CS 89.15/189.5, Fall 2015

Computational Aspects of Digital Photography

Image Formation & Camera Basics

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Dartmouth

Administrivia

Make sure to sign onto Piazza (some of you haven't)

- I'll be posting announcements there

Video introduction was due last night!

- If you haven't submitted, you can submit by tonight

Programming Assignment 0 is due tonight

"Programming" Assignment 1 is now available (start early!)

Schedule fix: no x-hour nor Saturday class this week

- We'll make up Saturday class during another x-hour this term

Today’s agenda

How do we see the world, and how can be replicate that to create a camera?

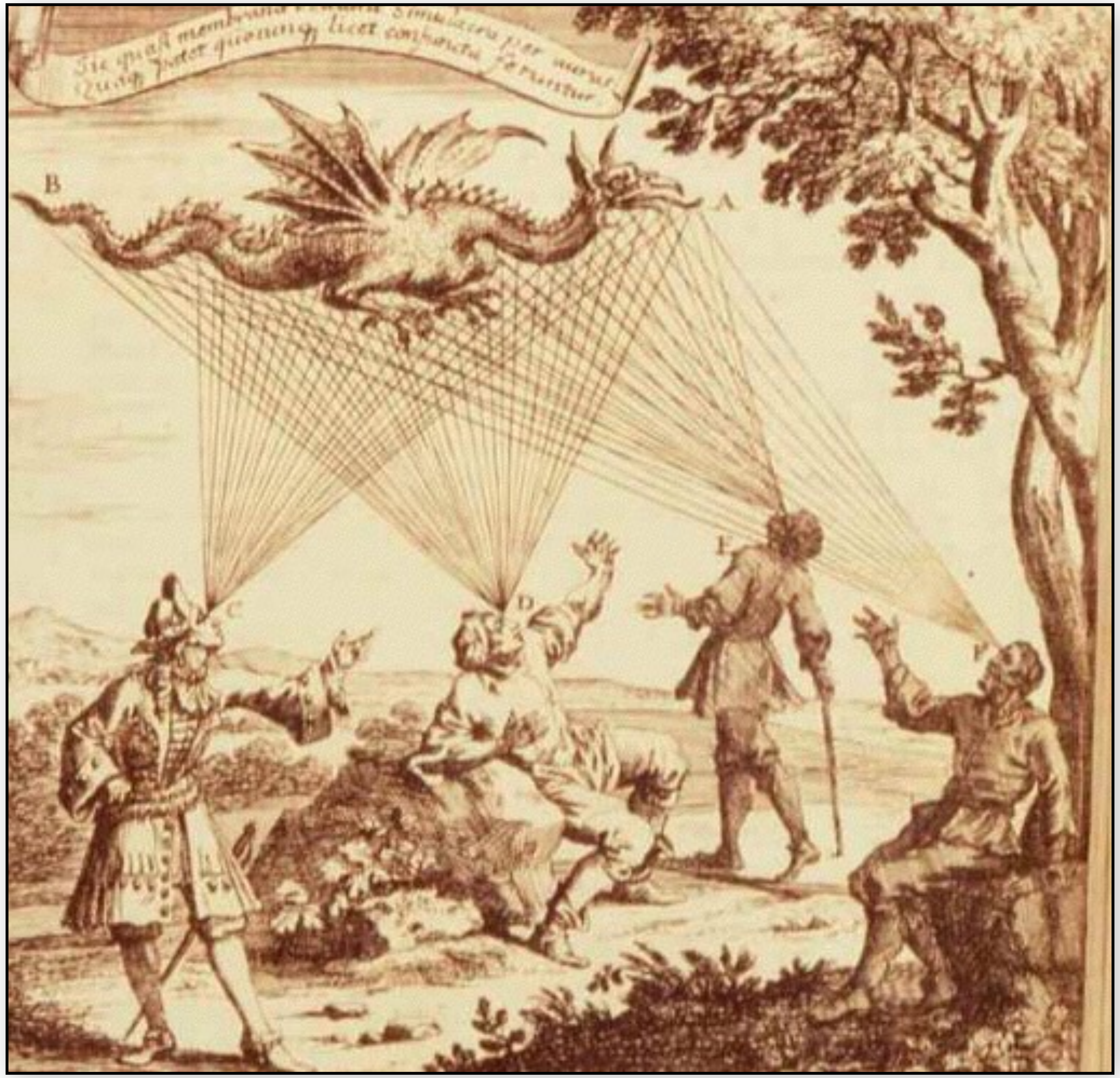
Pinhole optics

(Simplified) Lenses

Exposure

- shutter speed
- aperture
- ISO

Emission theory of vision



Eyes send out “feeling rays” into the world

“For every complex problem there is an answer that is clear, simple, and wrong.”
-- H. L. Mencken

Supported by:

- Empedocles
- Plato
- Euclid (kinda)
- Ptolemy

  …

- 50% of US college students*

*http://www.ncbi.nlm.nih.gov/pubmed/12094435?dopt=Abstract

Exciting New Study!

☰ MENU | the ONION | Study: People Far Away From You Not Actually Smaller | SEARCH | TOP HEADLINES

Study: People Far Away From You Not Actually Smaller

NEWS

August 22, 2013

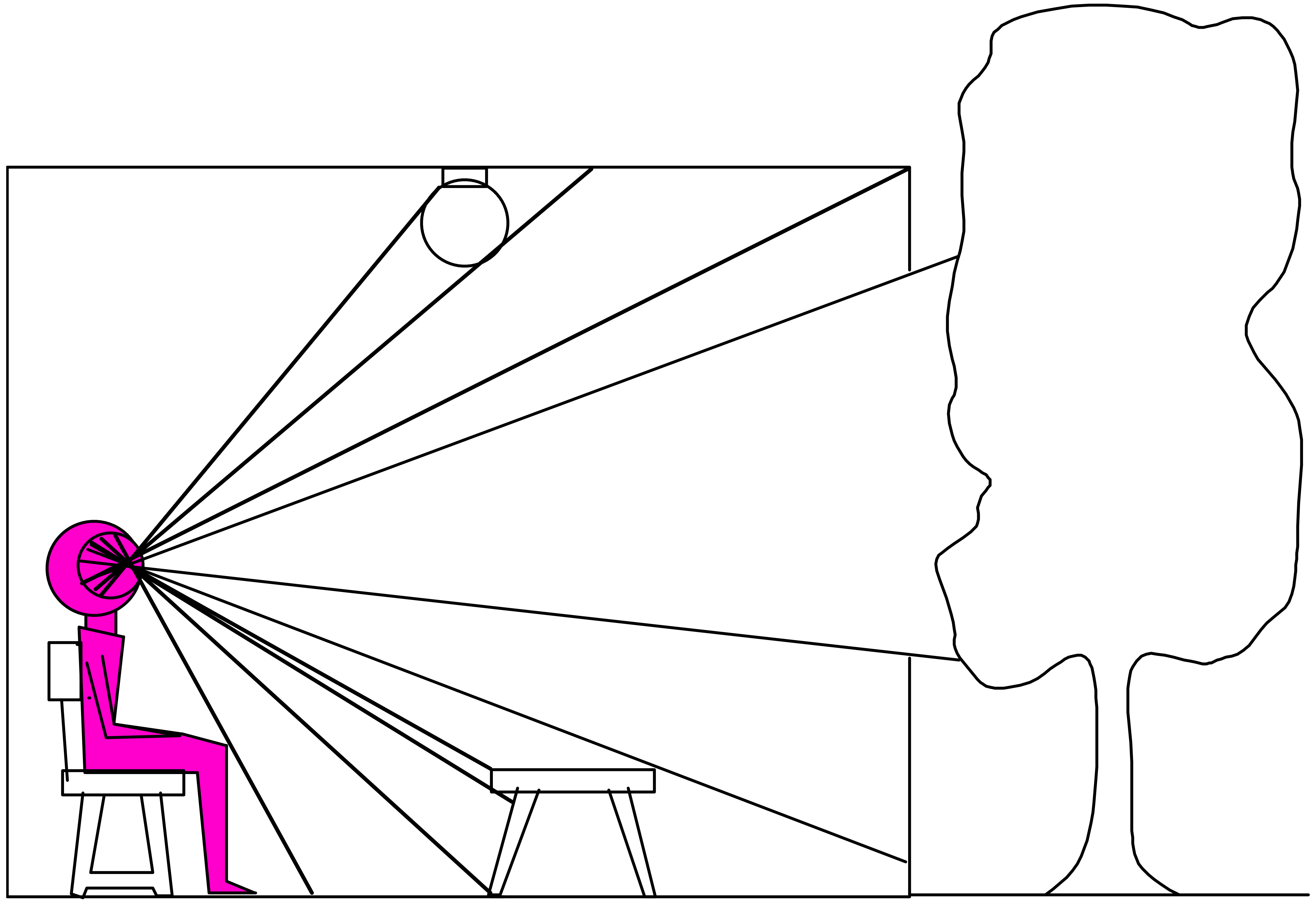
VOL 49 ISSUE 34

Science & Technology

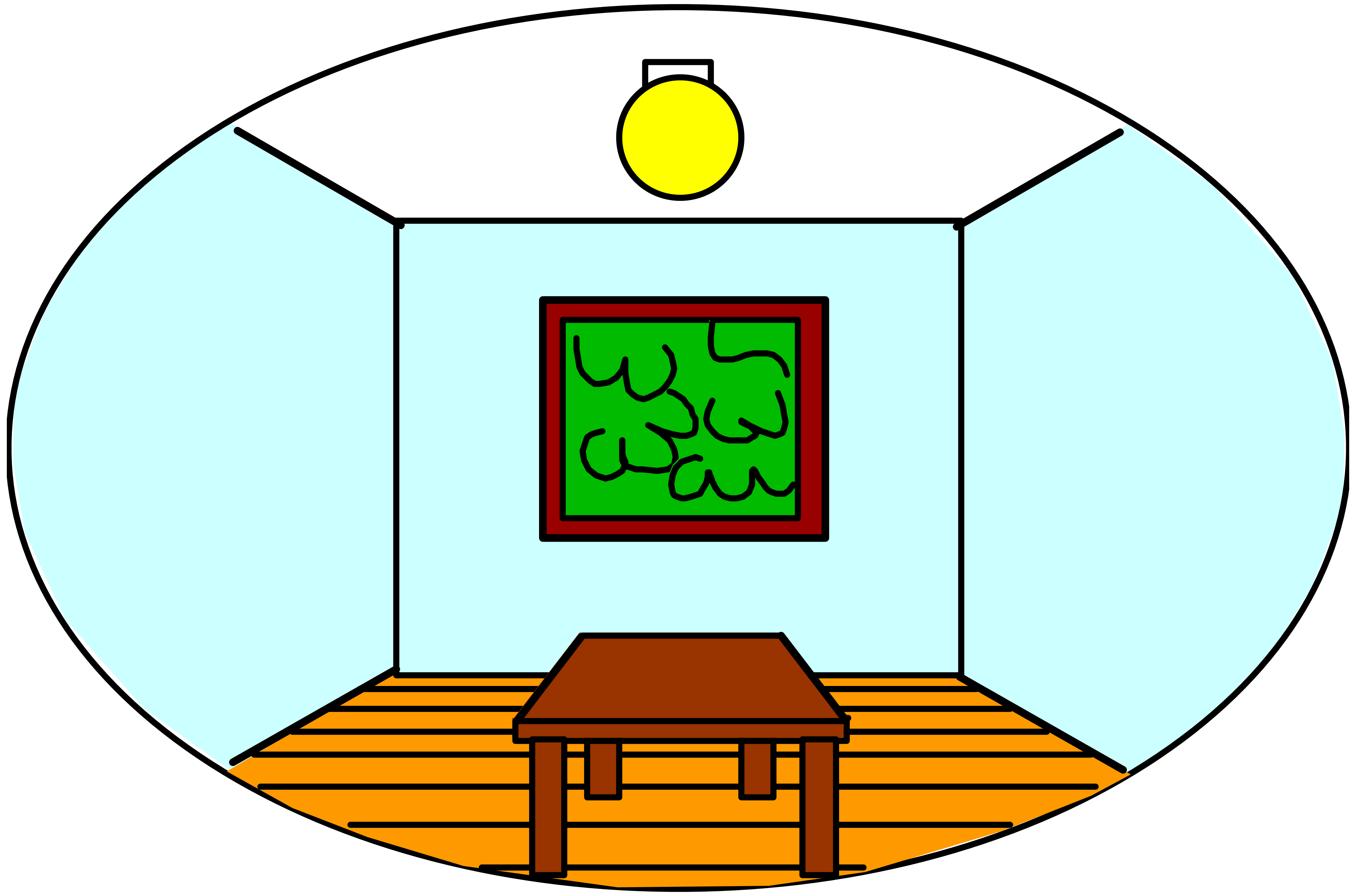
Researchers say that, contrary to prior assertions, the subject above stands at equal height at left and at right, and does not grow smaller as he walks away from the camera.

Dimensionality reduction machine (3D to 2D)

3D world



2D image



What do we lose?

Exciting New Study!

MENU the ONION Study: People Far Away From You Not Actually Smaller SEARCH TOP HEADLINES

Study: People Far Away From You Not Actually Smaller

NEWS
August 22, 2013
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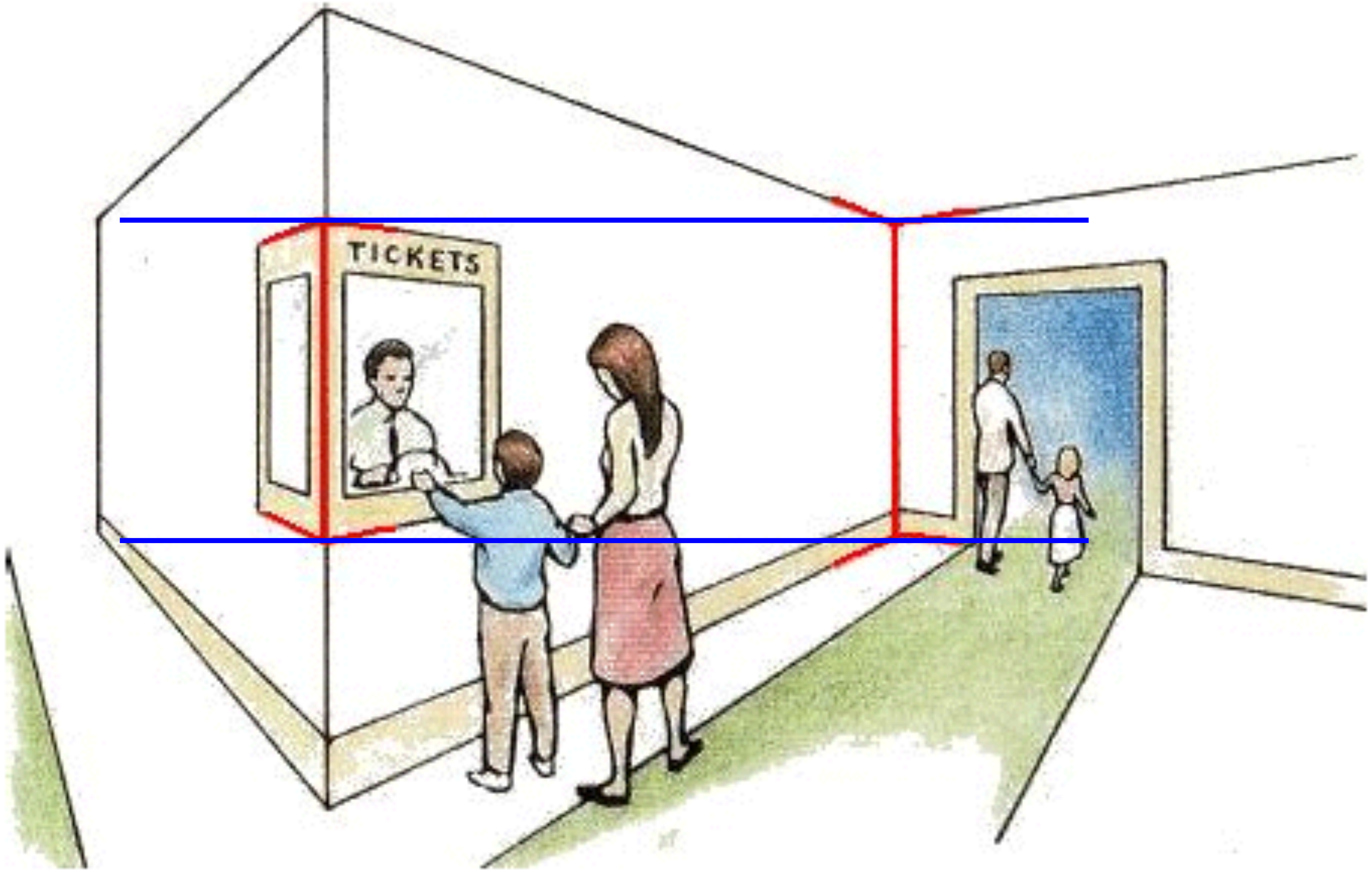
Researchers say that, contrary to prior assertions, the subject above stands at equal height at left and at right, and does not grow smaller as he walks away from the camera.

Lengths can't be trusted...

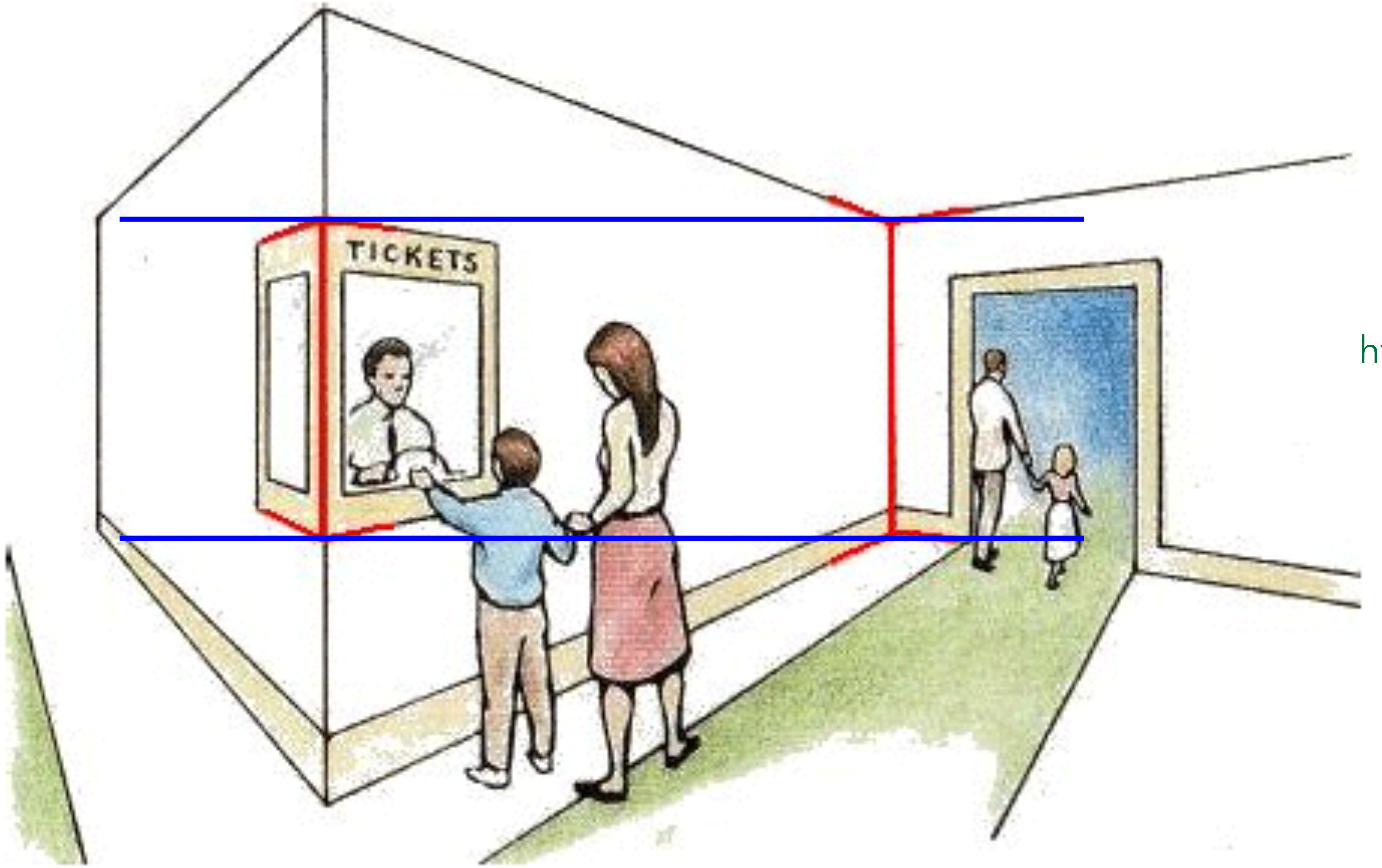
Angles also…

…but humans adapt!

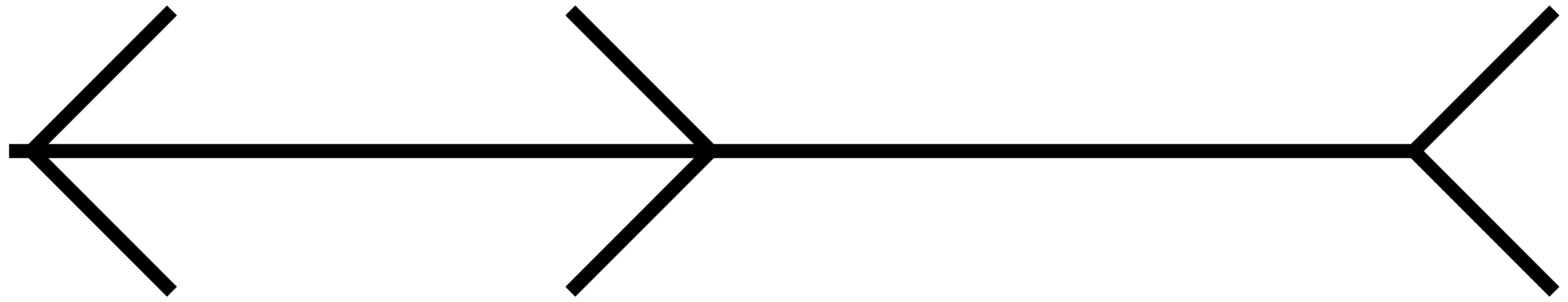


We don't make measurements in the image plane

…but humans adapt!



http://www.michaelbach.de/ot/sze_muelue/index.html



Müller-Lyer Illusion

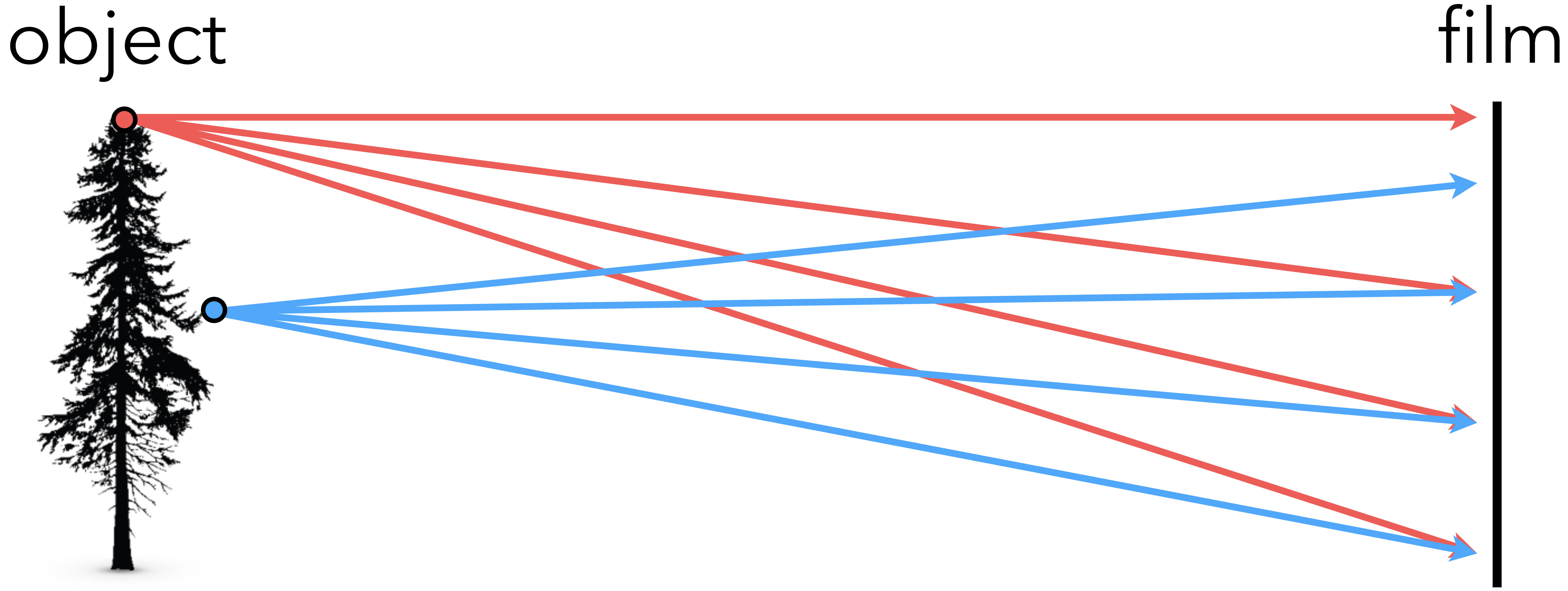
We don't make measurements in the image plane

Fooling the eye

Fooling the eye

Making of 3D sidewalk art: http://www.youtube.com/watch?v=3SNYtd0Ayt0

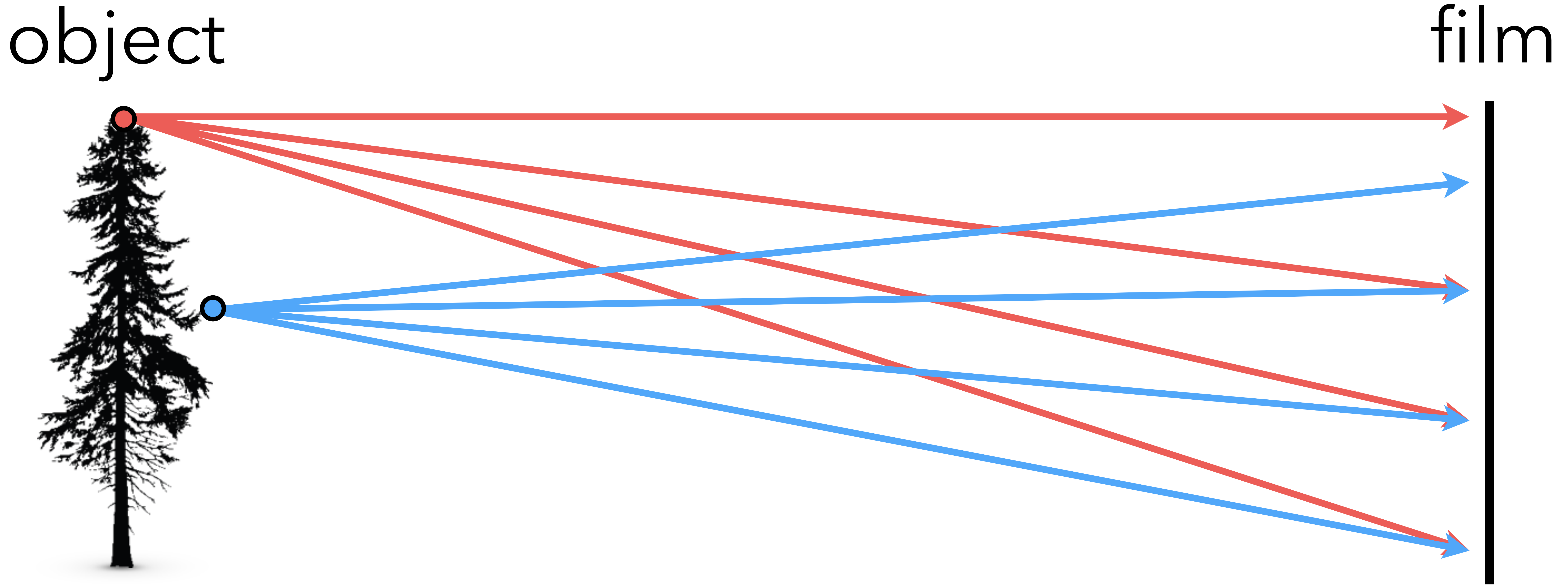
How do we see the world?



Let's design a camera

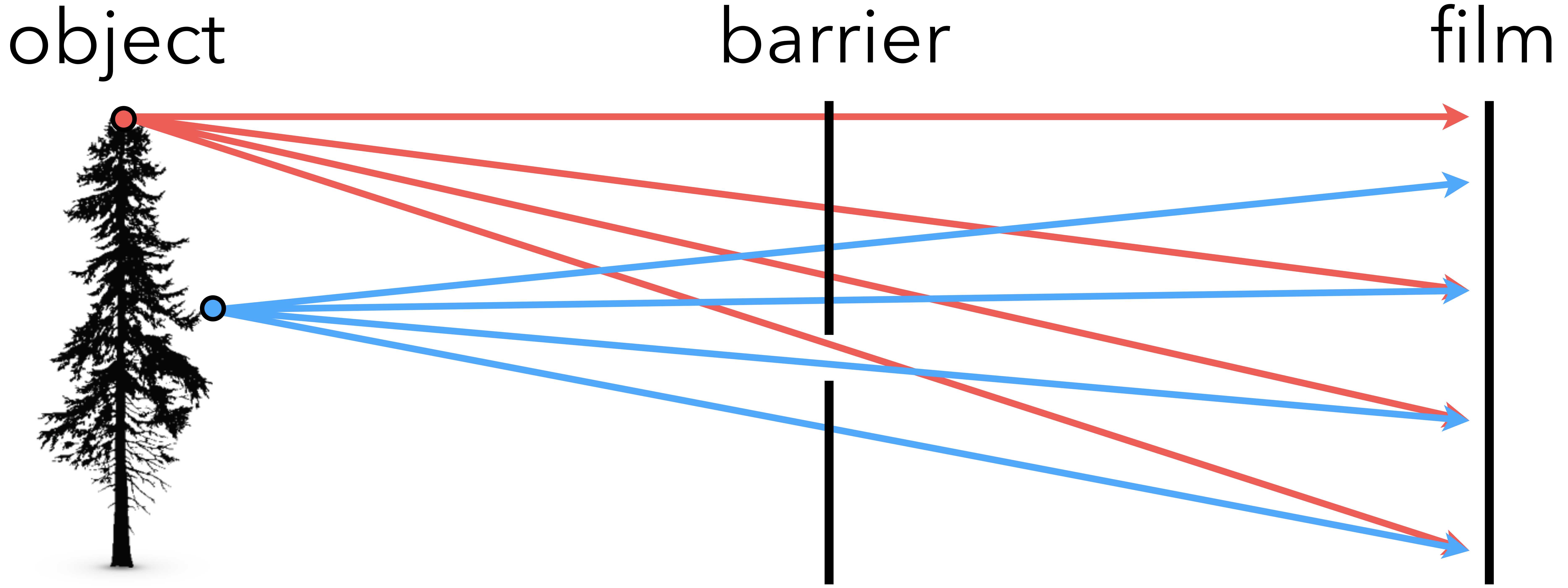
- Idea 1: put a piece of film in front of an object
- Do we get a reasonable image?

How do we see the world?



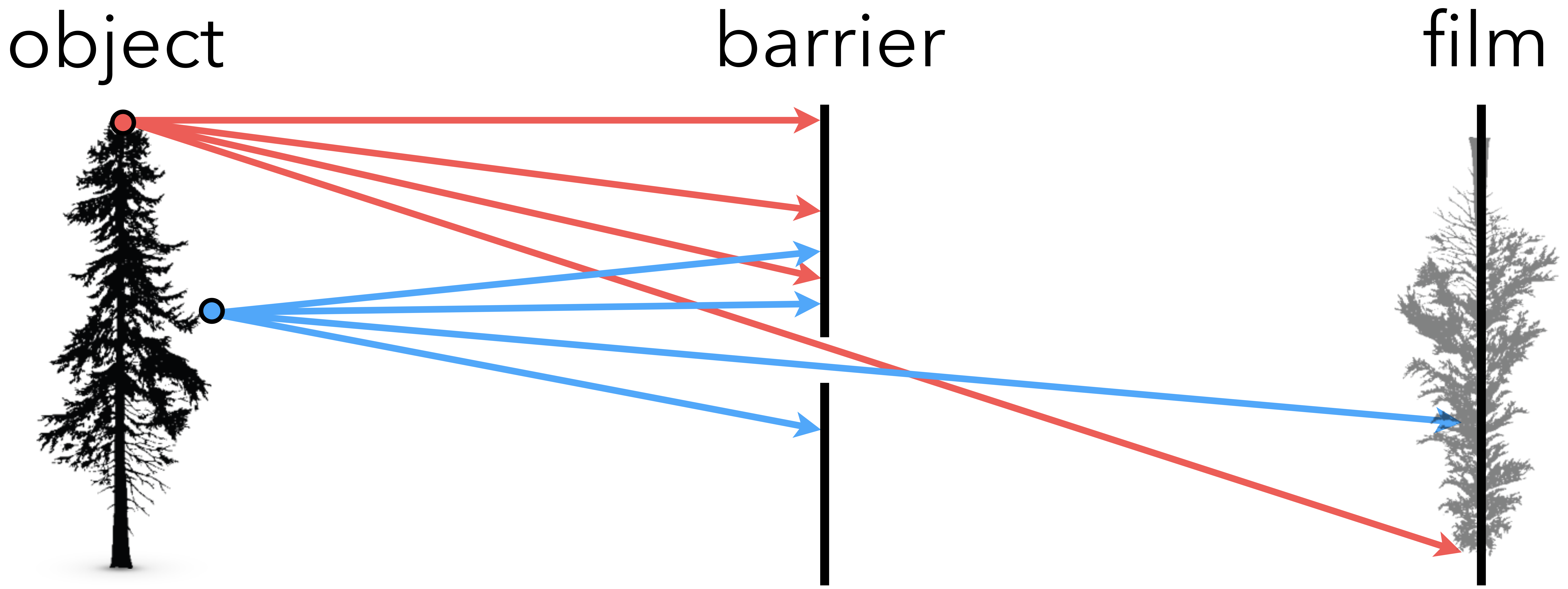
- Receives light from all directions
- Gets all possible images from all possible viewpoints
- Need to be more selective. How?

How do we see the world?



Add a barrier to block off most of the rays

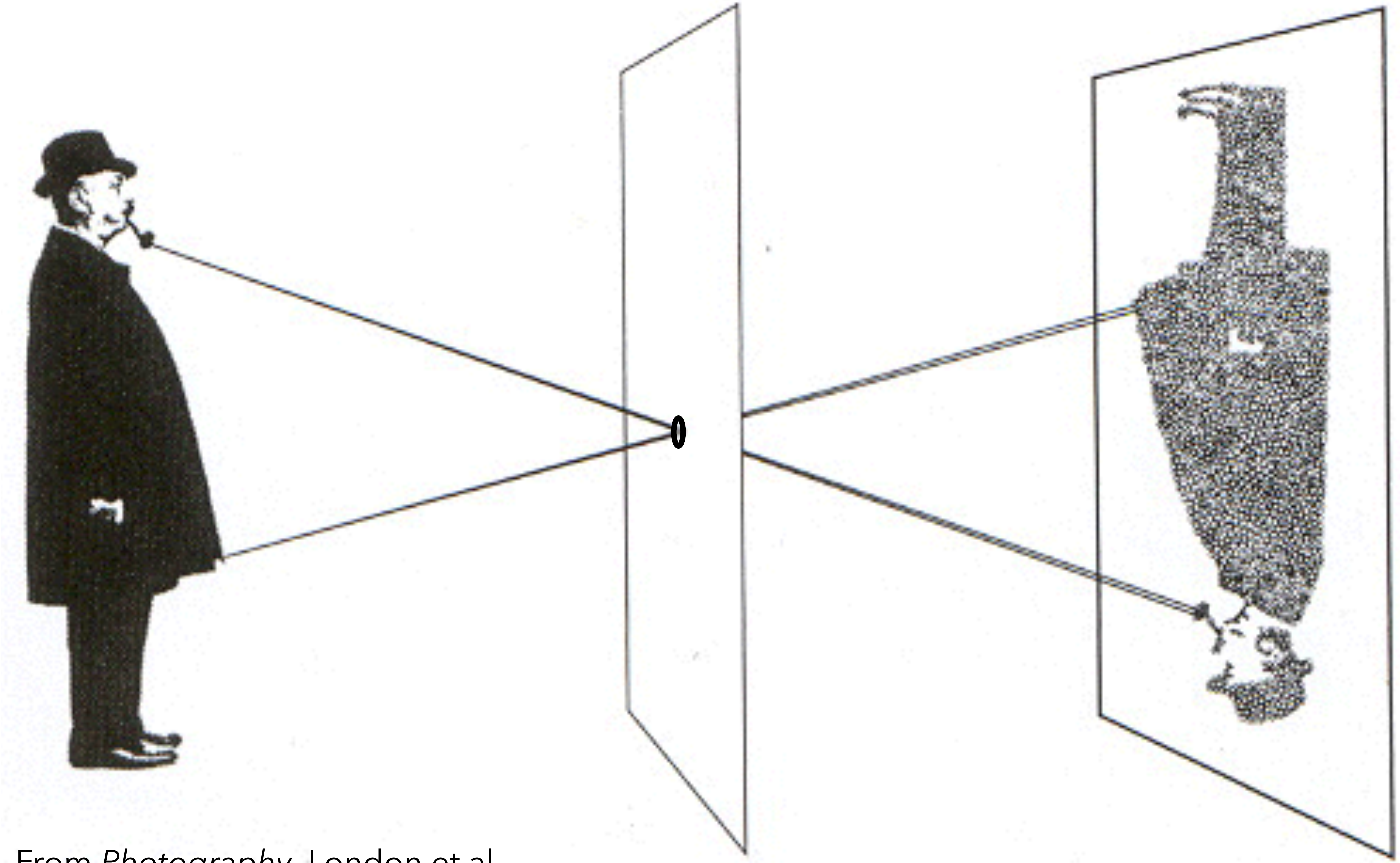
How do we see the world?



Add a barrier to block off most of the rays

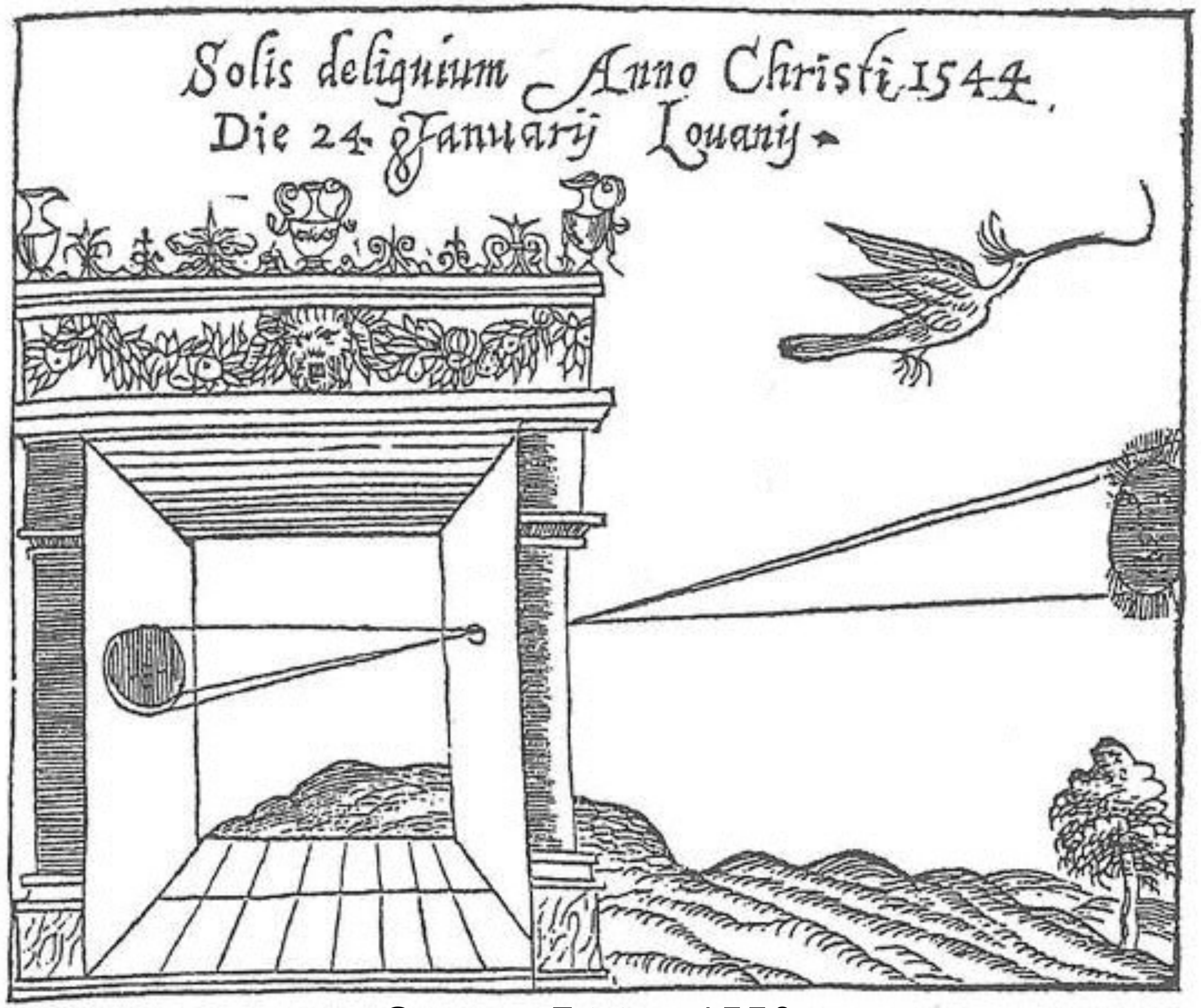
- Opening known as the aperture
- Reduces blurring

Pinhole camera



From *Photography*, London et al.

Pinhole camera (aka camera obscura)



Gemma Frisius, 1558

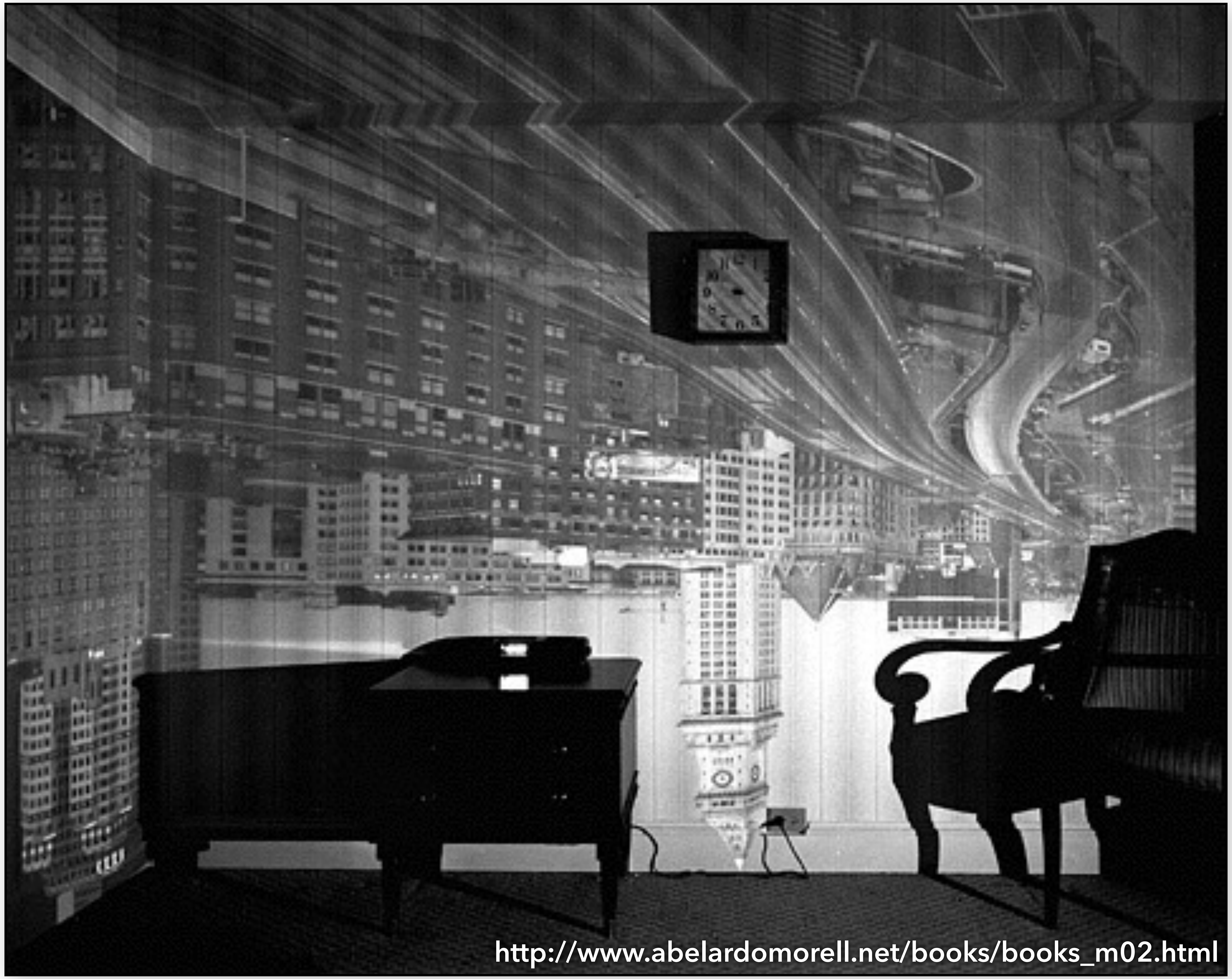
First idea: Mo-Ti, China (470-390 BC)

First built: Alhazen, Iraq/Egypt (965-1039 AD)

Drawing aid for artists: described by Leonardo da Vinci (1452-1519)

http://en.wikipedia.org/wiki/Pinhole_camera

8-hour exposure (Abelardo Morell)



Abelardo Morell

Pinhole cameras everywhere


[Nils van der Burg]

Tree shadow
during solar eclipse

Other pinholes

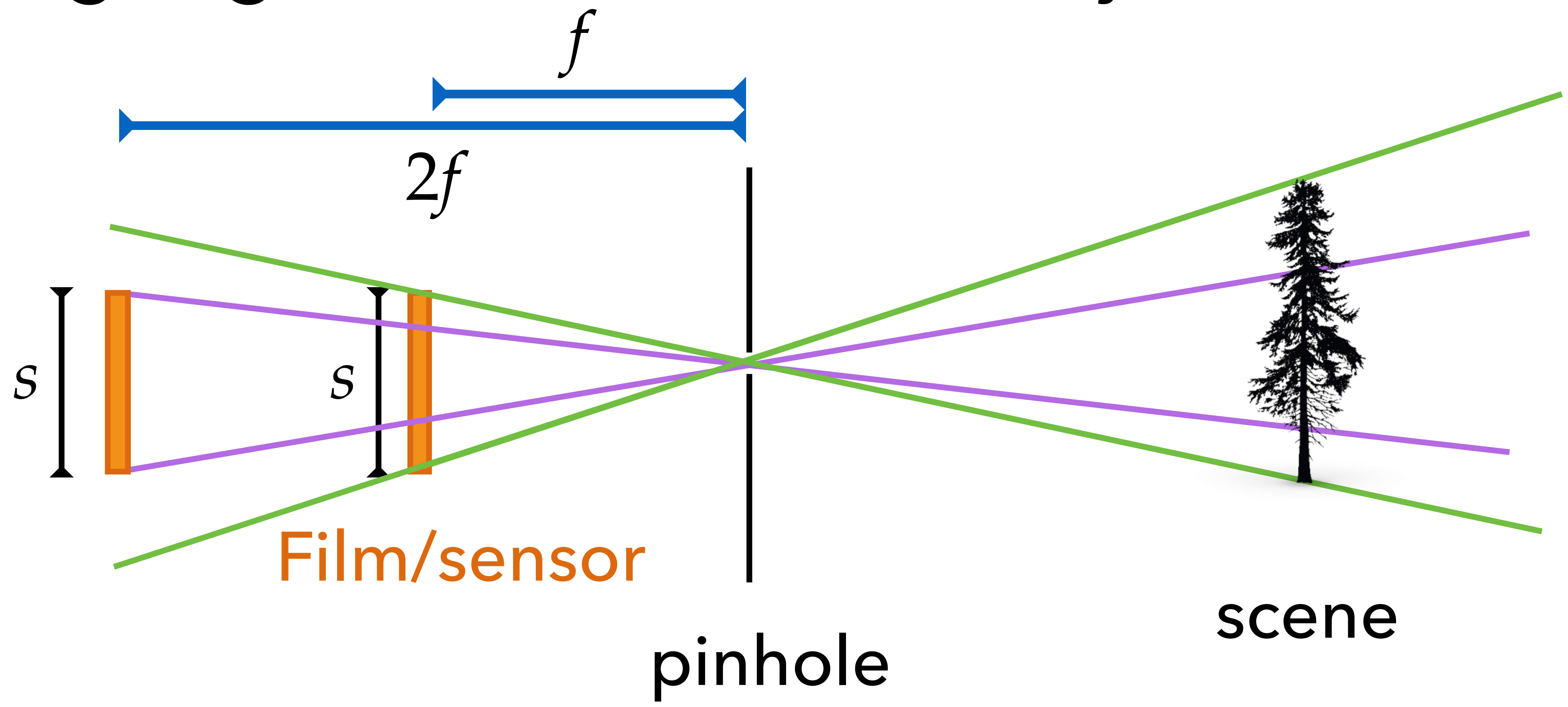
http://www.petapixel.com/2012/04/18/german-garbage-men-turn-dumpsters-into-giant-pinhole-cameras/

Another way to make a pinhole camera

Pinhole optics: "focal length"

What happens when the "focal length" is doubled?

- Projected object size is doubled
- Amount of light gathered is divided by 4



tree image: NRC Canada

Field of view

Determines how much of scene is in frame

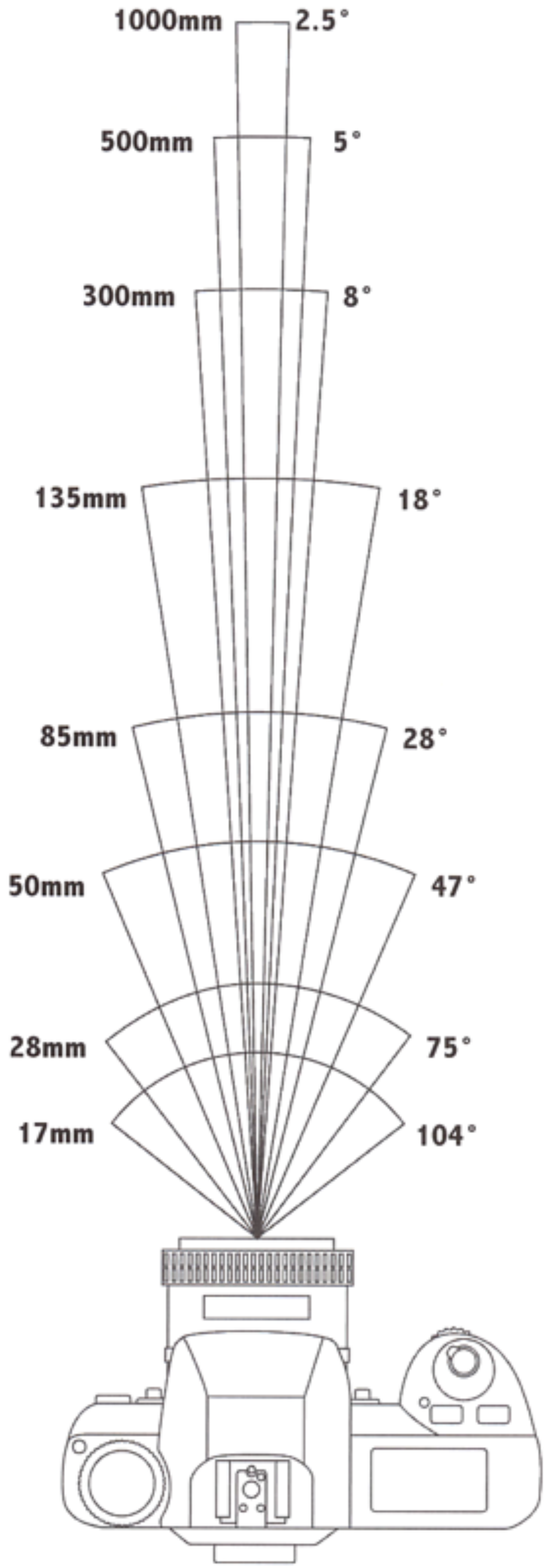
Traditionally specified by focal length

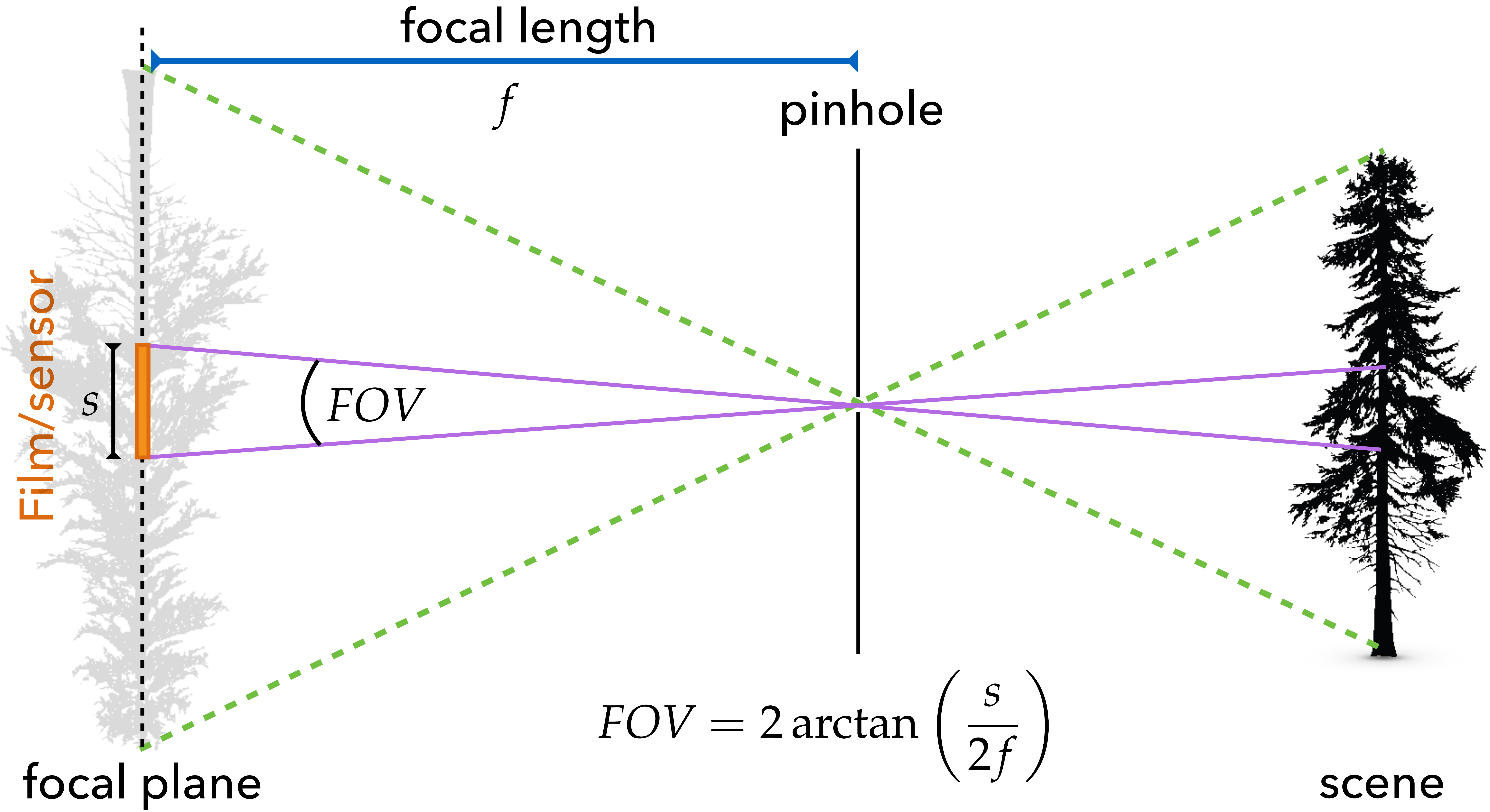
- but interpreting this number requires considering the "format," or size of the film or sensor

After decades of 35mm, we are stuck with that standard

- fields of view are usually discussed using the numbers that would be written on a lens for the 35mm format

FOV depends on focal length





$$FOV = 2\arctan\left(\frac{s}{2f}\right)$$

tree image: NRC Canada

Questions?

Another way to make a pinhole camera

Why so blurry?

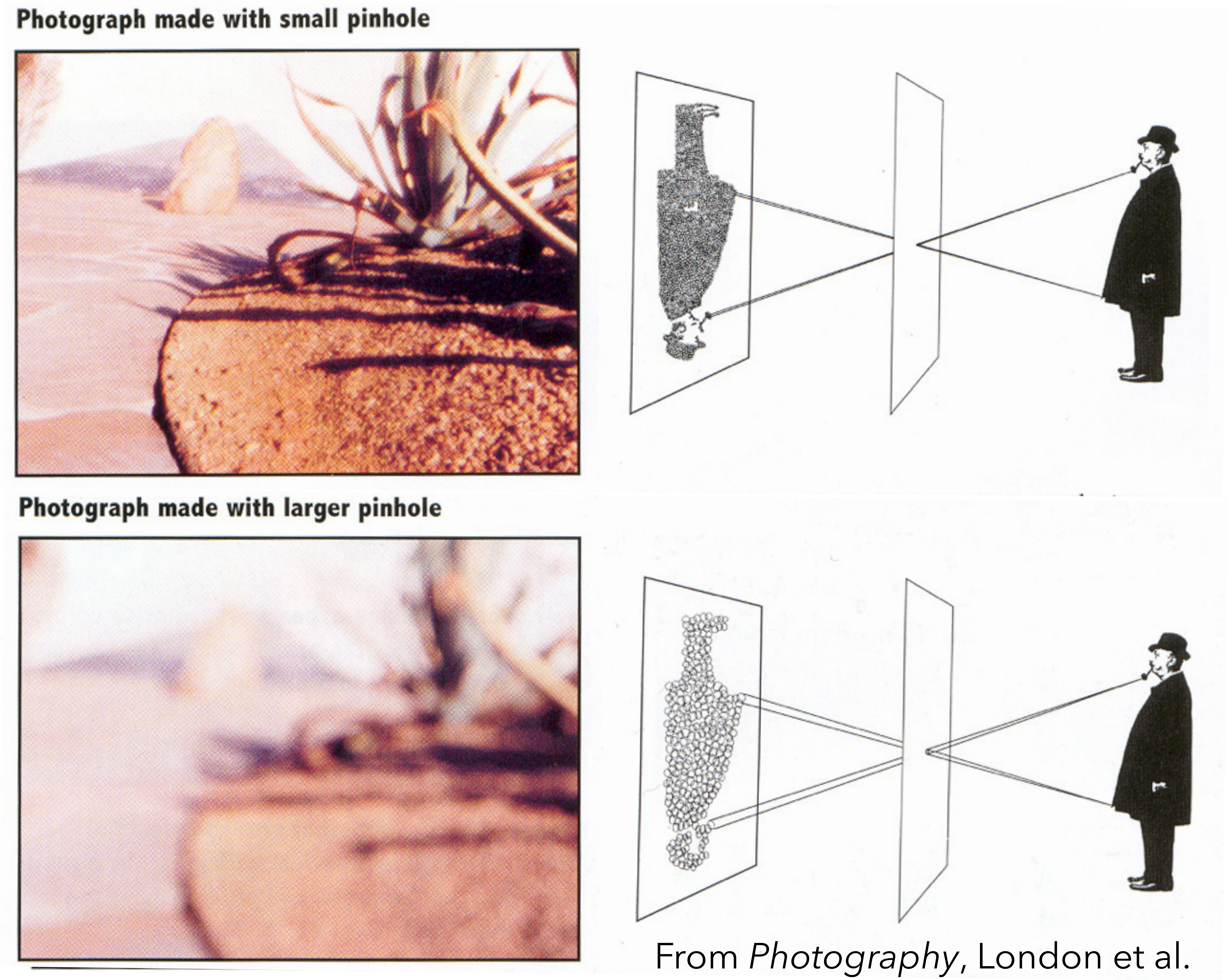
Pinhole size?

Small pinhole:

- sharper image

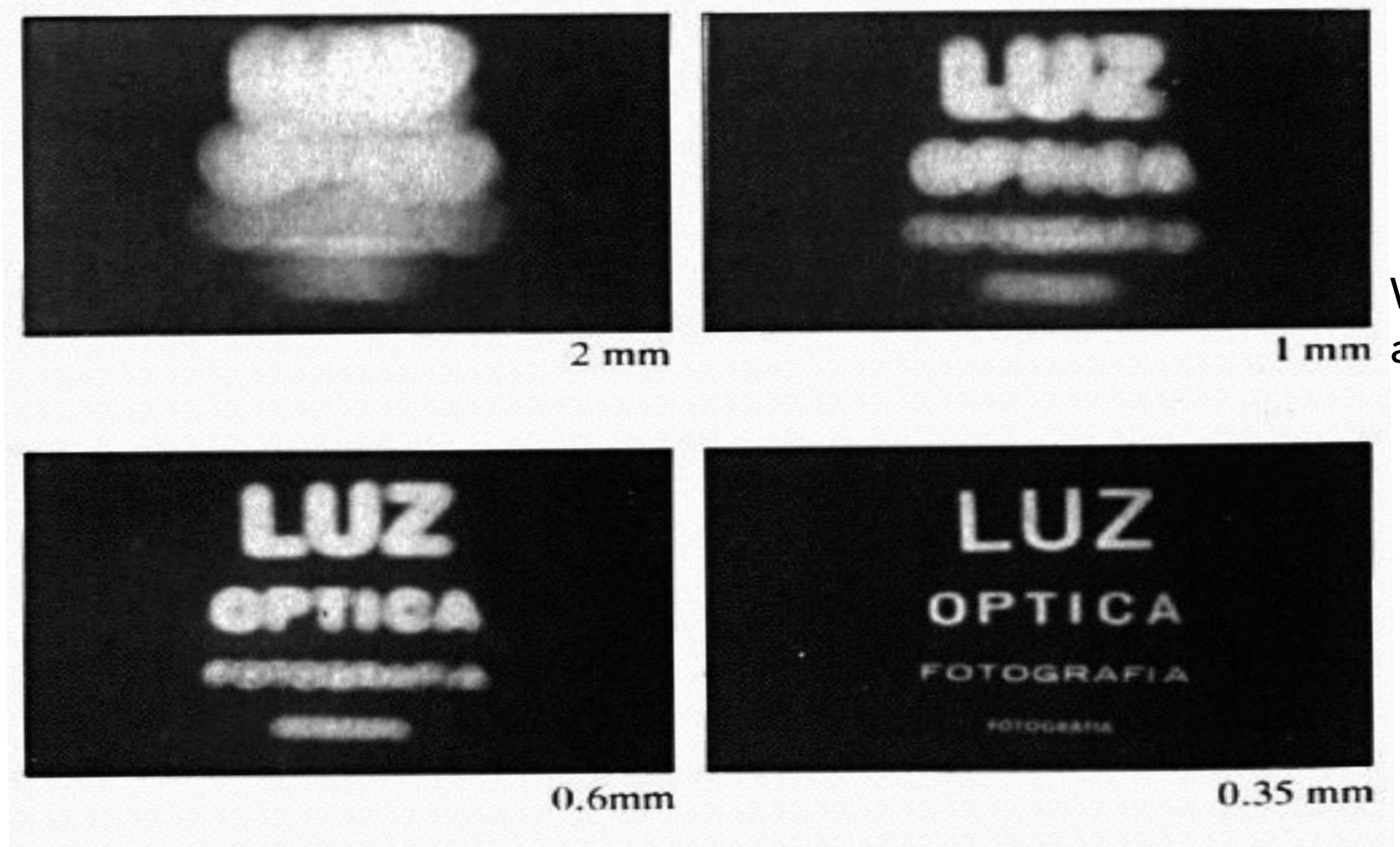
Larger pinhole:

- blurrier image



From *Photography*, London et al.

Shrinking the aperture



Why not make aperture as small as possible?

- Less light gets through
- Why does it get blurrier?

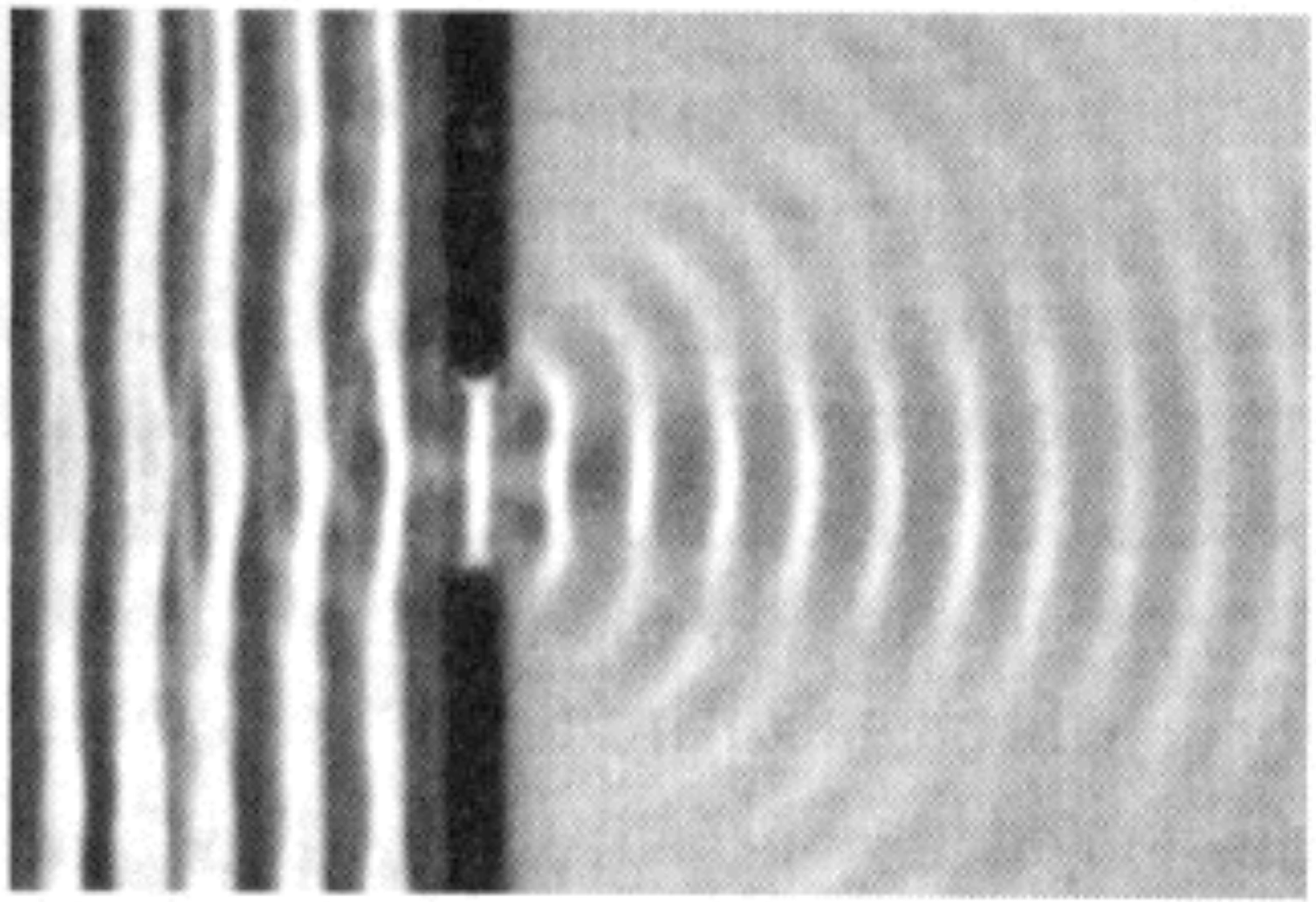
Diffraction

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

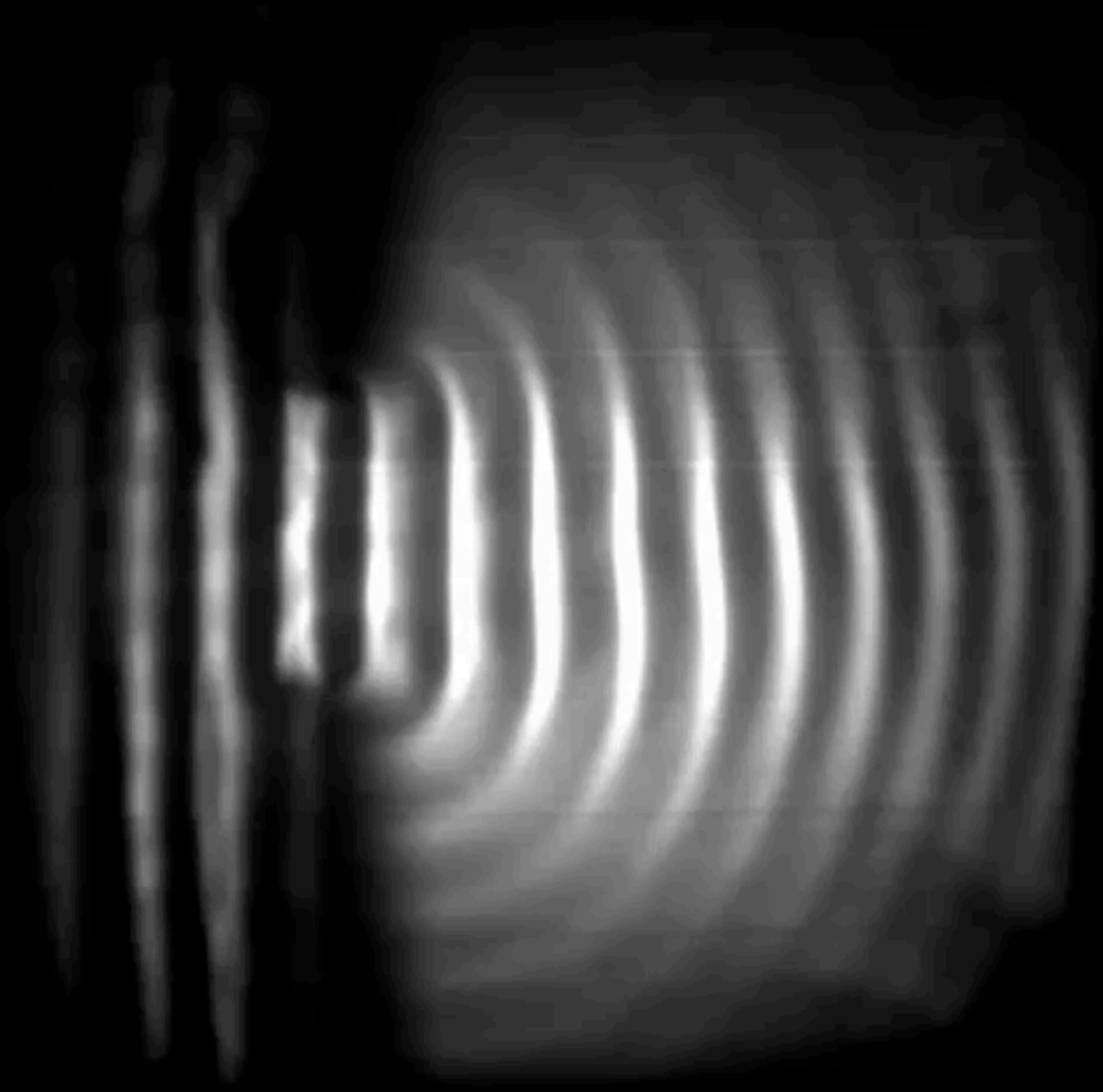
http://www.youtube.com/watch?v=kH57Di7Sj0c

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



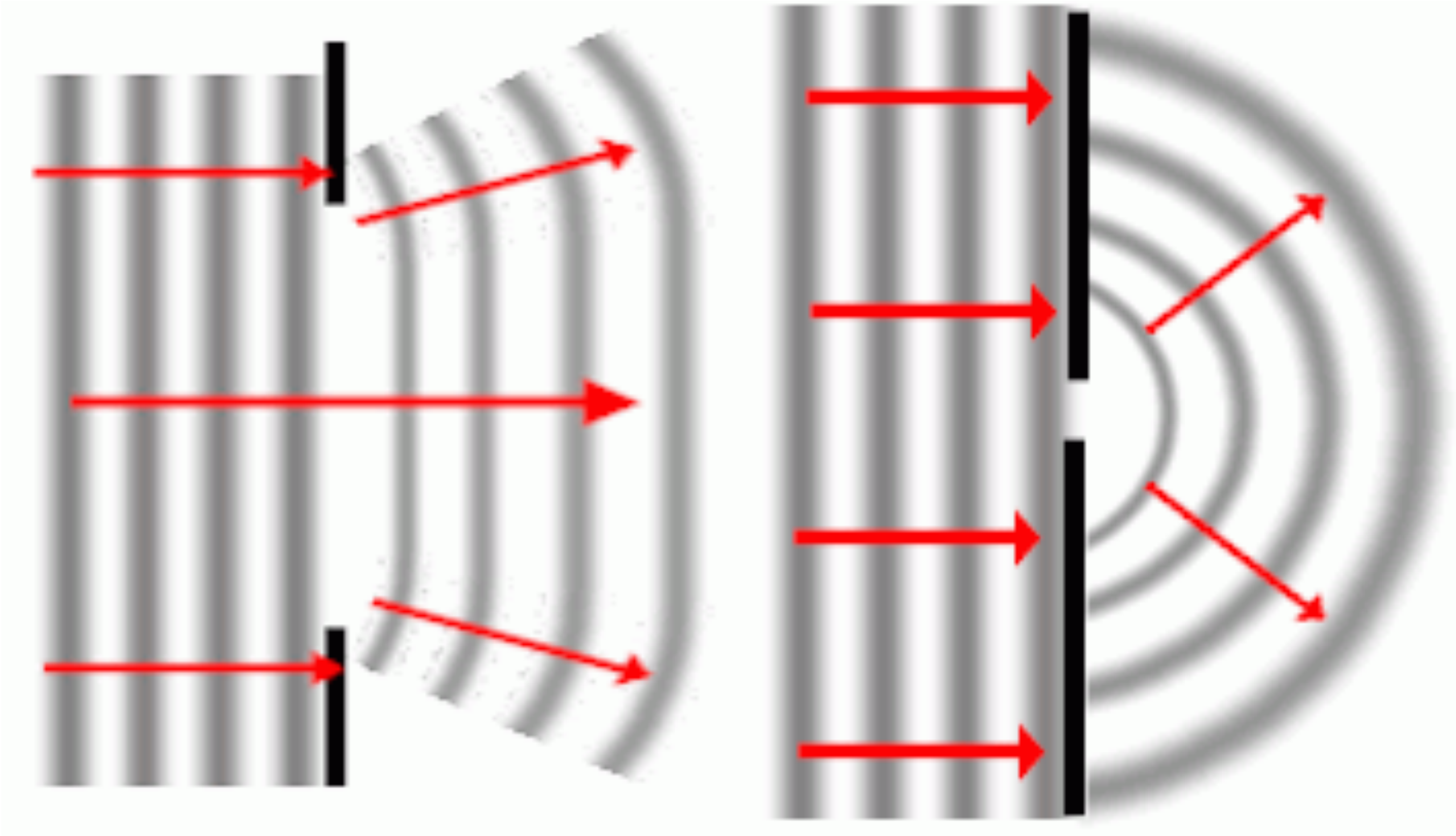
Bottom line

The smaller the hole, the more diffraction

Depends on wavelength of wave (~500 nm for green)

Where is the sweet spot between blurring and diffraction?

$$A \approx 2\sqrt{f\lambda}$$



https://en.wikipedia.org/wiki/Pinhole_camera#Selection_of_pinhole_size

http://www.mashpedia.com/Ripple_tank

Camera, version 0: Box with hole

Pinhole recap:

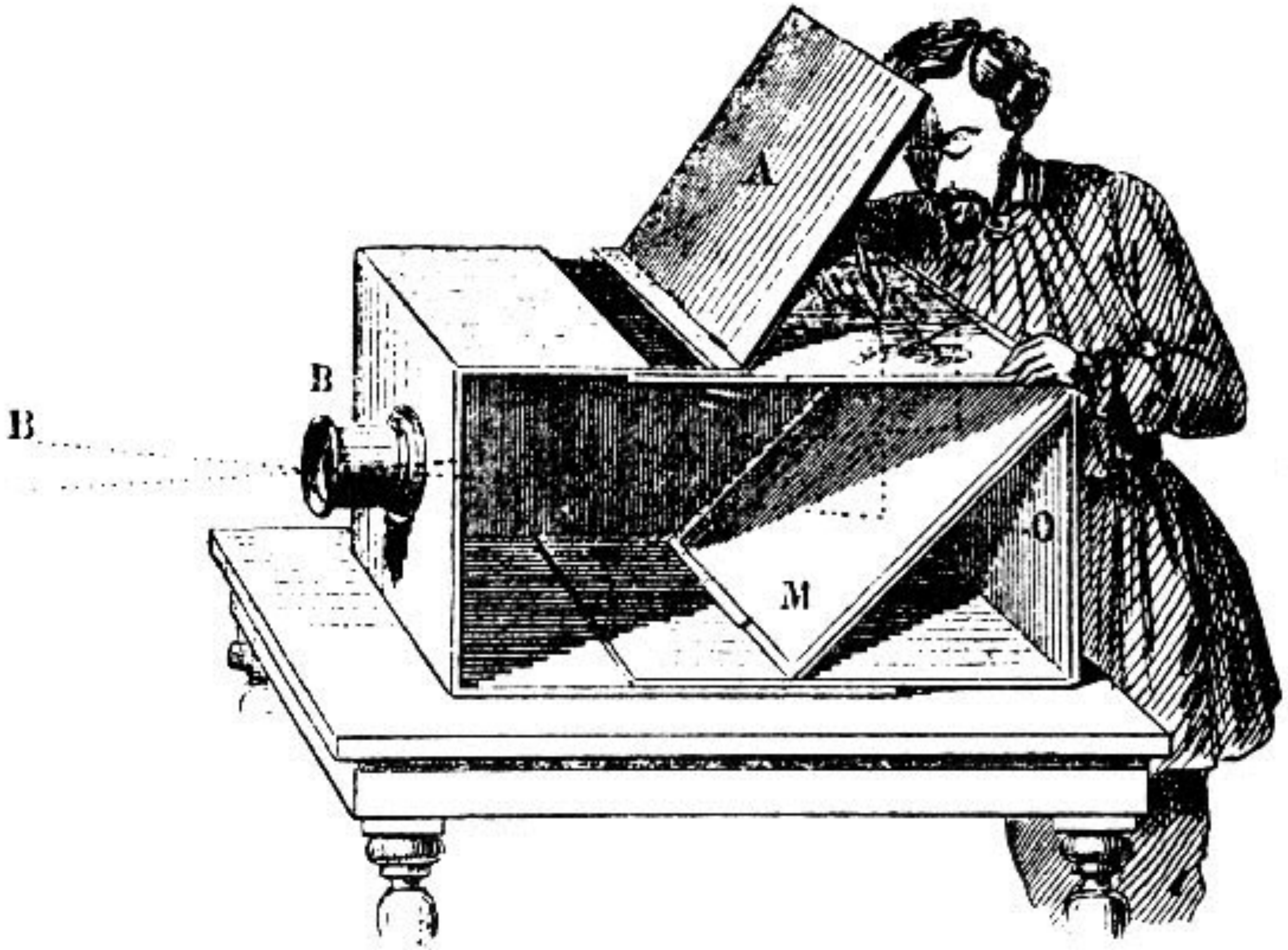
- Large pinholes produce blurry images
- Small pinholes produce dim images
- Diffraction limits sharpness for tiny pinholes

Questions?


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

Assignment 1: Shoe-box Camera Obscura

Due next week. Start early! Can work with a partner.



Be careful…

http://www.petapixel.com/2011/05/25/university-mistakes-pinhole-camera-for-a-bomb-ruins-photo-project/

University Mistakes Pinhole Camera for a Bomb, Ruins Photo Project

Michael Zhang · May 25, 2011 Tweet 101 Like 88

Replacing pinholes with lenses

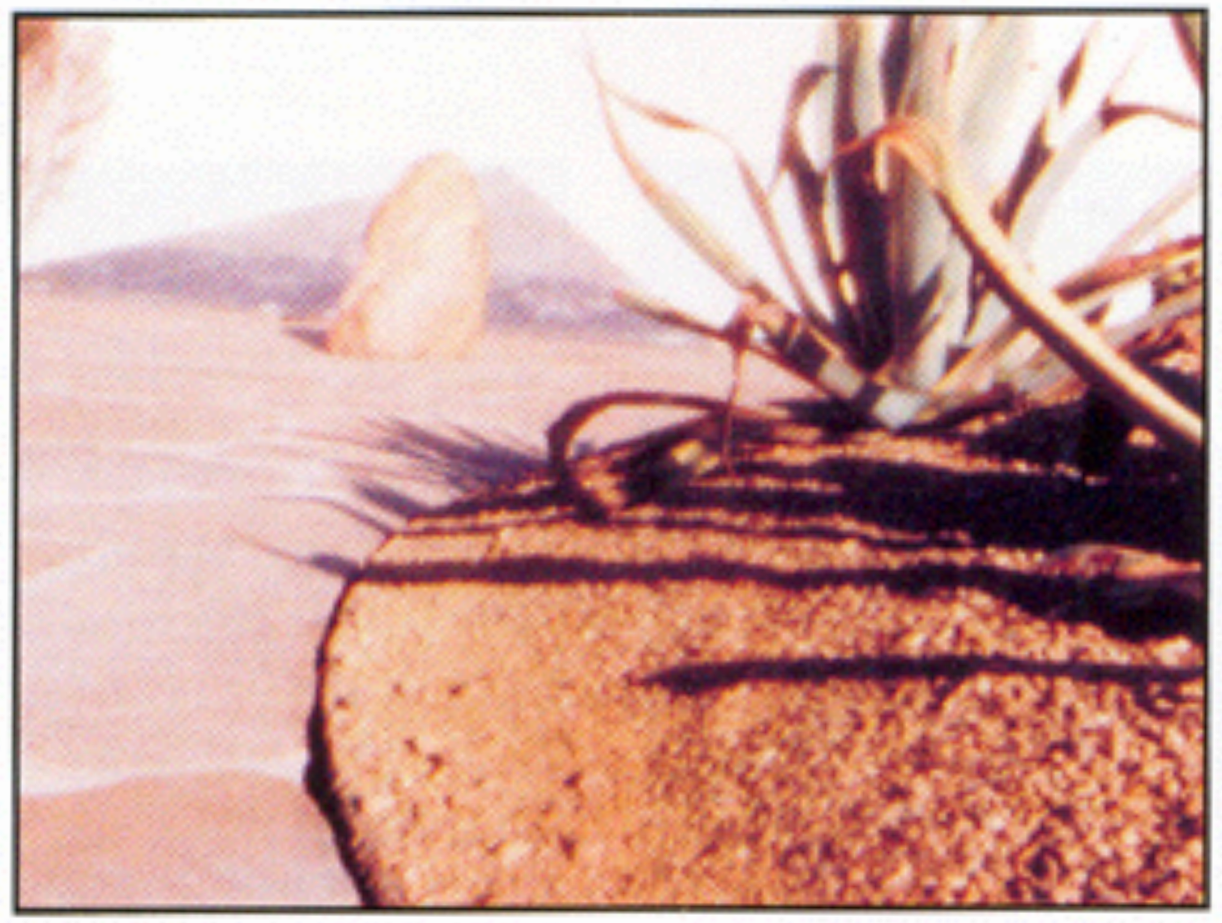
From *Photography*, London et al.

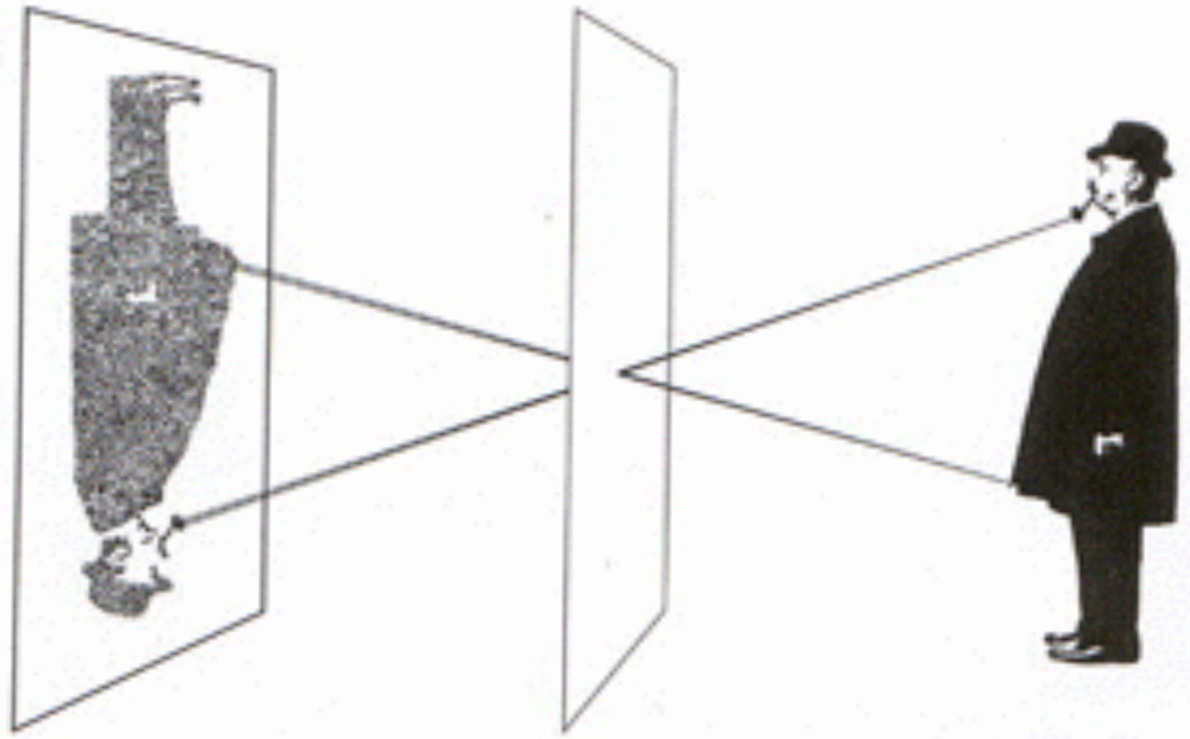
Lenses

Gather more light!

But need to be focused

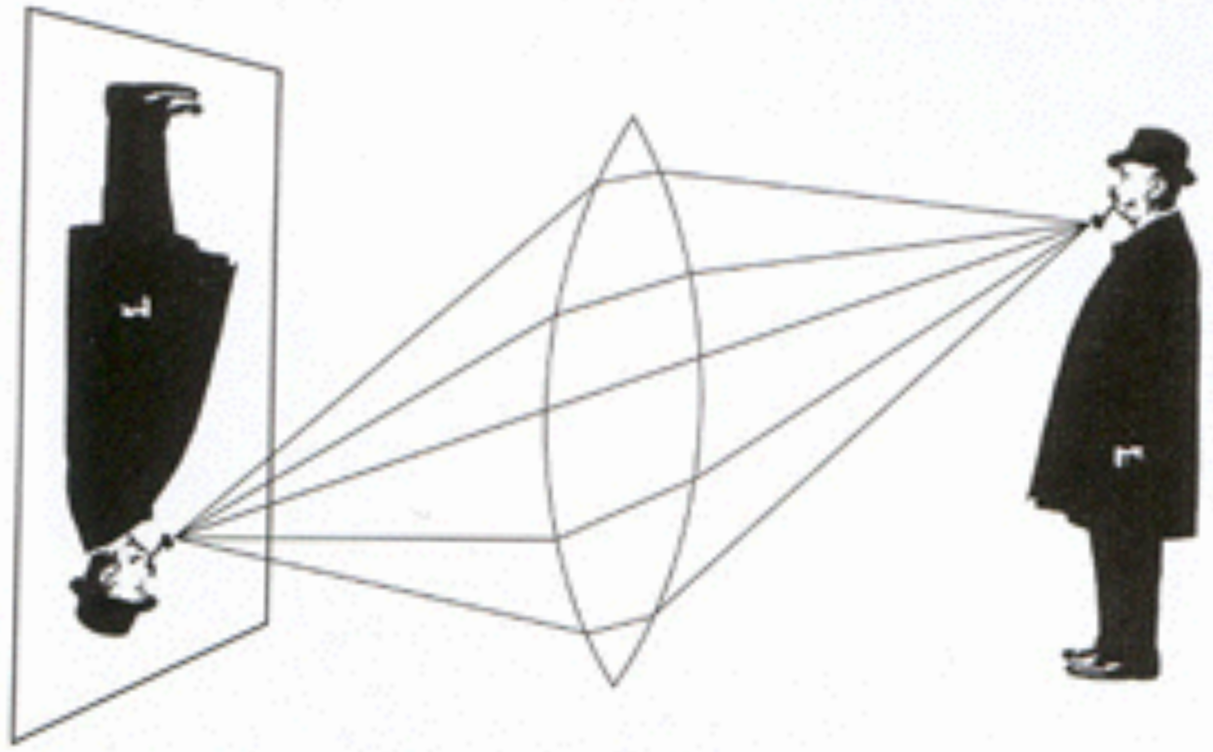
Photograph made with small pinhole





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.*

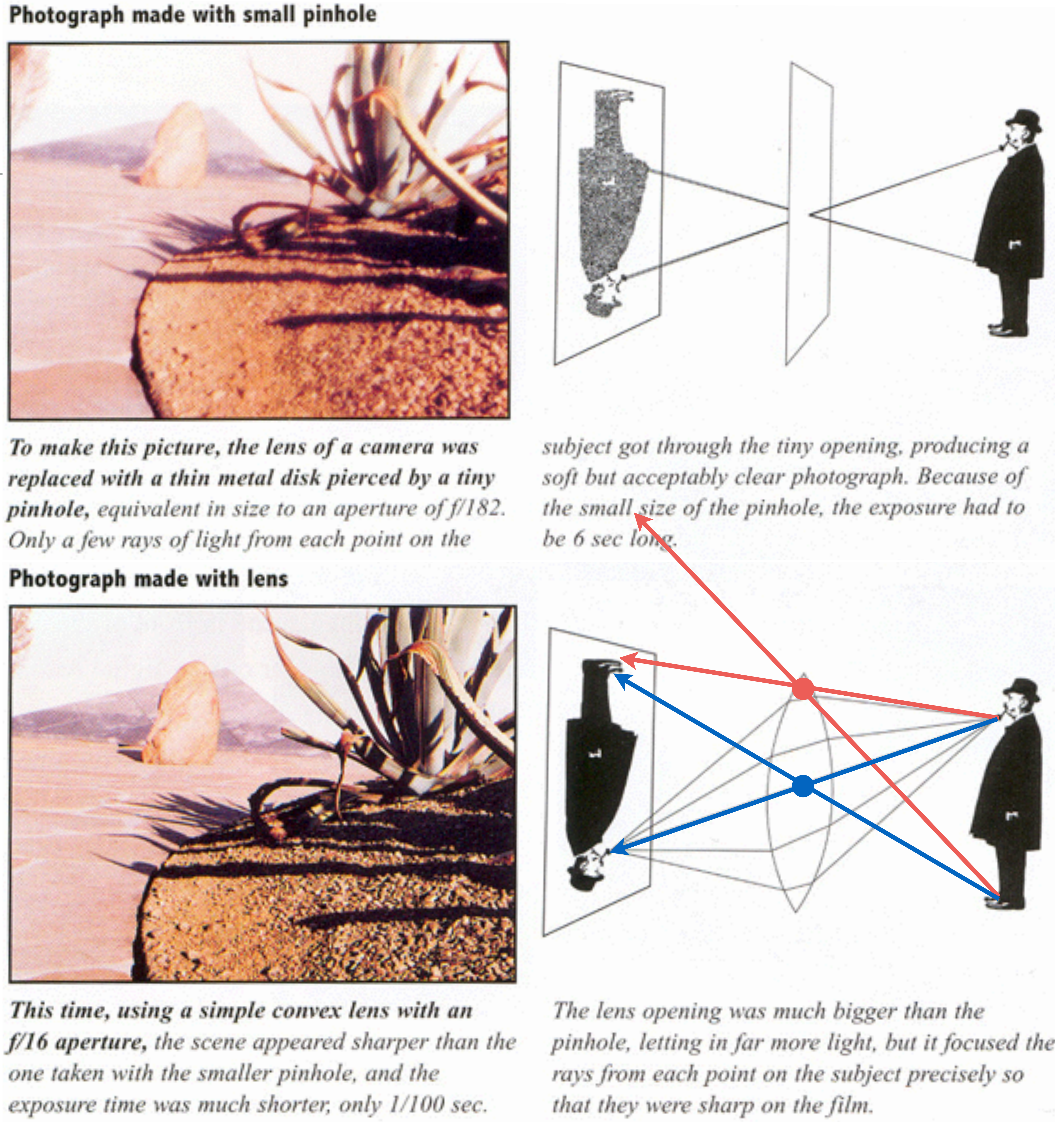
From *Photography*, London et al.

Lenses

Essentially add multiple pinhole images

~ shift them to align (refraction)

Alignment works only for one distance


Photograph made with small pinhole

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From *Photography*, London et al.

Camera, v. 1: Box with lens & shutter

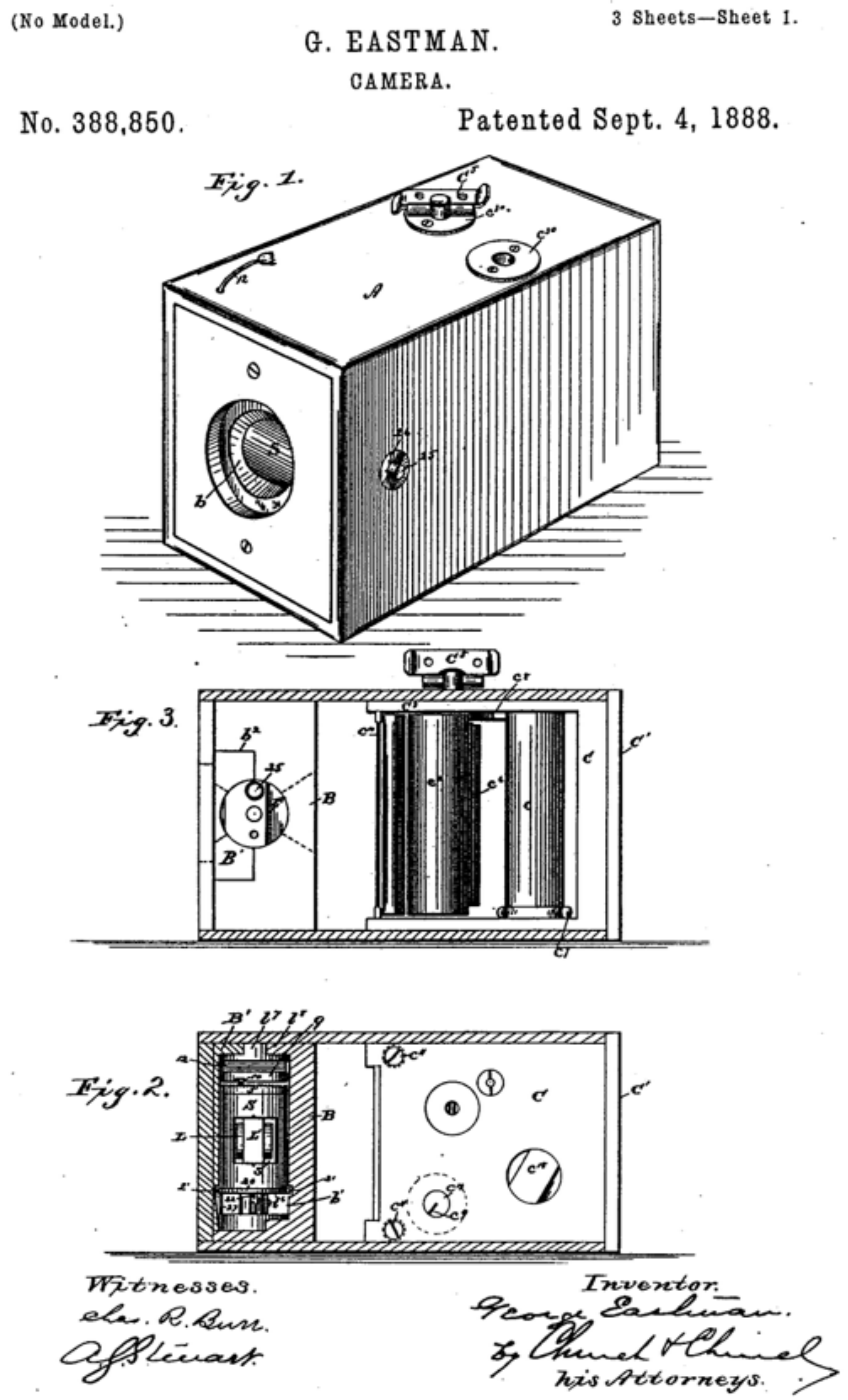
First practical cameras had

- 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 phone camera today)
- want to be outdoors in strong light

George Eastman
Kodak Camera
1888



More ingredients

Timed shutter

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

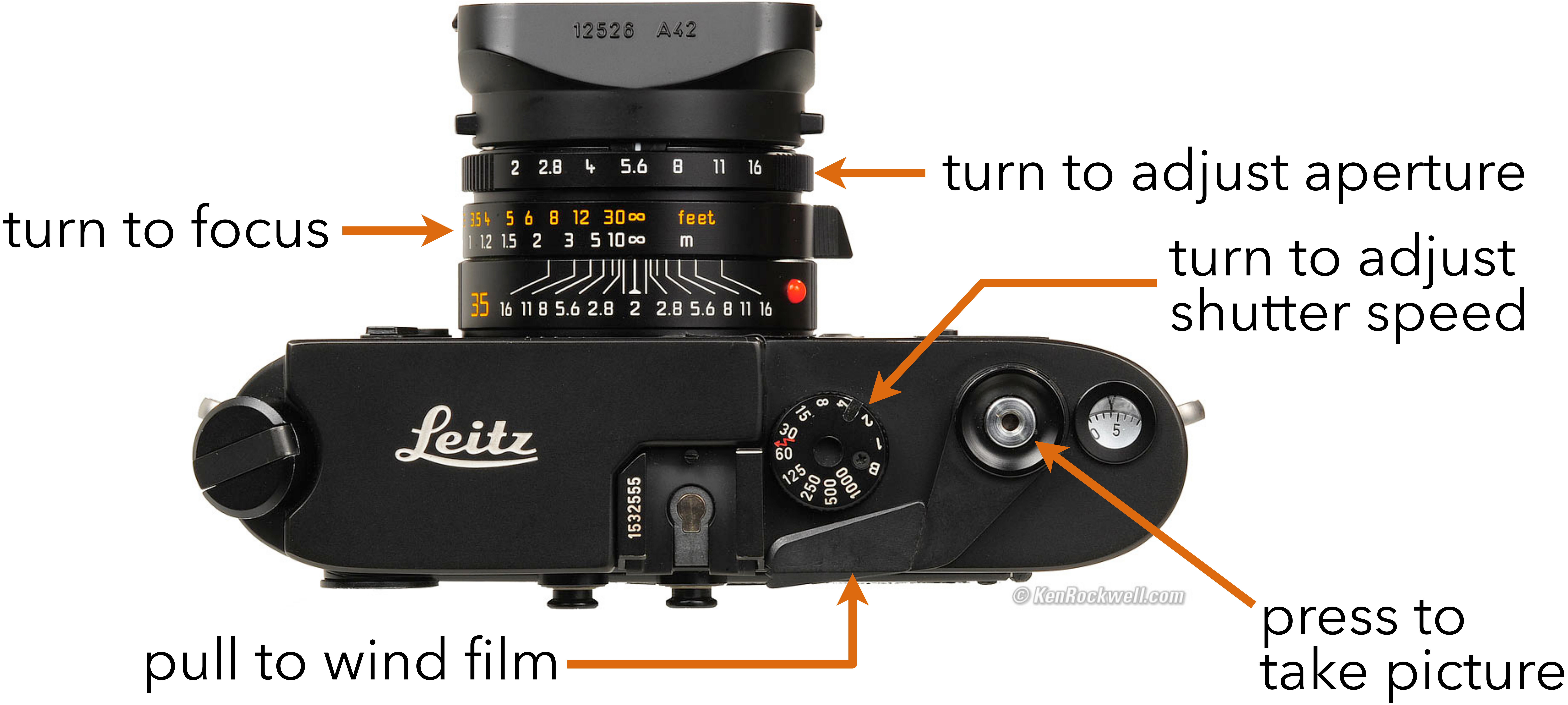
Variable aperture

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

Viewfinder

- to frame what you are photographing
- some way better than guessing

Camera, v. 2: 3 variables, 5 controls



Basic camera controls

Focus

Shutter speed

Aperture size

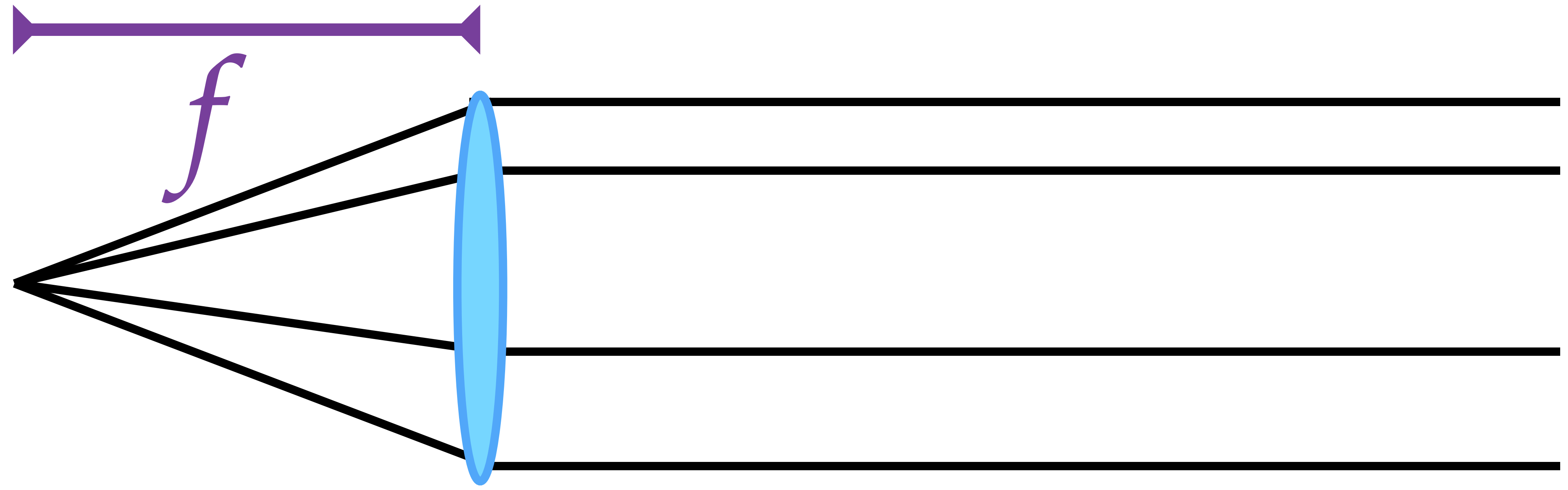
Adjustments that must be set for each image

- by you or by the camera's software
- modern consumers cameras hide these, but they are still there

Thin lens optics

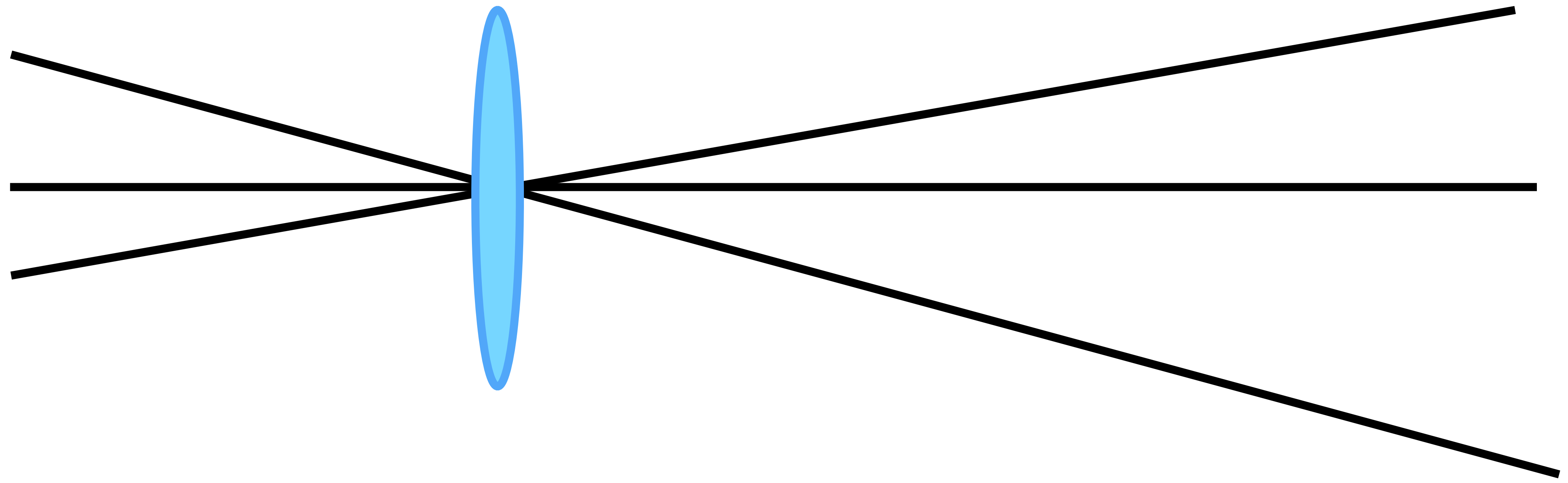
Simplification of geometrical optics for well-behaved lenses

Parallel rays converge to a point on a plane located at the focal length f from lens



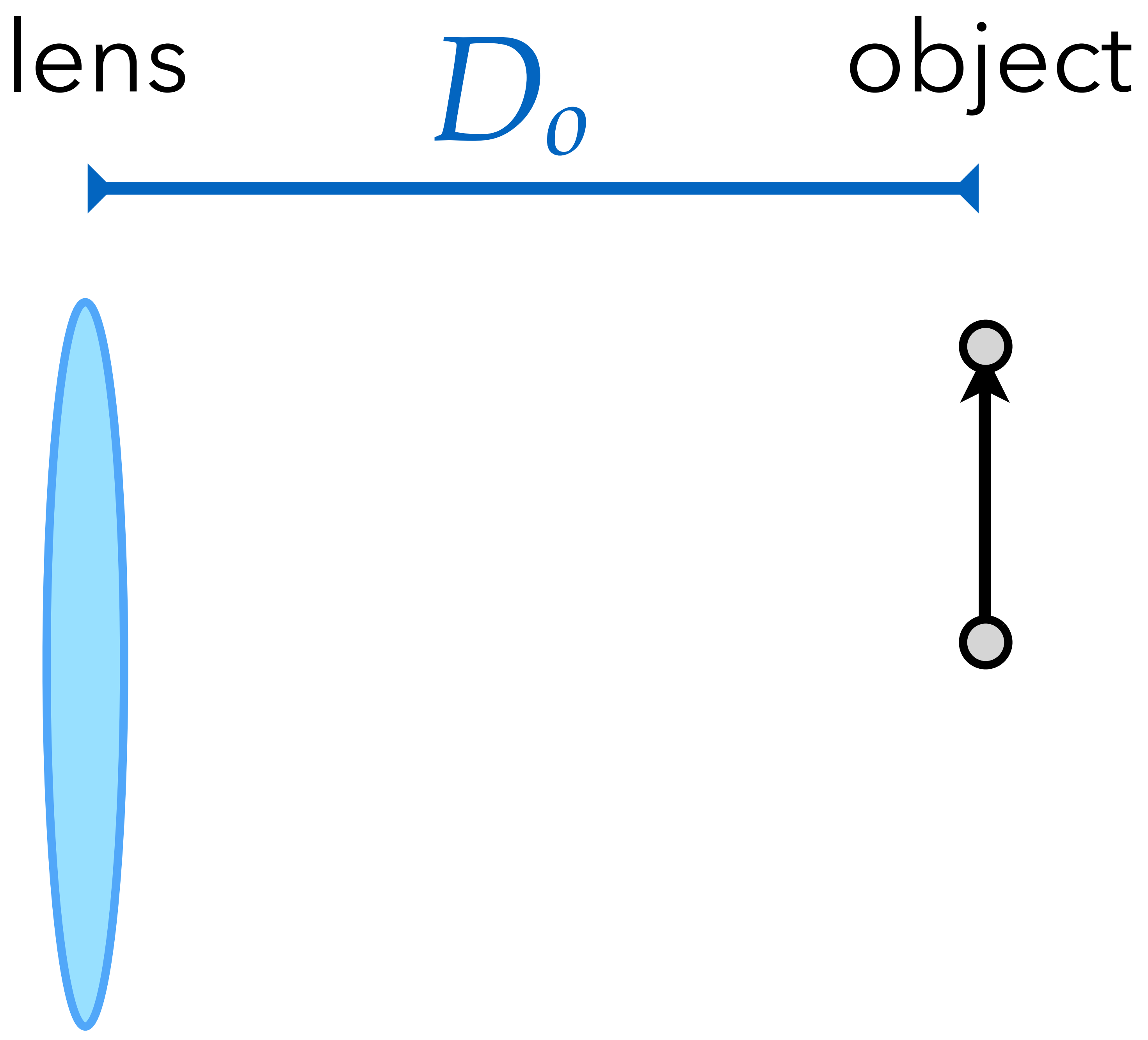
Rays going through the center are not deviated

- hence, same perspective as pinhole



How lenses focus

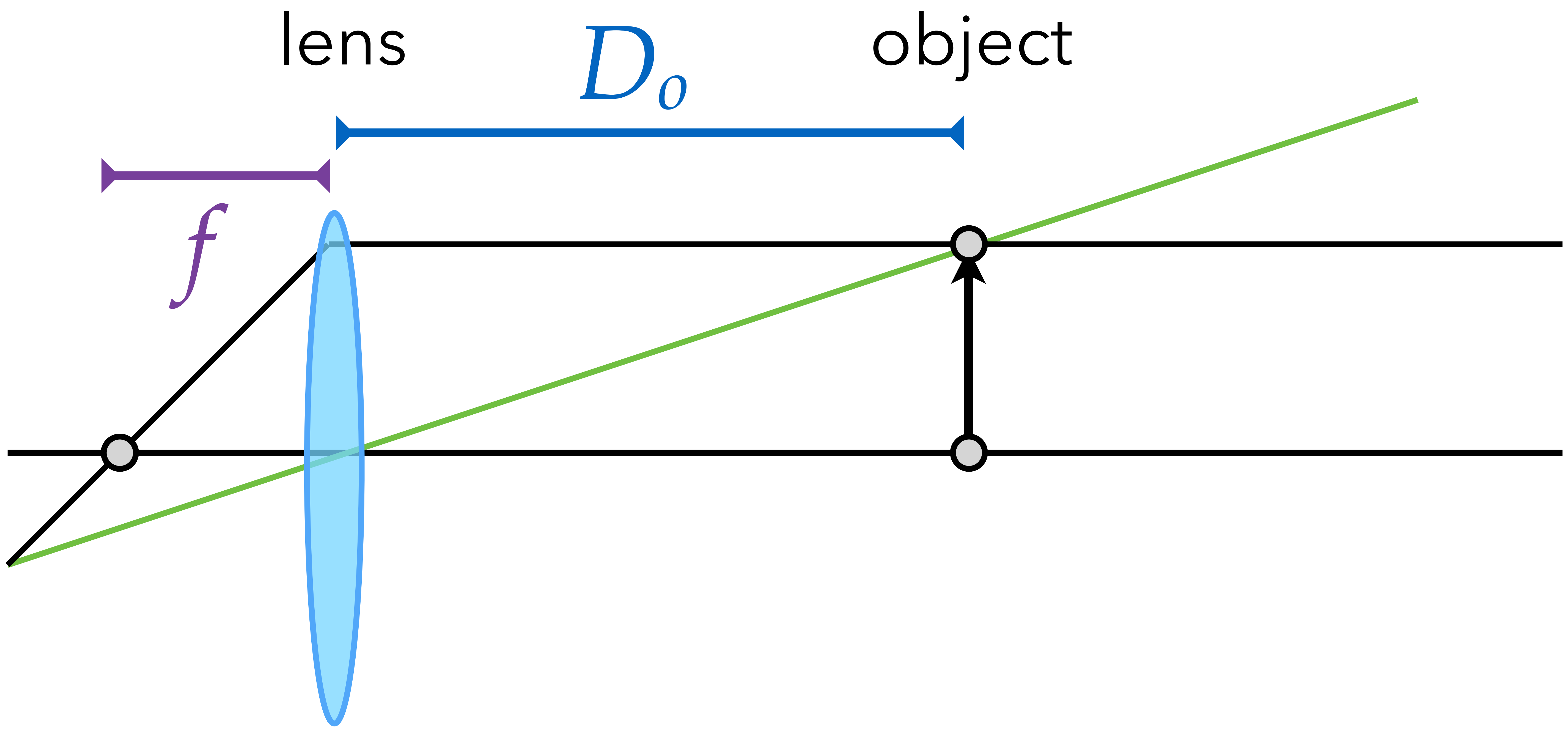
Let's look at an object at distance D_o



How to trace rays

Start by rays through the center

Choose focal length, trace parallels

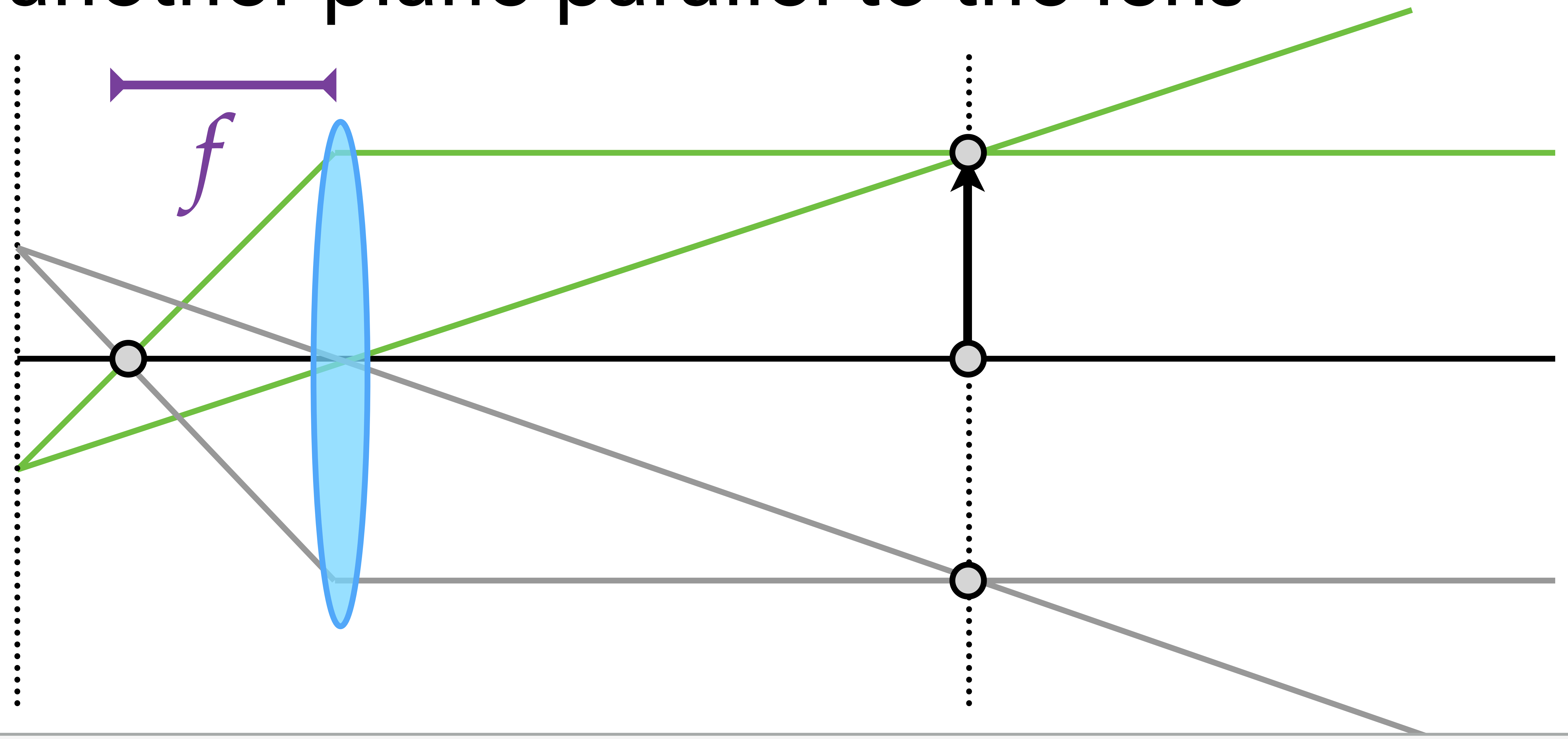


How to trace rays

Start by rays through the center

Choose focal length, trace parallels

All rays coming from points on a plane parallel to the lens are focused on another plane parallel to the lens



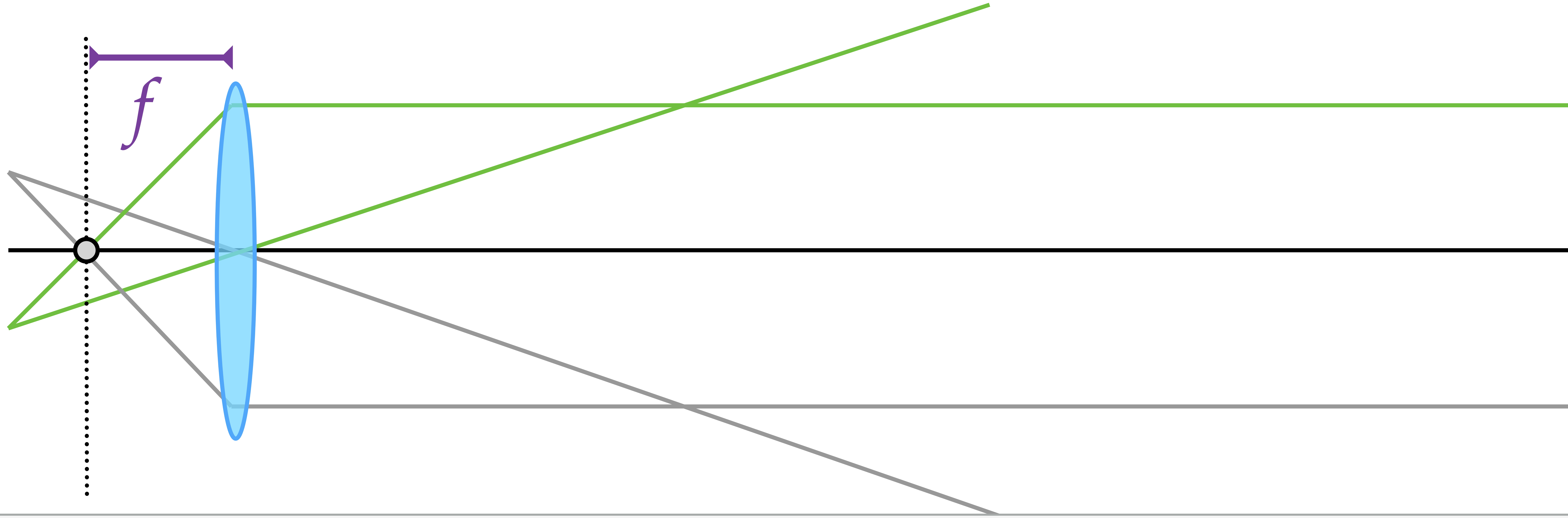
Demo!

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

Focusing

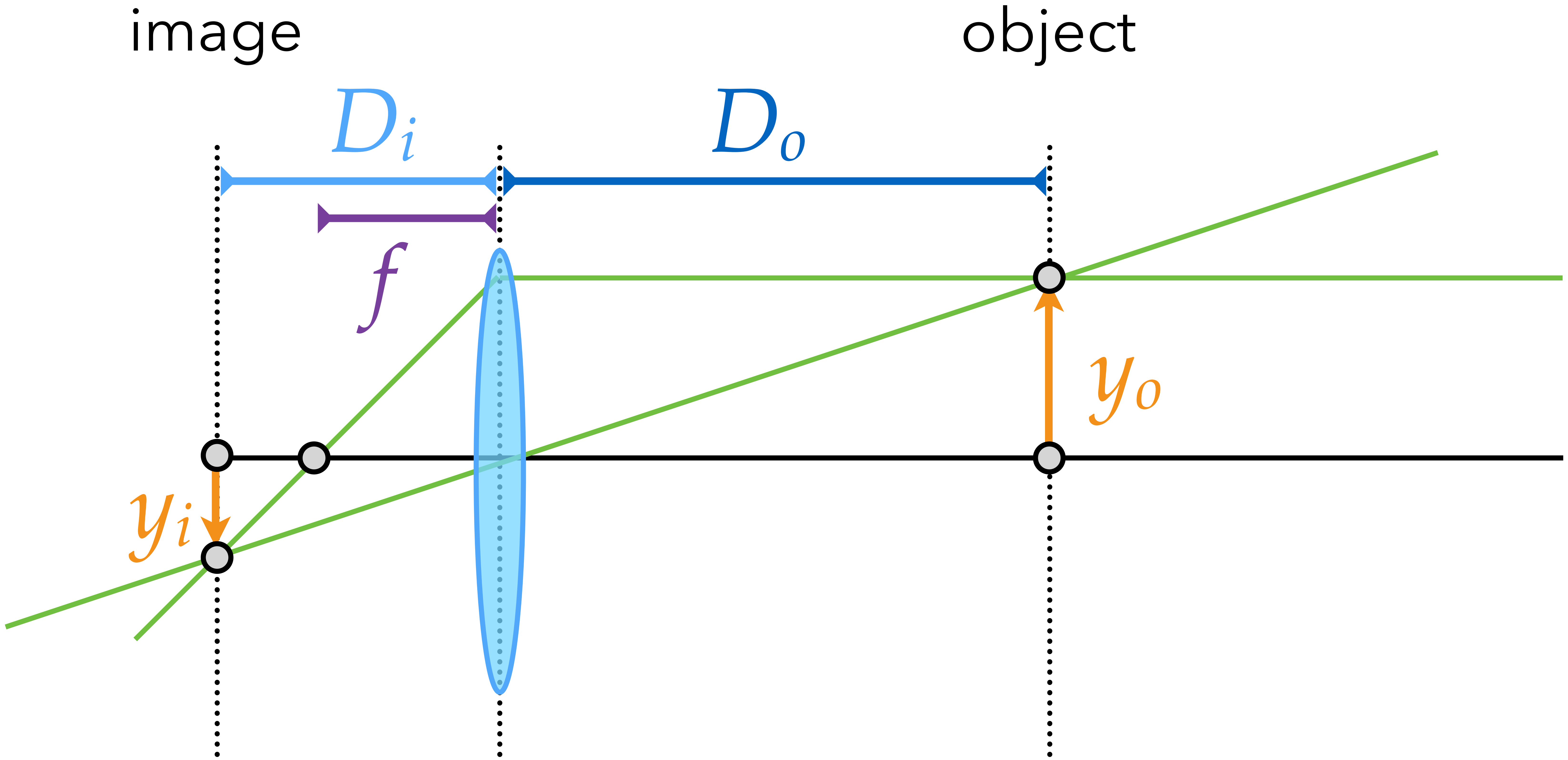
Focus closer than infinity?

- Move the sensor/film *further* than the focal length



Thin lens formula

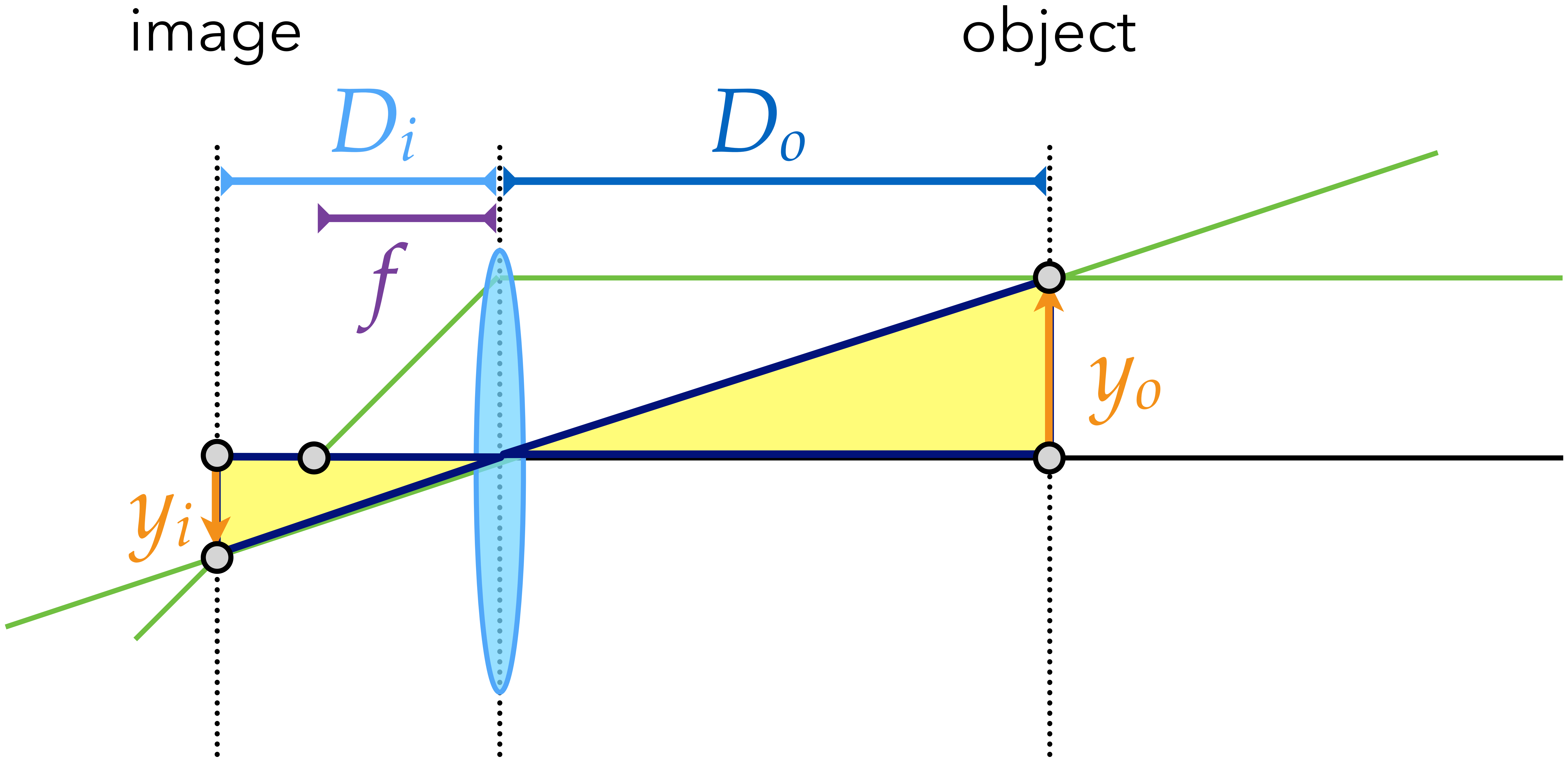
Similar triangles everywhere!



Thin lens formula

Similar triangles everywhere!

$y_i \,/\, y_o = D_i \,/\, D_o$

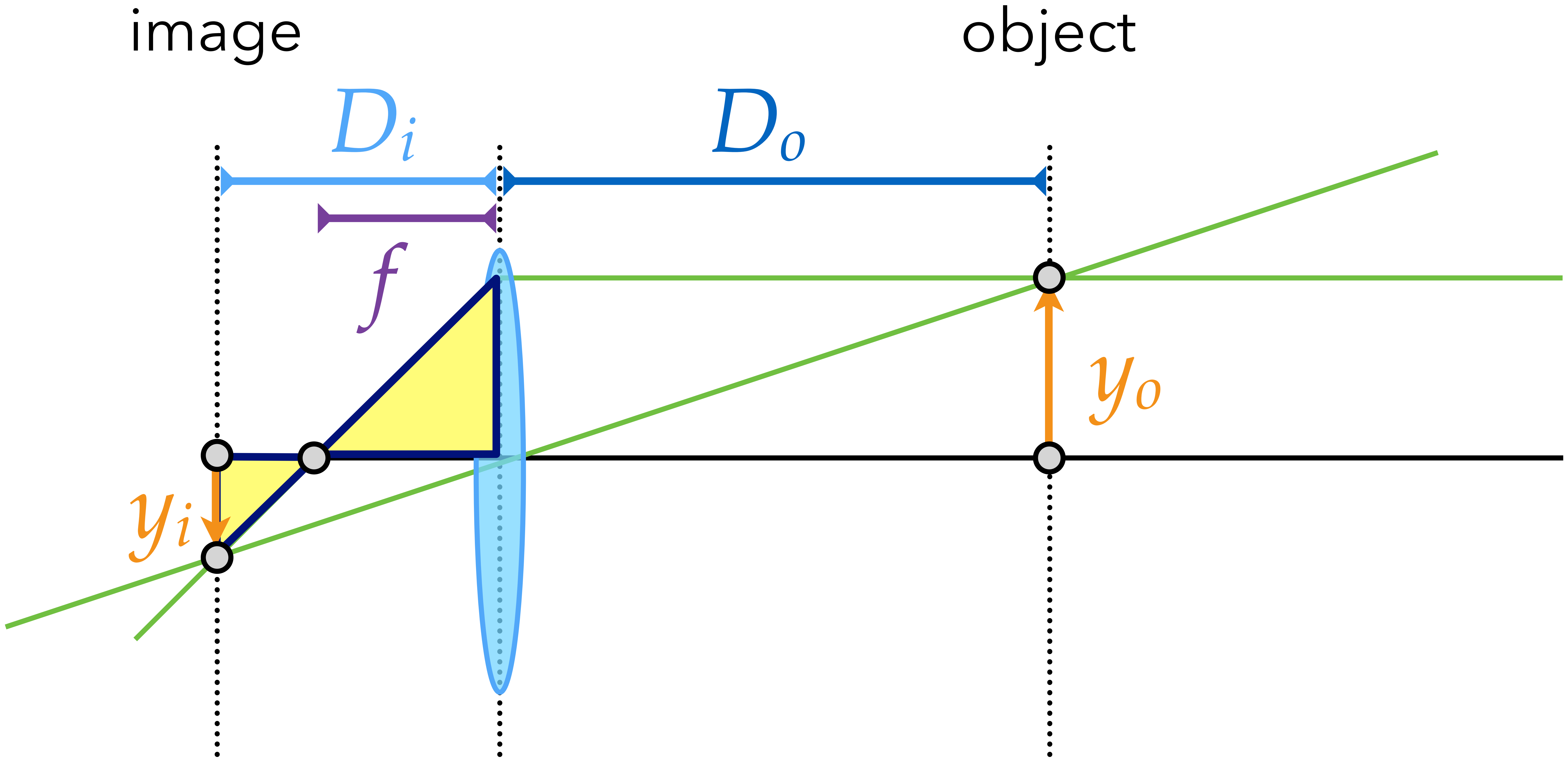


Thin lens formula

Similar triangles everywhere!

$$y_i \,/\, y_o = D_i \,/\, D_o$$

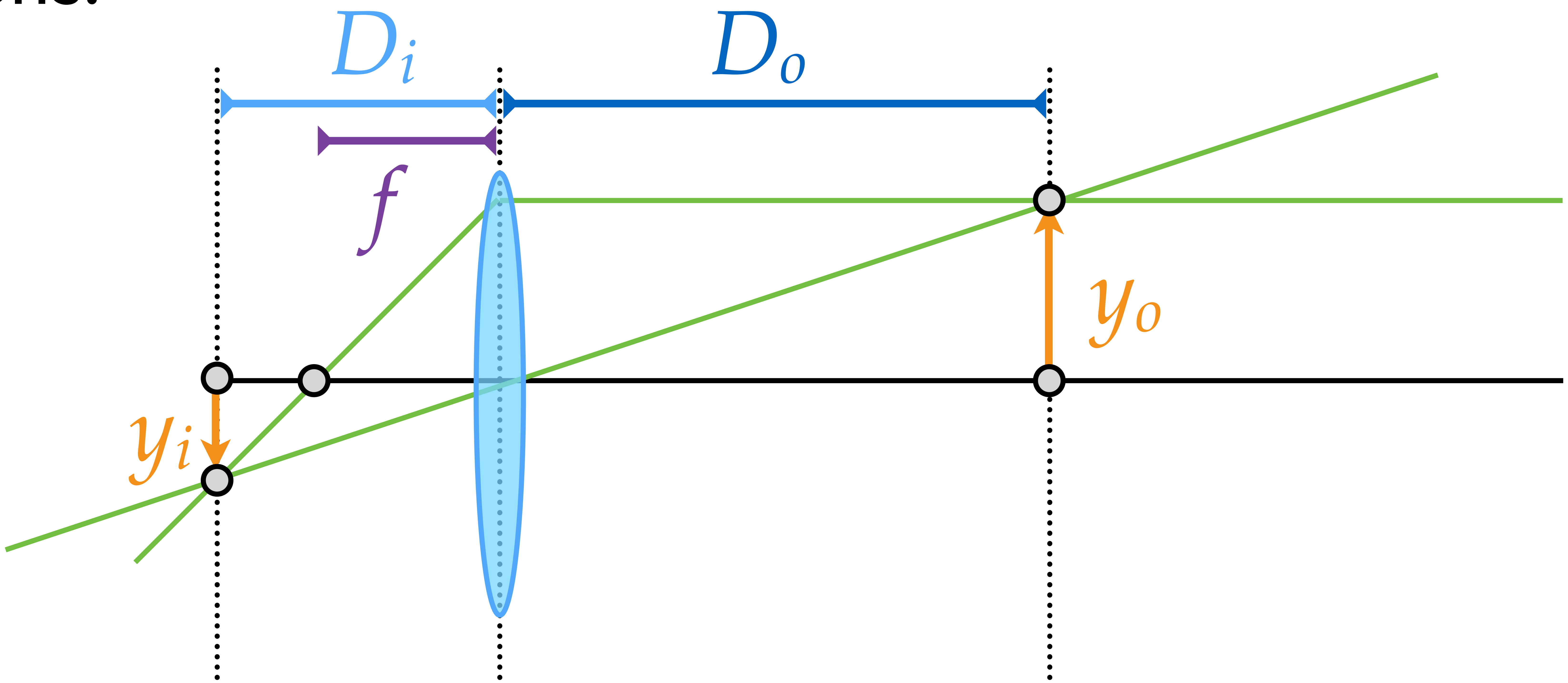
$$y_i \,/\, y_o = (D_i - f) \,/\, f$$



Thin lens formula

All rays passing through a single point y_o on a plane at distance D_o in front of the lens will pass through a single point y_i at distance D_i behind the lens.

$$\frac{1}{D_i} + \frac{1}{D_o} = \frac{1}{f}$$



Changing the focus distance

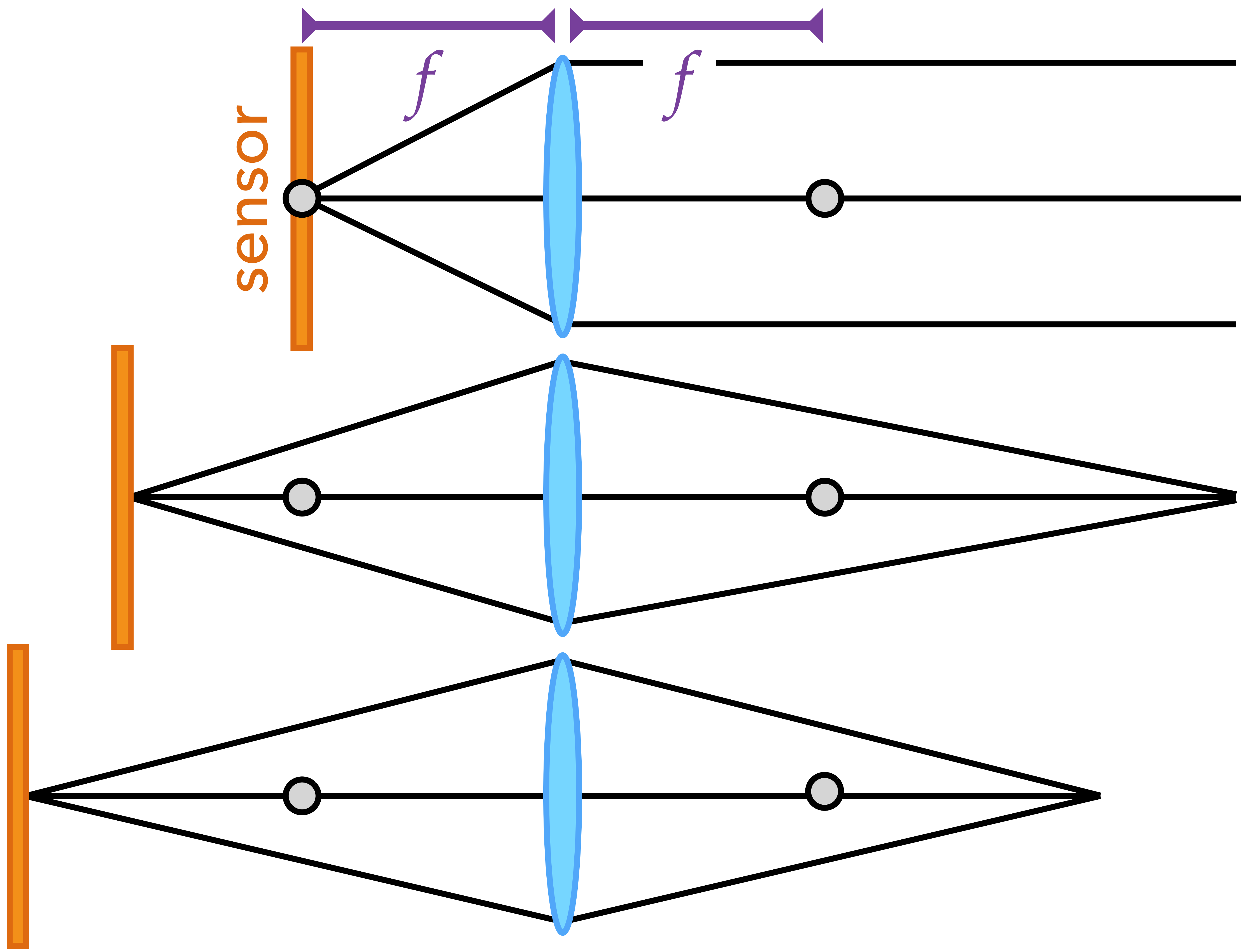
$$\frac{1}{D_i} + \frac{1}{D_o} = \frac{1}{f}$$

To focus objects at different distances, move sensor relative to lens.

At $D_o = D_i = 2f$ 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.



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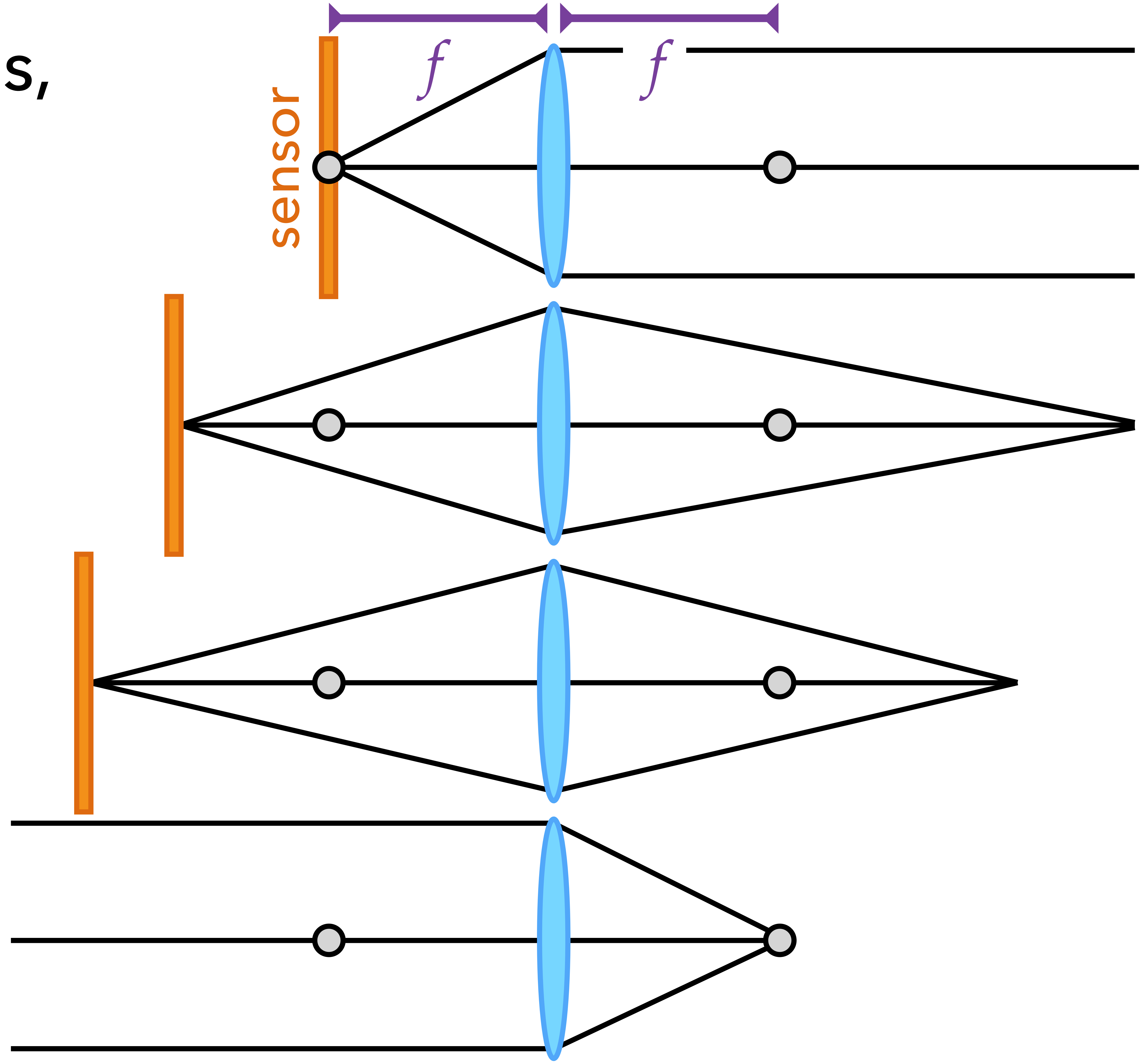
At $D_o = D_i = 2f$ we have 1:1 imaging, because

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

Can't focus on objects closer than its focal length f

- requires sensor at infinity



Demo

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

Virtual optical bench

By Andrew Adams

- http://graphics.stanford.edu/~abadams/lenstoy.swf

Also

- http://www.arachnoid.com/OpticalRayTracer/index.html

Extensions tubes

Allow us to put sensor/film farther

- focus closer

Properties of real lenses

Mostly undesired!

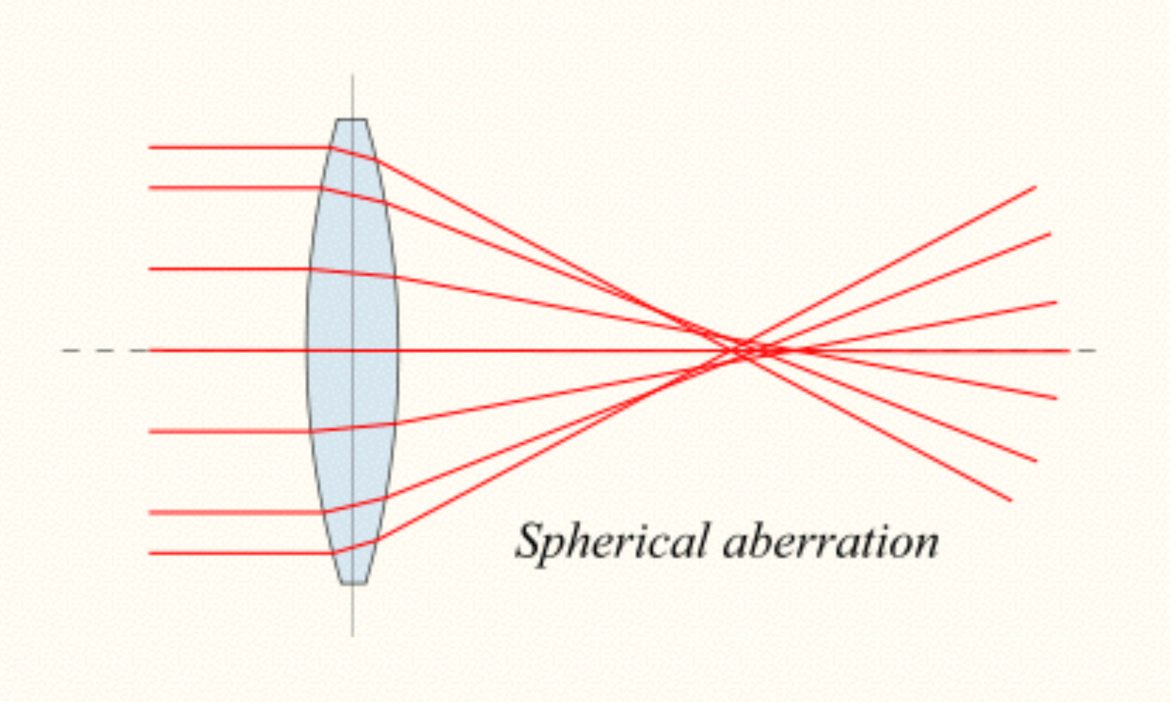
Aberrations

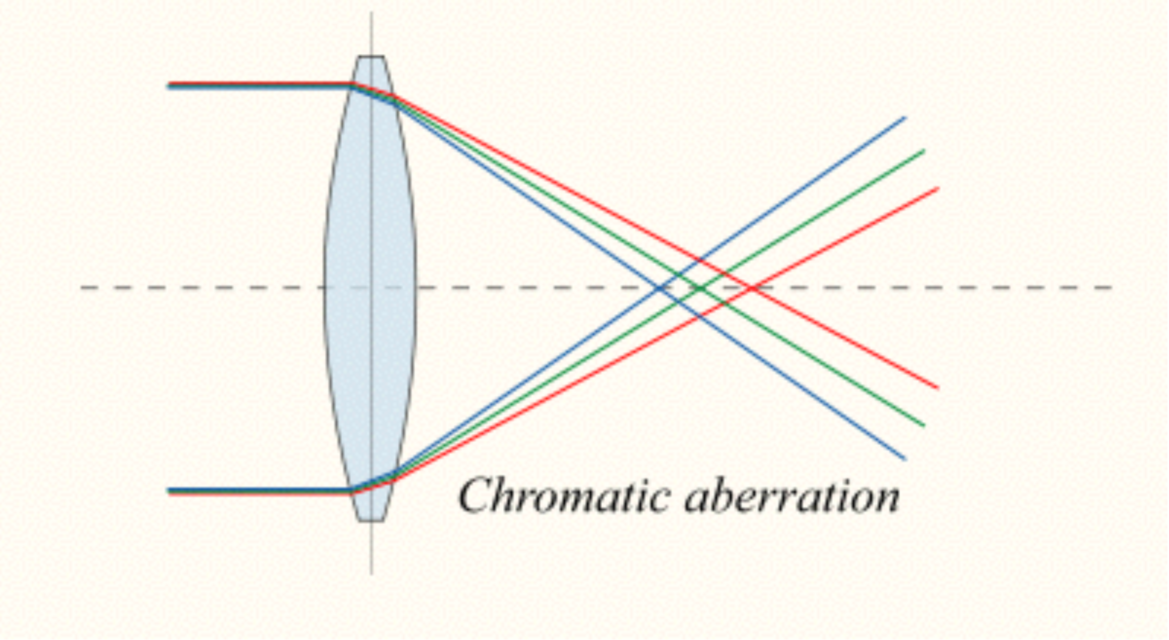
- Spherical aberration
- Chromatic aberration

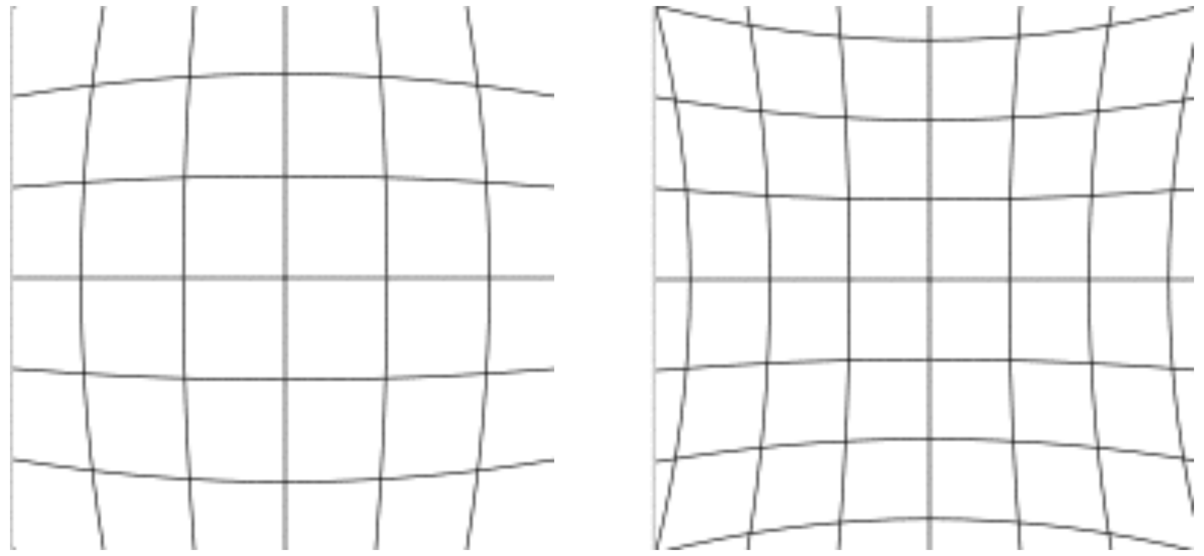
Distortion

- Barrel distortion
- Pincushion distortion

Etc.







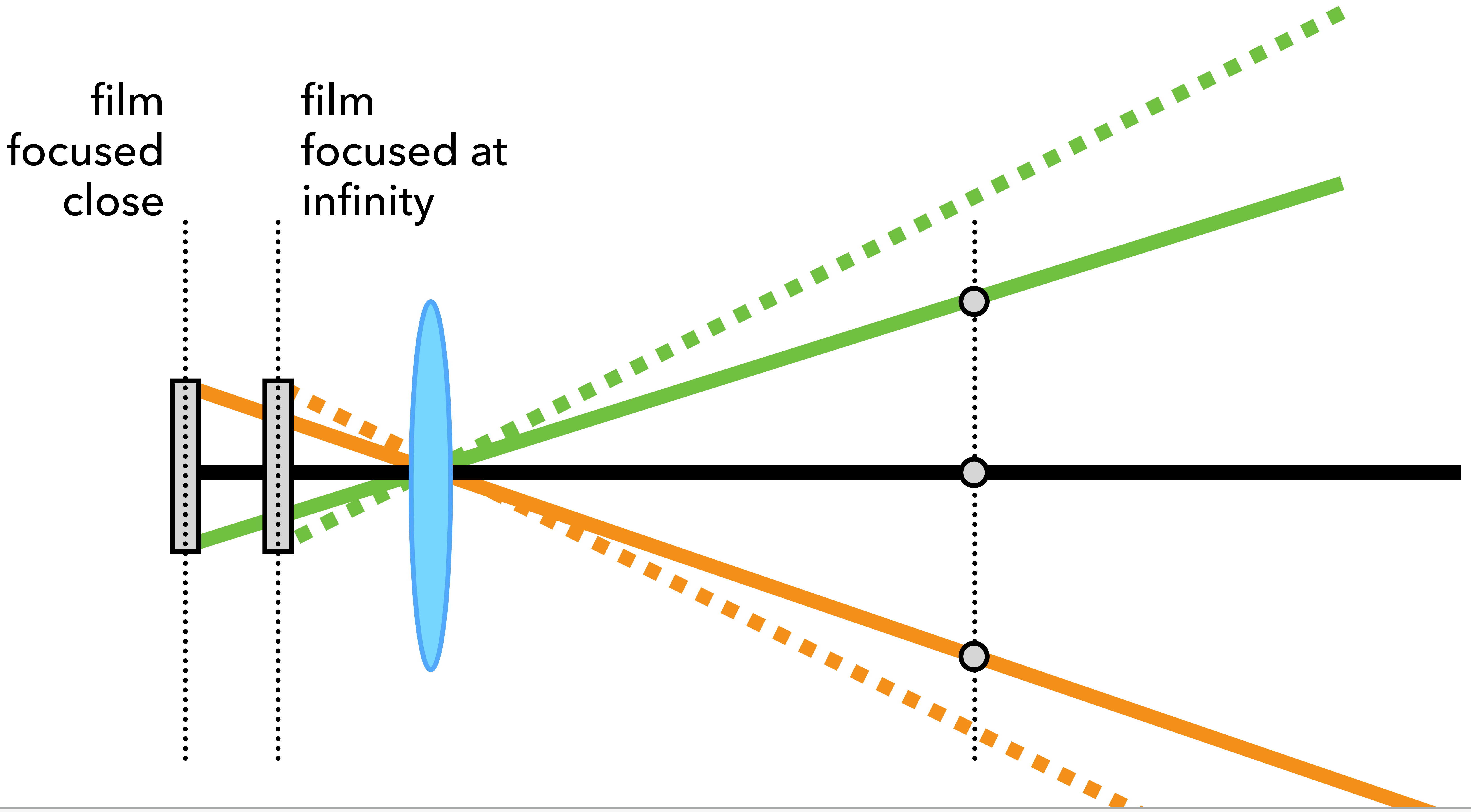
Barrel & pincushion distortion

Questions?

Field of view & focusing

What happens to the field of view when one focuses closer?

- It's reduced
- "breathing"



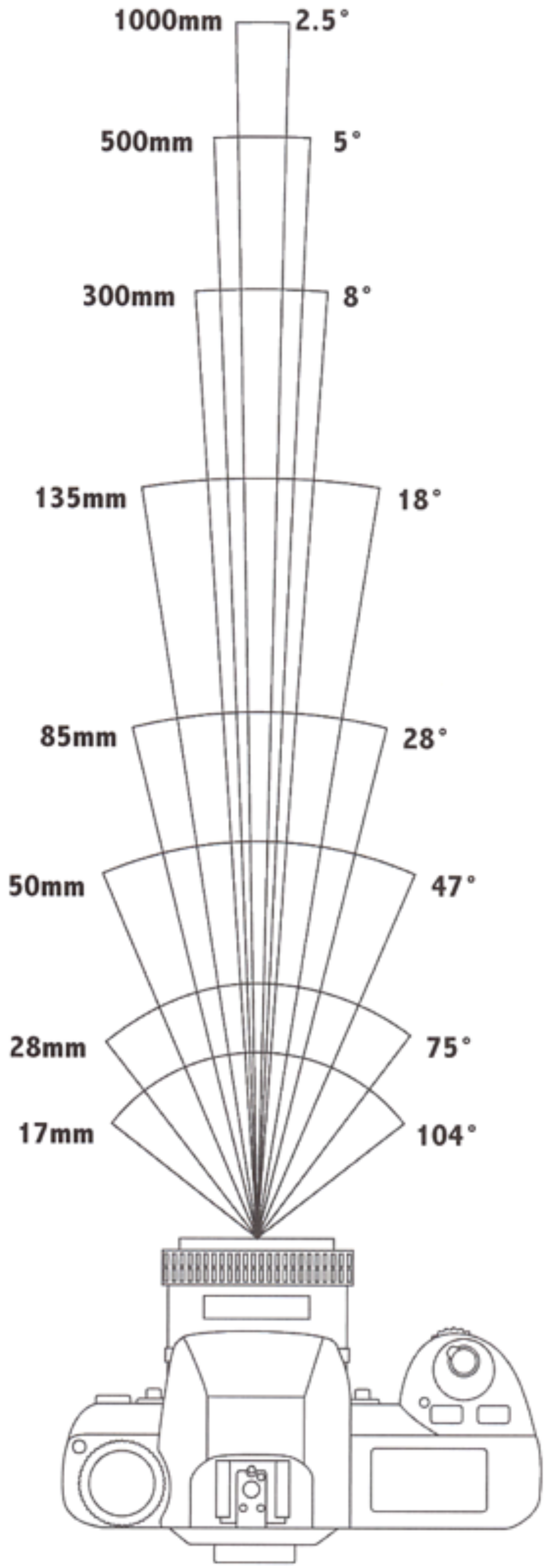
https://youtu.be/bIrJUFtYxiQ

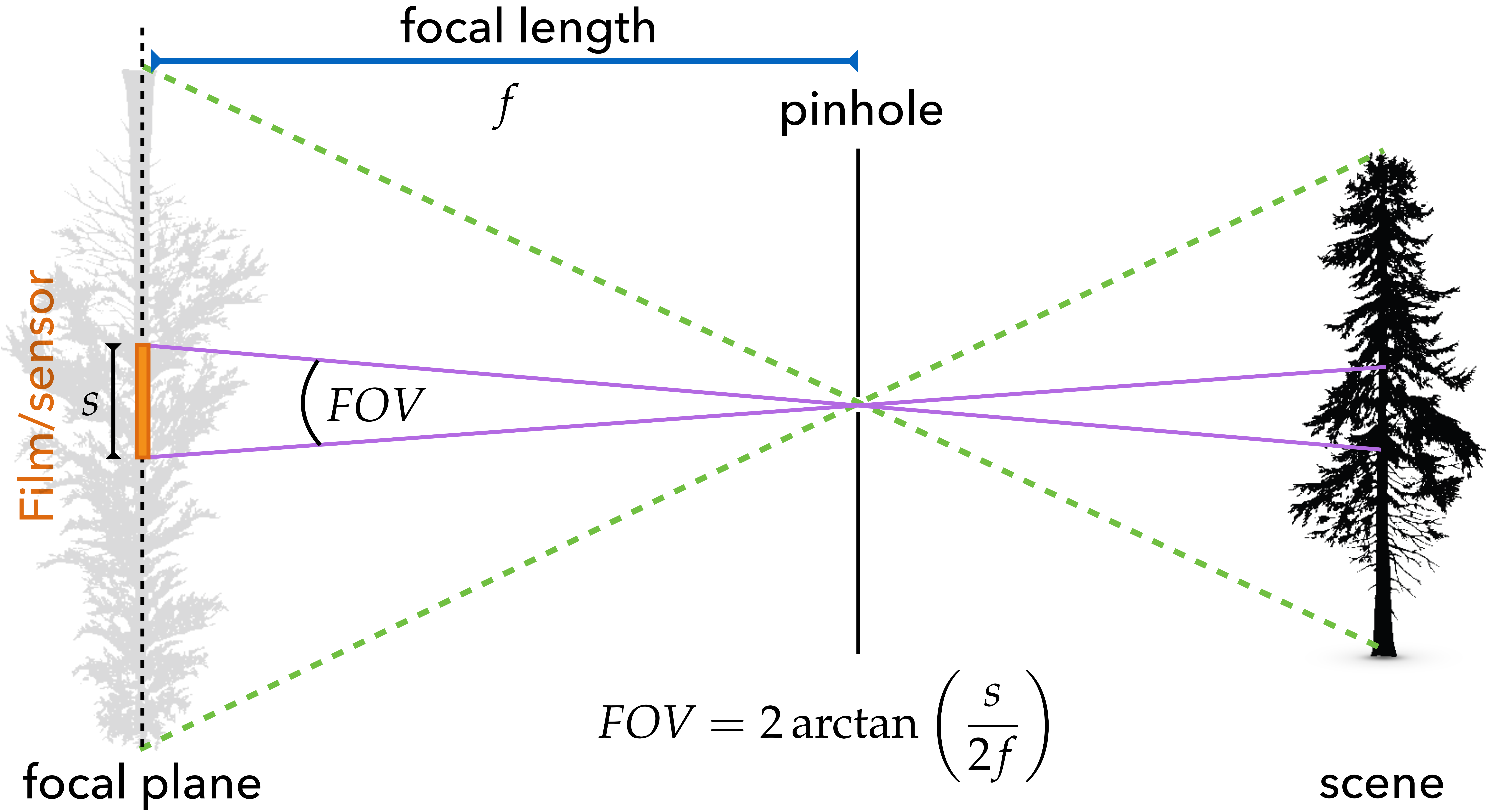
Question

What’s the advantage of a lens with a short focal length? In what situation would this be useful?

What’s the advantage of a lens with a long focal length? In what situation would this be useful?

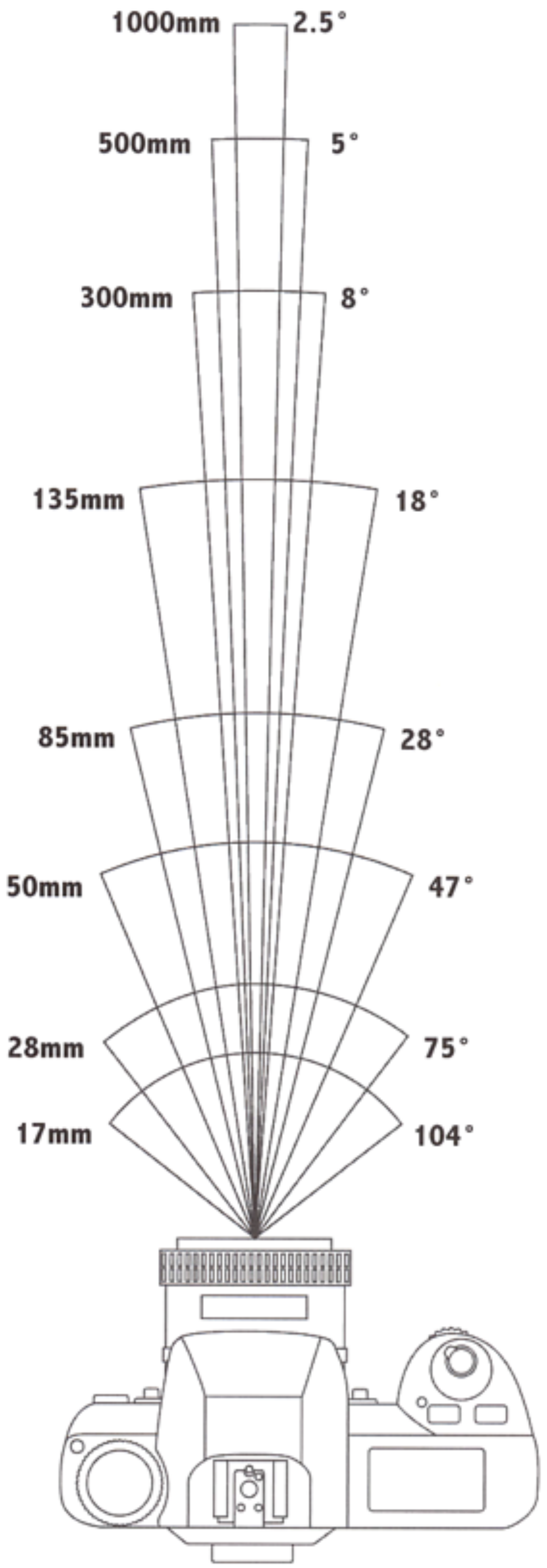
Recall: Focal length impacts FOV





$$FOV = 2\arctan\left(\frac{s}{2f}\right)$$

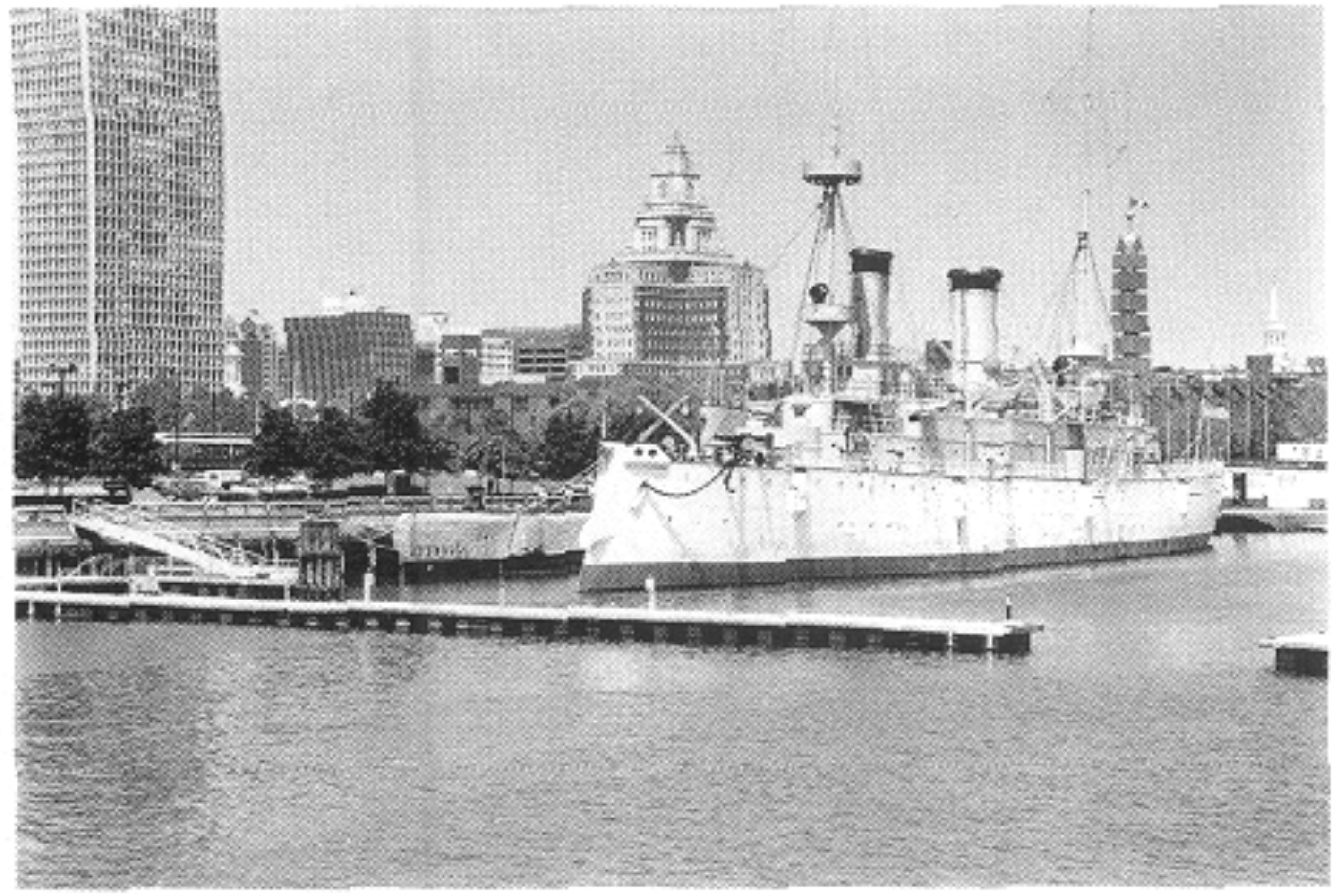
Focal length & field of view



17mm

28mm

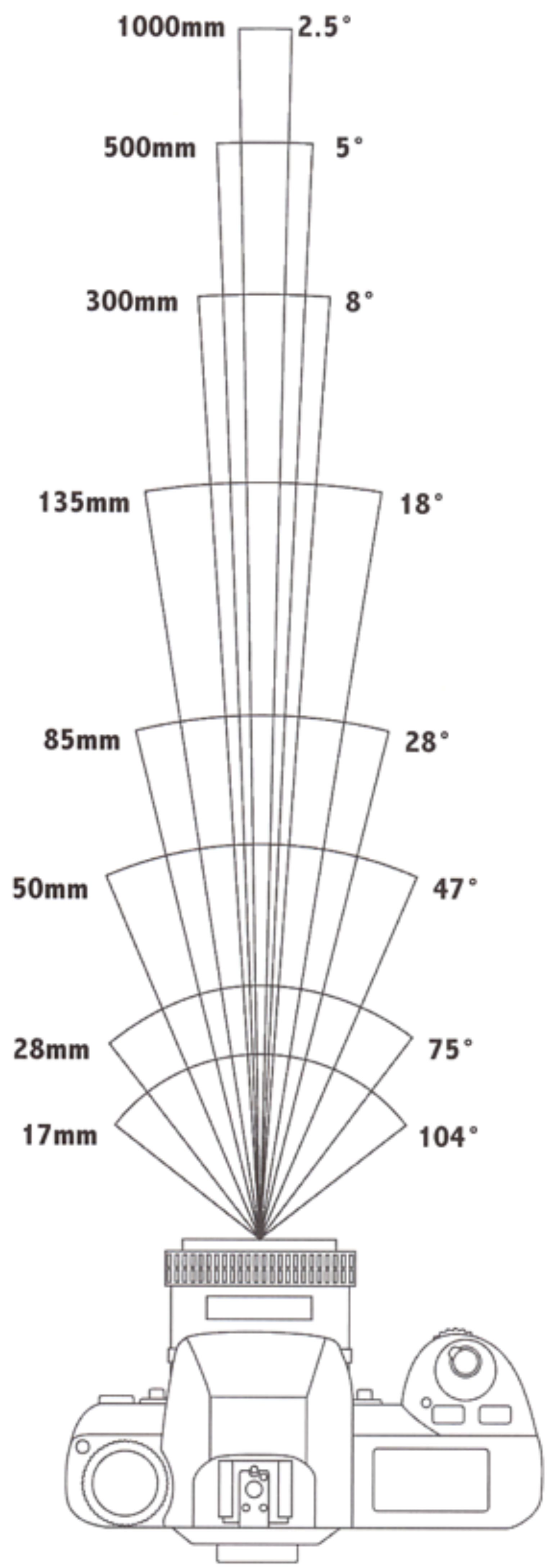
50mm

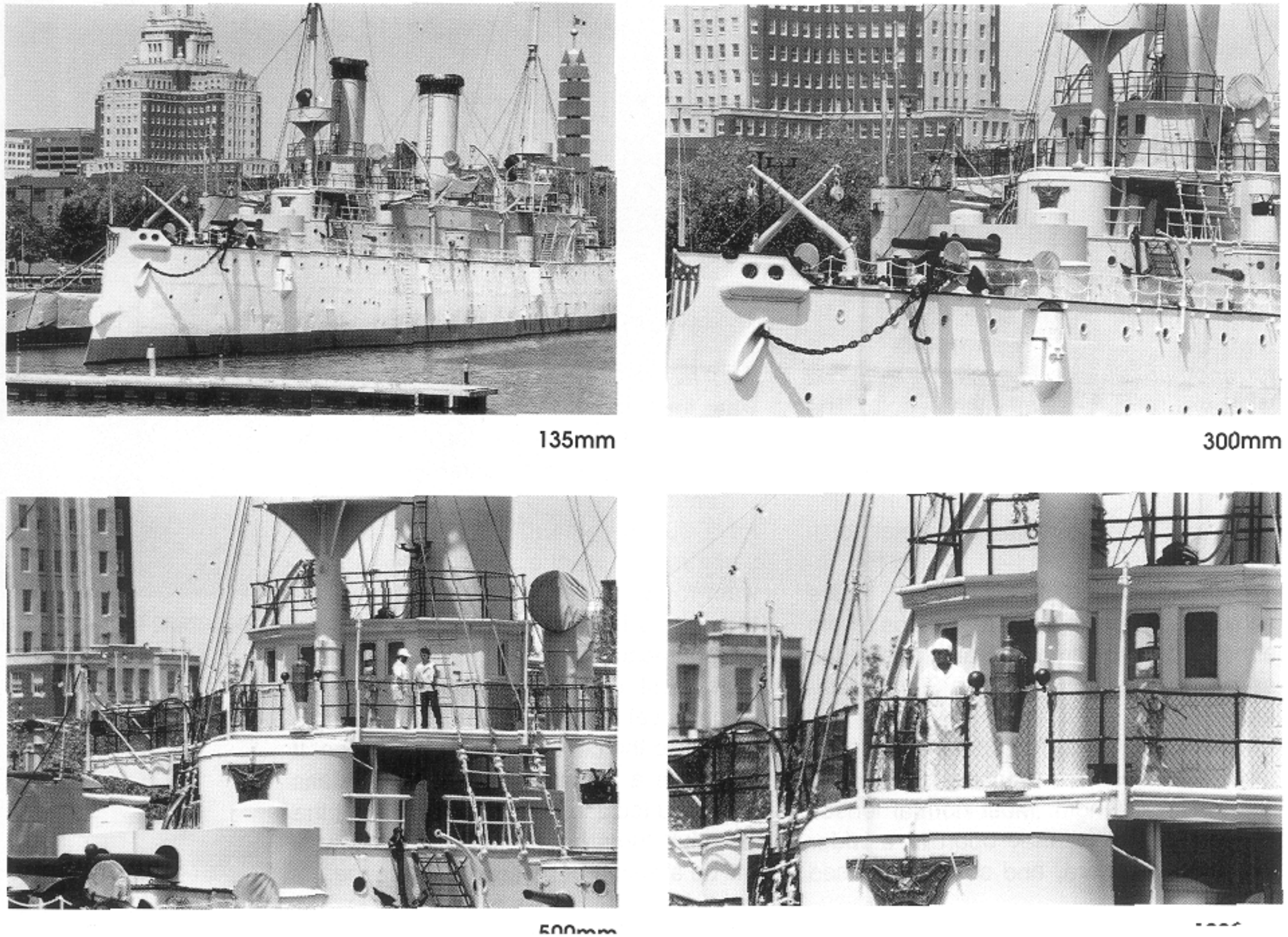


85mm

From *Photography*, London et al.

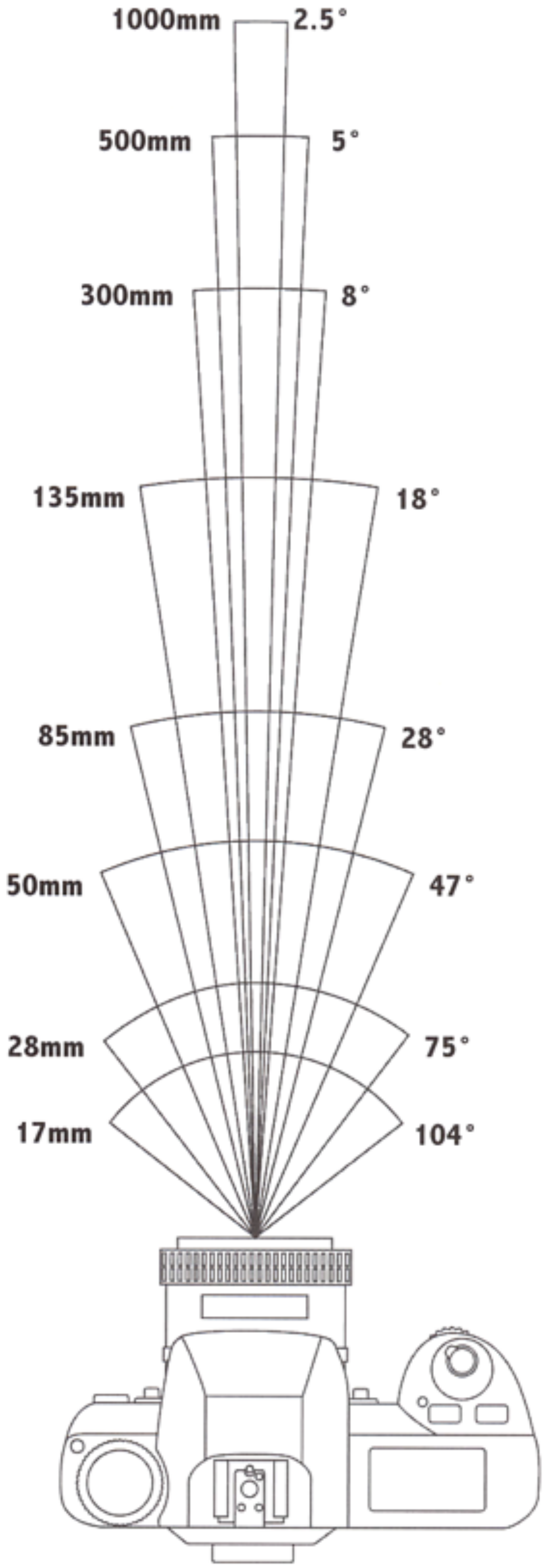
Focal length & field of view

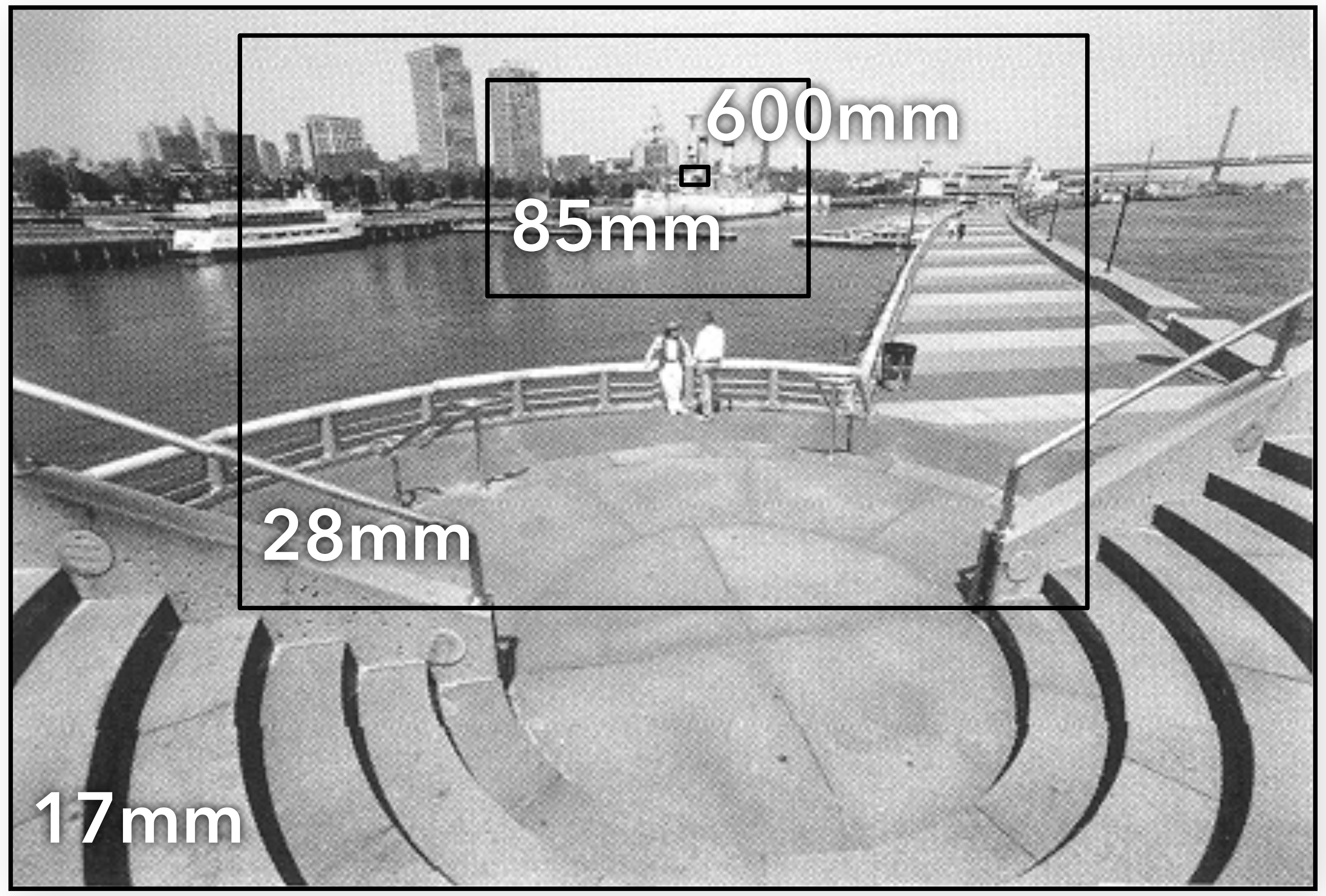




From *Photography*, London et al.

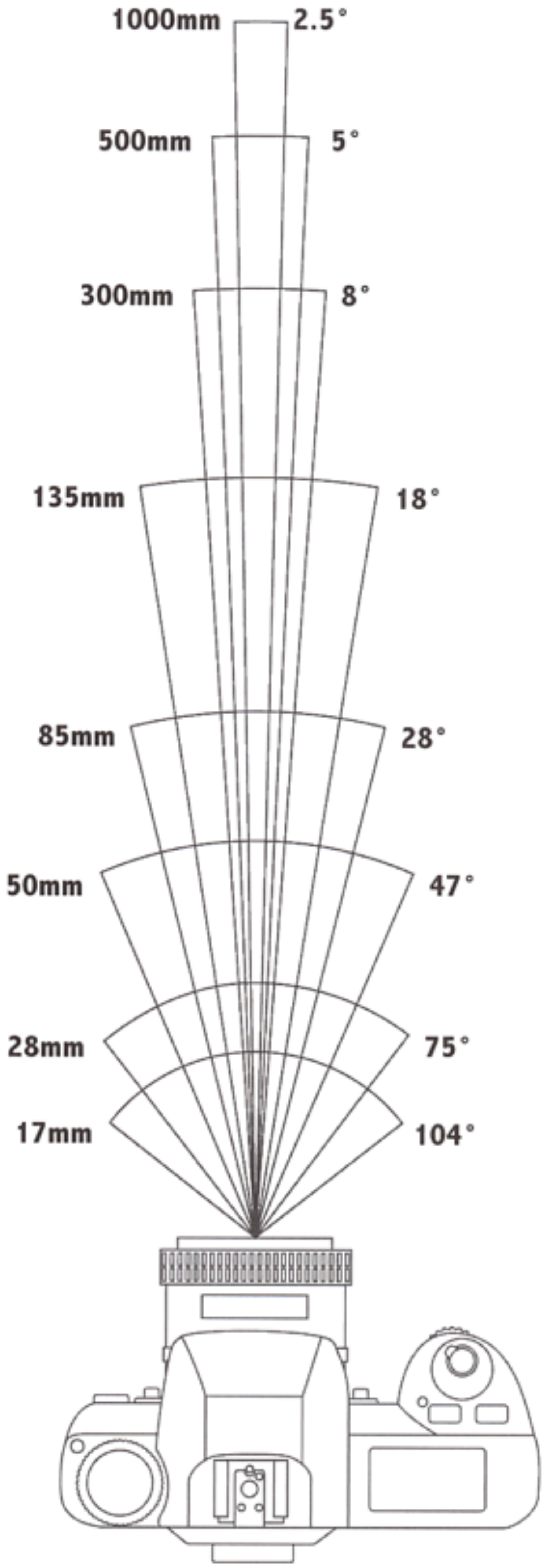
Focal length = cropping

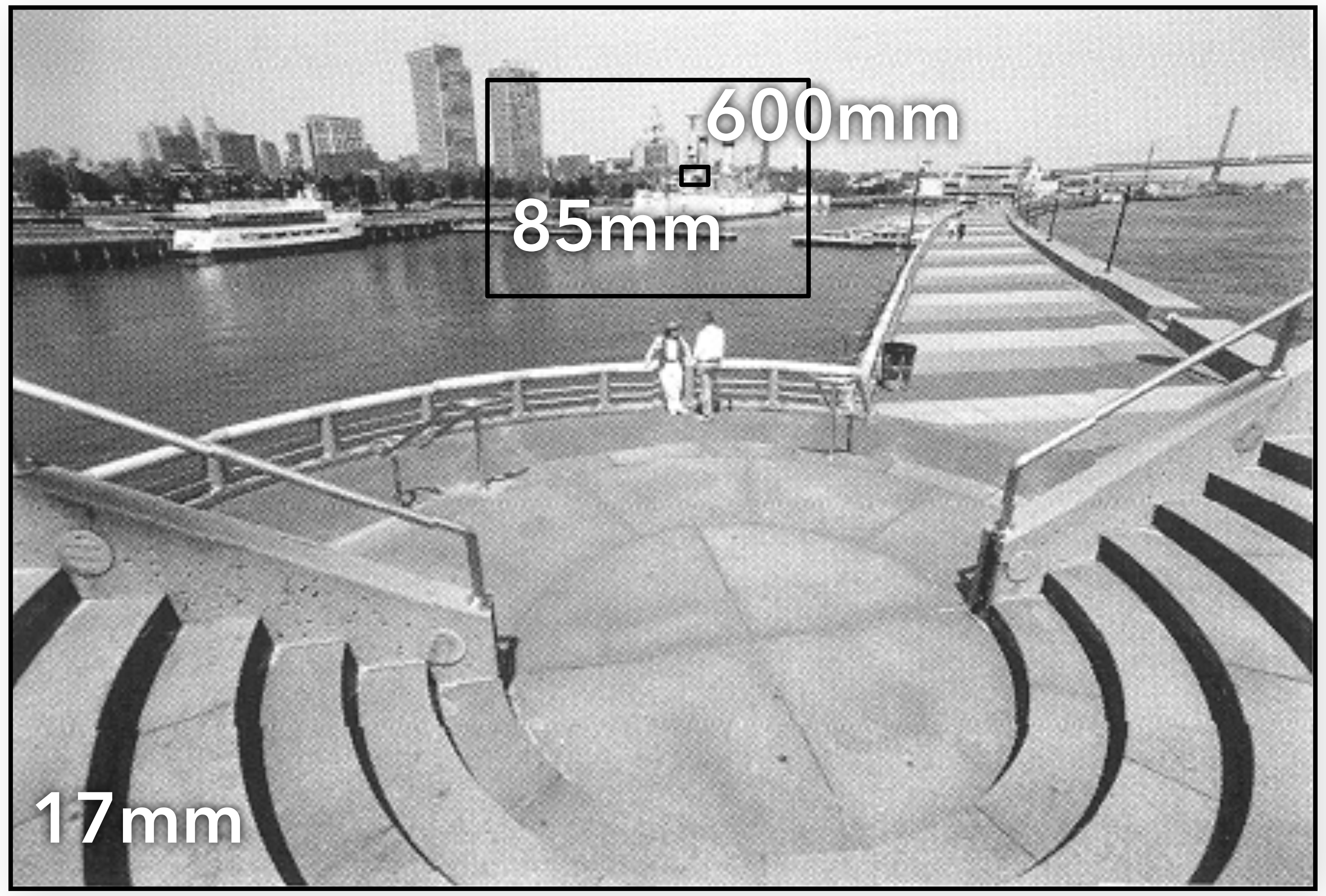


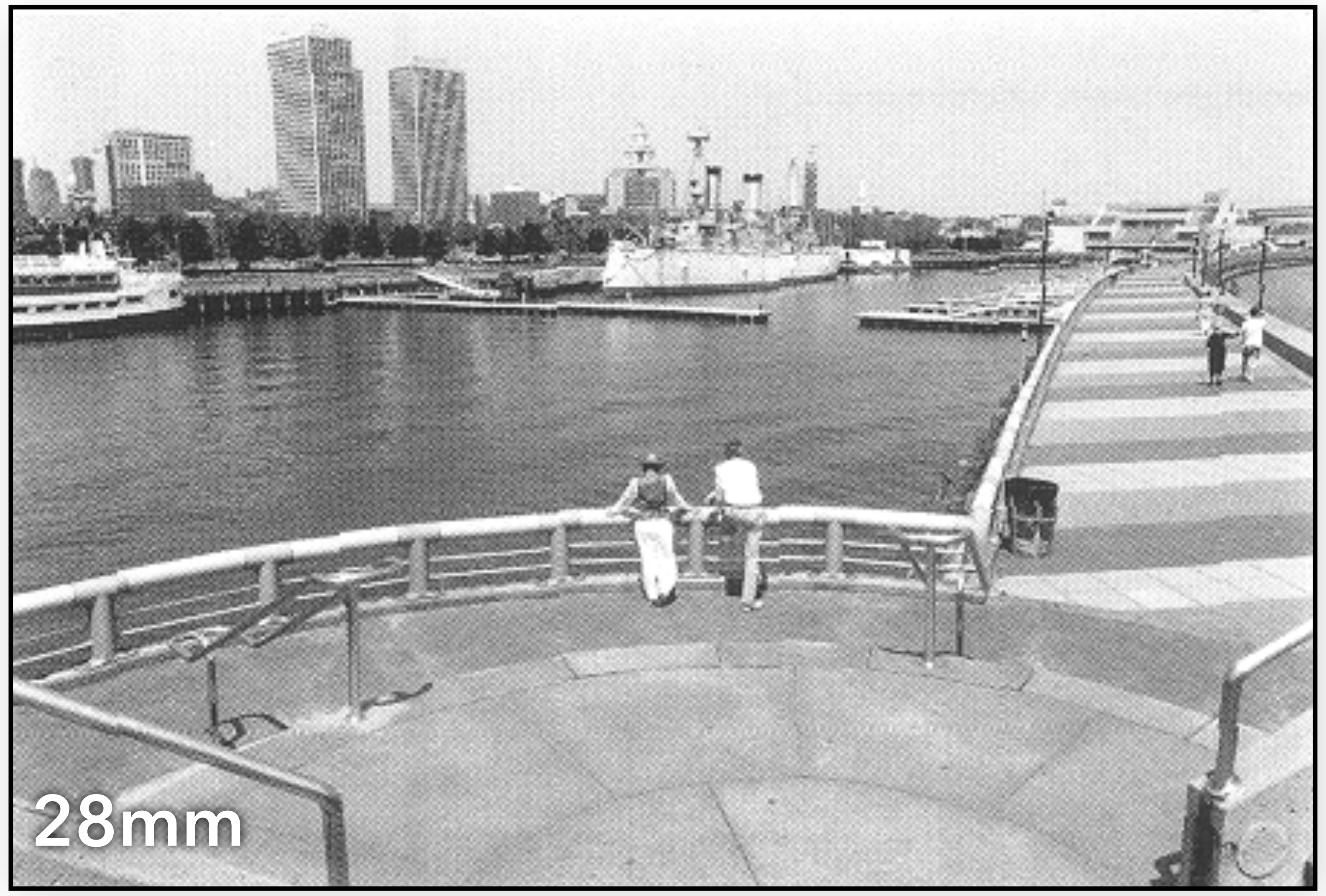


From *Photography*, London et al.

Focal length = cropping

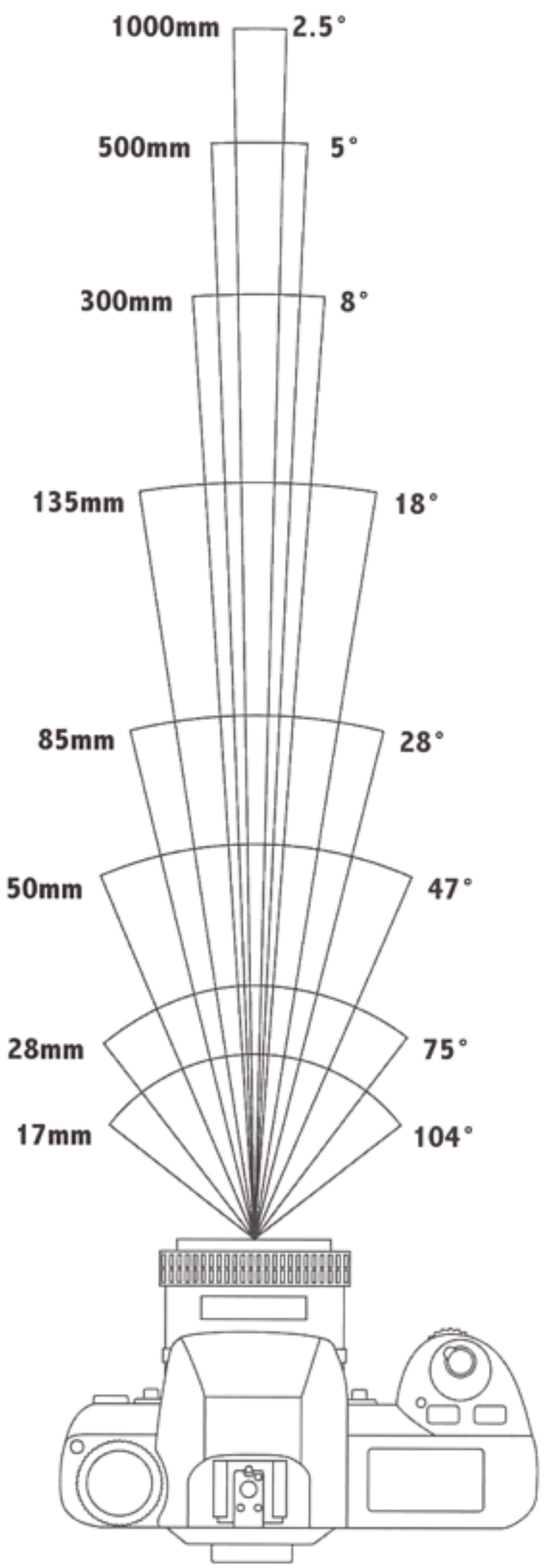


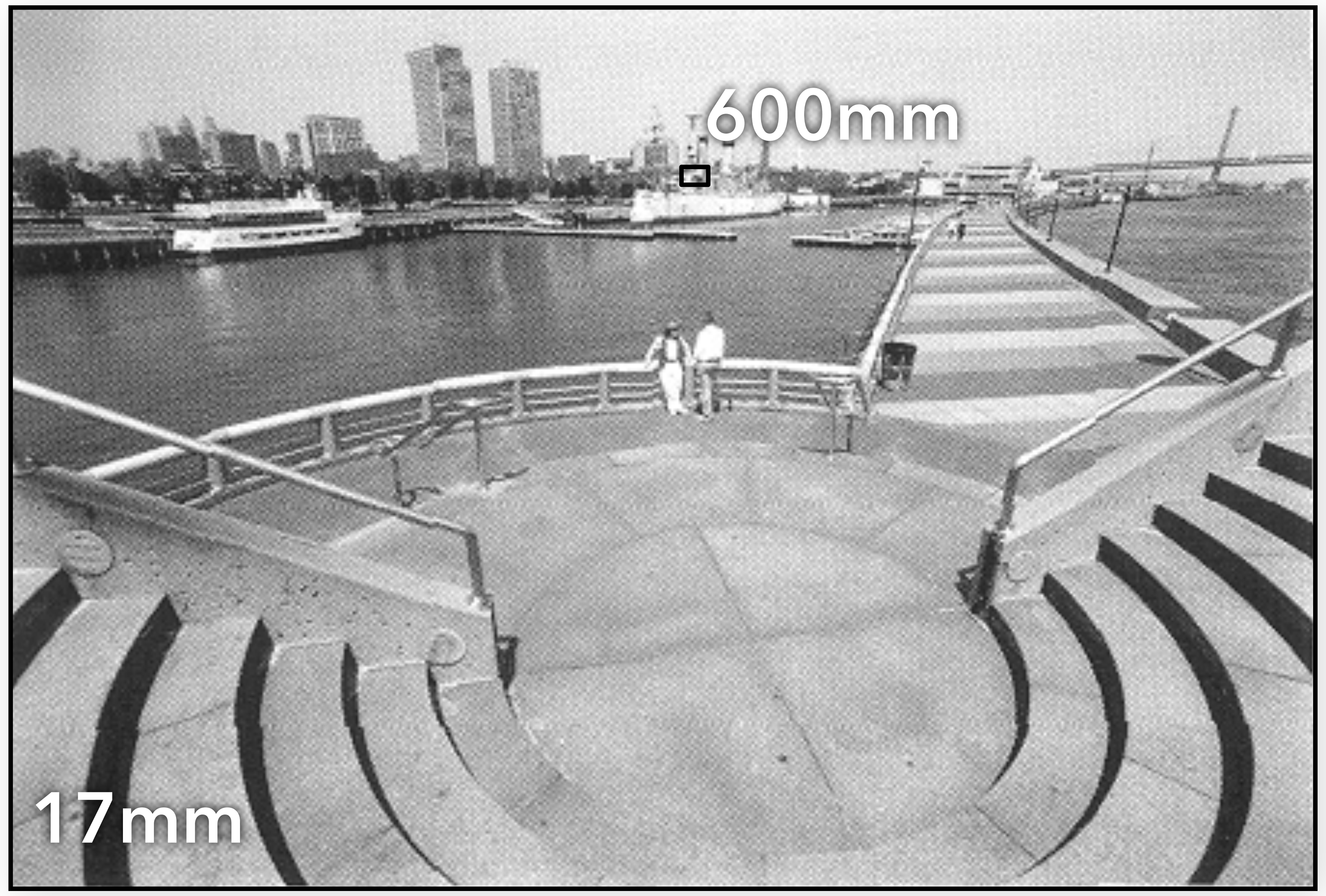


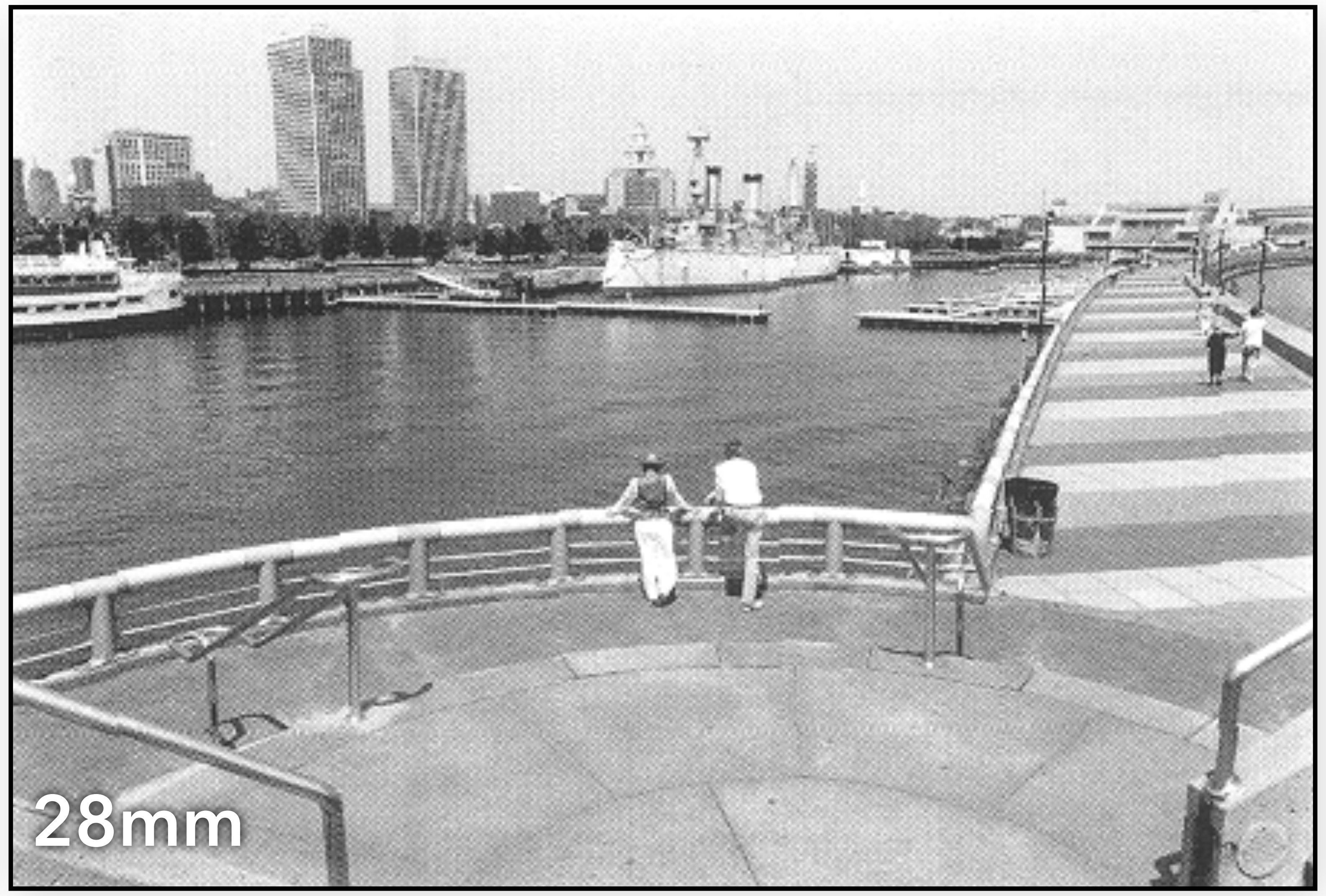


From *Photography*, London et al.

Focal length = cropping

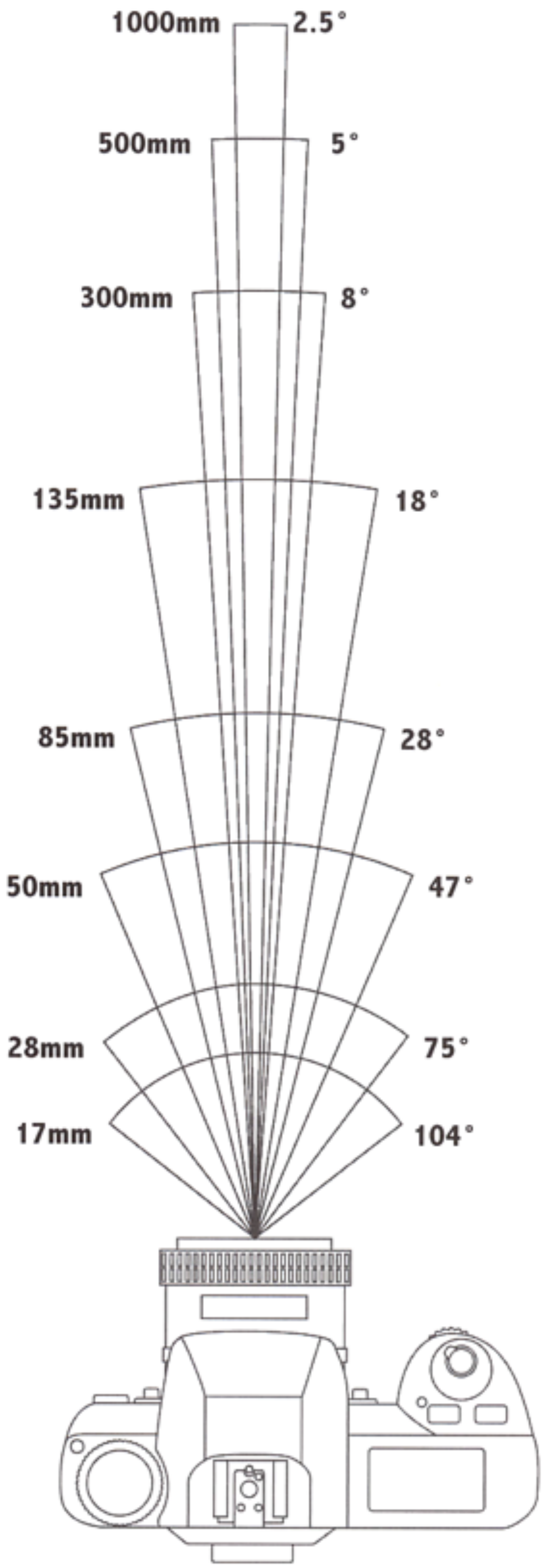






From *Photography*, London et al.

Focal length = cropping



Changing focal length vs. viewpoint

wide-angle

telephoto & moved back

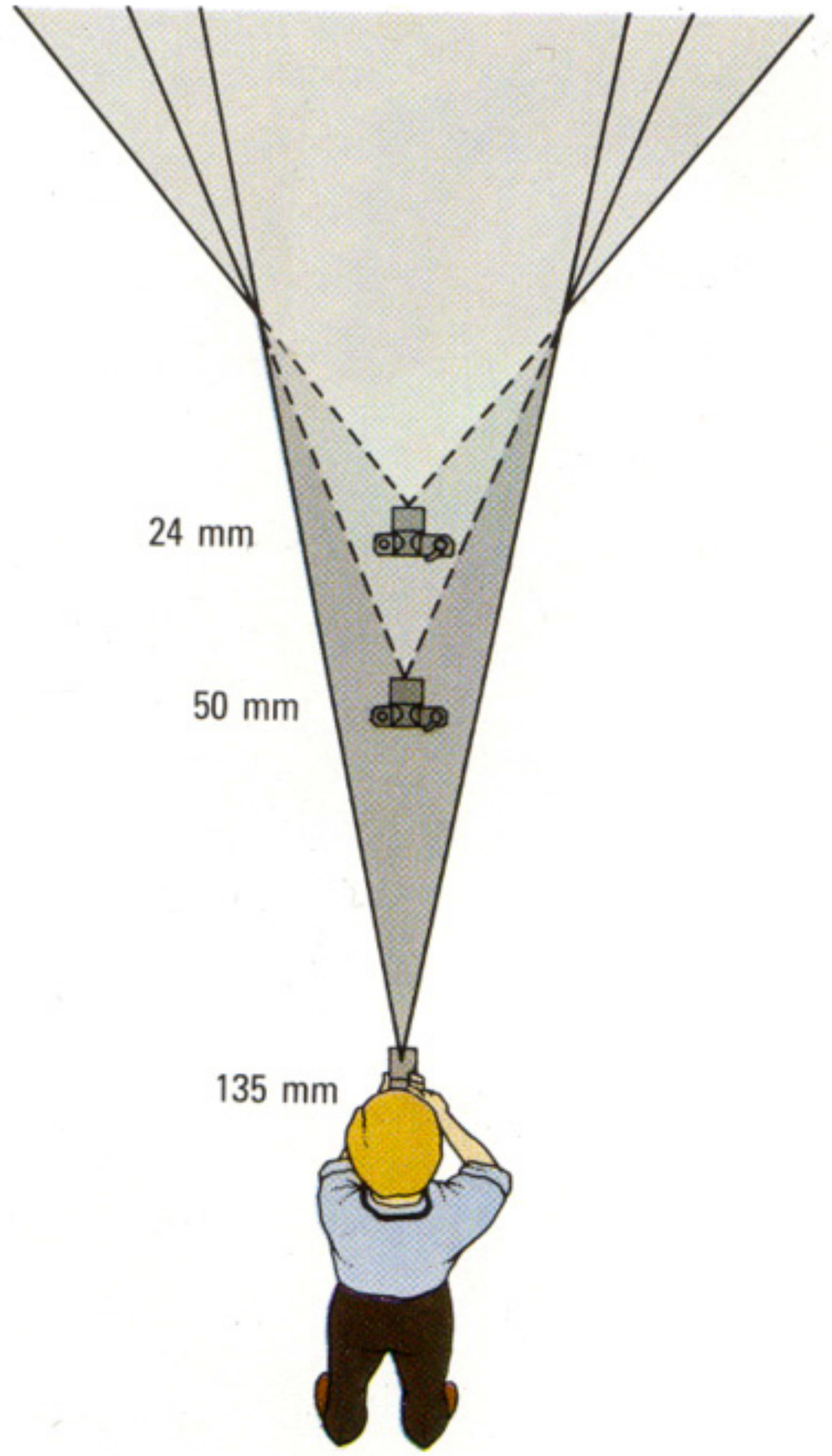
changing the focal length lets us move back from a subject, while maintaining its size in the image

but moving back changes perspective relationships

Changing focal length vs. viewpoint

Moving forward while shortening focal length lets you keep objects <u>at one depth</u> the same size

In cinematography, this is called the dolly-zoom, or "Vertigo effect" after Hitchcock's movie



Changing FOV, magnification constant

"Hitchcock zoom"

"Vertigo effect"

"Dolly-zoom"

Perspective vs. viewpoint

Portrait: distortion with wide angle. Why?

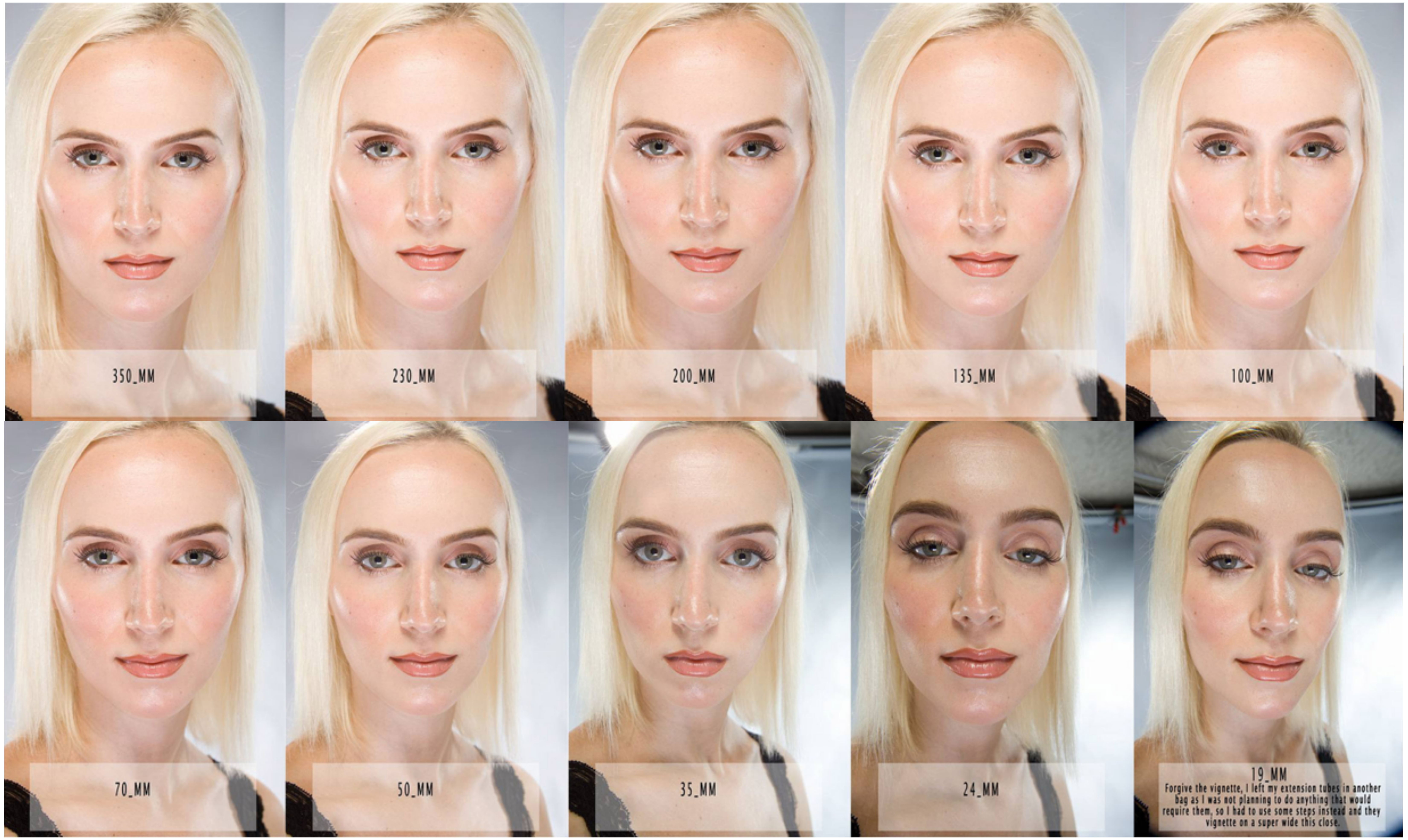
Wide angle

Standard

Telephoto

Portrait distortion

http://stepheneastwood.com/tutorials/lensdistortion/strippage.htm

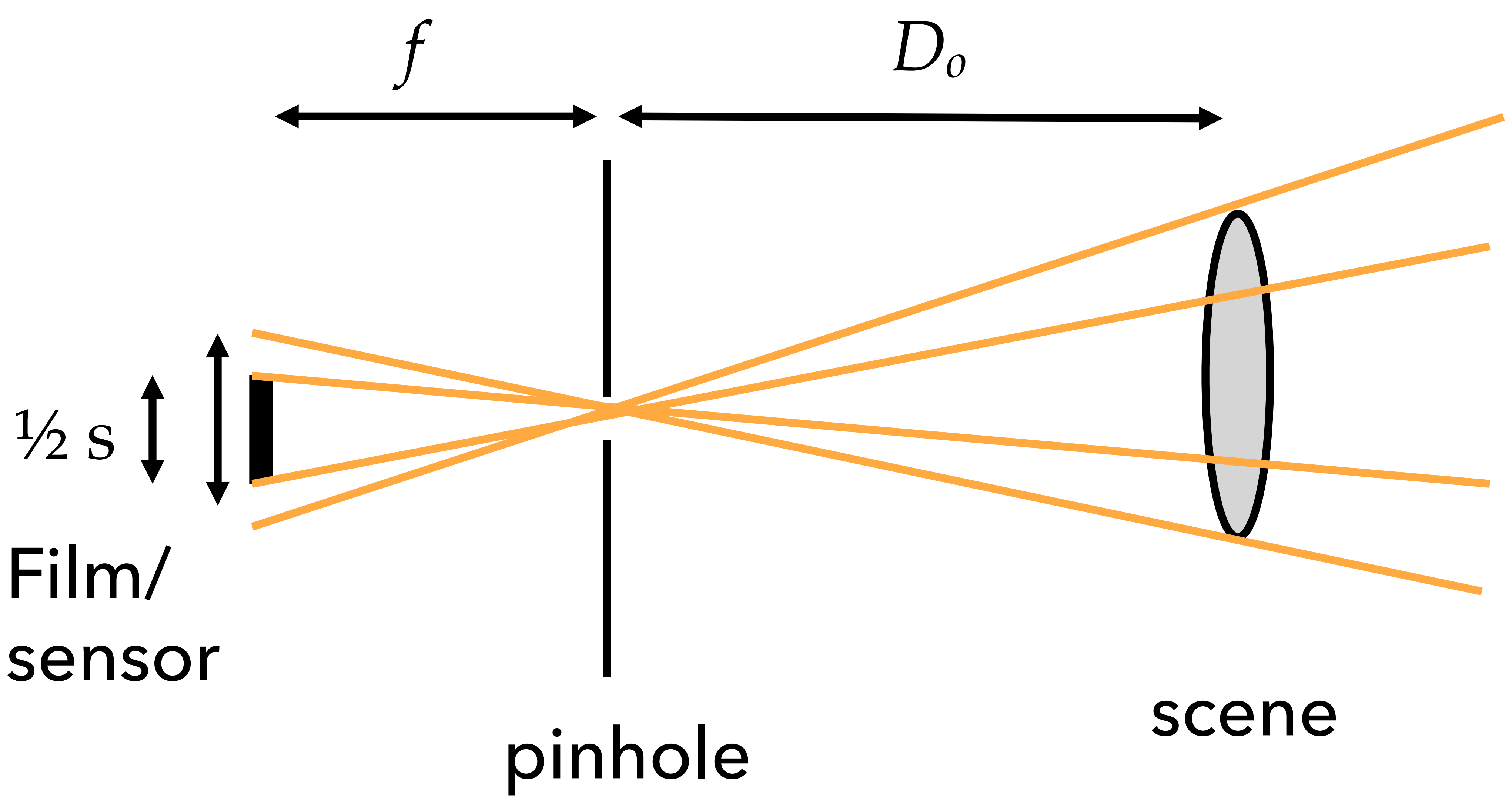


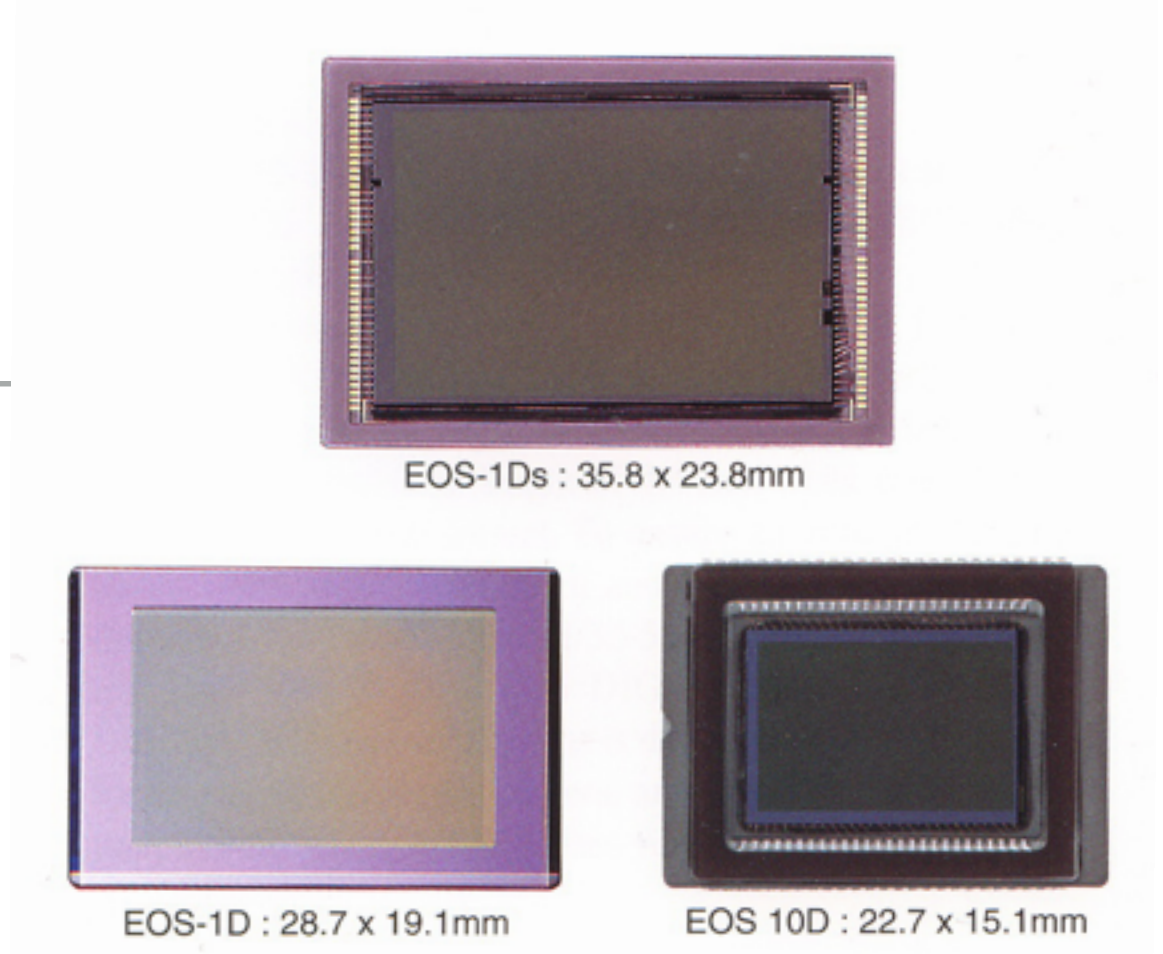
Focal length & sensor size

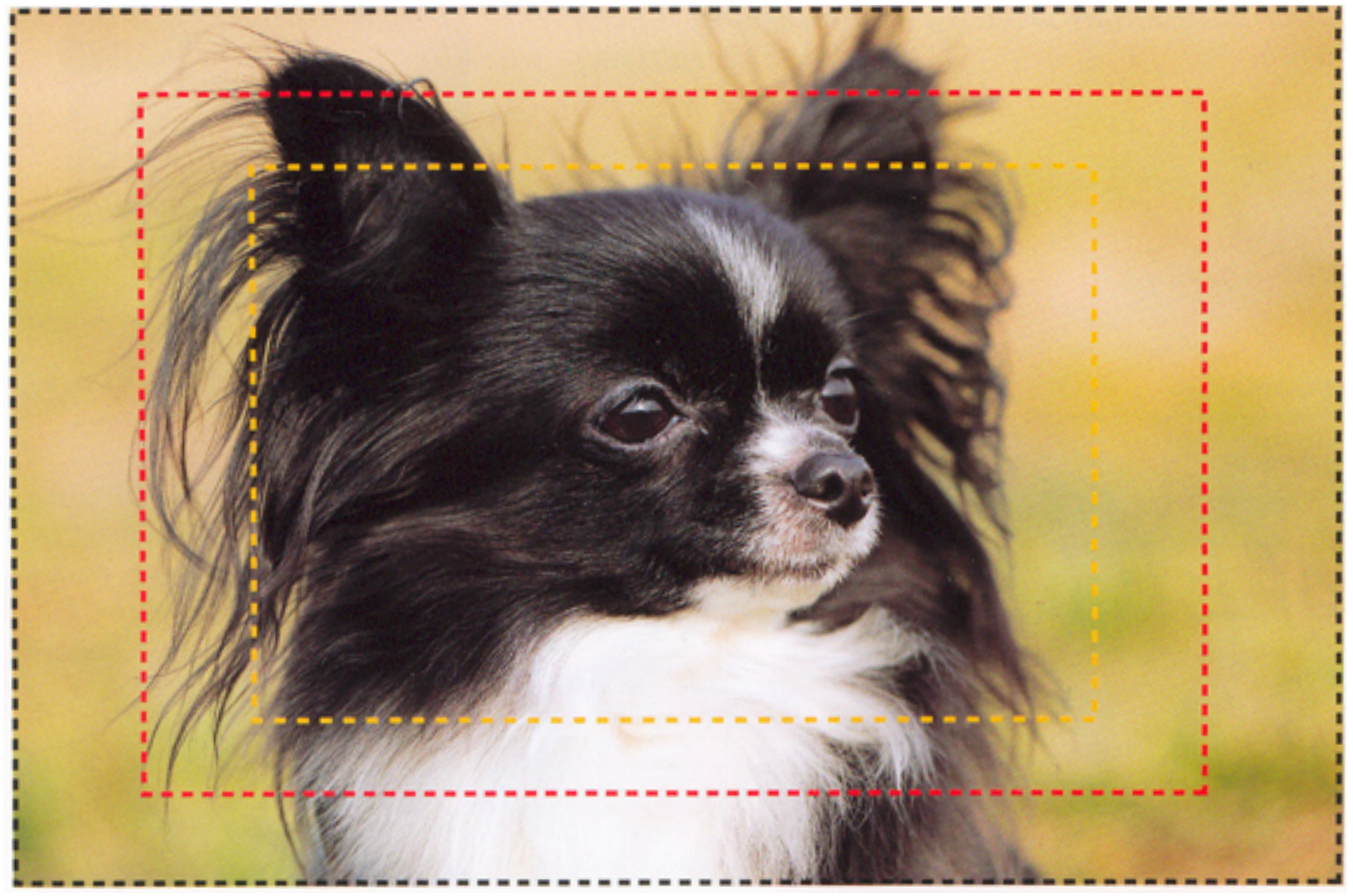
What happens when the film is half the size?

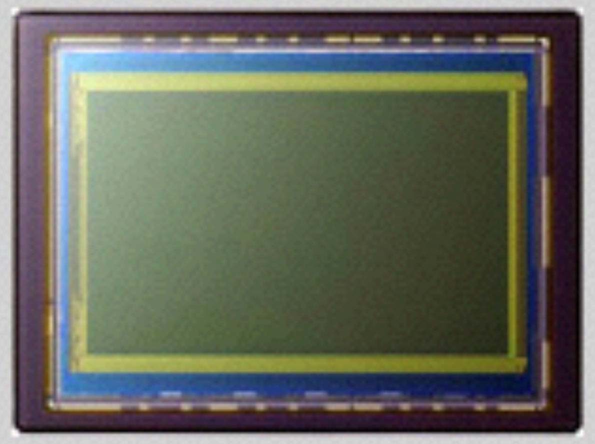
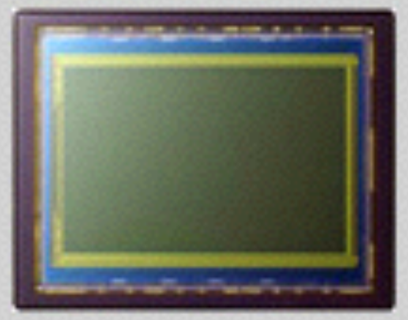
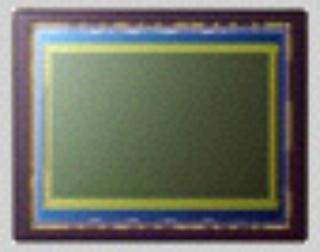
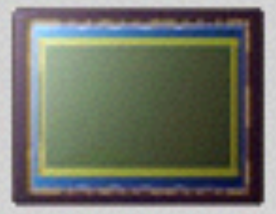
Application:

- Real film is 36x24mm
- On the 10D, the sensor is 22.5 x 15.0 mm
- Crop/conversion factor on the 10D?







Sensor Name	Medium Format	Full Frame	APS-H	APS-C	4/3	1"	1/1.63"	1/2.3"	1/3.2"
Sensor Size	53.7 x 40.2mm	36 x 23.9mm	27.9x18.6mm	23.6x15.8mm	17.3x13mm	13.2x8.8mm	8.38x5.59mm	6.16x4.62mm	4.54x3.42mm
Sensor Area	21.59 cm^2	8.6 cm^2	5.19 cm^2	3.73 cm^2	2.25 cm^2	1.16 cm^2	0.47 cm^2	0.28 cm^2	0.15 cm^2
Crop Factor	0.64	1.0	1.29	1.52	2.0	2.7	4.3	5.62	7.61
Image									
Example									

LensVid

https://lensvid.com/technique/why-depth-of-field-is-not-effected-by-sensor-size-a-demonstration/

Recap

Pinhole is the simplest model of image formation

- But dark
- Diffraction limited

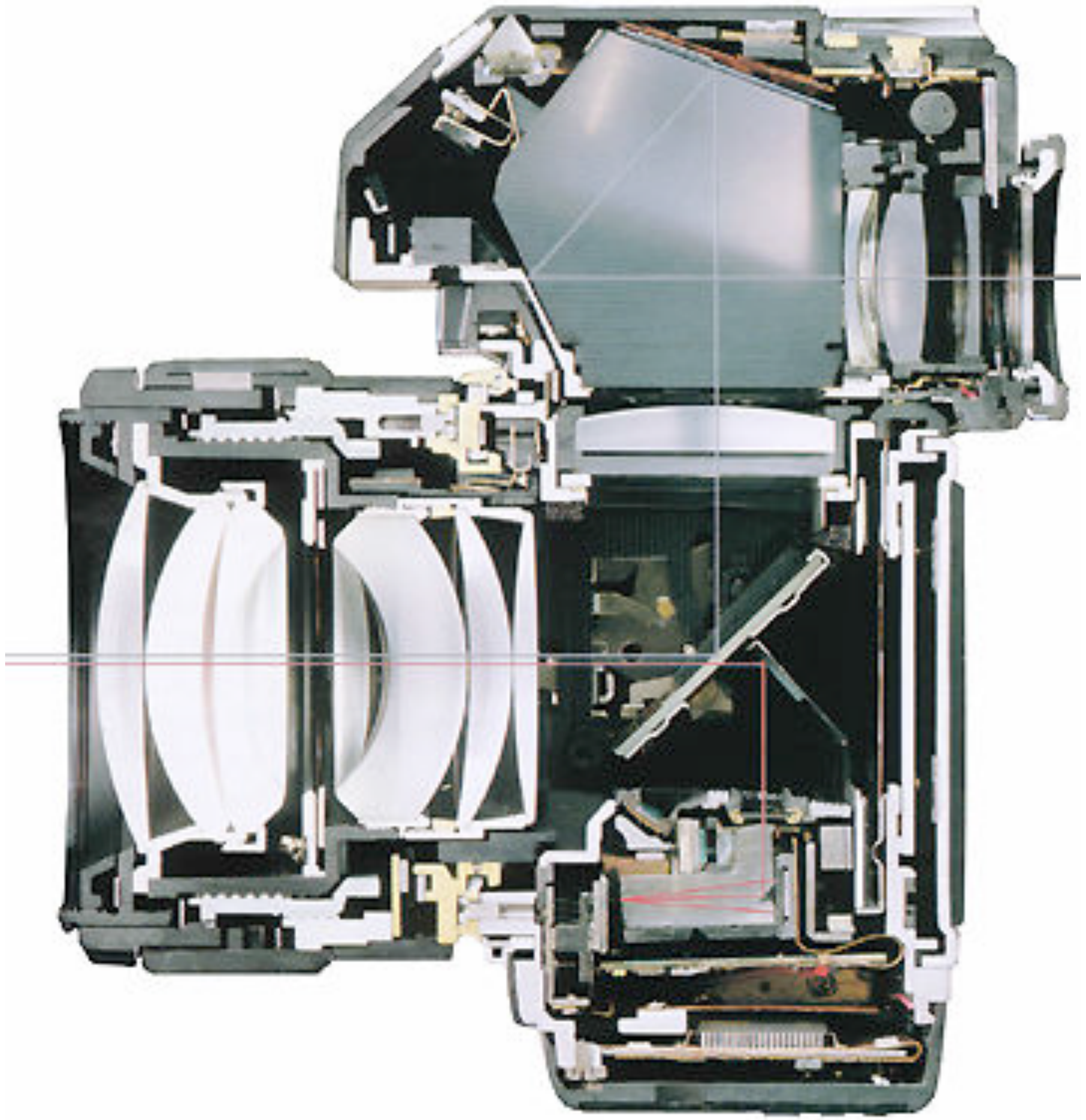
Lenses gather more light

- But get only one plane focused
- Distance from lens to this plane is called *focus distance*
- Focus by moving sensor/film
- Cannot focus infinitely close

Focal length determines field of view

- From wide angle to telephoto
- Depends on sensor size

Questions?



Exposure

Get the right amount of light to sensor/film

Two main parameters:

- Shutter speed
- Aperture (area of lens)

\+ sensor/film sensitivity (ISO)

Exposure

Exposure = Irradiance x Time

Exposure time

- in seconds
- controlled by **shutter**

Irradiance

- amount of light falling on a unit area of sensor per second
- controlled by **aperture**

Shutter speed

Controls how long the film/sensor is exposed

Pretty much linear effect on exposure (until sensor saturates)

Denoted in fractions of a second:

- 1/30 s, 1/60 s, 1/125 s, 1/250 s, 1/500 s
- See a pattern?

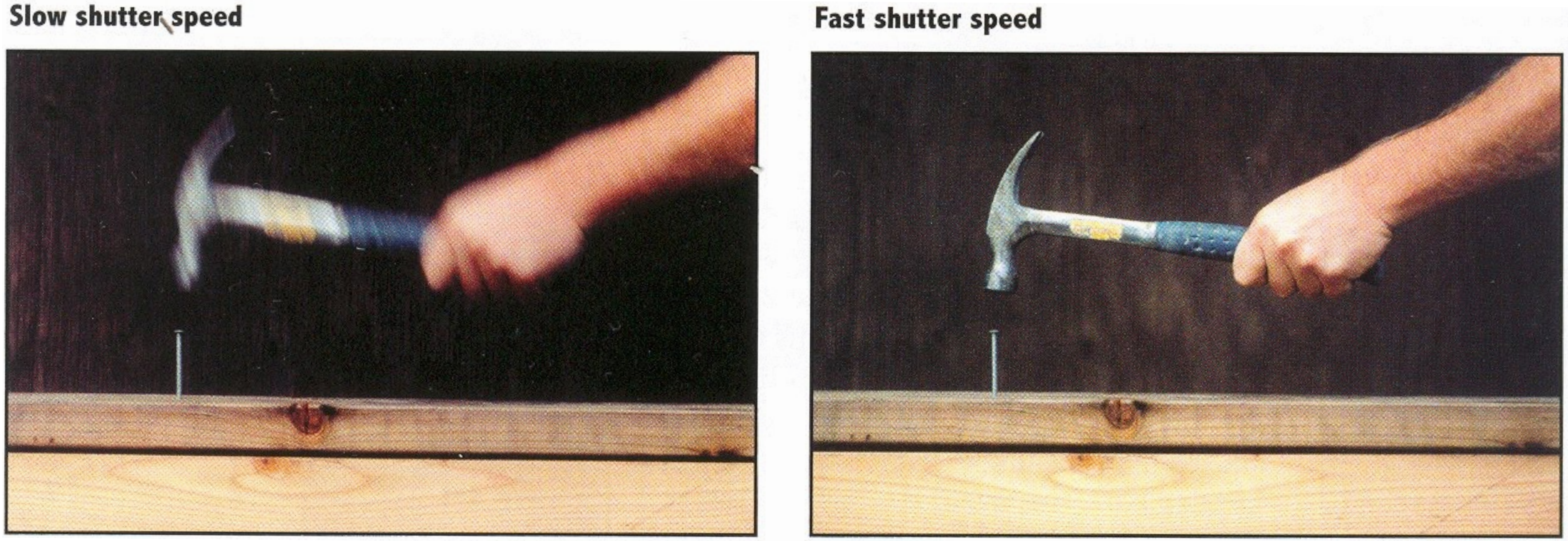
On a normal lens, normal humans can hand-hold down to 1/60

- In general, the rule of thumb says that the limit is the inverse of focal length, e.g. 1/500s for 500mm

Main effect of shutter speed

Motion blur

Doubling exposure time doubles motion blur (const. velocity)



From *Photography*, London et al.

Shutter

Various technologies

Goal: achieve uniform exposure across image

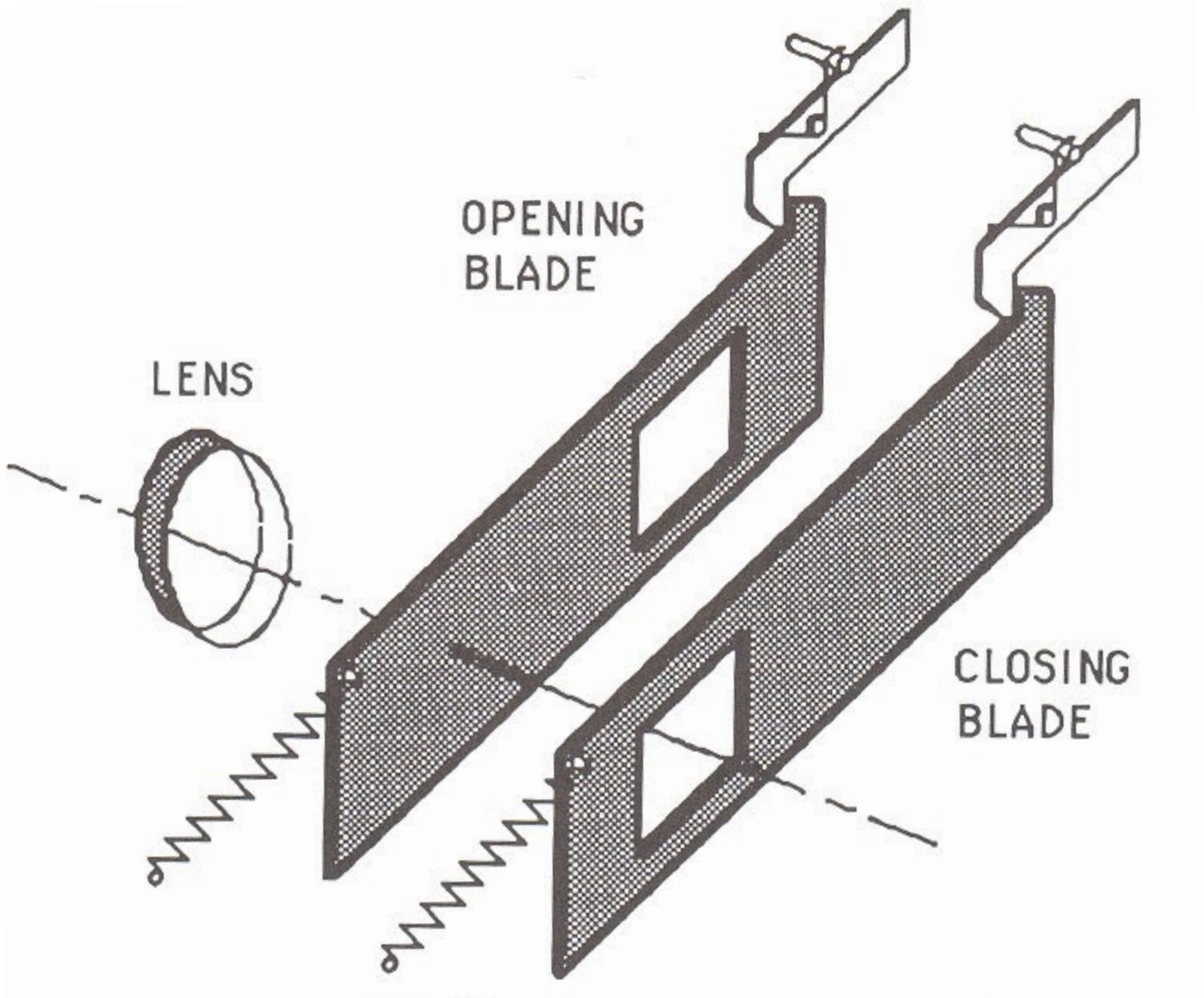


FIG. 2.8 Two-blade guillotine shutter.

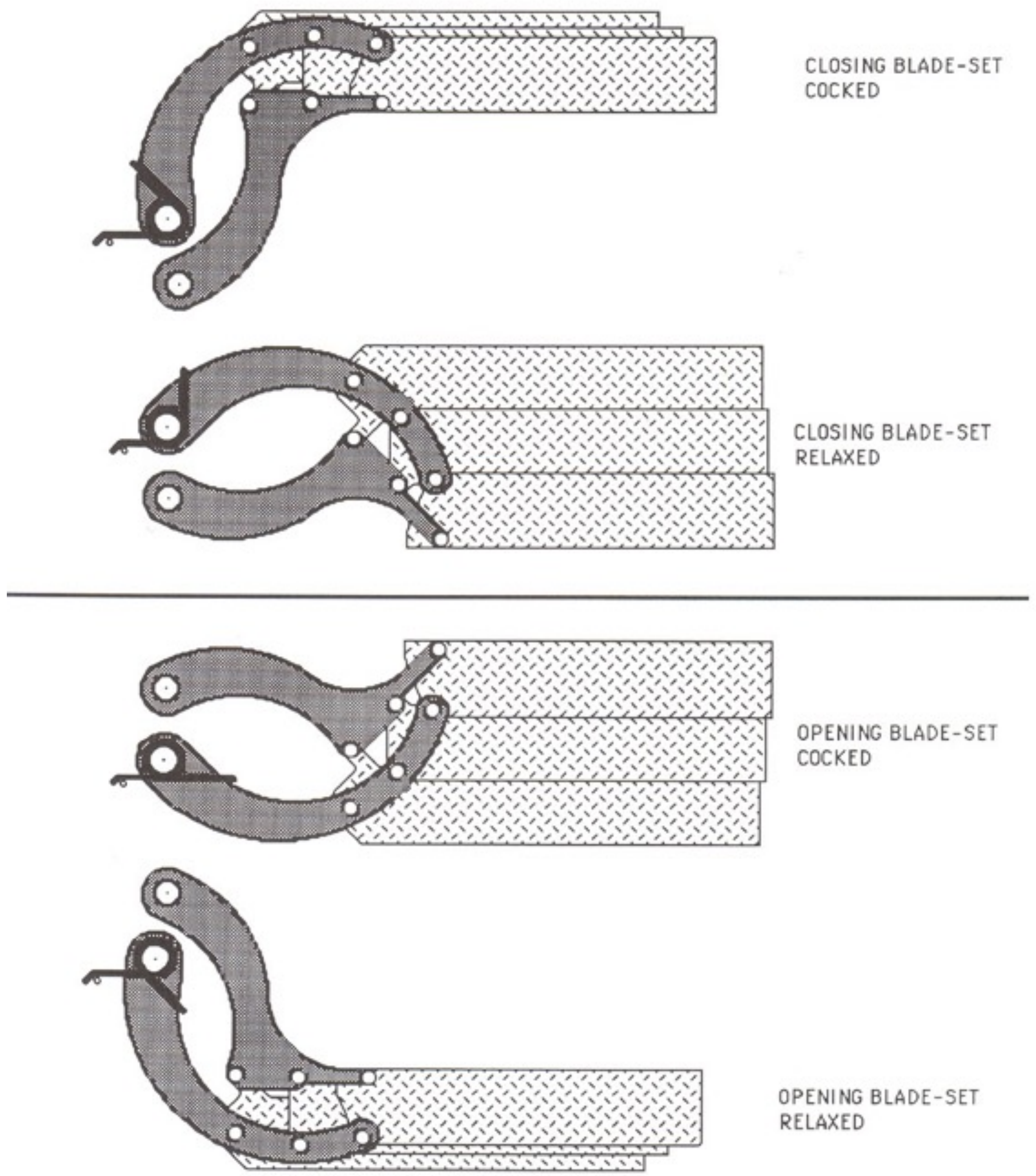


FIG. 2.12 Copal square.

From *Camera Technology*, Goldberg

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.)

Camera movement

The solution:

- (yes, it's a pain to carry)

Exposure

Exposure = Irradiance x Time

Exposure time

- in seconds
- controlled by shutter

Irradiance

- amount of light falling on a unit area of sensor per second
- controlled by aperture

Aperture

only got here

Diameter of the lens opening (controlled by diaphragm)

Irradiance on sensor is proportional to

- square of aperture diameter A
- inverse square of distance to sensor (~ focal length f)

As diameter A of the aperture doubles, its area (hence the light that can get through it) increases by 4x. (circle area: πA^2)

If the distance to sensor is doubled, light projects onto an area 4x larger, so light falling per unit area decreases by 4x

F-number

So that aperture values give irradiance regardless of focal length, *aperture number N* is defined relative to focal length

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

A relative aperture size (also F-number or just N) of N=2 is denoted "f/2" to reflect the above formula.

- f/2.0 on a 50mm means that the aperture is
- f/2.0 on a 100mm means that the aperture is

low F-number with long focal length

Sigma 200-500mm F2.8 EX DG lens

What does 1600mm lens look like?

http://www.digitalpixels.net/varia/the-web/sigma-200-500mm-f28-ex-dg-lens-on-the-field/

http://dancarrphotography.com/blog/wp-content/uploads/2011/05/Canon_super_tele_comparison.jpg

F-number

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 a pattern?
  - aperture area gets halved in each step (1 f-stop)
  - f-number doubles every other step

Youtube tutorial

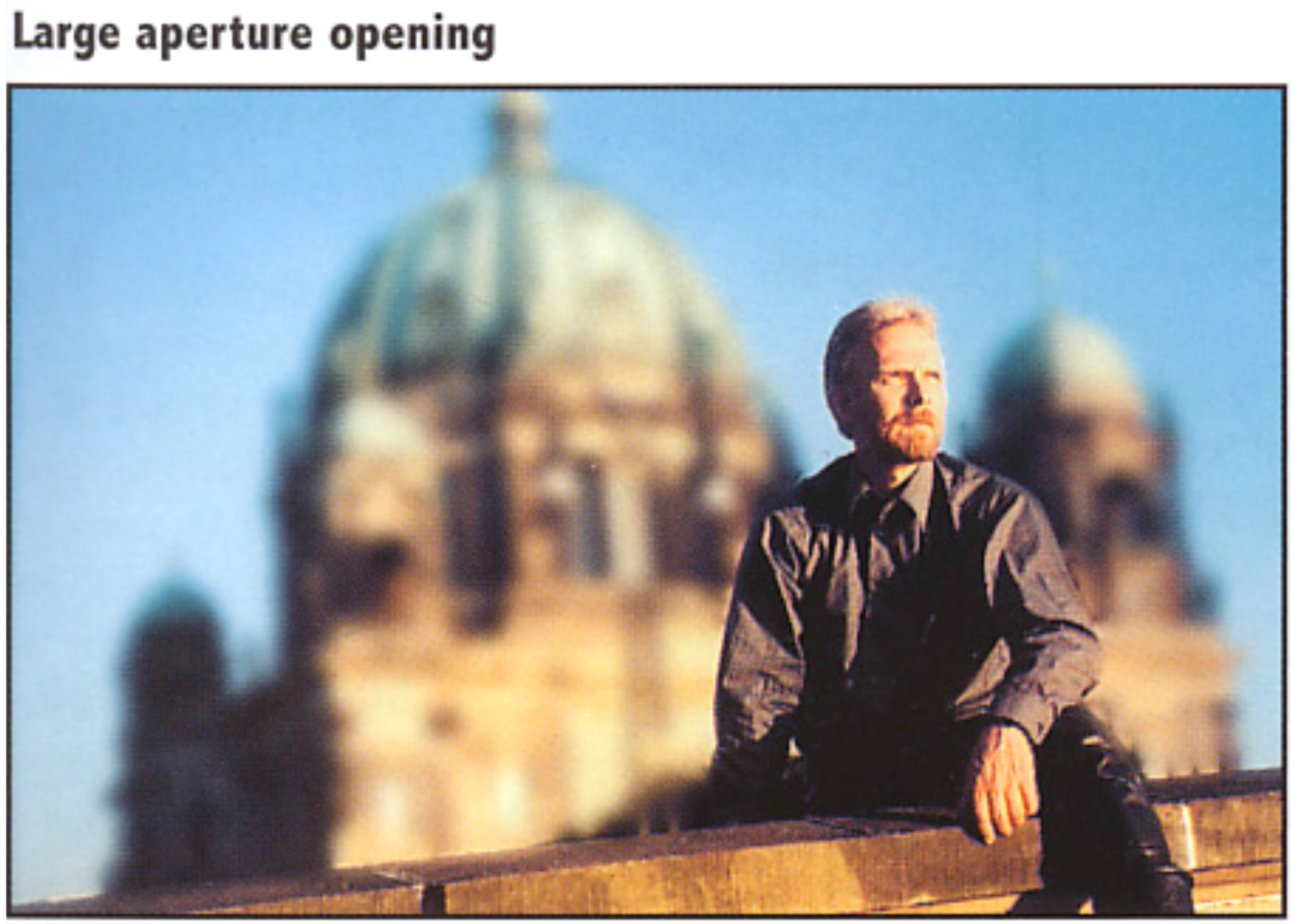
https://youtu.be/KmNIouLByJQ

Main effect of aperture

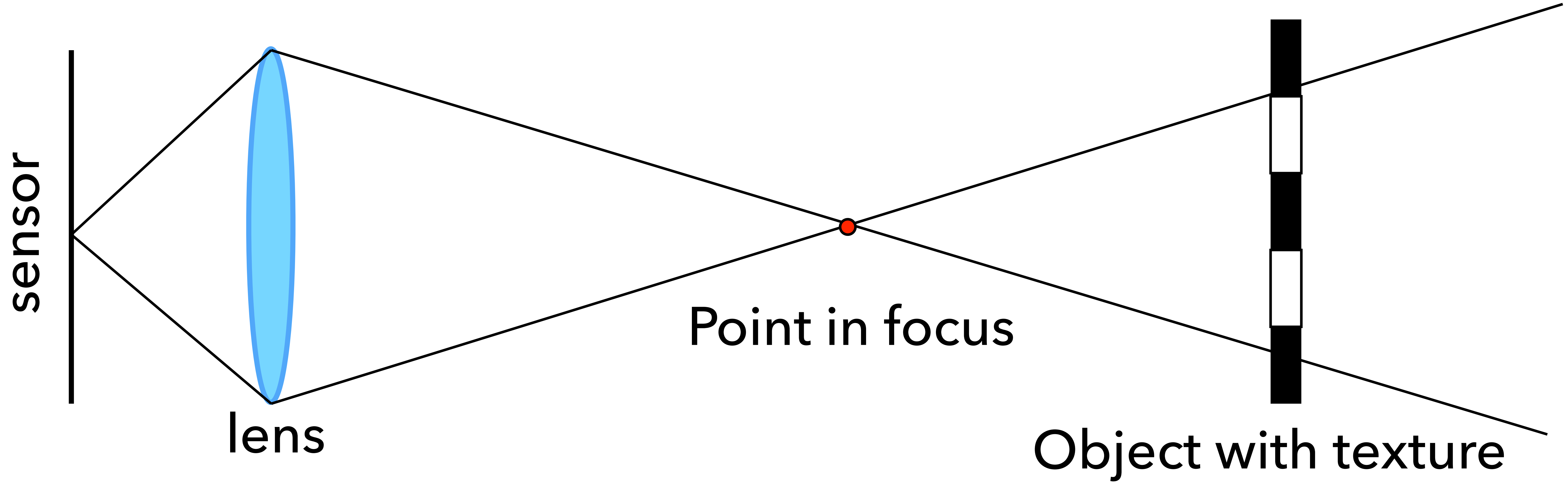
Depth of field

Doubling N (two f-stops) doubles depth of field

From *Photography*, London et al.

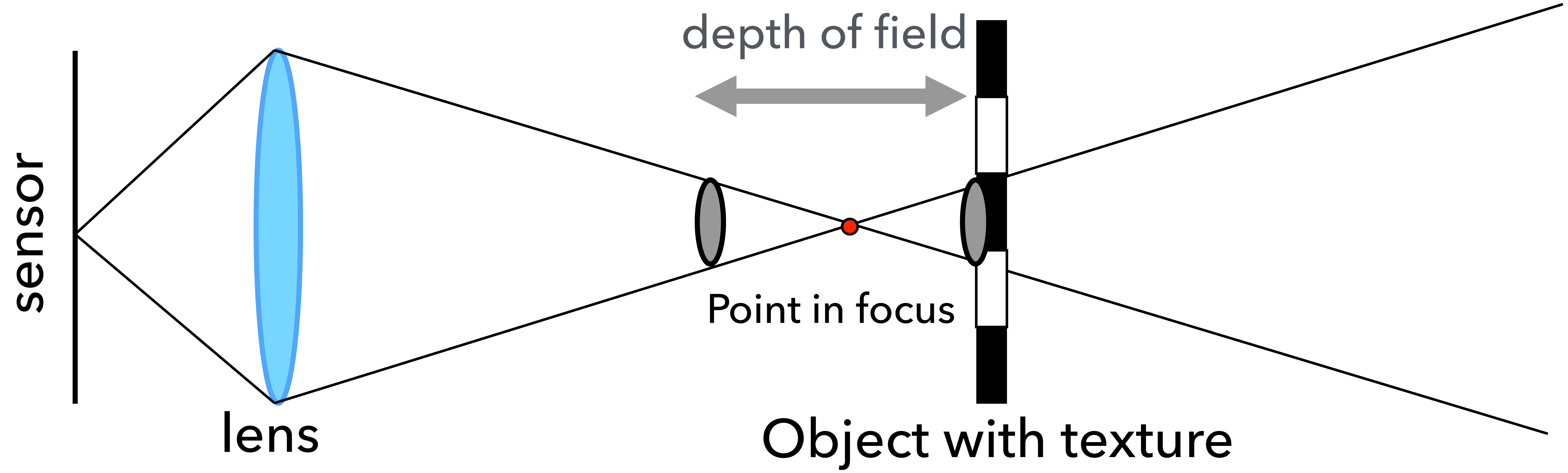


Depth of field

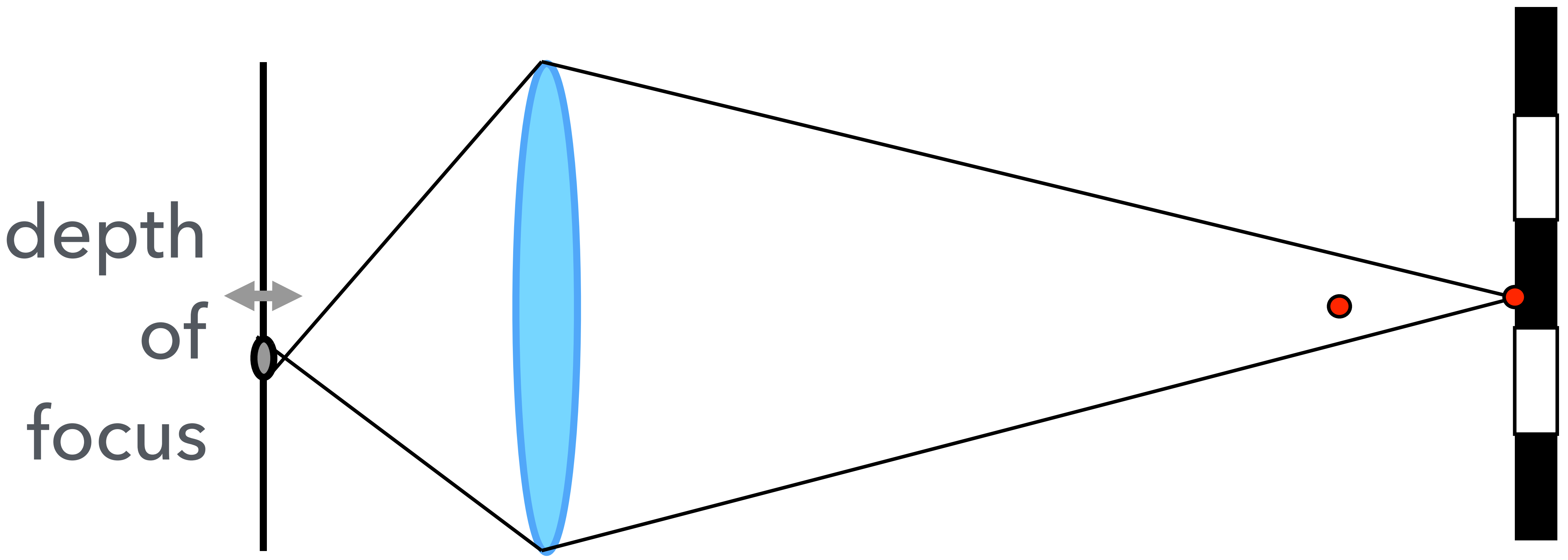


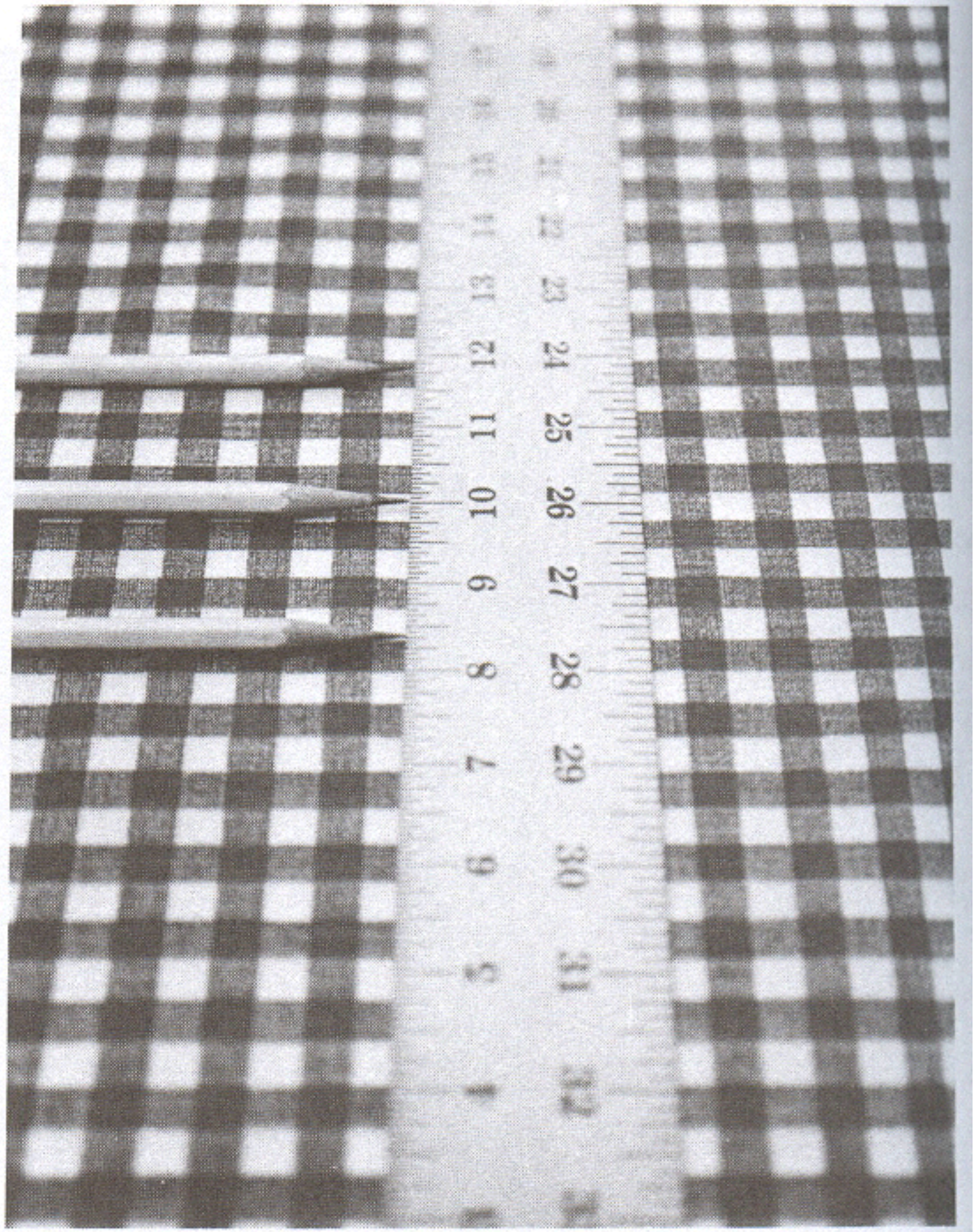
Depth of field

We allow for some tolerance



Max acceptable circle of confusion

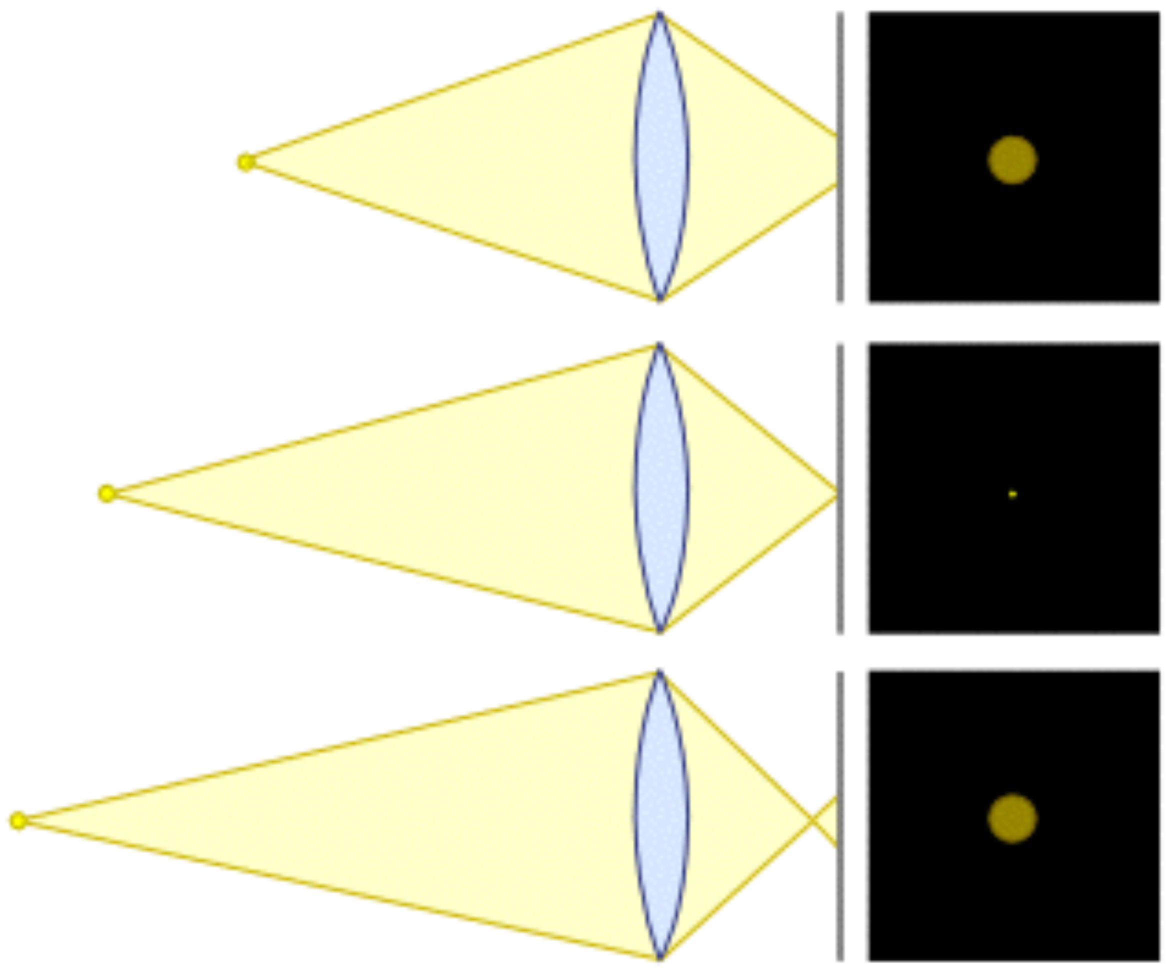




Circle of confusion http://en.wikipedia.org/wiki/Circle_of_confusion

Also called "blur circle"

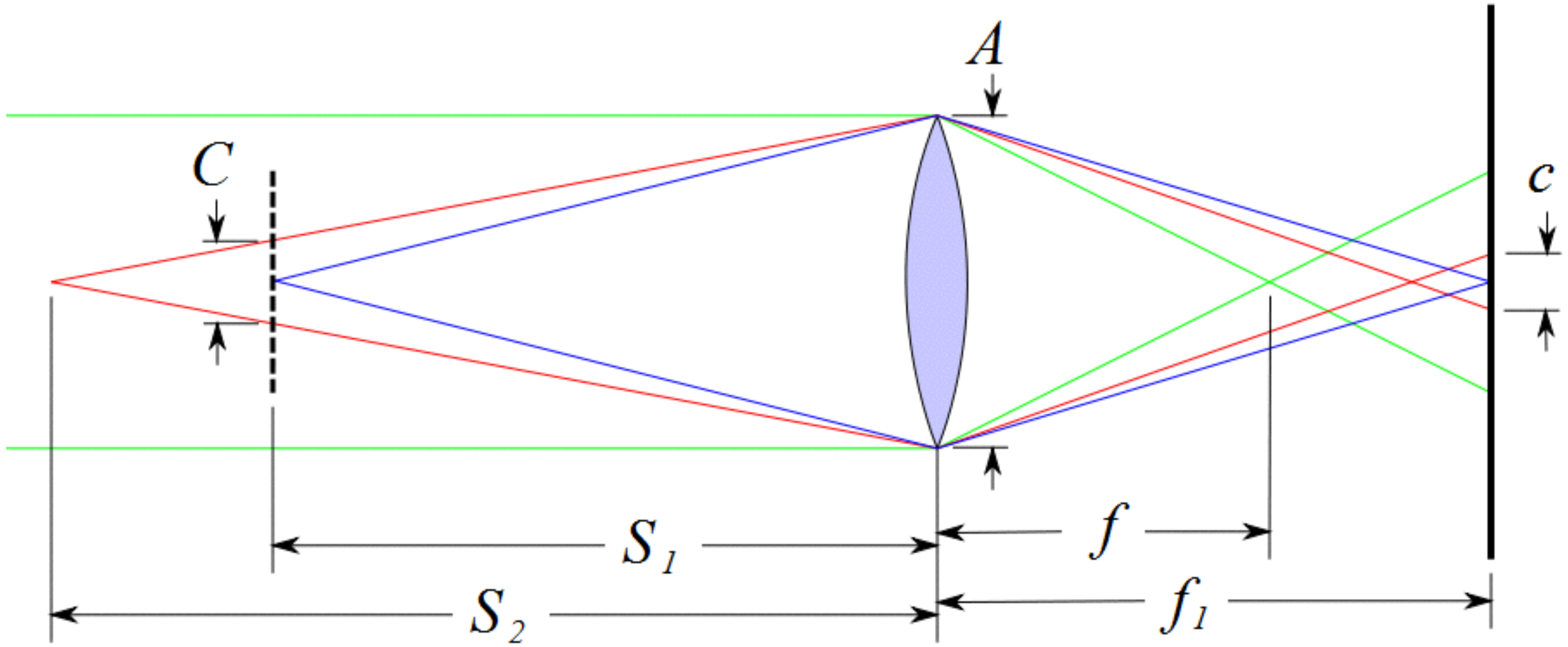
Calculation of radius c



- Lens focused at s_1
- Object at S_2
- Aperture A
- Focal length f

$$c = A \cdot \frac{|S_2 - S_1|}{S_2} \cdot \frac{f}{S_1 - f}$$

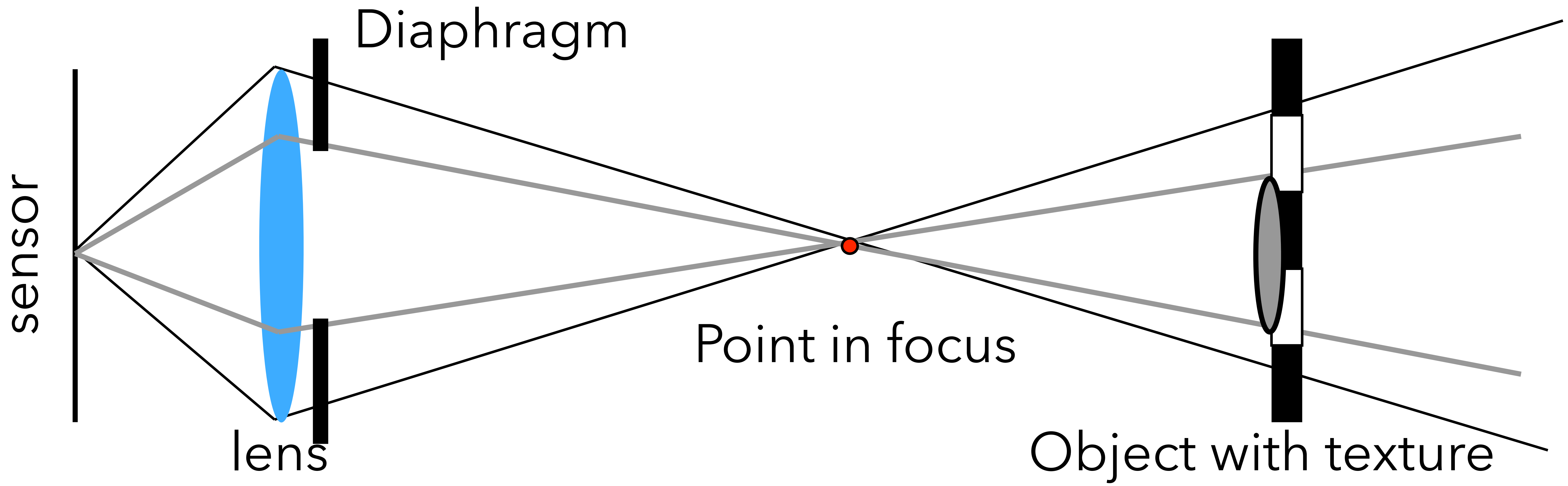
Proportional to A



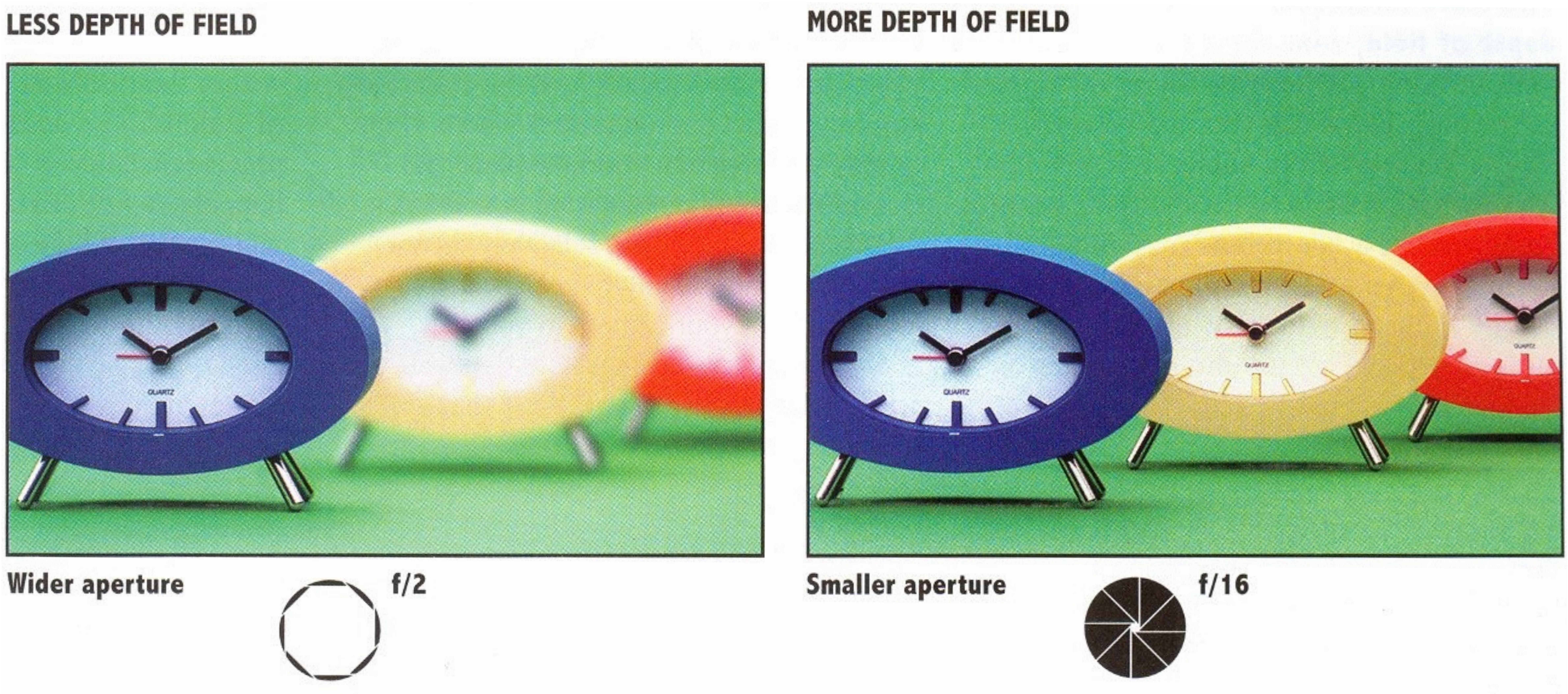
Depth of field

What happens when we close the aperture by two stop?

- Aperture diameter is divided by two
- Depth of field is doubled



Depth of field



From *Photography*, London et al.

F-number of the Human Eye

http://www.petapixel.com/2012/06/11/whats-the-f-number-of-the-human-eye/

Questions?

Exposure

Two main parameters:

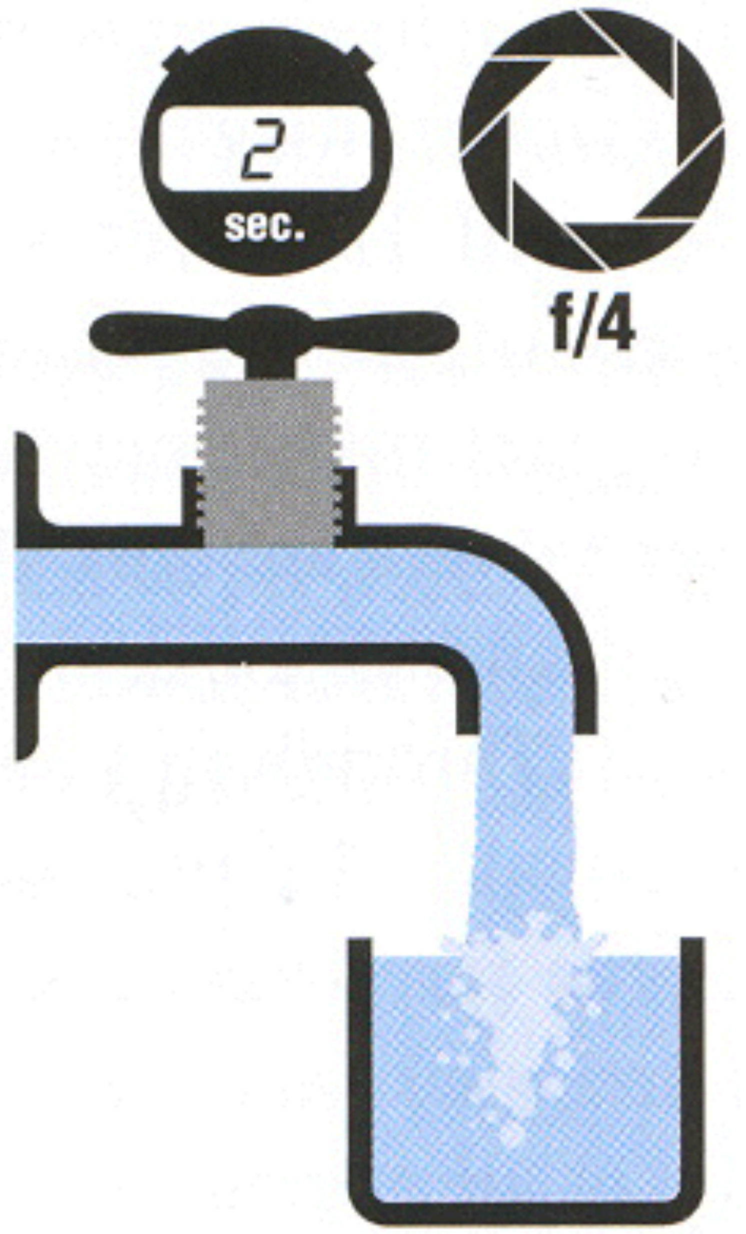
- Aperture (in f stop)
- Shutter speed (in fraction of a second)

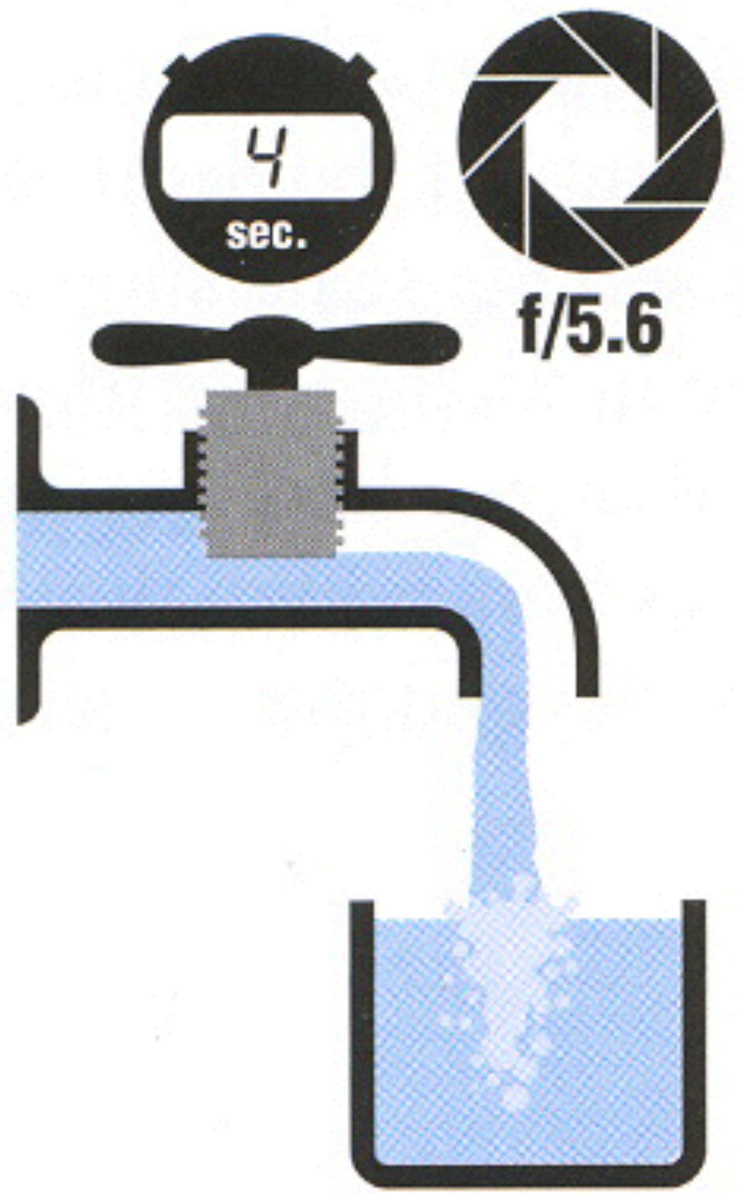
Reciprocity

- Amount of light captured stays the same if exposure is doubled and aperture *area* is halved (or vice versa)

Hence square-root of two progression of f stops vs. power of two progression of shutter speeds

Reciprocity can fail for very long exposures



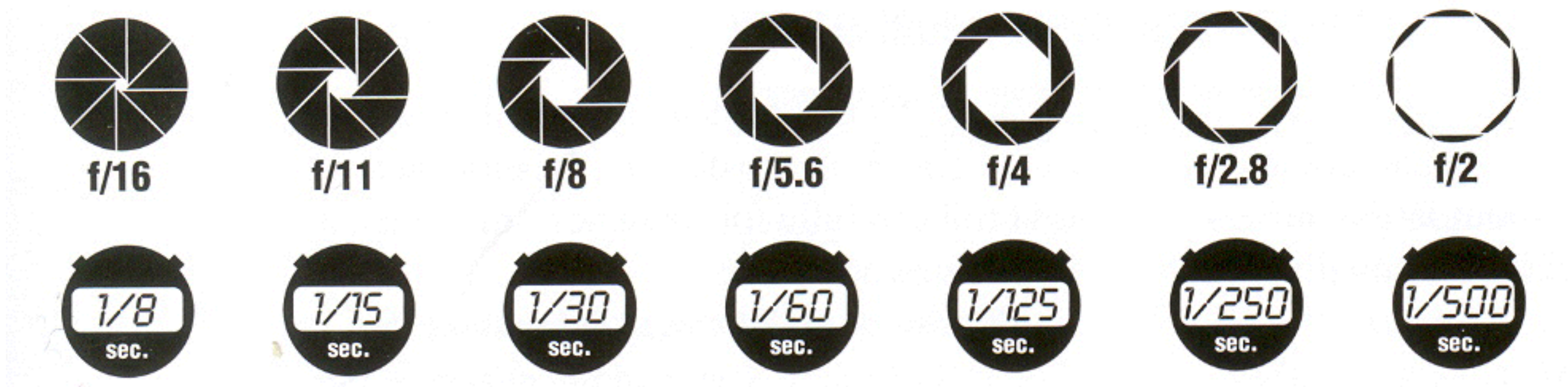


From *Photography*, London et al.

Reciprocity

Assume we know how much light we need

We have an infinite choice of shutter speed/aperture pairs

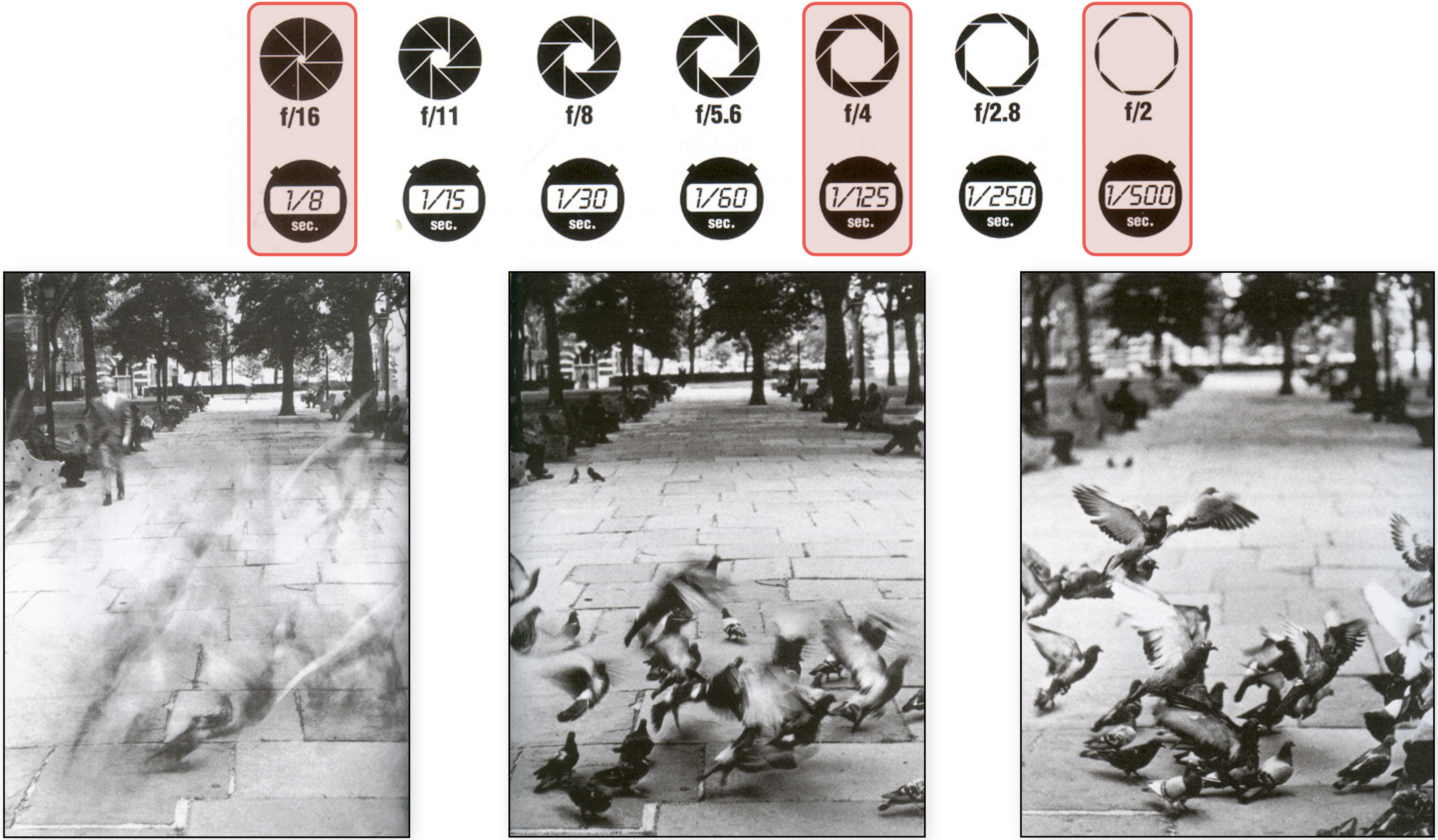


What will guide our choice of a shutter speed?

- Freeze motion vs. motion blur, camera shake

What will guide our choice of an aperture?

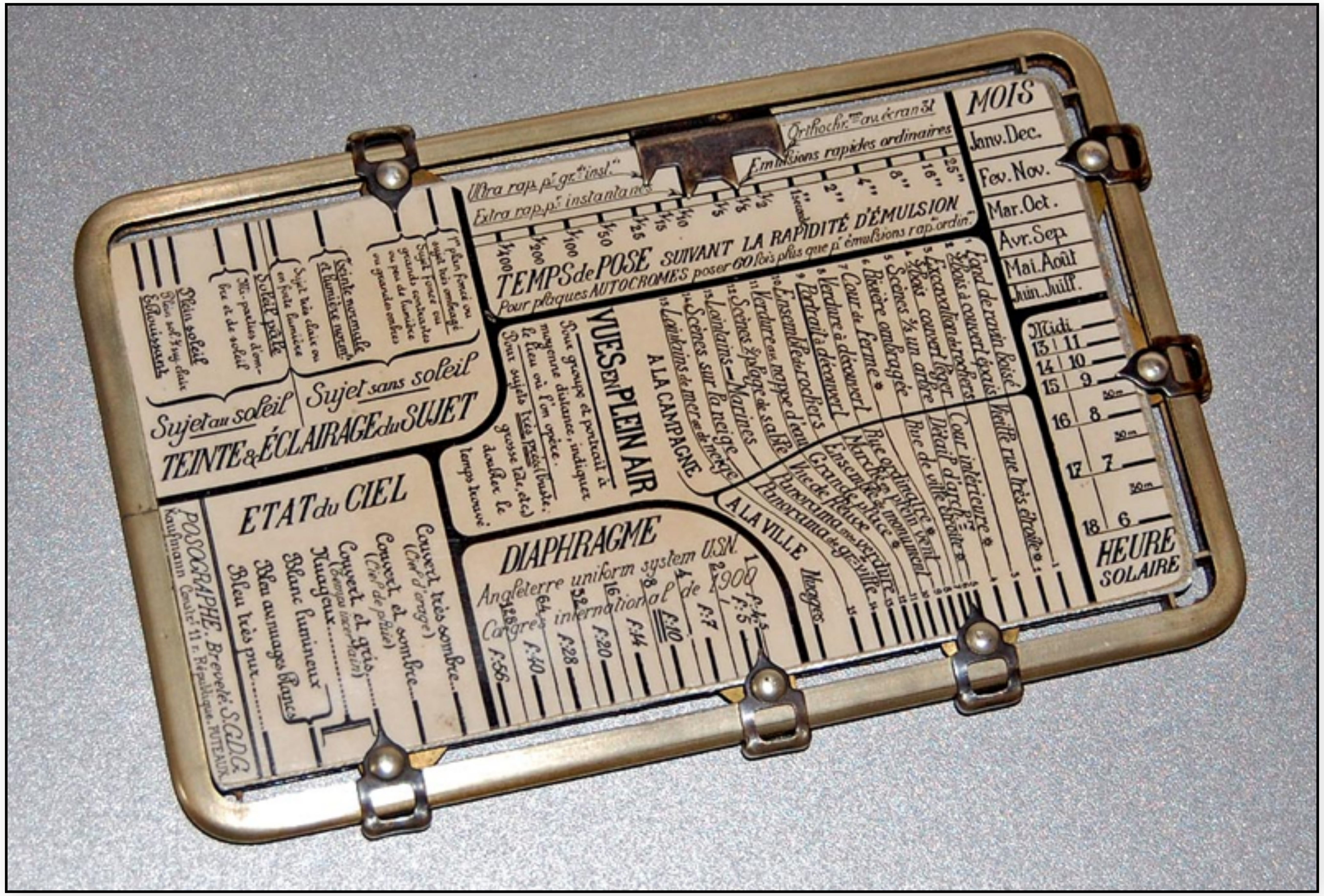
- Depth of field, diffraction limit

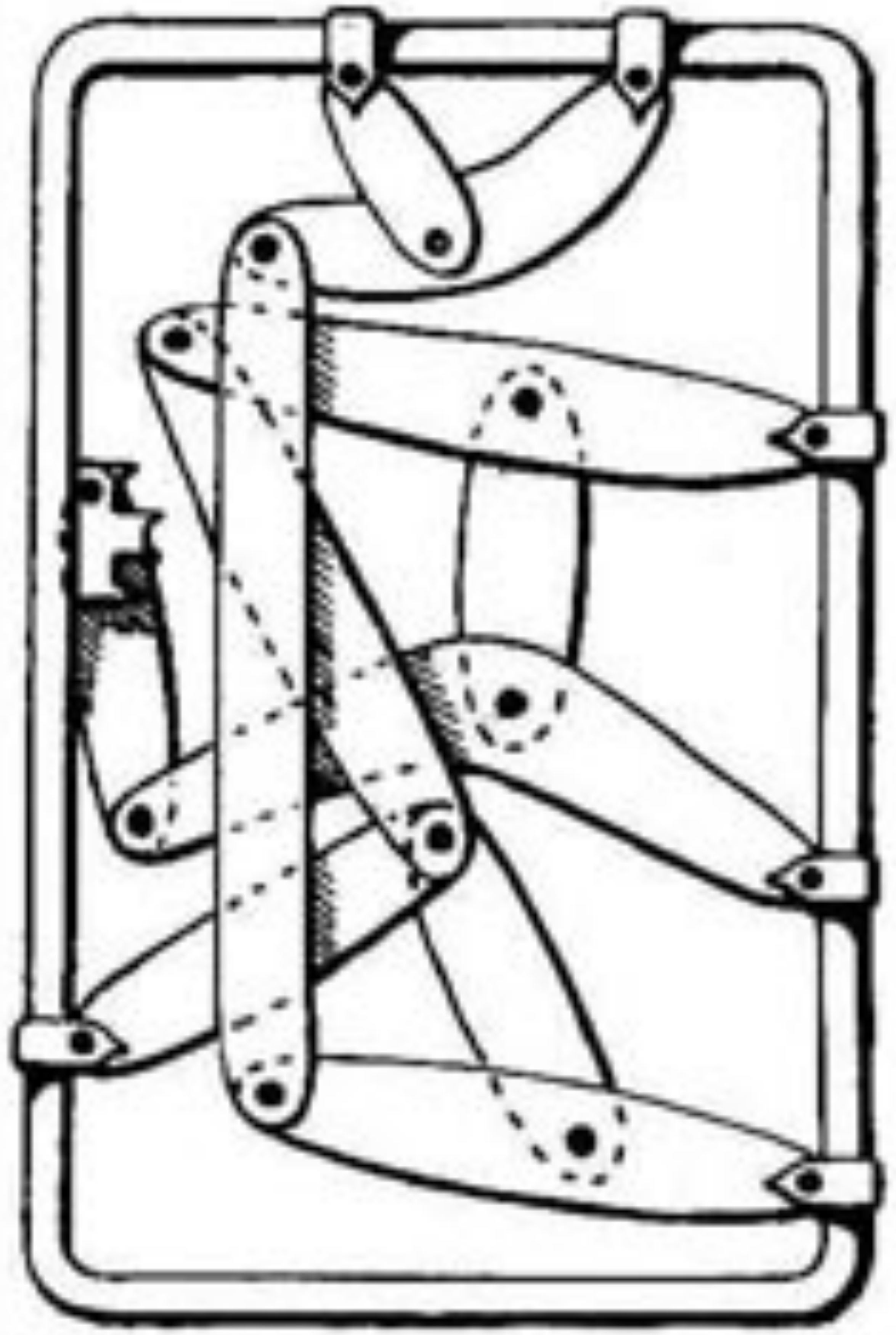


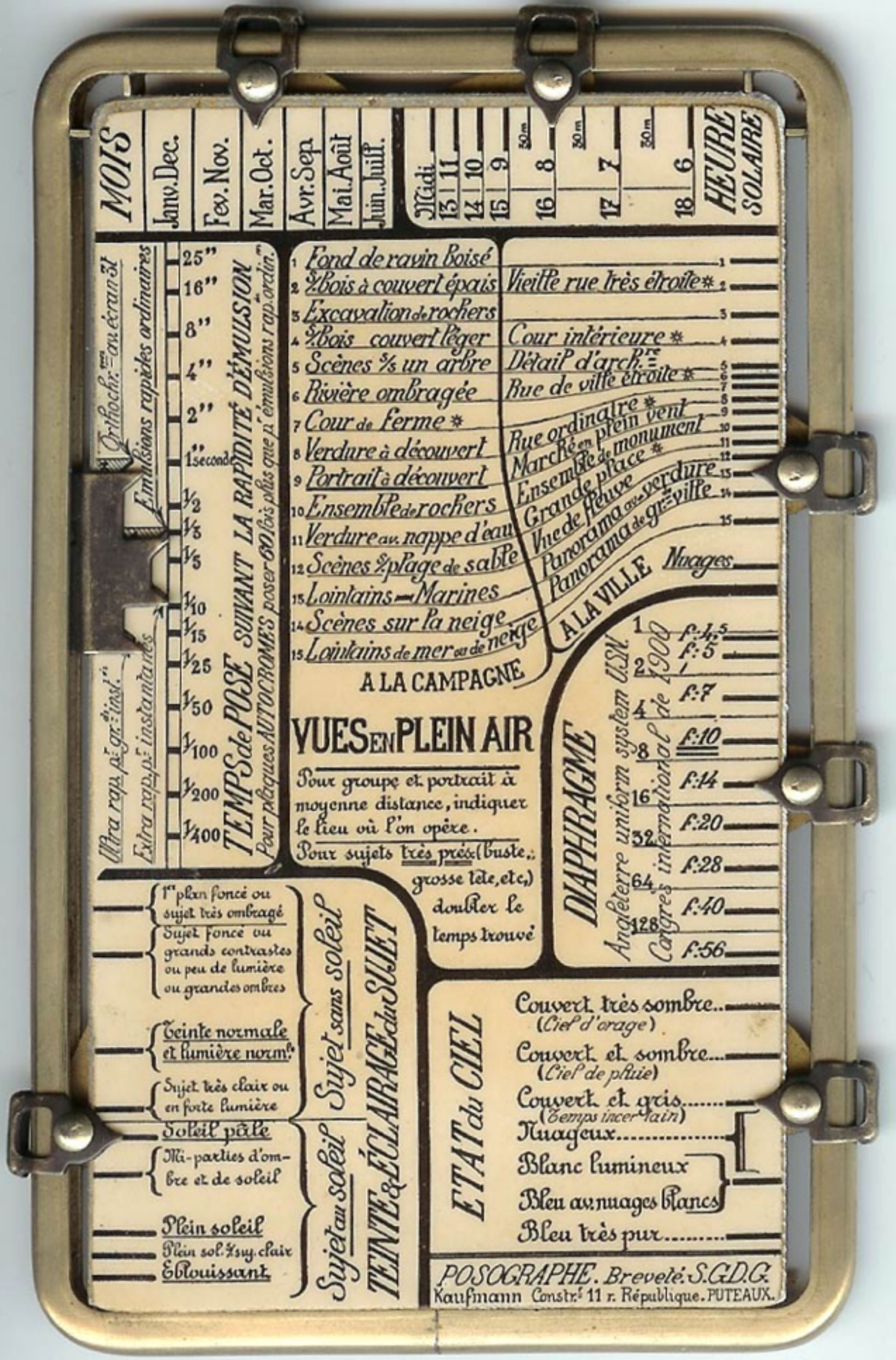
From *Photography*, London et al.

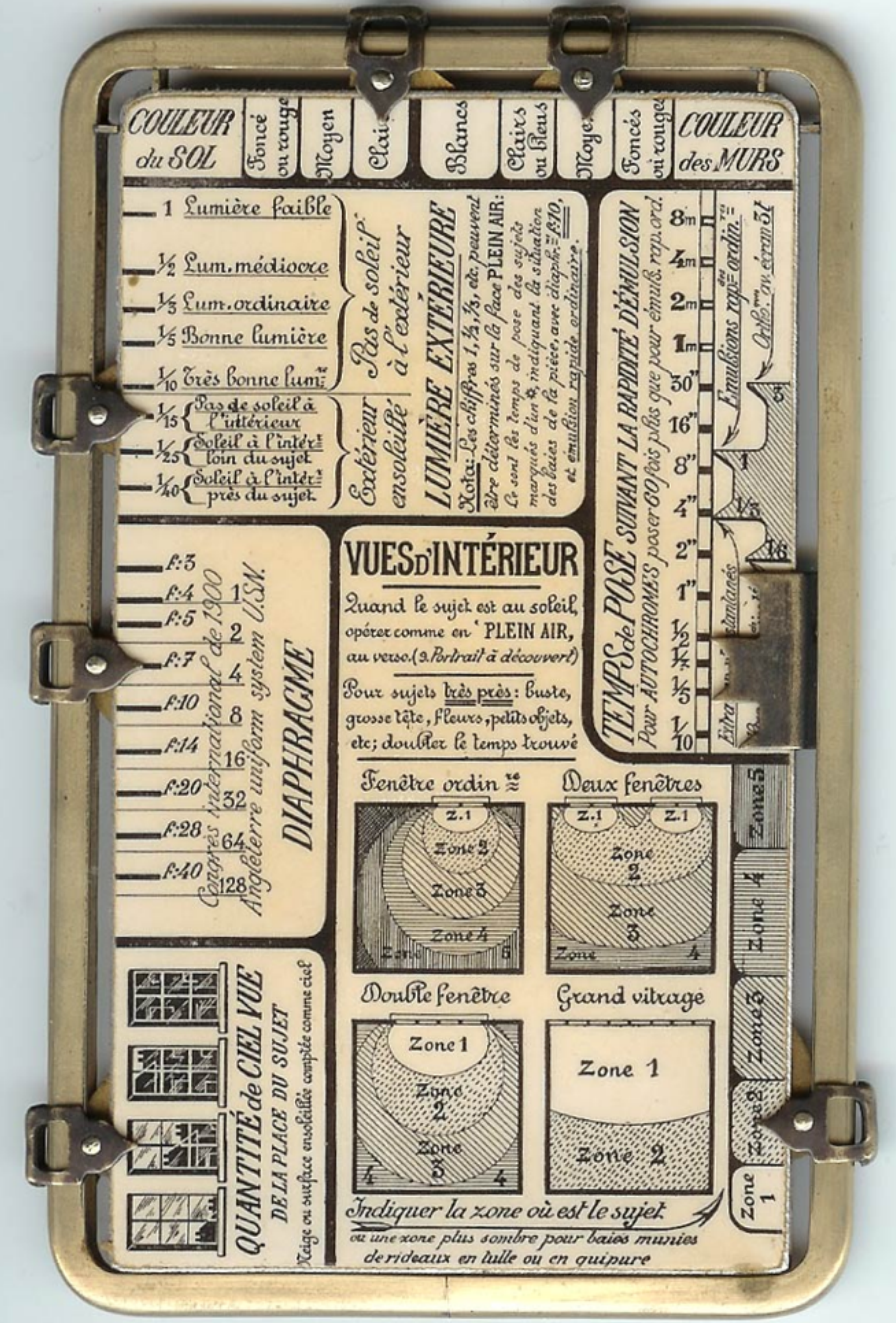
Analog

http://www.nzeldes.com/HOC/Posographe.htm






MOIS
Janv. Dec.
Fev. Nov.
Mar. Oct.
Avr. Sep.
Mai Août
Juin Juil.
Midi
HEURE SOLAIRE
TEMPS de POSE SUIVANT LA RAPIDITÉ D'ÉMULSION
Pour plaques AUTOCHROMES poser 60 fois plus que p. émulsion rap. ordin.
Émulsions rapides ordinaires
Ultra rap. p. gr. inst.
Extra rap. p. instantanés
1 Fond de ravin boisé
2 Bois à couvert épais
3 Excavation de rochers
4 Bois couvert léger
5 Scènes s/s un arbre
6 Rivière ombragée
7 Cour de ferme
8 Verdure à découvert
9 Portrait à découvert
10 Ensemble de rochers
11 Verdure au nappe d'eau
12 Scènes s/ plage de sable
13 Lointains - Marines
14 Scènes sur la neige
15 Lointains de mer ou de neige
Vieille rue très étroite
Cour intérieure
Détail d'arch.
Rue de ville étroite
Rue ordinaire
Marché en plein vent
Ensemble de monument
Grande place
Vue de fleuve ou verdure
Panorama ou verdure
Panorama de gr. ville
Nuages
A LA VILLE
A LA CAMPAGNE
VUES EN PLEIN AIR
Pour groupe et portrait à moyenne distance, indiquer le lieu où l'on opère.
Pour sujets très près (buste, grosse tête, etc.) doubler le temps trouvé
DIAPHRAGME
Angleterre uniform system U.S.N.
Congrès international de 1900
f:4,5
f:5
f:7
f:10
f:14
f:20
f:28
f:40
f:56
1er plan foncé ou sujet très ombragé
Sujet foncé ou grands contrastes ou peu de lumière ou grandes ombres
Teinte normale et lumière norm.
Sujet très clair ou en forte lumière
Soleil pâle
Mi-parties d'ombre et de soleil
Plein soleil
Éblouissant
Sujet sans soleil
Sujet au soleil
TEINTE & ÉCLAIRAGE du SUJET
ETAT du CIEL
Couvert très sombre (Ciel d'orage)
Couvert et sombre (Ciel de pluie)
Couvert et gris (Temps incertain)
Nuageux
Blanc lumineux
Bleu av. nuages blancs
Bleu très pur
POSOGRAPHE. Breveté S.G.D.G.
Kaufmann Constr. 11 r. République. PUTEAUX.


COULEUR du SOL
Foncé ou rouge
Moyen
Clair
Blancs
Clairs ou bleus
Moyen
Foncés ou rouges
COULEUR des MURS
1 Lumière faible
1/2 Lum. médiocre
1/3 Lum. ordinaire
1/5 Bonne lumière
1/10 Très bonne lum.
Pas de soleil à l'extérieur
1/15 Pas de soleil à l'intérieur
1/25 Soleil à l'intér. loin du sujet
1/40 Soleil à l'intér. près du sujet
Extérieur ensoleillé
LUMIÈRE EXTÉRIEURE
TEMPS de POSE SUIVANT LA RAPIDITÉ D'ÉMULSION
Pour AUTOCHROMES poser 60 fois plus que pour émuls. rap. ord.
Émulsions rap. ordin.
VUES D'INTÉRIEUR
Quand le sujet est au soleil, opérer comme en "PLEIN AIR, au verso. (9. Portrait à découvert)
Pour sujets très près: buste, grosse tête, fleurs, petits objets, etc; doubler le temps trouvé
DIAPHRAGME
Congrès international de 1900
Angleterre uniform system U.S.N.
f:3
f:4
f:5
f:7
f:10
f:14
f:20
f:28
f:40
Fenêtre ordin.
Deux fenêtres
Double fenêtre
Grand vitrage
Zone 1
Zone 2
Zone 3
Zone 4
Zone 5
QUANTITÉ de CIEL VUE DE LA PLACE DU SUJET
Indiquer la zone où est le sujet
ou une zone plus sombre pour baies munies de rideaux en tulle ou en guipure

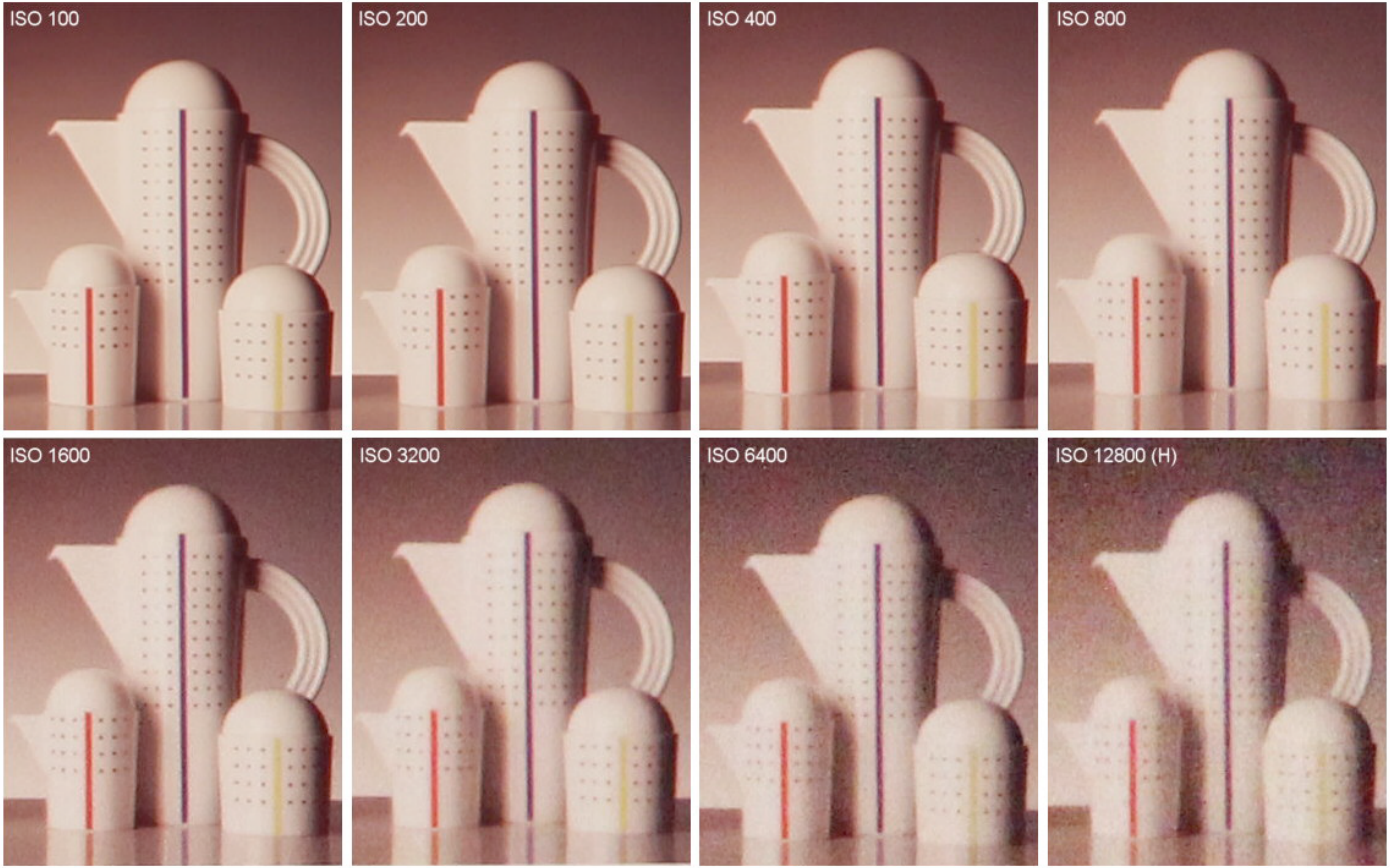
Sensitivity (ISO)

Third variable for exposure

Linear effect (200 ISO needs half the light as 100 ISO)

Film: trade sensitivity for grain

Digital: trade sensitivity for noise


ISO 100
ISO 200
ISO 400
ISO 800
ISO 1600
ISO 3200
ISO 6400
ISO 12800 (H)

Conclusions

Simple camera model

- Thin lens, aperture, shutter, sensor

Photographs often have undesired artifacts

- Distortions, color artifacts, blur, noise, under/overexposure

Goal: develop algorithms to remove artifacts after image is captured

Slide credits

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