View of Central Park Looking North—Fall by Abelardo Morell., 2008

BBM444

FUNDAMENTALS OF COMPUTATIONAL PHOTOGRAPHY

Lecture #02 – Image Formation

HACETTEPE UNIVERSITY COMPUTER VISION LAB

Erkut Erdem // Hacettepe University // Spring 2023

Today's Lecture

- Pinhole camera
- Basics of geometric optics and lenses
- Field of view
- Magnification and perspective
- Zooming
- Orthographic camera and telecentric lenses

Disclaimer: The material and slides for this lecture were borrowed from

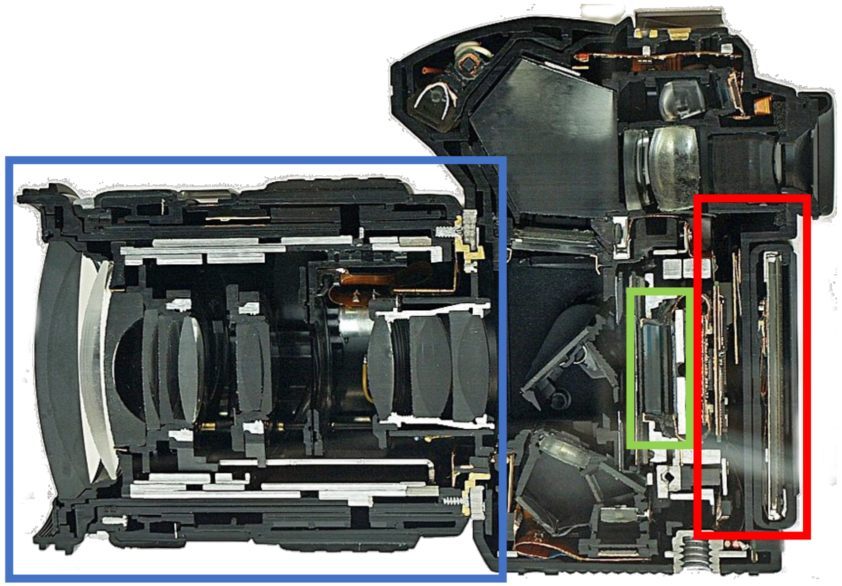
—Ioannis Gkioulekas' 15-463/15-663/15-862 "Computational Photography" class

—Steve Marschner's CS6640 "Computational Photography" class

—David Lindell's CSC2529 "Computational Imaging" class

The modern photography pipeline

post-capture processing



optics and optical controls → sensor, analog front-end, and color filter array → in-camera image processing pipeline

Some motivational imaging experiments

Let’s say we have a sensor…

... and an object we like to photograph

real-world
object

digital sensor
(CCD or CMOS)

What would an image taken like this look like?

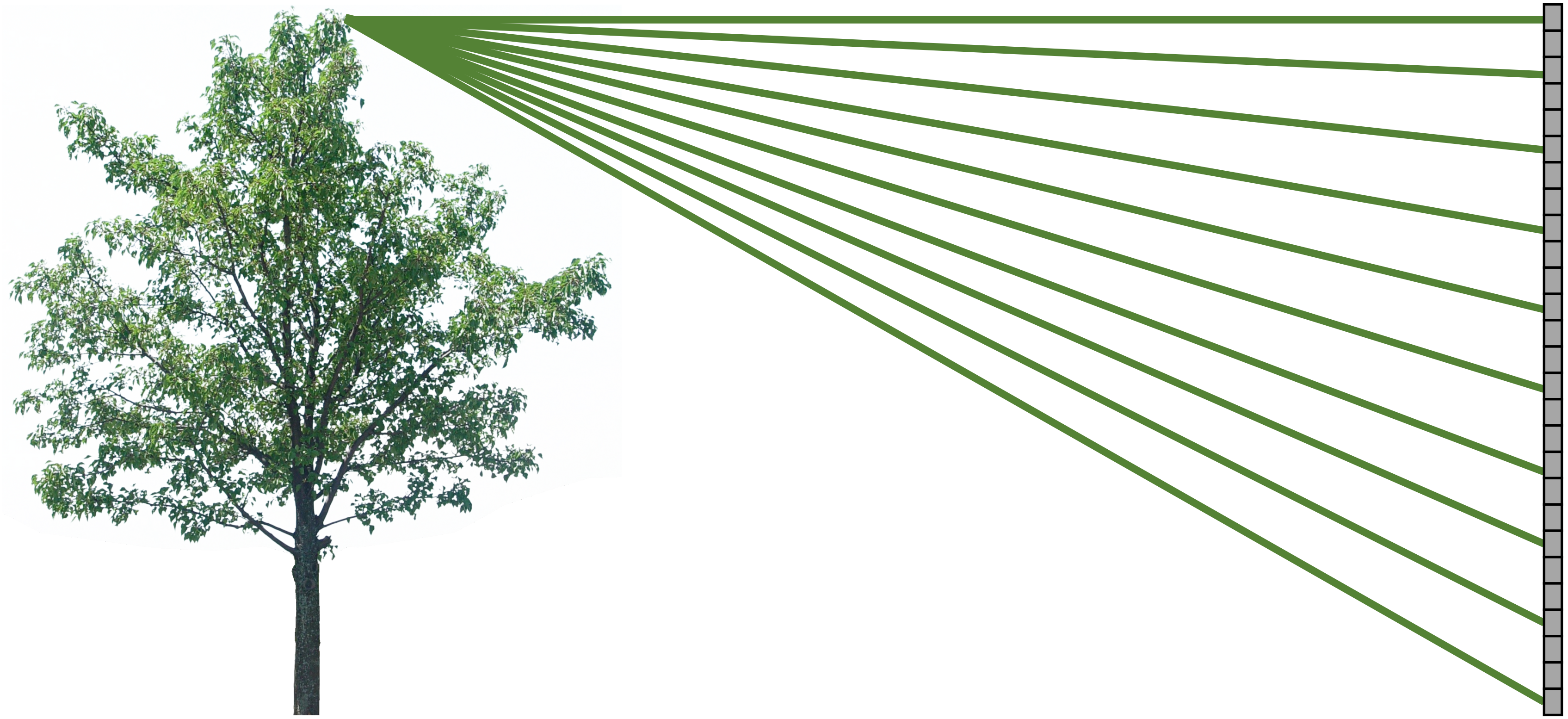
Bare-sensor imaging

real-world
object

digital sensor
(CCD or CMOS)

Bare-sensor imaging

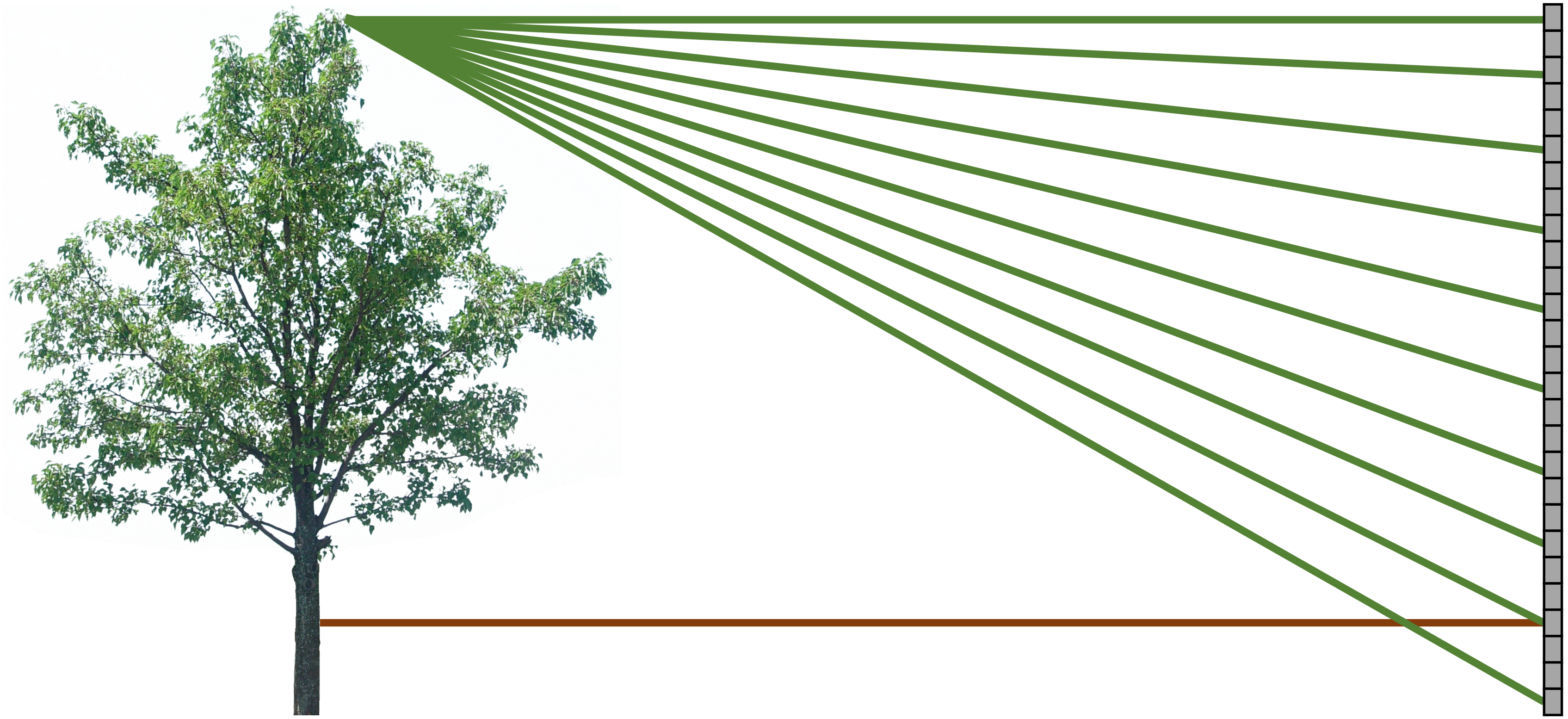
real-world
object



digital sensor
(CCD or CMOS)

Bare-sensor imaging

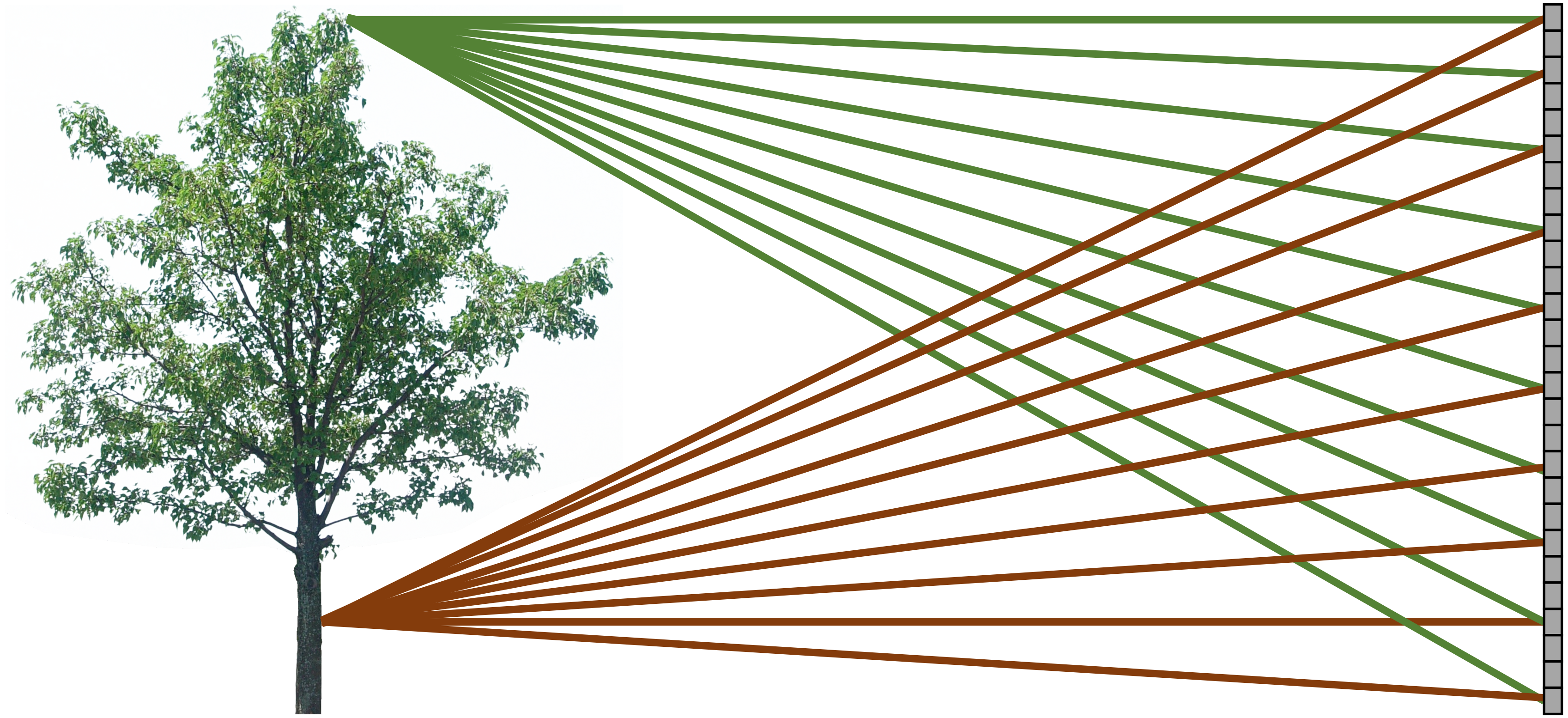
real-world
object



digital sensor
(CCD or CMOS)

Bare-sensor imaging

real-world
object



digital sensor
(CCD or CMOS)

All scene points contribute to all sensor pixels

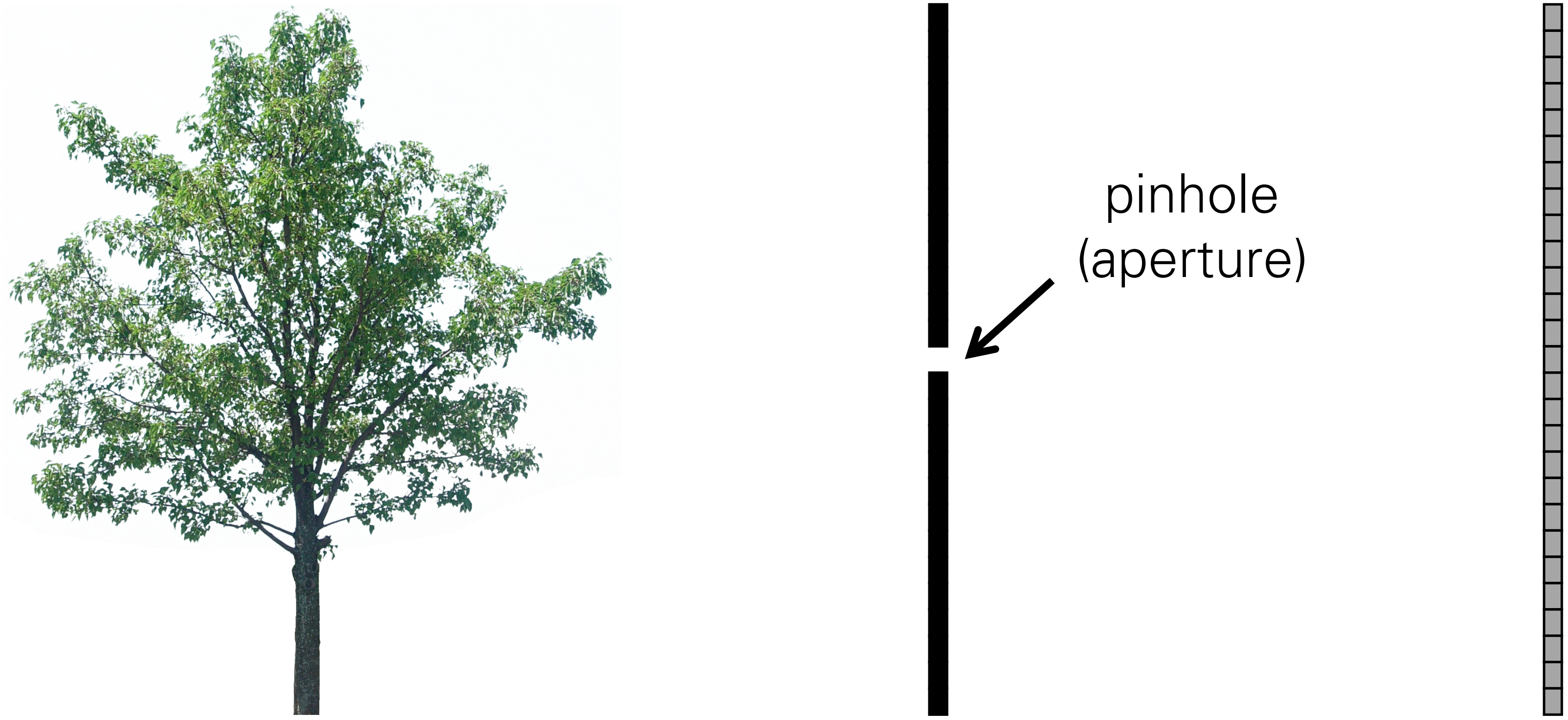
What does the image
on the sensor look like?

Bare-sensor imaging

All scene points contribute to all sensor pixels

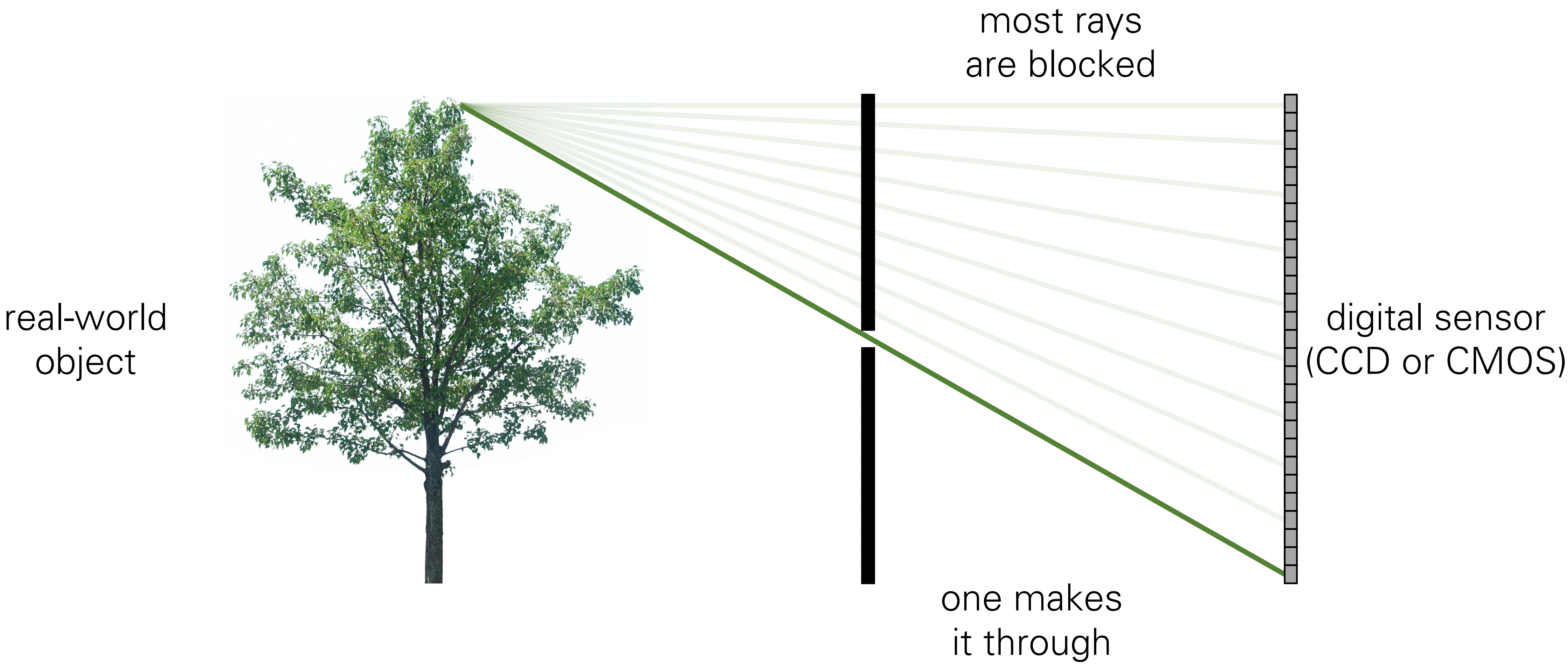
What can we do to make our image look better?

Let's add something to this scene

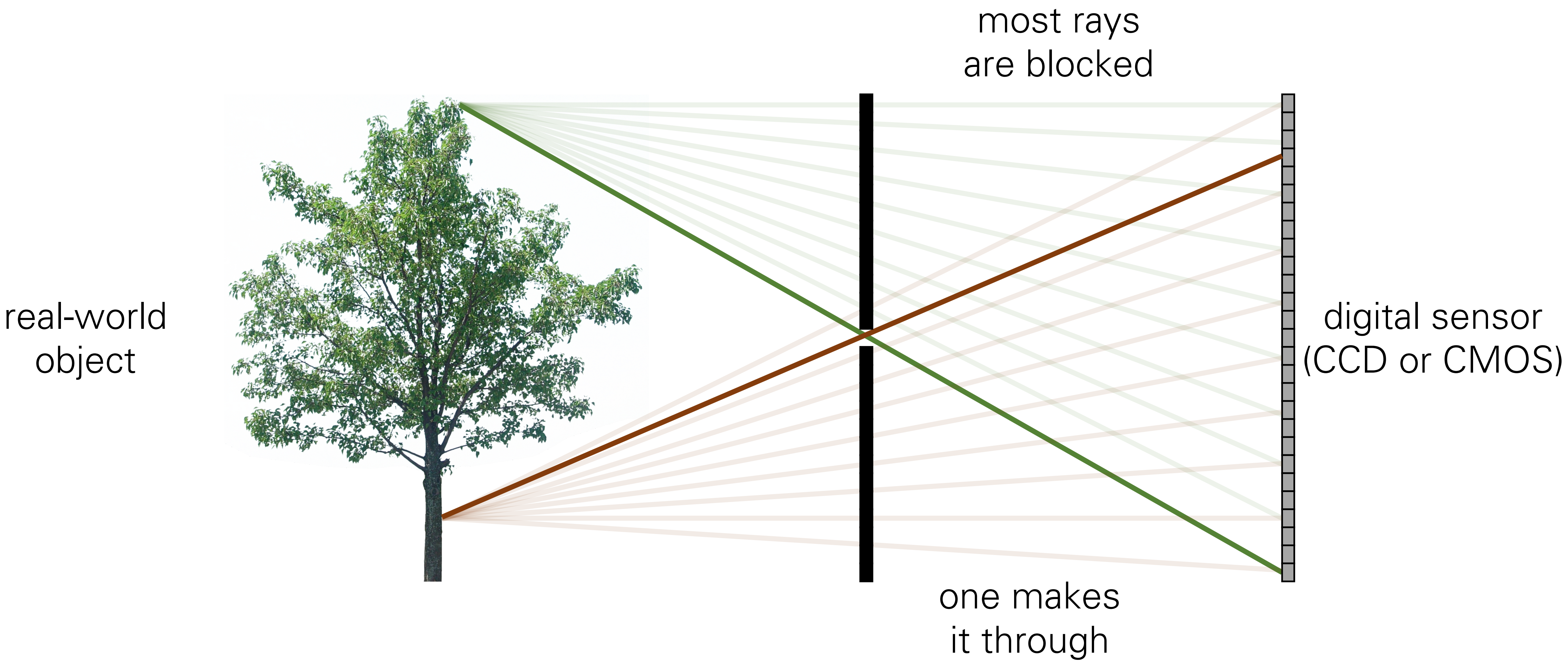


What would an image taken like this look like?

Pinhole imaging

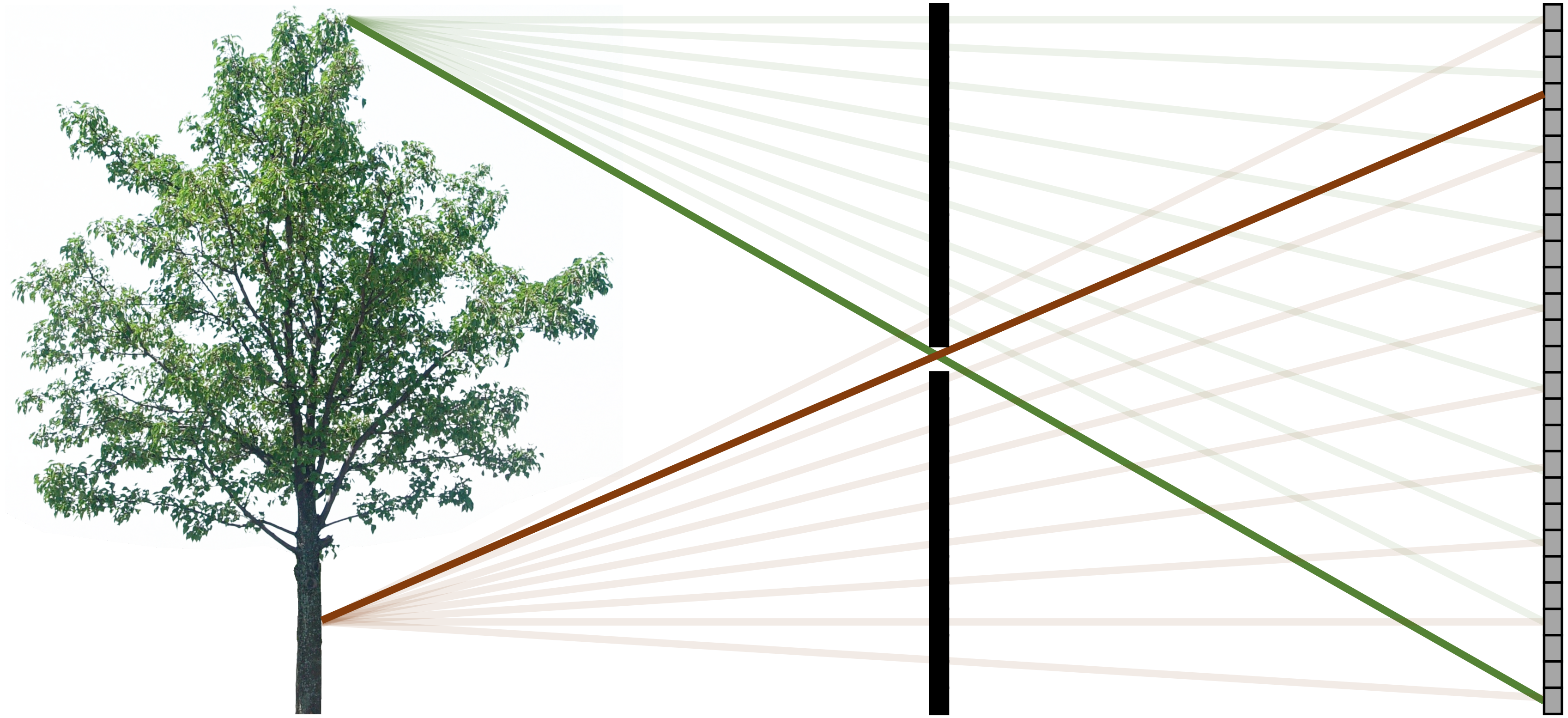


Pinhole imaging



Pinhole imaging

real-world
object



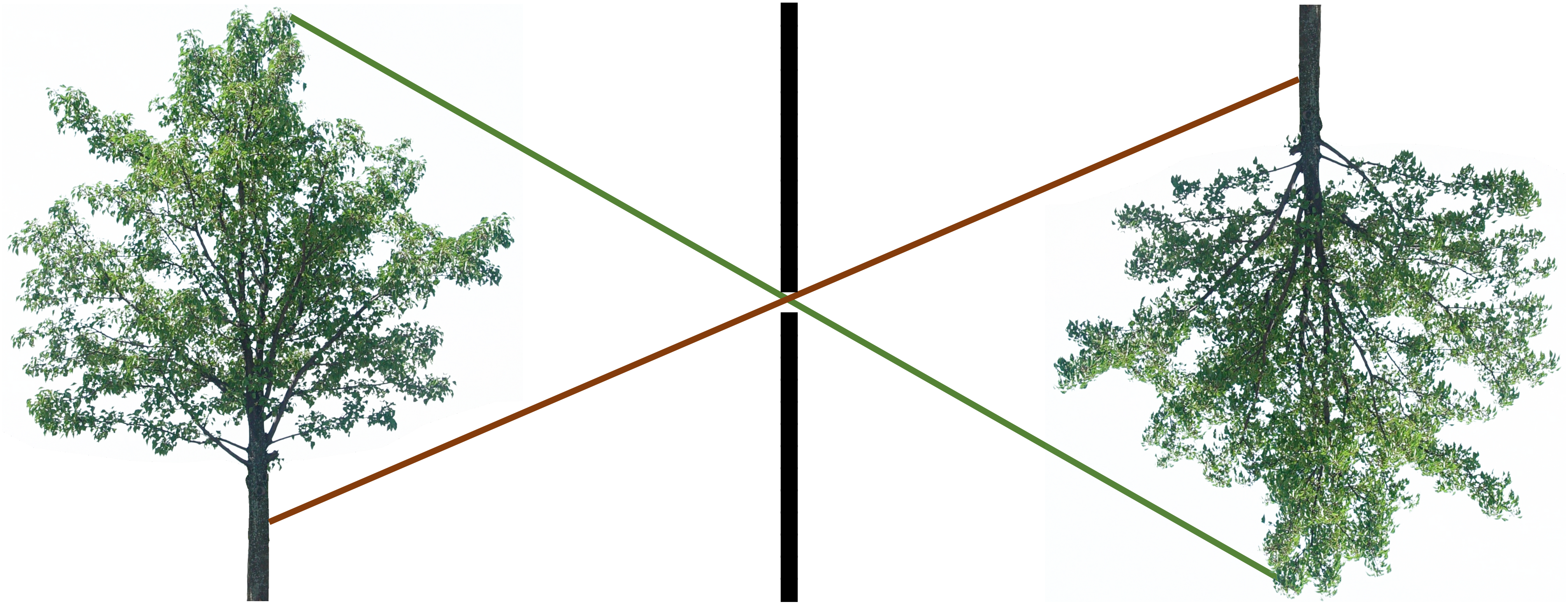
digital sensor
(CCD or CMOS)

Each scene point contributes to only one sensor pixel

What does the image
on the sensor look like?

Pinhole imaging

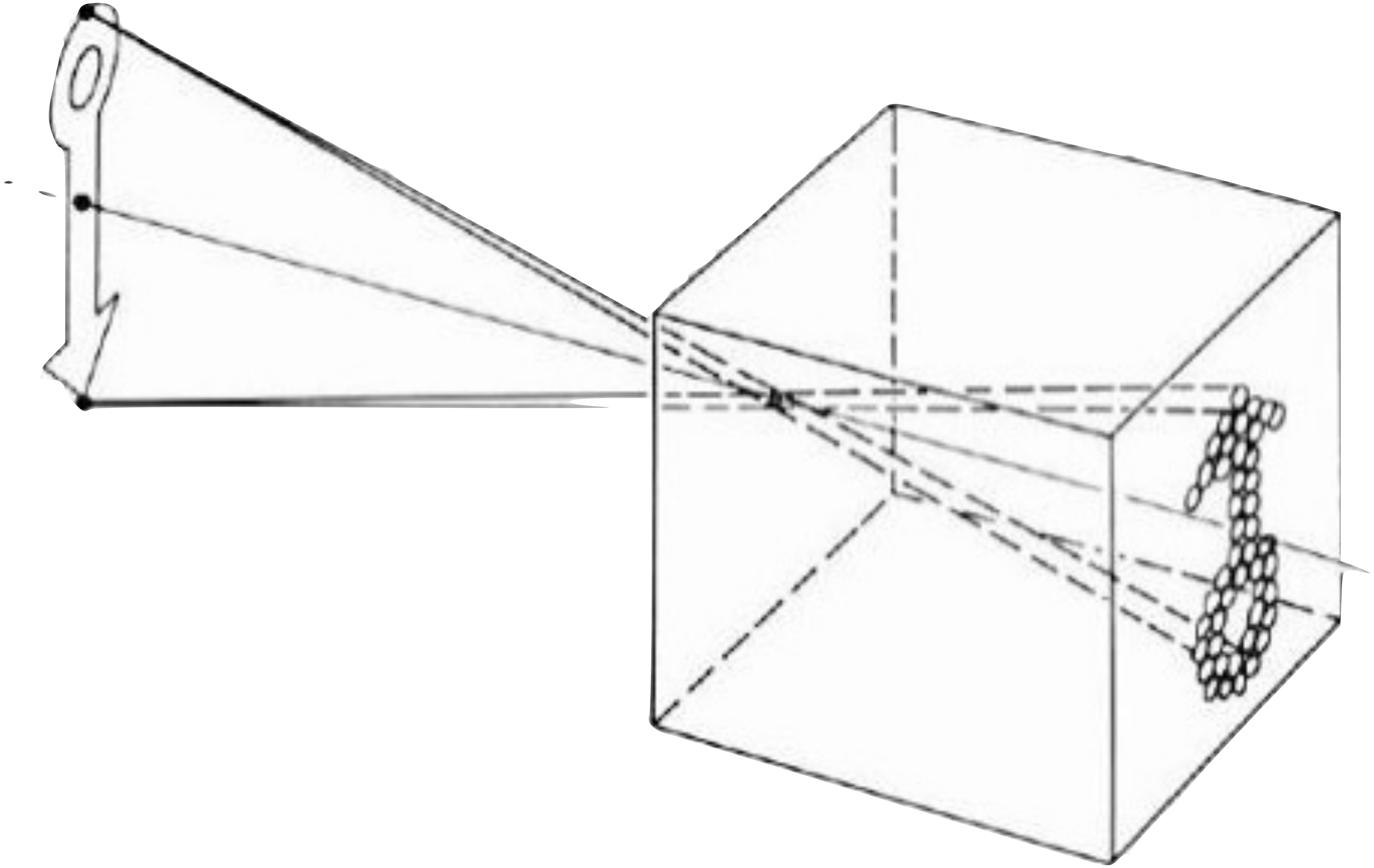
real-world
object



copy of real-world object
(inverted and scaled)

Pinhole camera

Pinhole camera a.k.a. camera obscura

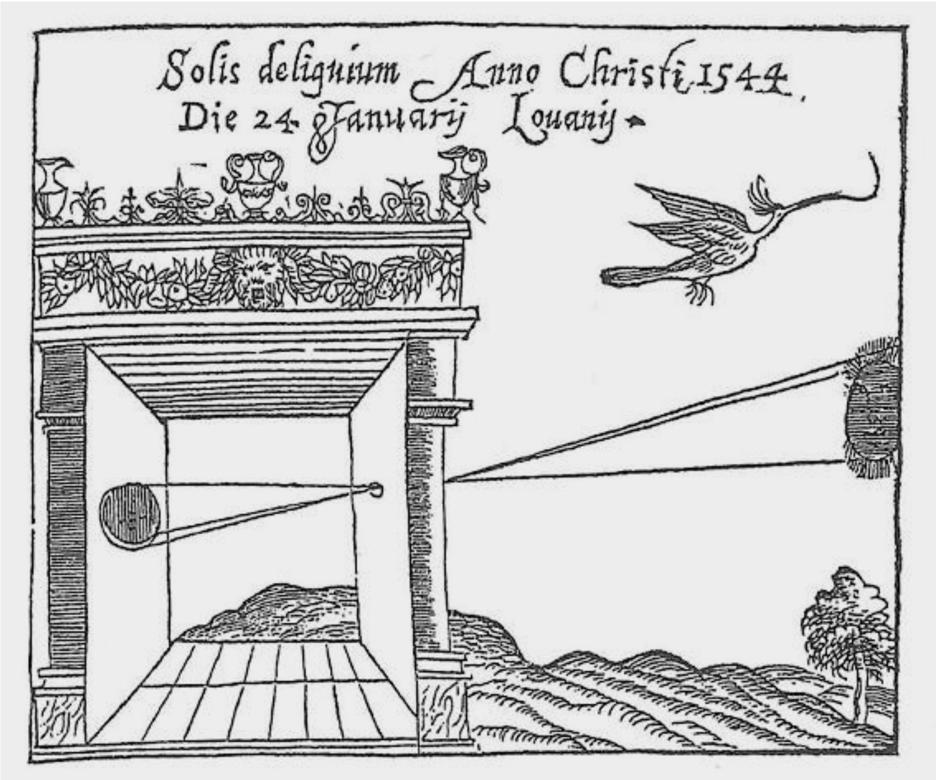


Pinhole camera a.k.a. camera obscura

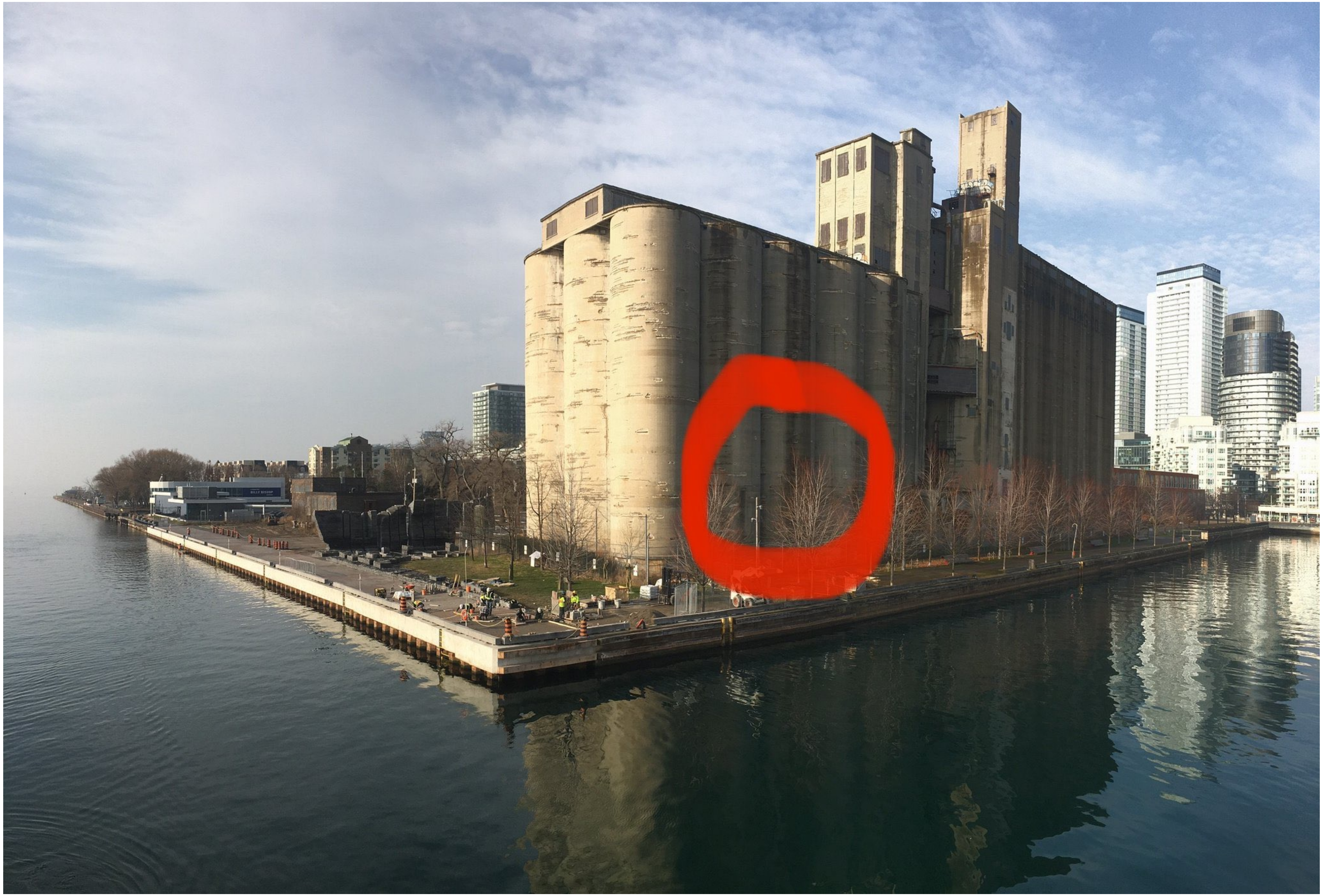
First mention …

Chinese philosopher Mozi
(470 to 390 BC)

First camera …

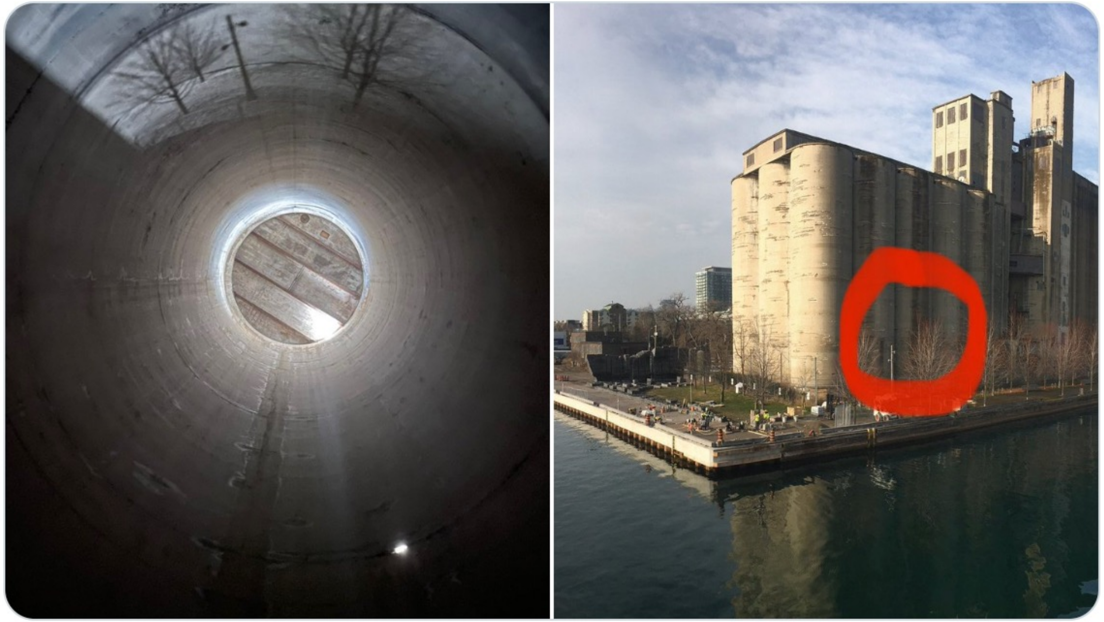


Greek philosopher Aristotle
(384 to 322 BC)


BILLY BISHOP

Bryan Bowen
@bryanmbowen

Fun discovery - a small crack in the eastern facade of the Canada Malting Co silos has created a perfect pinhole camera. The result: real time projection of Toronto's waterfront on the silo's interior curved surfaces. An unplugged projection show!



9:37 AM · Jan 27, 2022 · Twitter for iPhone

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Abelardo Morell

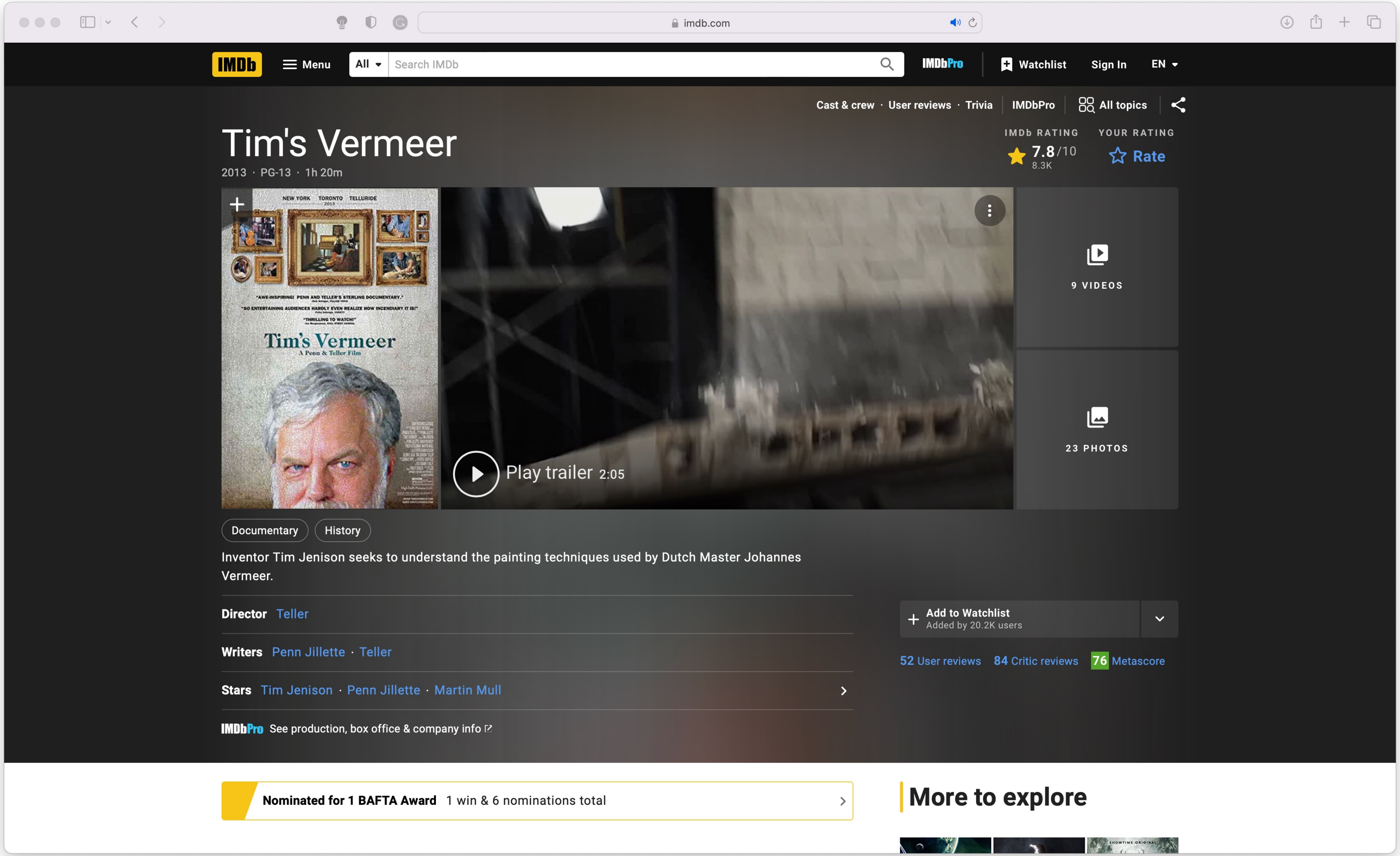

BBC FOUR

Vermeer and The Camera Obscura

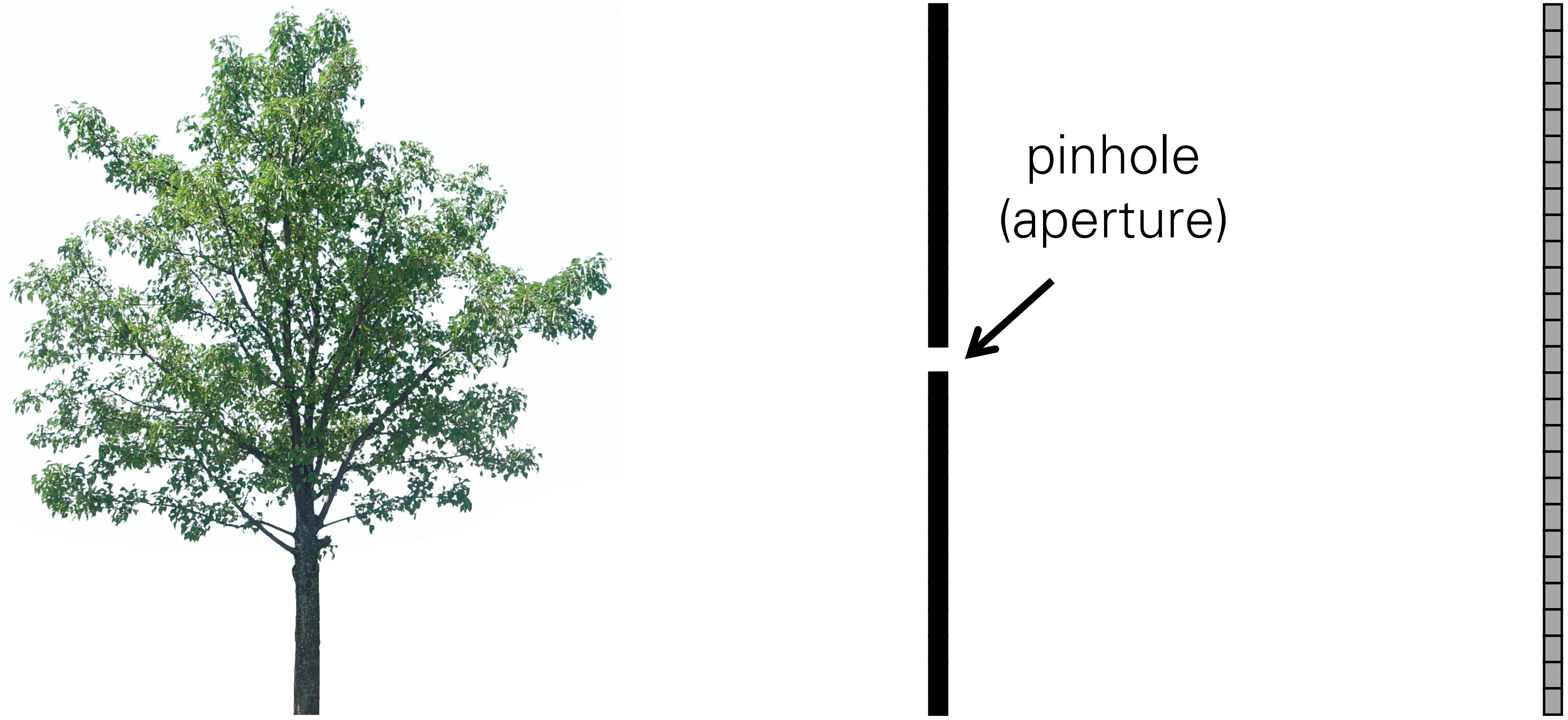
http://www.essentialvermeer.com/camera_obscura/co_one.html


Officer and Laughing Girl, 1657

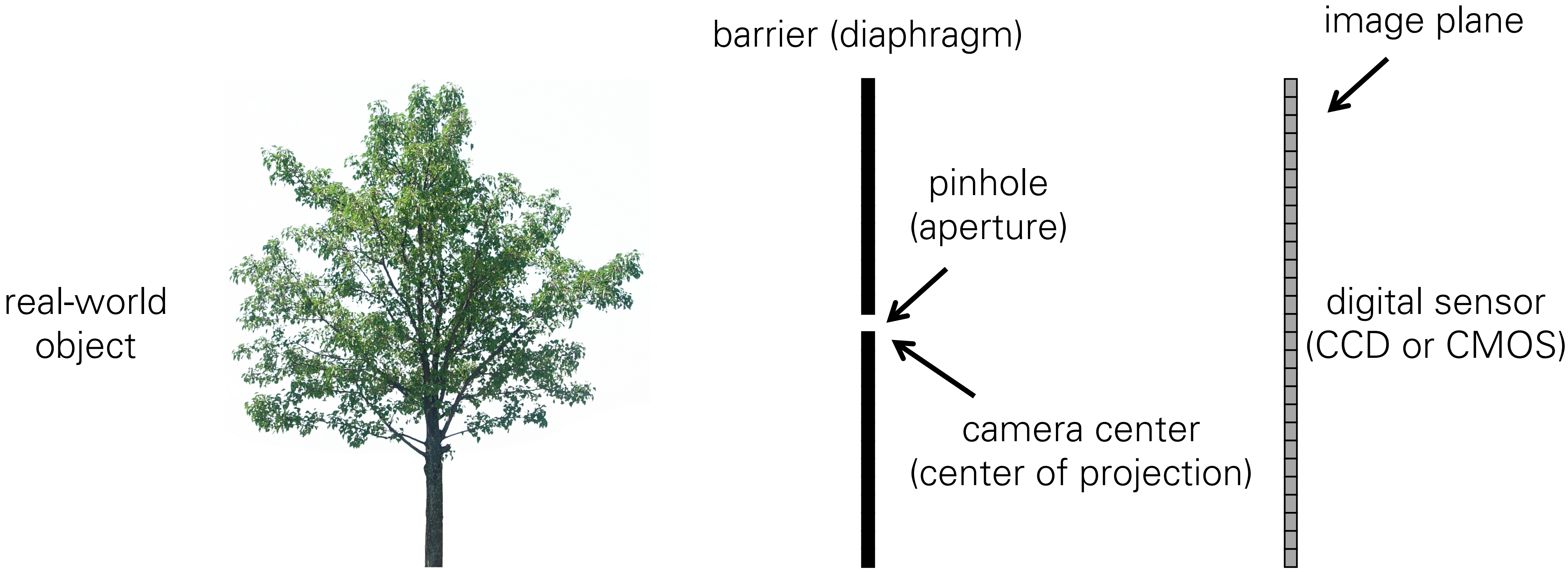
Vermeer and The Camera Obscura



Pinhole camera terms

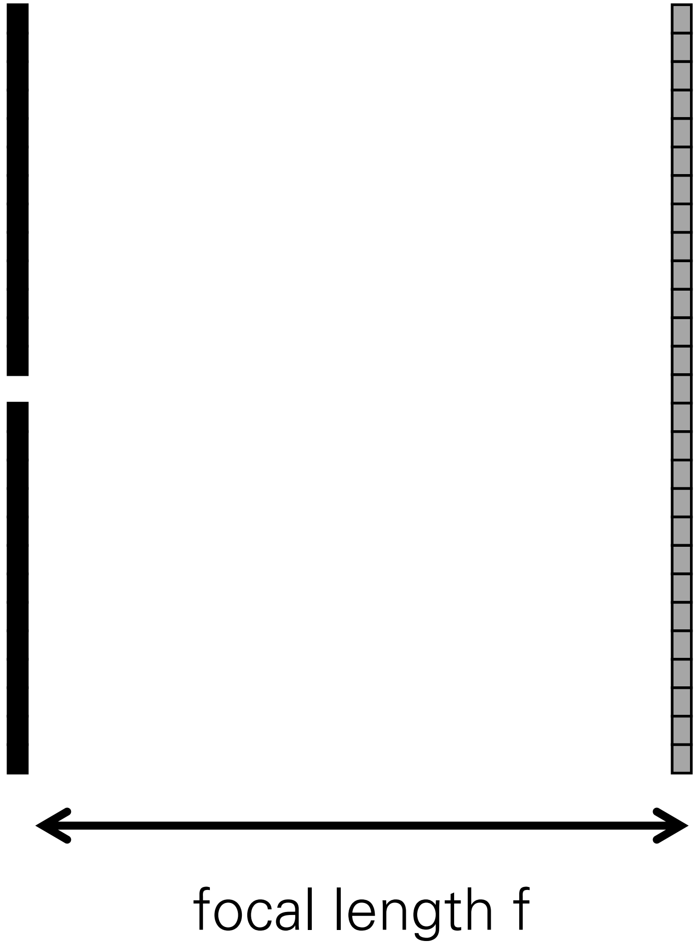


Pinhole camera terms



Focal length

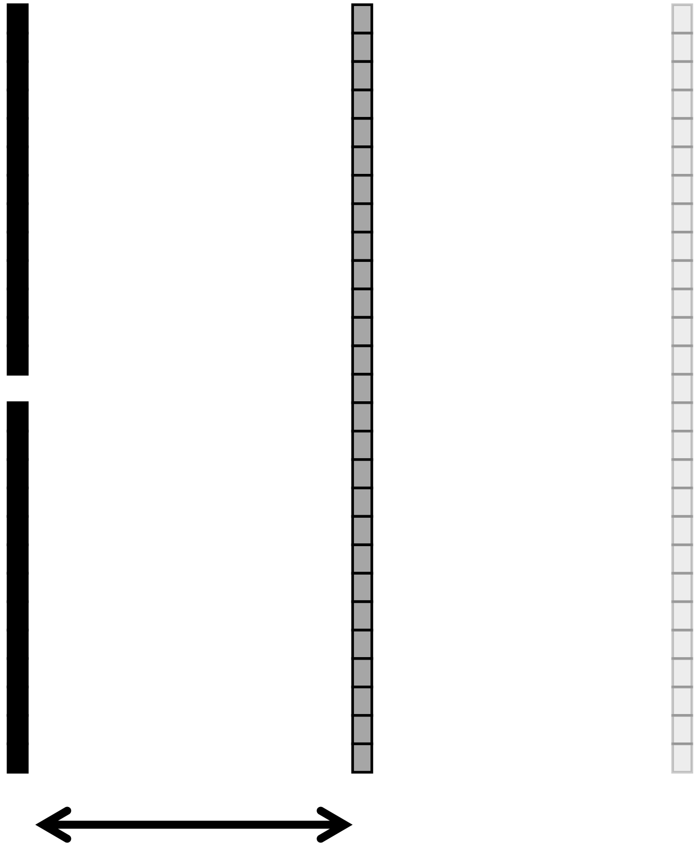
real-world
object



Focal length

What happens as we change the focal length?

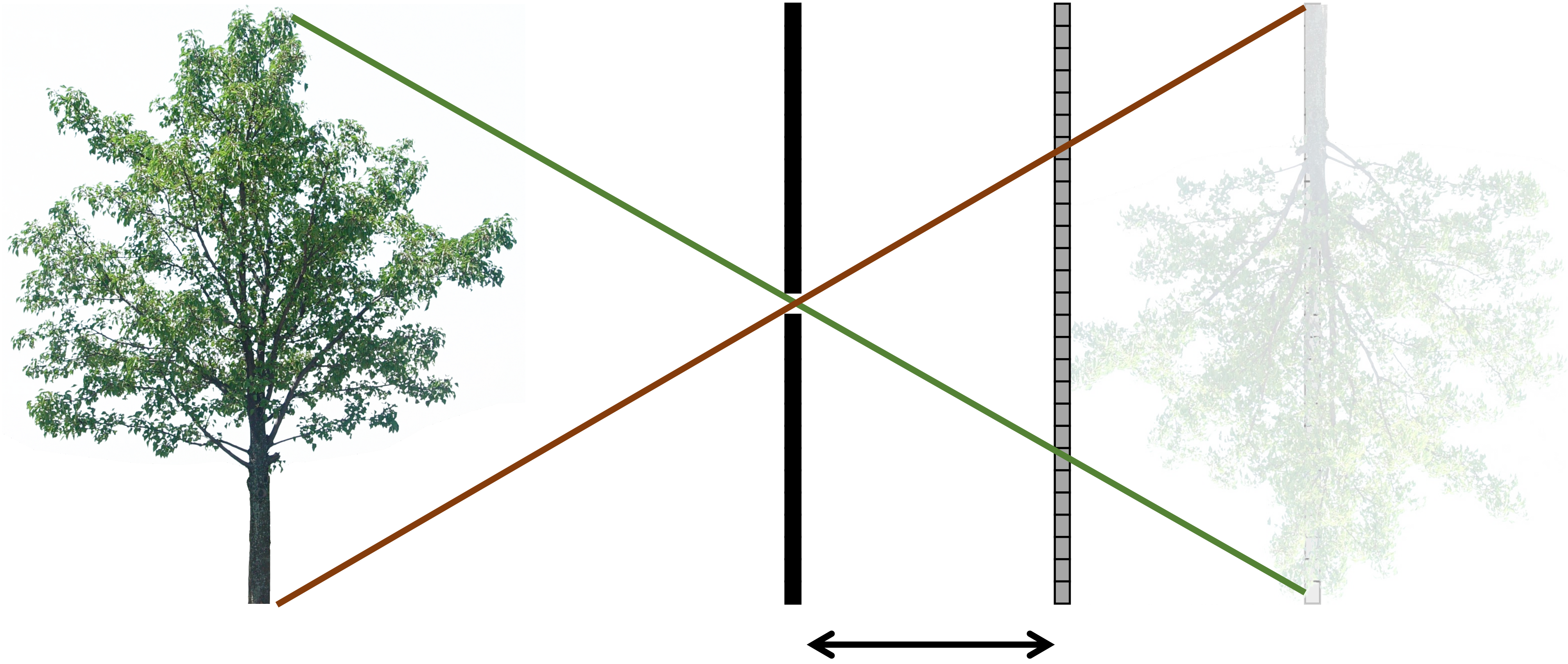
real-world
object



Focal length

What happens as we change the focal length?

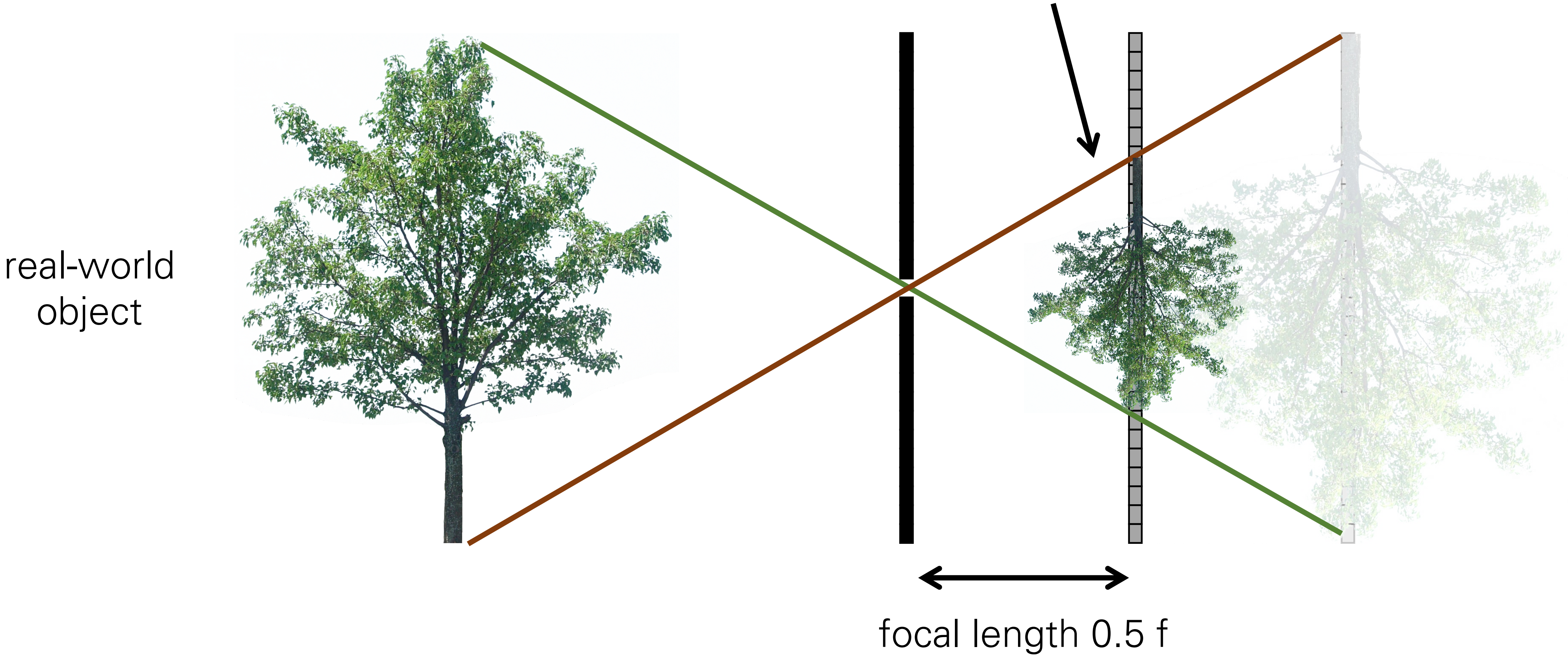
real-world object



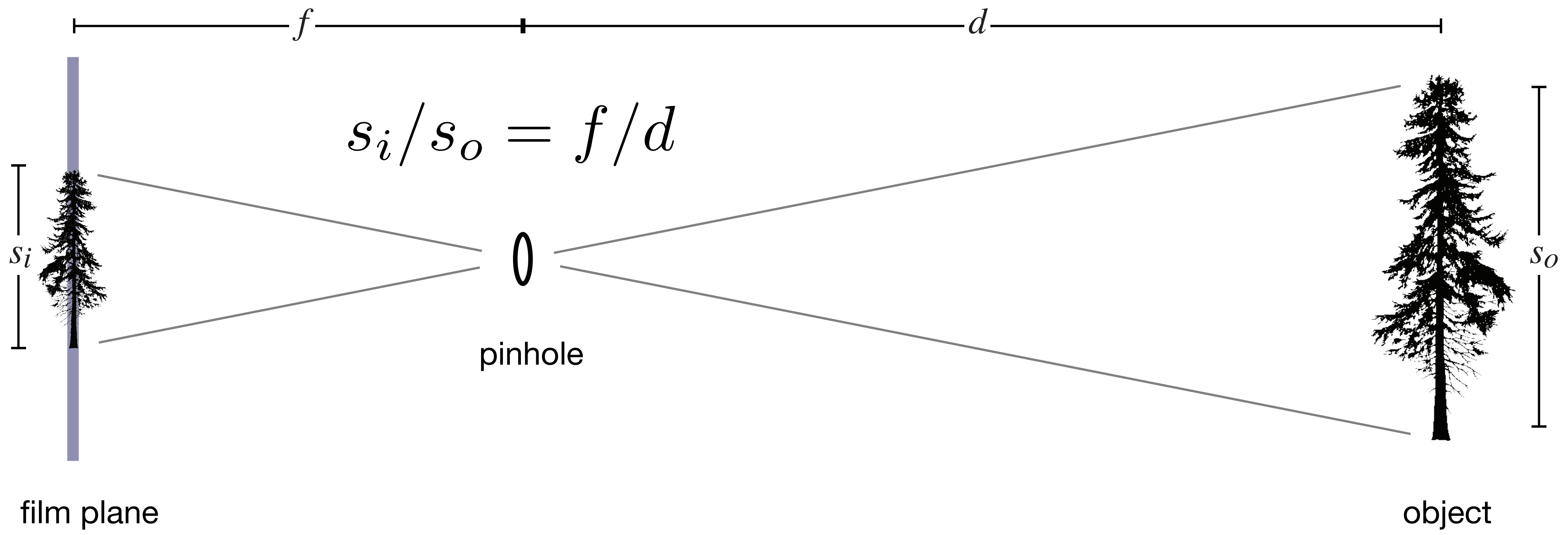
focal length 0.5 f

Focal length

What happens as we change the focal length?

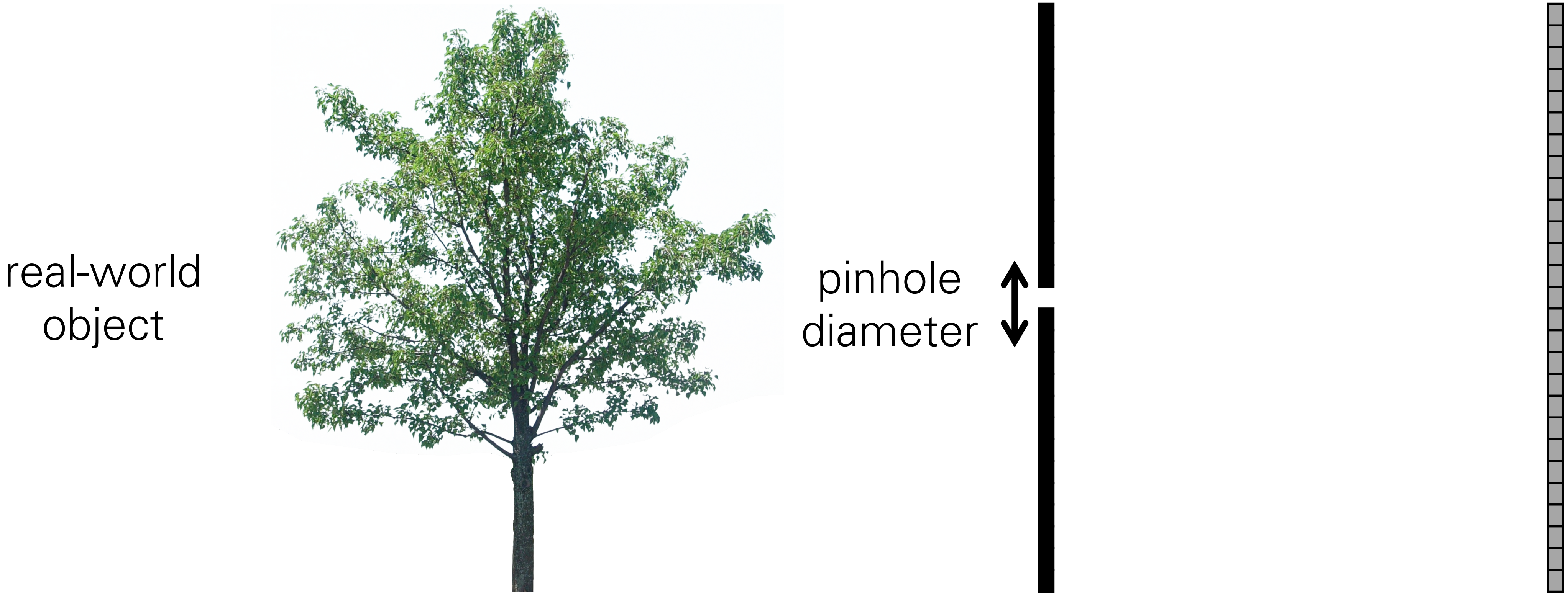


Focal length



- Double “focal length” leads to
  - image twice as large
  - one fourth as much illumination at image plane

Pinhole size

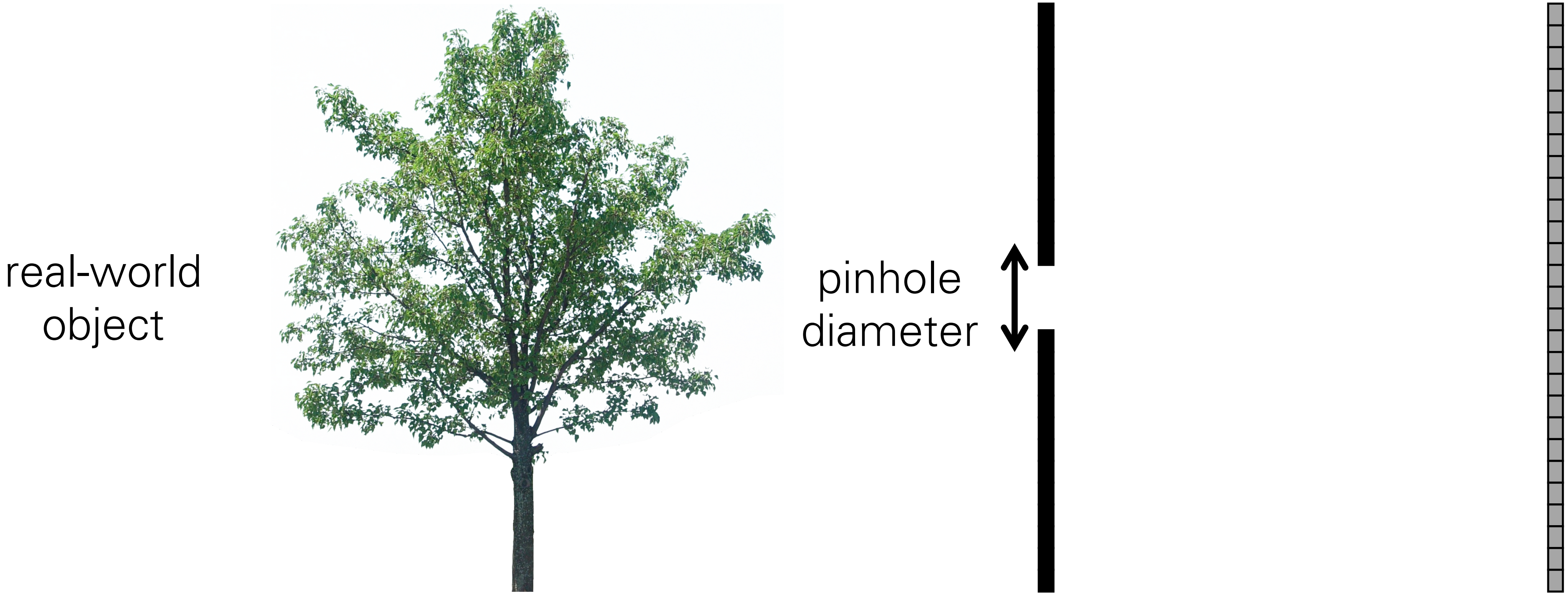


Ideal pinhole has infinitesimally small size

- In practice that is impossible.

Pinhole size

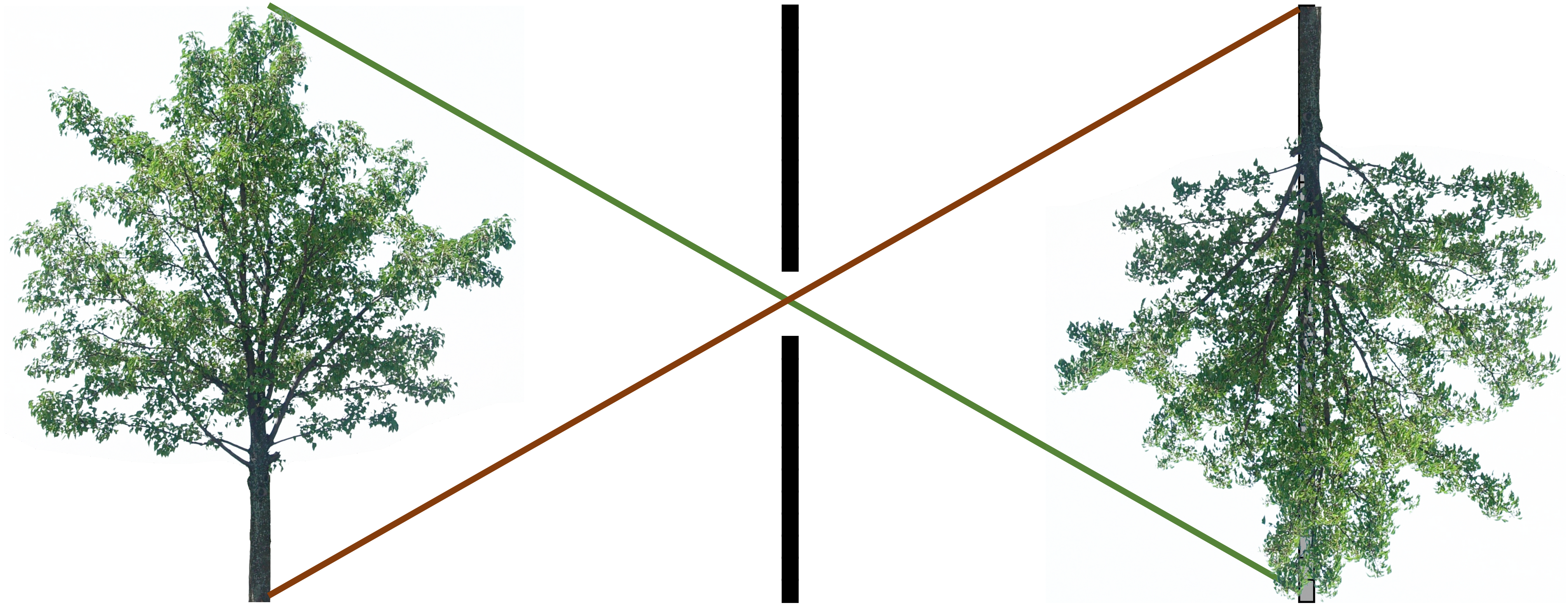
What happens as we change the pinhole diameter?



Pinhole size

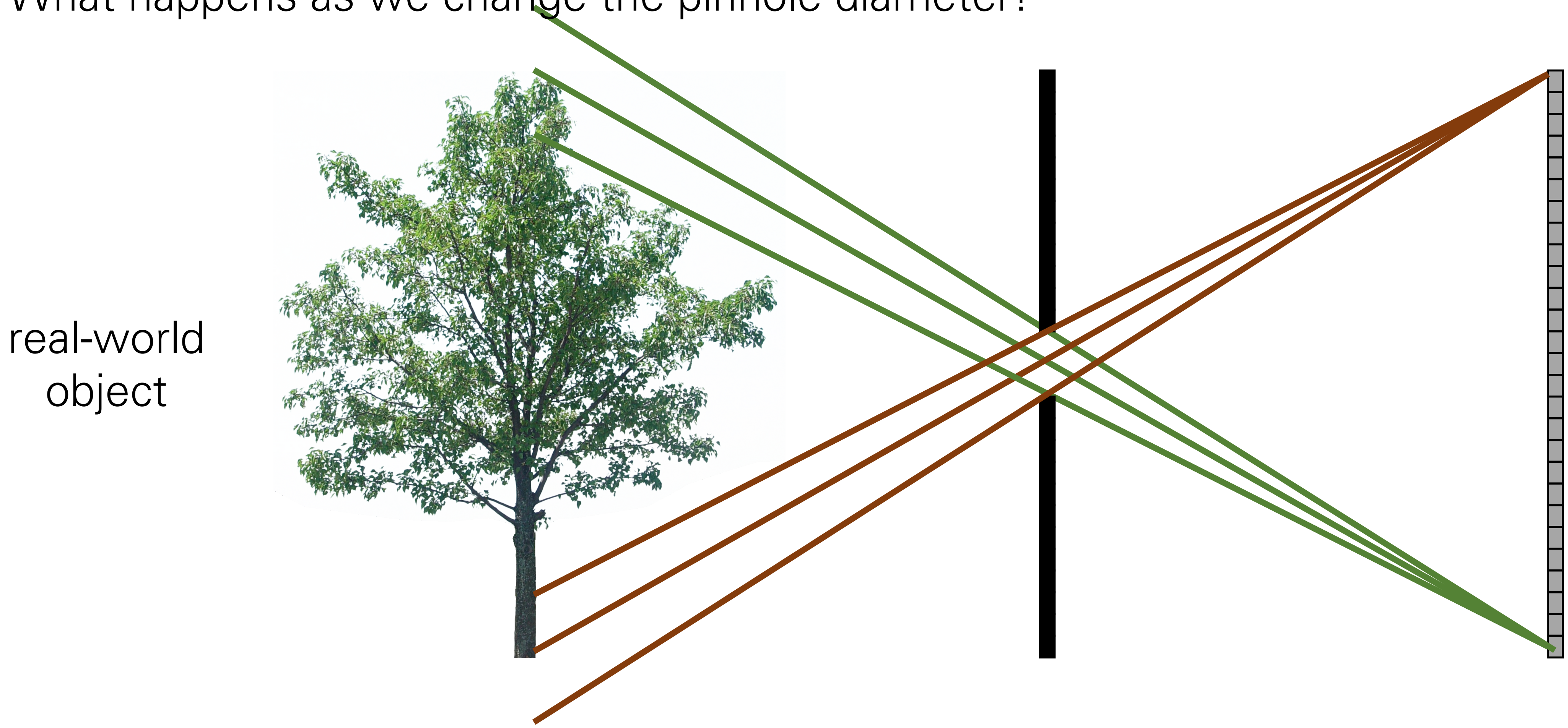
What happens as we change the pinhole diameter?

real-world
object



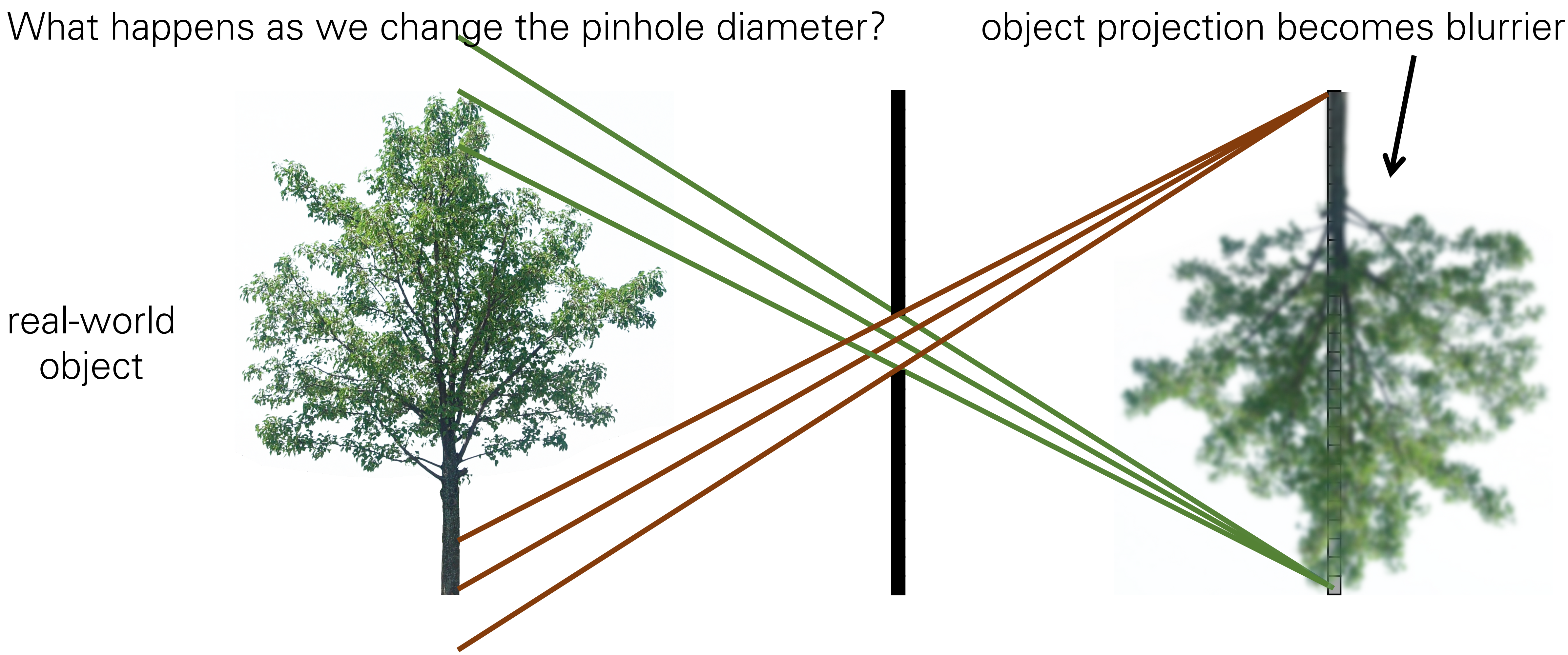
Pinhole size

What happens as we change the pinhole diameter?



Pinhole size

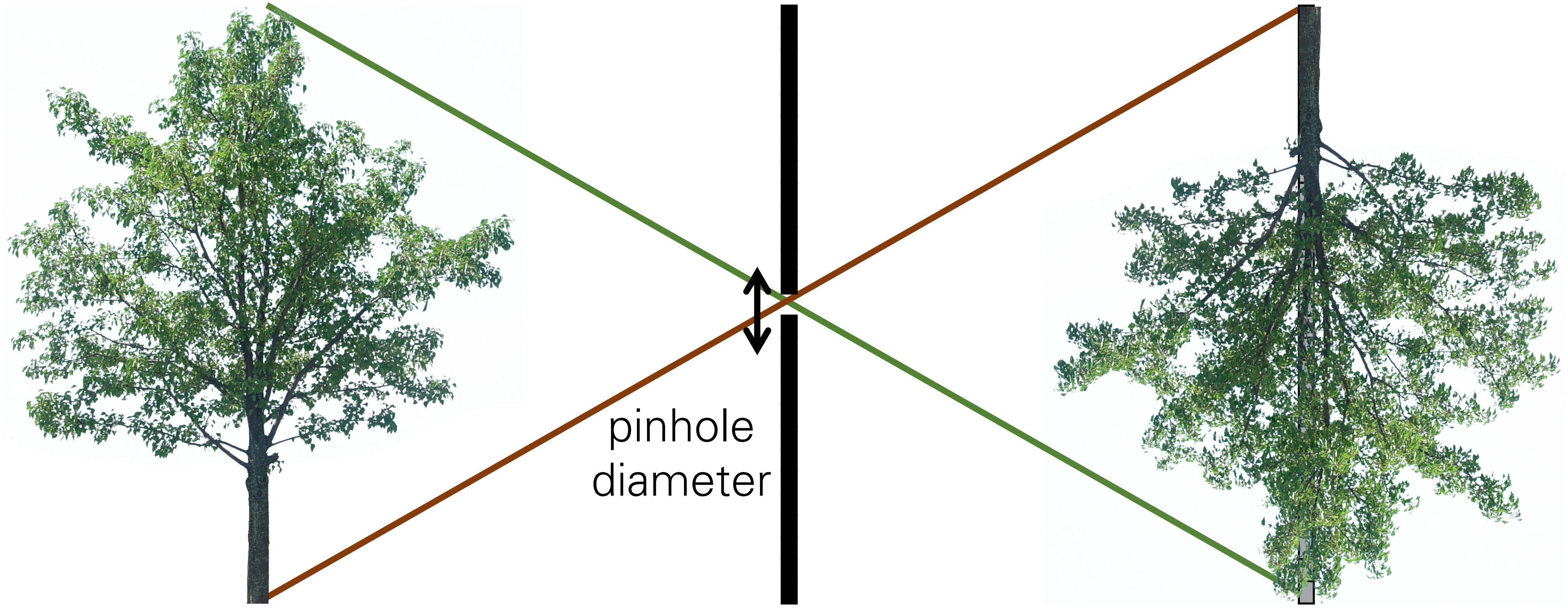
What happens as we change the pinhole diameter?



Pinhole size

What happens as we change the pinhole diameter?

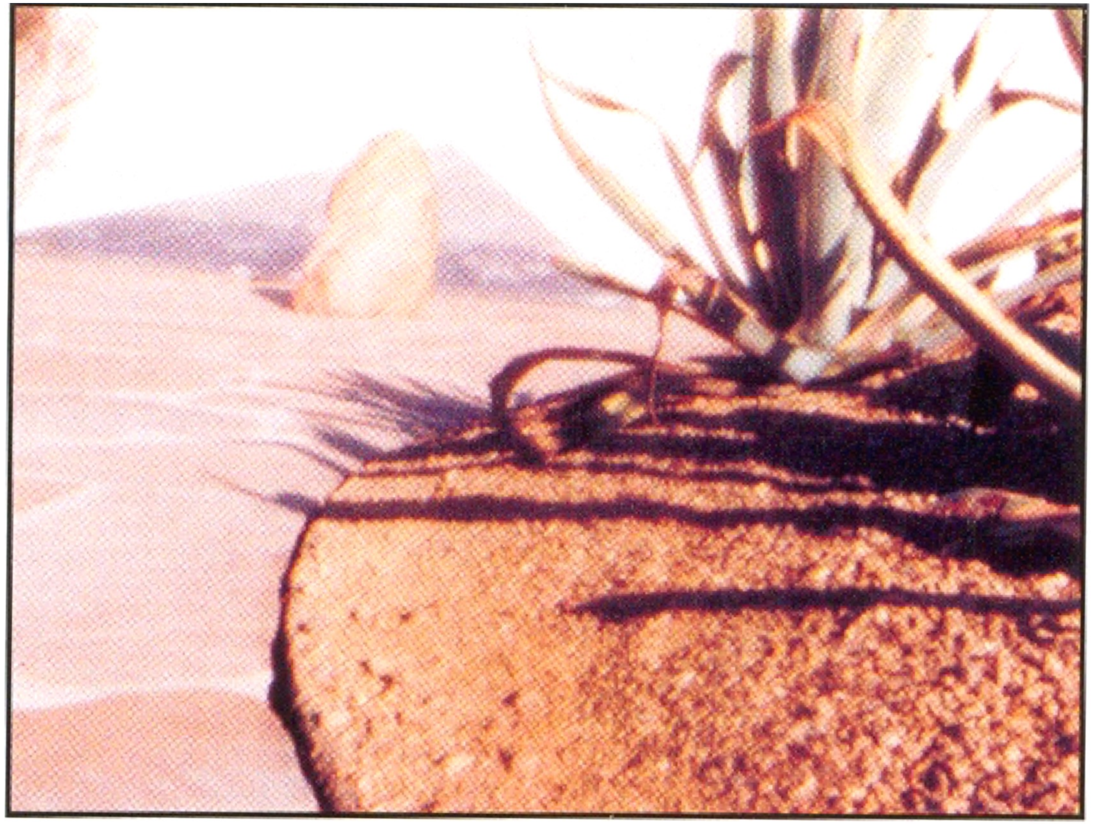
real-world
object

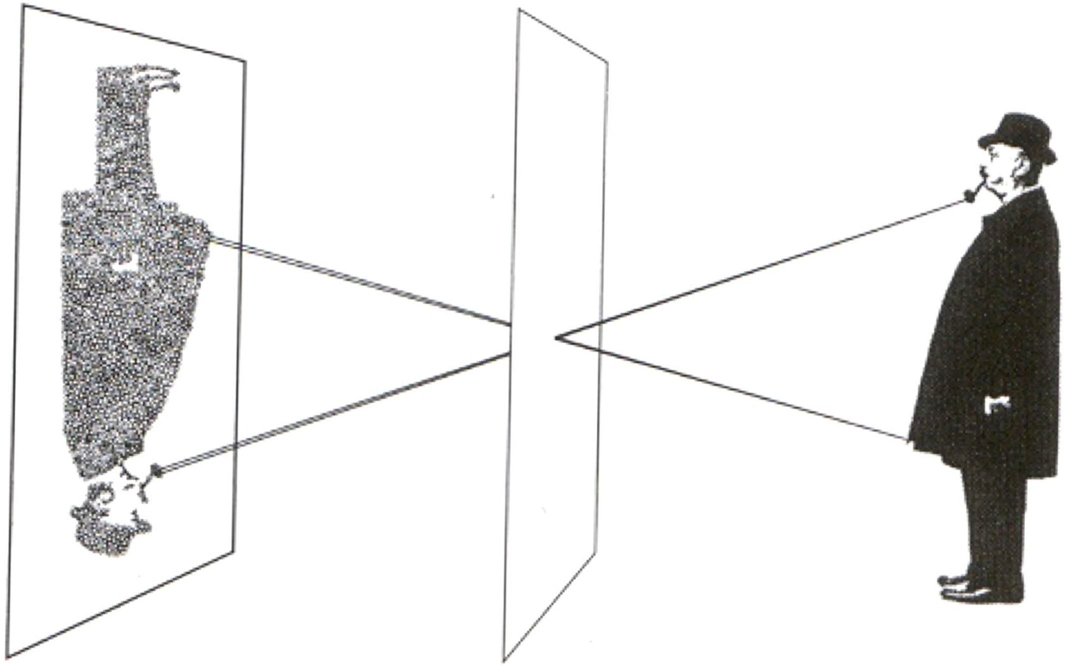


Will the image keep getting sharper the smaller we make the pinhole?

Effect of pinhole size

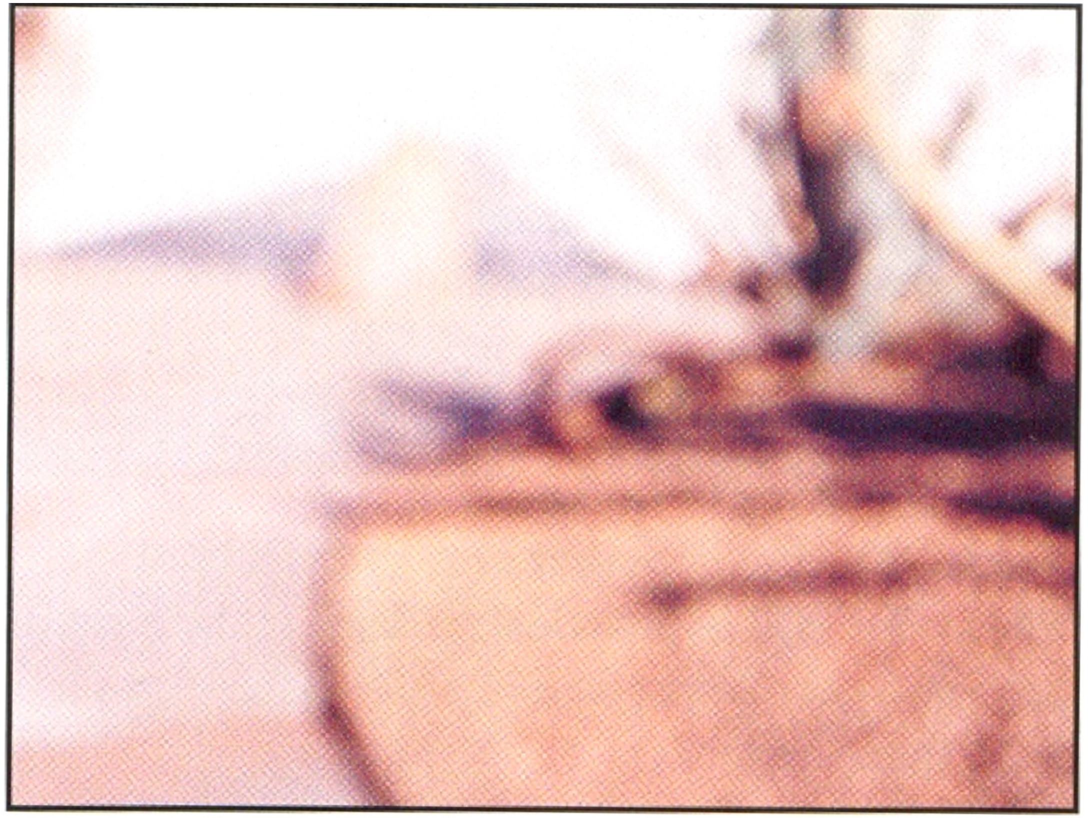
Photograph made with small pinhole

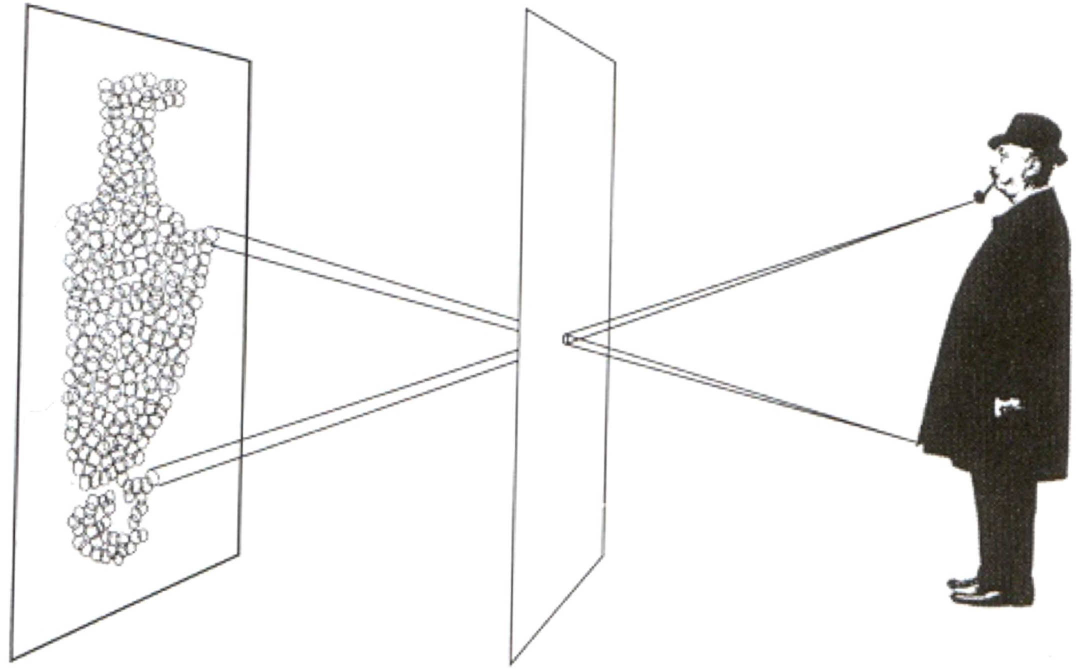




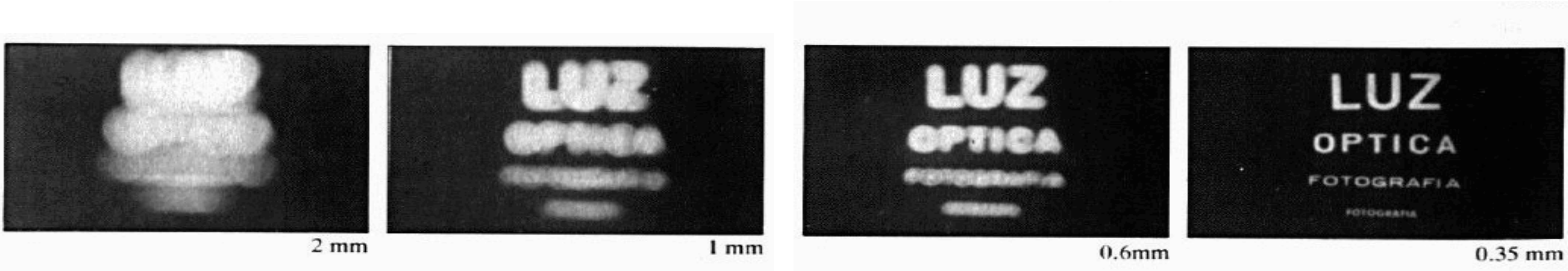
Effect of pinhole size

Photograph made with larger pinhole

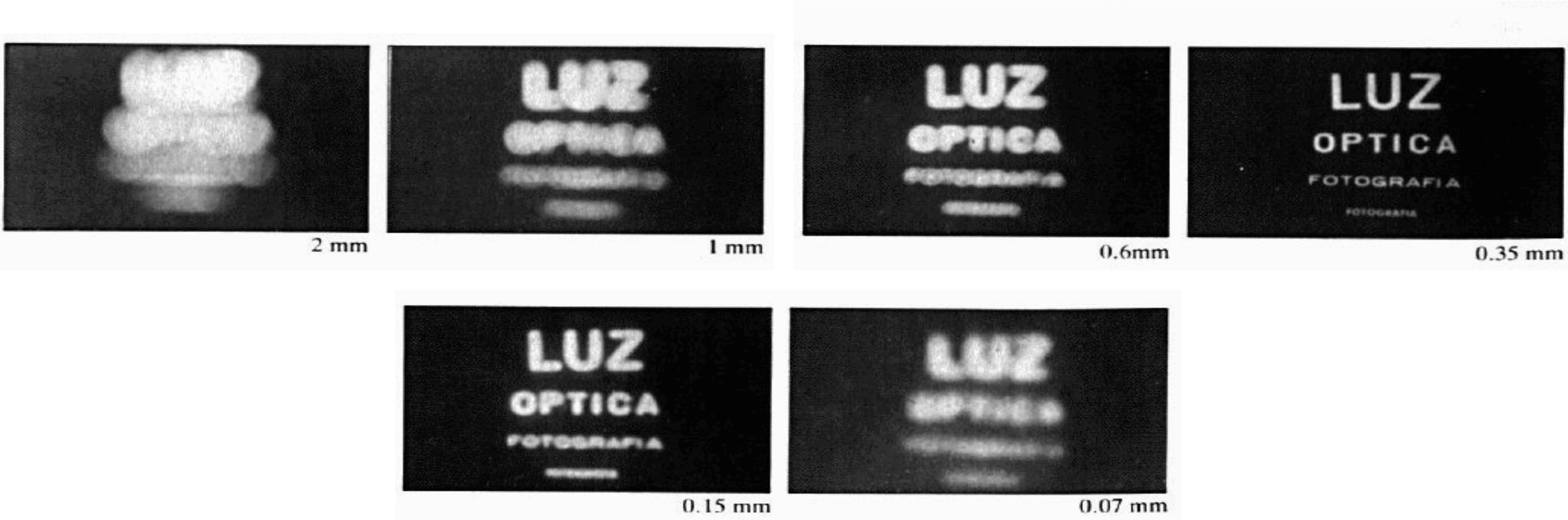




Smaller pinhole is sharper

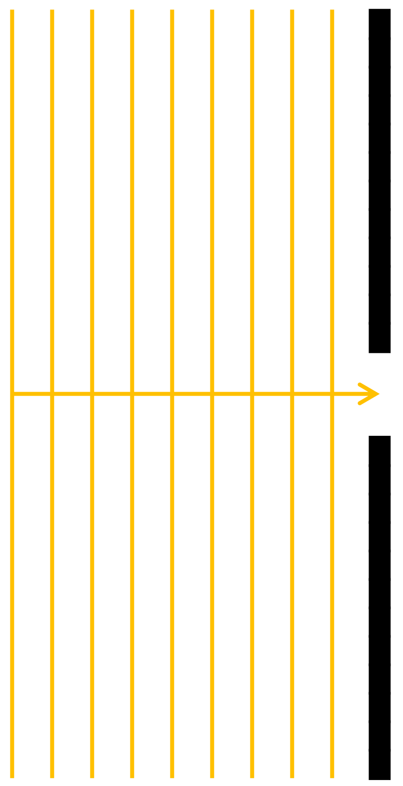


Smaller pinhole is sharper … to a point

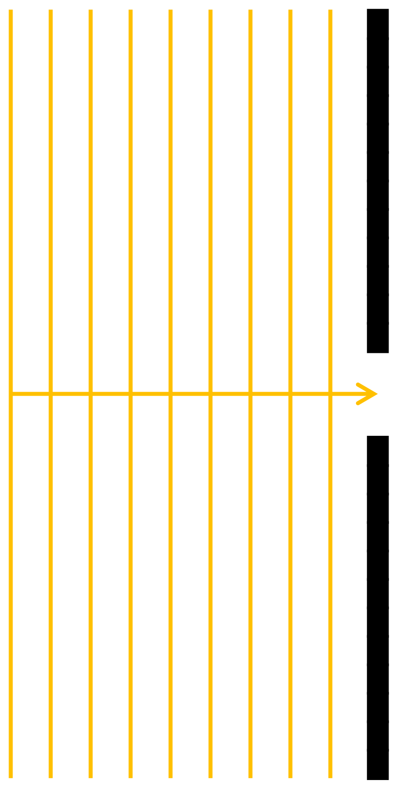


Diffraction limit

A consequence of the wave nature of light



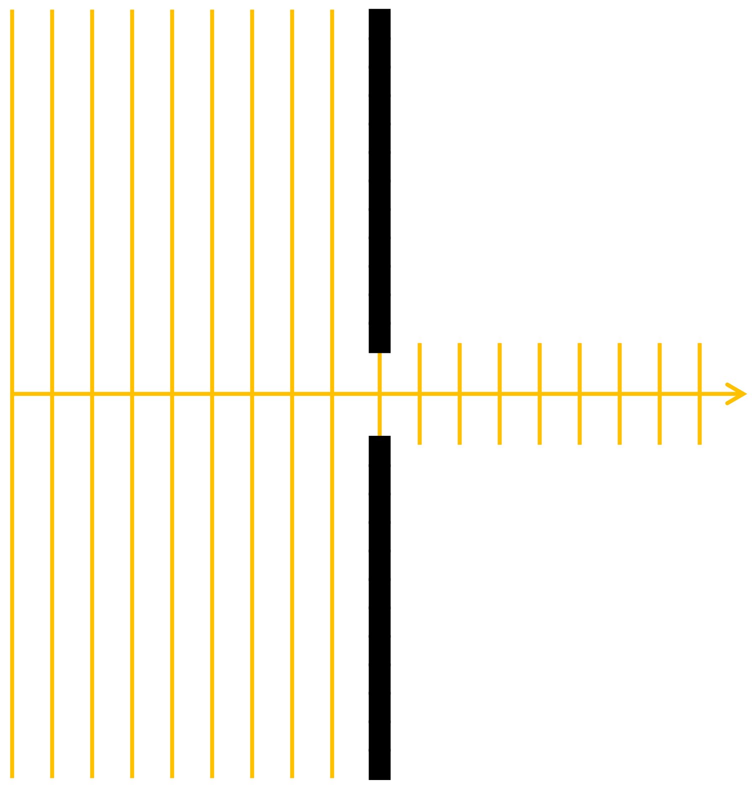
What do geometric optics predict will happen?



What do wave optics predict will happen?

Diffraction limit

A consequence of the wave nature of light



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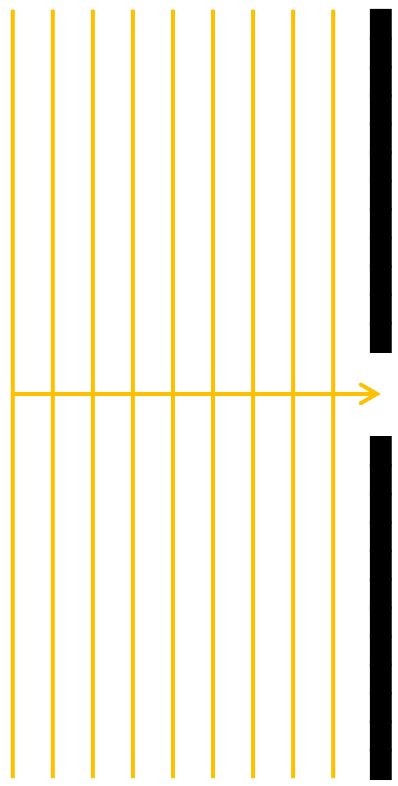
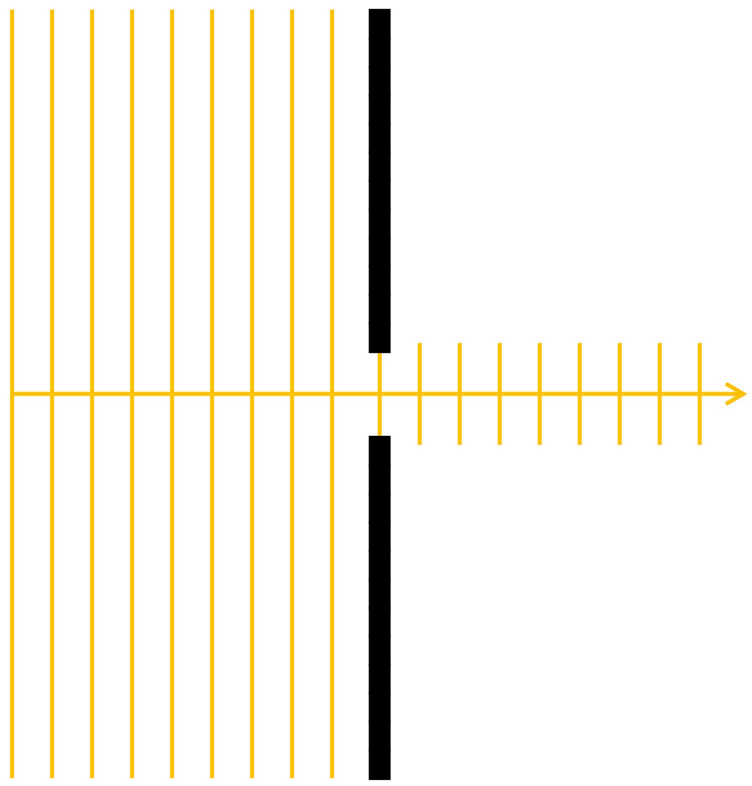


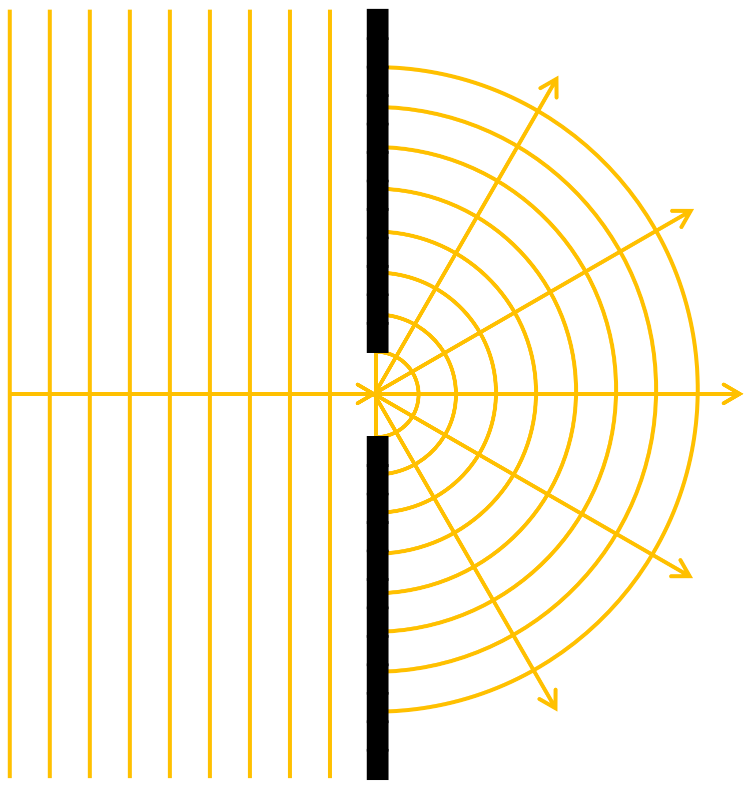
What do wave optics predict will happen?

Diffraction limit

A consequence of the wave nature of light



What do geometric optics predict will happen?

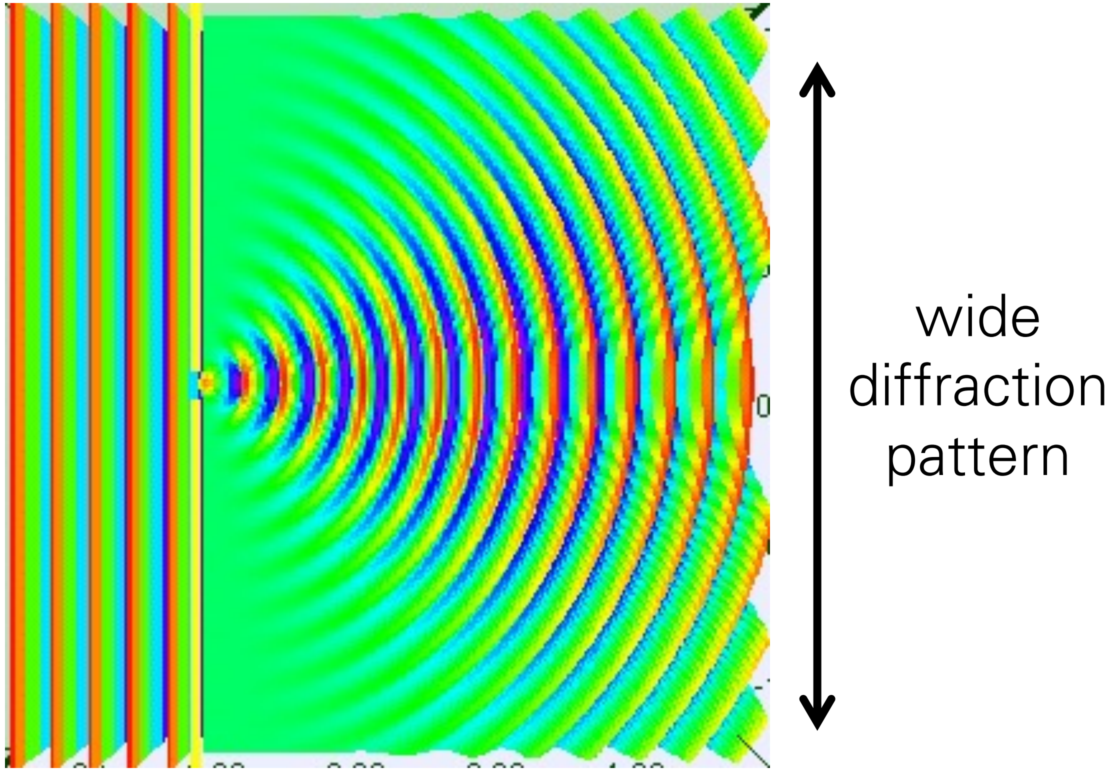


What do wave optics predict will happen?

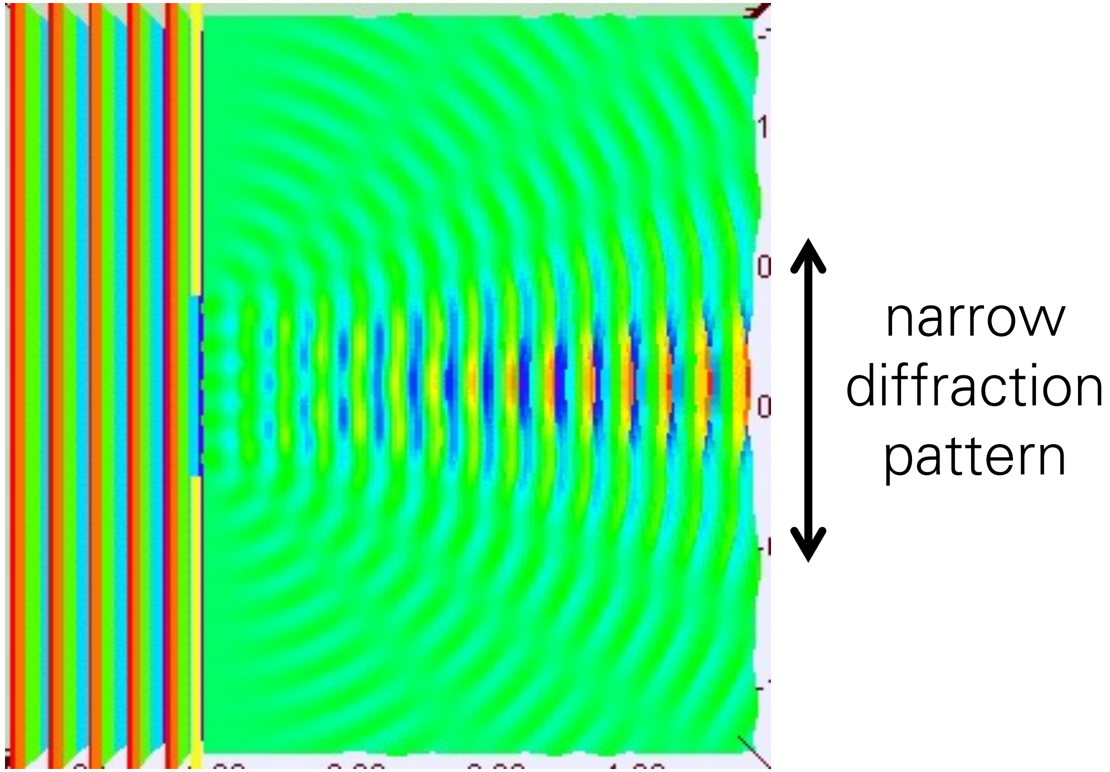
Diffraction limit

Diffraction pattern = Fourier transform of the pinhole.

- Smaller pinhole means bigger Fourier spectrum.
- Smaller pinhole means more diffraction.

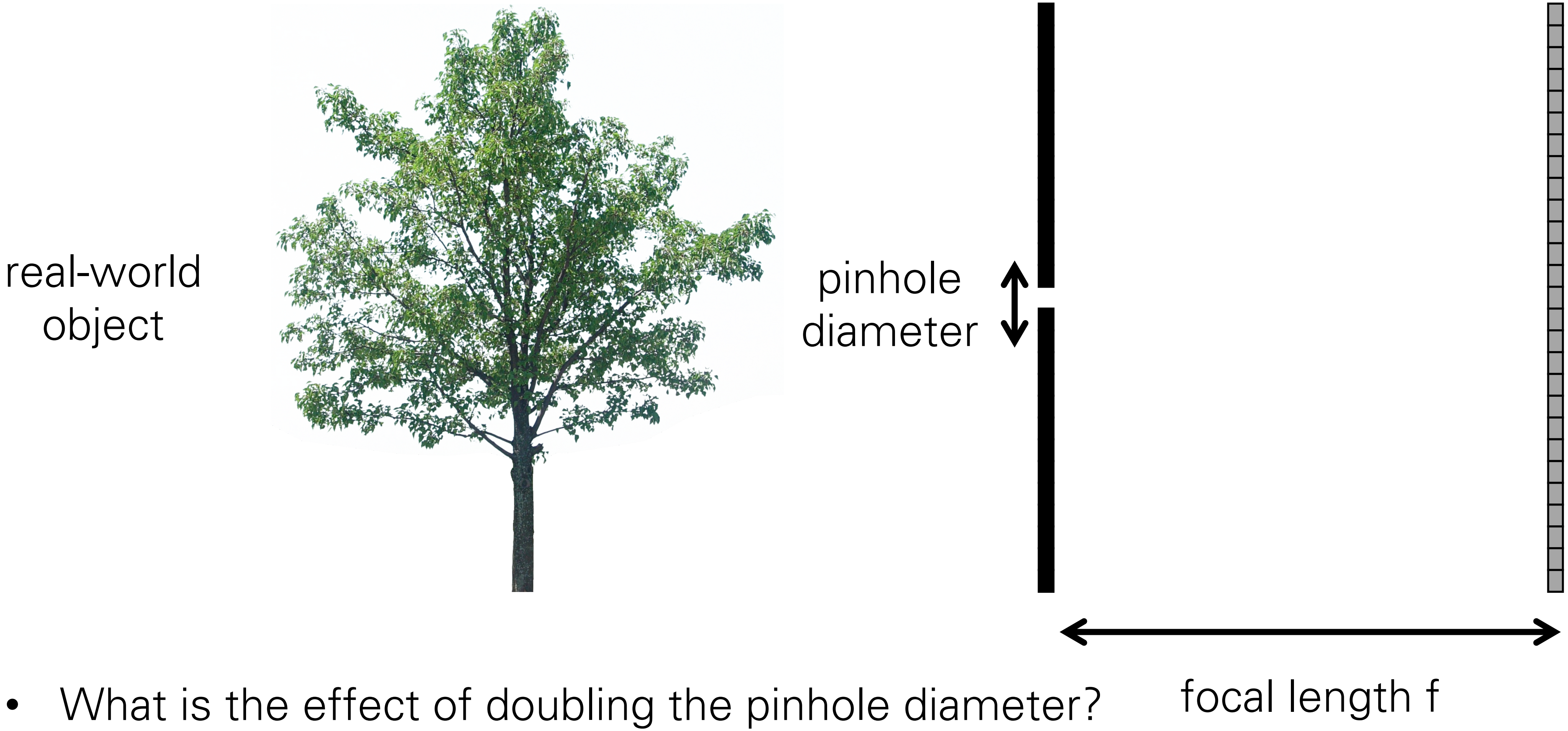


small pinhole



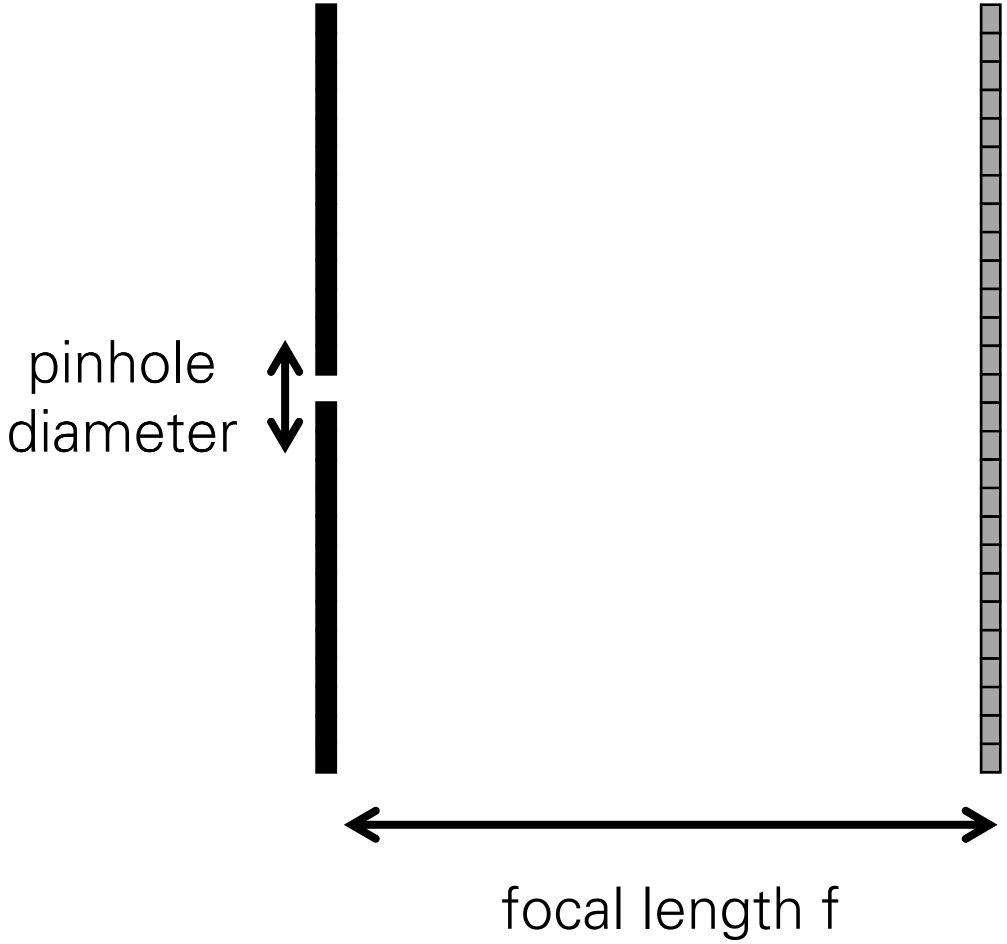
large pinhole

What about light efficiency?



- What is the effect of doubling the pinhole diameter?
- What is the effect of doubling the focal length?

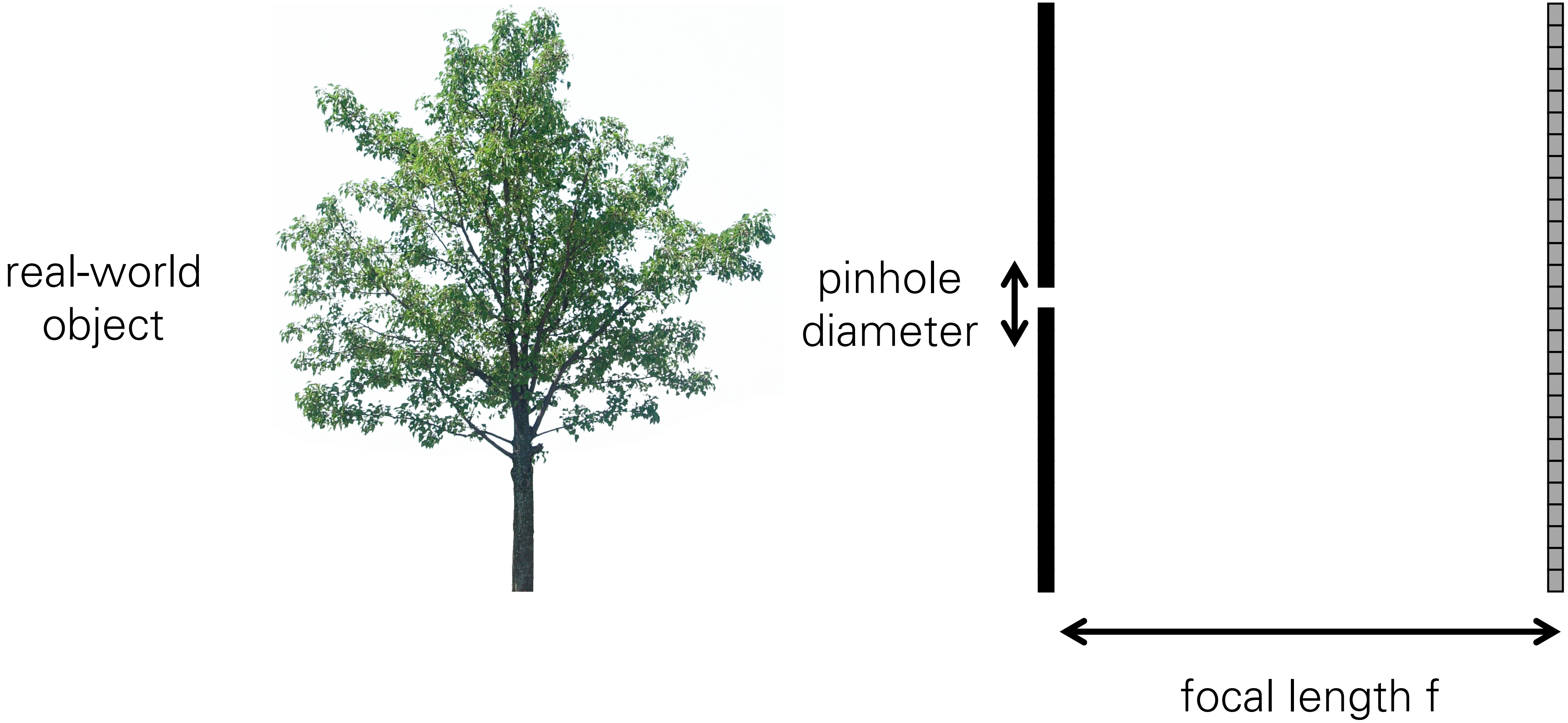
What about light efficiency?



- 2x pinhole diameter → 4x light
- 2x focal length → ¼x light

Some terminology notes

A “stop” is a change in camera settings that changes amount of light by a factor of 2



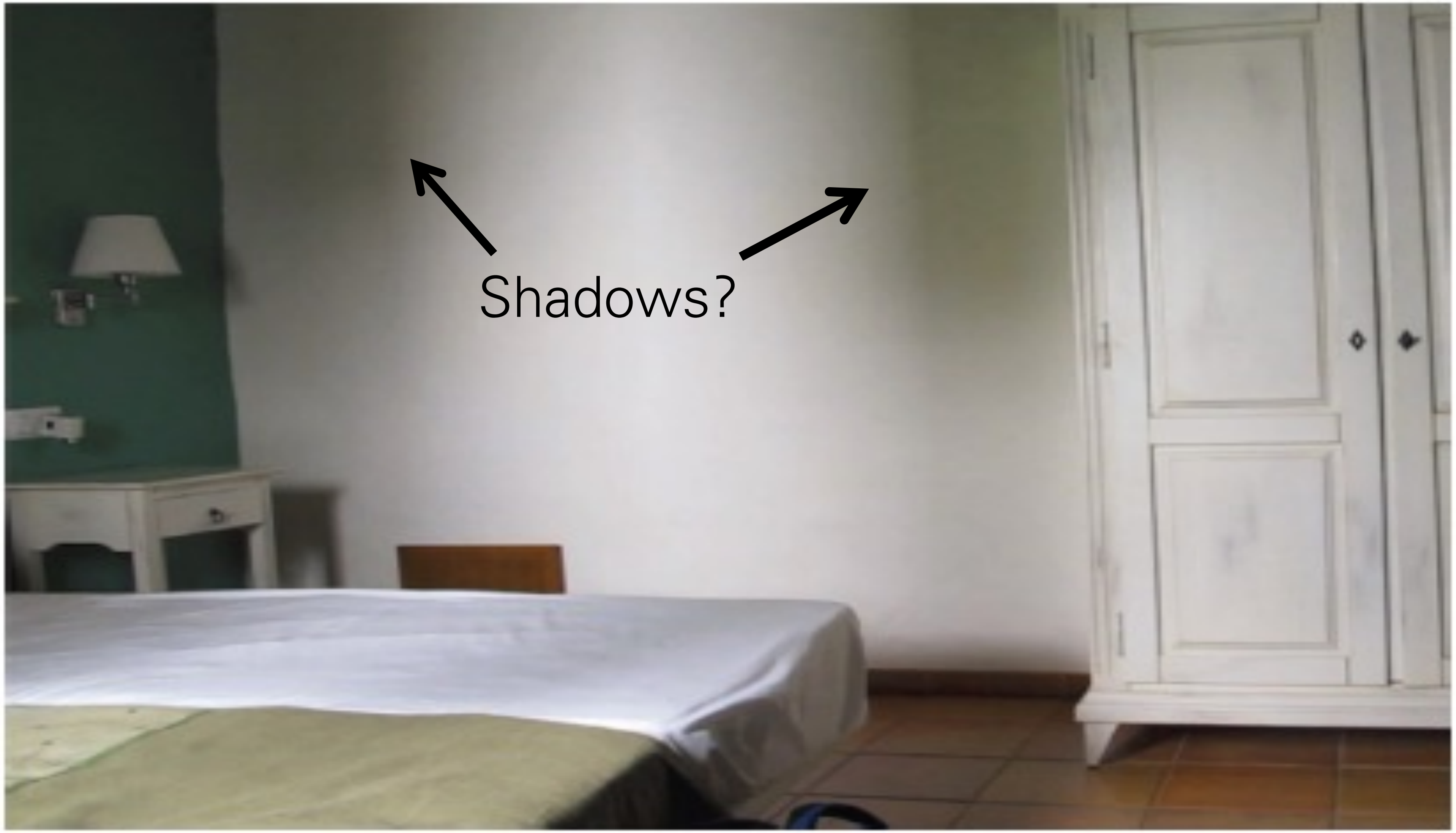
The “f-number” is the ratio: focal length / pinhole diameter

Accidental pinholes

What does this image say about the world outside?

Accidental pinhole camera

Accidental pinhole camera



Accidental pinhole camera

Accidental pinhole camera

Accidental pinhole camera

Accidental pinhole and pinspeck cameras: revealing the scene outside the picture

Antonio Torralba, William T. Freeman
Computer Science and Artificial Intelligence Laboratory (CSAIL)
MIT
torralba@mit.edu, billf@mit.edu

Anti-pinhole or Pinspeck cameras

OPTICA ACTA, 1982, VOL. 29, NO. 1, 63–67

Anti-pinhole imaging

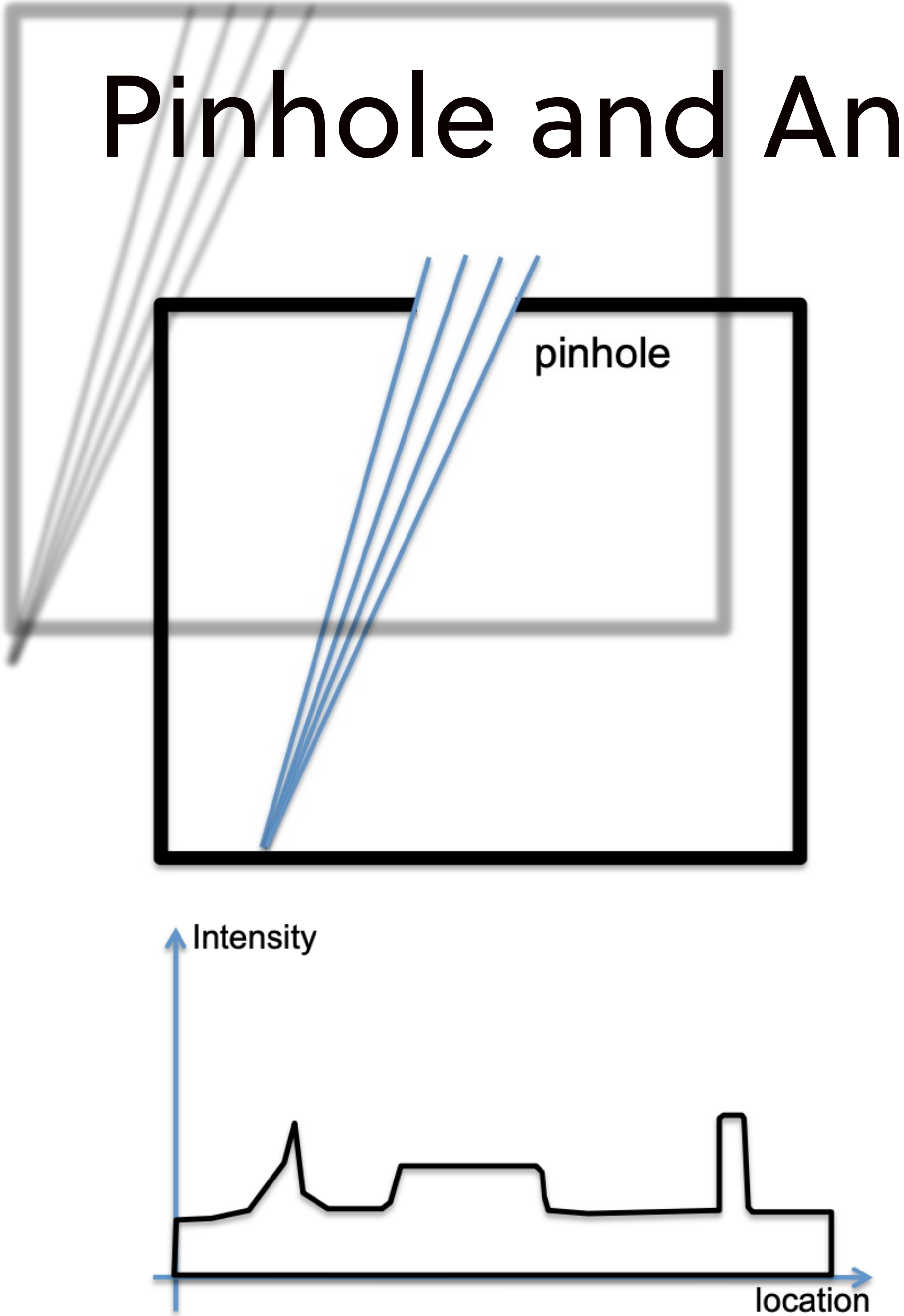
ADAM LLOYD COHEN
Parmly Research Institute, Loyola University of Chicago,
Chicago, Illinois 60626, U.S.A.

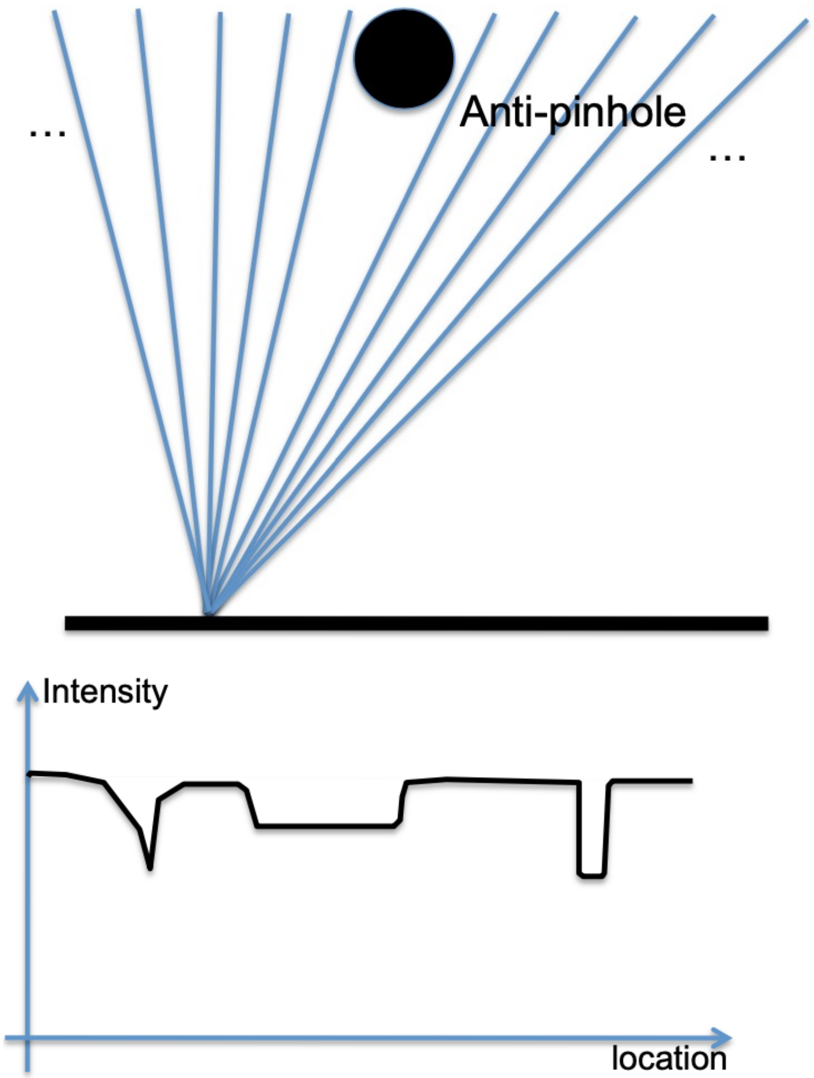
(Received 16 April 1981; revision received 8 July 1981)

Abstract. By complementing a pinhole to produce an isolated opaque spot, the light ordinarily blocked from the pinhole image is transmitted, and the light ordinarily transmitted is blocked. A negative geometrical image is formed, distinct from the familiar 'bright-spot' diffraction image. Anti-pinhole, or 'pinspeck' images are visible during a solar eclipse, when the shadows of objects appear crescent-shaped. Pinspecks demonstrate unlimited depth of field, freedom from distortion and large angular field. Images of different magnification may be formed simultaneously. Contrast is poor, but is improvable by averaging to remove noise and subtraction of a d.c. bias. Pinspecks may have application in X-ray space optics, and might be employed in the eyes of simple organisms.

Adam L. Cohen, 1982

Pinhole and Anti-pinhole cameras



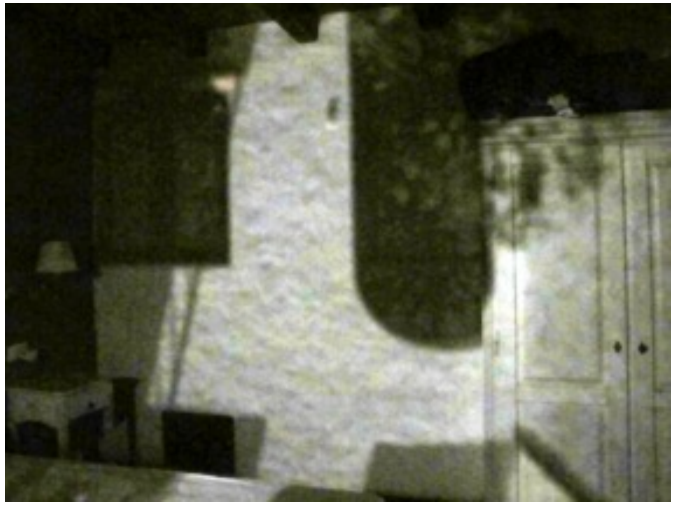


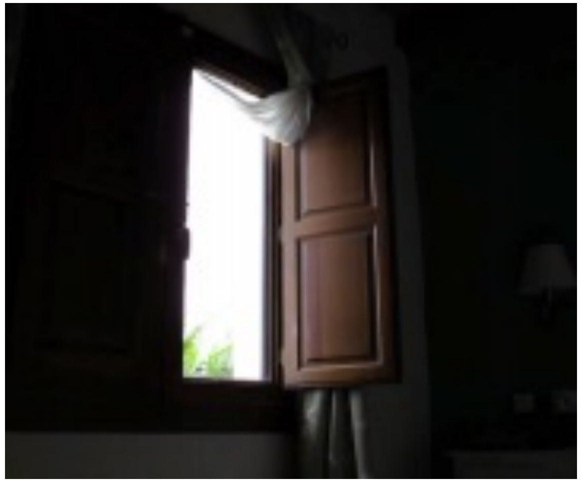
Adam L. Cohen, 1982

Accidental pinhole camera

projected pattern on the wall

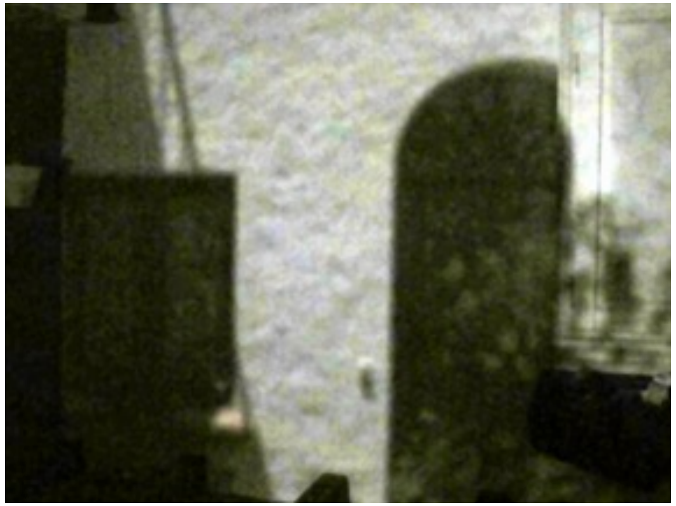
window with smaller gap





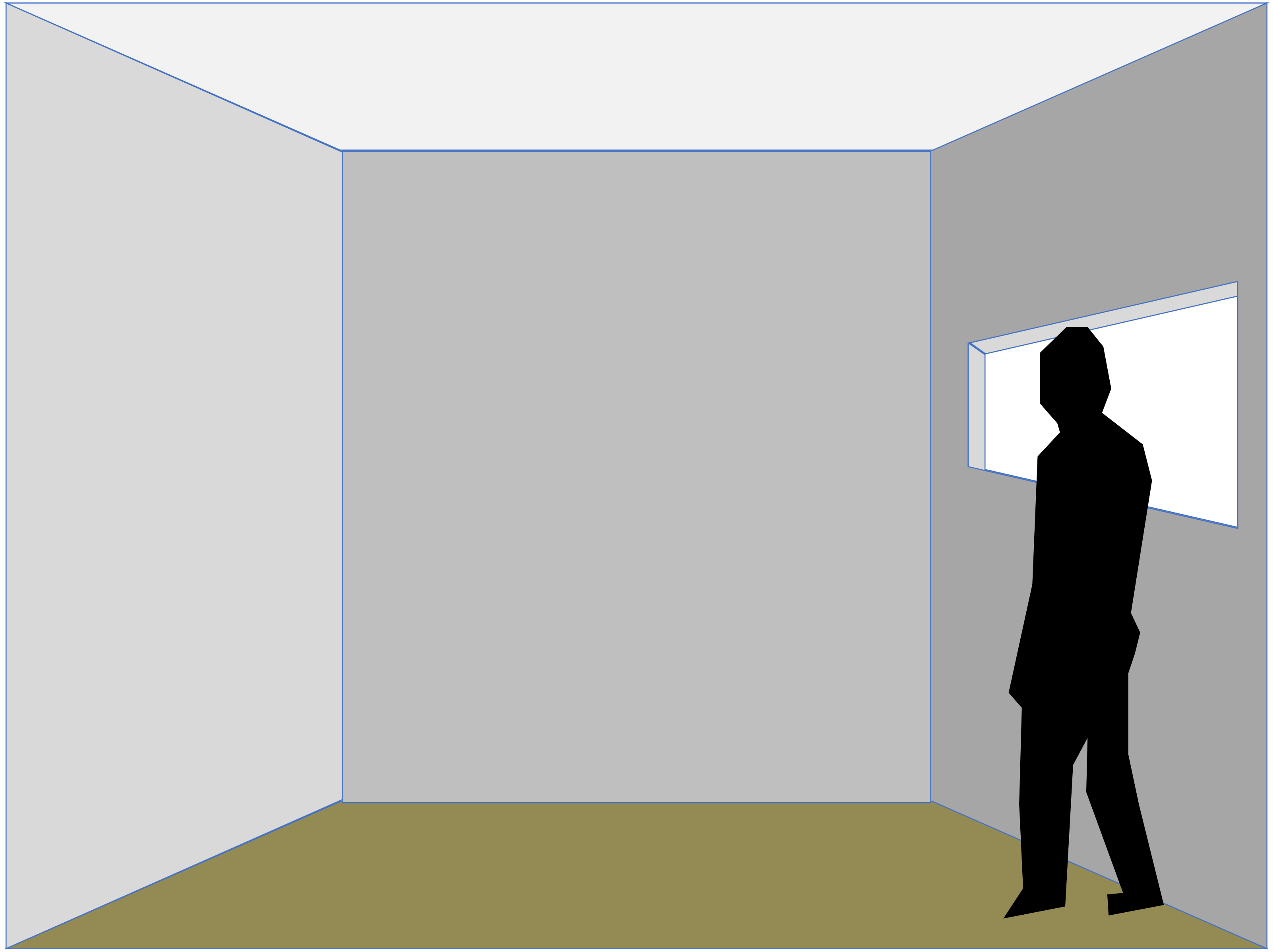
window is an
aperture

upside down

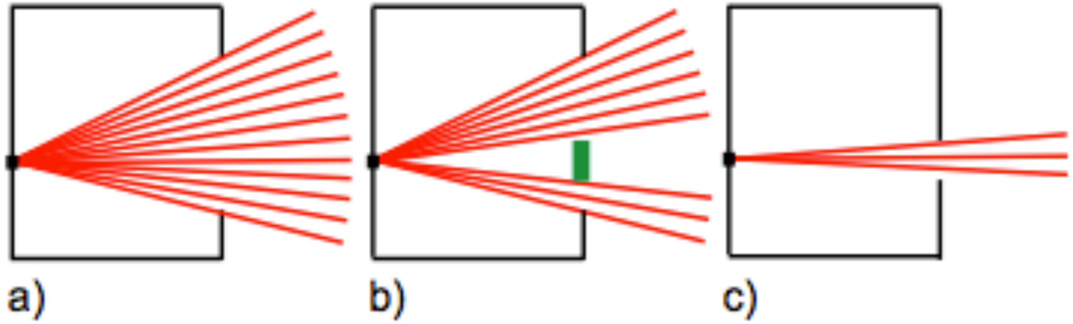


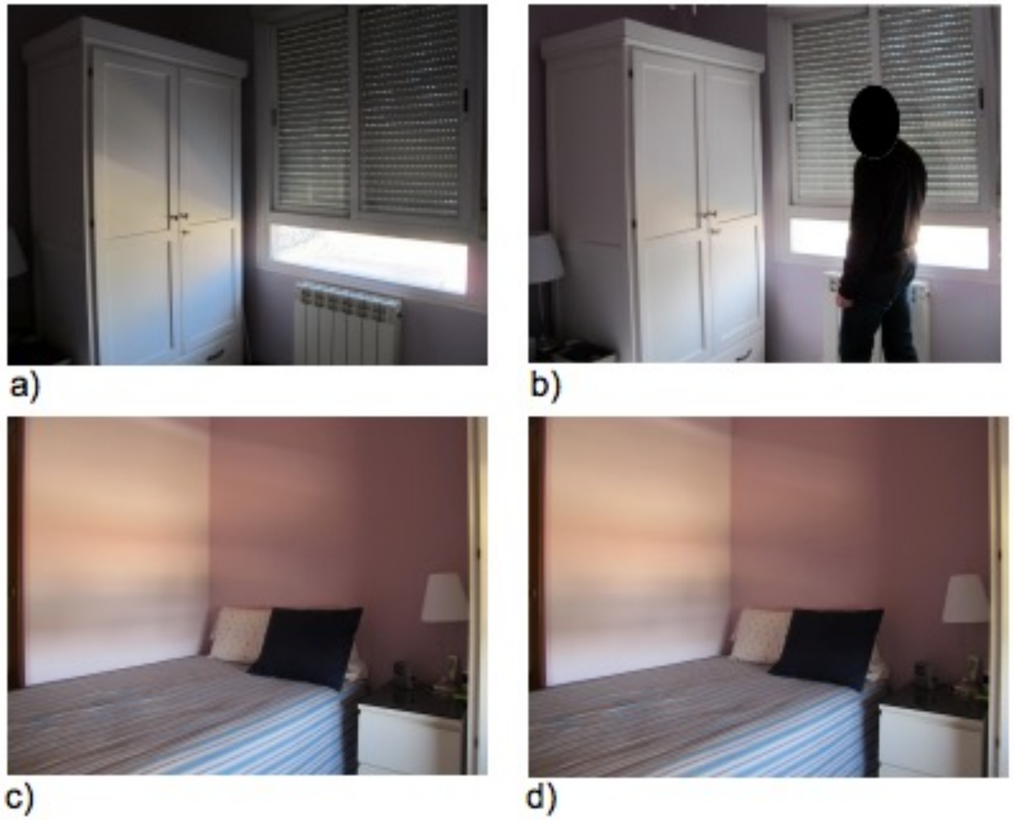
view outside window

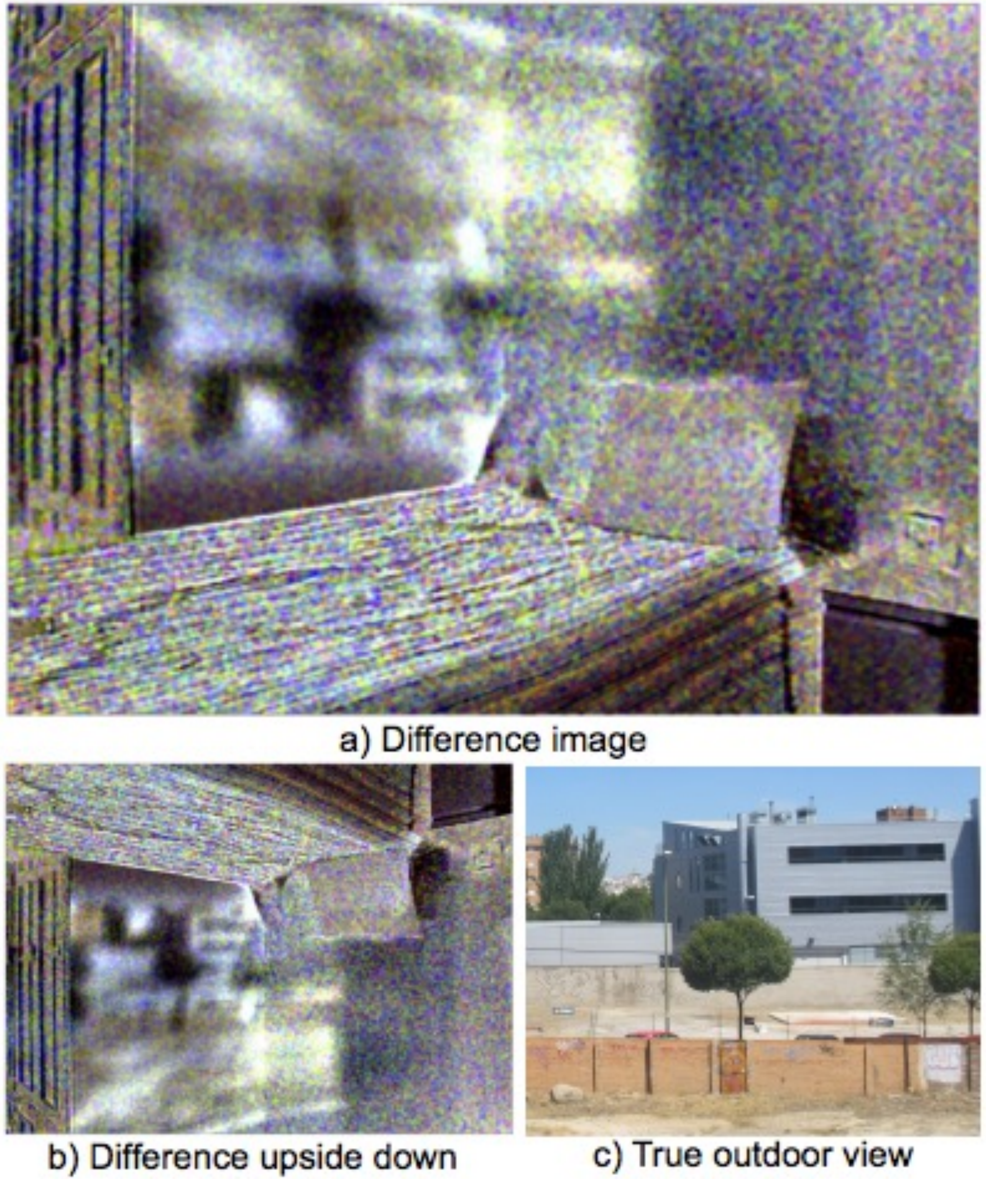
Mixed accidental pinhole and anti-pinhole cameras



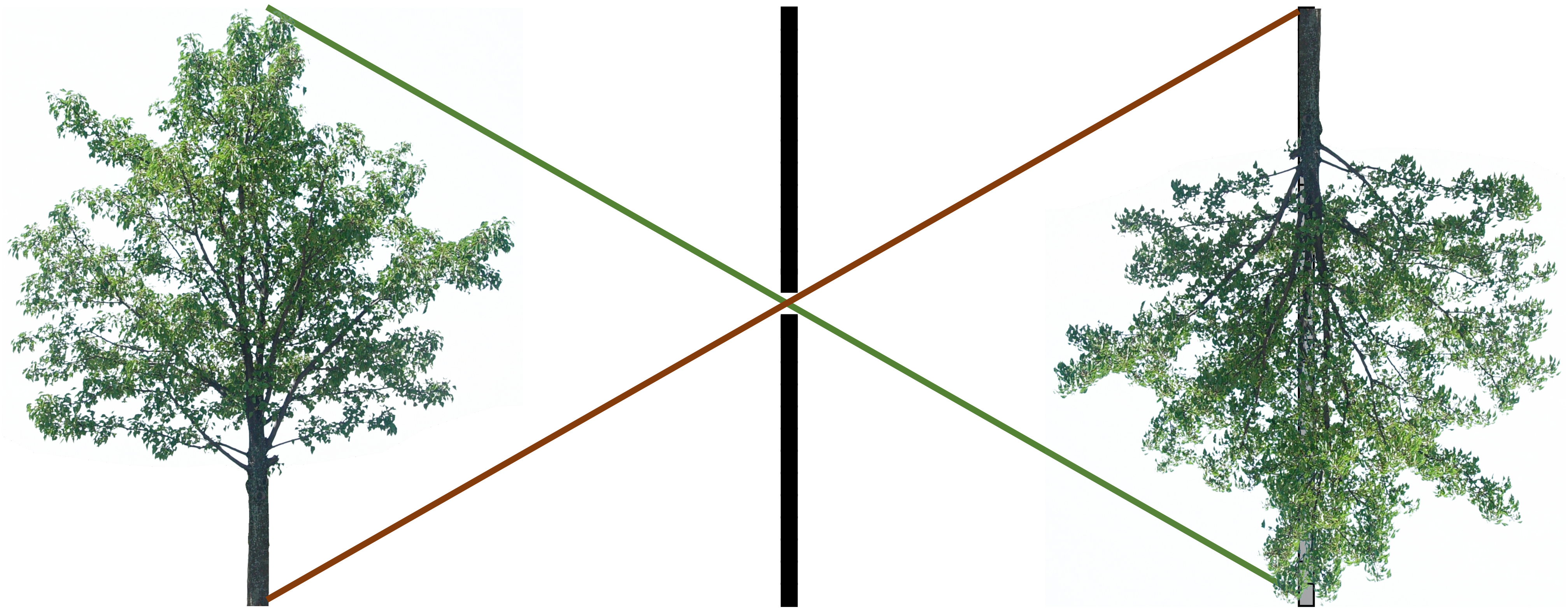
Accidental pinspeck camera





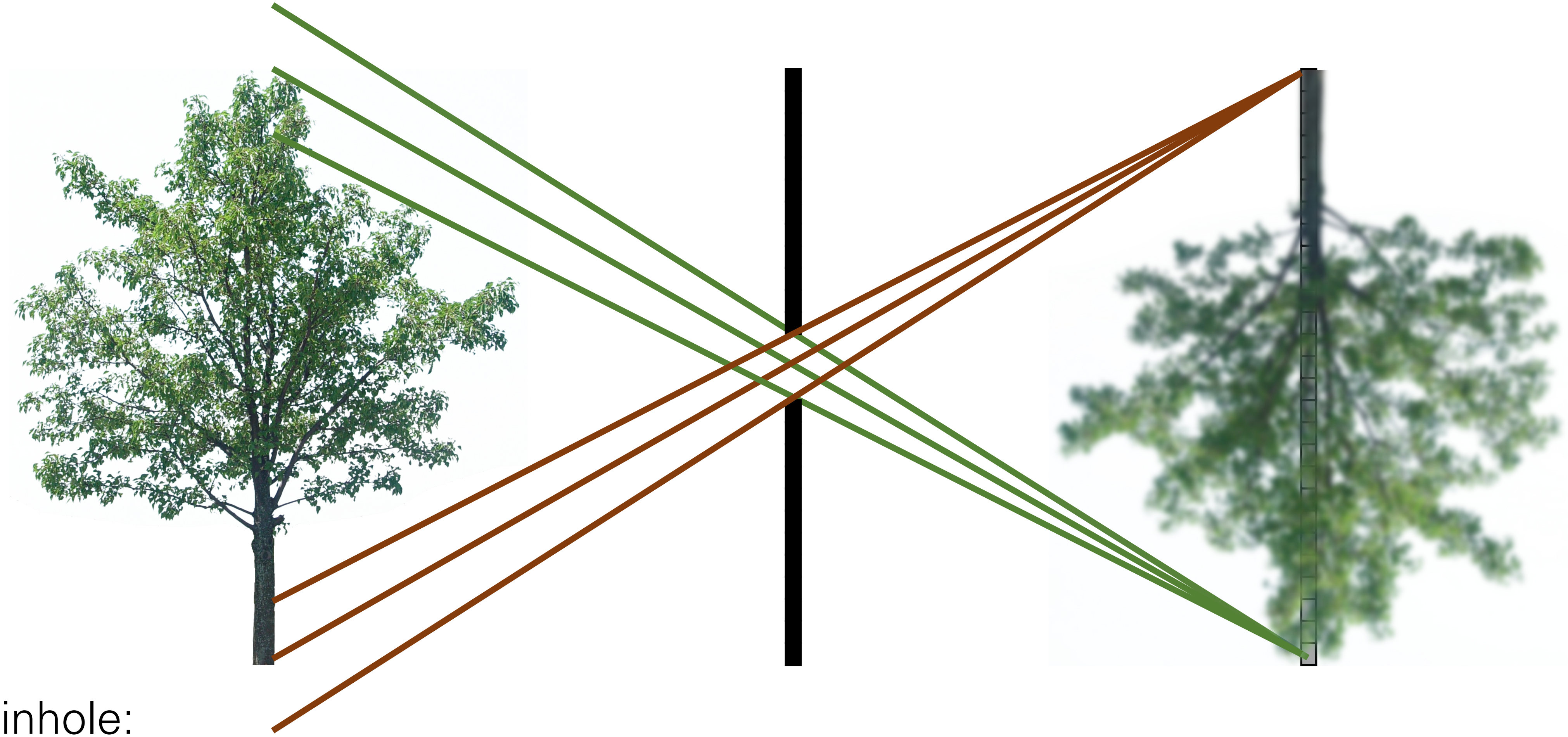


Pinhole camera trade-off



Small (ideal) pinhole:
1. Image is sharp.
2. Signal-to-noise ratio is low.

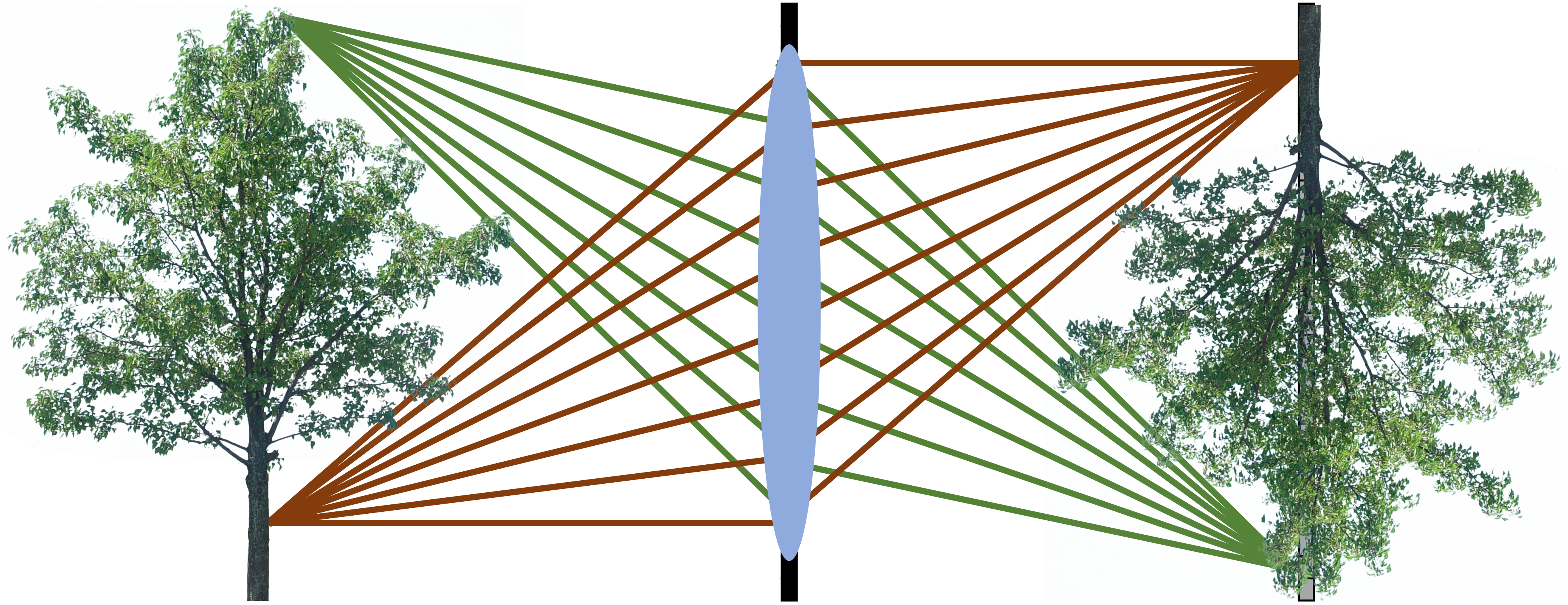
Pinhole camera trade-off



Large pinhole:
1. Image is blurry.
2. Signal-to-noise ratio is high.

Can we get best of both worlds?

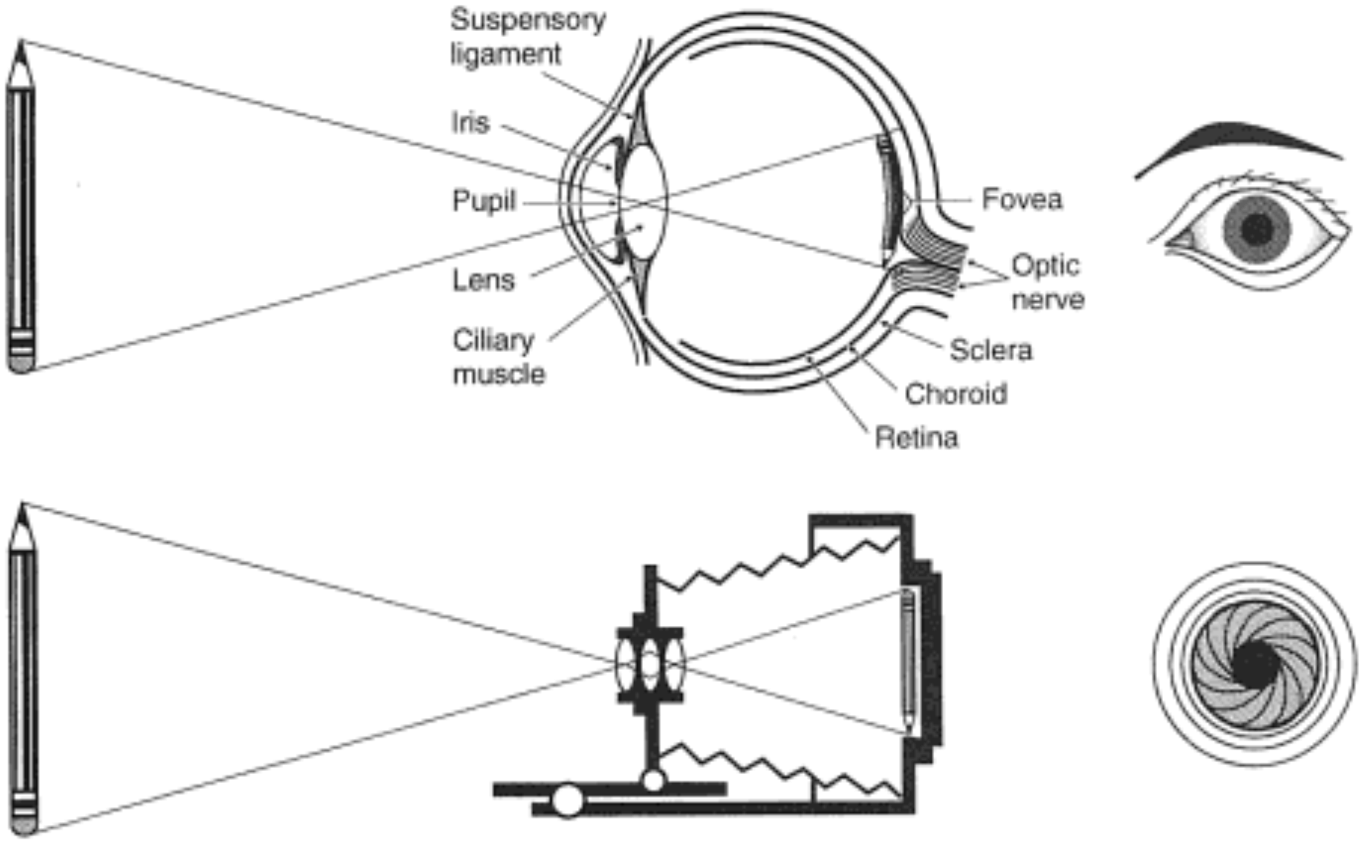
Almost, by using lenses



Lenses map “bundles” of rays from points on the scene to the sensor.

How does this mapping work exactly?

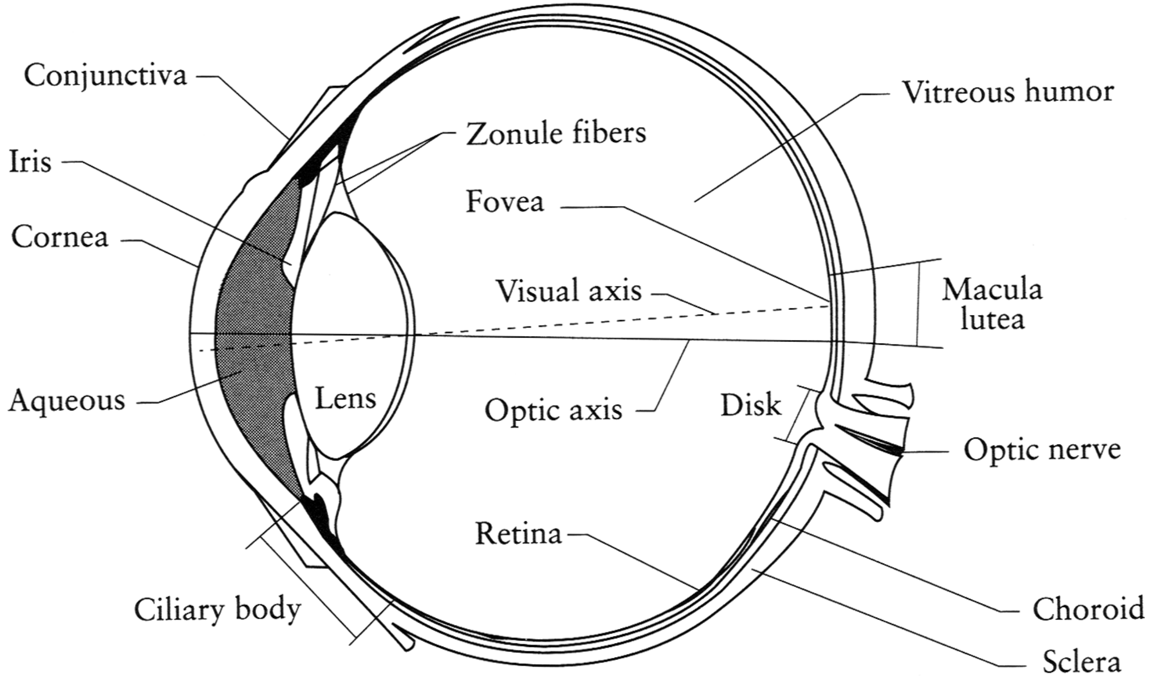
The Eye



Figures: Francis Crick, The Astonishing Hypothesis, 1995

- The human eye is a camera

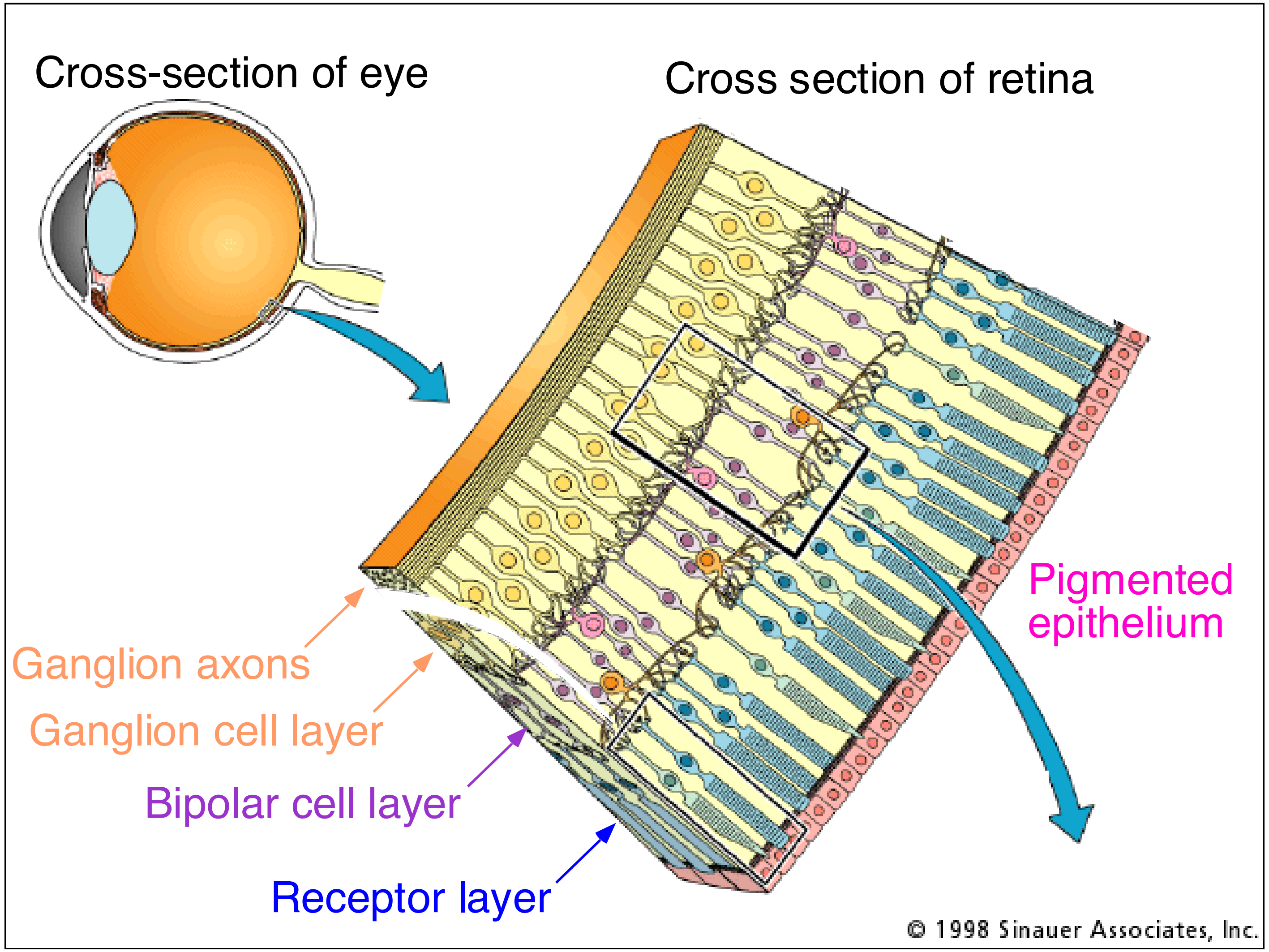
The Eye



- The human eye is a camera!
  - Iris - colored annulus with radial muscles
  - Pupil - the hole (aperture) whose size is controlled by the iris
  - What’s the “film”?
    - photoreceptor cells (rods and cones) in the retina

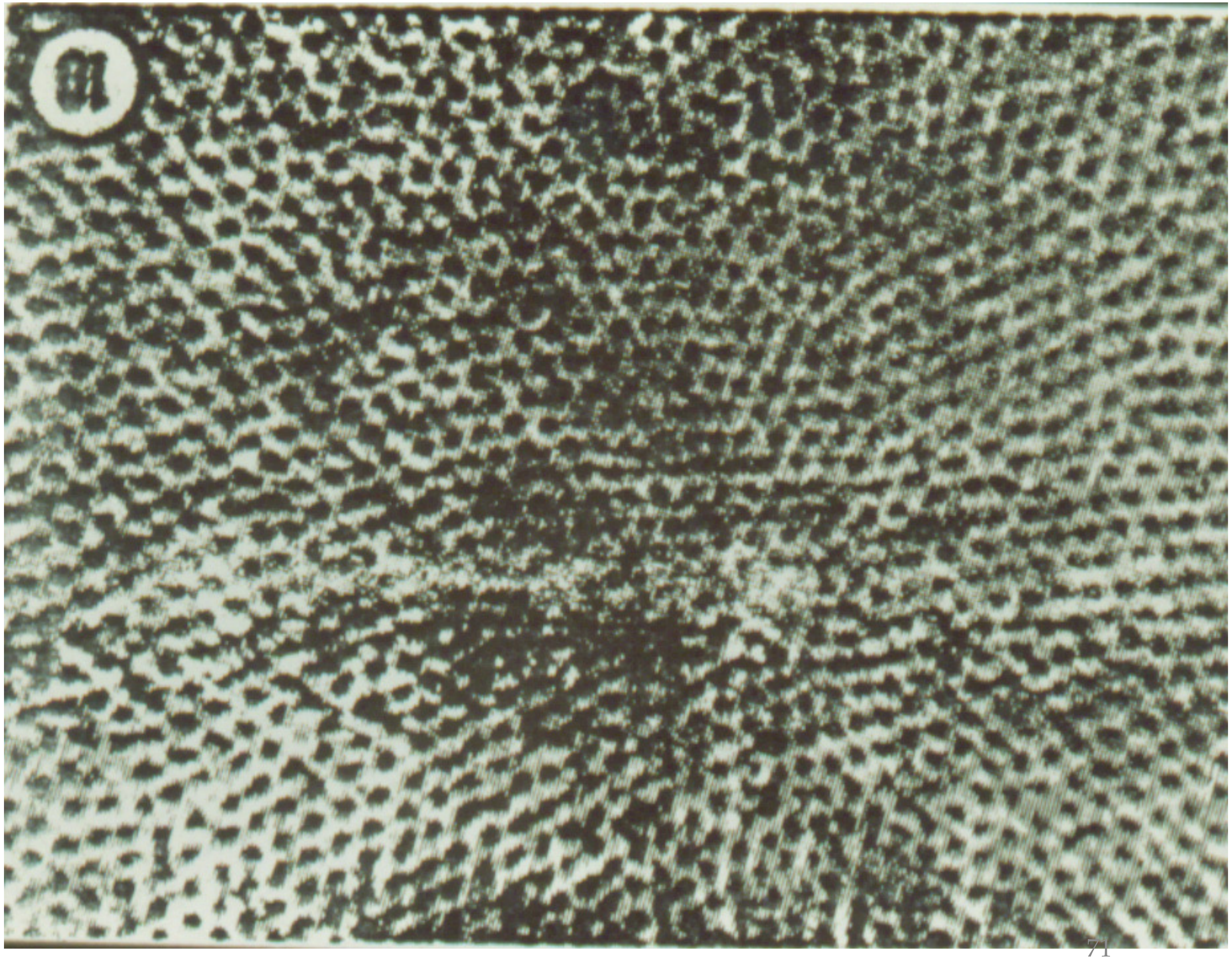
Slide credit: Steve Seitz

The Retina



Slide credit: Alyosha Efros

Receptors Density - Fovea



Slide credit: S. Ullman

Receptors Density - Fovea

64	66	76	85	99	100	101	101	106	112	117	118	105	77	57	50	51	43	52	55	62
65	69	76	84	97	89	93	107	121	121	121	122	125	101	71	43	45	41	52	52	68
66	72	78	83	91	86	91	102	108	104	106	113	136	118	86	43	49	47	60	55	64
73	79	83	85	94	93	90	83	79	79	85	92	124	124	108	62	58	43	57	57	64
78	84	86	86	69	71	68	68	86	108	115	109	117	135	139	93	73	37	49	58	70
75	75	73	77	75	80	62	84	90	94	98	102	102	110	114	100	80	58	51	51	51
77	72	73	83	84	91	80	77	71	70	73	80	80	87	99	103	93	67	53	50	51
74	66	69	88	98	101	95	65	56	55	55	60	64	70	93	114	112	82	56	47	53
64	59	66	86	108	103	98	54	52	57	54	54	67	77	103	124	125	96	64	46	53
56	57	66	83	112	108	104	59	55	60	59	60	78	94	115	125	121	98	68	43	46
56	58	66	80	114	121	117	85	71	67	69	76	87	101	116	117	112	94	68	43	46
61	57	61	77	111	125	119	114	98	87	87	94	97	102	111	113	108	90	65	43	44
63	52	54	73	103	117	107	126	119	108	103	104	106	103	108	115	112	91	65	48	42
66	63	58	63	94	115	120	108	102	104	106	108	105	108	107	105	105	97	72	47	41
68	65	58	61	86	108	115	106	102	103	103	104	98	99	97	97	103	101	81	57	43
72	68	62	64	78	102	111	105	101	101	101	103	99	98	96	97	104	104	86	63	48
74	71	64	64	69	93	104	99	94	93	96	101	99	101	102	103	108	106	90	69	53

Slide credit: S. Ullman

Animal Eyes

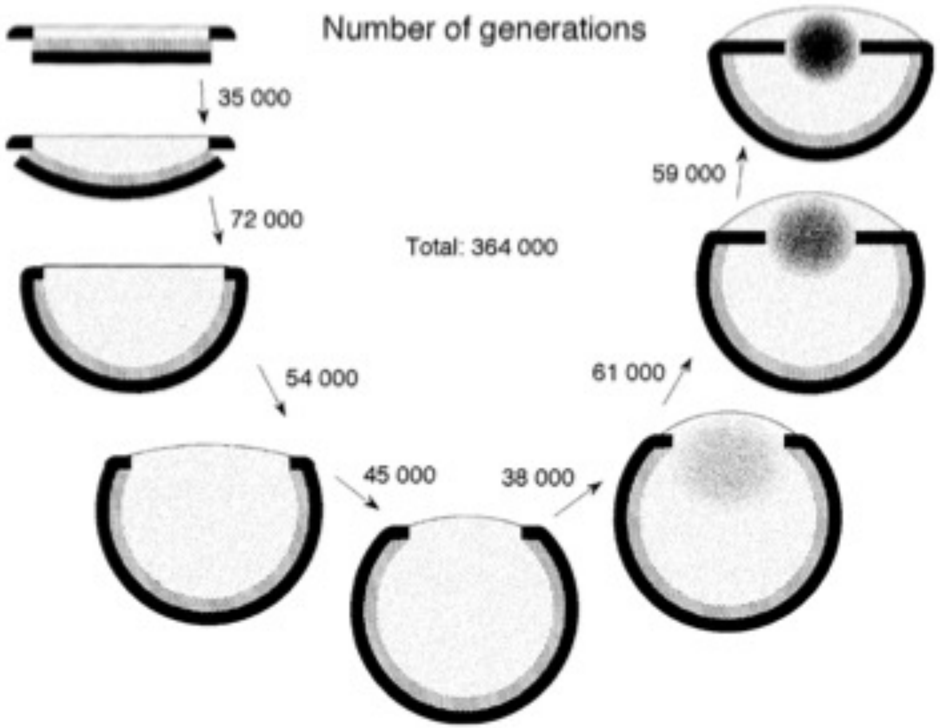


Fig. 1.6 A patch of light sensitive epithelium can be gradually turned into a perfectly focussed camera-type eye if there is a continuous selection for improved spatial vision. A theoretical model based on conservative assumptions about selection pressure and the amount of variation in natural populations suggest that the whole sequence can be accomplished amazingly fast, in less than 400 000 generations. The number of generations is also given between each of the consecutive intermediates that are drawn in the figure. The starting point is a flat piece of epithelium with an outer protective layer, an intermediate layer of receptor cells, and a bottom layer of pigment cells. The first half of the sequence is the formation of a pigment cup eye. When this principle cannot be improved any further, a lens gradually evolves. Modified from Nilsson and Pelger (1994).

Animal Eyes. Land & Nilsson. Oxford Univ. Press

Natural Eyes

Lens (very) basics

Replacing pinholes with lenses

Niepce "View from the Window at Le Gras", 1826

1826
8h exp

Daguerrotype

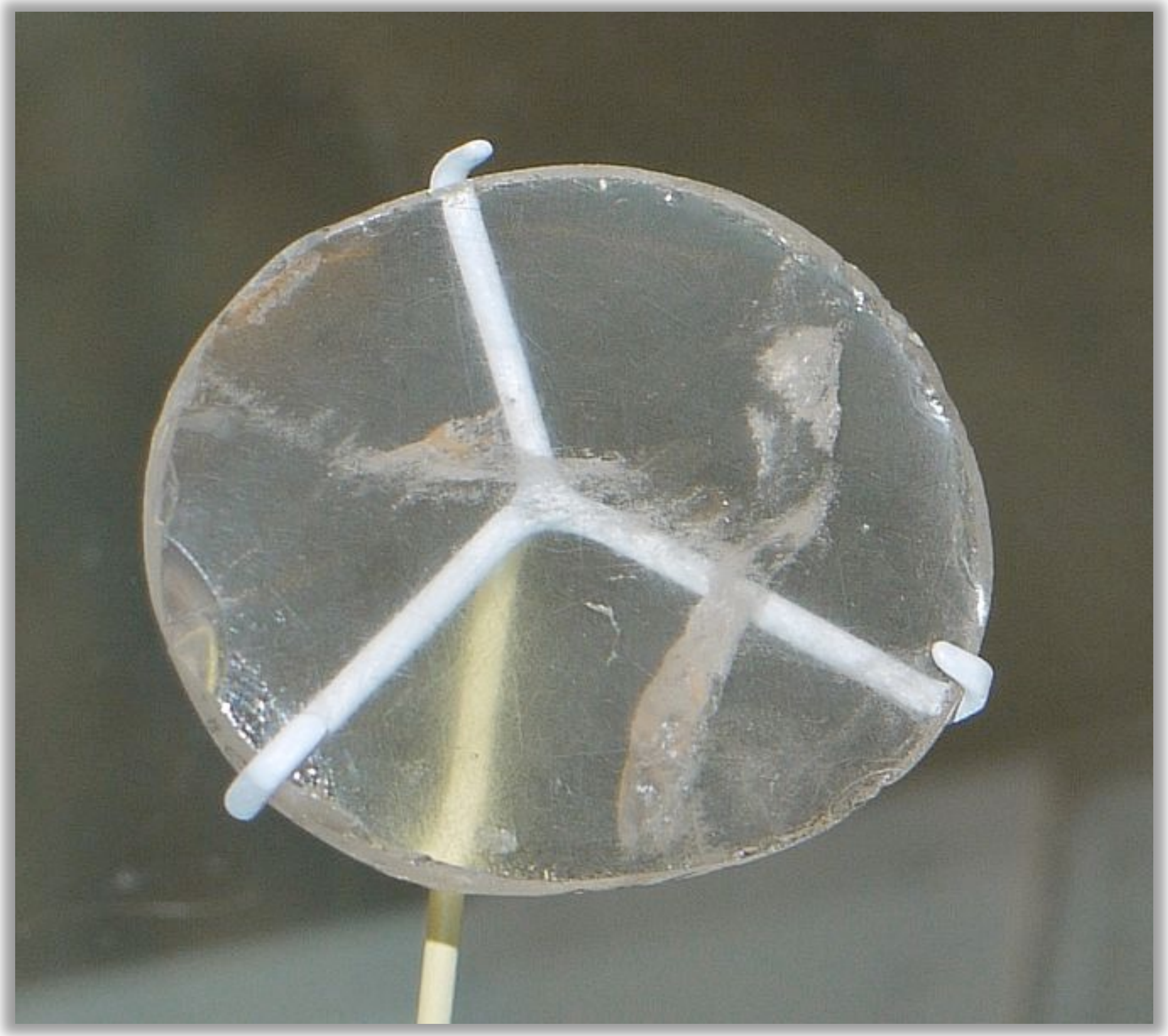
- invented in 1836 by Louis Daguerre
- lenses focus light, better chemicals!

Daguerre “Boulevard du Temple”, 1838

exposure
10-12 mins

Lenses

- focus light
- magnify objects



Nimrud lens - 2700 years old

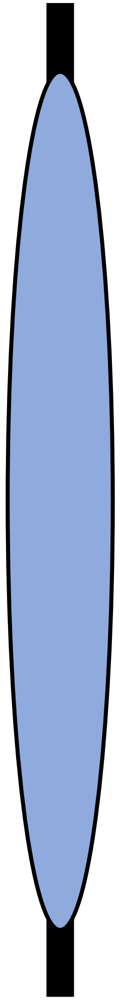
Lenses

Lenses

Lenses

What is a lens?

A piece of glass manufactured to have a specific shape



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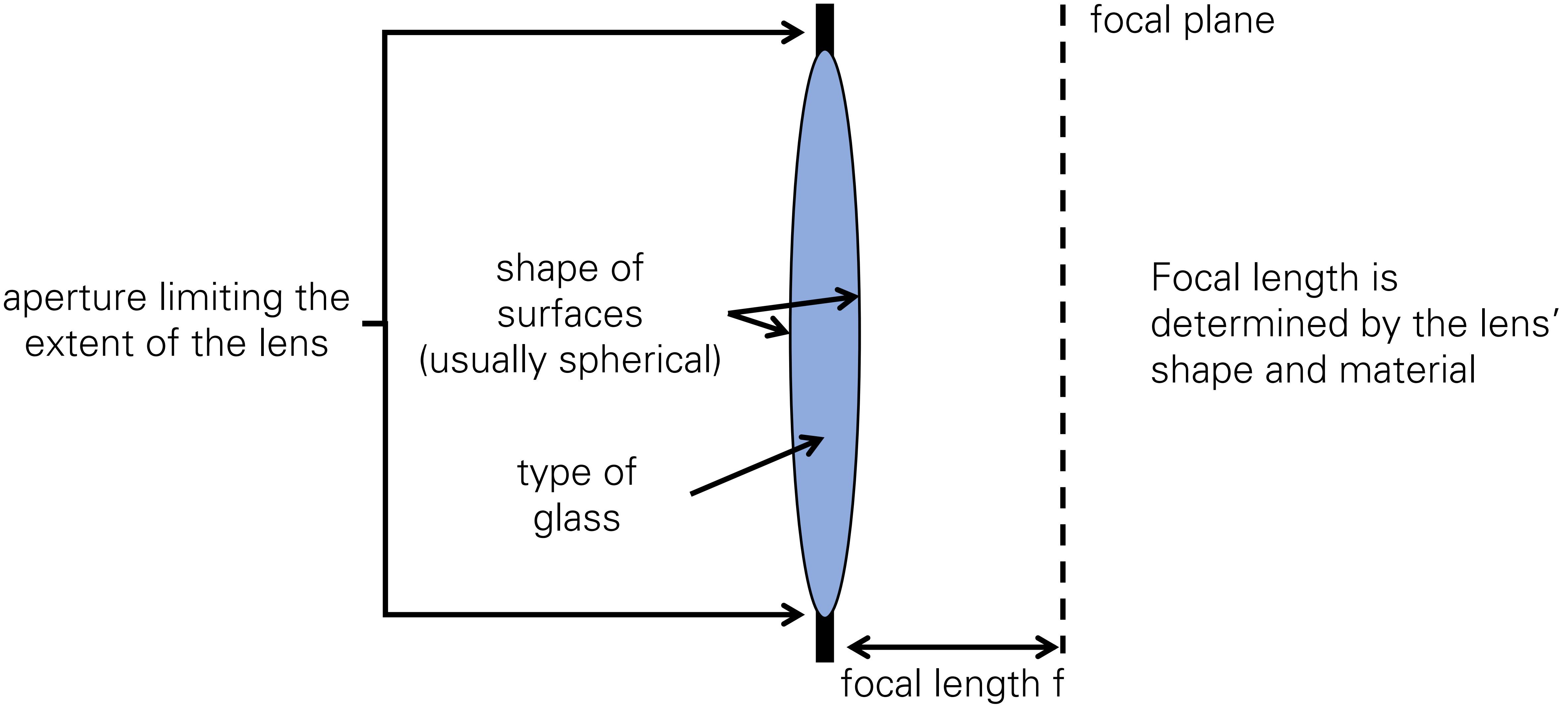
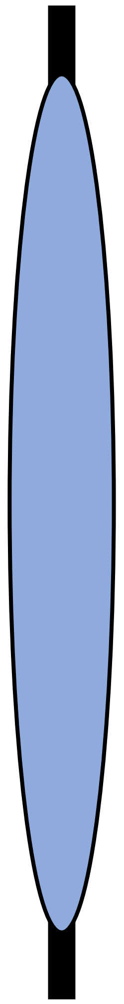


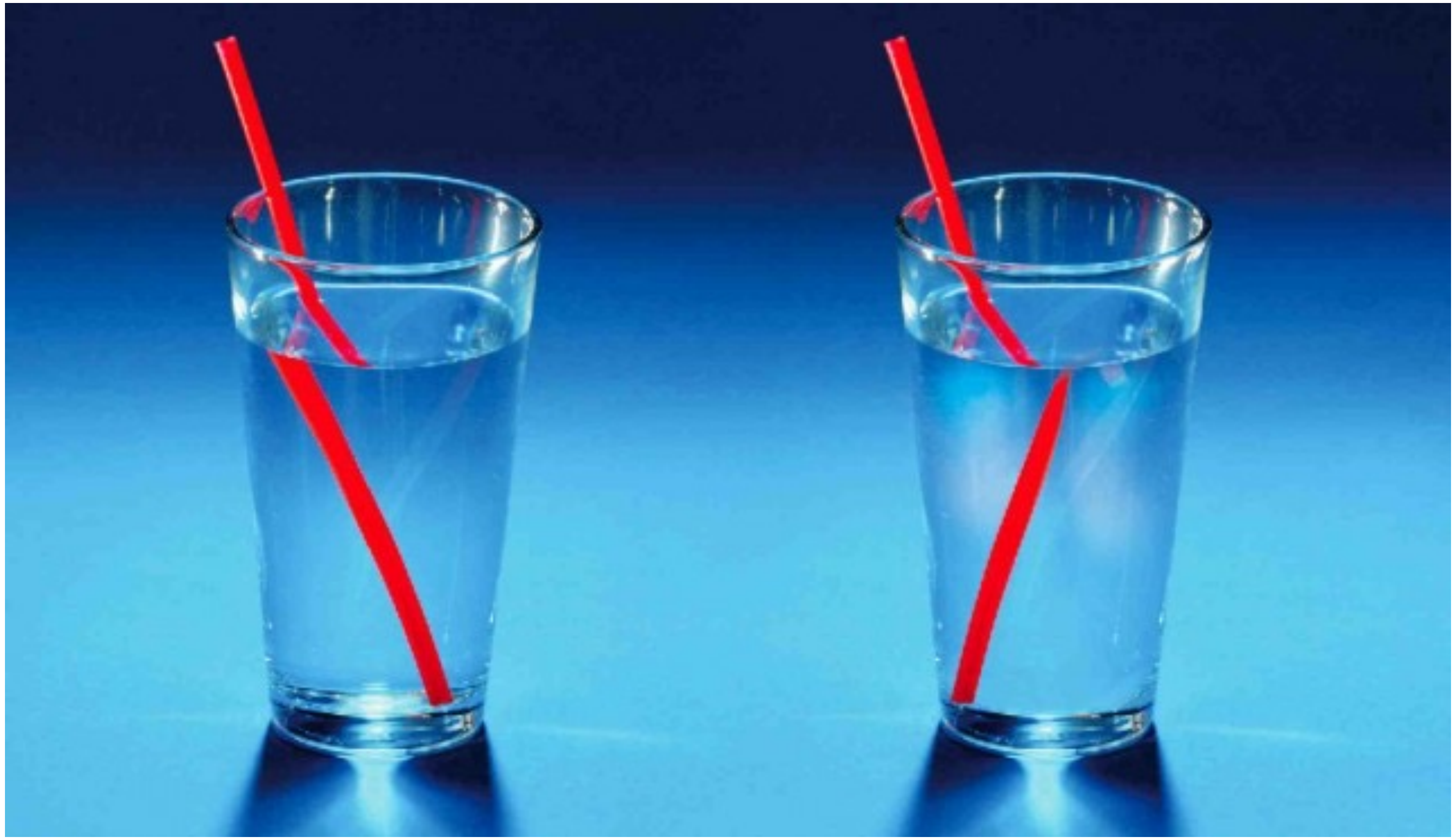
The lens on your camera

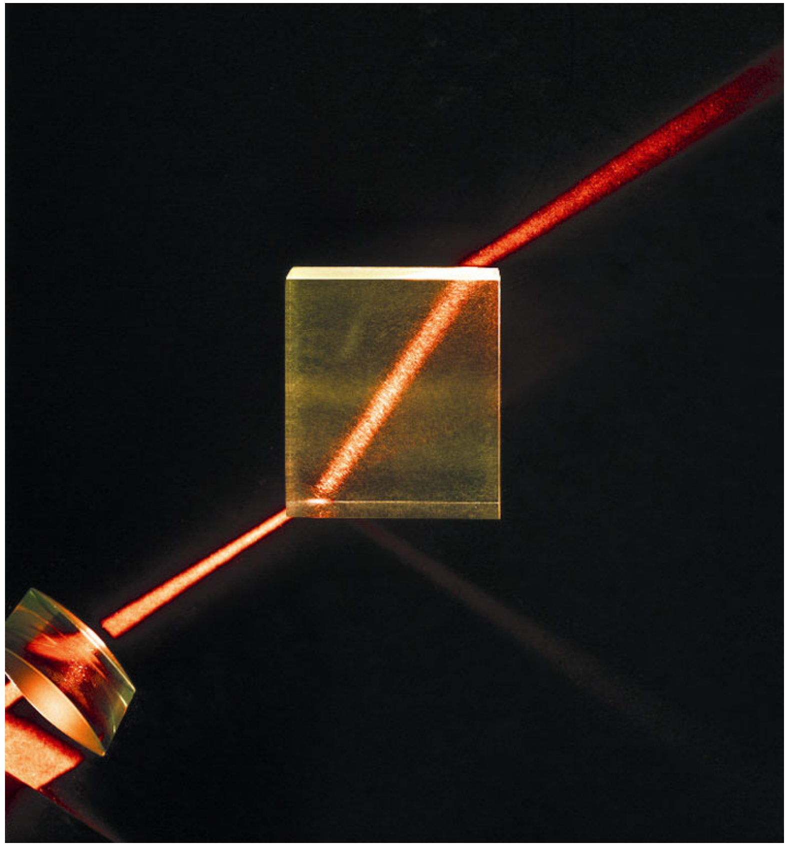
How does a lens work?



Refraction

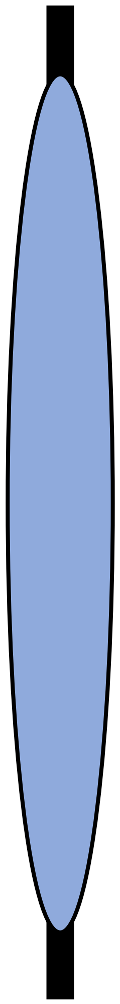
Refraction is the bending of rays of light when they move from one material to another





How does a lens work?

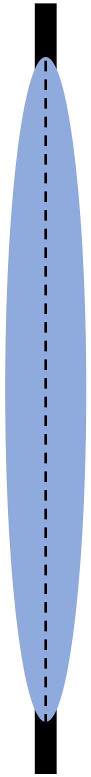
Lenses are designed so that their refraction makes light rays bend in a very specific way.



The thin lens model

Thin lens model

Simplification of geometric optics for well-designed lenses.



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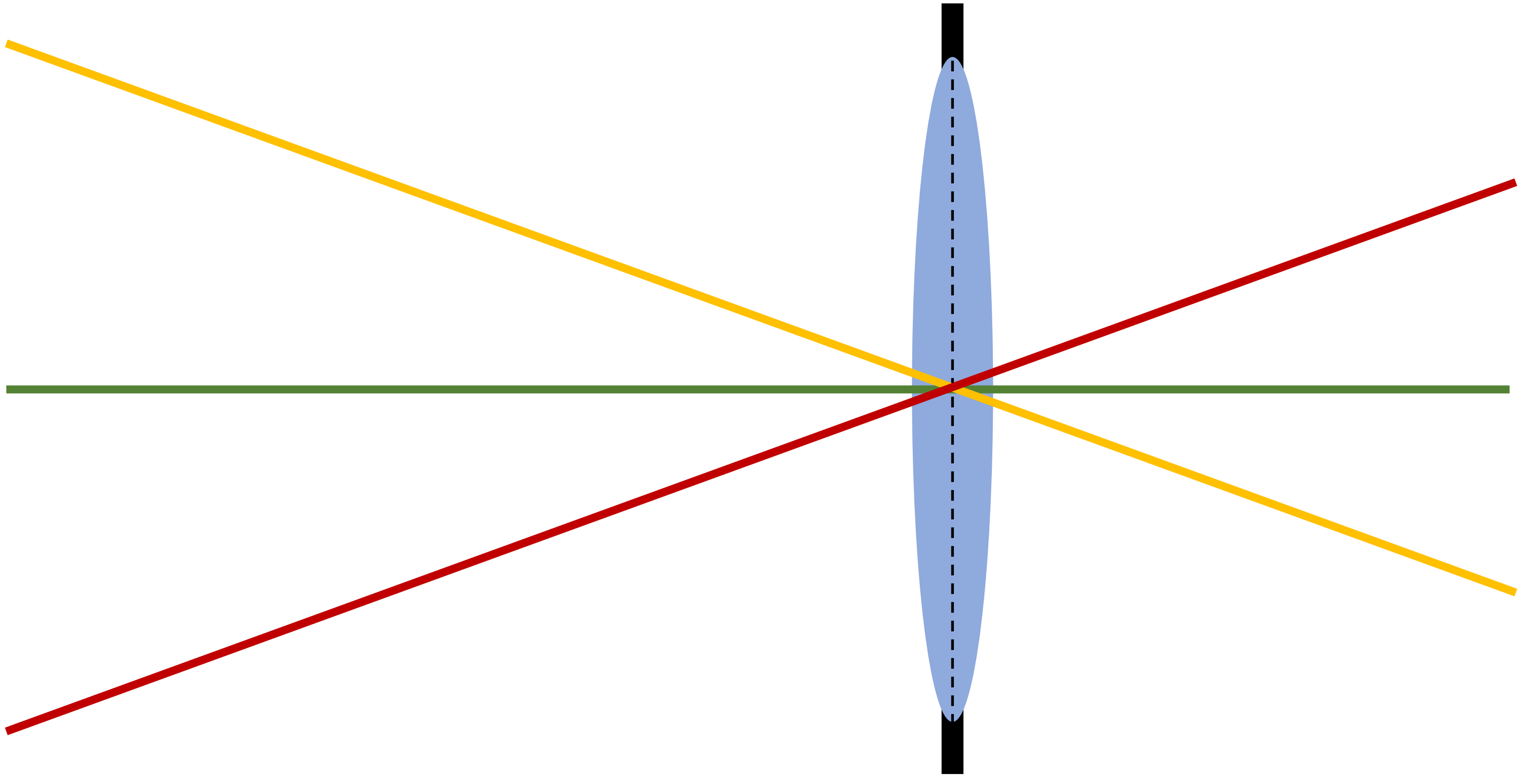

Two assumptions:

1. Rays passing through lens center are unaffected.

Thin lens model

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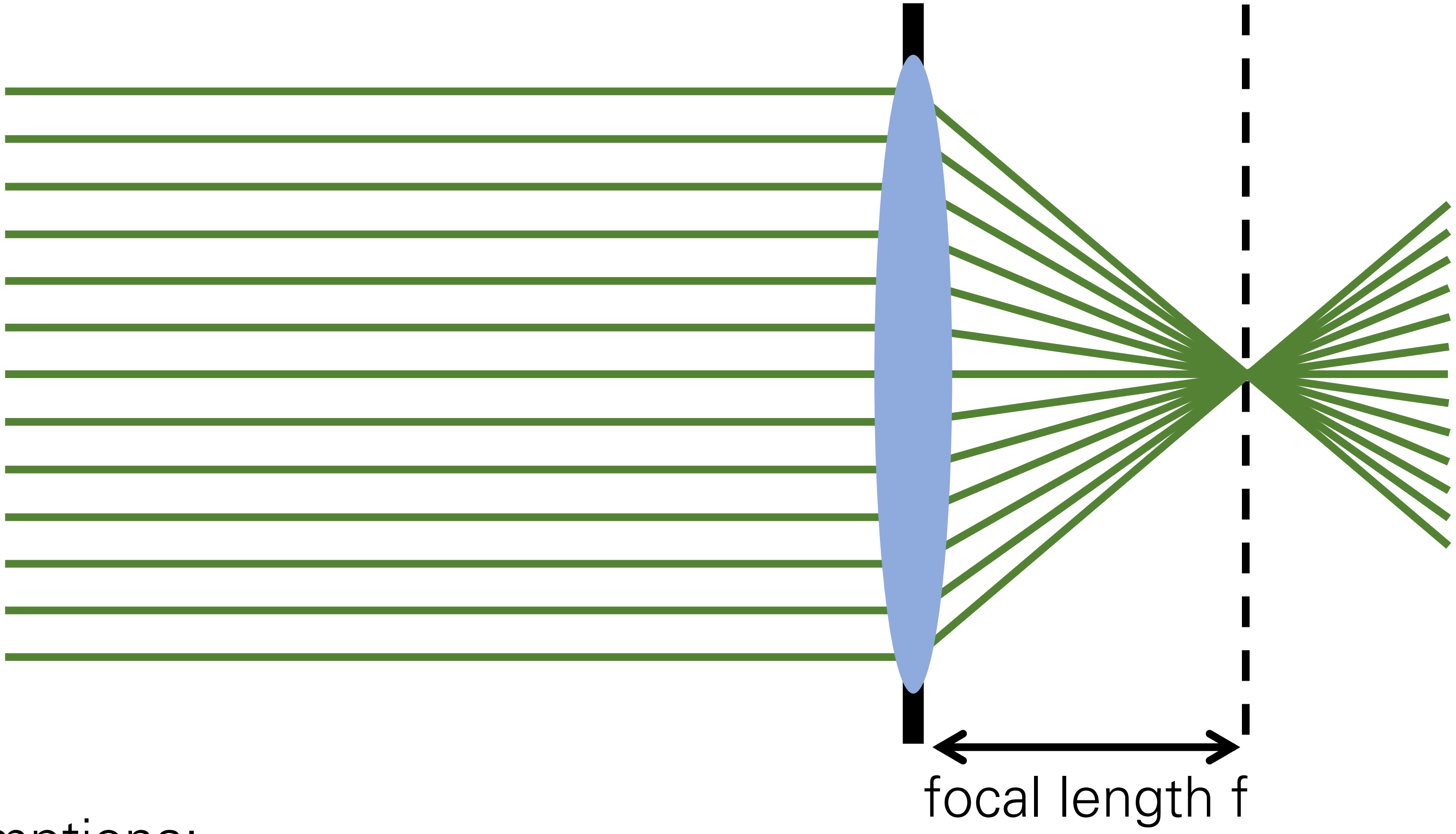

Two assumptions:

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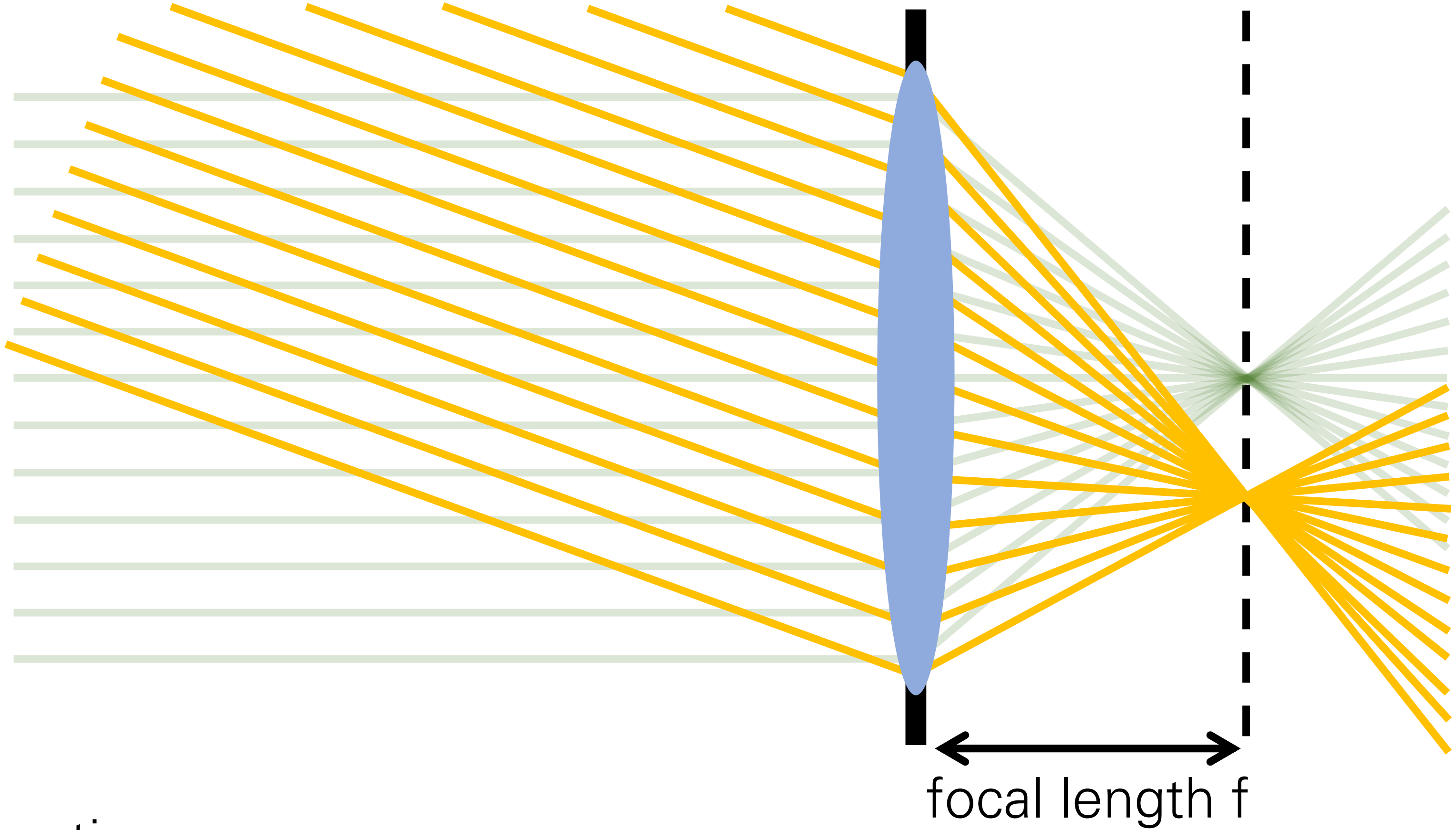

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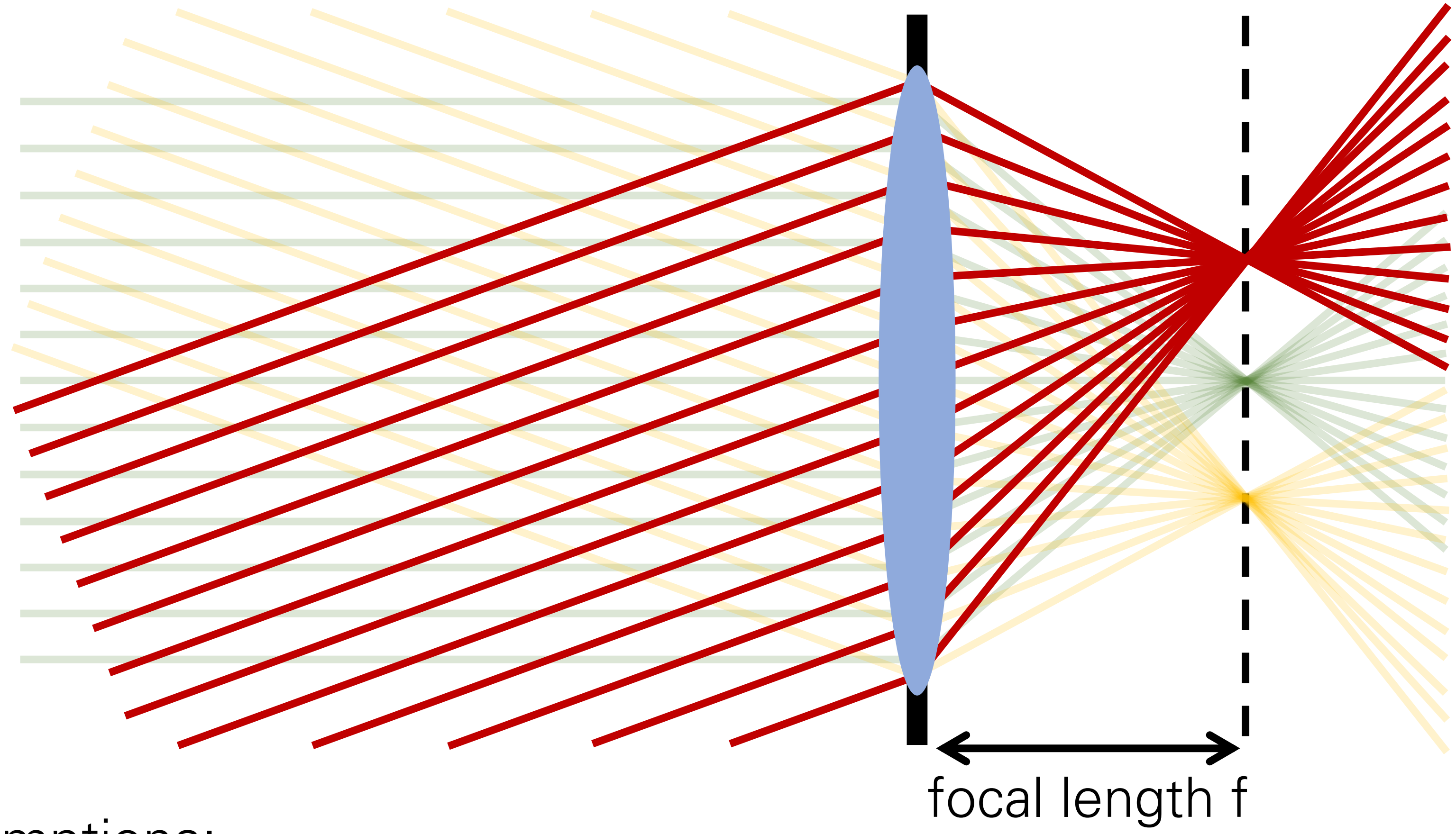

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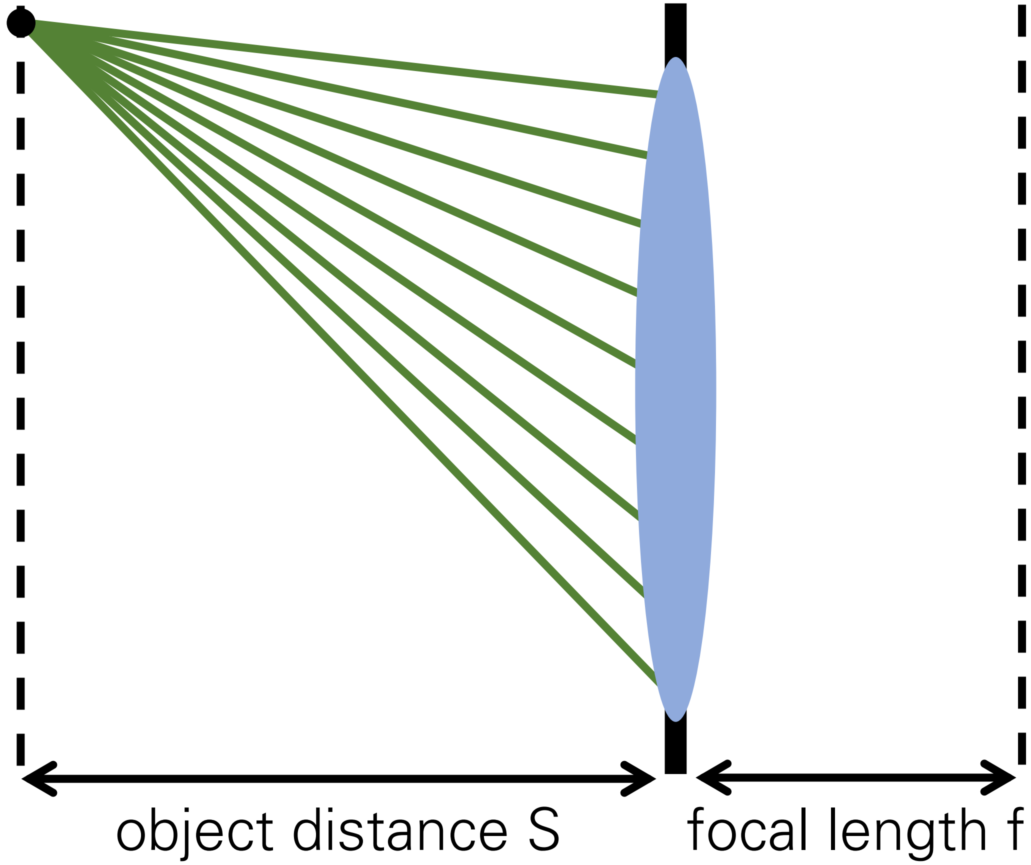
Tracing rays through a thin lens

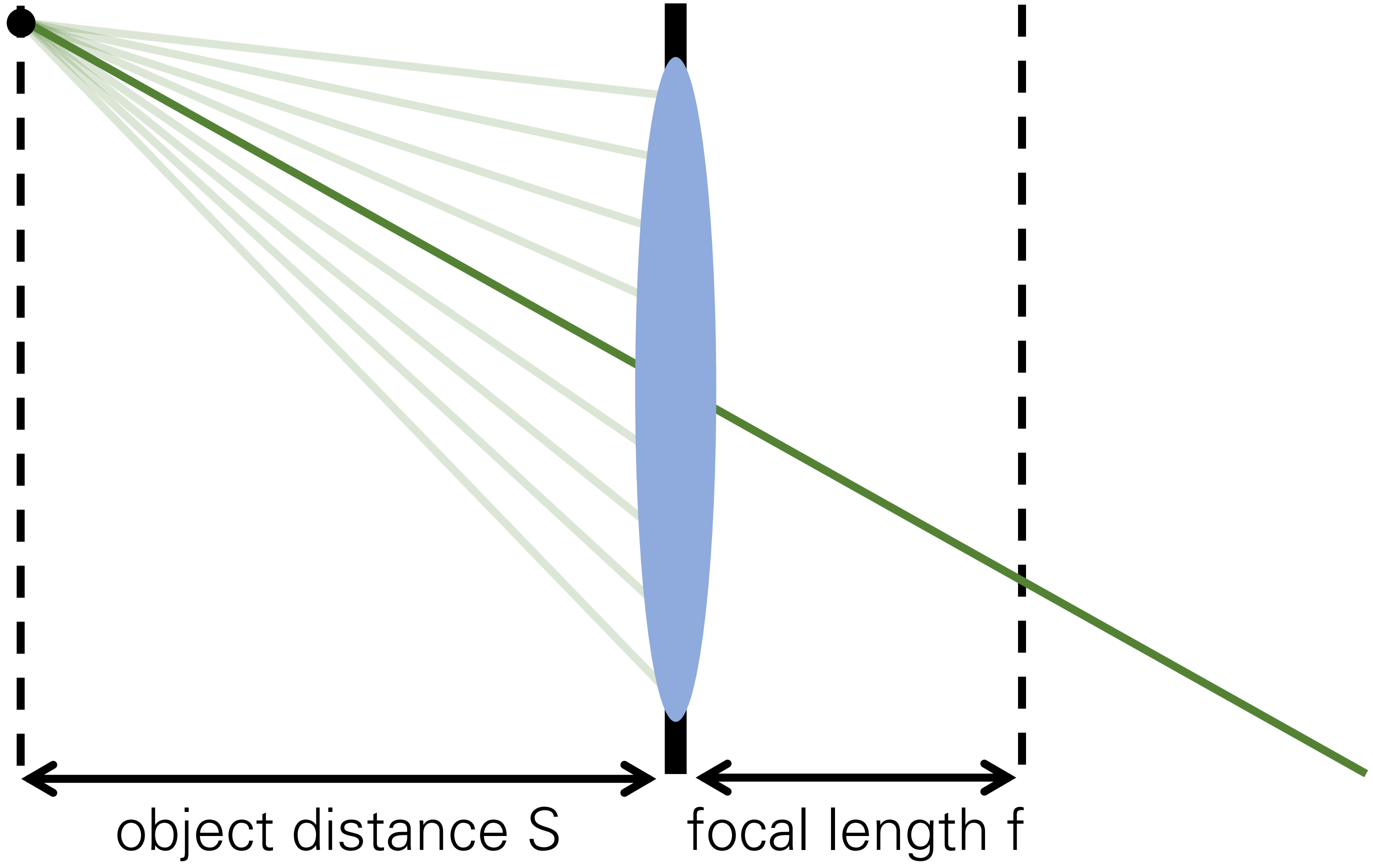
Consider an object emitting a bundle of rays. How do they propagate through the lens?



Tracing rays through a thin lens

Consider an object emitting a bundle of rays. How do they propagate through the lens?

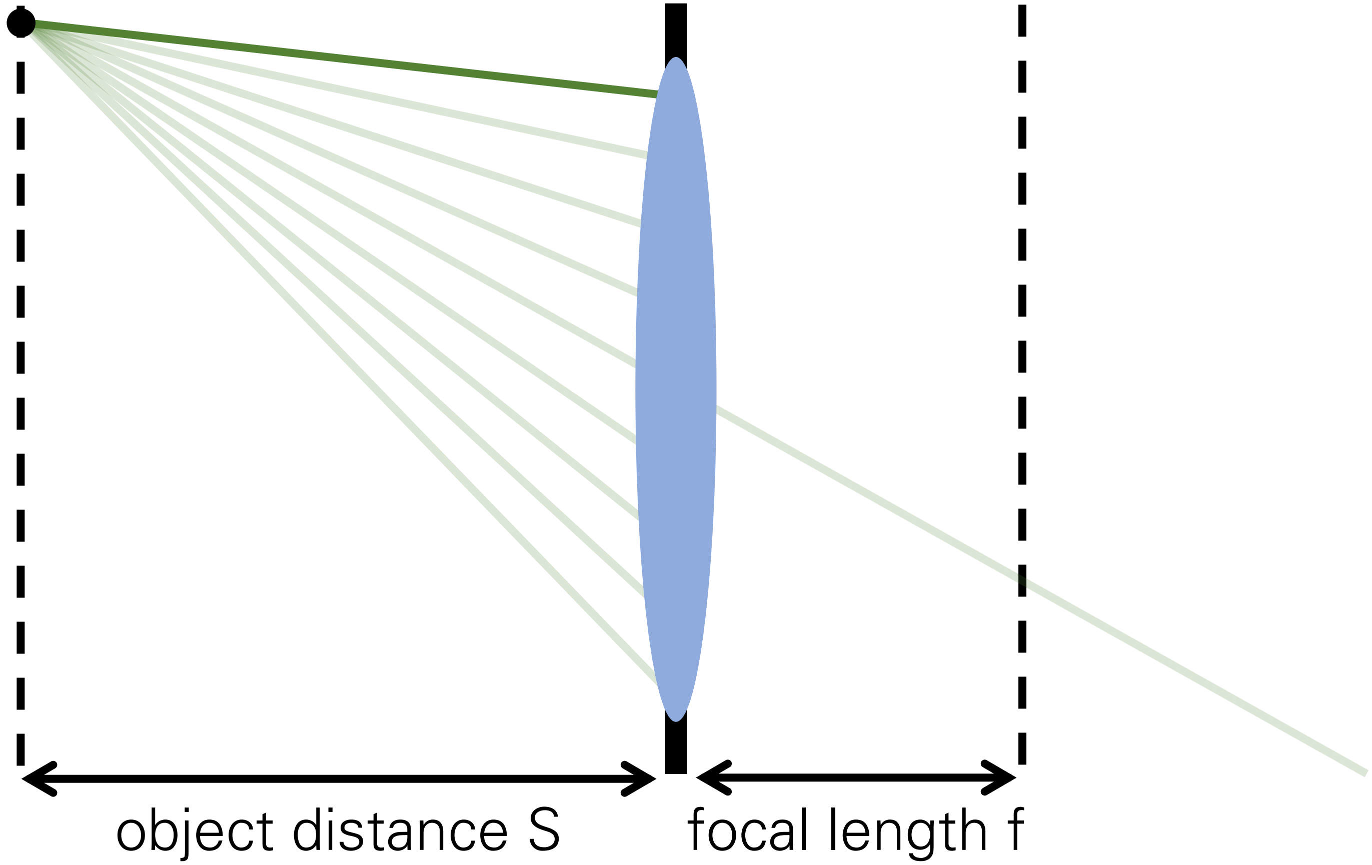
1. Trace rays through lens center.



Tracing rays through a thin lens

Consider an object emitting a bundle of rays. How do they propagate through the lens?

1. Trace rays through lens center.
2. For all other rays:



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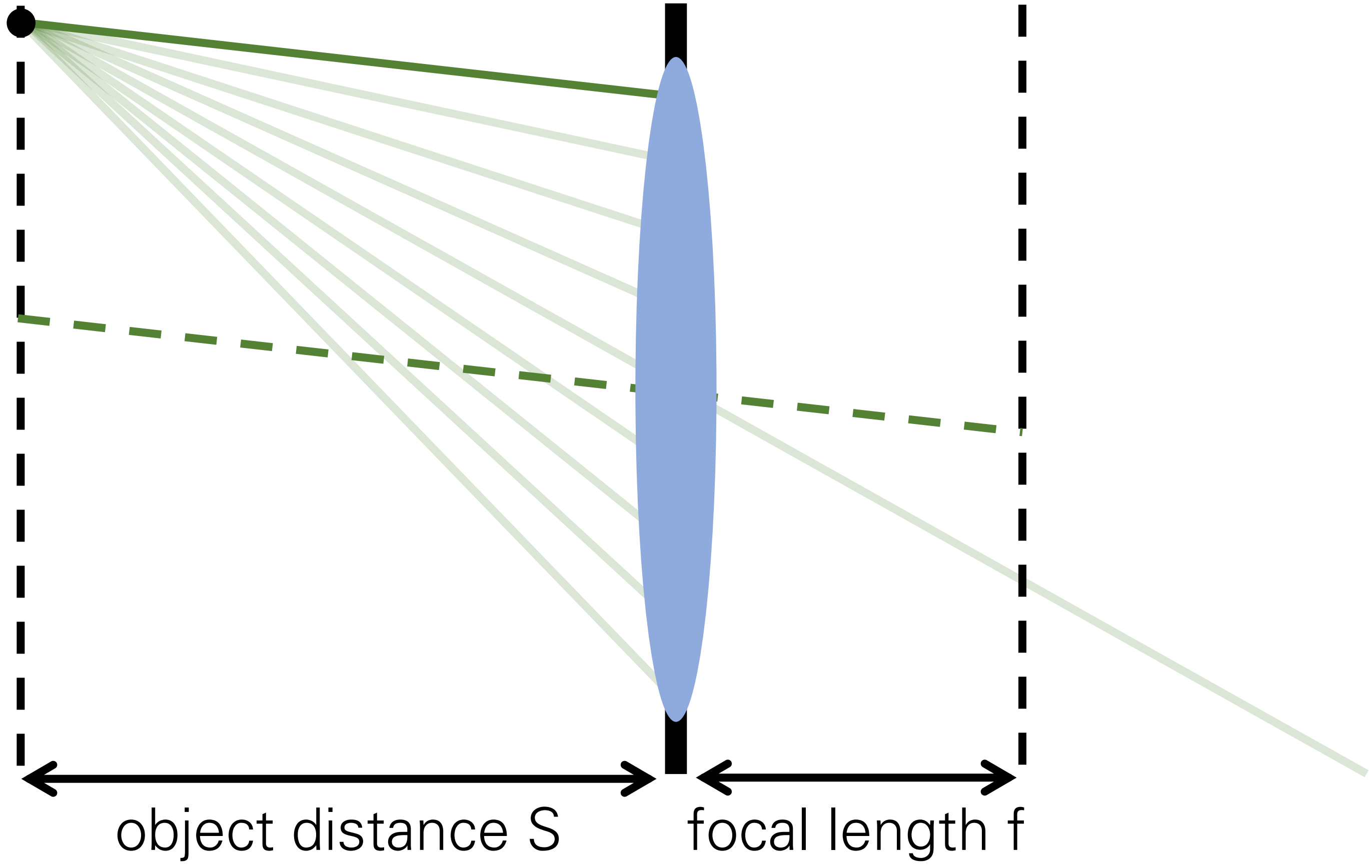
Consider an object emitting a bundle of rays. How do they propagate through the lens?

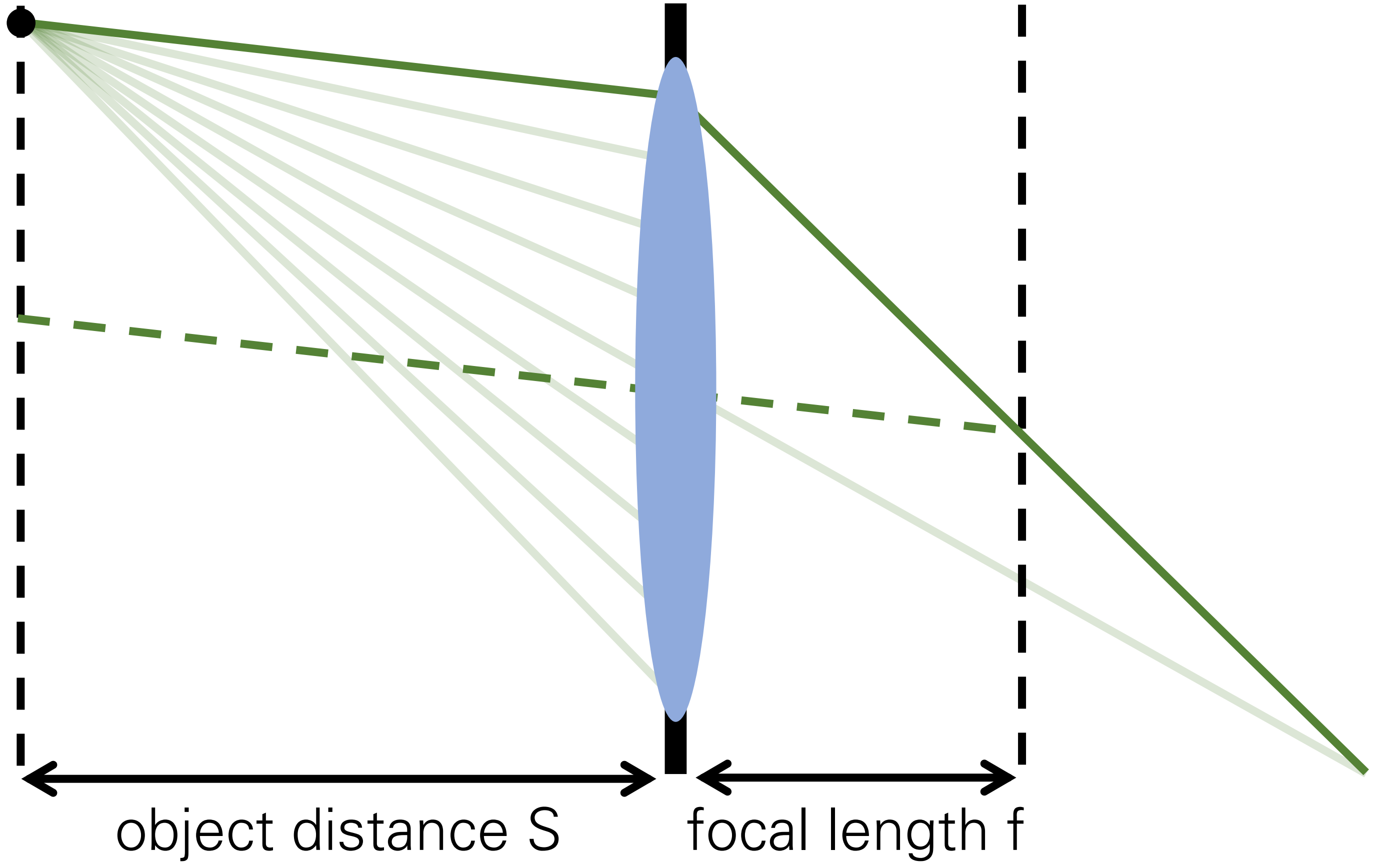
1. Trace rays through lens center.
2. For all other rays:
    a. Trace their parallel through lens center.



Tracing rays through a thin lens

Consider an object emitting a bundle of rays. How do they propagate through the lens?

1. Trace rays through lens center.
2. For all other rays:
   a. Trace their parallel through lens center.
   b. Connect on focal plane.



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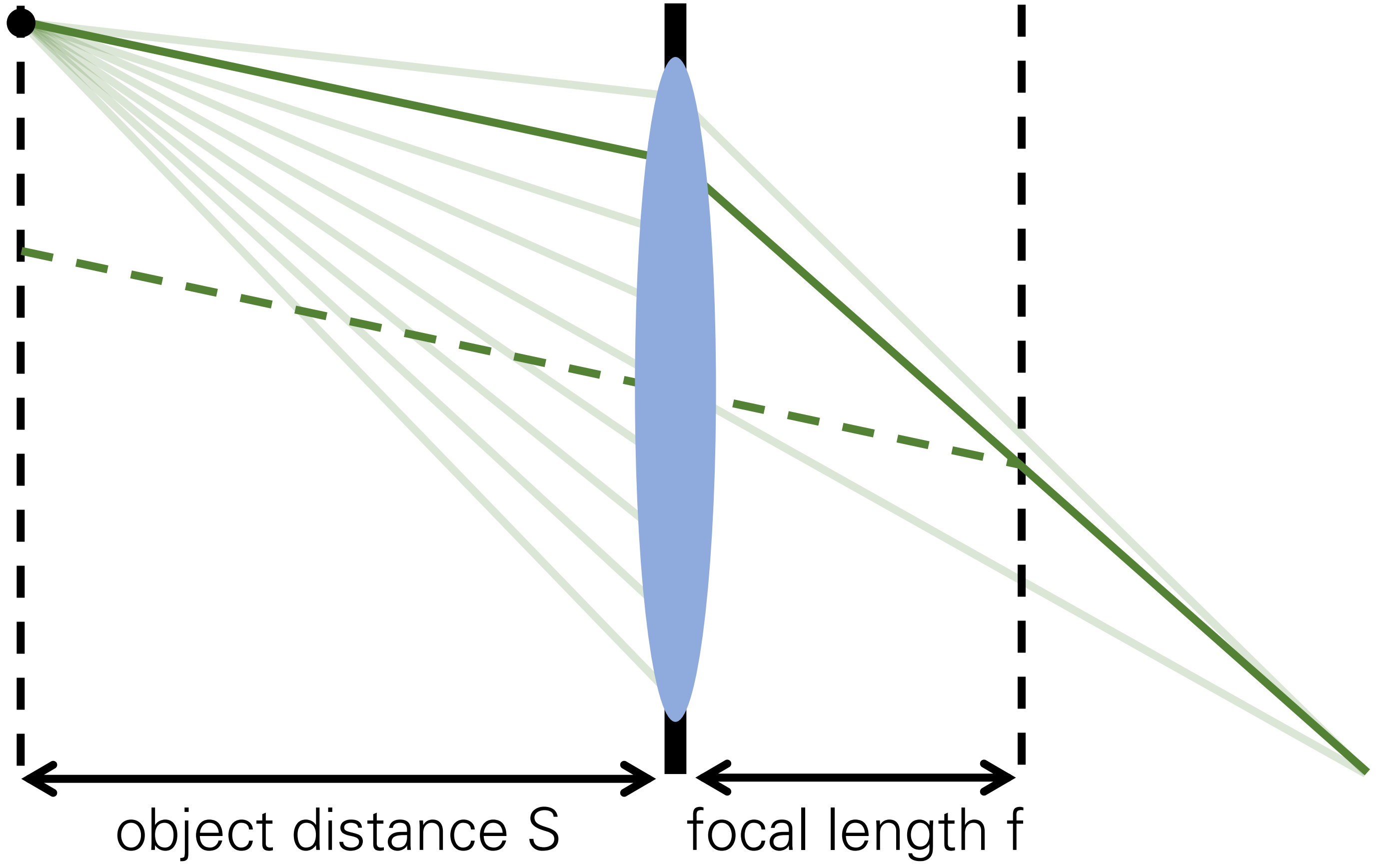

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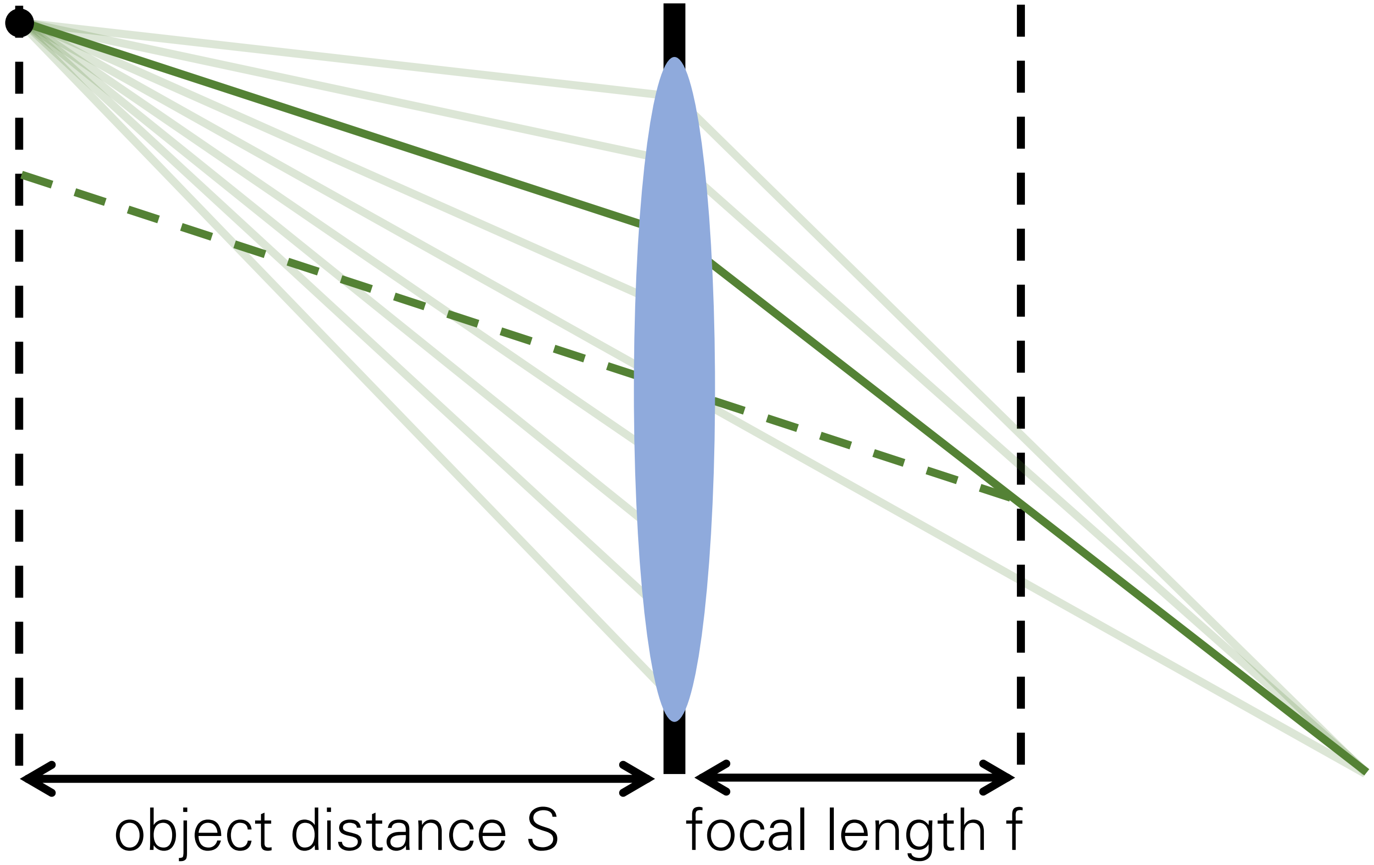

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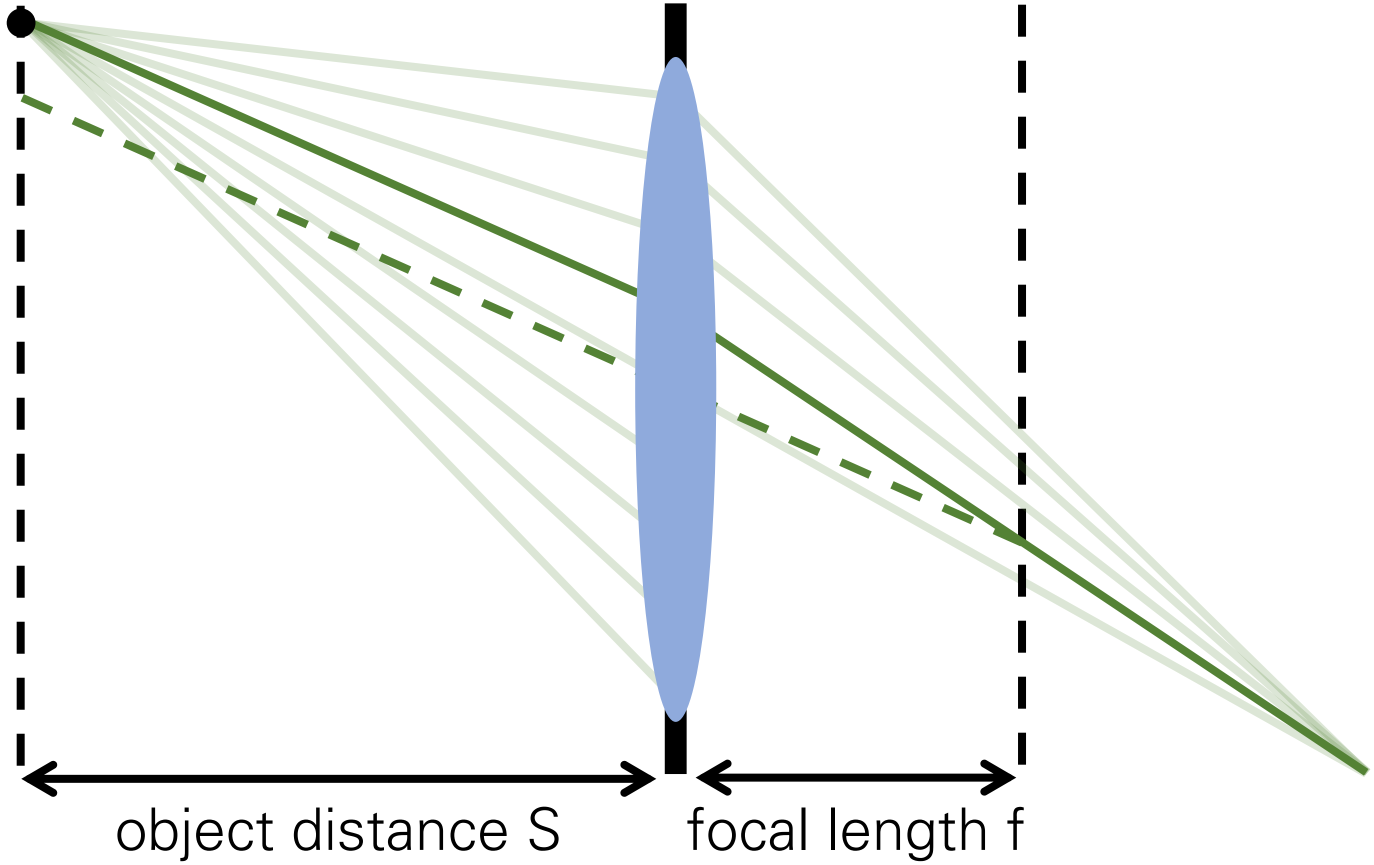

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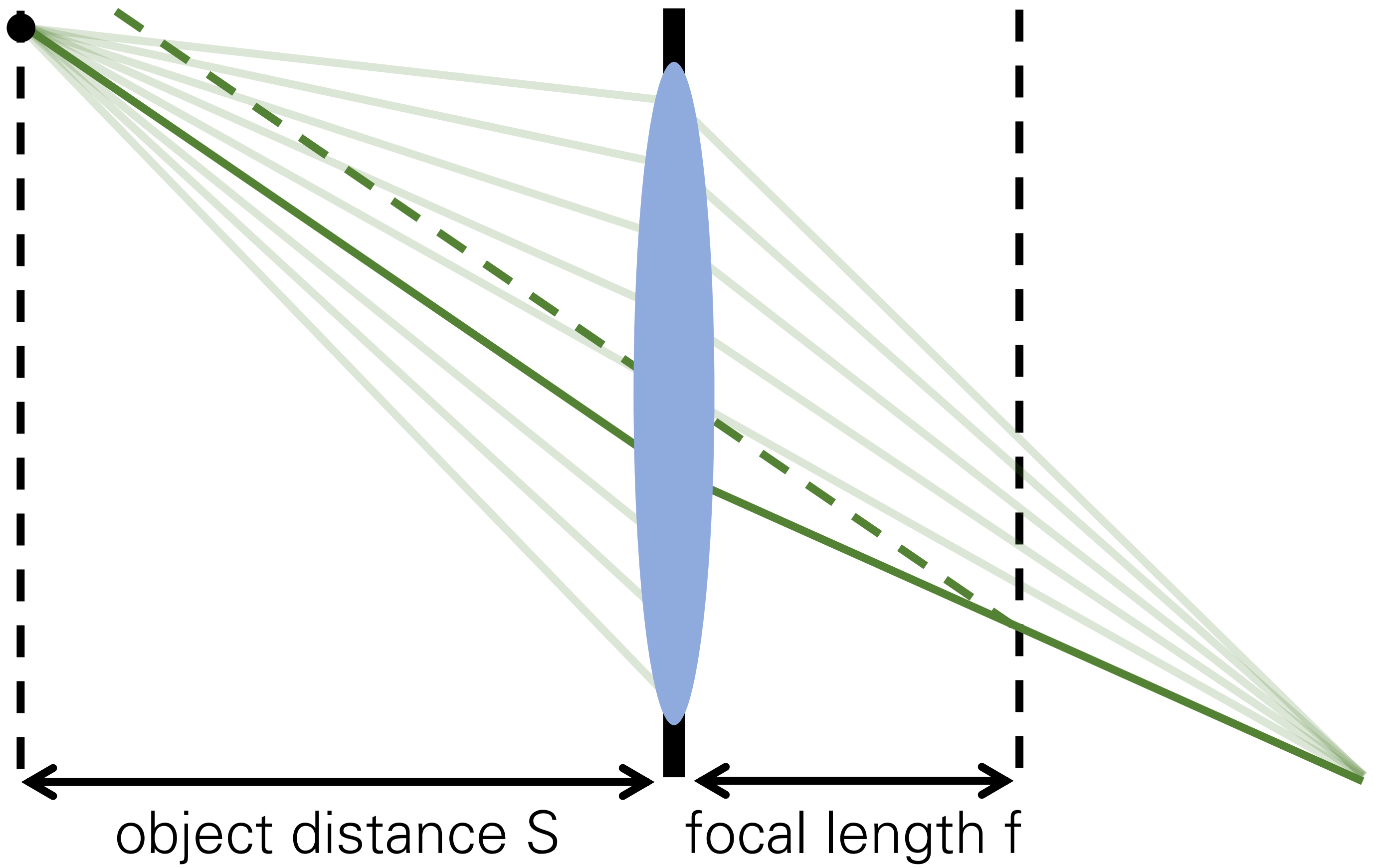

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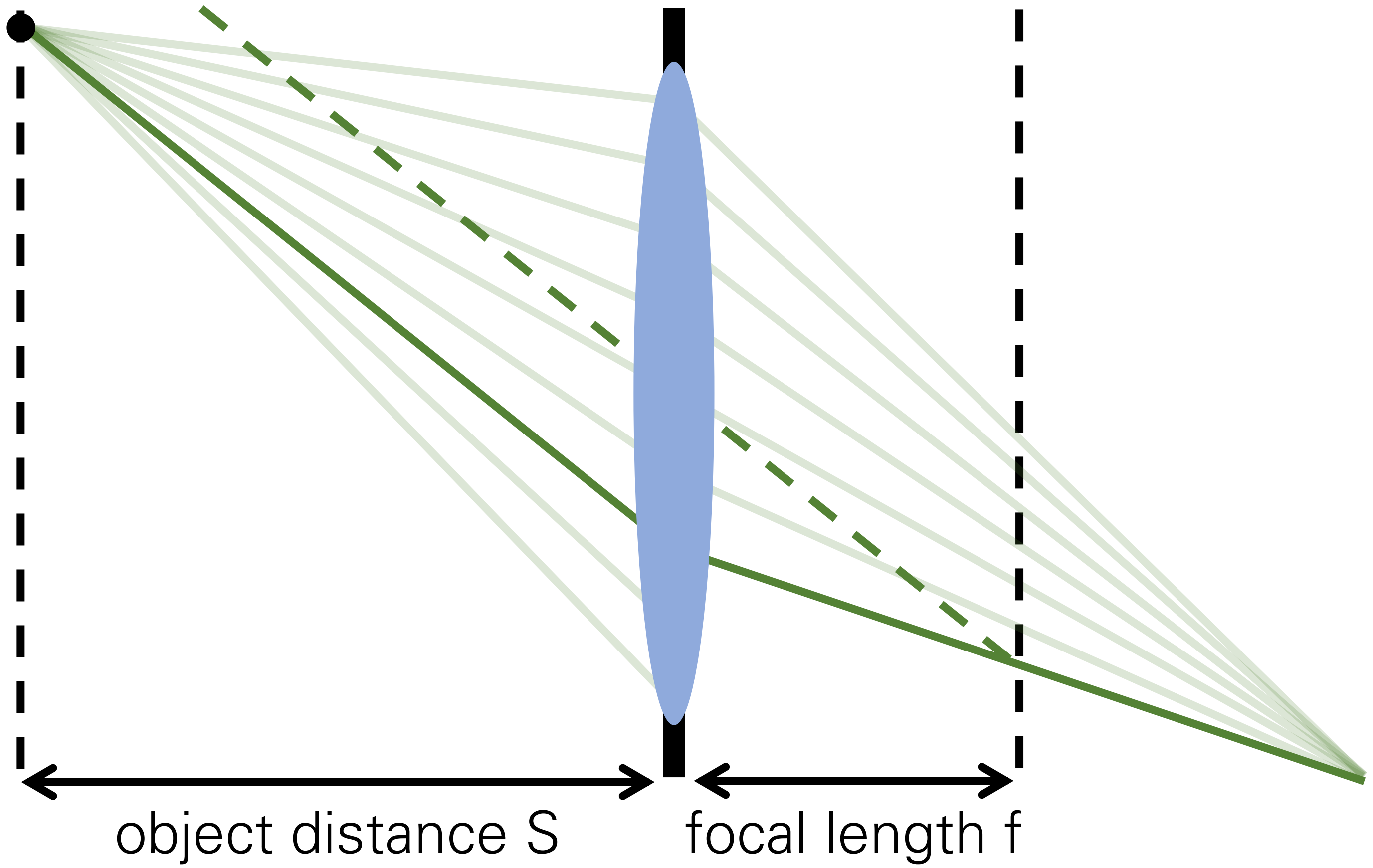

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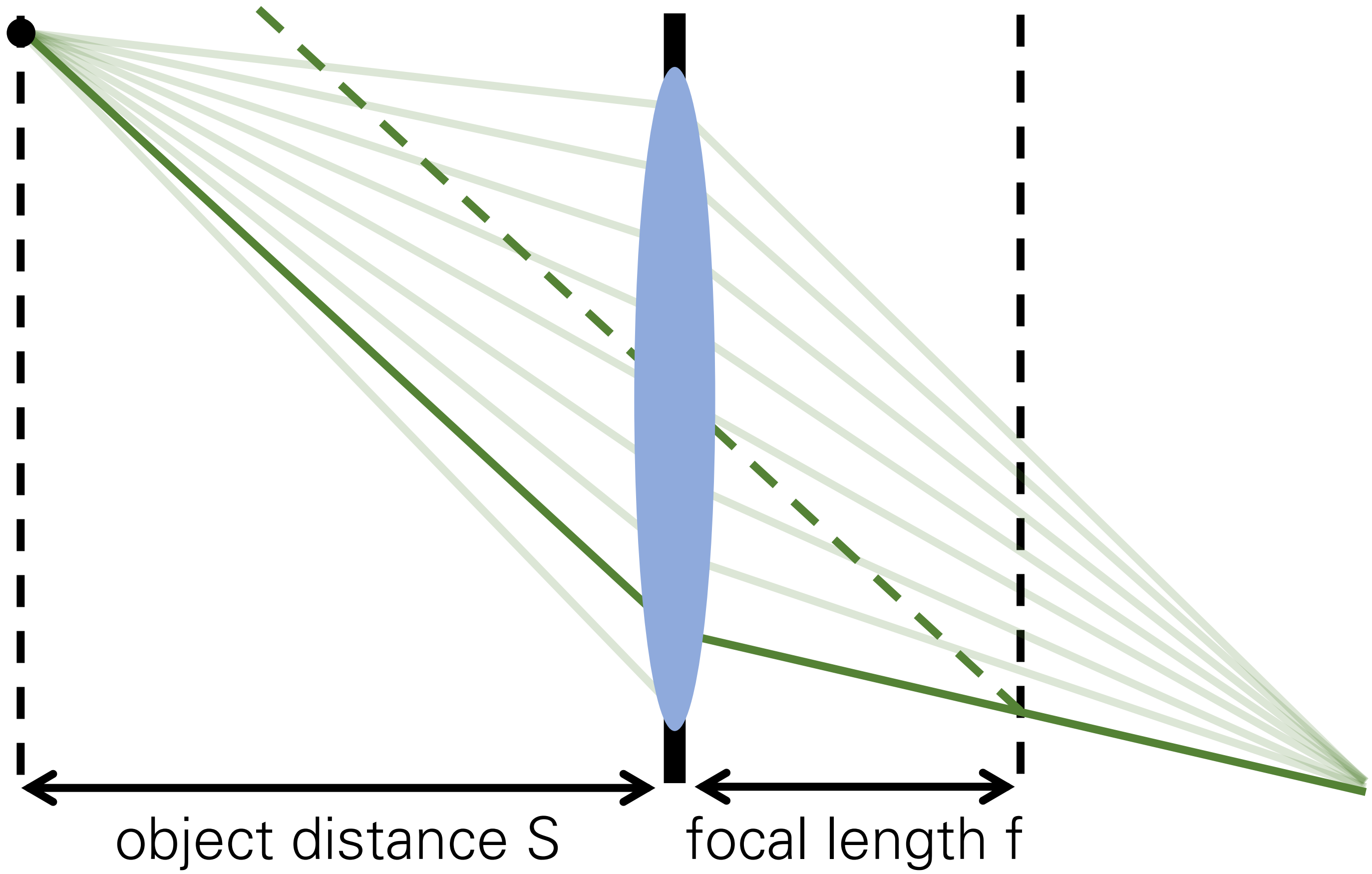

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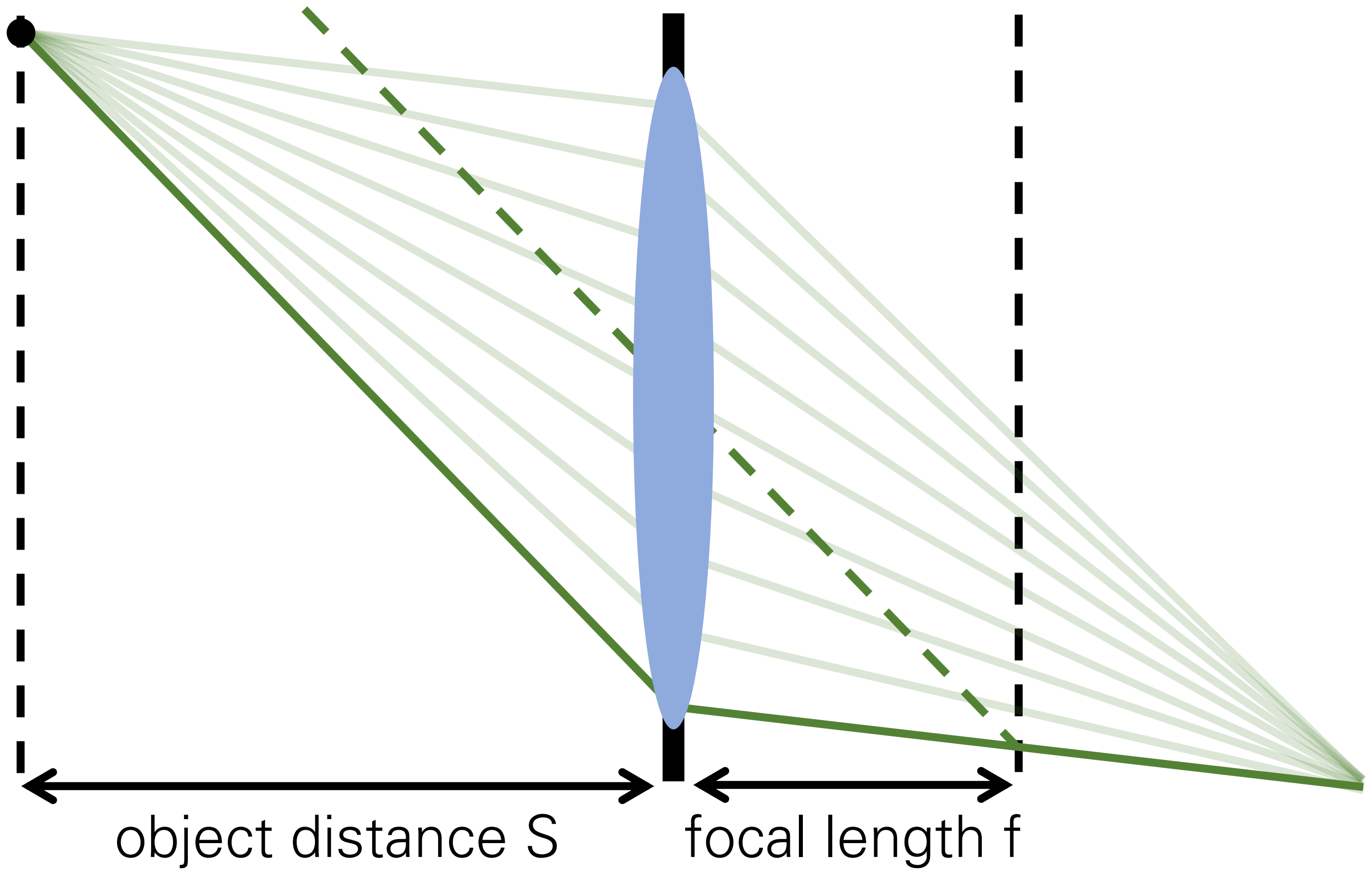

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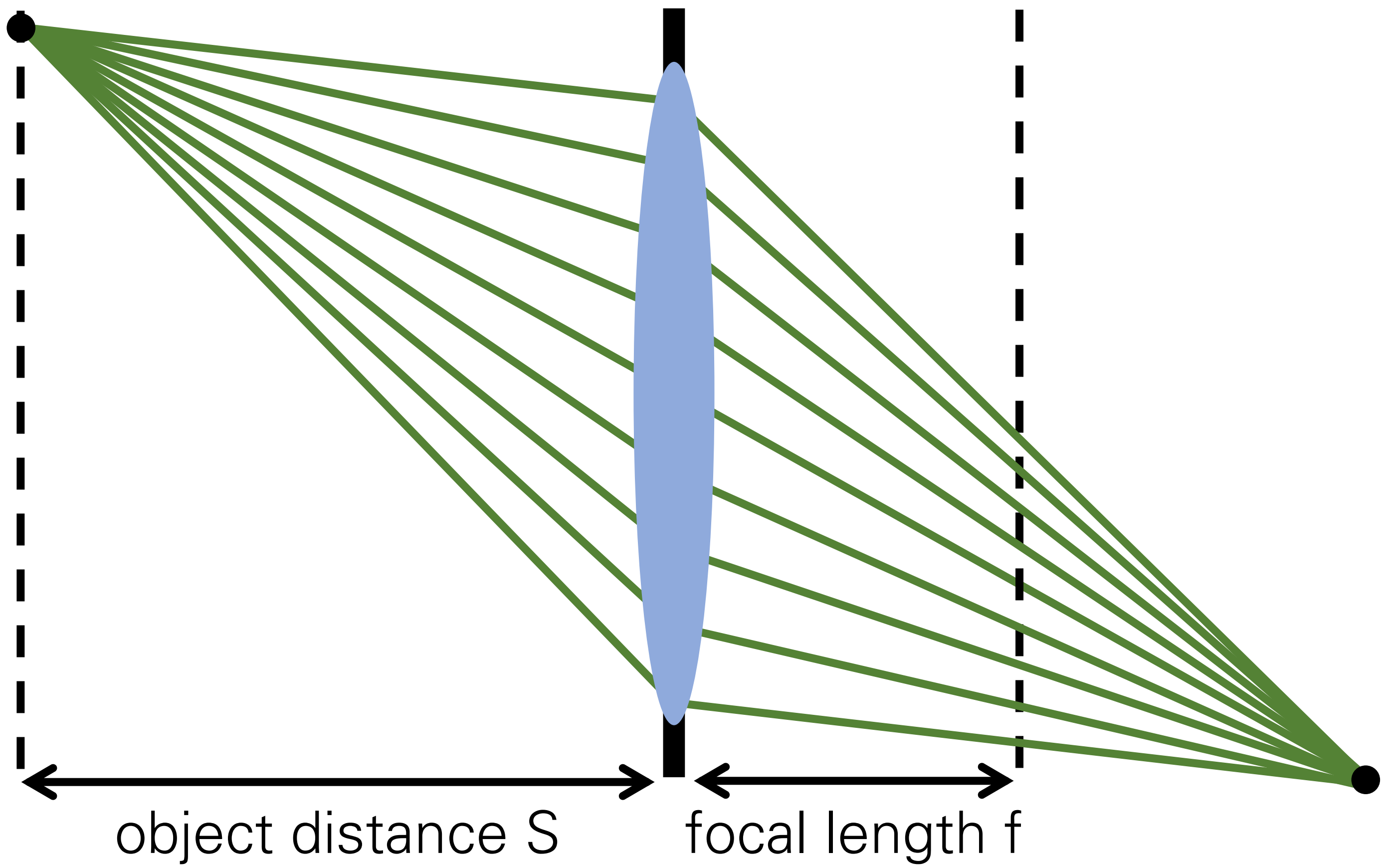

Focusing property:

1. Rays emitted from a point on one side converge to a point on the other side.

Tracing rays through a thin lens

Consider an object emitting a bundle of rays. How do they propagate through the lens?

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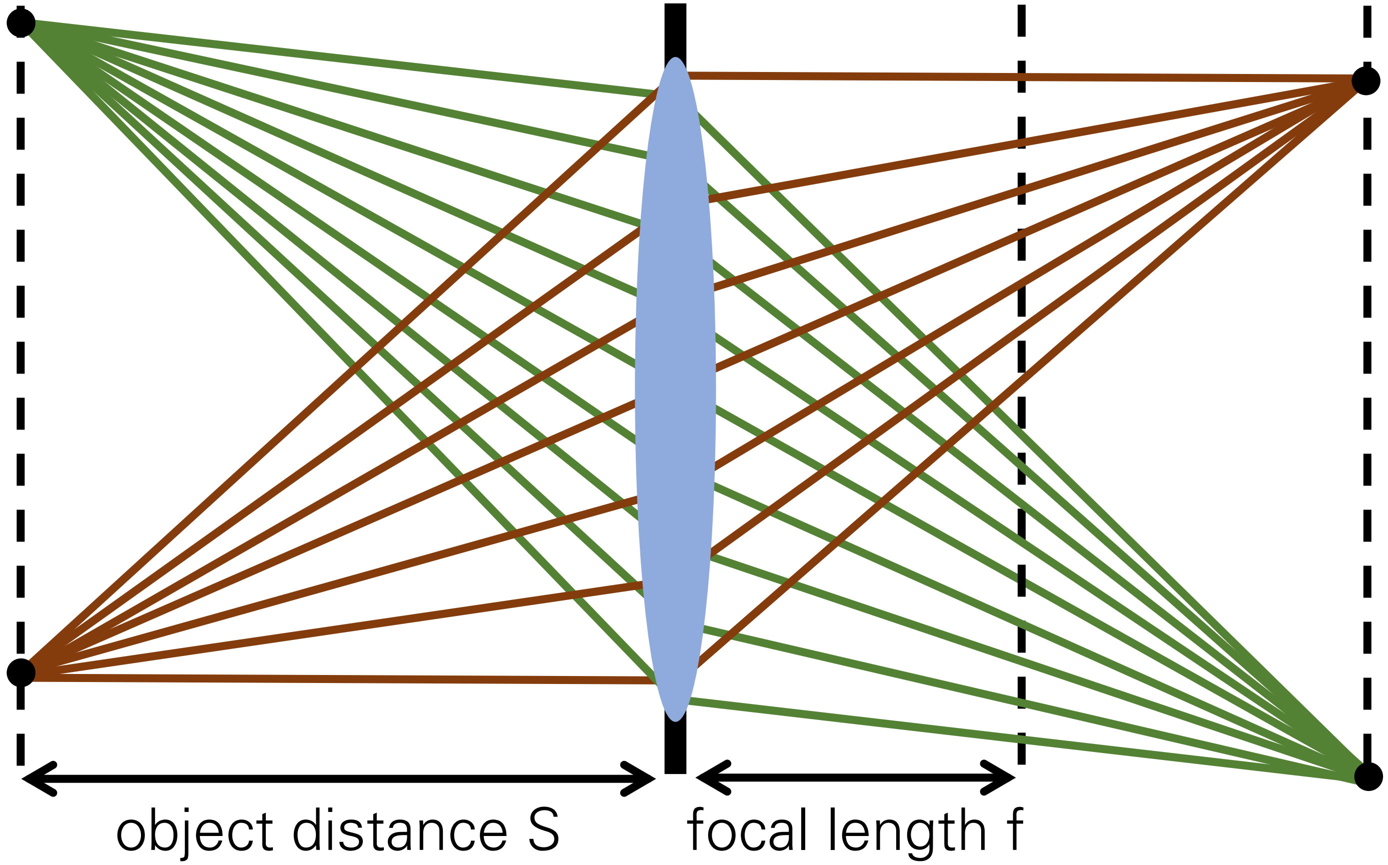
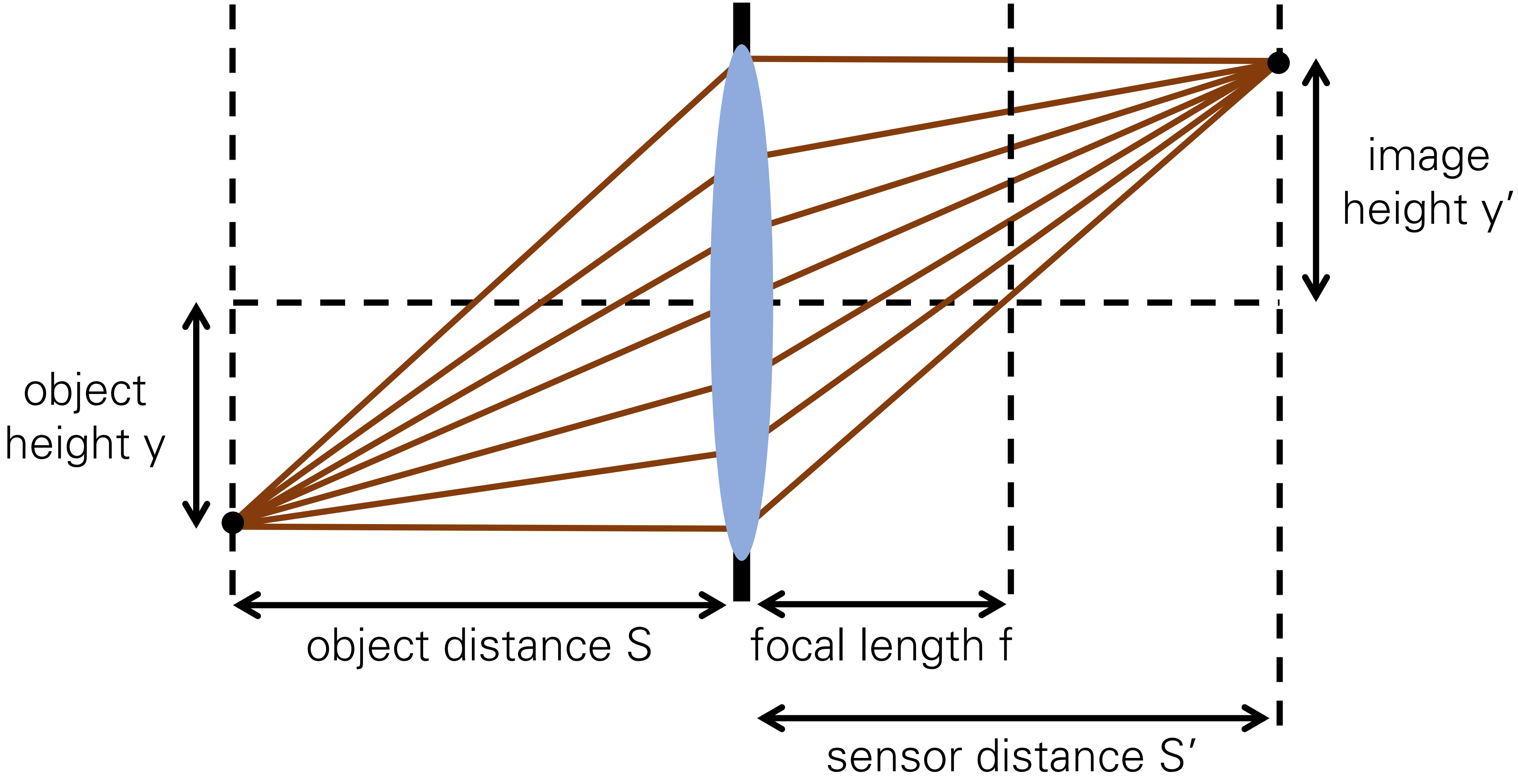


Focusing property:

1. Rays emitted from a point on one side converge to a point on the other side.
2. Bundles emitted from a plane parallel to the lens converge on a common plane.

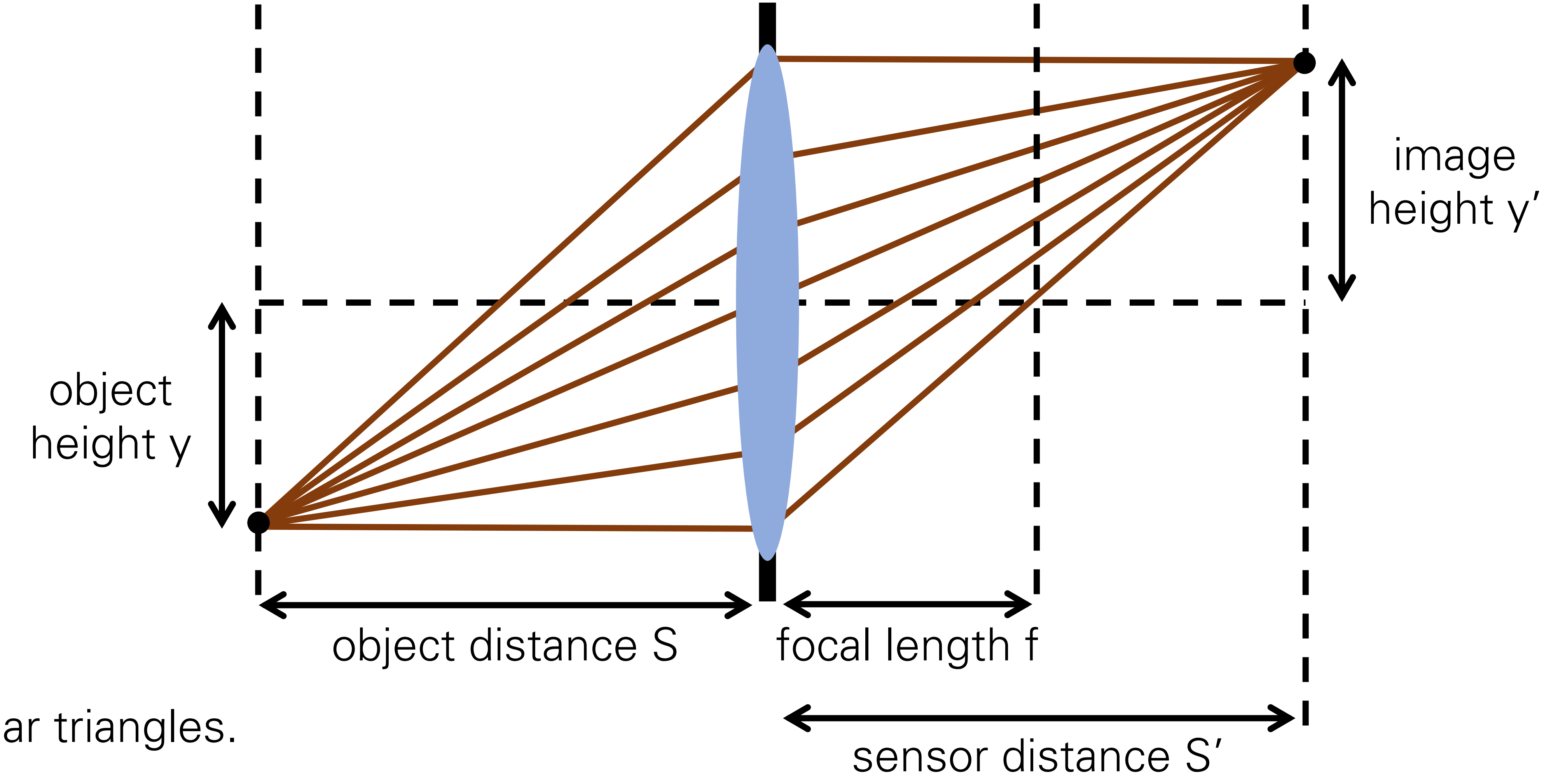
Gaussian lens formula

How can we relate scene-space (S, y) and image space (S', y') quantities?



Gaussian lens formula

How can we relate scene-space (S, y) and image space (S′, y′) quantities?

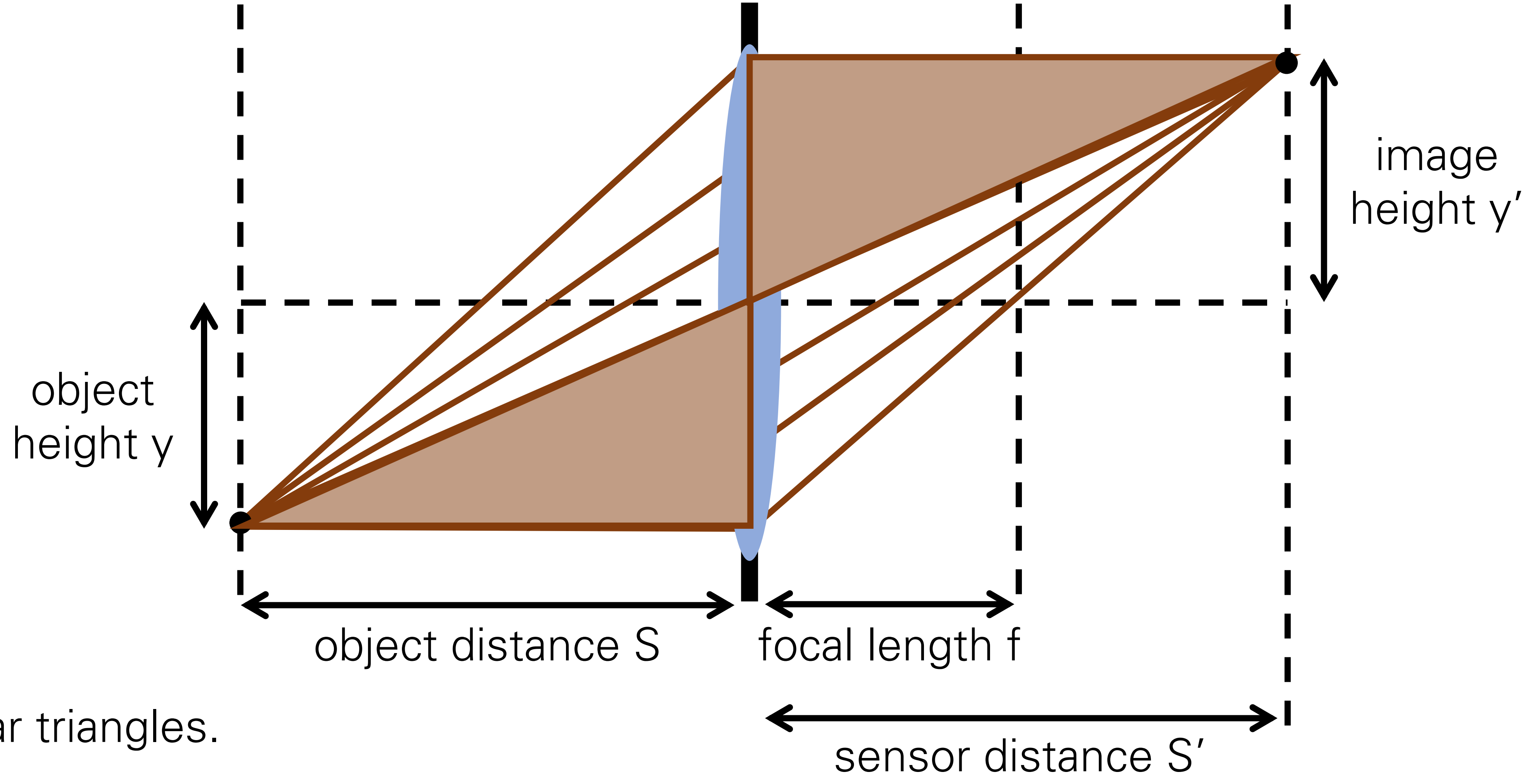


Use similar triangles.

Gaussian lens formula

How can we relate scene-space (S, y) and image space (S′, y′) quantities?

$$\frac{y'}{y} = ?$$

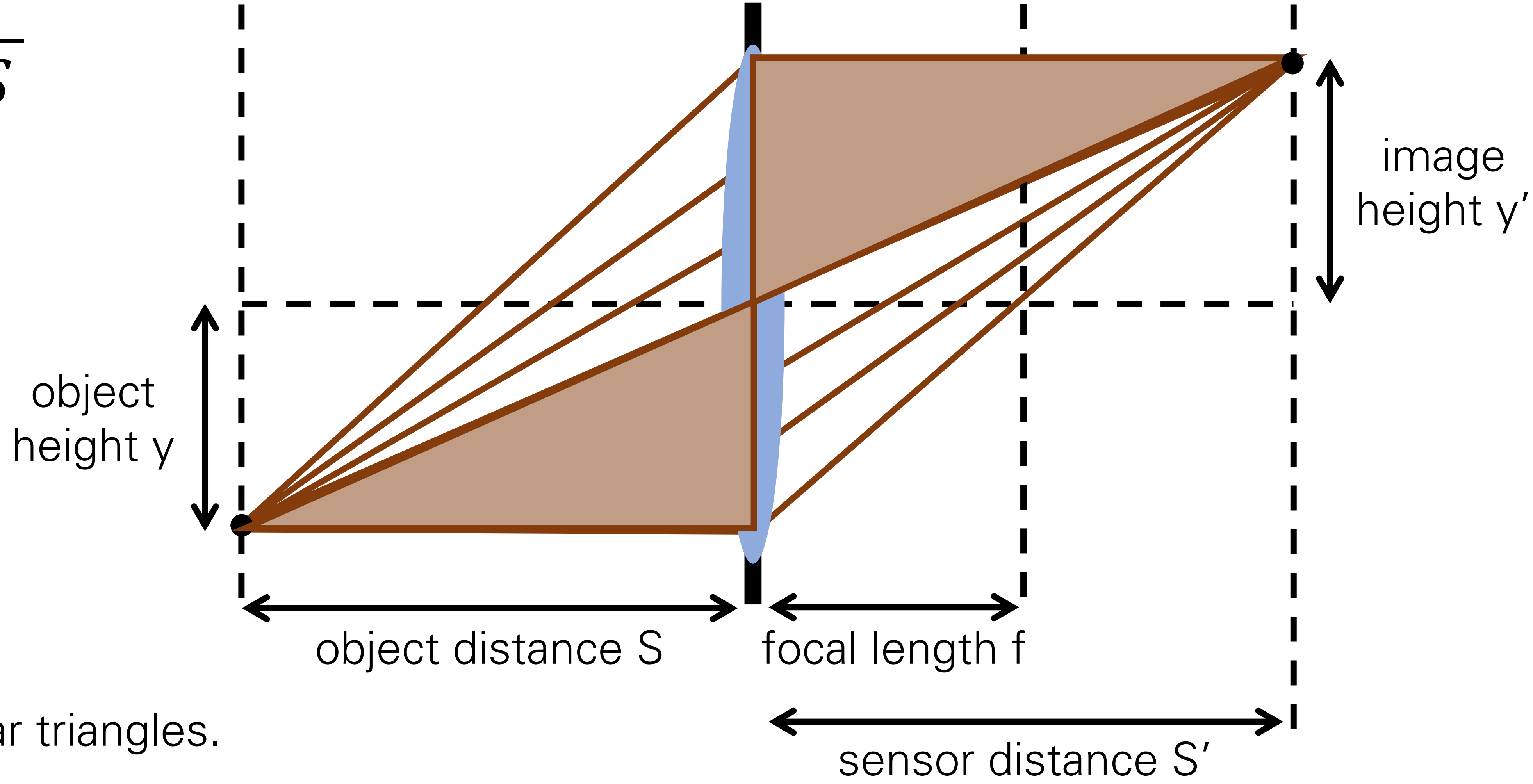


Use similar triangles.

Gaussian lens formula

How can we relate scene-space (S, y) and image space (S′, y′) quantities?

$$\frac{y'}{y} = \frac{S'}{S}$$



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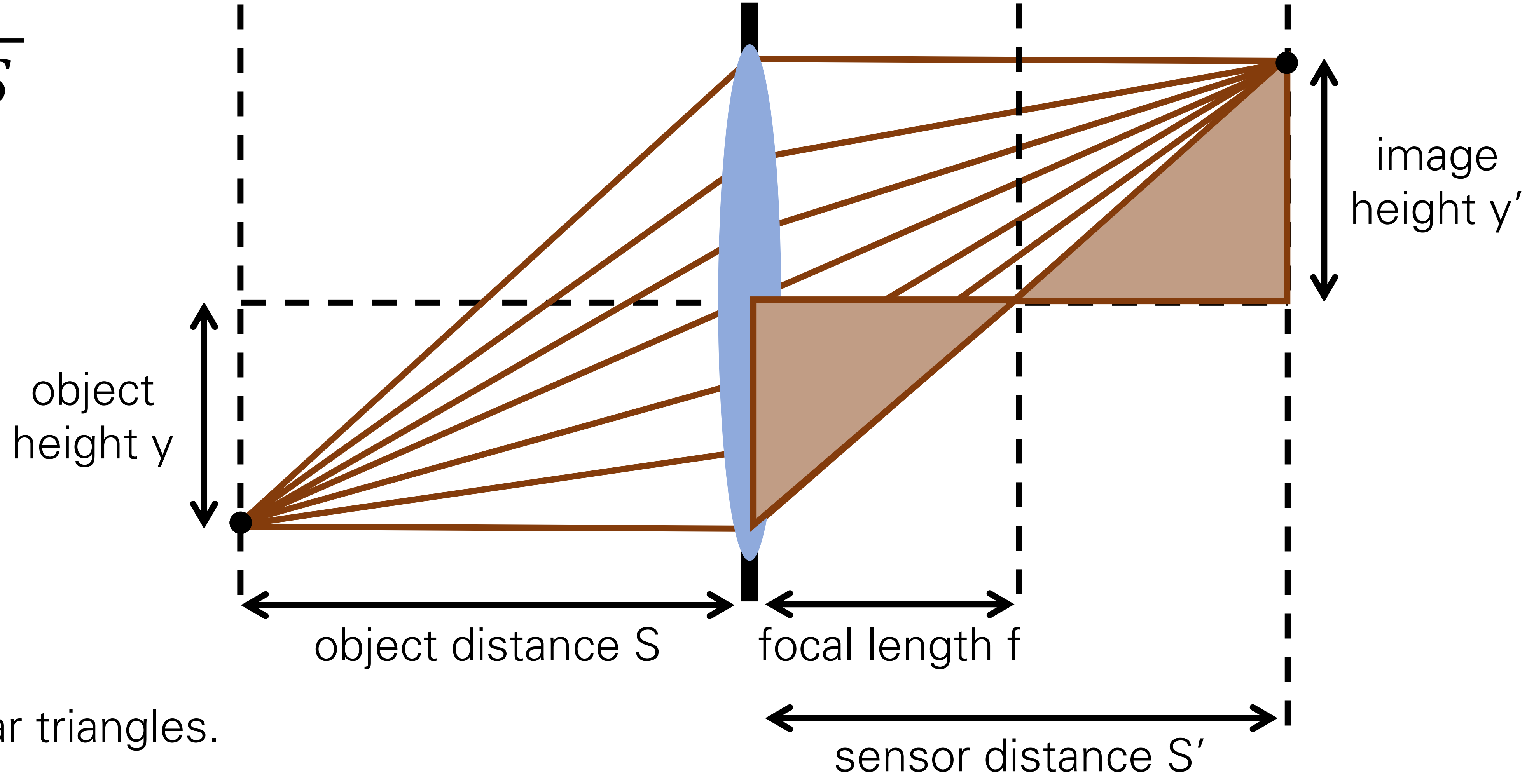


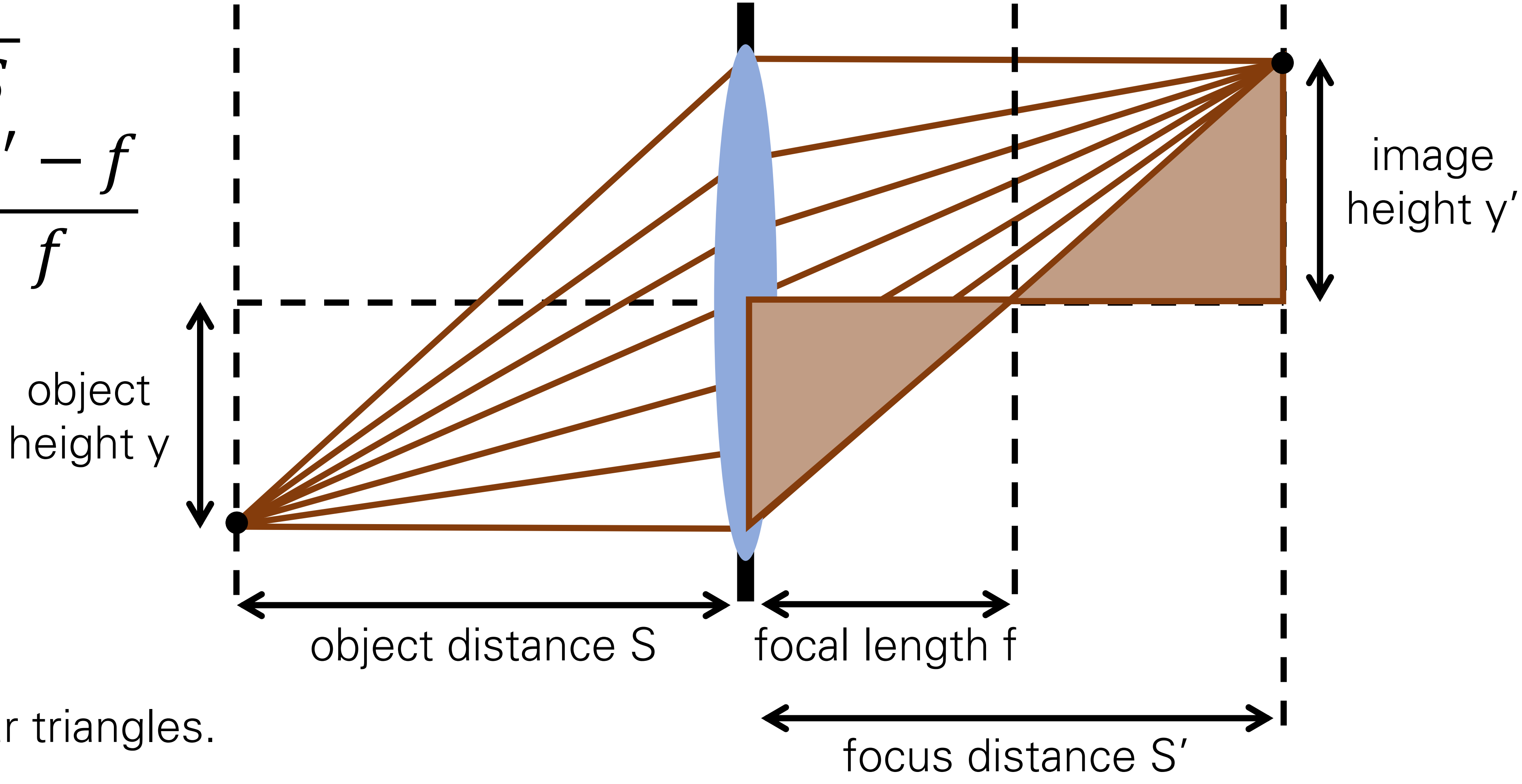
Use similar triangles.

Gaussian lens formula

How can we relate scene-space (S, y) and image space (S′, y′) quantities?

$$\frac{y'}{y} = \frac{S'}{S}$$

$$\frac{y'}{y} = \frac{S' - f}{f}$$



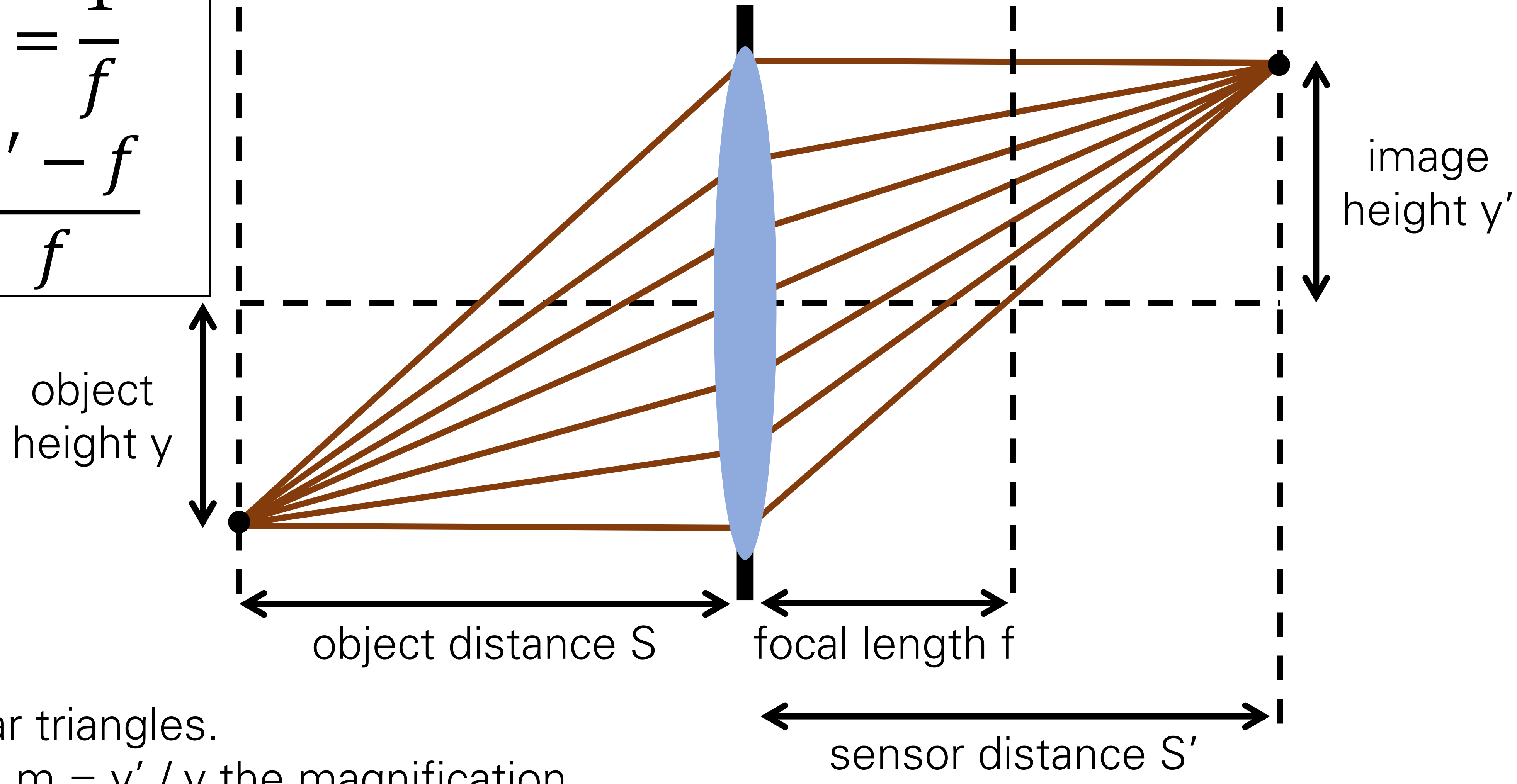
Use similar triangles.

Gaussian lens formula

How can we relate scene-space (S, y) and image space (S', y') quantities?

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

$$m = \frac{S' - f}{f}$$



Use similar triangles.

- We call m = y' / y the magnification.

Special focus distances

S’ = f, S = ?, m = ?

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

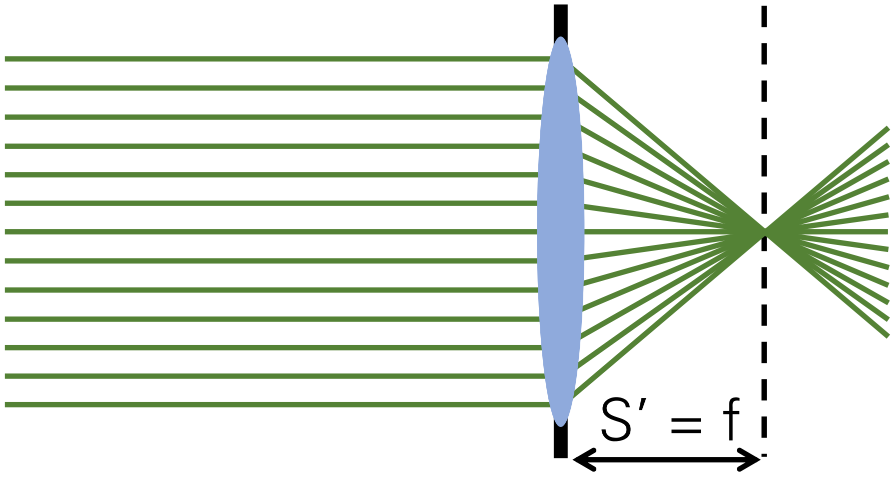
$$m = \frac{S' - f}{f}$$

Special focus distances

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

$$m = \frac{S' - f}{f}$$

$S' = f$, $S = \infty$, $m = 0$ → infinity focus (parallel rays)



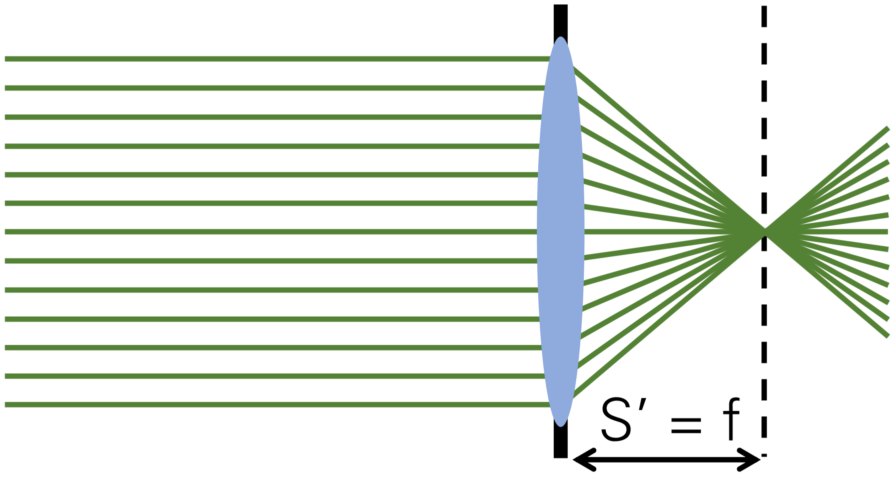
$S' = S = ?$, $m = ?$

Special focus distances

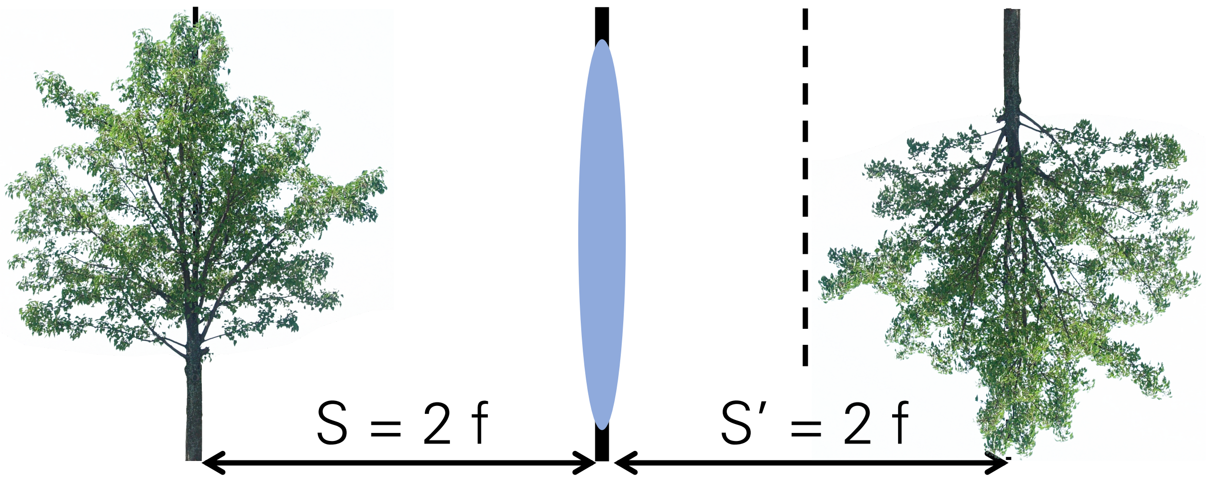
$$\frac{1}{S'} + \frac{1}{S} = \frac{1}{f}$$

$$m = \frac{S' - f}{f}$$

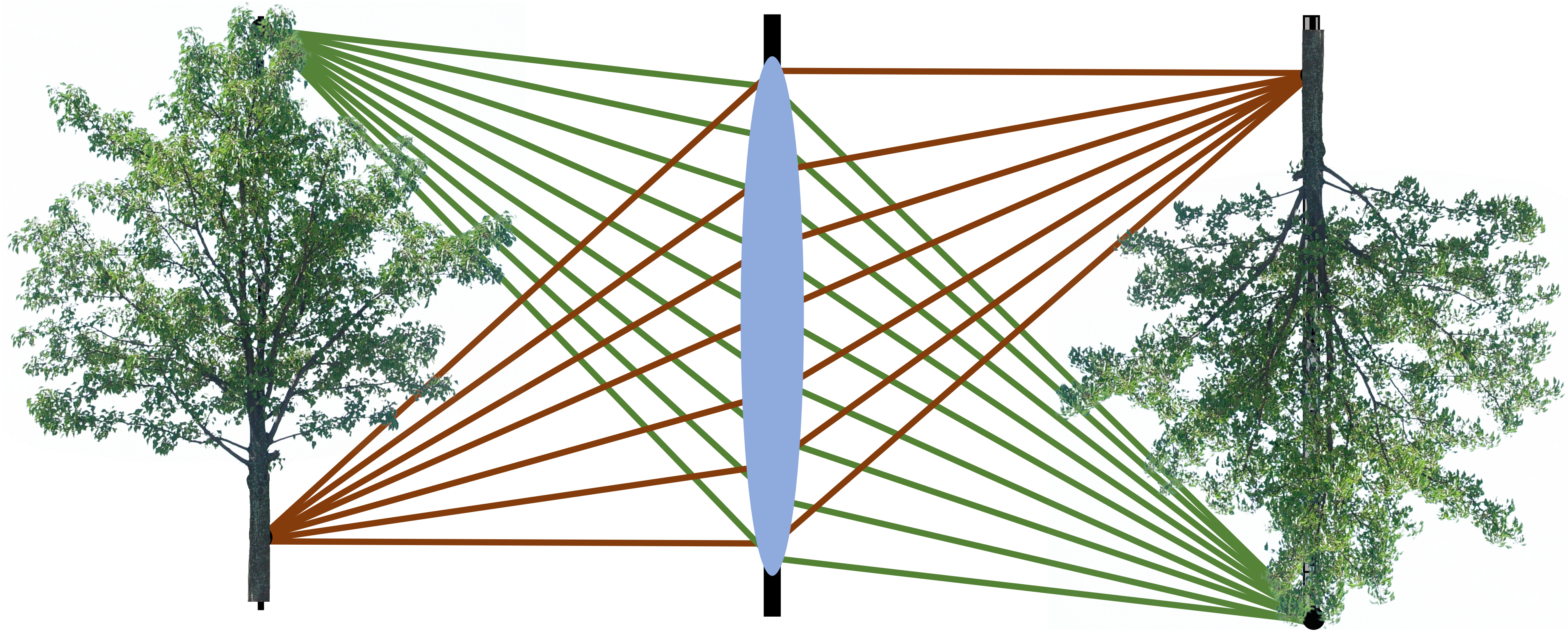
S′ = f, S = ∞, m = 0 → infinity focus (parallel rays)



S′ = S = 2 f, m = 1 → object is reproduced in real-life size



Free lunch?

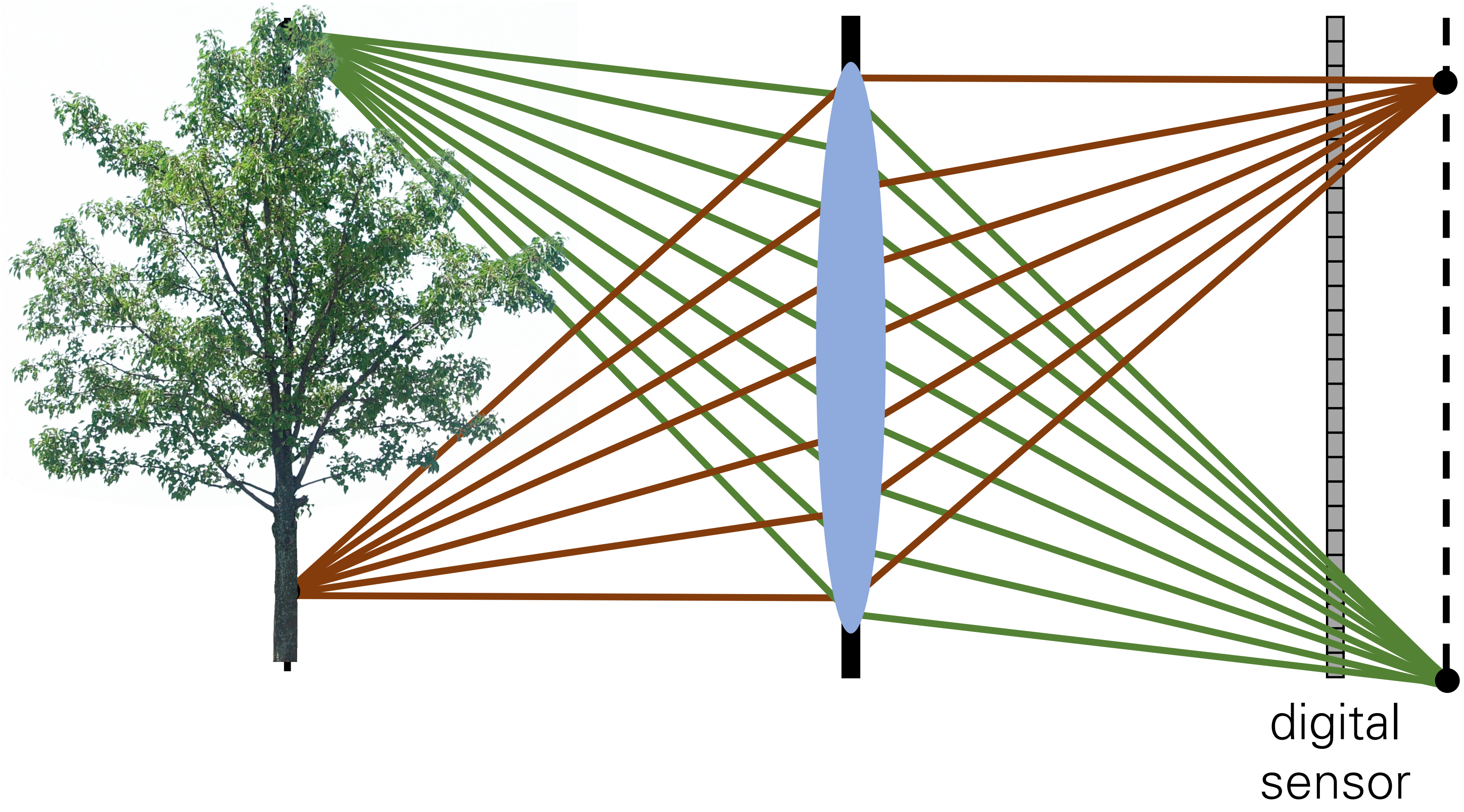


By using a lens, we simultaneously achieve:
1. Image is sharp.
2. Signal-to-noise ratio is high.

Do we lose anything by using a lens?

Defocus

What happens if we don't place the sensor at the focus distance?



Defocus

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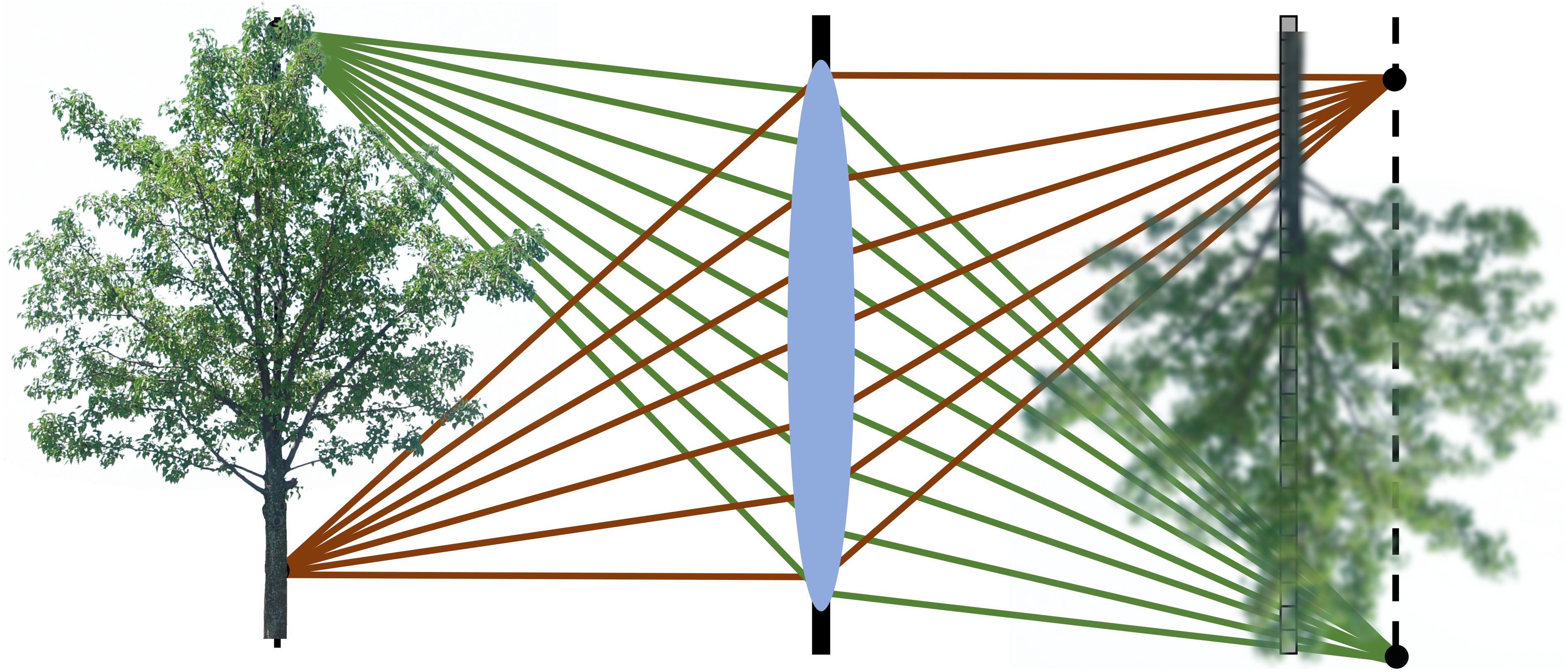


We get a blurry image. This is called defocus.

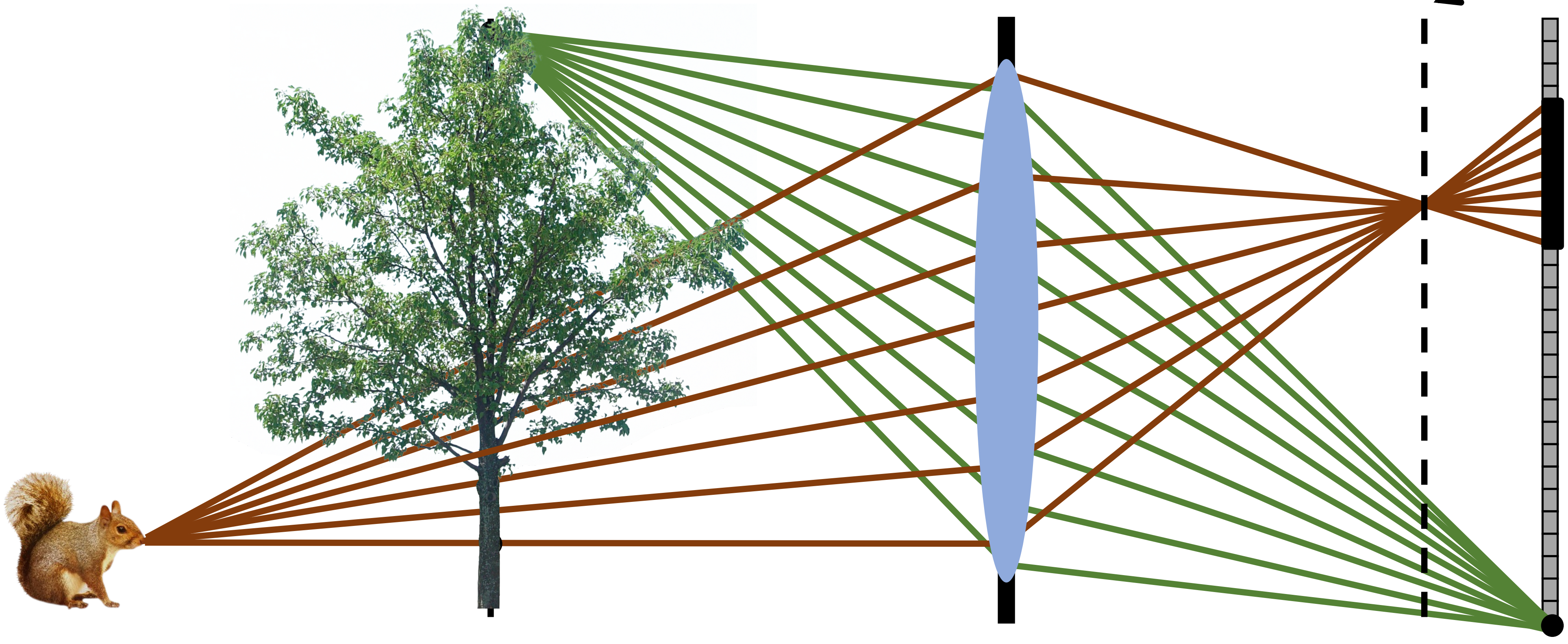
- Defocus never happens with an ideal pinhole camera.

Defocus

Can’t we just move the sensor to the correct distance?

Defocus

Can't we just move the sensor to the correct distance?



Unless our scene is just one plane, part of it will always be out of focus.

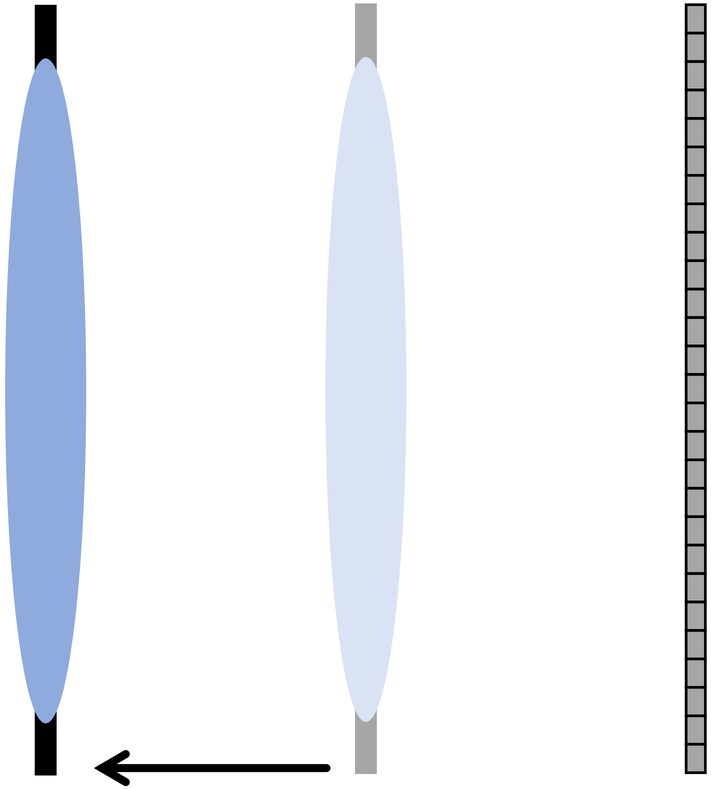
How do we control what is in focus?

How do we control what is in focus?

We change the distance between the sensor and the lens

How do we control what is in focus?

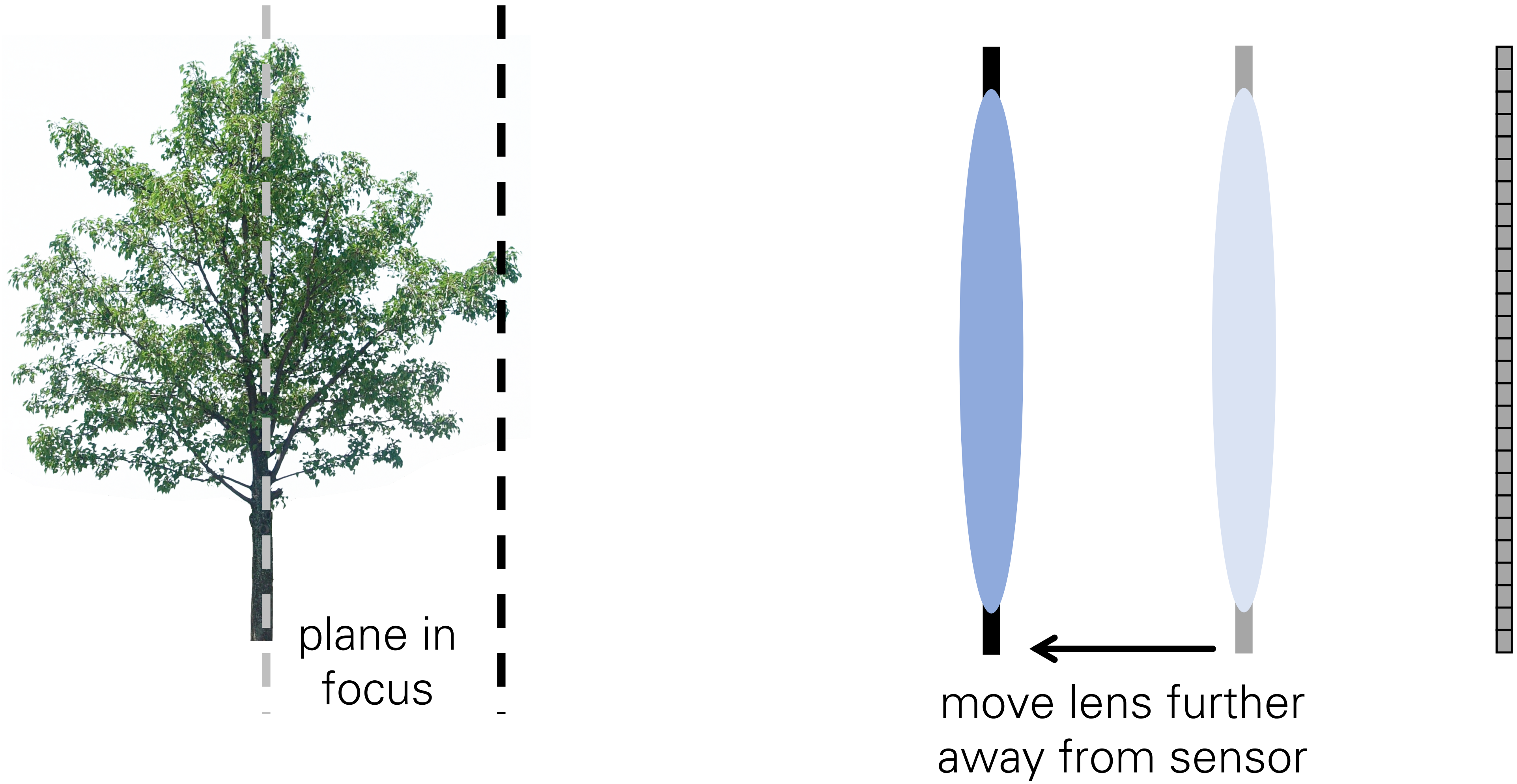
We change the distance between the sensor and the lens



- What happens to plane in focus?

How do we control what is in focus?

We change the distance between the sensor and the lens



- What happens to plane in focus? → It moves closer.

The lens on your camera

Focus ring: controls distance of lens from sensor

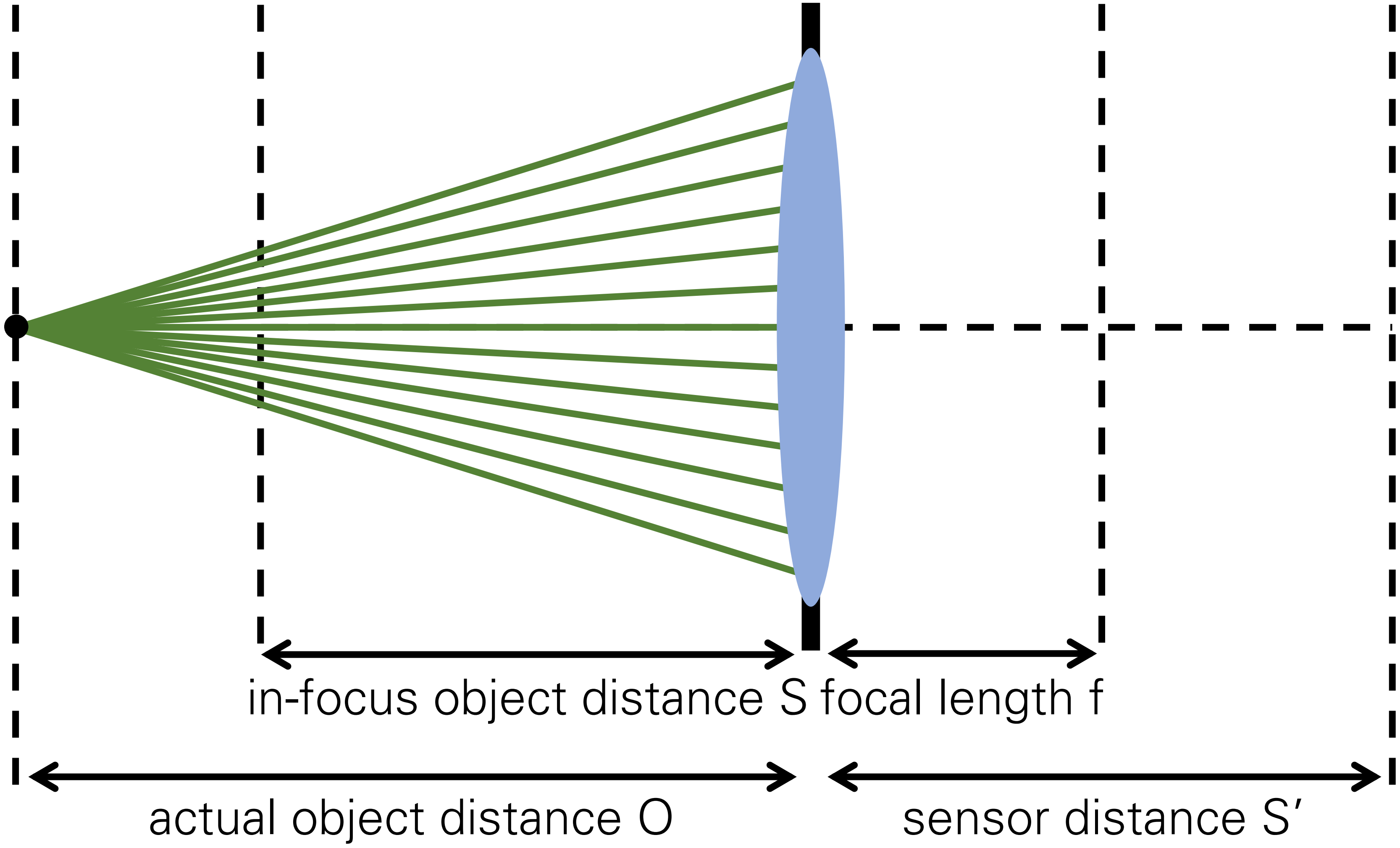
Demonstration

Defocus

Does the mean that lenses are only good for planar scenes?

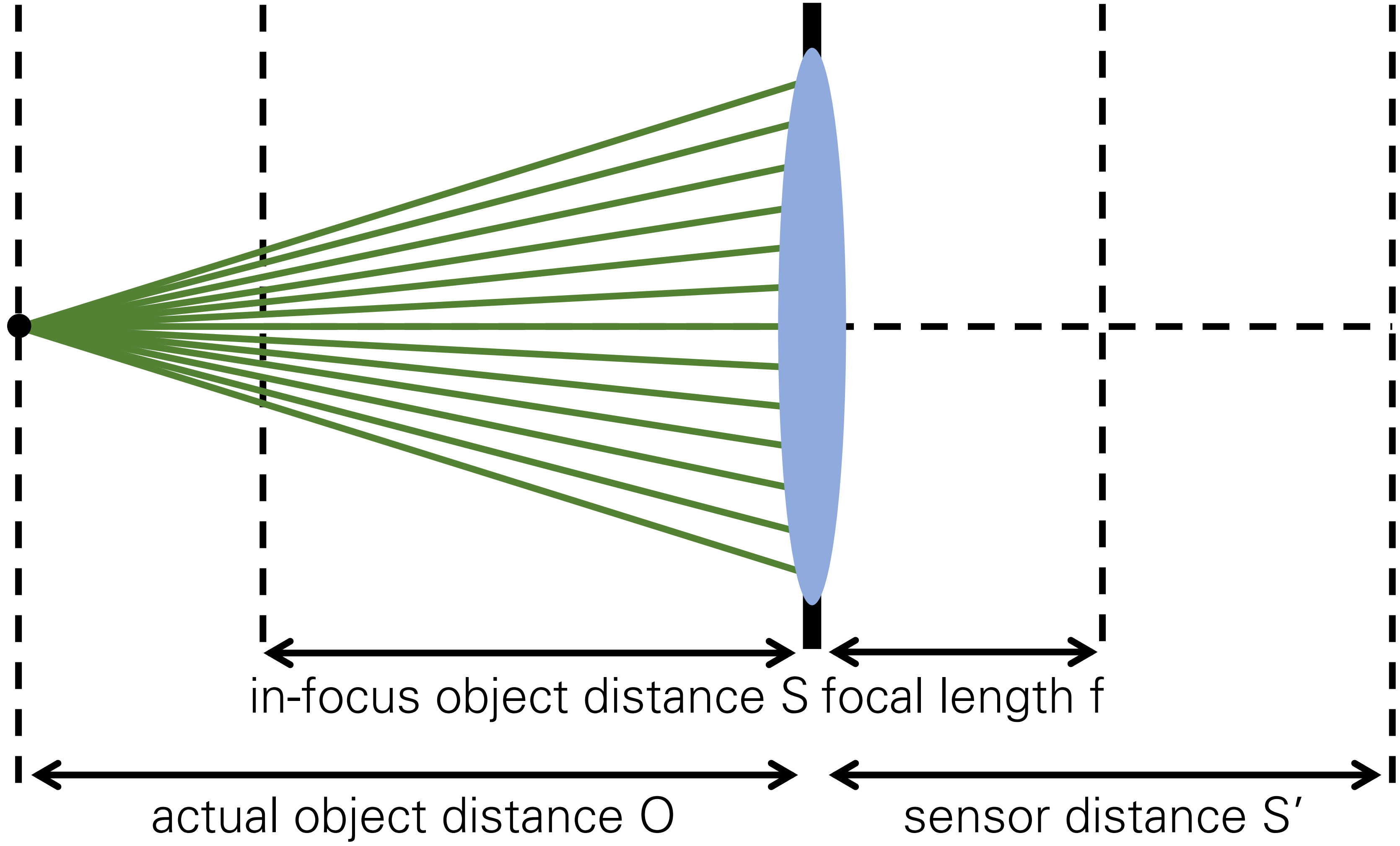
Circle of confusion

How do we find where the point will focus?



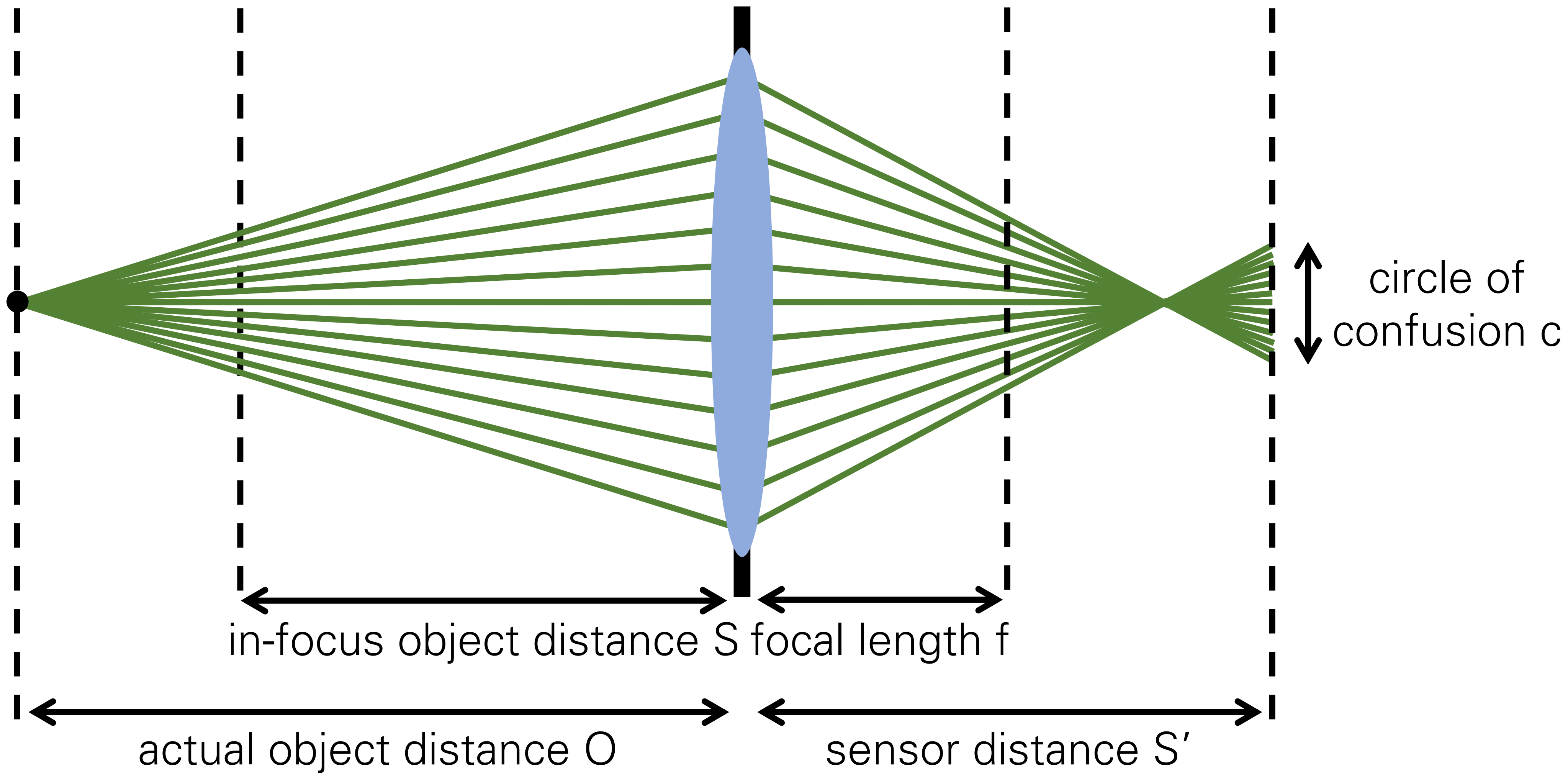
Circle of confusion

Will the point focus at a distance smaller or larger than S′?



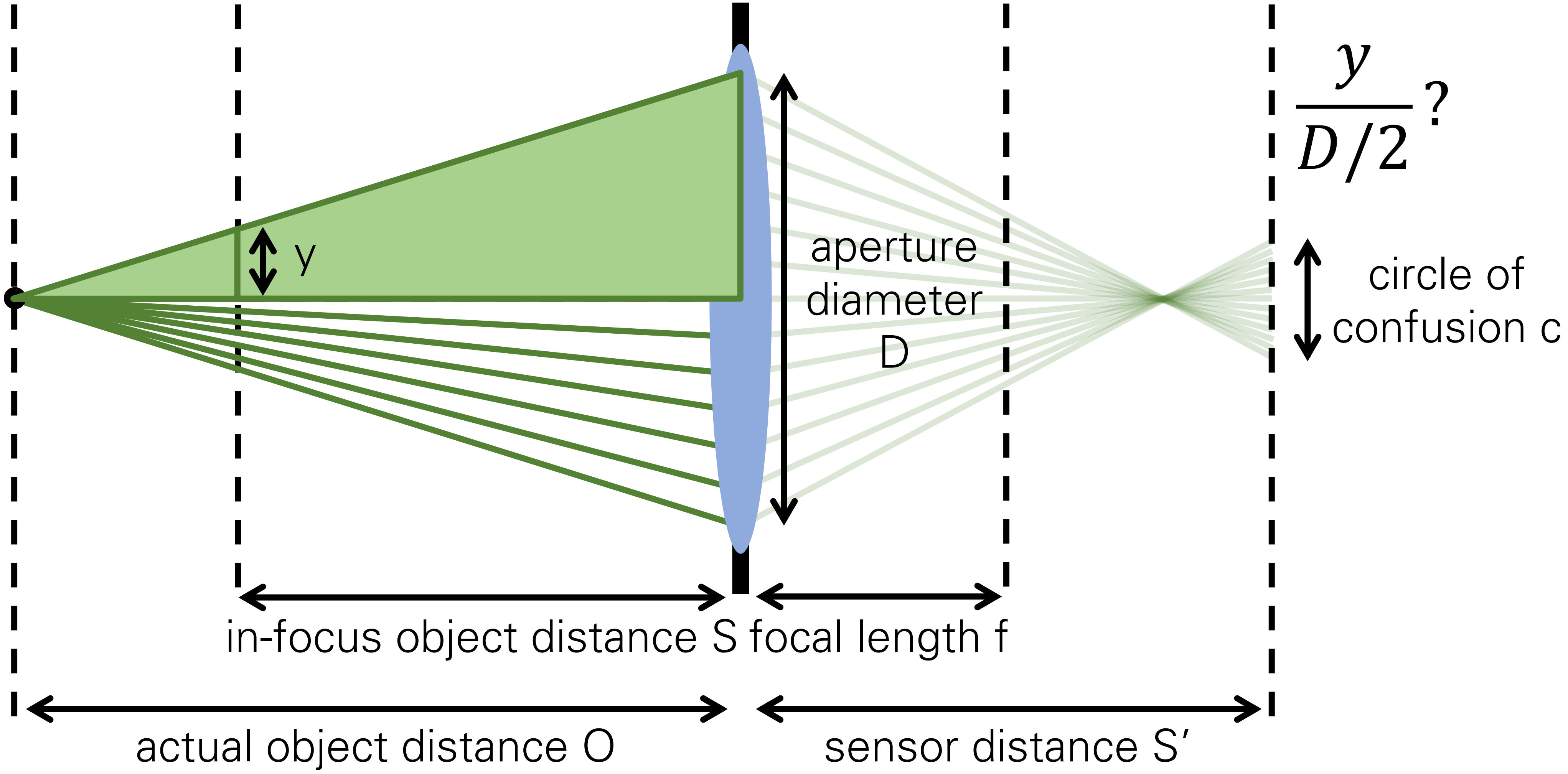
Circle of confusion

How can we compute the diameter of the circle of confusion?



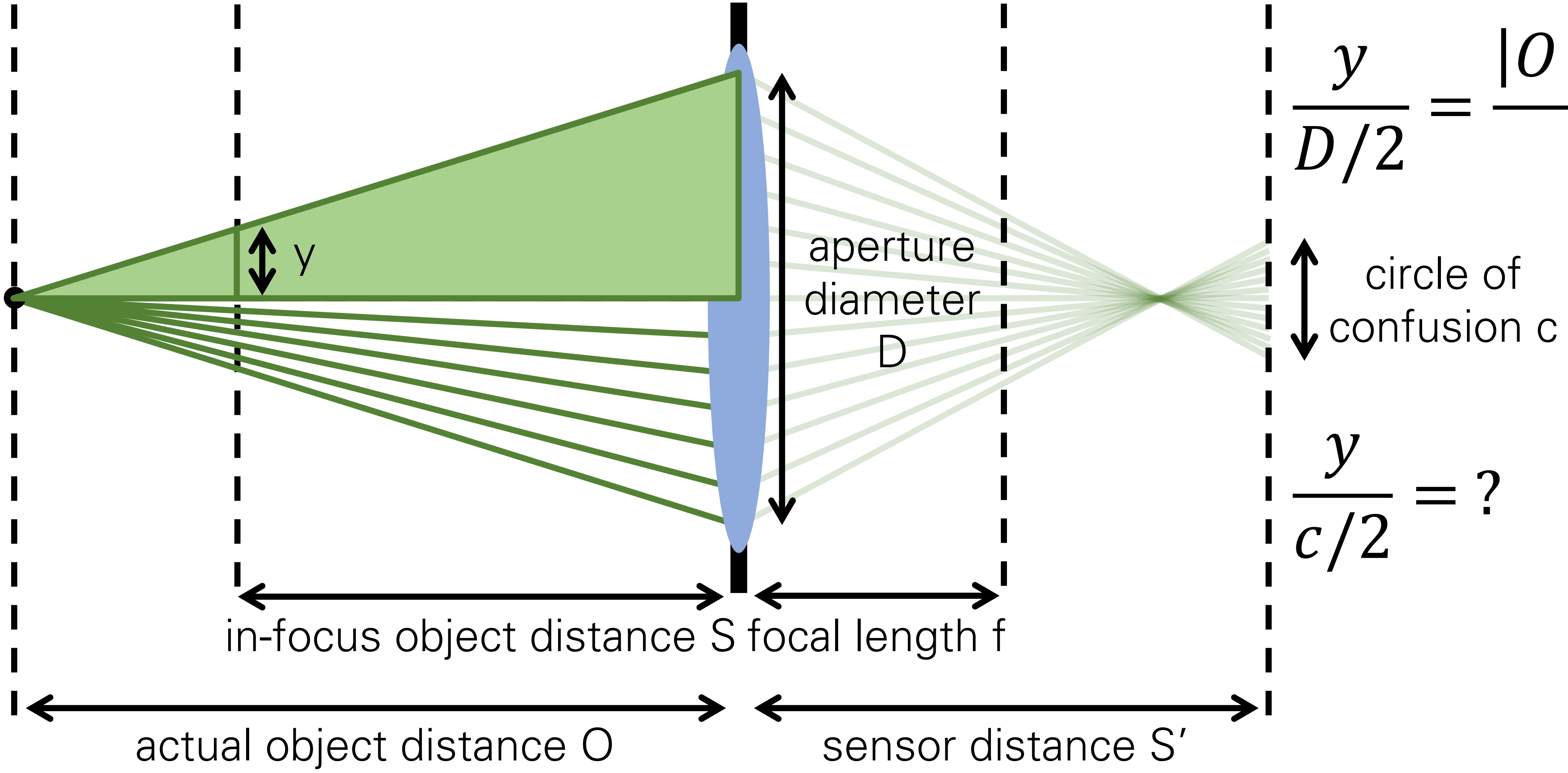
Circle of confusion

How can we compute the diameter of the circle of confusion? → Use similar triangles.



Circle of confusion

How can we compute the diameter of the circle of confusion? → Use similar triangles.

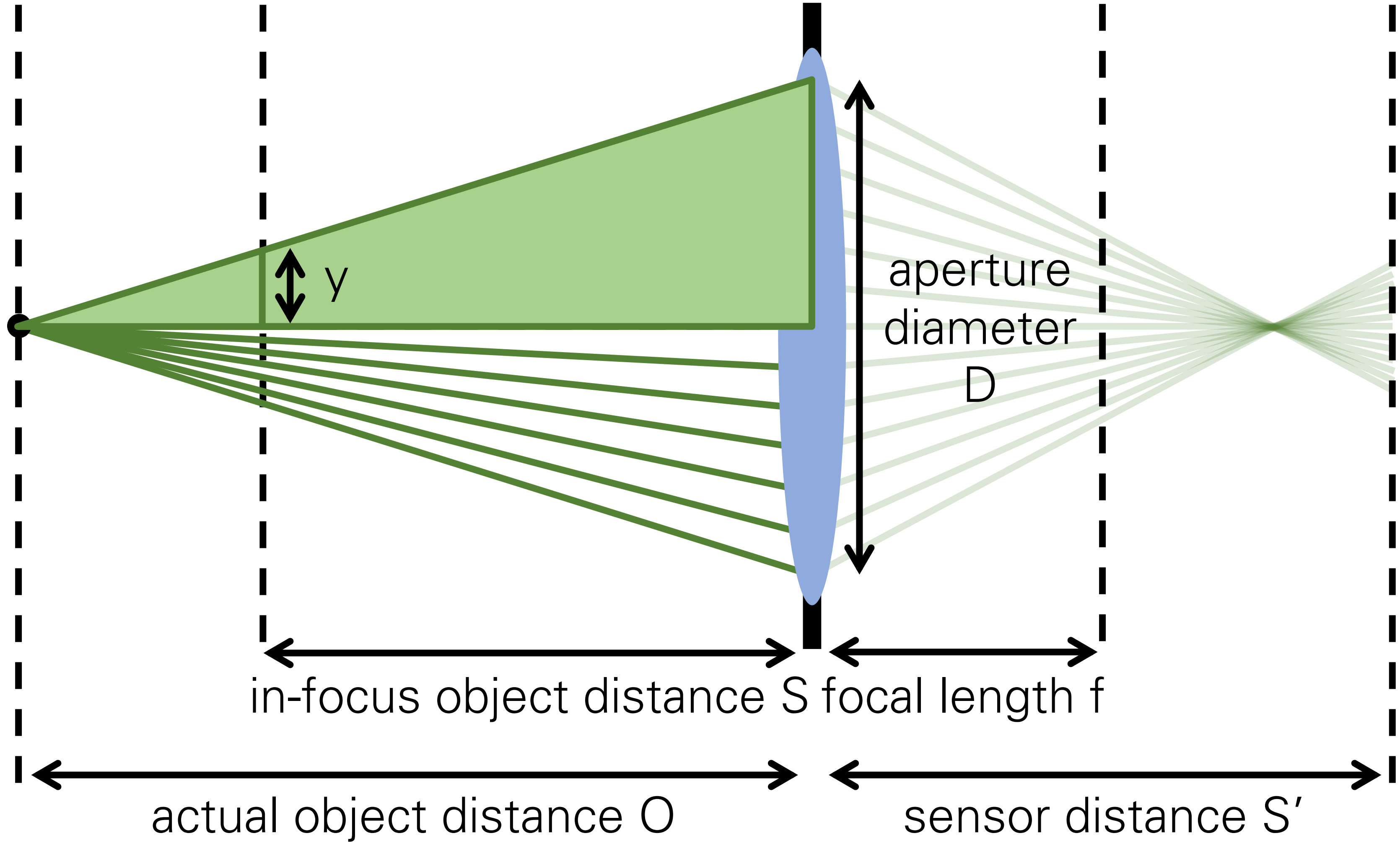


$$\frac{y}{D/2} = \frac{|O - S|}{O}$$

$$\frac{y}{c/2} = ?$$

Circle of confusion

How can we compute the diameter of the circle of confusion? → Use similar triangles.

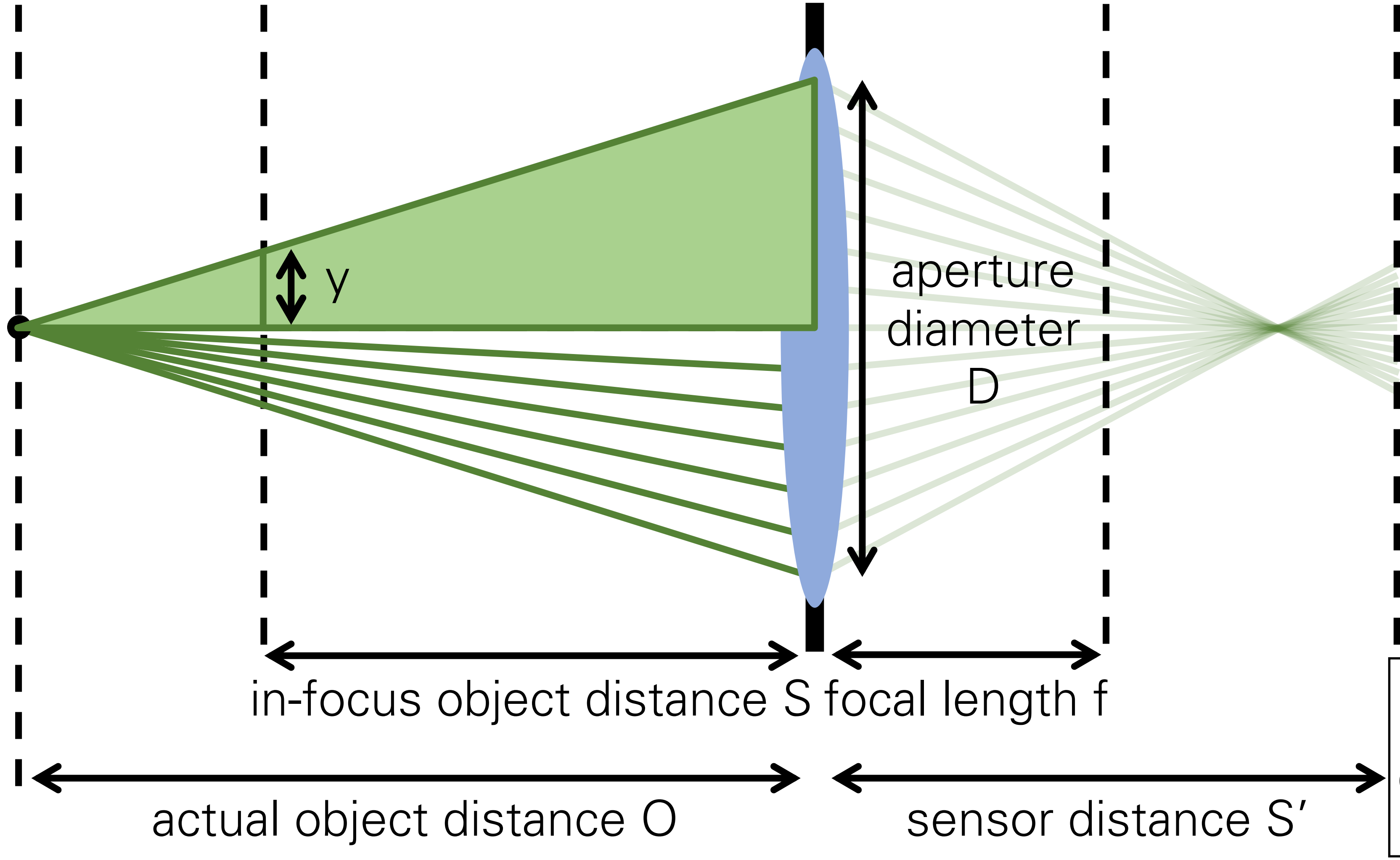


$$\frac{y}{D/2} = \frac{|O - S|}{O}$$

$$\frac{y}{c/2} = \frac{1}{m}$$

Circle of confusion

How can we compute the diameter of the circle of confusion? → Use similar triangles.



$$\frac{y}{D/2} = \frac{|O - S|}{O}$$

$$\frac{y}{c/2} = \frac{1}{m}$$

$$c = mD\frac{|O - S|}{O}$$

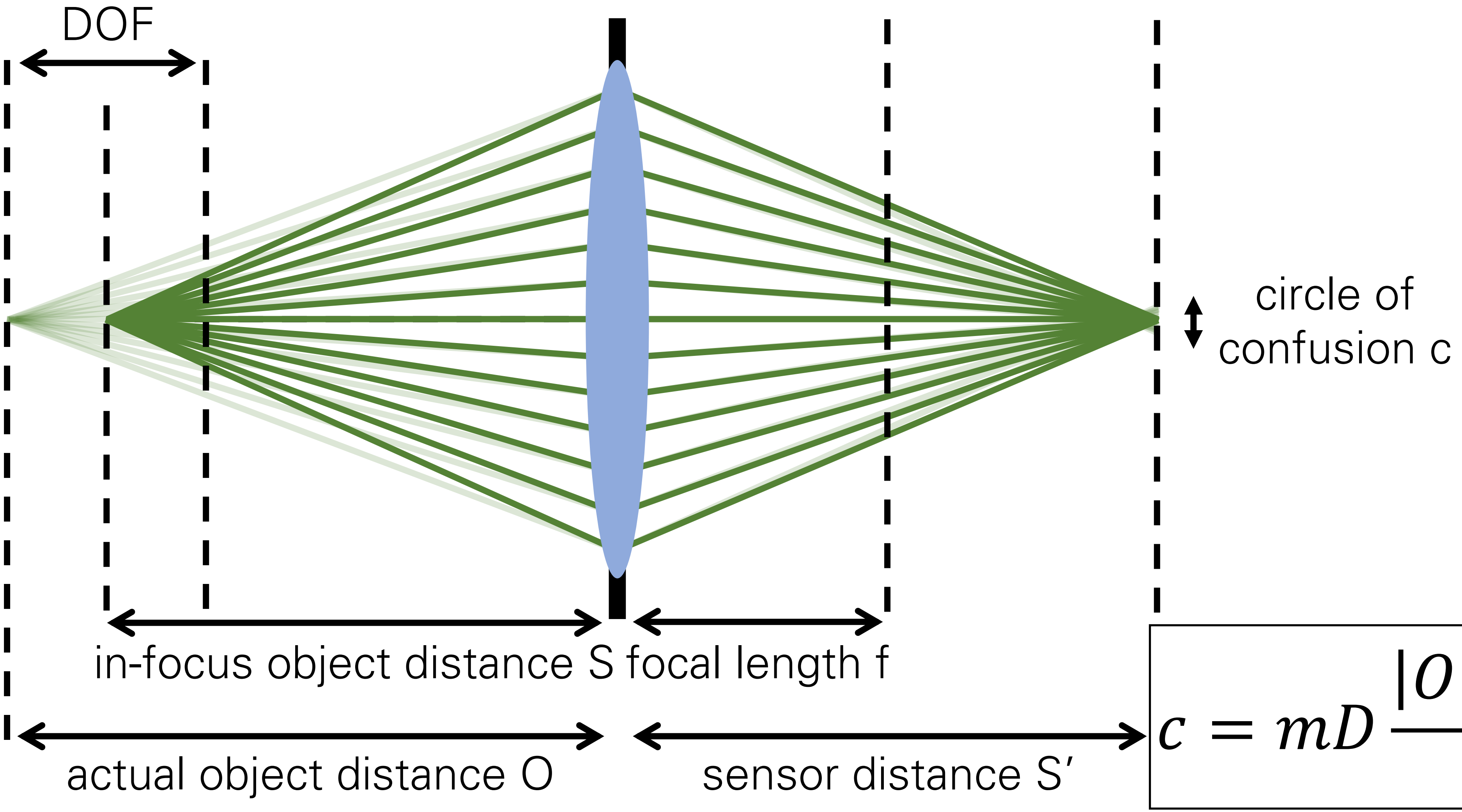
Depth of field

Distance from the in-focus object plane where the circle of confusion is acceptably small.

e.g., equal to 4-5 pixels

$$c < \varepsilon \Rightarrow$$

$$\text{DOF} = \frac{2\varepsilon O}{mD}$$

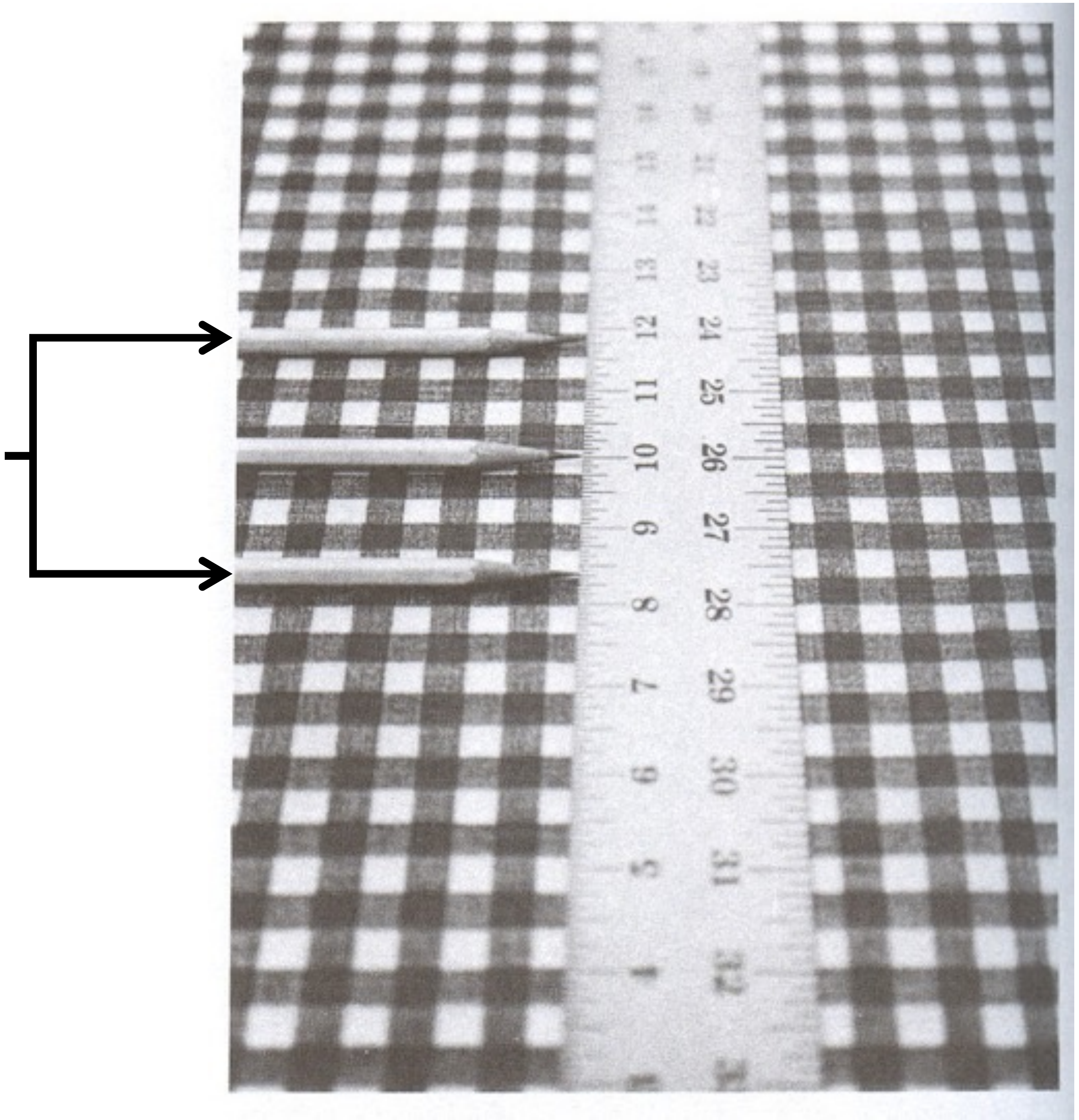


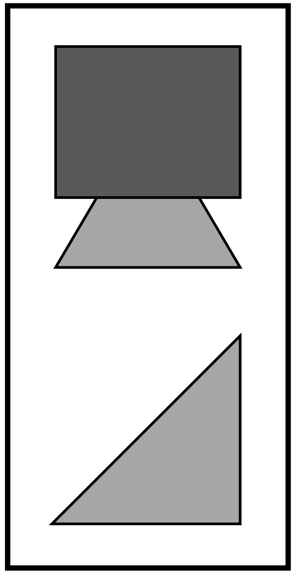
$$c = mD\,\frac{|O - S|}{O}$$

Note: in reality, DOF is slightly asymmetrical.

Depth of field

depth of field



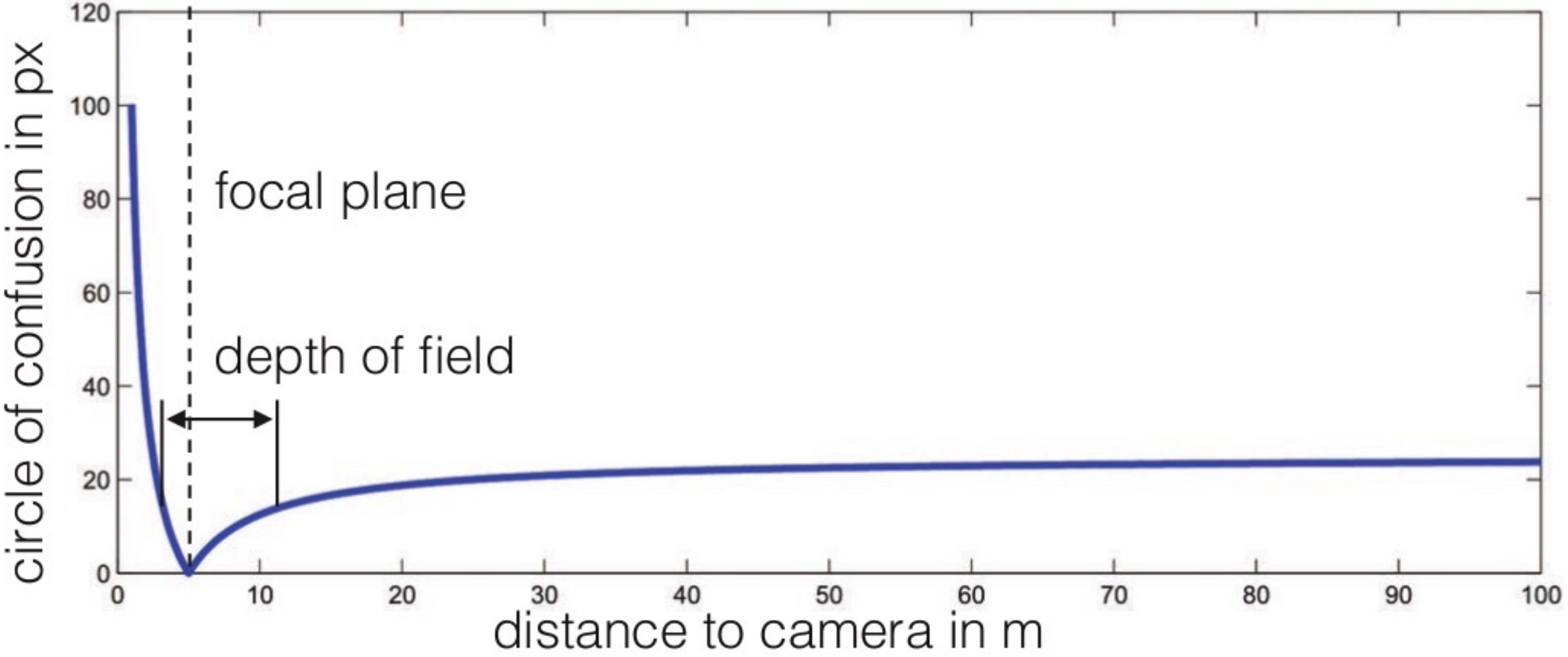


scene

Circle of confusion

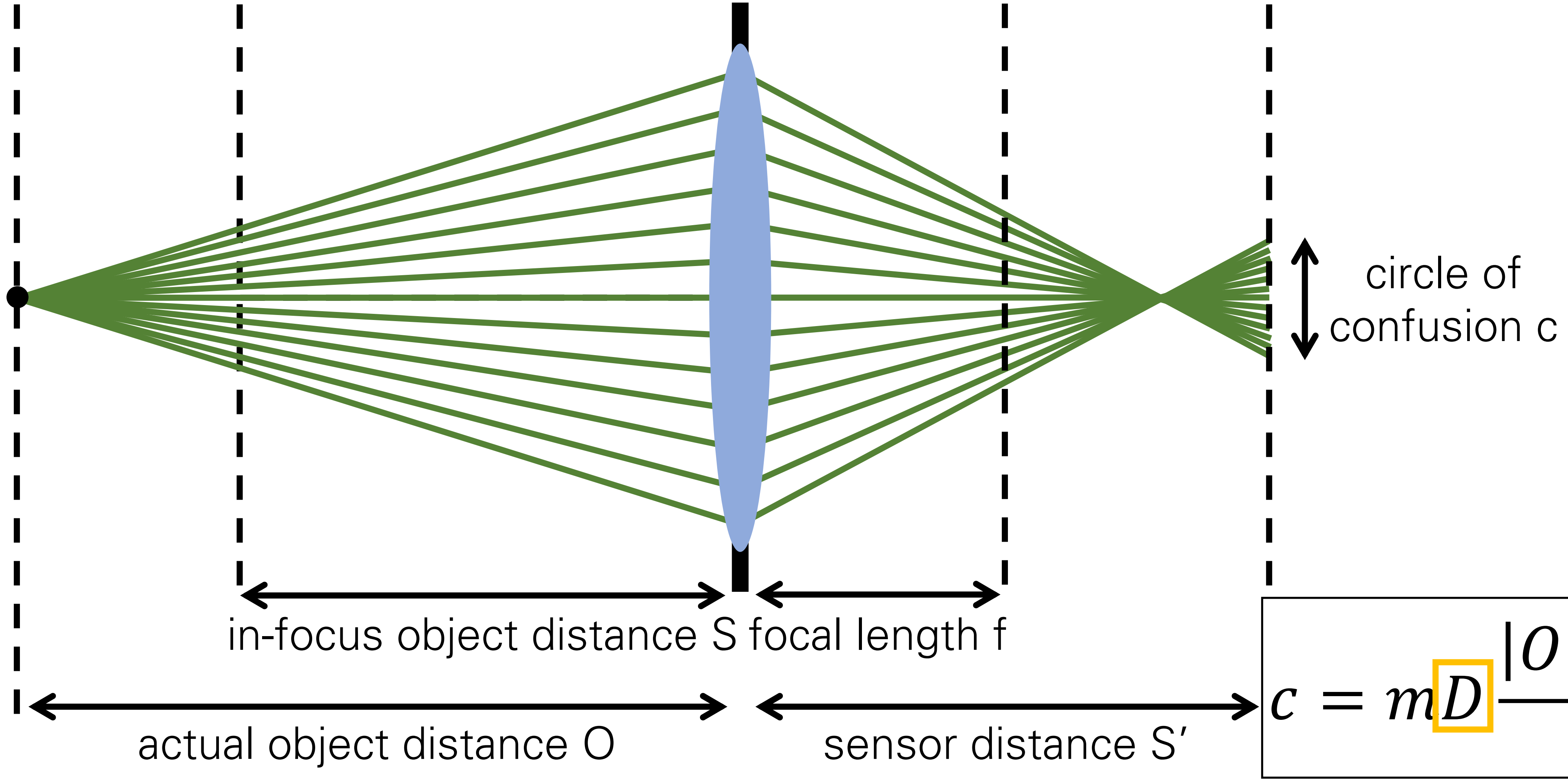
$$c = M \cdot D \cdot \frac{|S - S_1|}{S}$$

Canon 5D Mark III: f=50mm, f/2.8 (N=2.8), focused at 5m, pixel size=7.5um



Defocus depends on aperture diameter

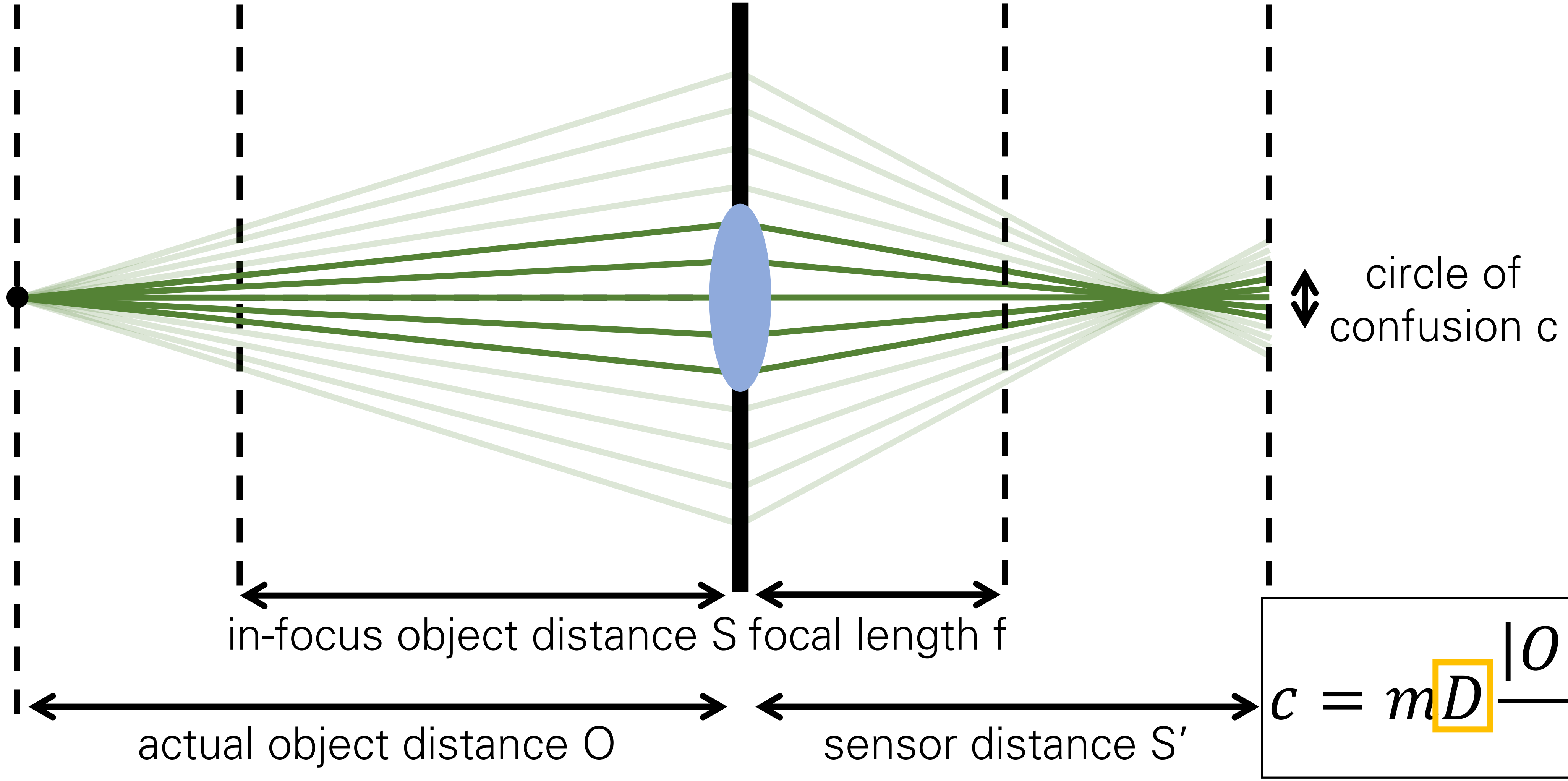
What happens to the circle of confusion as the aperture diameter is reduced?



$$c = m\boxed{D}\frac{|O - S|}{O}$$

Defocus depends on aperture diameter

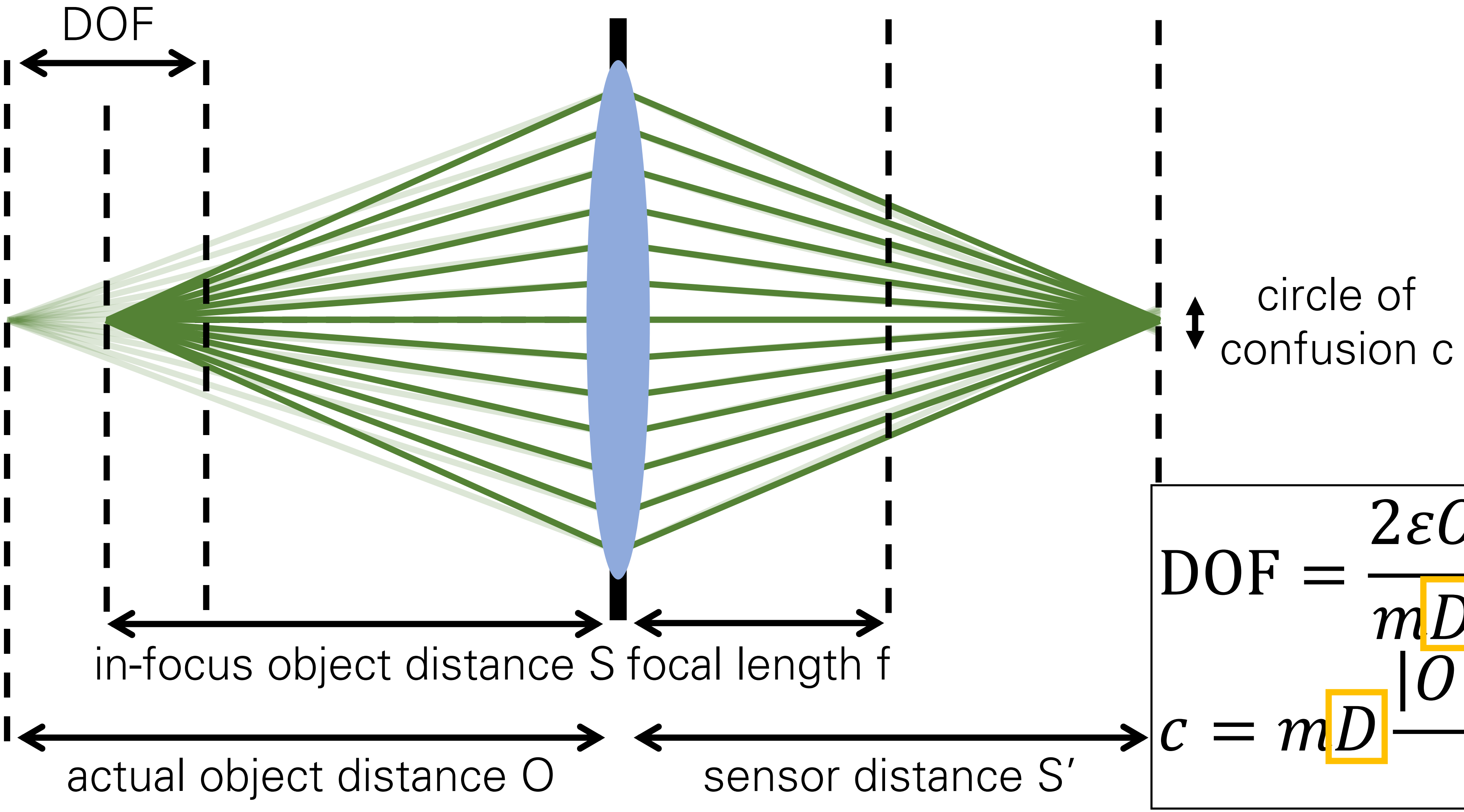
What happens to the circle of confusion as the aperture diameter is reduced? → It shrinks.



$$c = mD\frac{|O - S|}{O}$$

Defocus depends on aperture diameter

What happens to the depth of field as the aperture diameter is reduced?

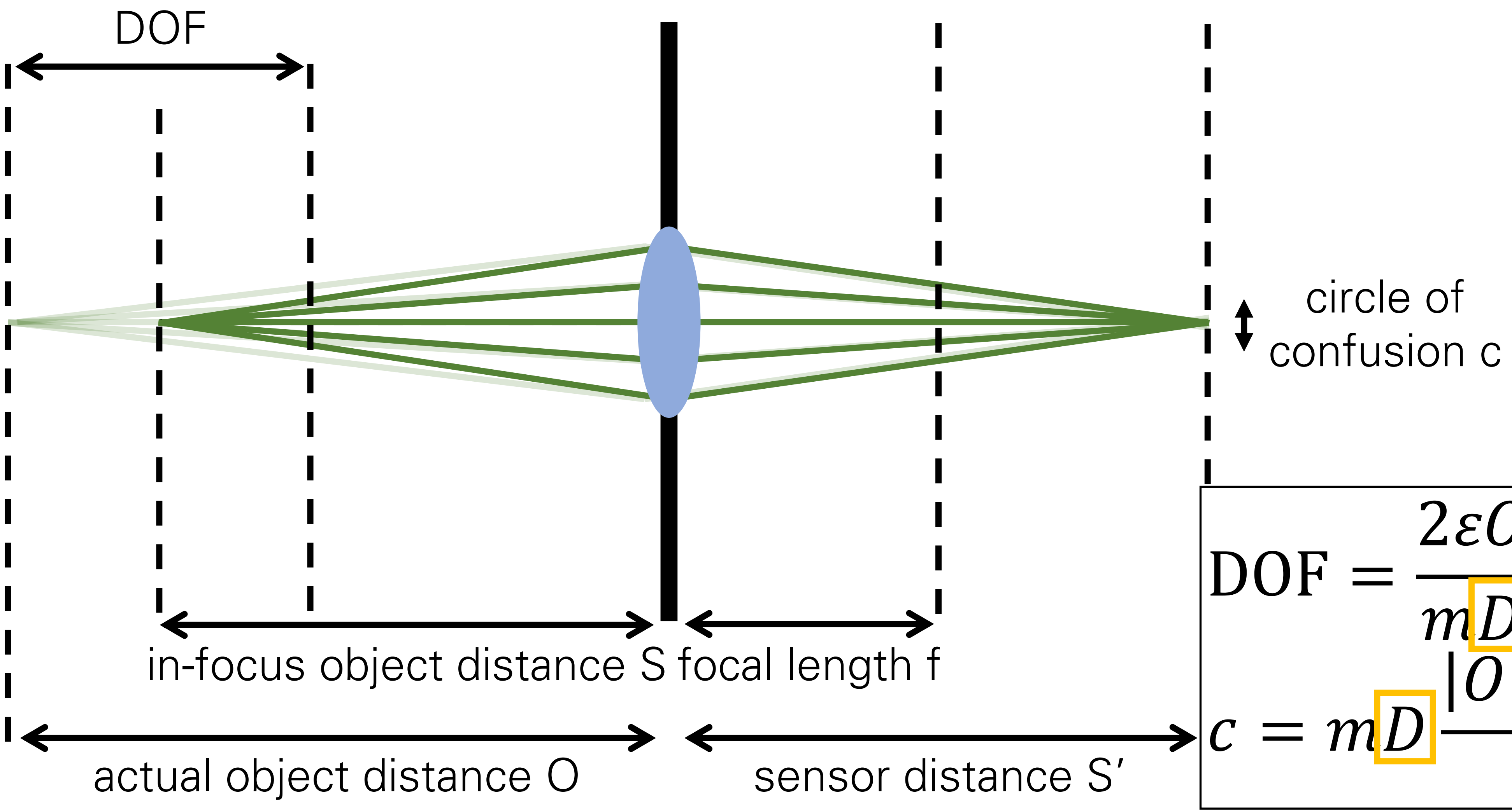


$$\mathrm{DOF} = \frac{2\varepsilon O}{mD}$$

$$c = mD\frac{|O - S|}{O}$$

Defocus depends on aperture diameter

What happens to the depth of field as the aperture diameter is reduced? → It expands.



$$\mathrm{DOF} = \frac{2\varepsilon O}{mD}$$

$$c = mD\frac{|O - S|}{O}$$

Aperture size

Most lenses have apertures of variable size.

- The size of the aperture is expressed as the “f-number”: The bigger this number, the smaller the aperture.

f / 1.4 f / 2.8 f / 4 f / 8 f / 16

You can see the aperture by removing the lens and looking inside it.

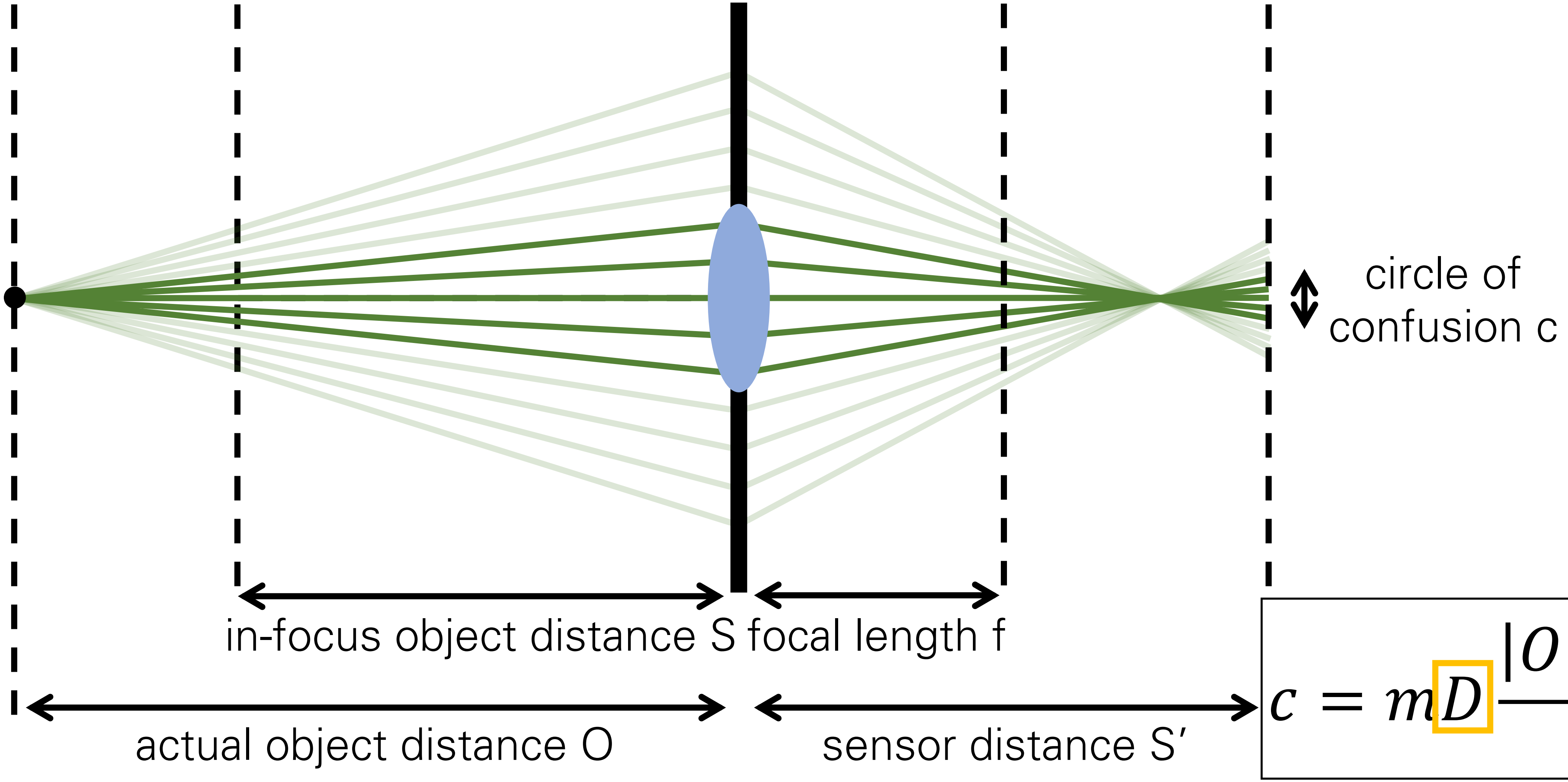
Demonstration

Depth of Field

Form of defocus blur is determined by shape of aperture.

Defocus depends on aperture diameter

If small aperture sizes reduce defocus blur, should we always use the smallest aperture?

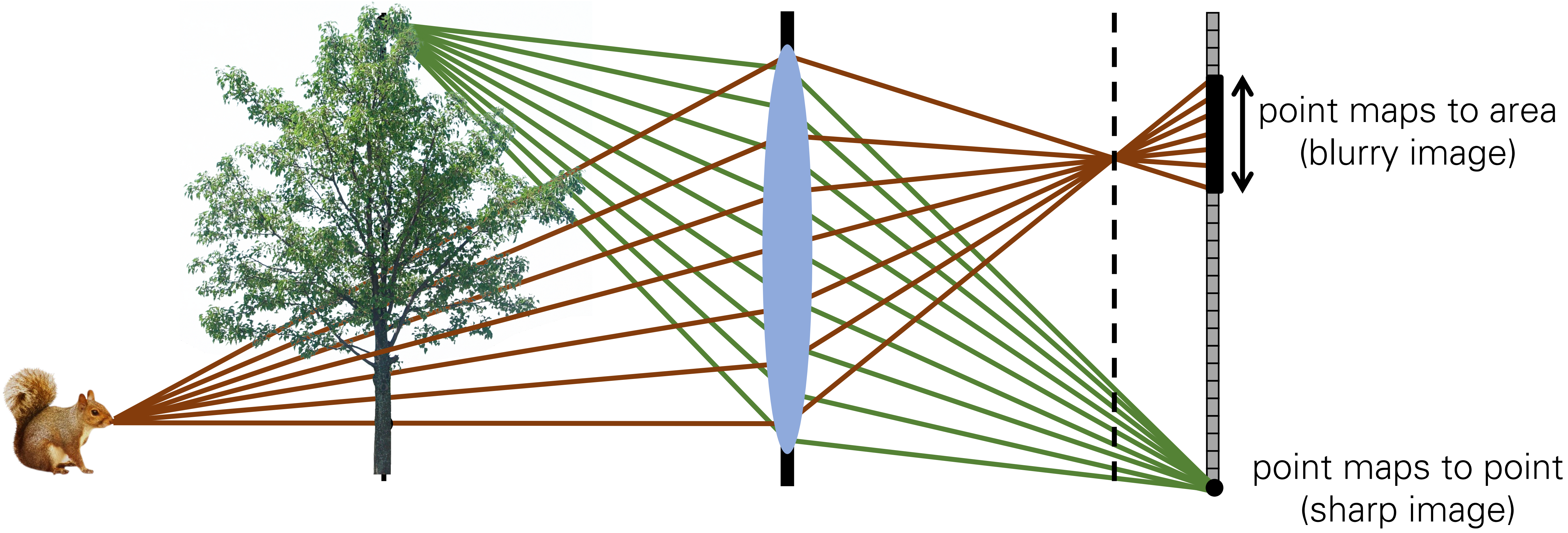


$$c = mD\frac{|O - S|}{O}$$

Bokeh

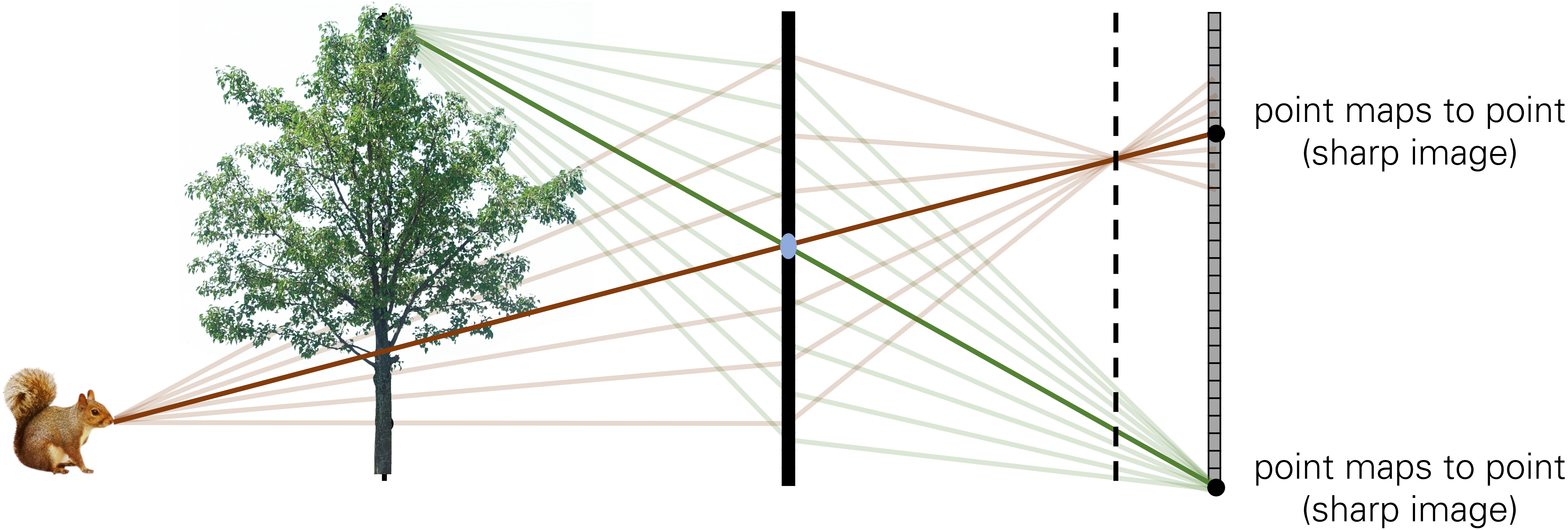
Sharp depth of field ("bokeh") is often desirable.

What happens as the aperture keeps getting smaller?



What happens as the aperture keeps getting smaller?

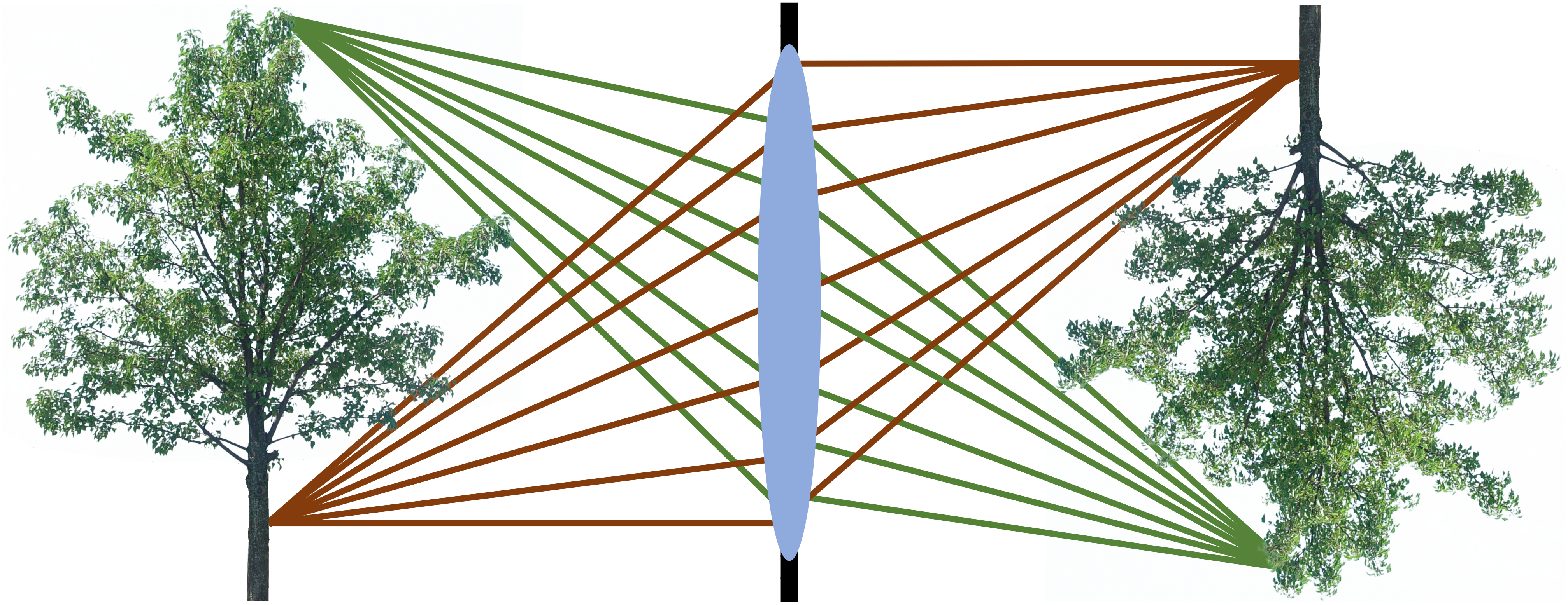
Lens becomes equivalent to a pinhole.



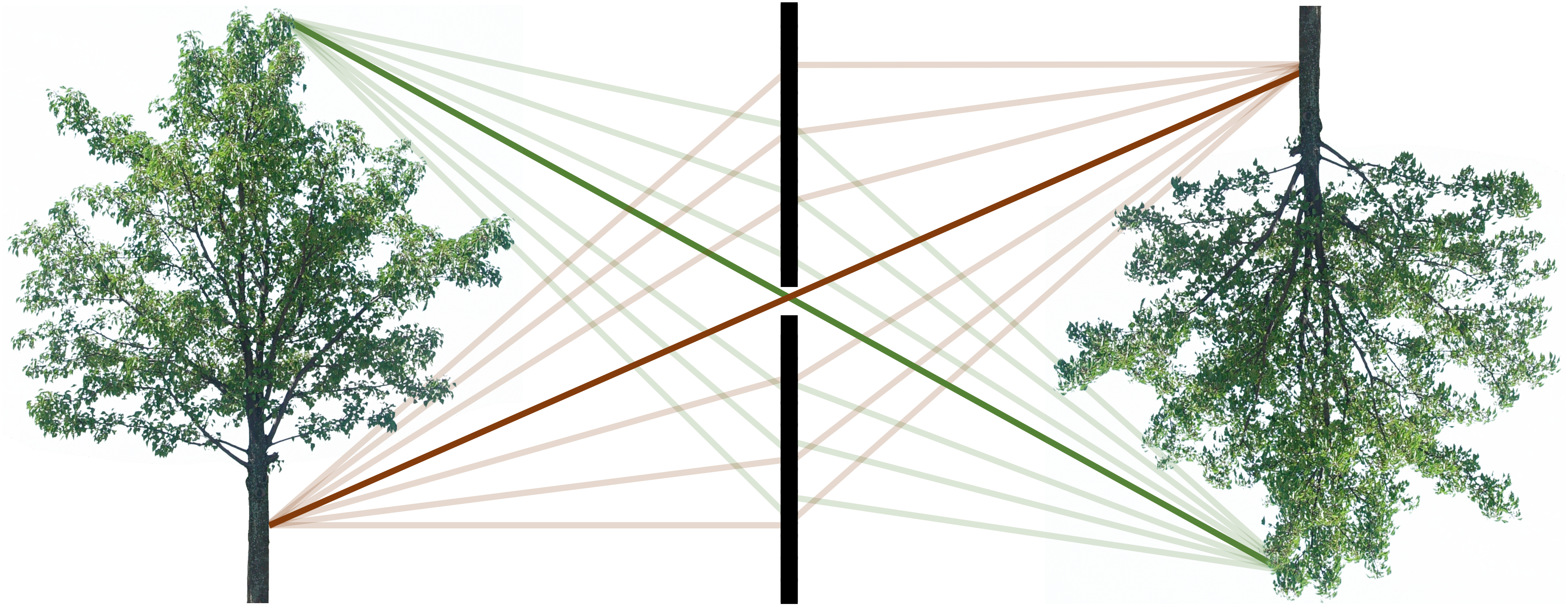
- No defocus, everything is sharp regardless of depth.
- Very little light, signal-to-noise ratio is just as bad as pinhole.

Lens camera and pinhole camera

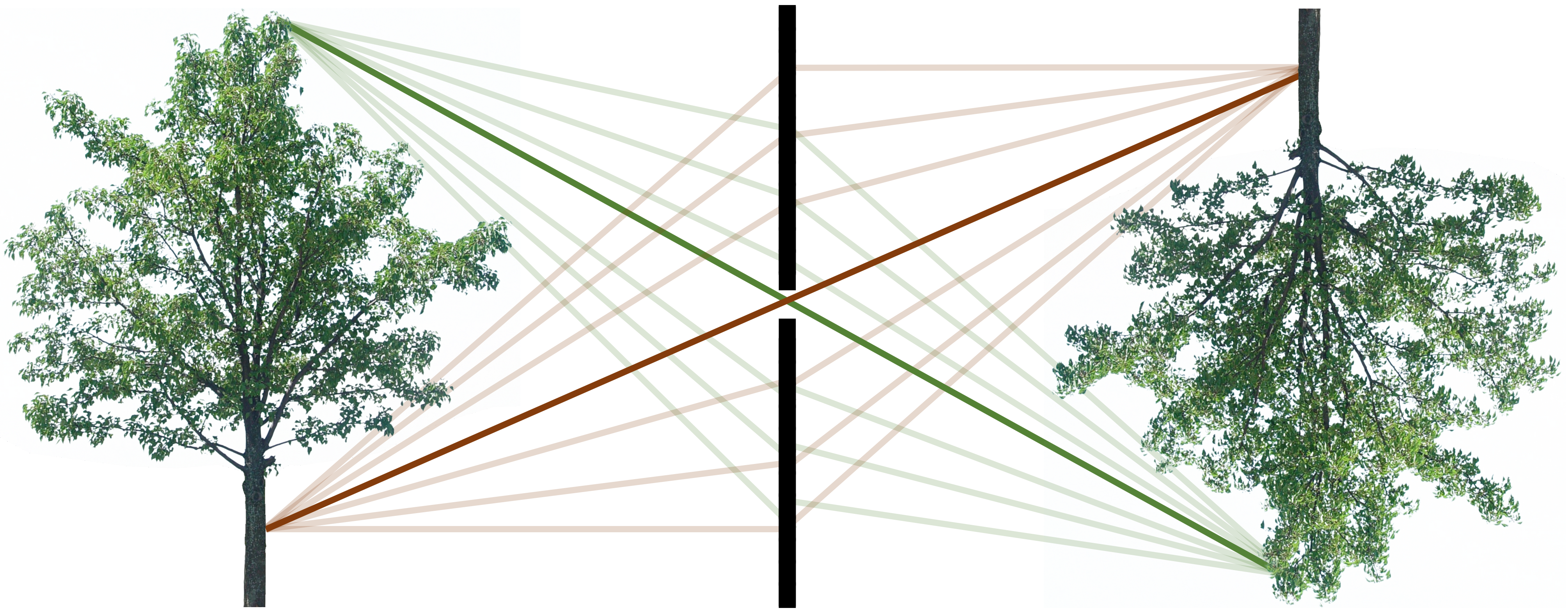
The lens camera



The pinhole camera

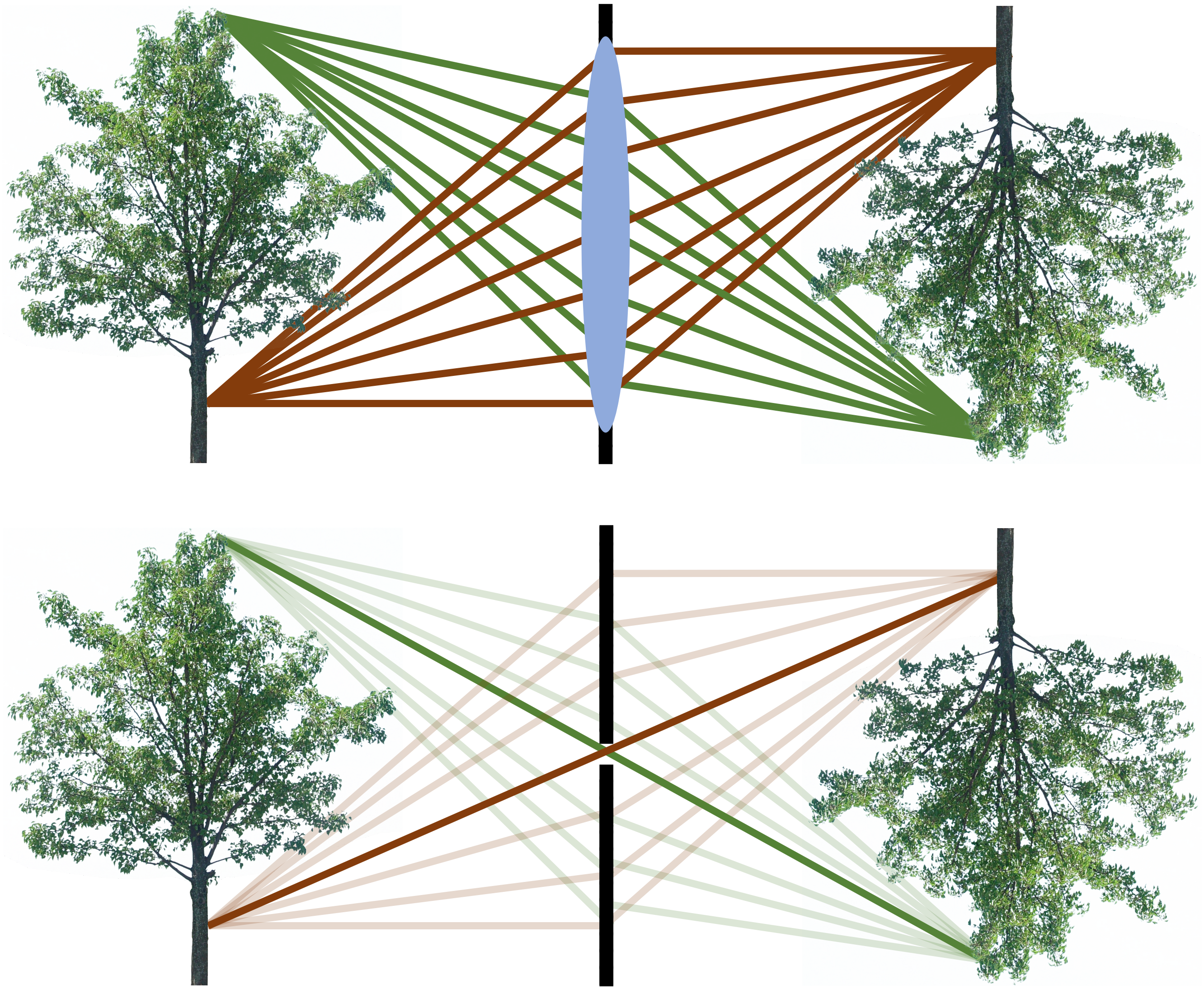


The pinhole camera



Central rays propagate in the same way for both models!

Describing both lens and pinhole cameras

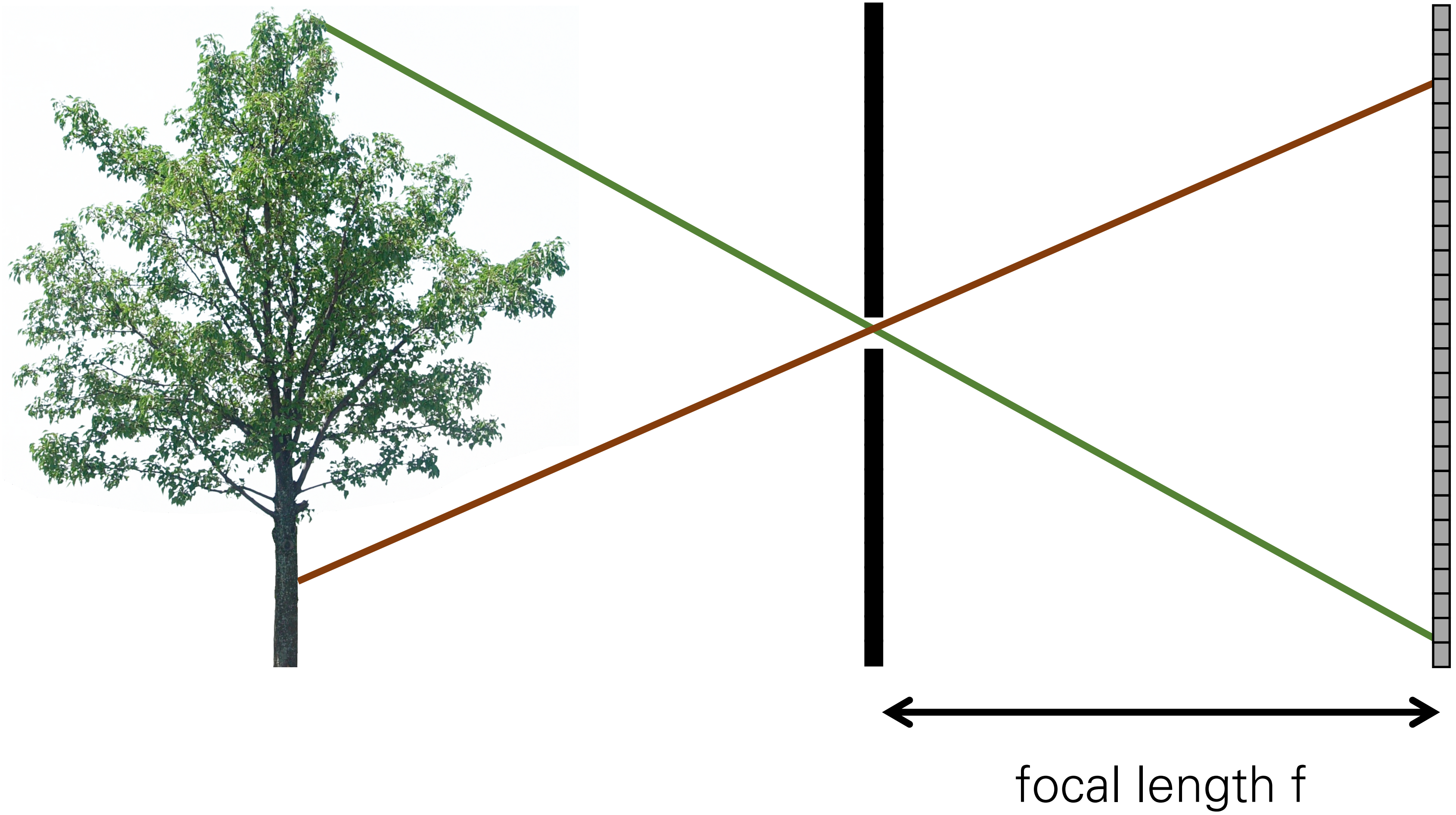


We can derive properties and descriptions that hold for both camera models if:

- We consider only central rays.
- We assume that everything of interest in the scene is within the depth of field.

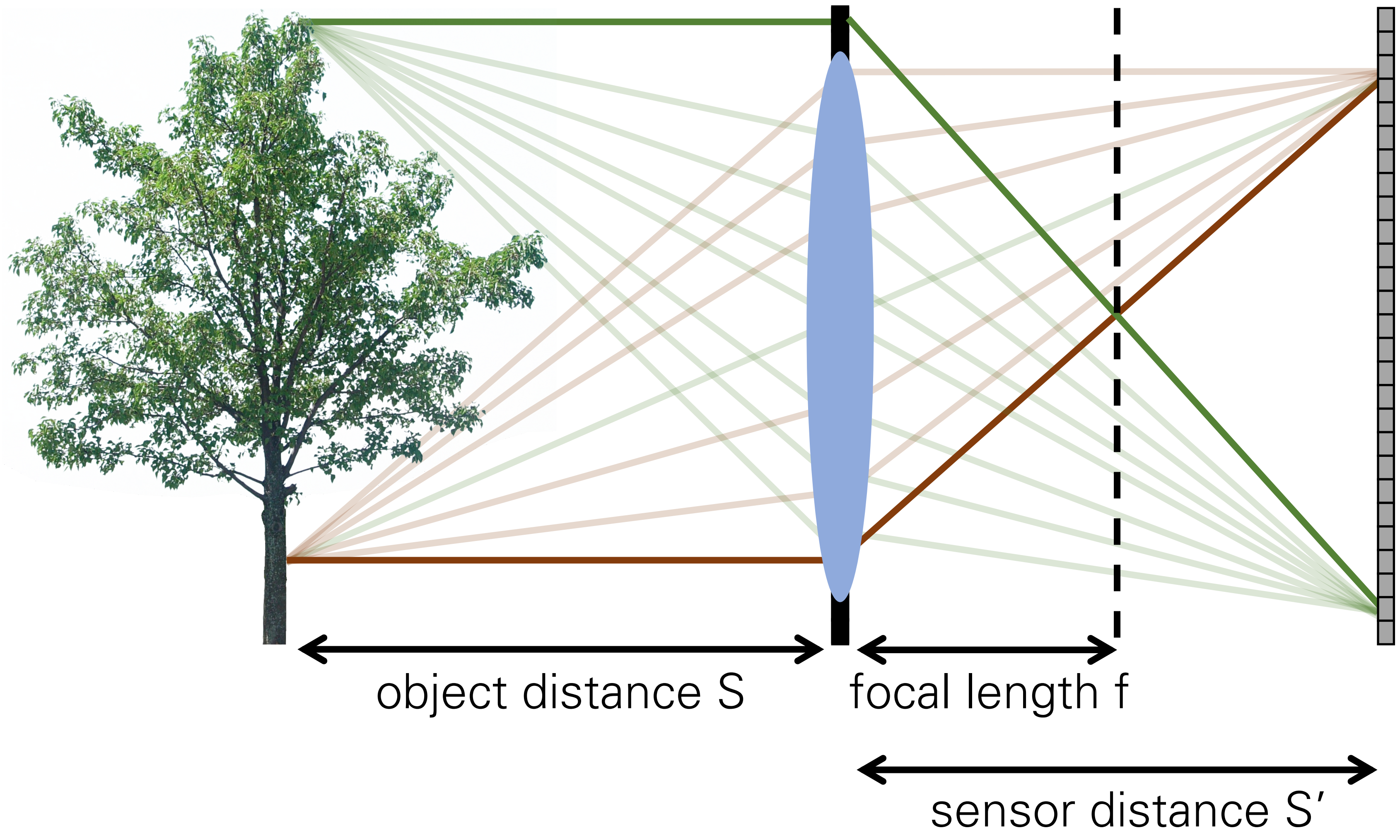
Important difference: focal length

In a pinhole camera, focal length is distance between aperture and sensor

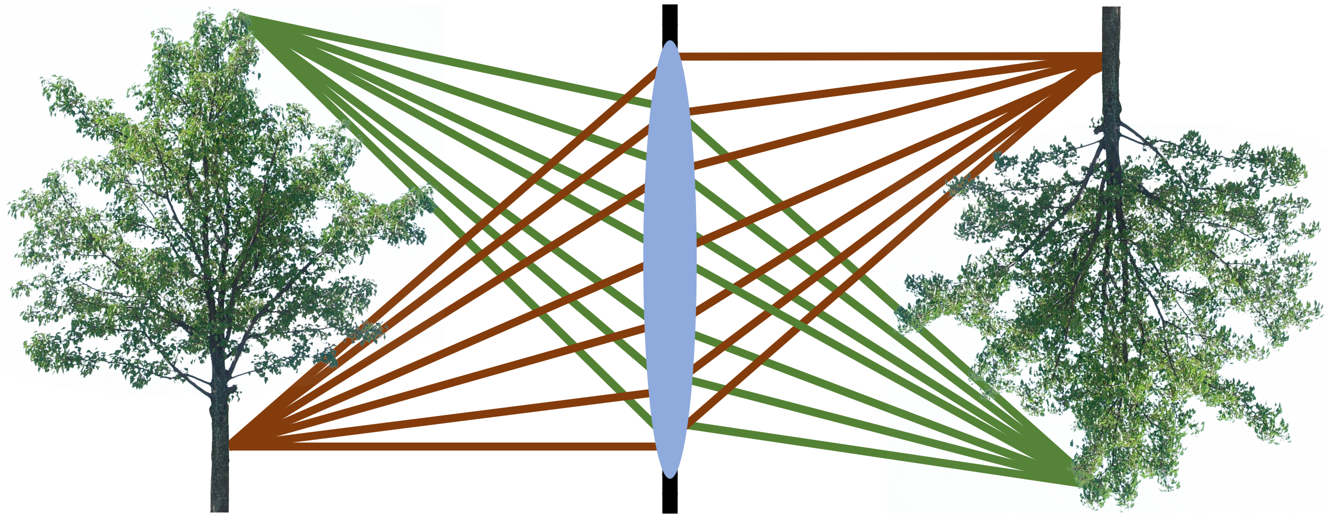


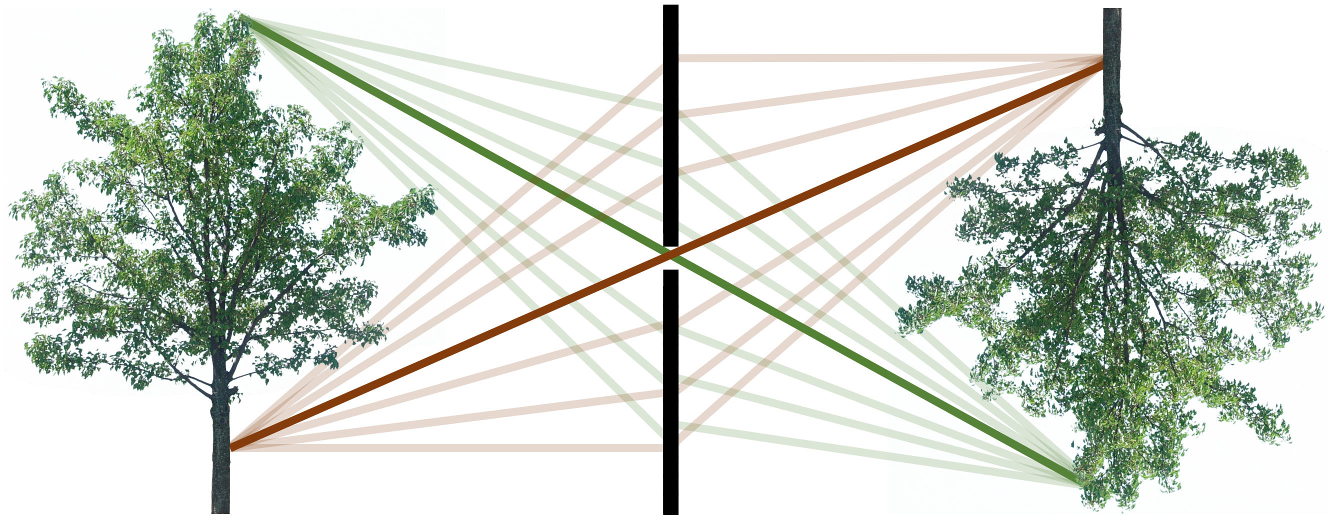
Important difference: focal length

In a lens camera, focal length is distance where parallel rays intersect



Describing both lens and pinhole cameras

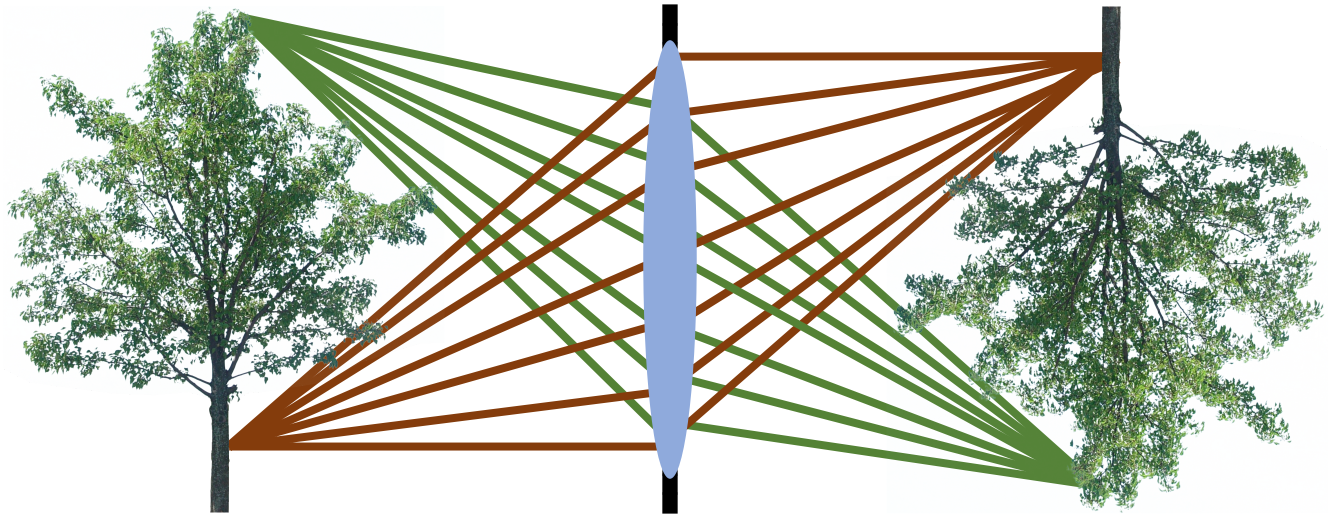




We can derive properties and descriptions that hold for both camera models if:

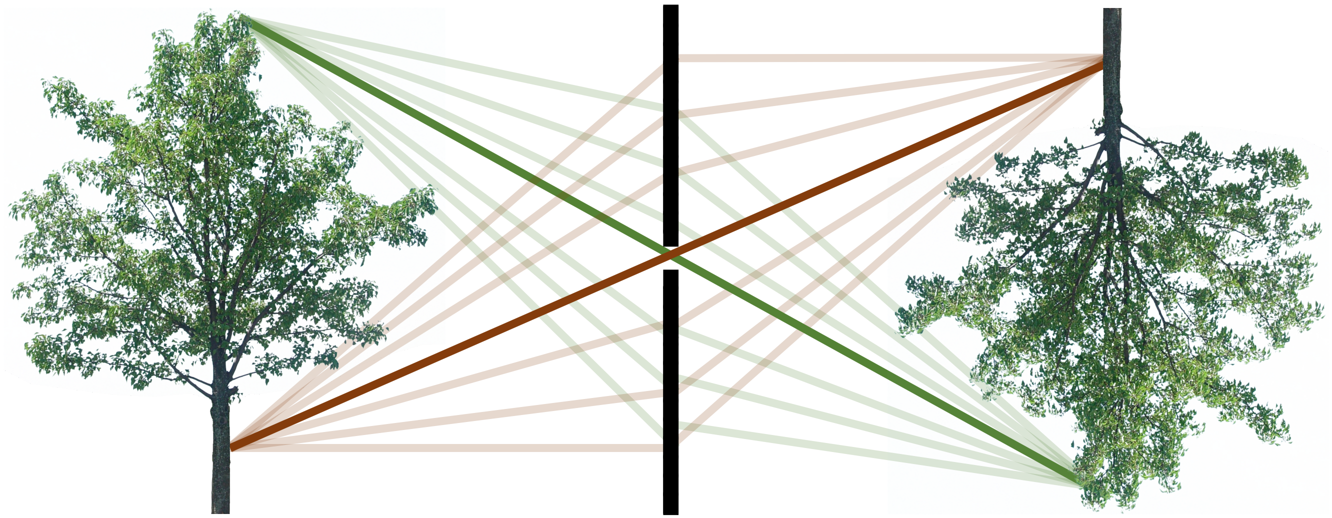
- We consider only central rays.
- We assume everything of interest in the scene is within the depth of field.
- We assume that the focus distance of the lens camera is equal to the focal length of the pinhole camera.

Effect of aperture size on lens and pinhole cameras



Doubling the aperture diameter:

- Increases light throughput by four times.
- Increases circle of confusion for out-of-focus plane by two times.
- Decreases depth of field by two times.



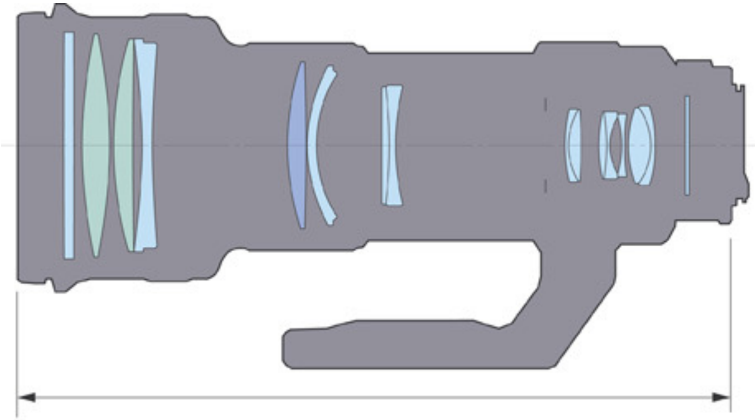
Doubling the aperture diameter:

- Increases light throughput by four times.
- Increases circle of confusion for all planes by two times.

Thin lenses are fiction!

Thin lenses are a fiction

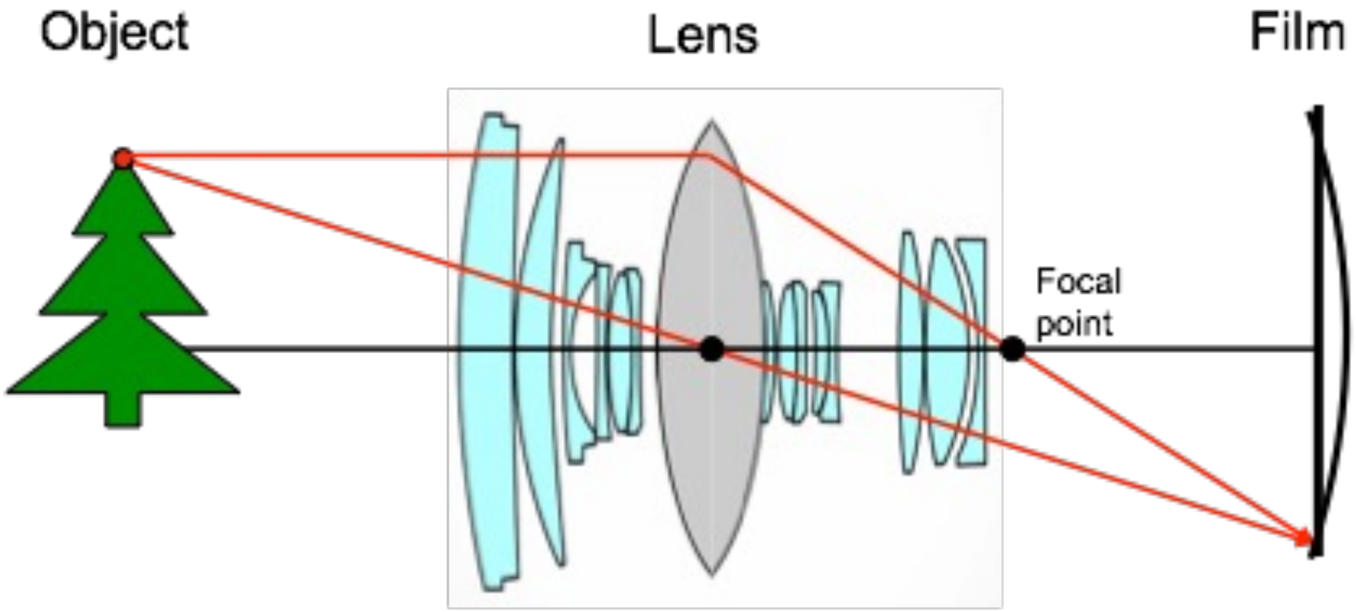
The thin lens model assumes that the lens has no thickness, but this is rarely true...



To make real lenses behave like ideal thin lenses, we have to use combinations of multiple lens elements (compound lenses).

Thin lenses are a fiction

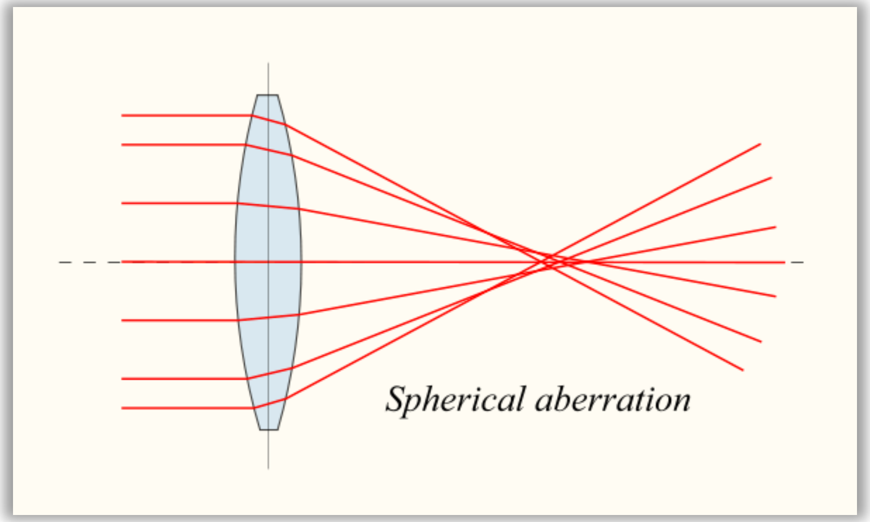
The thin lens model assumes that the lens has no thickness, but this is rarely true...

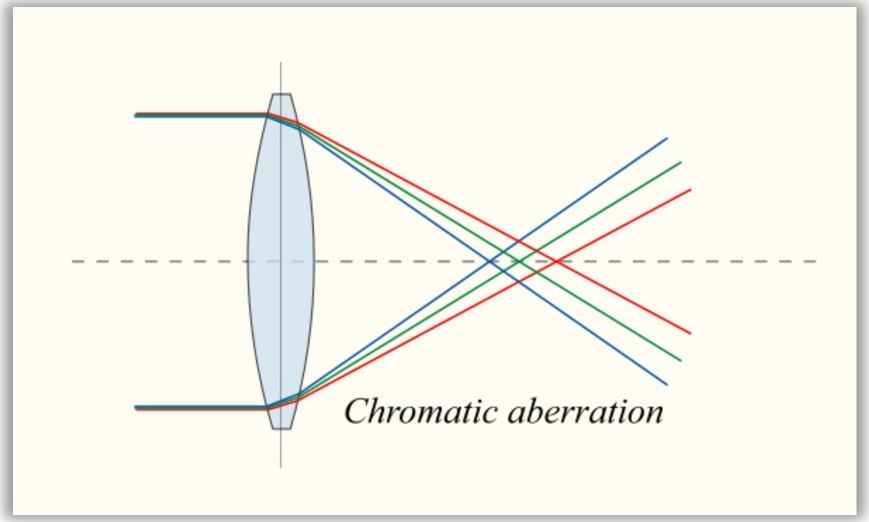


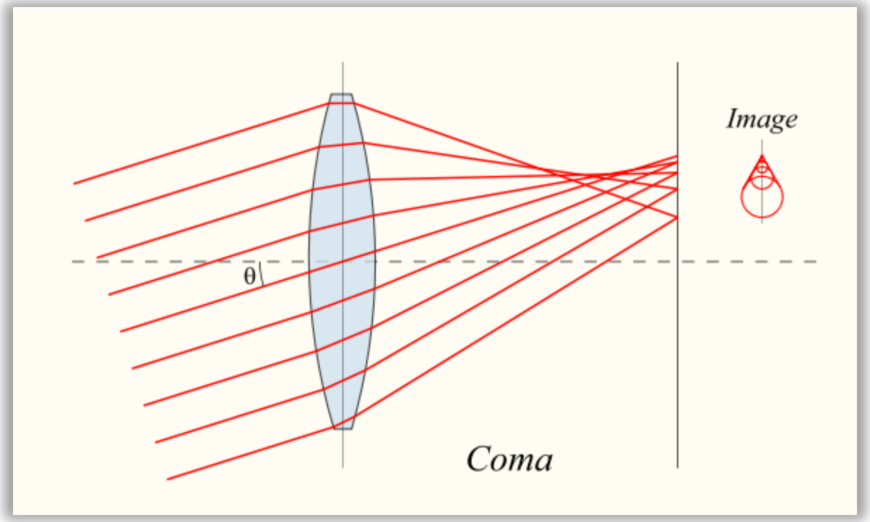
Even though we have multiple lenses, the entire optical system can be (paraxially) described using a single thin lens of some equivalent focal length and aperture number.

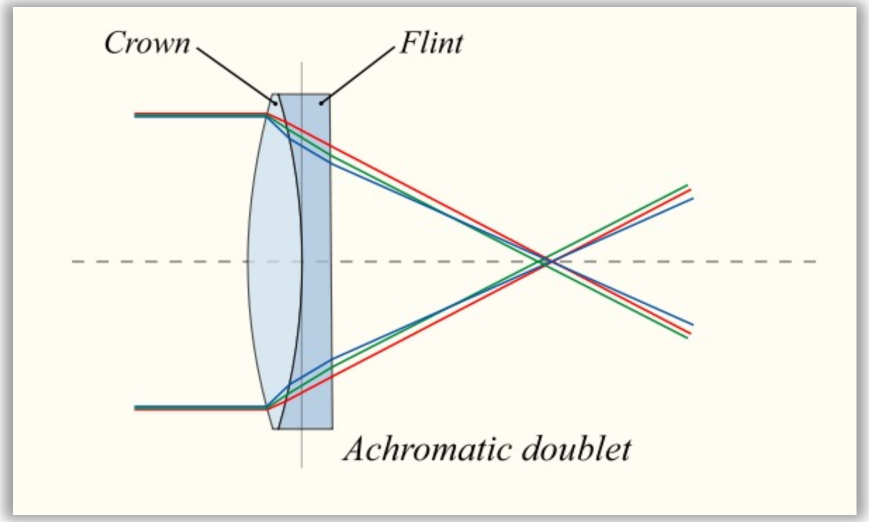
To make real lenses behave like ideal thin lenses, we have to use combinations of multiple lens elements (compound lenses).

Lenses - Aberrations

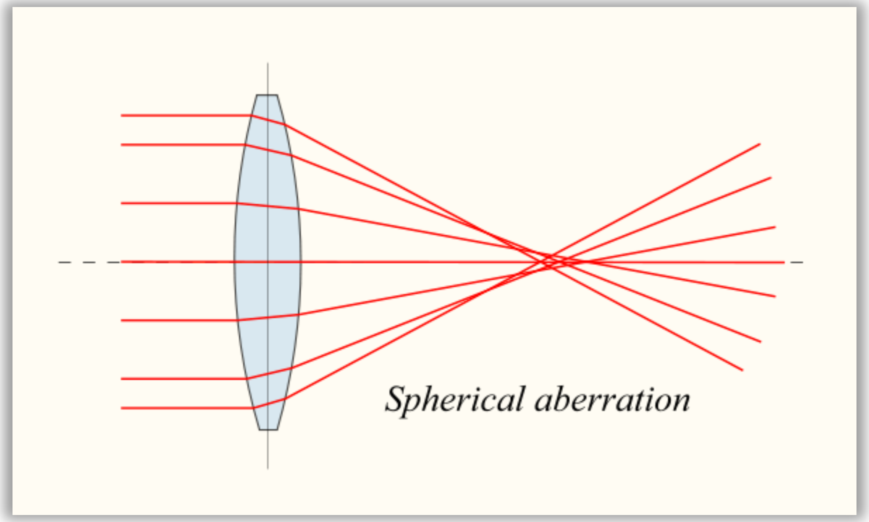


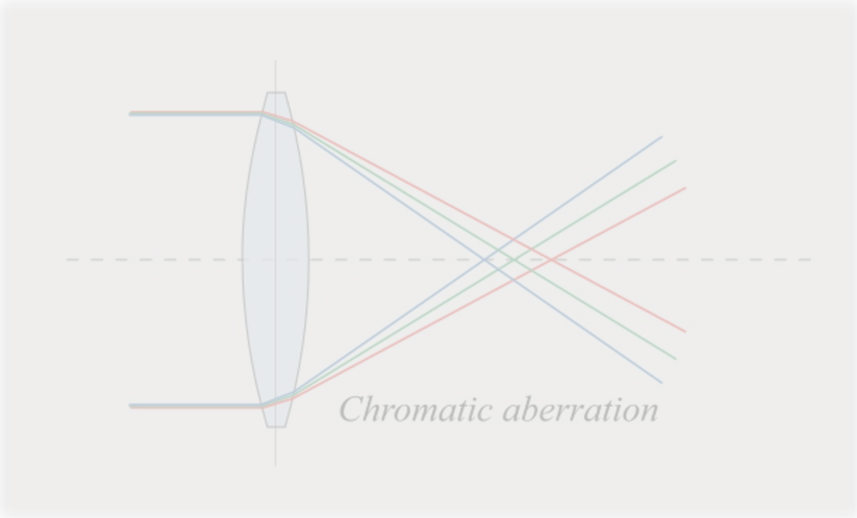


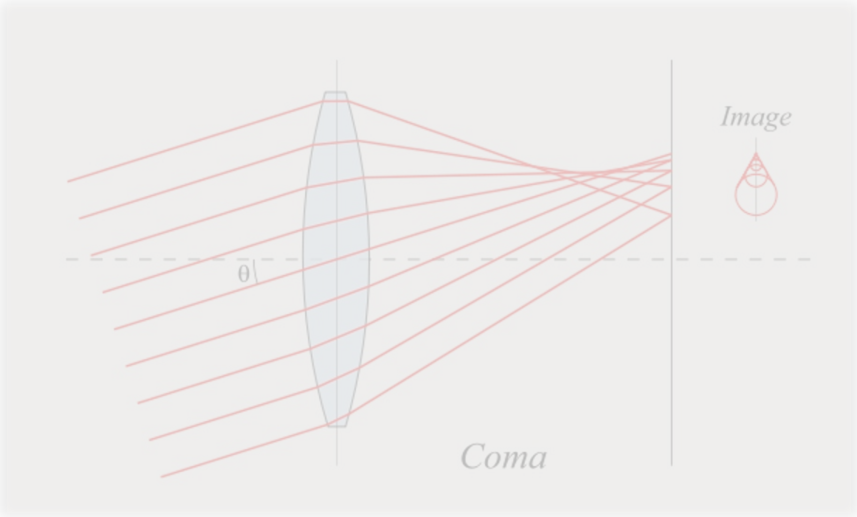


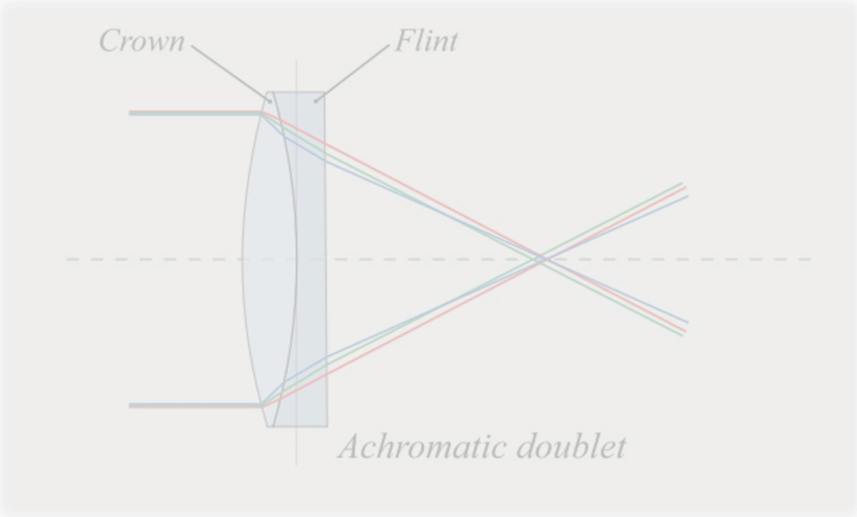


Lenses - Aberrations



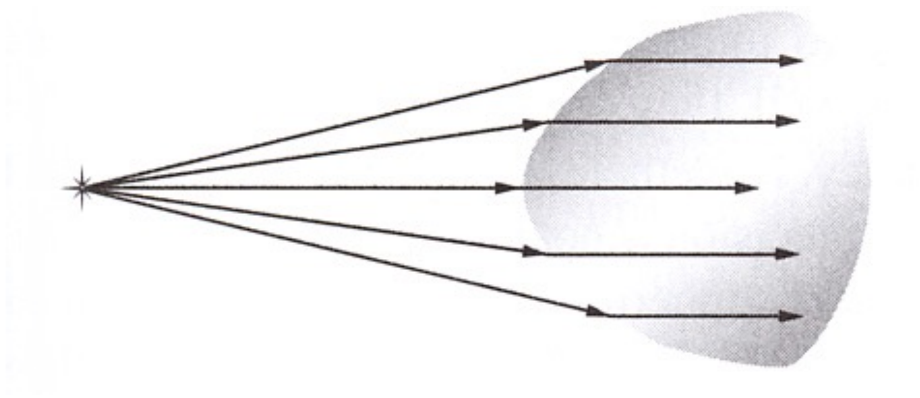






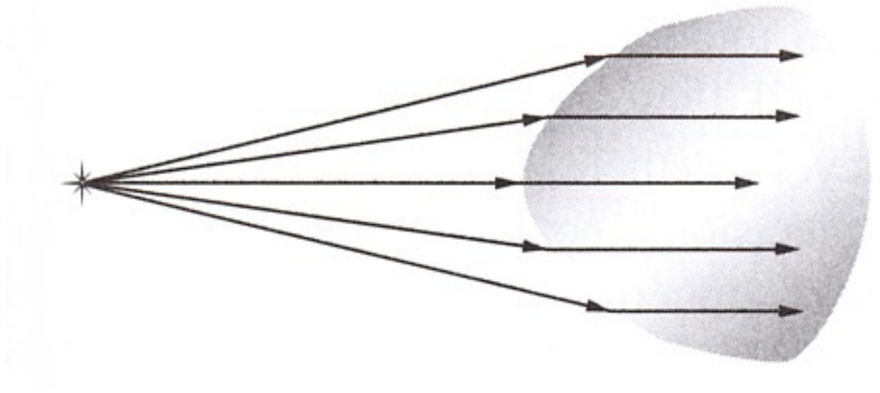
Refraction at interfaces of complicated shapes

What shape should an interface have to make parallel rays converge to a point?



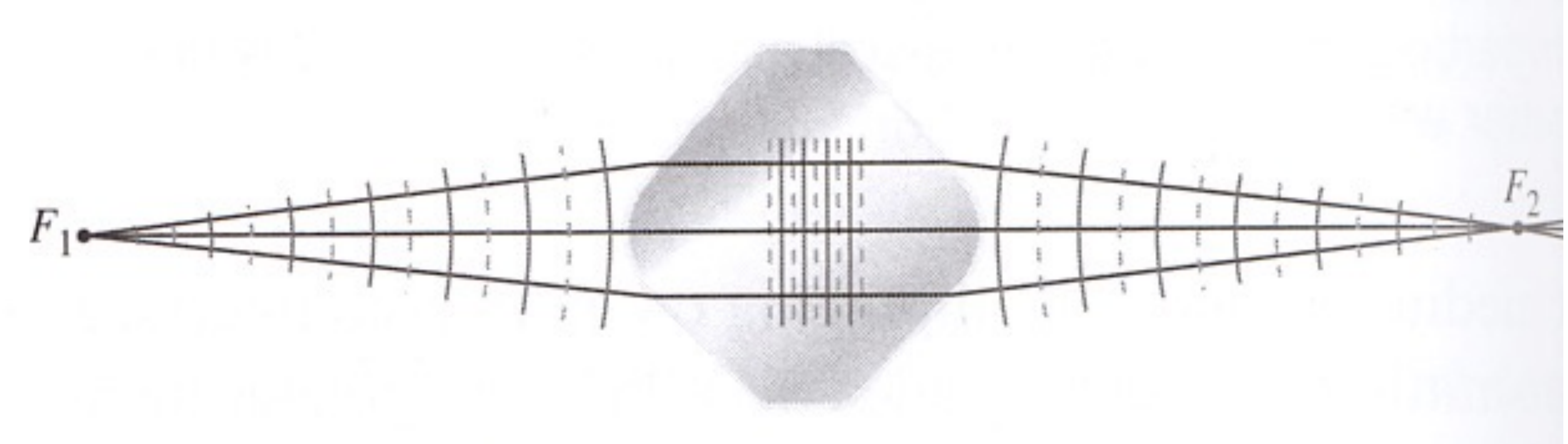
Refraction at interfaces of complicated shapes

What shape should an interface have to make parallel rays converge to a point?



Single hyperbolic interface:
point to parallel rays

Double hyperbolic interface:
point to point rays

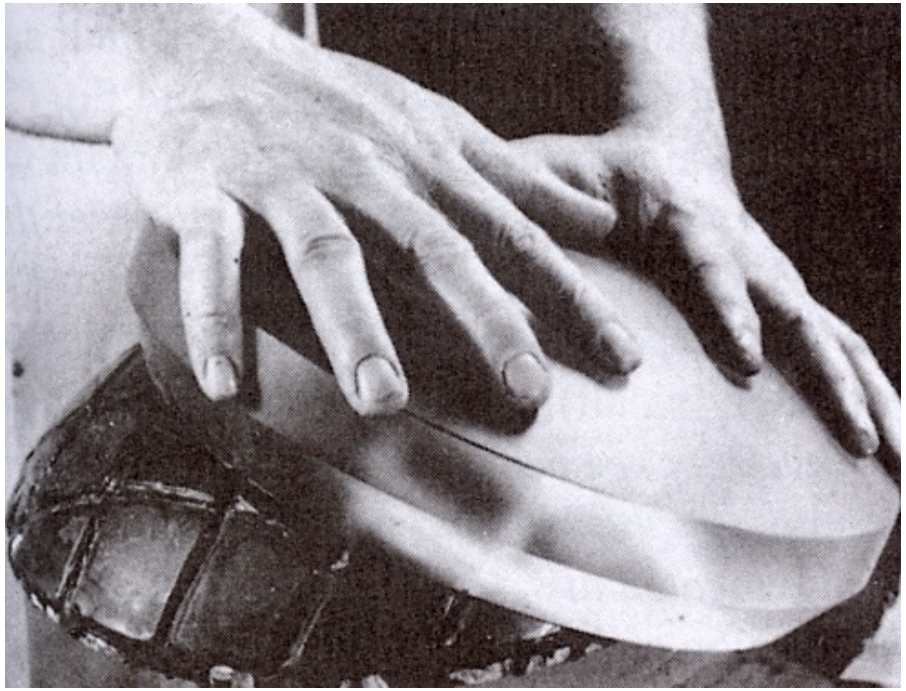


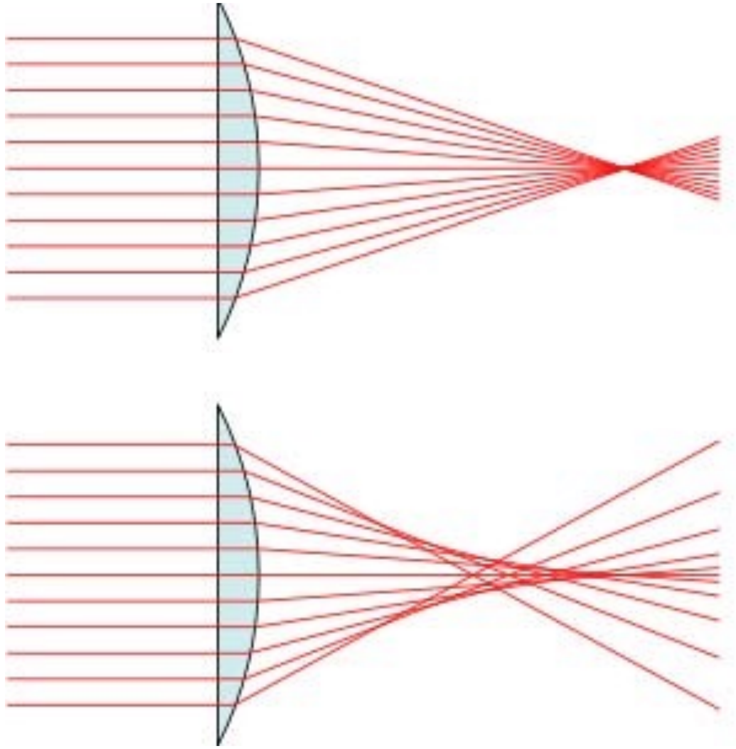
What shape should an interface have to make parallel rays converge to a point?

Spherical lenses

In practice, lenses are often made to have spherical interfaces for ease of fabrication.

- Two roughly fitting curved surfaces ground together will eventually become spherical.





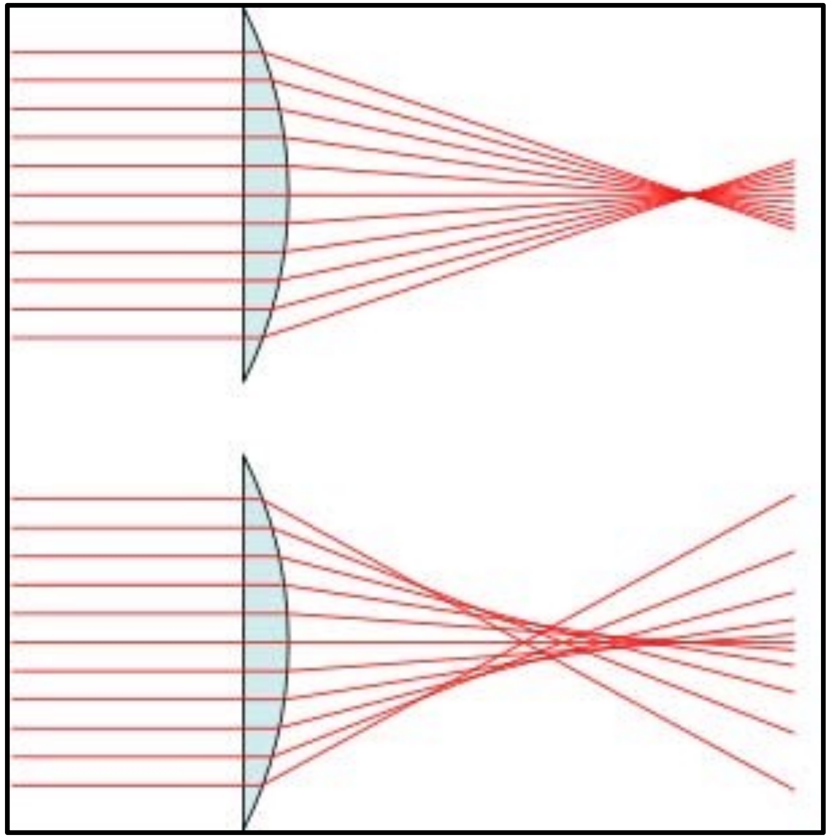
Spherical lenses don't bring parallel rays to a point.

- This is called spherical aberration.
- Approximately axial (i.e., paraxial) rays behave better.

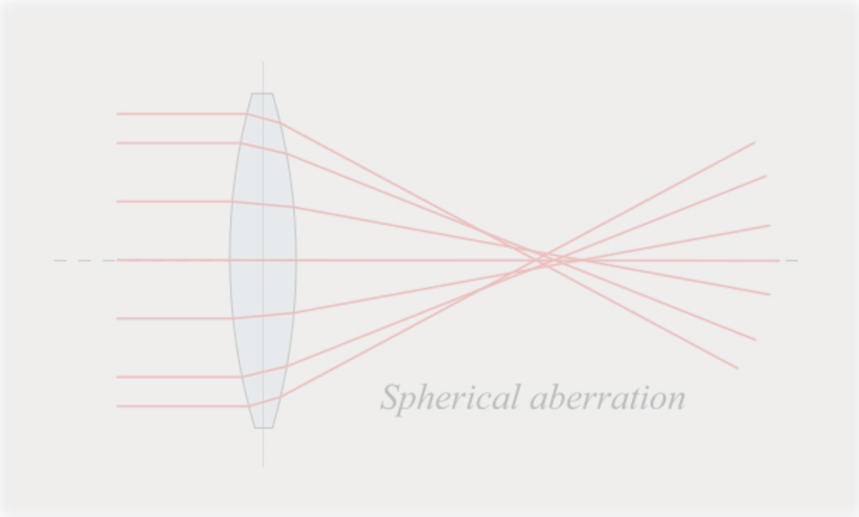
Aberrations

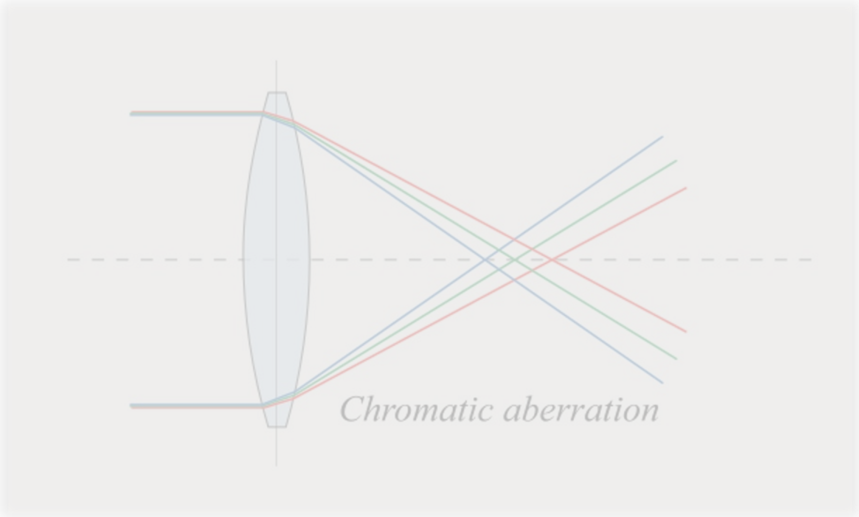
Deviations from ideal thin lens behavior (e.g., imperfect focus).

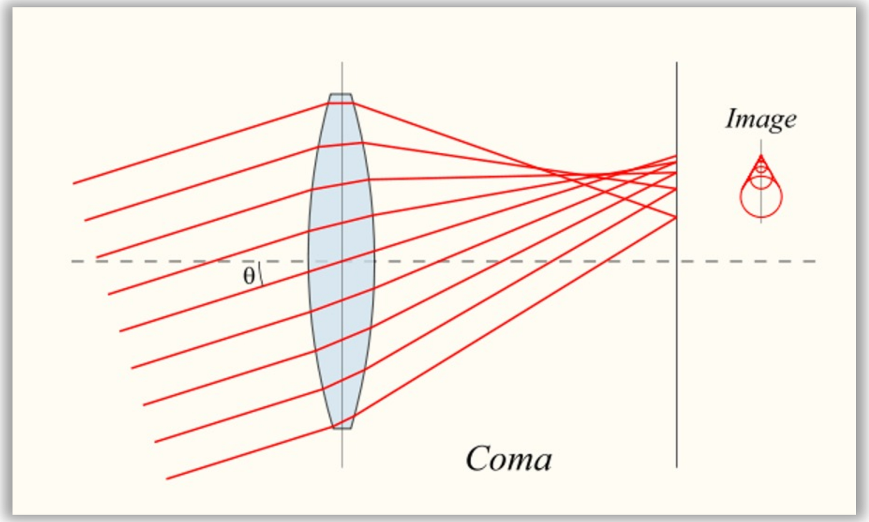
- Example: spherical aberration.

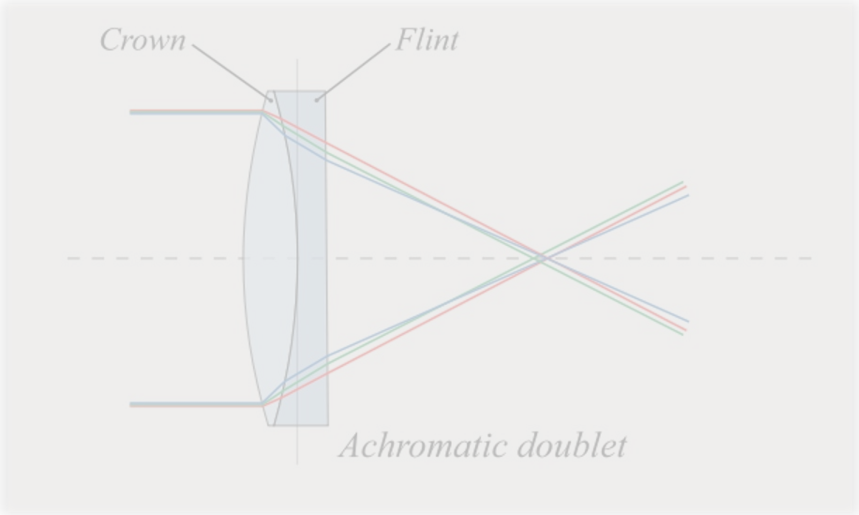


Lenses - Aberrations





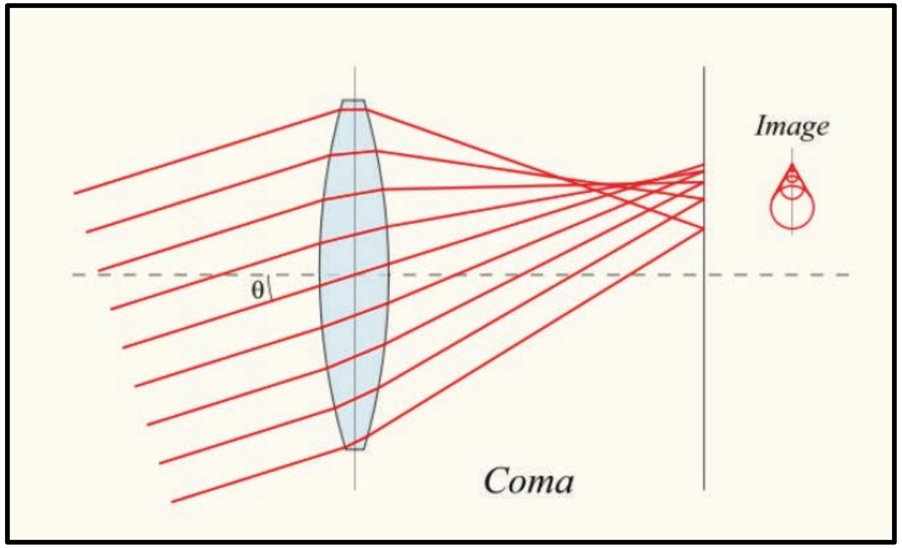




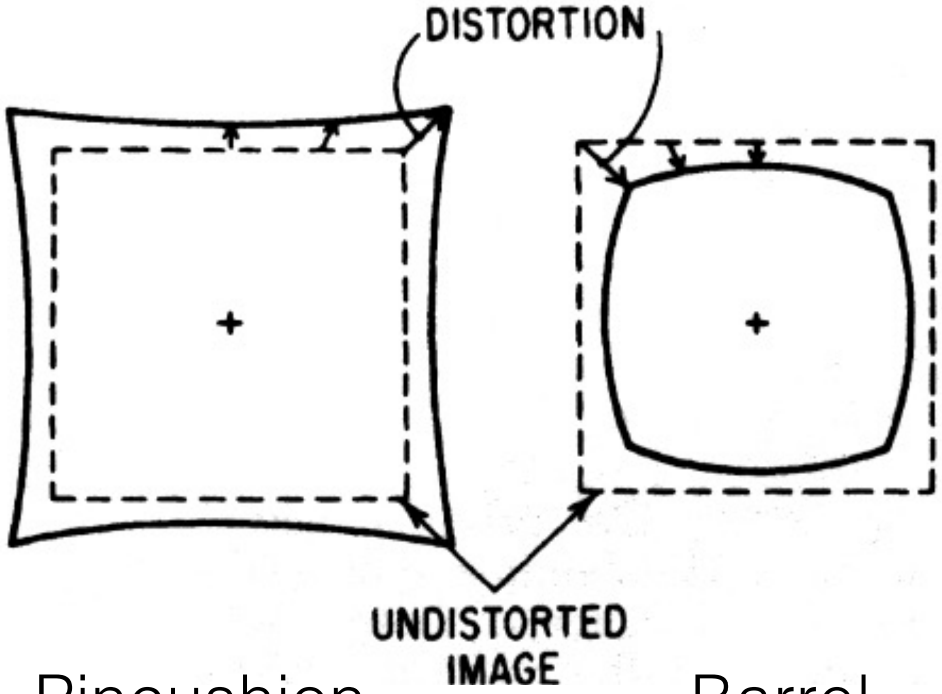
Oblique aberrations

These appear only as we move further from the center of the field of view.

- Contrast with spherical and chromatic, which appear everywhere.
- Many other examples (astigmatism, field curvature, etc.).



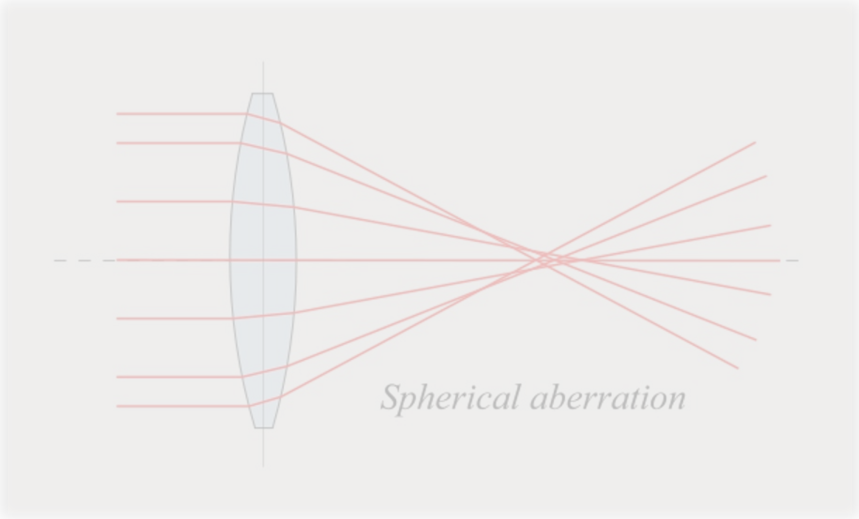
Coma

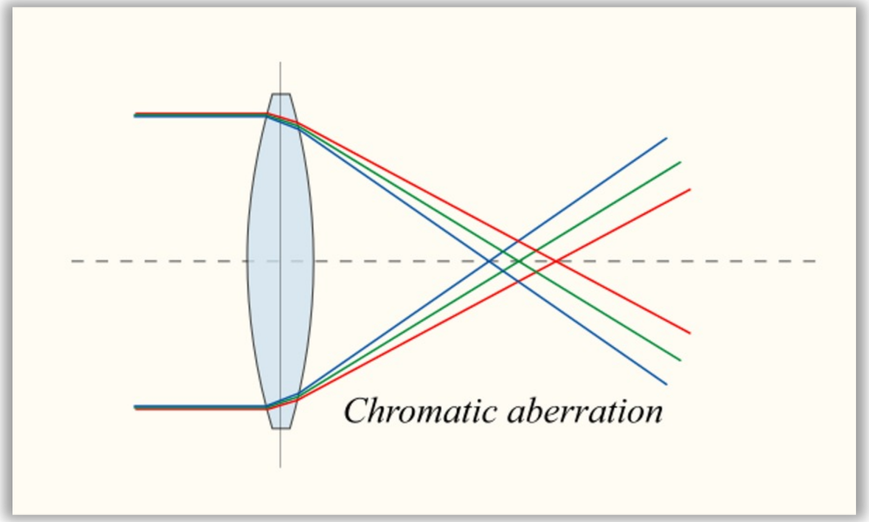


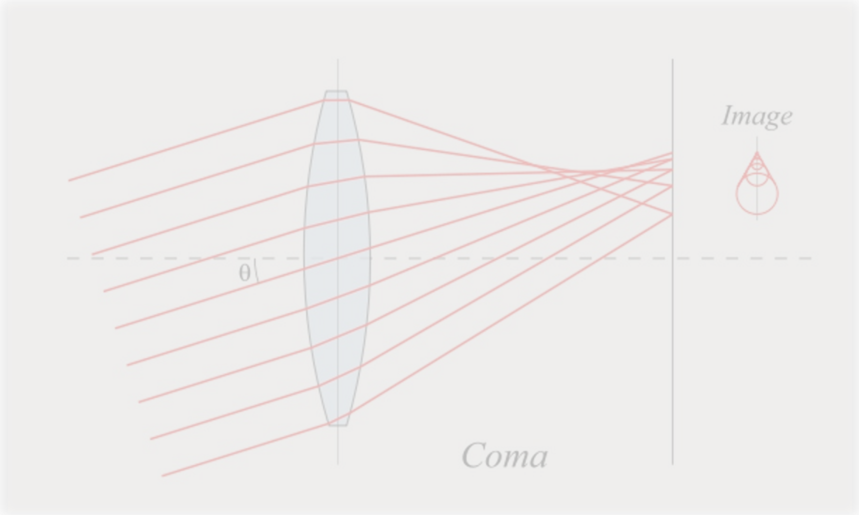
Pincushion Barrel

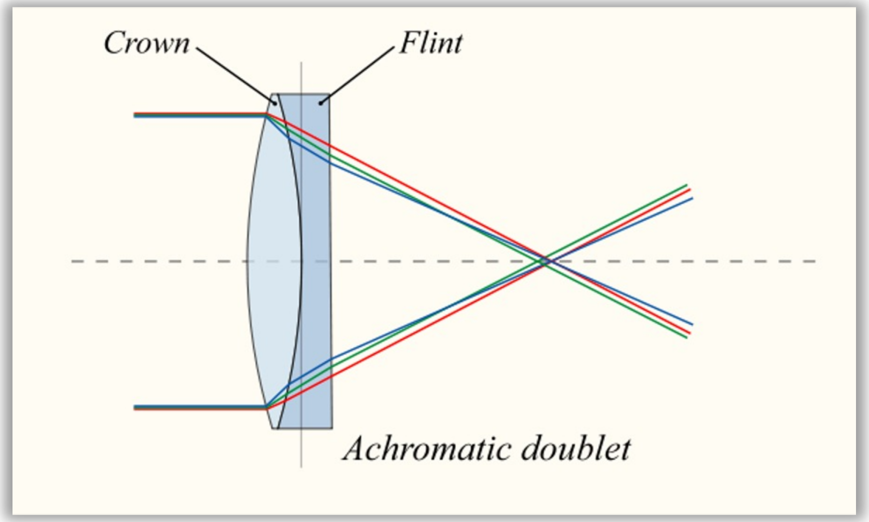
Distortion example

Lenses - Aberrations







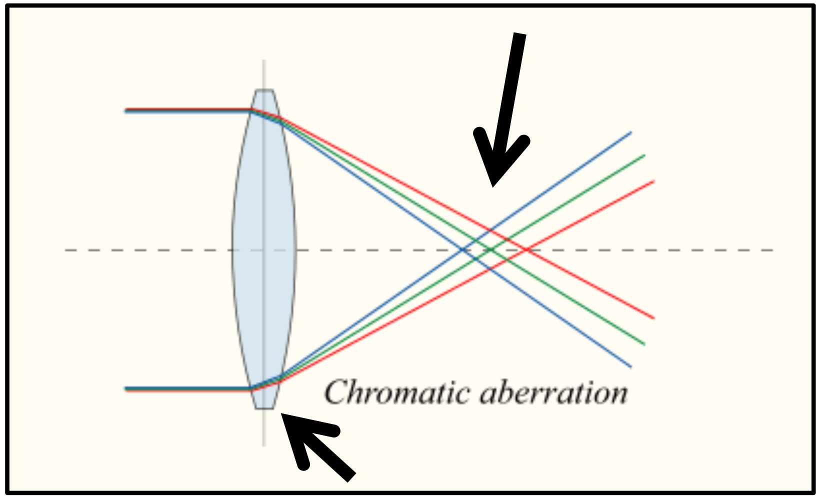


Aberrations

Deviations from ideal thin lens behavior (e.g., imperfect focus).

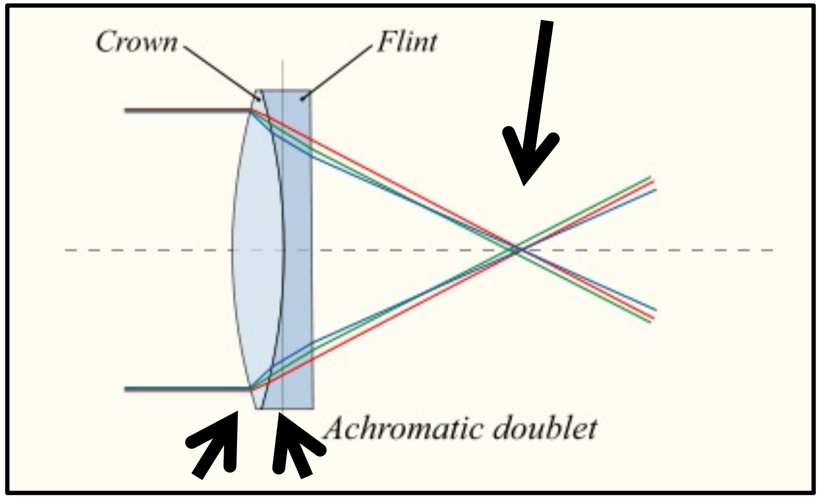
- Example: chromatic aberration.

focal length shifts with wavelength



glass has dispersion (refractive index changes with wavelength)

one lens cancels out dispersion of other



glasses of different refractive index

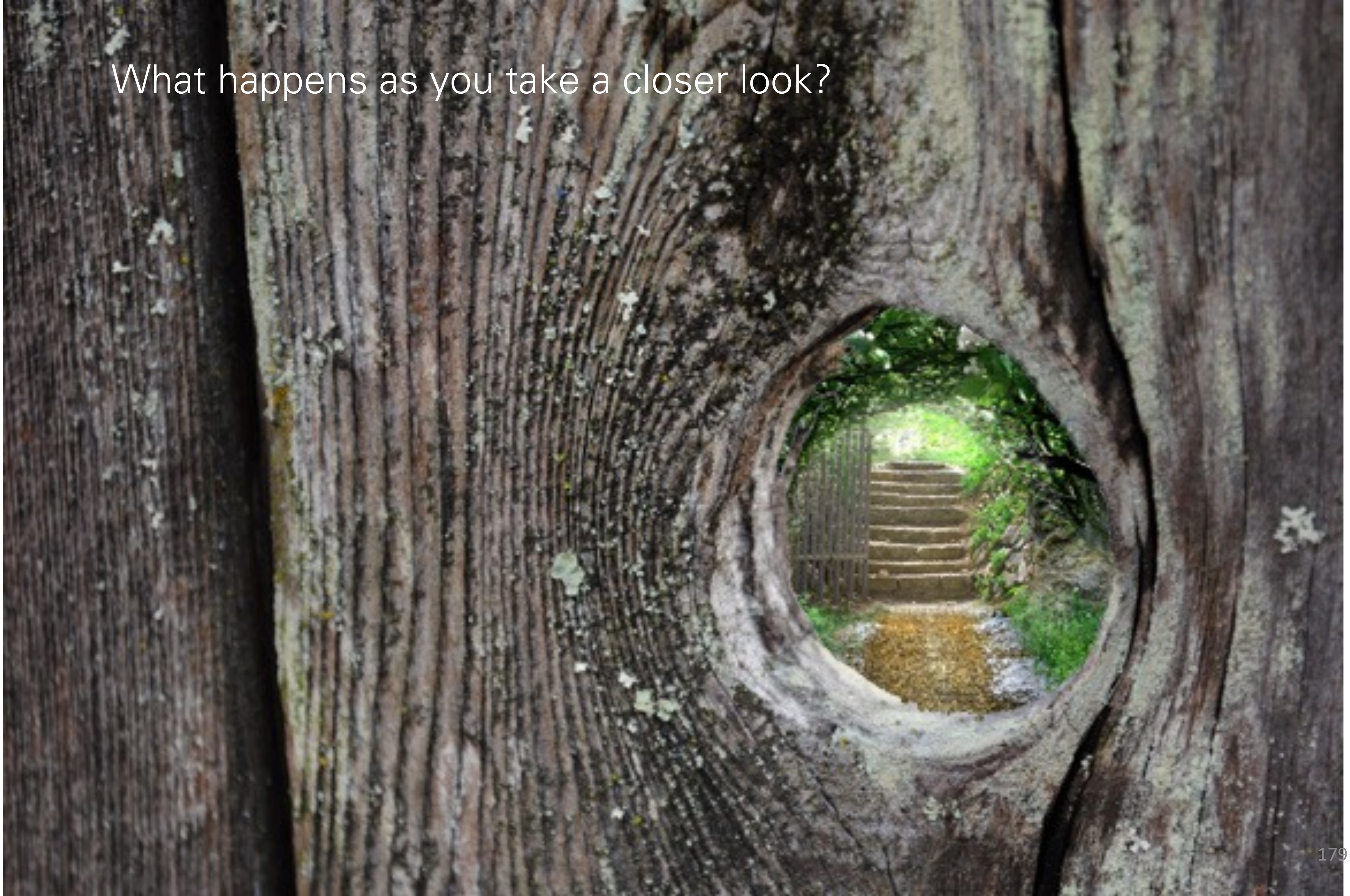
Using a doublet (two-element compound lens), we can reduce chromatic aberration.

Chromatic aberration examples

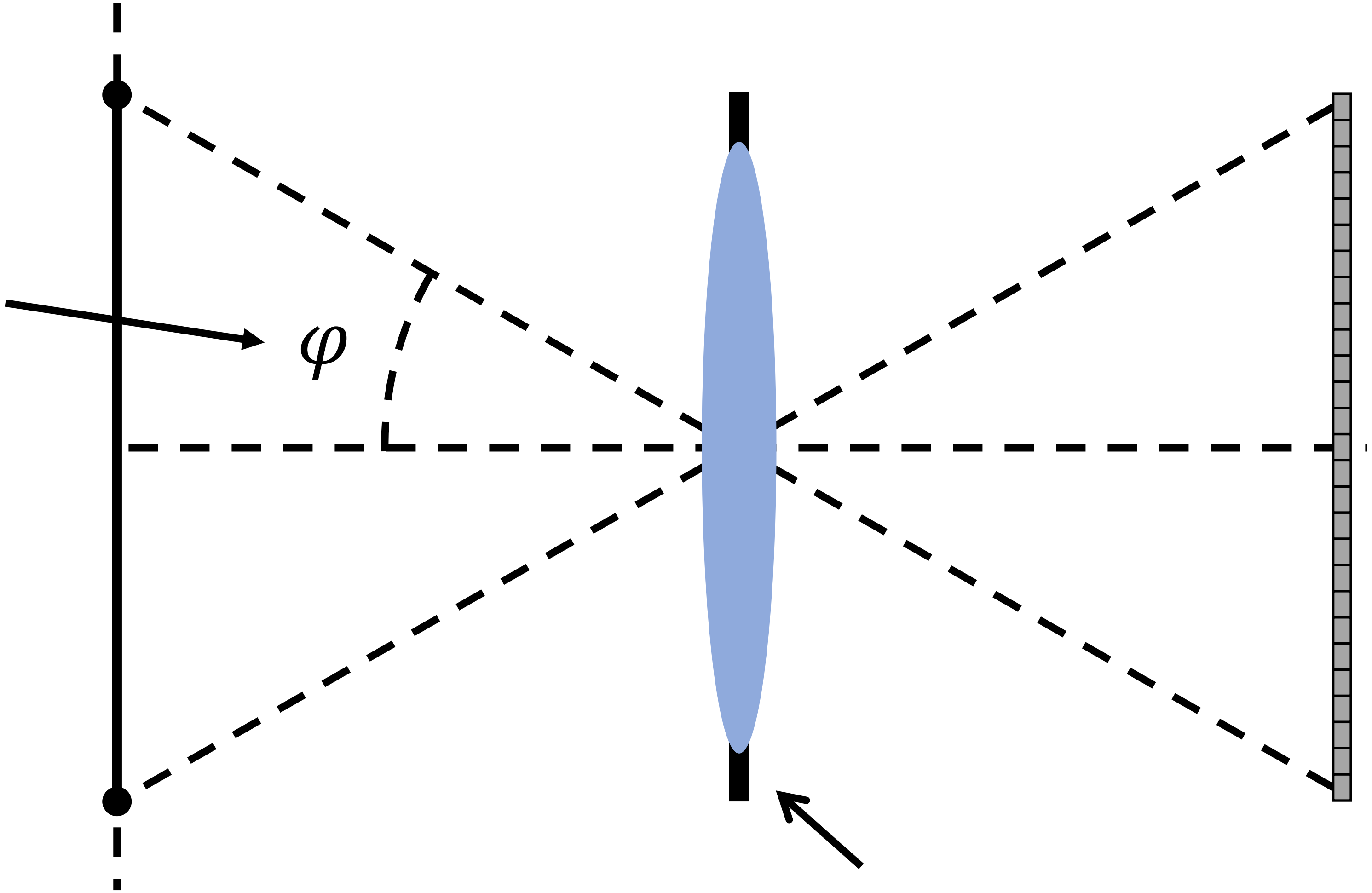
Field of view

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


What happens as you take a closer look?
179

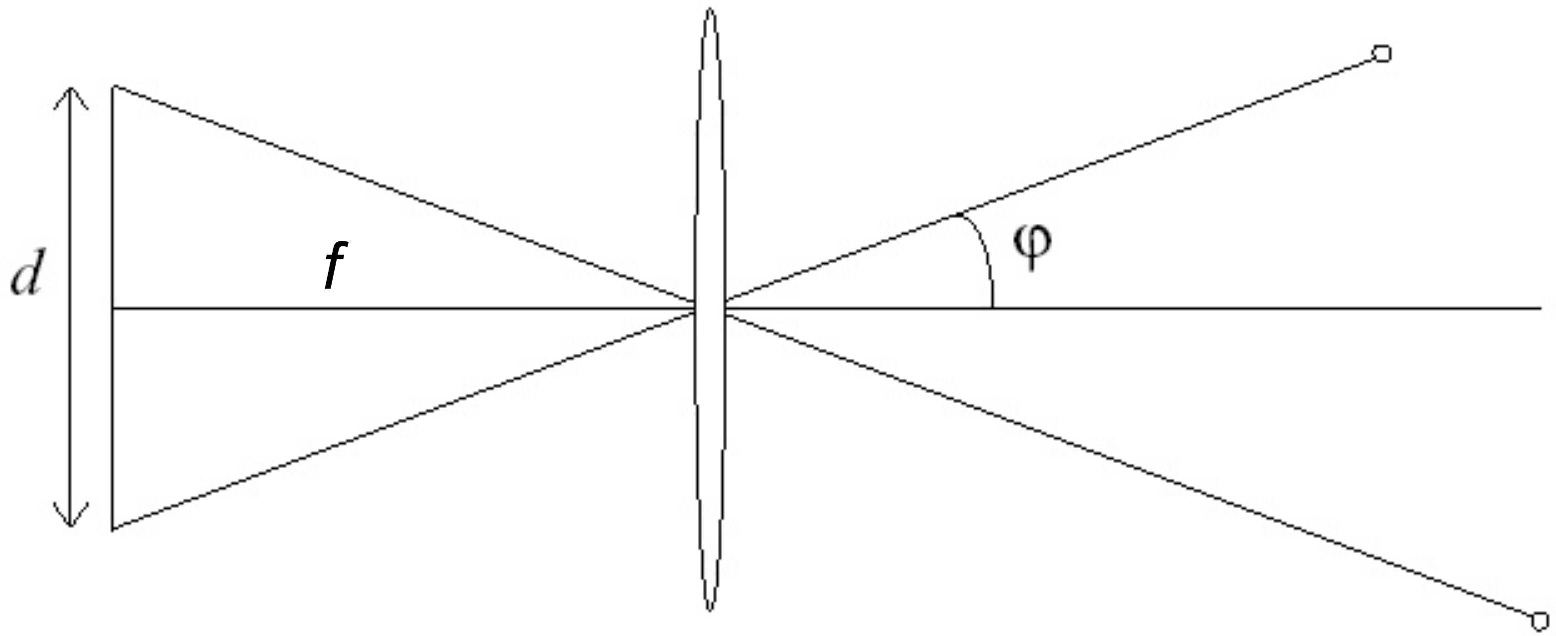
Field of view



also described using angle of view

Note: here I drew a lens, but I could have just as well drawn a pinhole

Field of view depends of focal length



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

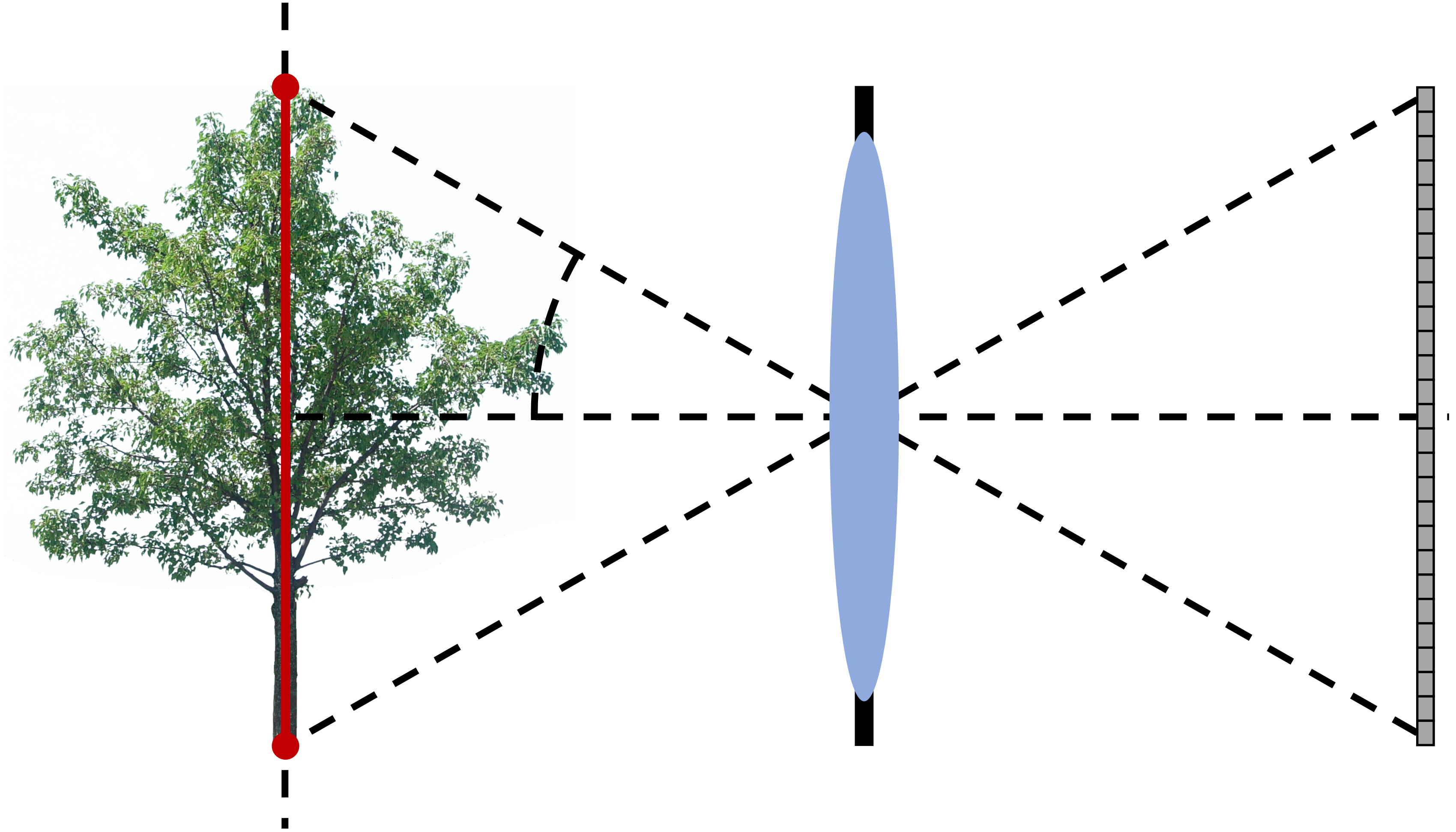
$$\varphi = \tan^{-1}\left(\frac{d}{2f}\right)$$

Smaller field of view = larger focal length

Field of view

The part of the in-focus plane that gets mapped on the sensor.

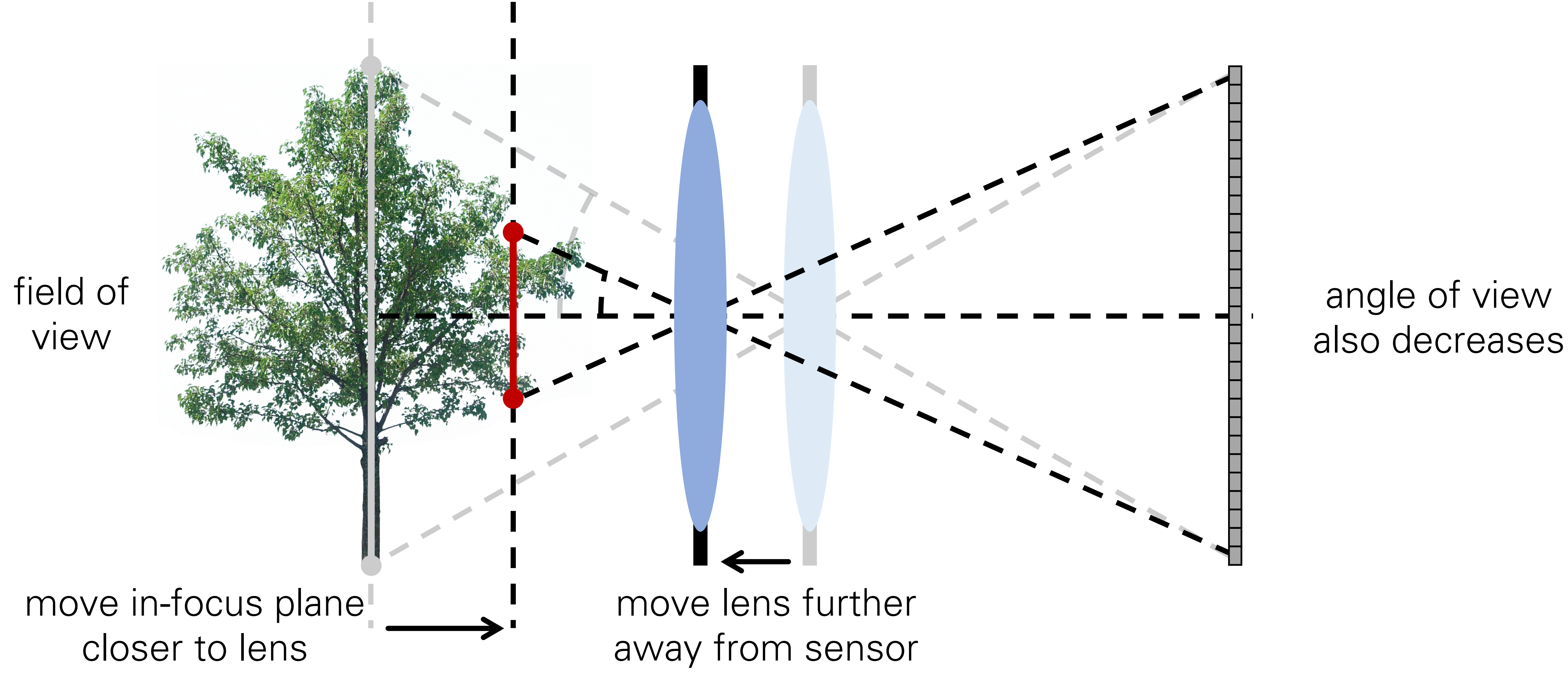
field of view



- What happens to field of view as we focus closer?

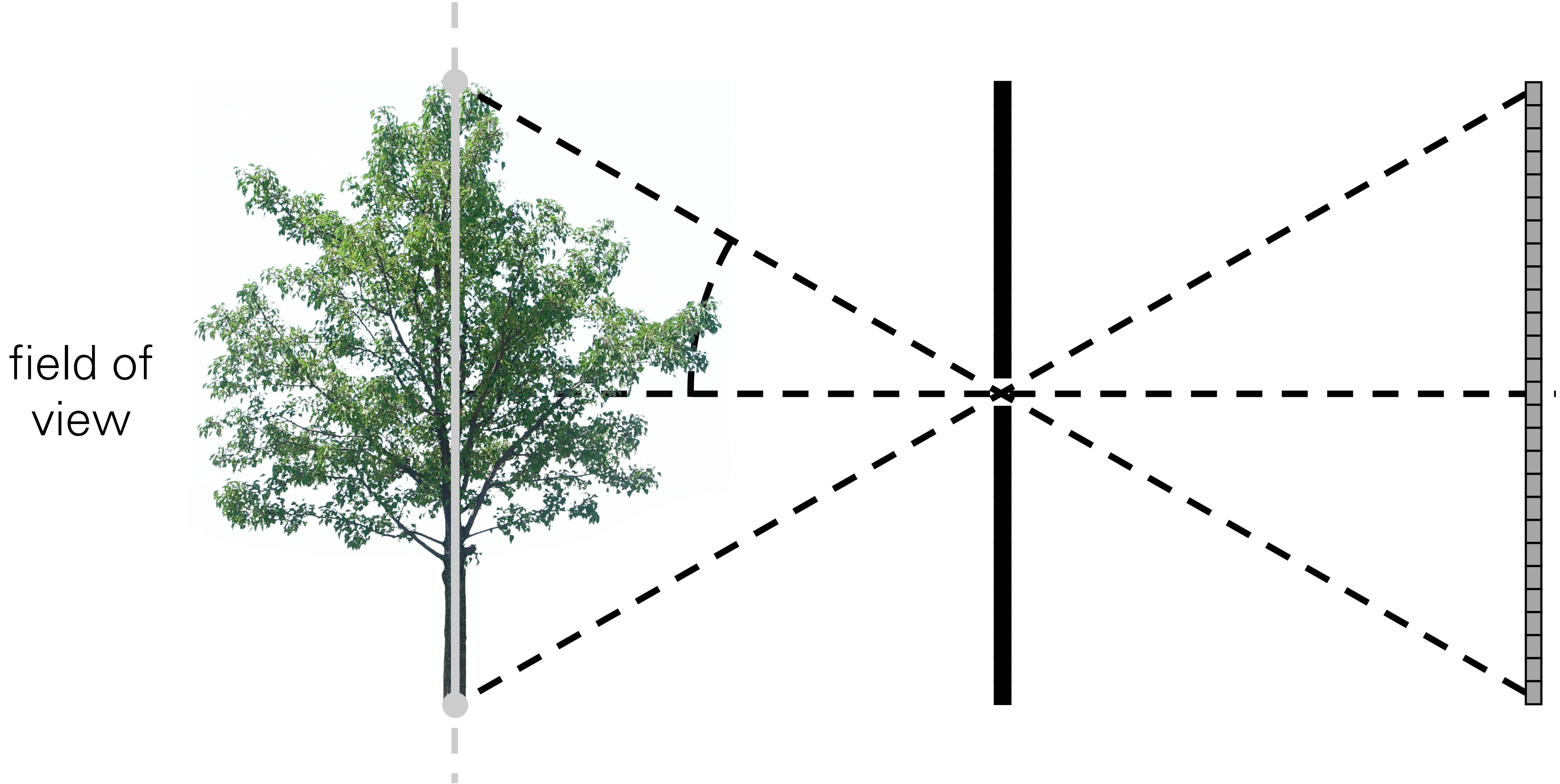
Field of view

The part of the in-focus plane that gets mapped on the sensor.



- What happens to field of view as we focus closer? → It becomes smaller.

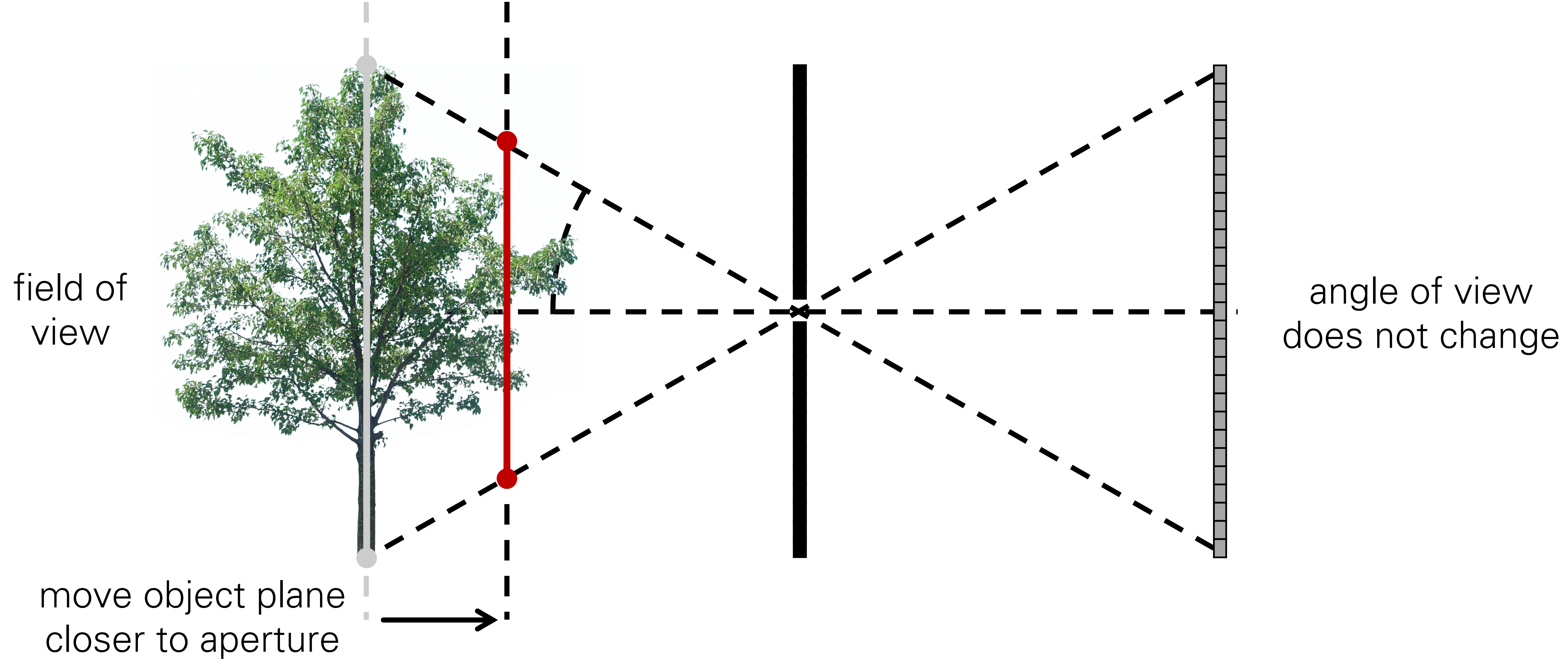
Comparison with pinhole camera



- What happens to field of view as we move closer?

Comparison with pinhole camera

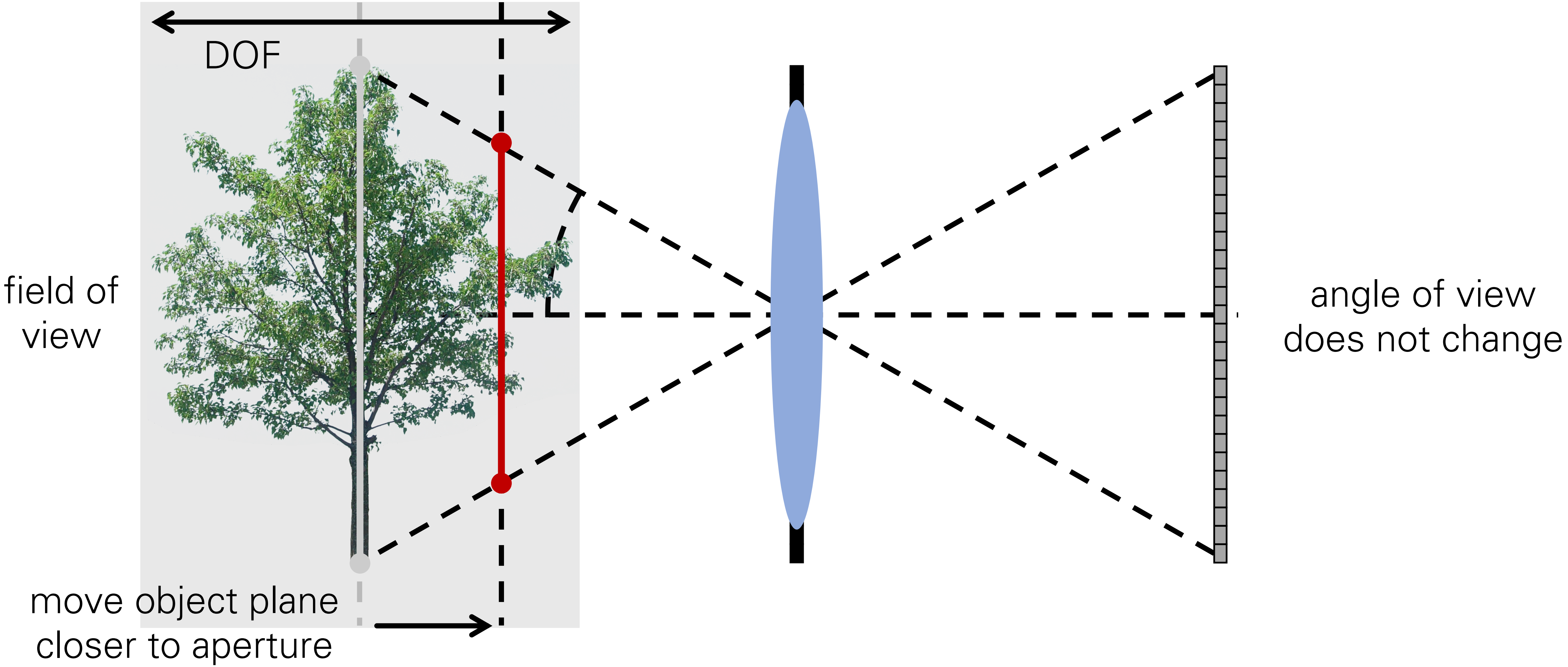
No need to refocus: we can move object closer without changing aperture-sensor distance.



- What happens to field of view as we move closer? → It becomes smaller, but amount differs.

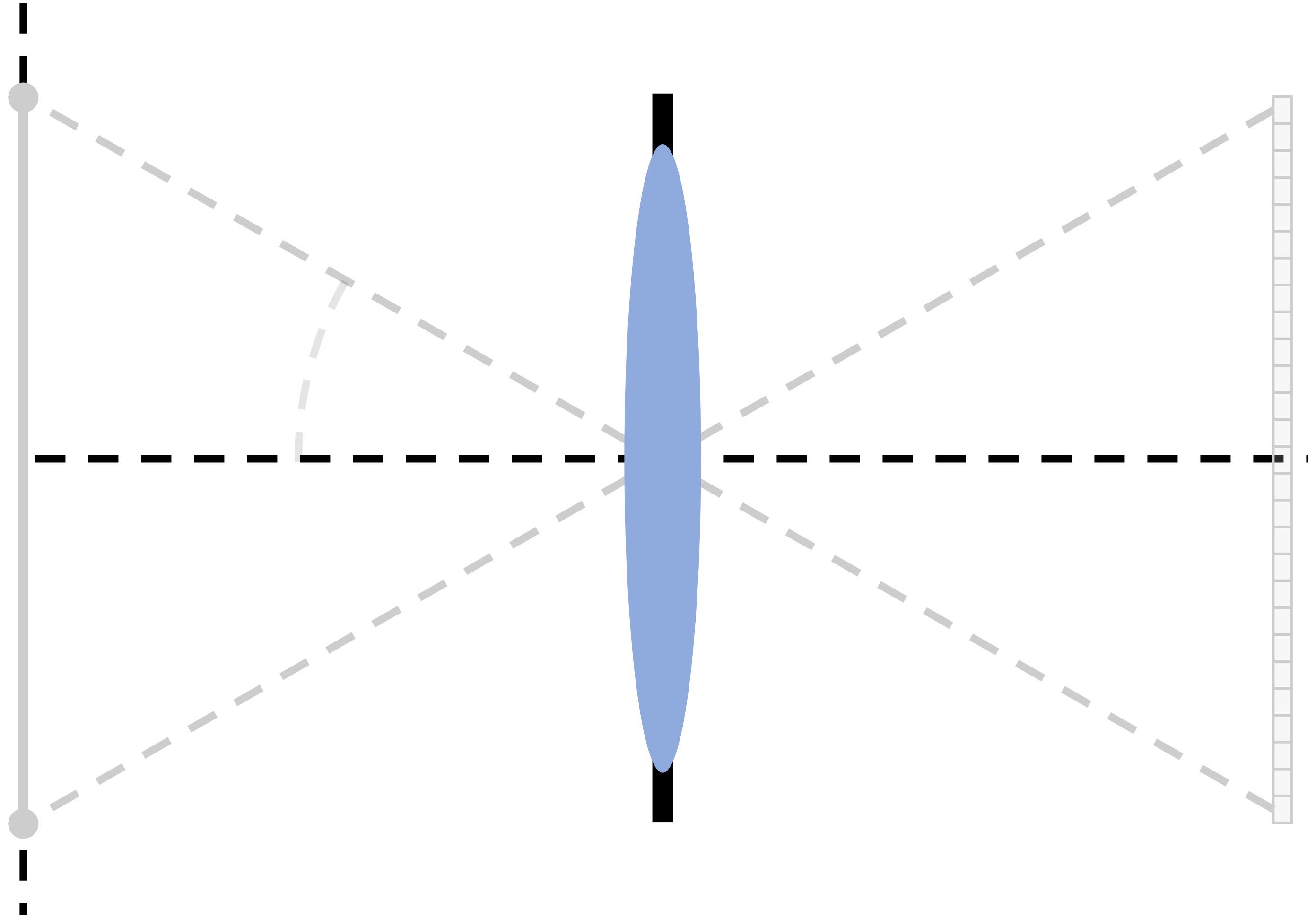
Comparison with pinhole camera

No need to refocus: we can move object closer without changing aperture-sensor distance.



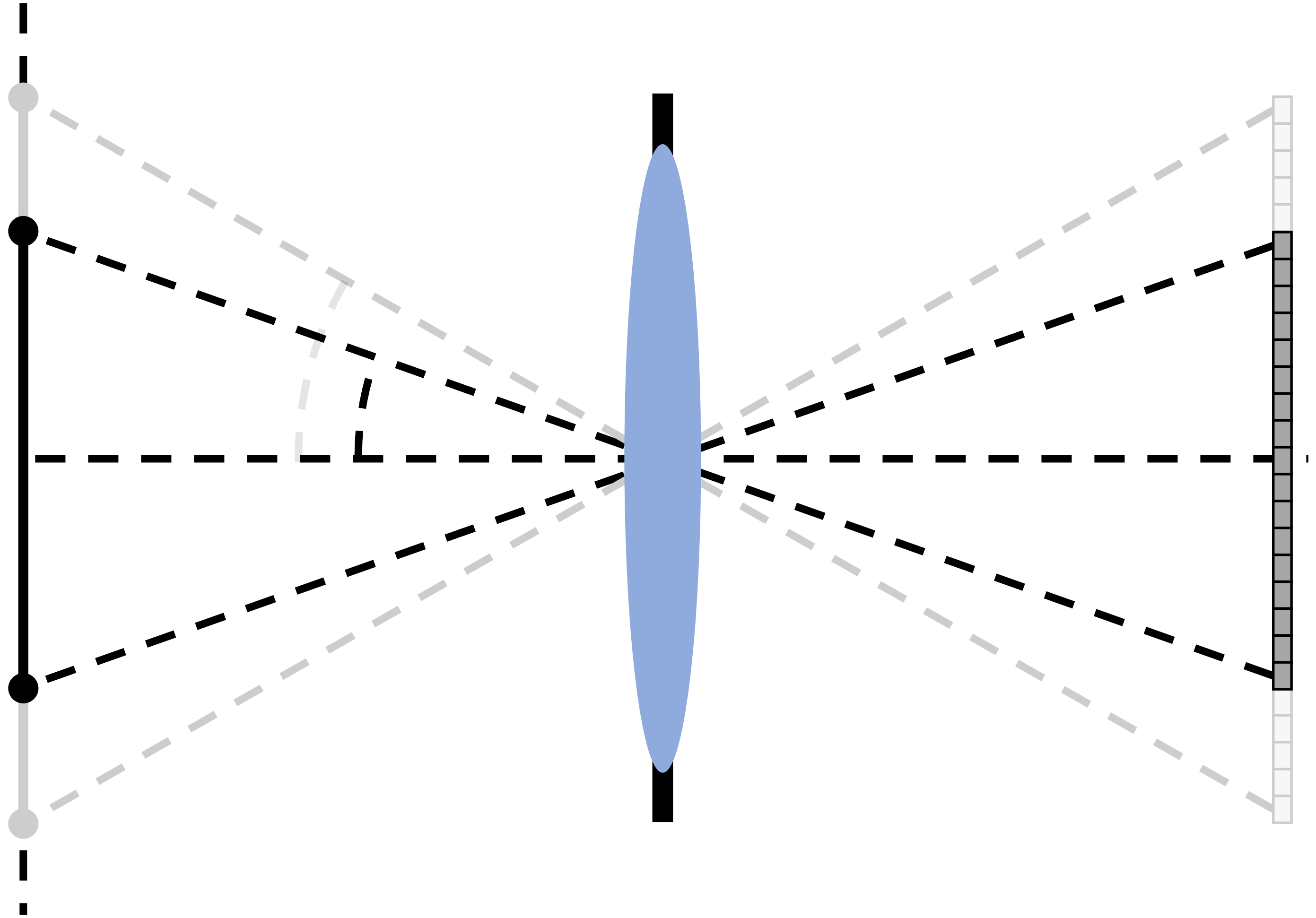
This can be done with a lens only if depth of field is large enough. Then the two behave the same.

Field of view also depends on sensor size



- What happens to field of view when we reduce sensor size?

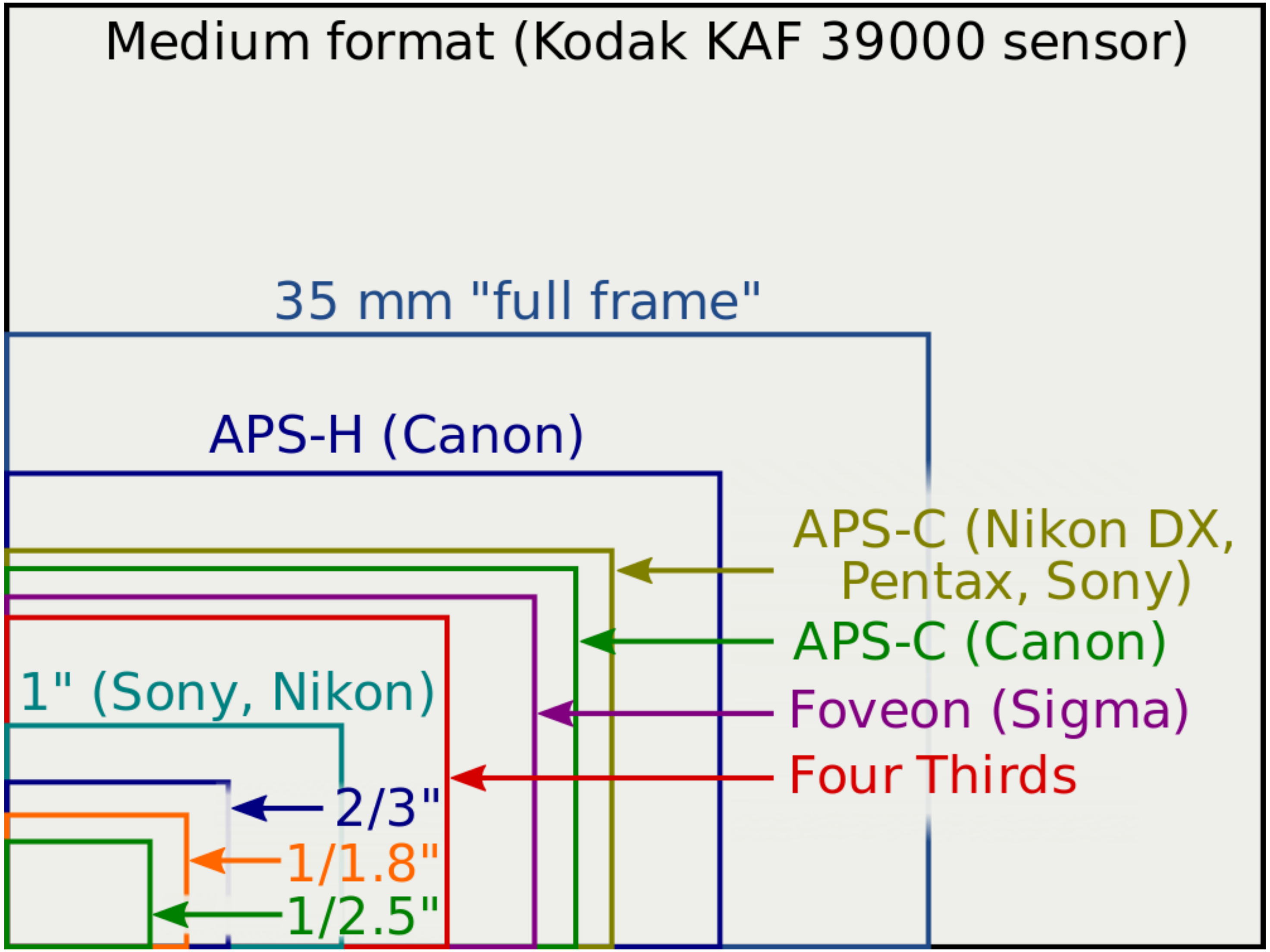
Field of view also depends on sensor size



Lens and pinhole cameras behave the same in this case.

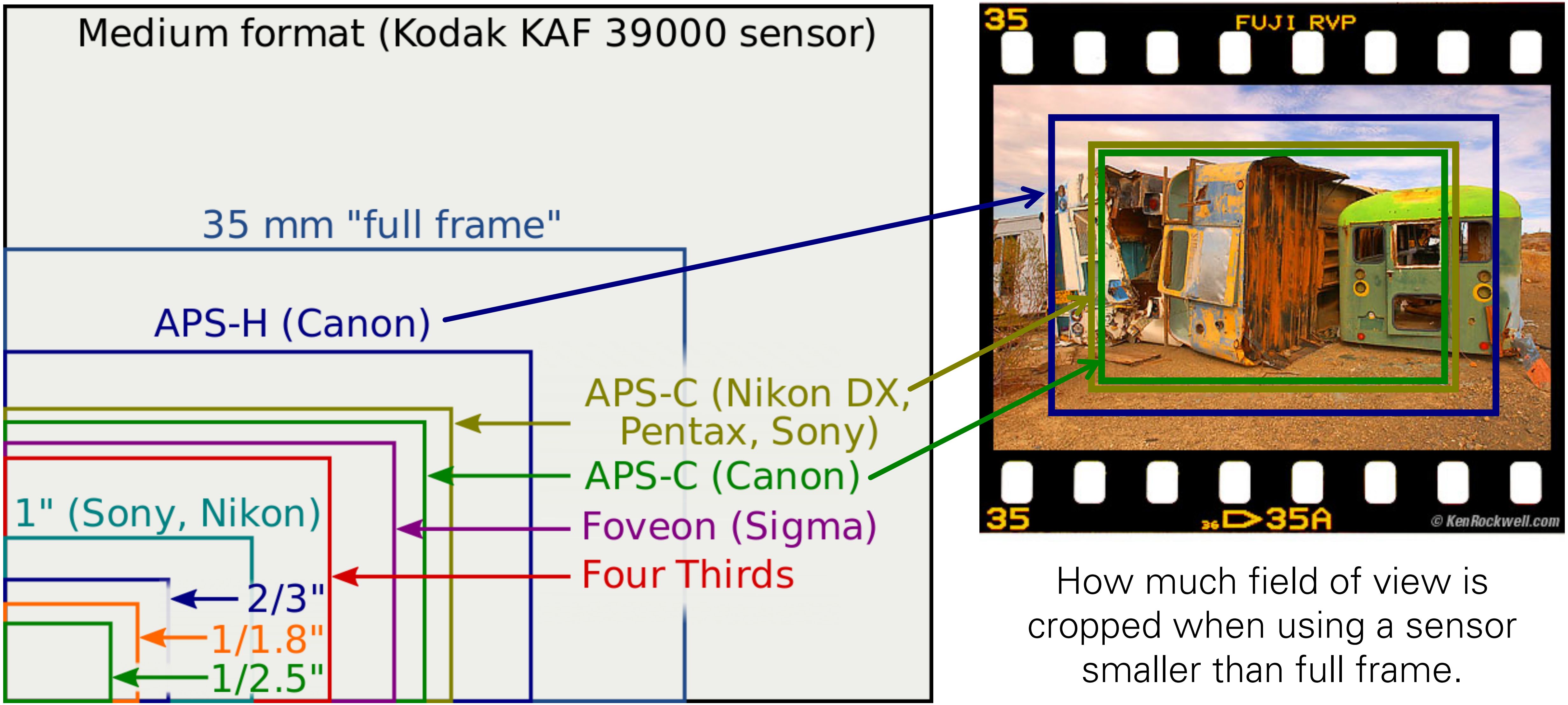
- What happens to field of view when we reduce sensor size? → It decreases.

Field of view also depends on sensor size



- "Full frame" corresponds to standard film size.
- Digital sensors come in smaller formats due to manufacturing limitations (now mostly overcome).
- Lenses are often described in terms of field of view on film instead of focal length.
- These descriptions are invalid when not using full-frame sensor.

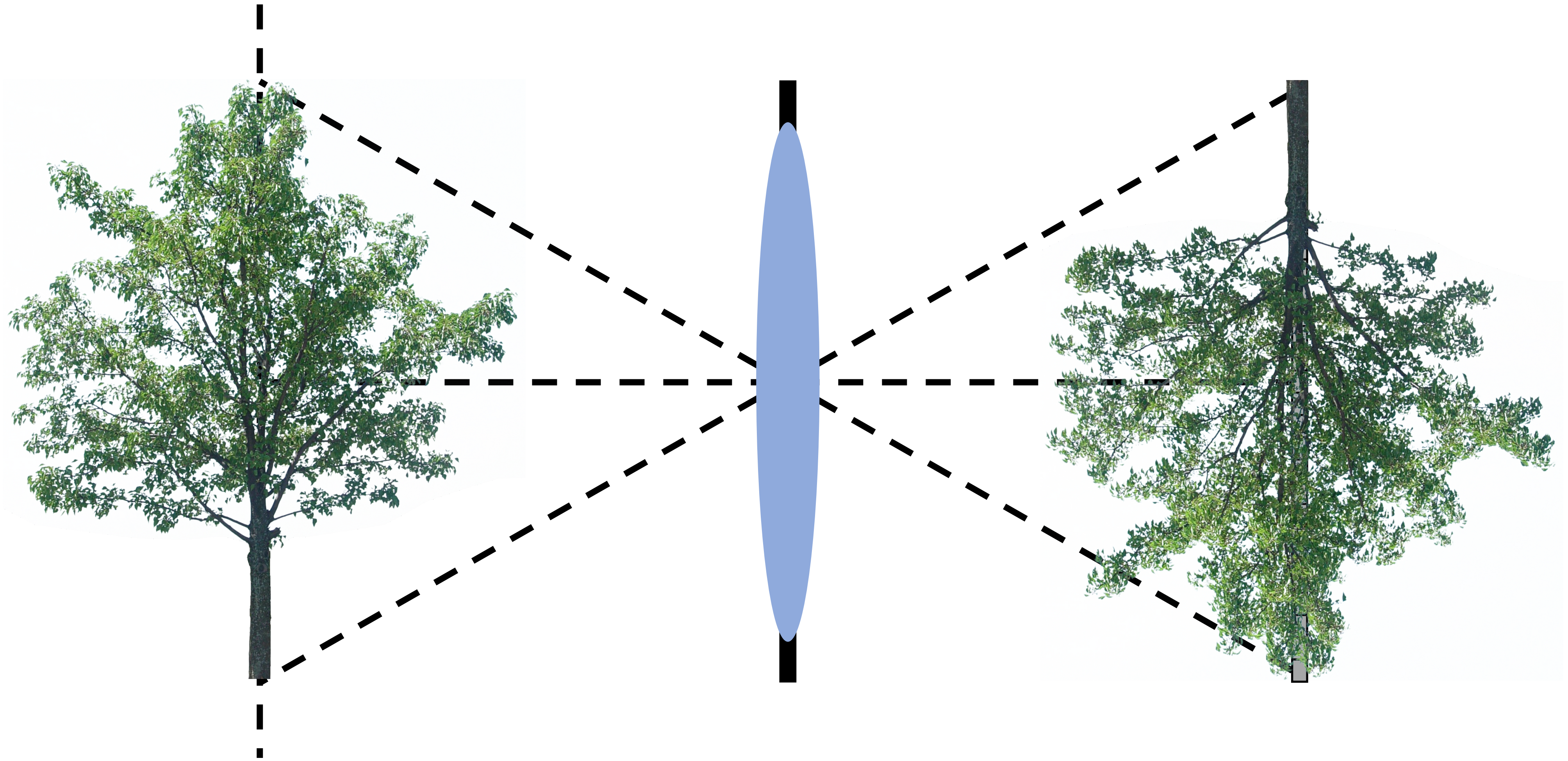
Crop factor



How much field of view is cropped when using a sensor smaller than full frame.

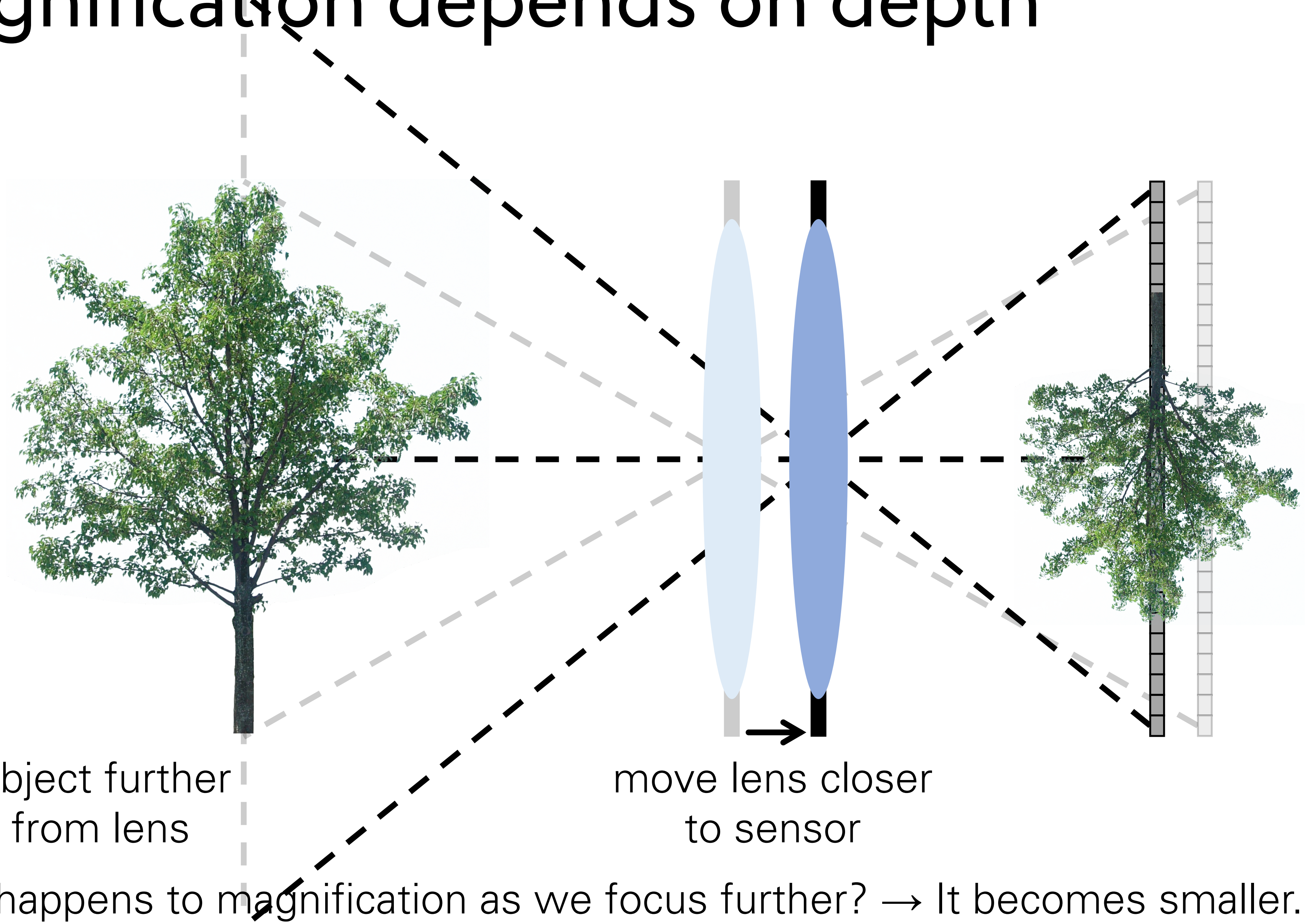
Magnification and perspective

Magnification depends on depth



- What happens to magnification as we focus further away?

Magnification depends on depth



move object further away from lens

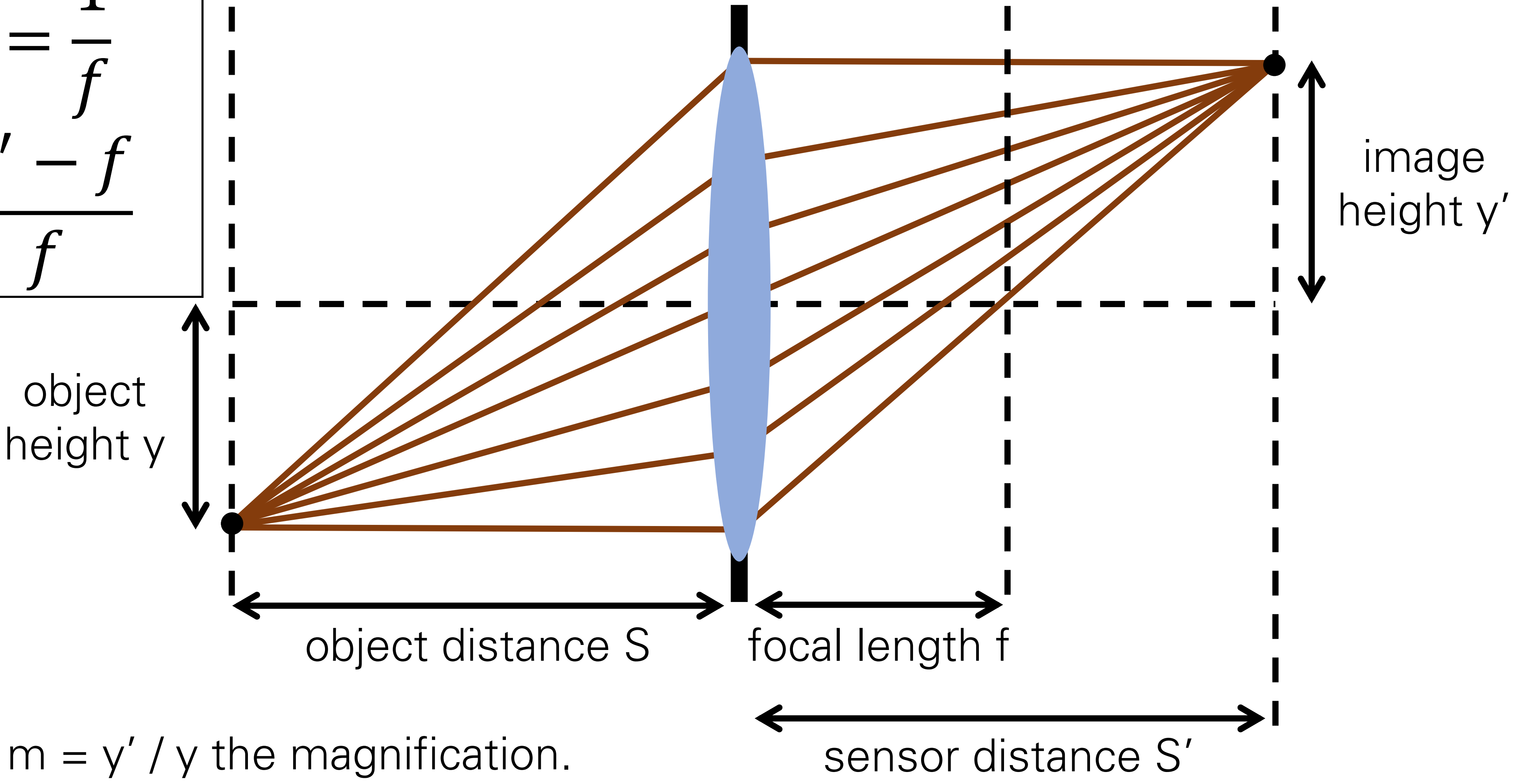
move lens closer to sensor

- What happens to magnification as we focus further? → It becomes smaller.

Magnification depends on depth

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

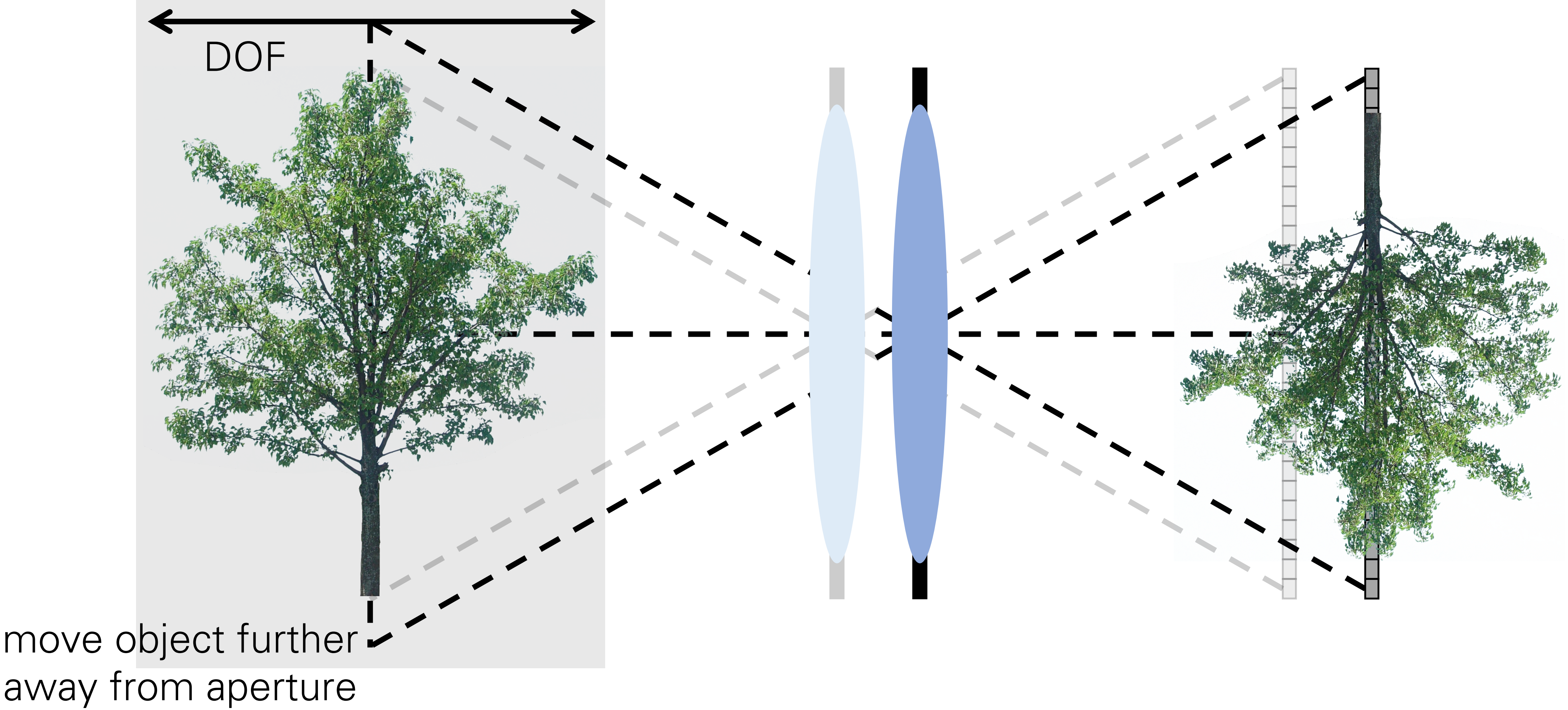
$$m = \frac{S' - f}{f}$$



- We call m = y′ / y the magnification.

Comparison with pinhole camera

No need to refocus: we can move object further without changing aperture-sensor distance.

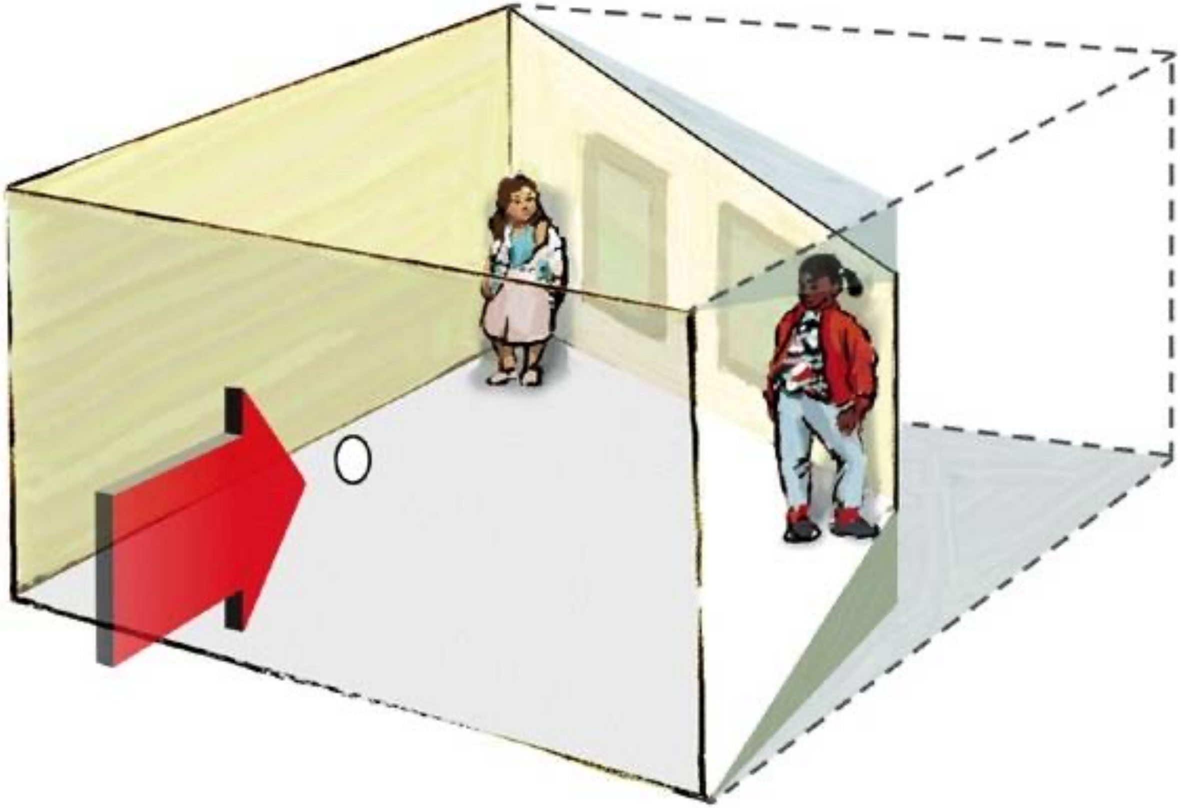


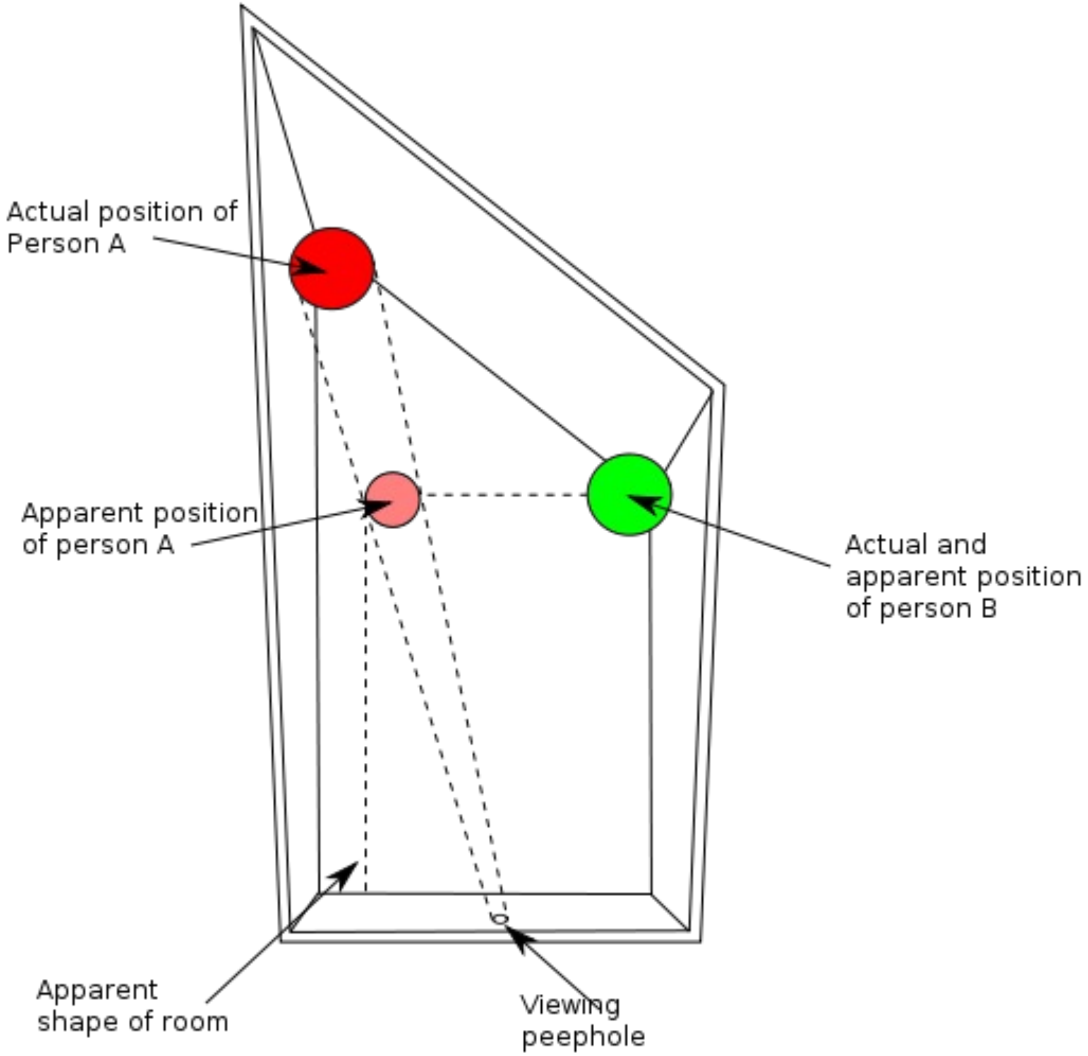
This can be done with a lens only if depth of field is large enough. Then the two behave the same.

Forced perspective

The Ames room illusion

The Ames room illusion





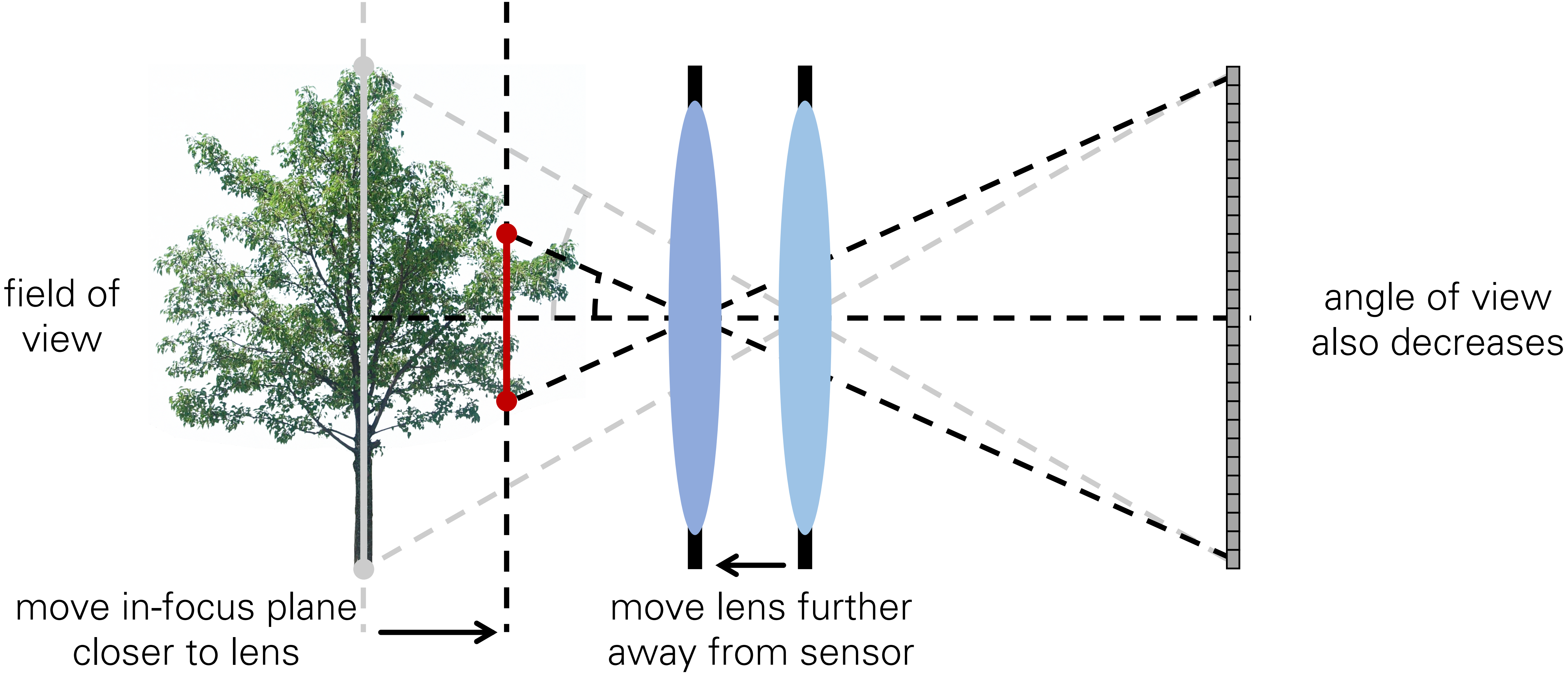
The arrow illusion

Prof. Kokichi Sugihara has many other amazing illusions involving perspective distortion, check them out on YouTube or on his website:
http://www.isc.meiji.ac.jp/~kokichis/

Zooming

Field of view

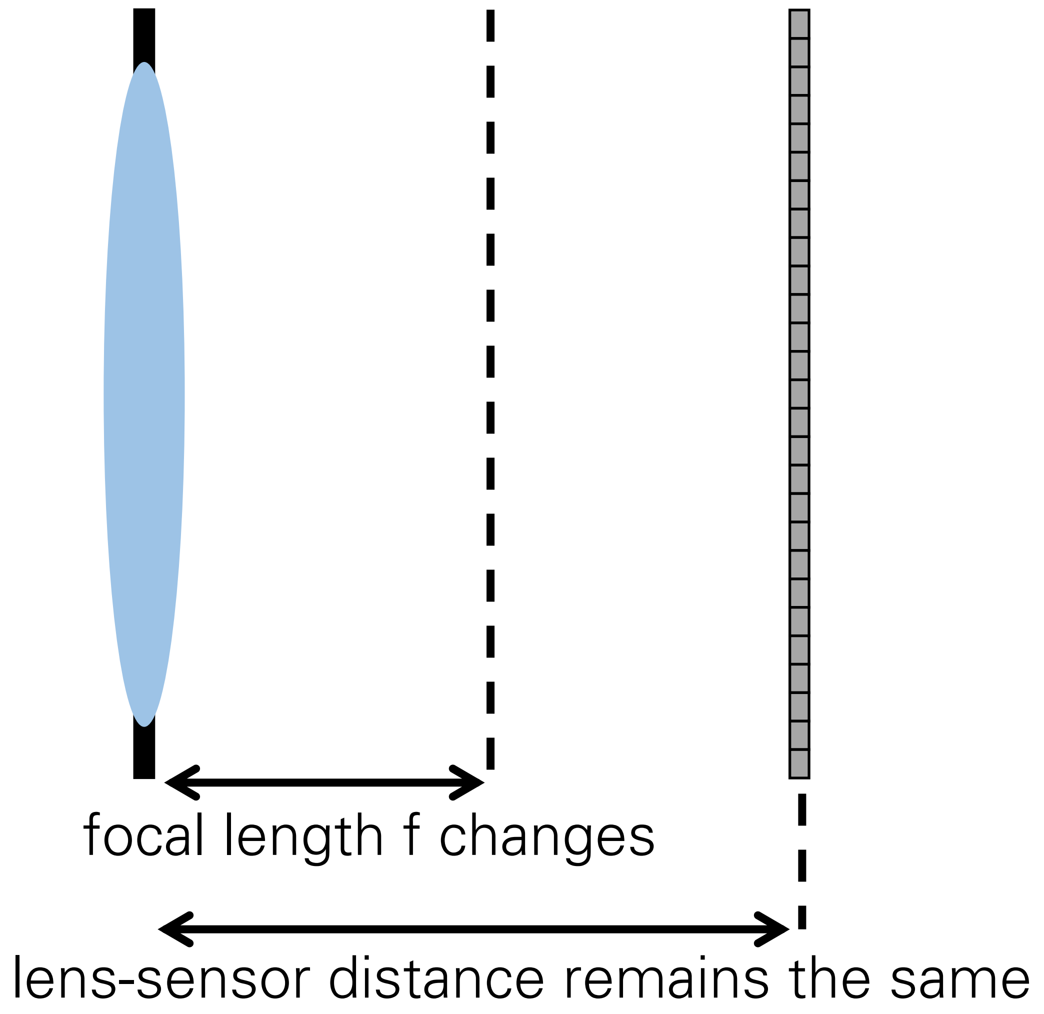
The part of the in-focus plane that gets mapped on the sensor.



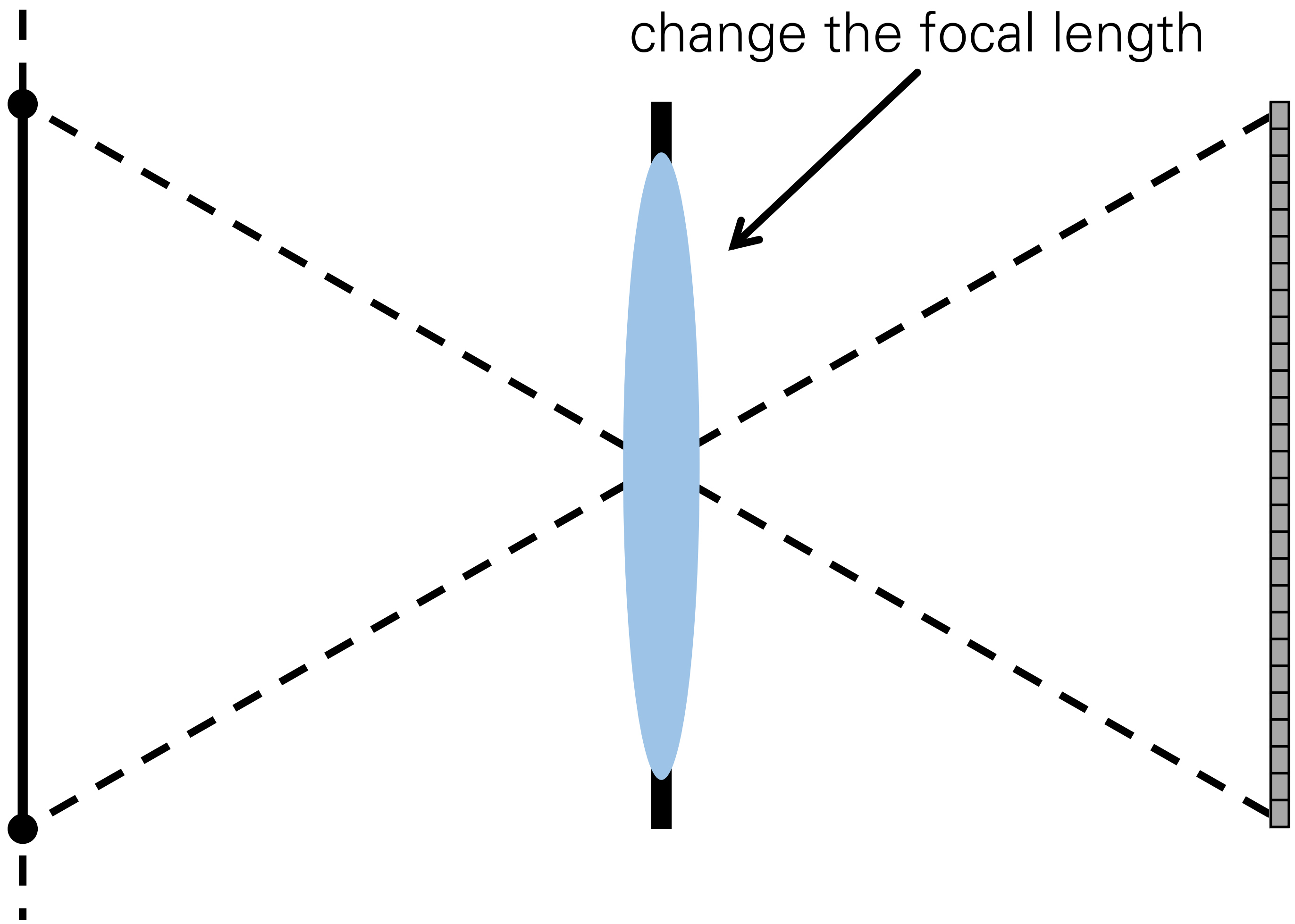
- What happens to field of view as we focus closer? → It becomes smaller.

Zooming means changing the focal length

Very different process from refocusing

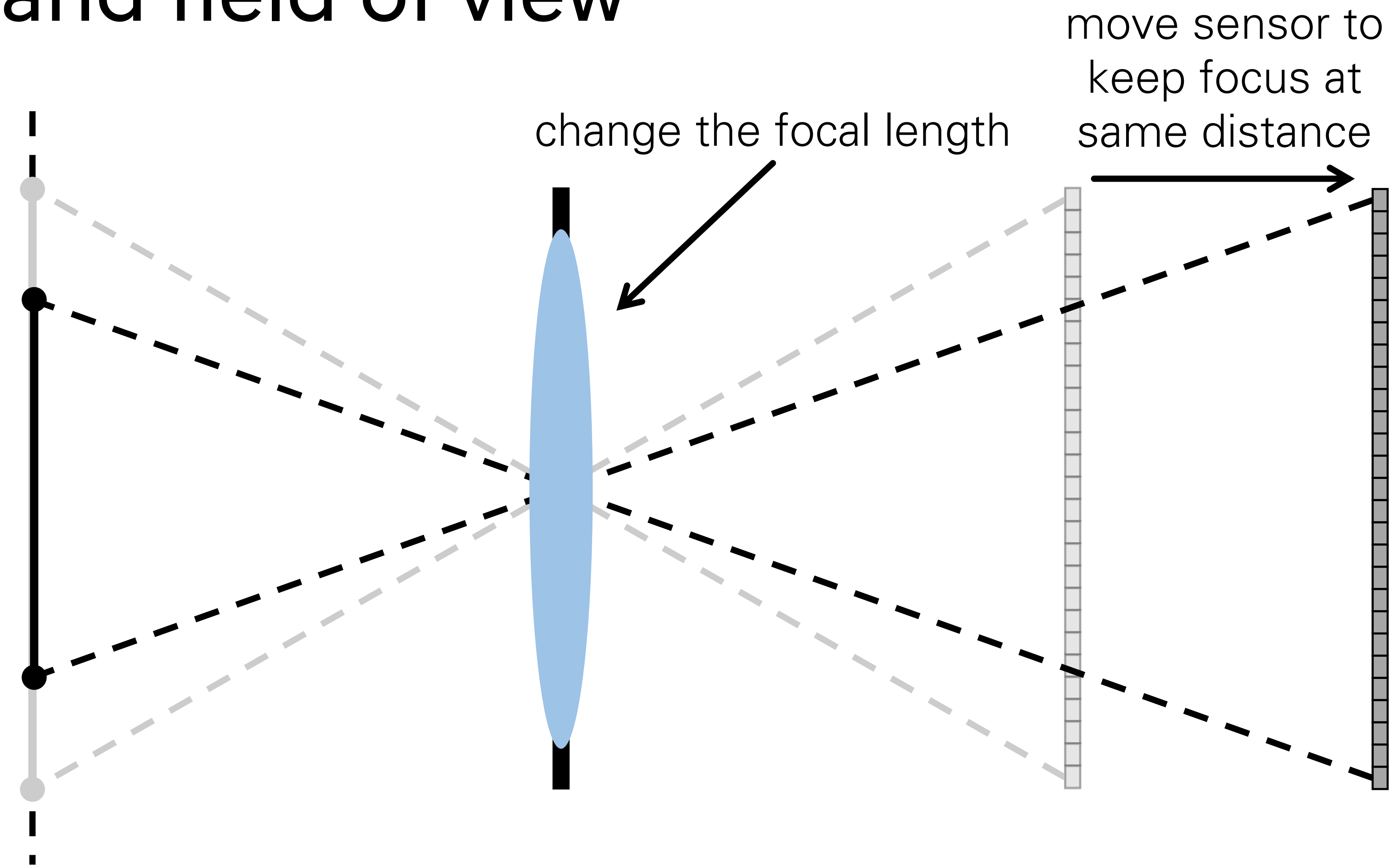


Zooming and field of view



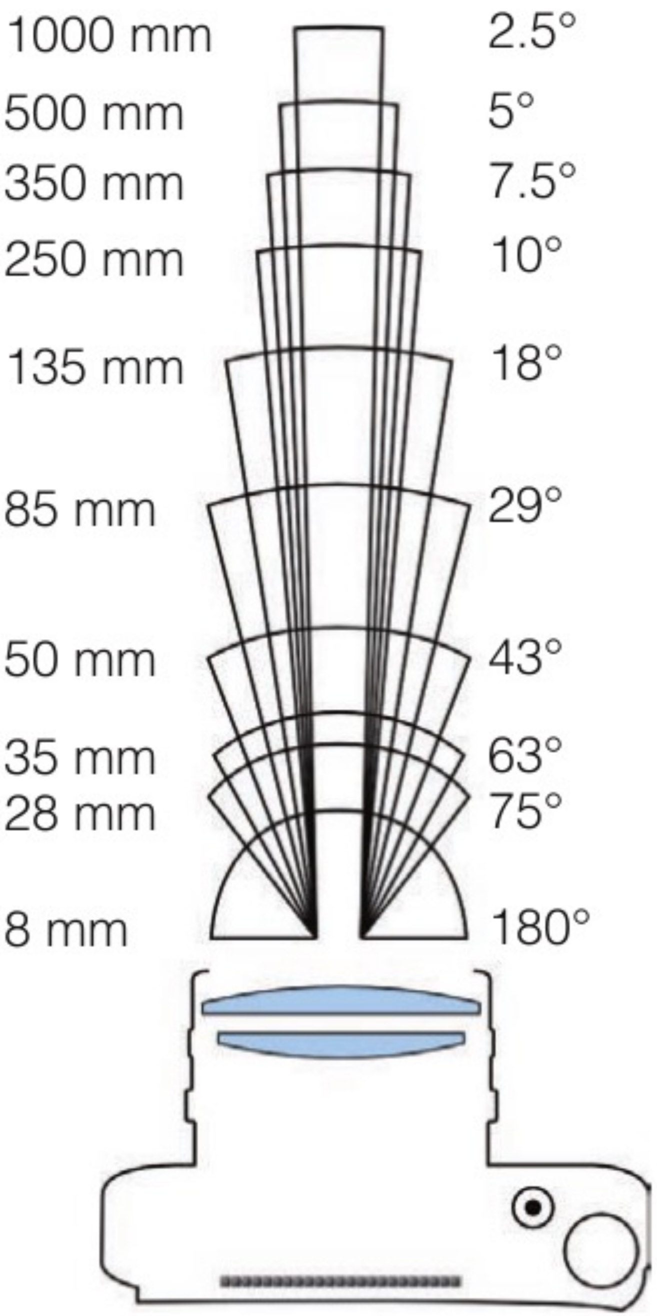
- What happens to field of view when we focus closer? → It decreases.
- What happens to field of view when we increase <u>lens</u> focal length?

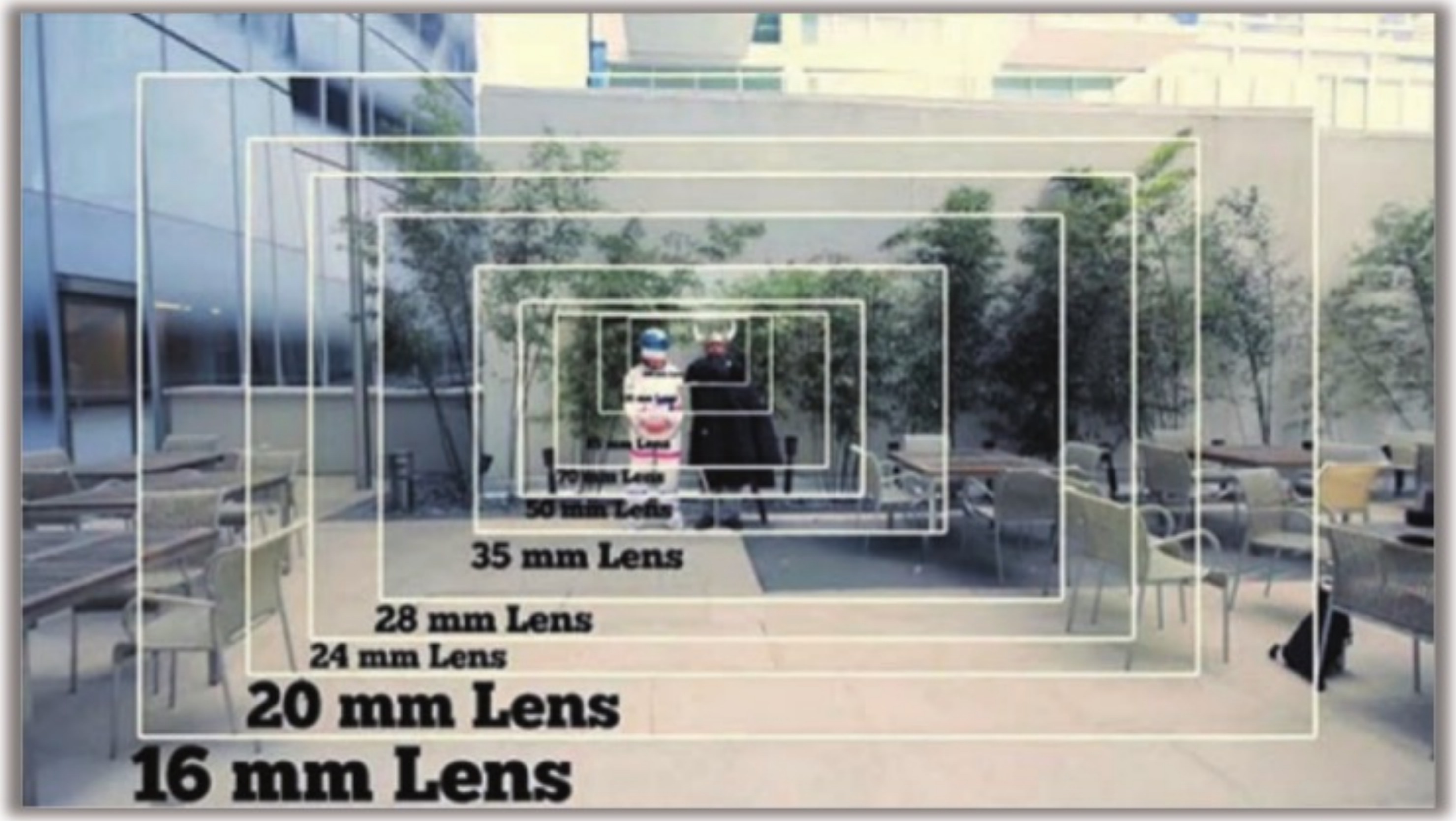
Zooming and field of view



- When we increase lens focal length, field of view decreases (we "zoom in").

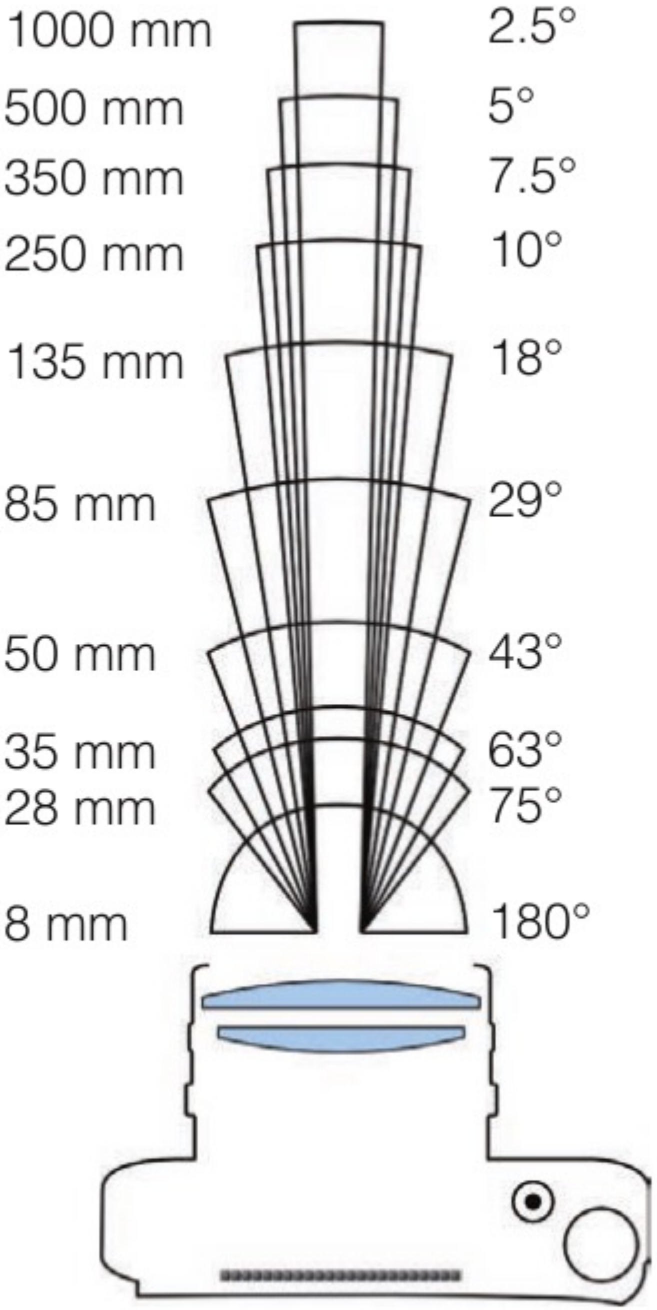
Field of view



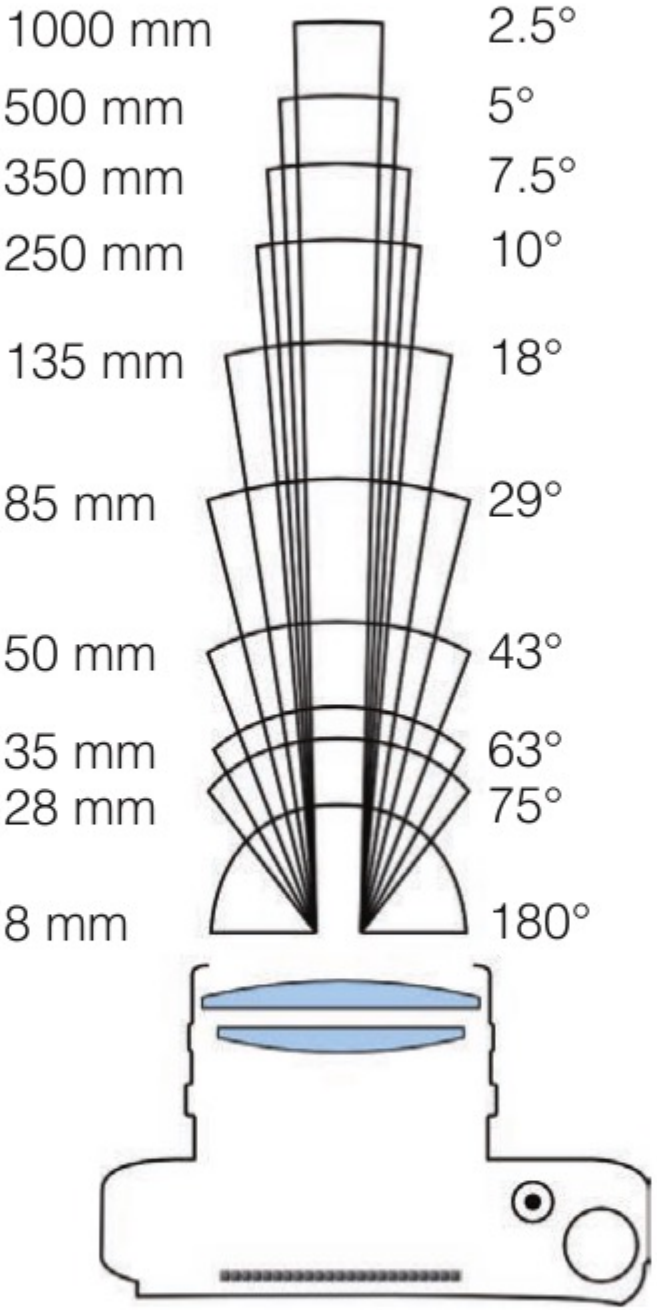


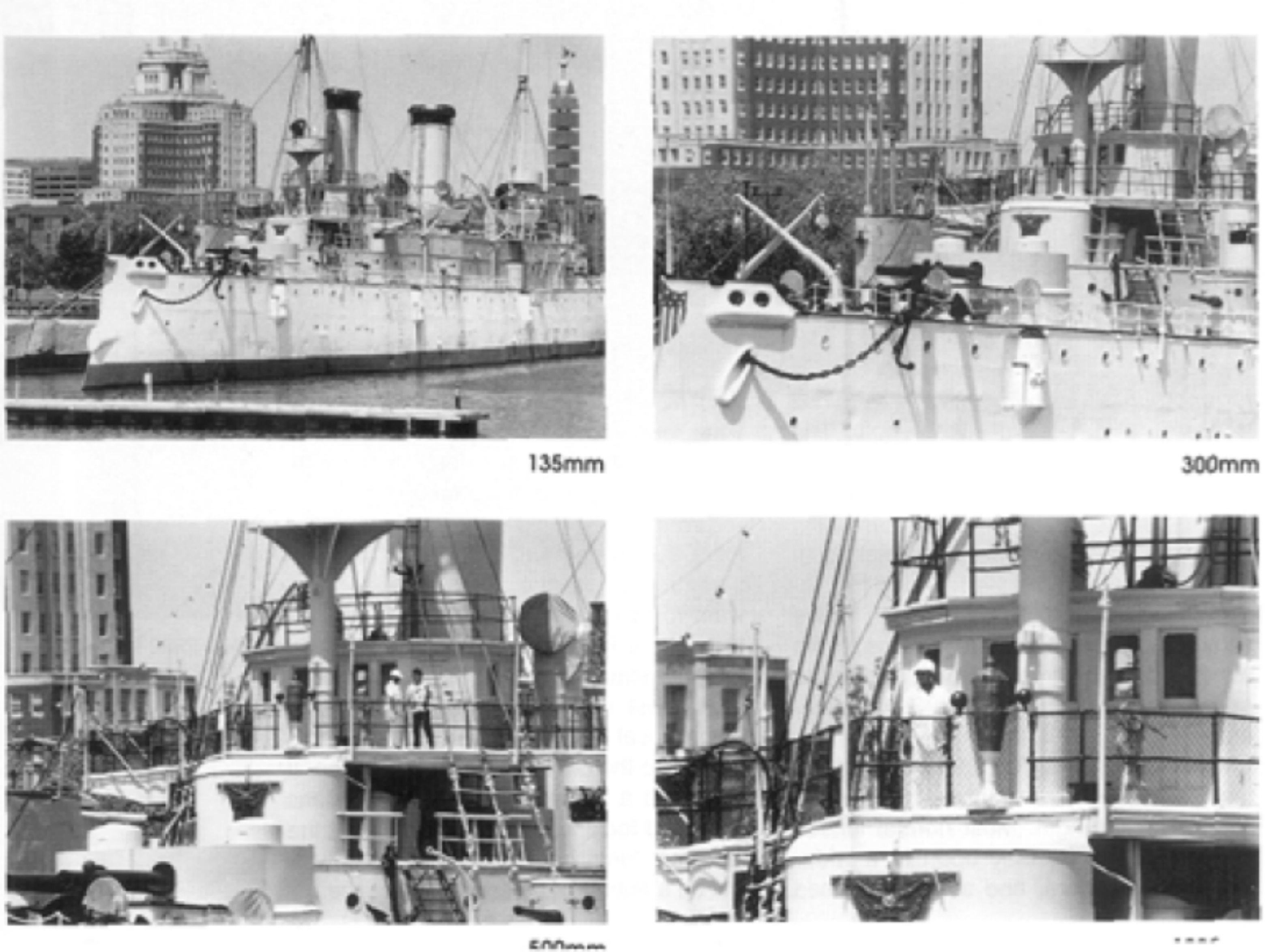
Andrew McWilliams

Field of view



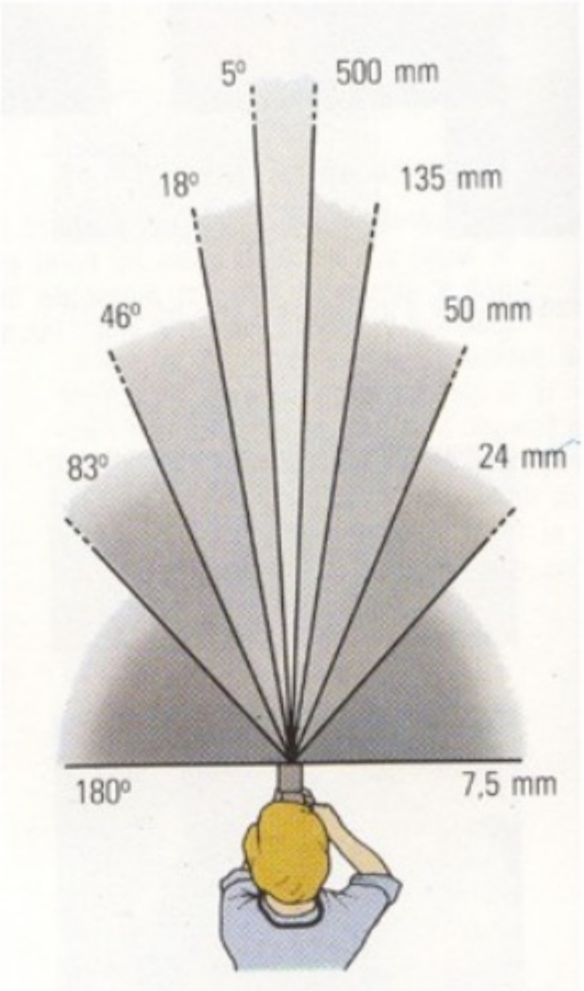
Field of view





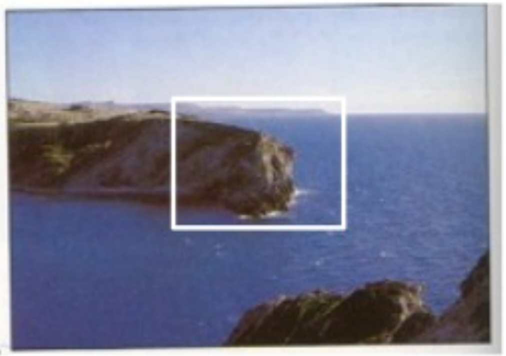
Field of view

Increasing the lens focal length is similar to cropping



f = 25 mm

f = 50 mm



f = 135 mm

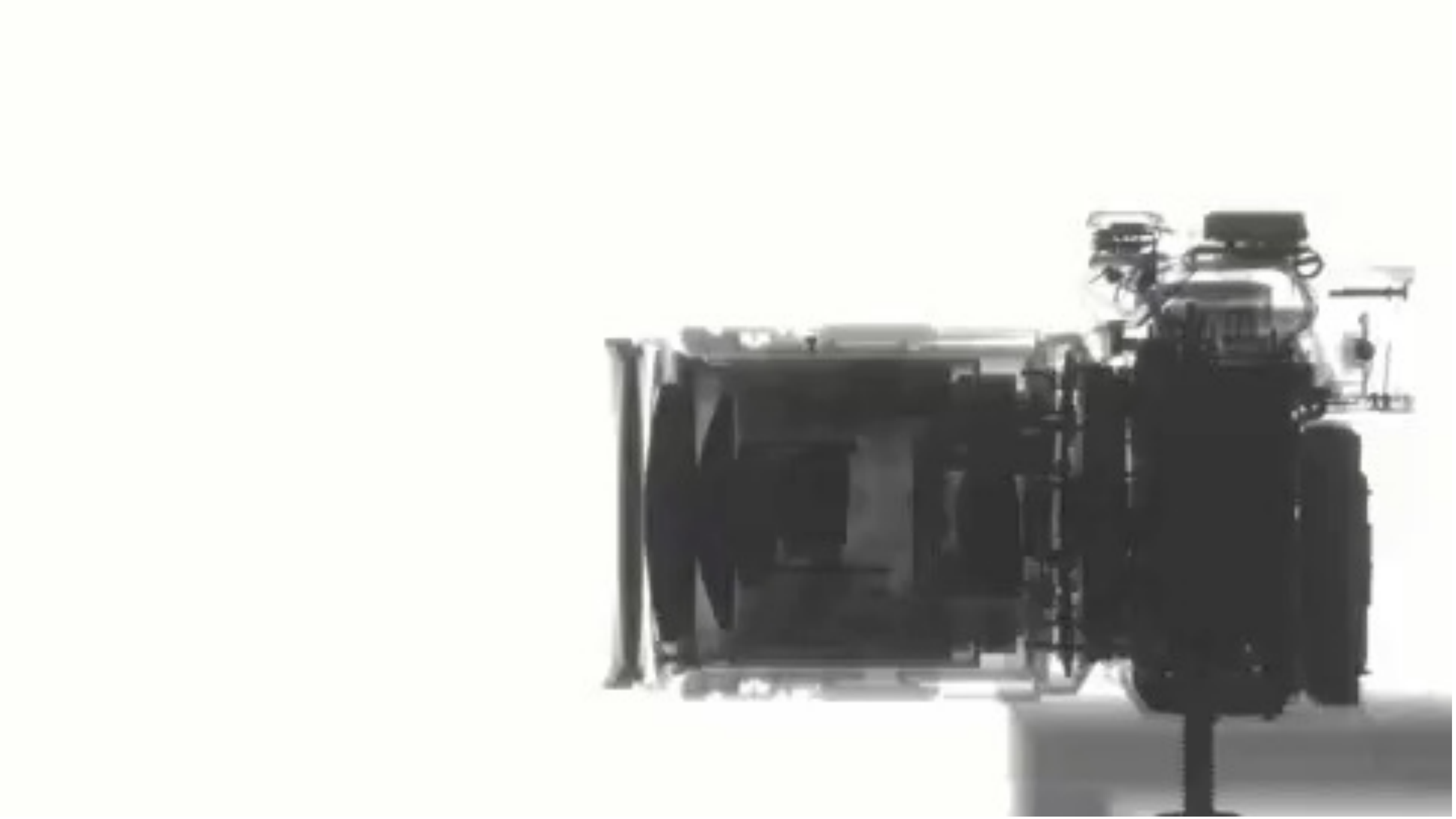
Is this effect identical to cropping?

The lens on your camera

Focus ring: controls distance of lens from sensor

Zoom ring: controls focal length of lens

The lens on your camera



Credit: P. Milanfar

Focusing versus zooming

When you turn the focus ring to bring lens further-away from the sensor:
1. The in-focus distance decreases (you need to get closer to object).
2. The field of view decreases (you see a smaller part of the object).
3. The magnification increases (same part of the object is bigger on sensor).

When you turn the zoom ring to decrease the focal length of the lens:
1. The in-focus distance increases (you need to move away from the object).
2. The field of view increases (you see a larger part of the object).
3. The magnification decreases (same part of the object is smaller on sensor).

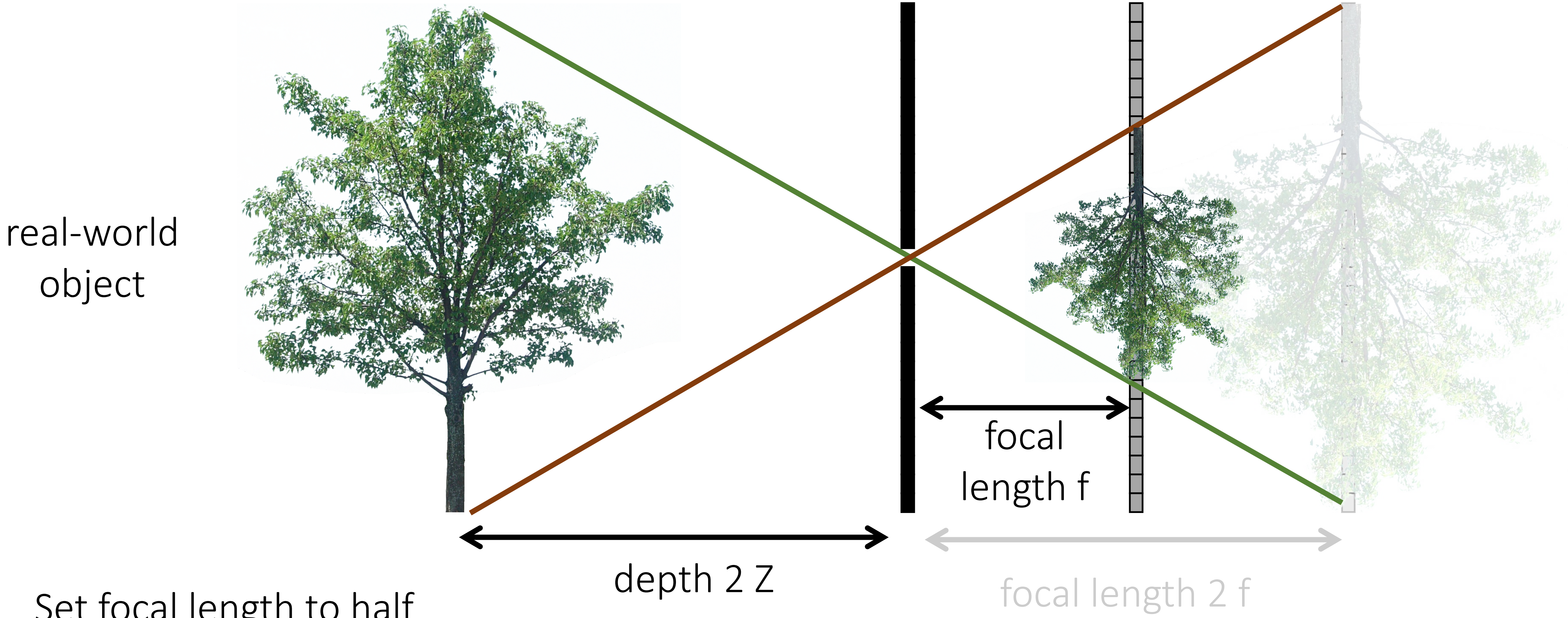
Focusing versus zooming

When you turn the focus ring to bring lens further-away from the sensor:
1. The in-focus distance decreases (you need to get closer to object).
2. The field of view decreases (you see a smaller part of the object).
3. The magnification increases (same part of the object is bigger on sensor).

When you turn the zoom ring to decrease the focal length of the lens:
1. The in-focus distance increases (you need to move away from the object).
2. The field of view increases (you see a larger part of the object).
3. The magnification decreases (same part of the object is smaller on sensor).

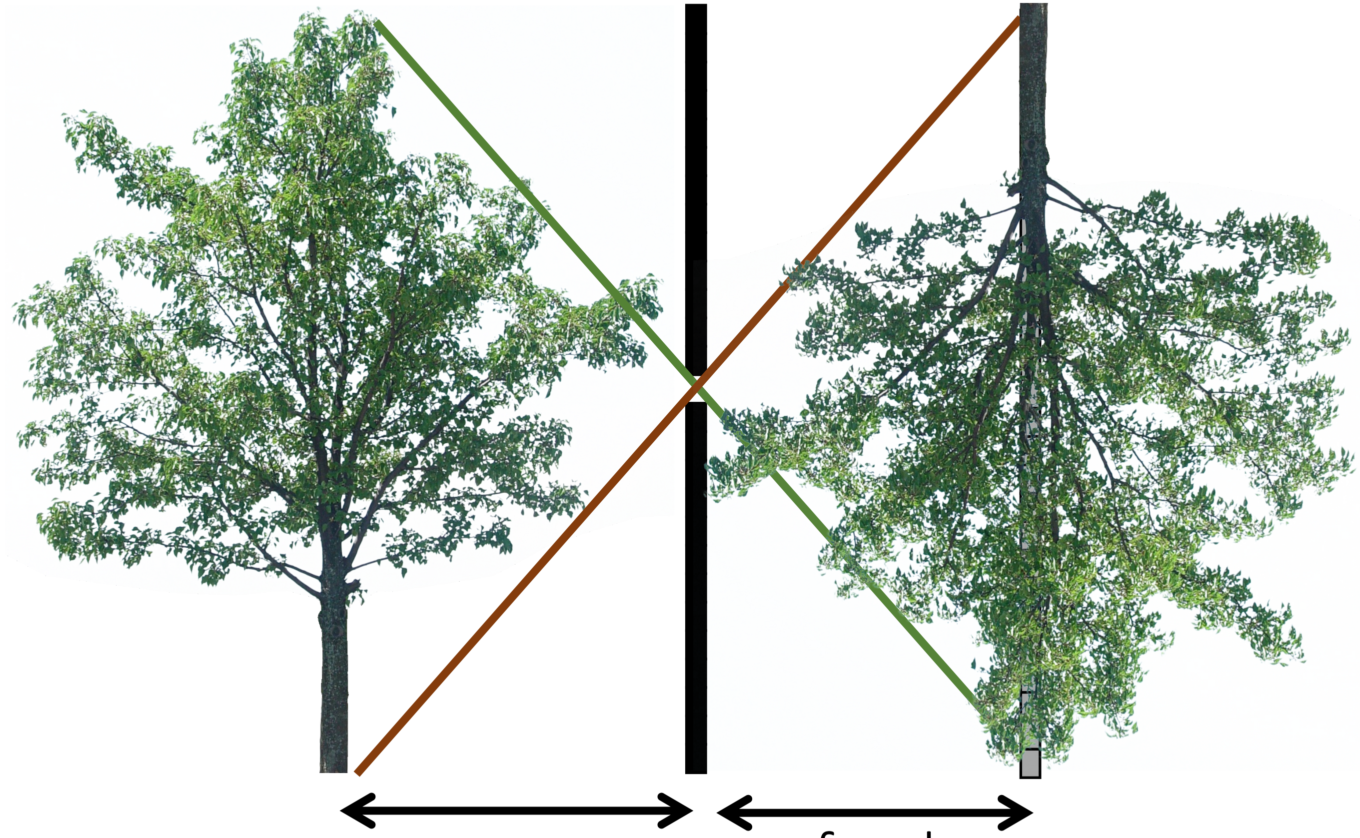
We can use both focus and zoom to cancel out their effects.

What if...



1. Set focal length to half

What if…



Is this the same image as the one we had at focal length 2f and distance 2Z?

1. Set focal length to half
2. Set depth to half

Similar construction can be done with lenses, after taking care of refocusing.

Perspective distortion

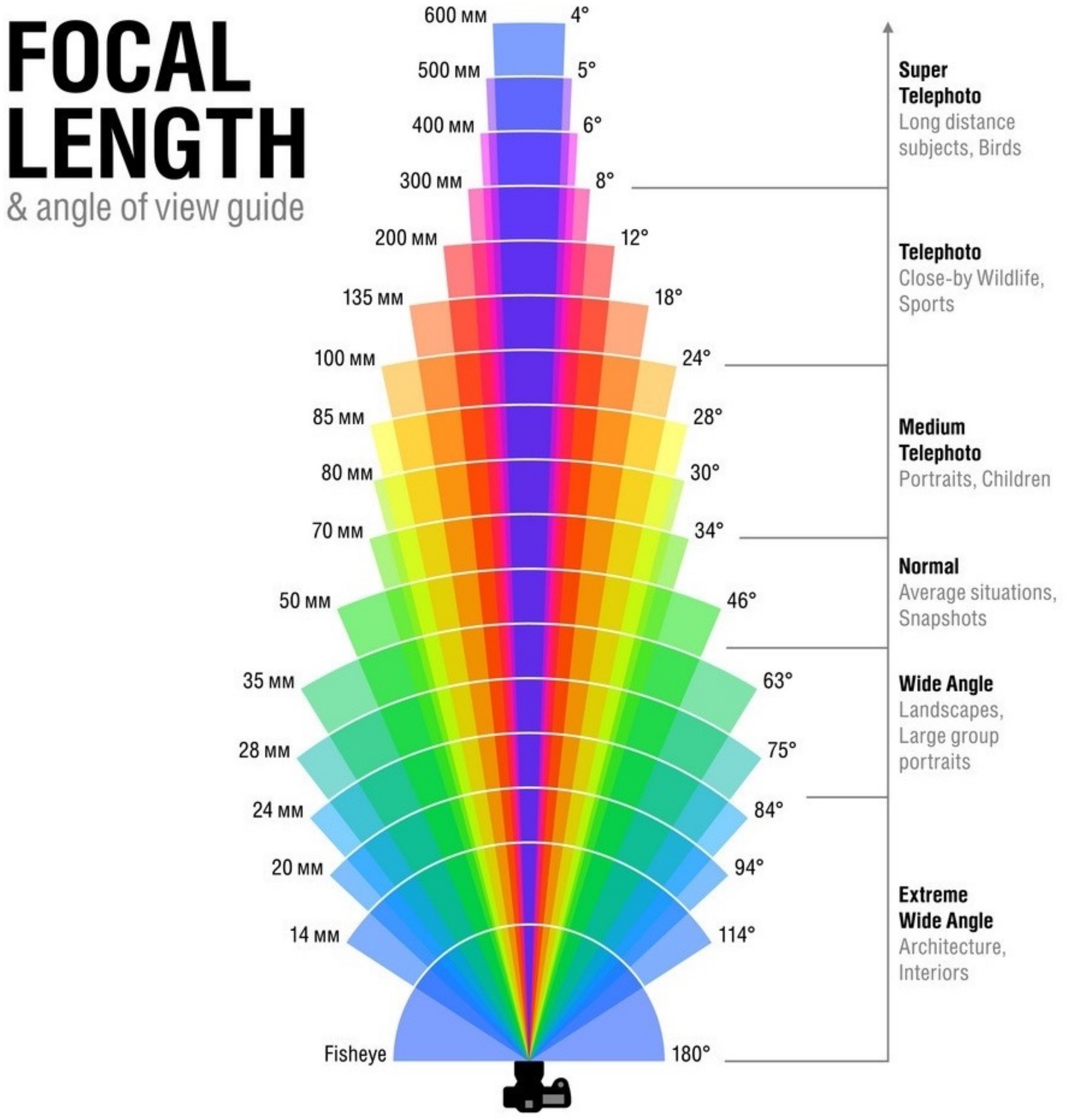

long focal length


mid focal length


short focal length

Perspective distortion

Perspective distortion



Credit: P. Milanfar

What is the best focal length for portraits?

That's like asking which is better, vi or emacs…

long focal length

mid focal length

short focal length

Vertigo effect

Named after Alfred Hitchcock's movie

- also known as "dolly zoom"

Vertigo effect

How would you create this effect?

Long focal length

When the focal length is long,
the field of view becomes very small
and the resulting image appears
more flat.

Credit: P. Milanfar

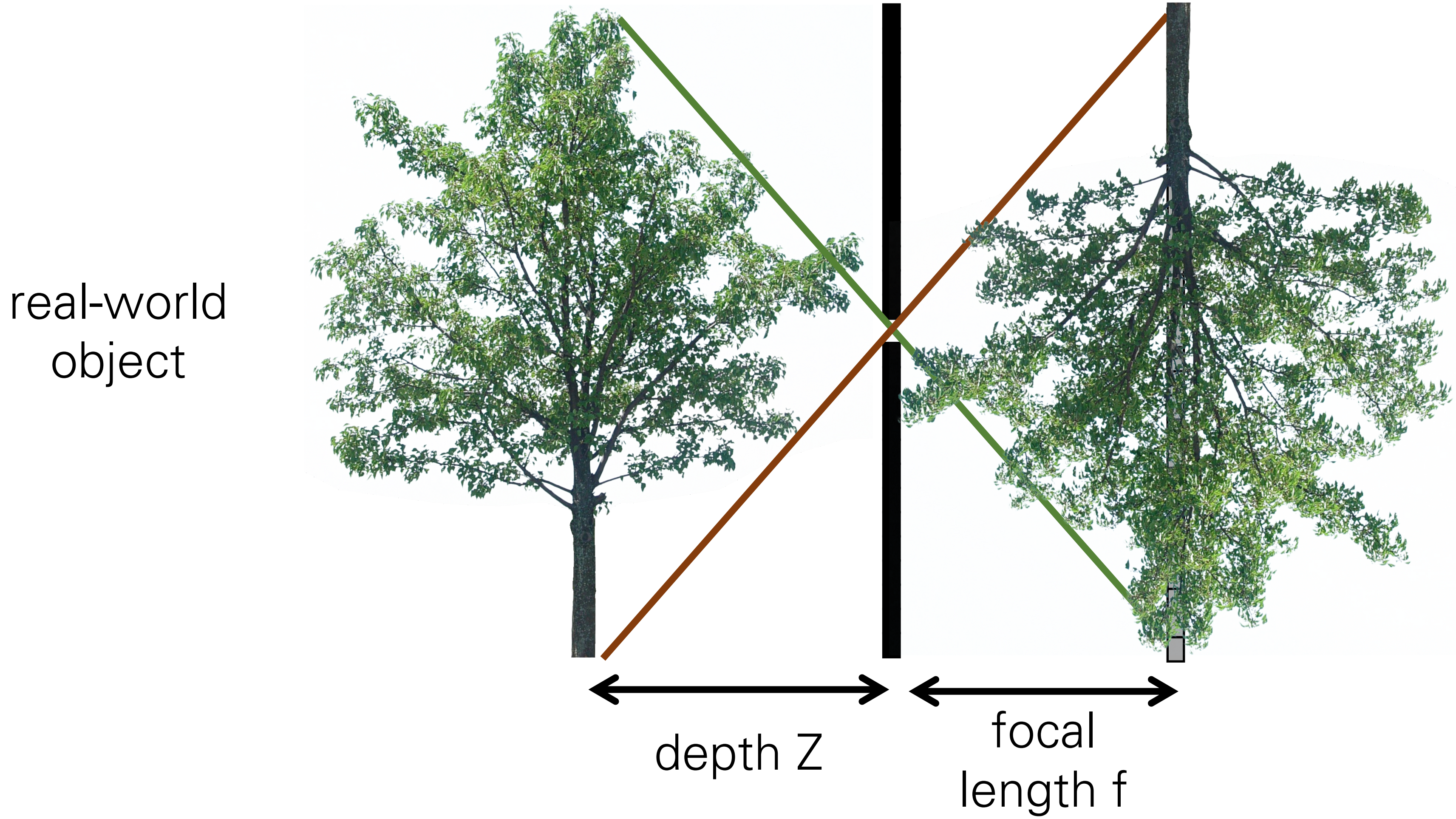
Long focal length

Here's another example:
Empire State building and the Statue of Liberty are about 4.5 miles apart, and the former is 5x taller.

Credit: P. Milanfar

Orthographic camera and telecentric lenses

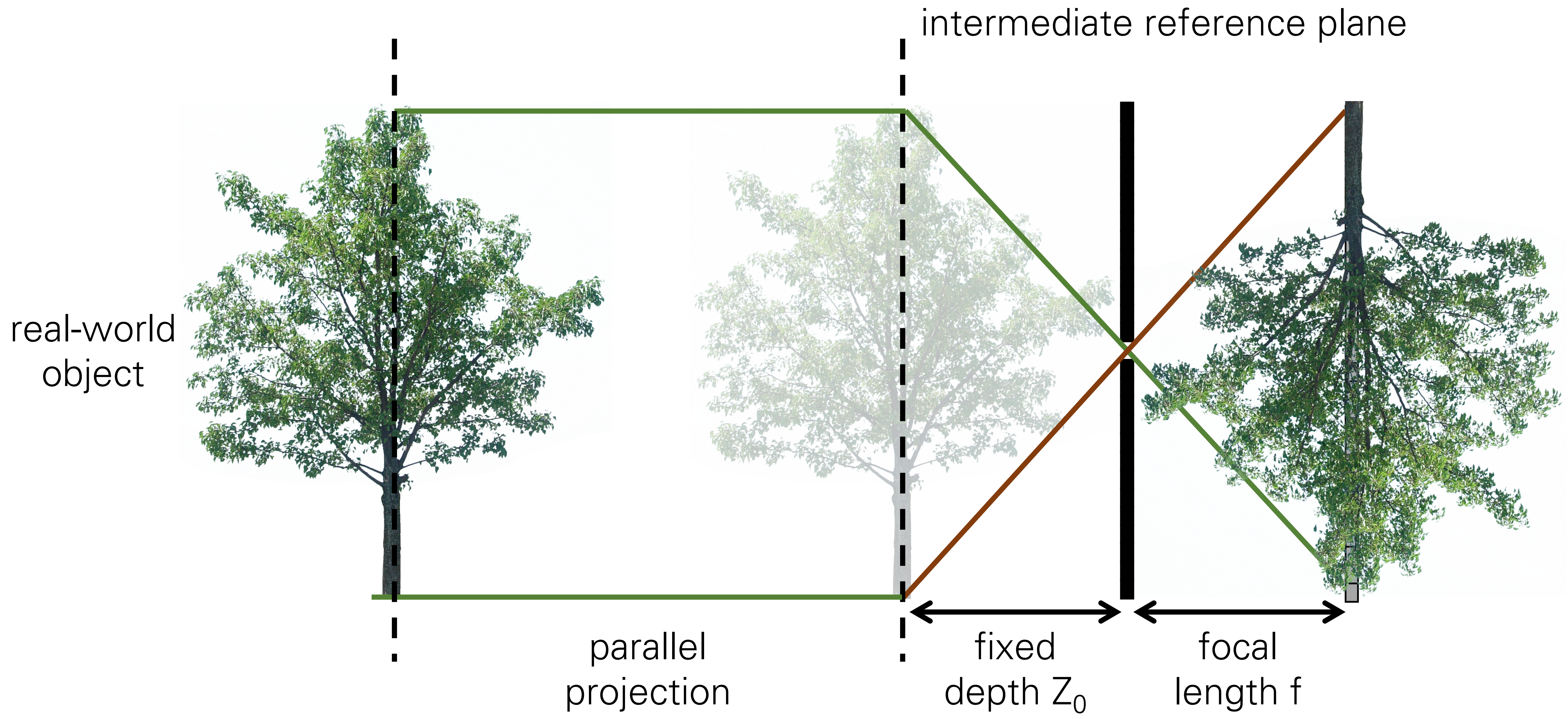
What if...



Continue increasing Z and f while maintaining same magnification?

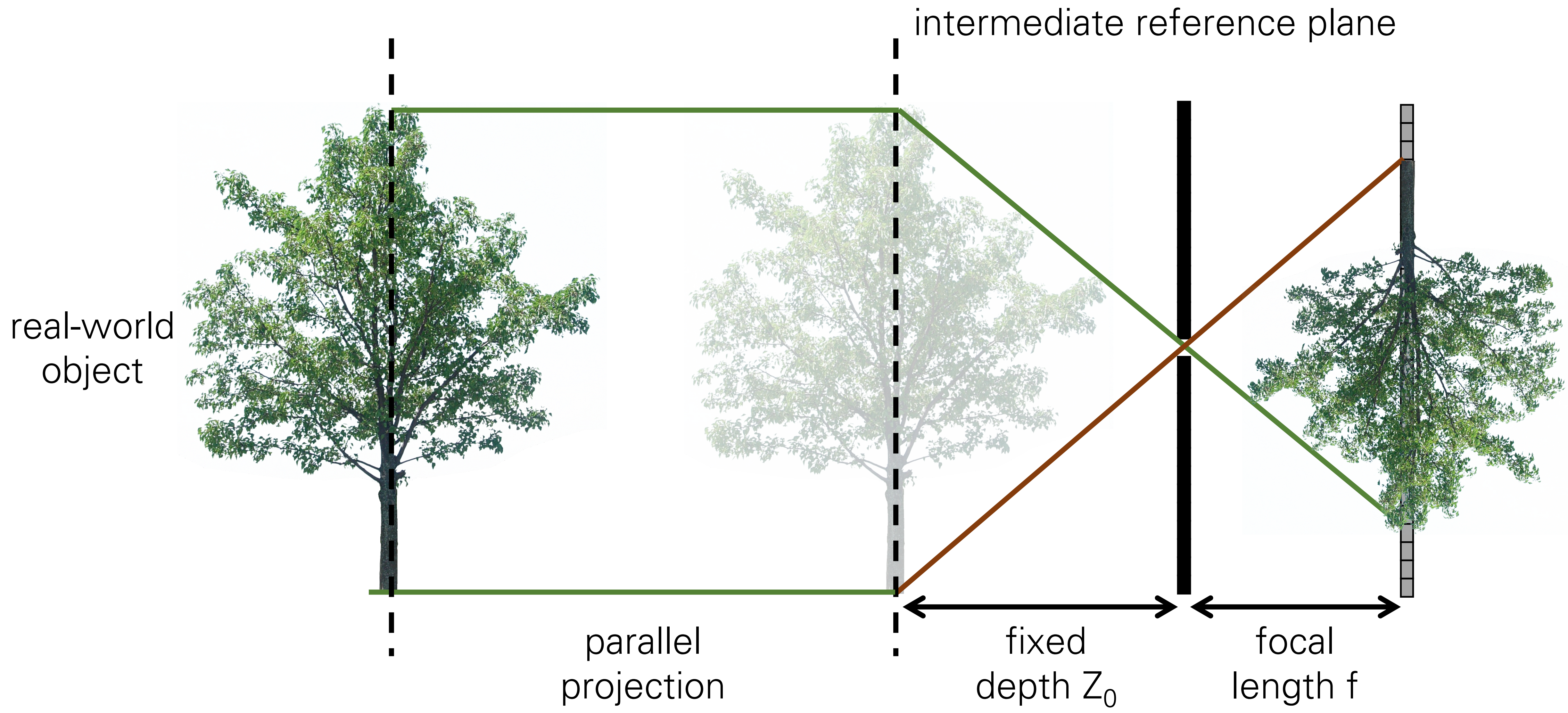
$$f \to \infty \text{ and } \frac{f}{Z} = \text{constant}$$

Orthographic camera



Depth-independent magnification m = 1 (real-life size).

Weak-perspective camera

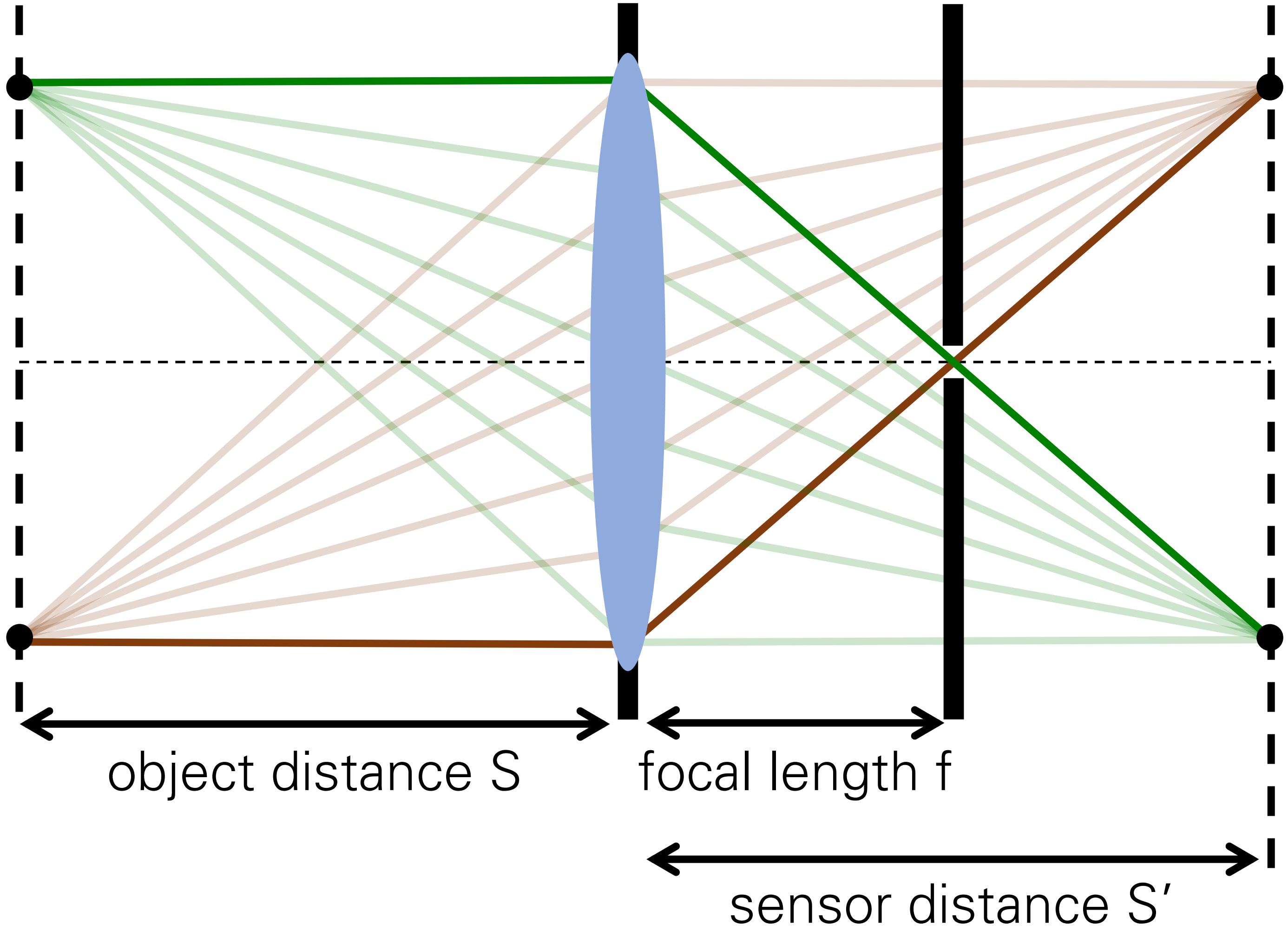


Depth-independent magnification $m = f / Z_0$.

How can we implement such a camera with lenses?

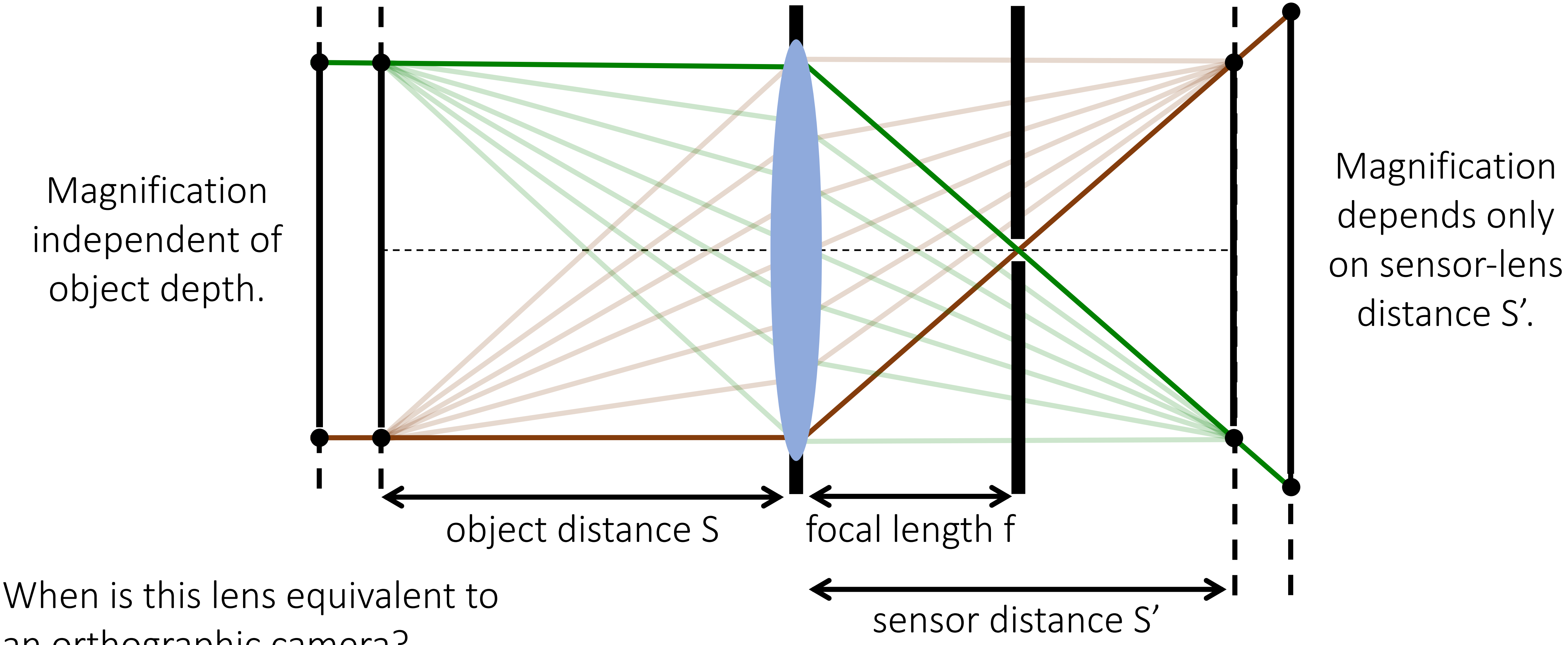
Telecentric lens

Place a pinhole at focal length, so that only rays parallel to primary ray pass through.



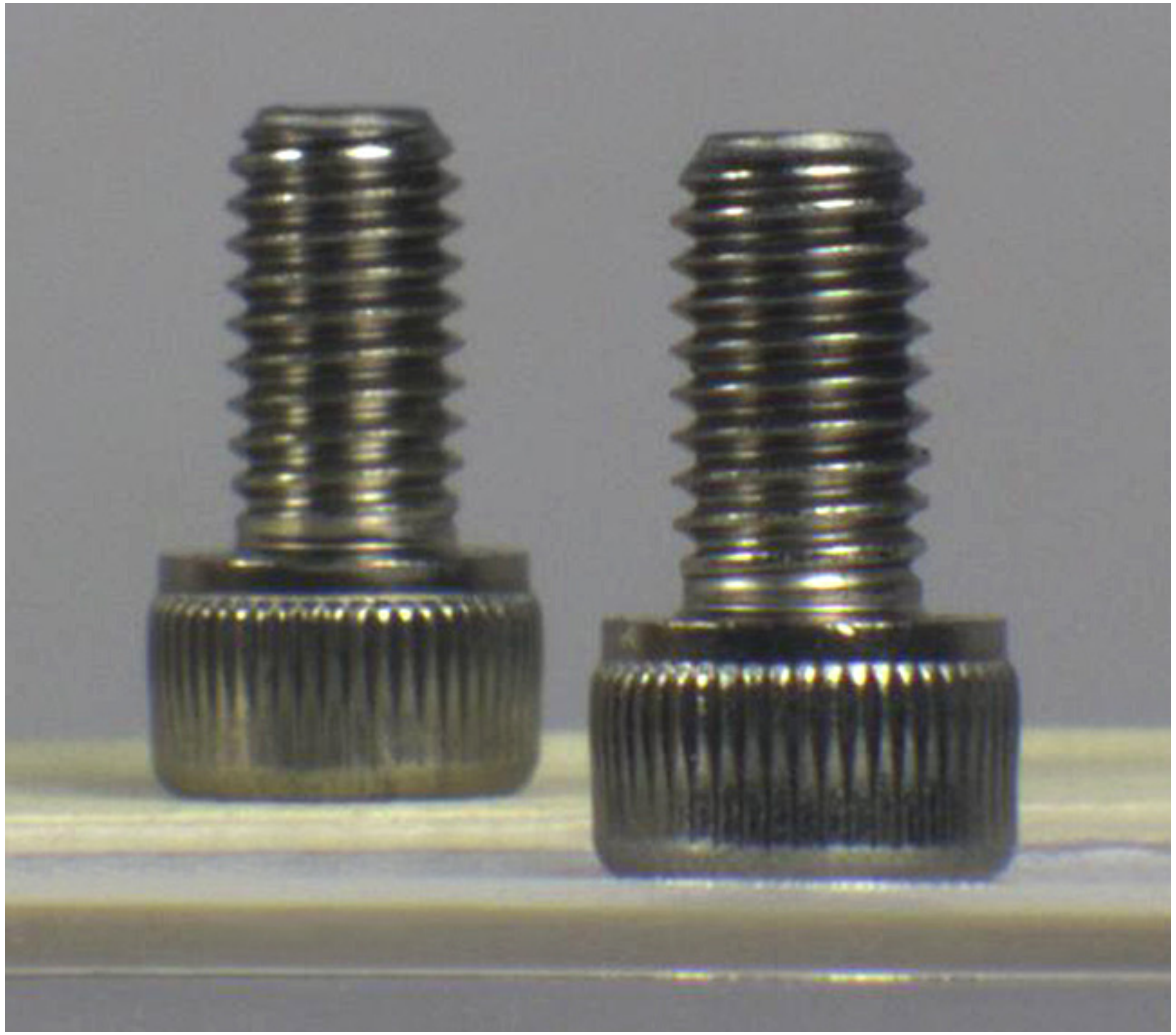
Telecentric lens

Place a pinhole at focal length, so that only rays parallel to primary ray pass through.

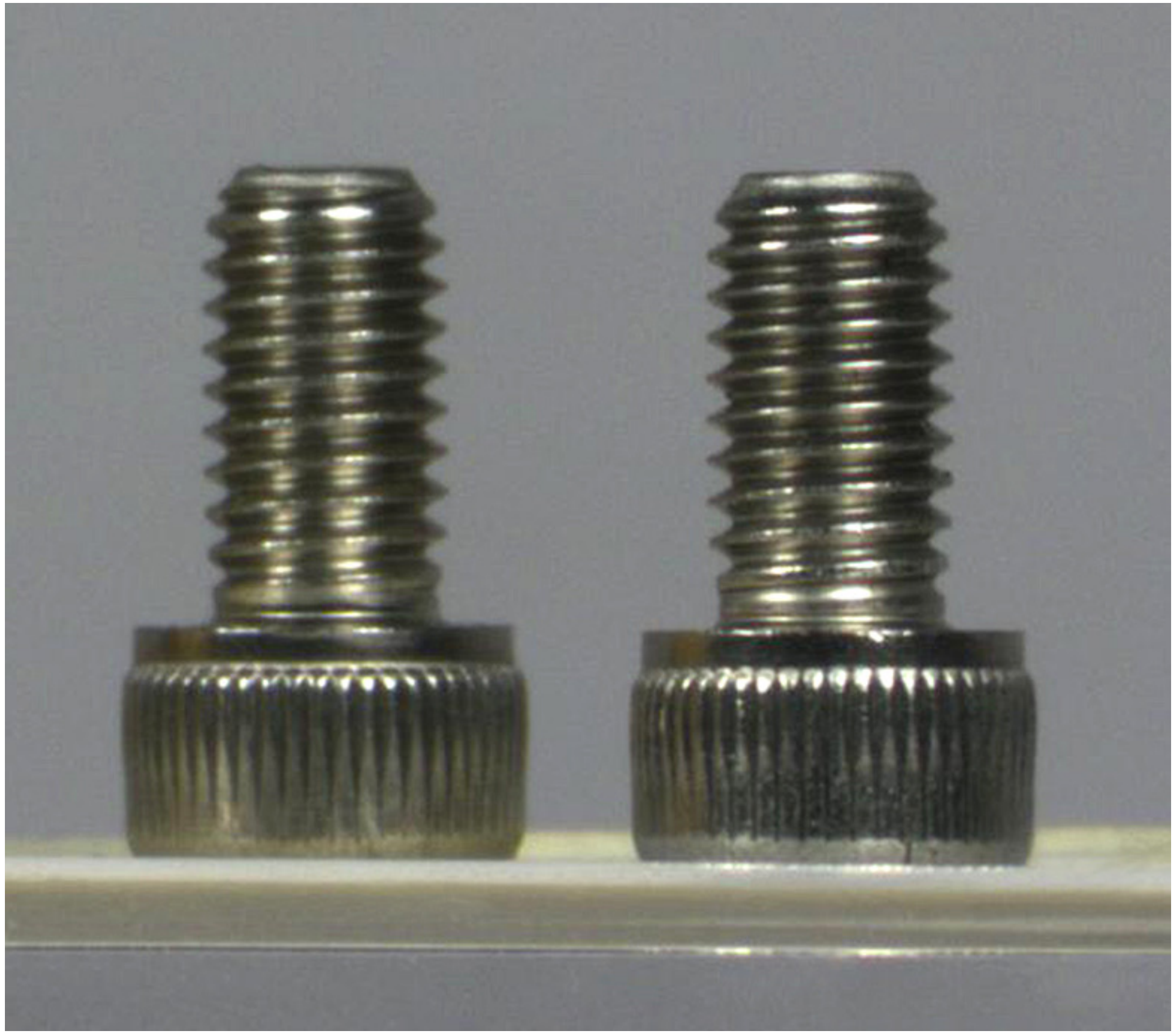


When is this lens equivalent to an orthographic camera?

Regular vs telecentric lens



regular lens



telecentric lens

Next Lecture:
Noise and Color