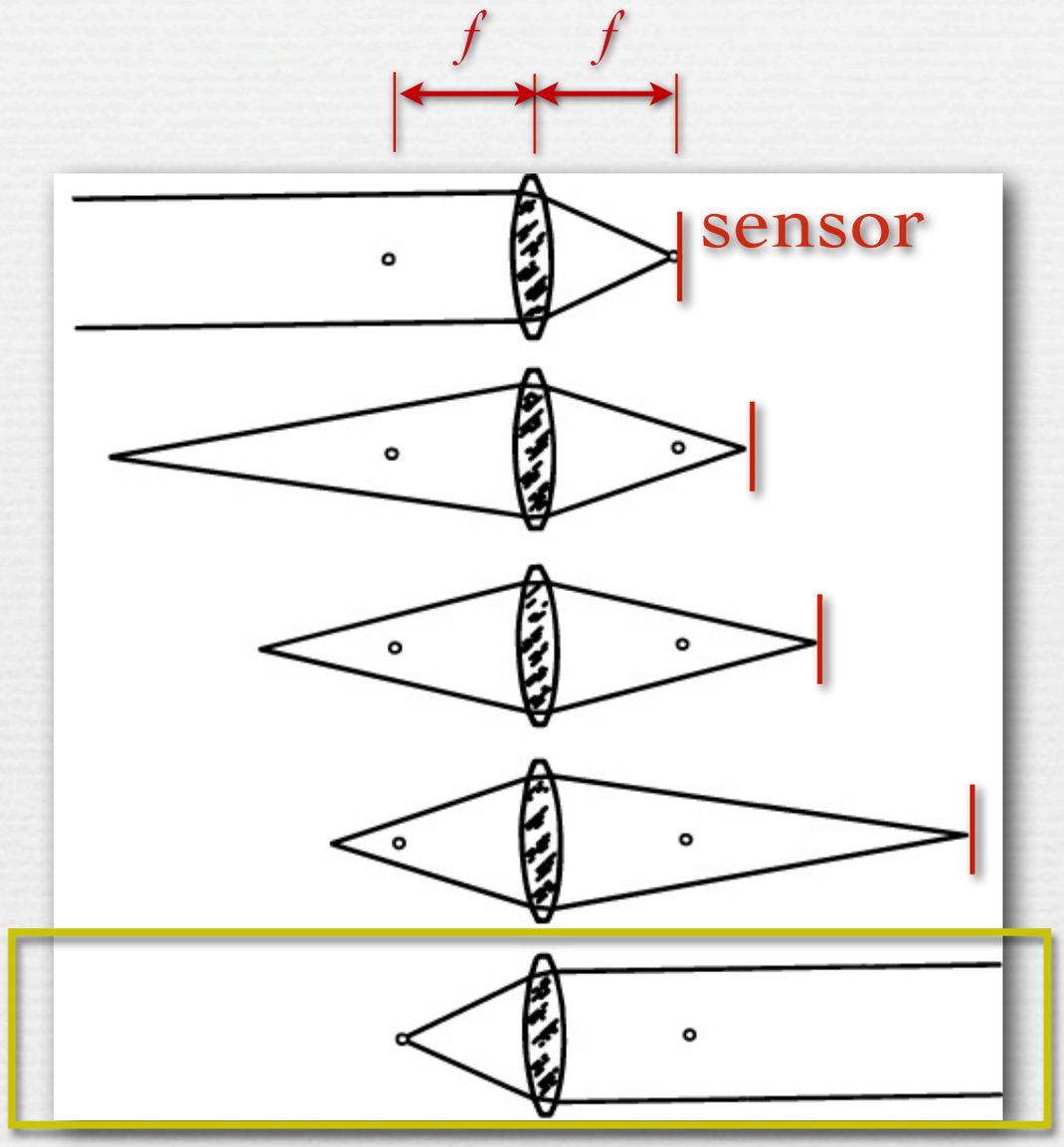
$$\frac{1}{2f} + \frac{1}{2f} = \frac{1}{f}$$

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

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

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

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

Demo!

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

Questions?

Shutter speed

- **Controls how long the film/sensor is exposed**
- **Linear effect on exposure**

  except for weird film behavior in extreme cases
- **Usually in fraction of a second:**

  1/2, 1/4, 1/8, 1/15, 1/30, 1/60, 1/125, 1/250, 1/500

  Get the pattern ?
- **On a normal lens, most people can hand-hold exposures as long as 1/60**

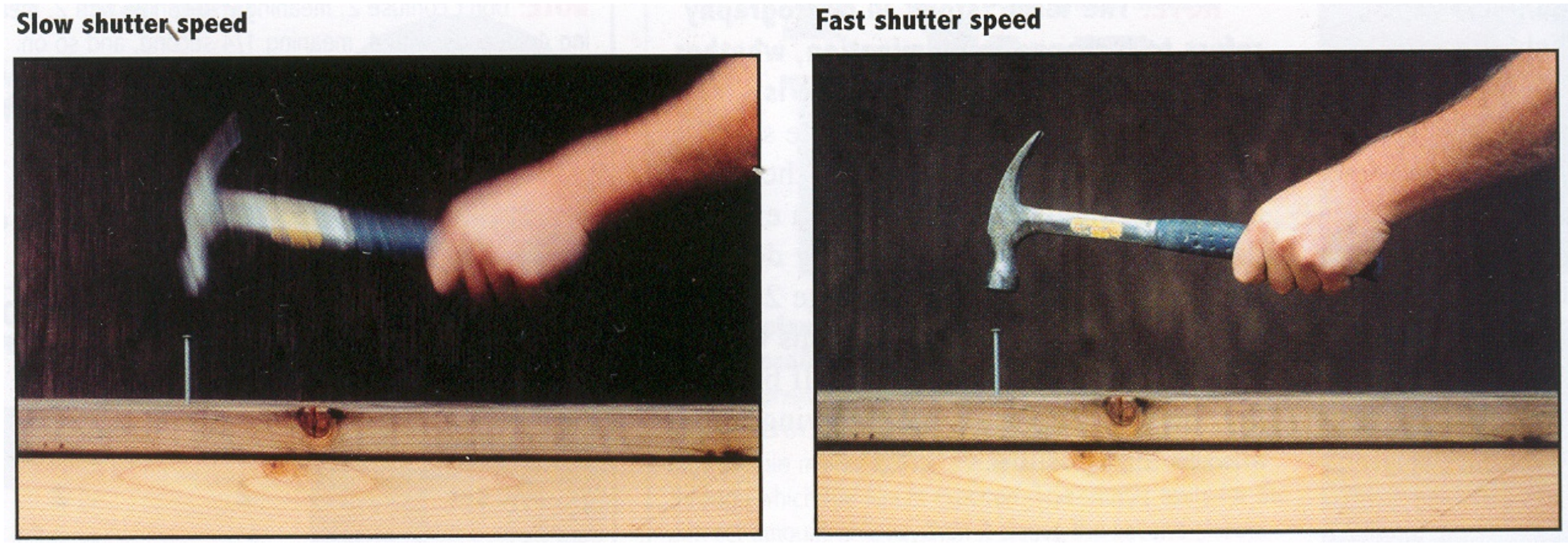
  In general, the rule of thumb says that the limit is the inverse of (35mm equivalent) focal length, e.g. 1/500 for a 500mm lens

Main effect of shutter speed

From Photography, London et al.

Main effect of shutter speed

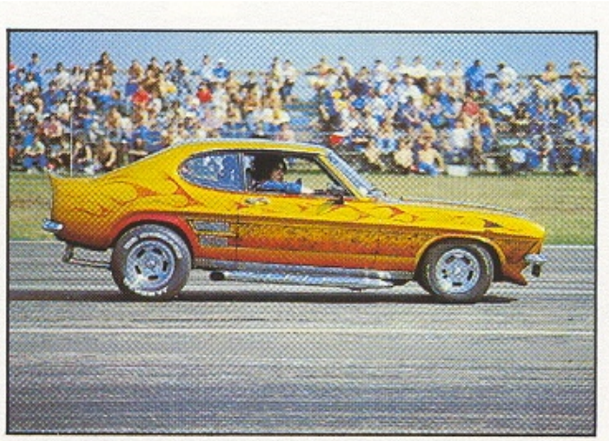
- **Motion blur**



From Photography, London et al.

Effect of shutter speed

- **Freezing motion**

Walking people	Running people	Car	Fast train
			
1/125	1/250	1/500	1/1000

Note: it doesn't mean that shutter speed is proportional to the absolute speed of the object. Object distance is very important, and a photographer often tracks the subject.

Shutter

- **Various technologies**
- **Goal: achieve uniform exposure across image**

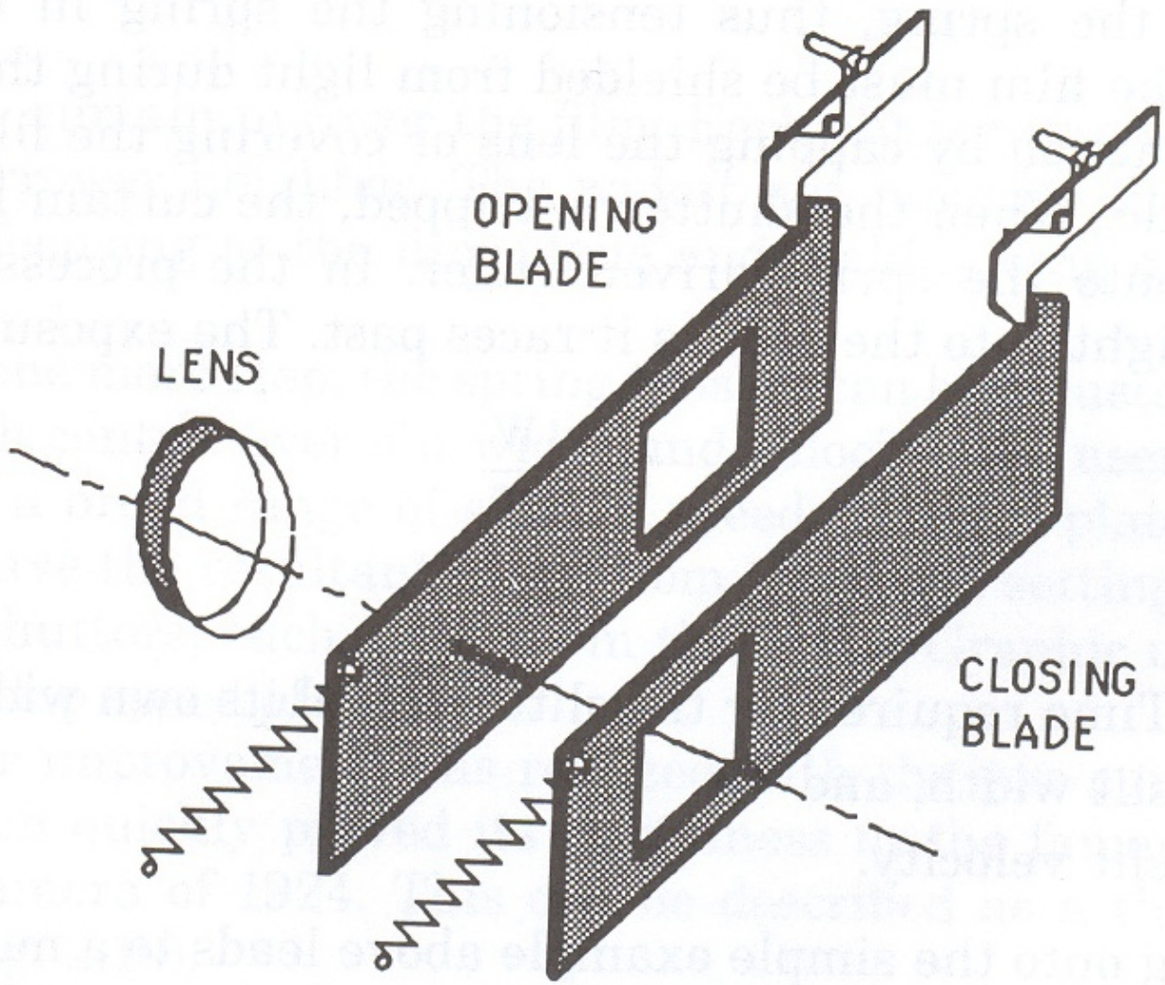


FIG. 2.8 Two-blade guillotine shutter.

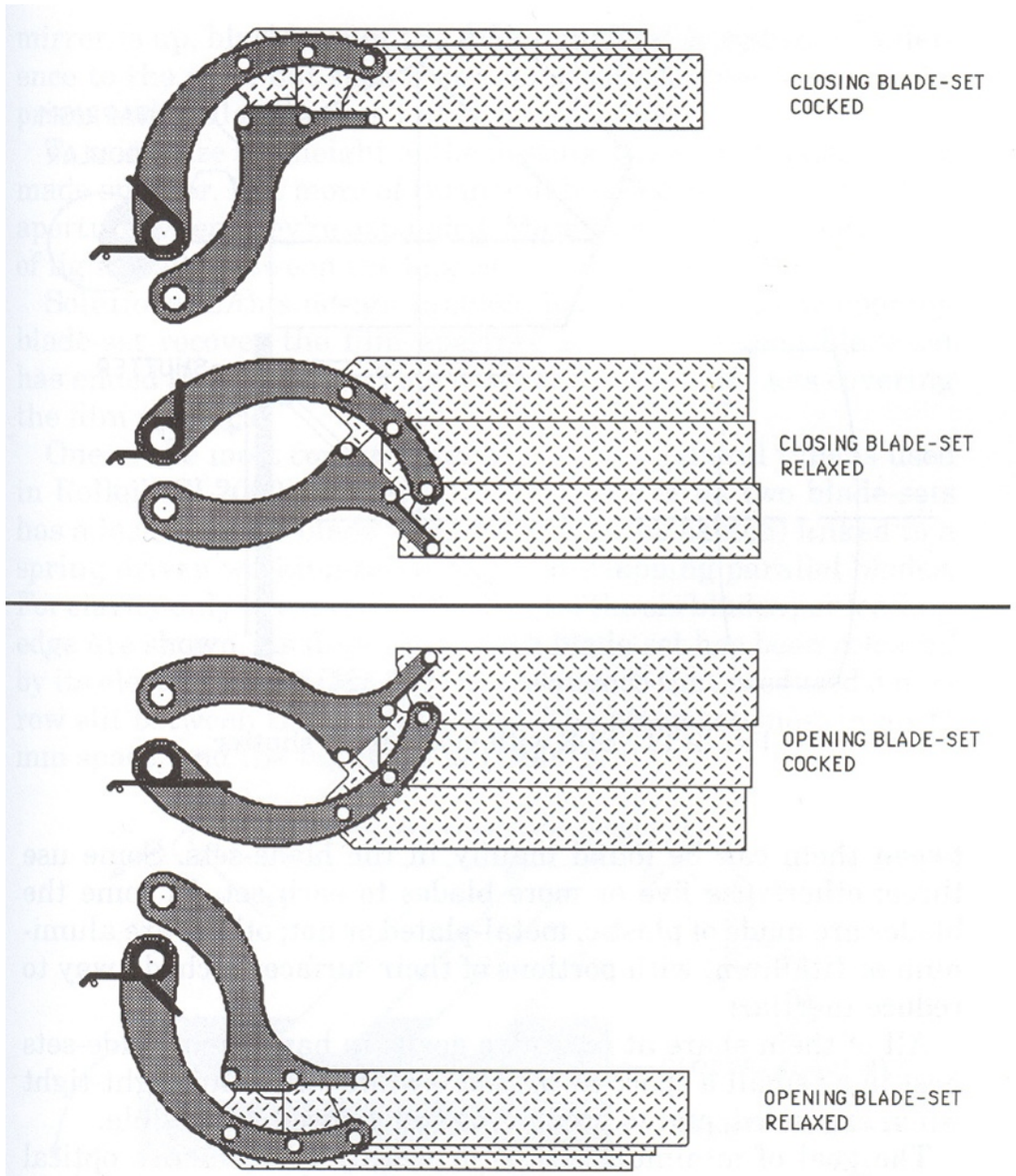


FIG. 2.12 Copal square.

From Camera Technology, Goldberg

slide by Frédo Durand, MIT

Figure 6–6. Jacques Henri Lartigue, *Grand Prix of the Automobile Club of France, 1912.* This classic photograph provides an exaggerated example of the distortion that can be caused by a focal-plane shutter. The oval shape of the automobile tire is caused by the motion of the car between the time the bottom of the tire was exposed and the top. (Remember–the image is upside-down on the negative.) The same principle caused the leaning appearance of the spectators. Lartigue turned the camera to follow the automobile (panning), and thus the image of the spectators moved at the film plane during the exposure. (Courtesy International Museum of Photography at George Eastman House.)

Sharpness spoiled by motion blur

Sharpness spoiled by motion blur

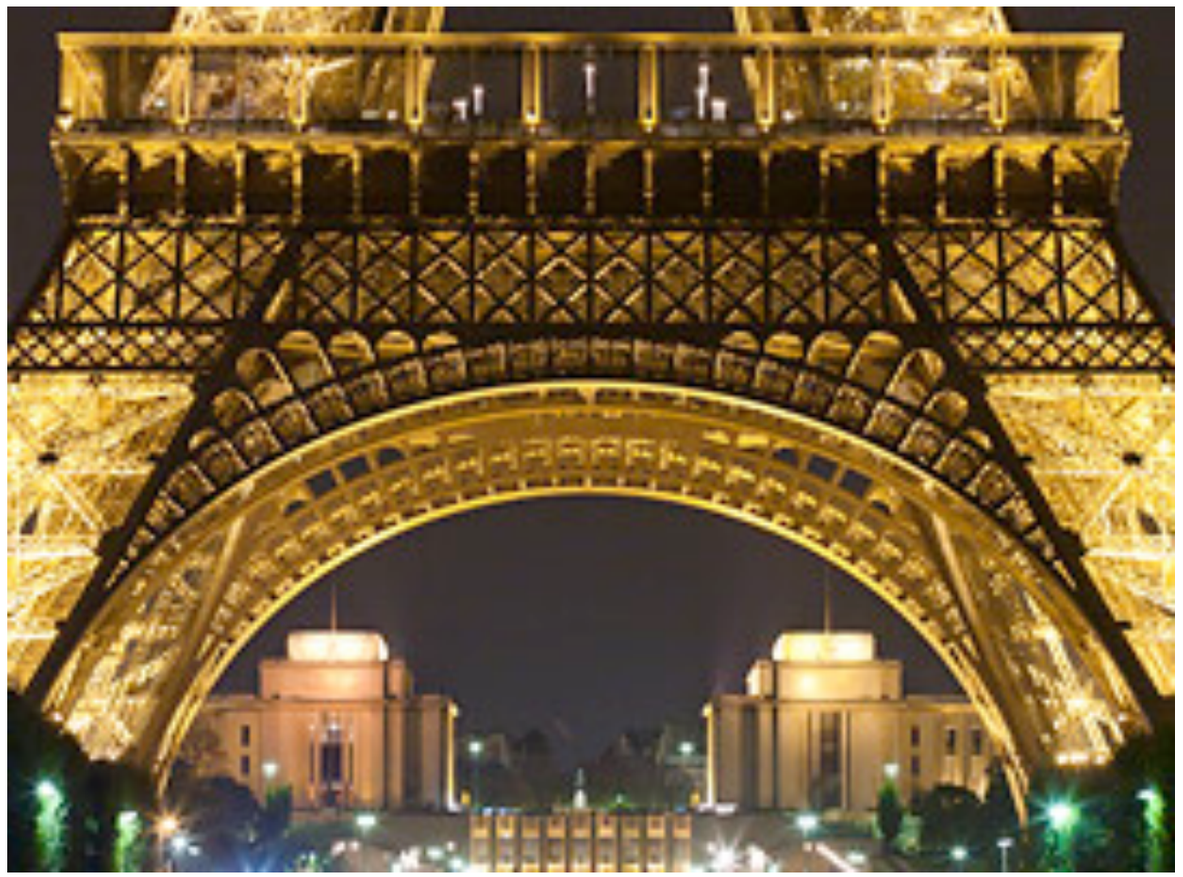
Sharpness spoiled by camera shake

- **Motion blur (camera or object) very often limits sharpness**

  extreme example below but you get the idea

  in many (most?) cases, holding the camera still will do more for sharpness than a better lens

Camera moving



Camera stationary

Camera movement

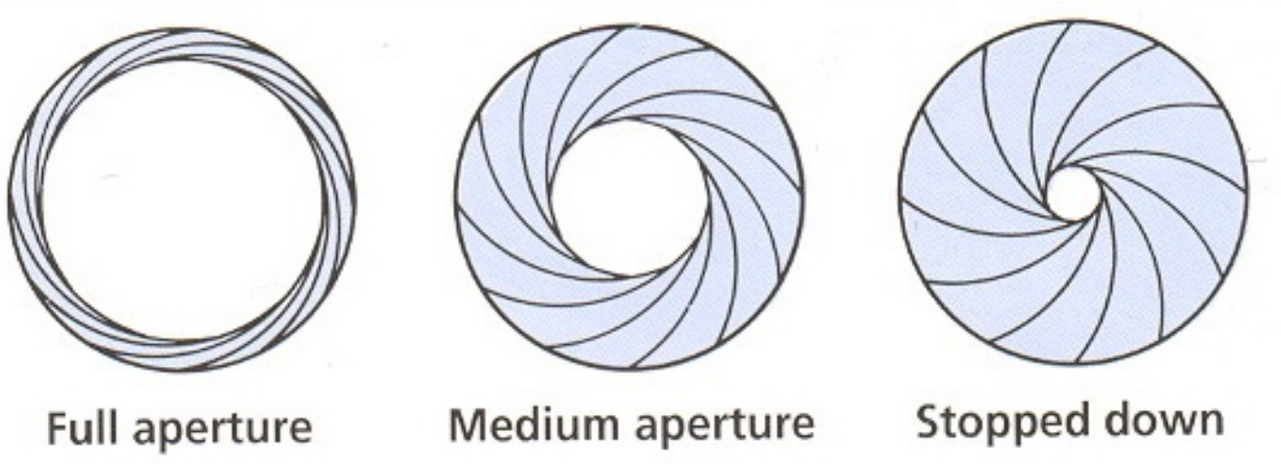
- **The solution:**

  (yes, I know it's a pain to carry)

Questions?

Aperture

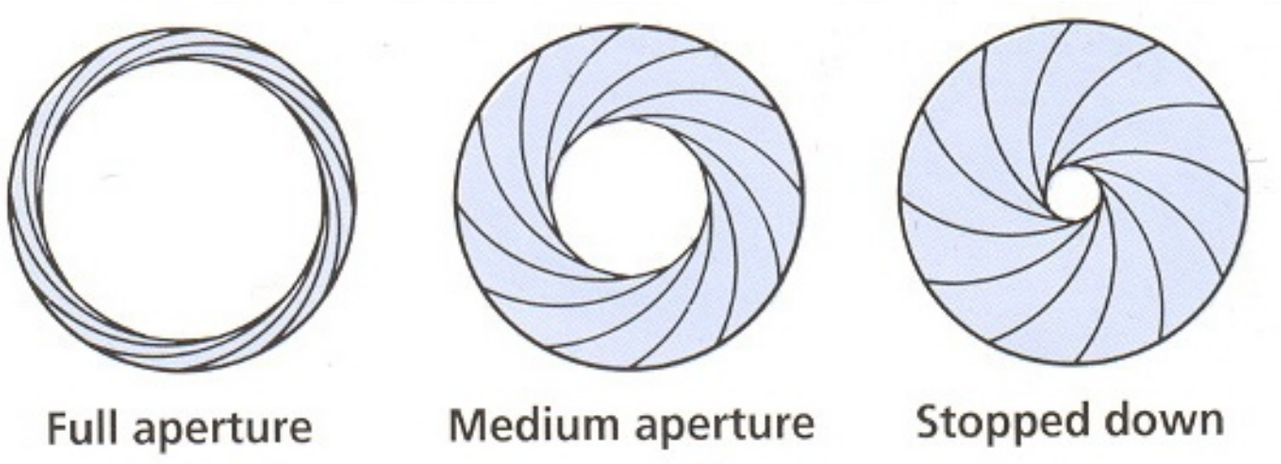
- **Diameter of the lens opening (controlled by diaphragm)**
- **Expressed as a fraction of focal length, in f-number**
  - f/2.0 on a 50mm means that the aperture is
  - f/2.0 on a 100mm means that the aperture is



Worth a look:
www.youtube.com/
watch?v=KmNIouLByJQ

Aperture

- **Diameter of the lens opening (controlled by diaphragm)**
- **Expressed as a fraction of focal length, in f-number**
  - f/2.0 on a 50mm means that the aperture is 25mm
  - f/2.0 on a 100mm means that the aperture is



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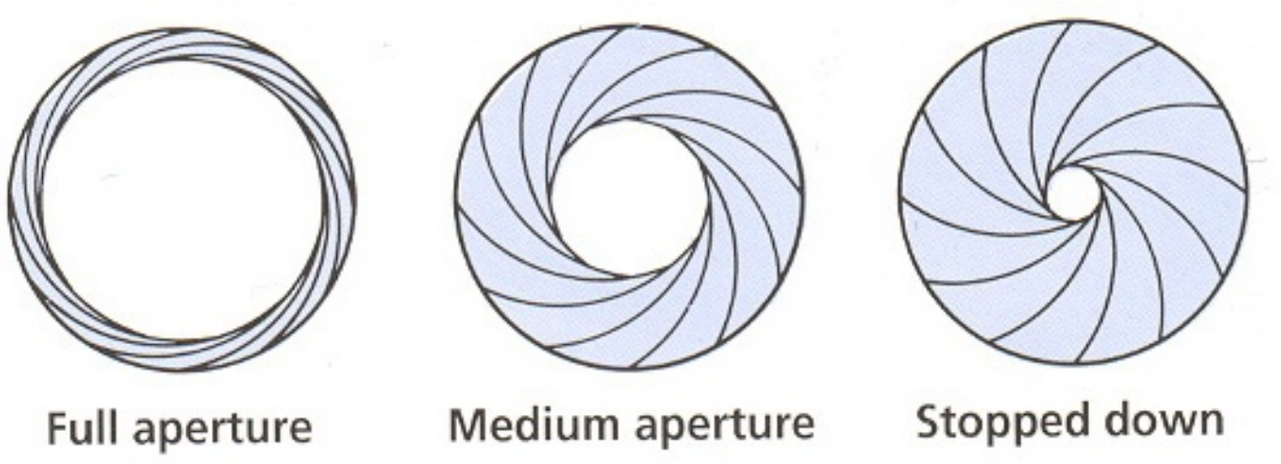

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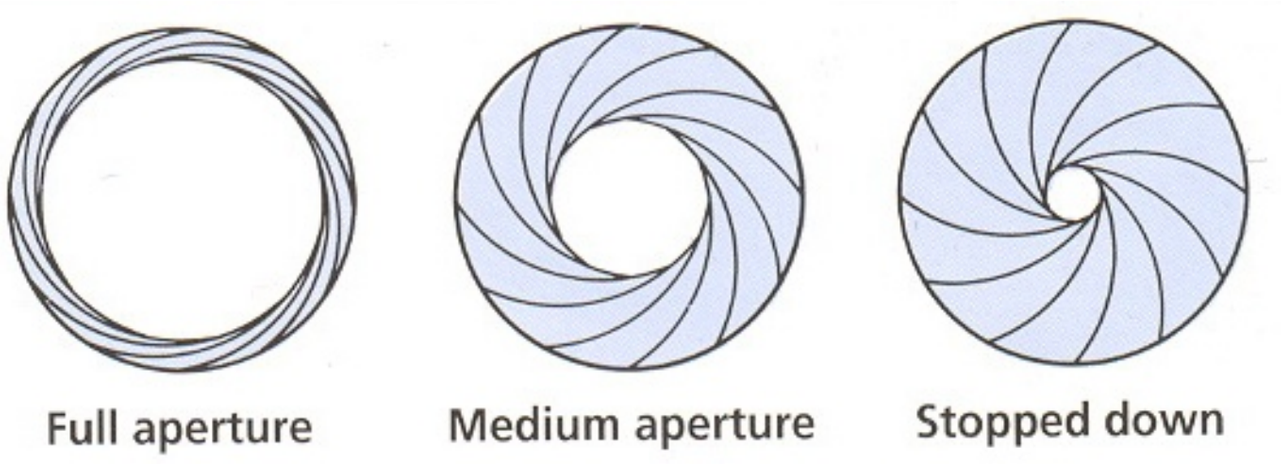
- **Expressed as a fraction of focal length, in f-number**
  - f/2.0 on a 50mm means that the aperture is 25mm
  - f/2.0 on a 100mm means that the aperture is 50mm
- **Disconcerting: small f number = big aperture**



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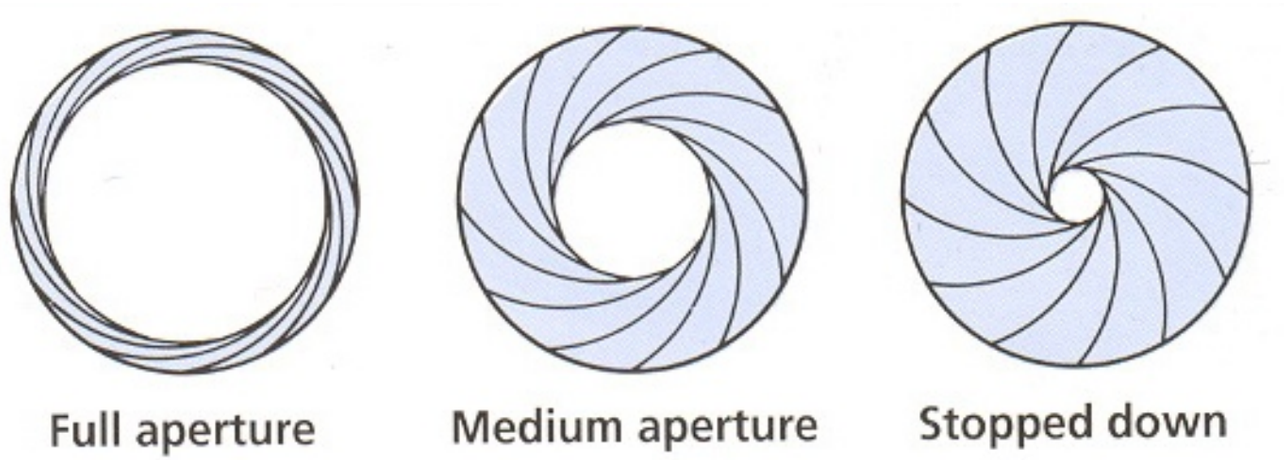
  - f/2.0 on a 100mm means that the aperture is 50mm
- **Disconcerting: small f number = big aperture**
- **What happens to the area of the aperture when going from f/2.0 to f/4.0?**

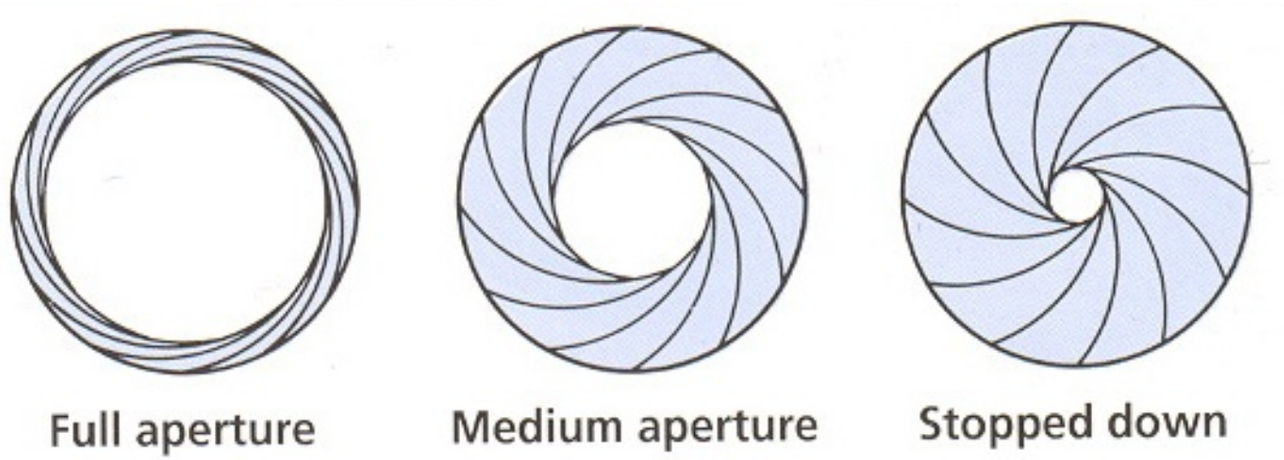


Worth a look:
www.youtube.com/watch?v=KmNIouLByJQ

slide by Frédo Durand, MIT

Aperture

- **Diameter of the lens opening (controlled by diaphragm)**
- **Expressed as a fraction of focal length, in f-number**
  - f/2.0 on a 50mm means that the aperture is 25mm
  - f/2.0 on a 100mm means that the aperture is 50mm
- **Disconcerting: small f number = big aperture**
- **What happens to the area of the aperture when going from f/2.0 to f/4.0?** divided by 4 (square of f number ratio)



Worth a look:
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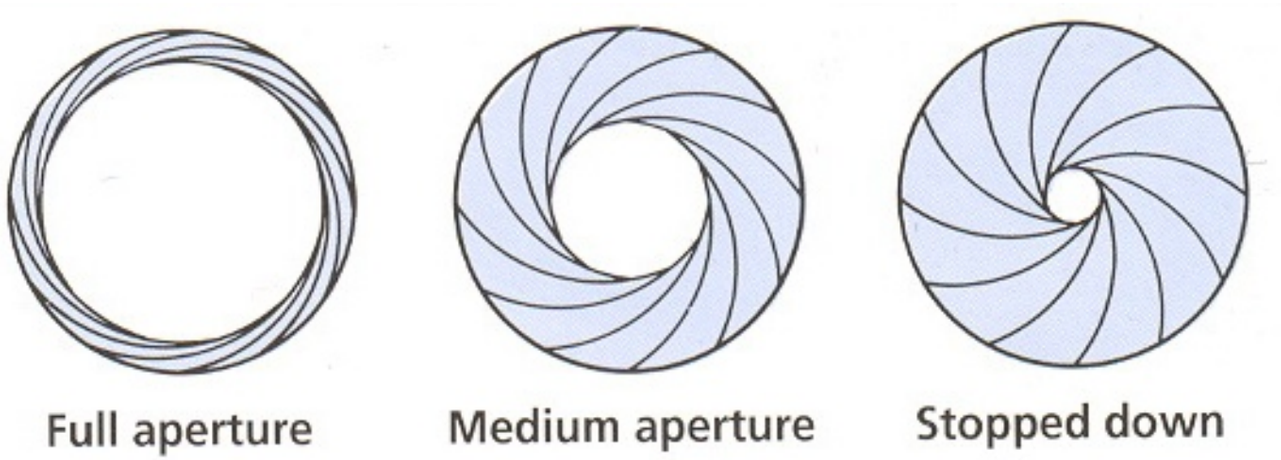
slide by Frédo Durand, MIT

Aperture

- **Diameter of the lens opening (controlled by diaphragm)**
- **Expressed as a fraction of focal length, in f-number**
  - f/2.0 on a 50mm means that the aperture is 25mm
  - f/2.0 on a 100mm means that the aperture is 50mm
- **Disconcerting: small f number = big aperture**
- **What happens to the area of the aperture when going from f/2.0 to f/4.0?** divided by 4 (square of f number ratio)
- **Typical f numbers are**
  f/2.0, f/2.8, f/4, f/5.6, f/8, f/11, f/16, f/22, f/32
  - See the pattern?



Worth a look:
www.youtube.com/
watch?v=KmNIouLByJQ

slide by Frédo Durand, MIT

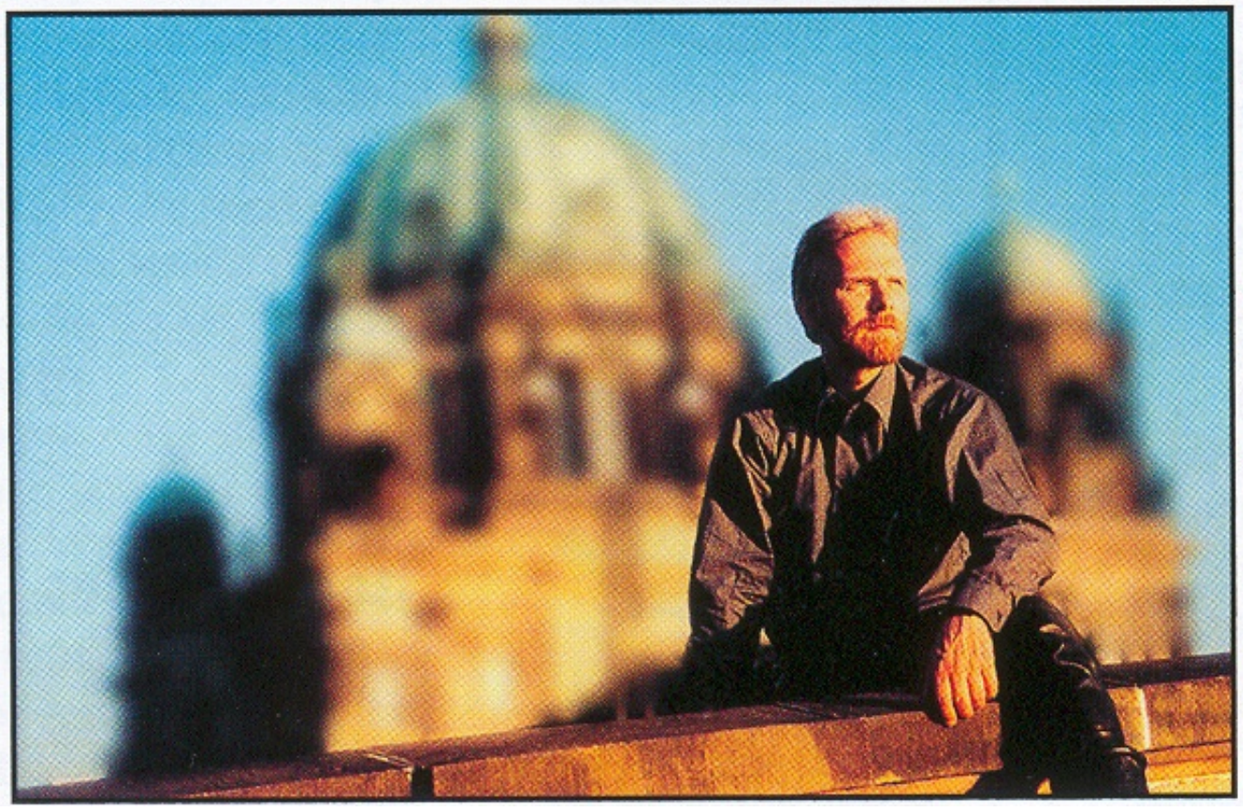
Main effect of aperture

From Photography, London et al.

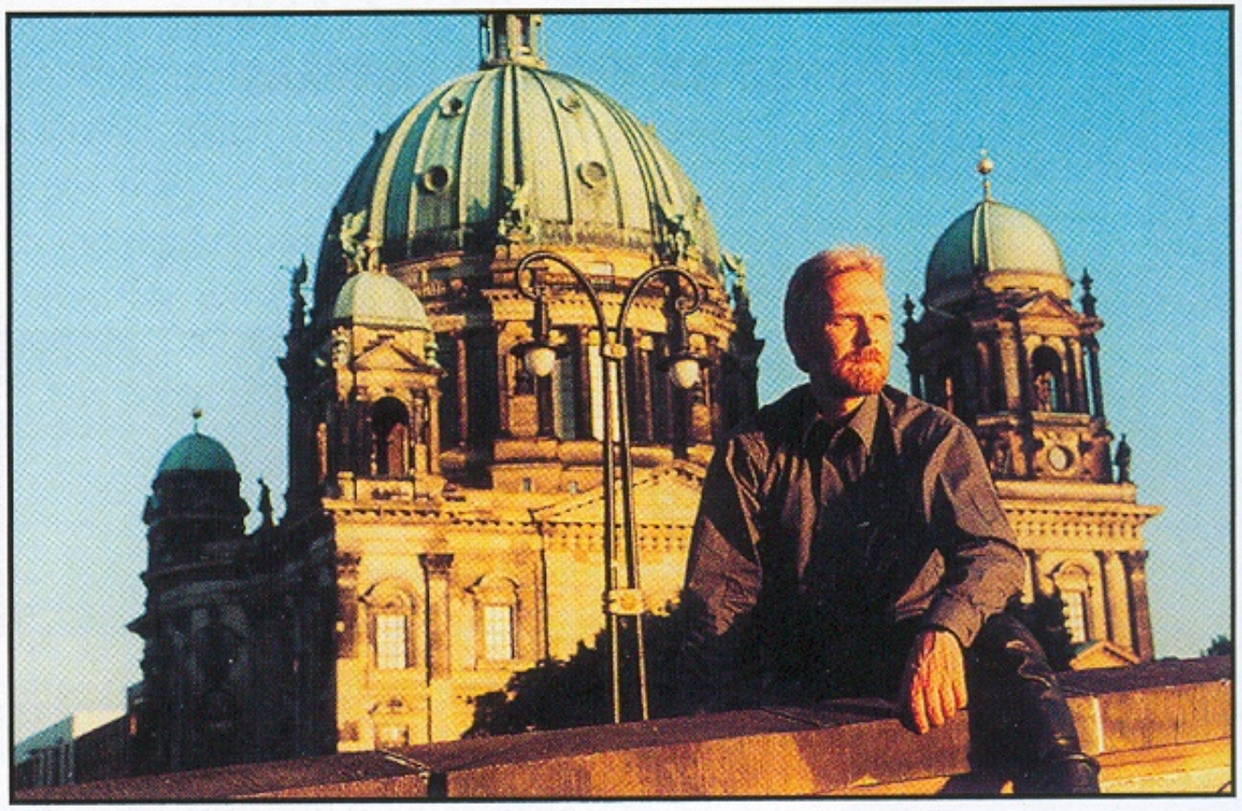
Main effect of aperture

- **Depth of field**

Large aperture opening



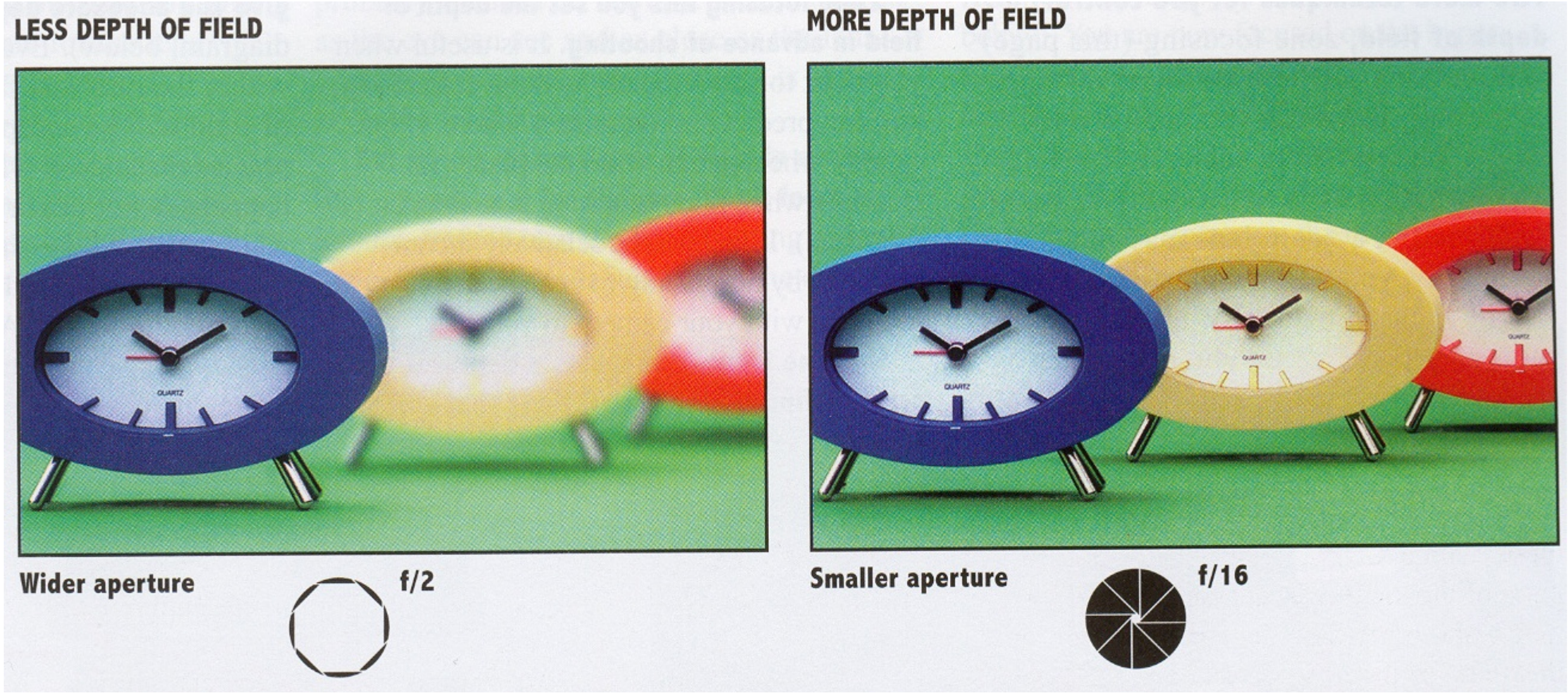
Small aperture opening



From Photography, London et al.

slide by Frédo Durand, MIT

Depth of field



From Photography, London et al.

Lenses in practice

- **focal length**

  (determines field of view)

  (a range, for a zoom lens)

- **maximum aperture**

  (light collecting ability, “speed”)

  (a range, for many zoom lenses—
  smaller f number for shorter focal length)

prime lenses

zoom lenses

photos: Ken Rockwell

Cinematography by candlelight

Stanley Kubrick,
Barry Lyndon,
1975

slide by Marc Levoy, Stanford

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

Stanley Kubrick,
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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)

slide by Marc Levoy, Stanford

Questions?

Exposure

- **Shutter speed**

  want low for nice sharp images

- **Aperture size**

  want smallish for nice in-focus images

- **Sensitivity**

  want low for nice low-noise images

- **But…**

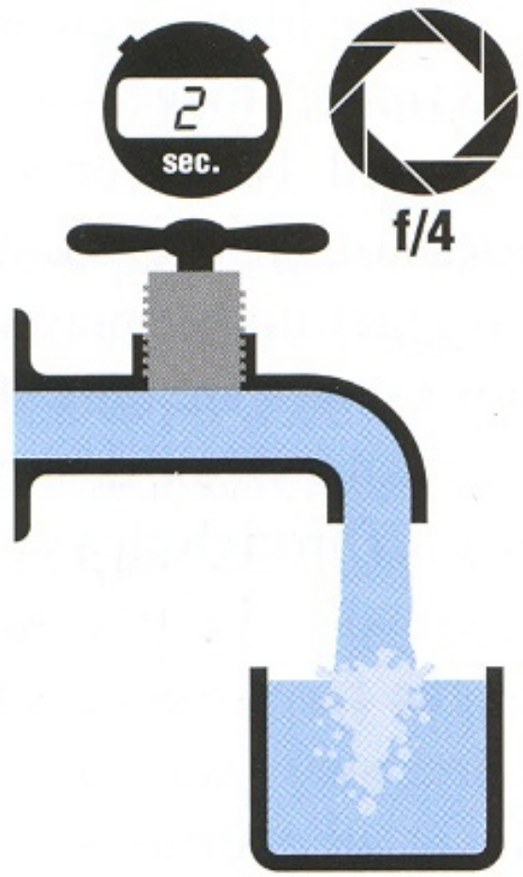
  we have to have enough light!

Exposure

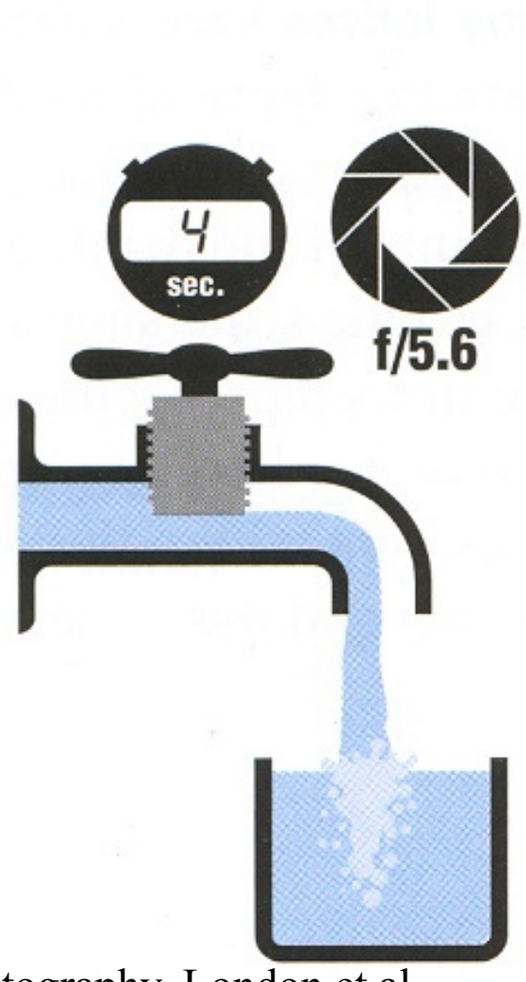
- **Two main parameters:**
  - Aperture (in f stop)
  - Shutter speed (in fraction of a second)

Exposure

- **Two main parameters:**
  - Aperture (in f stop)
  - Shutter speed (in fraction of a second)
- **Reciprocity**

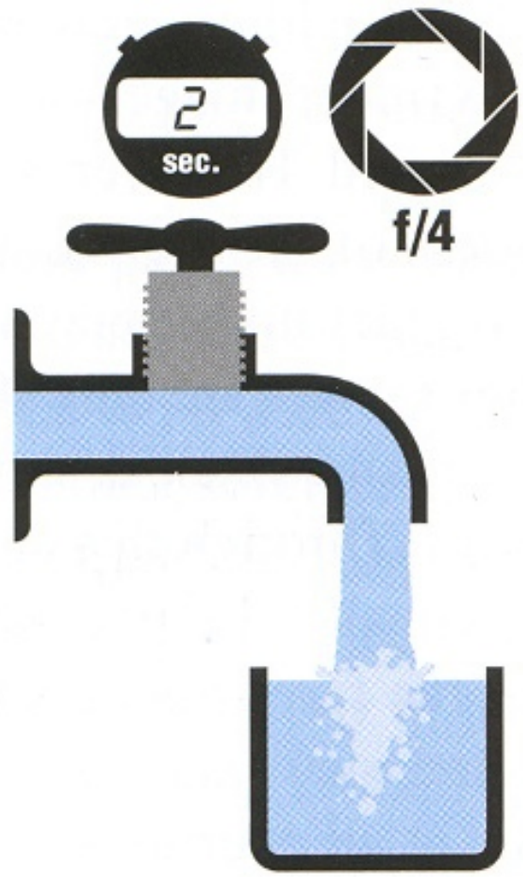


The same exposure is obtained with an exposure twice as long and an aperture *area* half as big



From Photography, London et al.

Exposure



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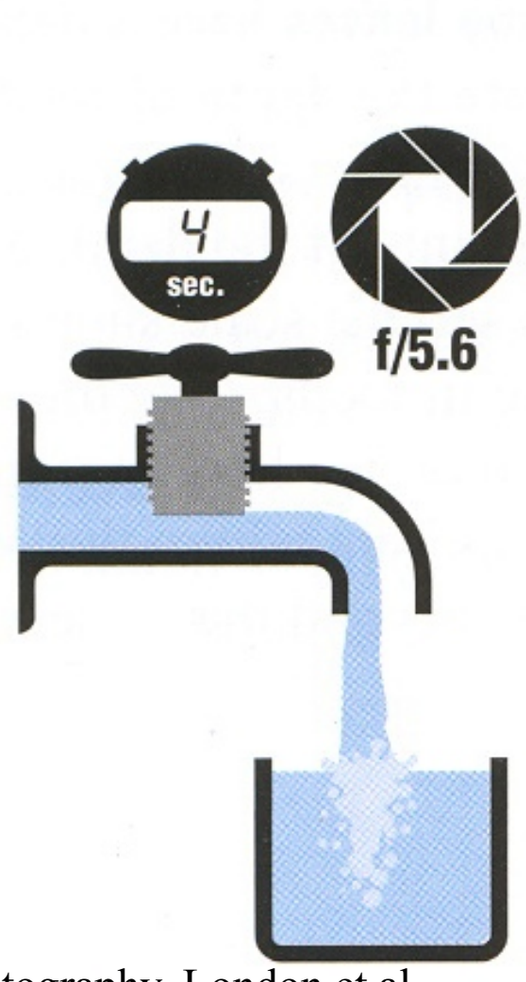
  - Aperture (in f stop)
  - Shutter speed (in fraction of a second)
- **Reciprocity**

The same exposure is obtained with an exposure twice as long and an aperture *area* half as big

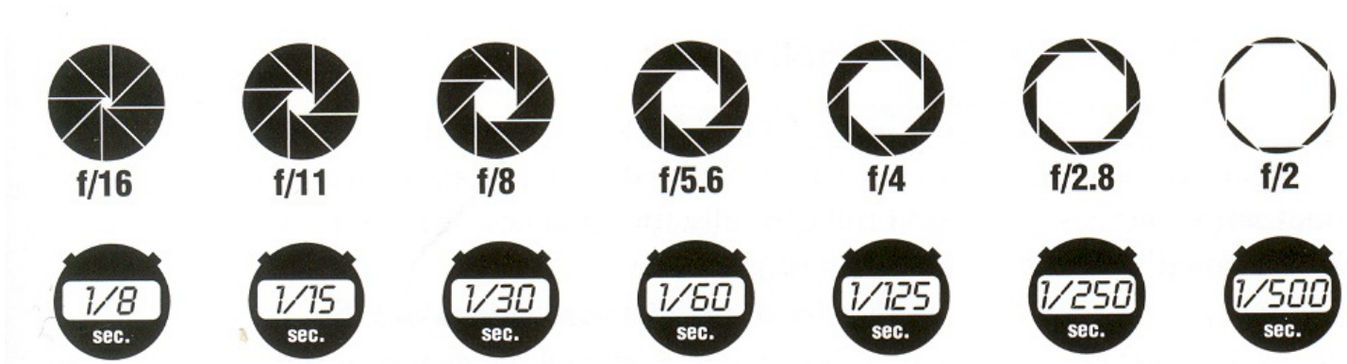


From Photography, London et al.

  - Hence square root of two progression of f stops vs. power of two progression of shutter speed
  - Reciprocity can fail for very long exposures

Reciprocity

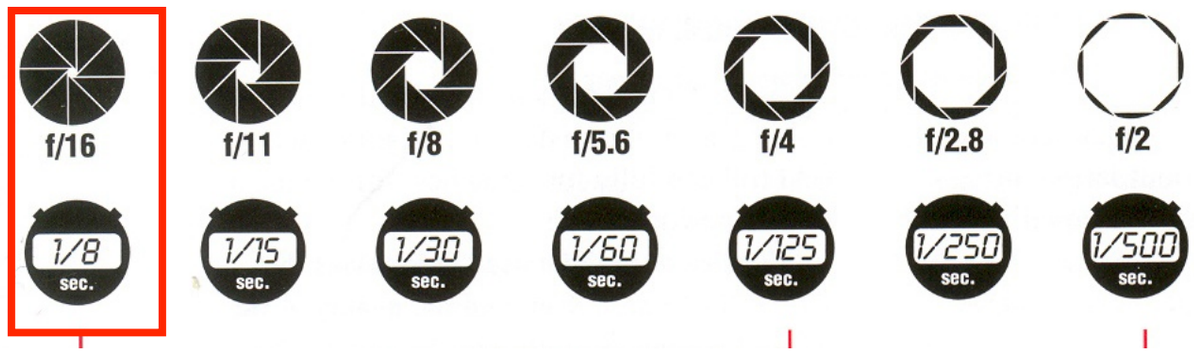
- **Assume we know how much light we need**
- **We have the choice of an infinity of shutter speed/ aperture pairs**



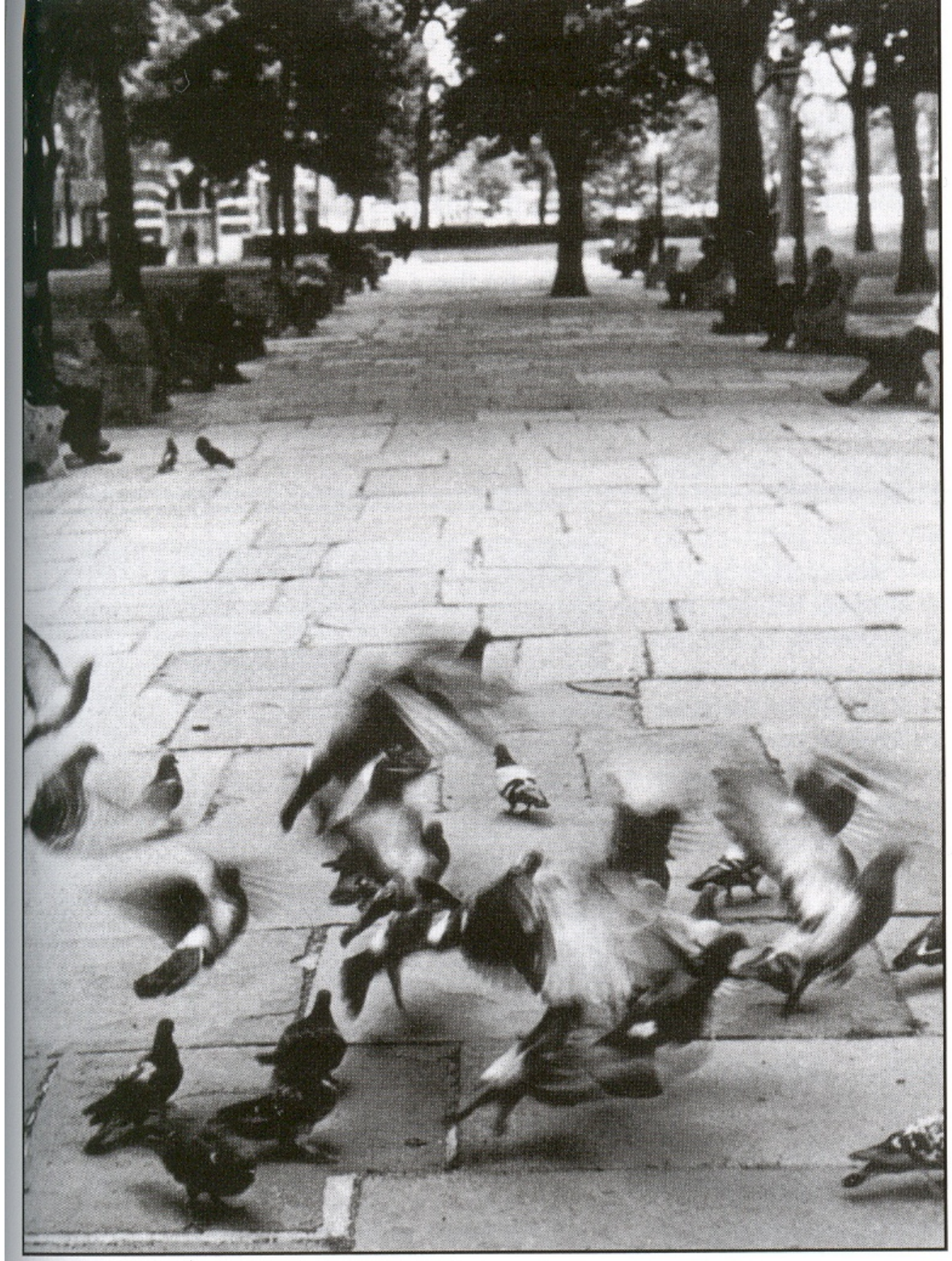
- **What will guide our choice of a shutter speed?**
  - Freeze motion vs. motion blur, camera shake
- **What will guide our choice of an aperture?**
  - Depth of field, diffraction limit
- **Often we must compromise**
  - Open more to enable faster speed (but shallow DoF)

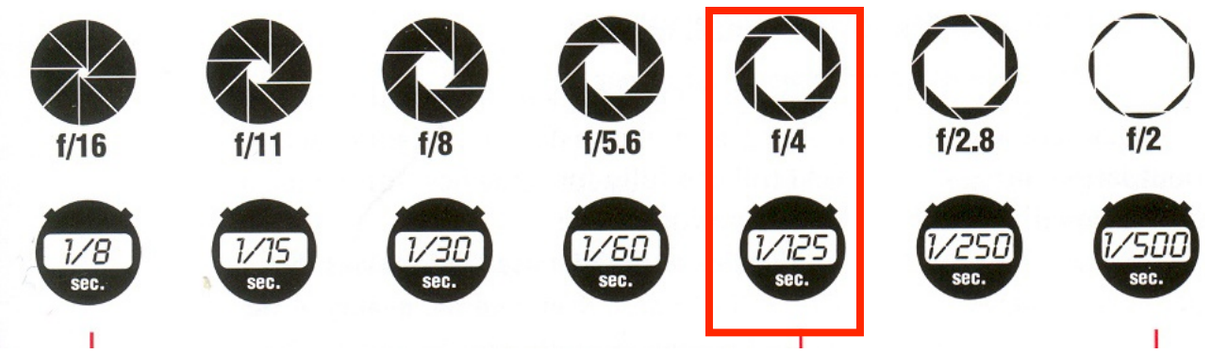
slide by Frédo Durand, MIT

Small aperture (deep depth of field), slow shutter speed (motion blurred). *In this scene, a small aperture (f/16) produced great depth of field; the nearest paving stones as well as the farthest trees are sharp. But to admit enough light, a slow shutter speed (1/8 sec) was needed; it was too slow to show moving pigeons sharp. It also meant that a tripod had to be used to hold the camera steady.*



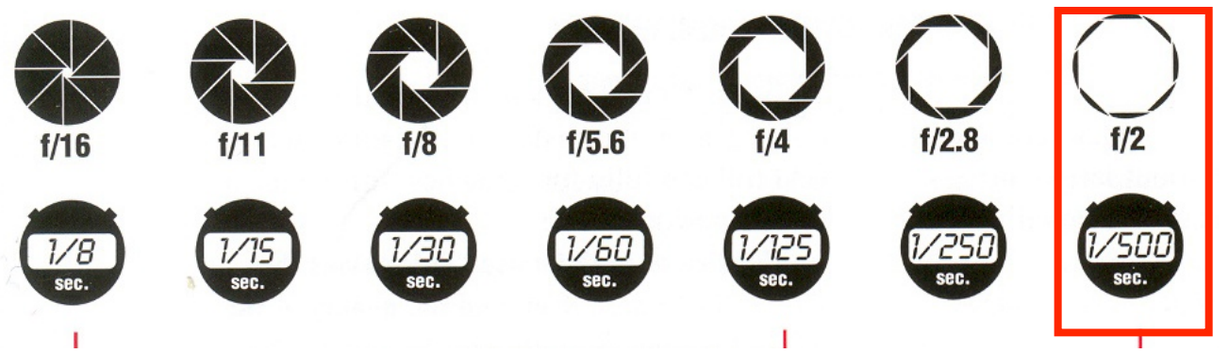
From Photography, London et al.





Medium aperture (moderate depth of field), medium shutter speed (some motion sharp). *A medium aperture (f/4) and shutter speed (1/125 sec) sacrifice some background detail to produce recognizable images of the birds. But the exposure is still too long to show the motion of the birds' wings sharply.*

From Photography, London et al.

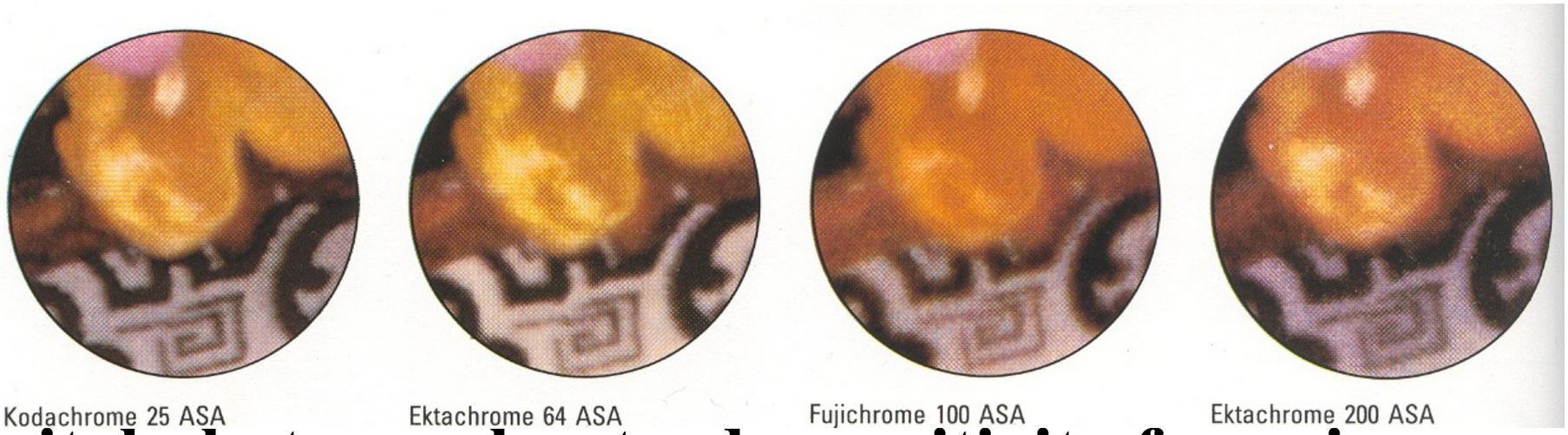


Large aperture (shallow depth of field), fast shutter speed (motion sharp). *A fa*
shutter speed (1/500 sec) stops the motion of the pigeons so completely that the
flapping wings are frozen. But the wide aperture (f/2) needed gives so little depti
of field that the background is now out of focus.

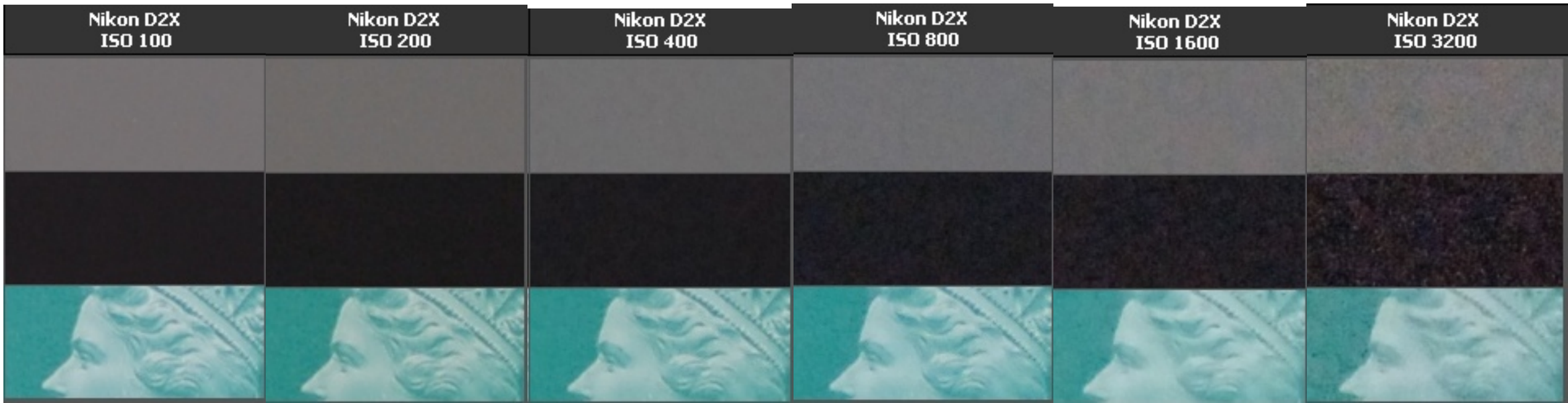
From Photography, London et al.

Sensitivity (ISO)

- **Third variable for exposure**
- **Linear effect (200 ISO needs half the light as 100 ISO)**
- **Film photography: trade sensitivity for grain**



- **Digital photography: trade sensitivity for noise**
  - Gain



From dpreview.com

slide by Frédo Durand, MIT

turn to focus

turn to adjust aperture

turn to adjust shutter speed

press to take picture

pull to wind film

photo: Ken Rockwell

Questions?