

BBM444

FUNDAMENTALS OF COMPUTATIONAL PHOTOGRAPHY

Lecture #02 – Image Formation

Today's Lecture

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

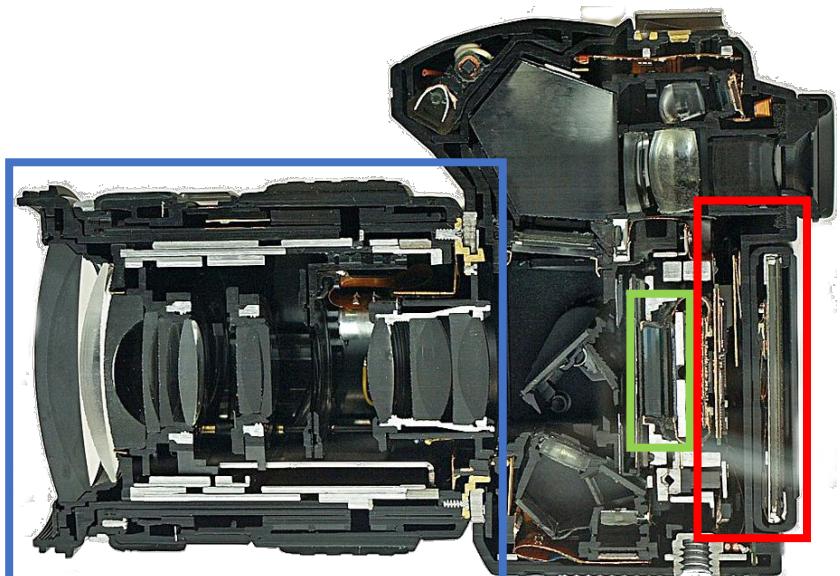
Disclaimer: The material and slides for this lecture were borrowed from

- Alexei Efros's CS194-26/294-26 "Intro to Computer Vision and Computational Photography" class
- Steve Marschner's CS6640 "Computational Photography" class

The modern photography pipeline



post-capture processing
(lectures 5-10)



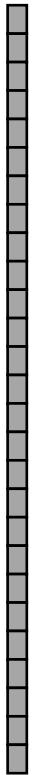
optics and optical controls

sensor, analog front-end, and color filter array

in-camera image processing pipeline

Some motivational imaging experiments

Let's say we have a sensor...



digital sensor
(CCD or CMOS)

... and an object we like to photograph

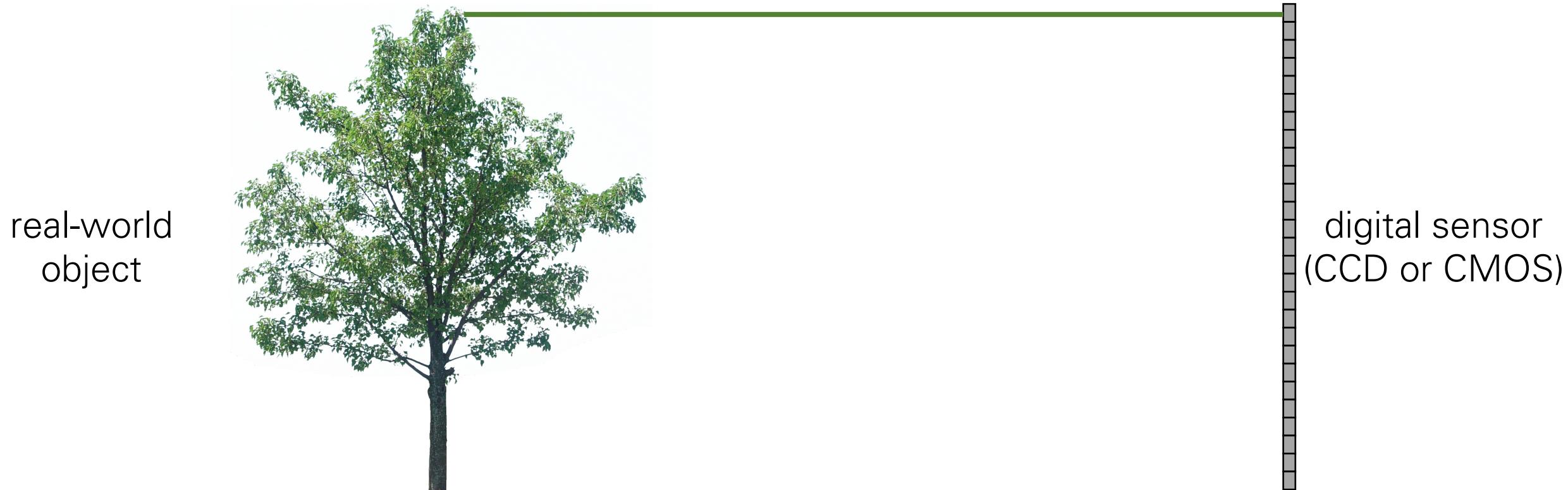
real-world
object



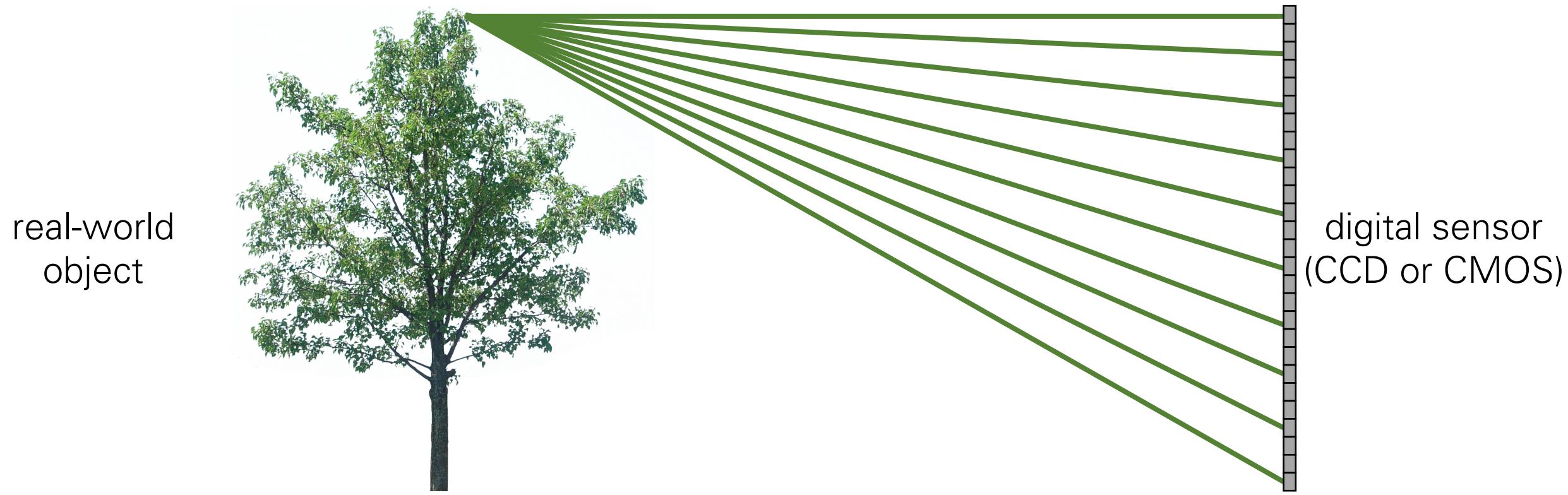
digital sensor
(CCD or CMOS)

What would an image taken like this look like?

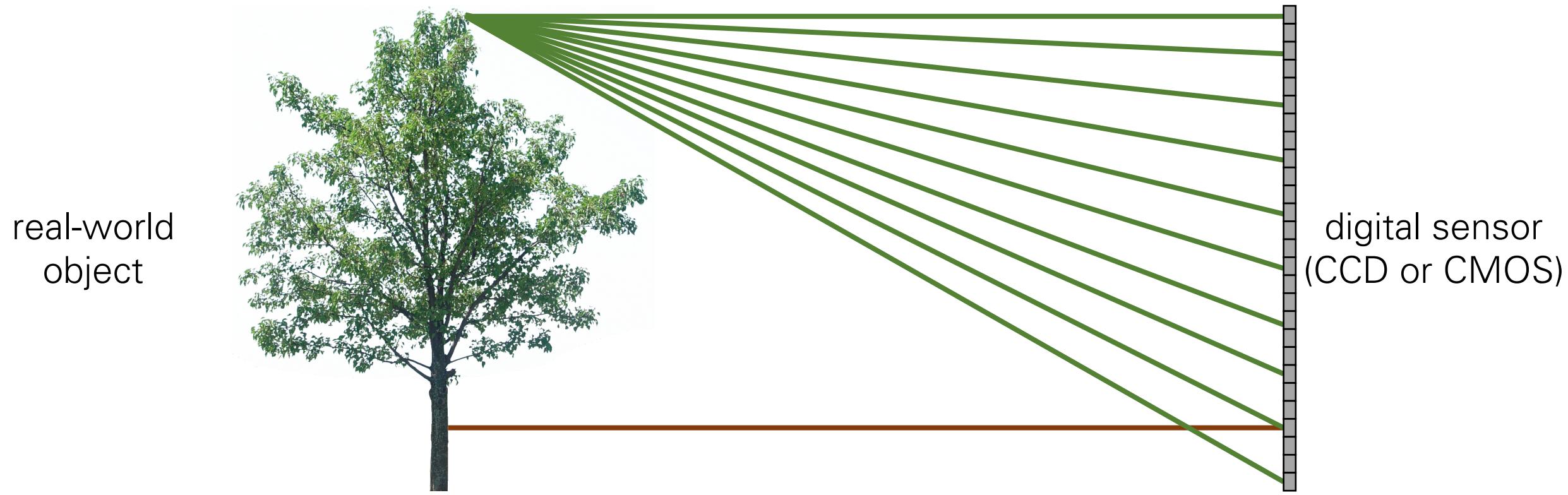
Bare-sensor imaging



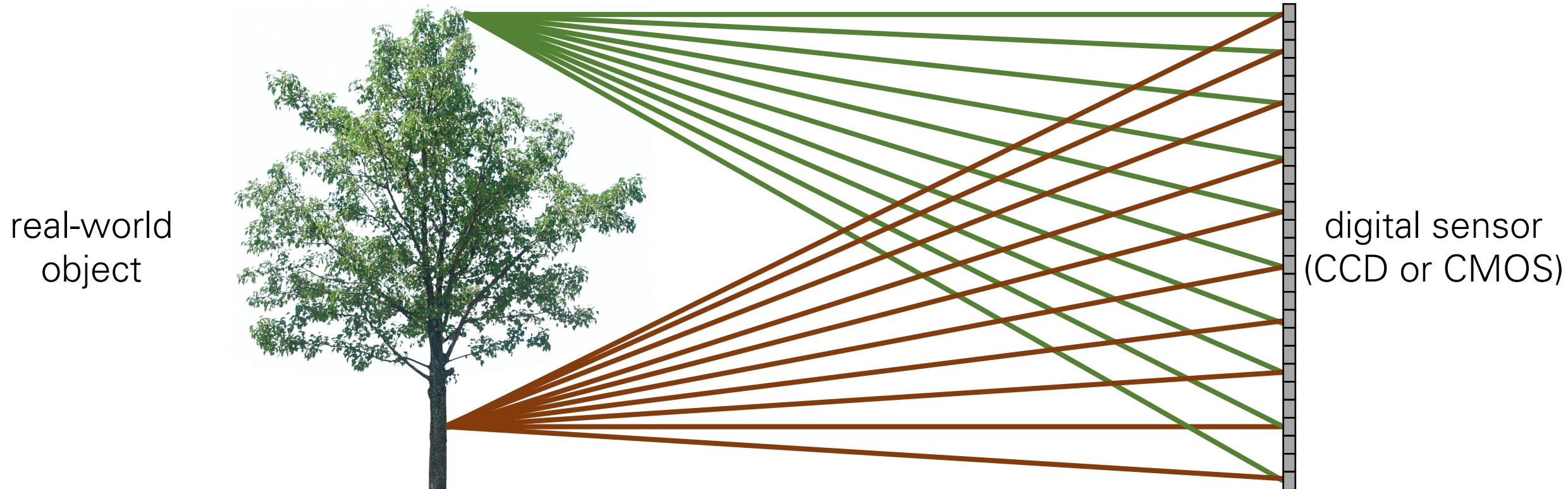
Bare-sensor imaging



Bare-sensor imaging



Bare-sensor imaging



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?

real-world
object



digital sensor
(CCD or CMOS)

Let's add something to this scene



real-world object

barrier (diaphragm)



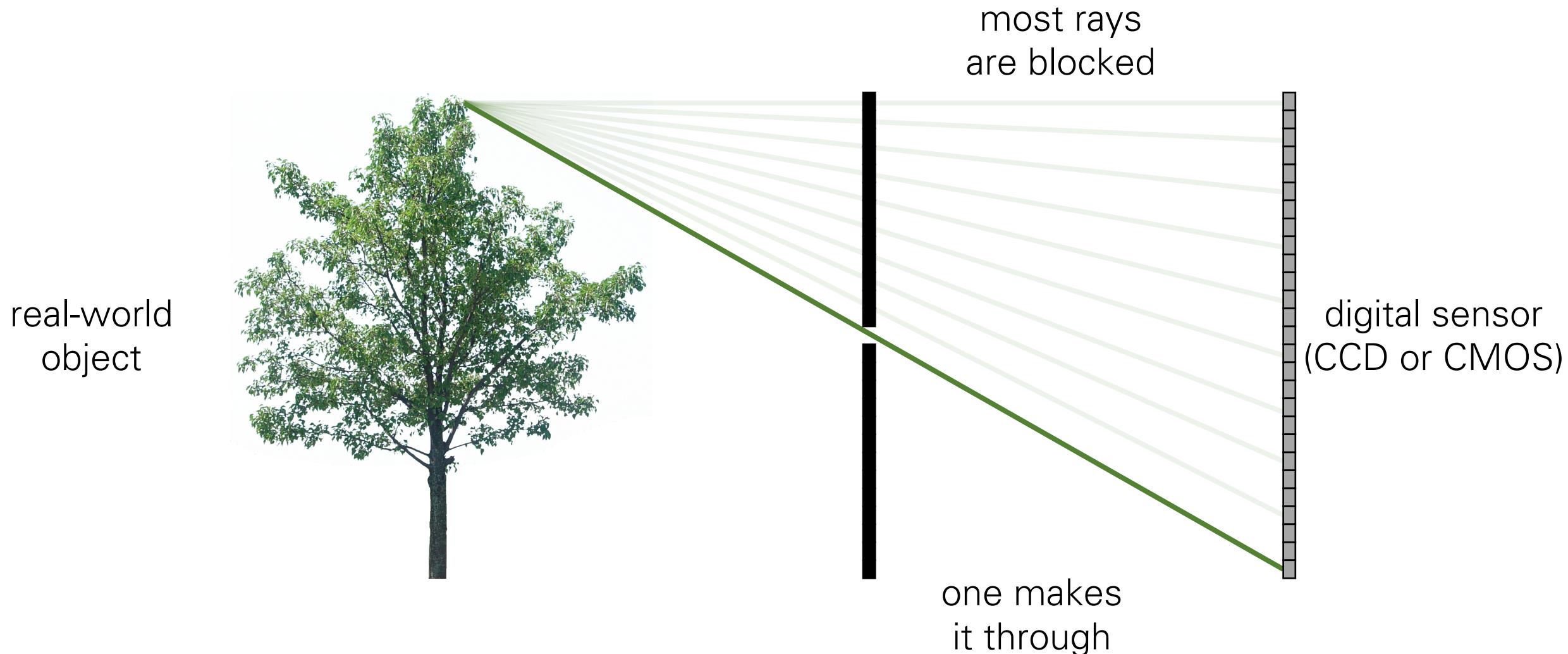
pinhole
(aperture)



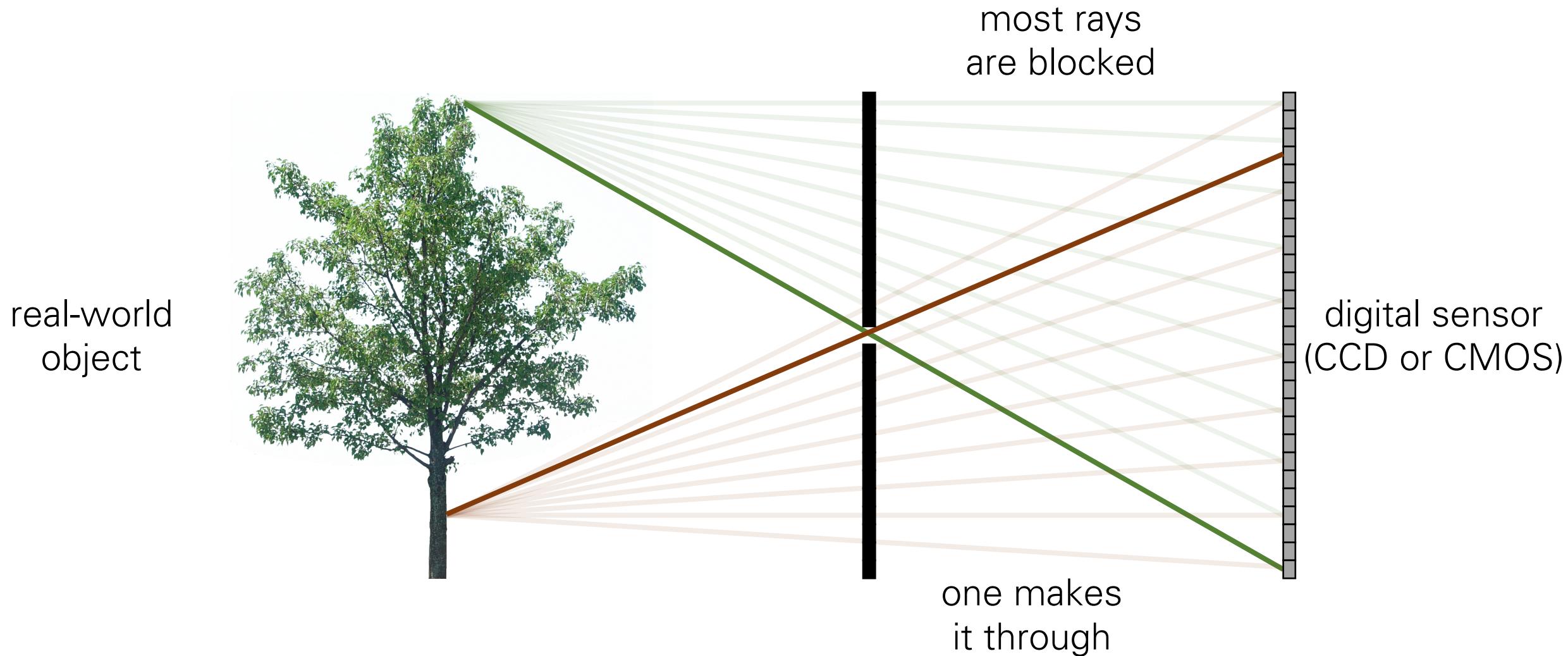
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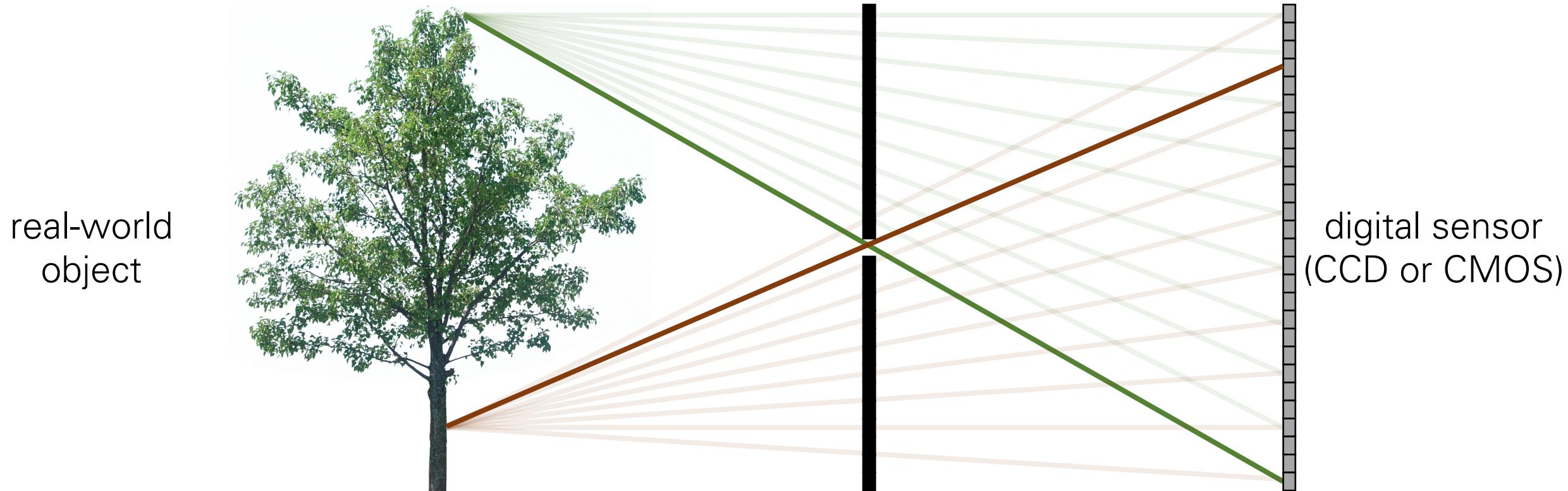
Pinhole imaging



Pinhole imaging



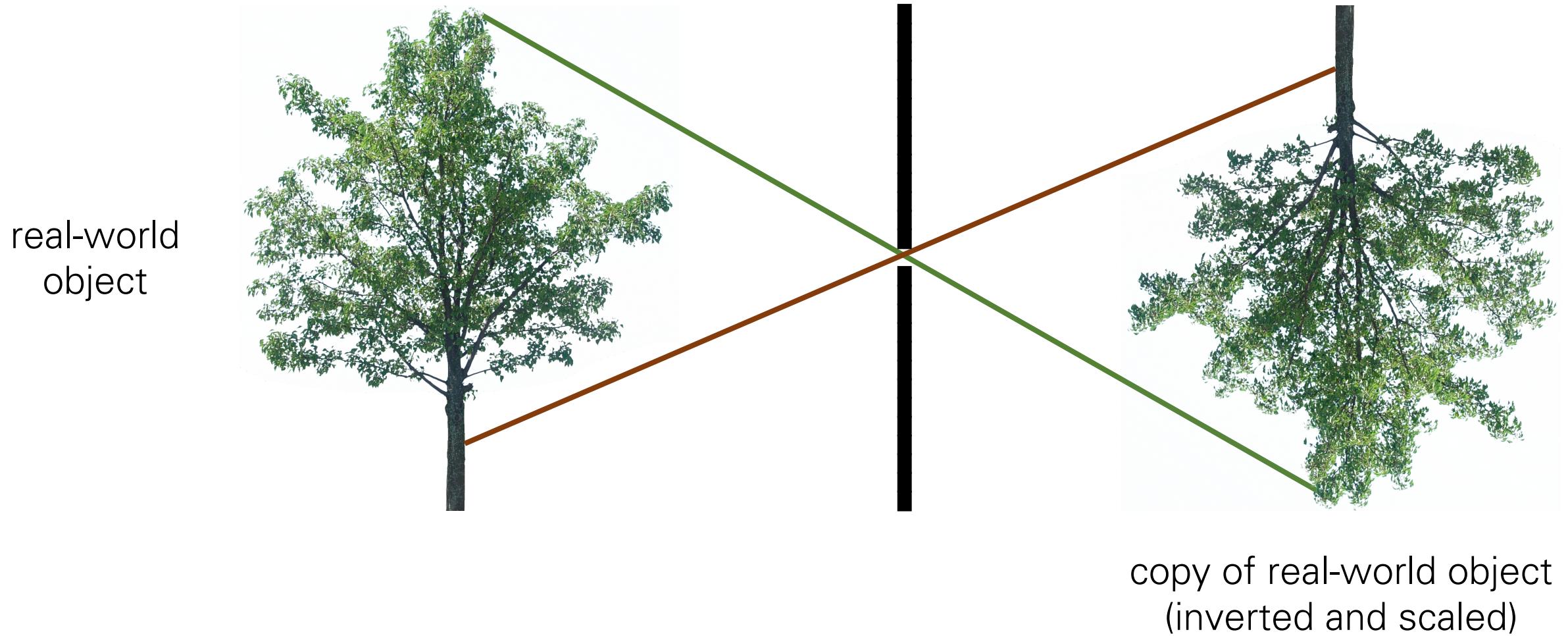
Pinhole imaging



Each scene point contributes to only one sensor pixel

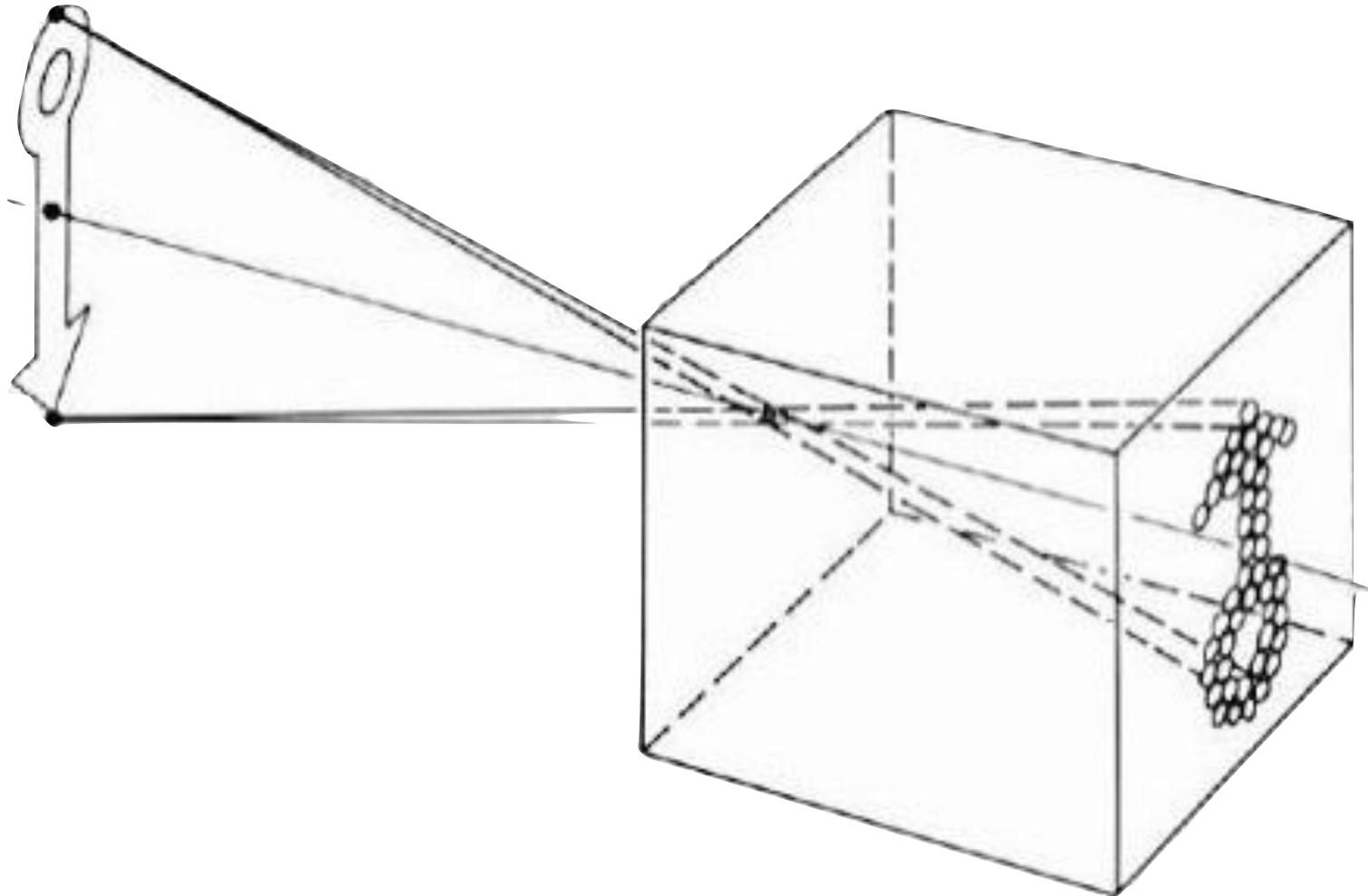
What does the image on the sensor look like?

Pinhole imaging



Pinhole camera

Pinhole camera a.k.a. camera obscura



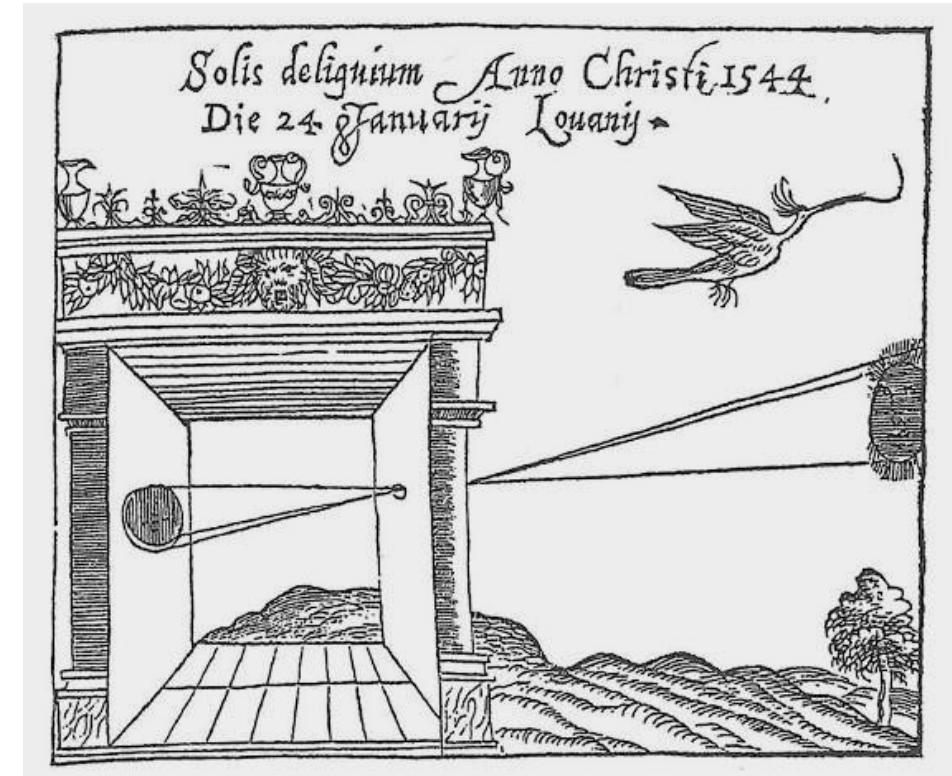
Pinhole camera a.k.a. camera obscura

First mention ...



Chinese philosopher Mozi
(470 to 390 BC)

First camera ...



Greek philosopher Aristotle
(384 to 322 BC)

Pinhole camera terms

real-world
object



barrier (diaphragm)



pinhole
(aperture)



digital sensor
(CCD or CMOS)

Pinhole camera terms

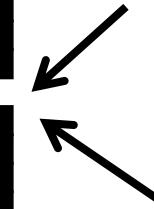
real-world
object



barrier (diaphragm)



pinhole
(aperture)



camera center
(center of projection)

image plane

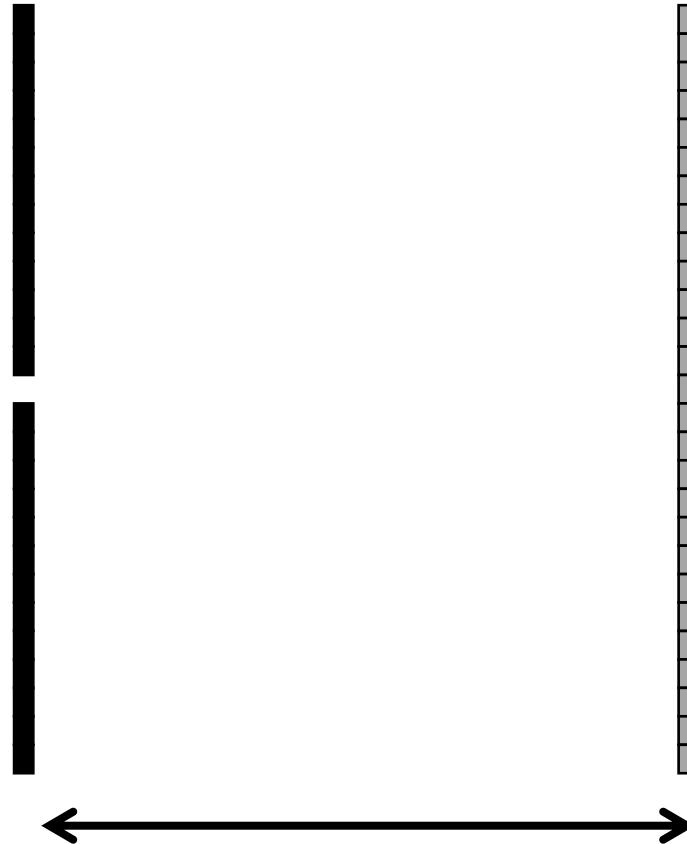


digital sensor
(CCD or CMOS)



Focal length

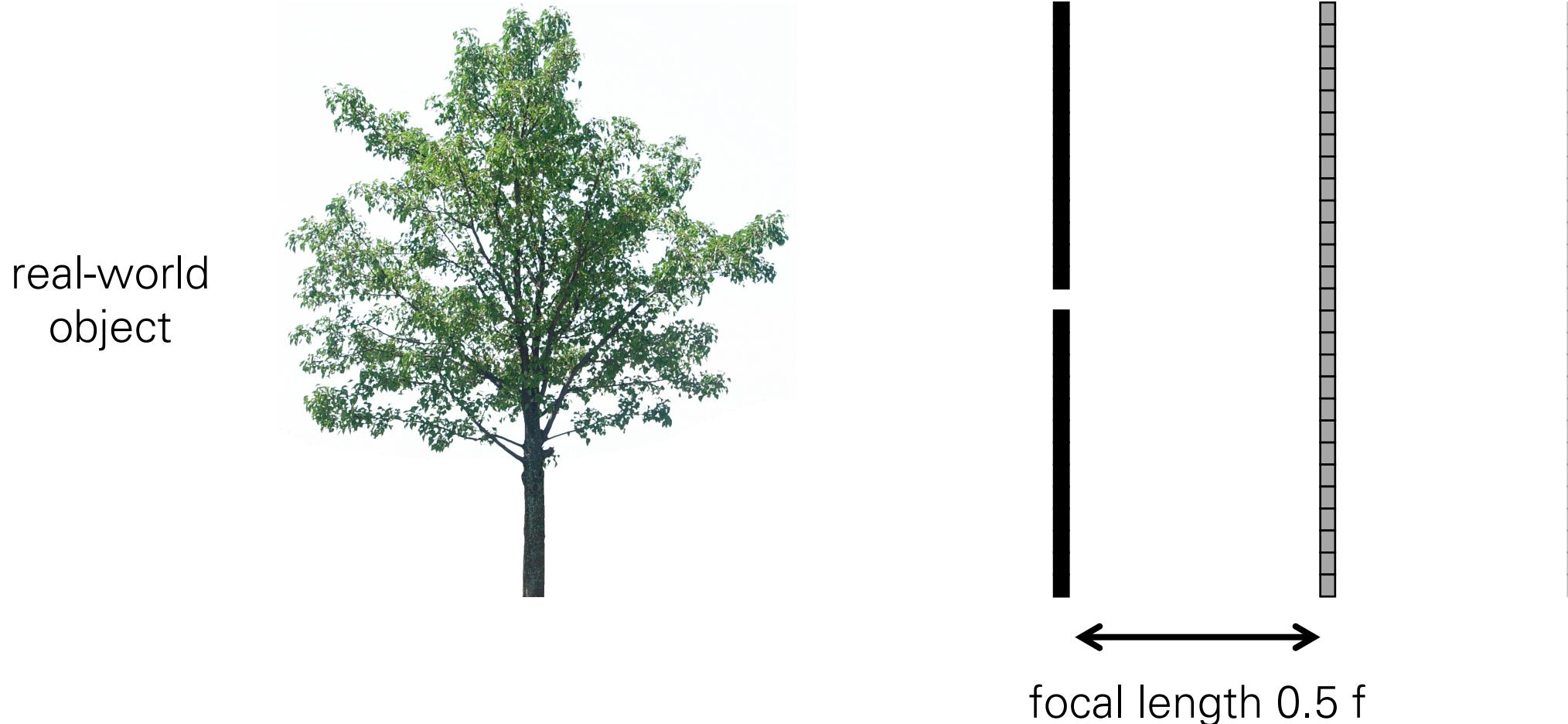
real-world
object



focal length f

Focal length

What happens as we change the focal length?



Focal length

What happens as we change the focal length?

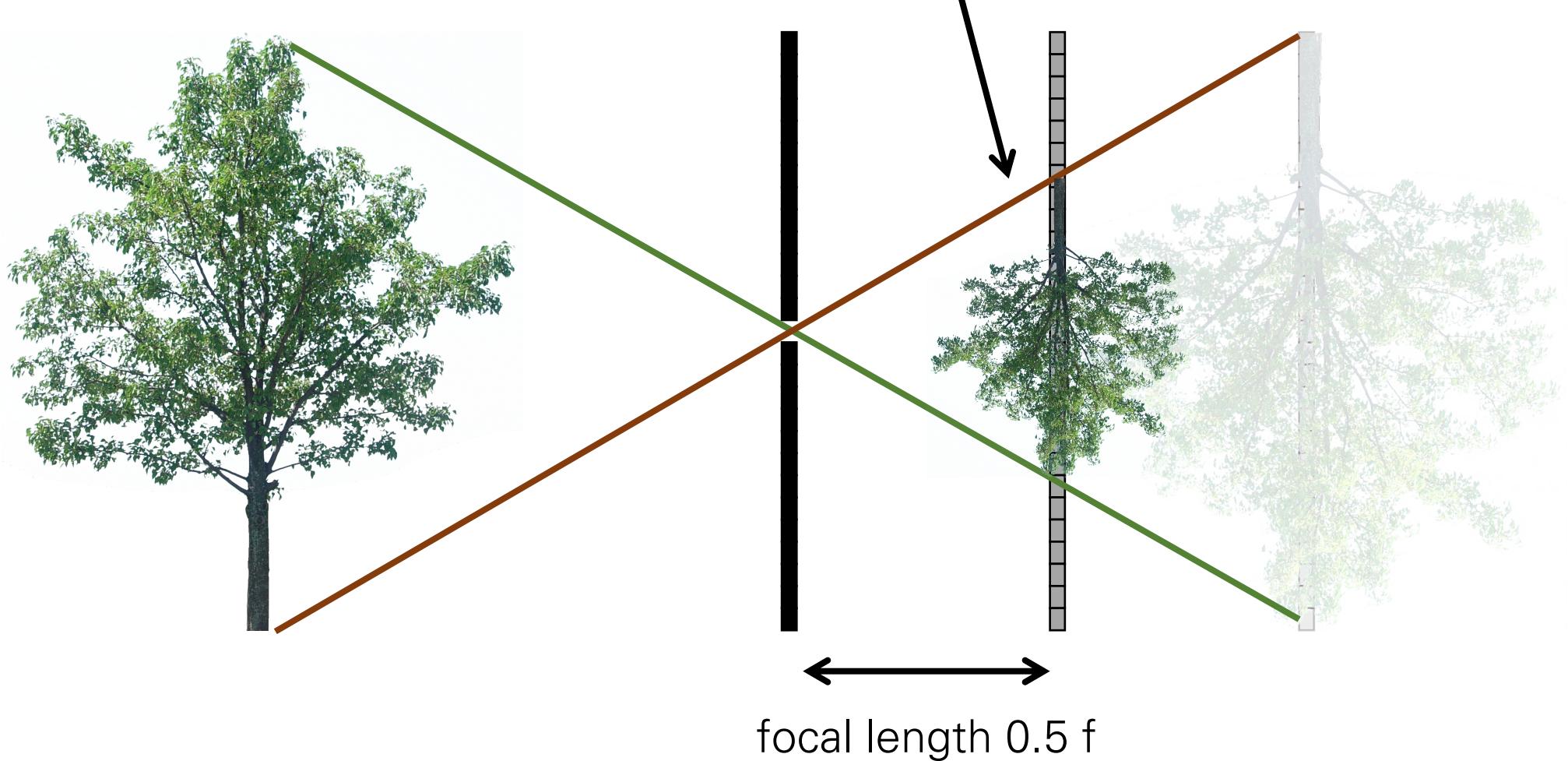


Focal length

What happens as we change the focal length?

real-world object

object projection is half the size



Pinhole size

real-world
object



pinhole
diameter



Ideal pinhole has infinitesimally small size

- In practice that is impossible.

Pinhole size

What happens as we change the pinhole diameter?

real-world
object

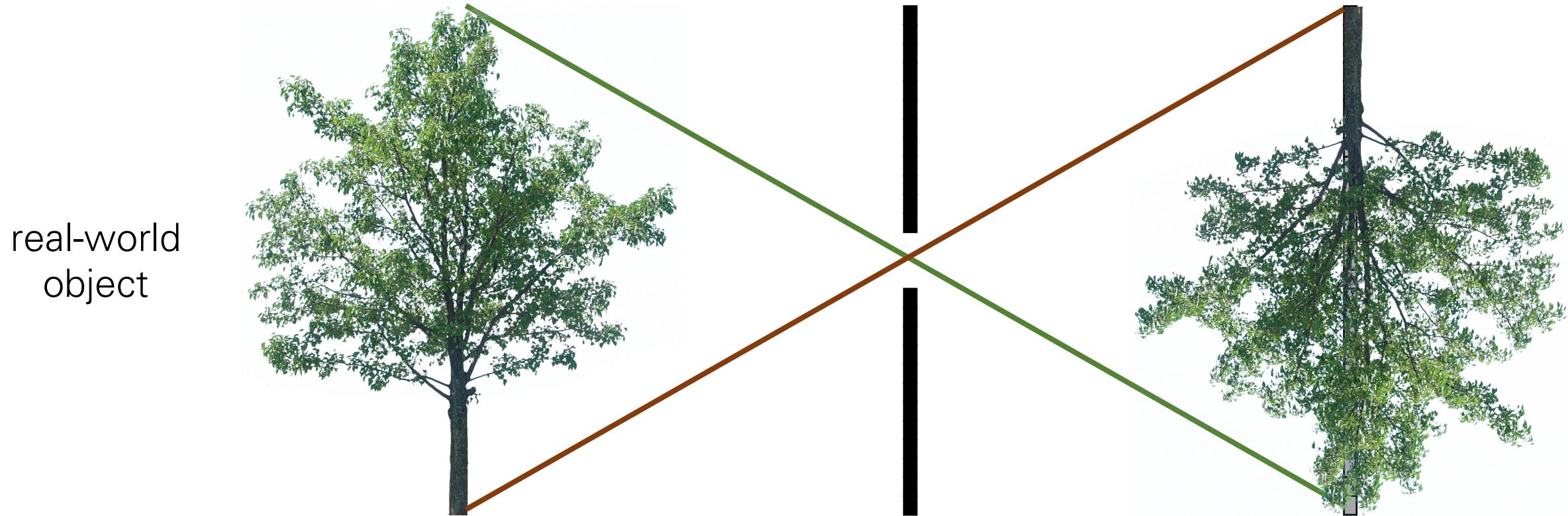


pinhole
diameter



Pinhole size

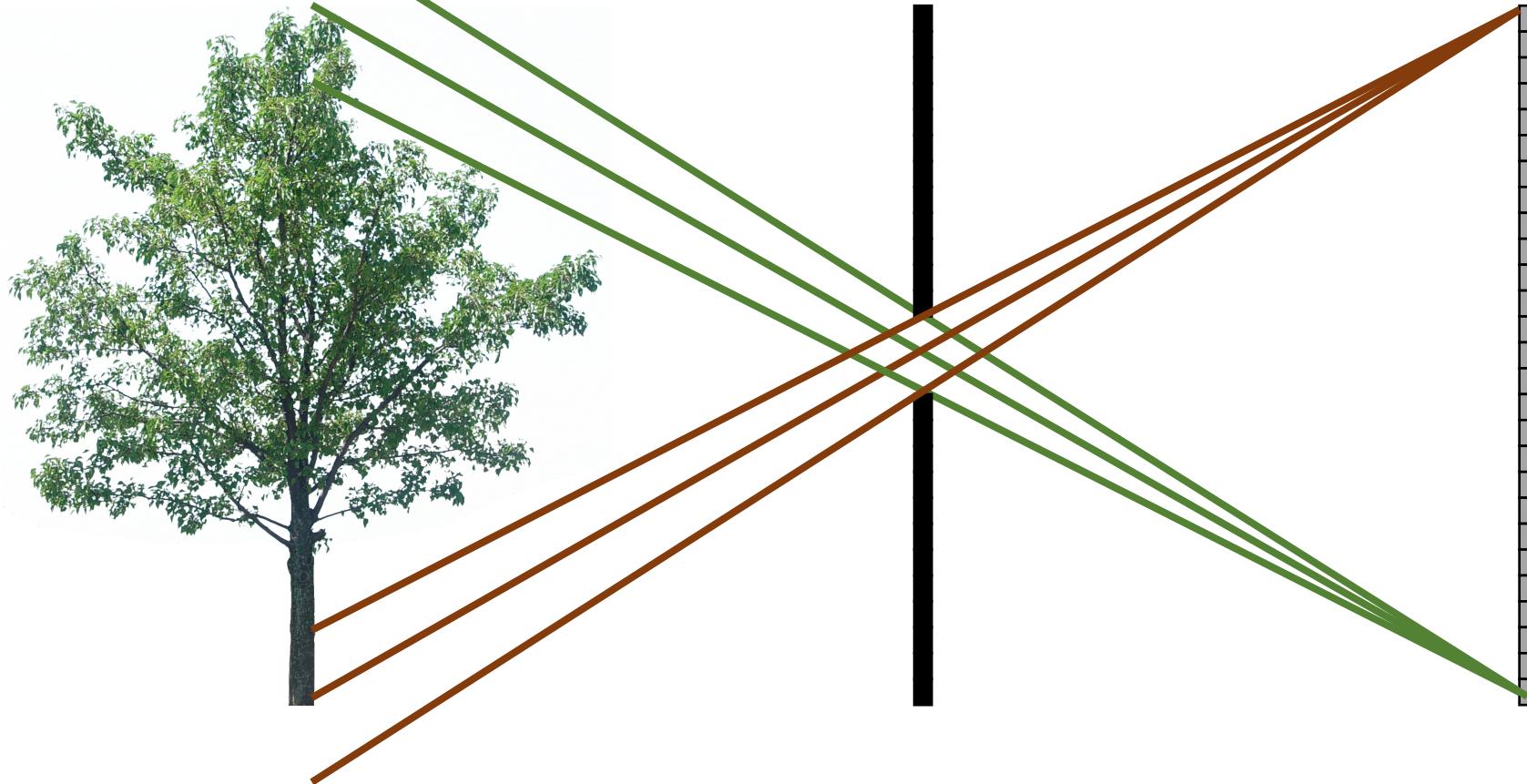
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Pinhole size

What happens as we change the pinhole diameter?

real-world
object

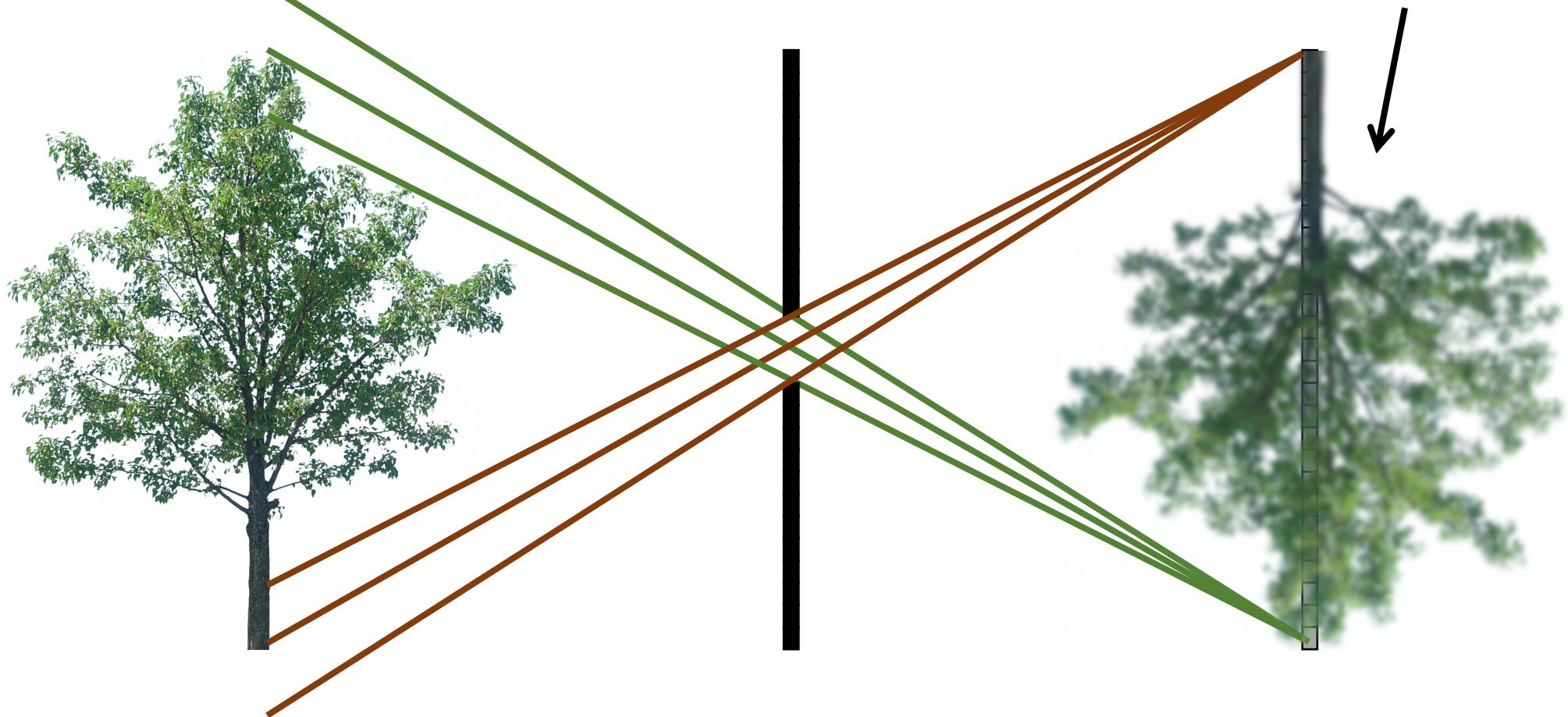


Pinhole size

What happens as we change the pinhole diameter?

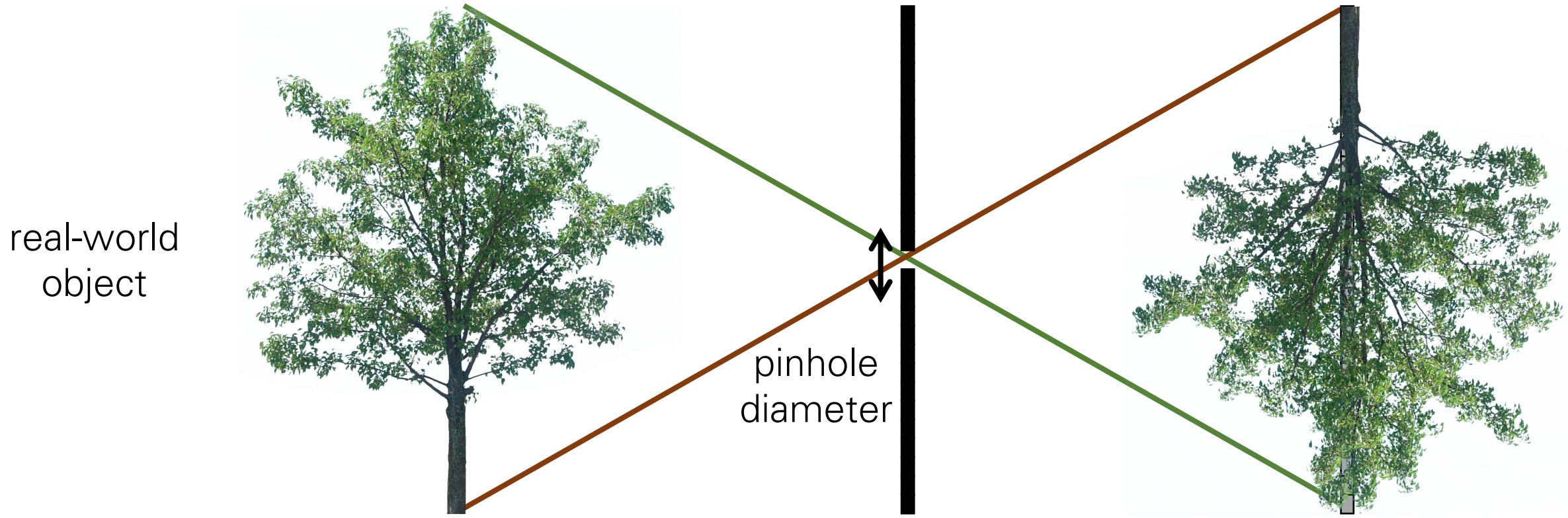
object projection becomes blurrier

real-world
object



Pinhole size

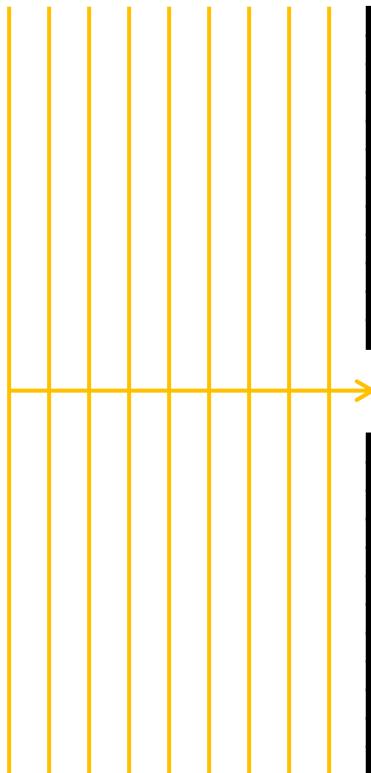
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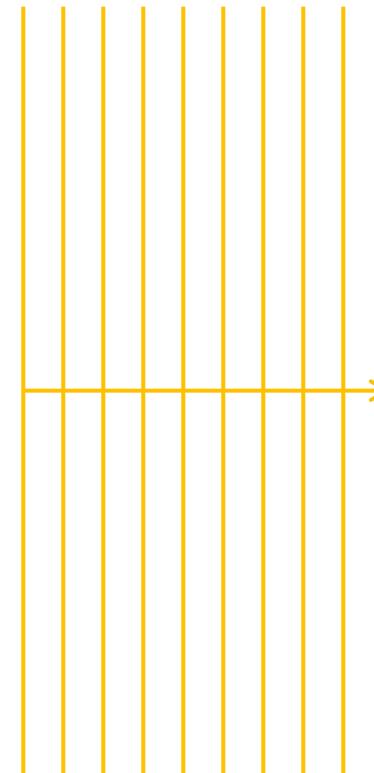
Will the image keep getting sharper the smaller we make the pinhole?

Diffraction limit

A consequence of the wave nature of light



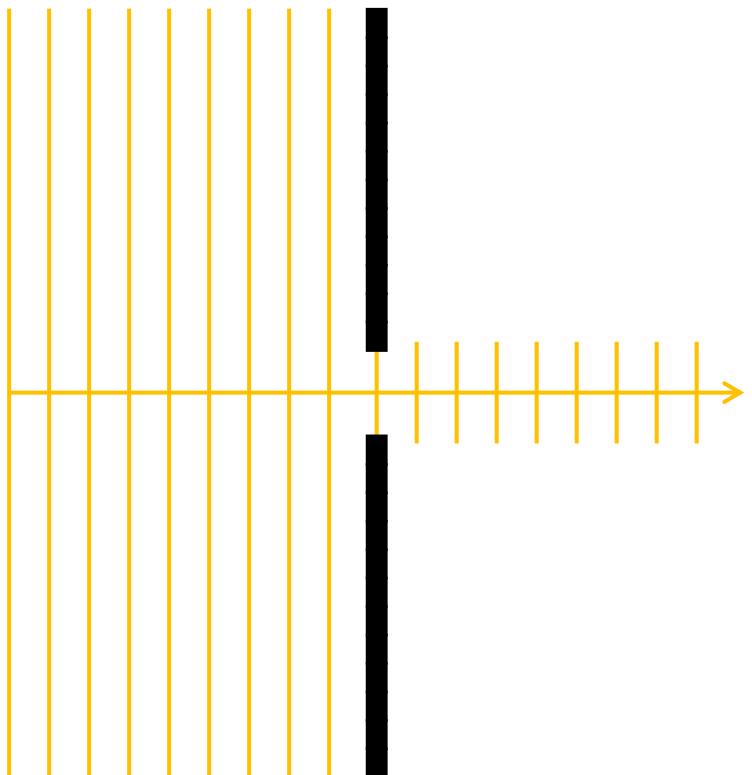
What do geometric optics
predict will happen?



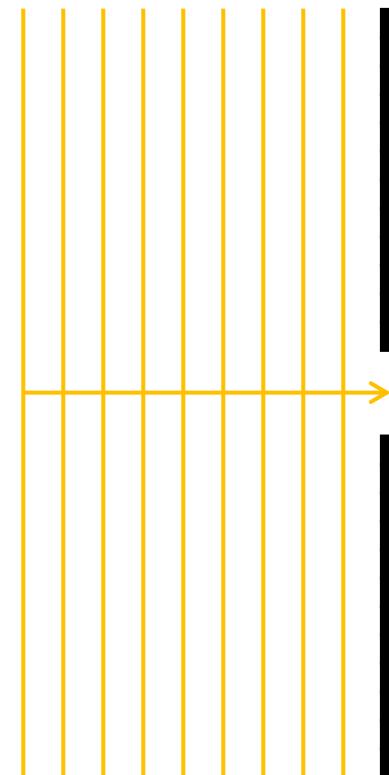
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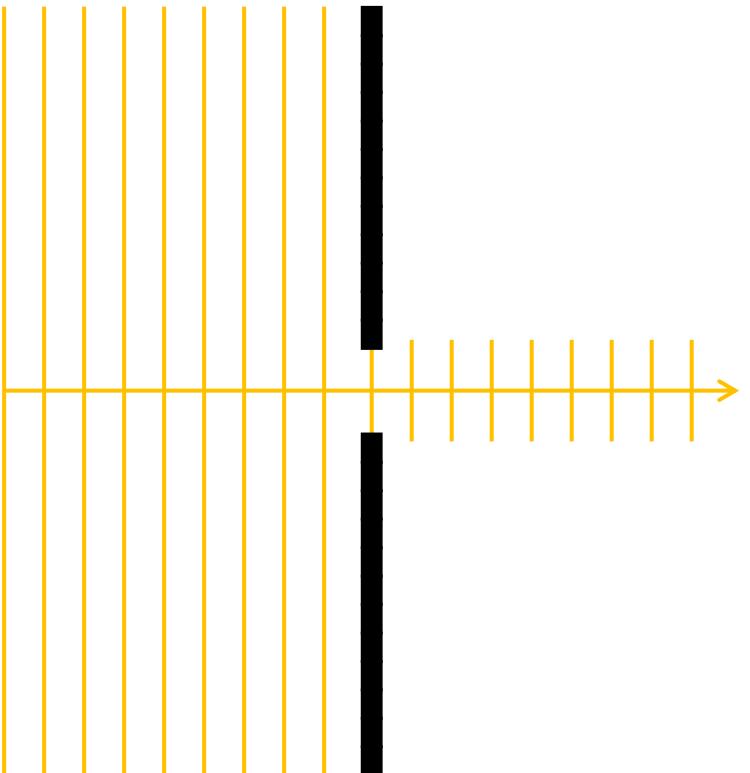
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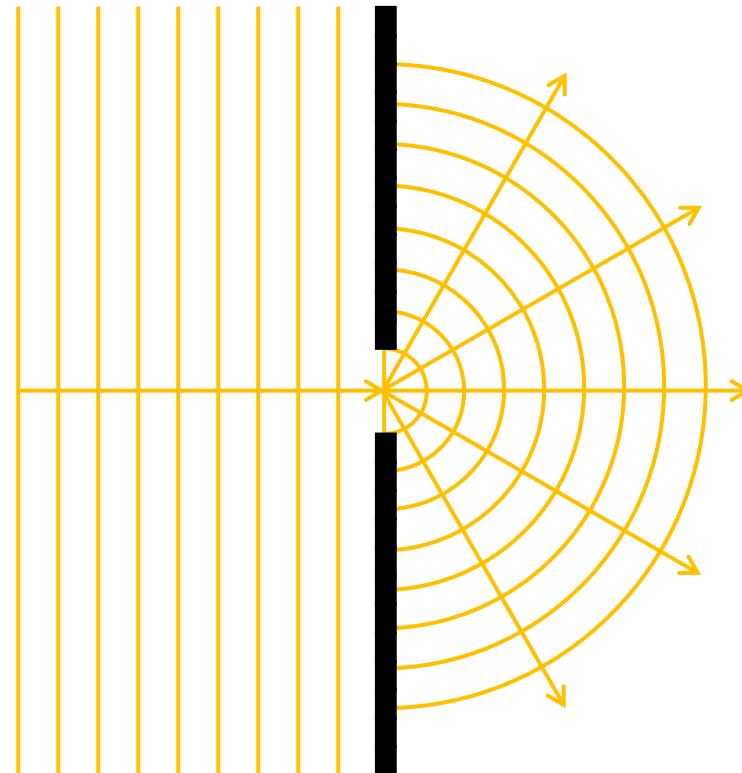
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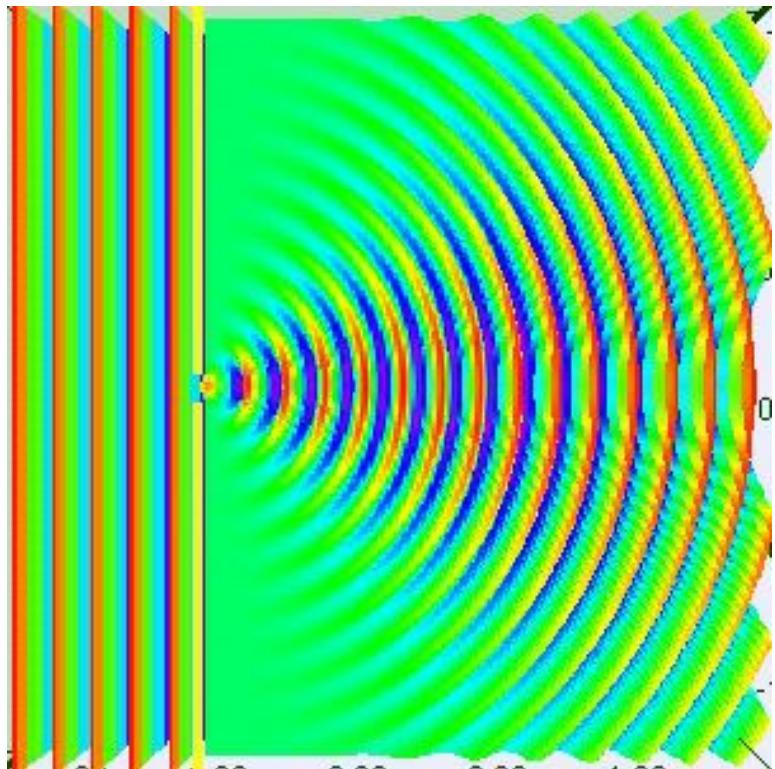


What do wave optics
predict will happen?

Diffraction limit

Diffraction pattern = Fourier transform of the pinhole.

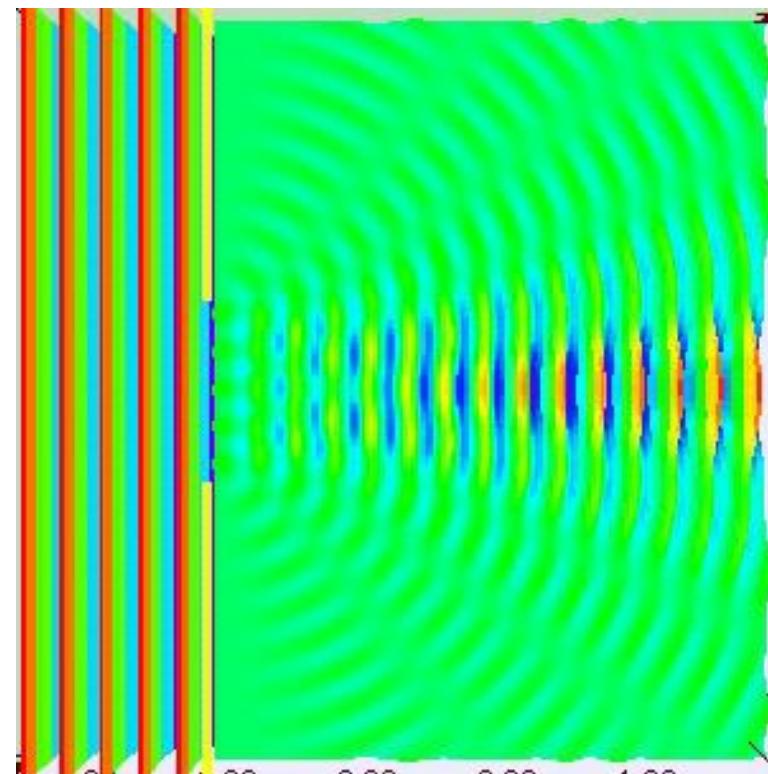
- Smaller pinhole means bigger Fourier spectrum.
- Smaller pinhole means more diffraction.



small pinhole



wide
diffraction
pattern

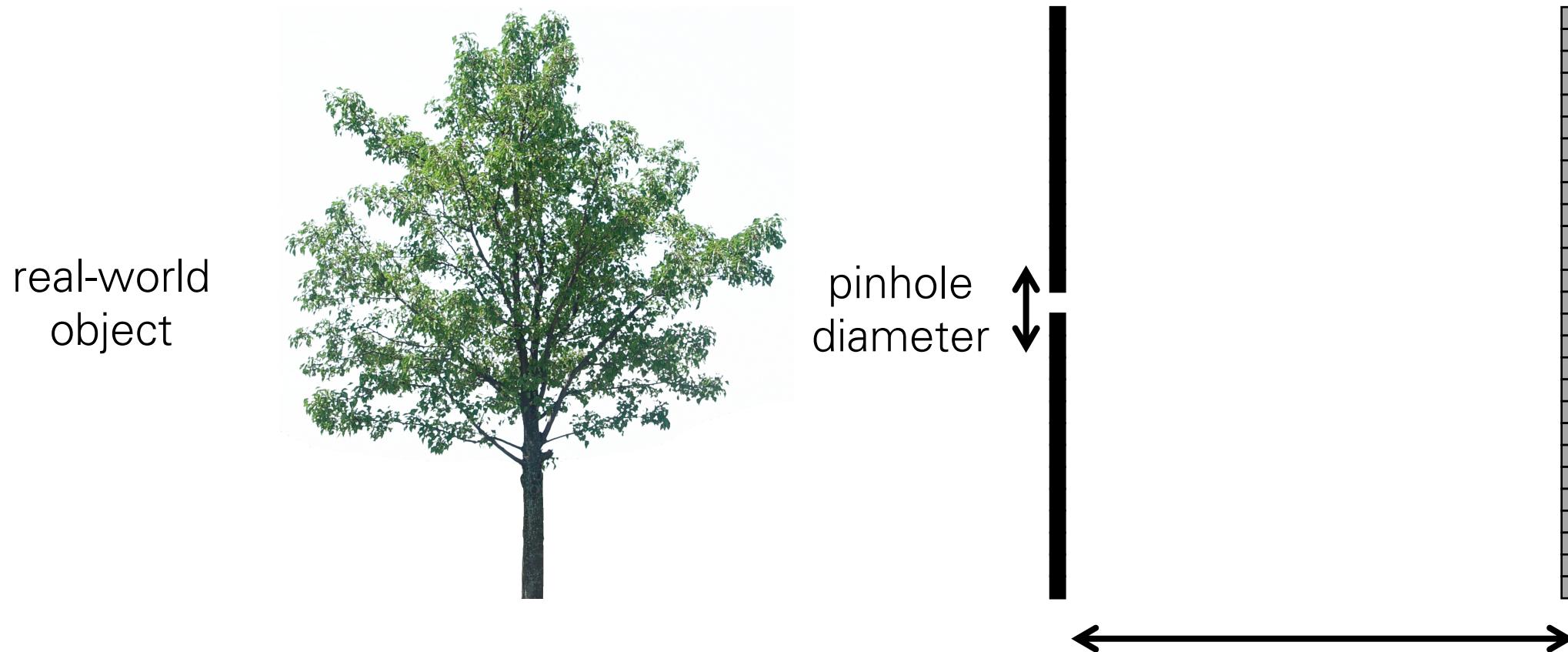


large pinhole



narrow
diffraction
pattern

What about light efficiency?



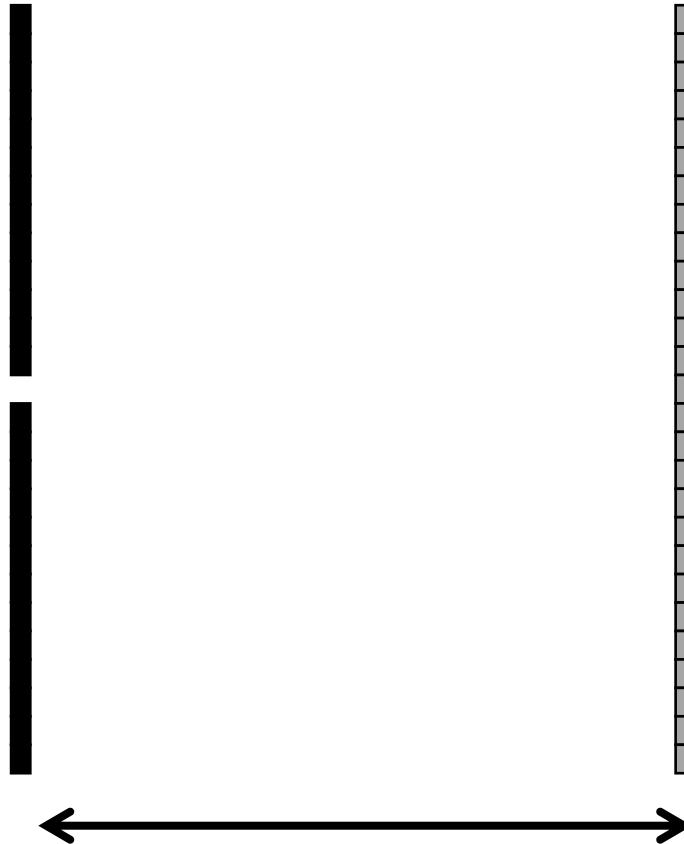
- What is the effect of doubling the pinhole diameter?
- What is the effect of doubling the focal length?

What about light efficiency?

real-world
object



pinhole
diameter

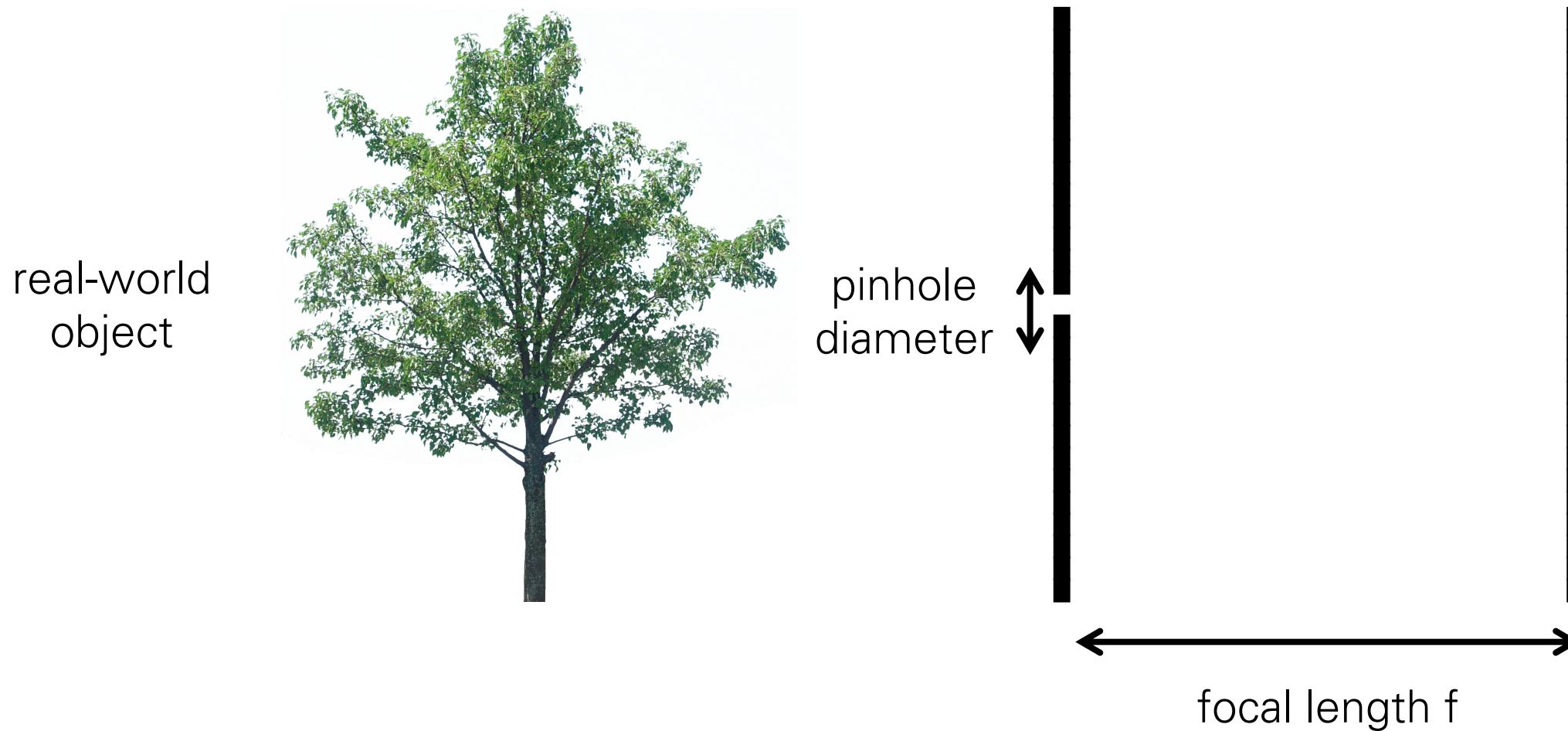


focal length f

- 2x pinhole diameter → 4x light
- 2x focal length → $\frac{1}{4}$ x 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?

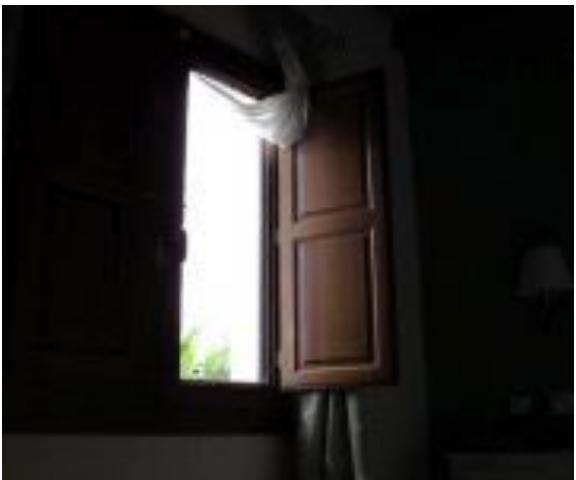


Accidental pinhole camera



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

Accidental pinhole camera



window is an
aperture

projected pattern on the wall



upside down



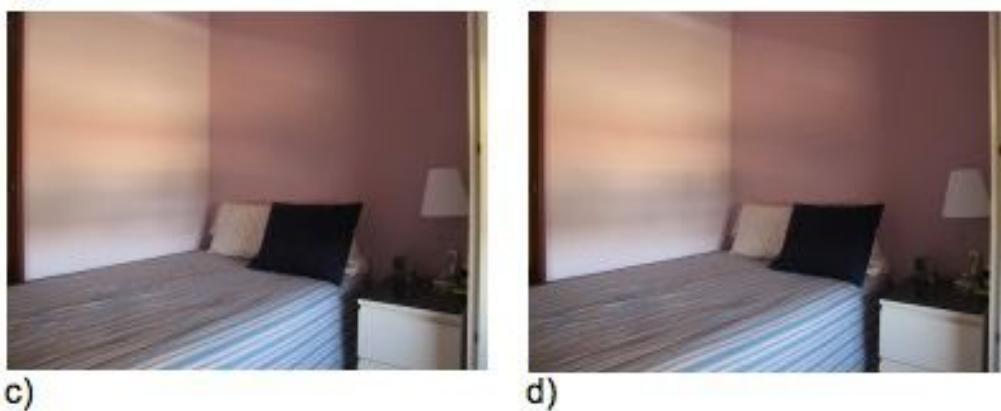
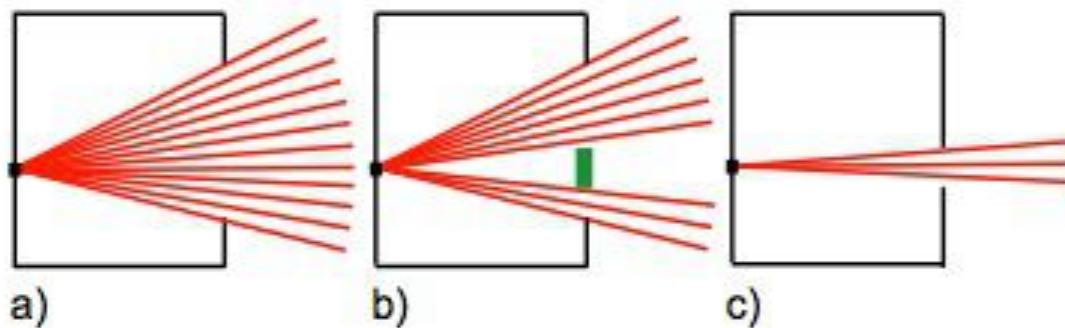
window with smaller gap



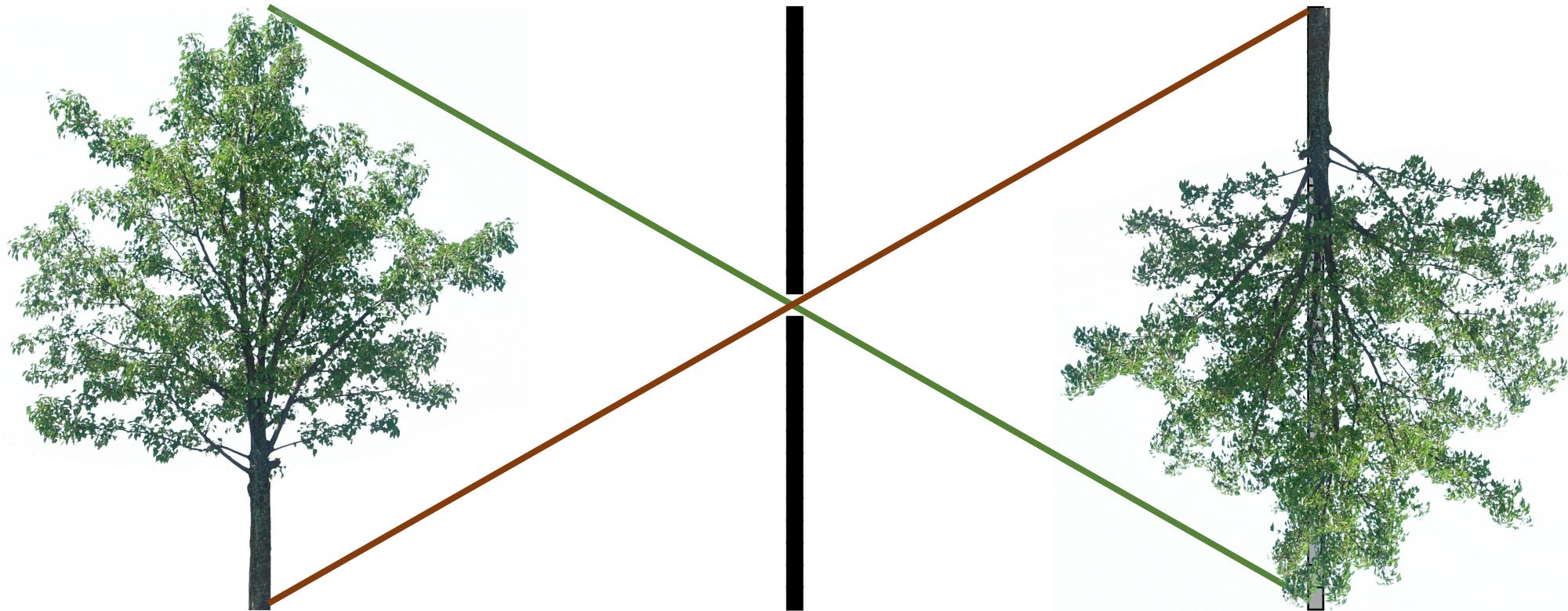
view outside window



Accidental pinspeck camera



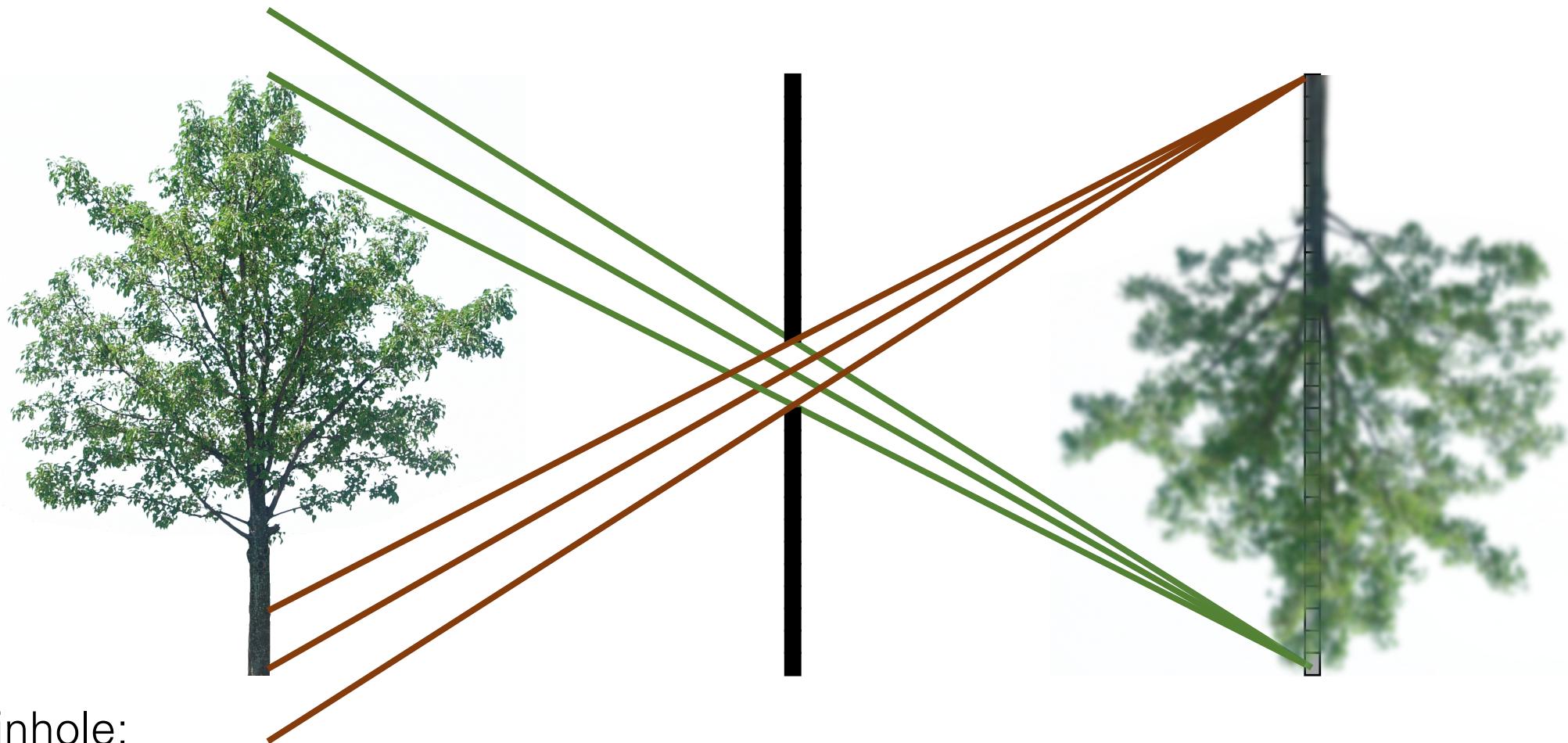
Pinhole camera trade-off



Small (ideal) pinhole:

1. Image is sharp.
2. Signal-to-noise ratio is low.

Pinhole camera trade-off

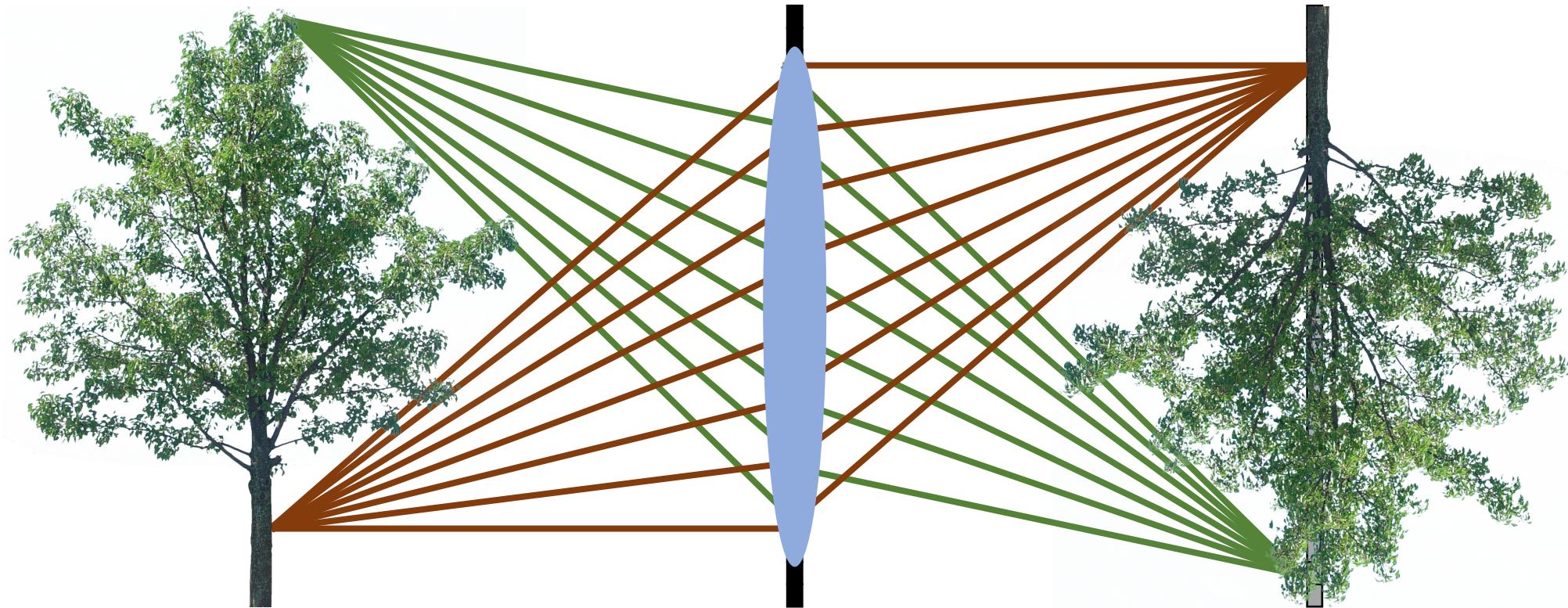


Large pinhole:

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?

Lens (very) basics

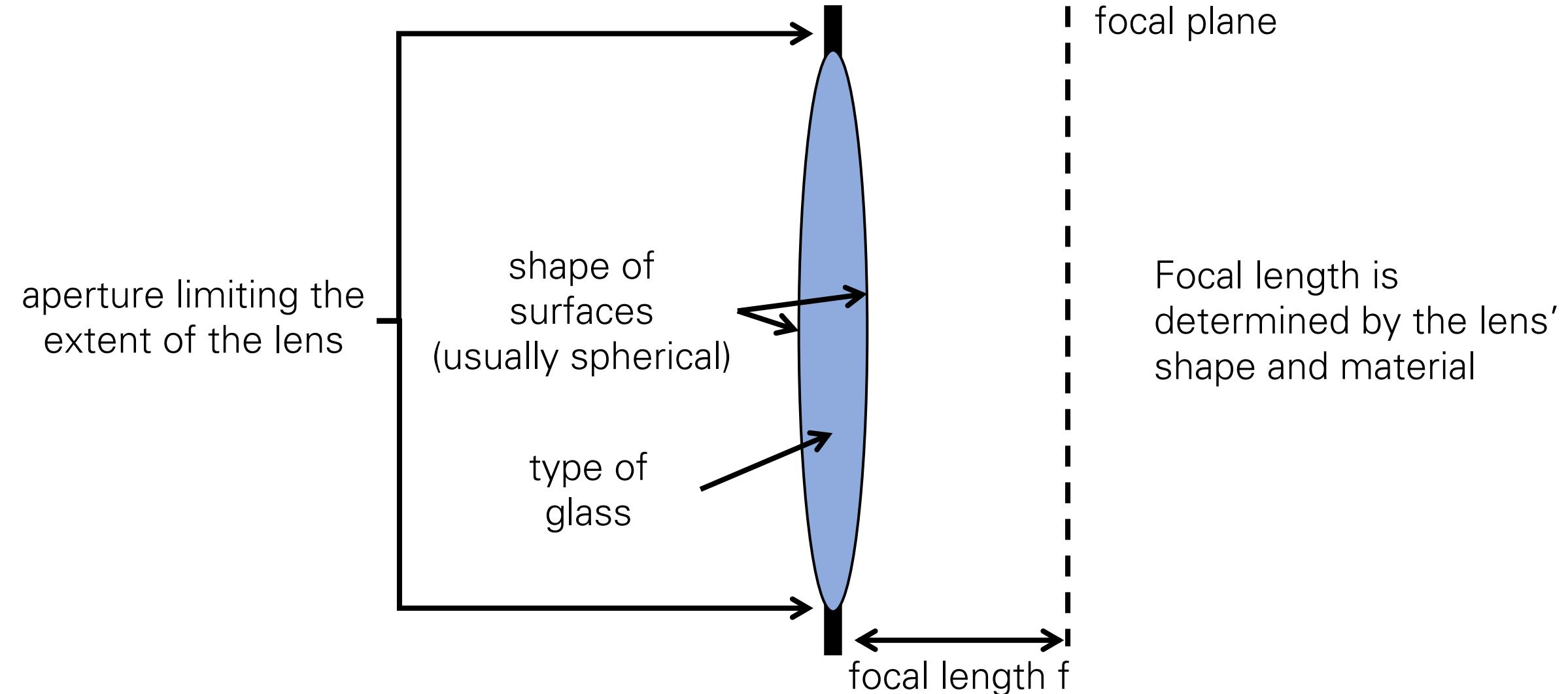
What is a lens?

A piece of glass manufactured to have a specific shape



What is a lens?

A piece of glass manufactured to have a specific shape



The lens on your camera

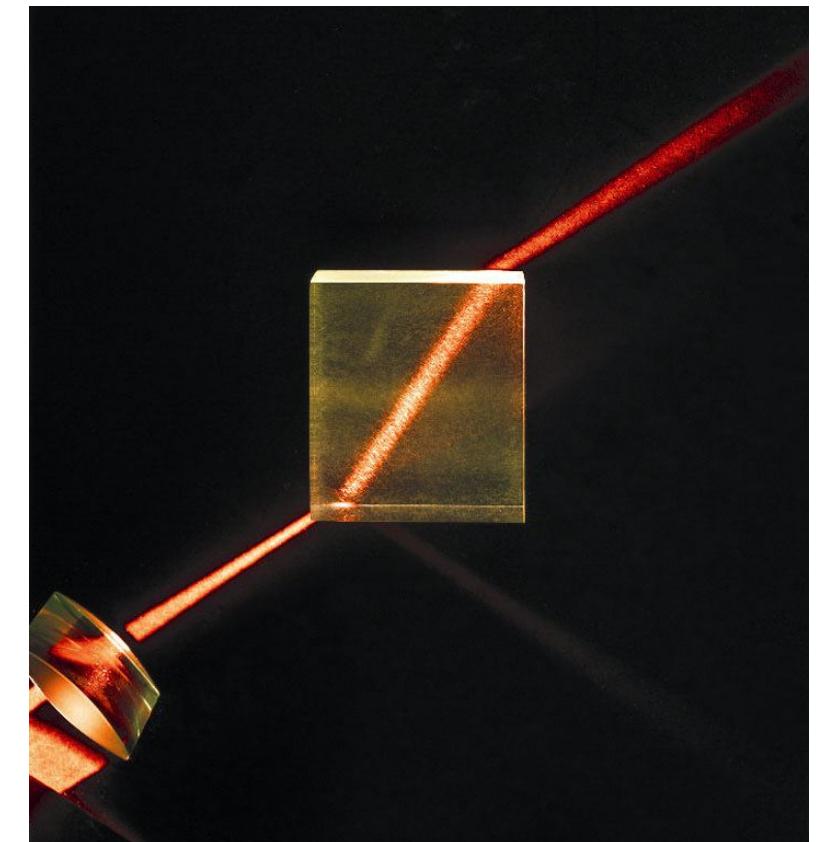
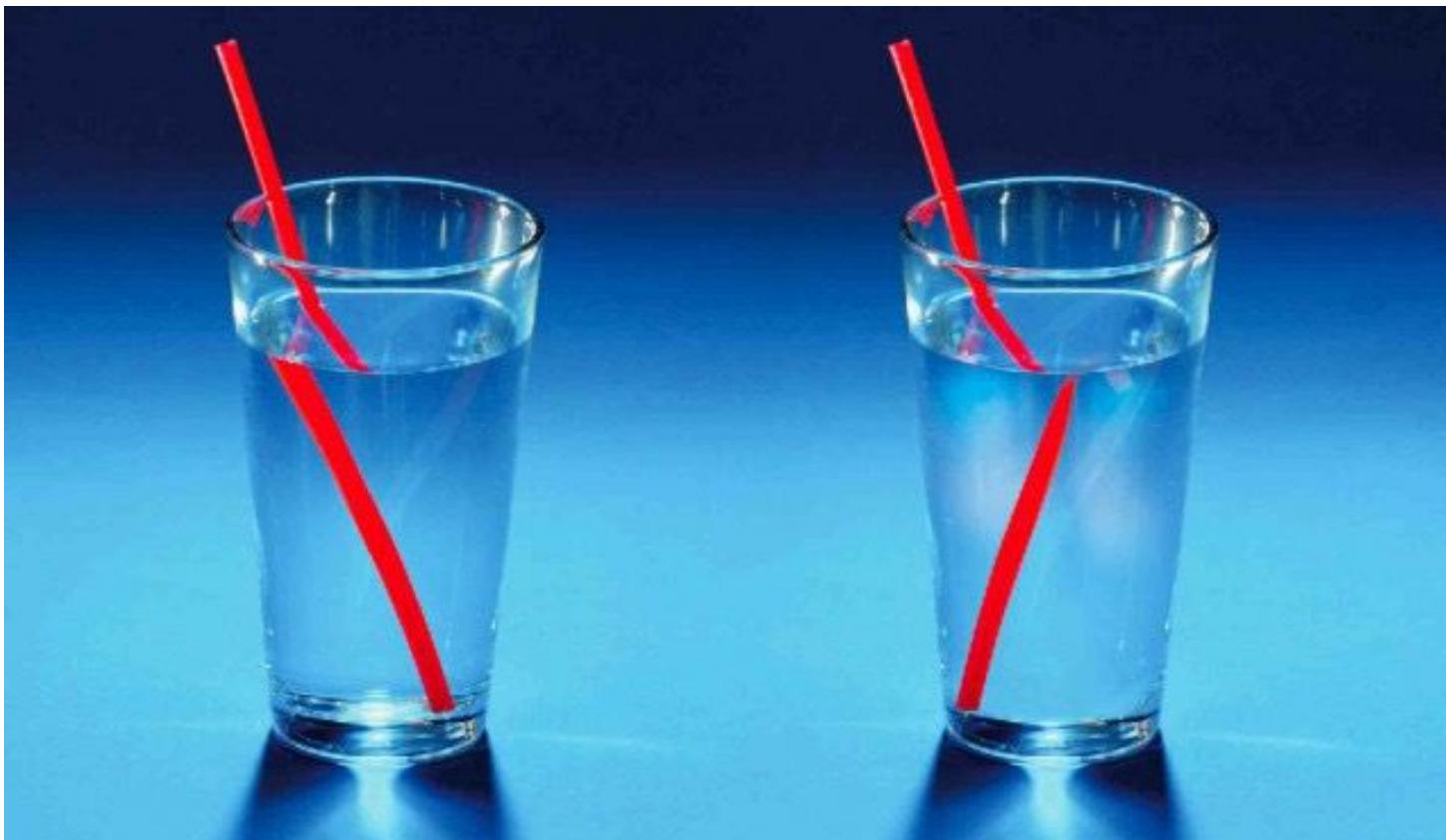


How does a lens work?



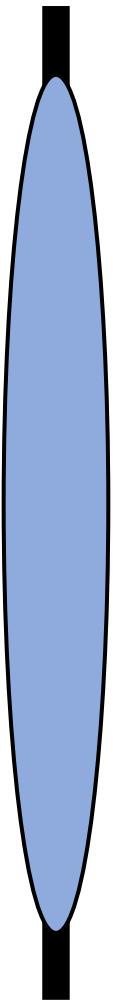
Refraction

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

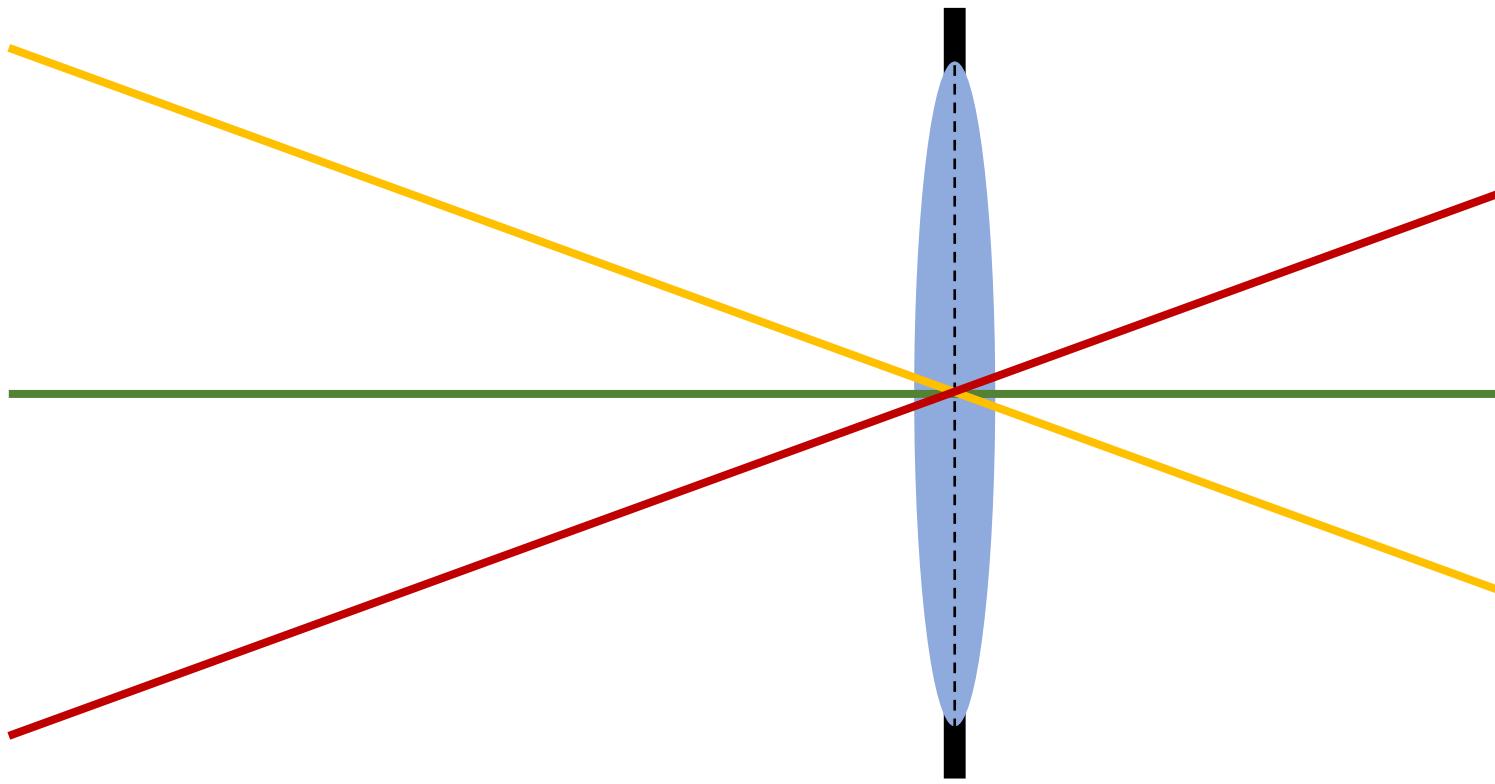
Thin lens model

Simplification of geometric optics for well-designed lenses.



Thin lens model

Simplification of geometric optics for well-designed lenses.

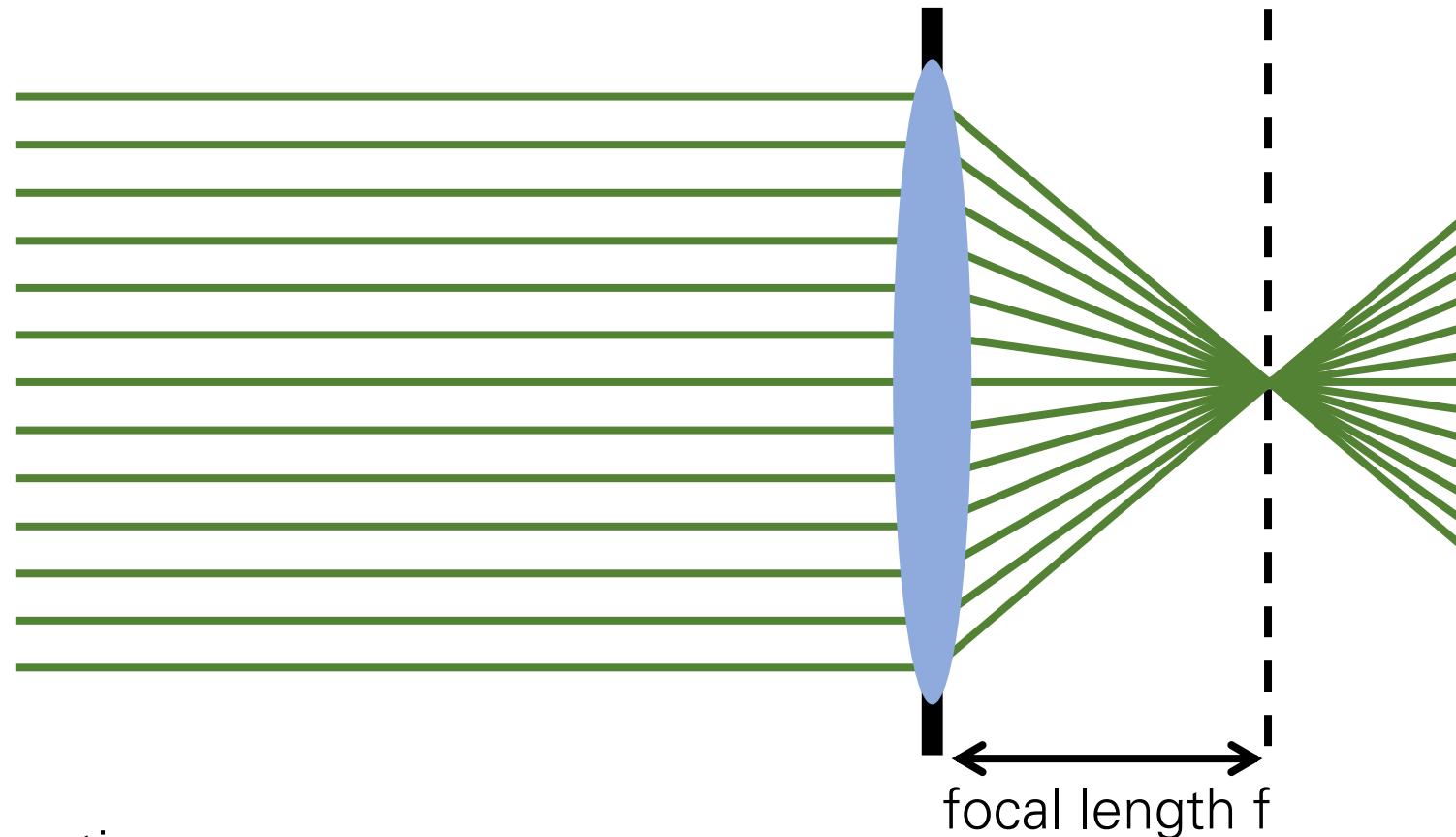


Two assumptions:

1. Rays passing through lens center are unaffected.

Thin lens model

Simplification of geometric optics for well-designed lenses.

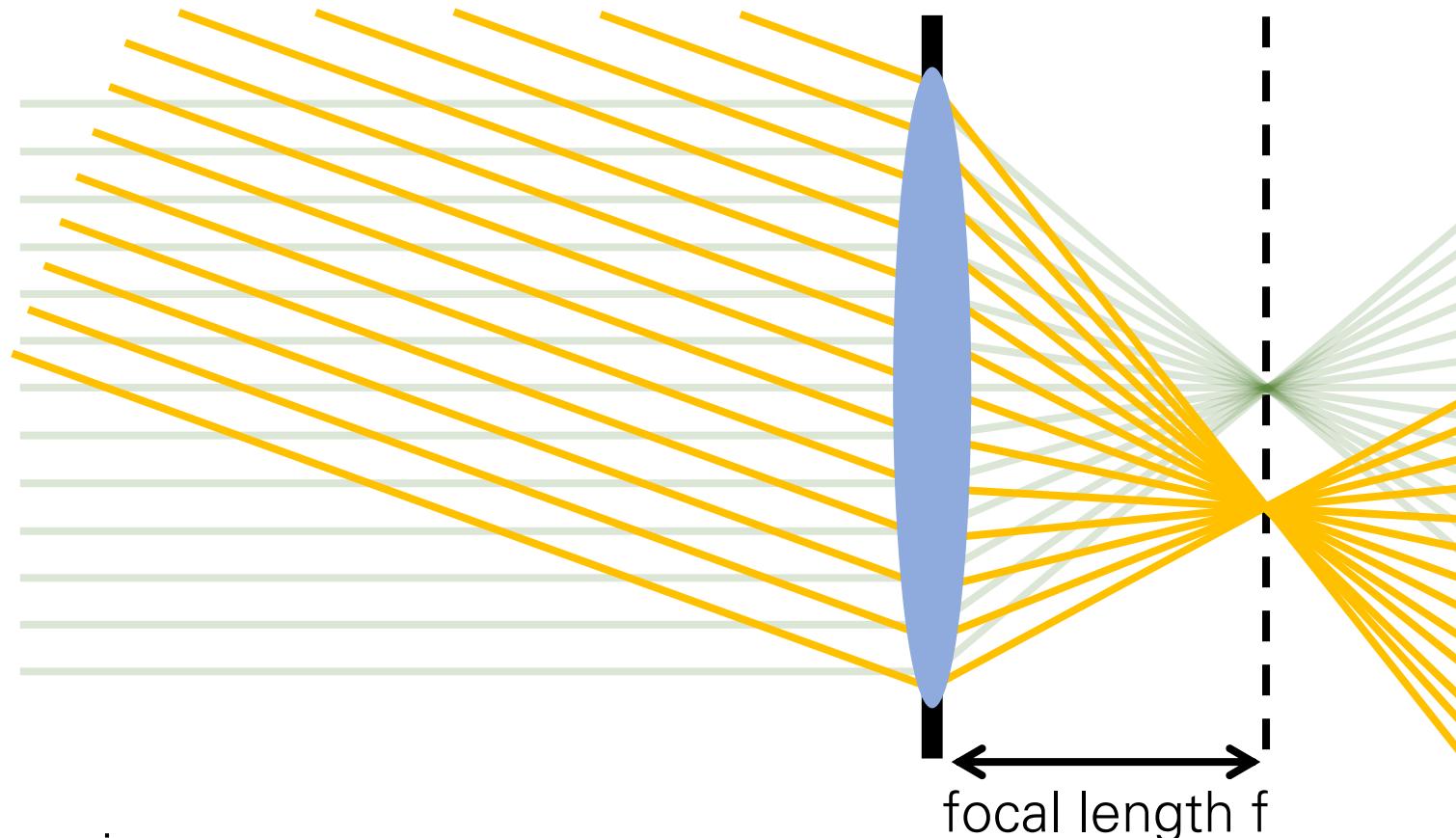


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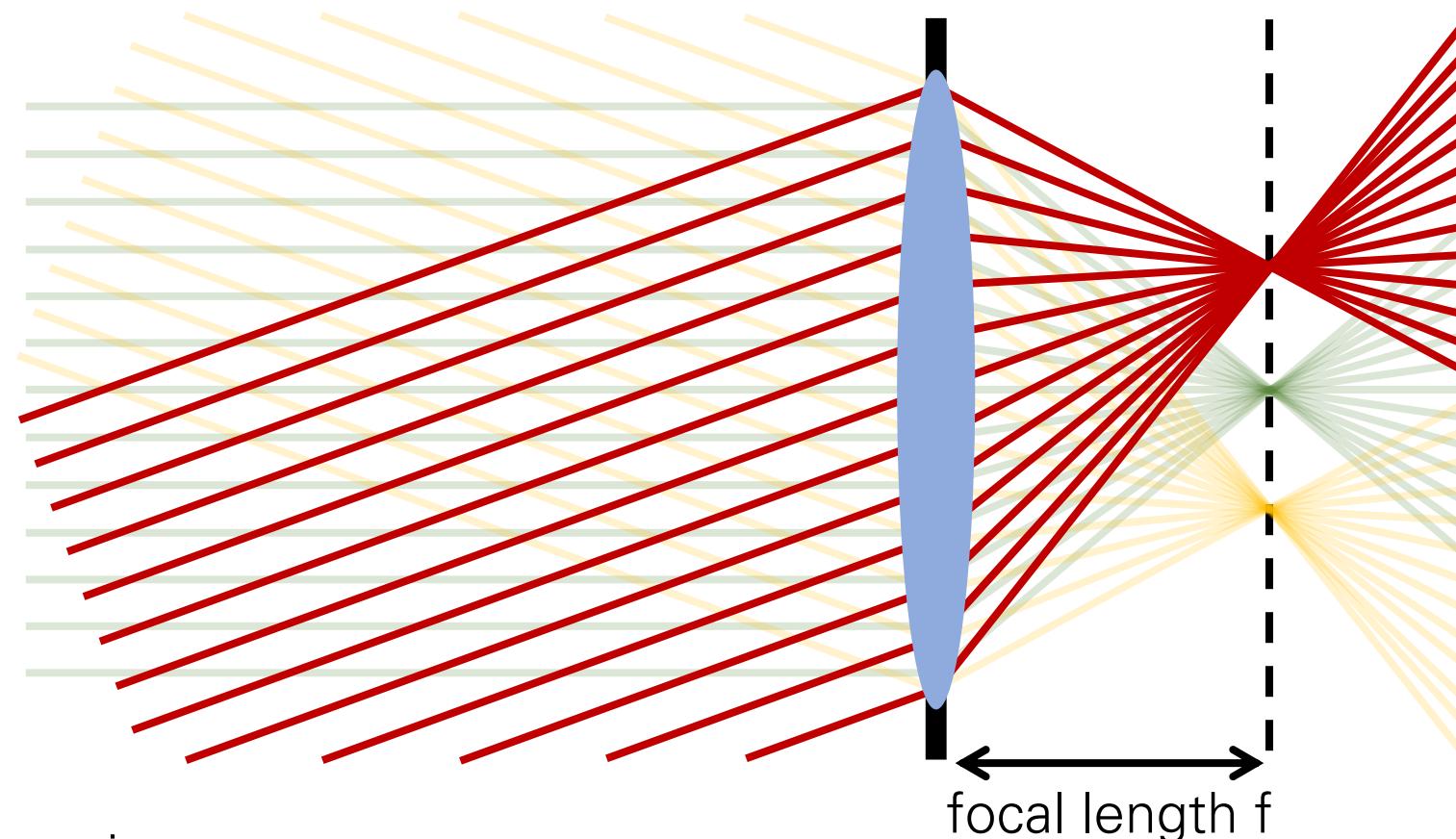


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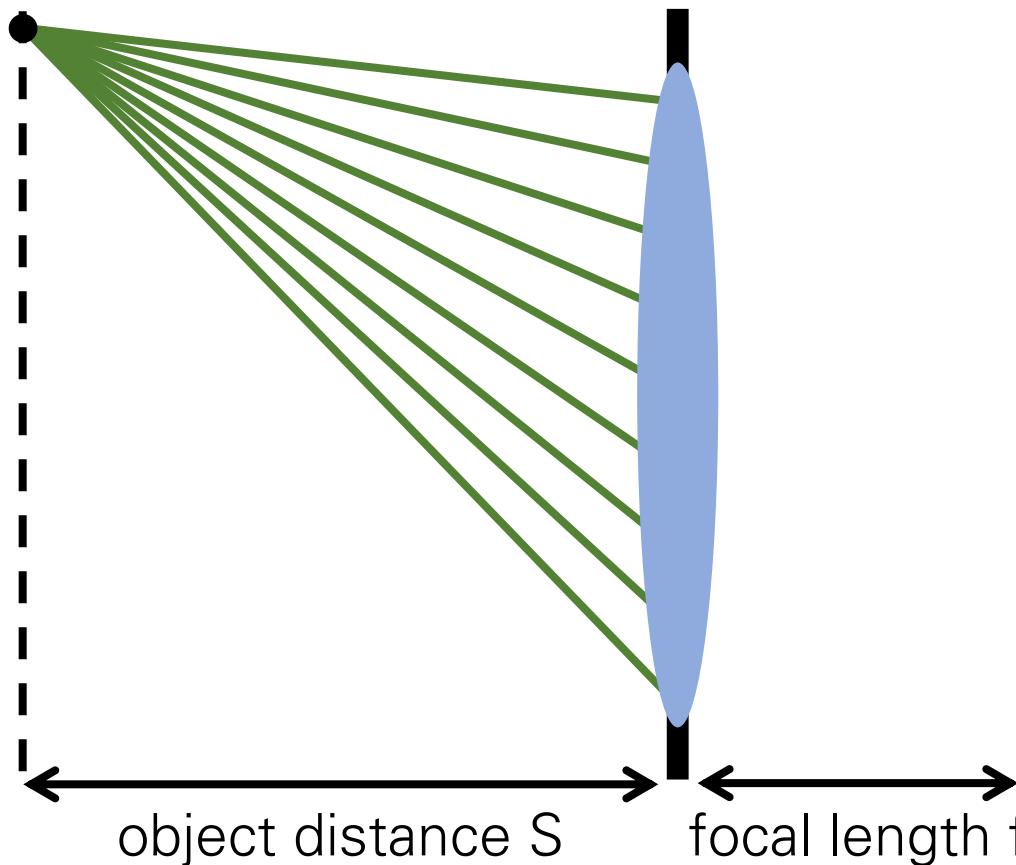


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Tracing rays through a thin lens

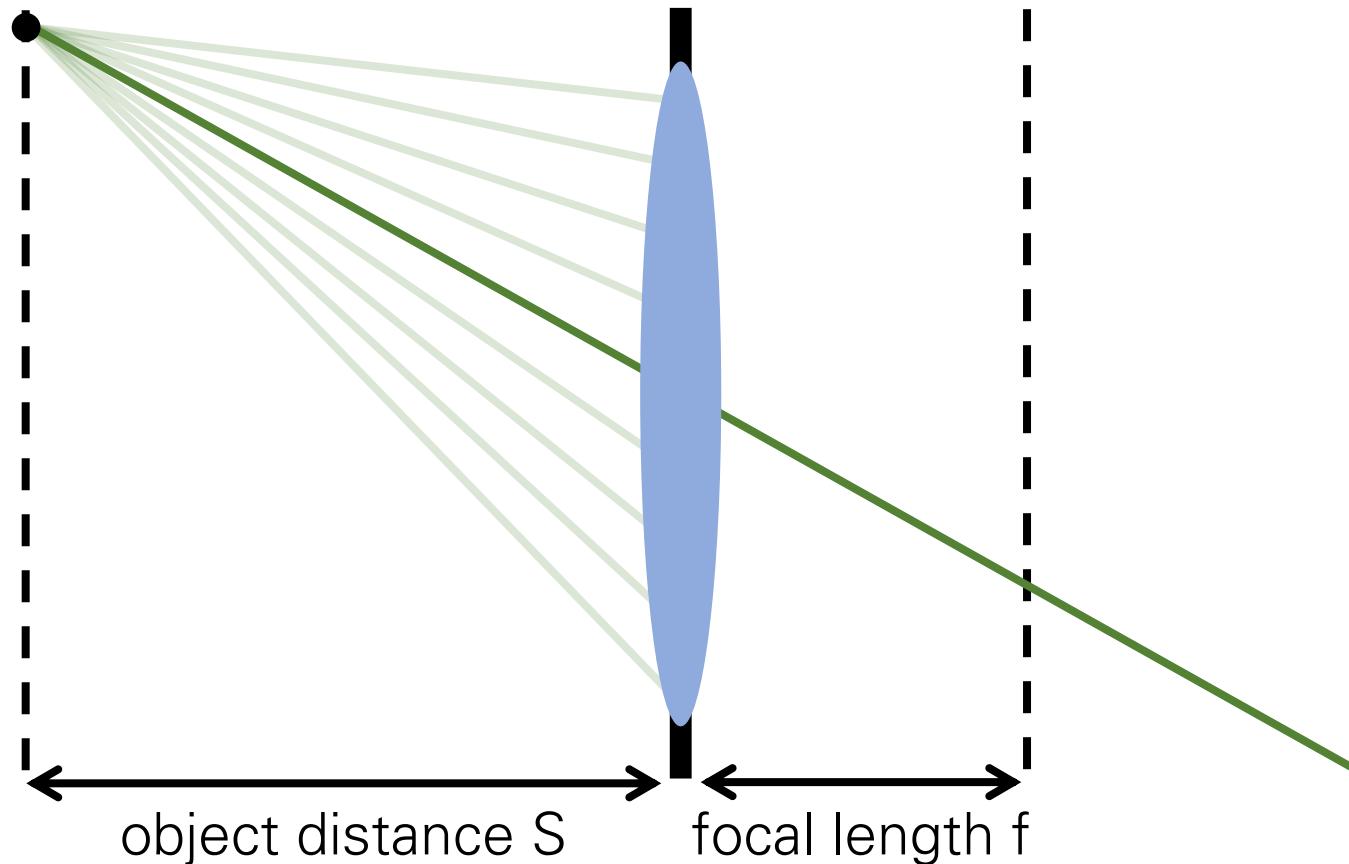
Consider an object emitting a bundle of rays. How do they propagate through the lens?



Tracing rays through a thin lens

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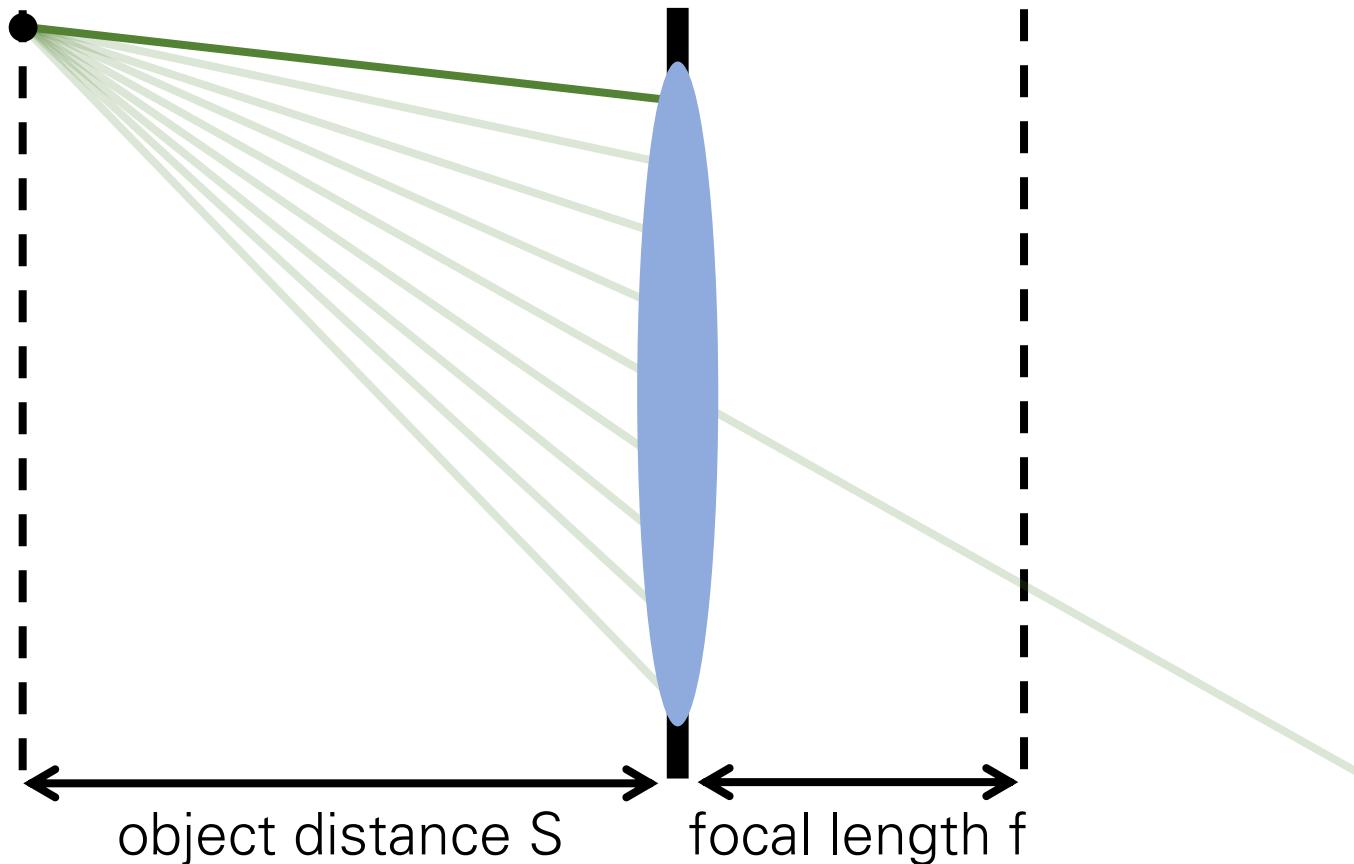
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Tracing rays through a thin lens

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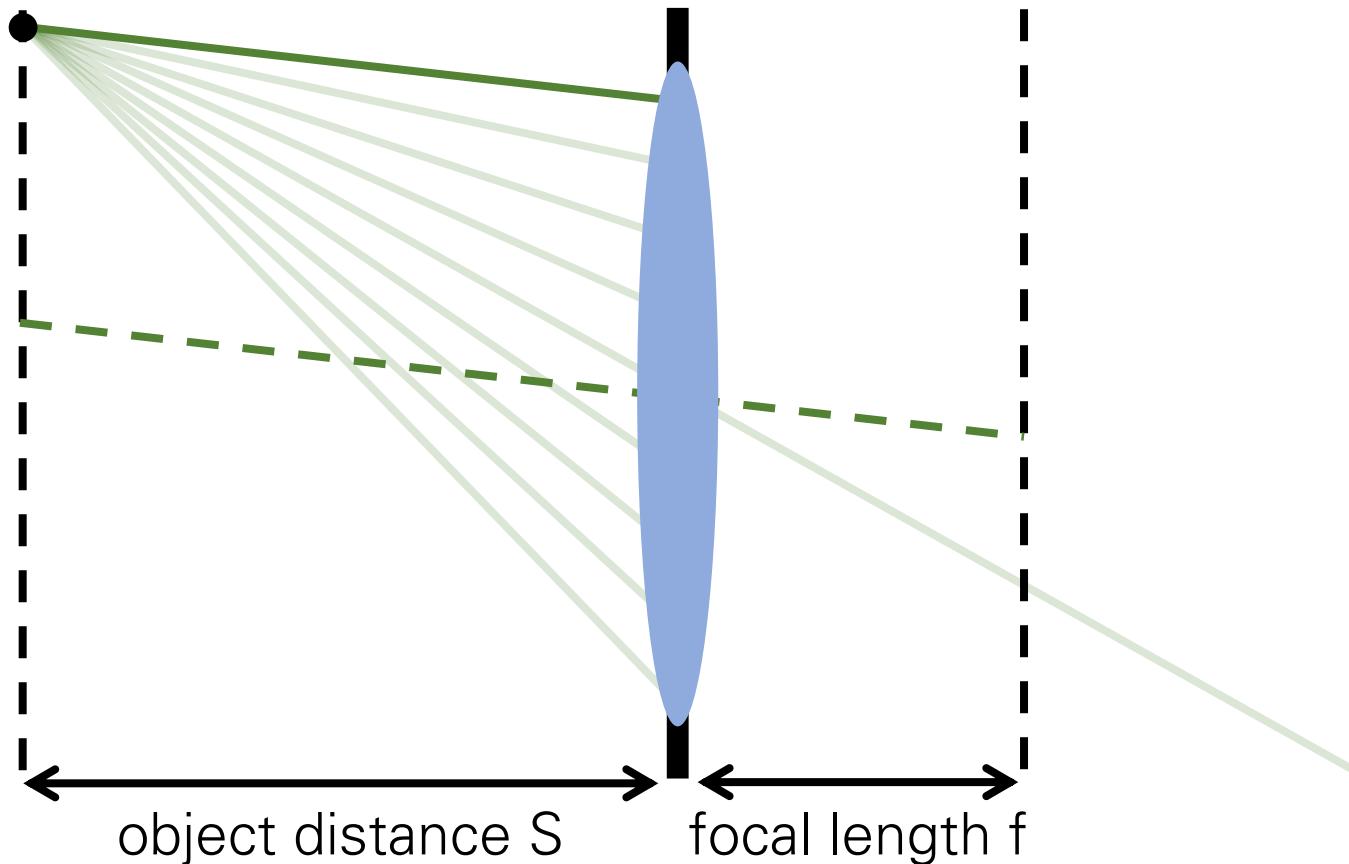
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2. For all other rays:



Tracing rays through a thin lens

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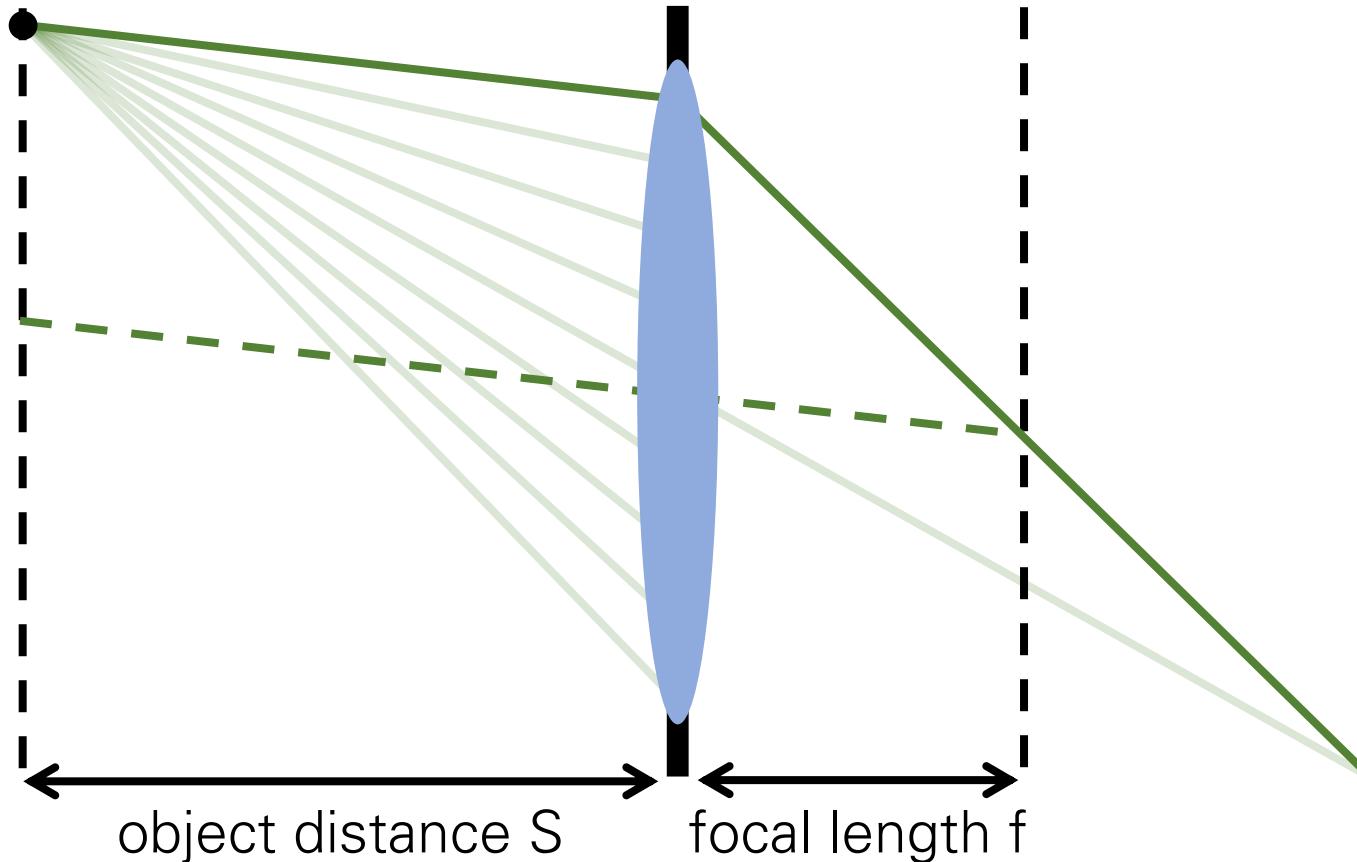
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Tracing rays through a thin lens

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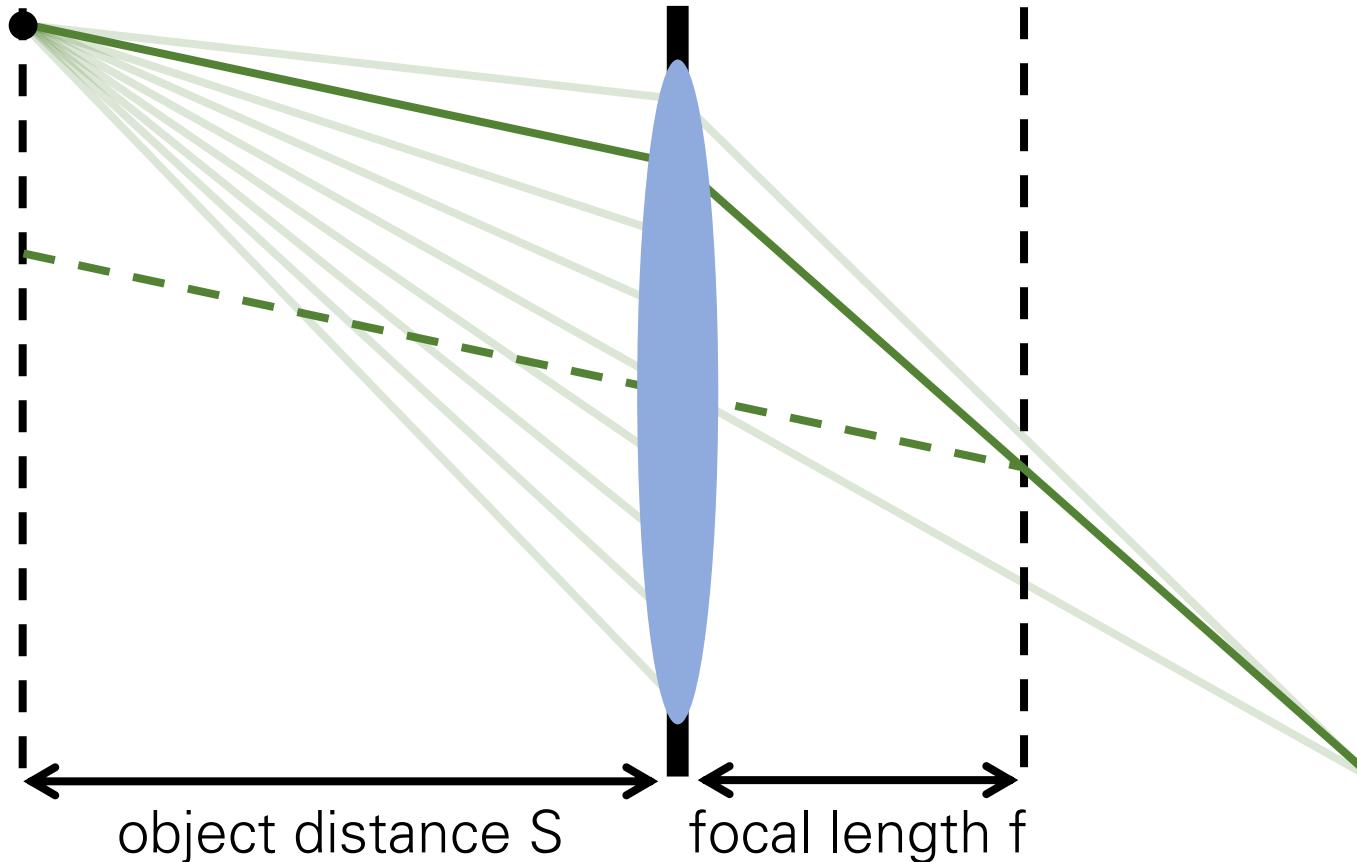
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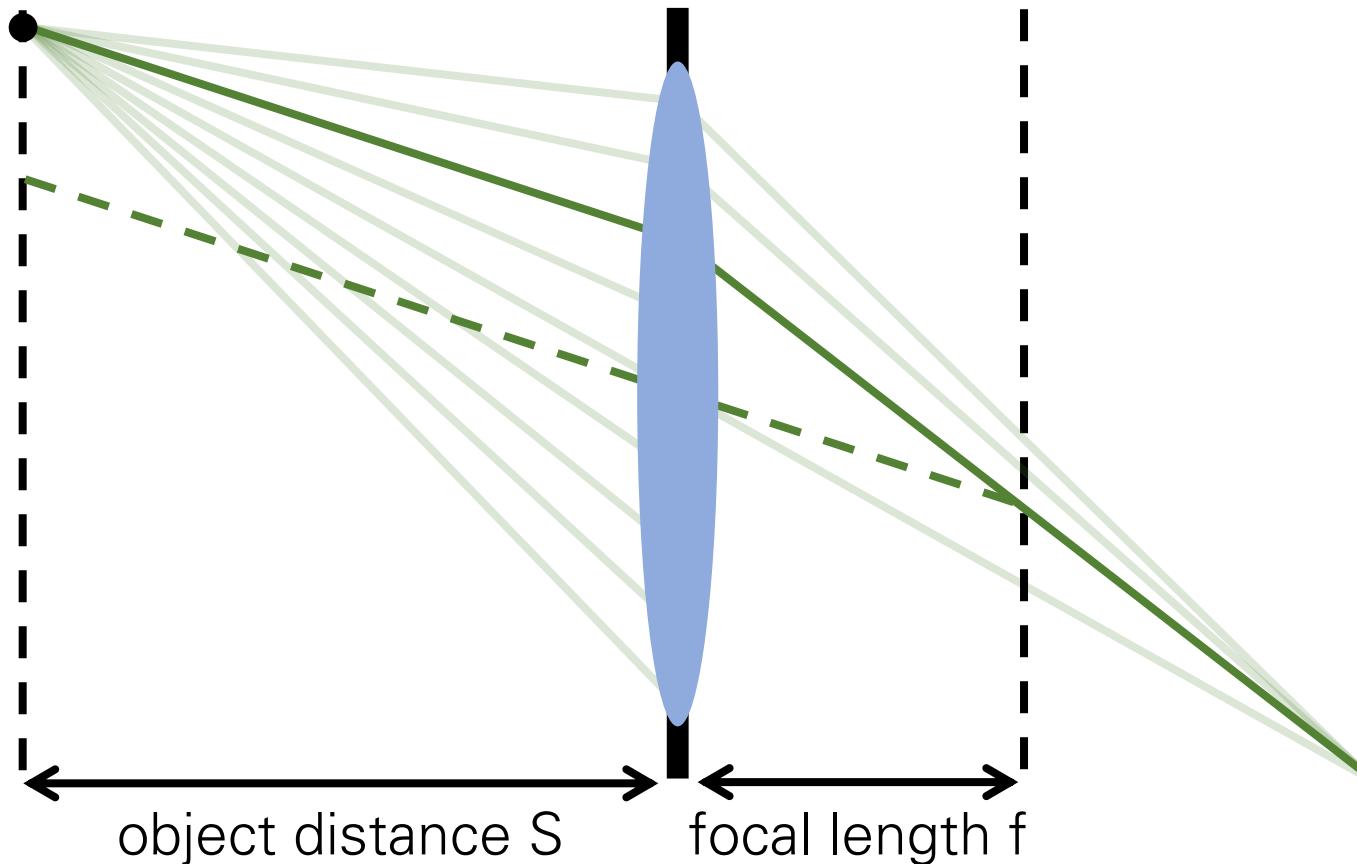
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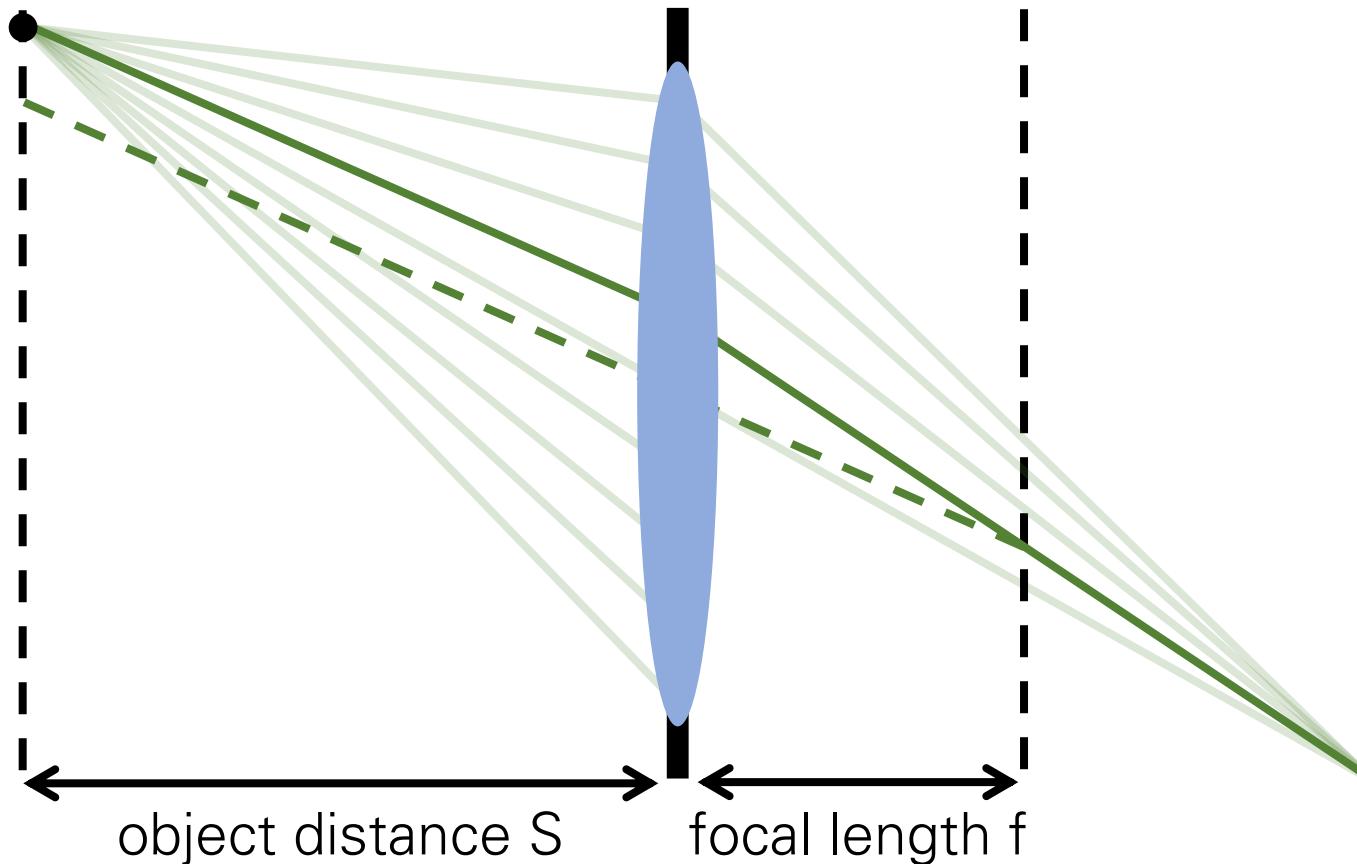
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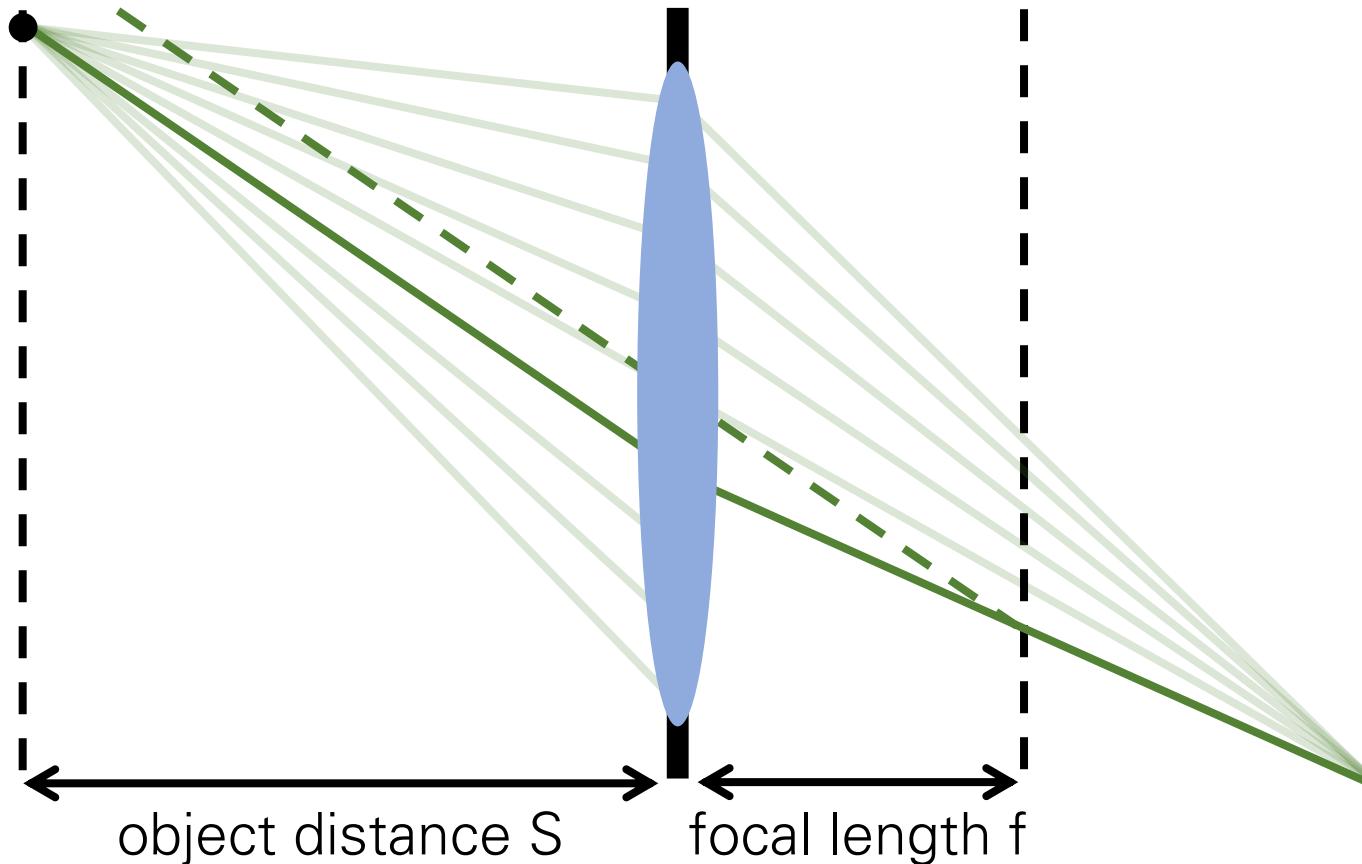
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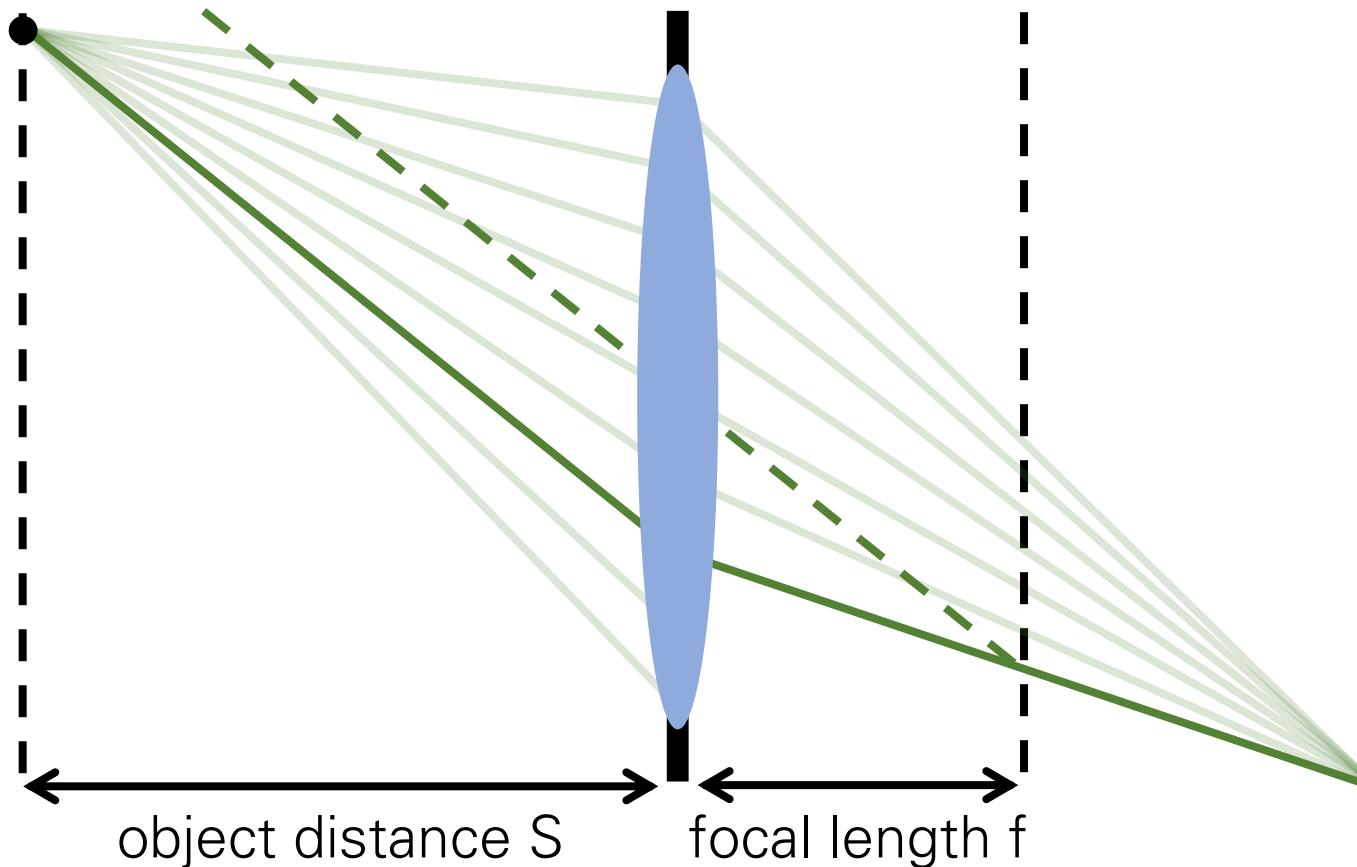
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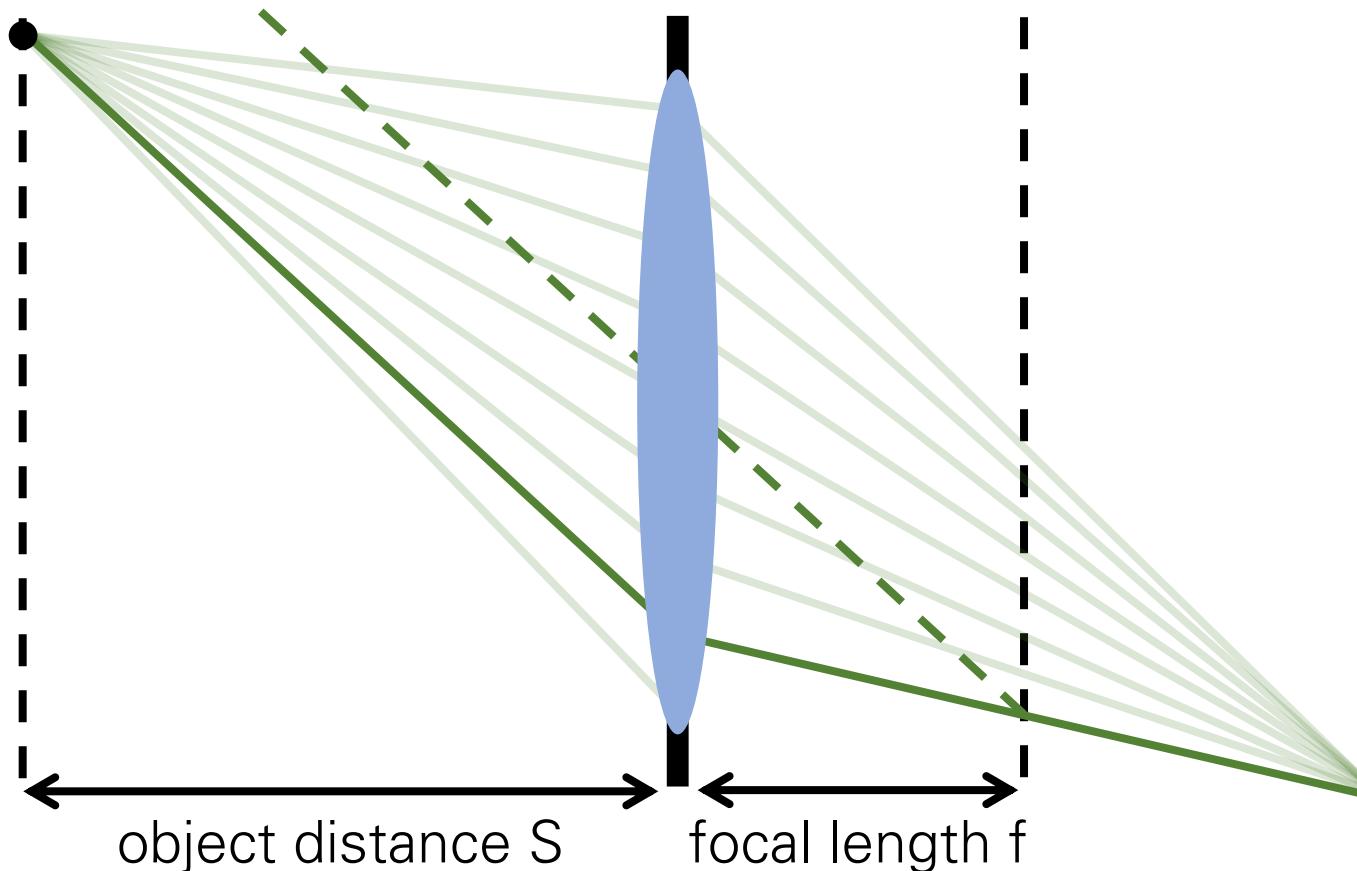
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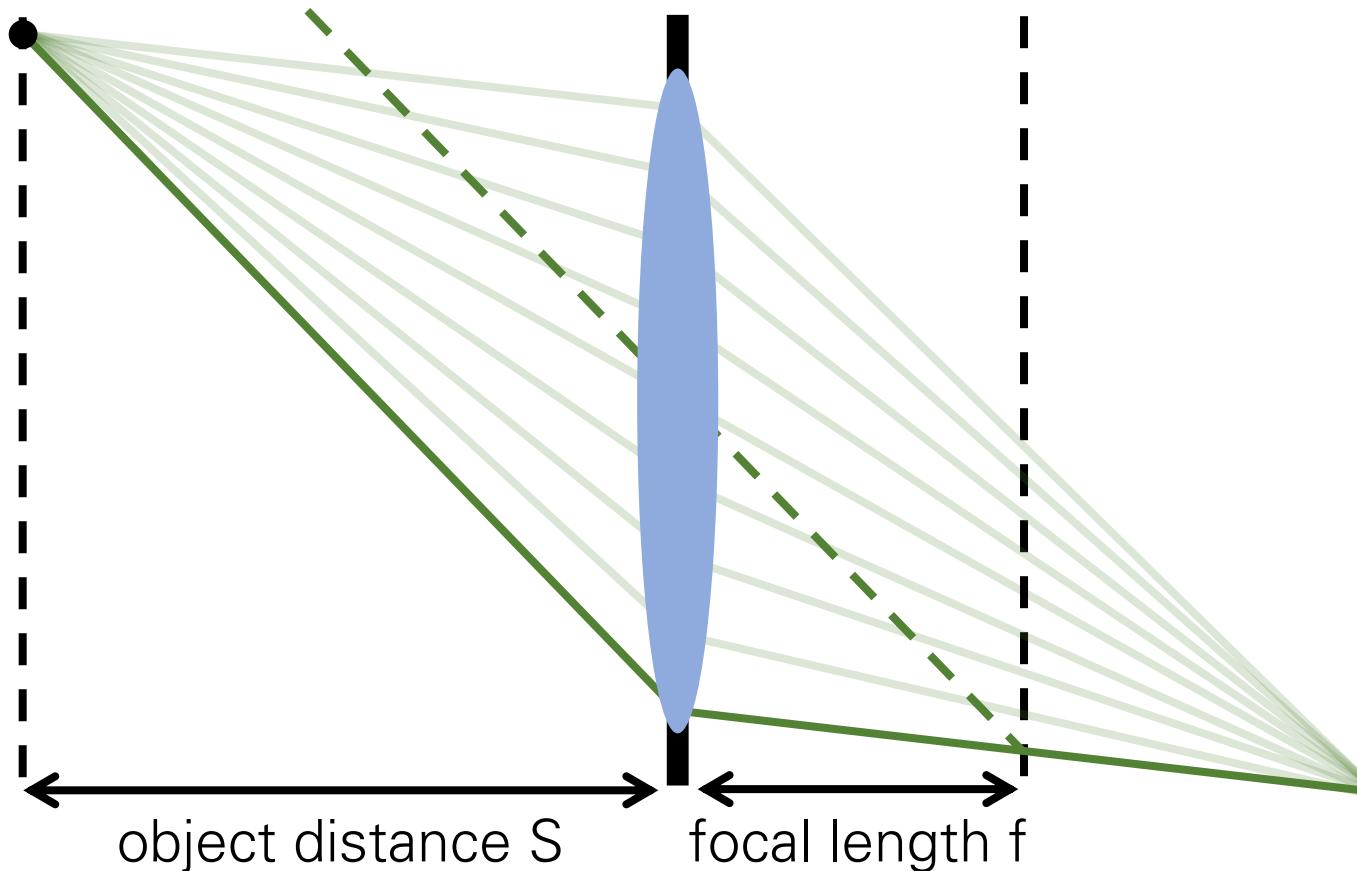
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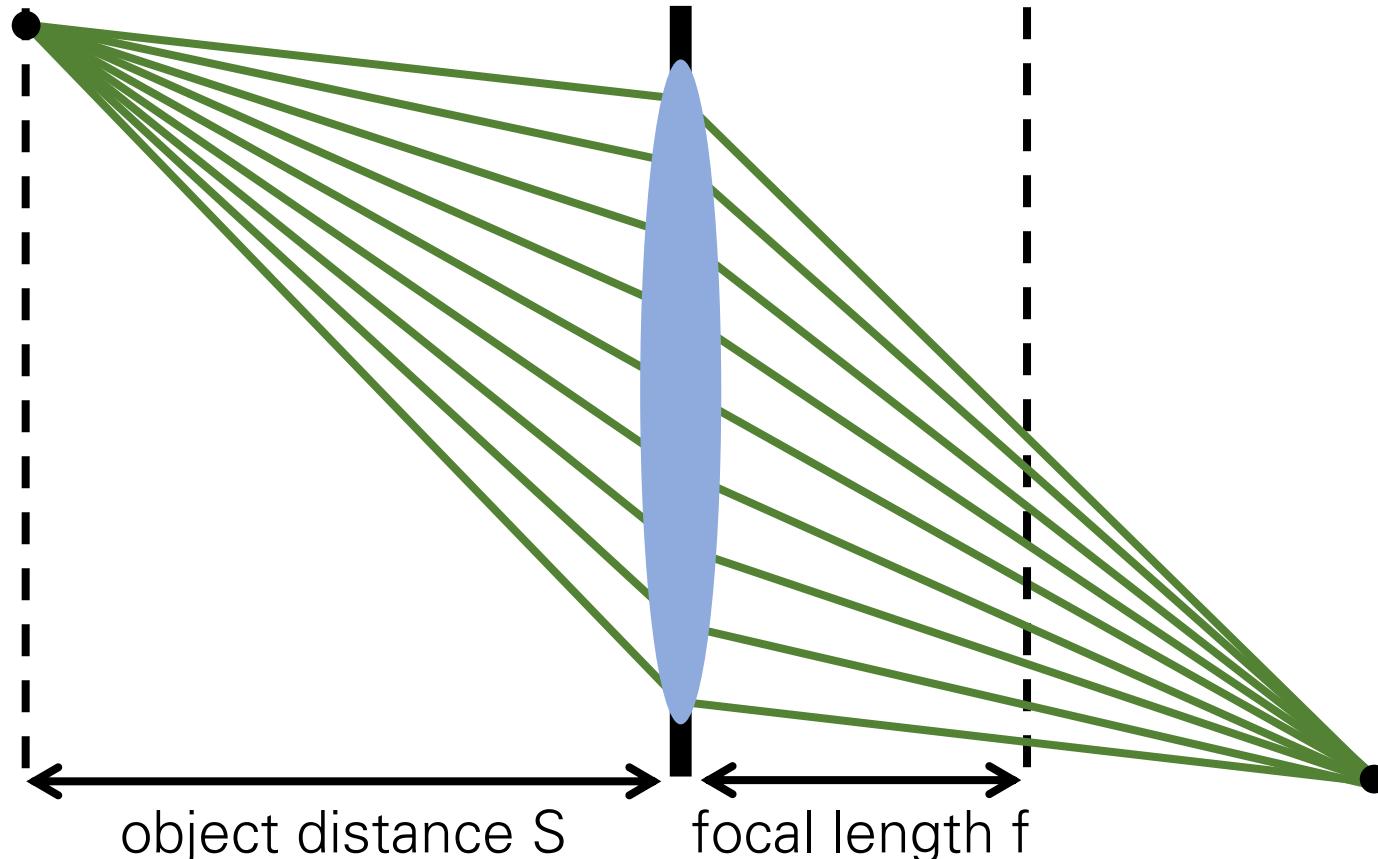
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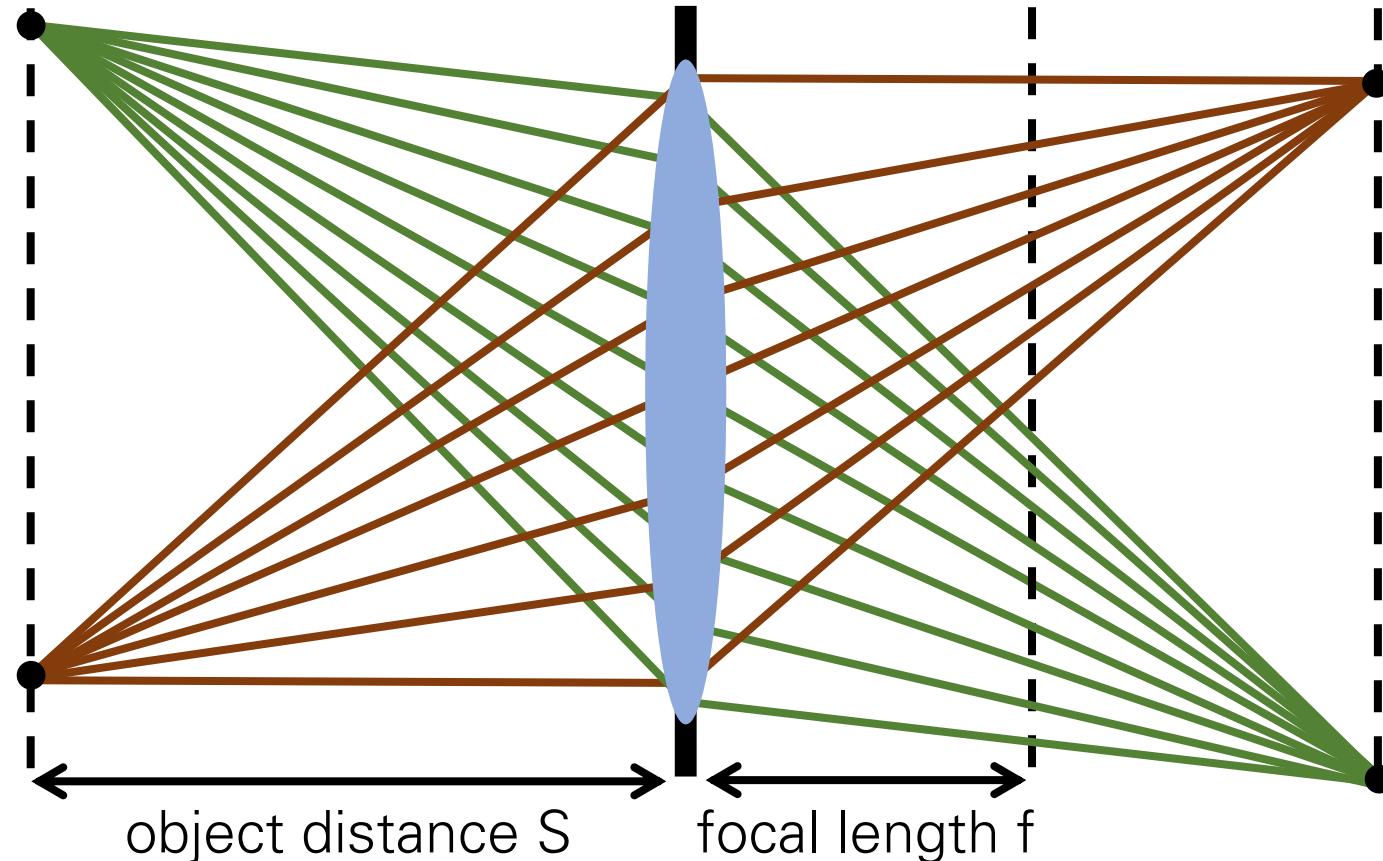
Focusing property:

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

Tracing rays through a thin lens

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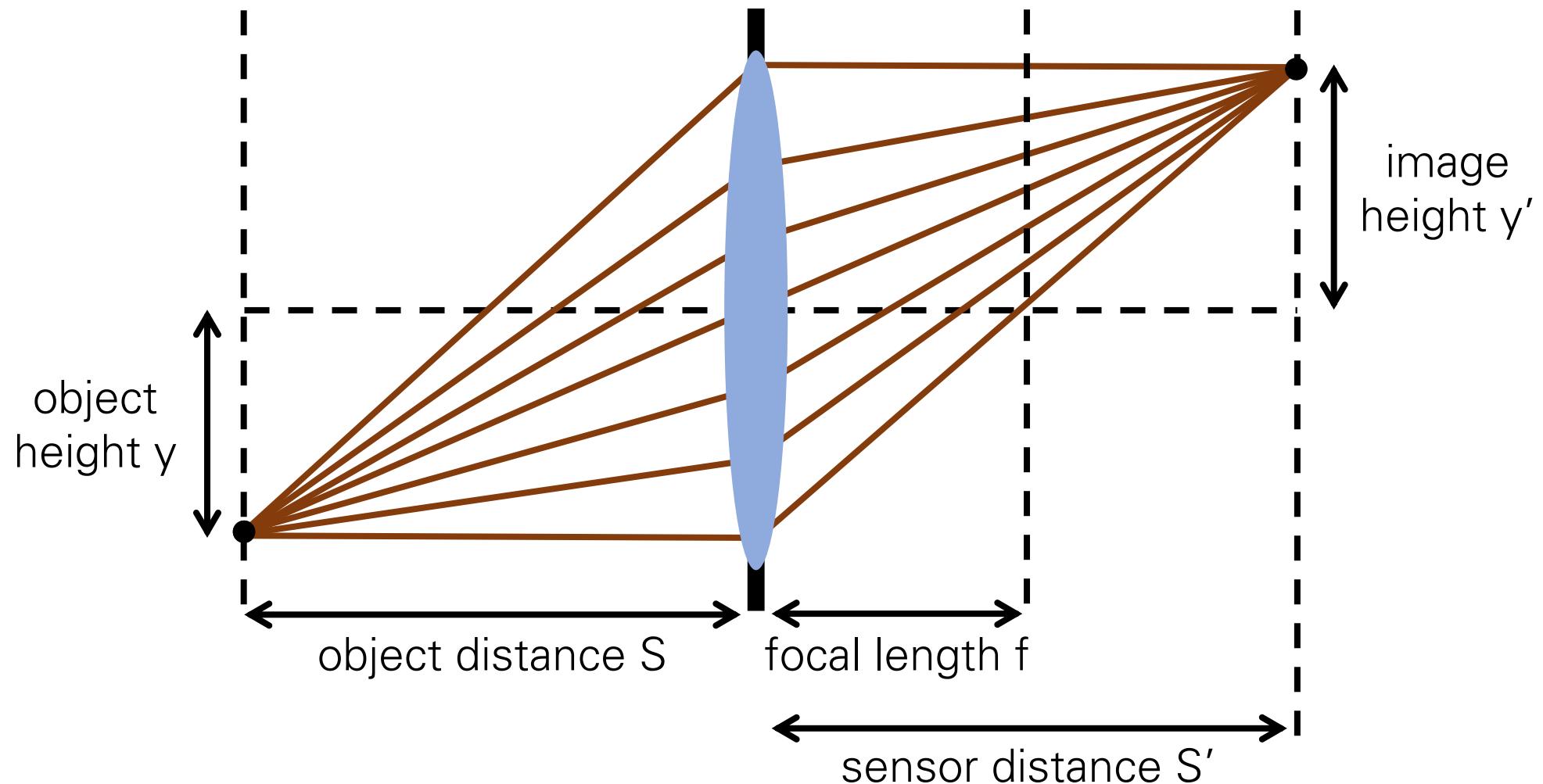


Focusing property:

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.

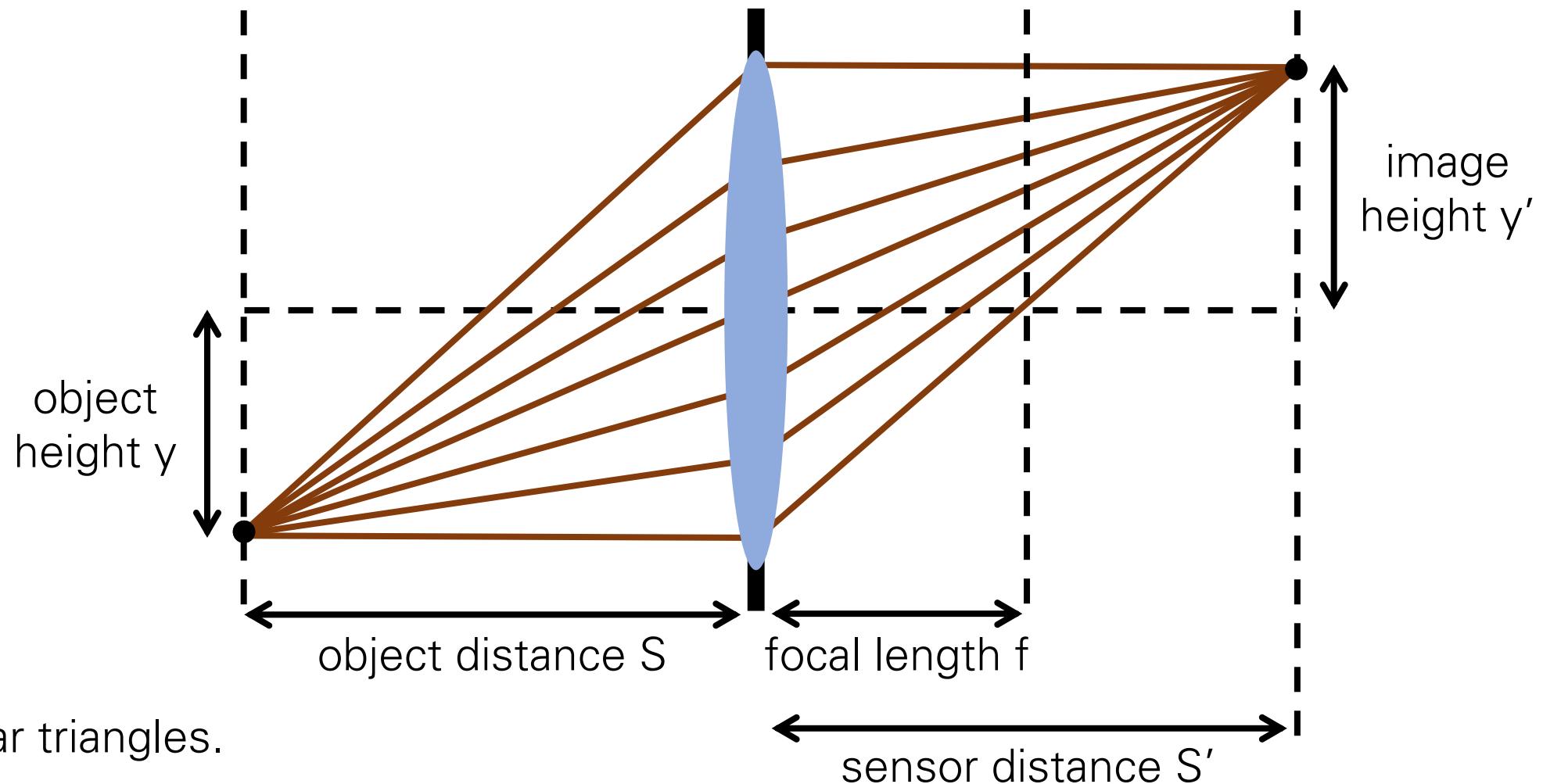
Gaussian lens formula

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



Gaussian lens formula

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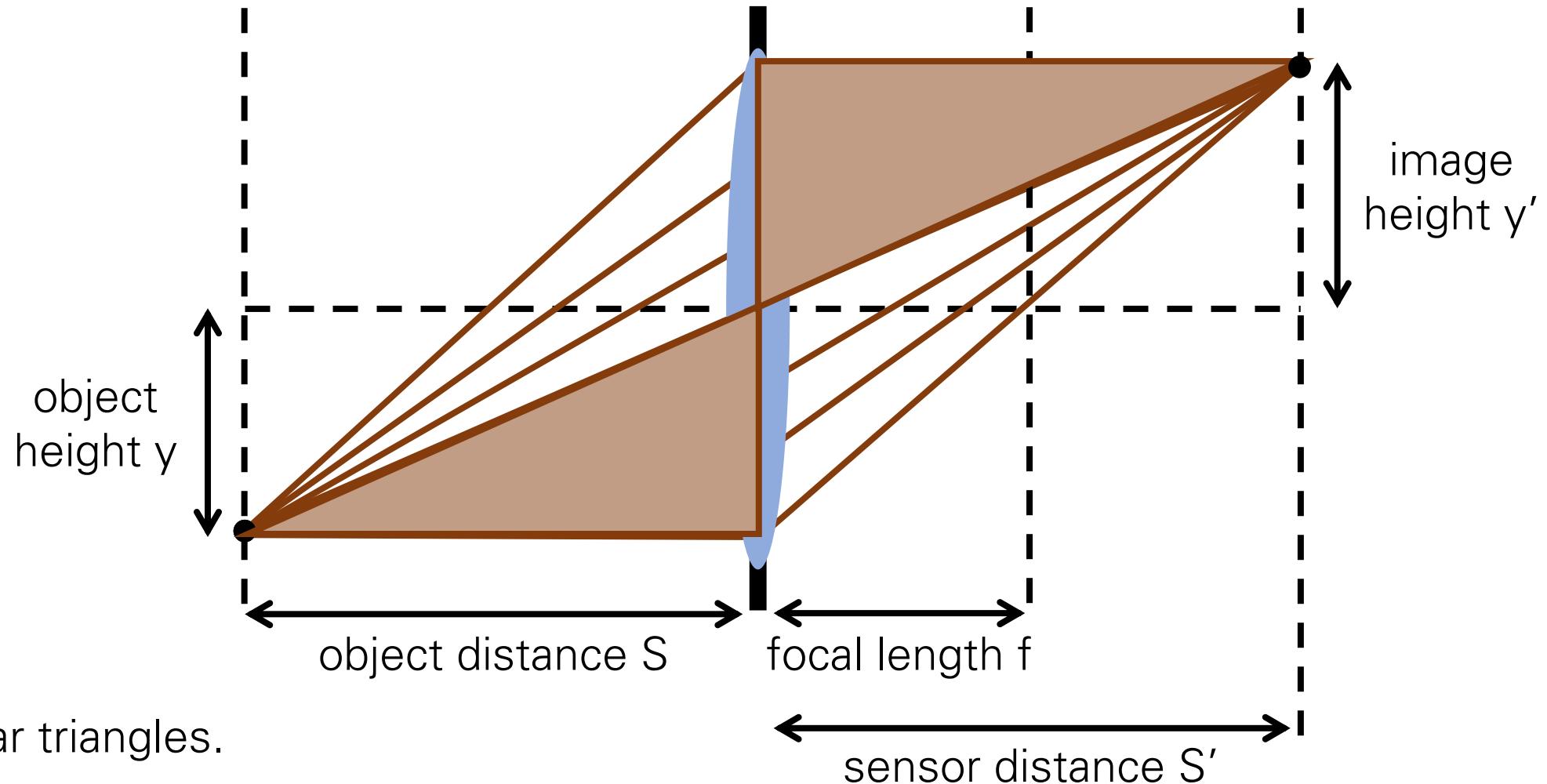


Use similar triangles.

Gaussian lens formula

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

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

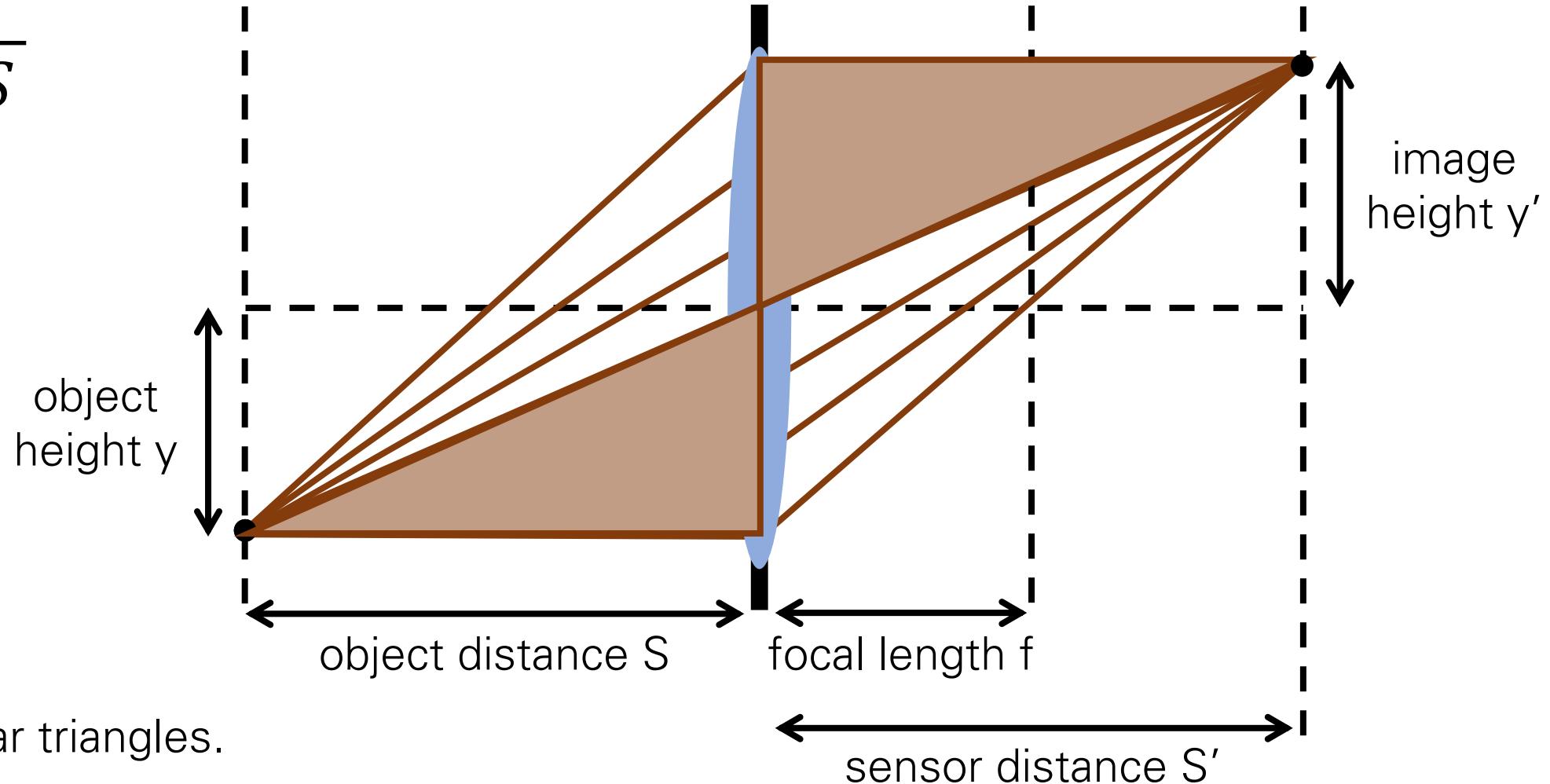


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Gaussian lens formula

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

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

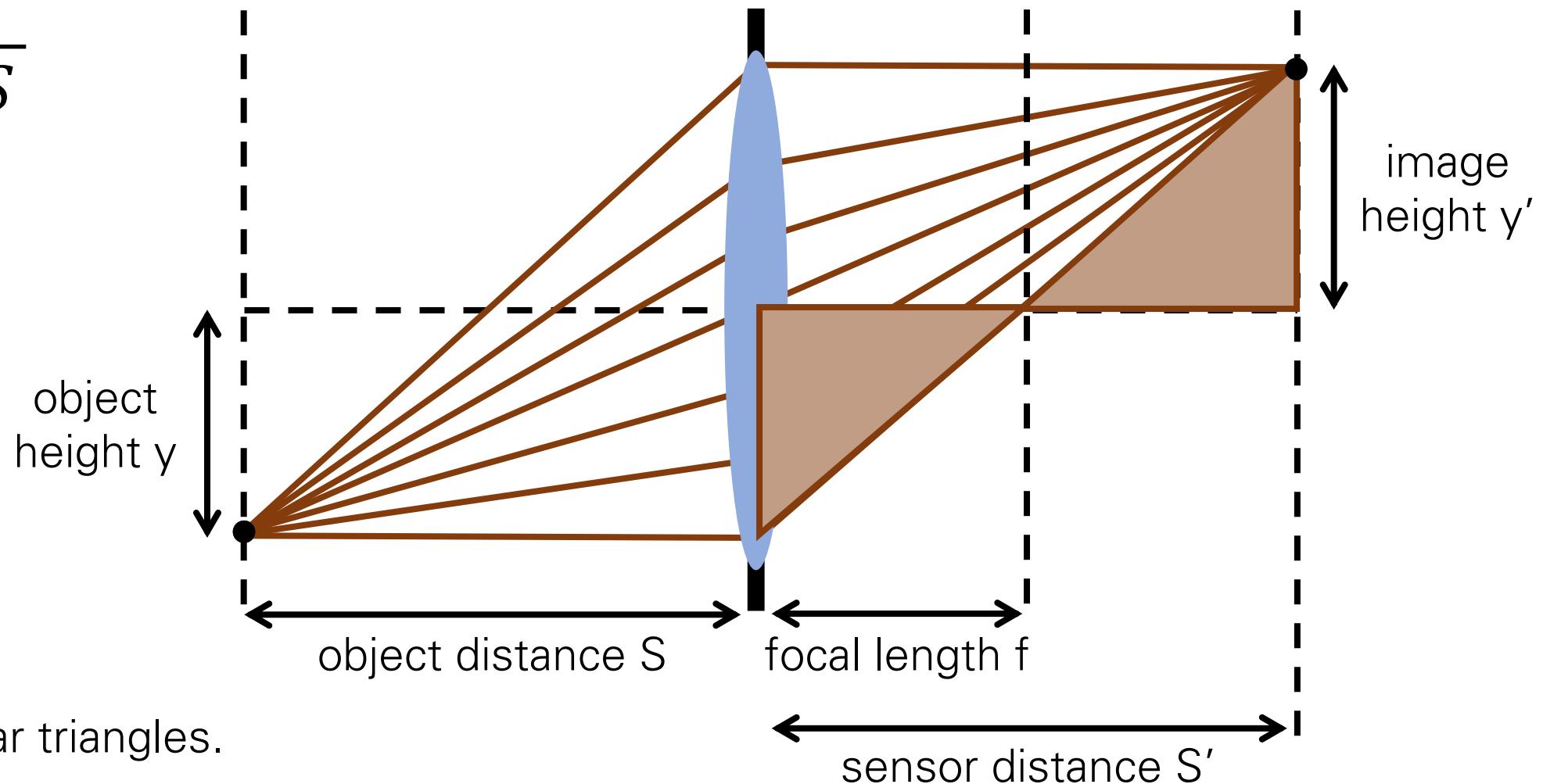


Use similar triangles.

Gaussian lens formula

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

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



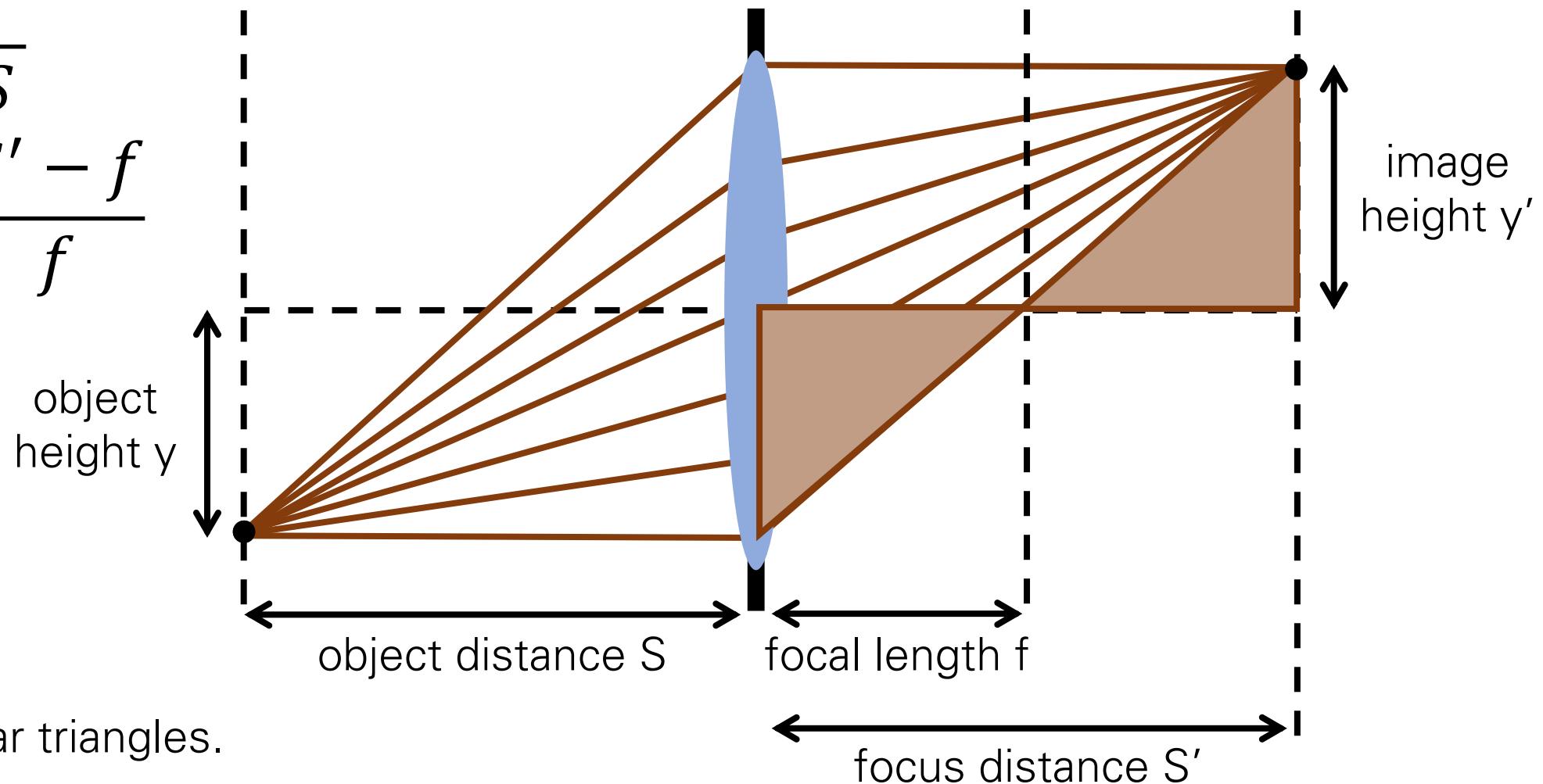
Use similar triangles.

Gaussian lens formula

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

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

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

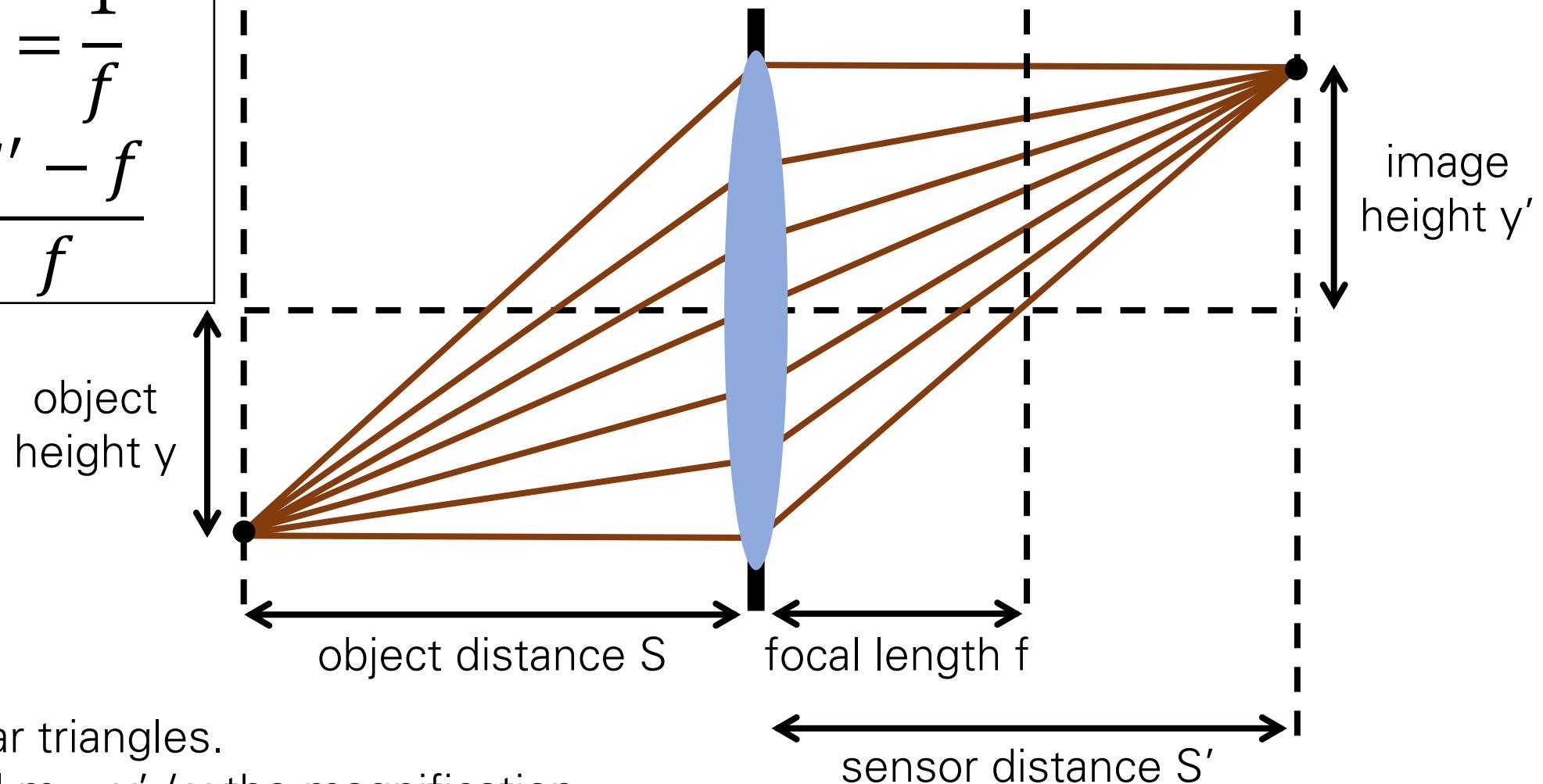


Use similar triangles.

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.

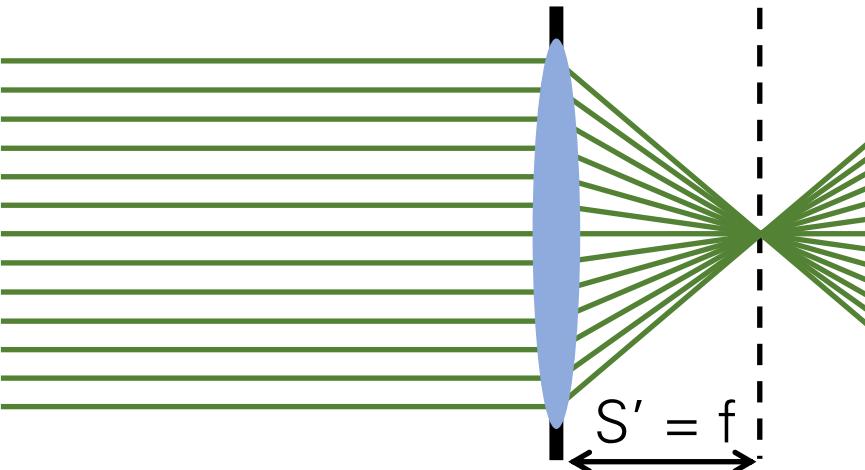
Special focus distances

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

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

Special focus distances

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



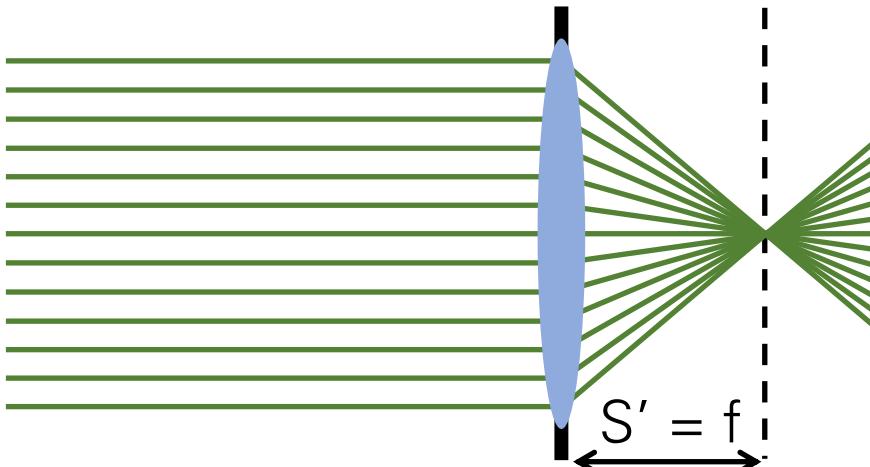
$$\frac{1}{S'} + \frac{1}{S} = \frac{1}{f}$$
$$m = \frac{S' - f}{f}$$

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

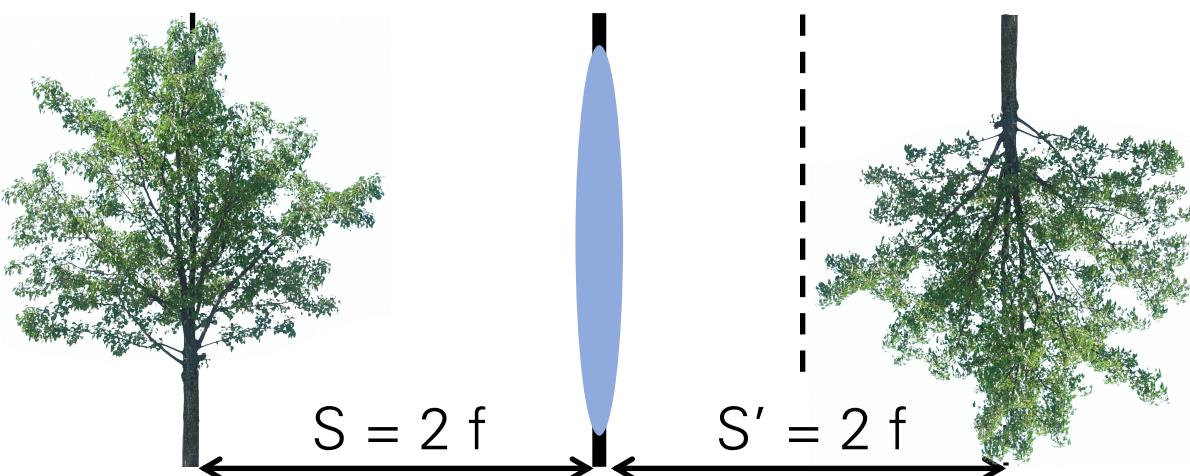
Special focus distances

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

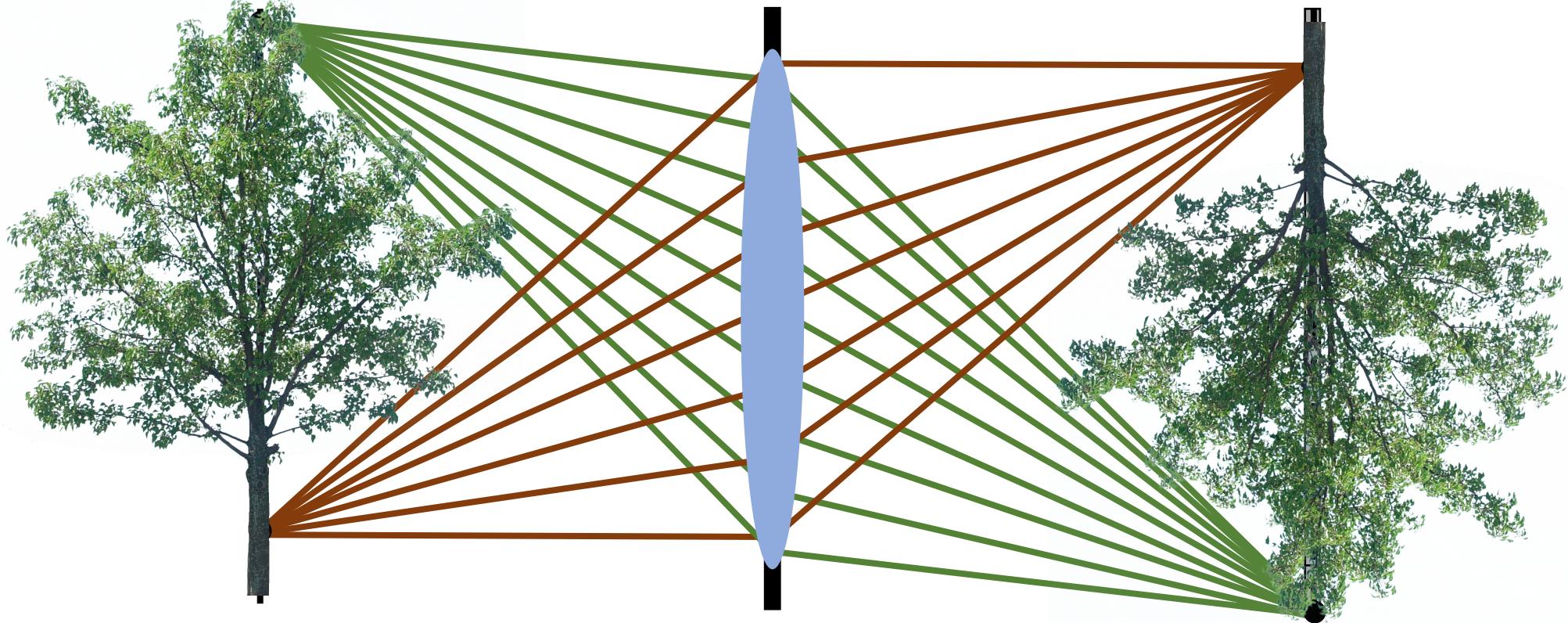
$$\frac{1}{S'} + \frac{1}{S} = \frac{1}{f}$$
$$m = \frac{S' - f}{f}$$



$S' = S = 2 f, m = 1 \rightarrow$ object is reproduced in real-life size



Free lunch?



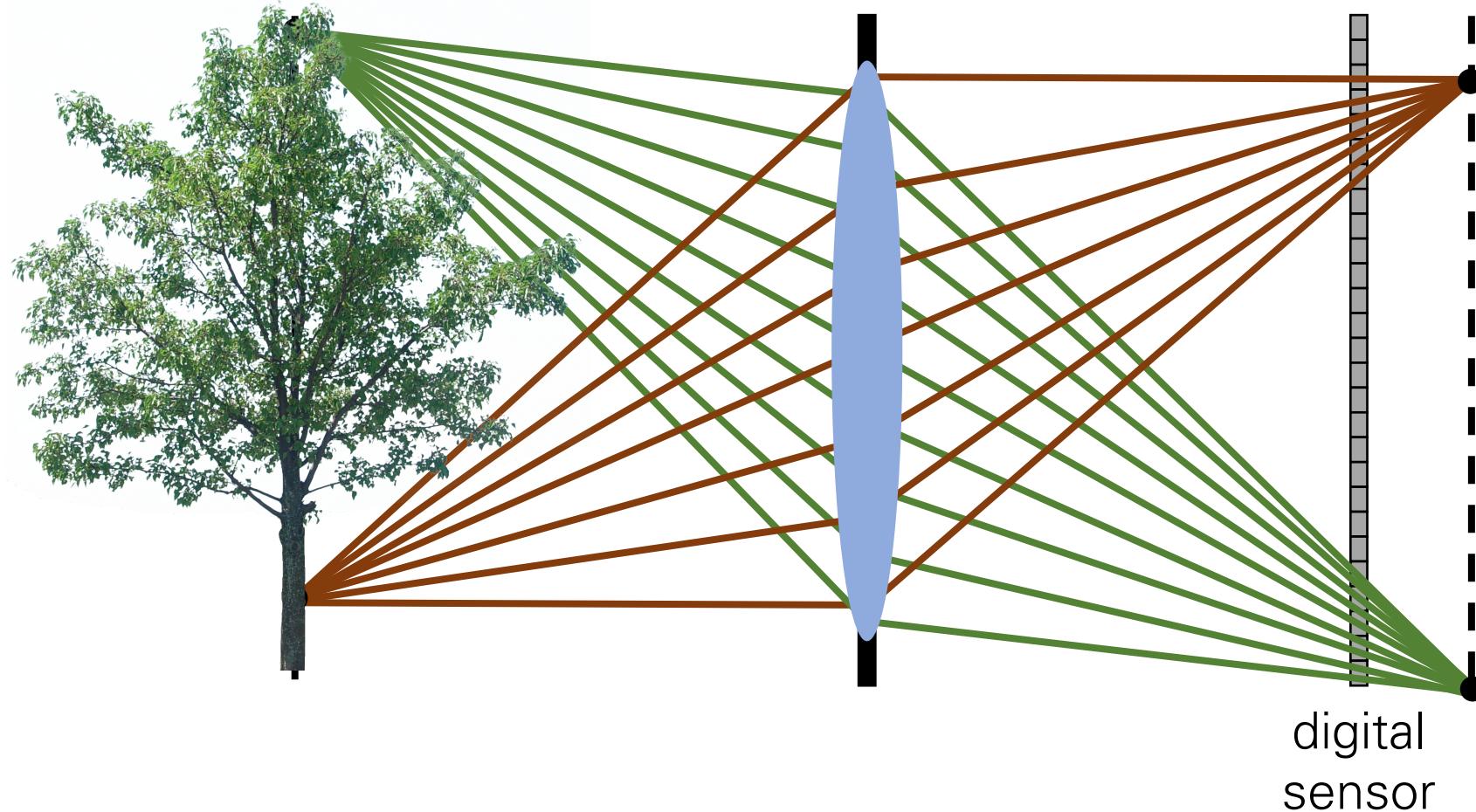
By using a lens, we simultaneously achieve:

1. Image is sharp.
2. Signal-to-noise ratio is high.

Do we lose anything by using a lens?

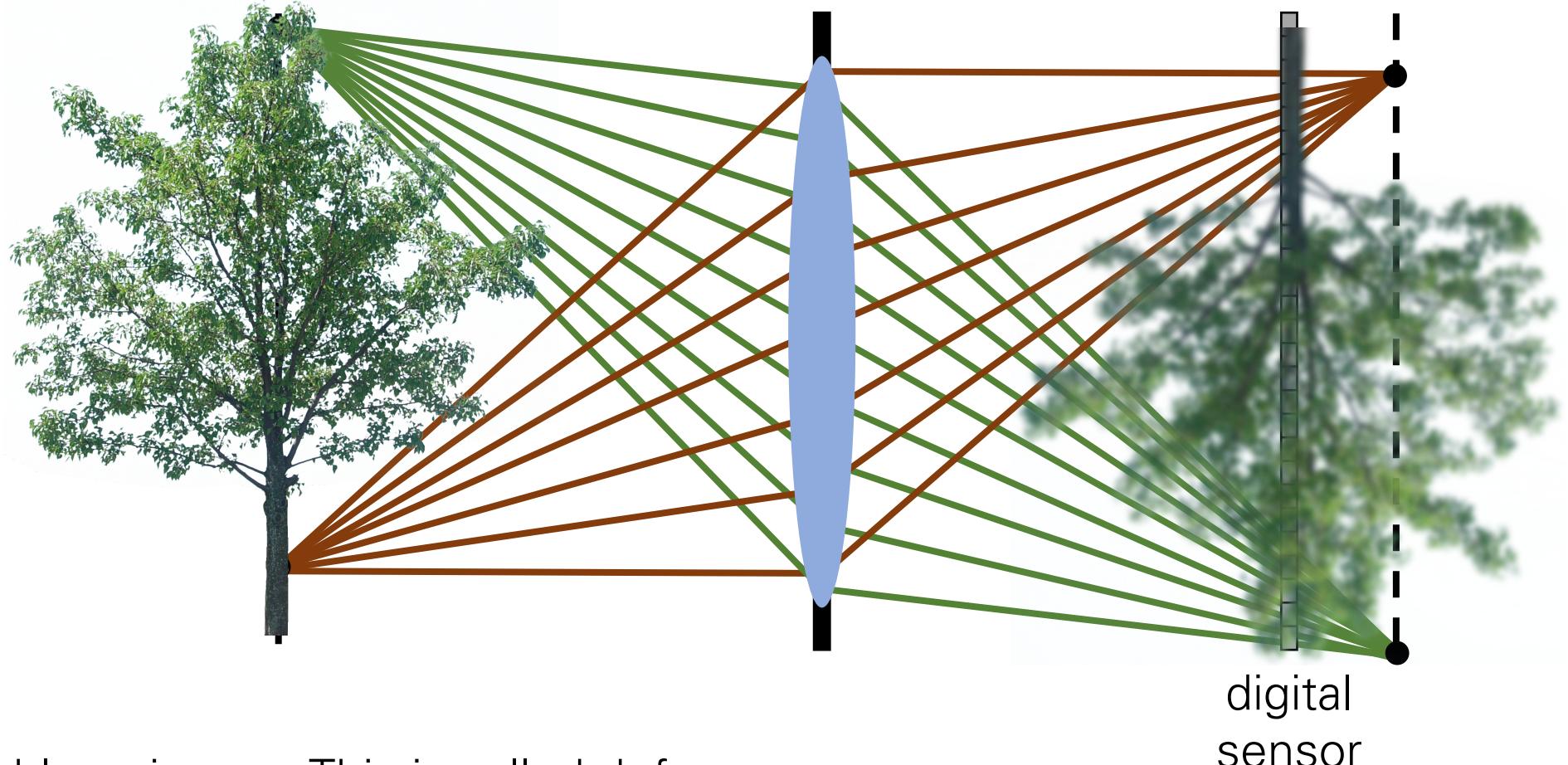
Defocus

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



Defocus

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



We get a blurry image. This is called defocus.

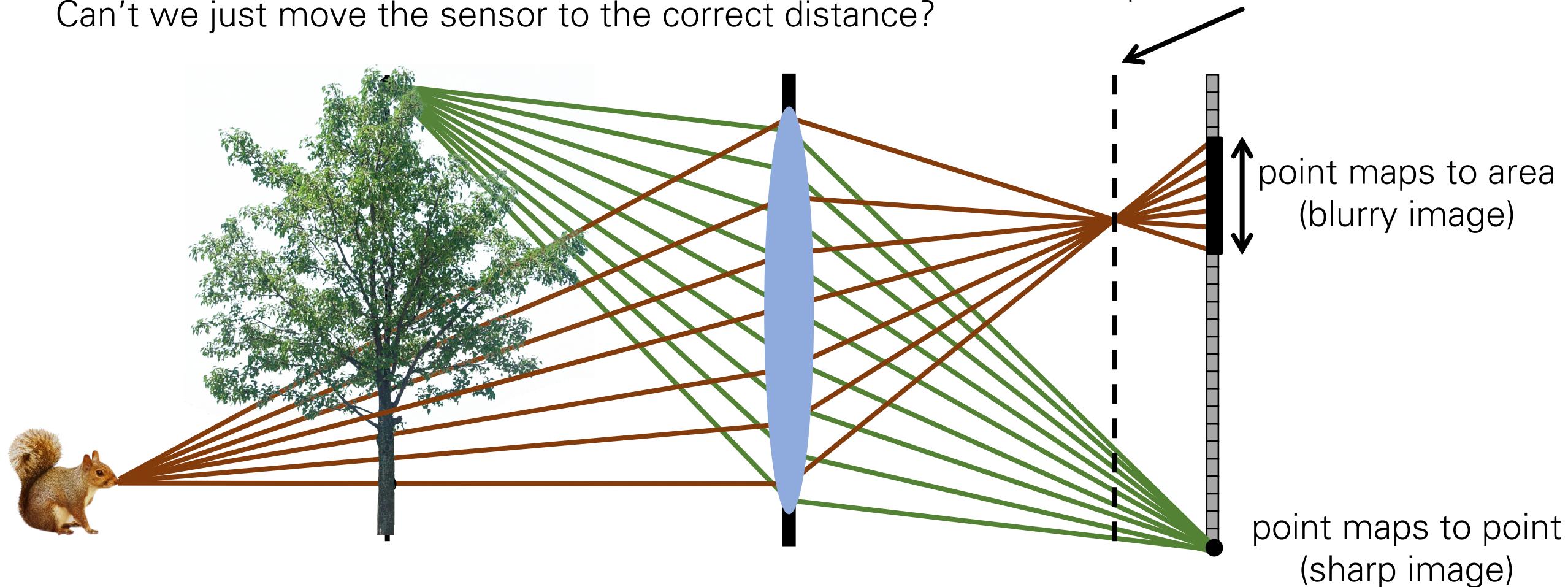
- Defocus never happens with an ideal pinhole camera.

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?

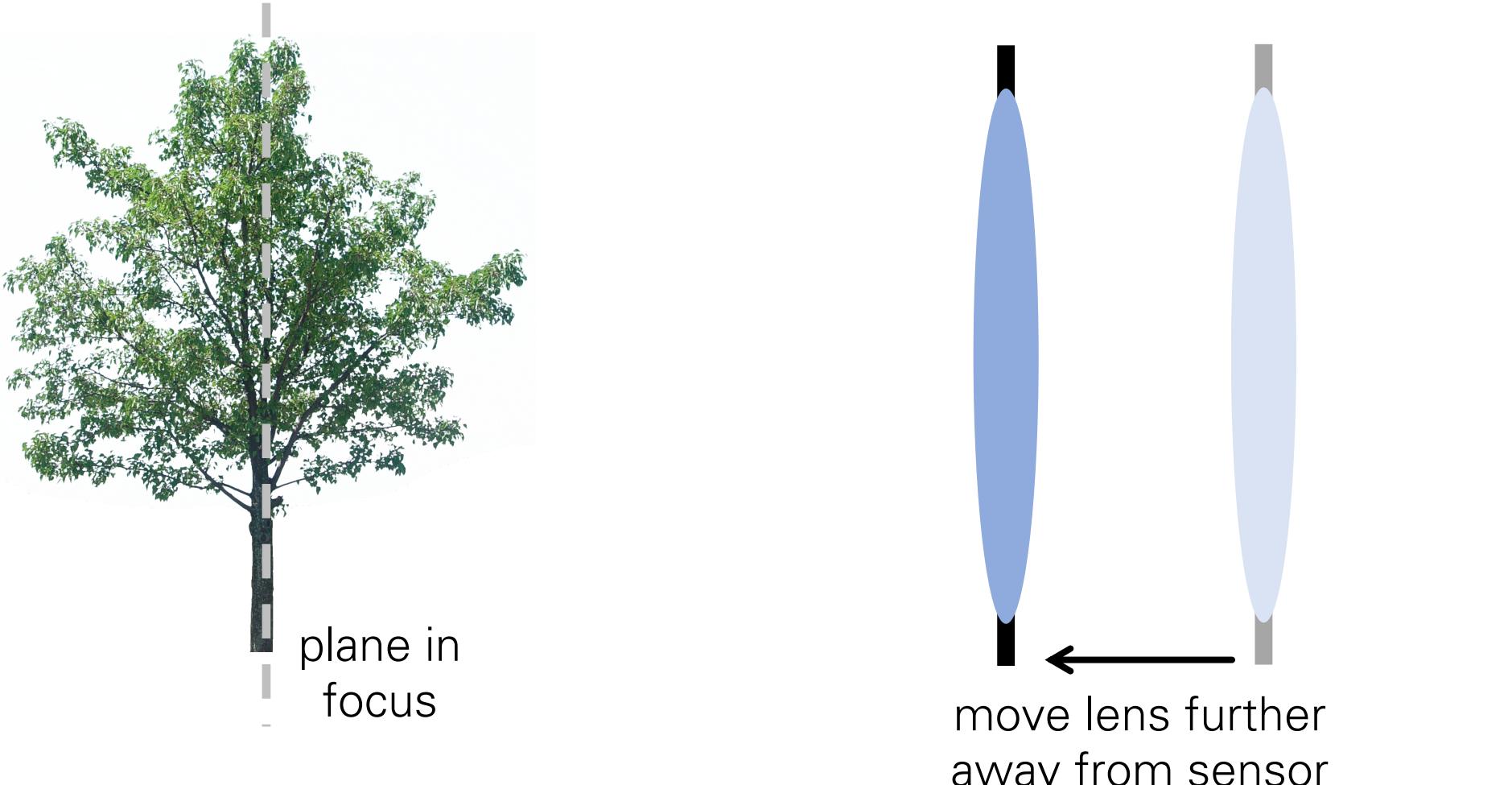
How do we control what is in focus?

We change the distance between the sensor and the lens



How do we control what is in focus?

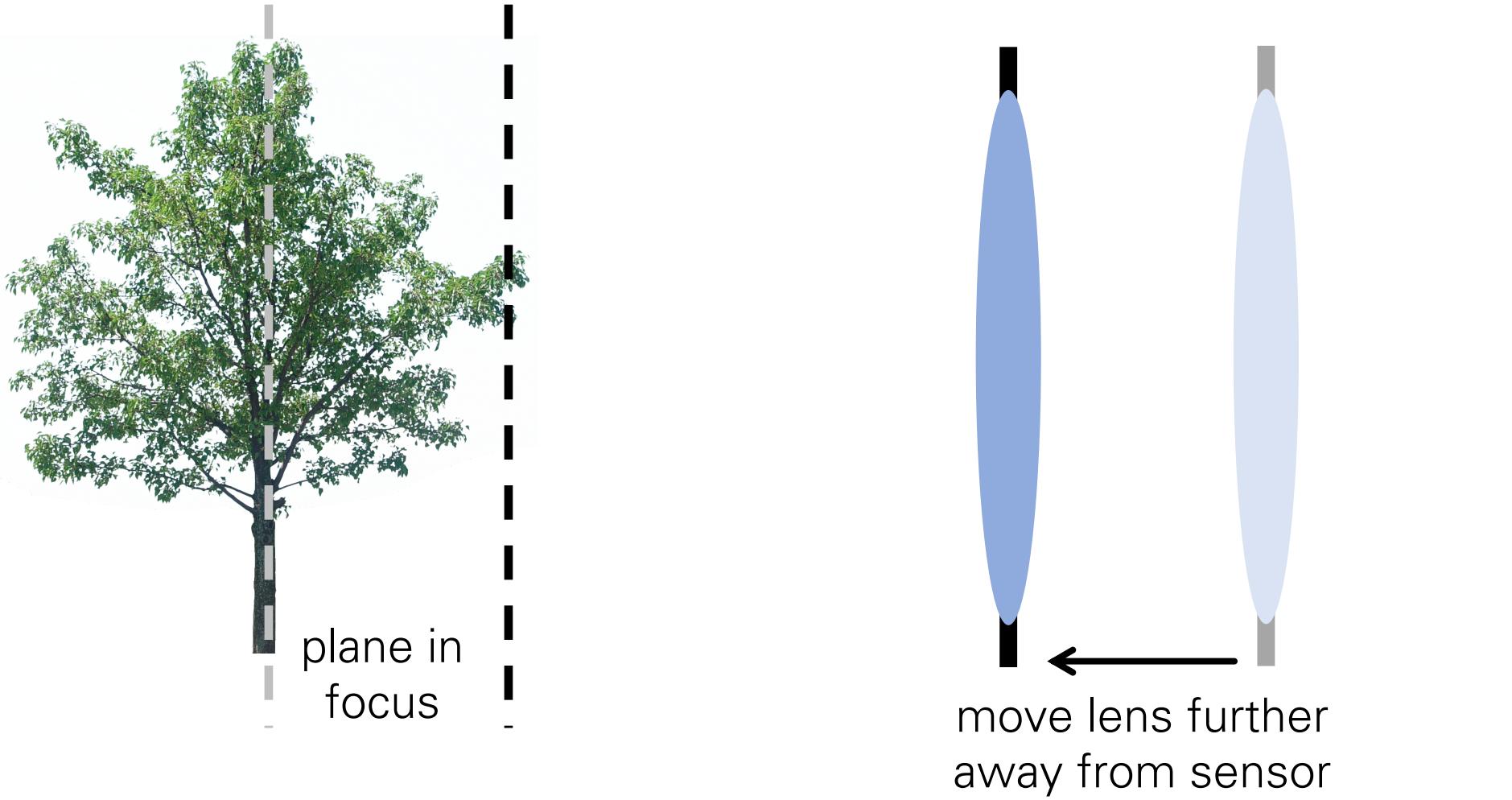
We change the distance between the sensor and the lens



- What happens to plane in focus?

How do we control what is in focus?

We change the distance between the sensor and the lens



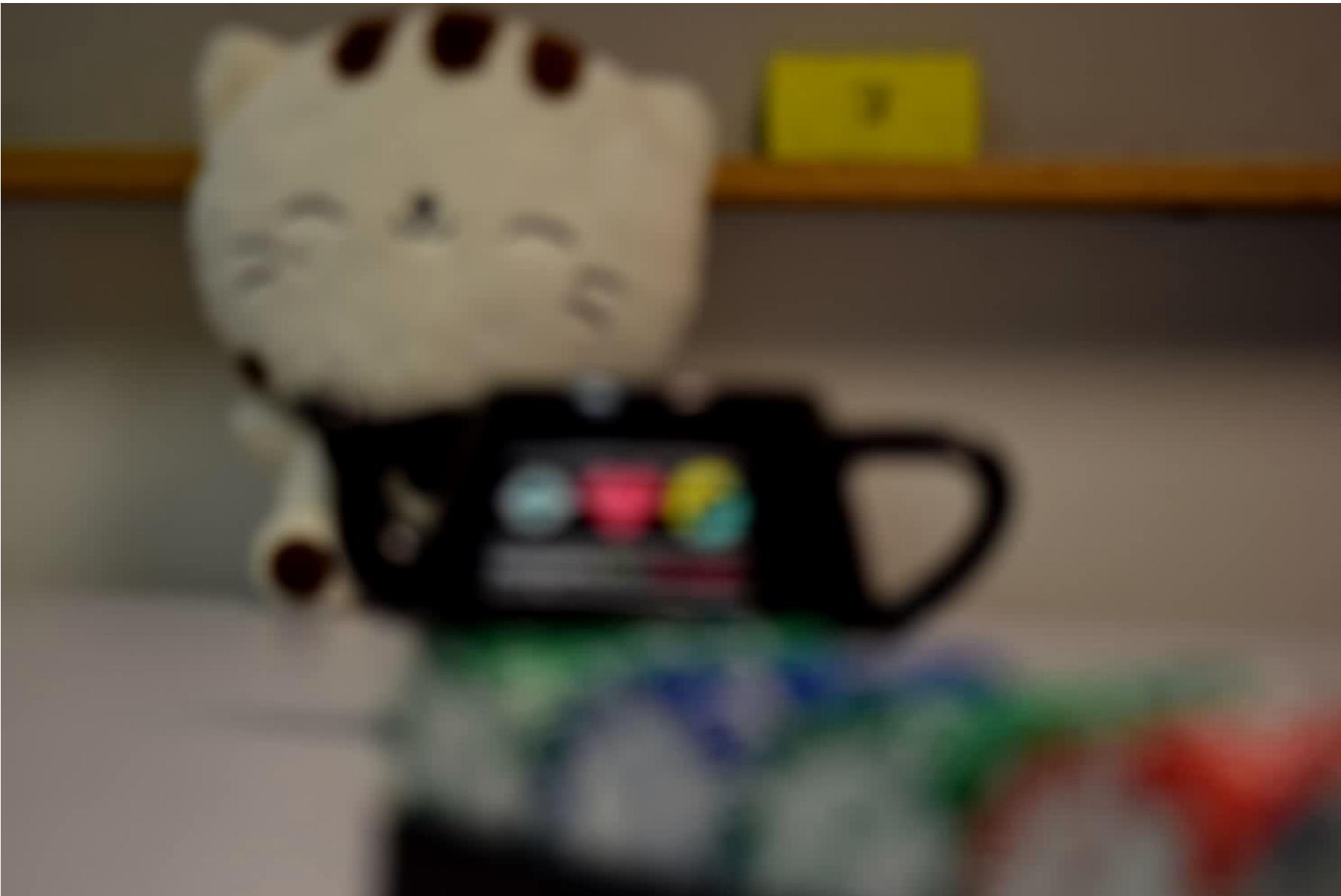
- What happens to plane in focus? → It moves closer.

The lens on your camera

Focus ring: controls distance of lens from sensor



Demonstration

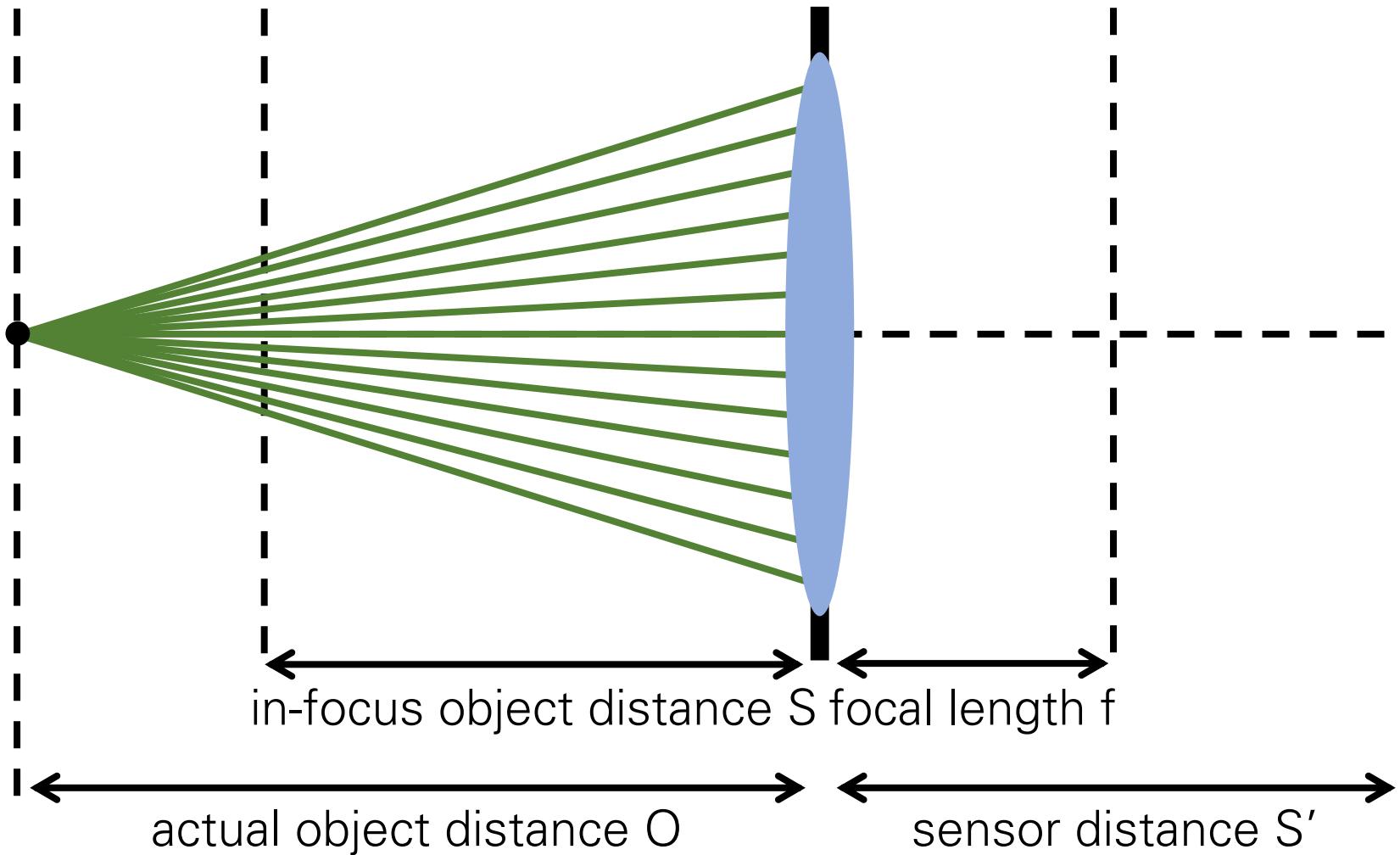


Defocus

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

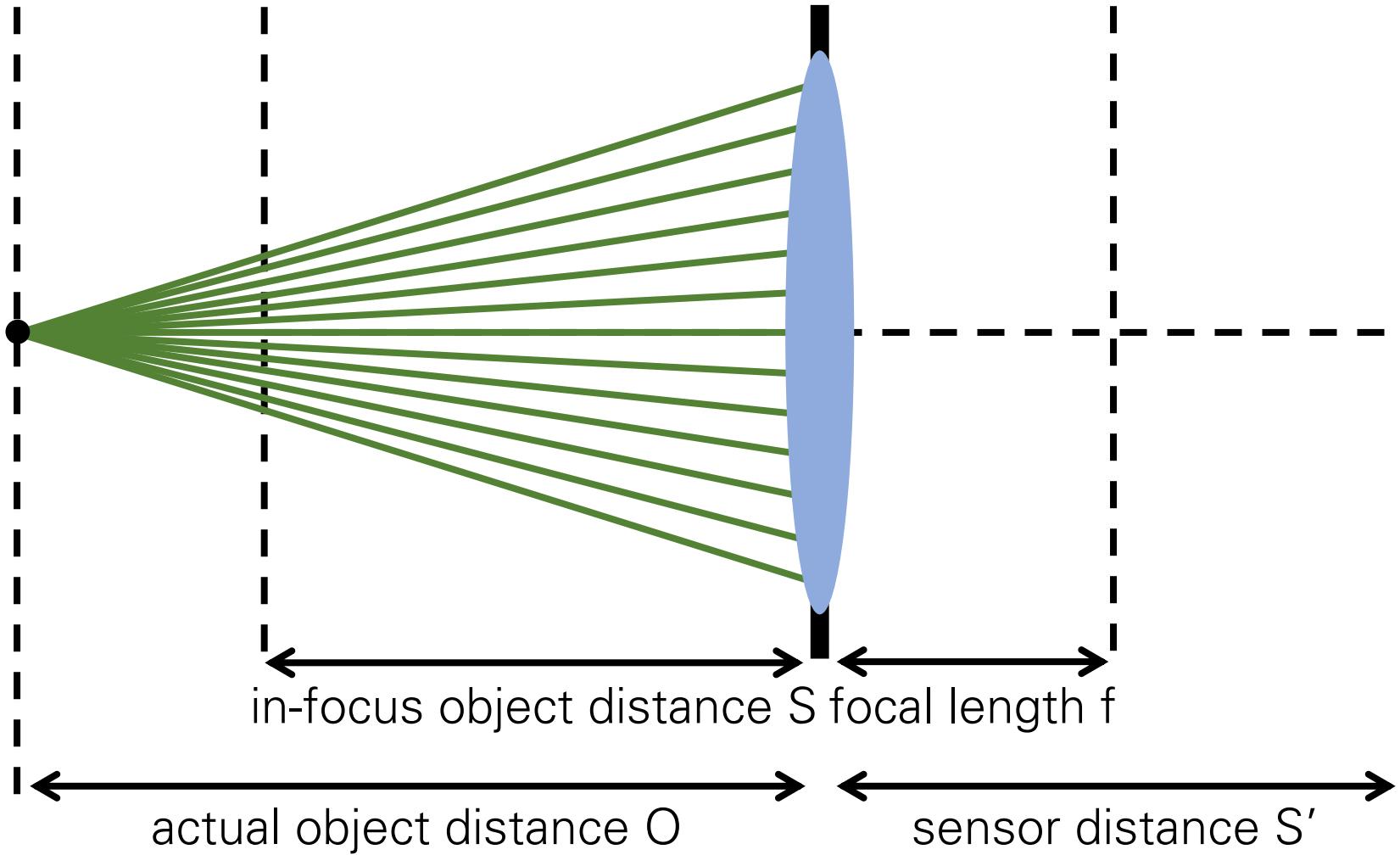
Circle of confusion

How do we find where the point will focus?



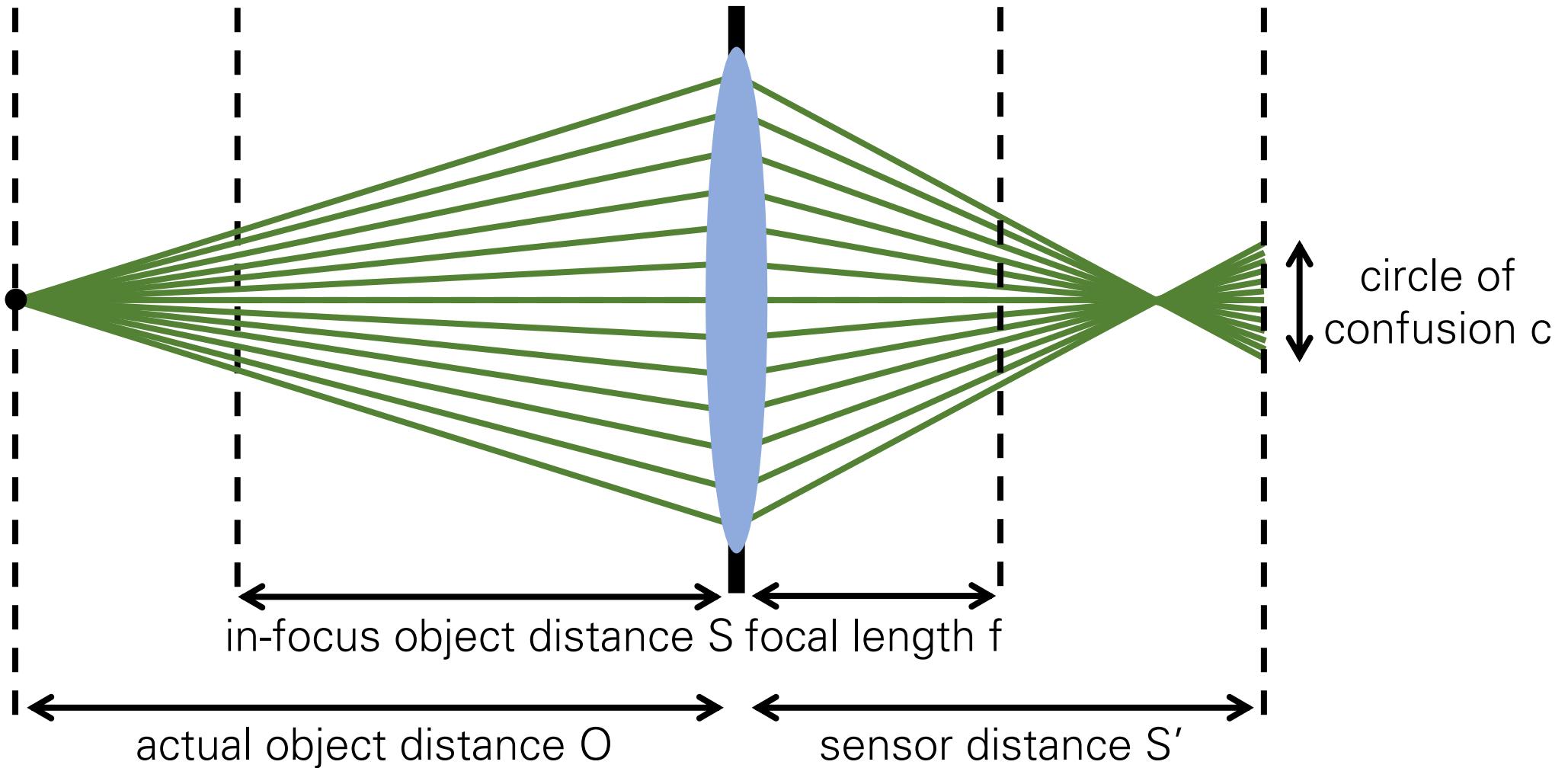
Circle of confusion

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



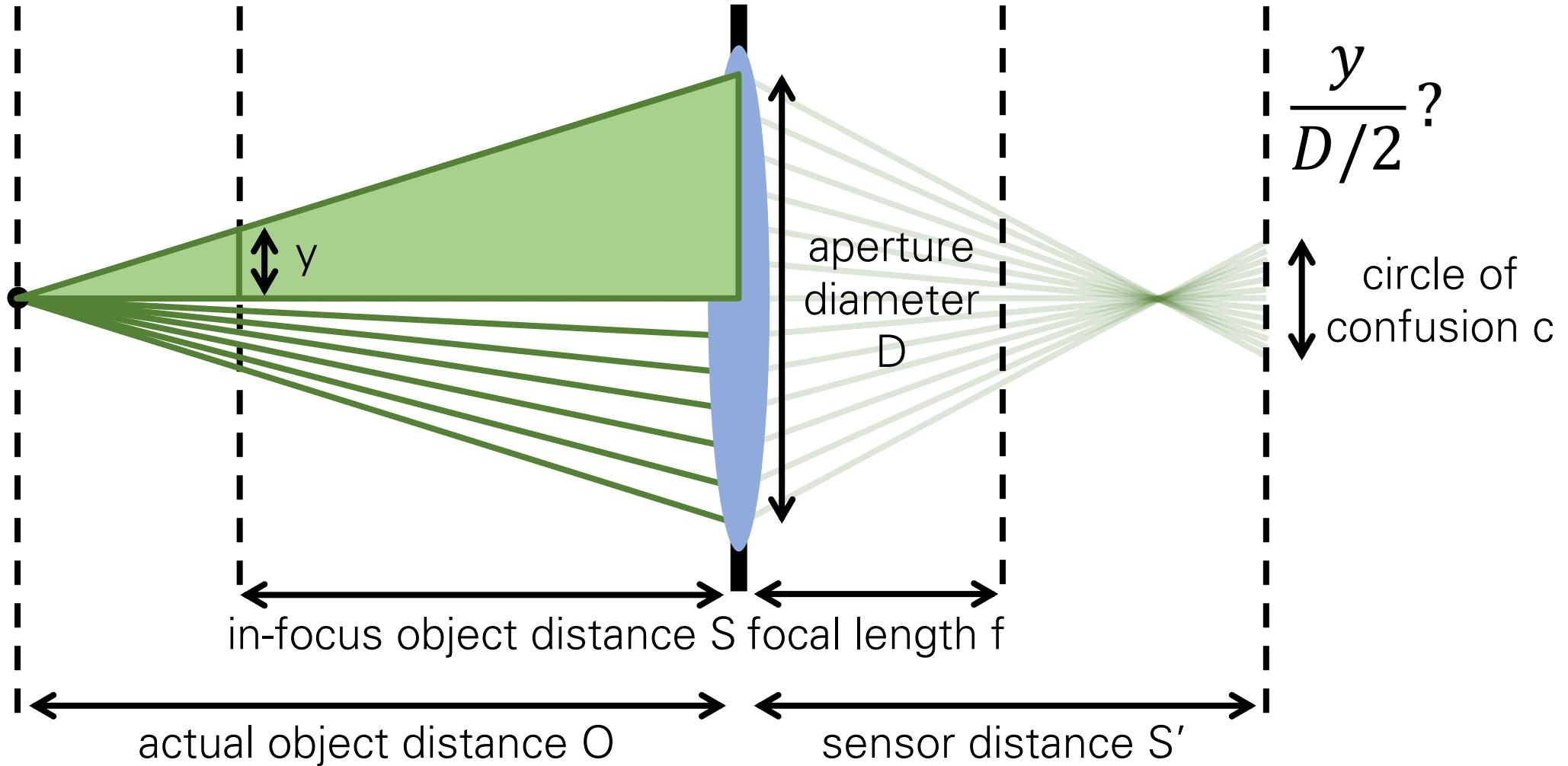
Circle of confusion

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



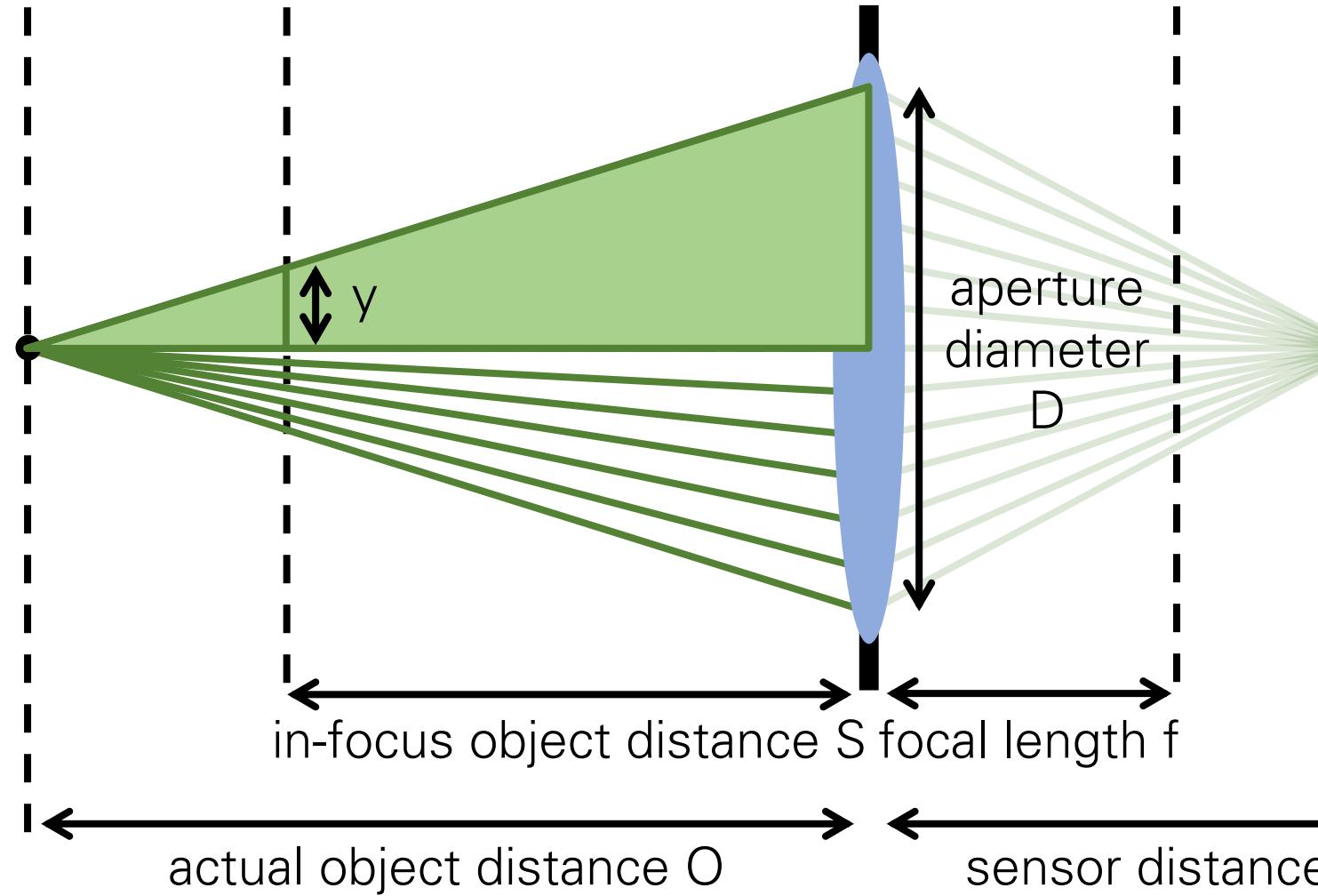
Circle of confusion

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.



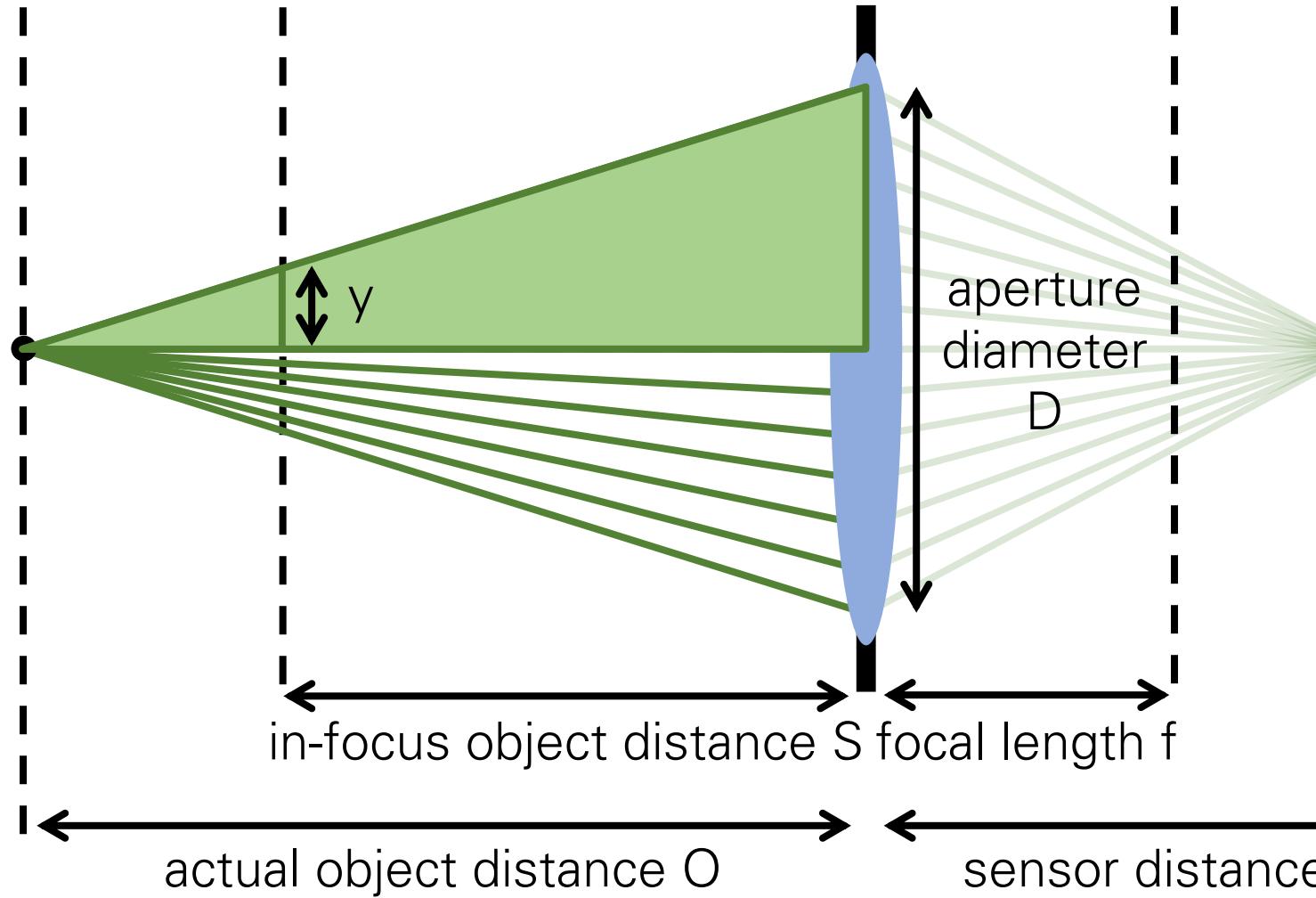
$$\frac{y}{D/2} = \frac{|O - S|}{O}$$

circle of
confusion c

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

Circle of confusion

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



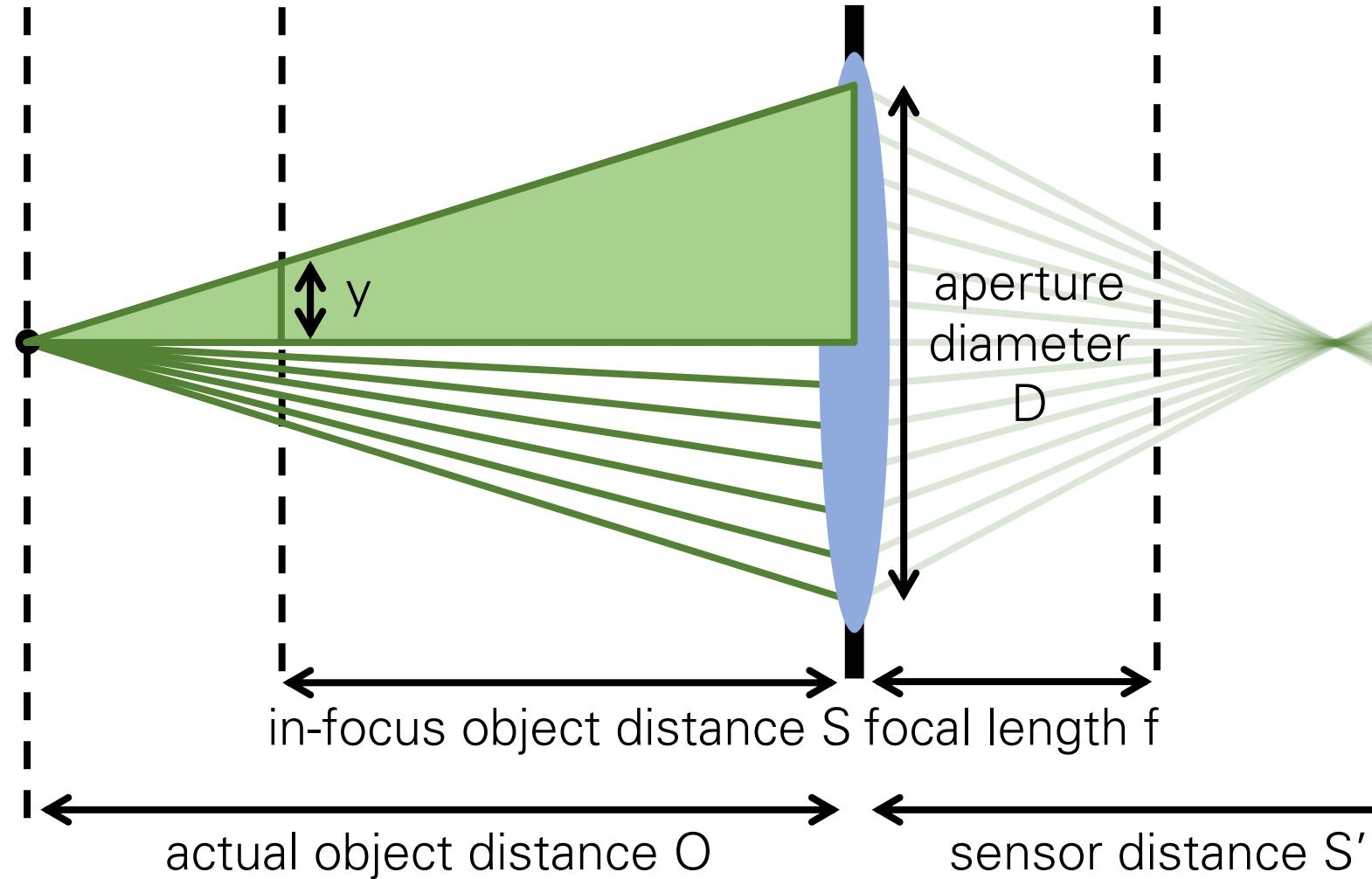
$$\frac{y}{D/2} = \frac{|O - S|}{O}$$

circle of
confusion c

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

Circle of confusion

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



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

circle of
confusion c

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

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

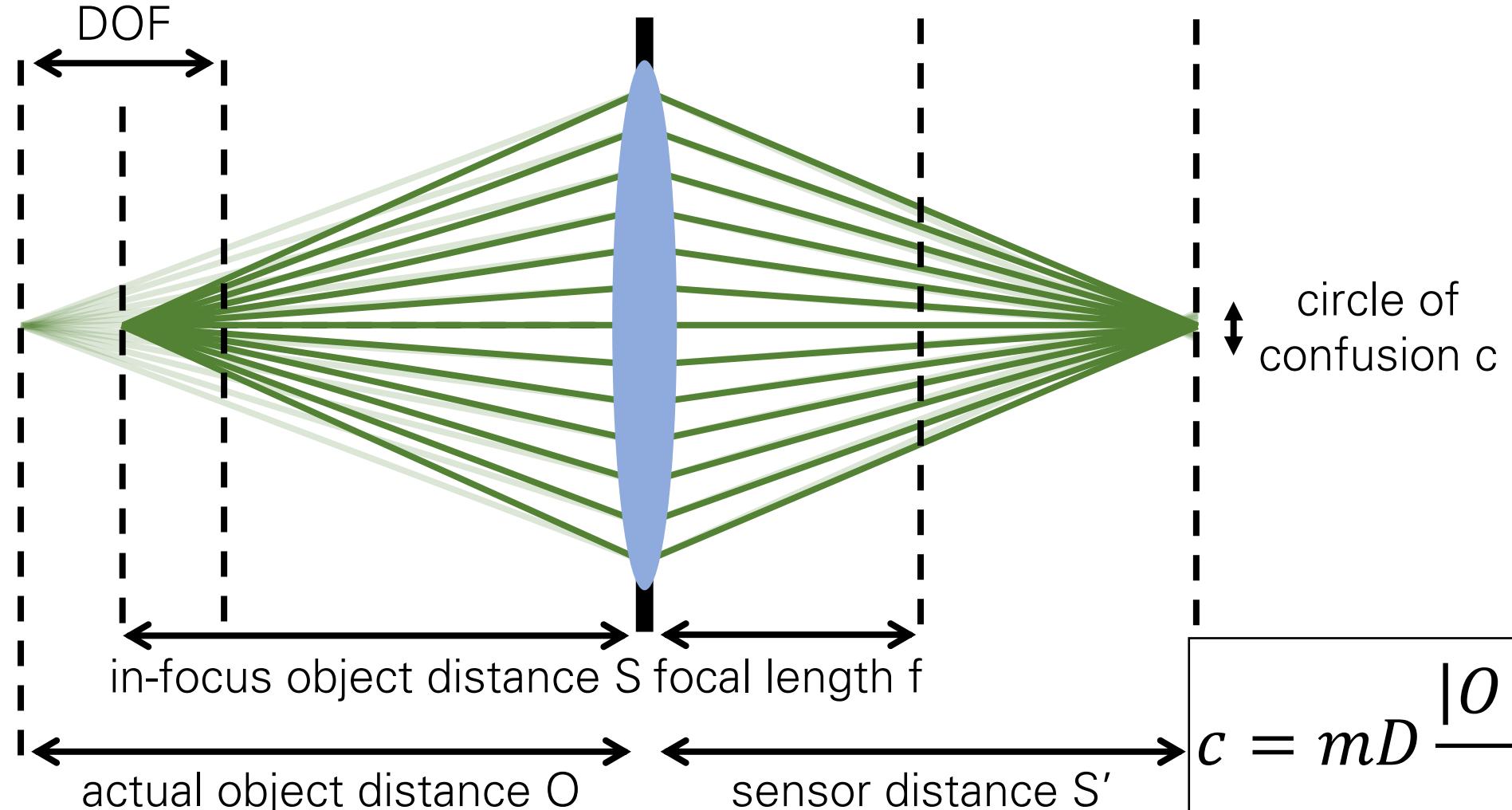
Depth of field

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

e.g., equal to
4-5 pixels

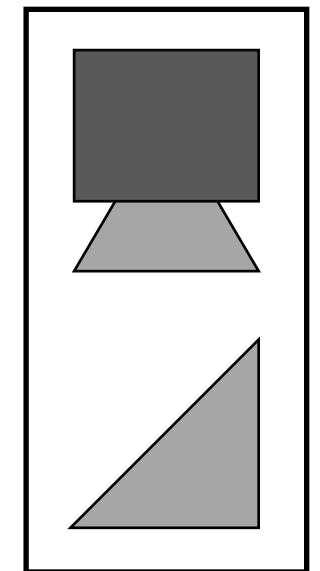
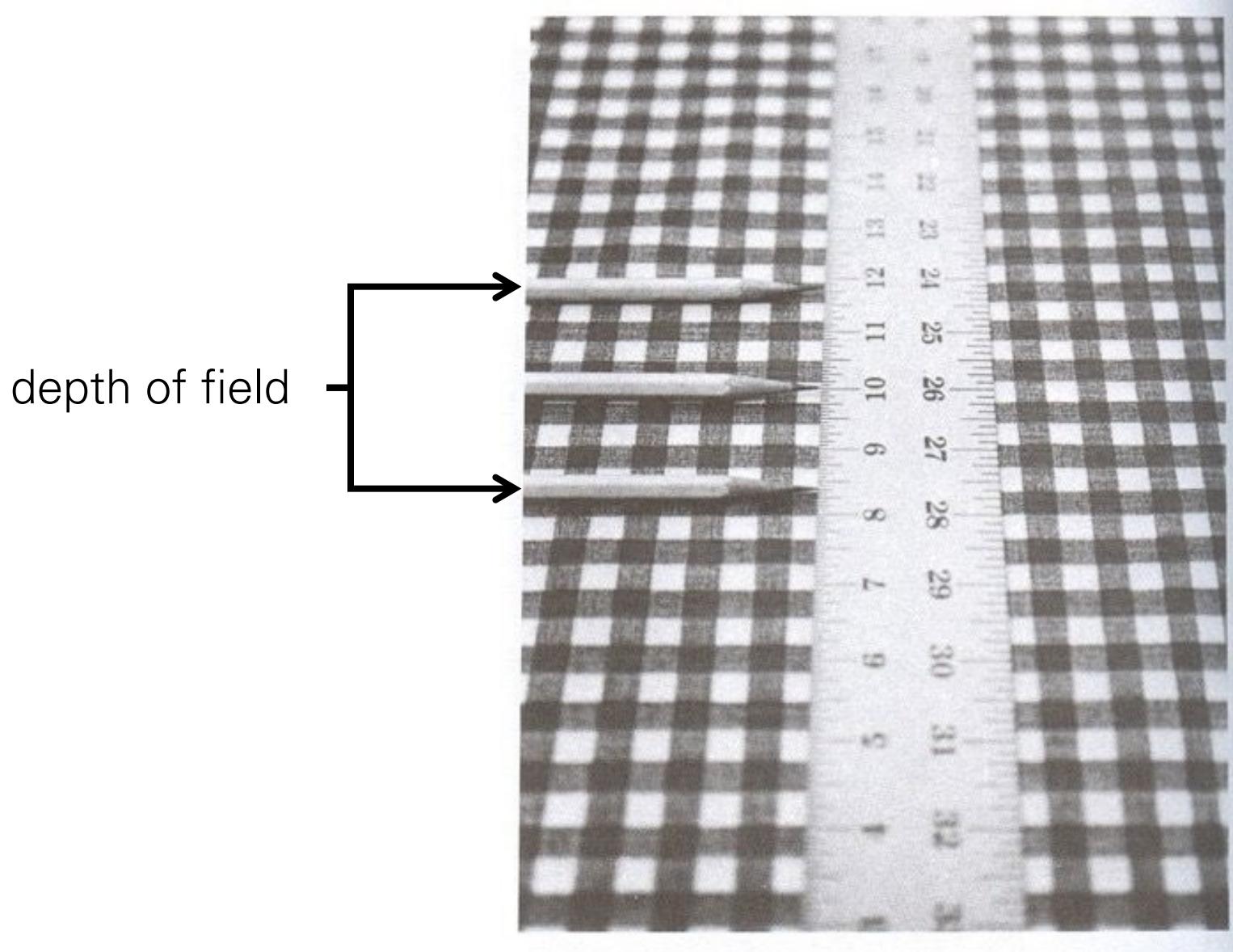
$$c < \varepsilon \Rightarrow \text{DOF} = \frac{2\varepsilon O}{mD}$$

Note: in reality,
DOF is slightly
asymmetrical.



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

Depth of field

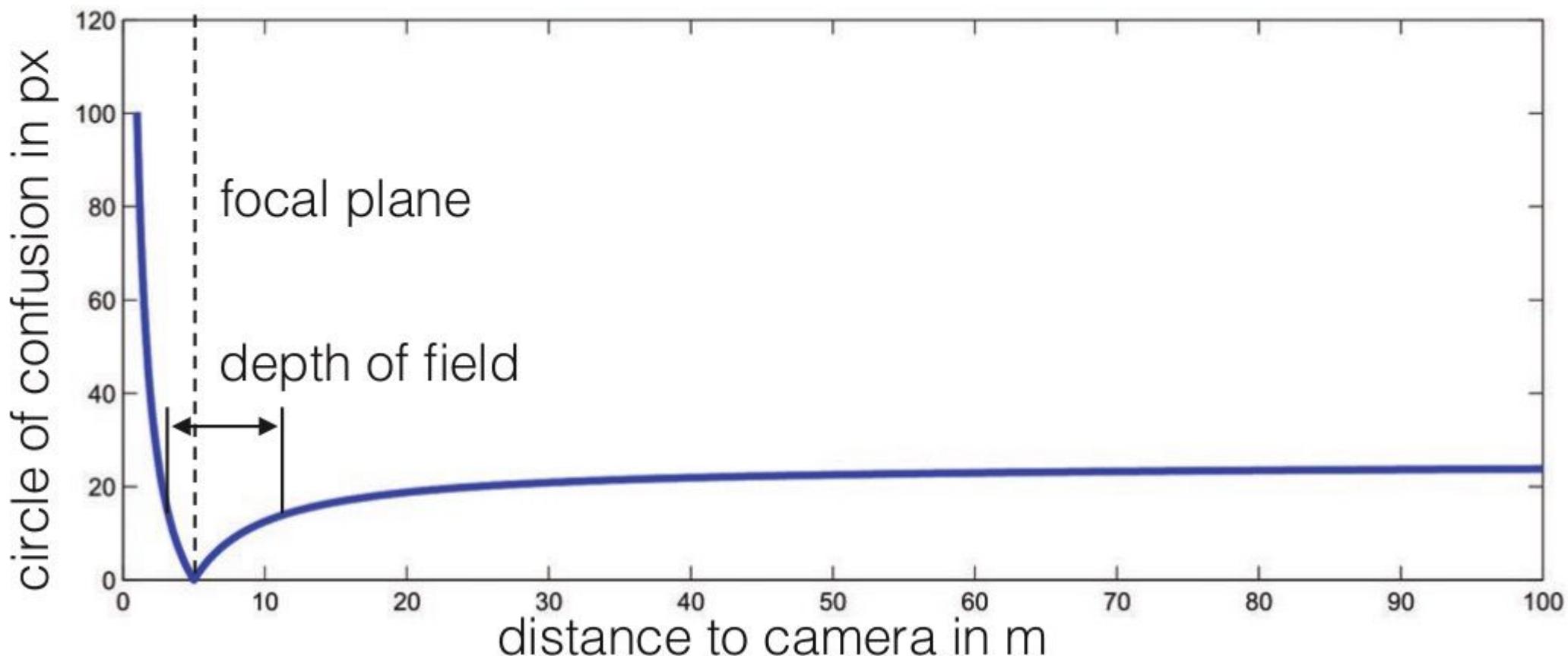


scene

Circle of confusion

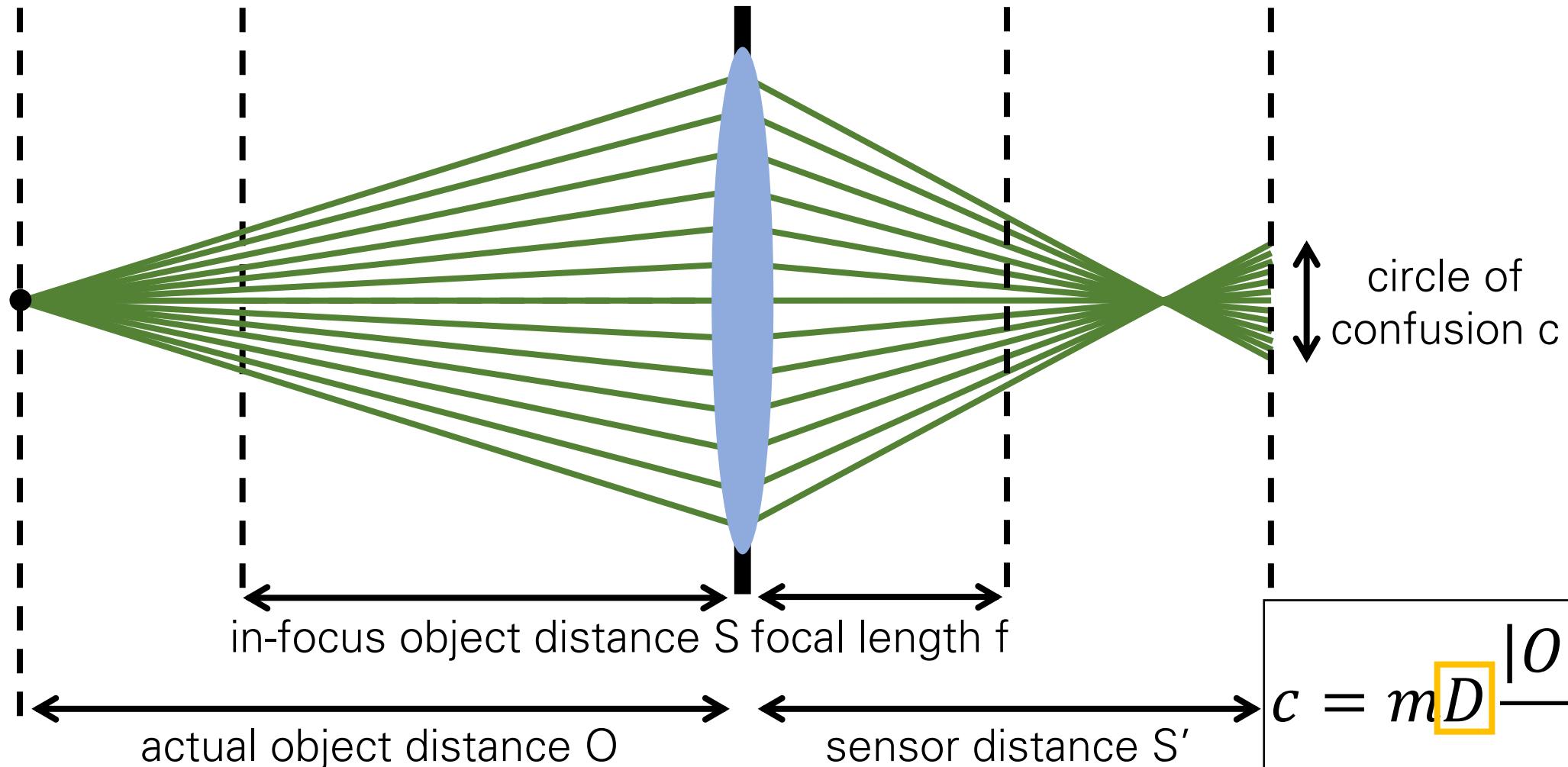
$$c = M \cdot D \cdot \frac{|S - S_1|}{S}$$

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



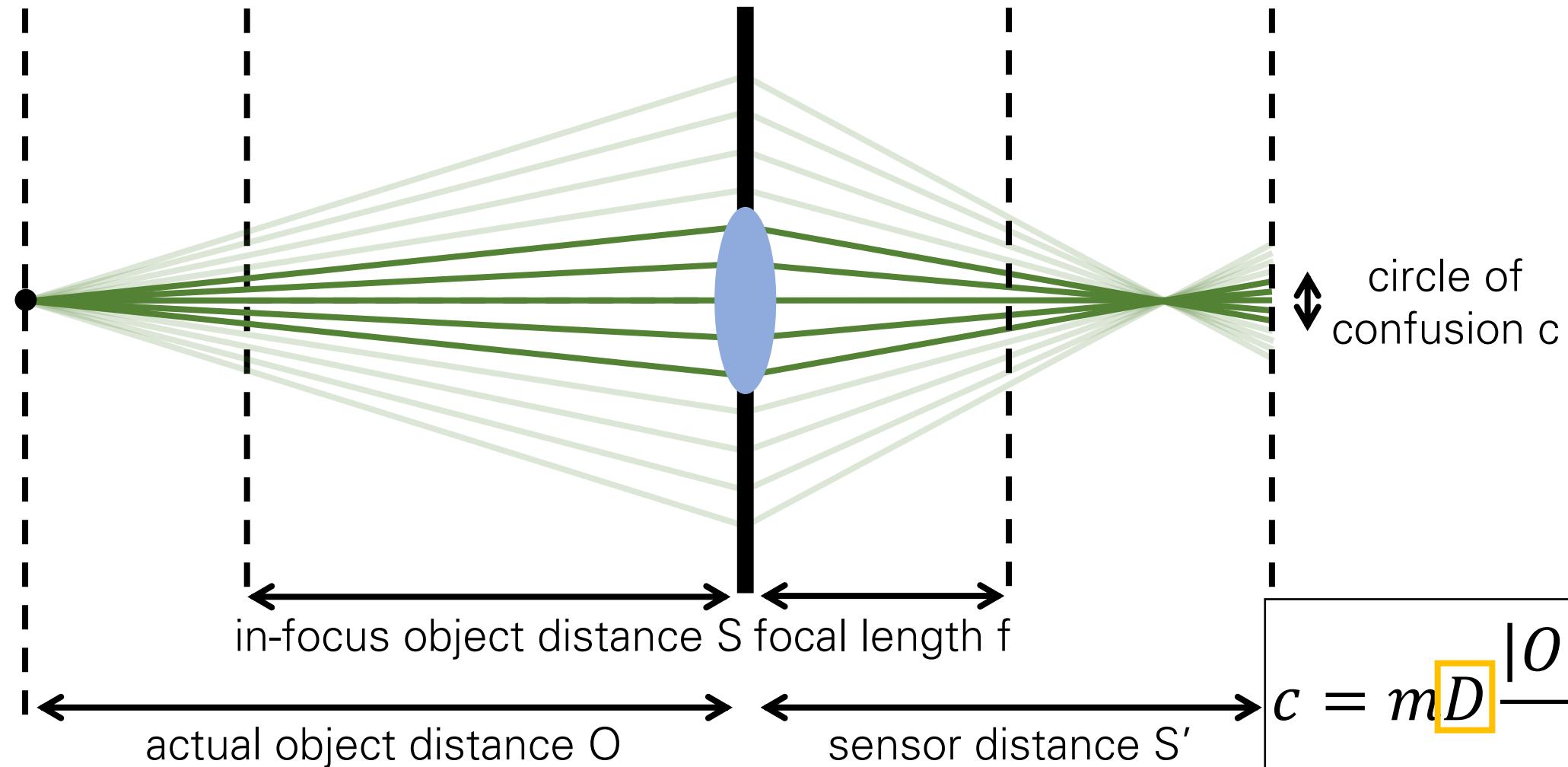
Defocus depends on aperture diameter

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



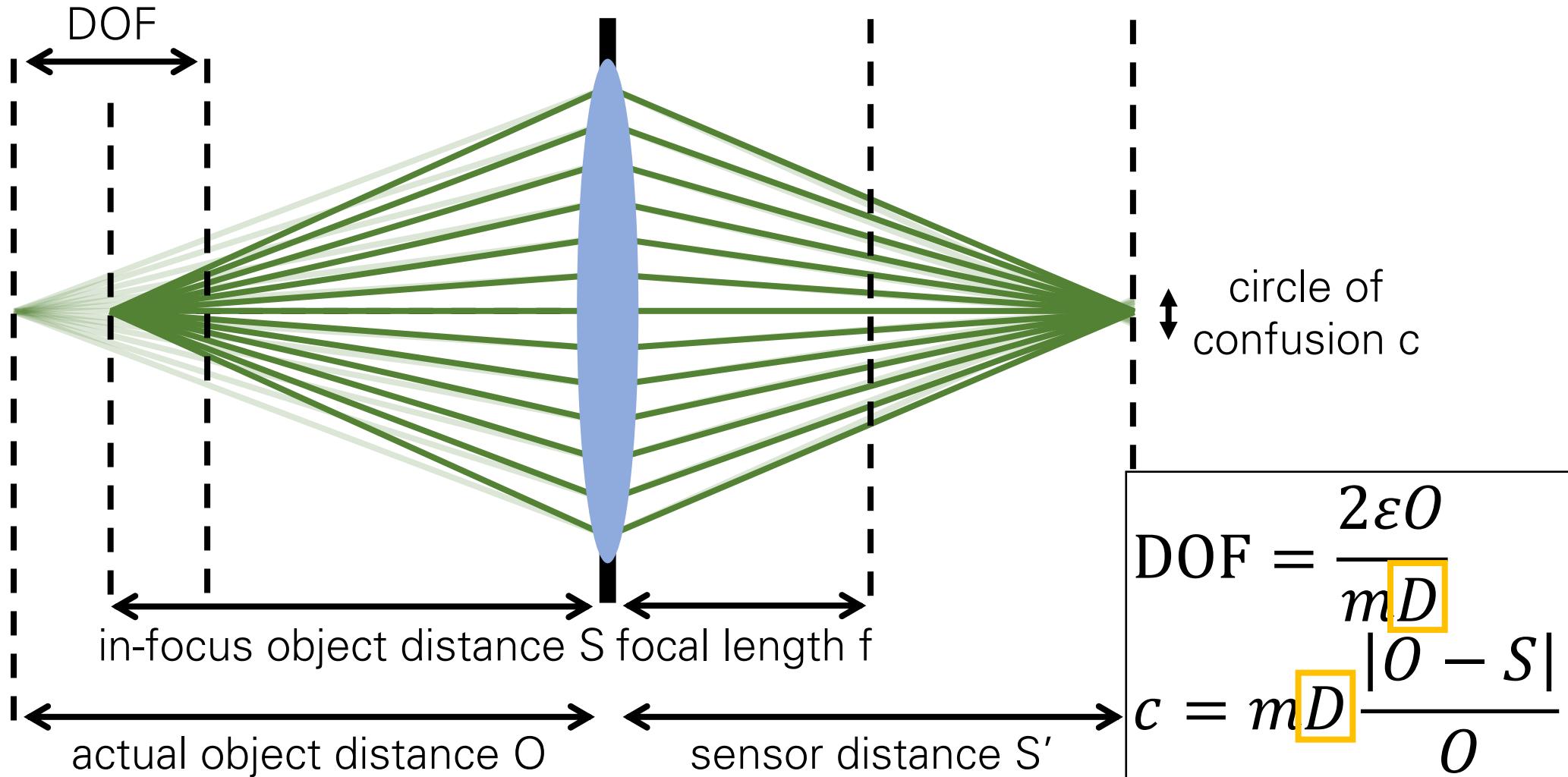
Defocus depends on aperture diameter

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



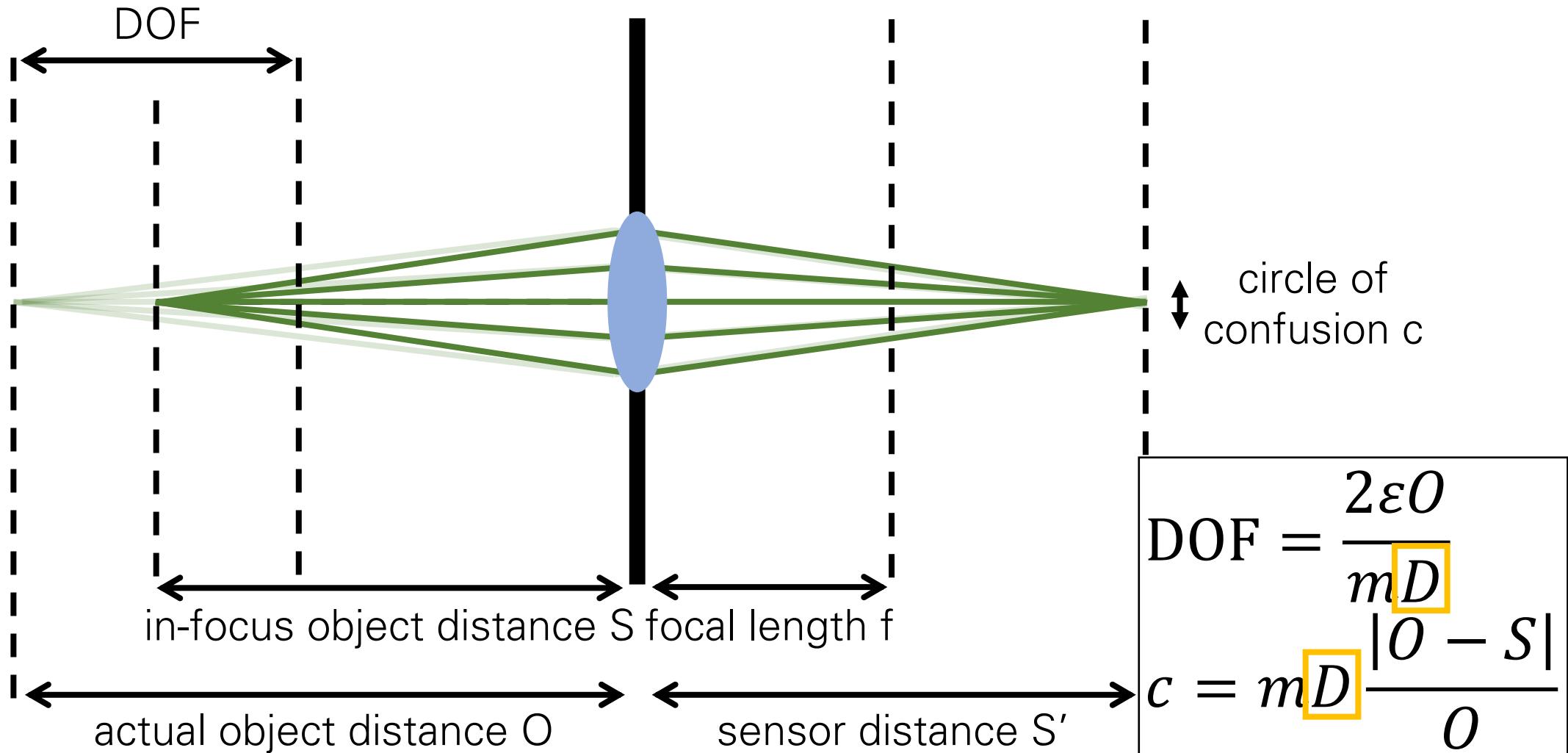
Defocus depends on aperture diameter

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



Defocus depends on aperture diameter

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



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

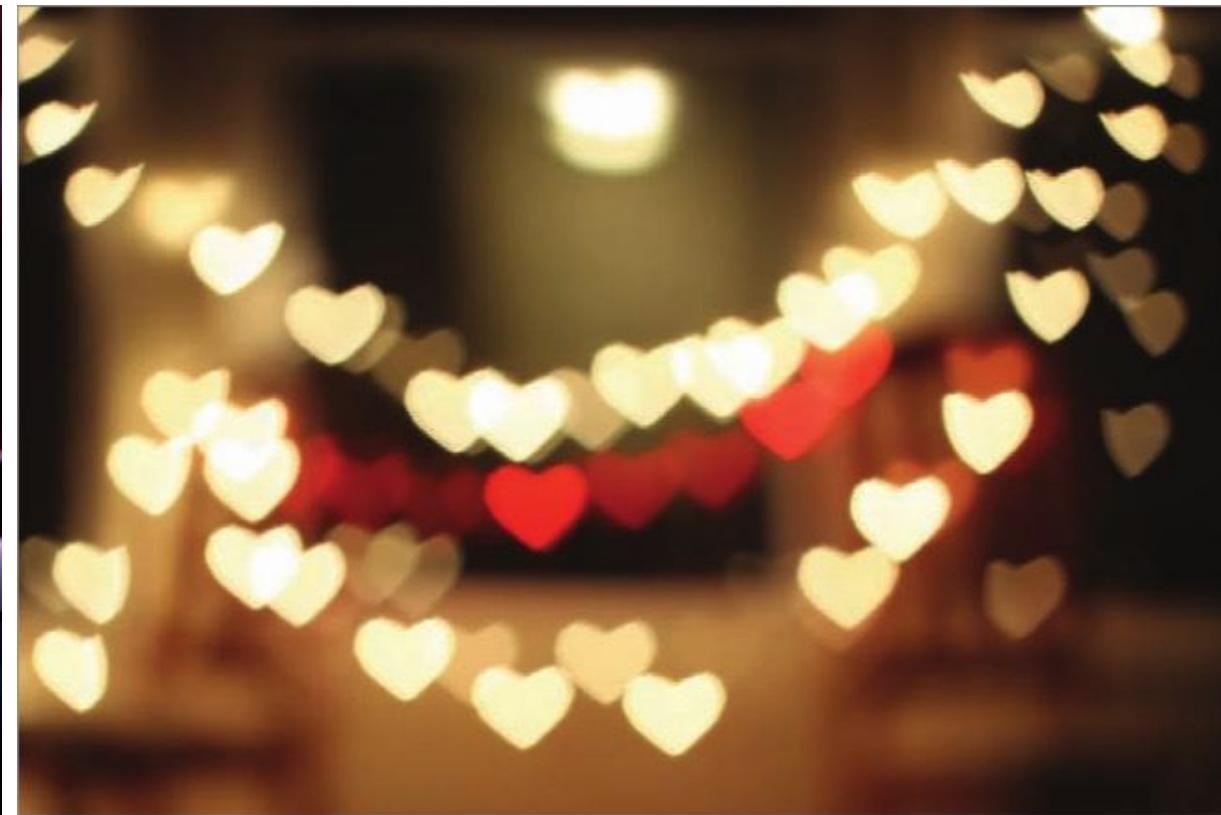
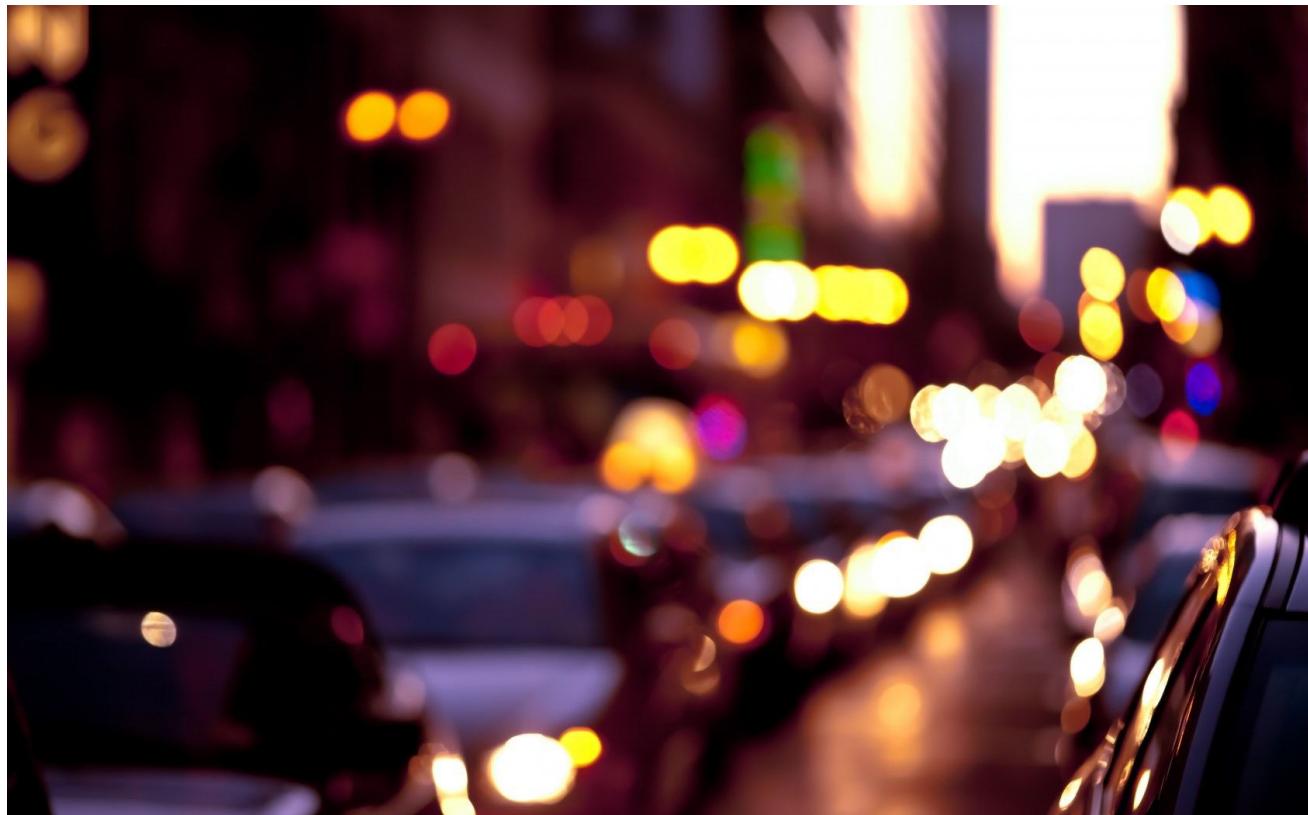
You can see the aperture by removing the lens and looking inside it.

Demonstration



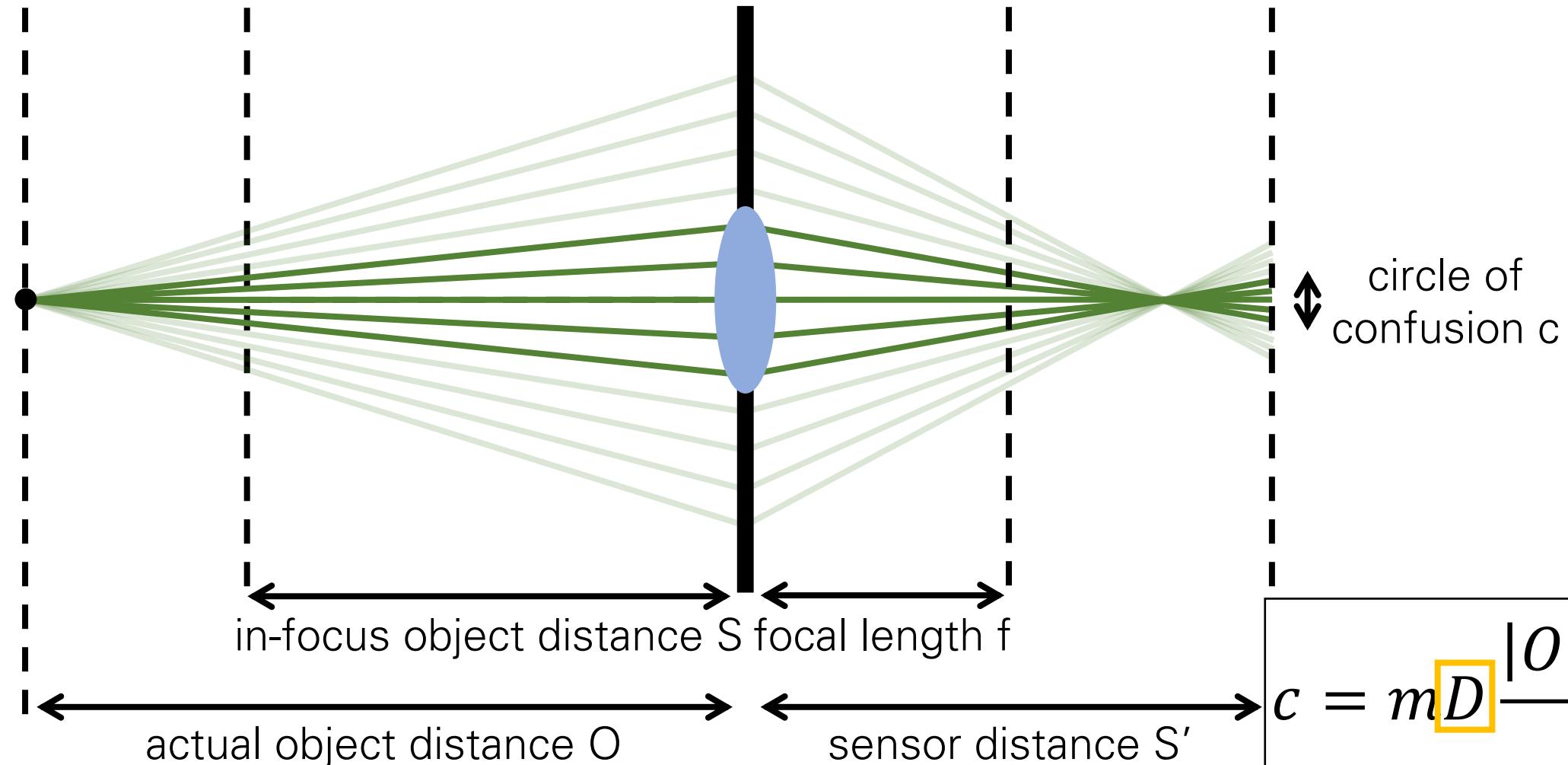
Depth of Field

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?

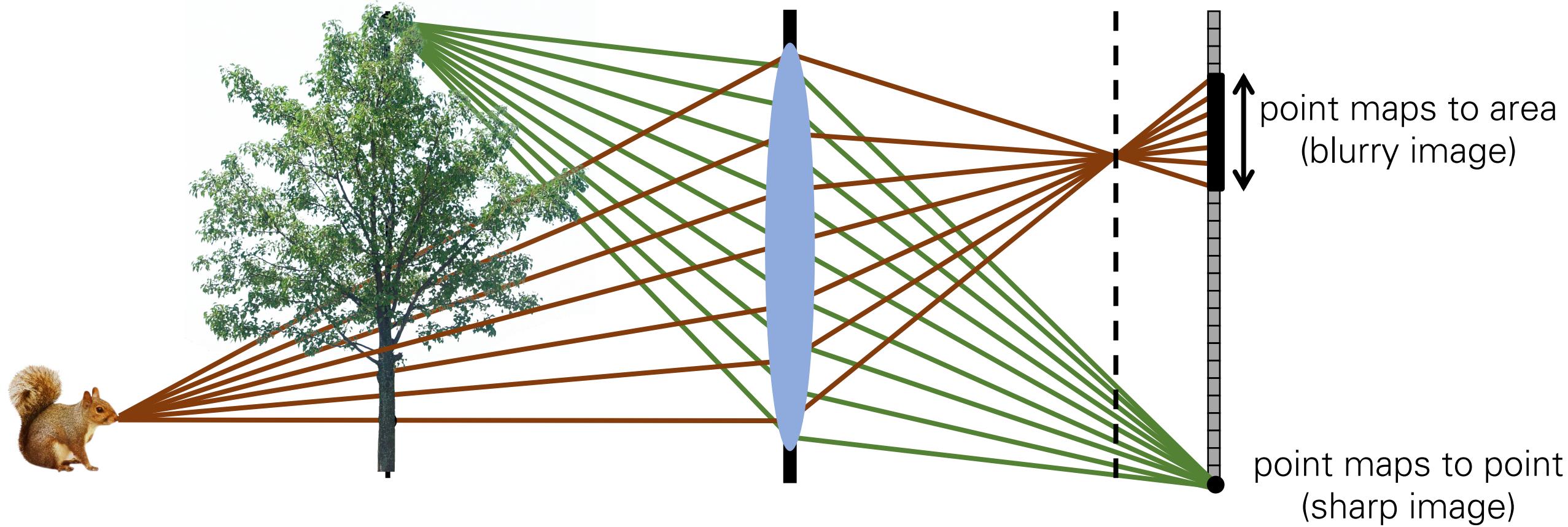


Bokeh

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

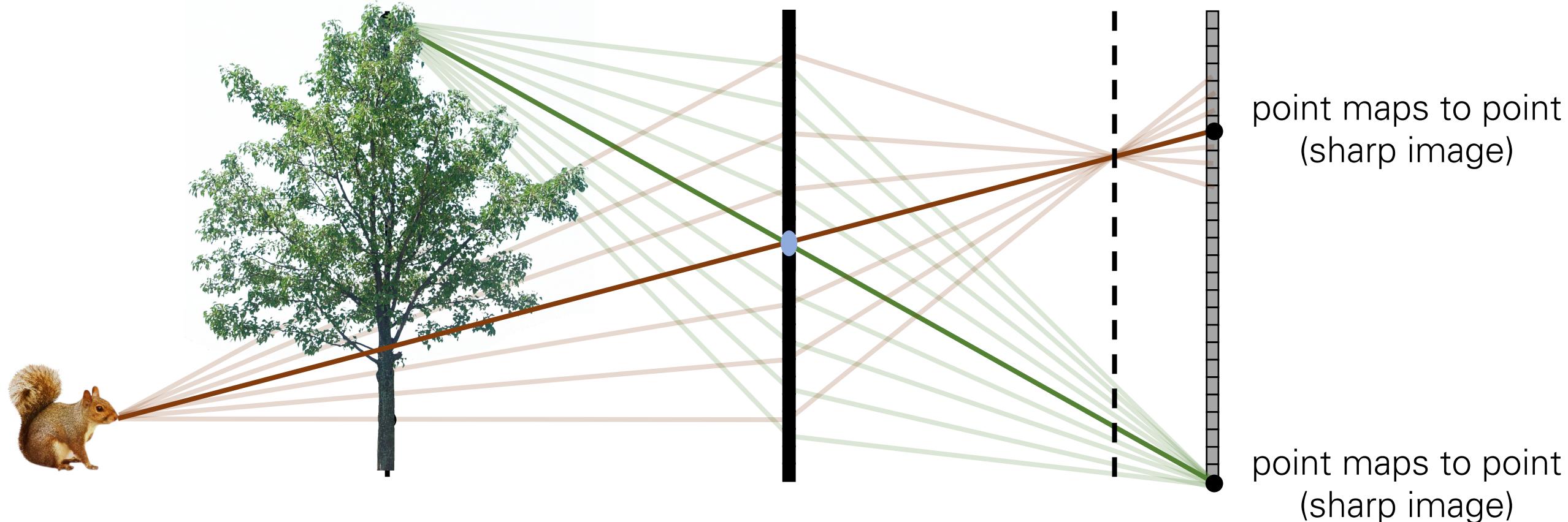


What happens as the aperture keeps getting smaller?



What happens as the aperture keeps getting smaller?

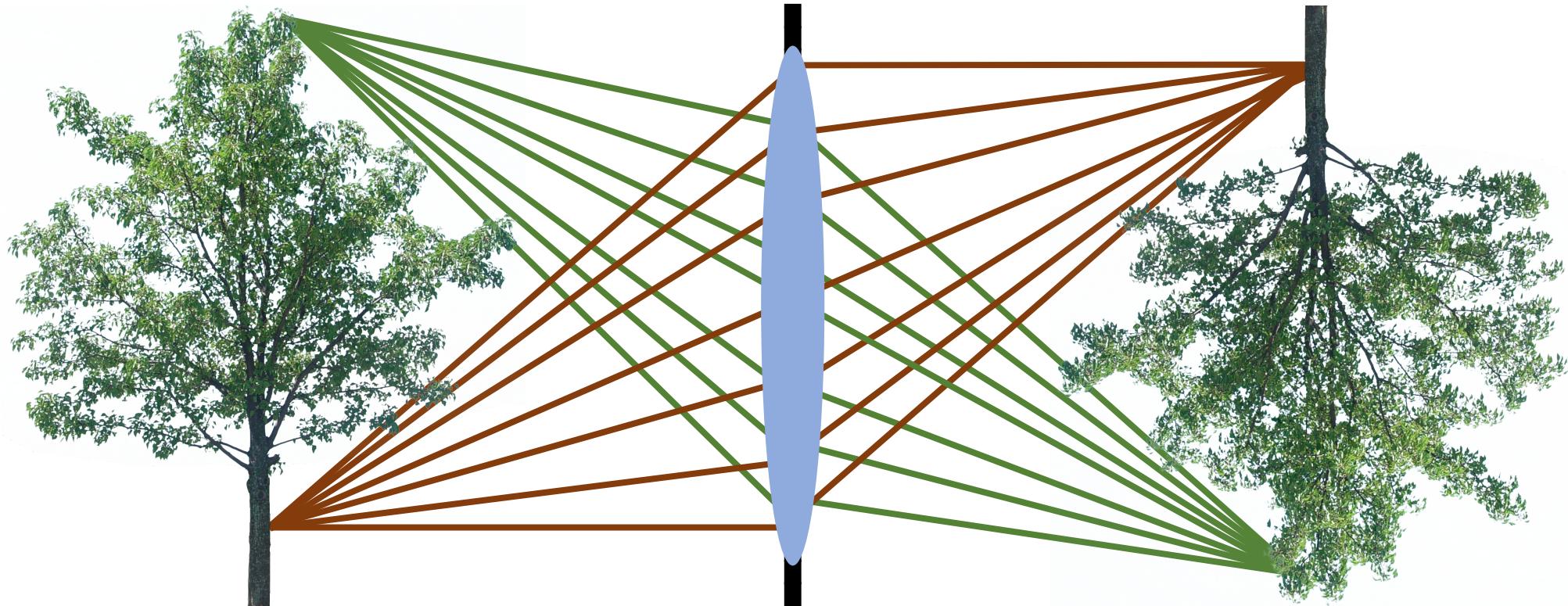
Lens becomes equivalent to a pinhole.



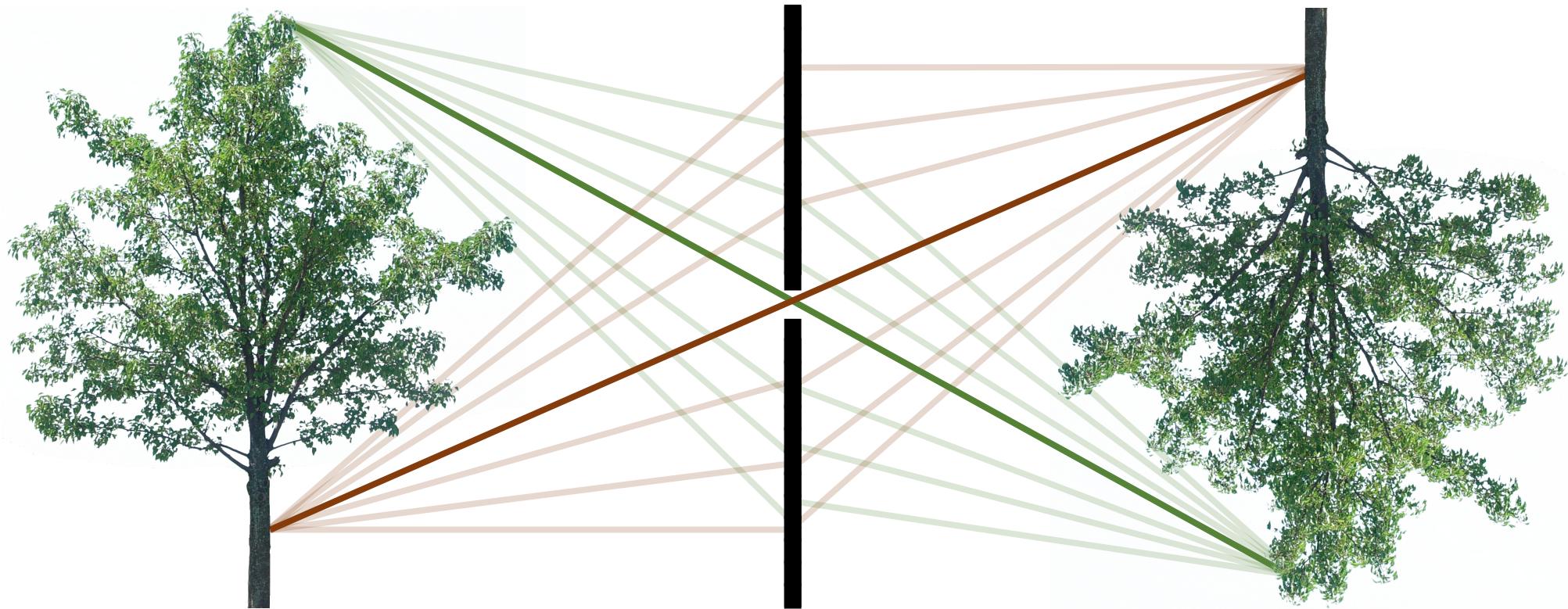
- No defocus, everything is sharp regardless of depth.
- Very little light, signal-to-noise ratio is just as bad as pinhole.

Lens camera and pinhole camera

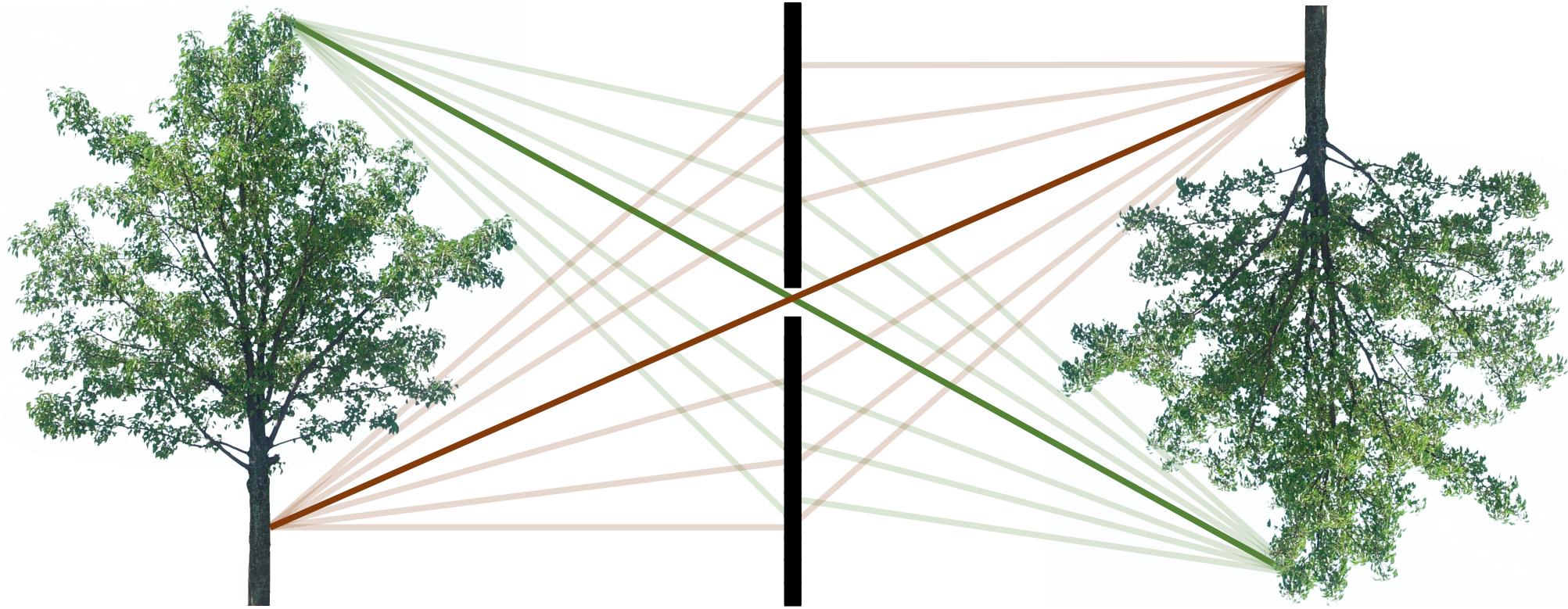
The lens camera



The pinhole camera

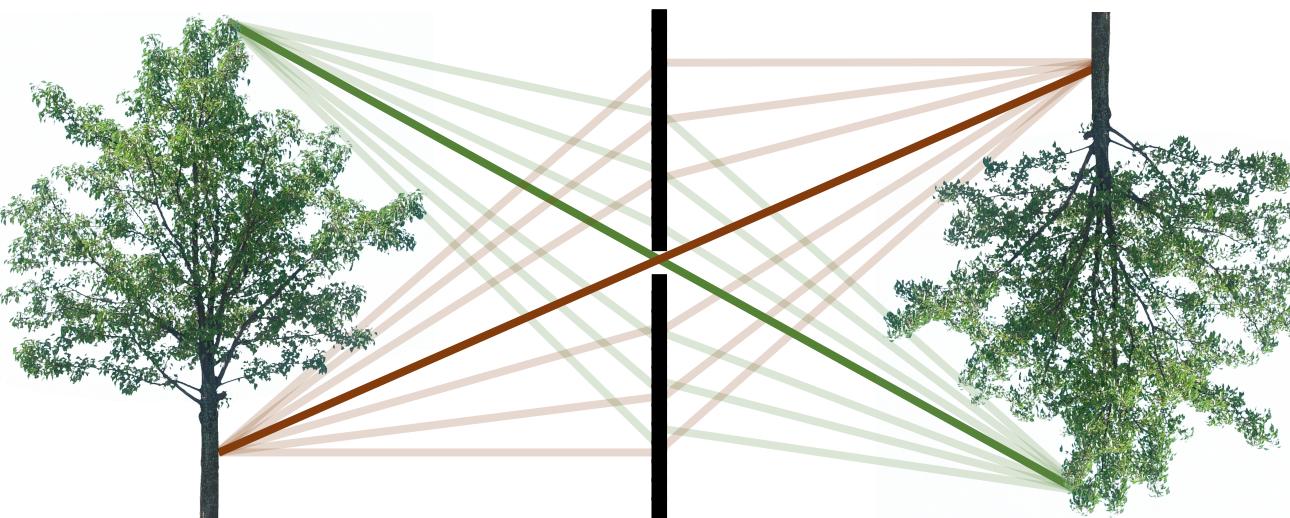
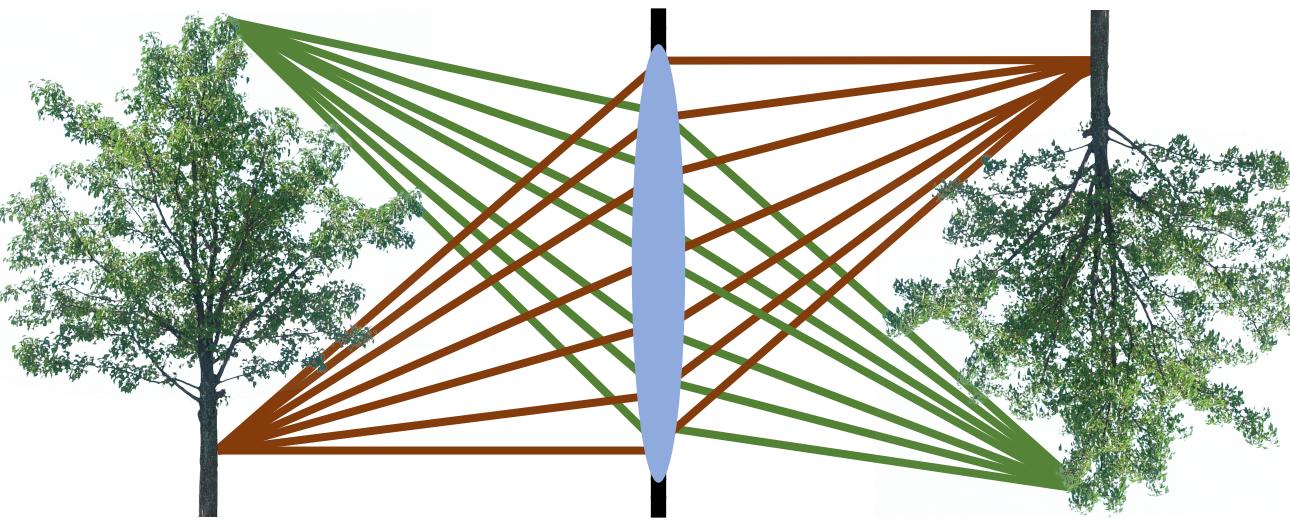


The pinhole camera



Central rays propagate in the same way for both models!

Describing both lens and pinhole cameras

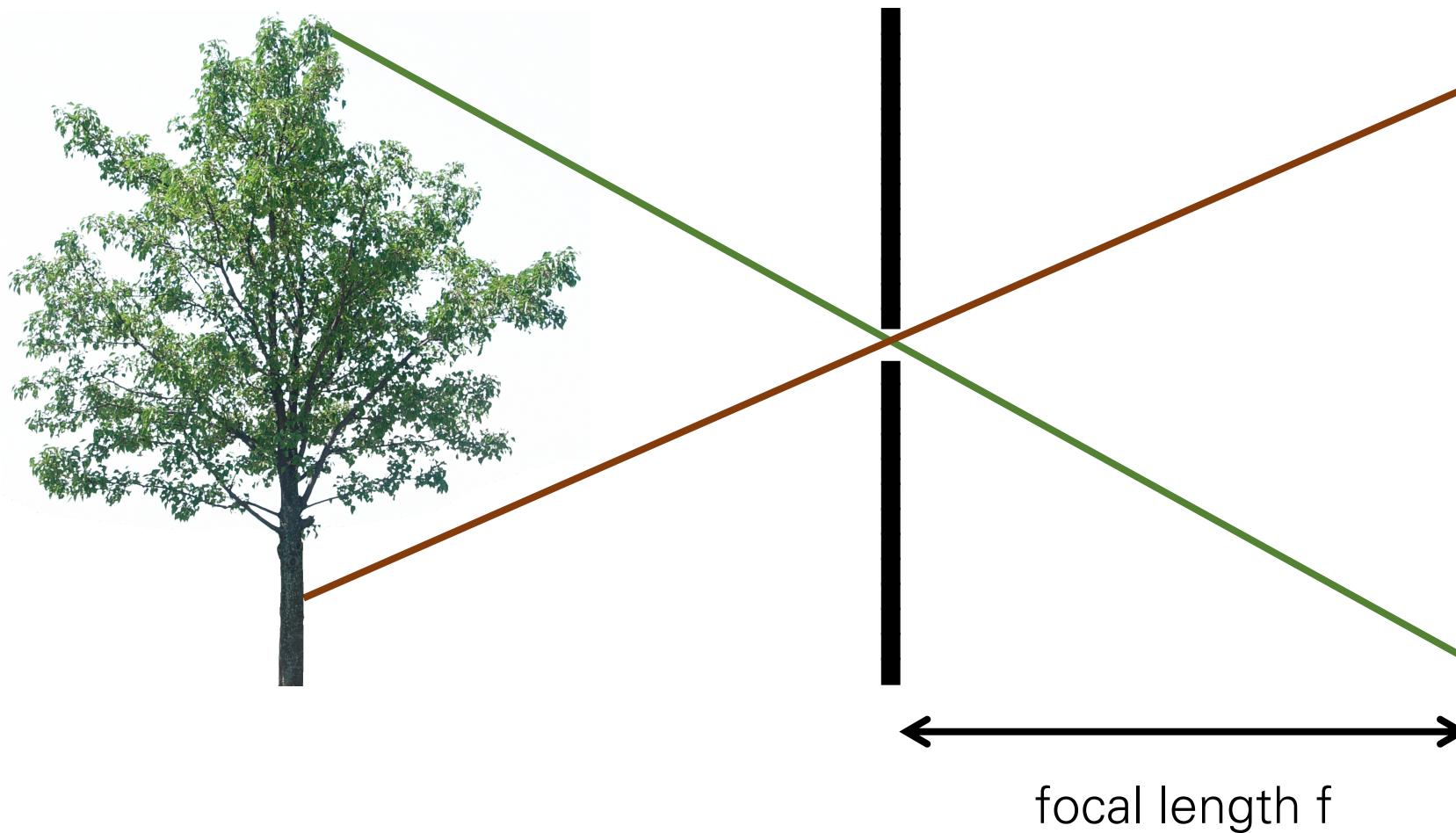


We can derive properties and descriptions that hold for both camera models if:

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

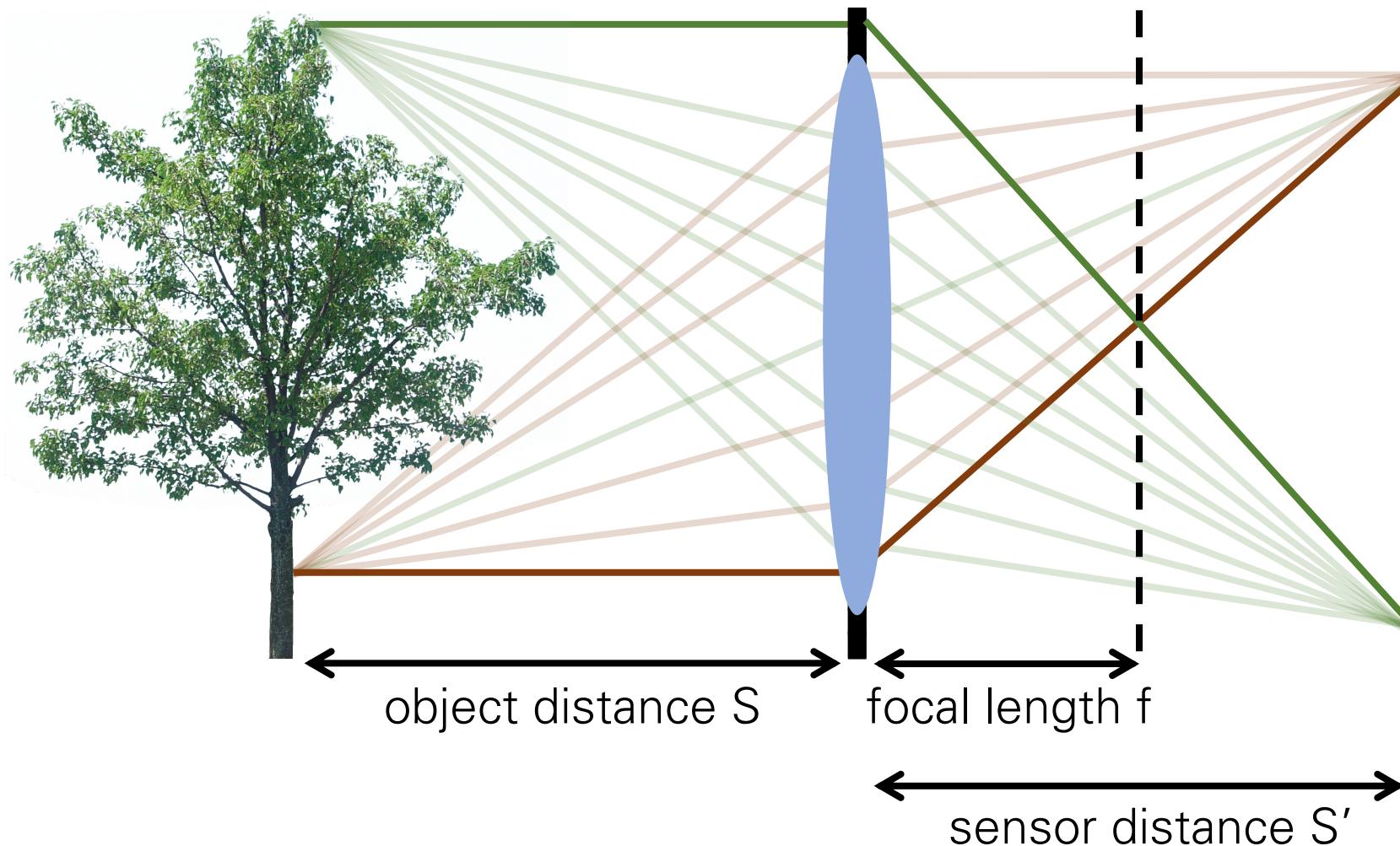
Important difference: focal length

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

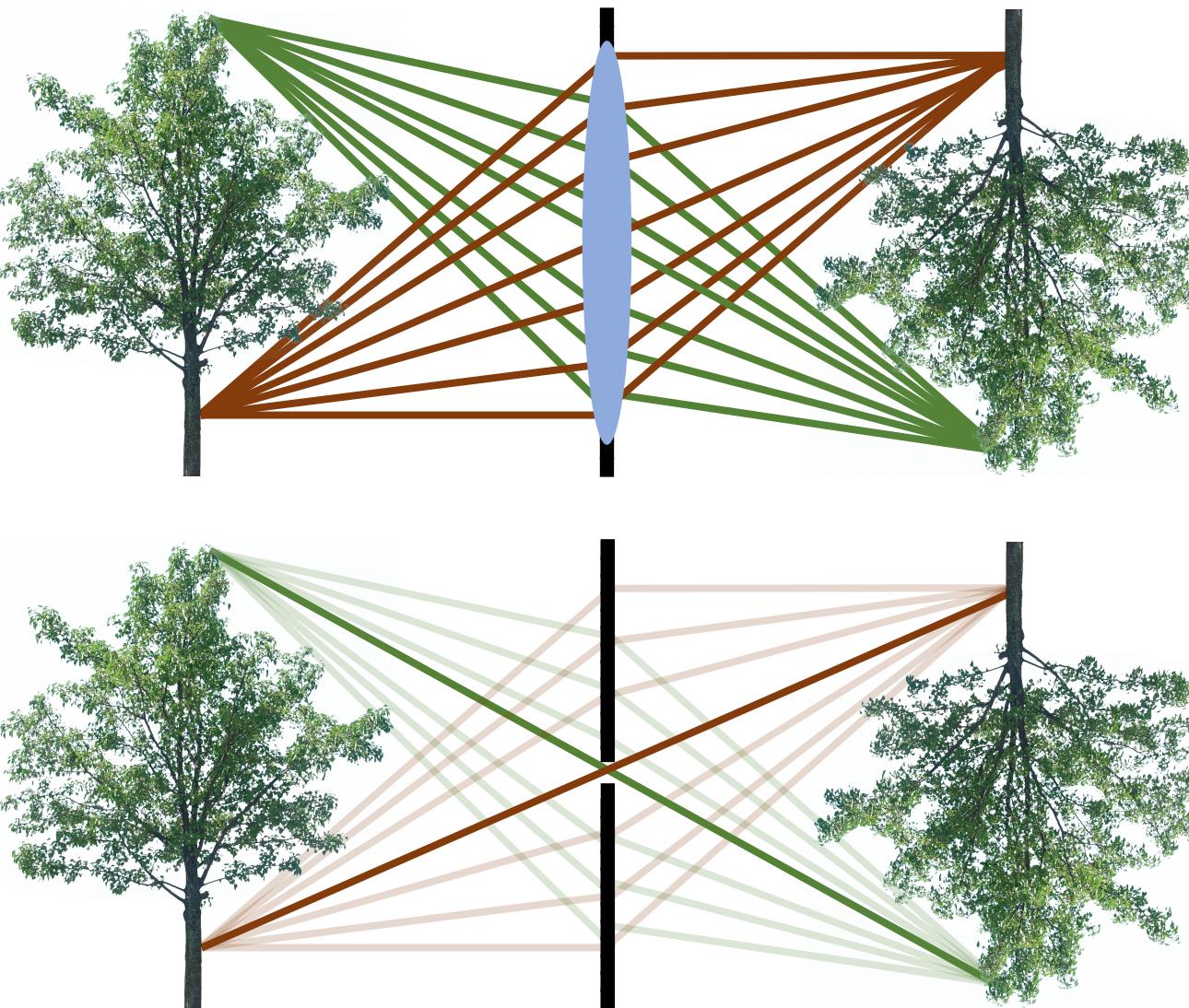


Important difference: focal length

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



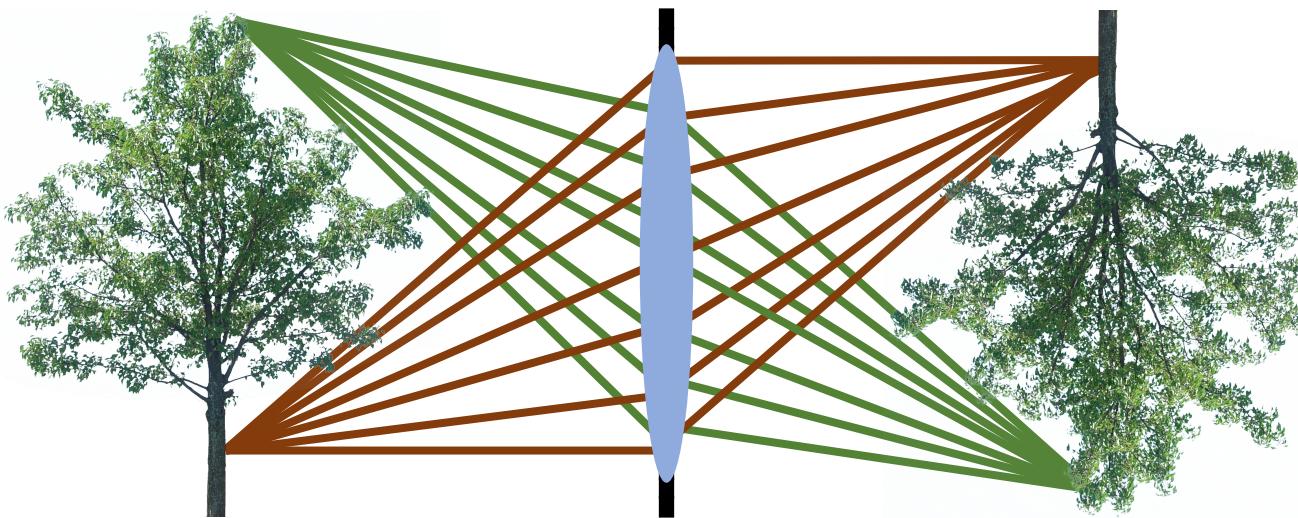
Describing both lens and pinhole cameras



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

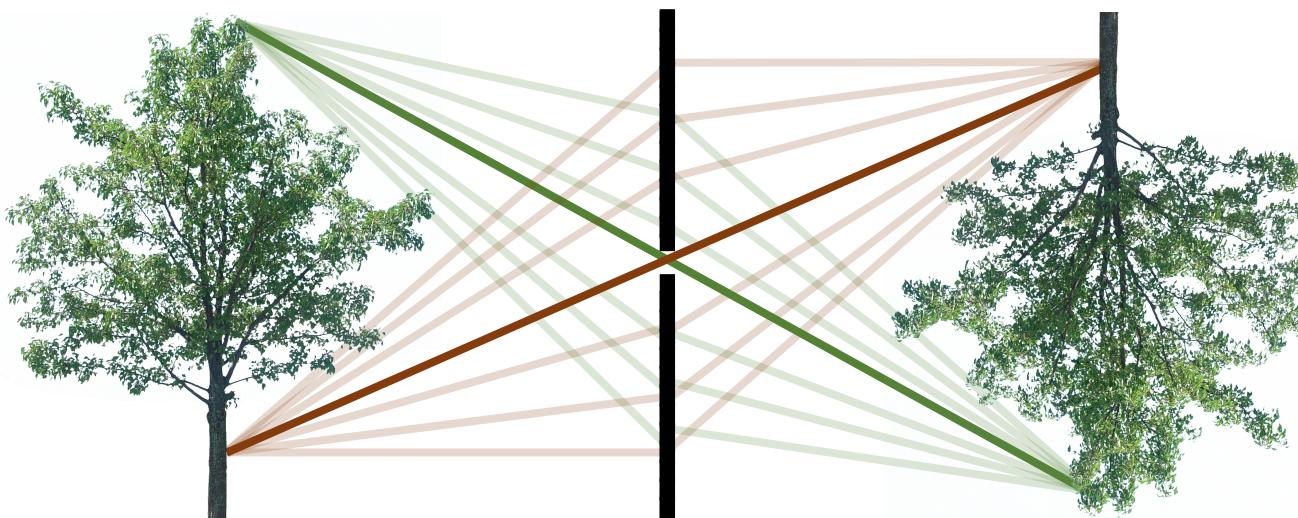
- We consider only central rays.
- We assume everything of interest in the scene is within the depth of field.
- We assume that the focus distance of the lens camera is equal to the focal length of the pinhole camera.

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.

Field of view

Field of view

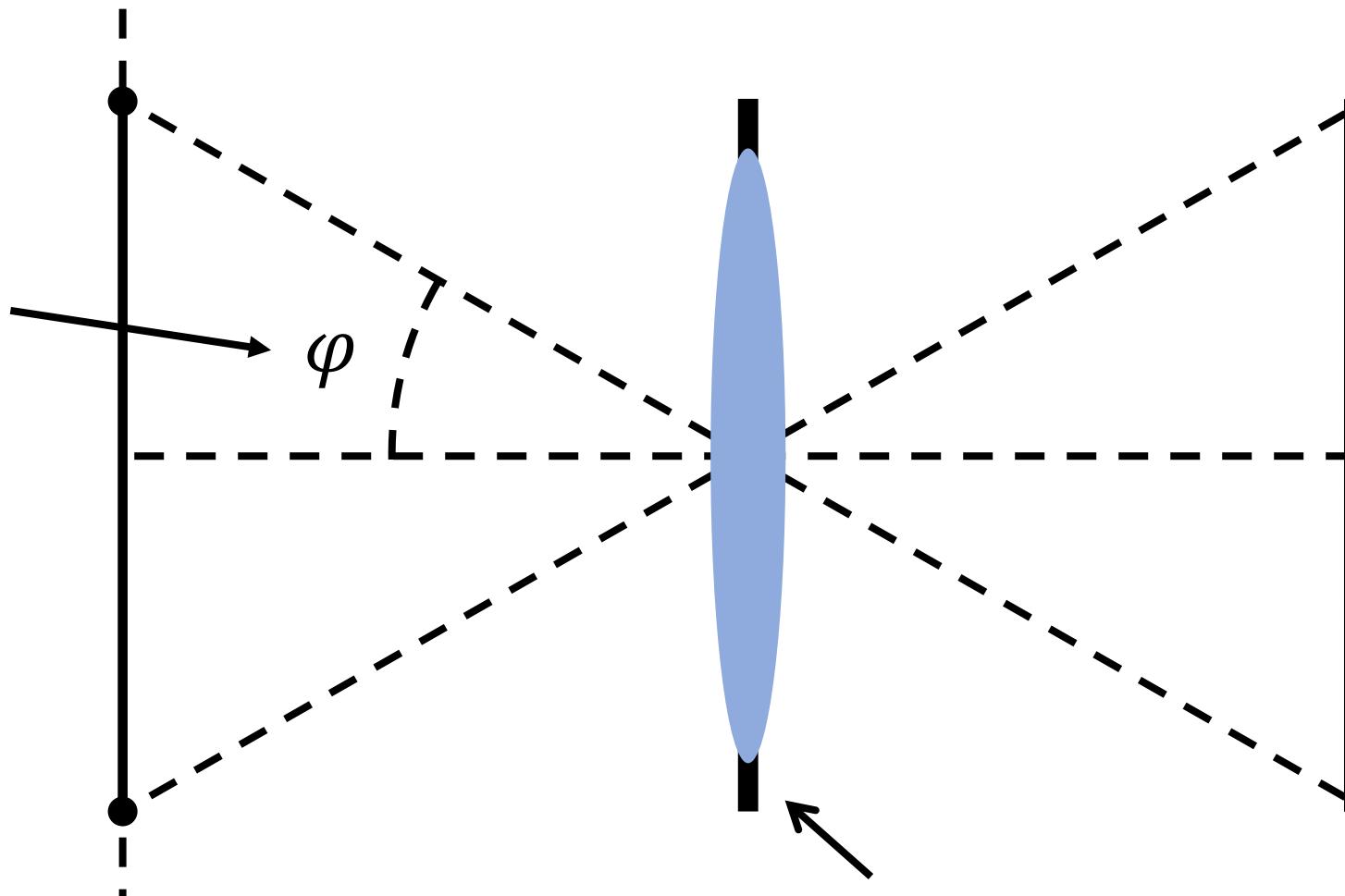
- Determines how much of scene is in frame
- Traditionally specified by focal length
 - but interpreting this number requires considering the “format,” or size of the film or sensor
- After decades of 35mm, that format is stuck in our heads
 - fields of view are usually discussed using the numbers that 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?



Field of view

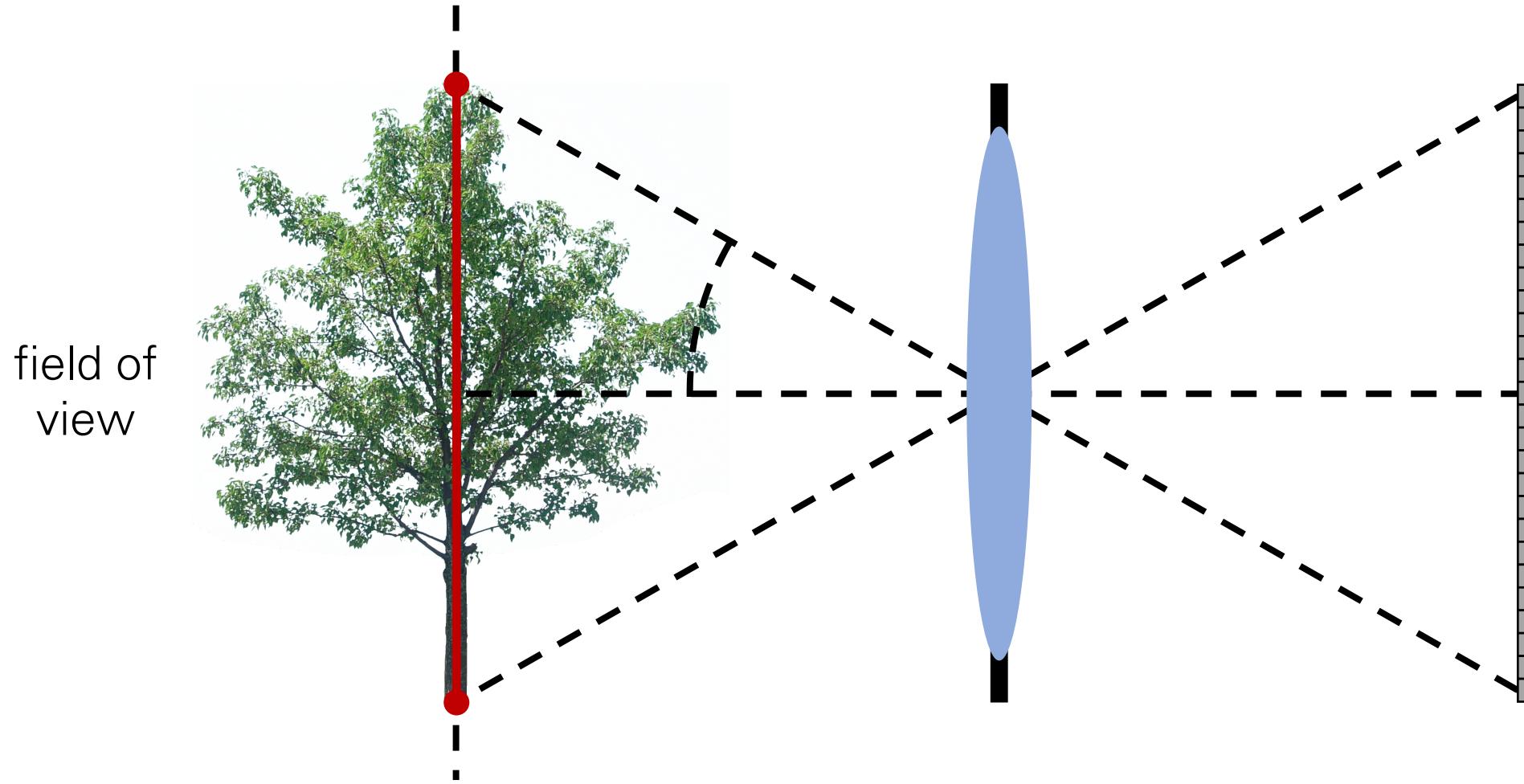
also described
using angle of
view



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

Field of view

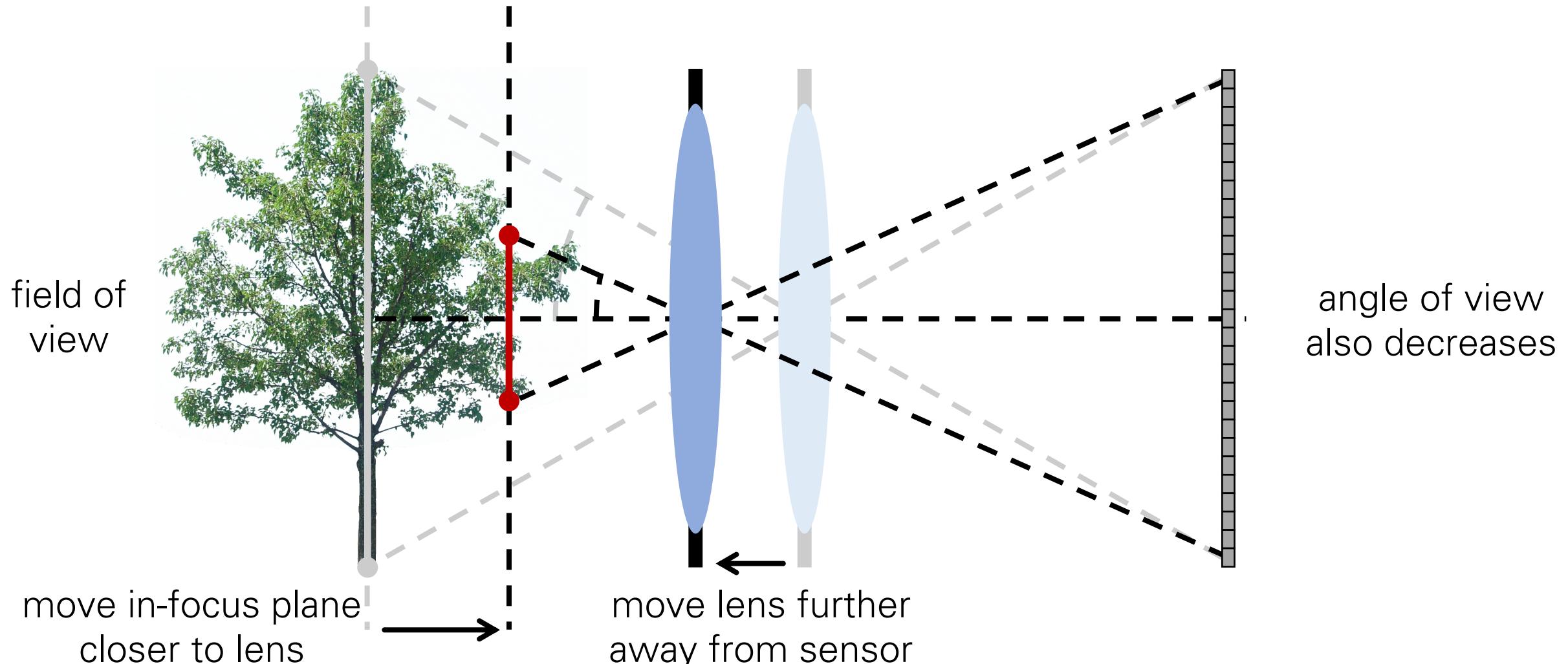
The part of the in-focus plane that gets mapped on the sensor.



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

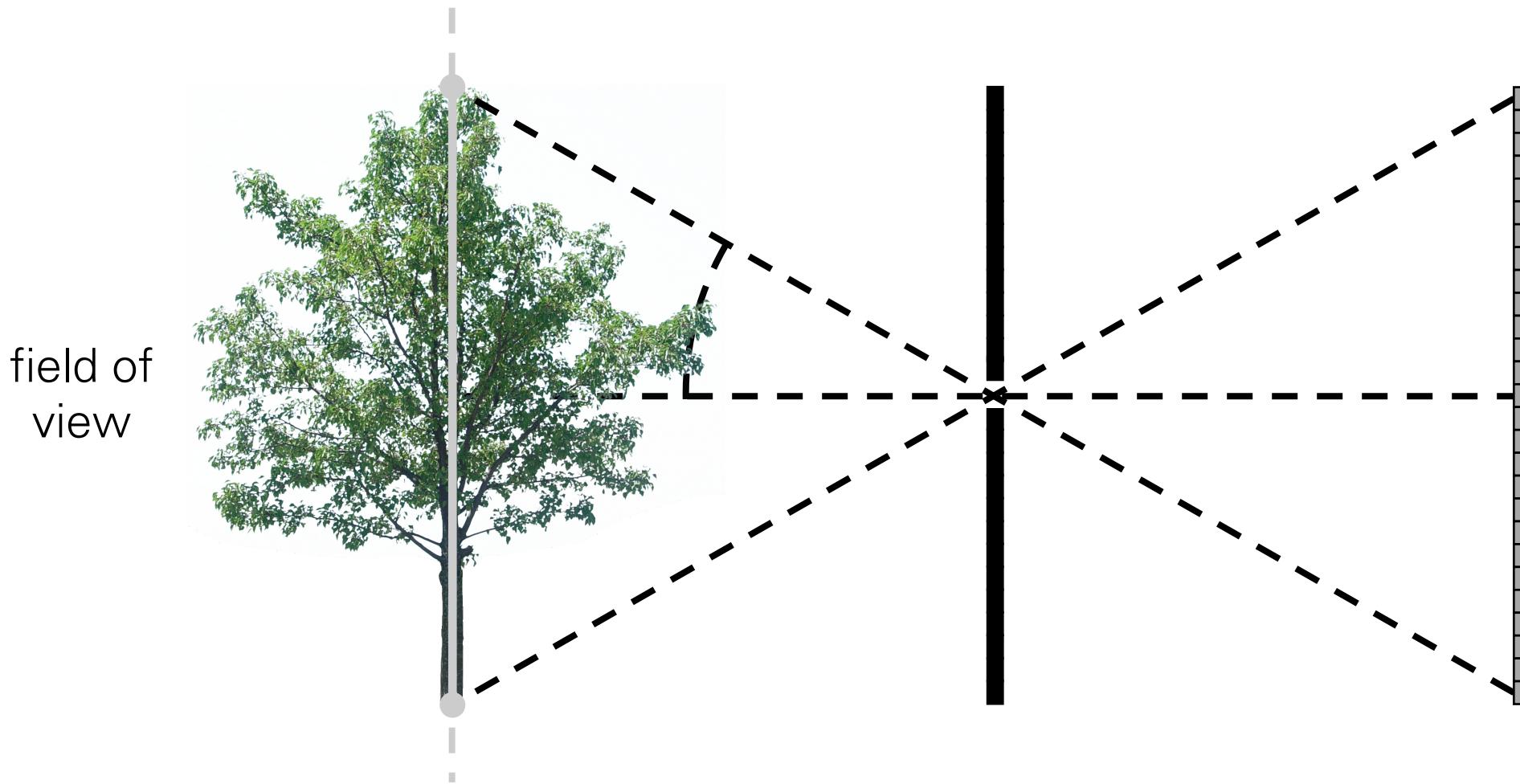
Field of view

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.

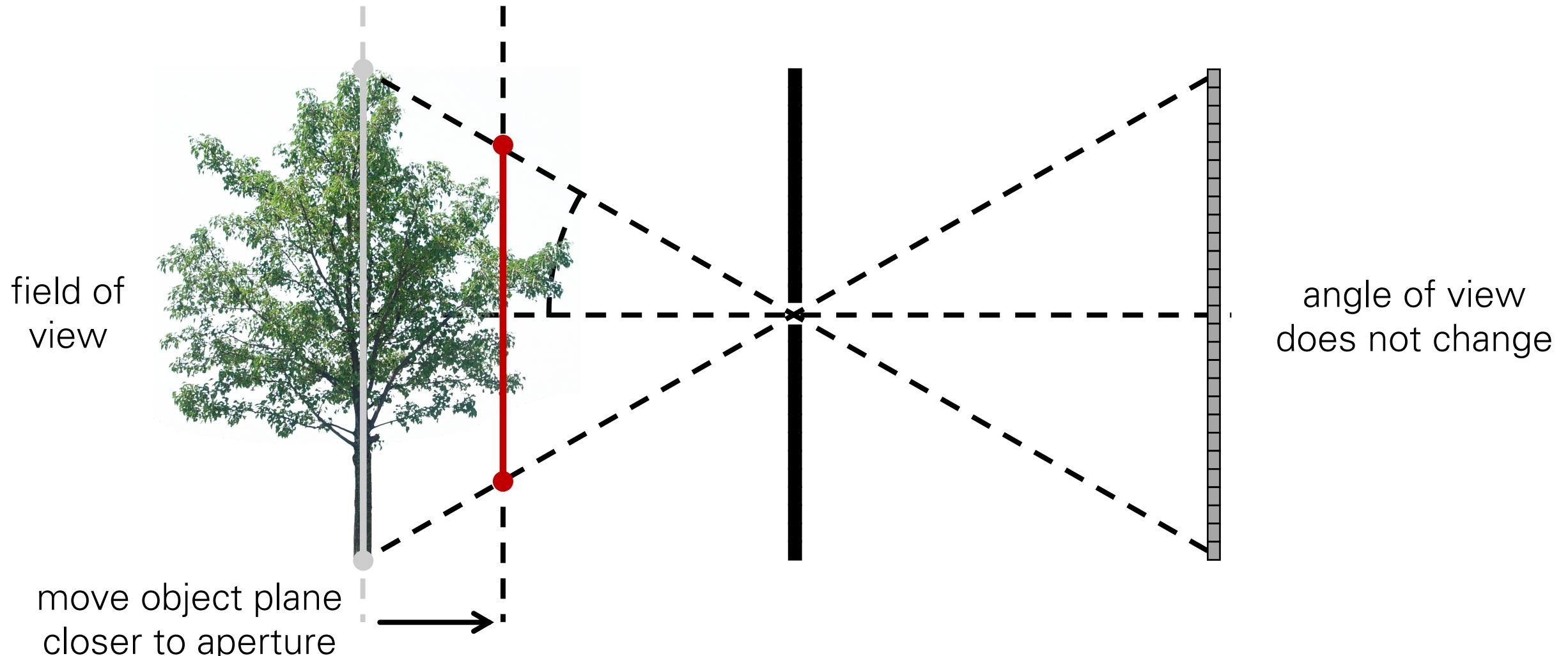
Comparison with pinhole camera



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

Comparison with pinhole camera

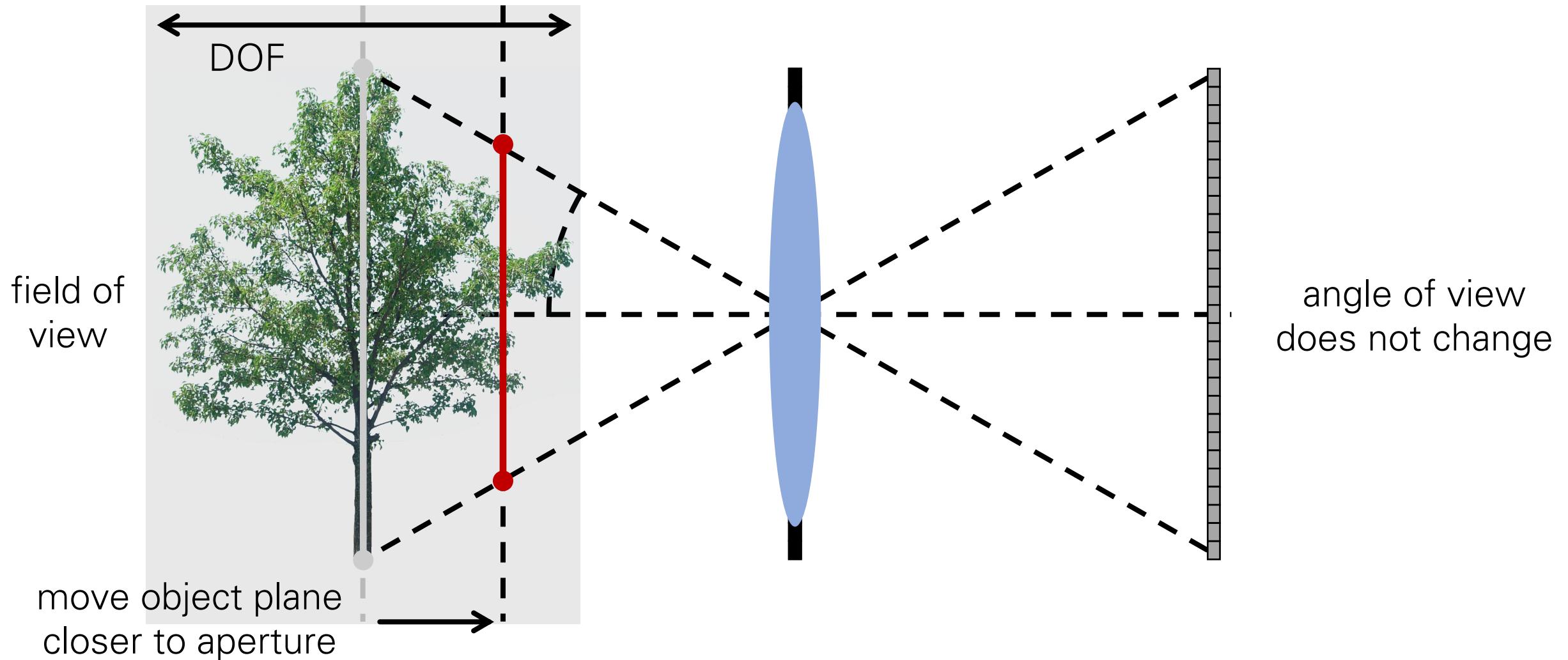
No need to refocus: we can move object closer without changing aperture-sensor distance.



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

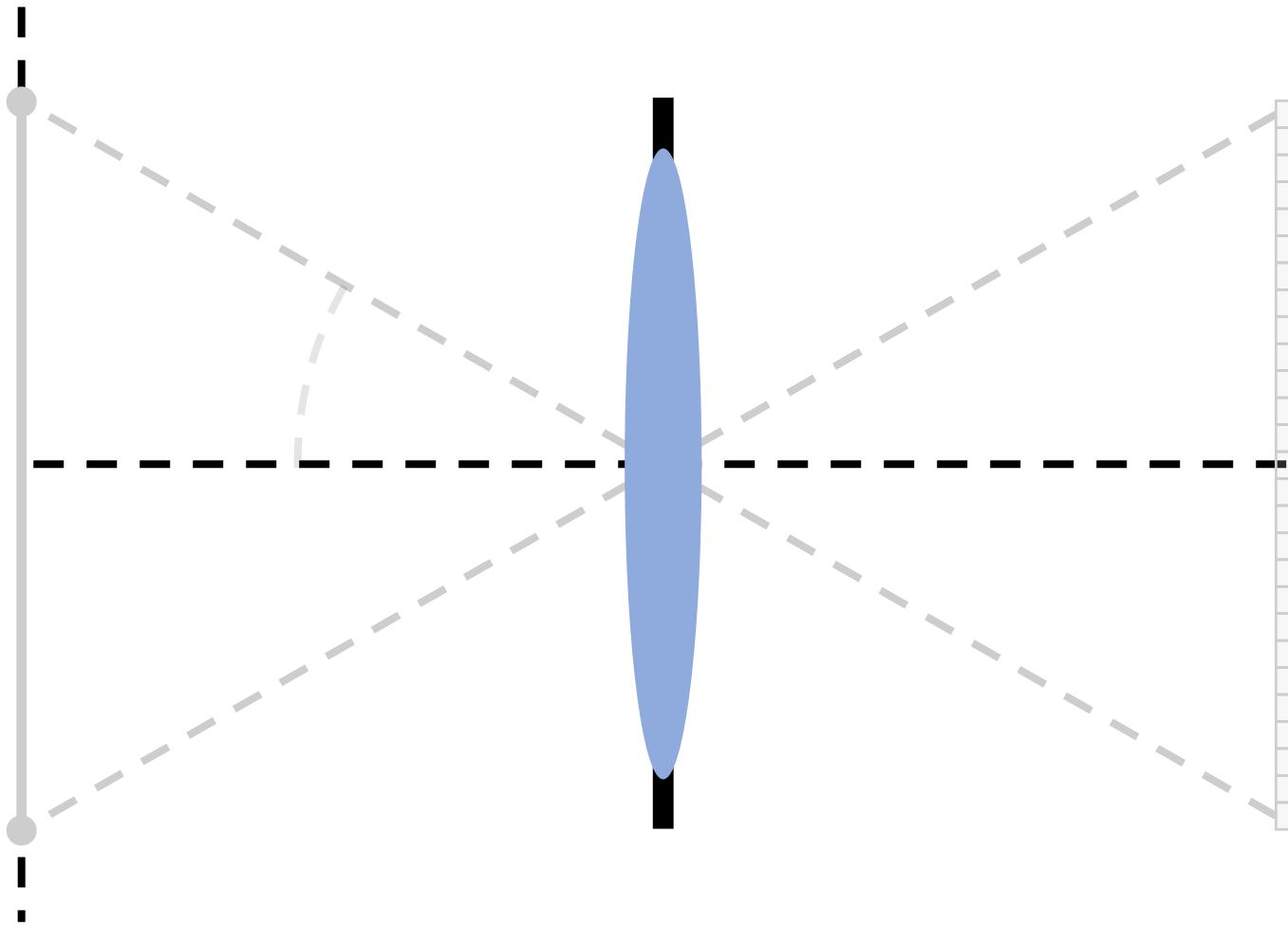
Comparison with pinhole camera

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



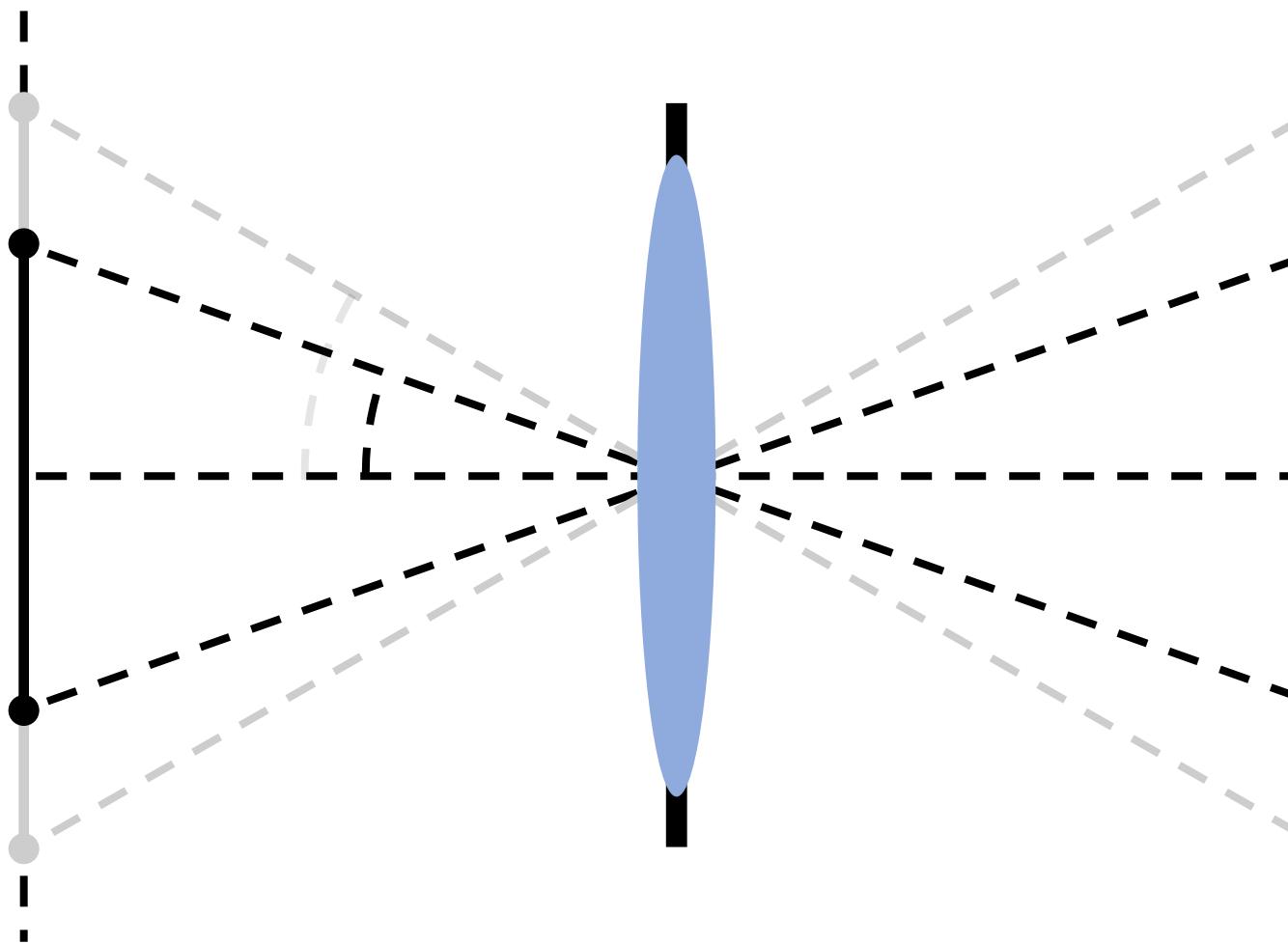
This can be done with a lens only if depth of field is large enough. Then the two behave the same.

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.

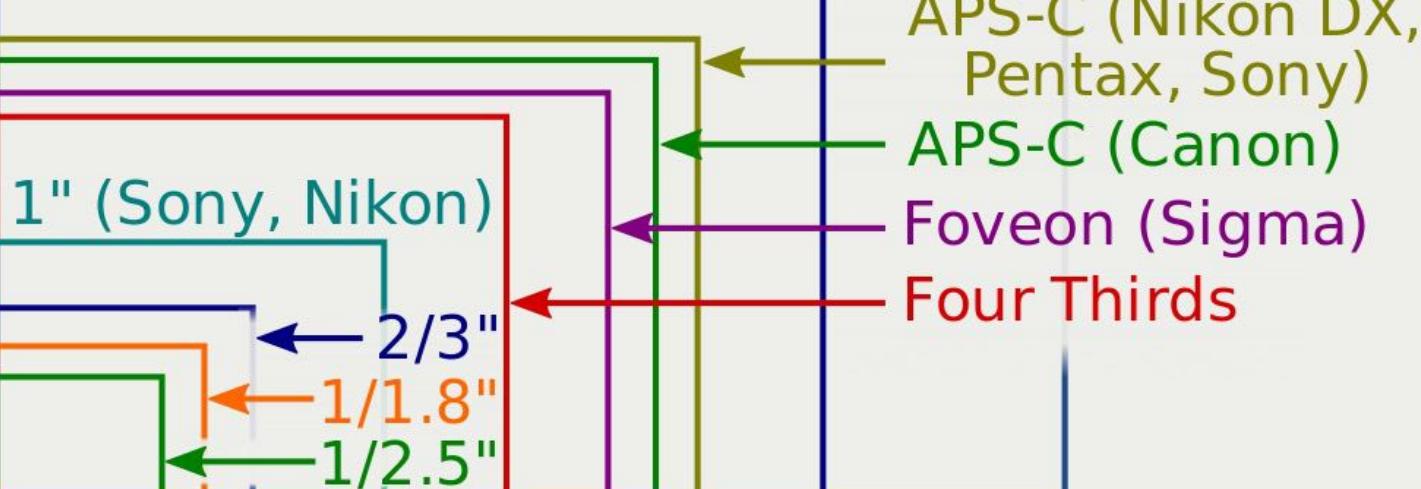
- What happens to field of view when we reduce sensor size? → It decreases.

Field of view also depends on sensor size

Medium format (Kodak KAF 39000 sensor)

35 mm "full frame"

APS-H (Canon)



- “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

Medium format (Kodak KAF 39000 sensor)

35 mm "full frame"

APS-H (Canon)

APS-C (Nikon DX,
Pentax, Sony)

APS-C (Canon)

1" (Sony, Nikon)

Foveon (Sigma)

Four Thirds

2/3"

1/1.8"

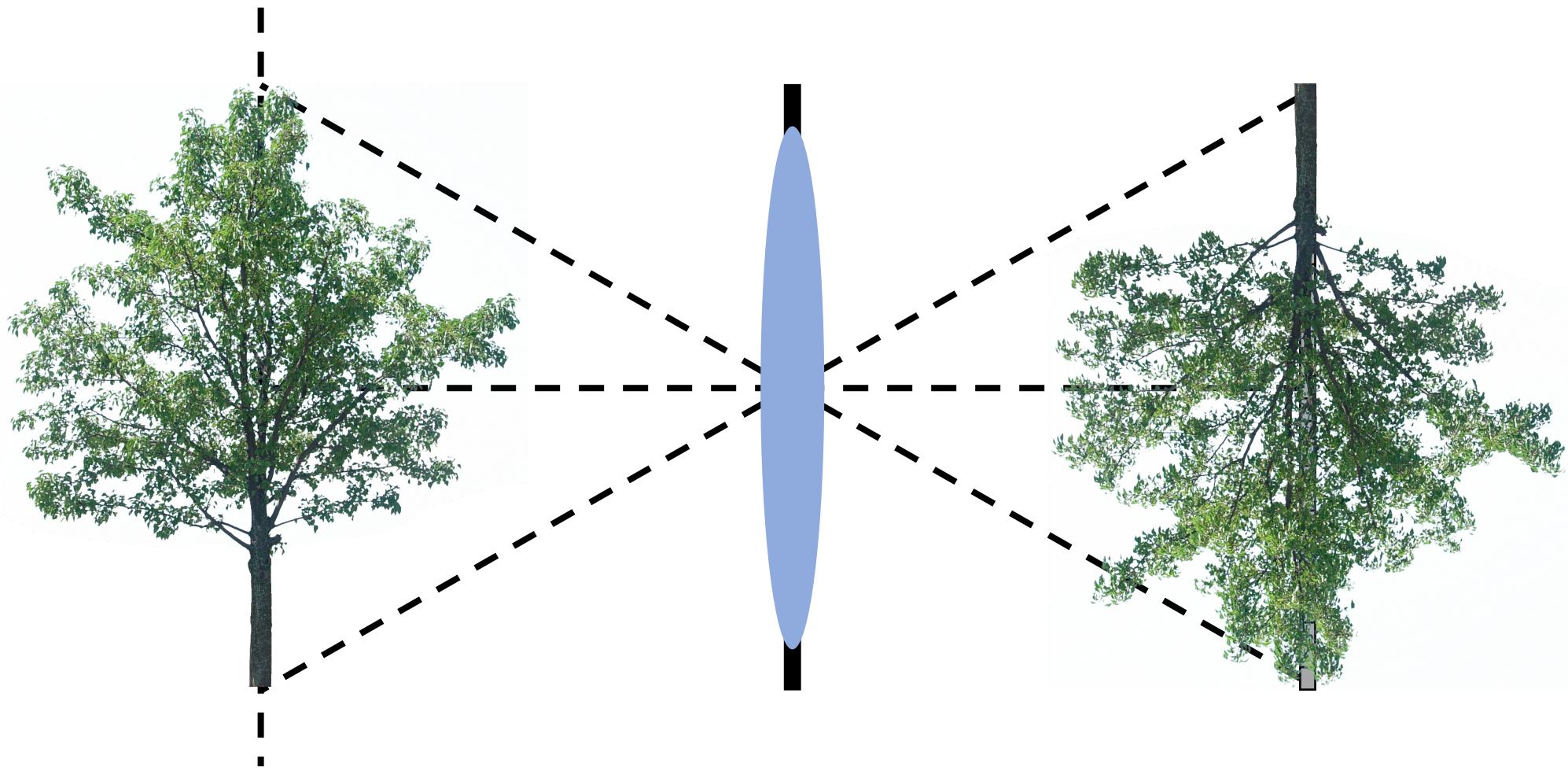
1/2.5"



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

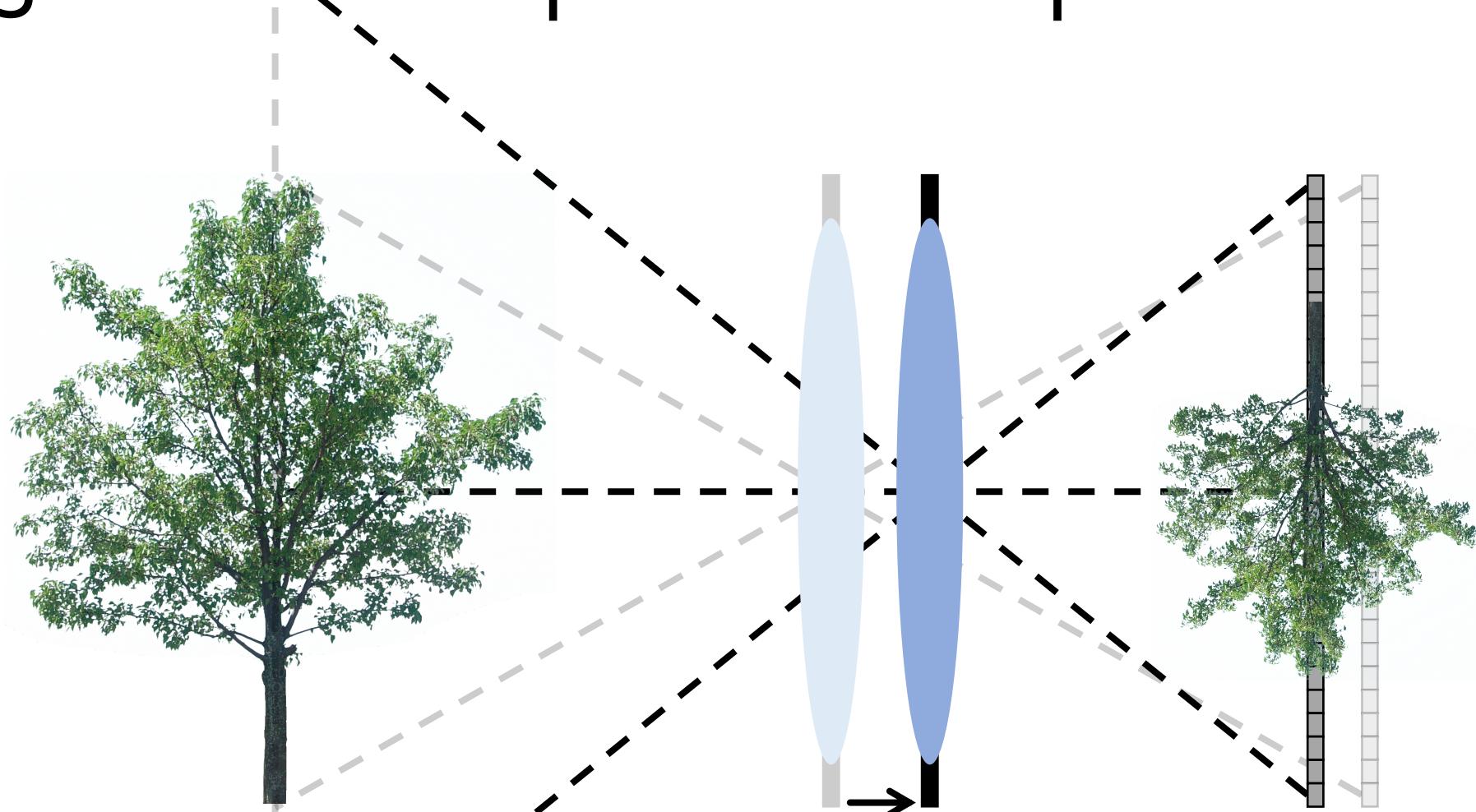
Magnification and perspective

Magnification depends on depth



- What happens to magnification as we focus further away?

Magnification depends on depth



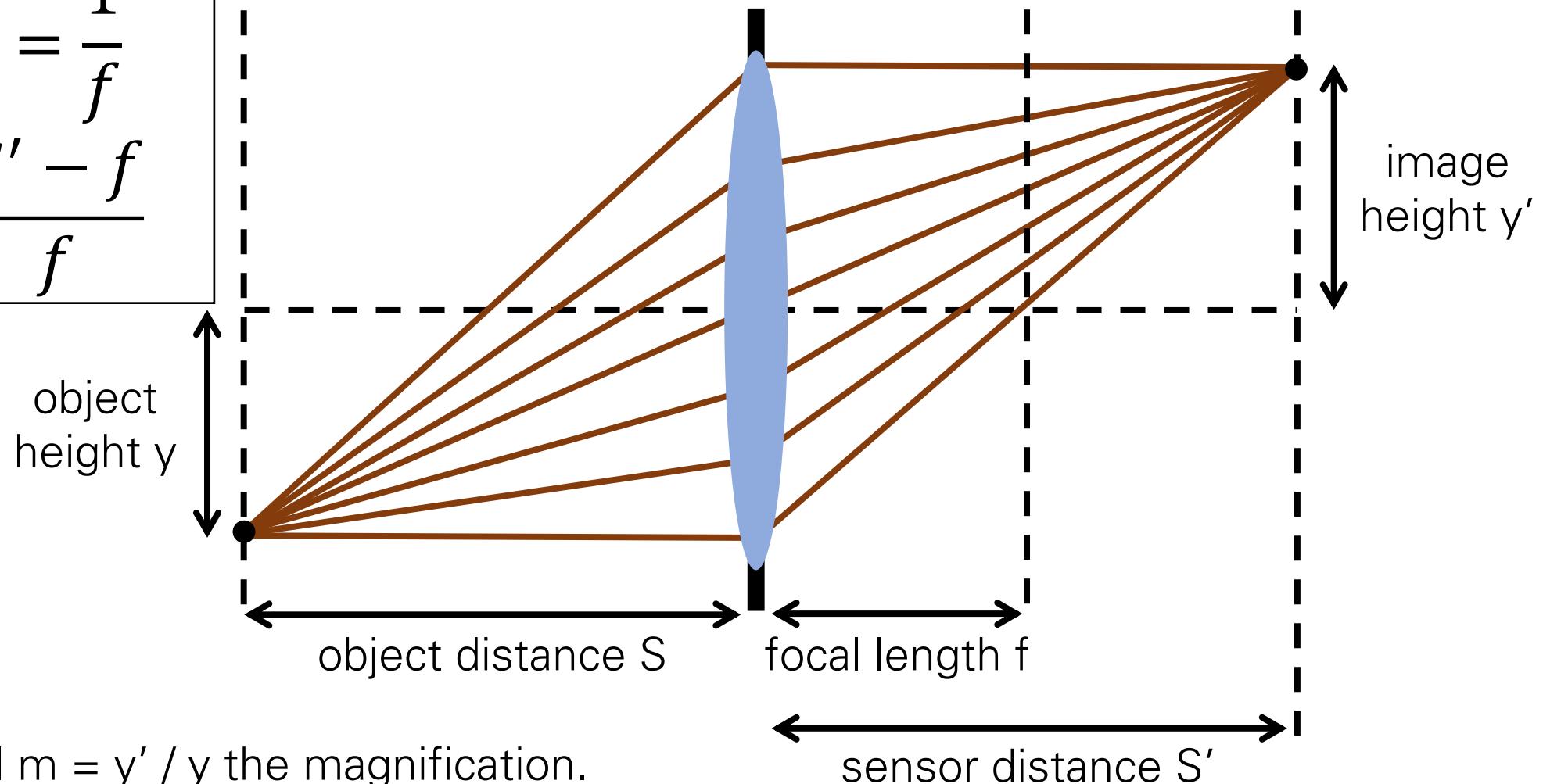
move object further
away from lens

move lens closer
to sensor

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

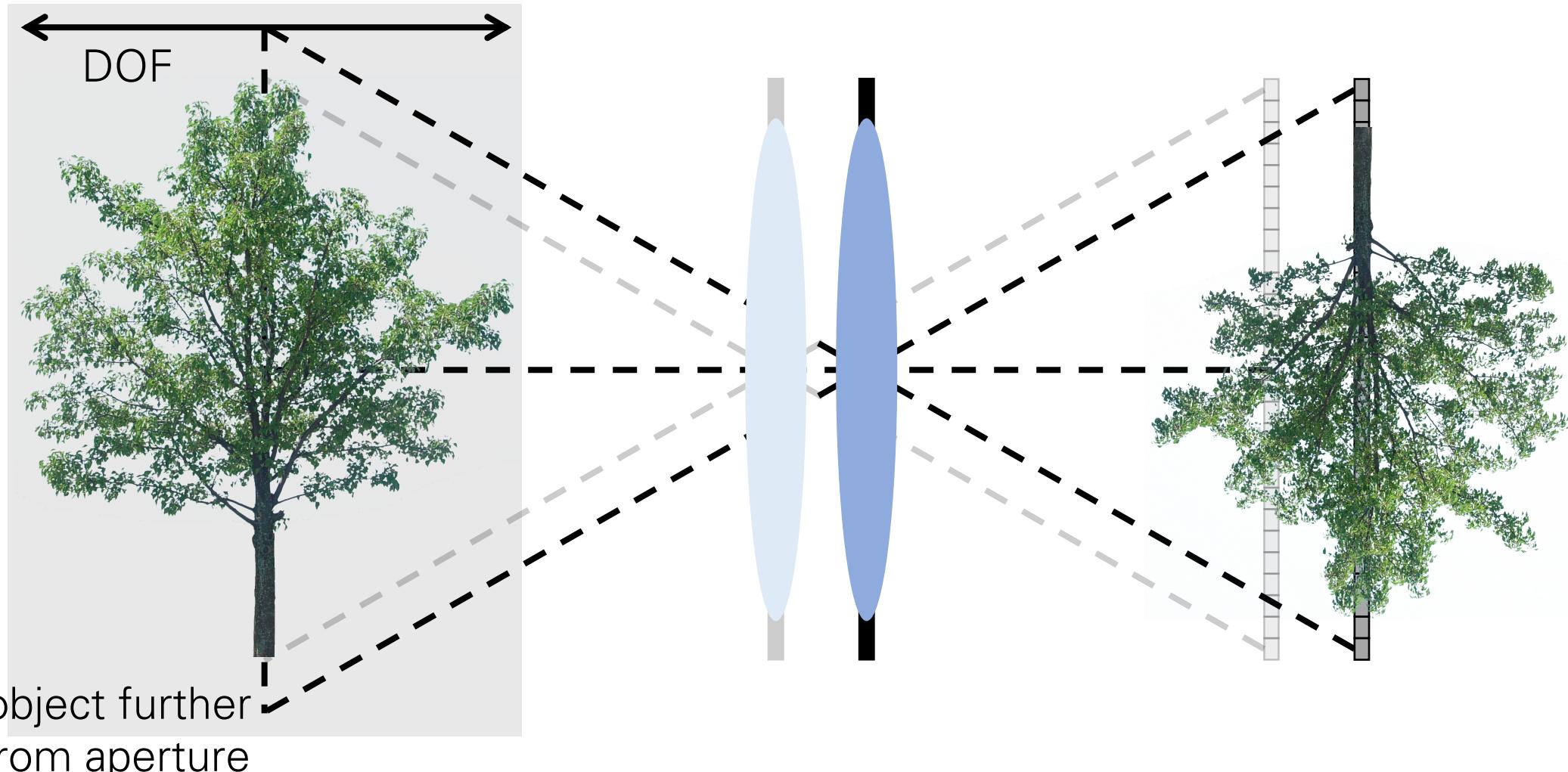
Magnification depends on depth

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



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.

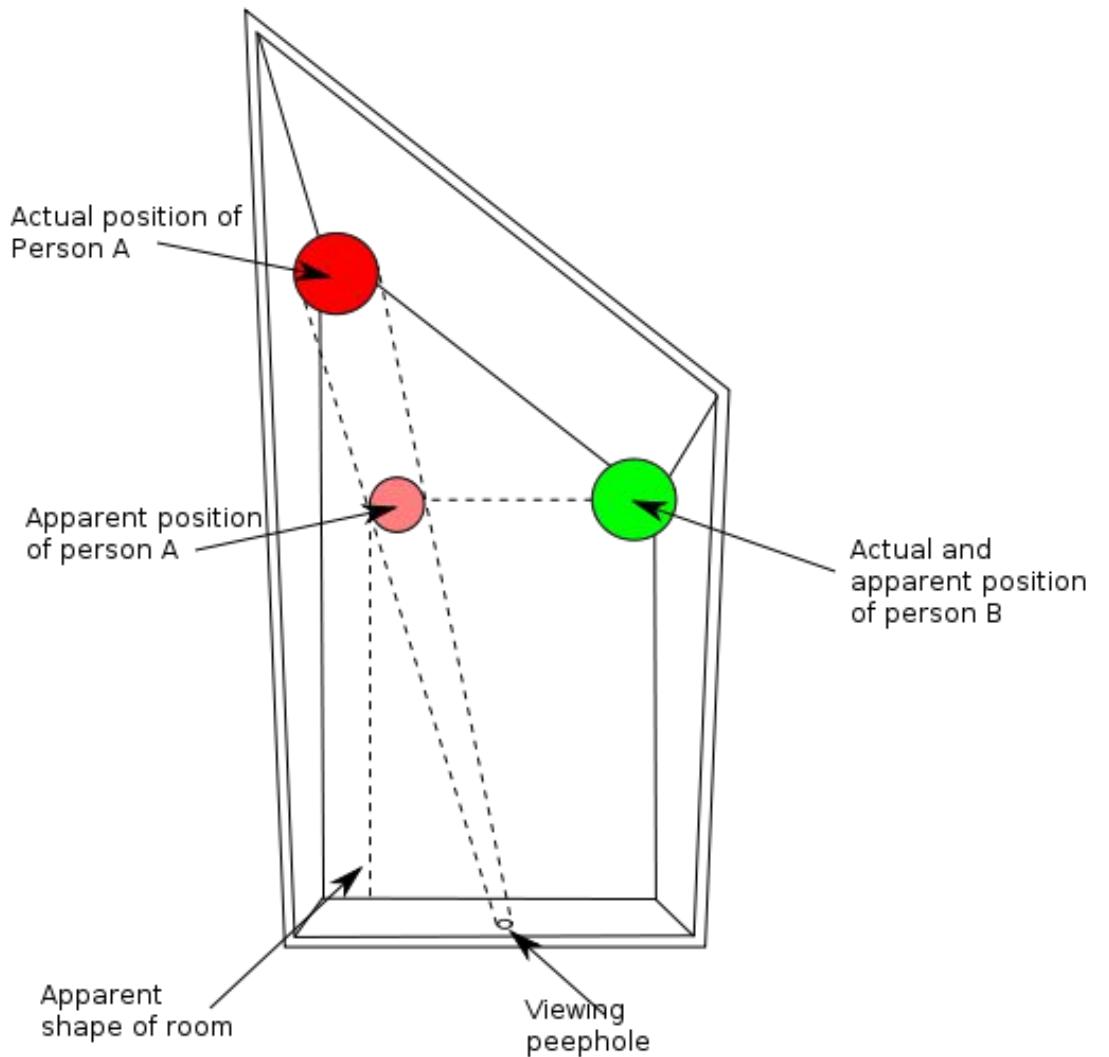
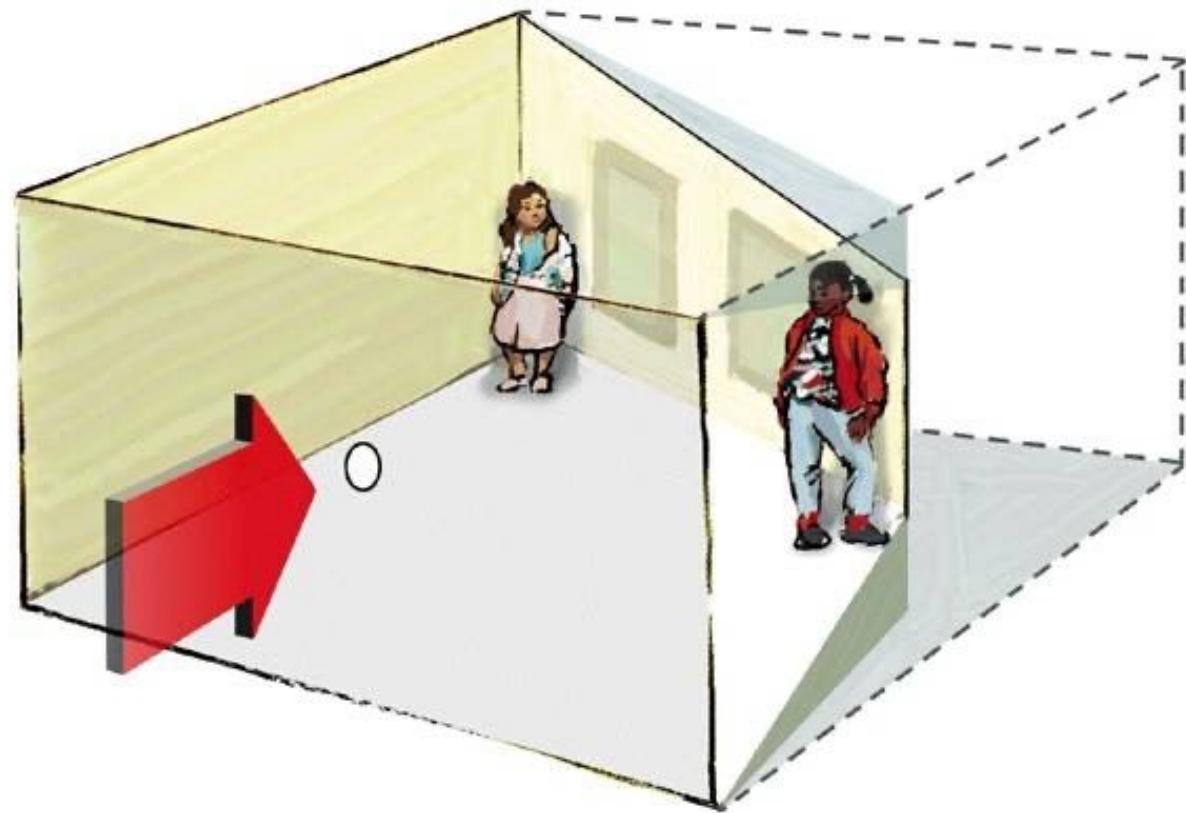
Forced perspective



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:

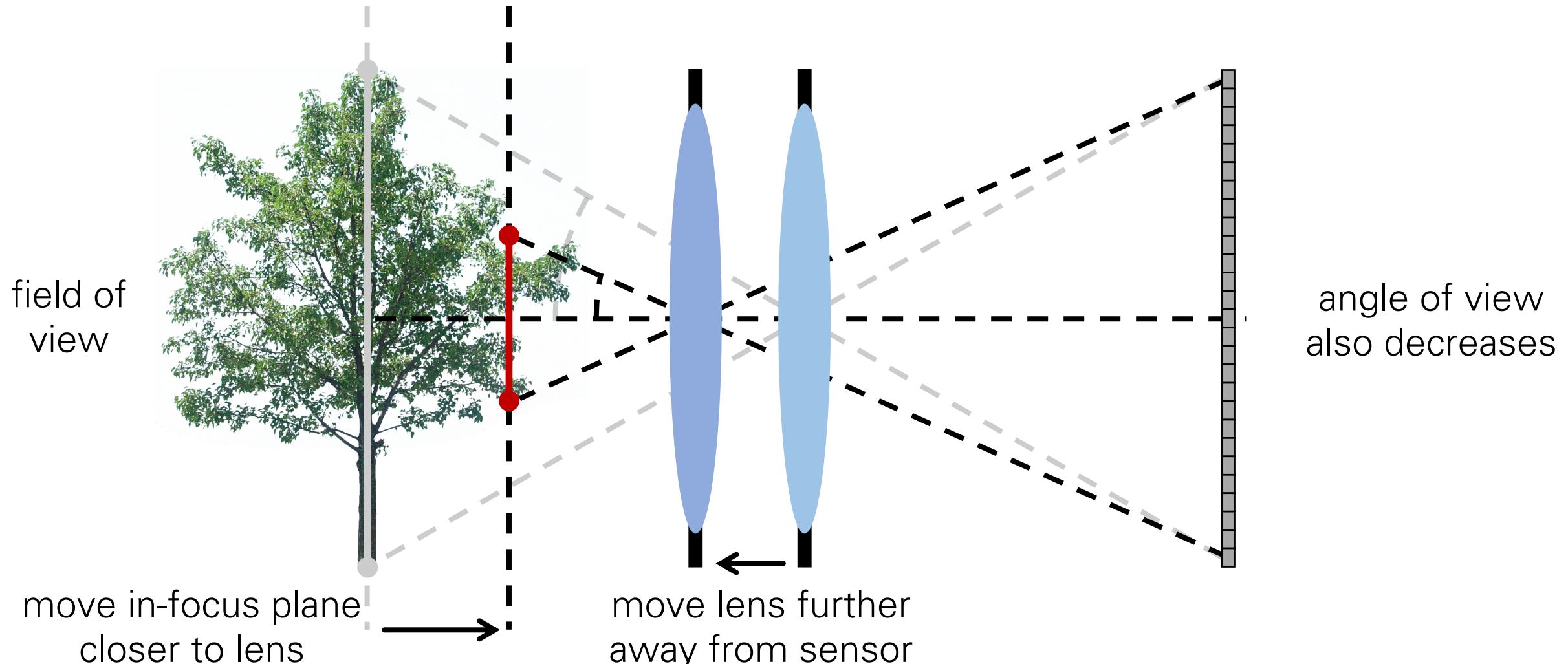
<http://www.isc.meiji.ac.jp/~kokichis/>



Zooming

Field of view

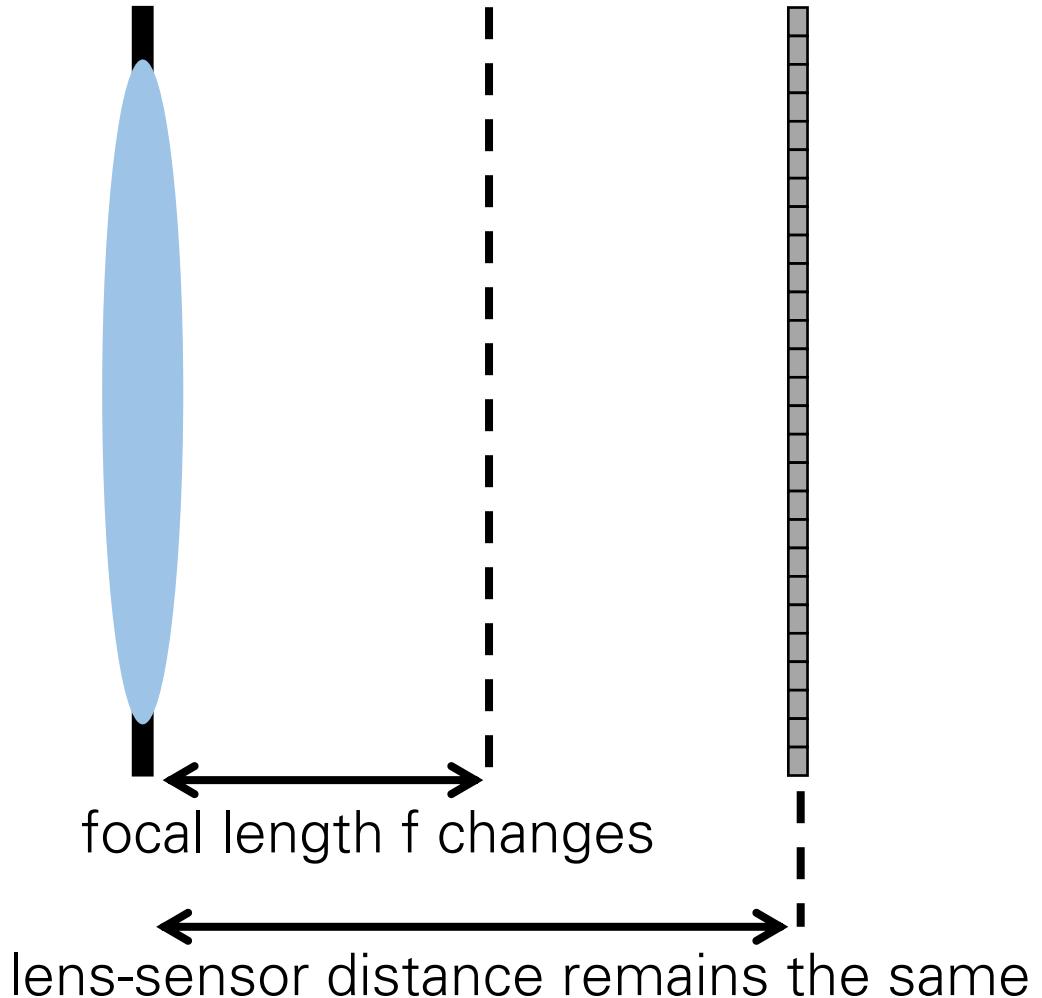
The part of the in-focus plane that gets mapped on the sensor.



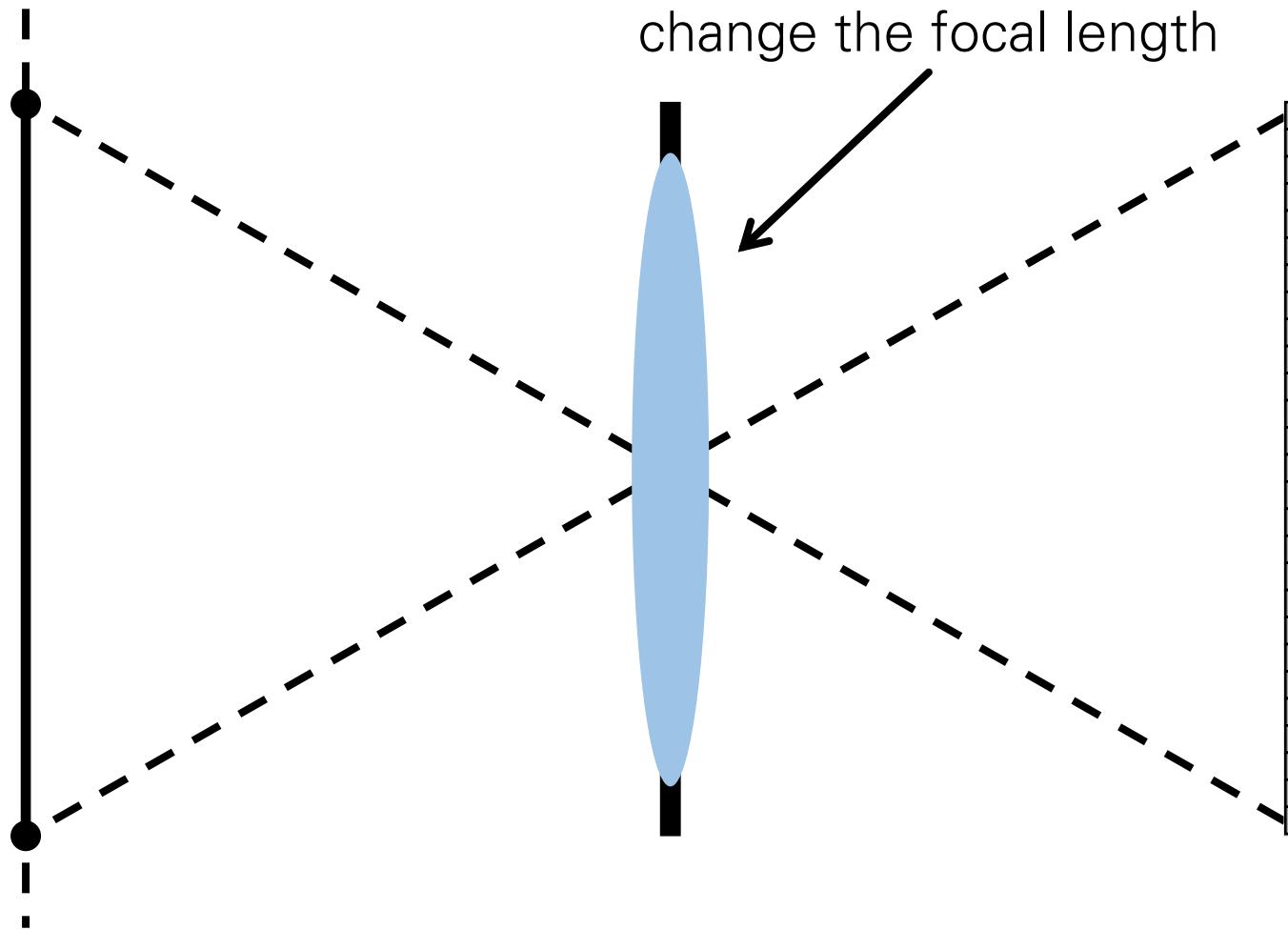
- What happens to field of view as we focus closer? → It becomes smaller.

Zooming means changing the focal length

Very different
process from
refocusing

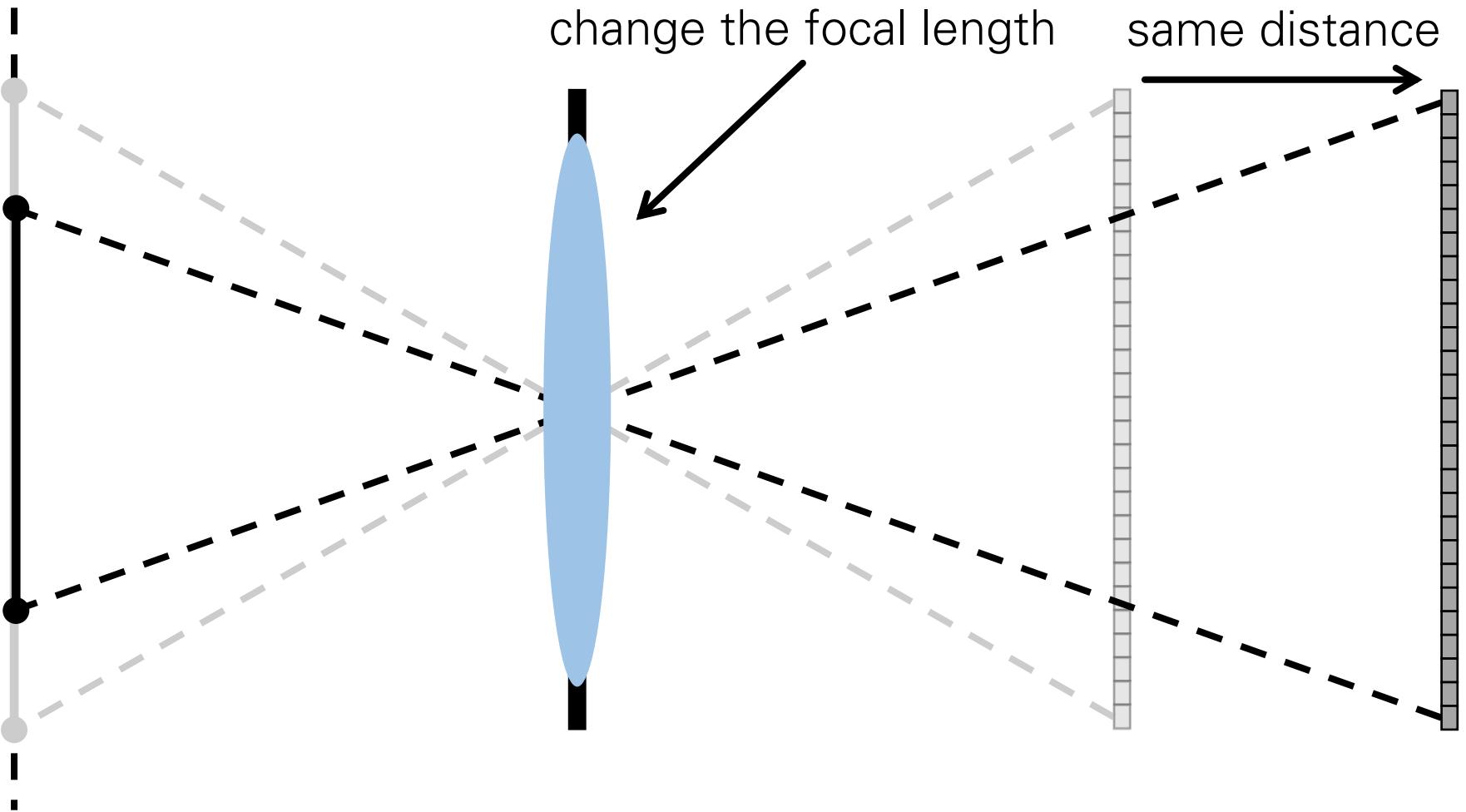


Zooming and field of view

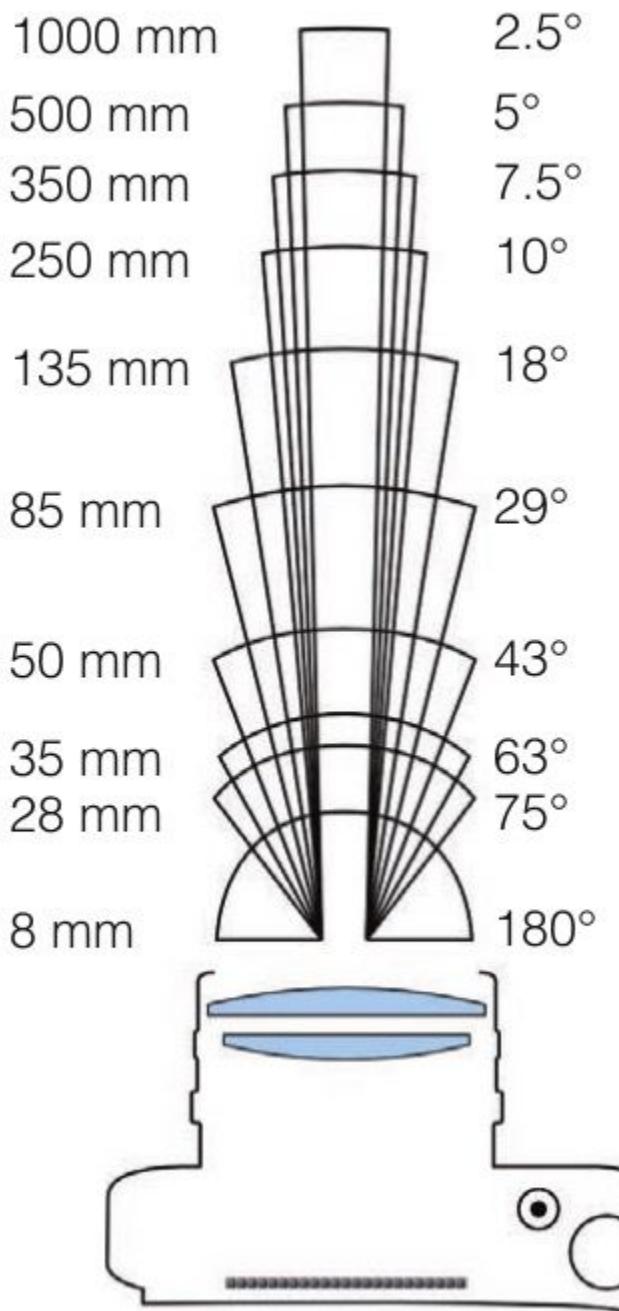


- What happens to field of view when we focus closer? → It decreases.
- What happens to field of view when we increase lens focal length?

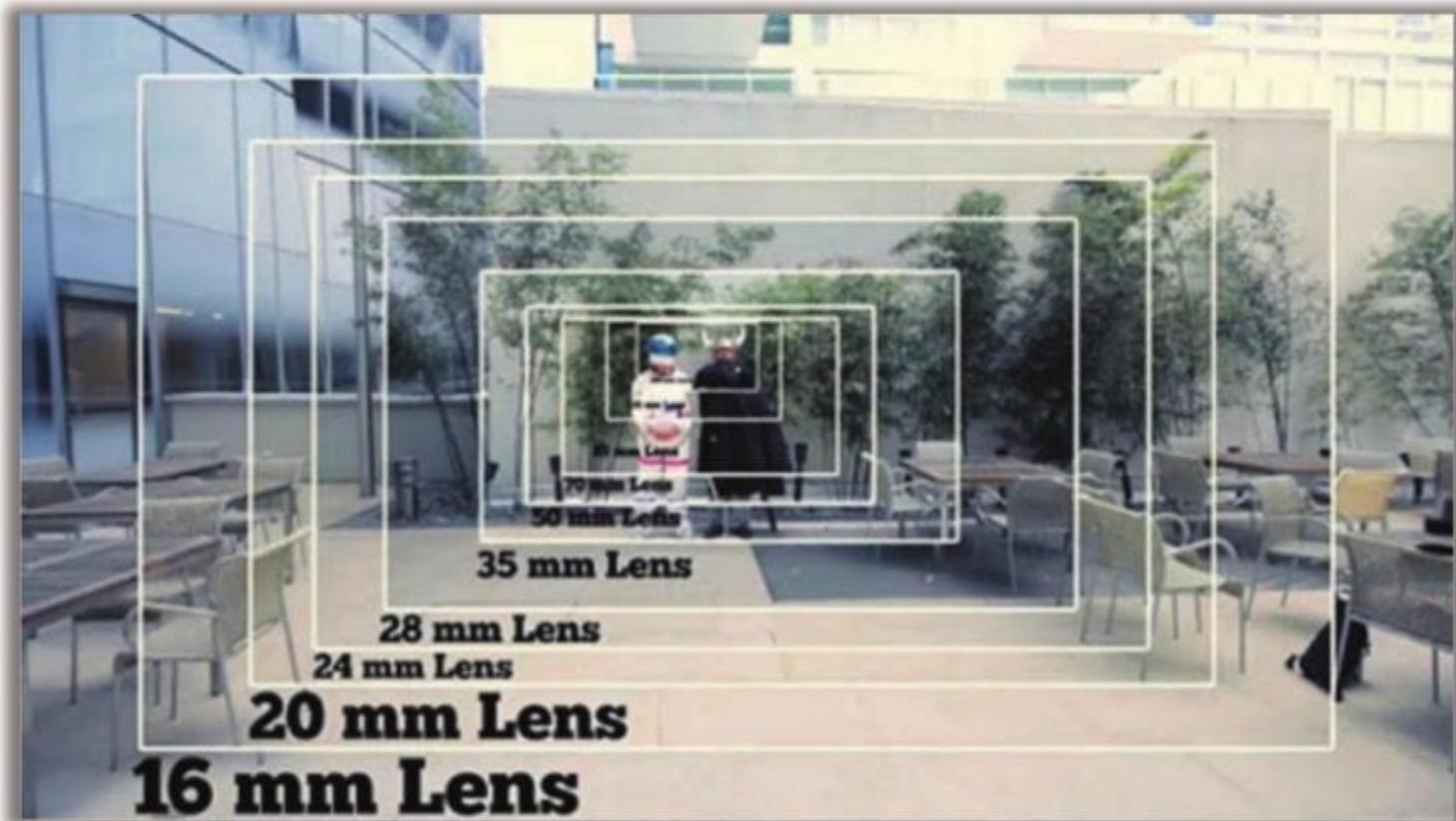
Zooming and field of view



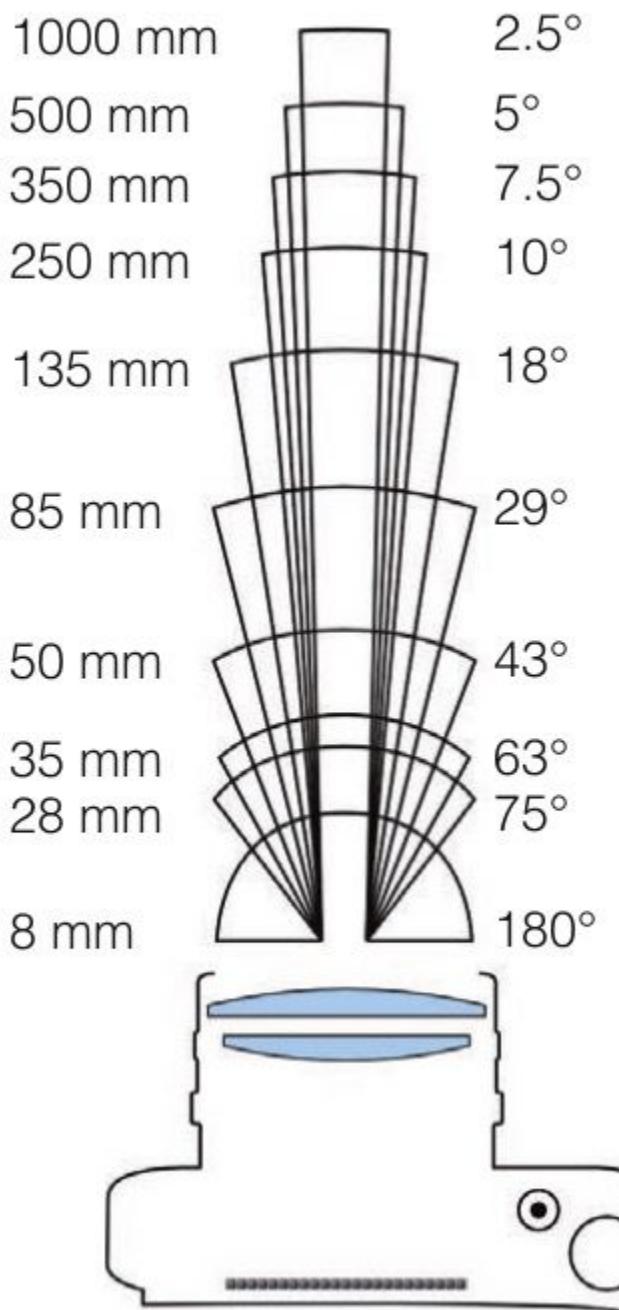
- When we increase lens focal length, field of view decreases (we “zoom in”).



Field of view

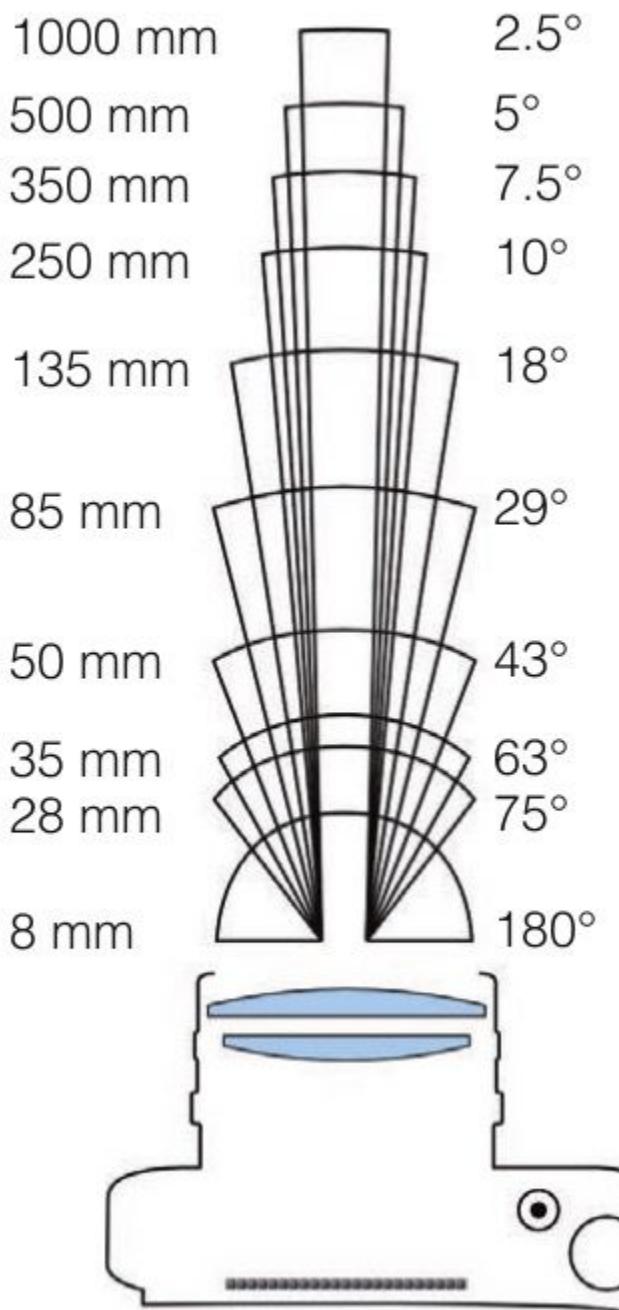


Andrew McWilliams



Field of view



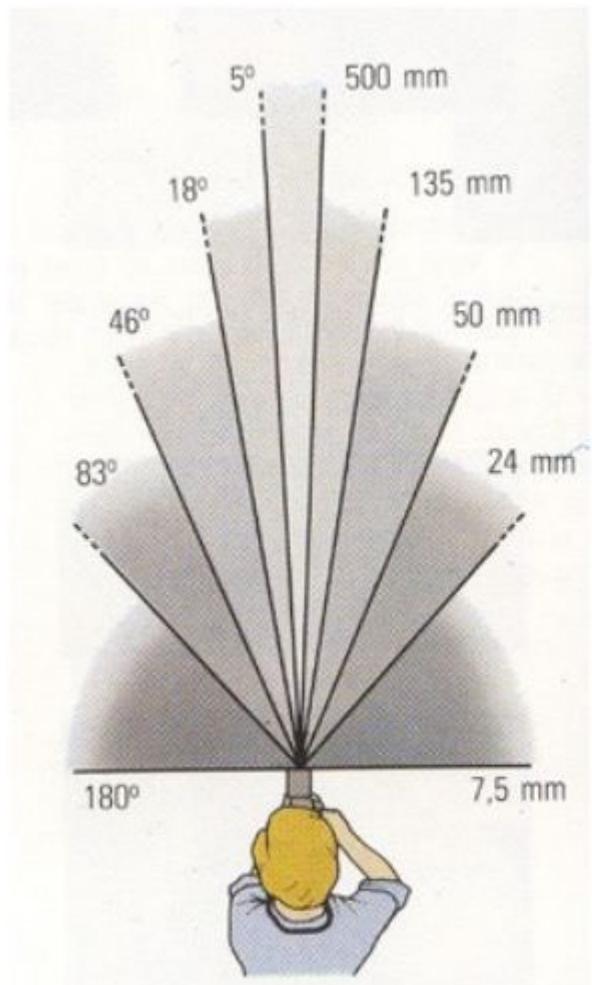


Field of view

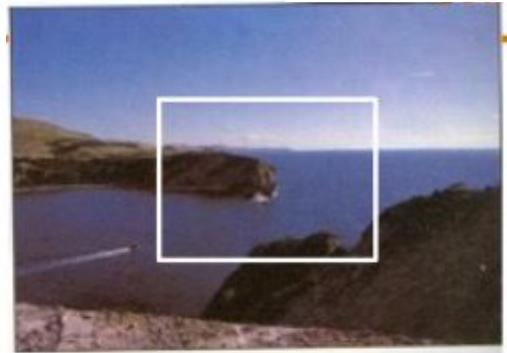


Field of view

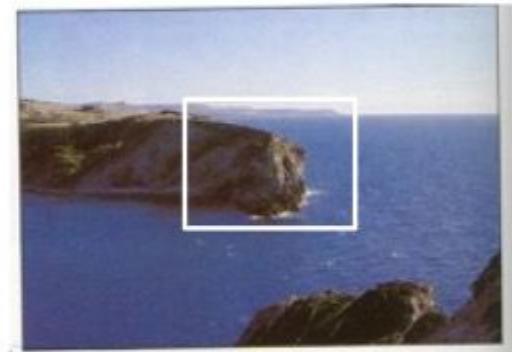
Increasing the lens focal length is similar to cropping



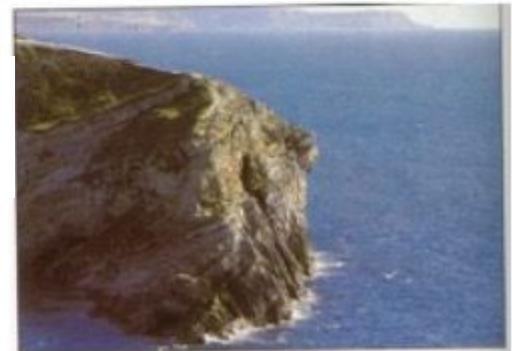
$f = 25 \text{ mm}$



$f = 50 \text{ mm}$



$f = 135 \text{ mm}$



Is this effect identical to cropping?

The lens on your camera



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:

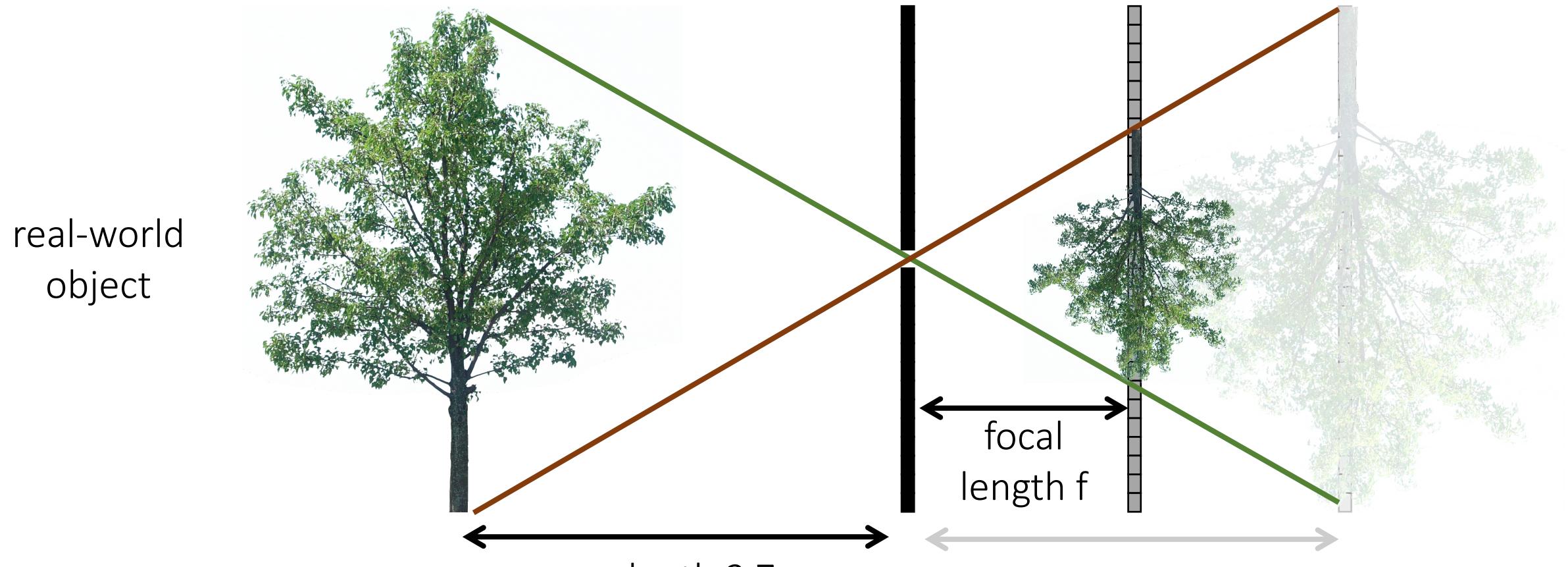
1. The in-focus distance decreases (you need to get closer to object).
2. The field of view decreases (you see a smaller part of the object).
3. The magnification increases (same part of the object is bigger on sensor).

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

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).

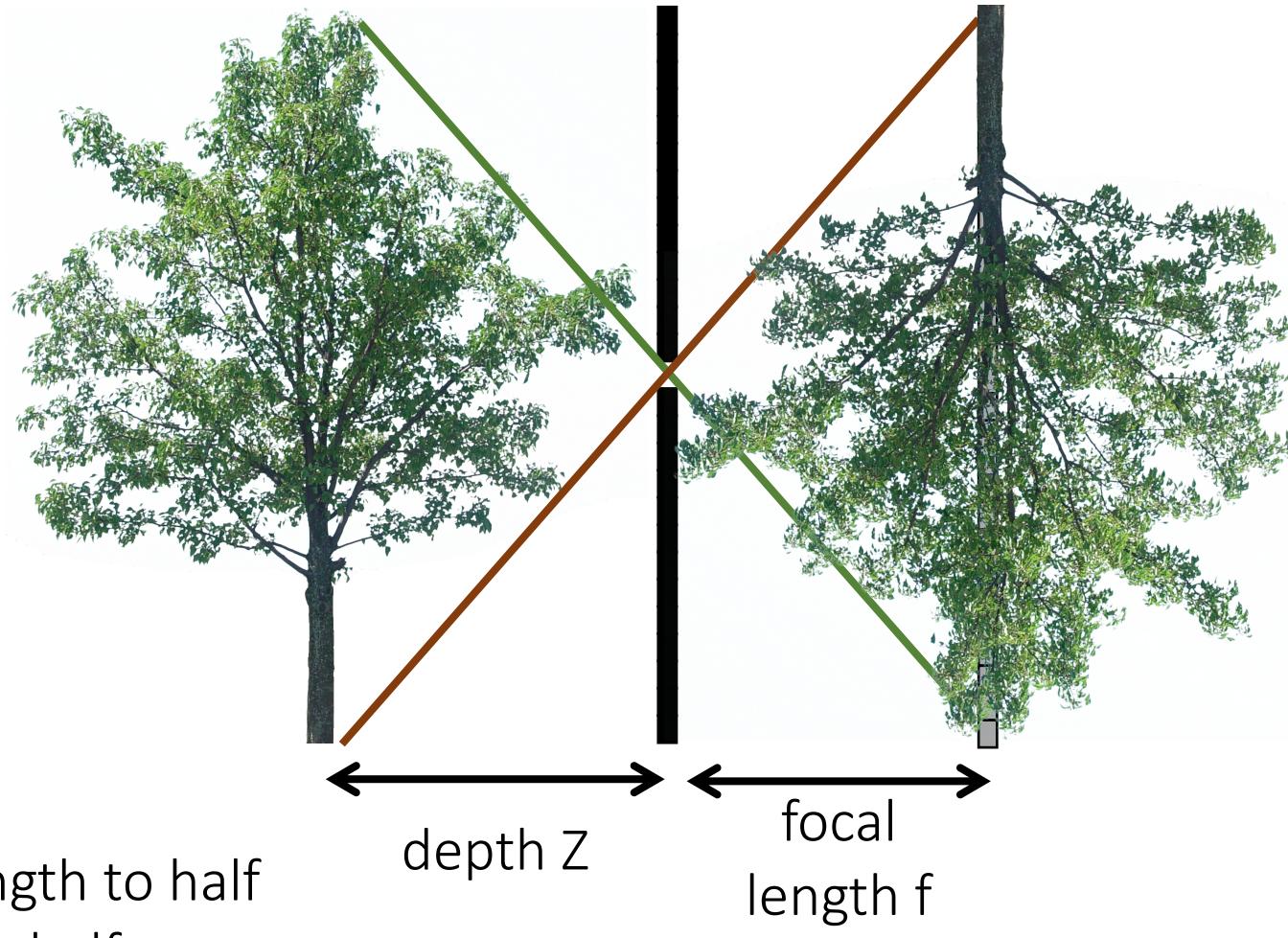
What if...



1. Set focal length to half

What if...

real-world
object



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

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

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

Perspective distortion



long focal length

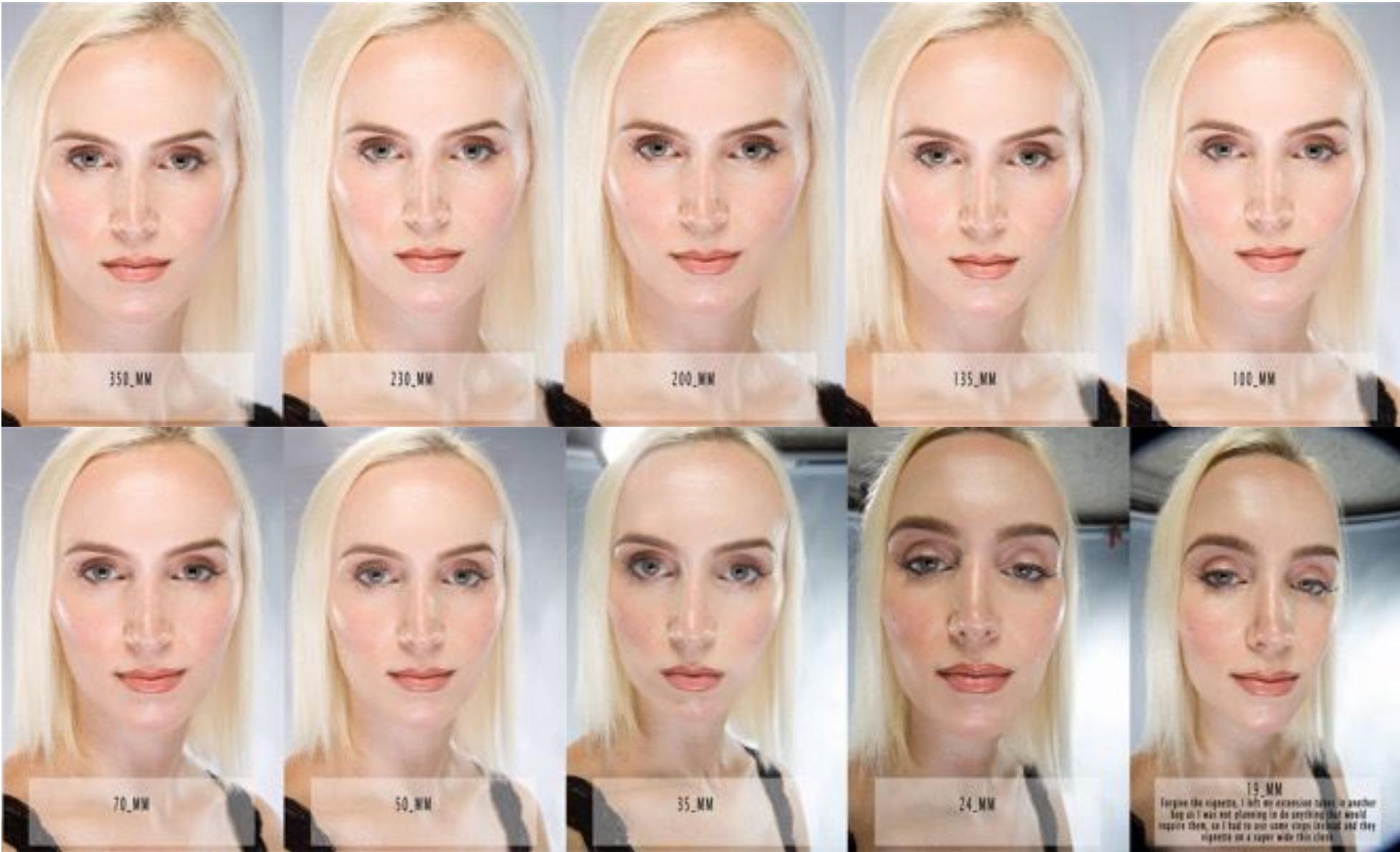


mid focal length



short focal length

Perspective distortion



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

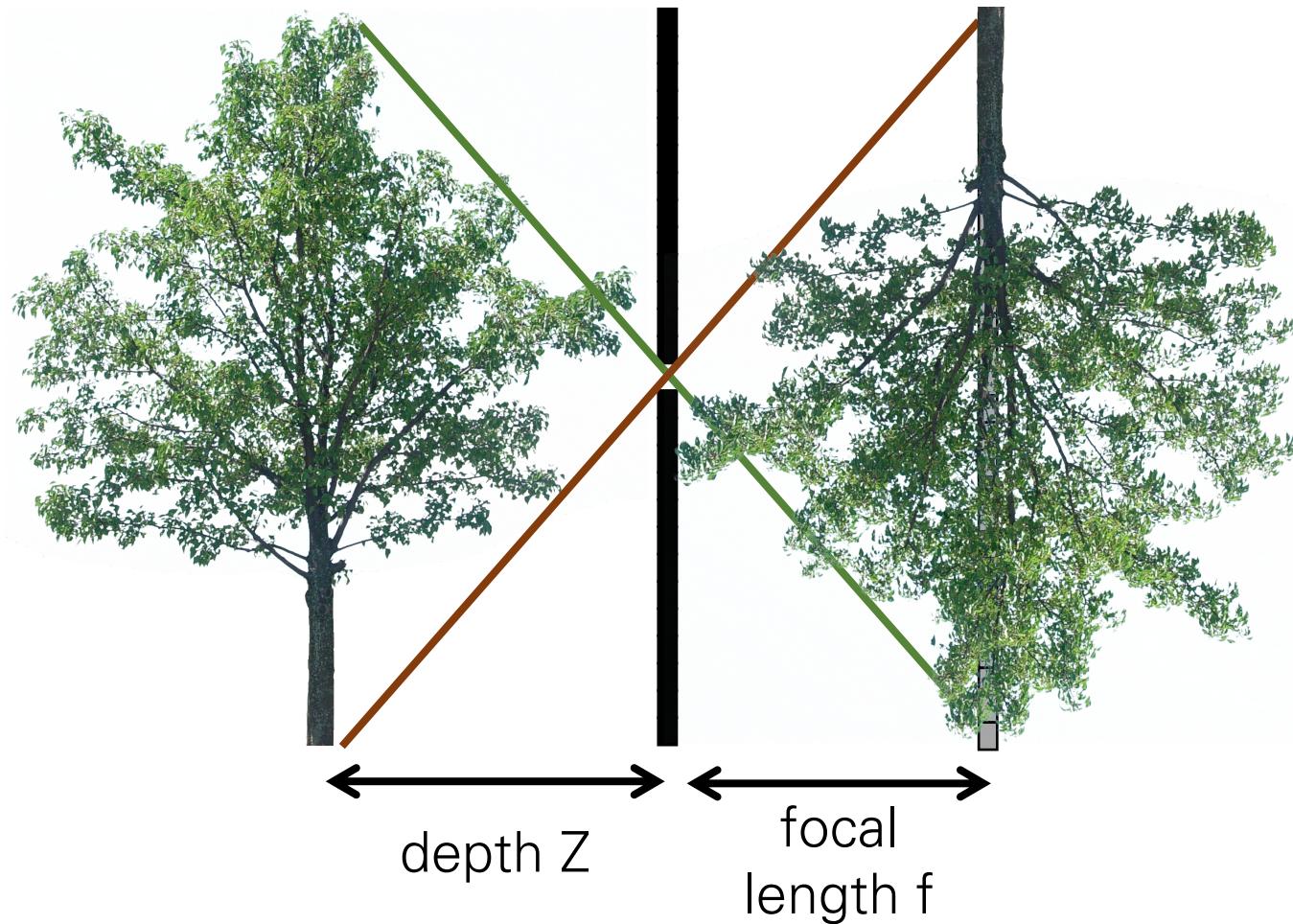


How would you
create this effect?

Orthographic camera and telecentric lenses

What if...

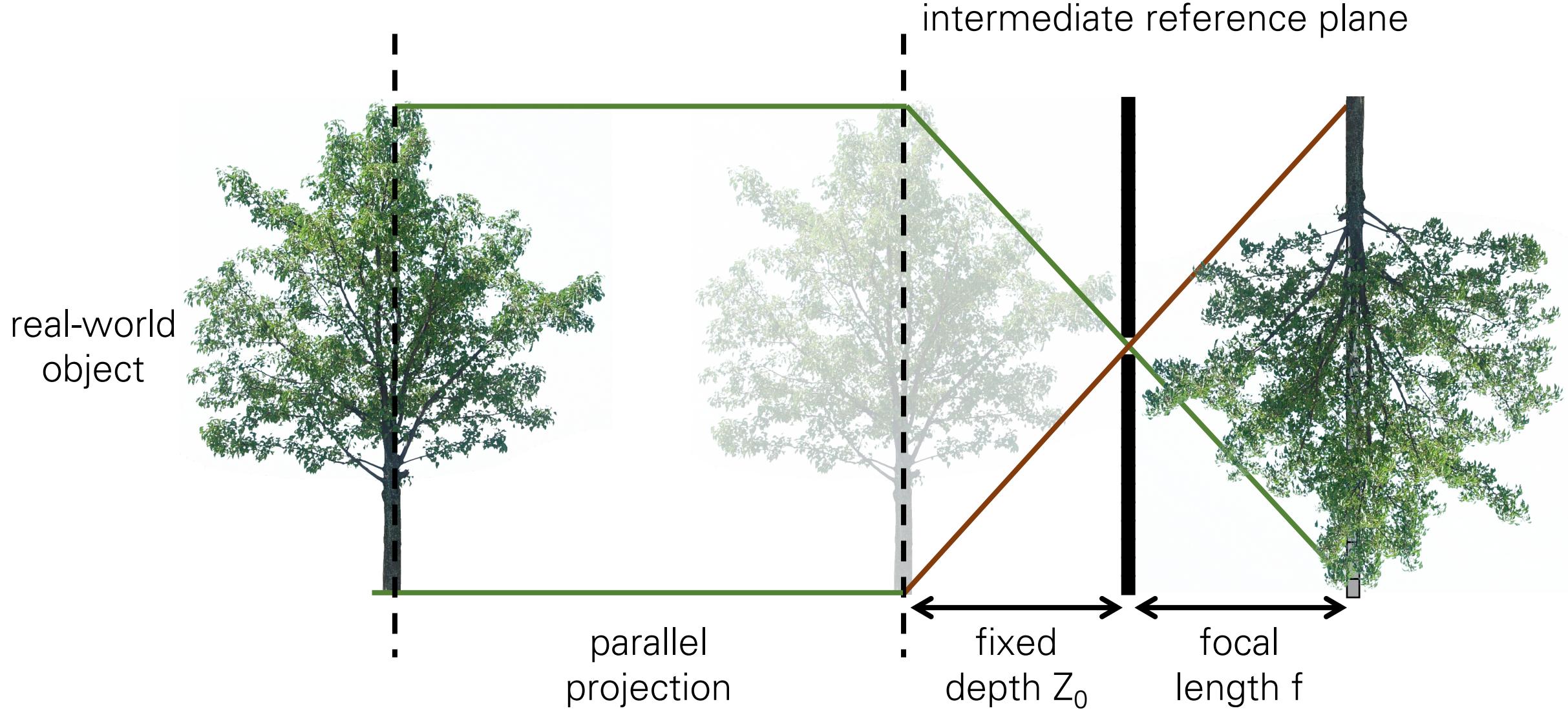
real-world
object



Continue increasing Z and f while maintaining same magnification?

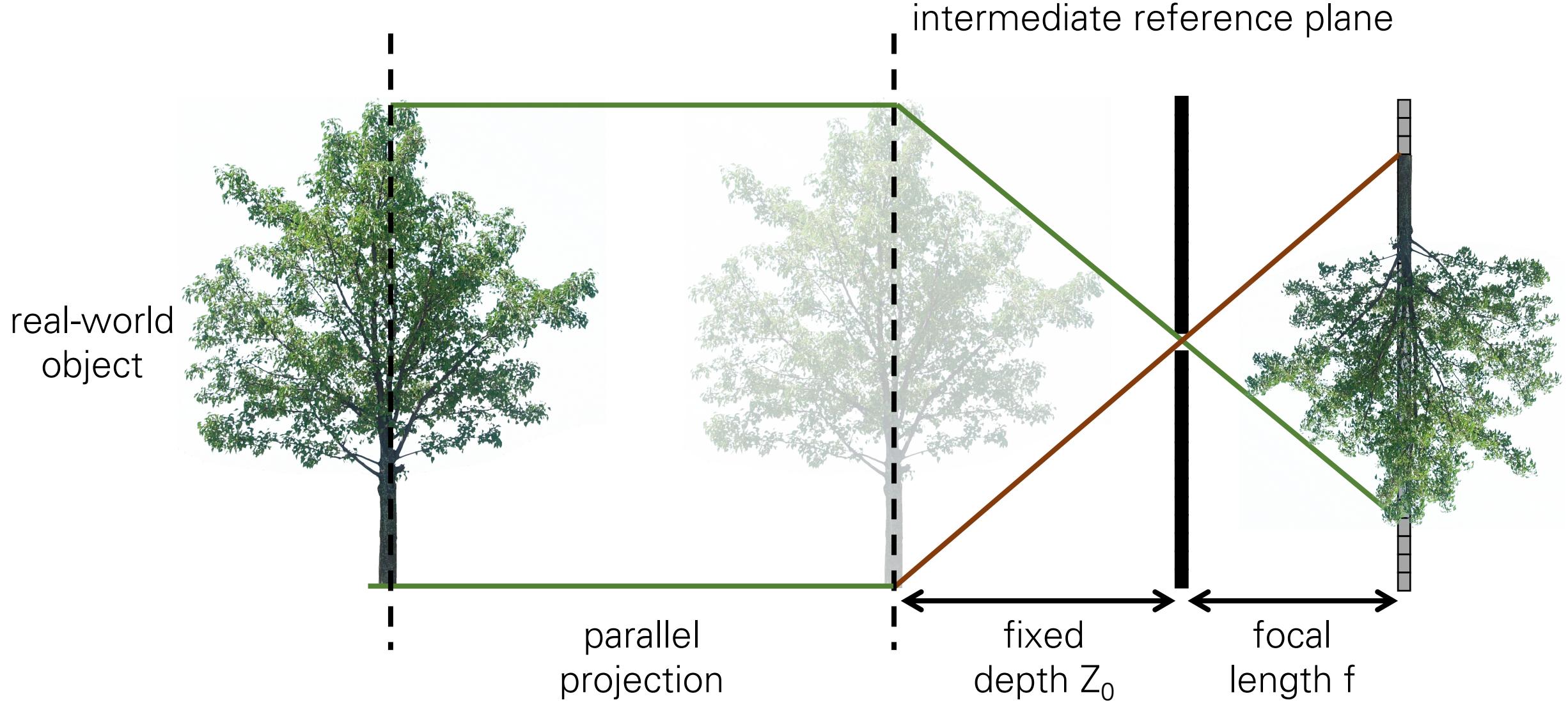
$$f \rightarrow \infty \text{ and } \frac{f}{Z} = \text{constant}$$

Orthographic camera



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

Weak-perspective camera

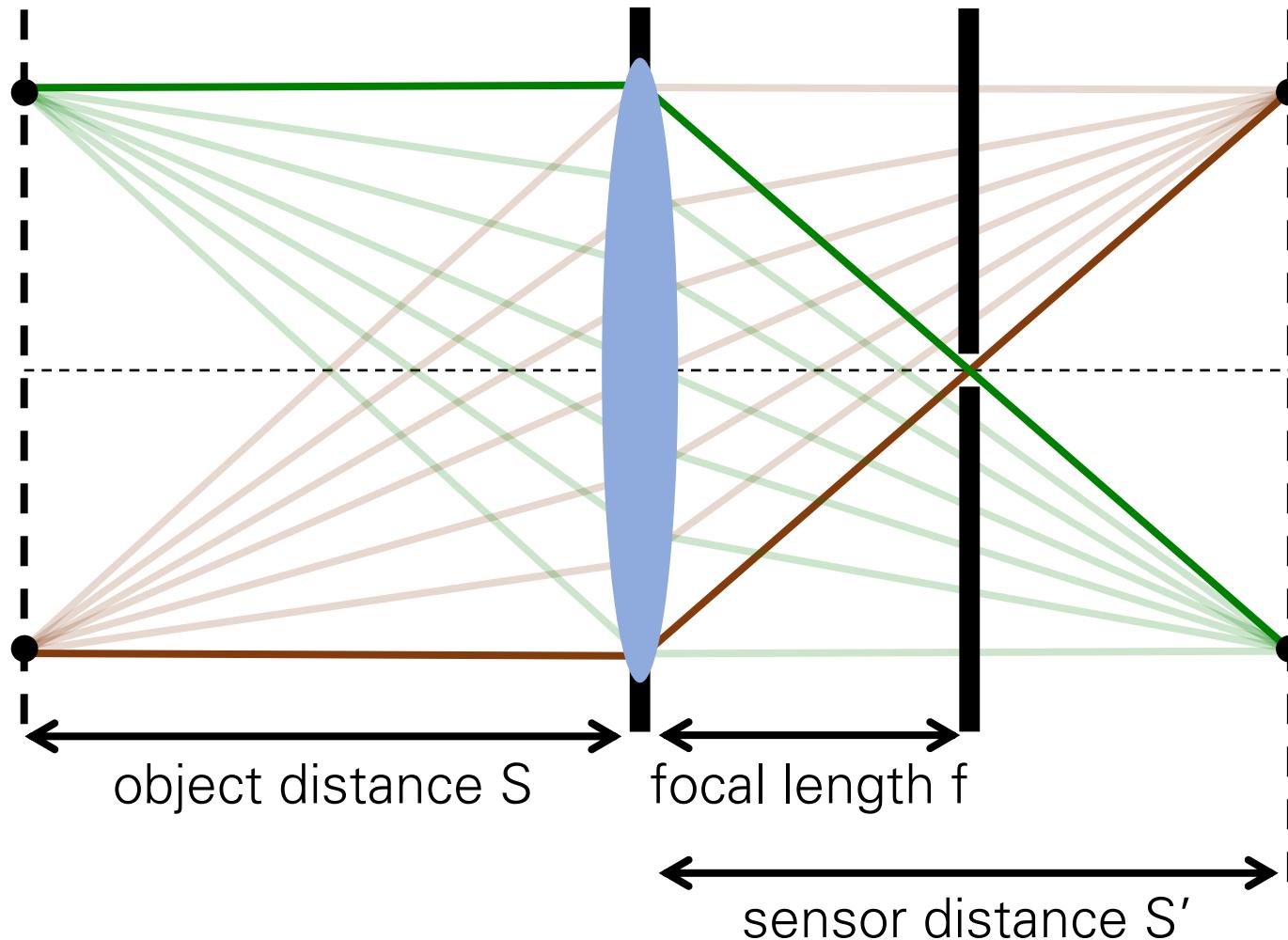


Depth-independent magnification $m = f / Z_0$.

How can we implement such a camera with lenses?

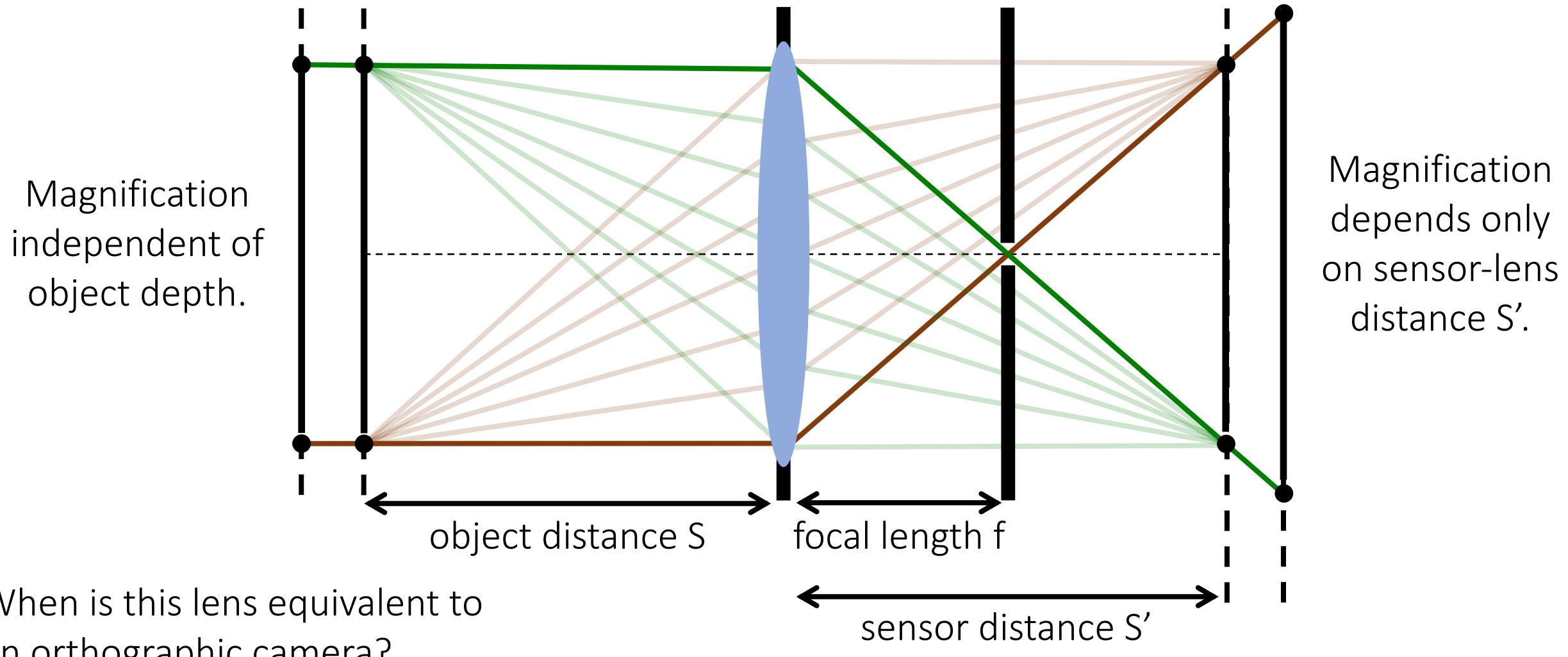
Telecentric lens

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

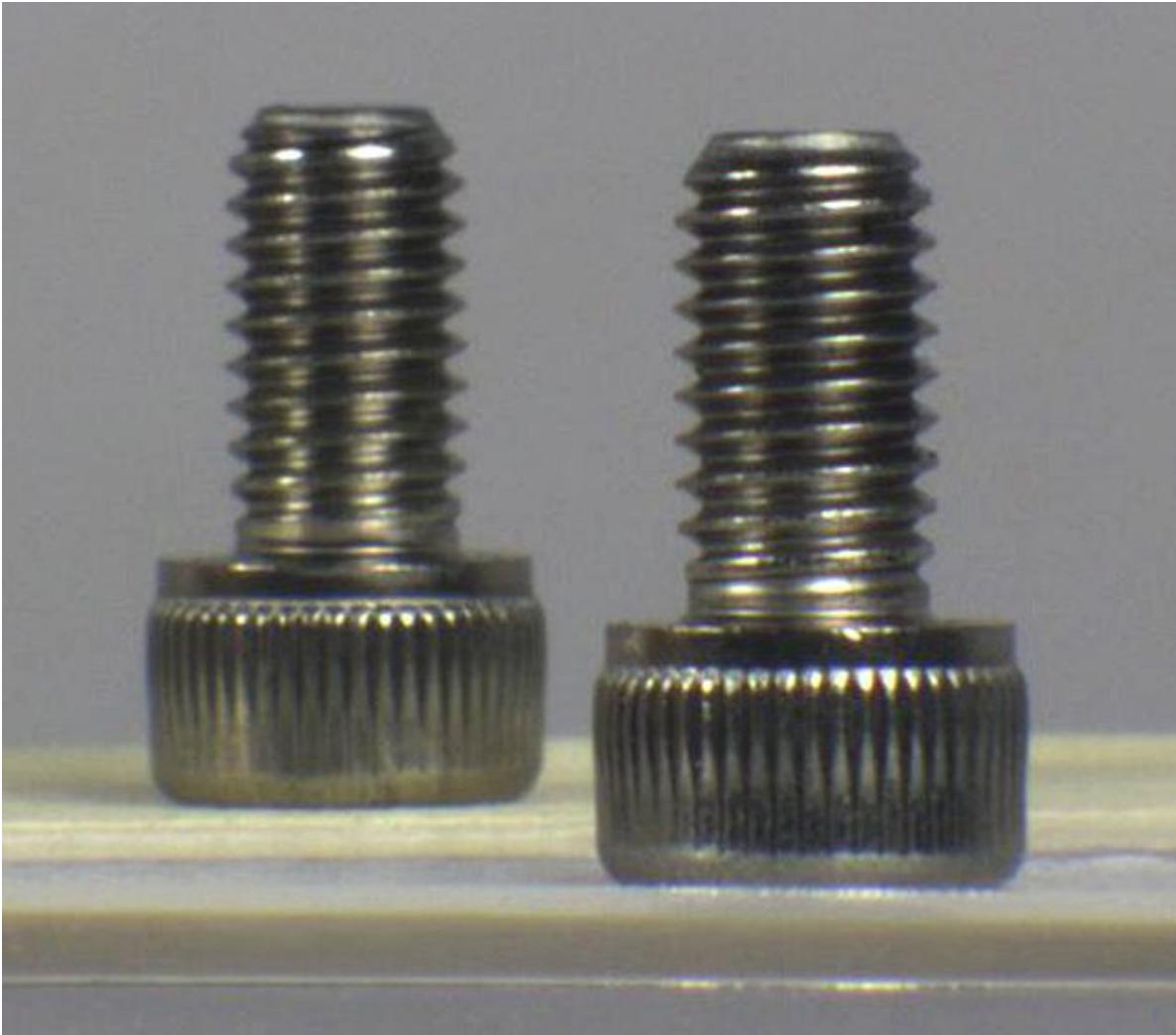


Telecentric lens

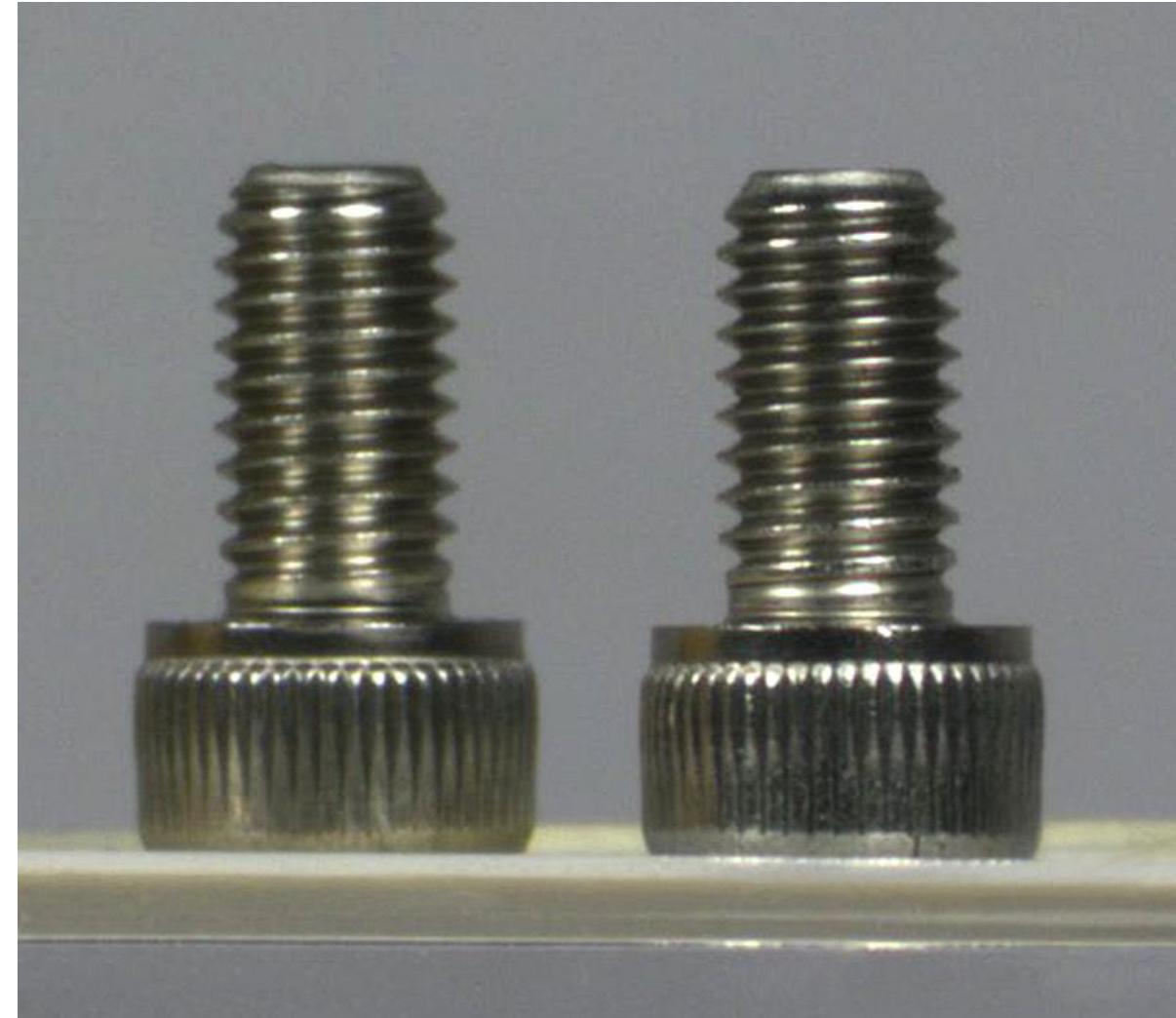
Place a pinhole at focal length, so that only rays parallel to primary ray pass through.



Regular vs elecentric lens



regular lens



telecentric lens

Next Lecture:
Exposure and
High-Dynamic-Range Imaging