Pinholes and lenses

15-463, 15-663, 15-862
Computational Photography
Fall 2020, Lecture 3

http://graphics.cs.cmu.edu/courses/15-463

Course announcements

- Changes to lecture format.
  - Questions posted in chat will be answered by TAs in the chat, or by Yannis at certain checkpoints during the lecture.
  - Questions asked orally work the same as before.
- Camera distribution has begun.
  - Make sure to sign up for a camera if you need one.
  - Second distribution session this afternoon 4 – 6 pm.
- Homework 1 is out.
  - Due September 18^{th}.
  - Any issues with homework 1?
- Office hours for the semester:
  - Beyongjoo: Tuesdays 3:30 – 5:30 pm.
  - Yannis: Wednesdays 3:30 – 5:30 pm.
  - Jenny: Thursdays 3:30 – 5:30 pm.
  - For this week only, Jenny will do Wednesday and Yannis Thursday office hours.

TA: Byeongjoo Ahn
(My first name pronounces as Be-Young-Joo)

- ECE PhD student
  - Advisors: Aswin C. Sankaranarayanan & Ioannis Gkioulekas
  - Research Interest: Computational Imaging

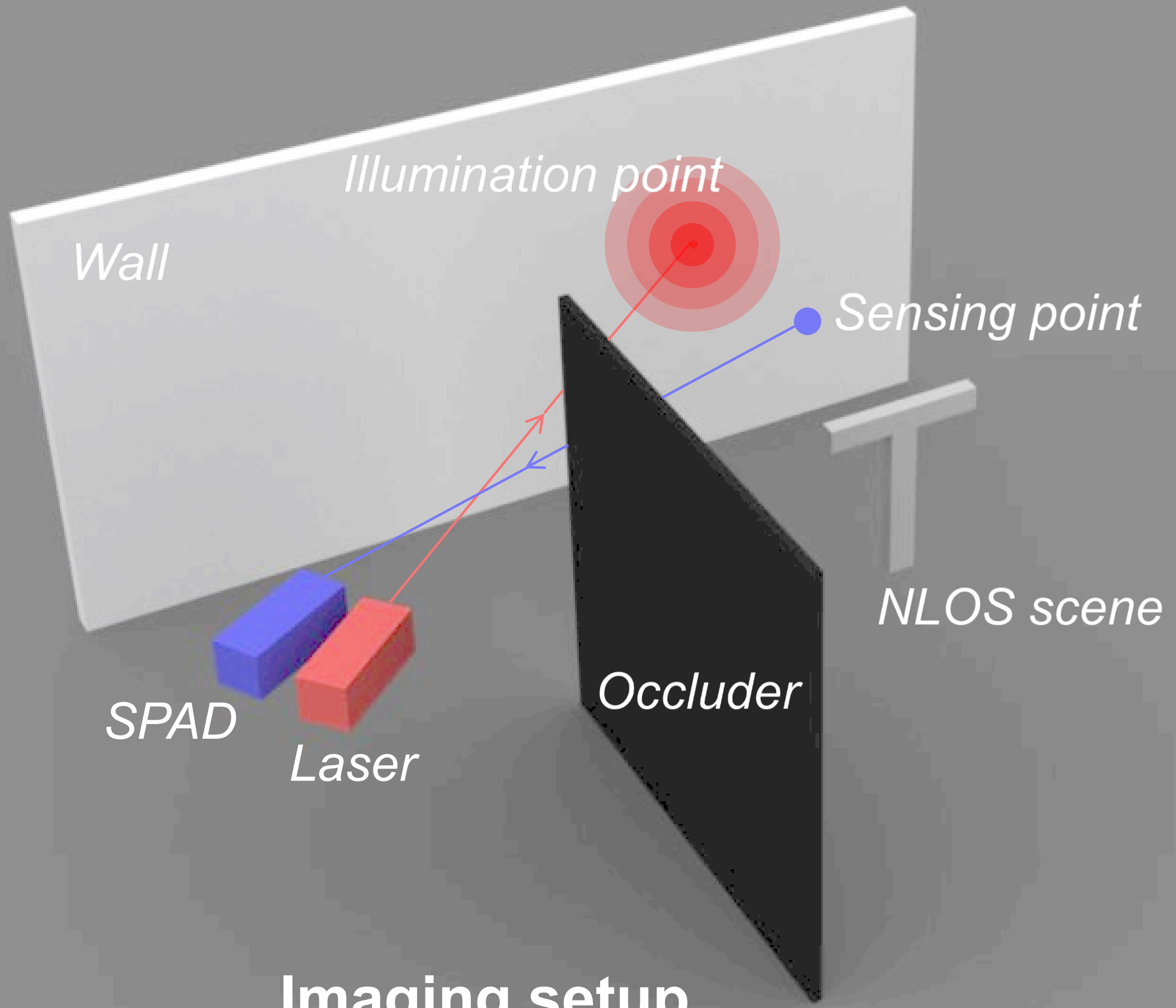
- Originally from South Korea
  - Seoul National University
  - Korea Institute of Science and Technology (KIST)

- My website: https://byeongjooahn.com

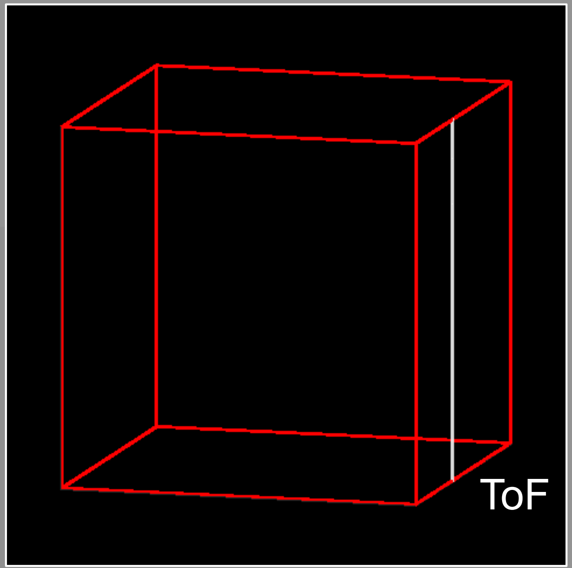
https://imaging.cs.cmu.edu/conv_nlos/

Non-Line-of-Sight (NLOS) Imaging

Looking around corner

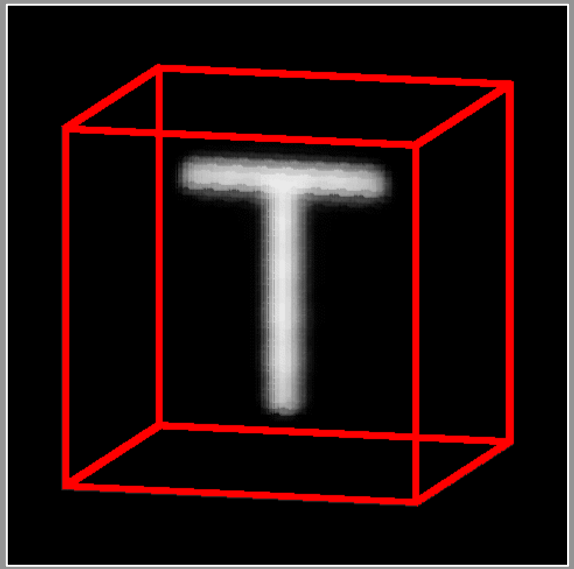


Imaging setup



Light transient

Measurement



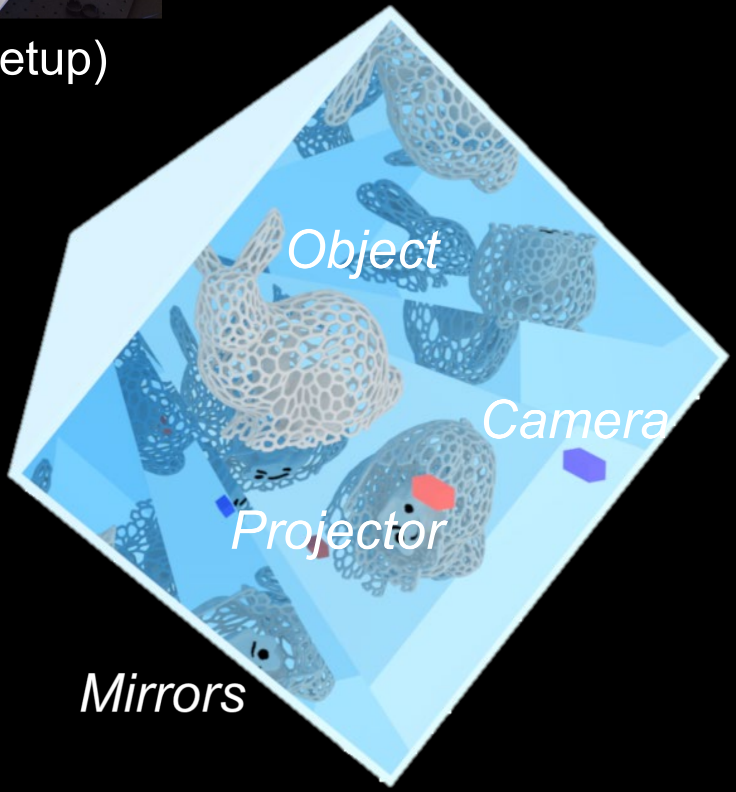
NLOS scene

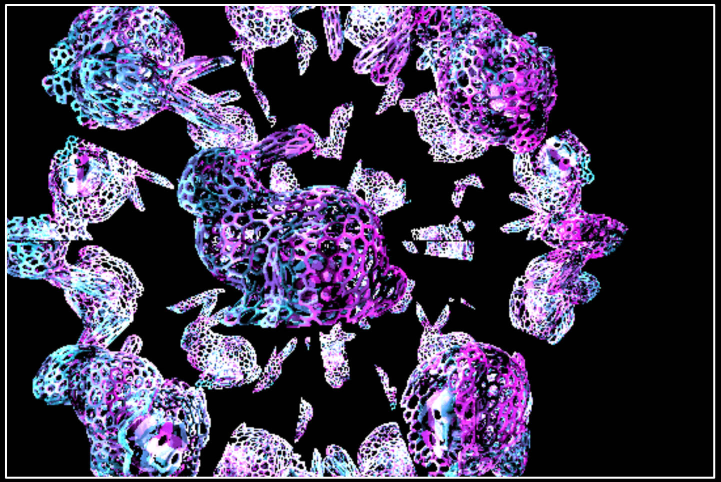
Reconstruction

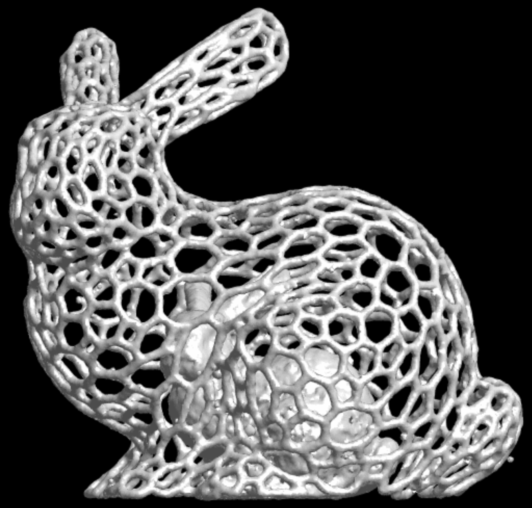
Trapping Structured Light

Full surround 3D imaging of intricate objects

(real setup)







Imaging setup **Measurement** **Reconstruction**

Overview of today's lecture

- Leftover from lecture 2: the image processing pipeline.
- Some motivational imaging experiments.
- Pinhole camera.
- Accidental pinholes.
- The thin lens model.
- Lens camera and pinhole camera.
- Perspective.
- Field of view.
- Orthographic camera and telecentric lenses.

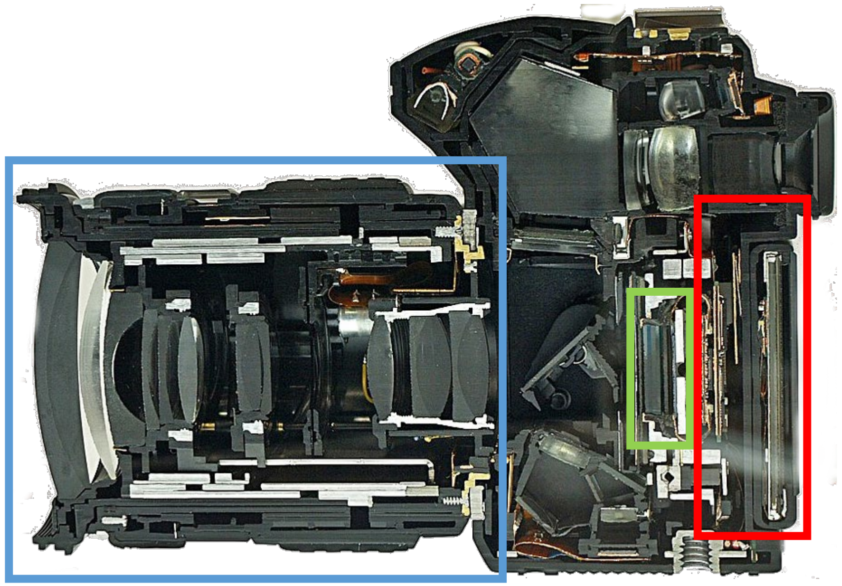
Slide credits

Many of these slides were adapted from:

- Kris Kitani (15-463, Fall 2016).
- Fredo Durand (MIT).
- Gordon Wetzstein (Stanford).

The modern photography pipeline

post-capture processing
(lectures 5-10)



optics and optical controls
(lectures 2-3, 11-20)

→ sensor, analog front-end, and color filter array
(lectures 2, 23)

→ in-camera image processing pipeline
(lecture 2)

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

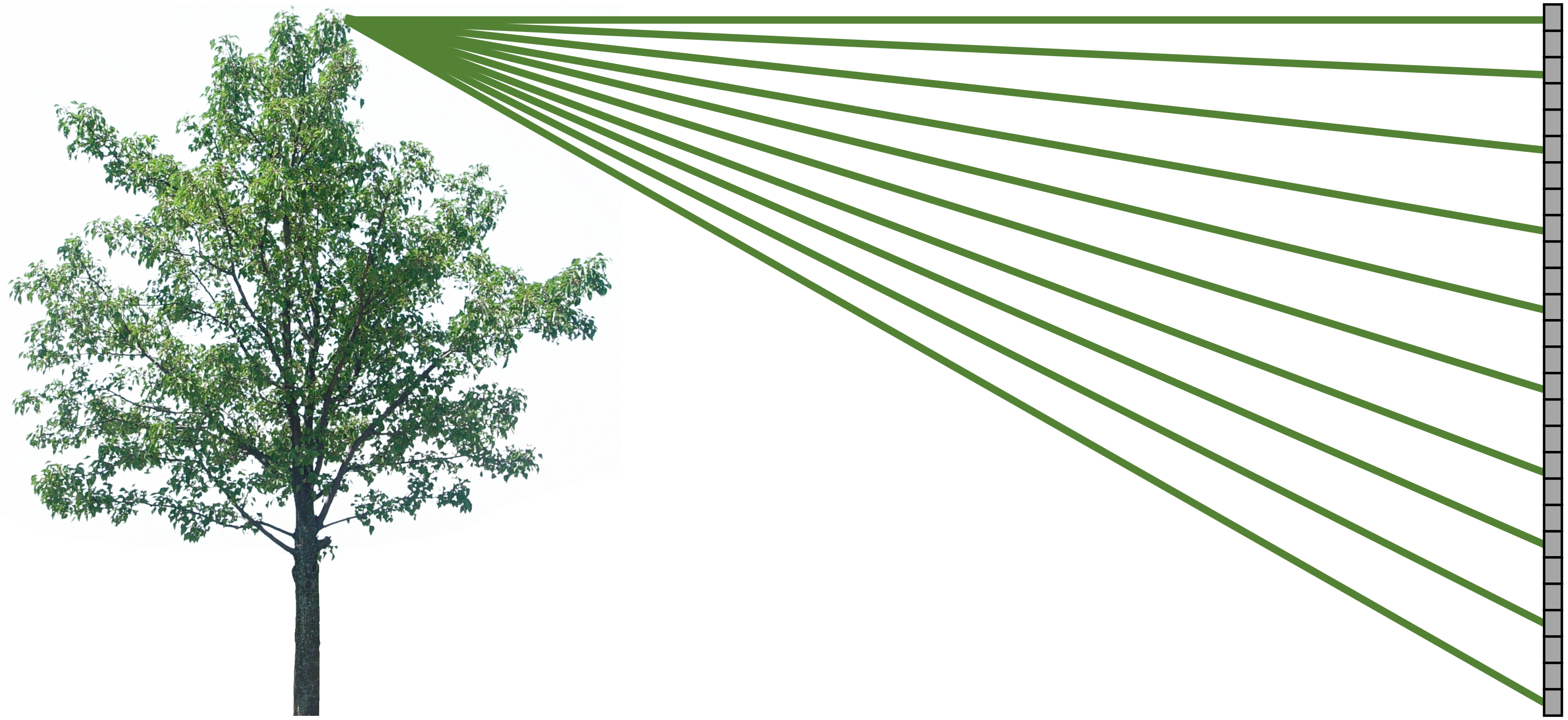
digital sensor
(CCD or CMOS)

What would an image taken like this look like?

Bare-sensor imaging

Bare-sensor imaging

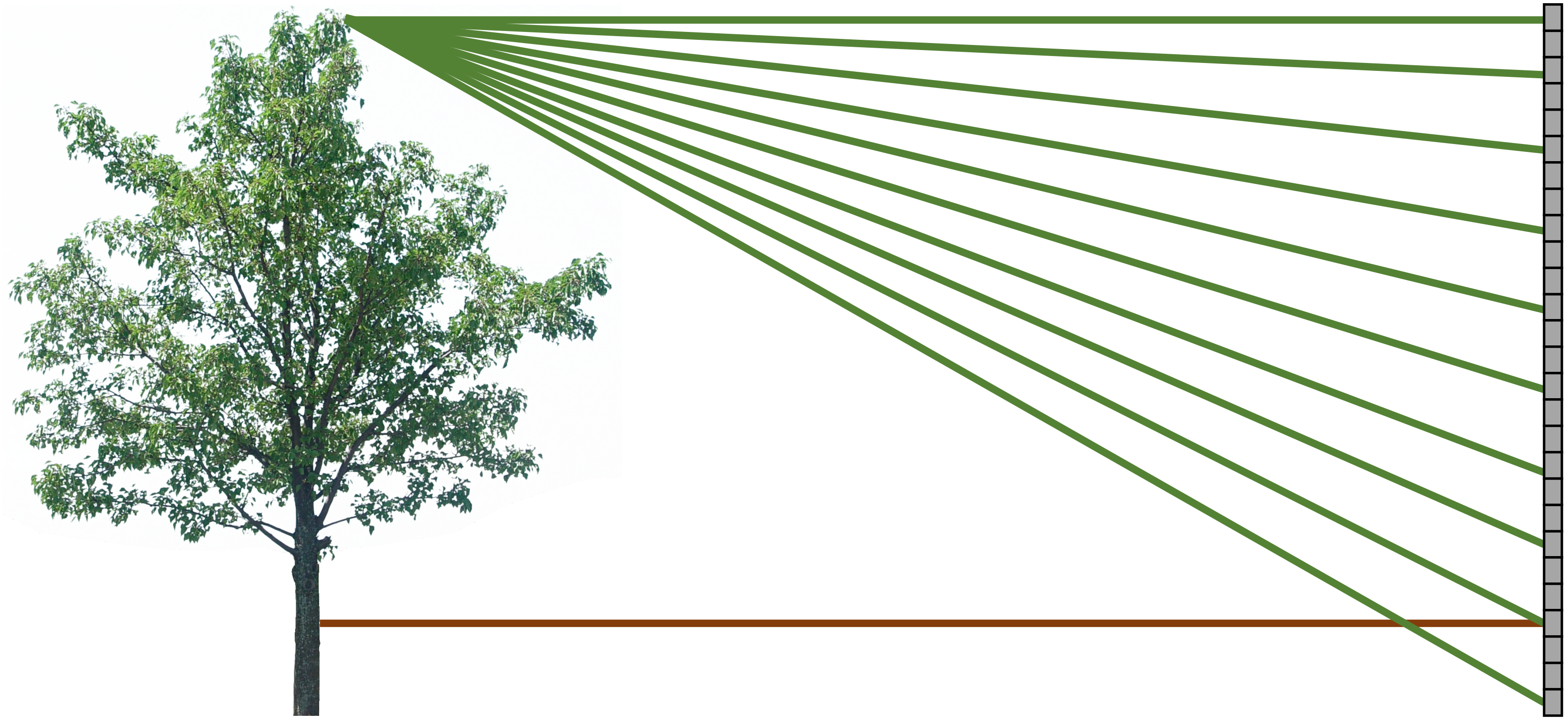
real-world
object



digital sensor
(CCD or CMOS)

Bare-sensor imaging

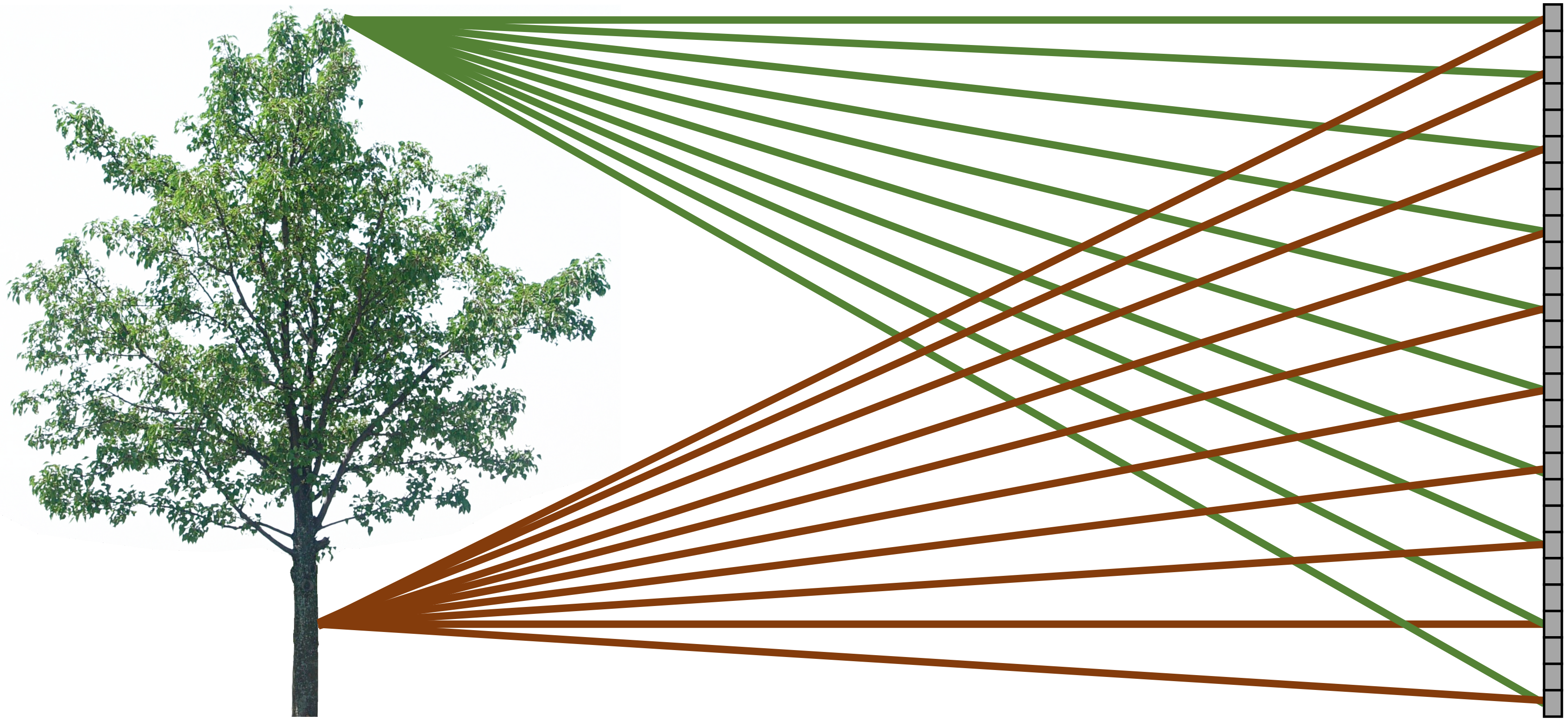
real-world
object



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

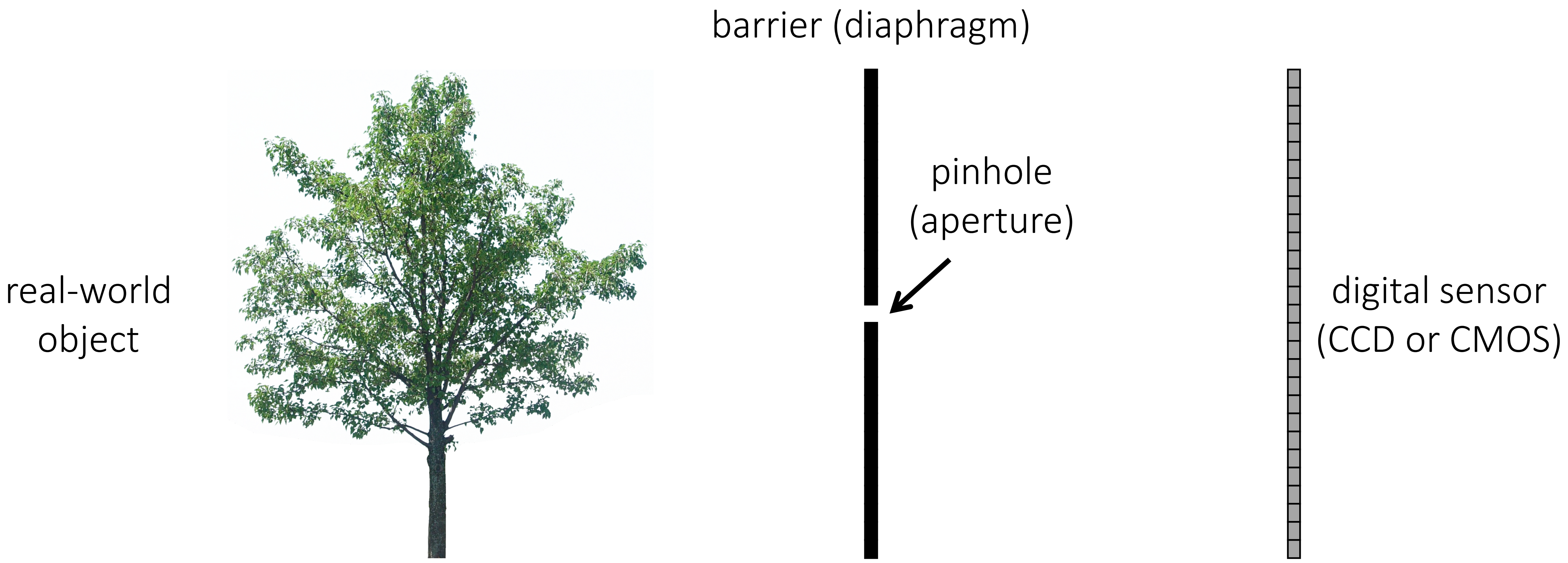
All scene points contribute to all sensor pixels

What can we do to make our image look better?

real-world
object

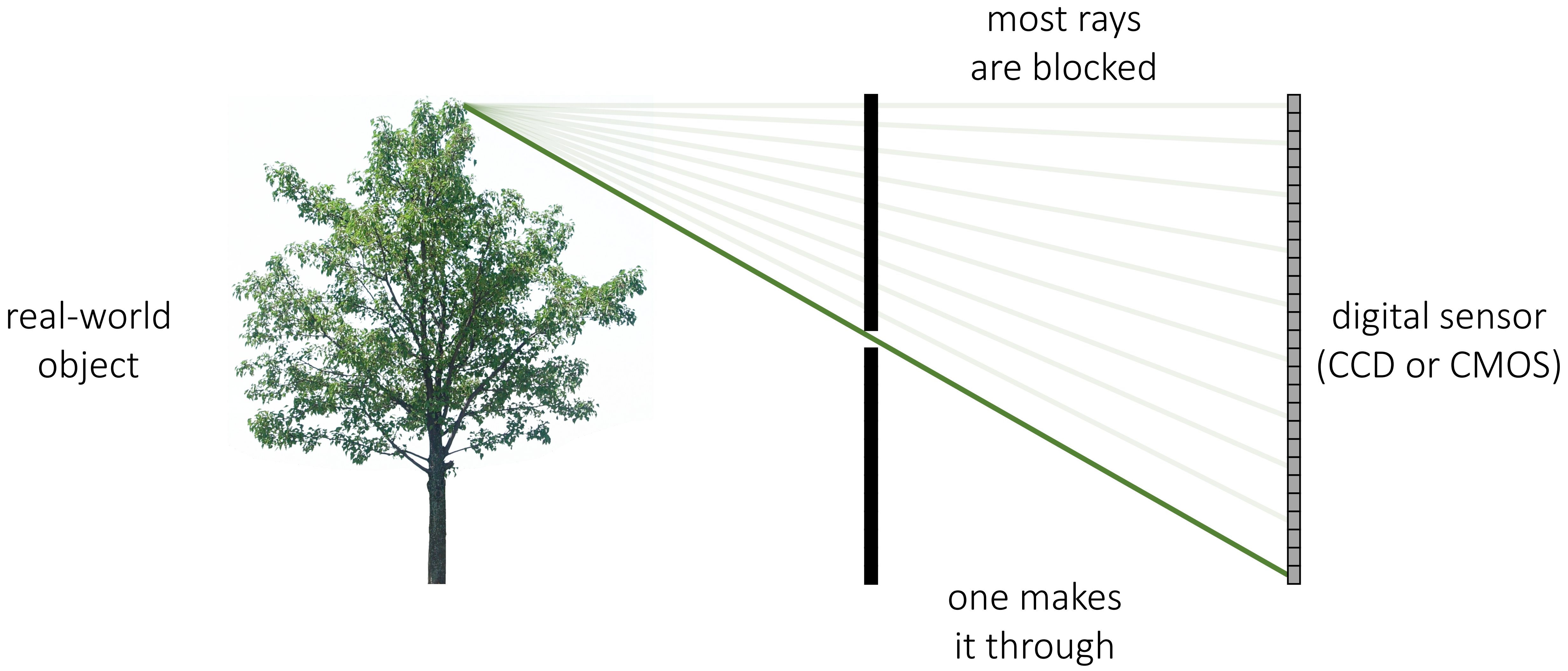
digital sensor
(CCD or CMOS)

Let's add something to this scene

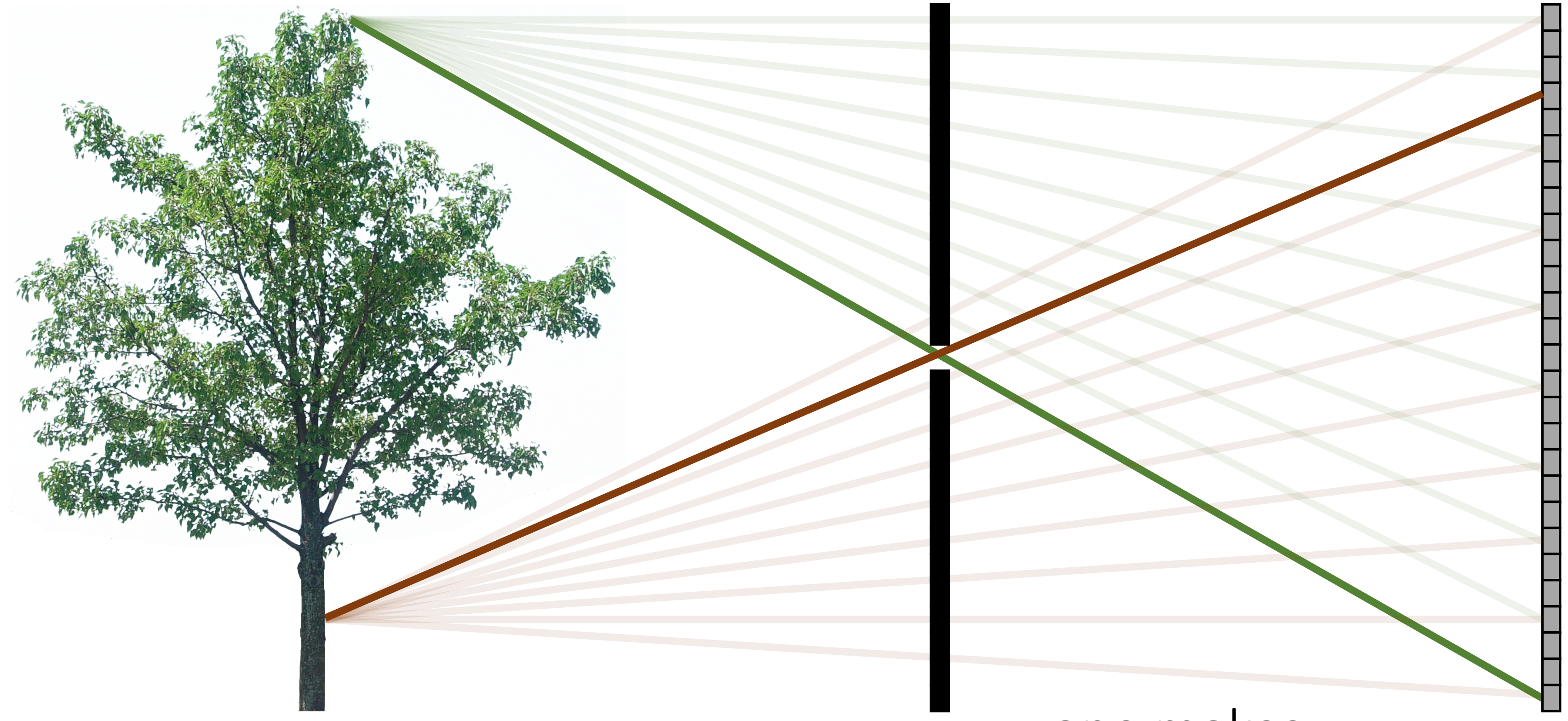


What would an image taken like this look like?

Pinhole imaging

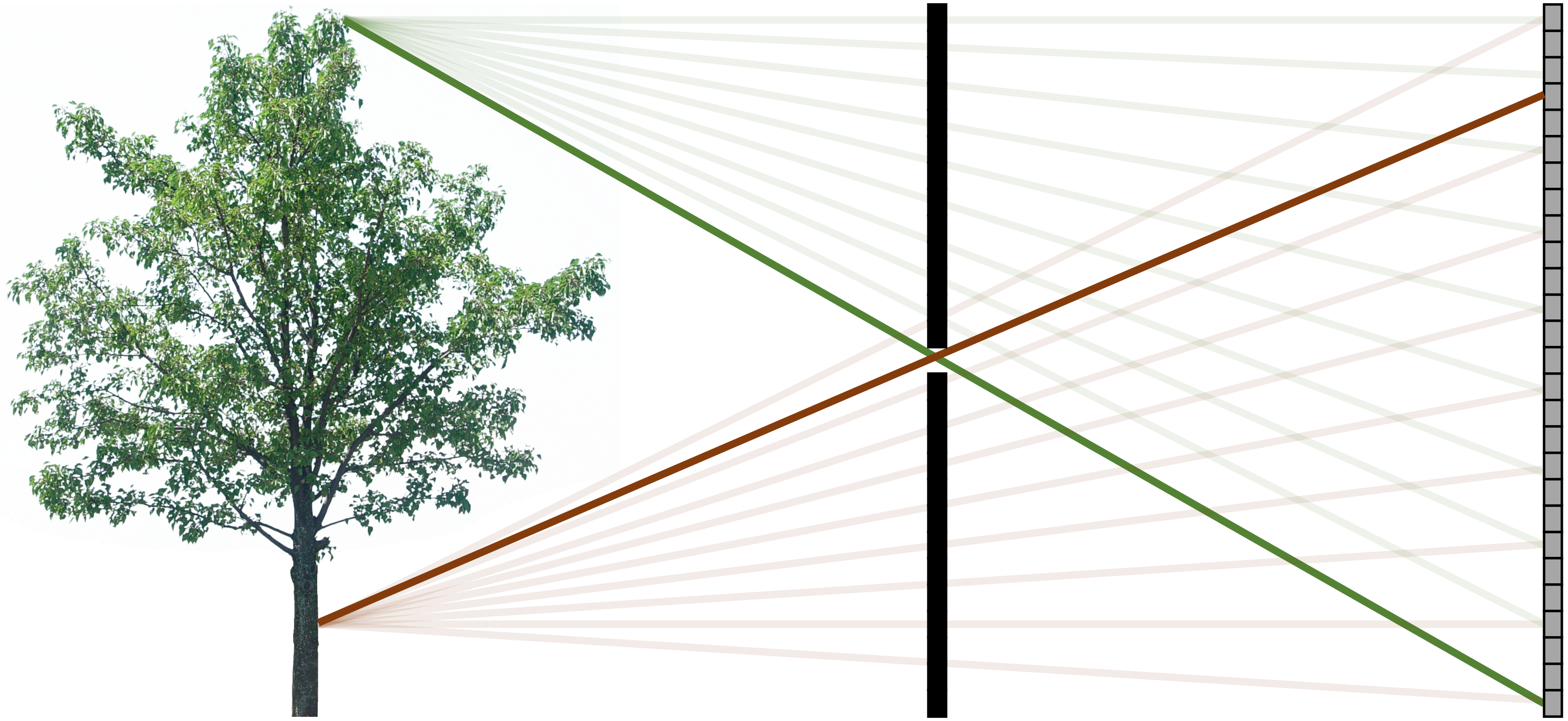


Pinhole imaging



Pinhole imaging

real-world object



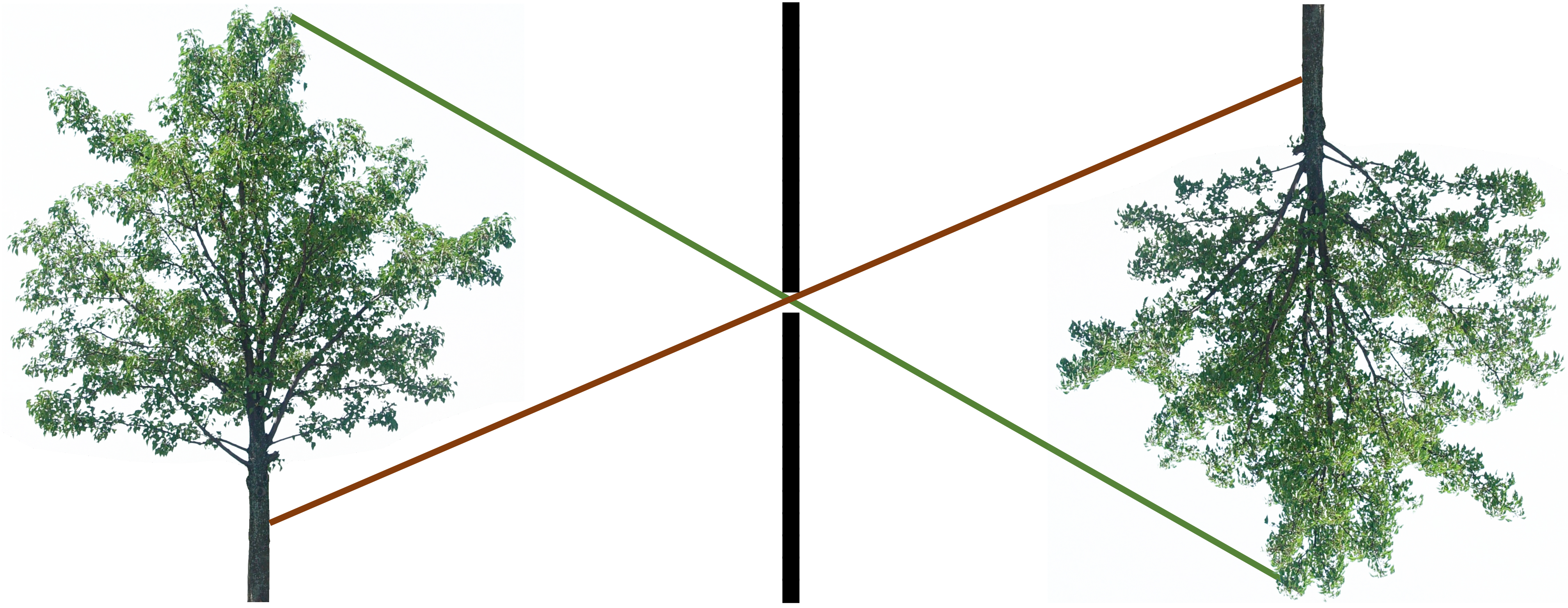
digital sensor (CCD or CMOS)

What does the image on the sensor look like?

Each scene point contributes to only one sensor pixel

Pinhole imaging

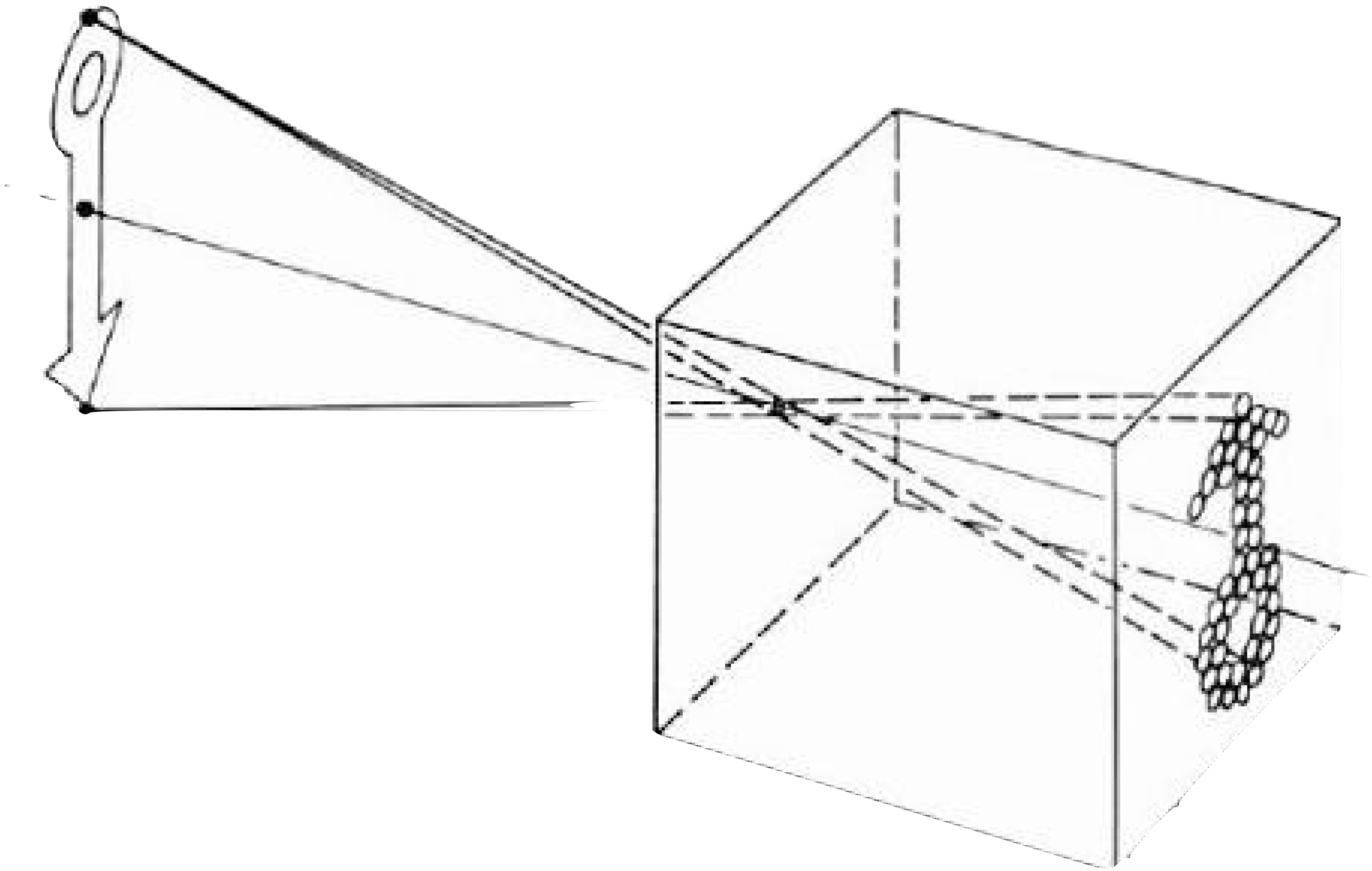
real-world object



copy of real-world object (inverted and scaled)

Pinhole camera

Pinhole camera a.k.a. camera obscura

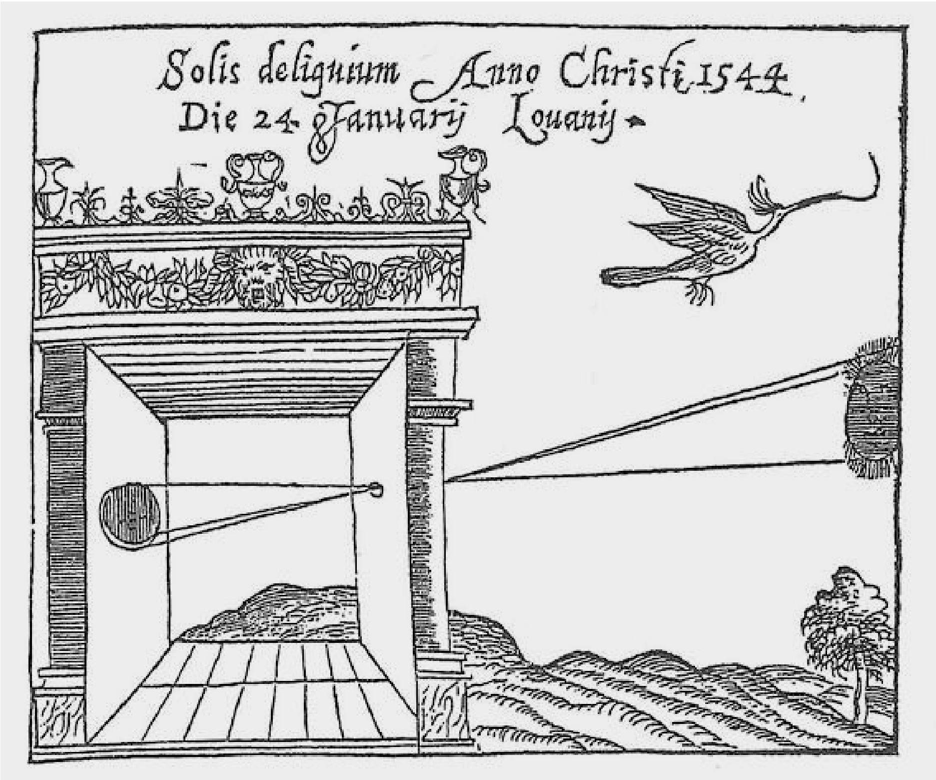


Pinhole camera a.k.a. camera obscura

First mention …

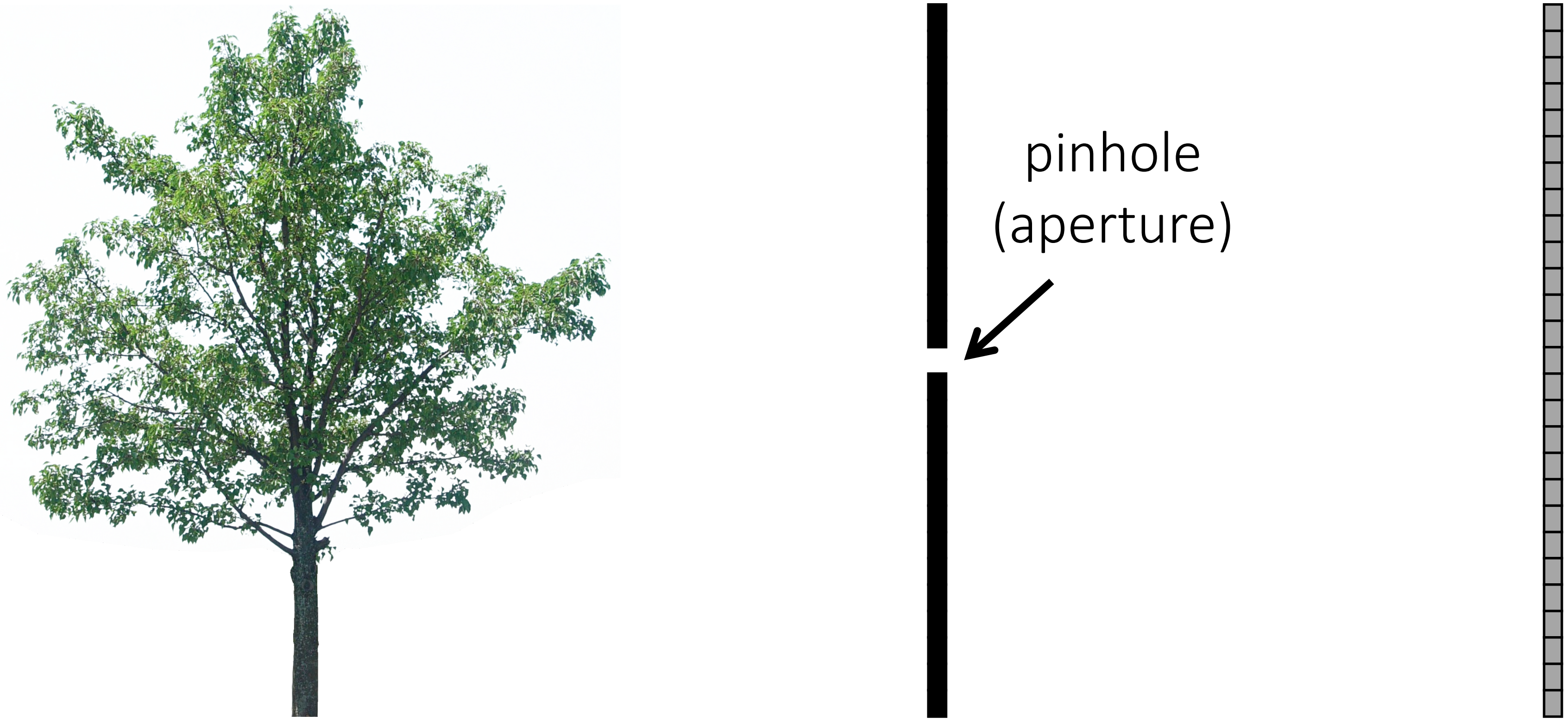
Chinese philosopher Mozi
(470 to 390 BC)

First camera …

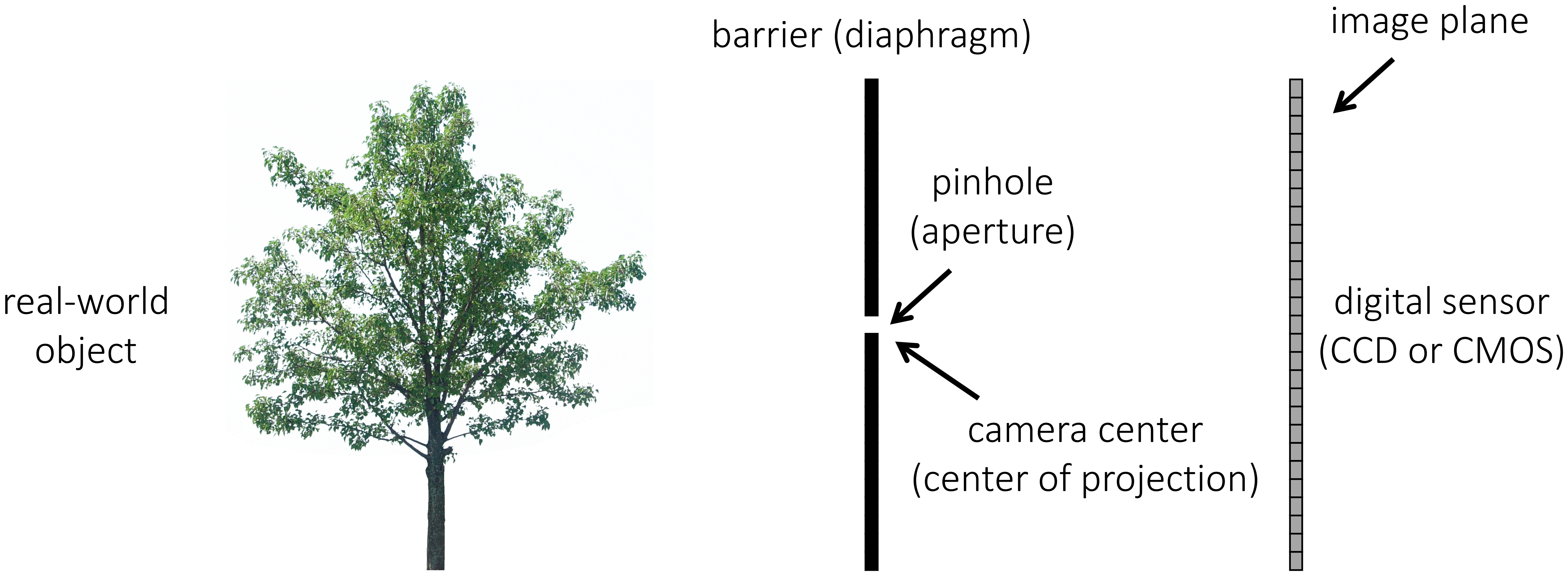


Greek philosopher Aristotle
(384 to 322 BC)

Pinhole camera terms

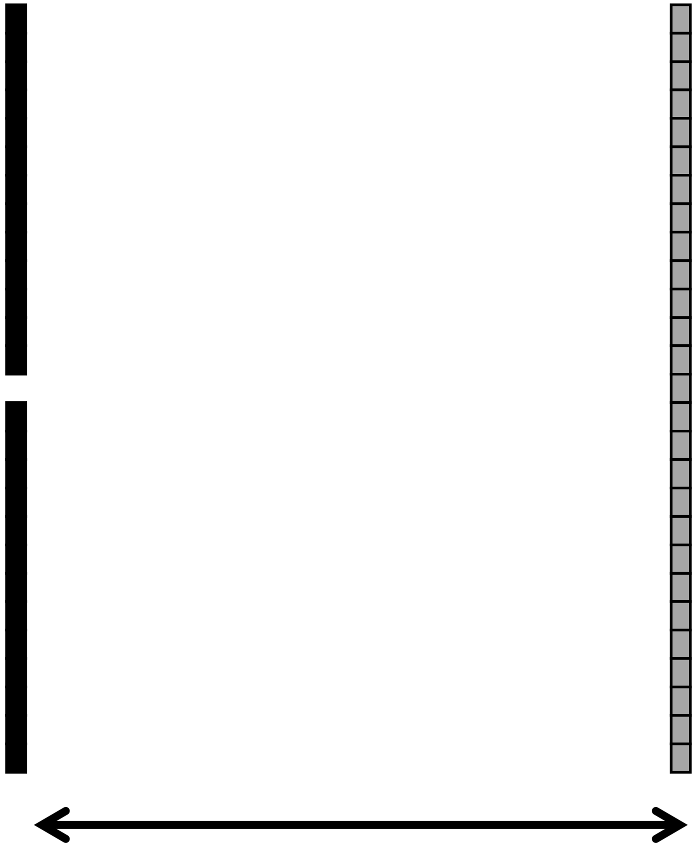


Pinhole camera terms



Focal length

real-world
object

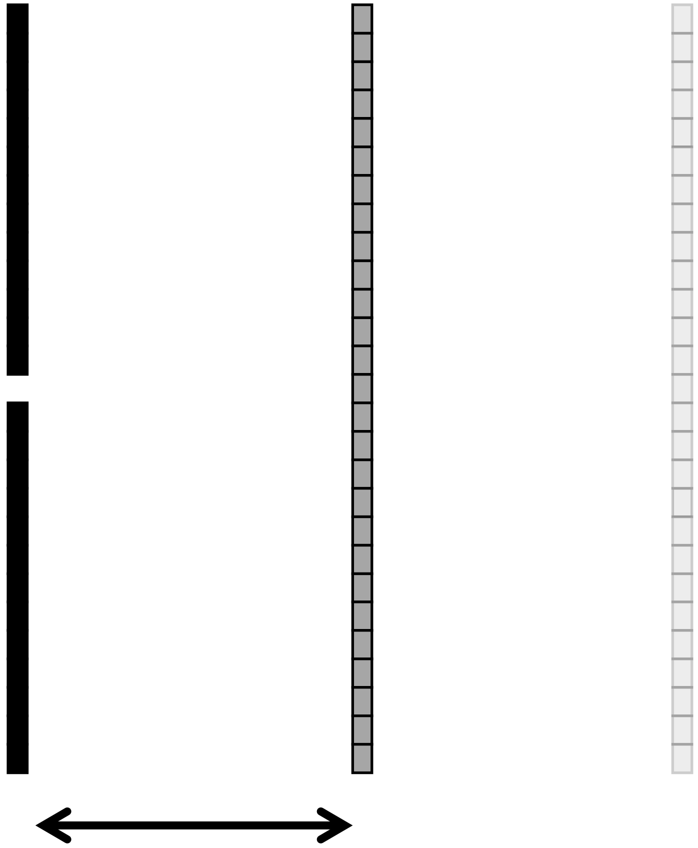


focal length f

Focal length

What happens as we change the focal length?

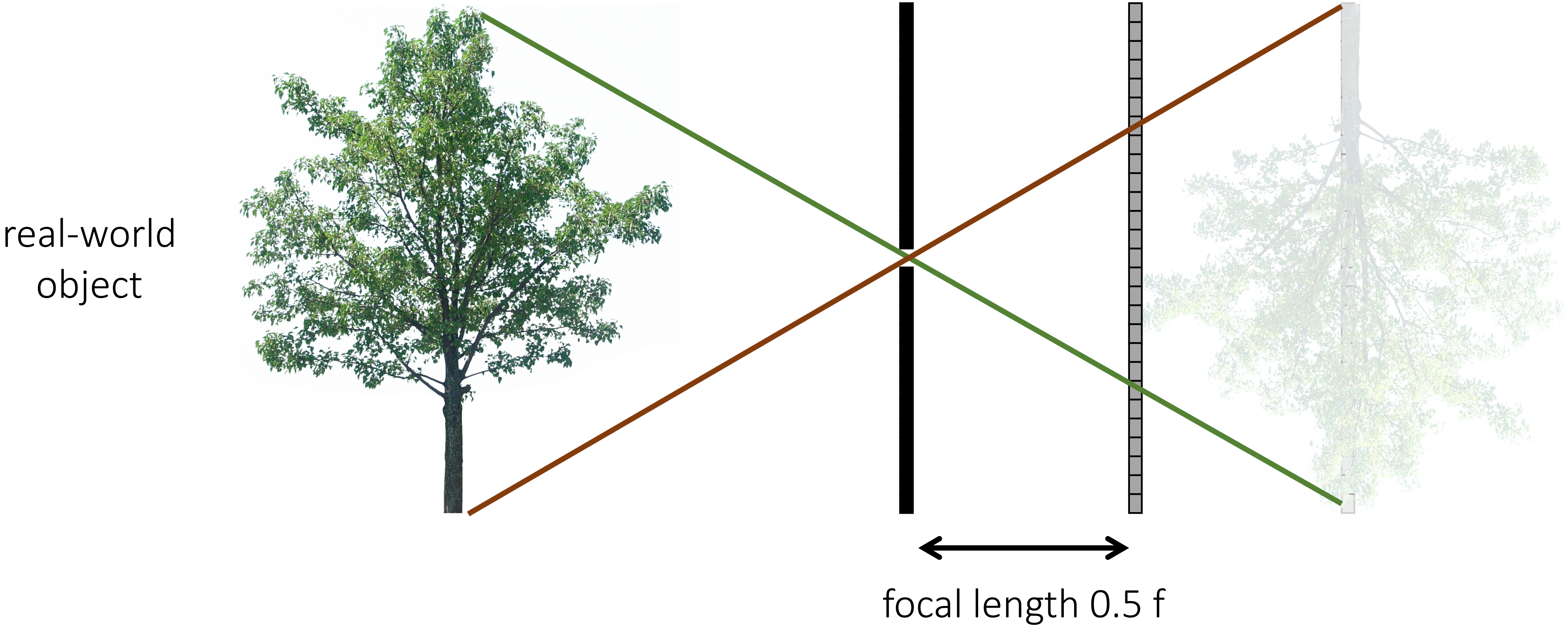
real-world
object



focal length 0.5 f

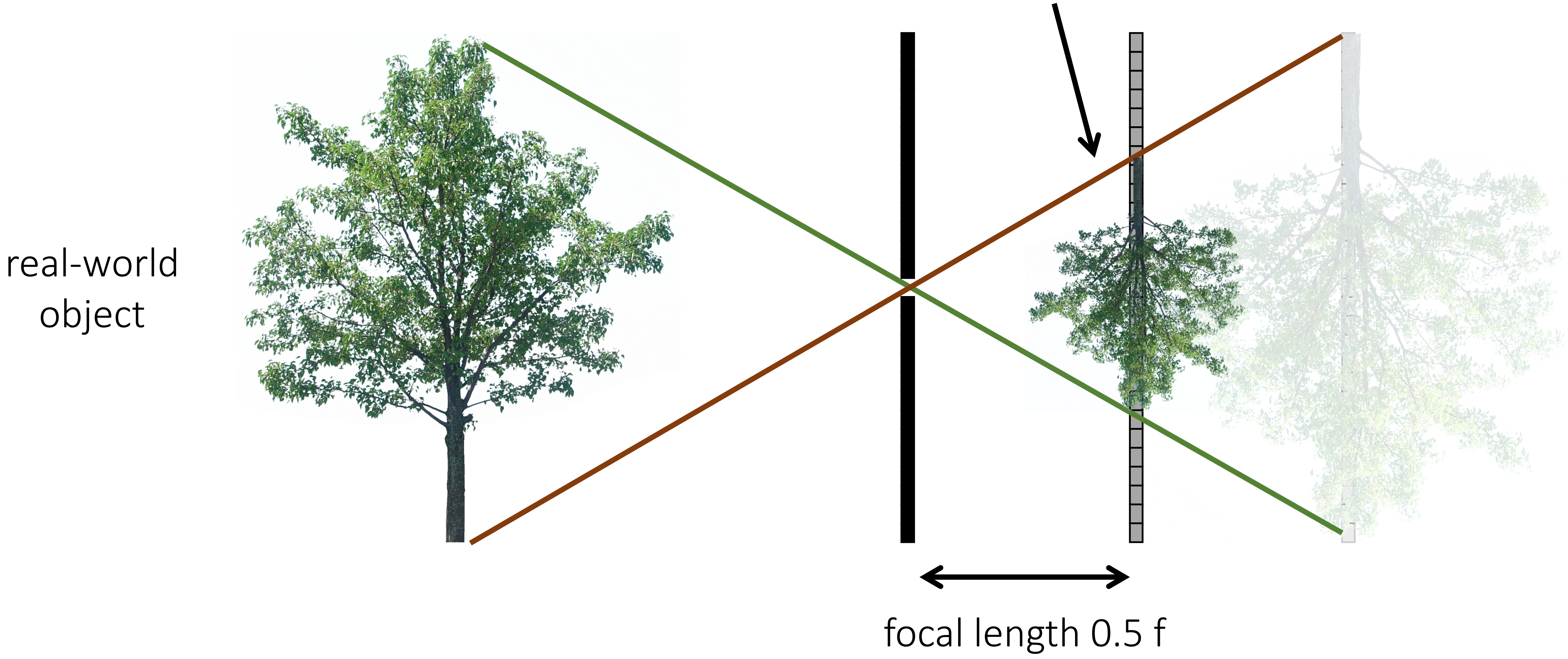
Focal length

What happens as we change the focal length?

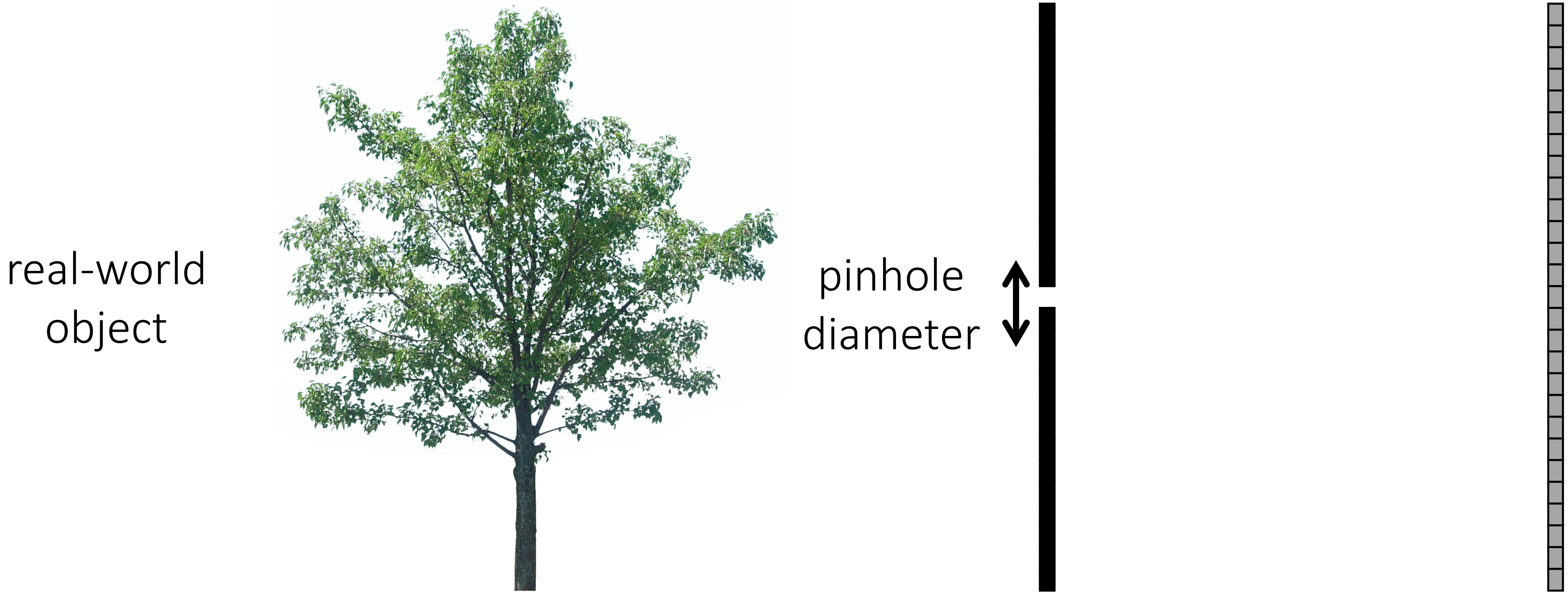


Focal length

What happens as we change the focal length?



Pinhole size

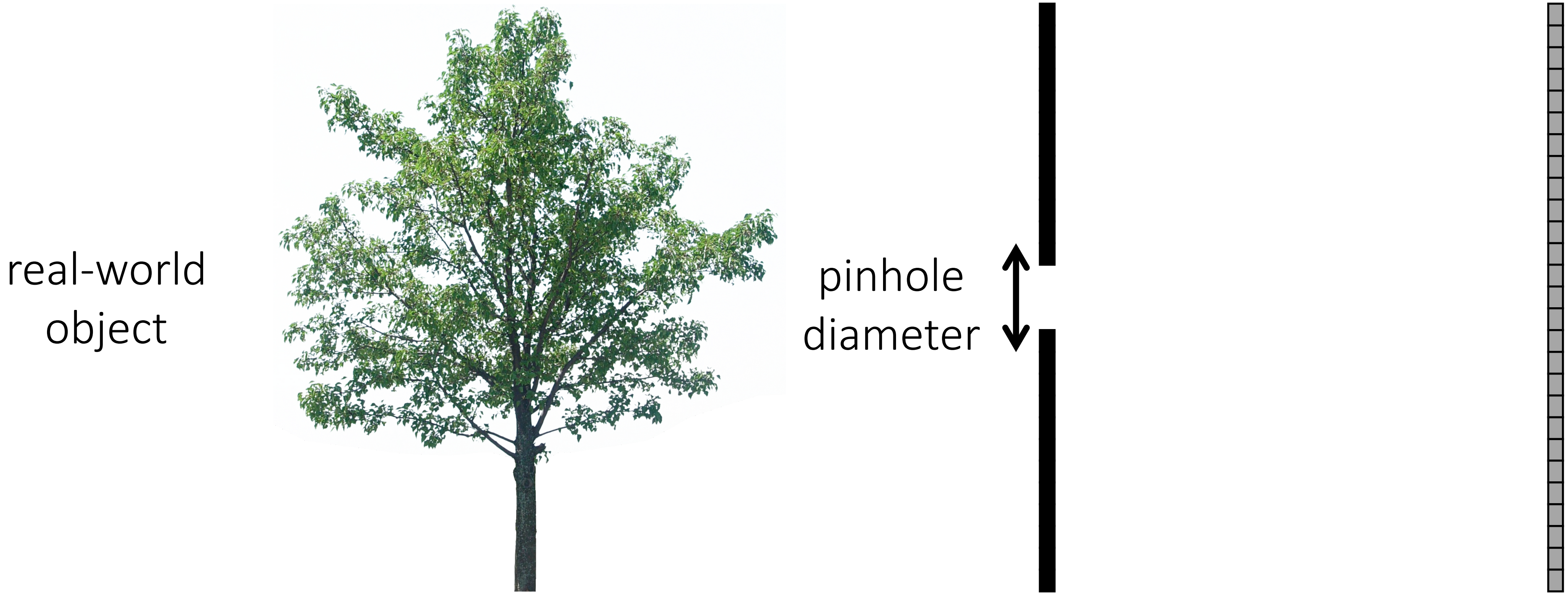


Ideal pinhole has infinitesimally small size

- In practice that is impossible.

Pinhole size

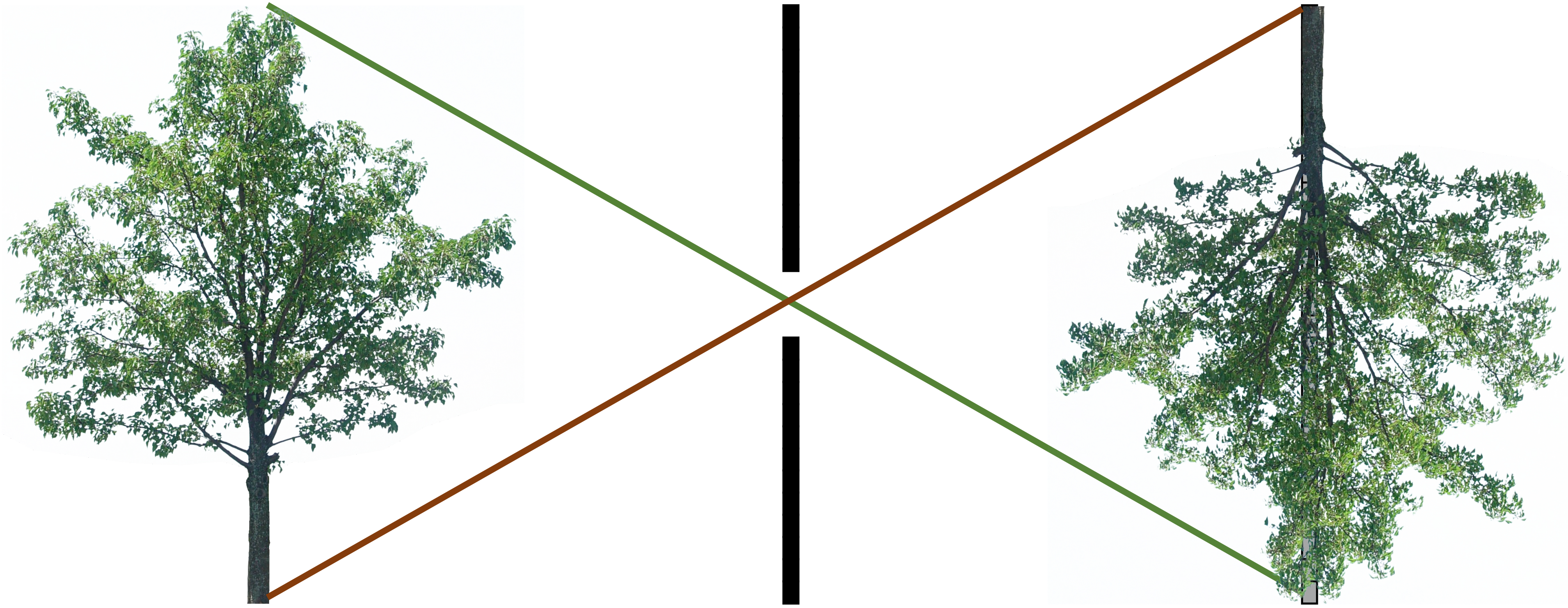
What happens as we change the pinhole diameter?



Pinhole size

What happens as we change the pinhole diameter?

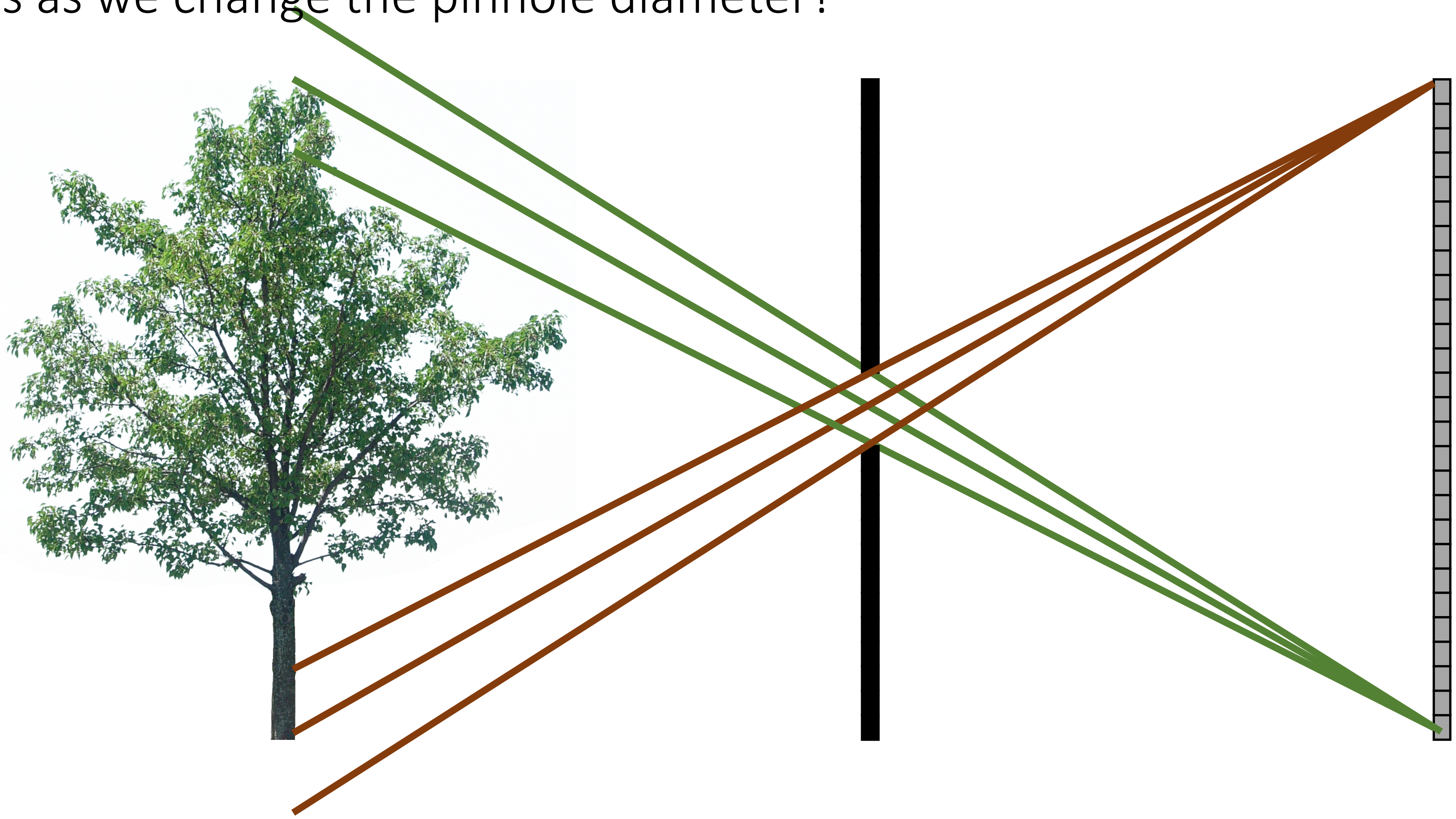
real-world object



Pinhole size

What happens as we change the pinhole diameter?

real-world
object

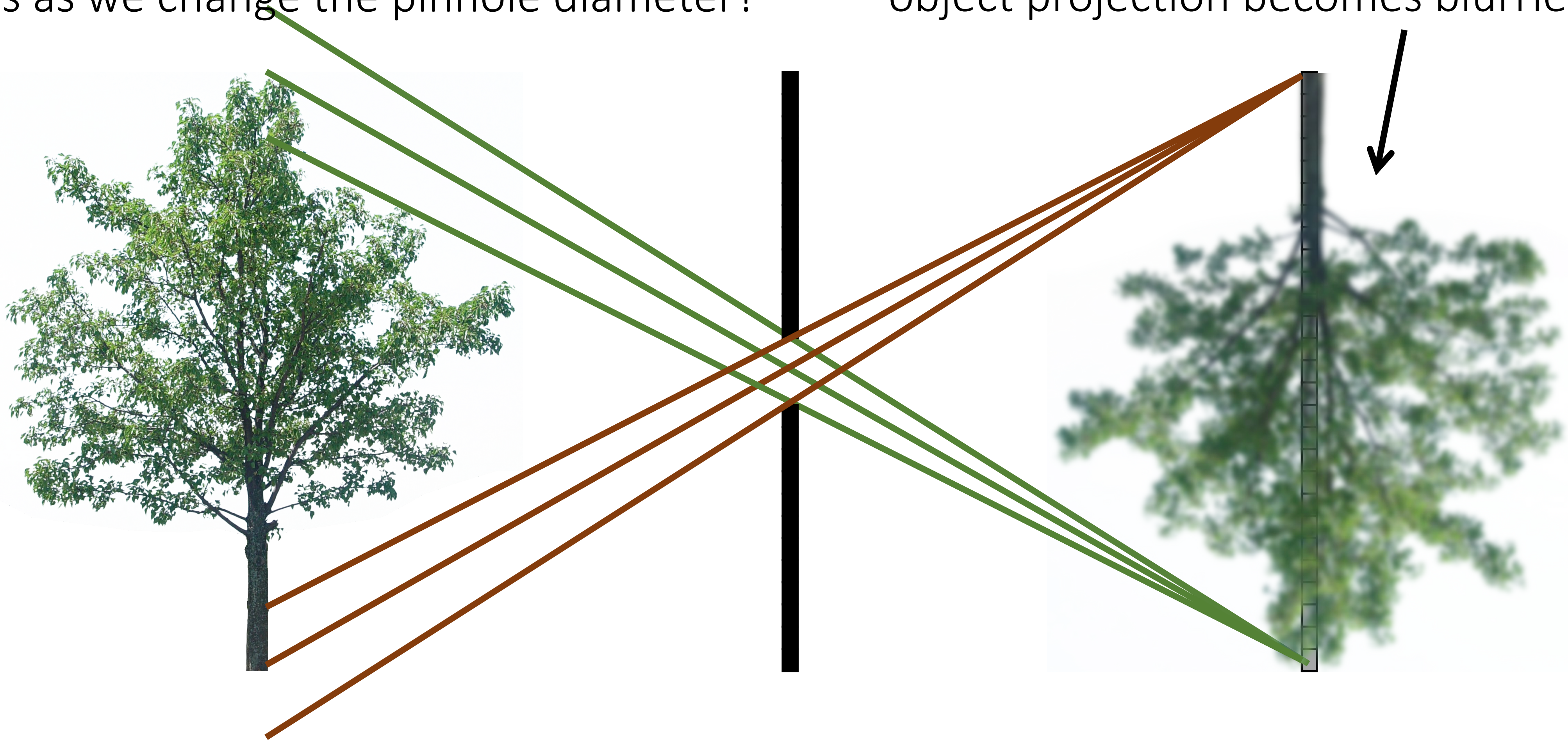


Pinhole size

What happens as we change the pinhole diameter?

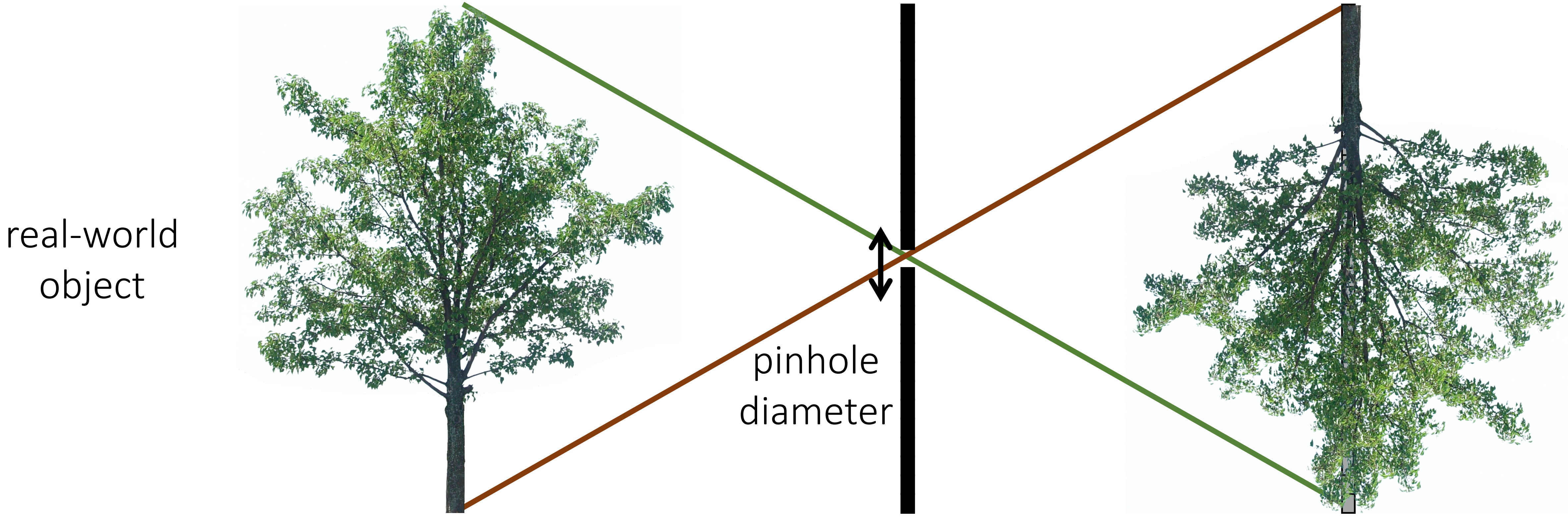
object projection becomes blurrier

real-world object



Pinhole size

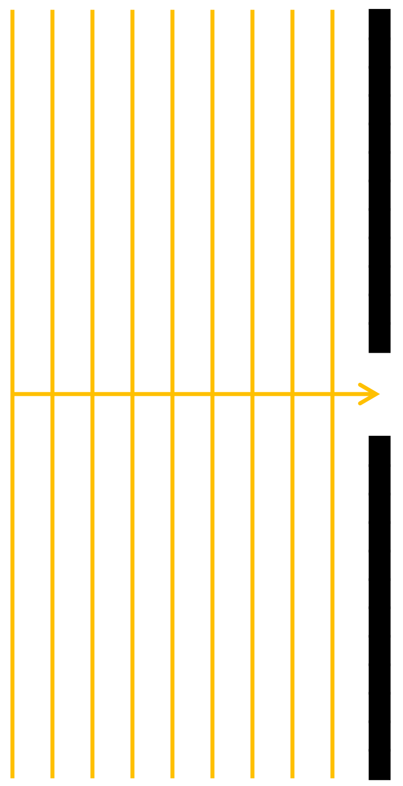
What happens as we change the pinhole diameter?



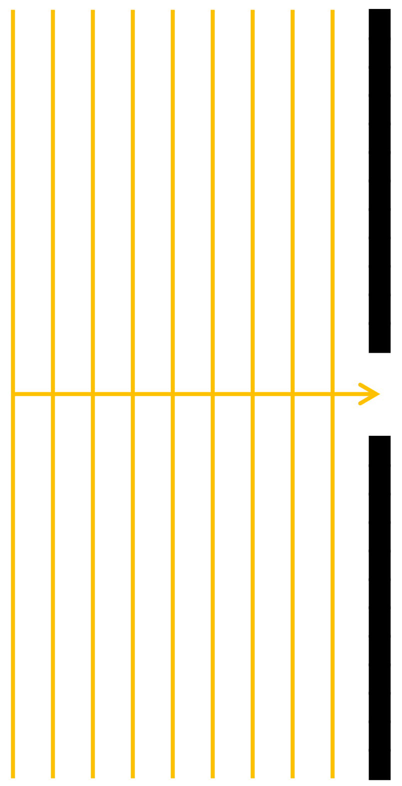
Will the image keep getting sharper the smaller we make the pinhole?

Diffraction limit

A consequence of the wave nature of light



What do geometric optics predict will happen?



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Diffraction limit

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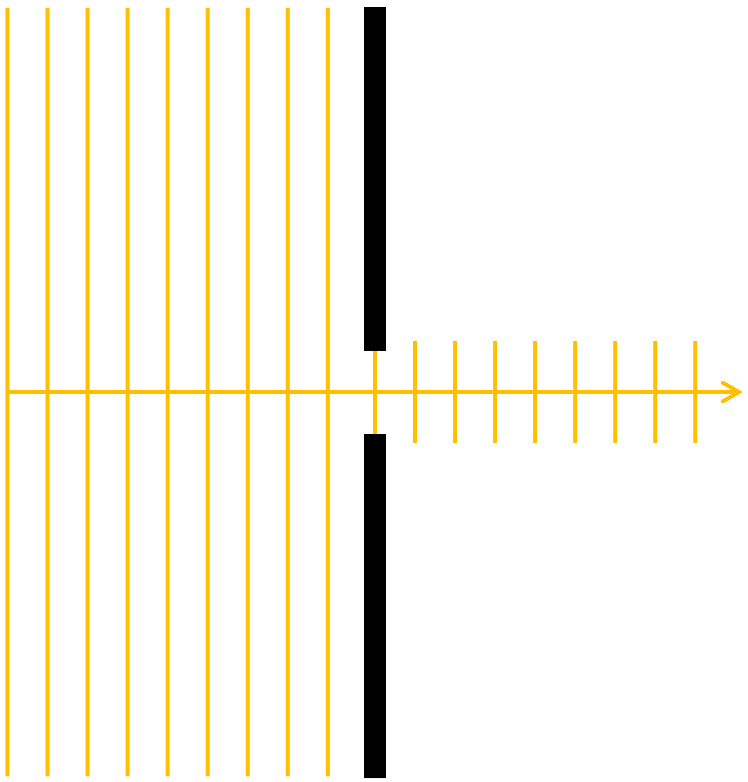

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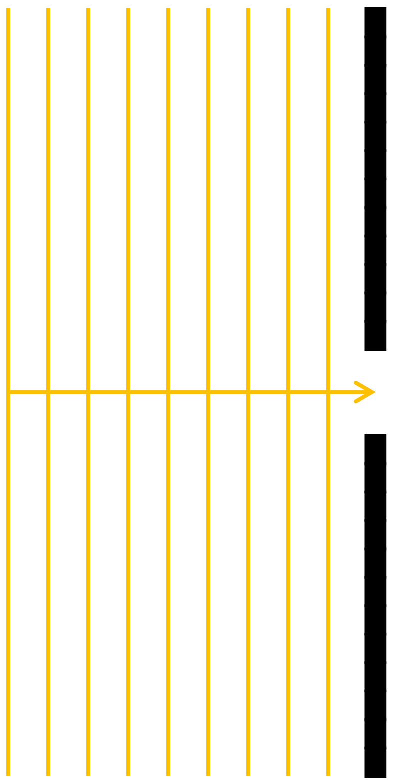

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Diffraction limit

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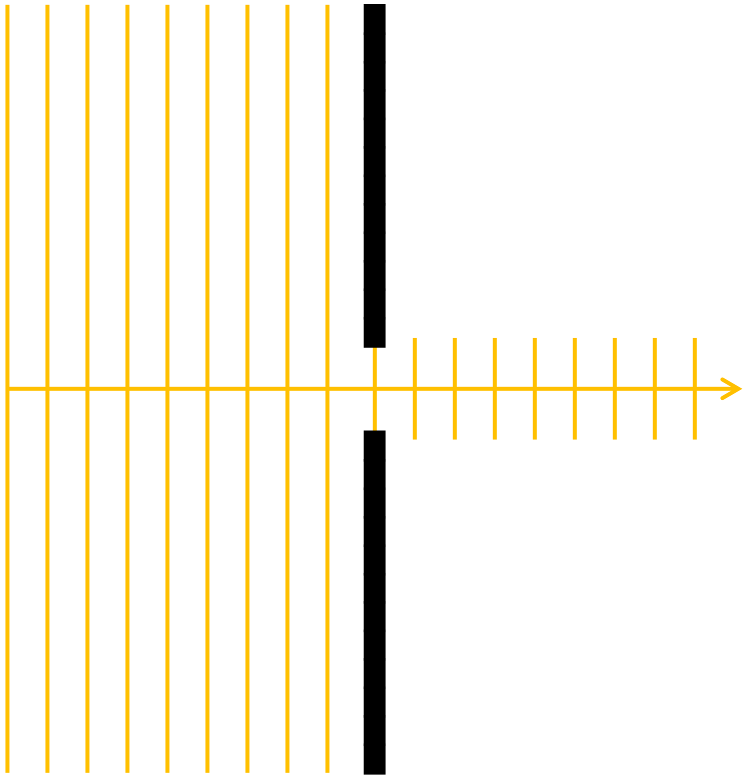
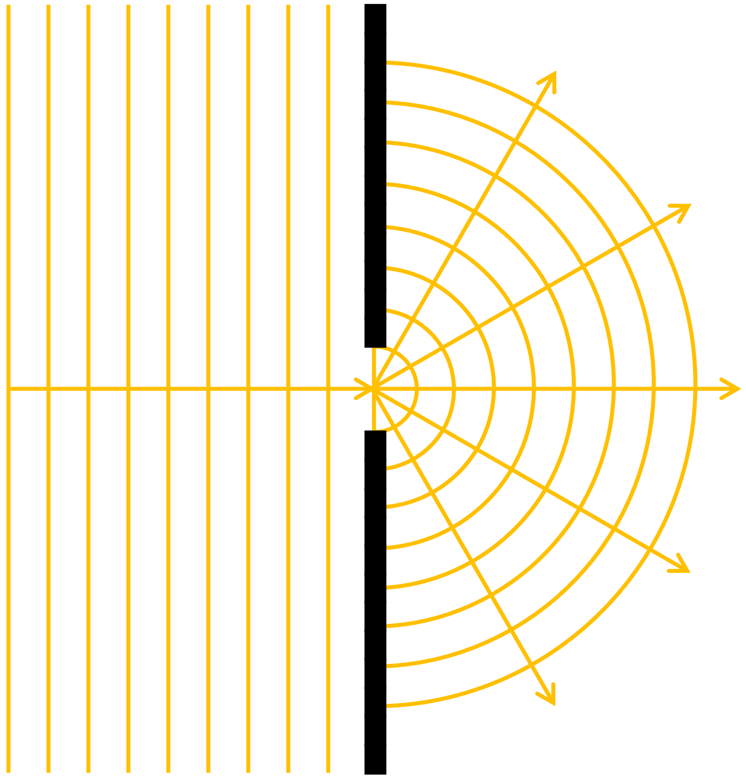


What do geometric optics predict will happen?

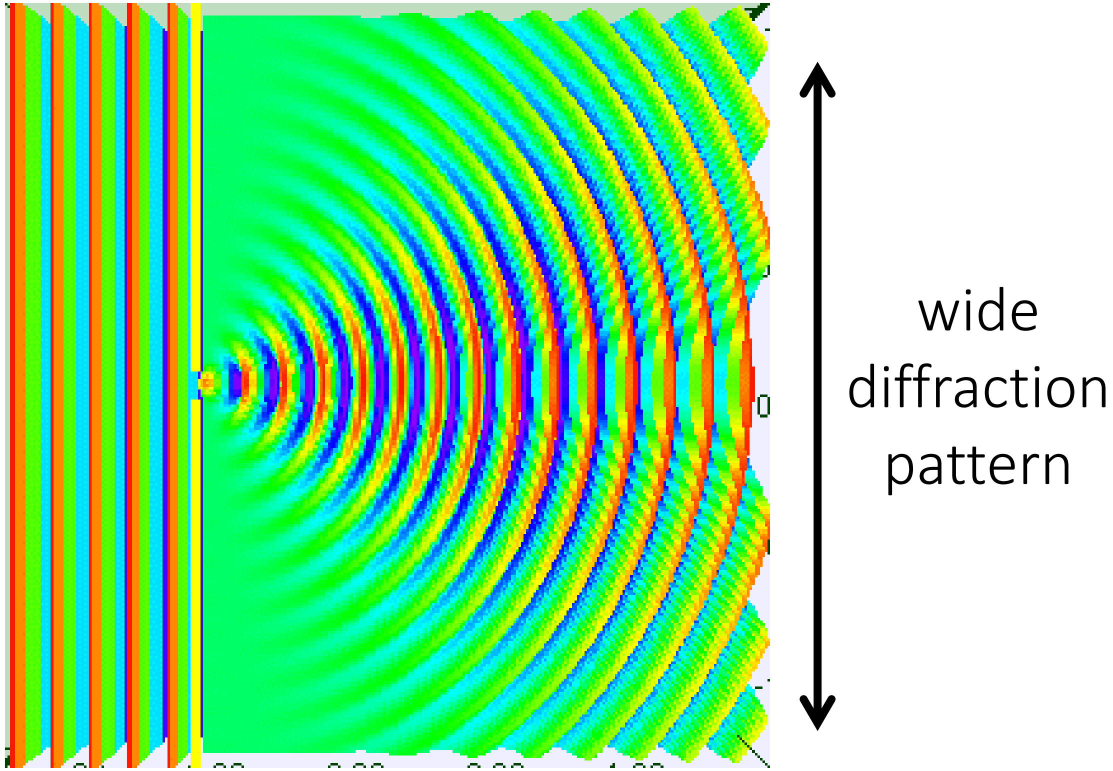


What do wave optics predict will happen?

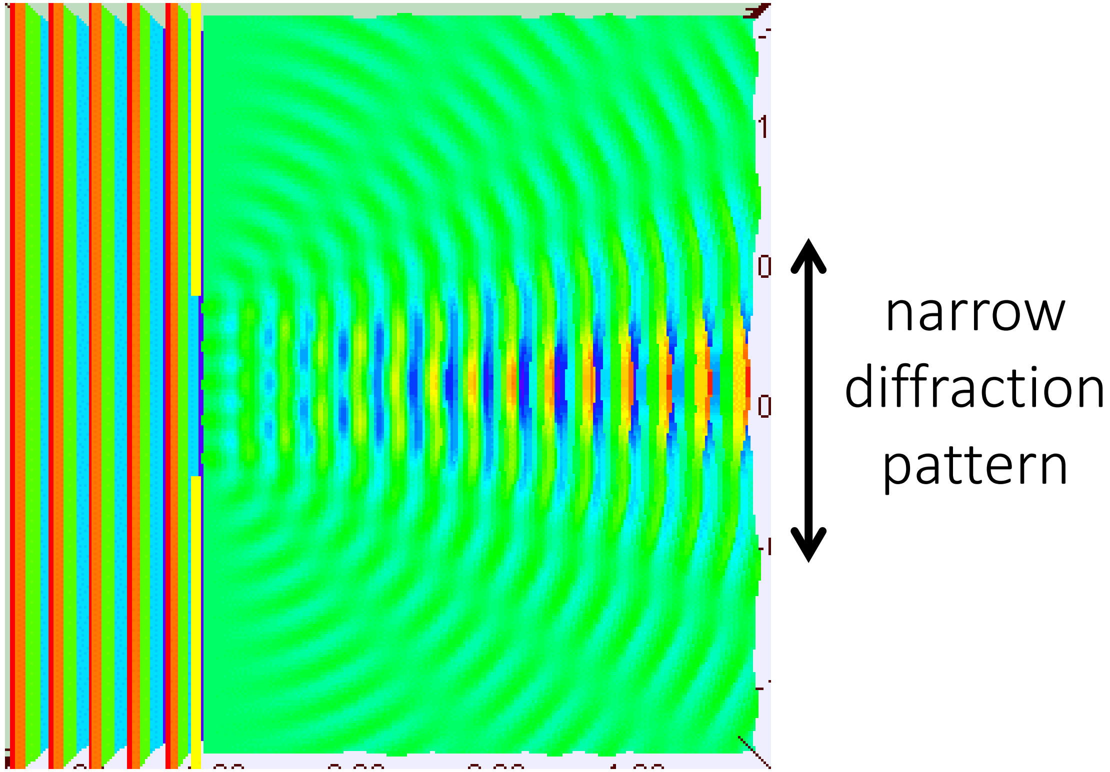
Diffraction limit

Diffraction pattern = Fourier transform of the pinhole.

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

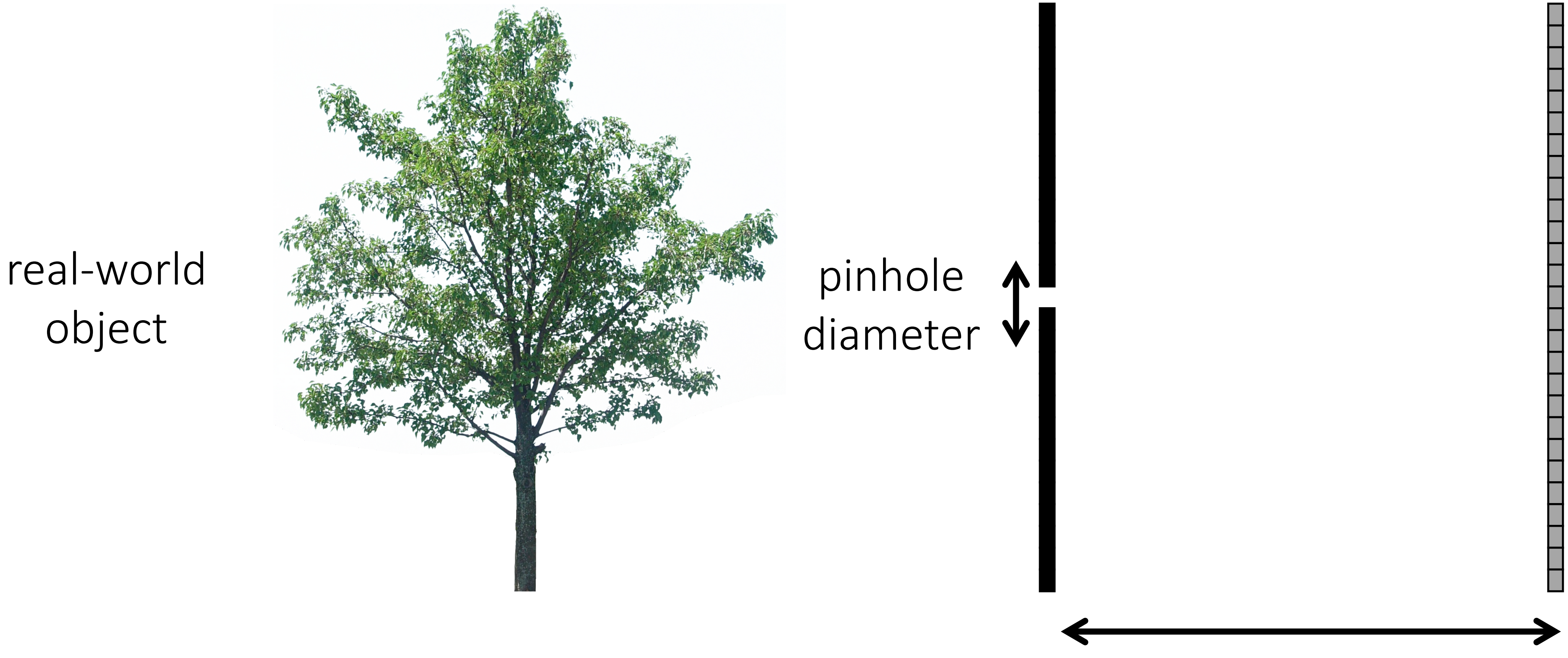


small pinhole



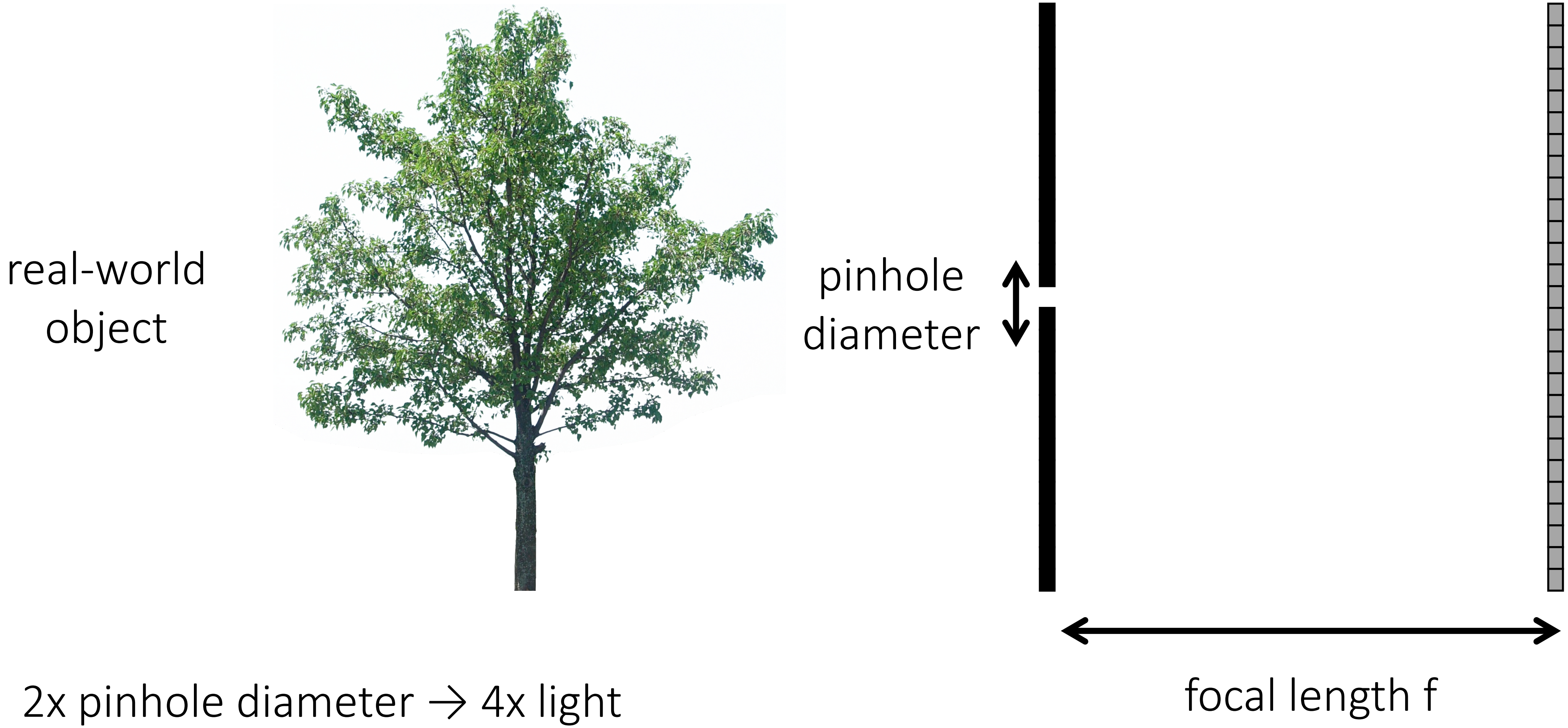
large pinhole

What about light efficiency?



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

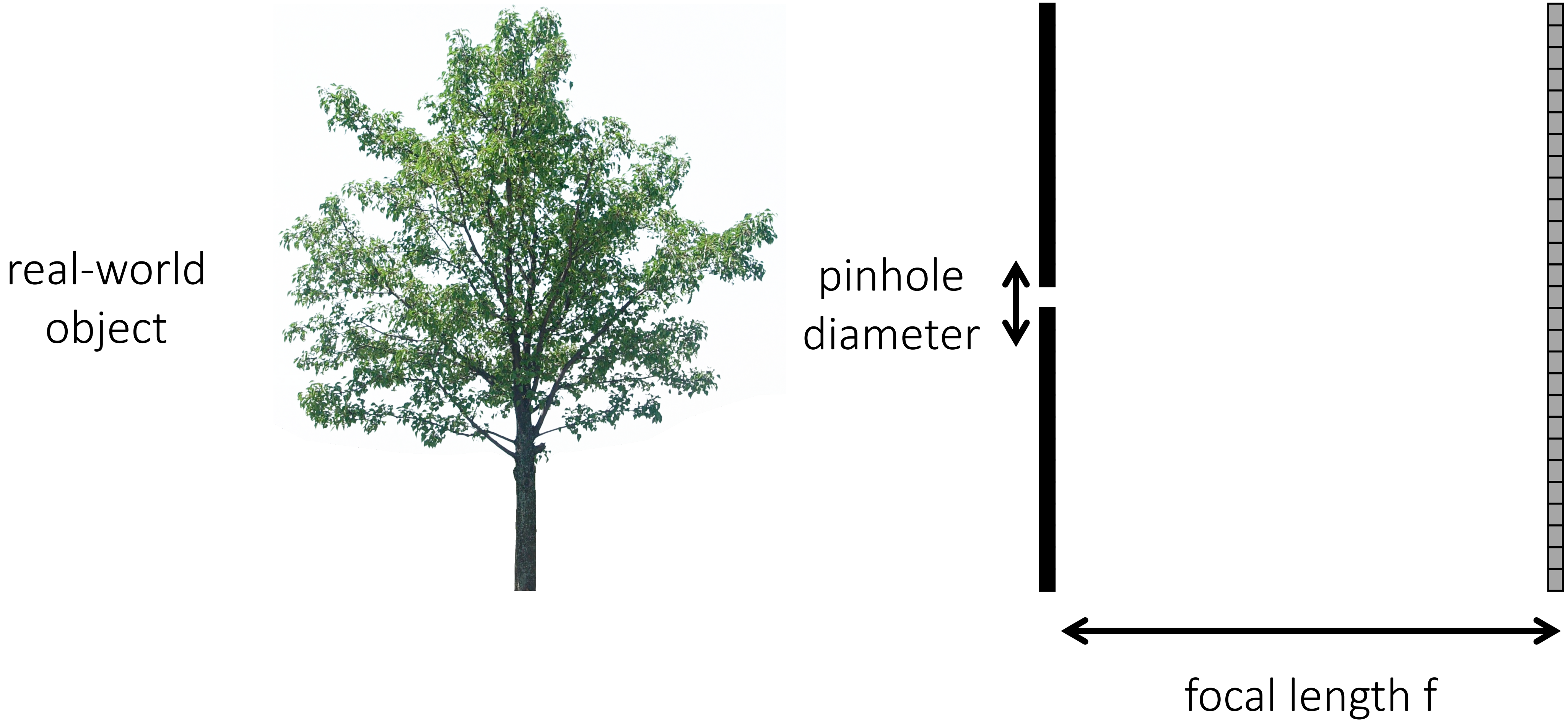
What about light efficiency?



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

Some terminology notes

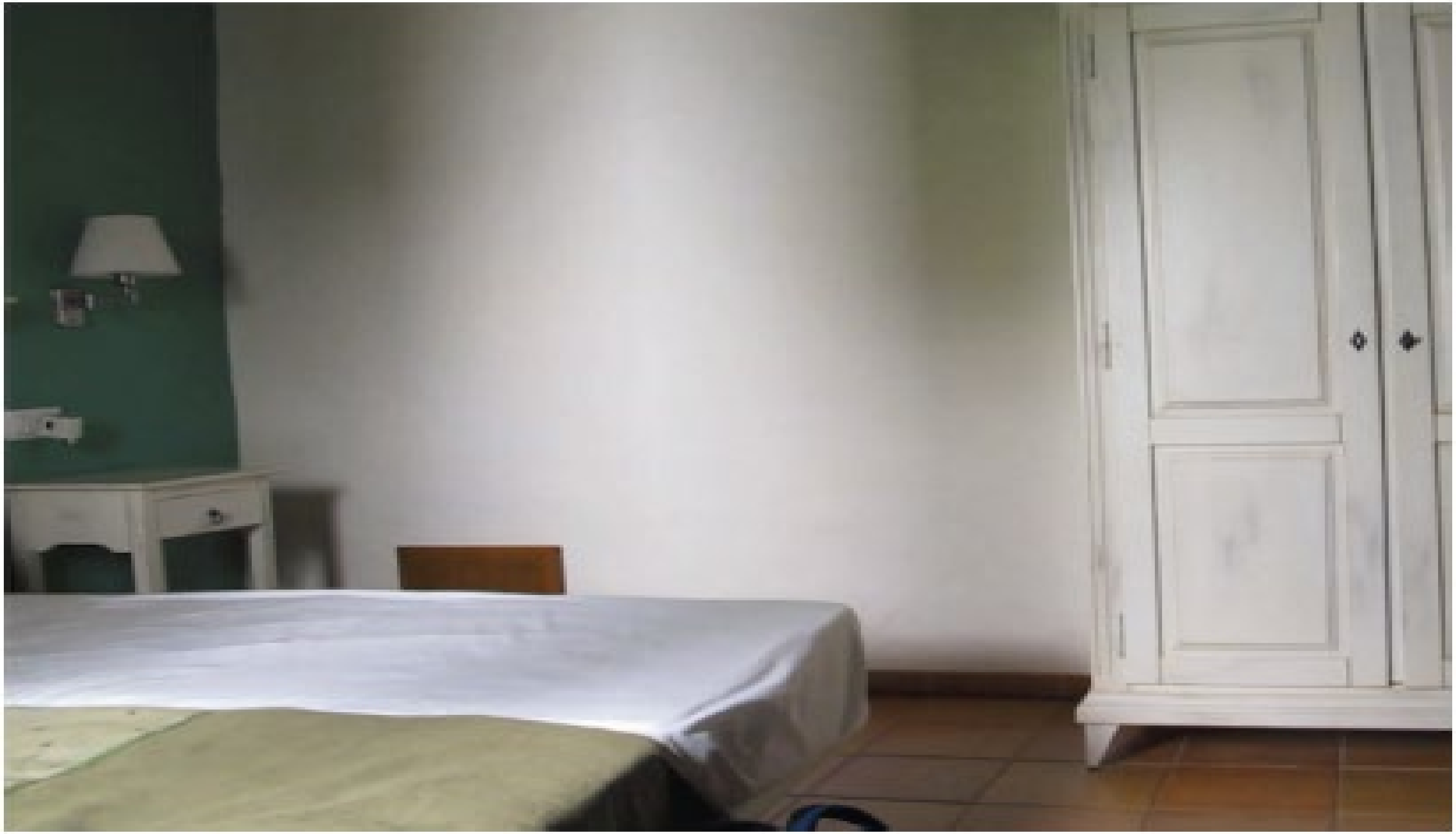
A “stop” is a change in camera settings that changes amount of light by a factor of 2



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

Accidental pinholes

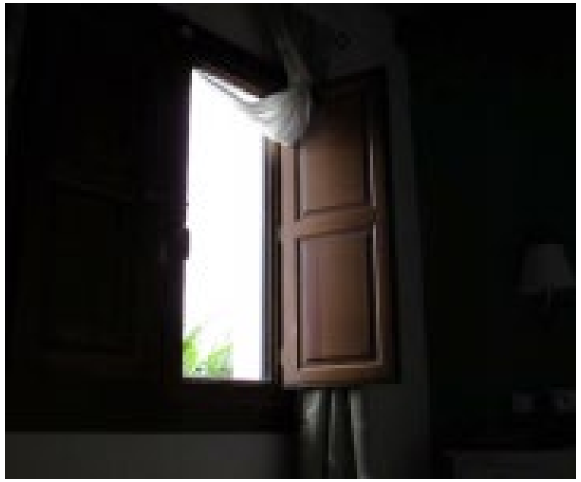
What does this image say about the world outside?



Accidental pinhole camera

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

Accidental pinhole camera

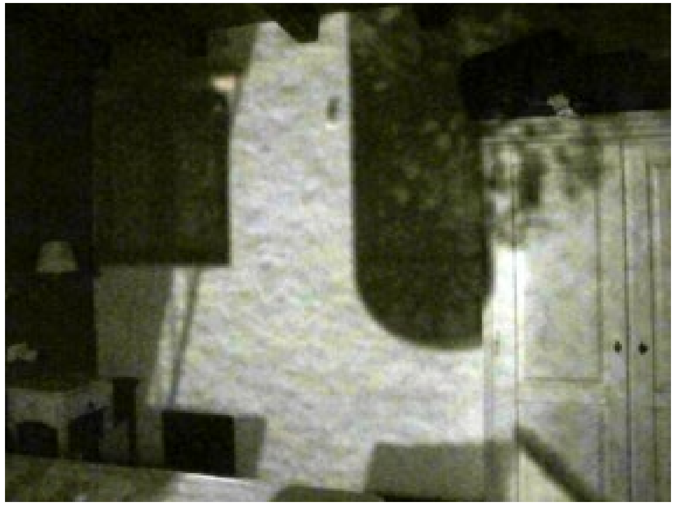


window is an aperture

projected pattern on the wall

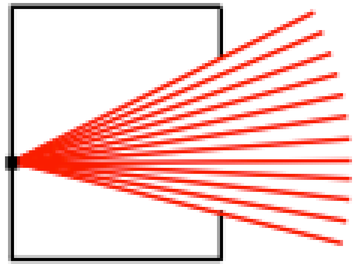
upside down

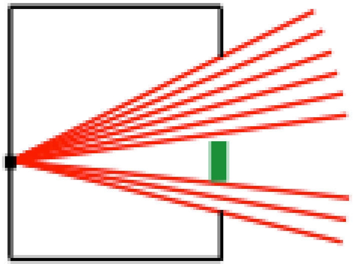
window with smaller gap

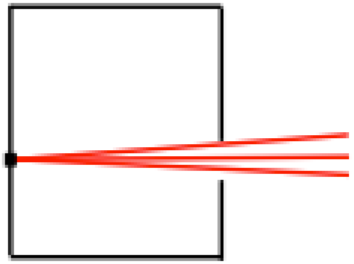


view outside window

Accidental pinspeck camera

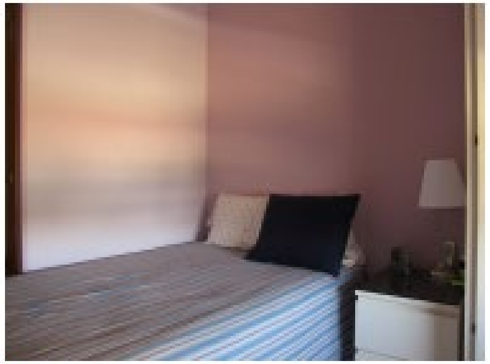

a)

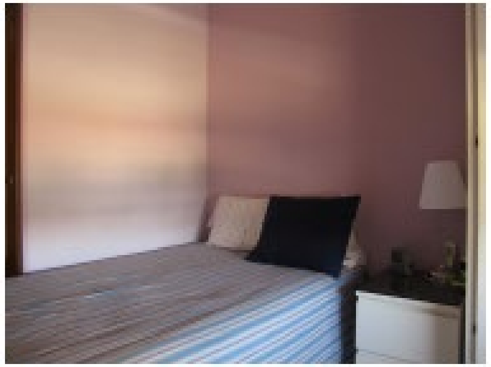

b)

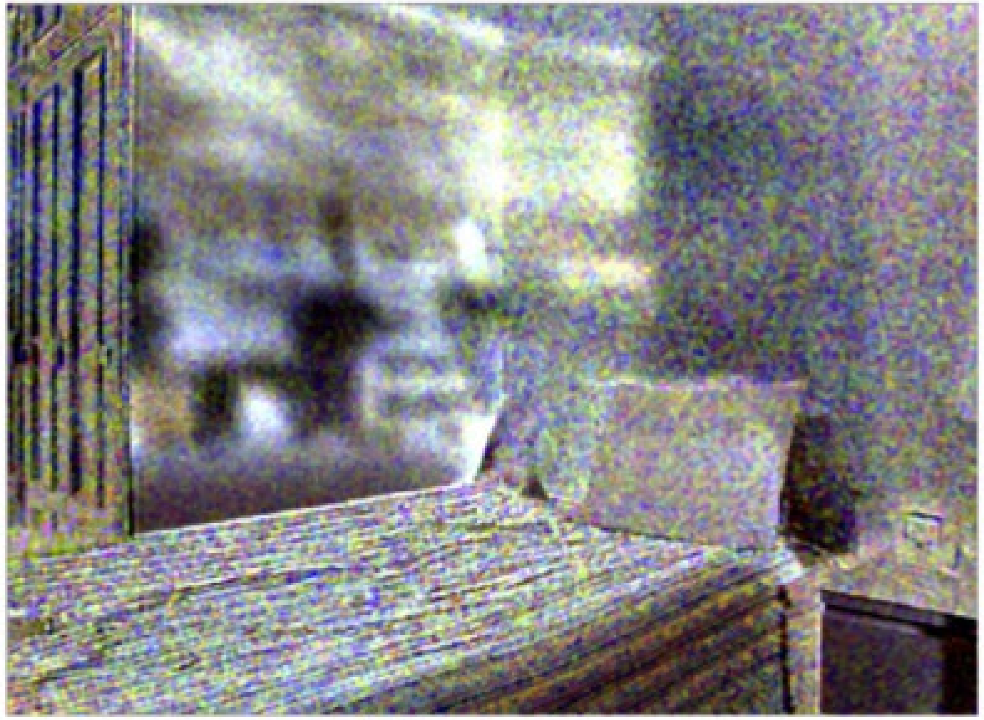

c)


a)


b)


c)

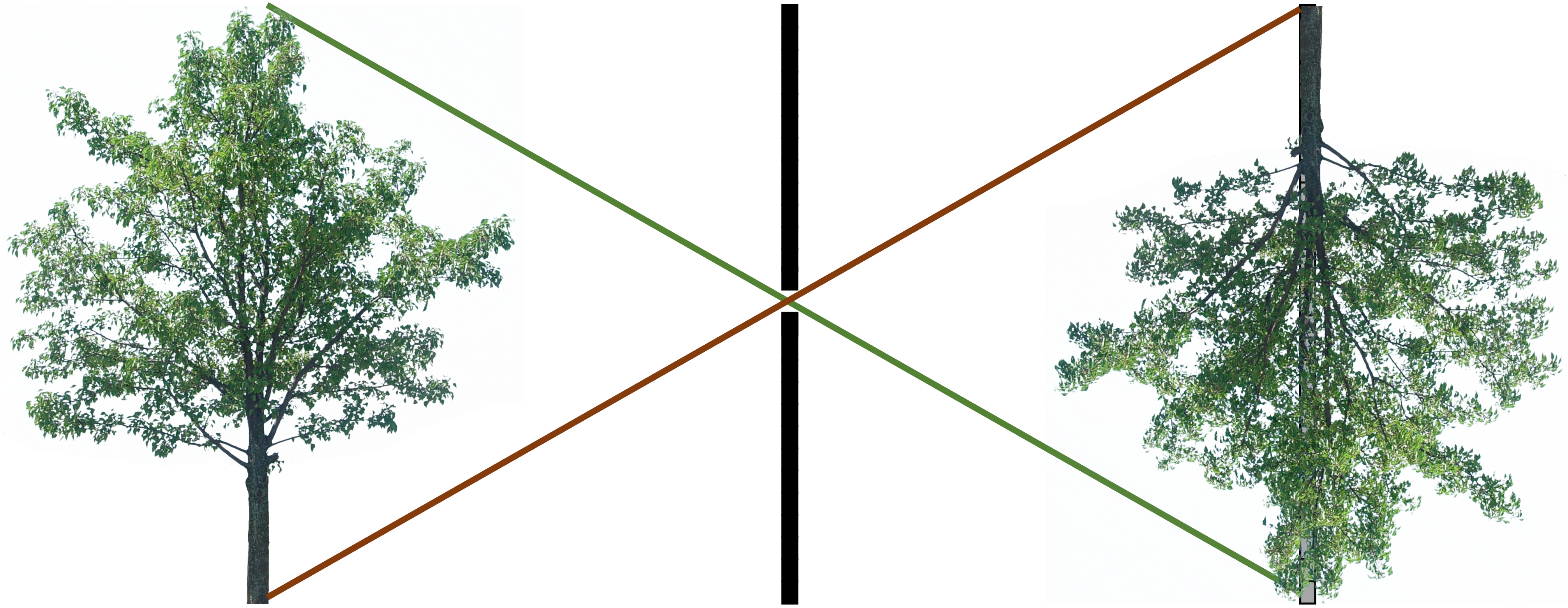

d)


a) Difference image


b) Difference upside down


c) True outdoor view

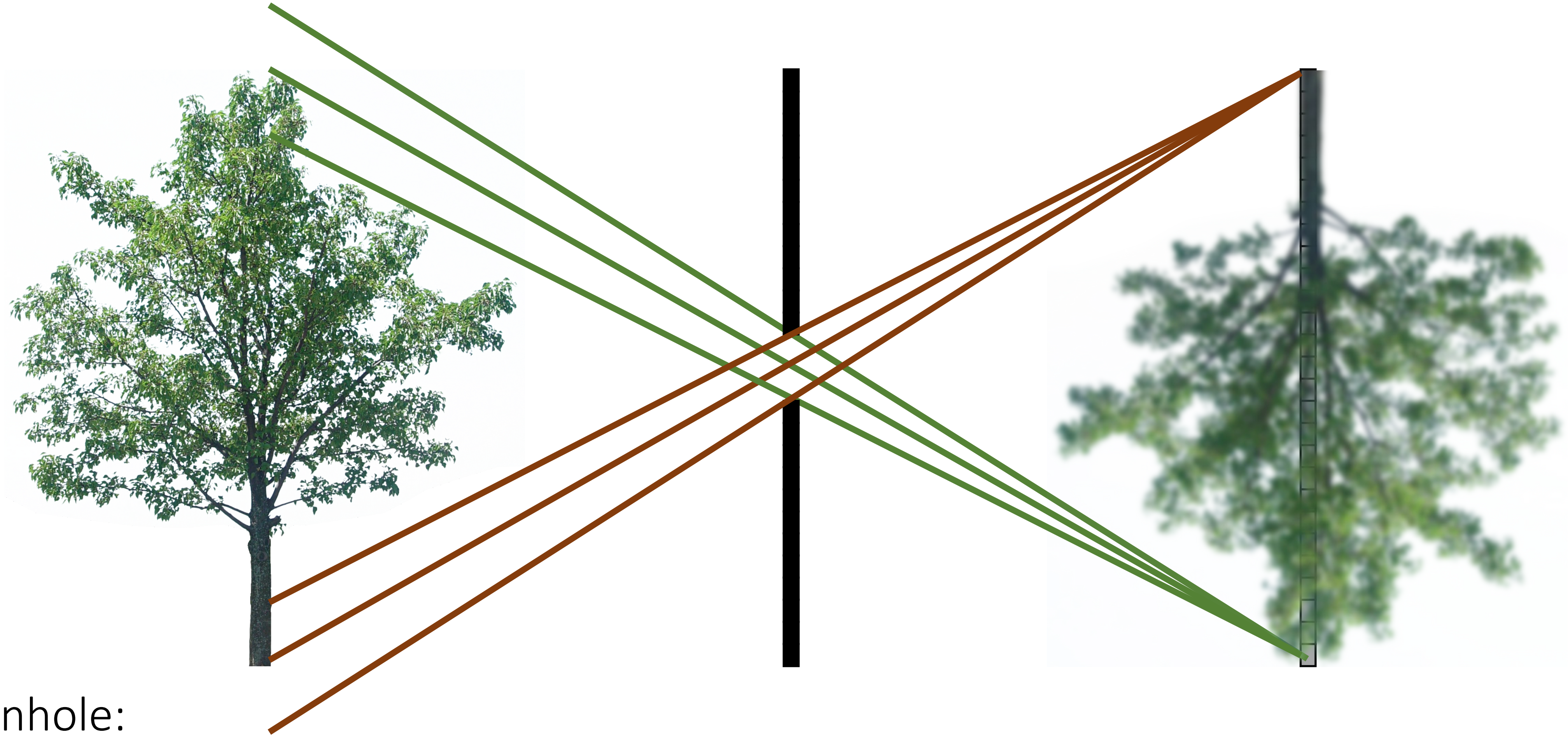
Pinhole camera trade-off



Small (ideal) pinhole:

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

Pinhole camera trade-off

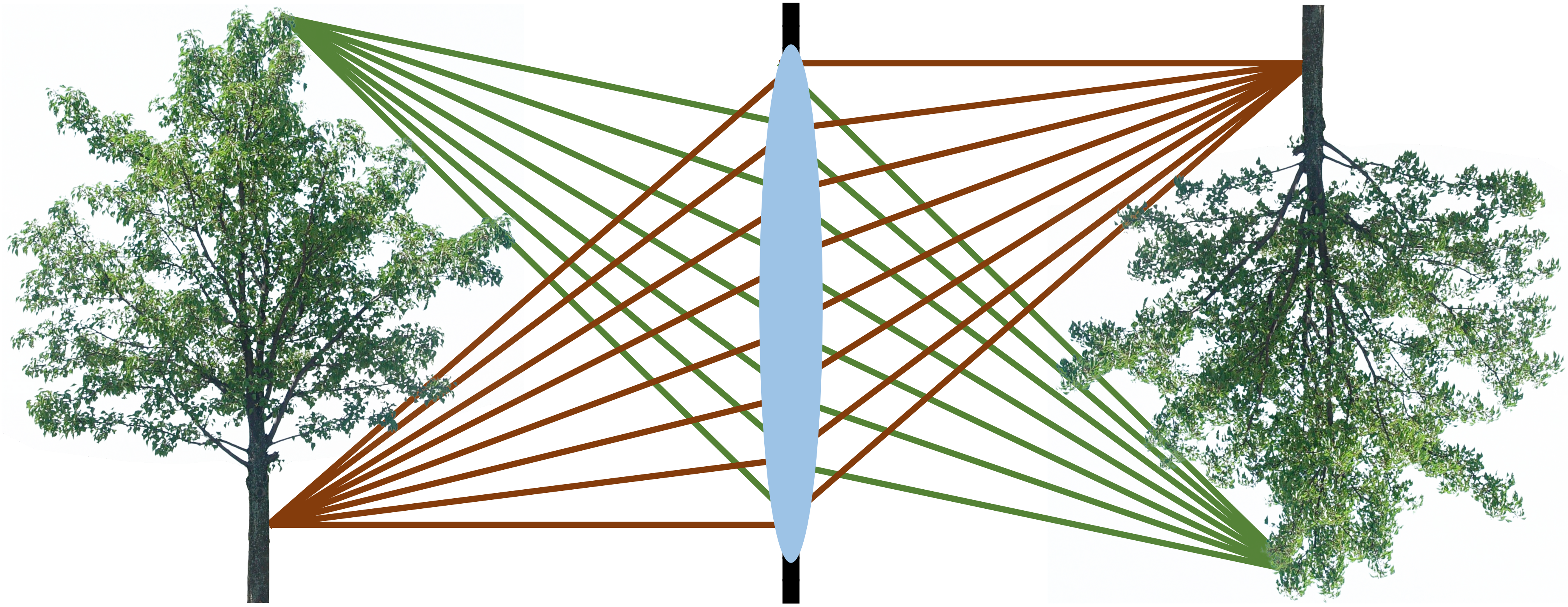


Large pinhole:

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

Can we get best of both worlds?

Almost, by using lenses



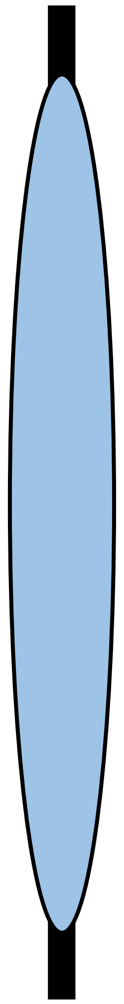
Lenses map “bundles” of rays from points on the scene to the sensor.

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?

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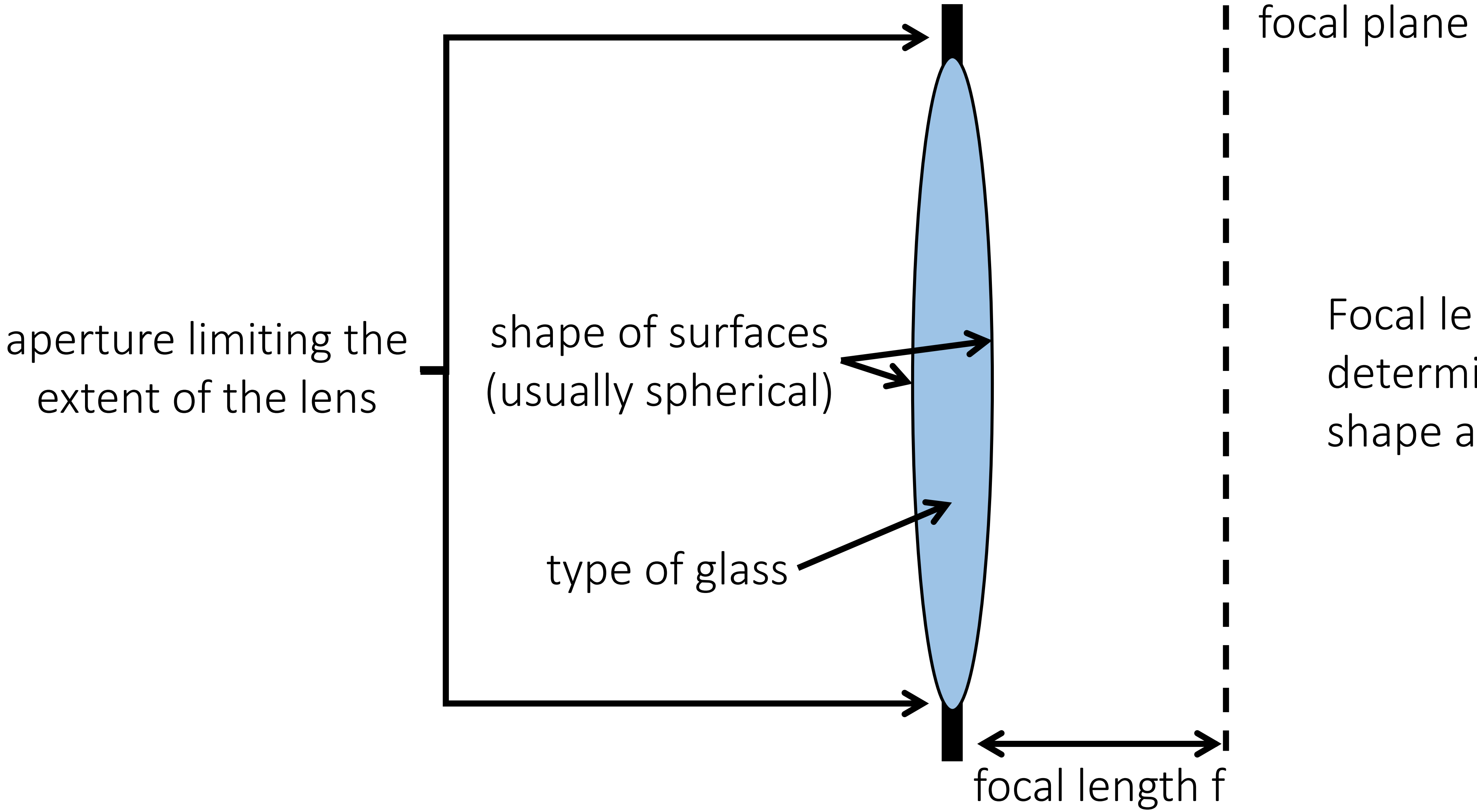


Focal length is determined by the lens' shape and material

The lens on your camera

Aperture size

Most lenses have apertures of variable size.

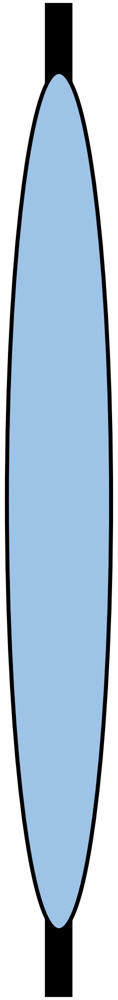
- The size of the aperture is expressed as the “f-number”: The bigger this number, the smaller the aperture.

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.

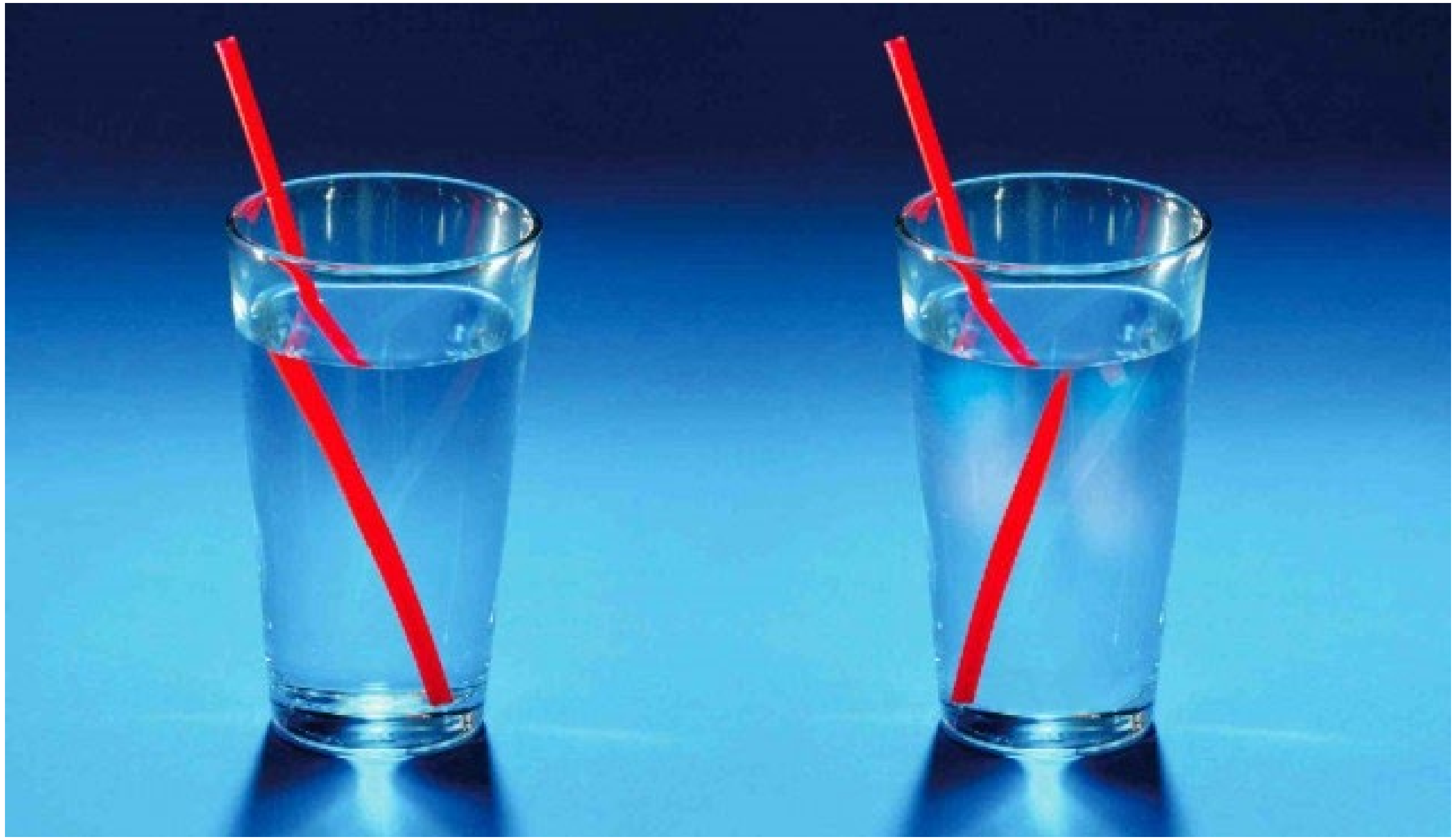
How does a lens work?

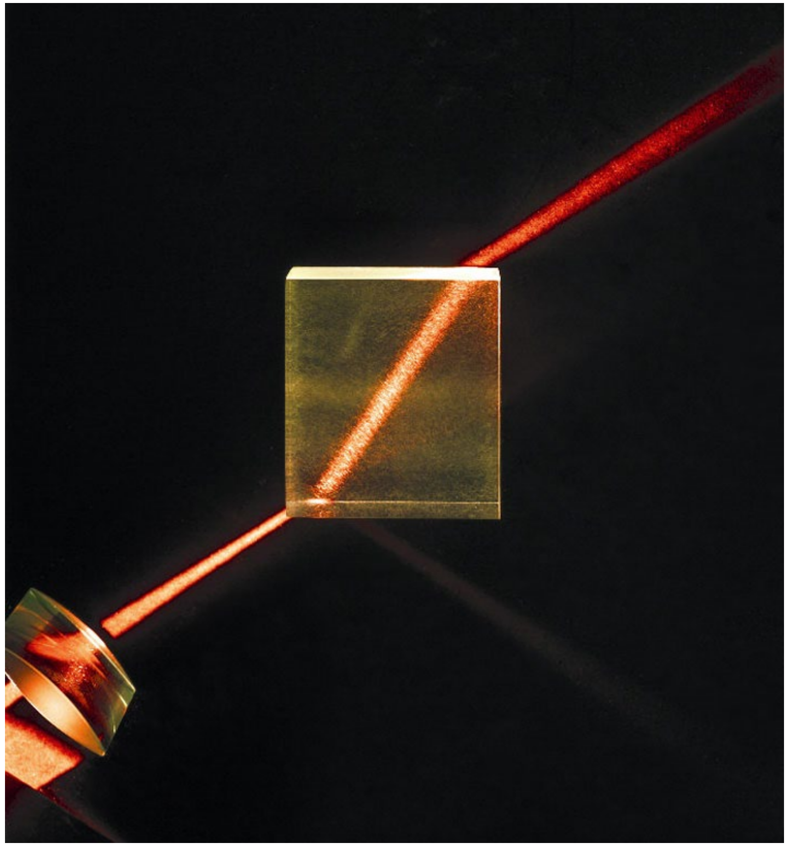
Lenses are design so that their refraction makes light rays bend in a very specific way.



Refraction

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

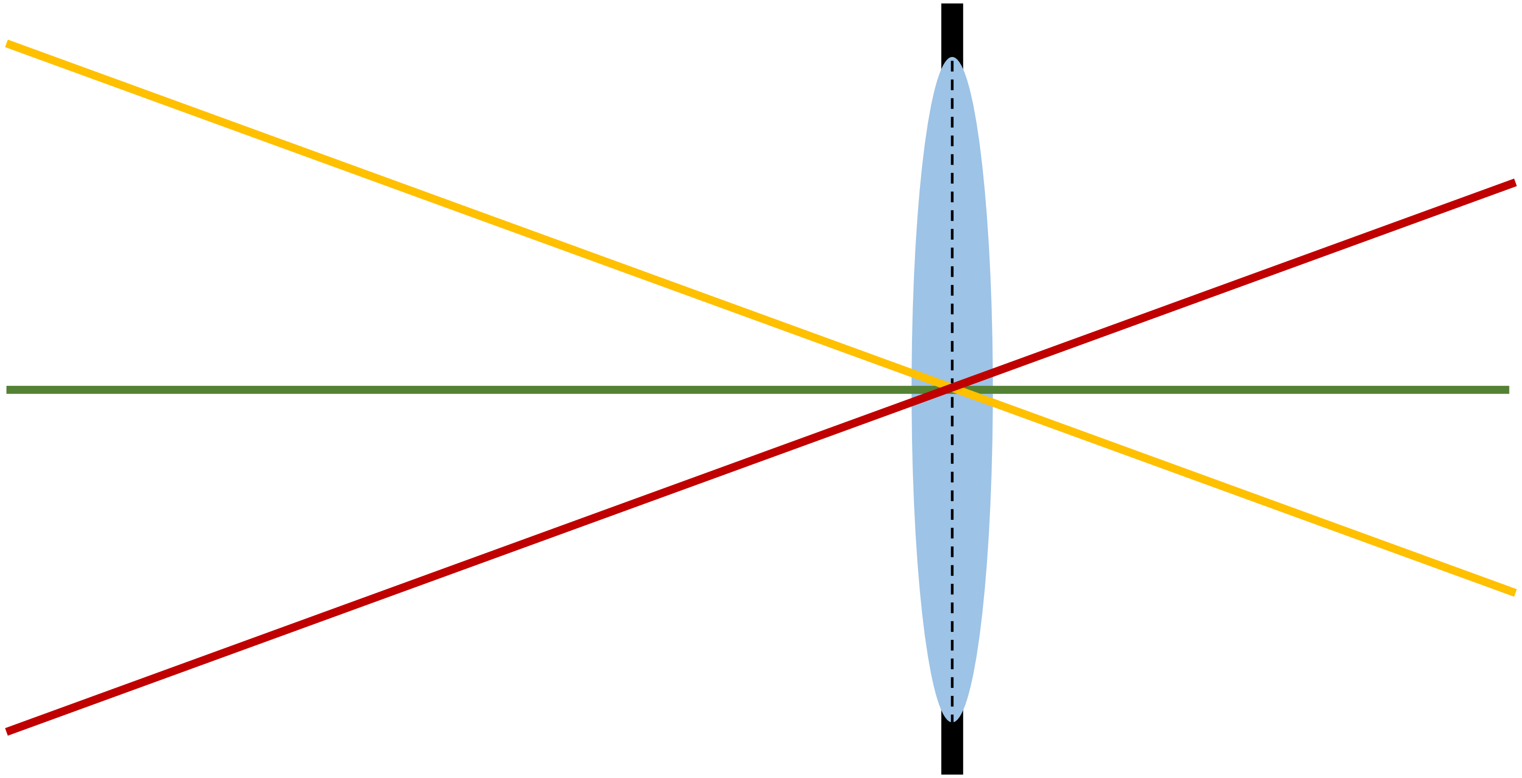




The thin lens model

Thin lens model

Simplification of geometric optics for <u>well-designed</u> lenses.

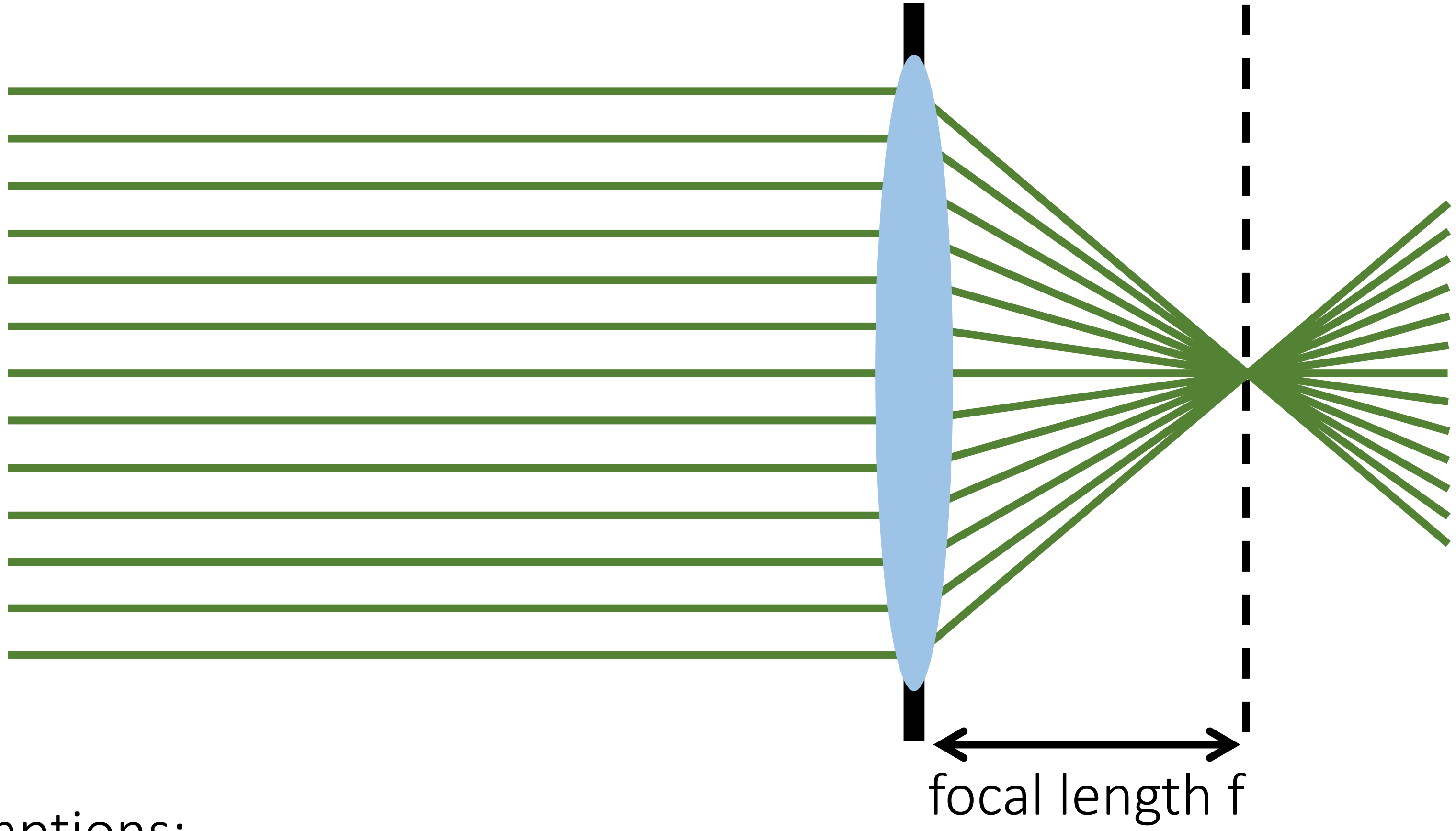


Two assumptions:

1. Rays passing through lens center are unaffected.

Thin lens model

Simplification of geometric optics for well-designed lenses.



Two assumptions:

1. Rays passing through lens center are unaffected.
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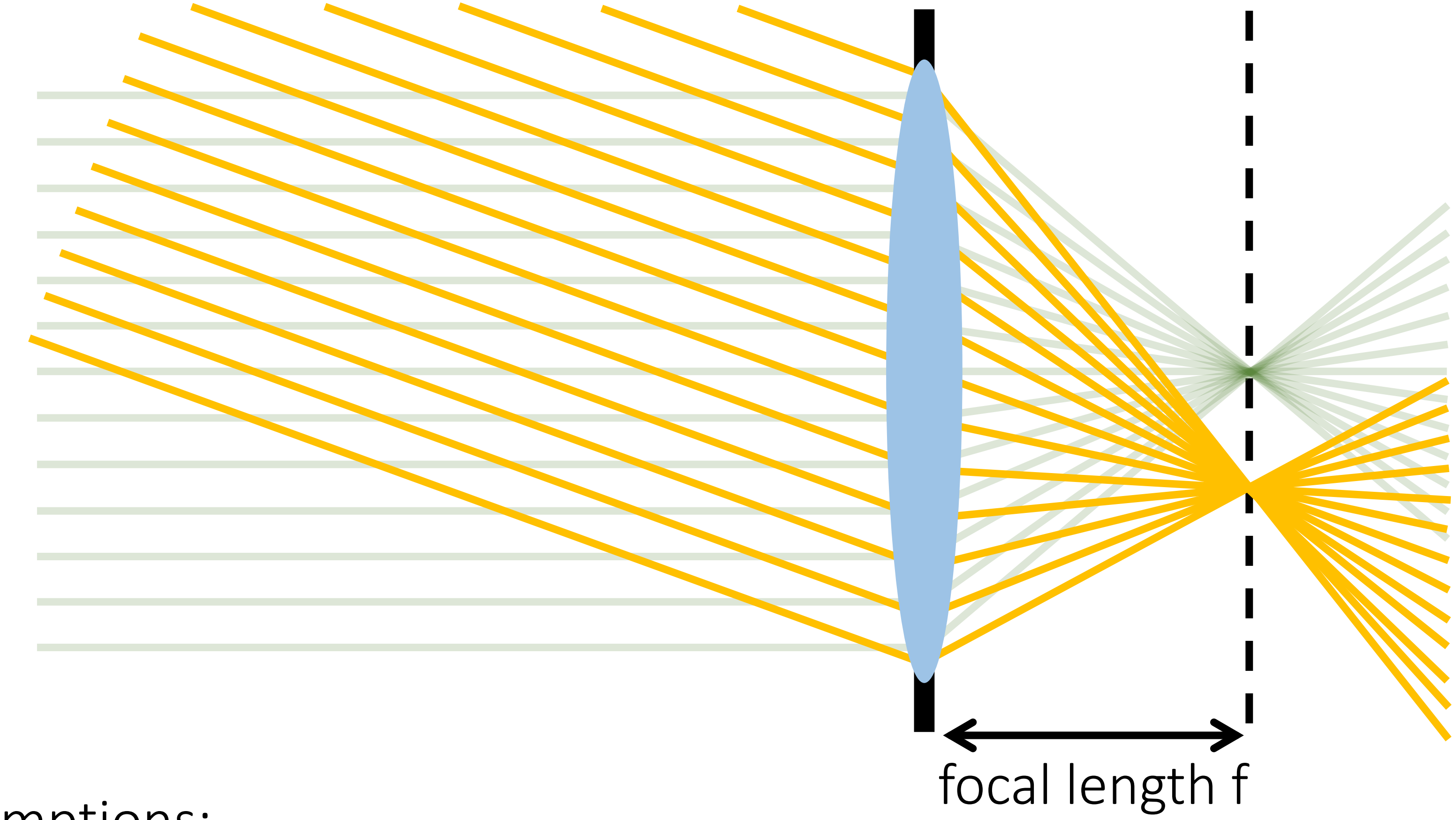

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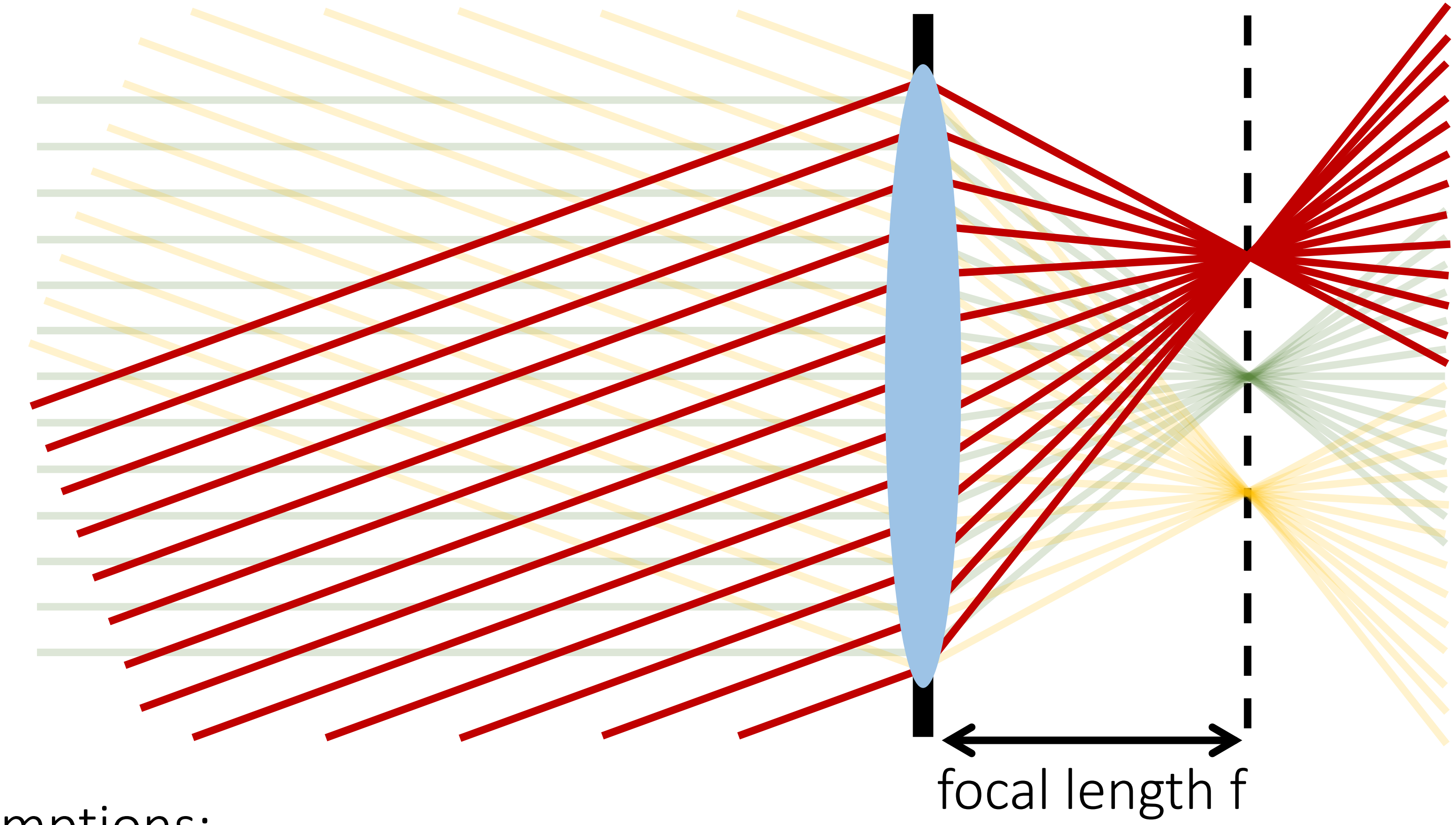

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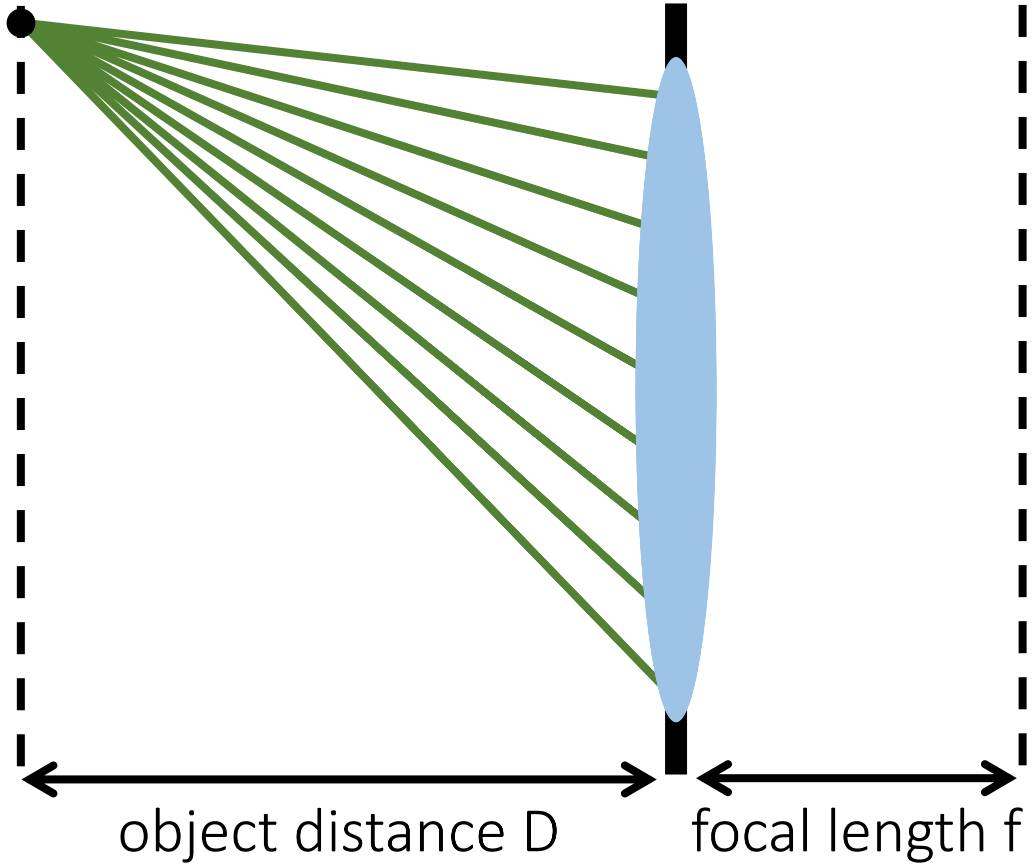
Tracing rays through a thin lens

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



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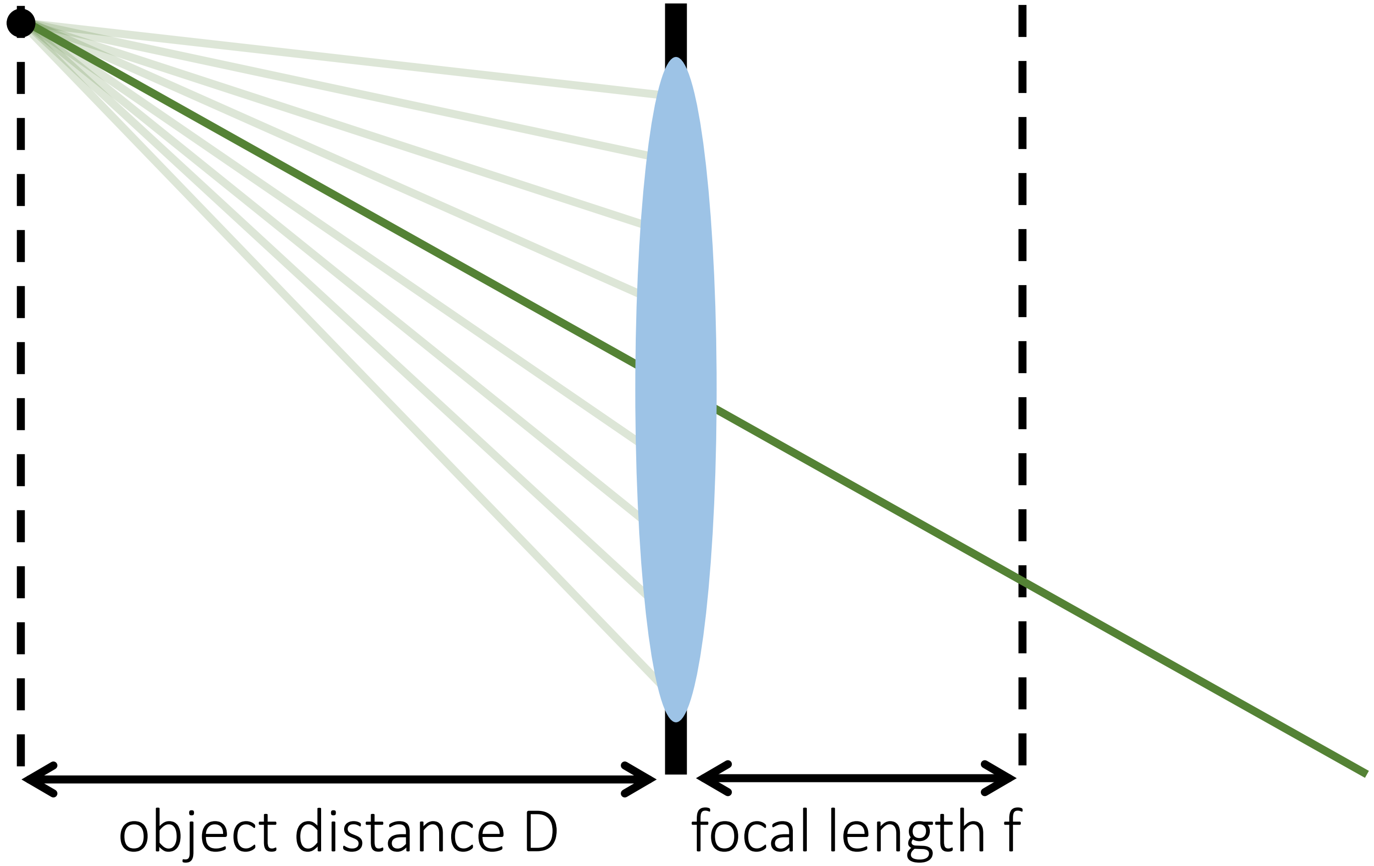

Tracing rays through a thin lens

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

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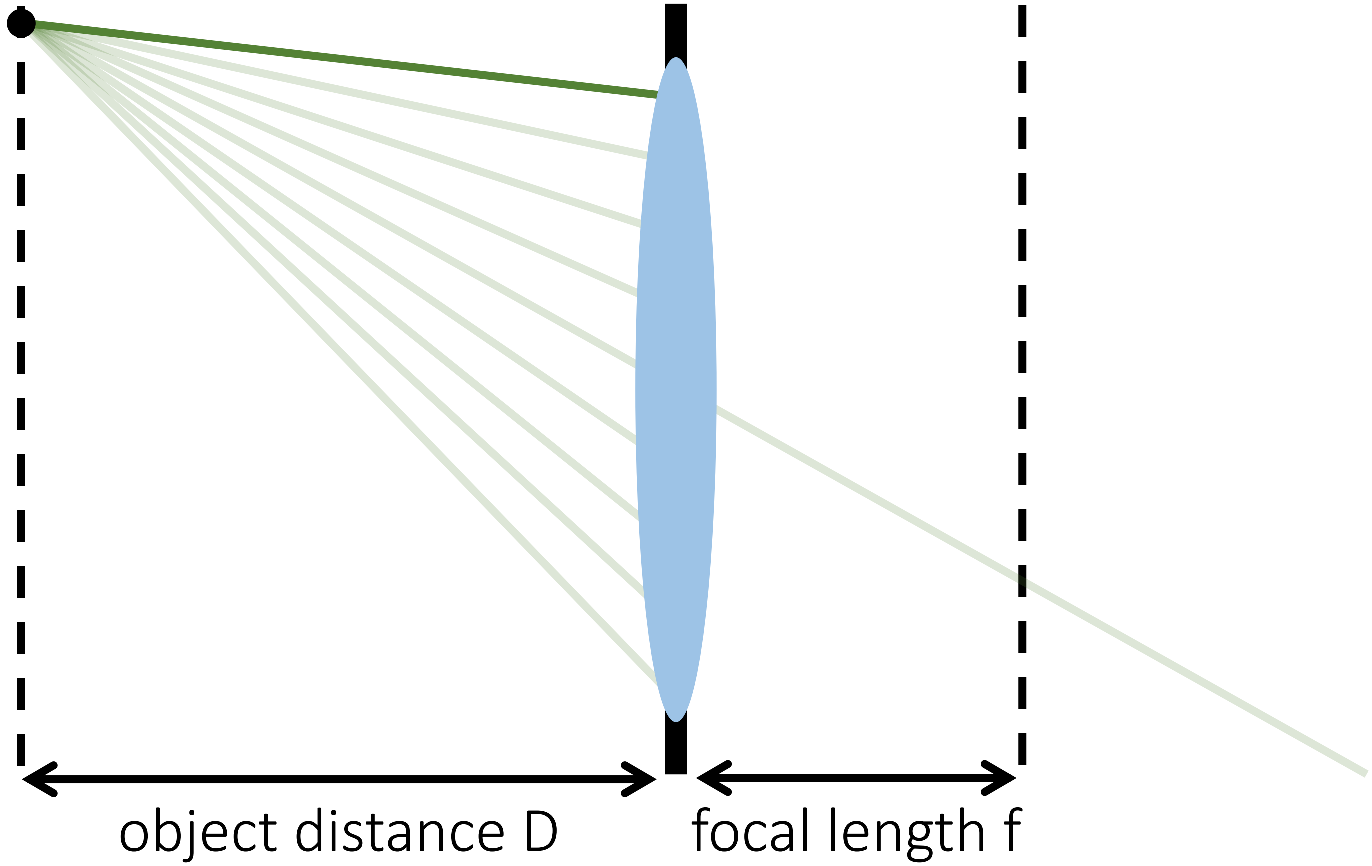
2. For all other rays:



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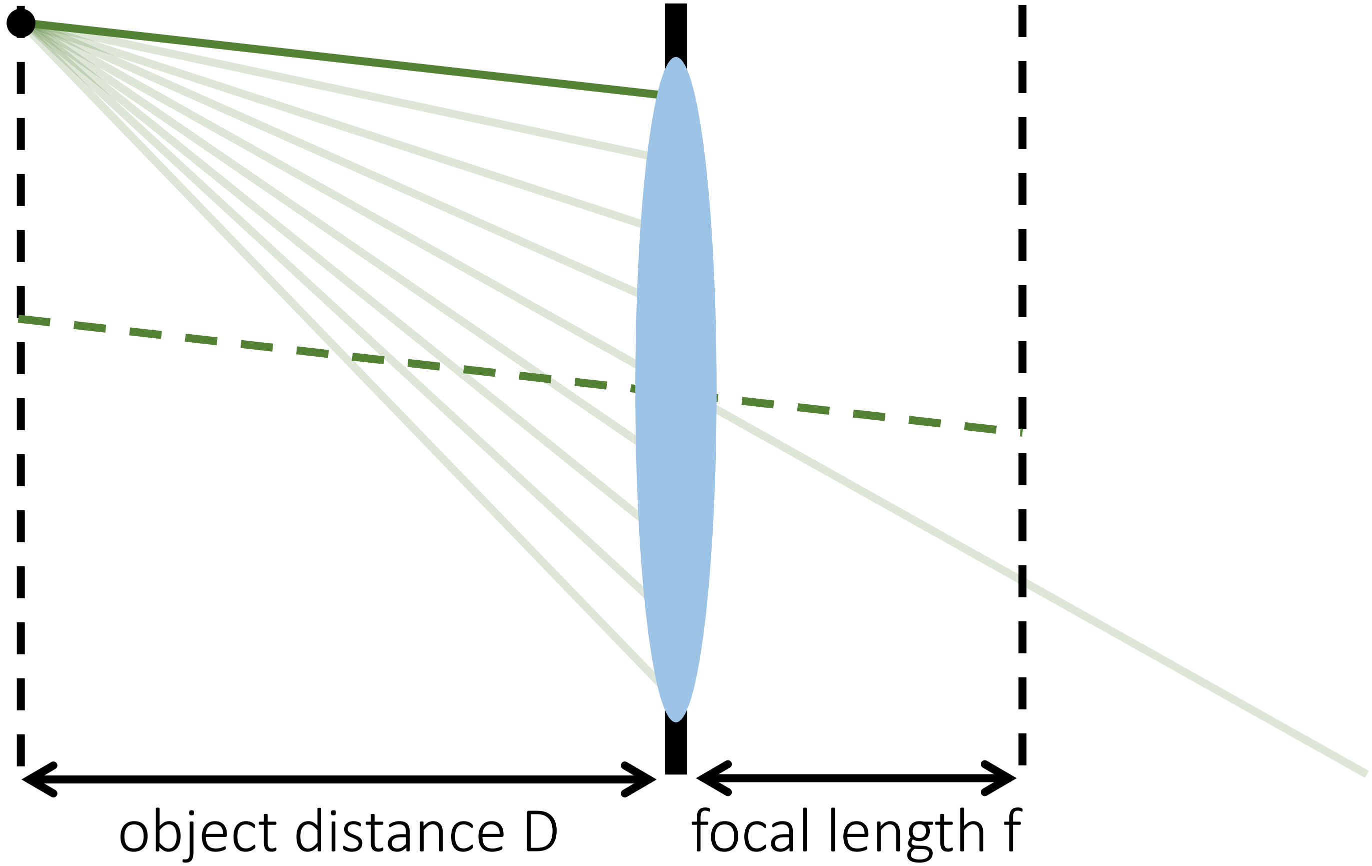

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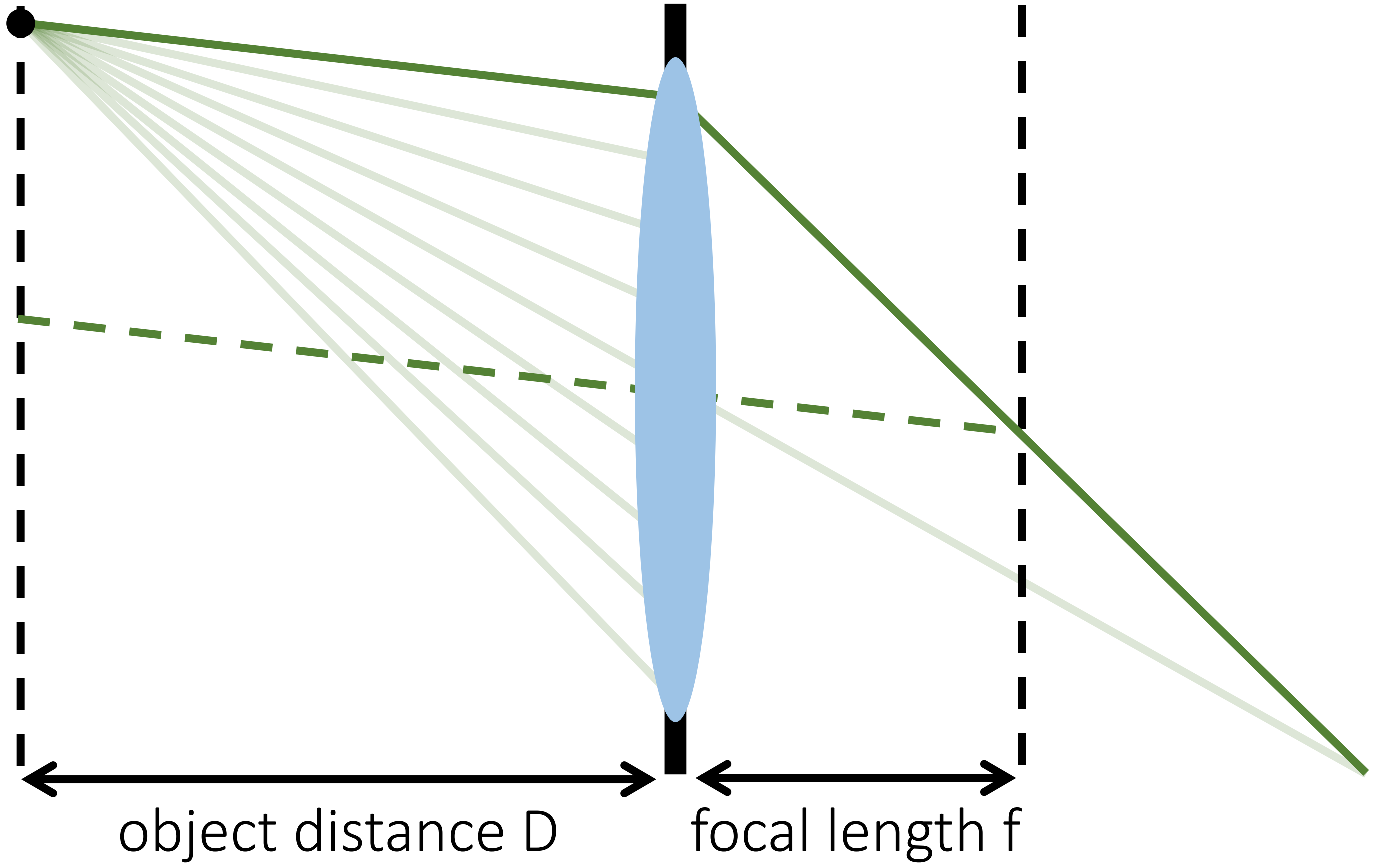

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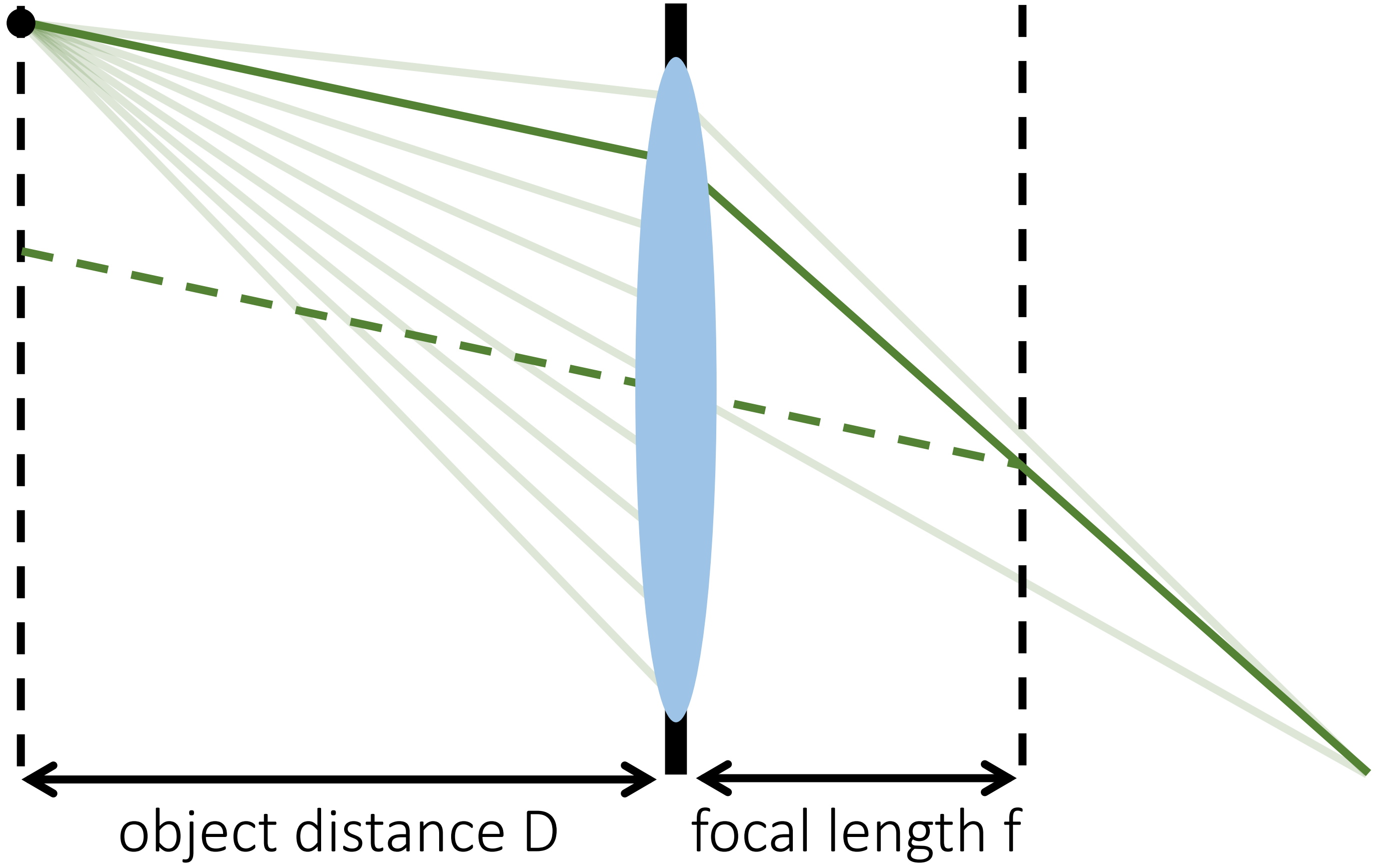

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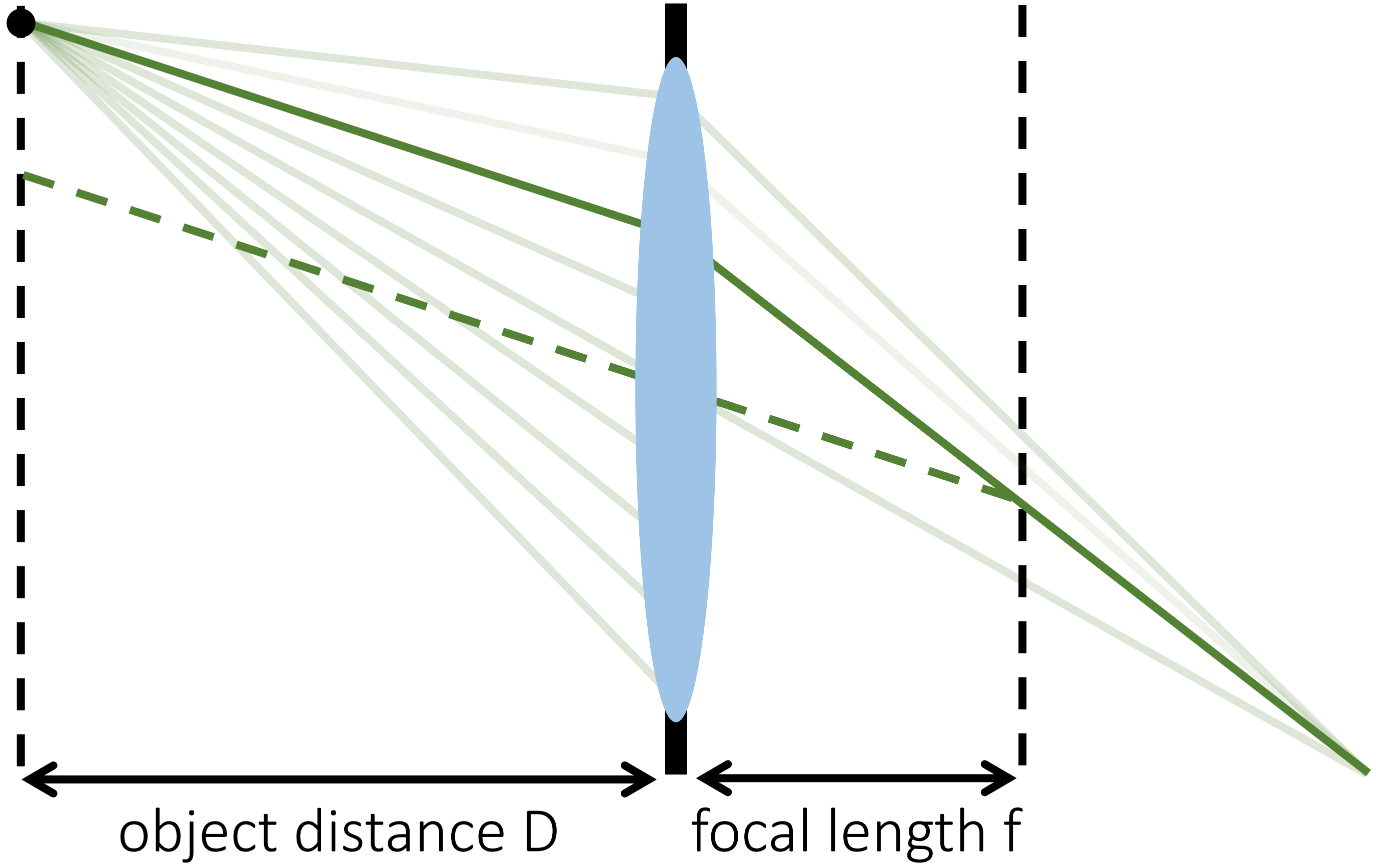

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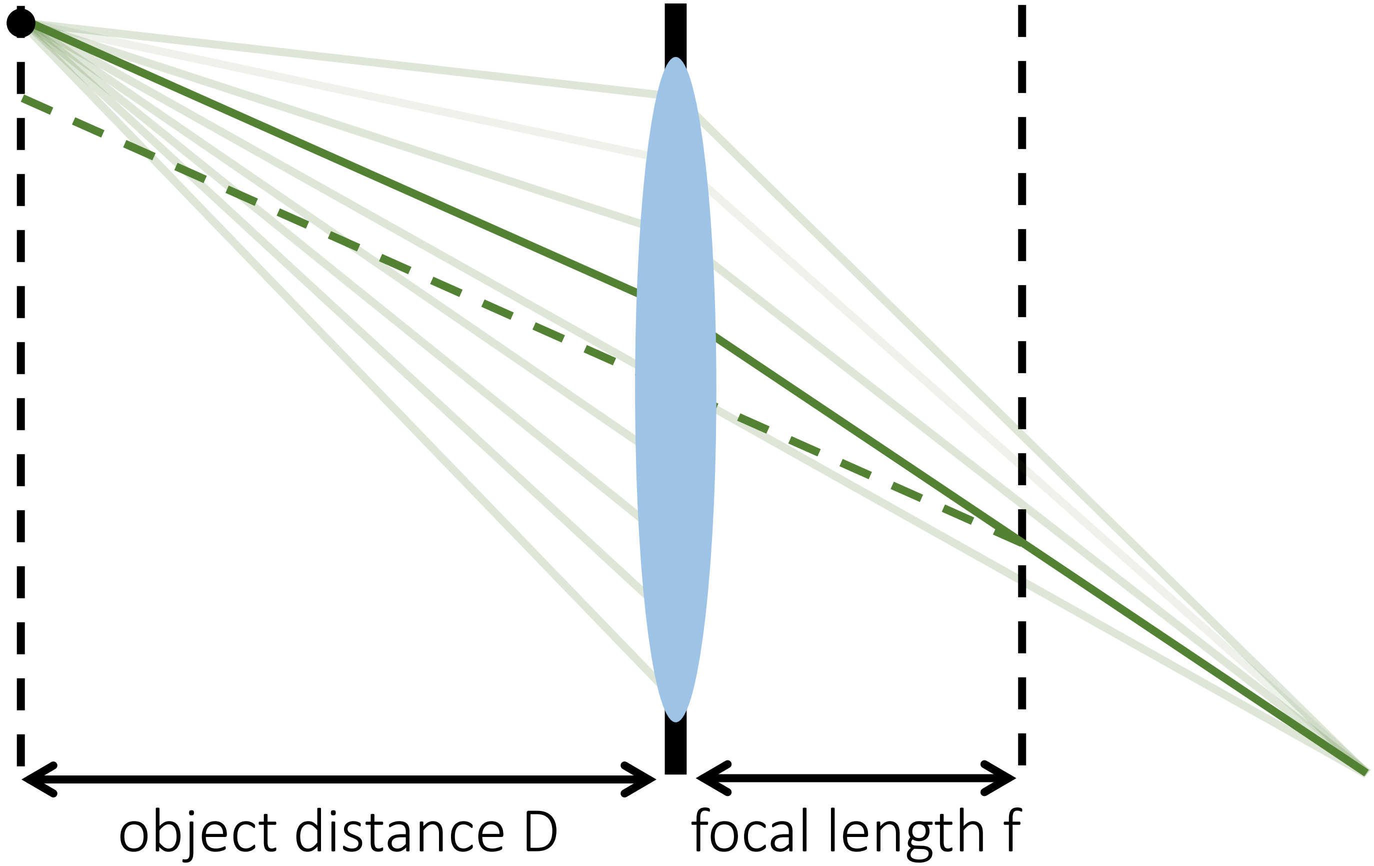

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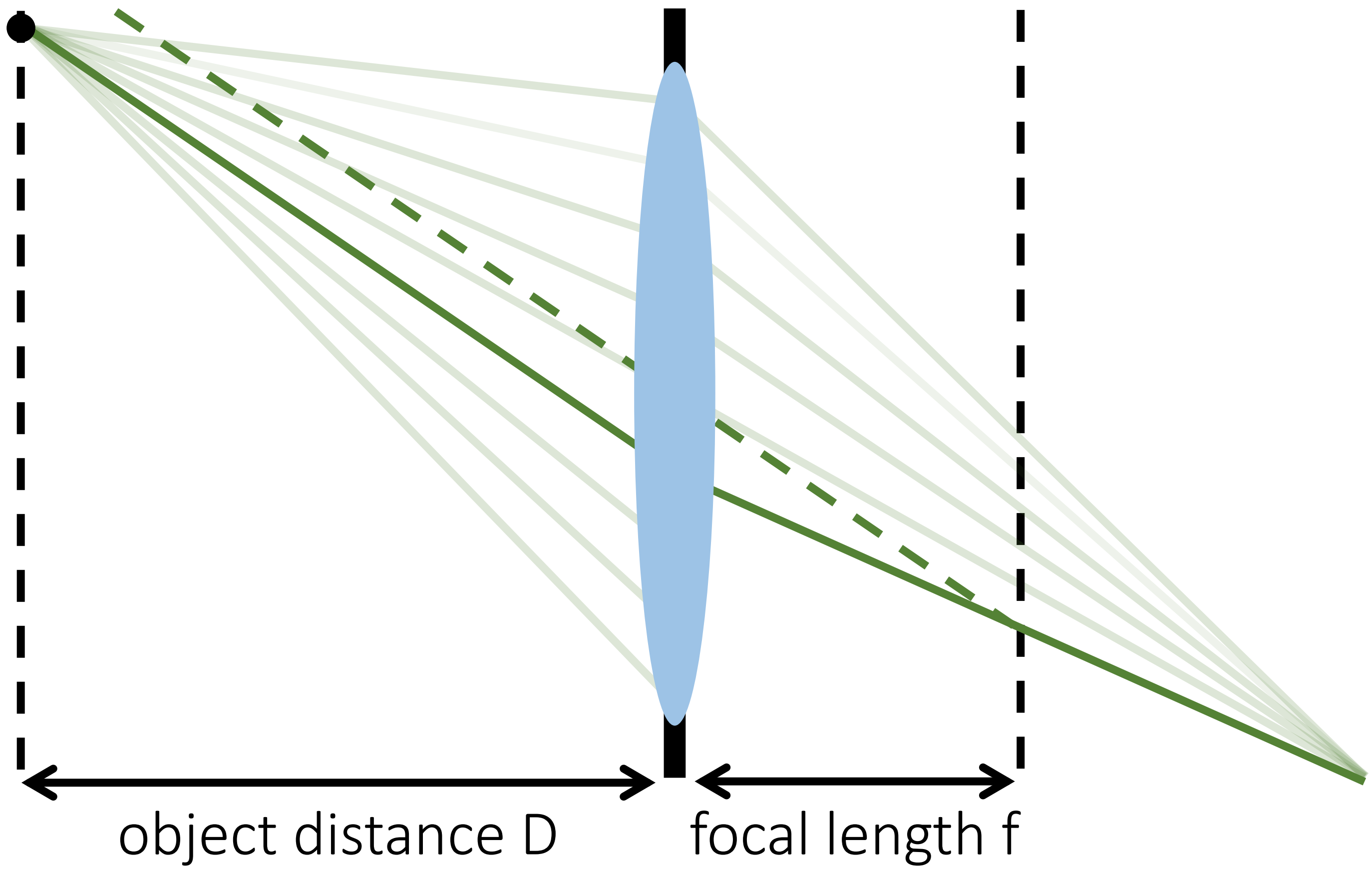

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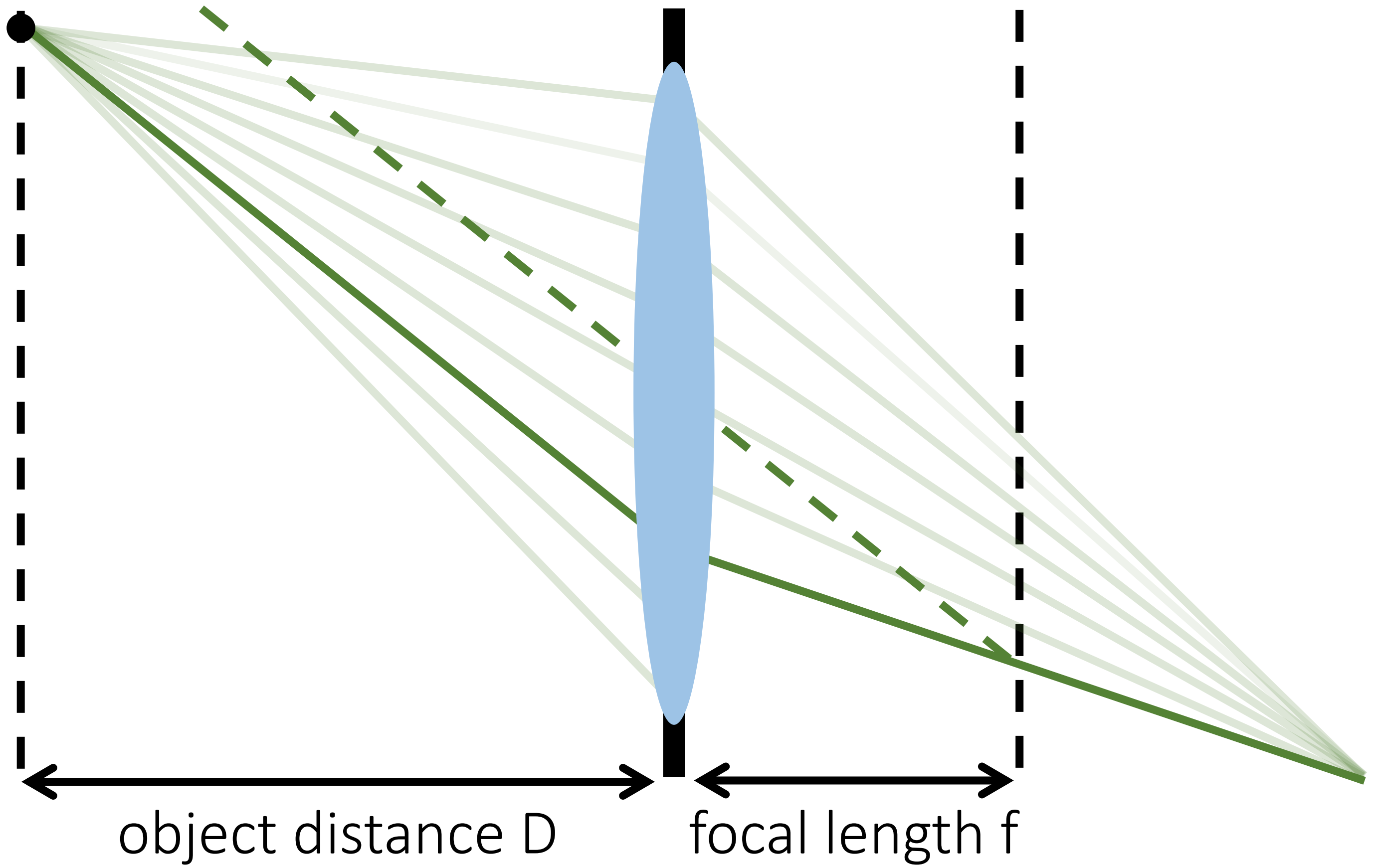

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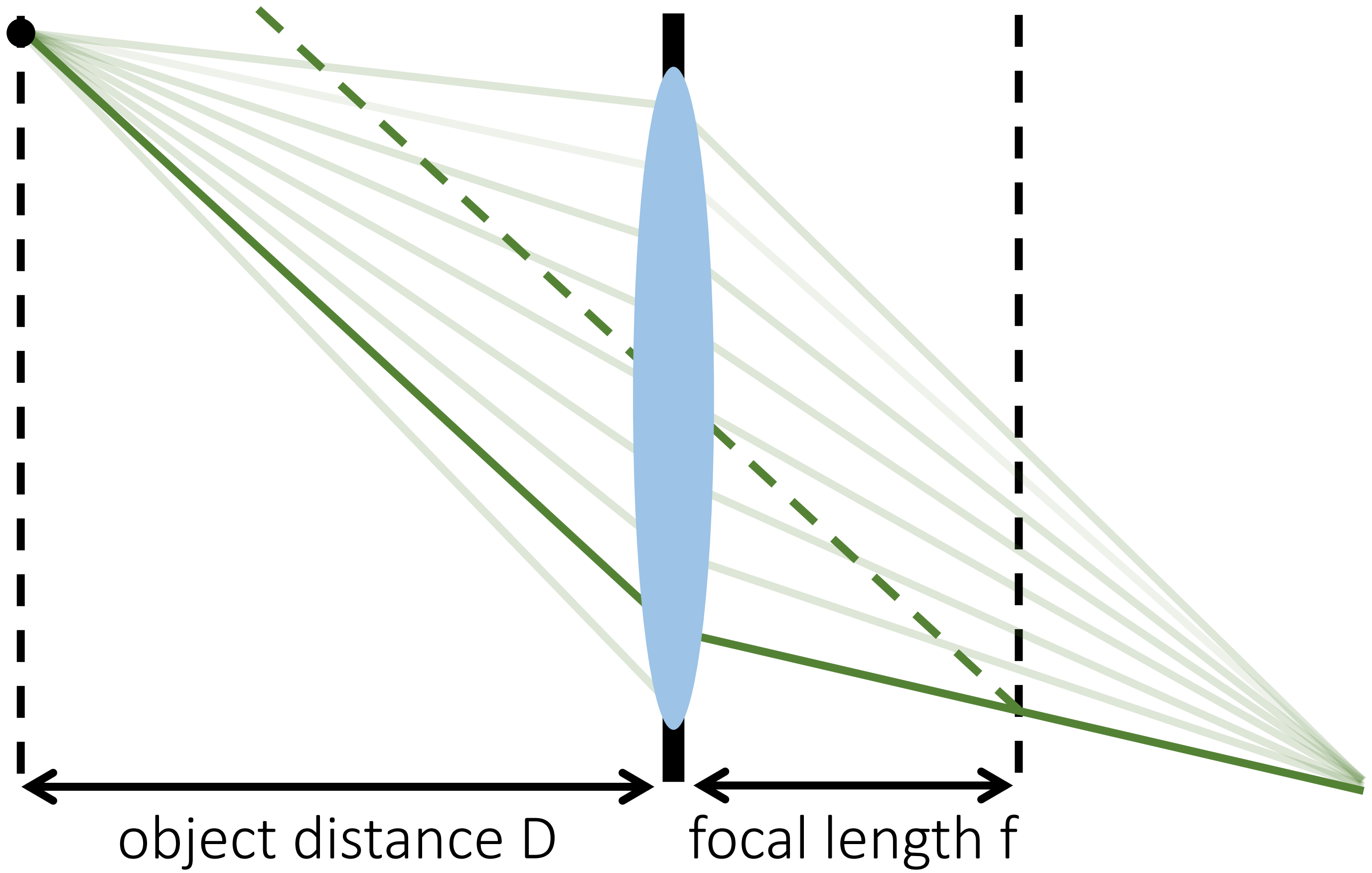

Tracing rays through a thin lens

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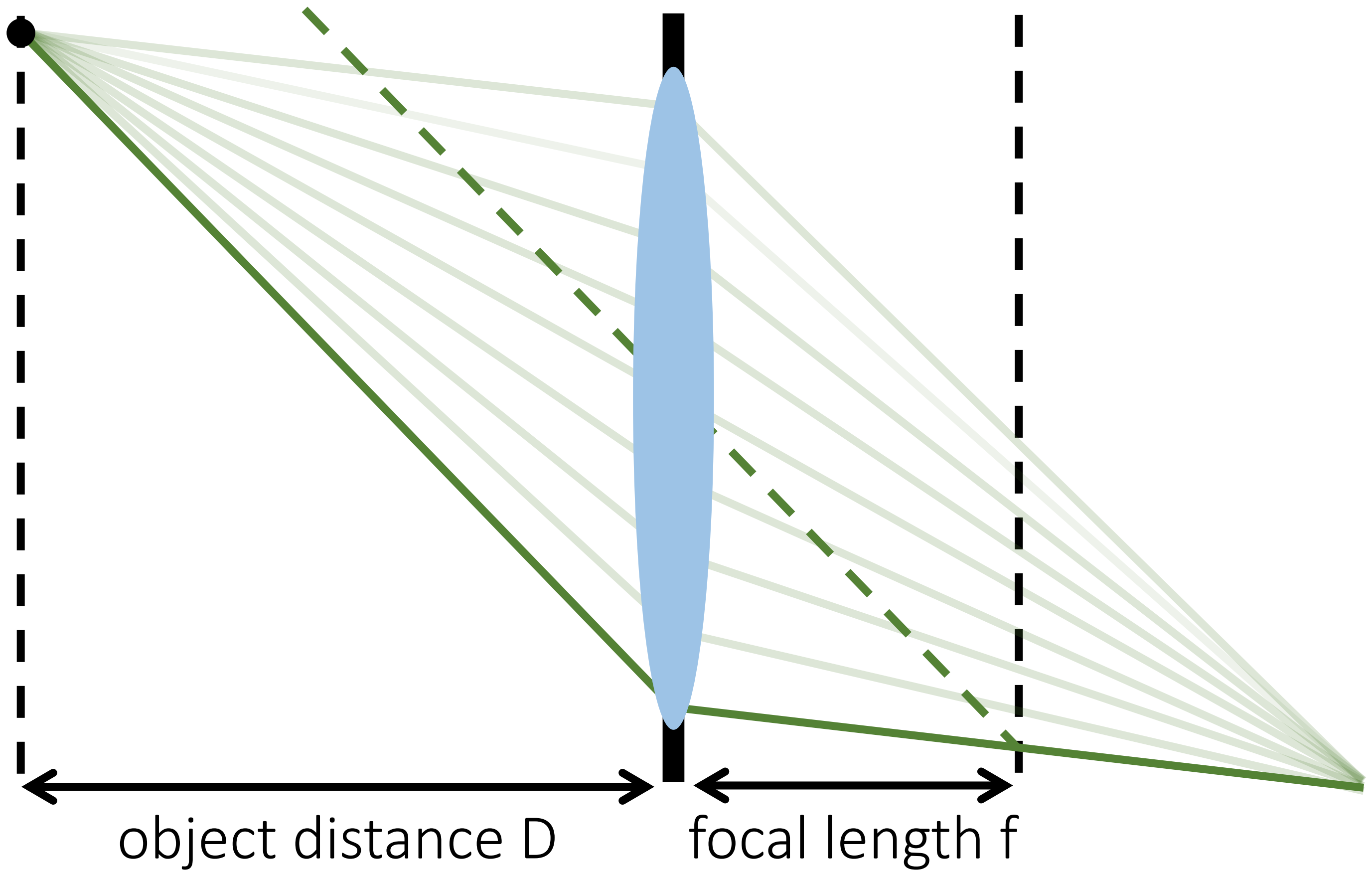

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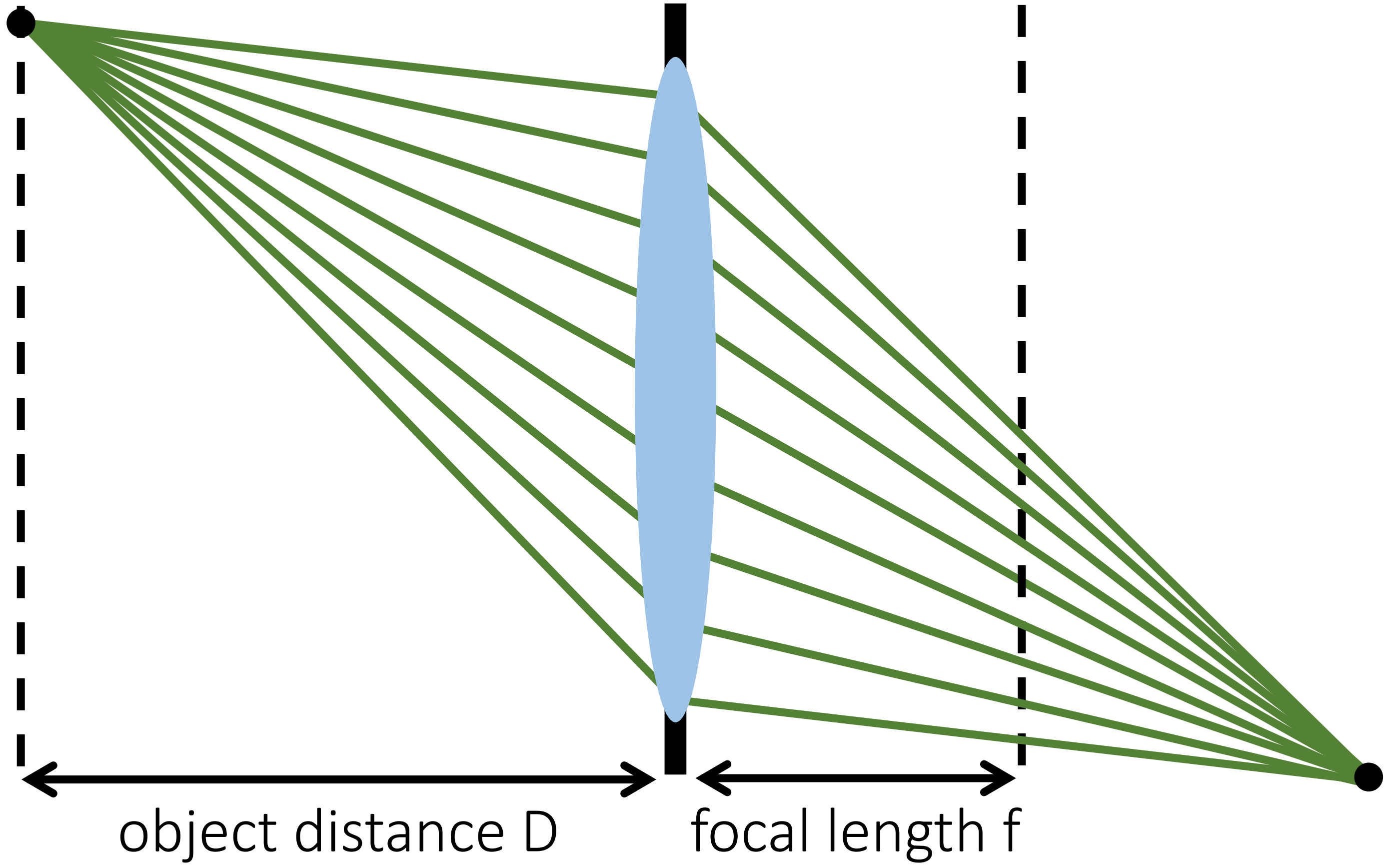

Focusing property:

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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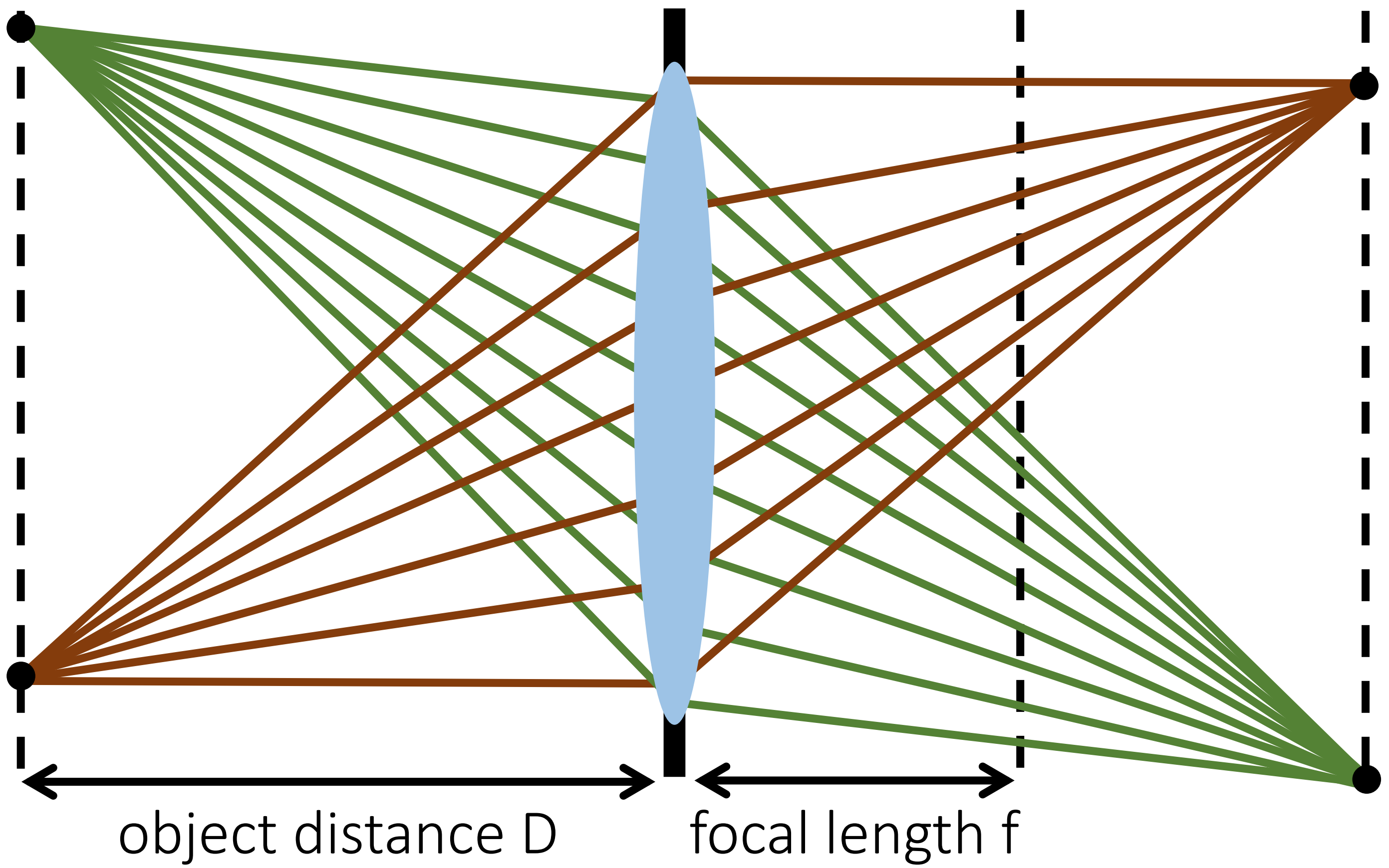
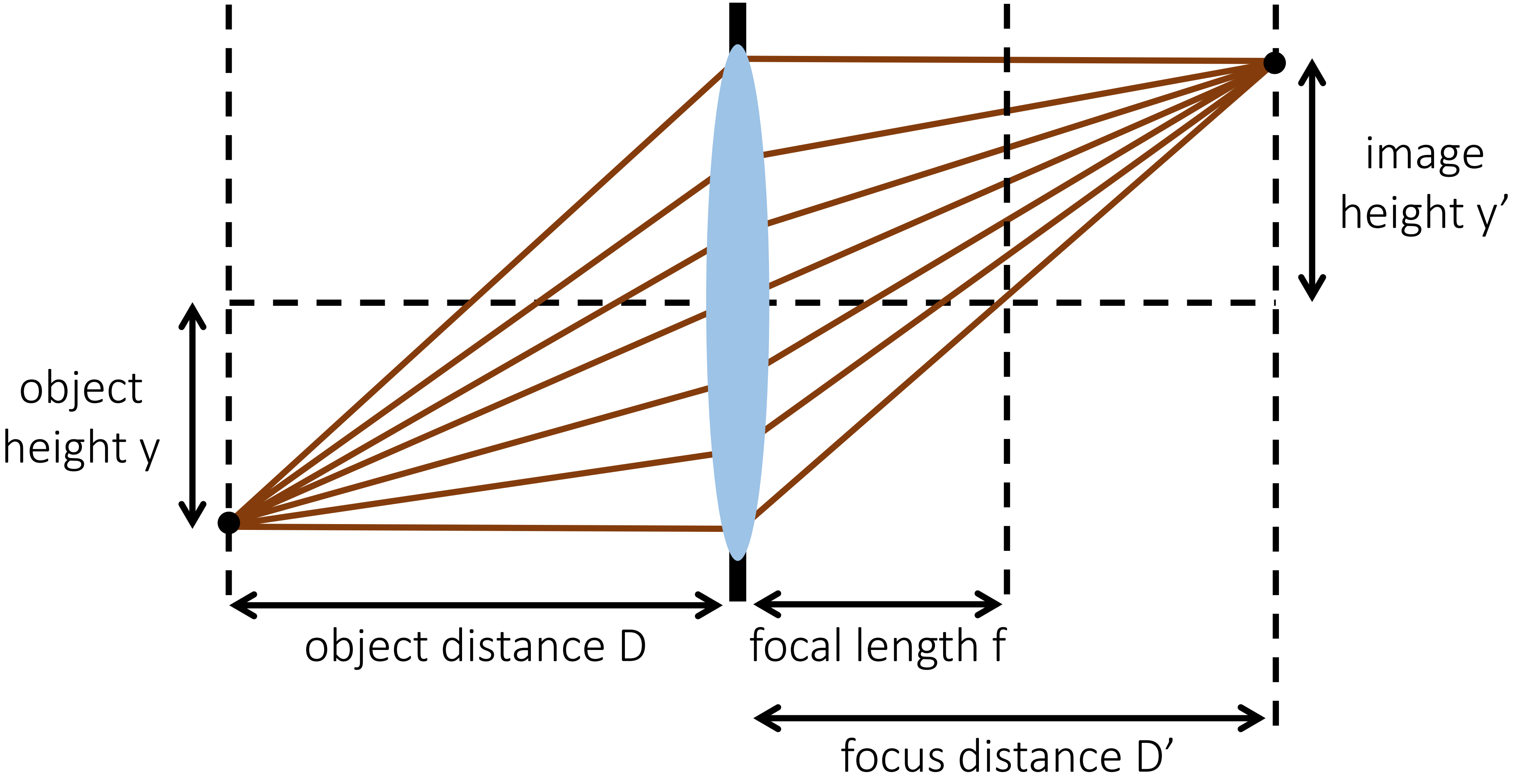


Focusing property:

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 (D, y) and image space (D’, y’) quantities?



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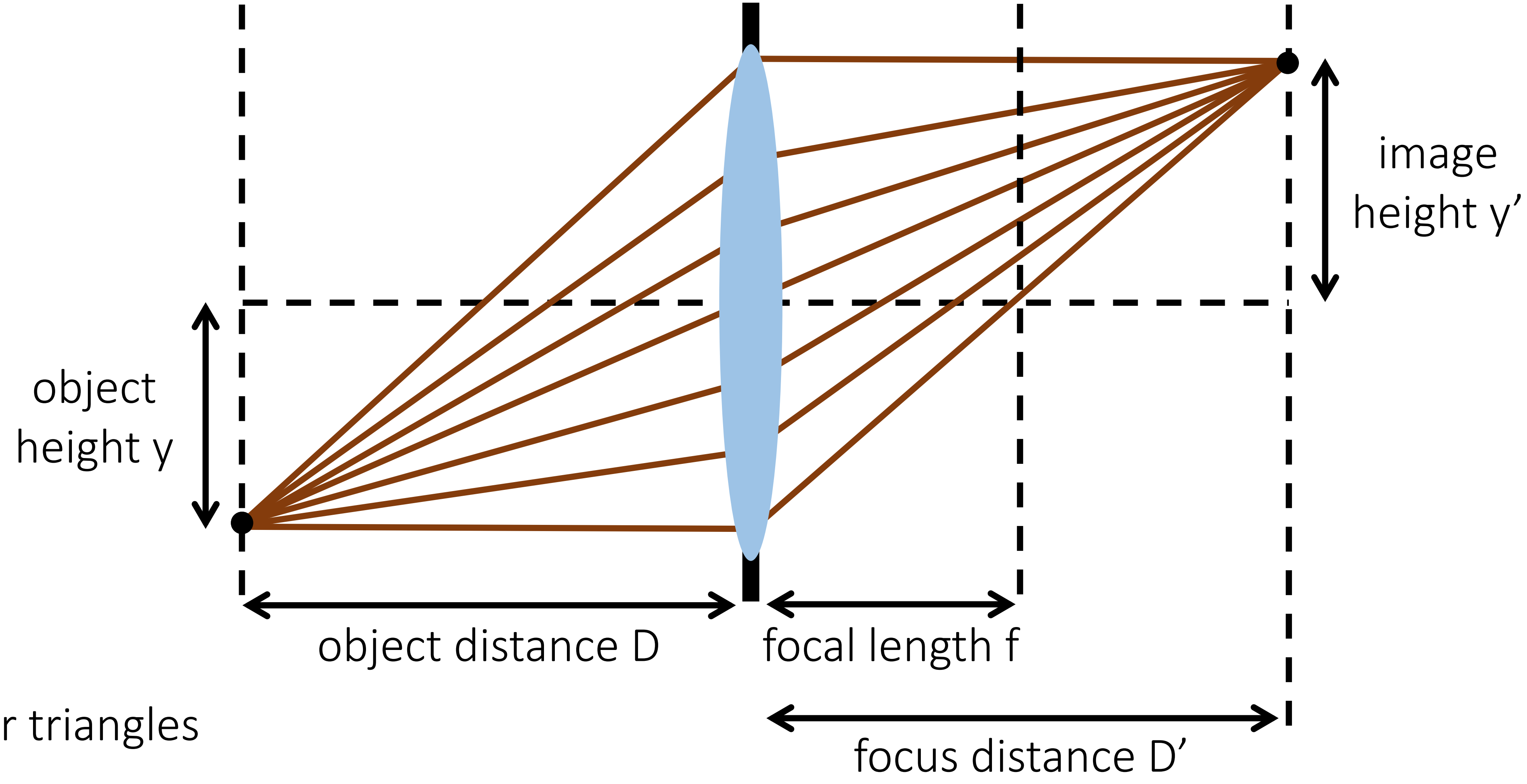
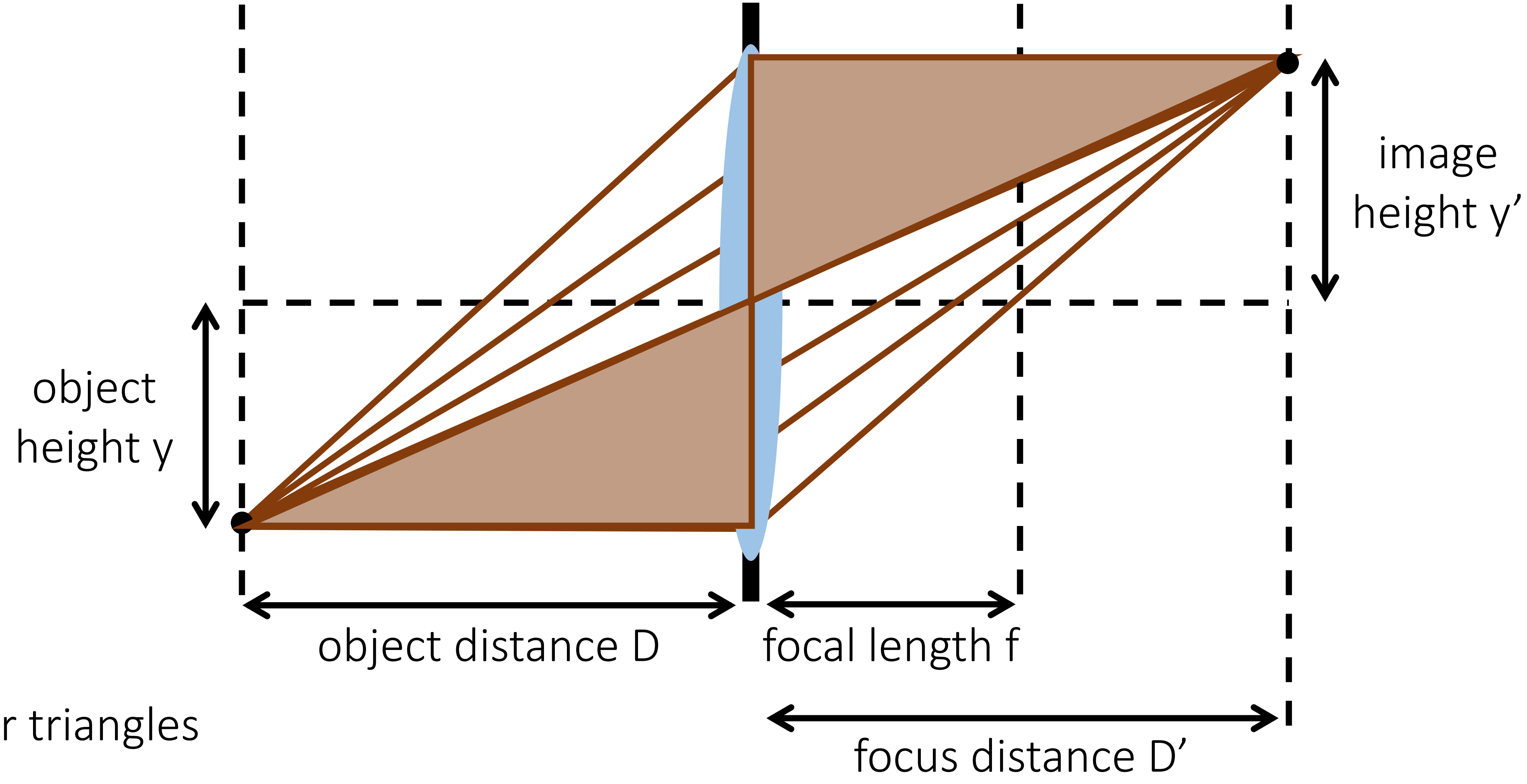


Use similar triangles

Gaussian lens formula

How can we relate scene-space (D, y) and image space (D’, y’) quantities?

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

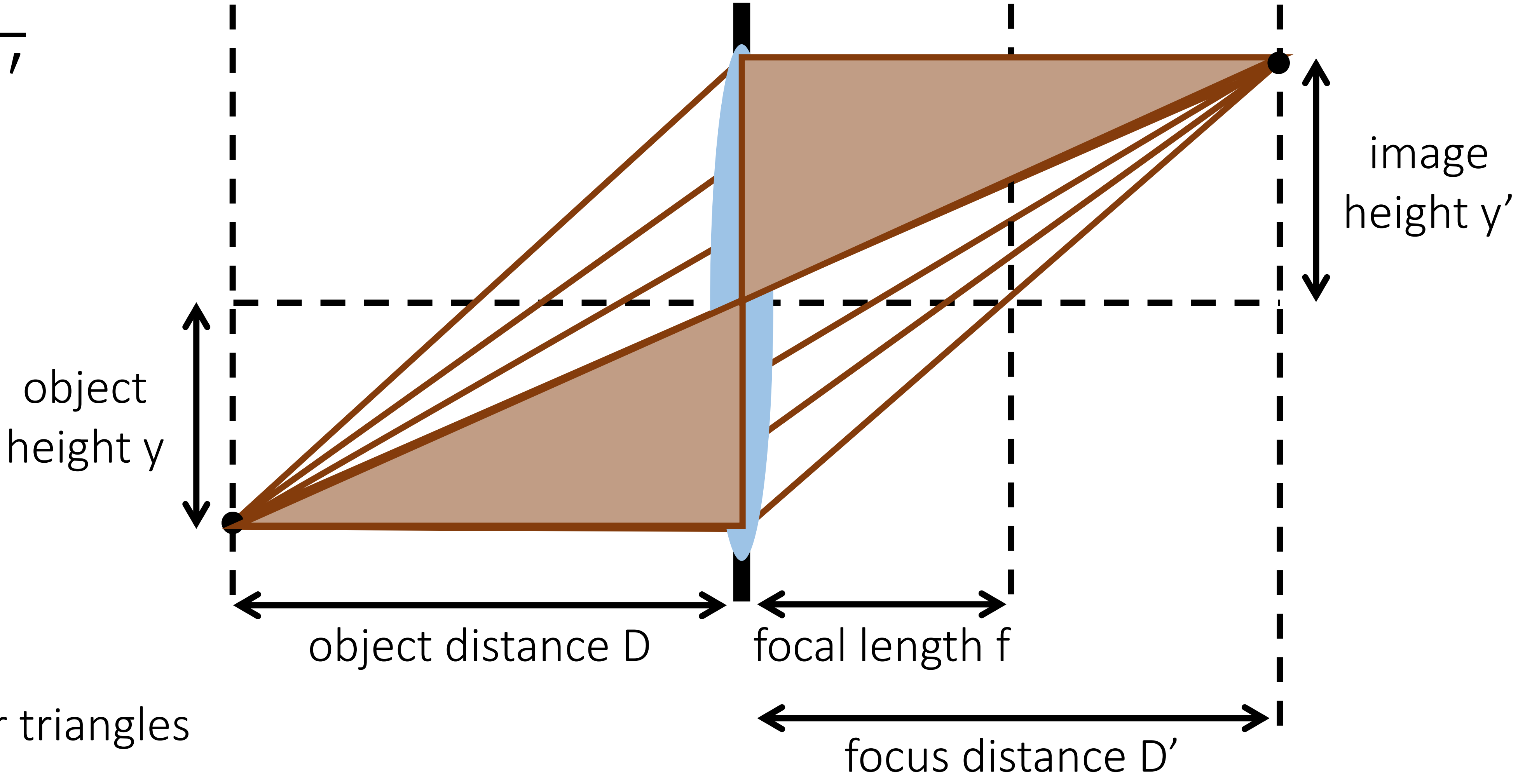


Use similar triangles

Gaussian lens formula

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

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



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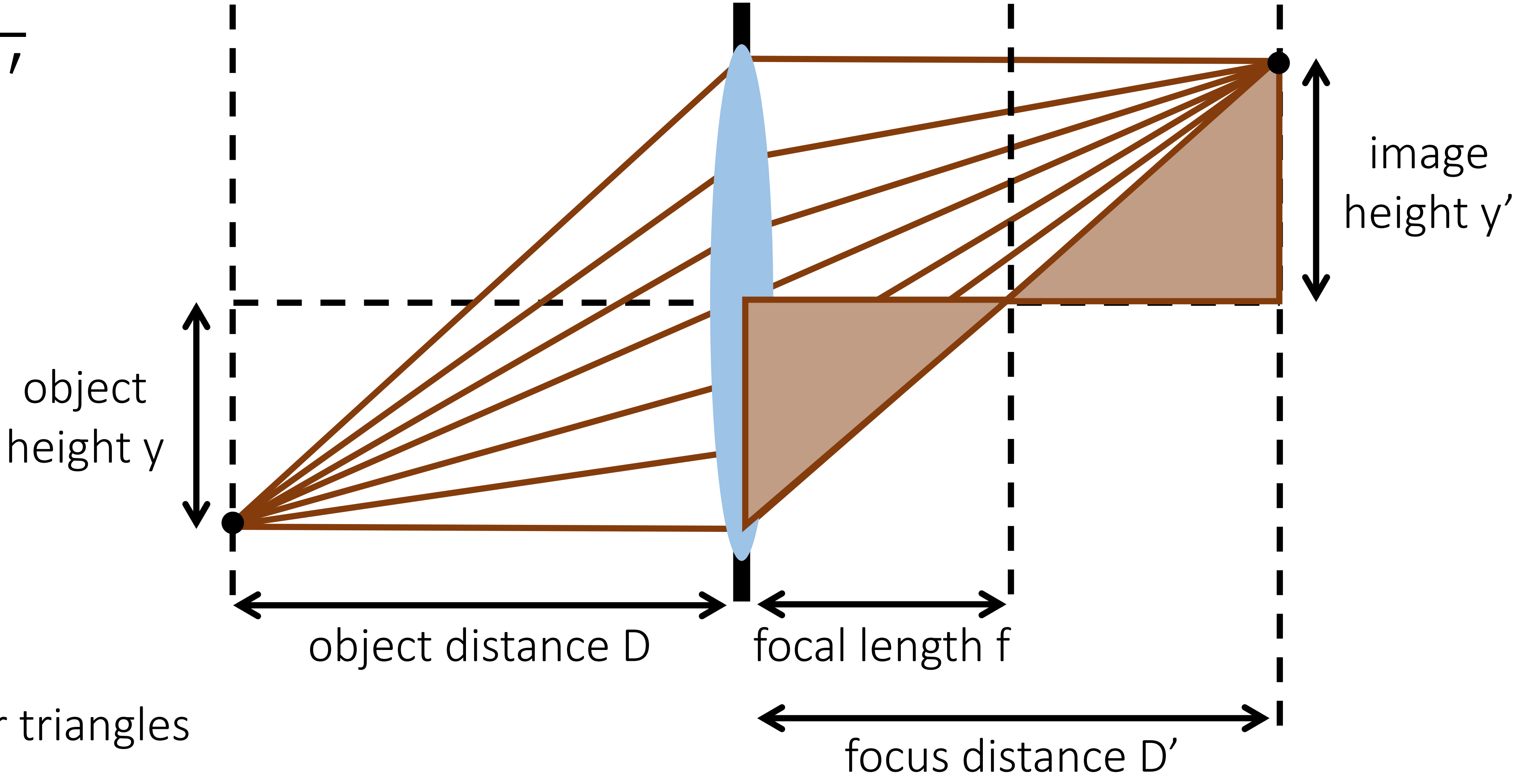


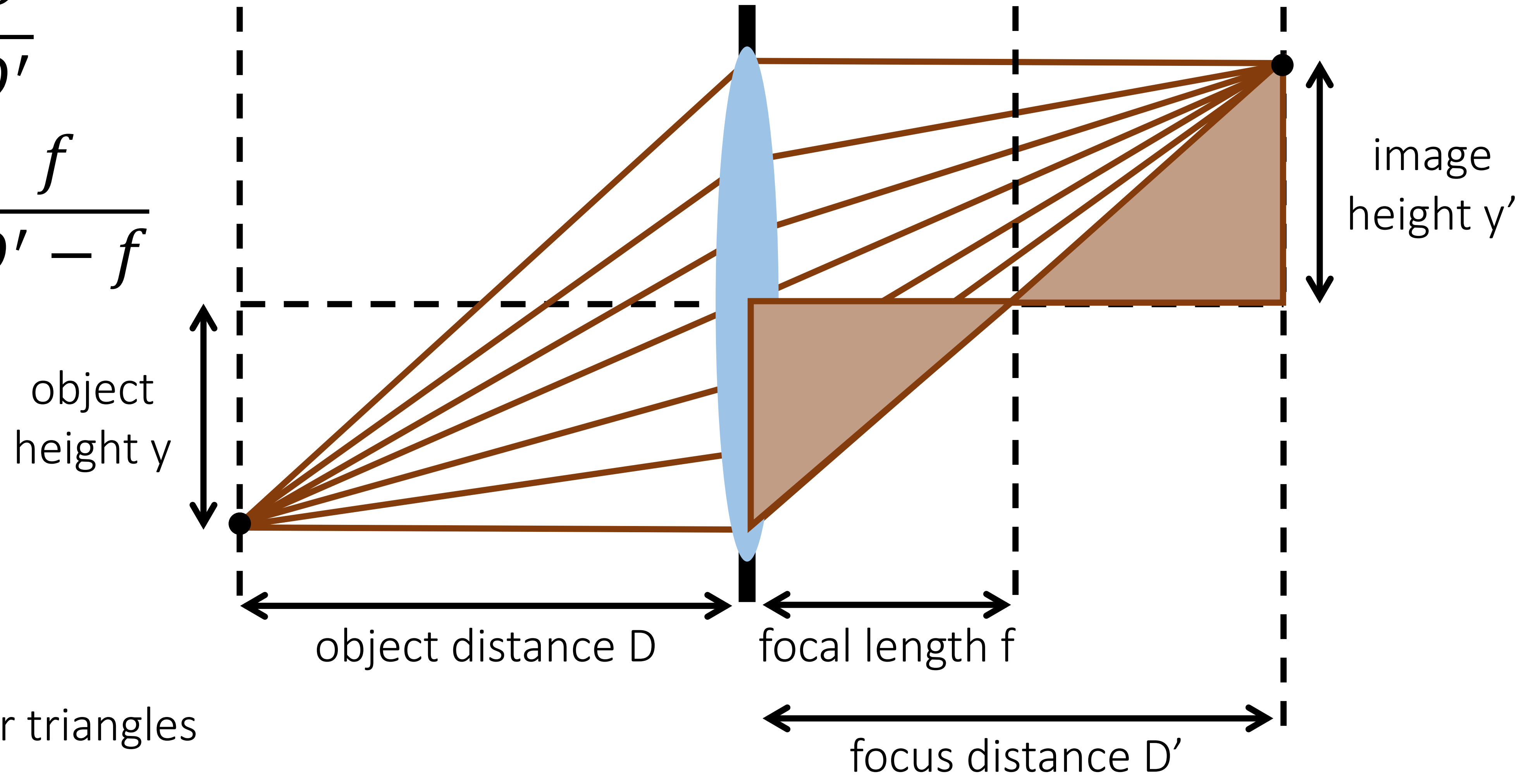
Use similar triangles

Gaussian lens formula

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

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

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



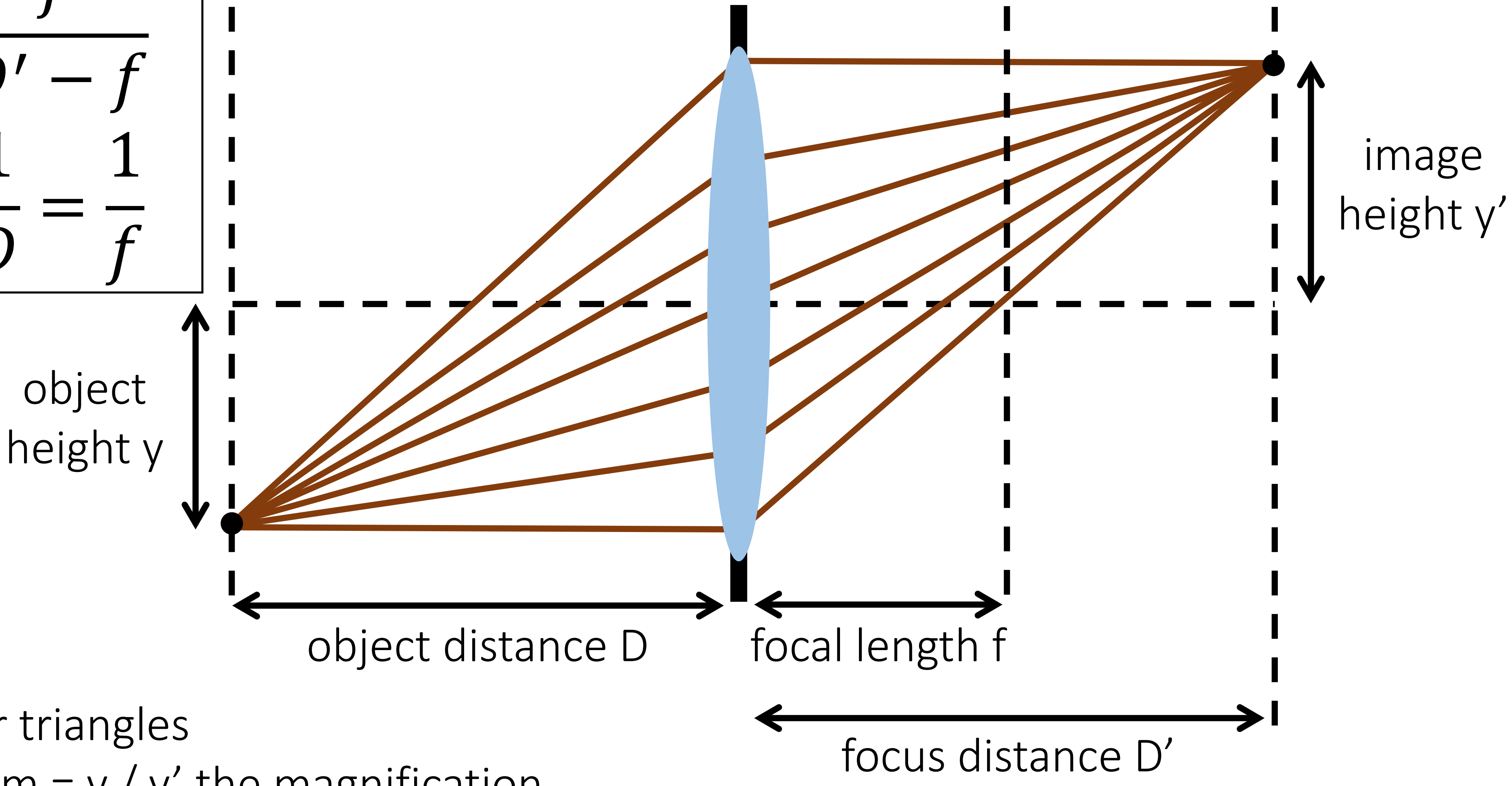
Use similar triangles

Gaussian lens formula

How can we relate scene-space (D, y) and image space (D’, y’) quantities?

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

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



Use similar triangles

- We call m = y / y’ the magnification

Special focus distances

D' = f, D = ?, m = ?

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

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Special focus distances

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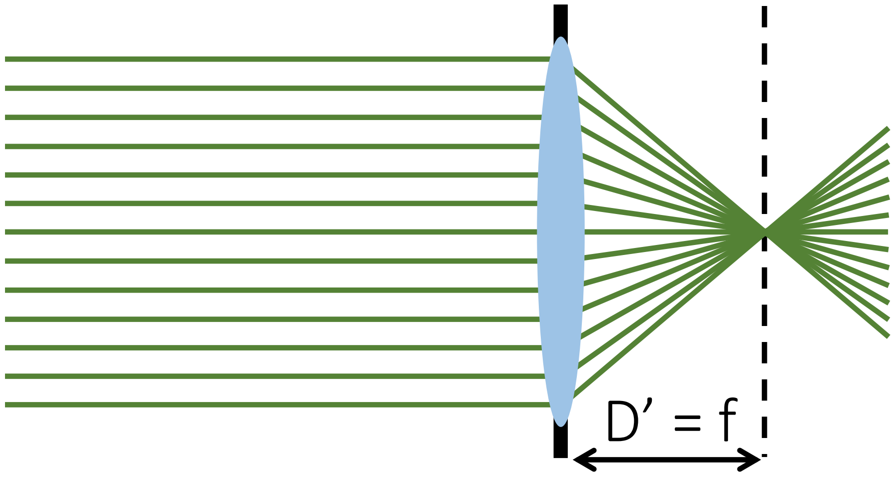
D’ = f, D = ∞, m = ∞ → infinity focus (parallel rays)



D’ = D = ?, m = ?

Special focus distances

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

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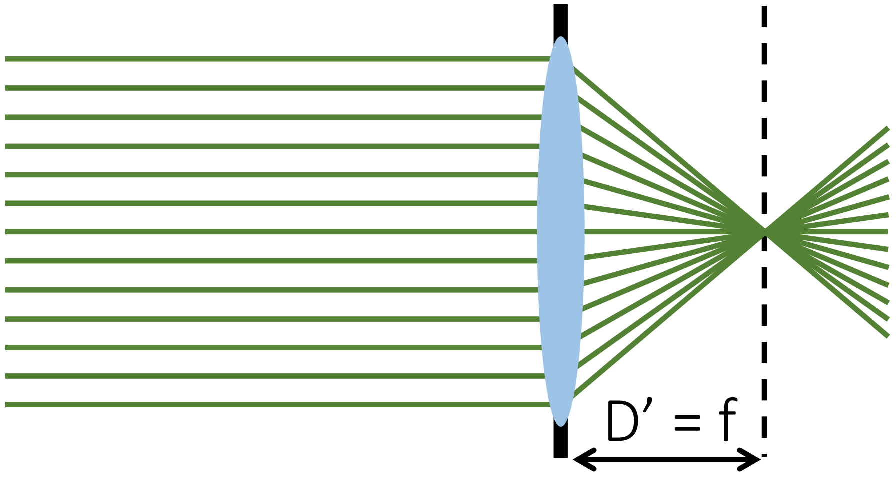
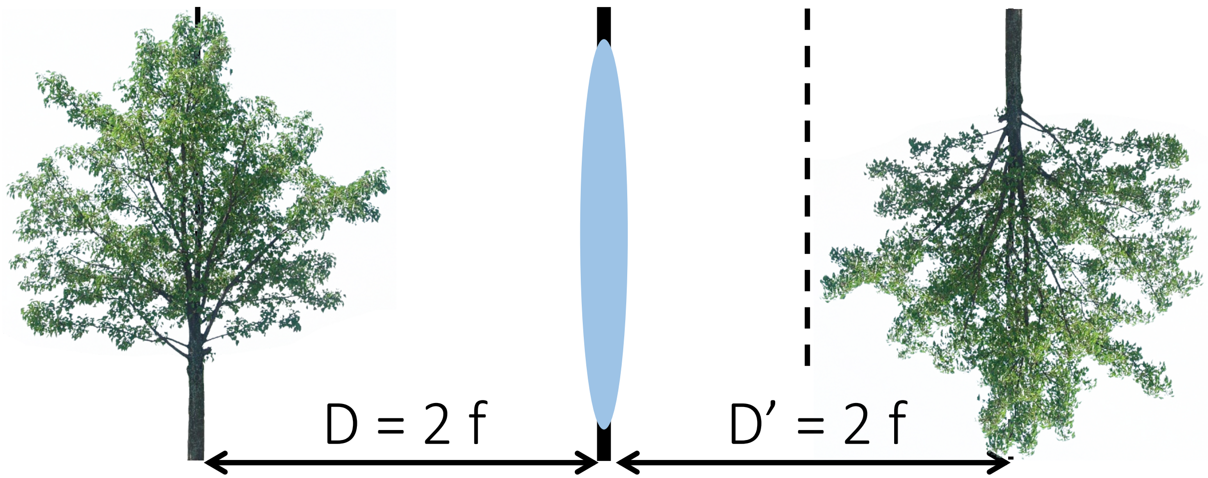
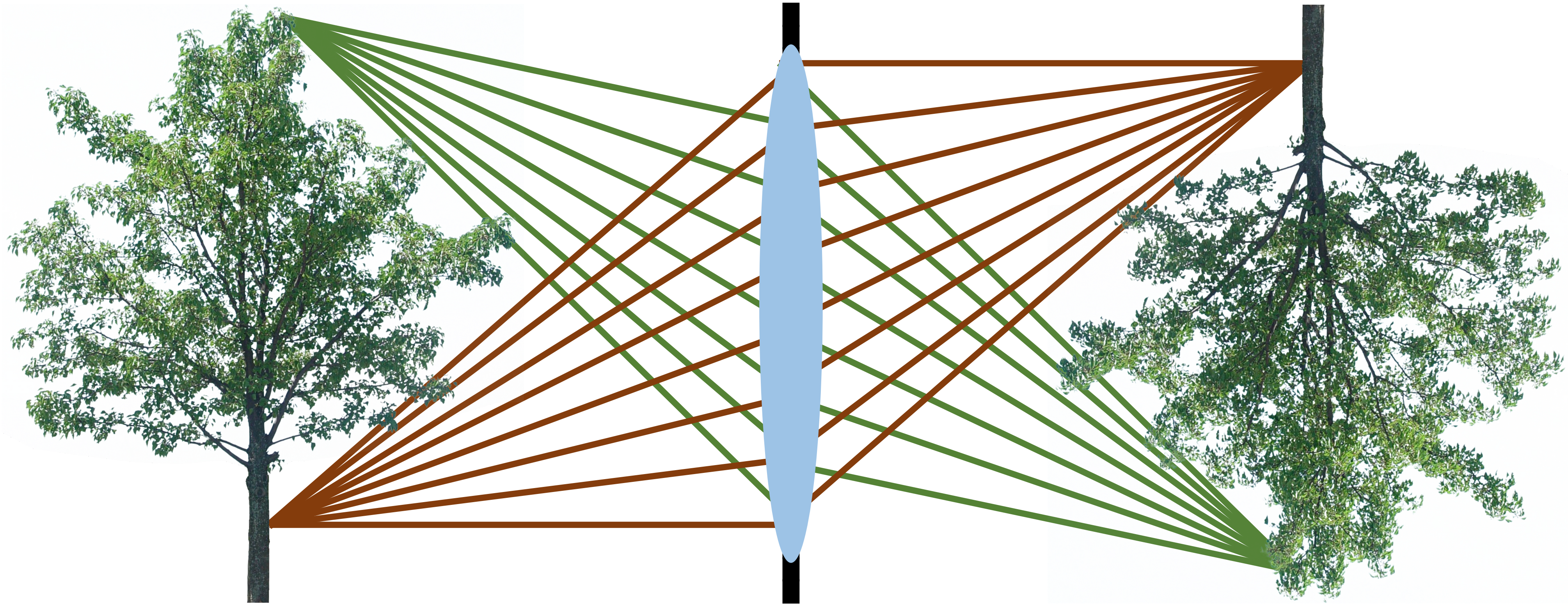


D’ = D = 2 f, m = 1 → object is reproduced in real-life size



Free lunch?



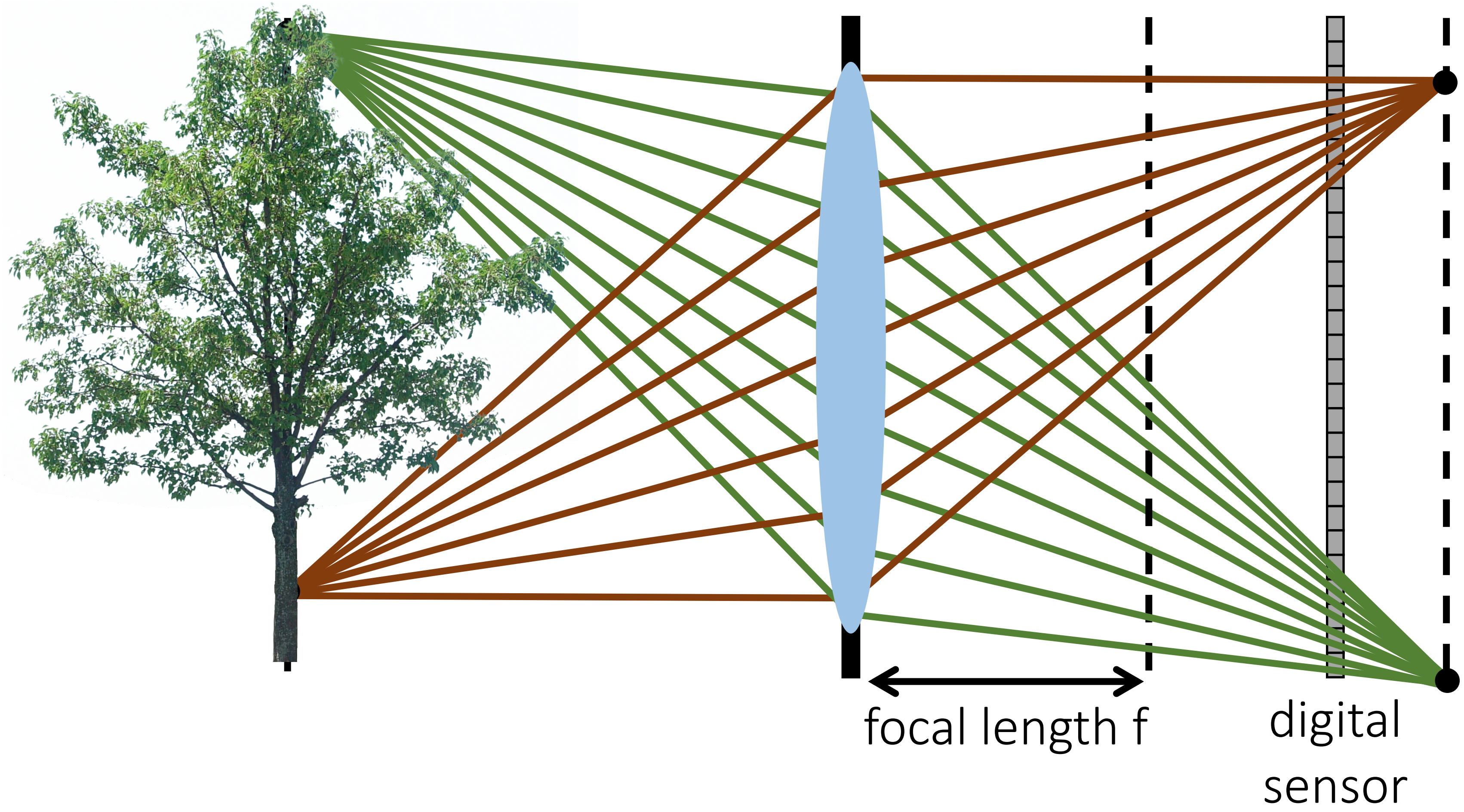
By using a lens we simultaneously achieve:

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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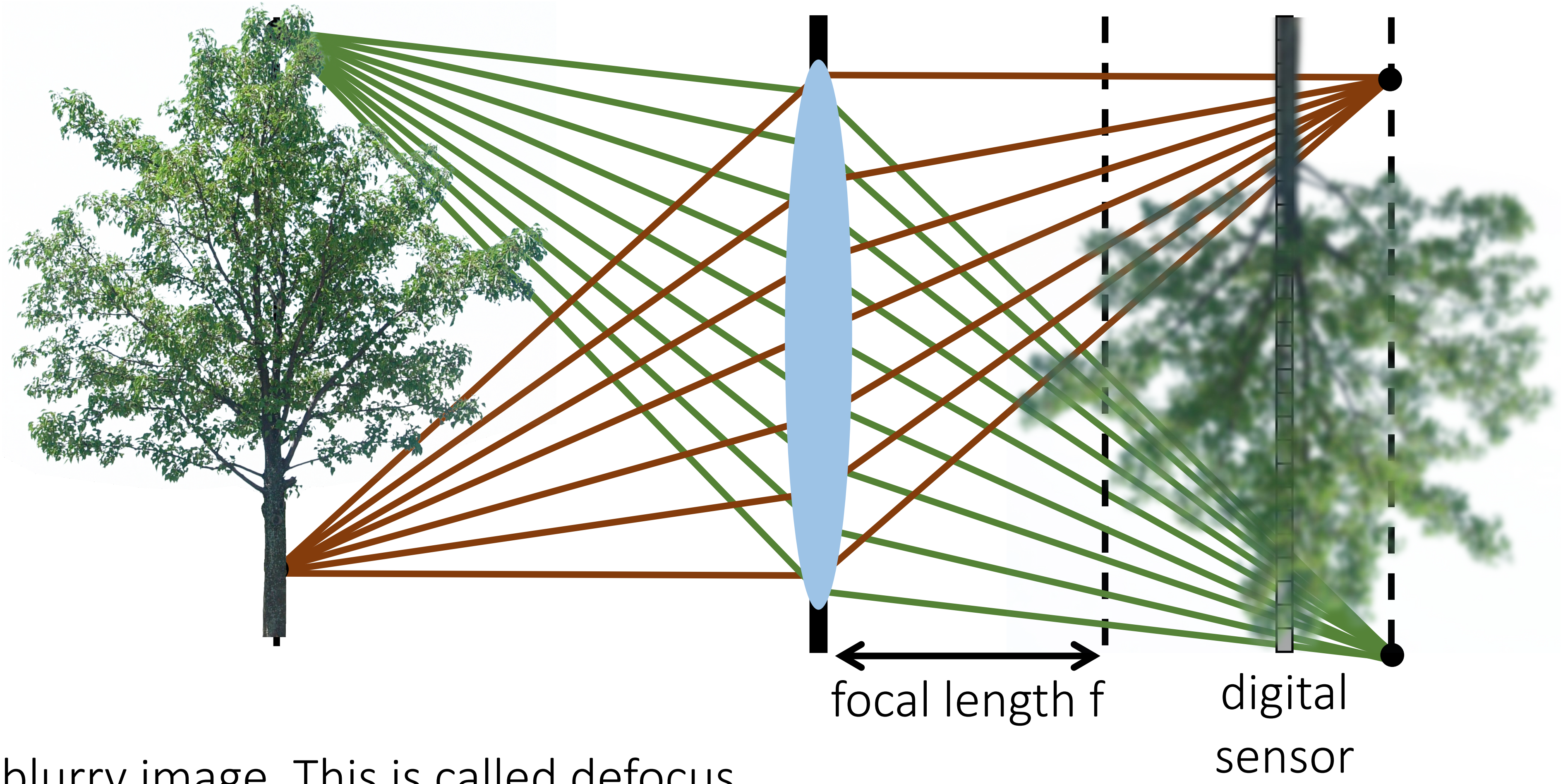


We get a blurry image. This is called defocus.

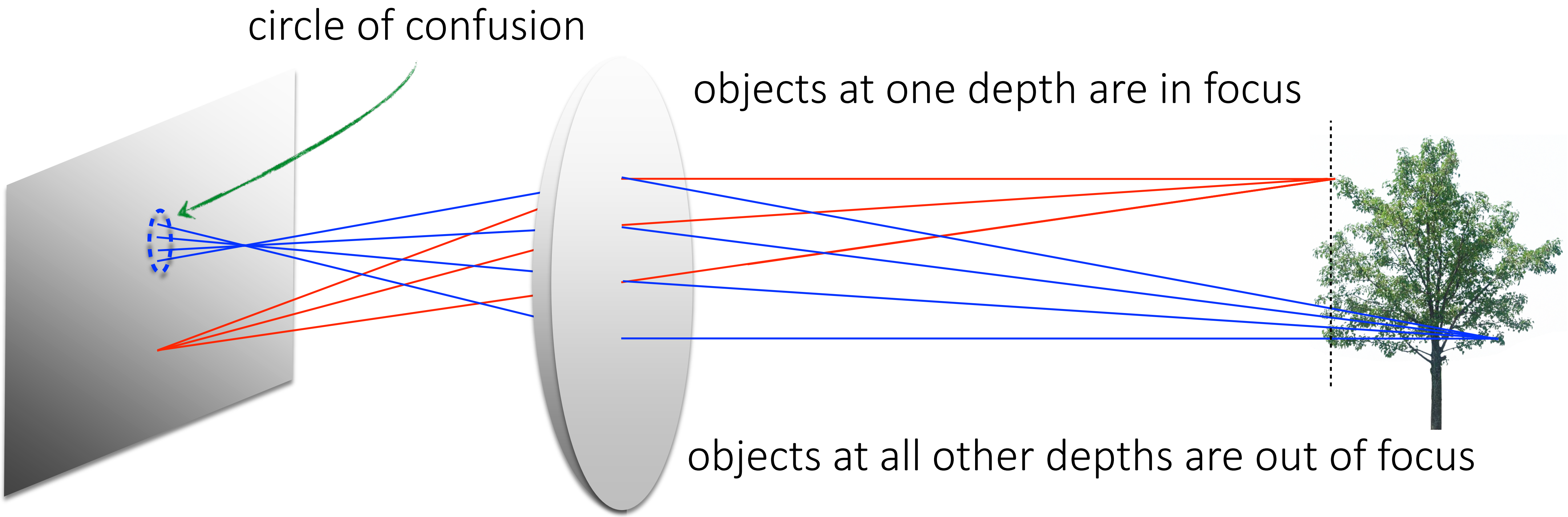
- Defocus never happens with a pinhole camera.

Defocus

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

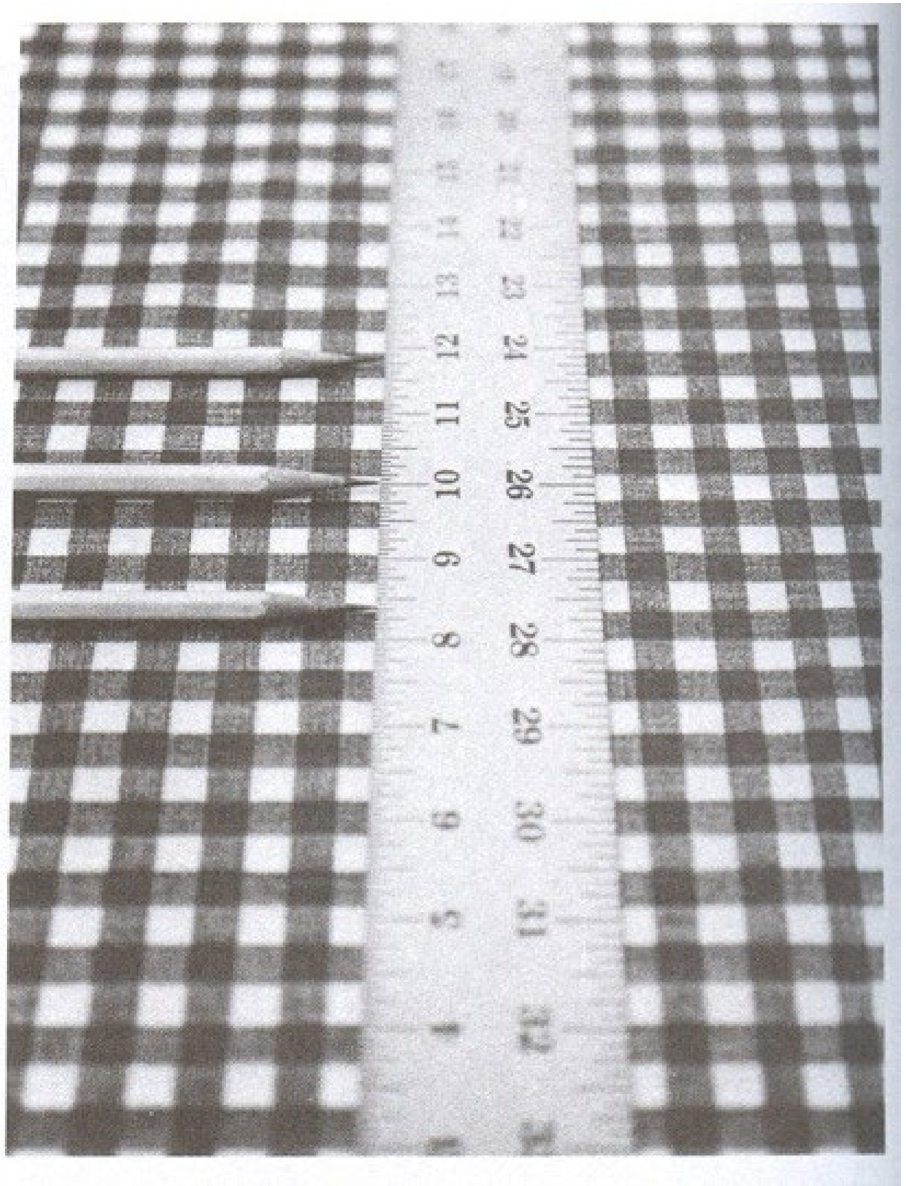
Defocus

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.

Change of focus for different depths



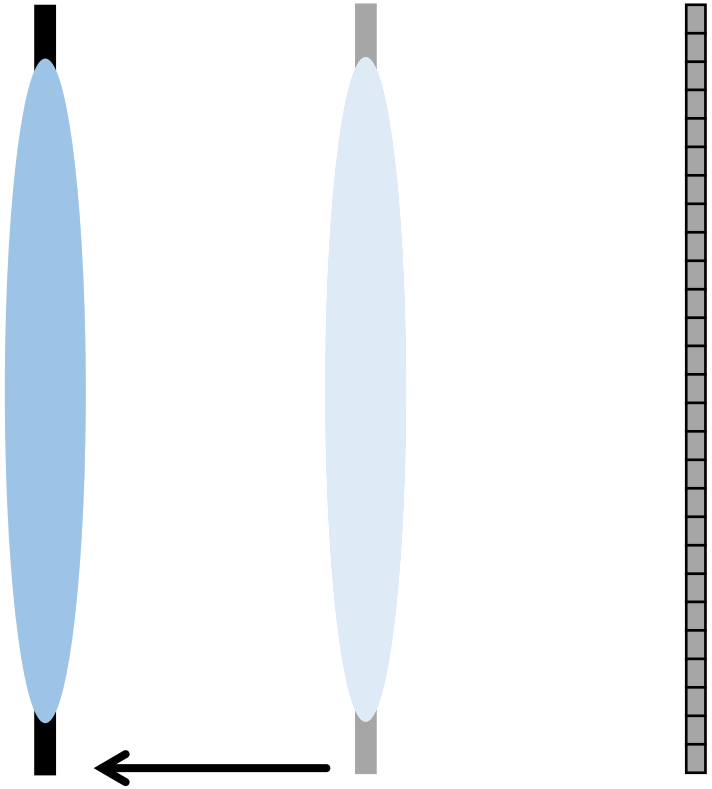
How do I control what is in focus?

How do I control what is in focus?

I change the distance between the sensor and the lens

How do I control what is in focus?

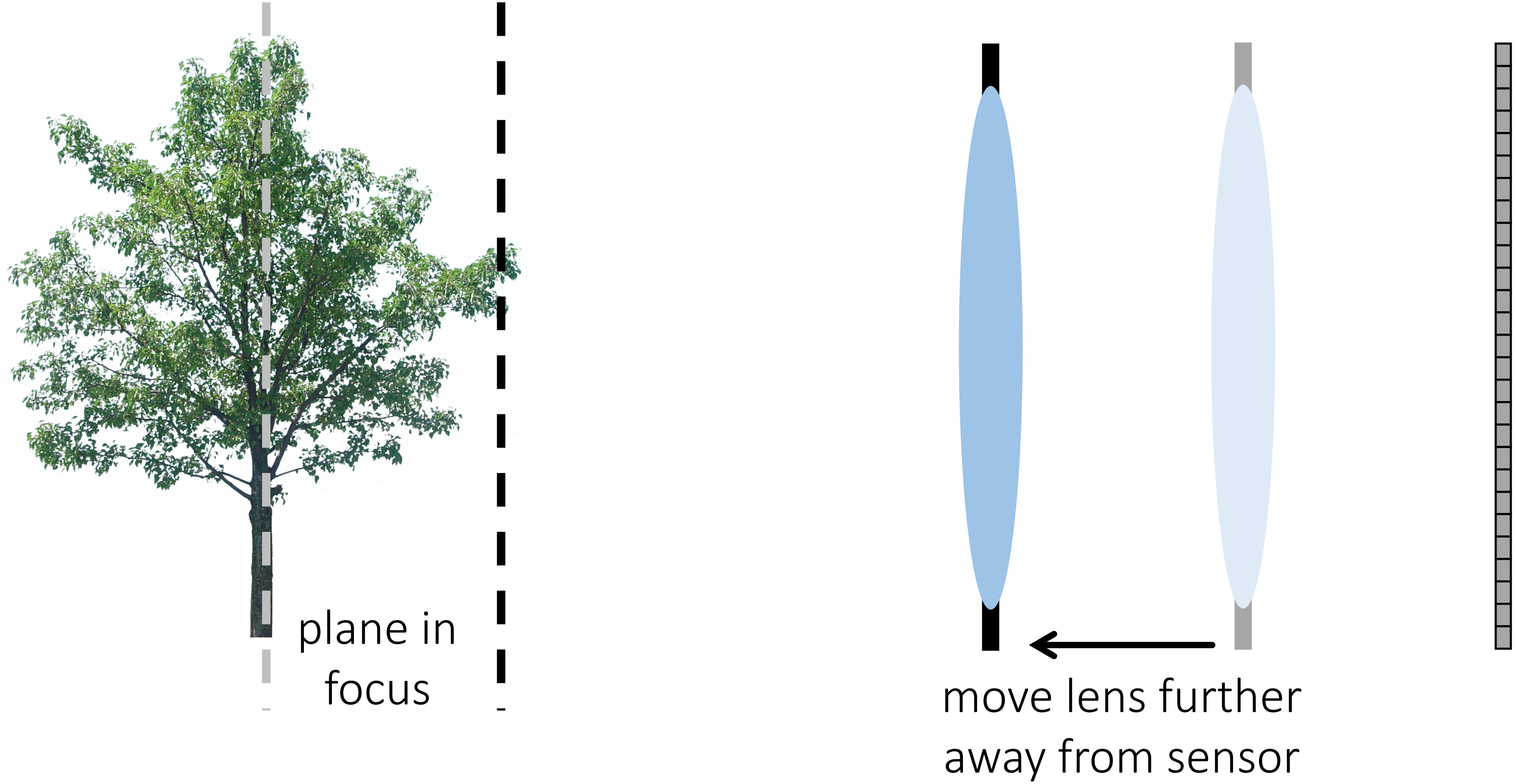
I change the distance between the sensor and the lens



- What happens to plane in focus?

How do I control what is in focus?

I change the distance between the sensor and the lens



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

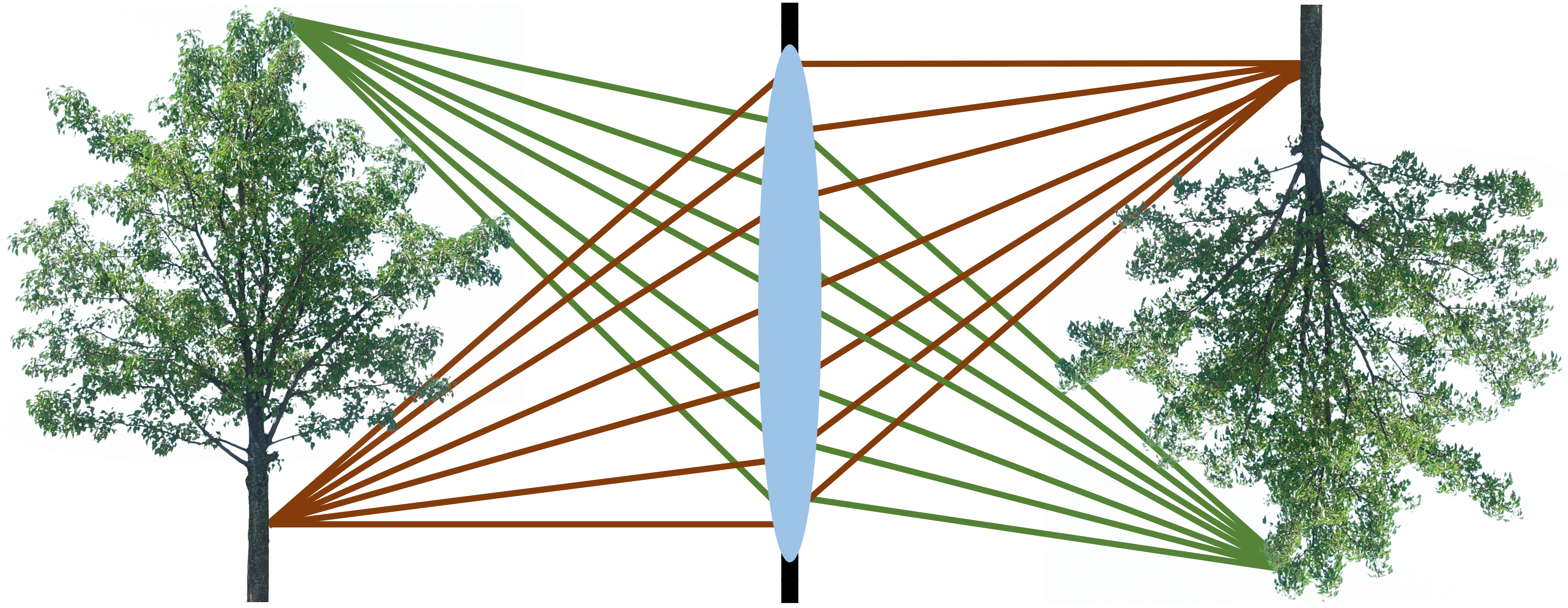
The lens on your camera

Focus ring: controls distance of lens from sensor

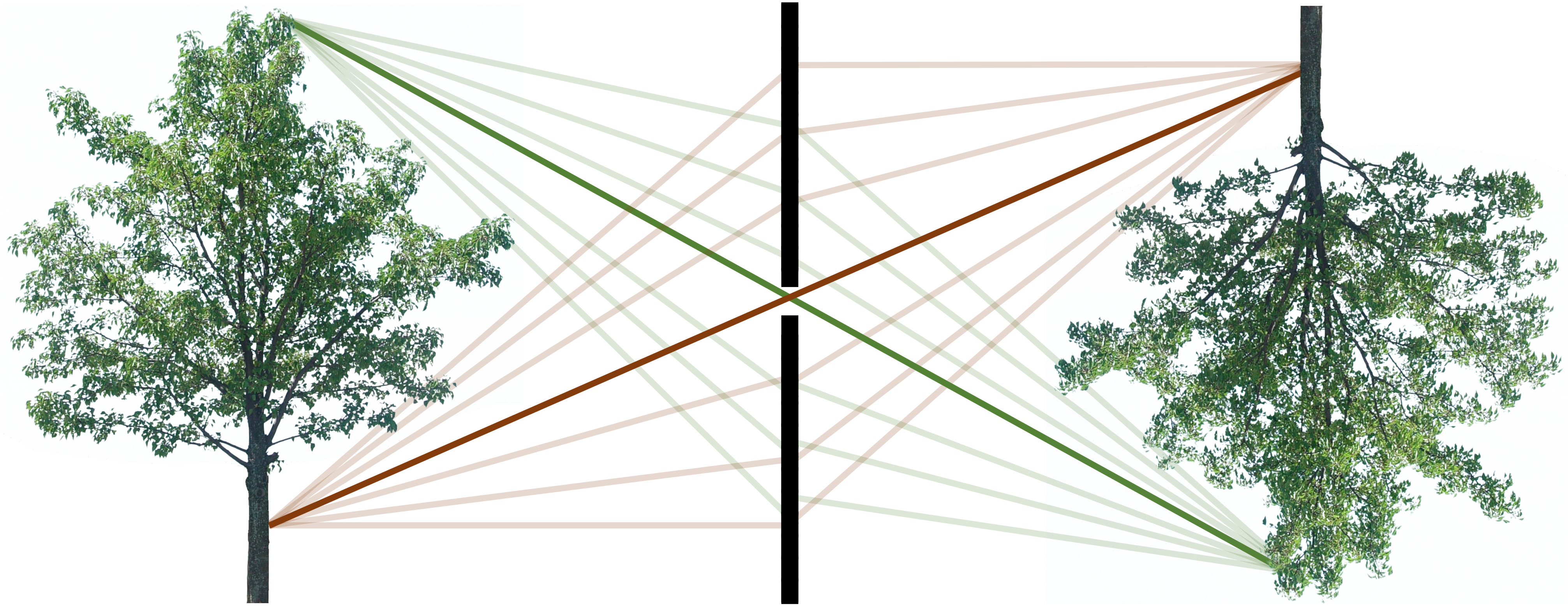
Sequence of images at different focus settings

Lens camera and pinhole camera

The lens camera



The pinhole camera



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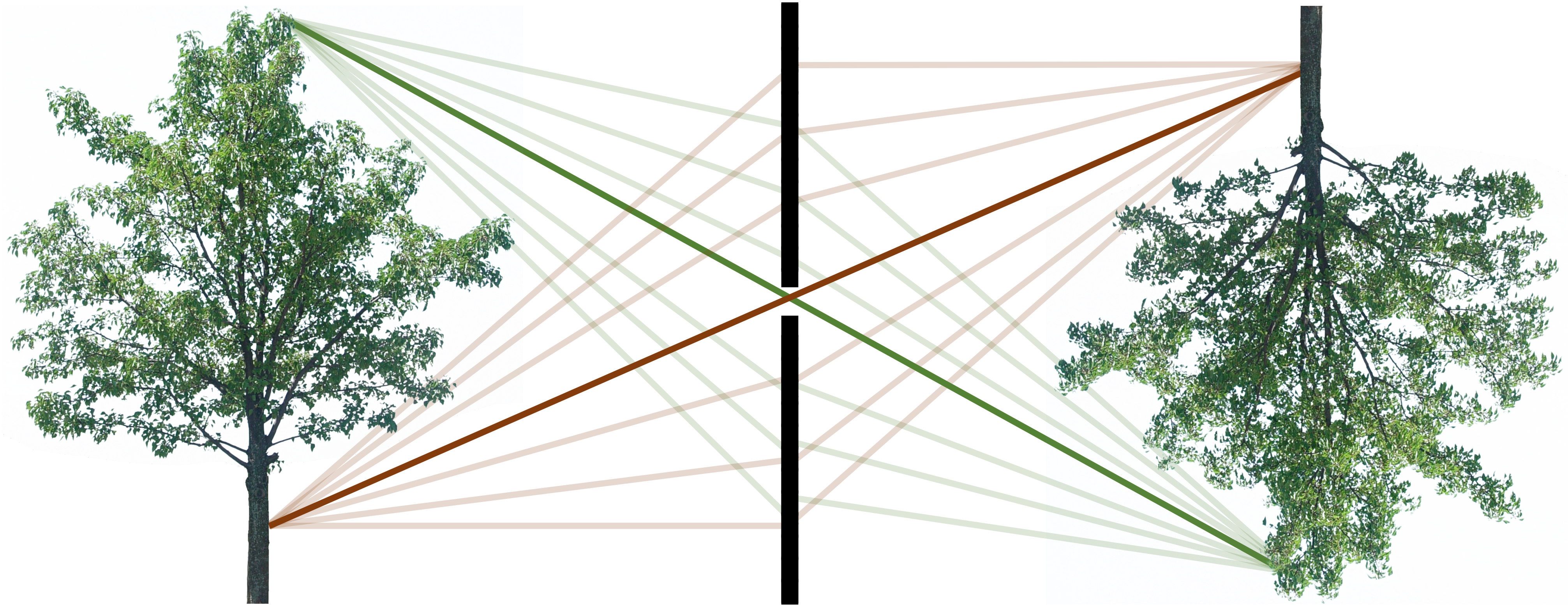
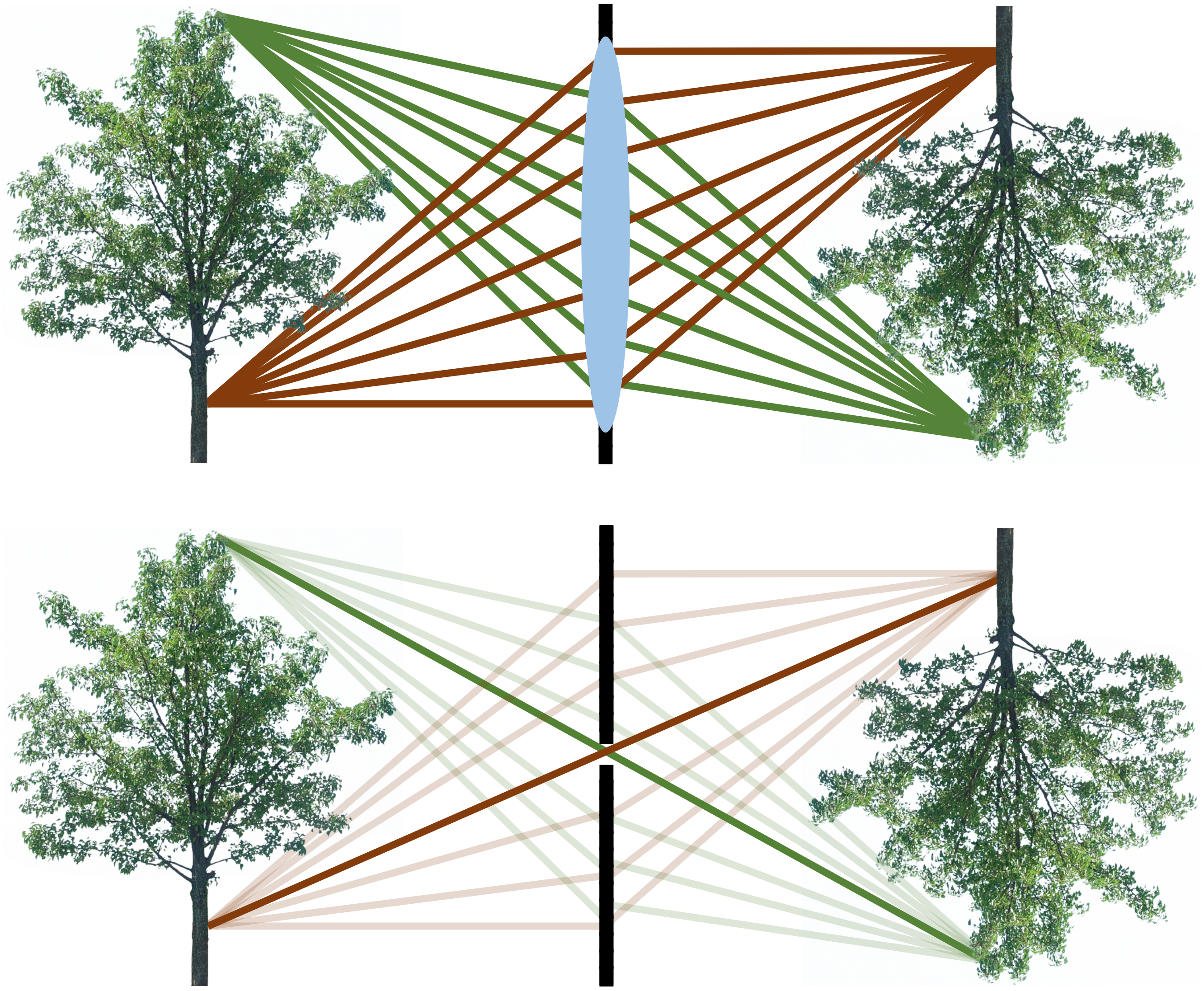


Central rays propagate in the same way for both models!

Describing both lens and pinhole cameras



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

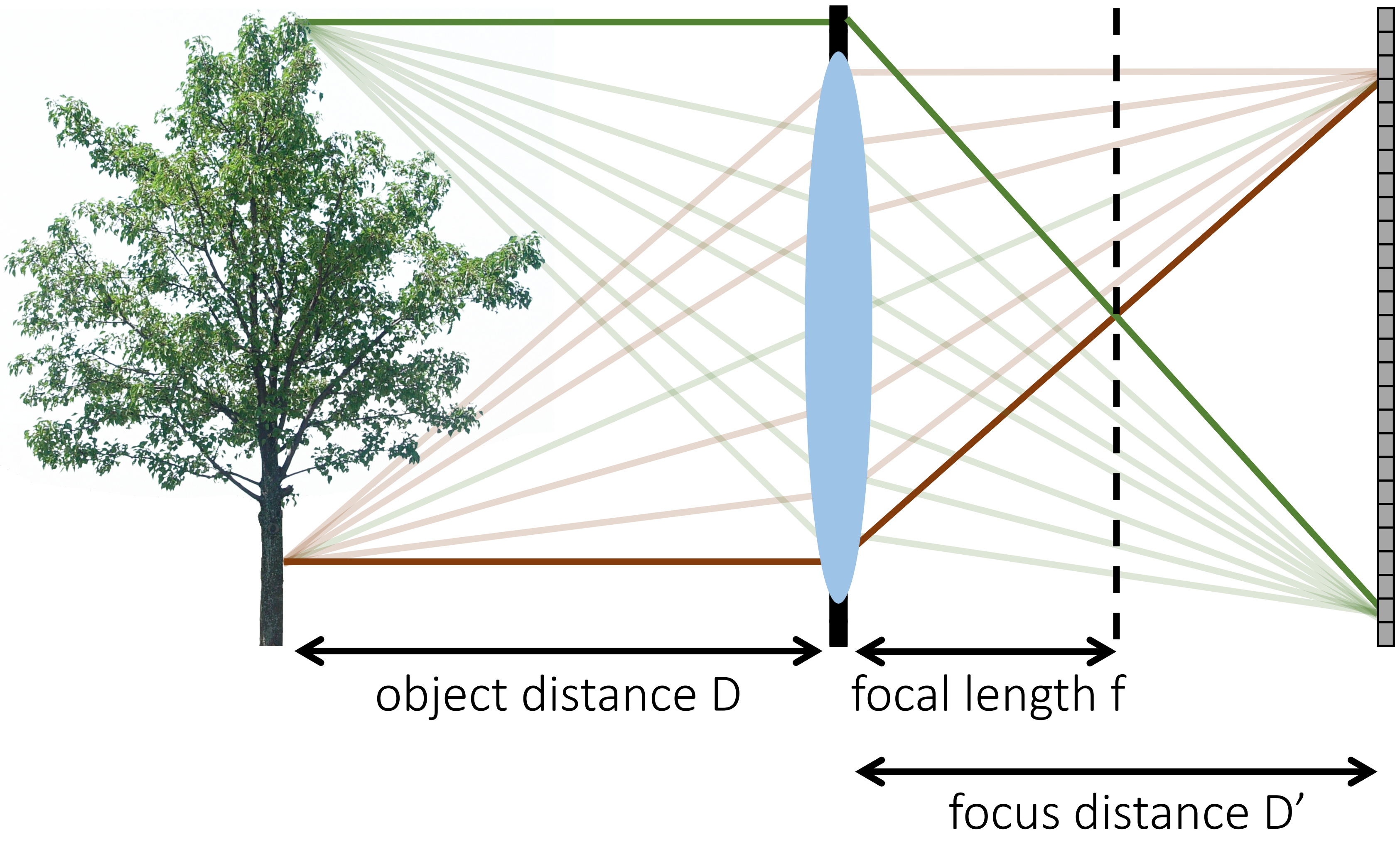
- We use only central rays.
- We assume the lens camera is in focus.

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



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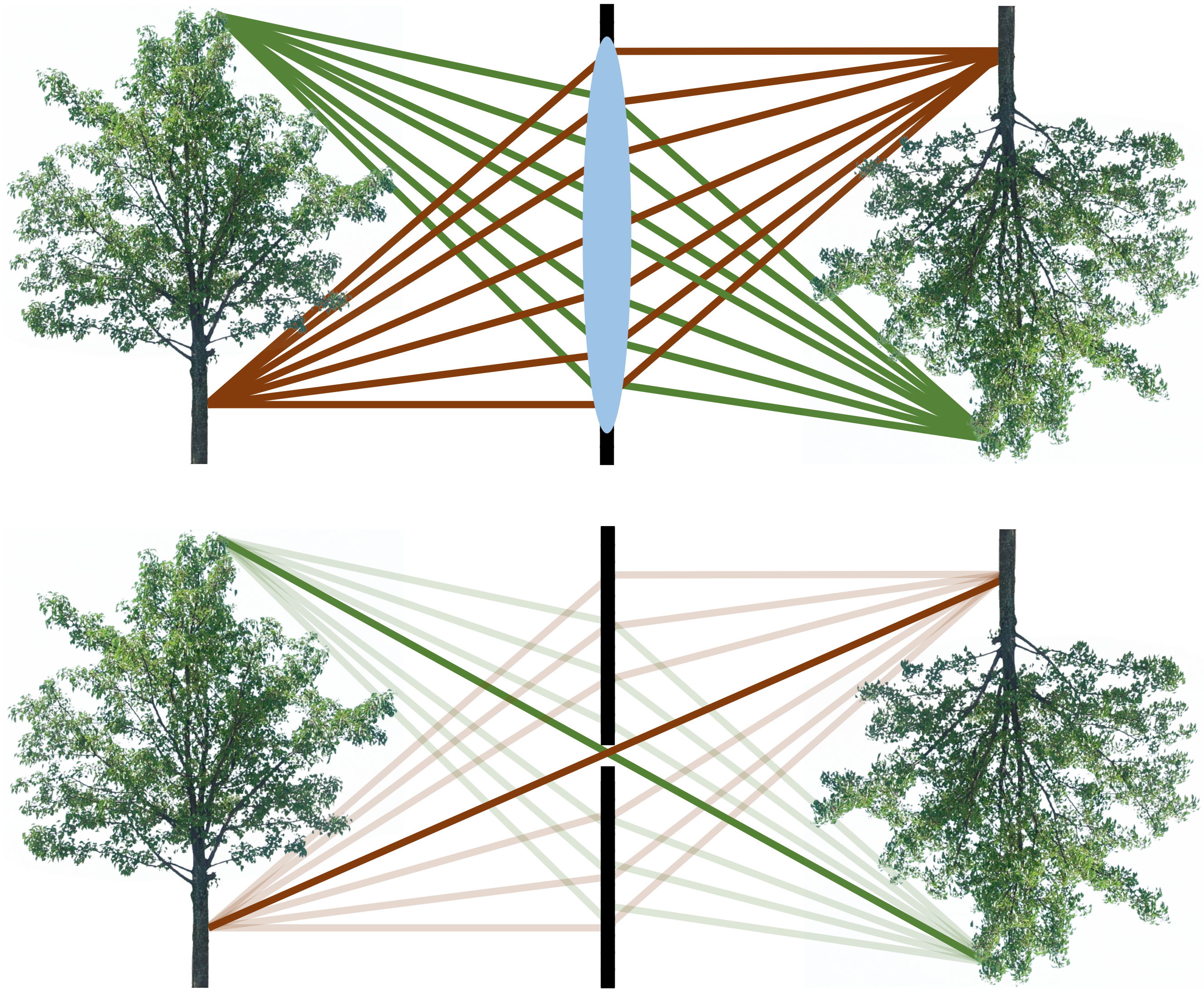
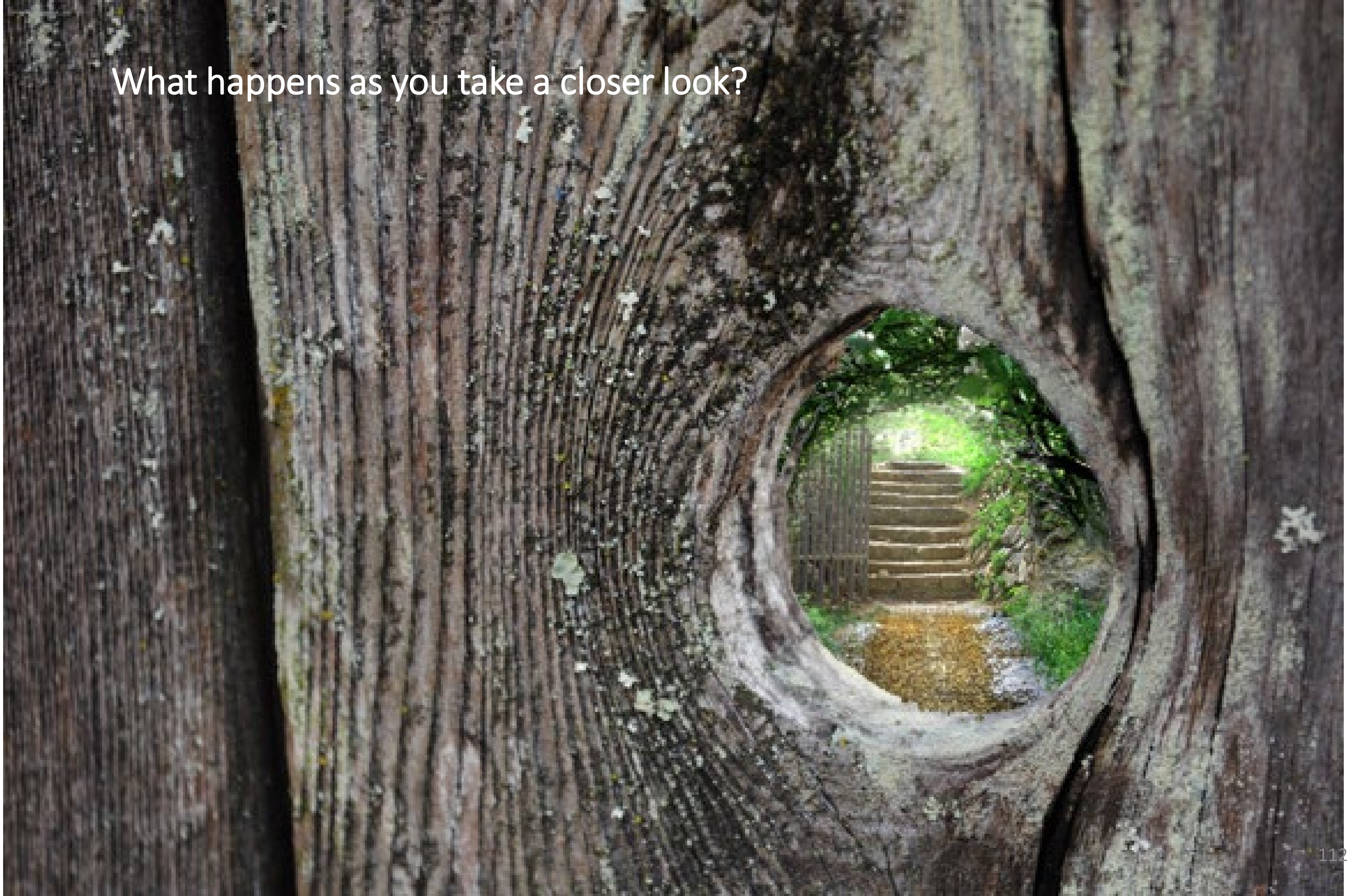


We can derive properties and descriptions that hold for both camera models if:

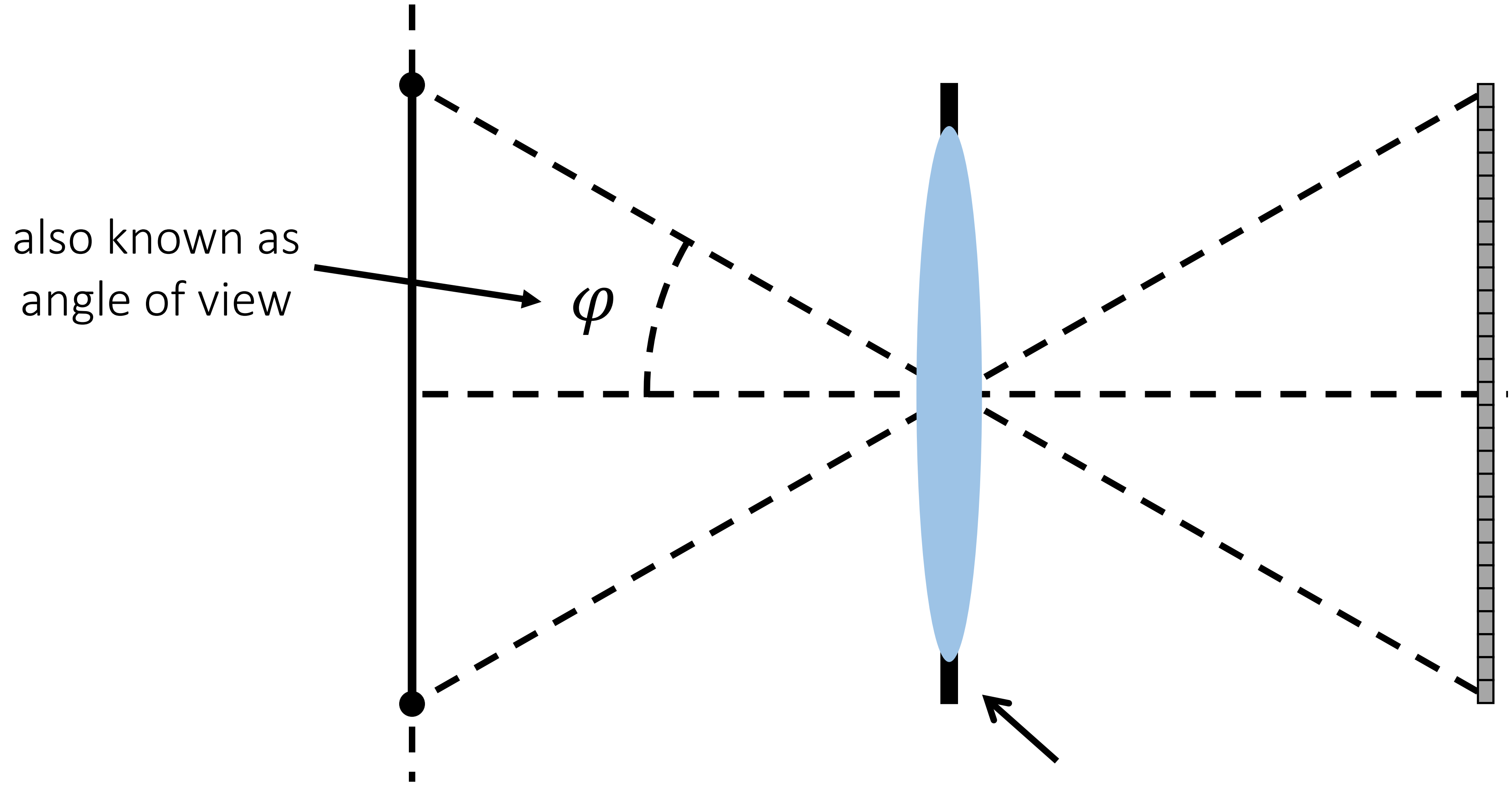
- We use only central rays.
- We assume the lens camera is in focus.
- We assume that the focus distance of the lens camera is equal to the focal length of the pinhole camera.

Field of view

What happens as you take a closer look?



Field of view

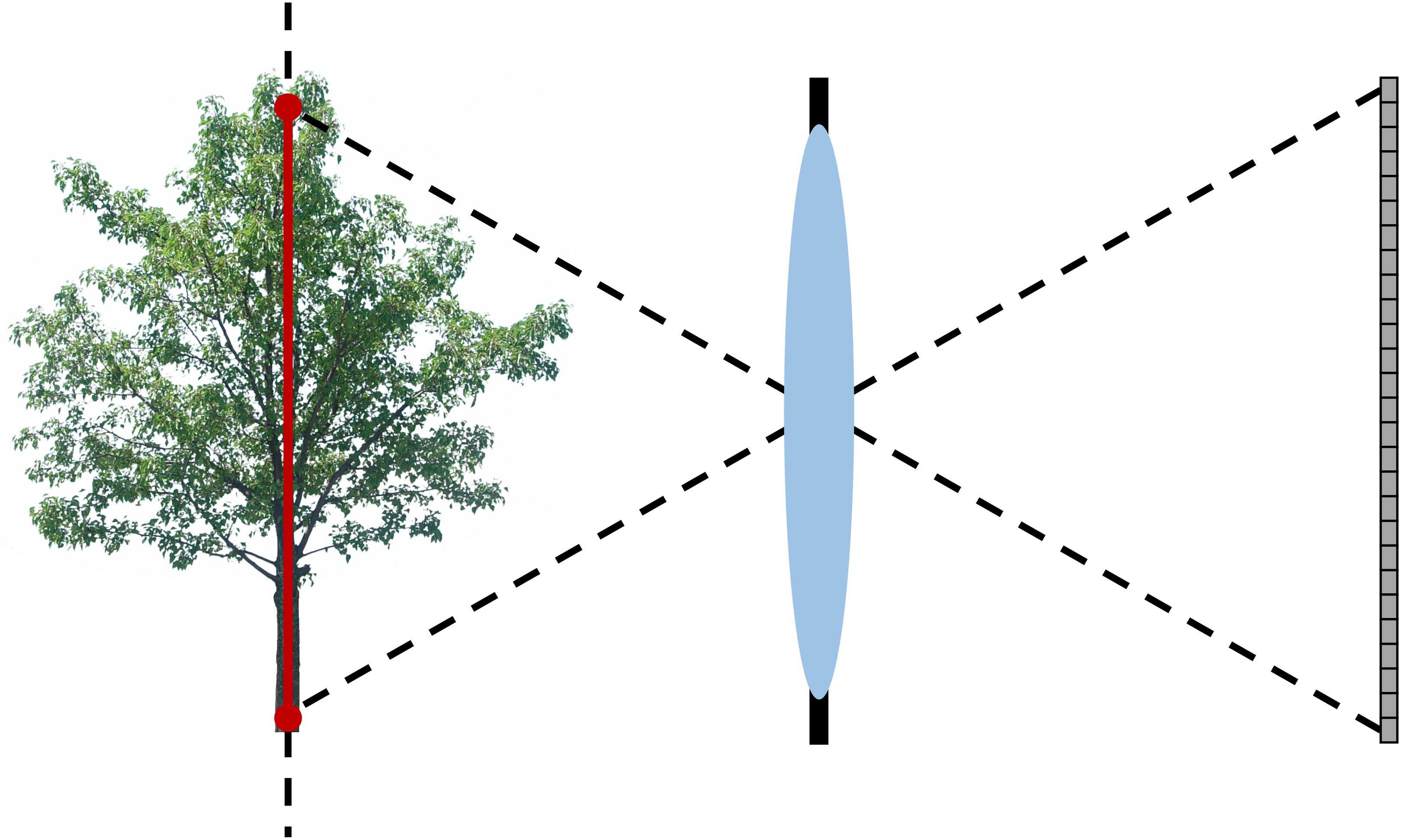


Note: here I drew a lens, but I could have just as well drawn a pinhole

Field of view

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

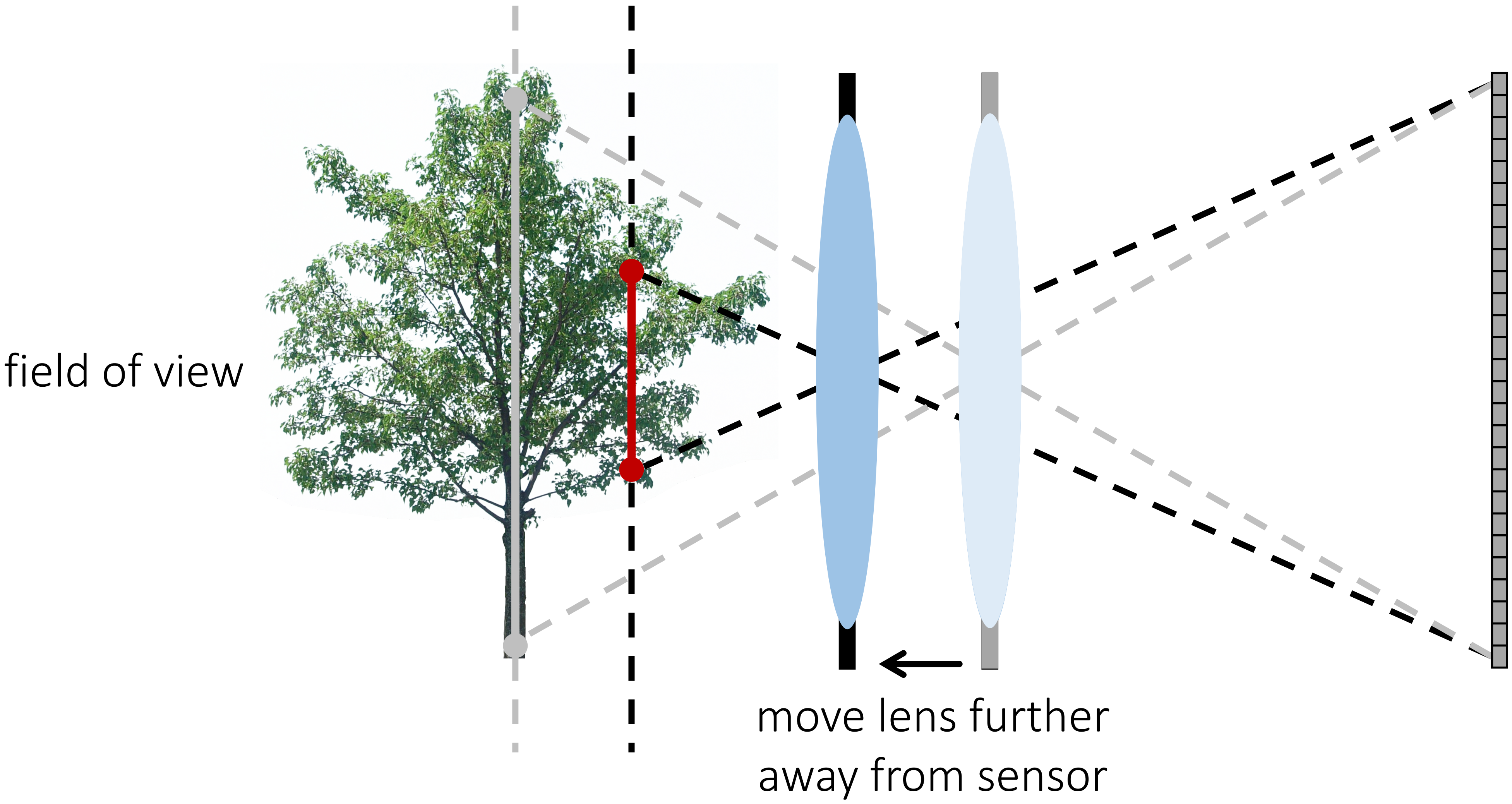
field of view



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

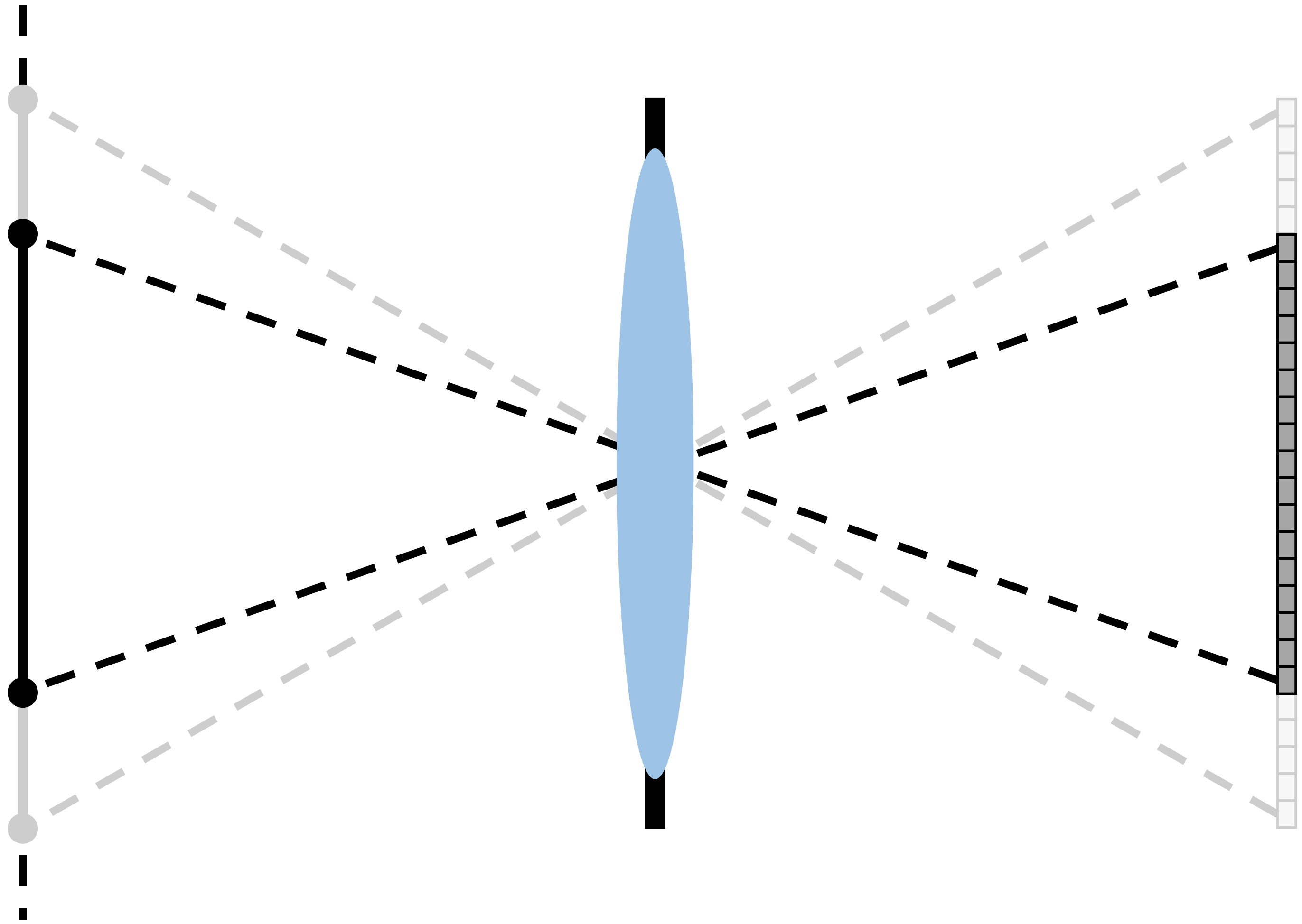
Field of view

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



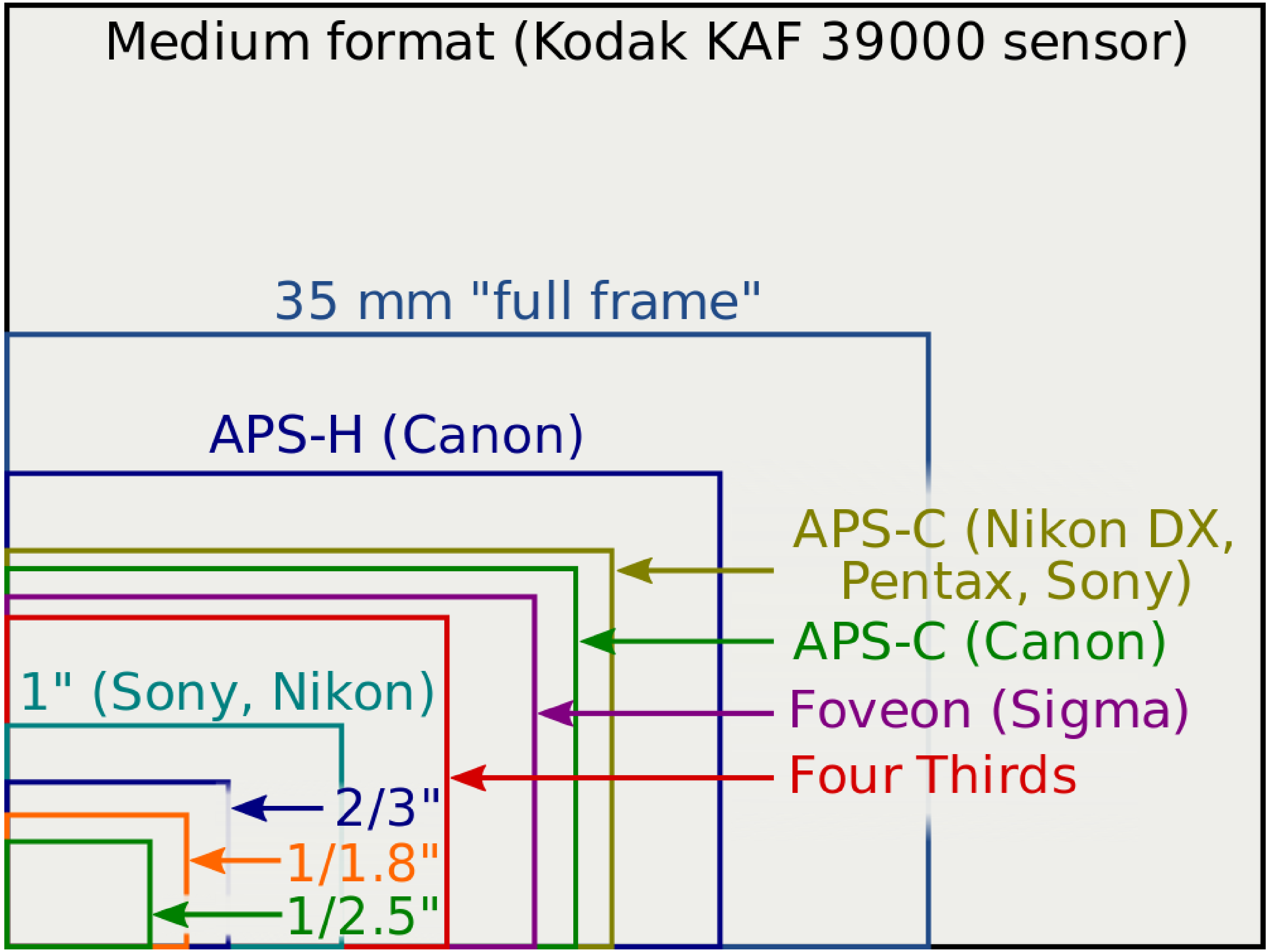
- What happens to field of view as we focus closer? → It becomes smaller.

Field of view also depends on sensor size



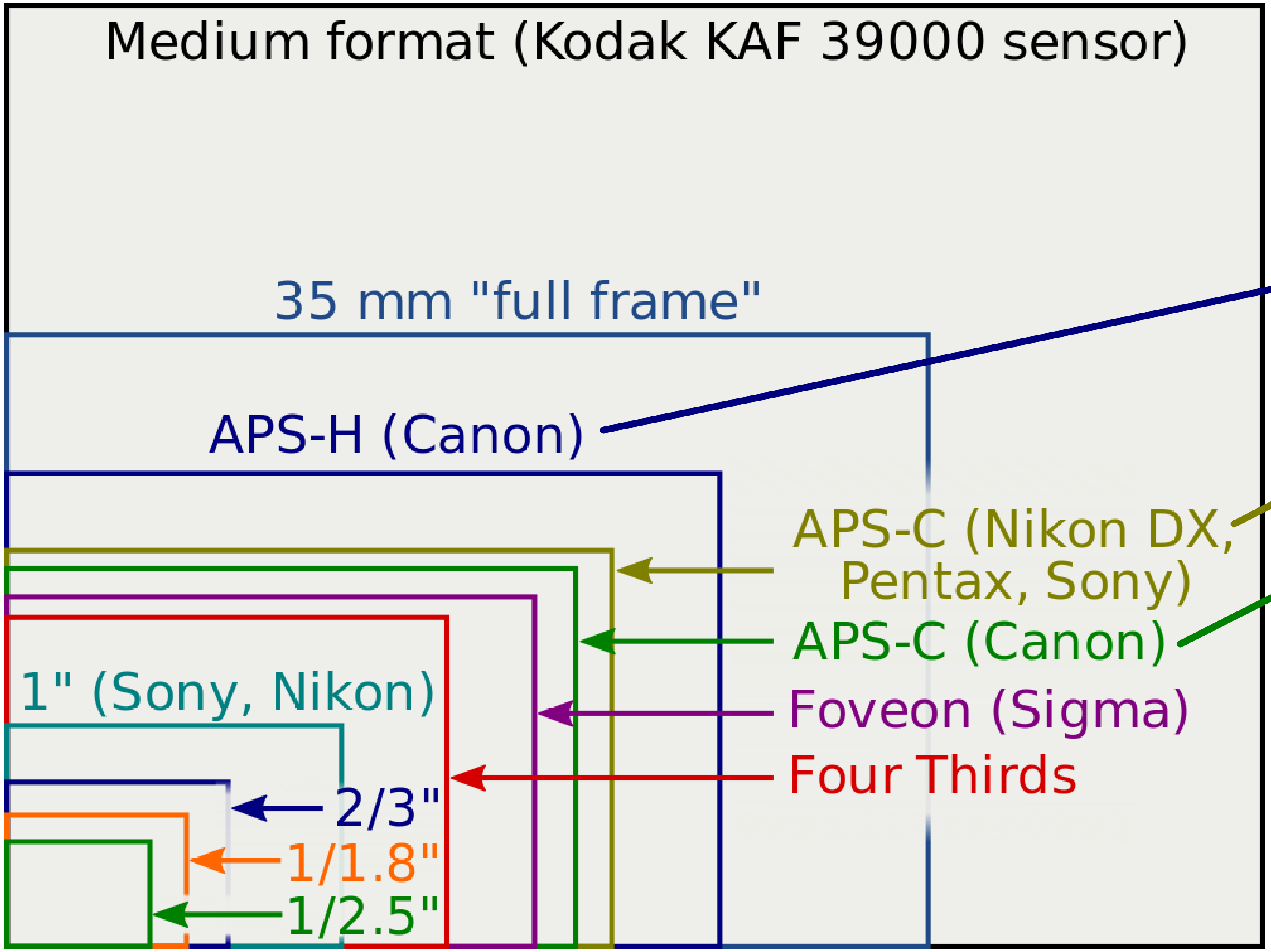
- What happens to field of view when we reduce sensor size? → It decreases.

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.

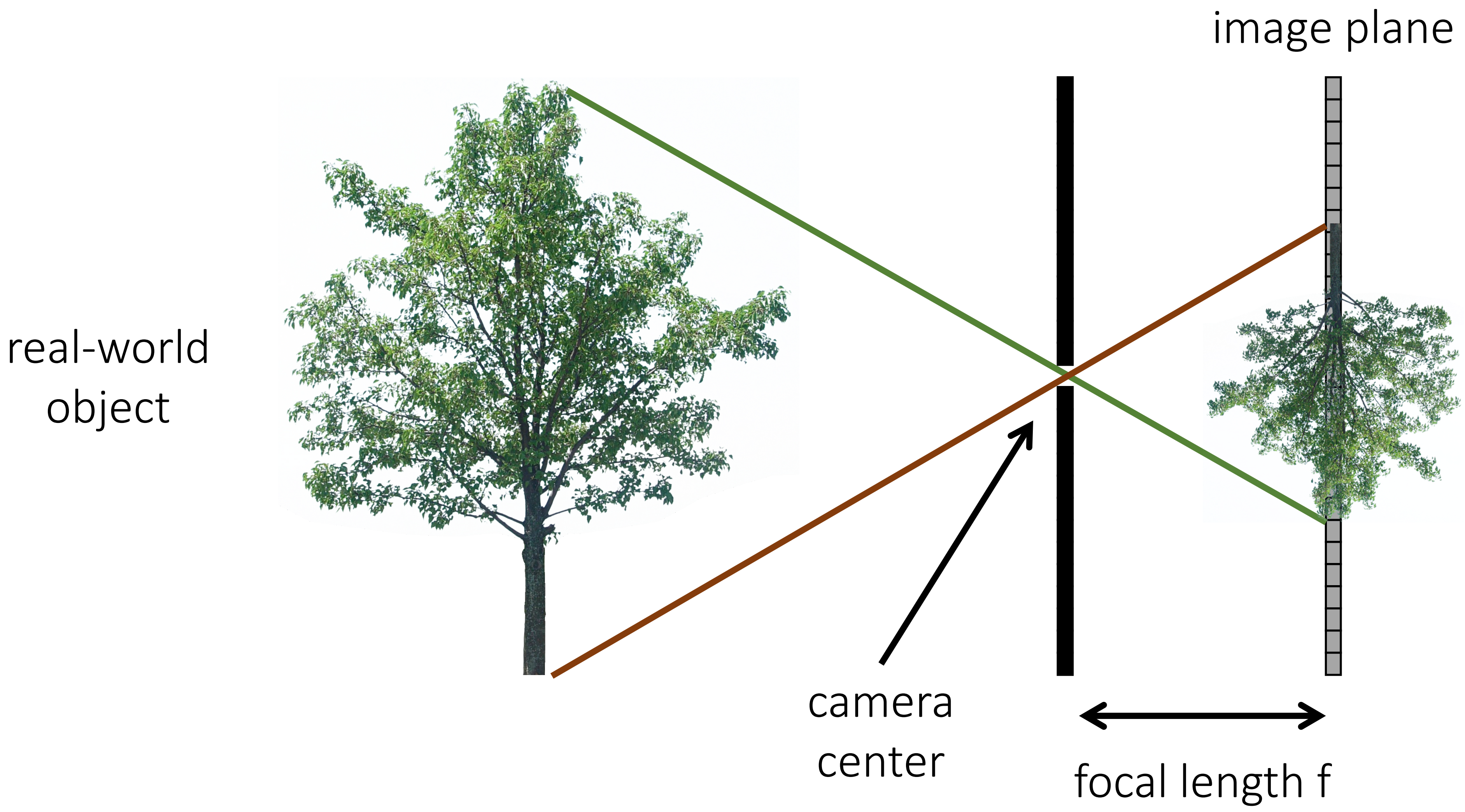
Crop factor



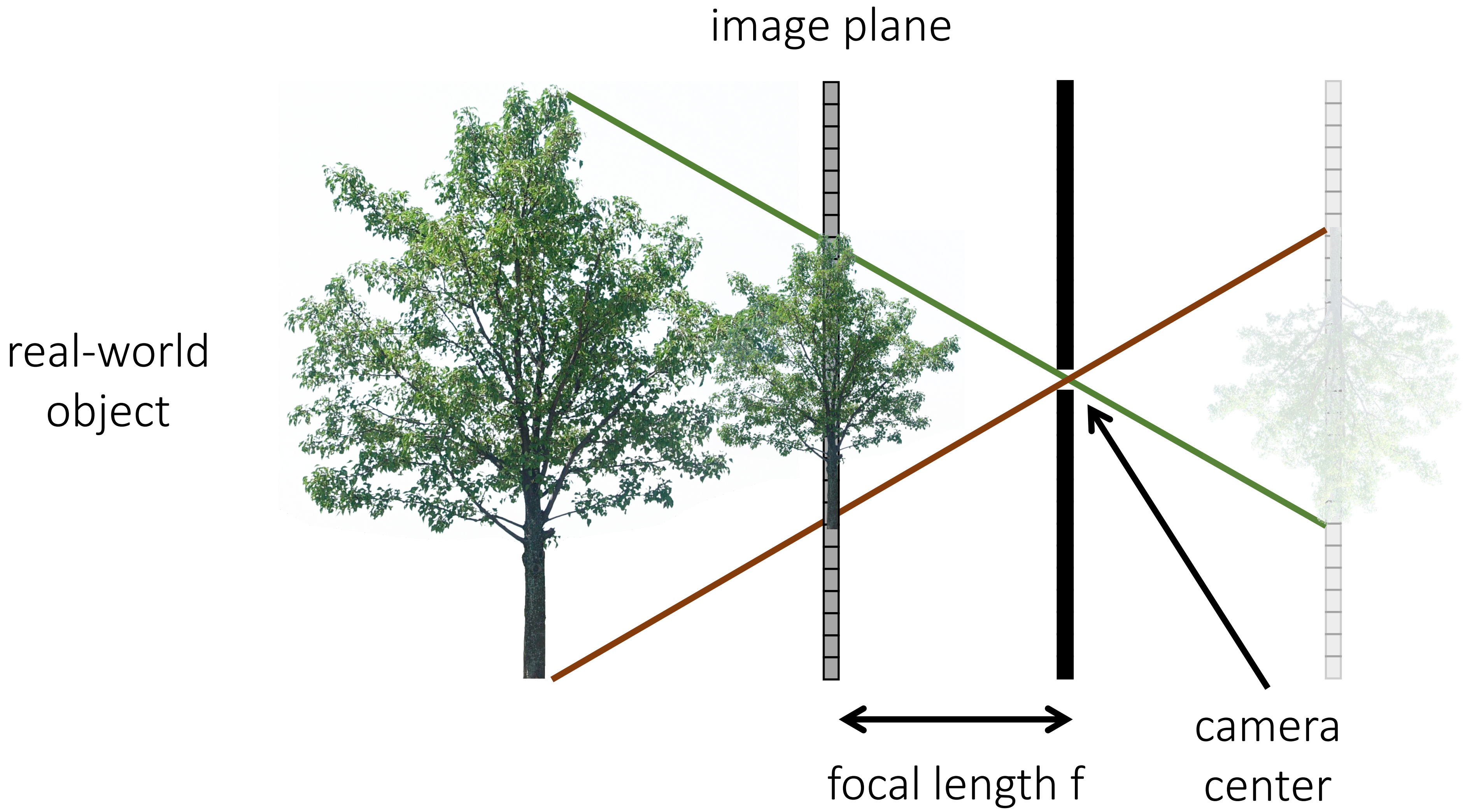
How much field of view is cropped when using a sensor smaller than full frame.

Magnification and perspective

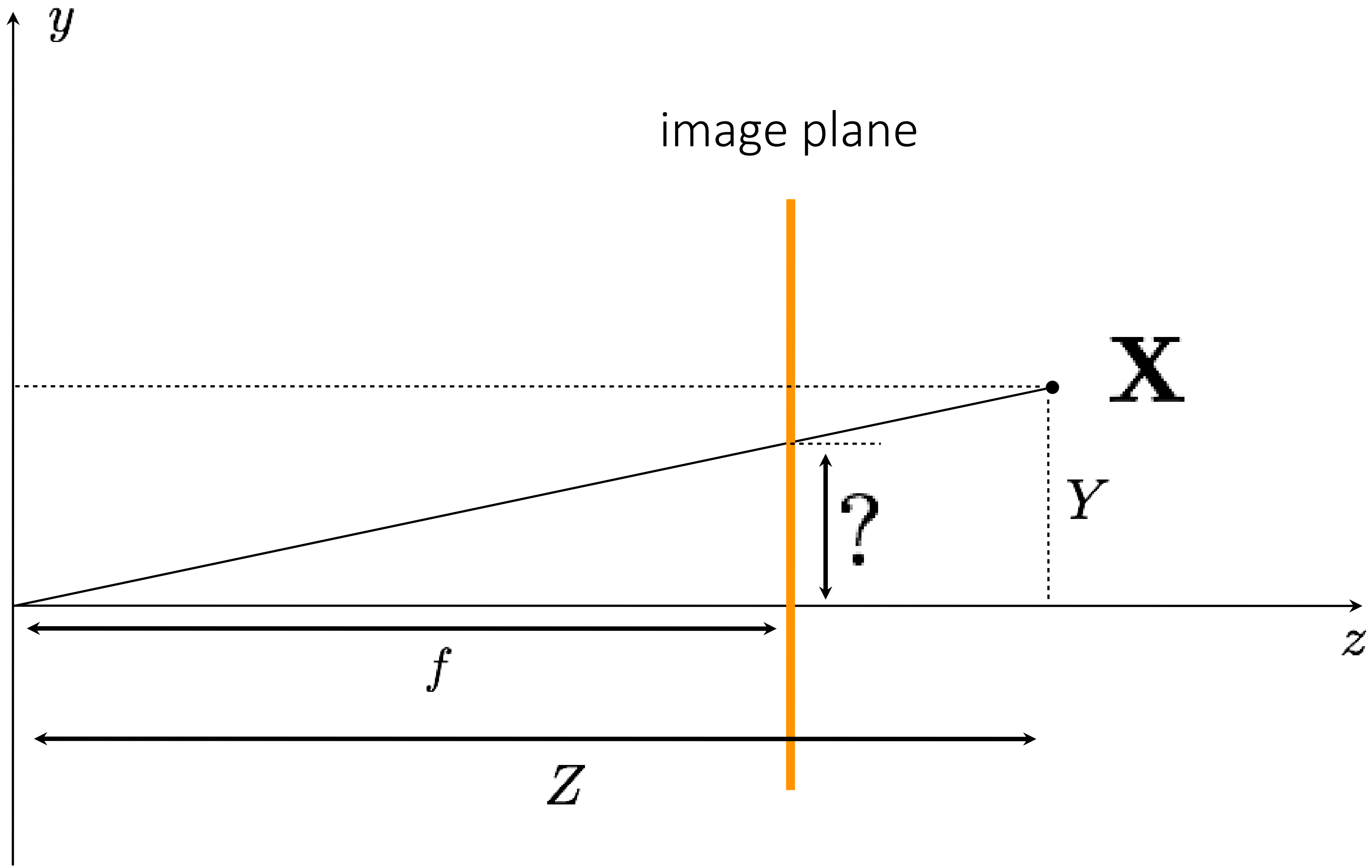
The pinhole camera



The (rearranged) pinhole camera

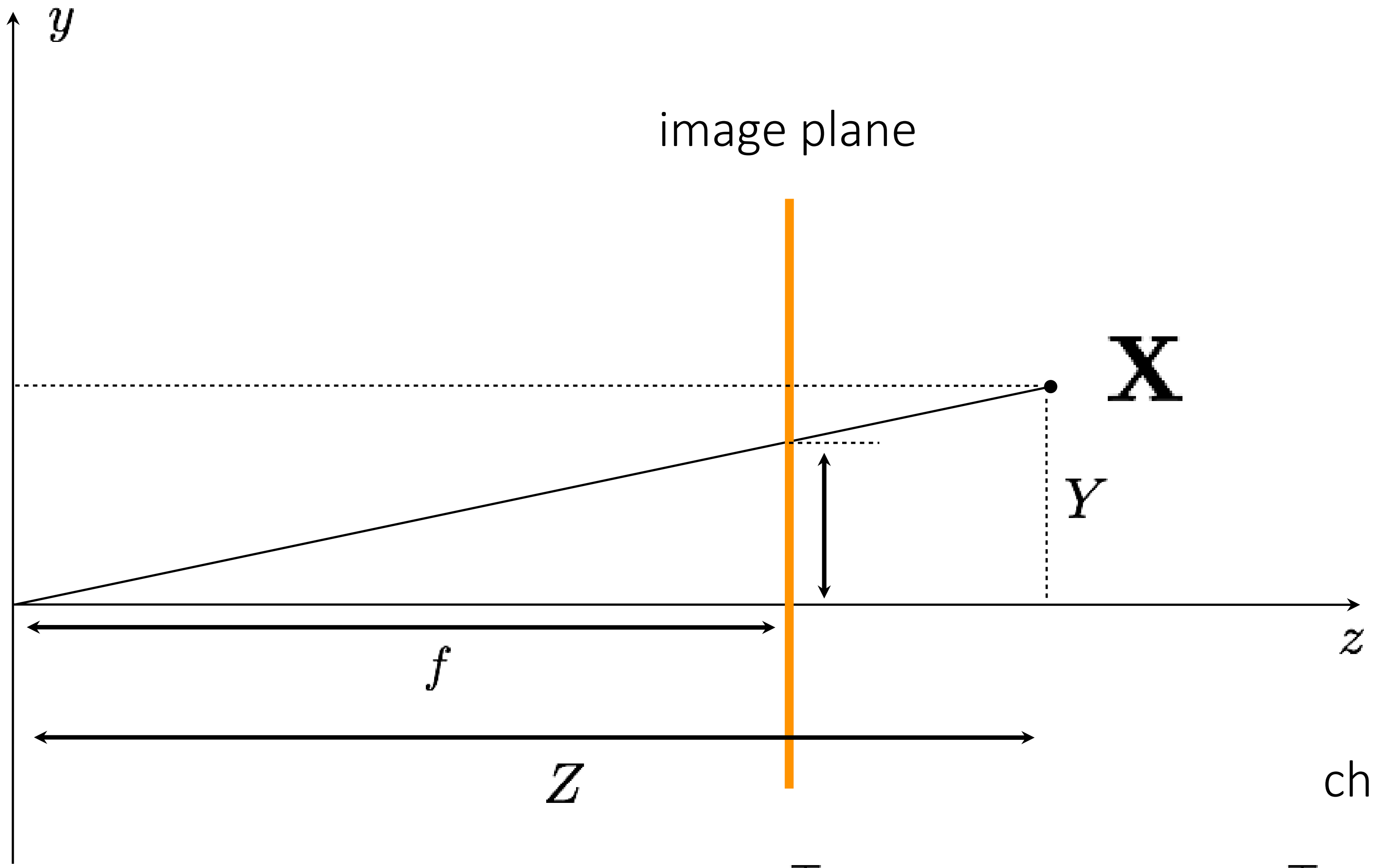


The 2D view of the (rearranged) pinhole camera



What is the equation for image coordinate **x** in terms of **X**?

The 2D view of the (rearranged) pinhole camera



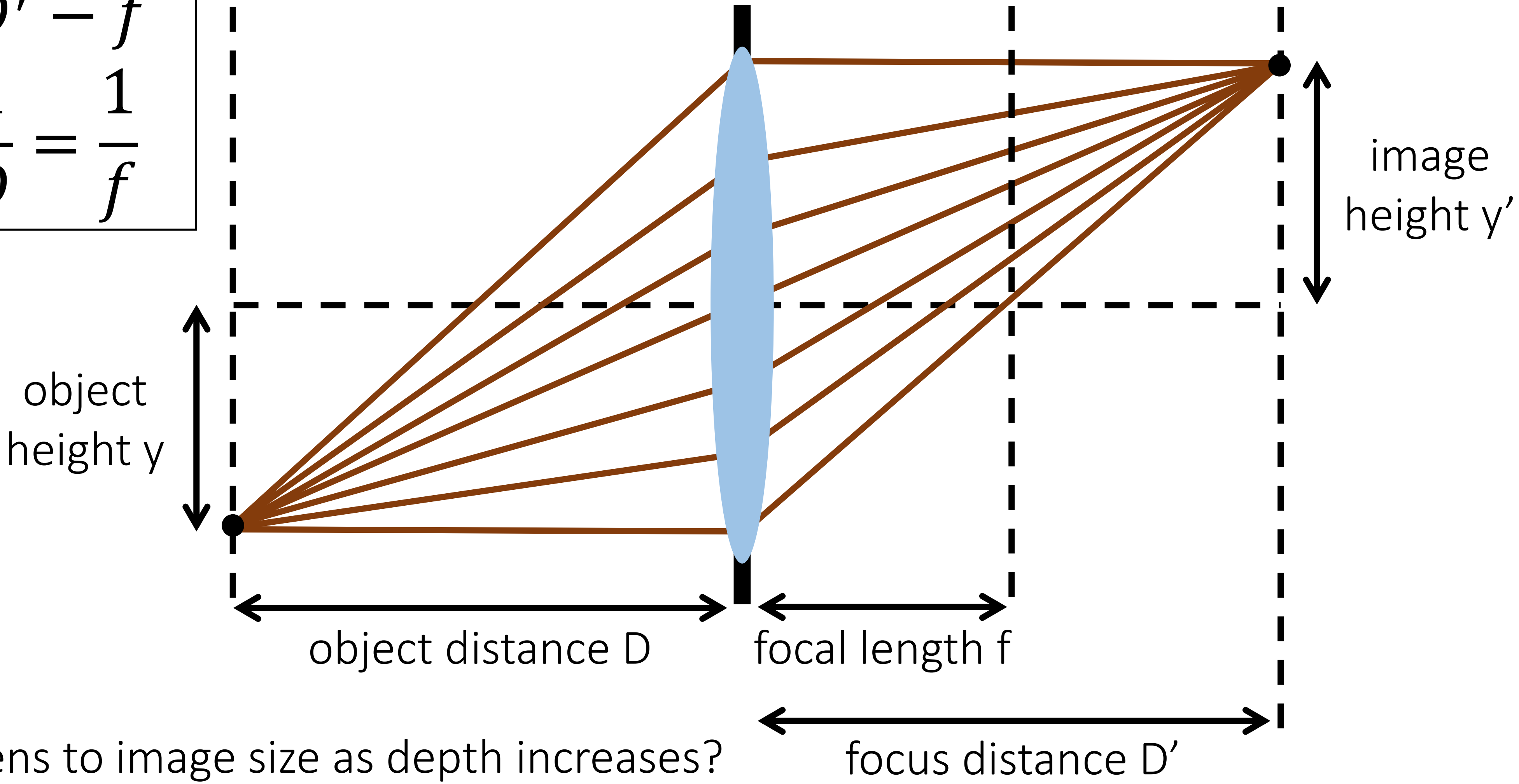
magnification changes with depth

$$[X \quad Y \quad Z]^\top \mapsto [fX/Z \quad fY/Z]^\top$$

Magnification depends on depth

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

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

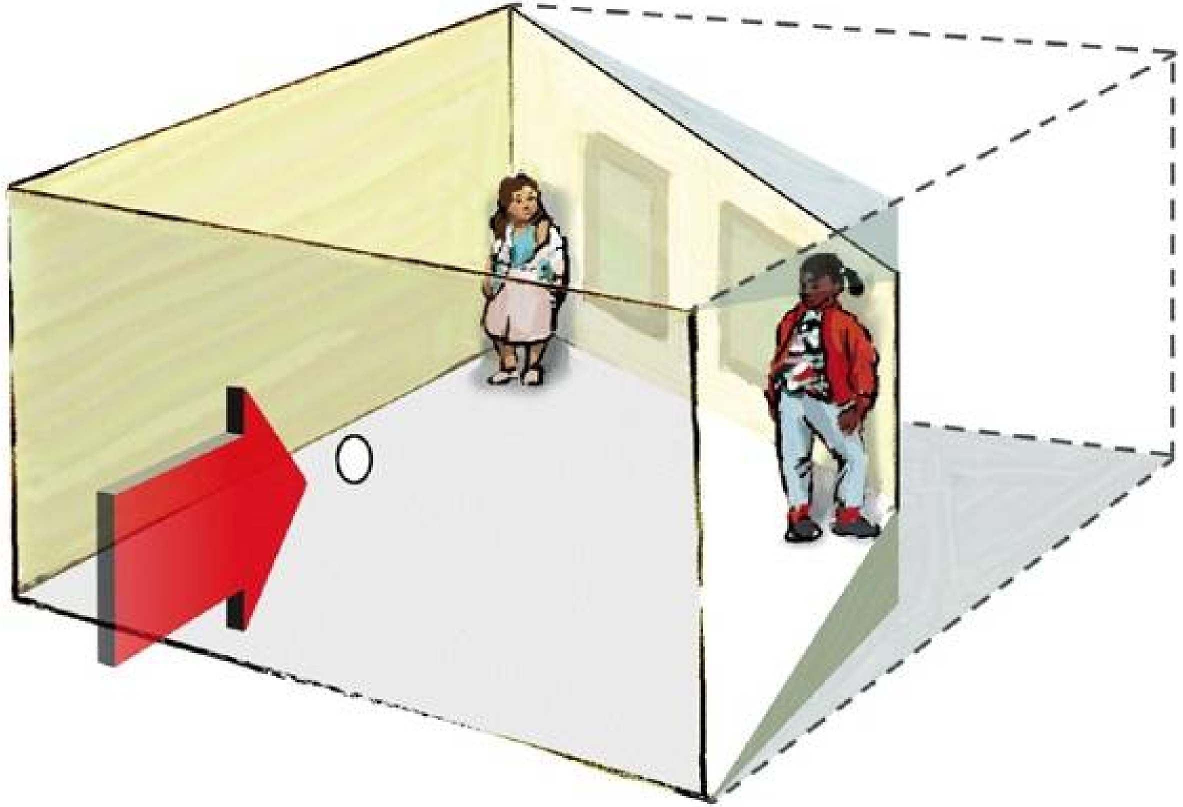


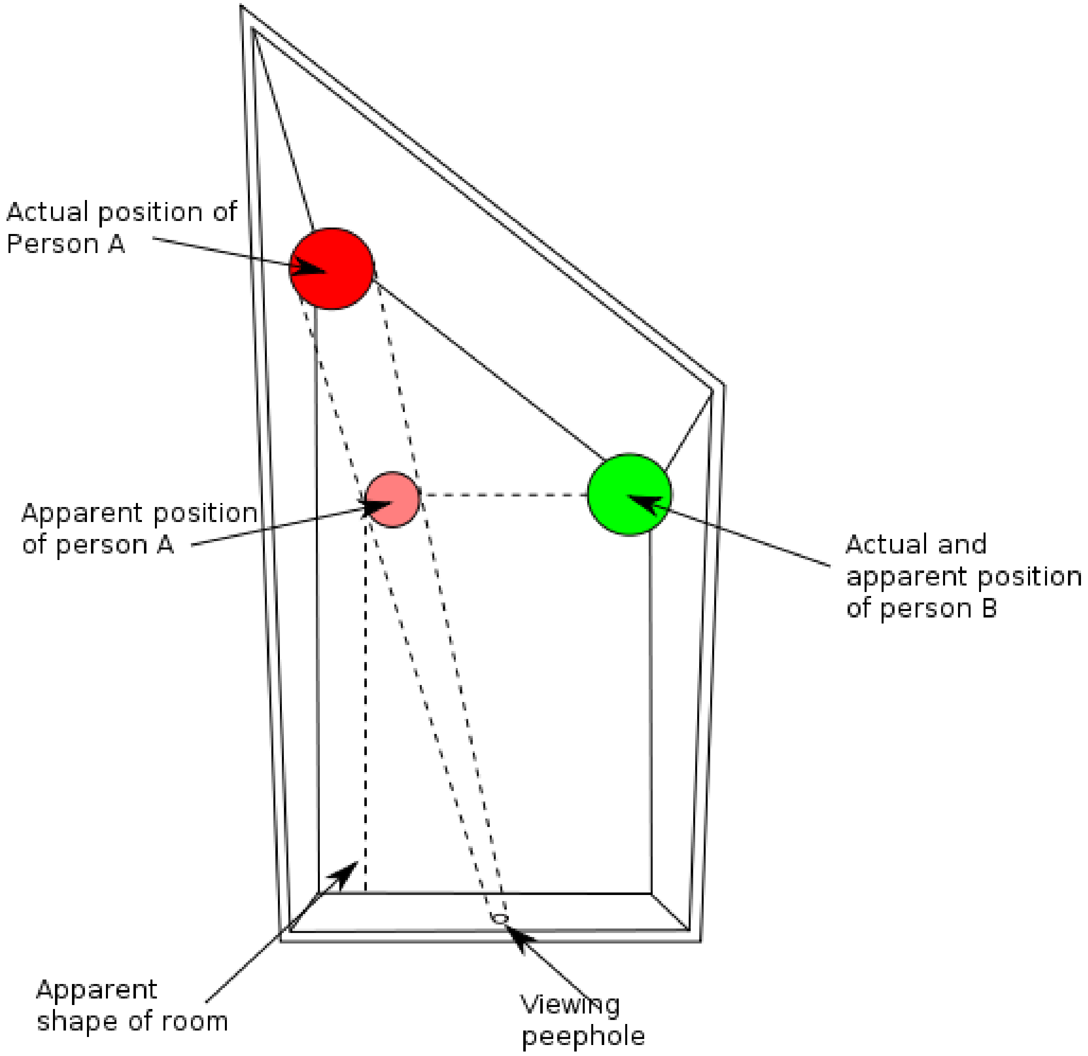
What happens to image size as depth increases?

Forced perspective

The Ames room illusion

The Ames room illusion





The arrow illusion

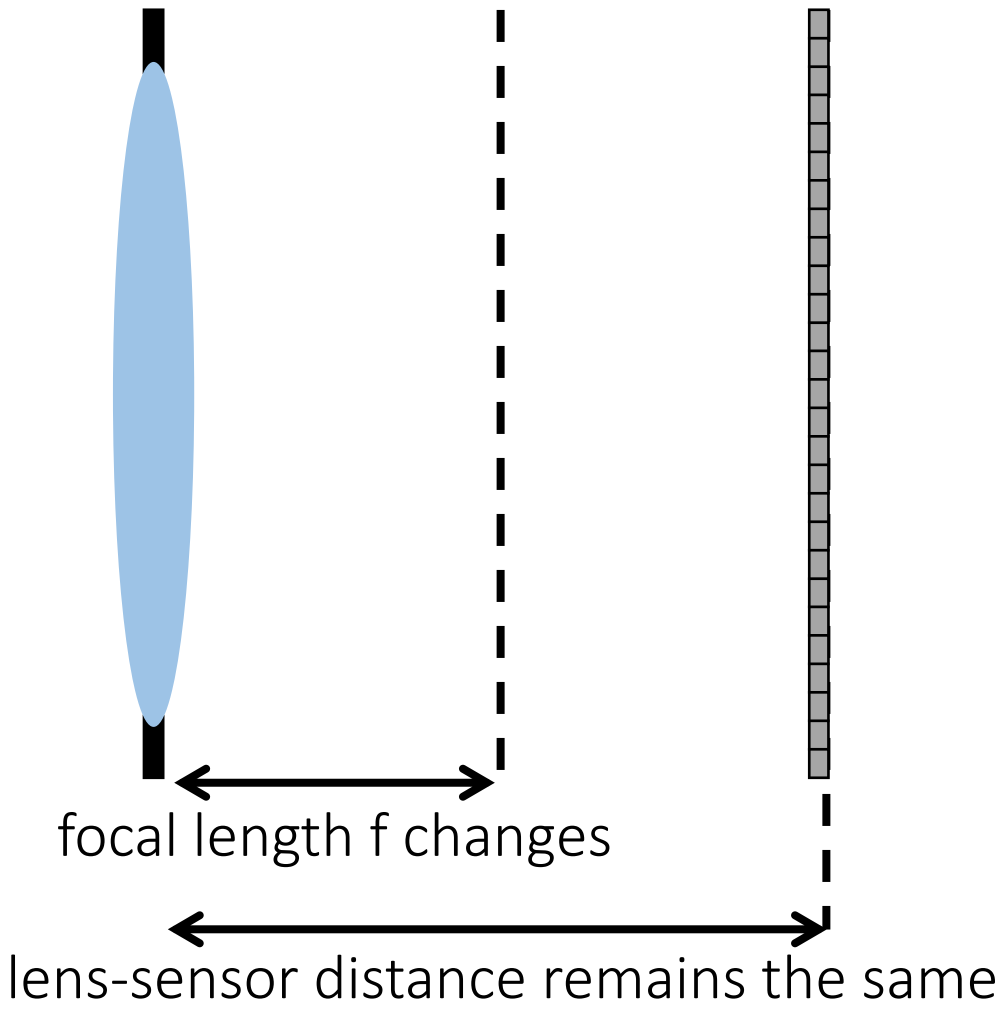
Prof. Kokichi Sugihara has many other amazing illusions involving perspective distortion, check them out on YouTube or on his website:

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

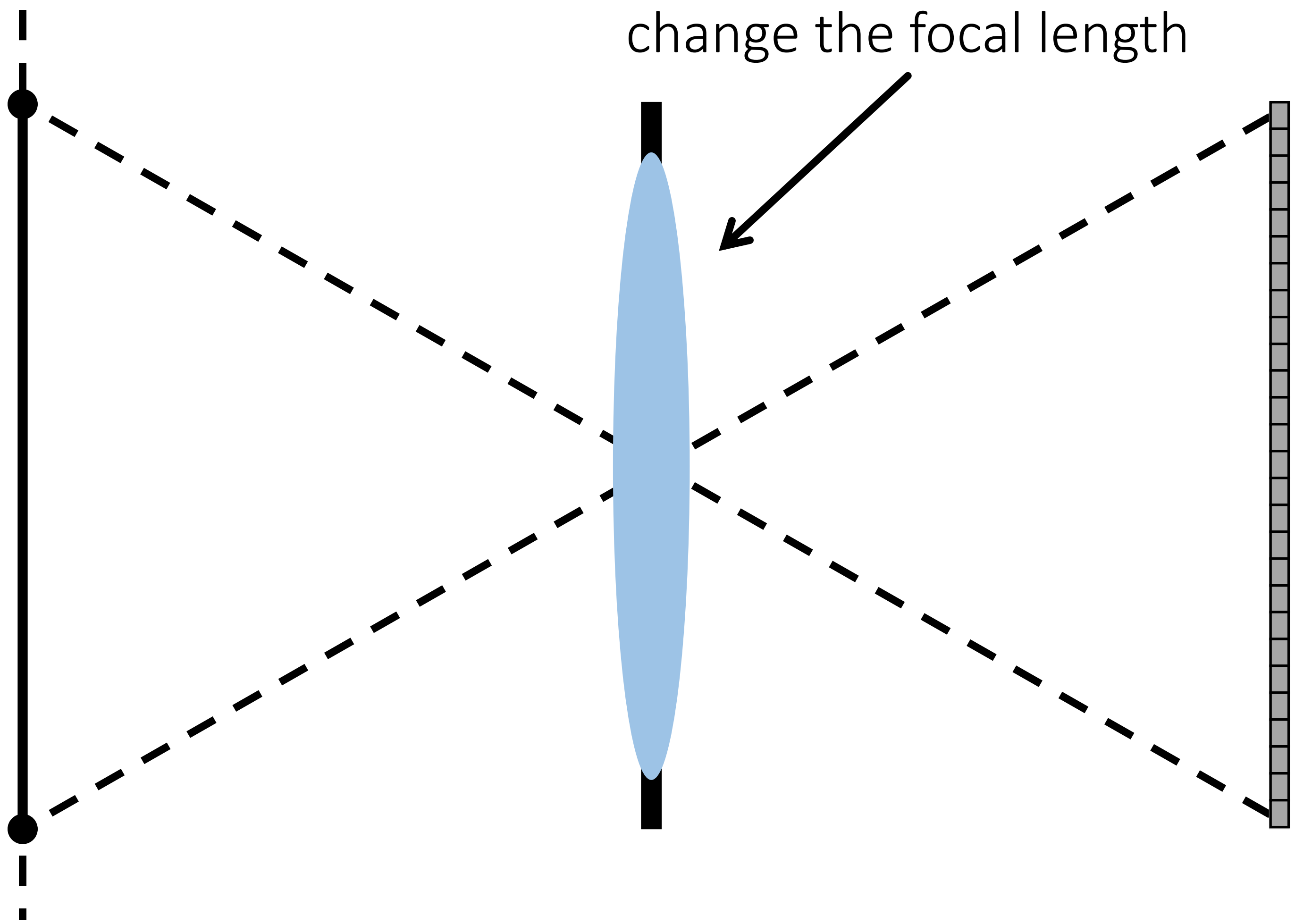
Zooming

Zooming means changing the focal length

Very different process from refocusing

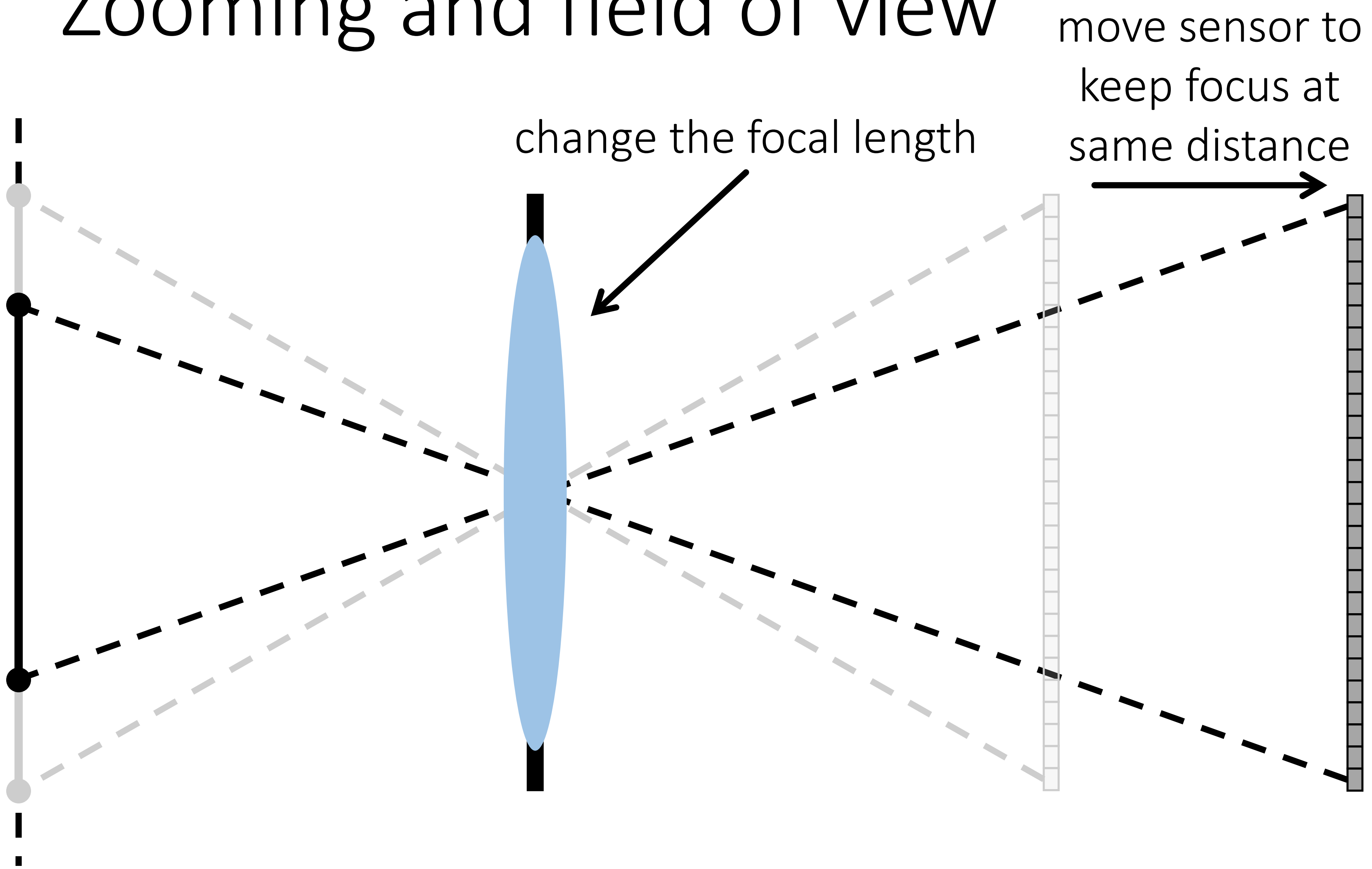


Zooming and field of view



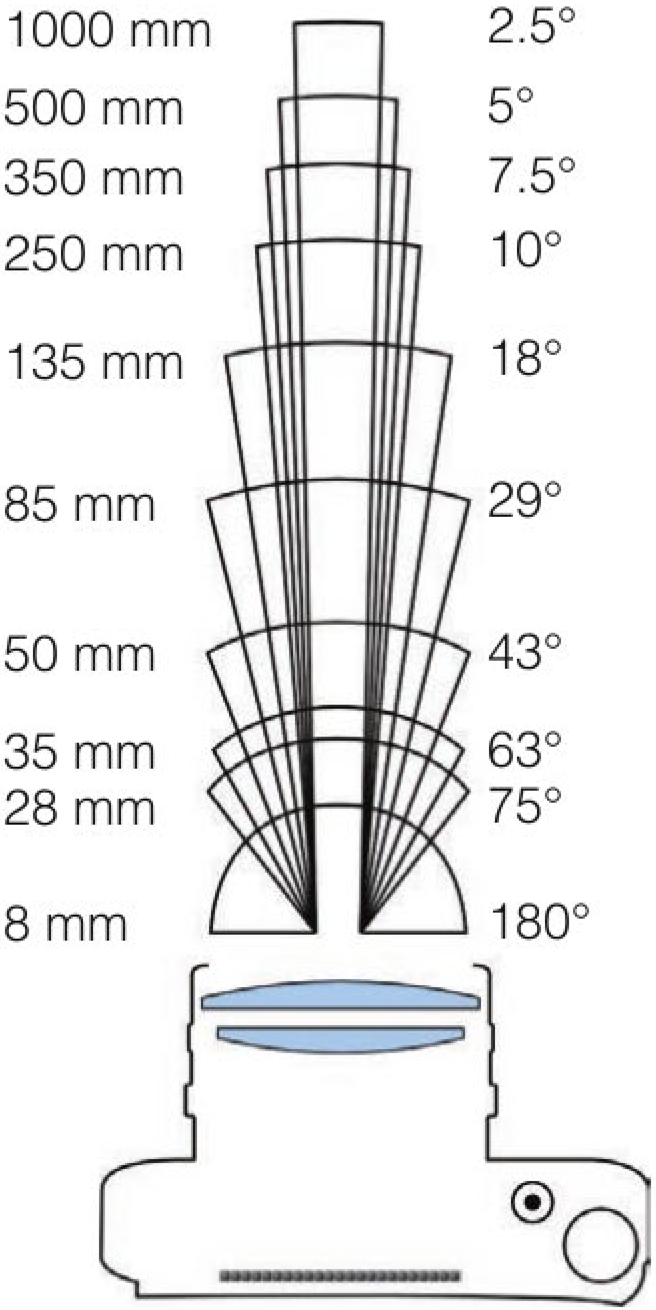
- What happens to field of view when we focus closer? → It decreases.
- What happens to field of view when we increase <u>lens</u> focal length?

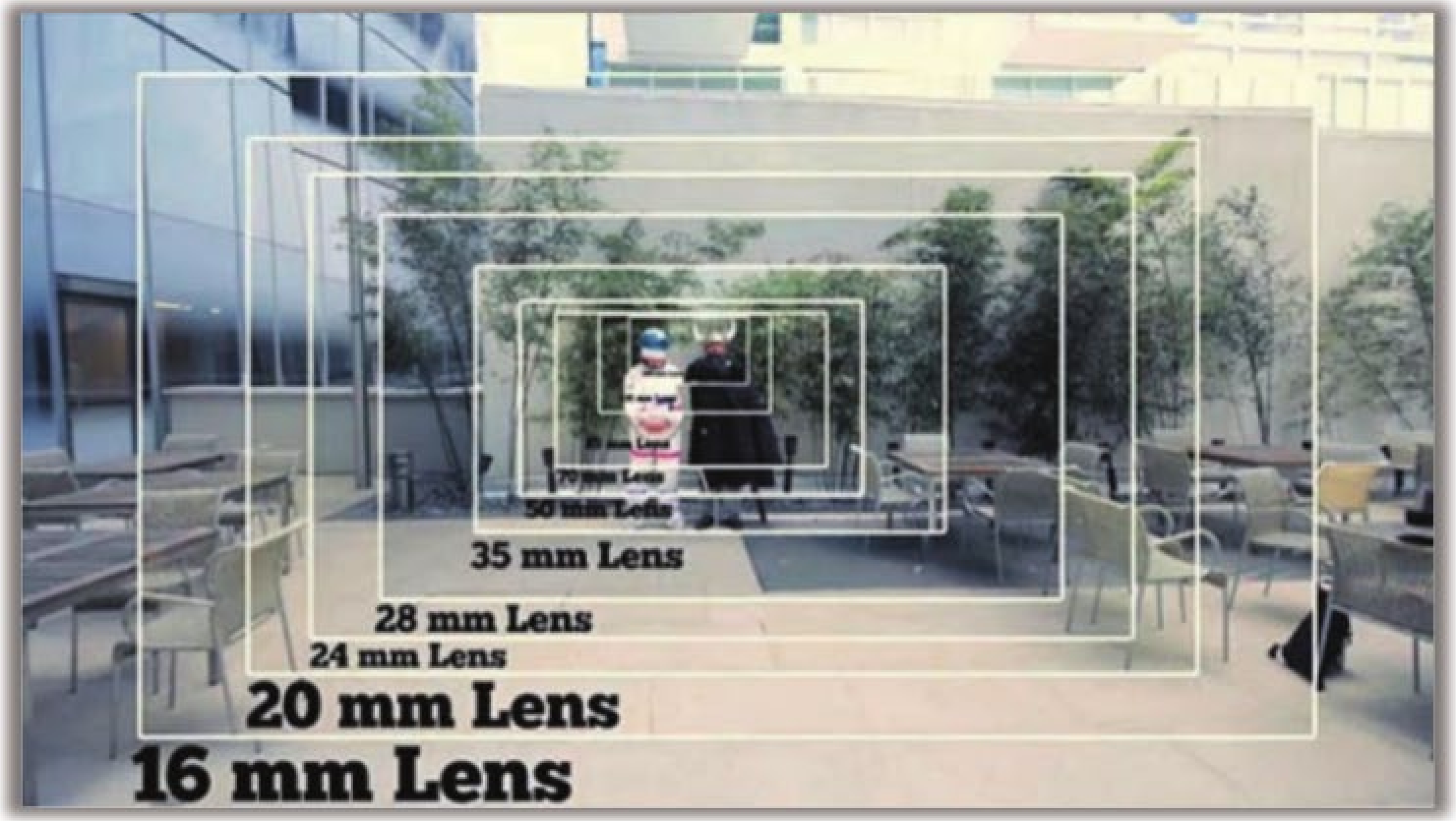
Zooming and field of view



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

Field of view

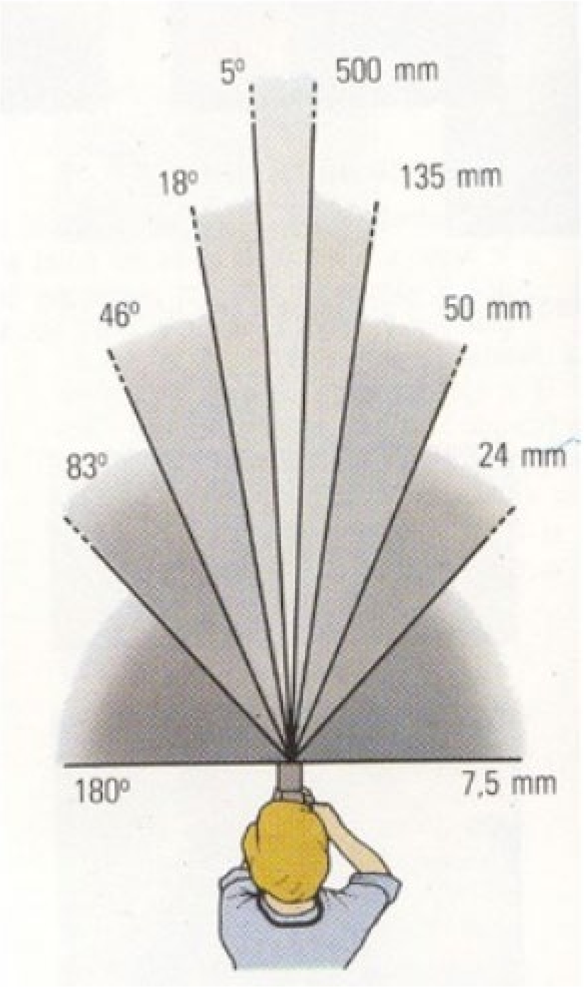




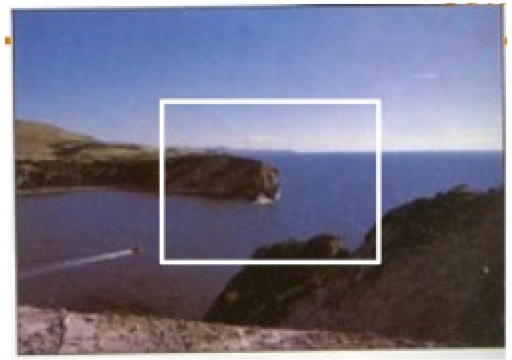
Andrew McWilliams

Field of view

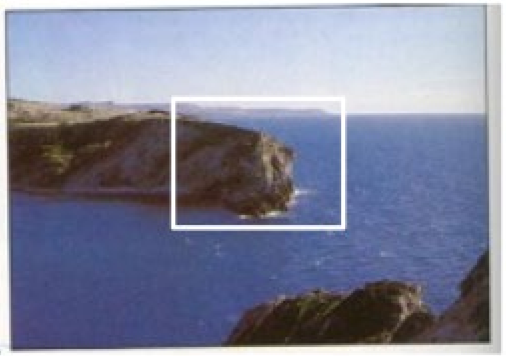
Increasing the <u>lens</u> focal length is similar to cropping



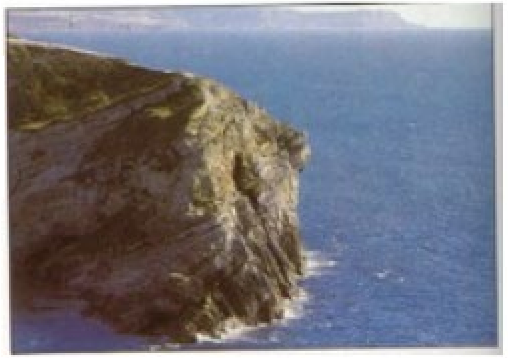
f = 25 mm



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

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

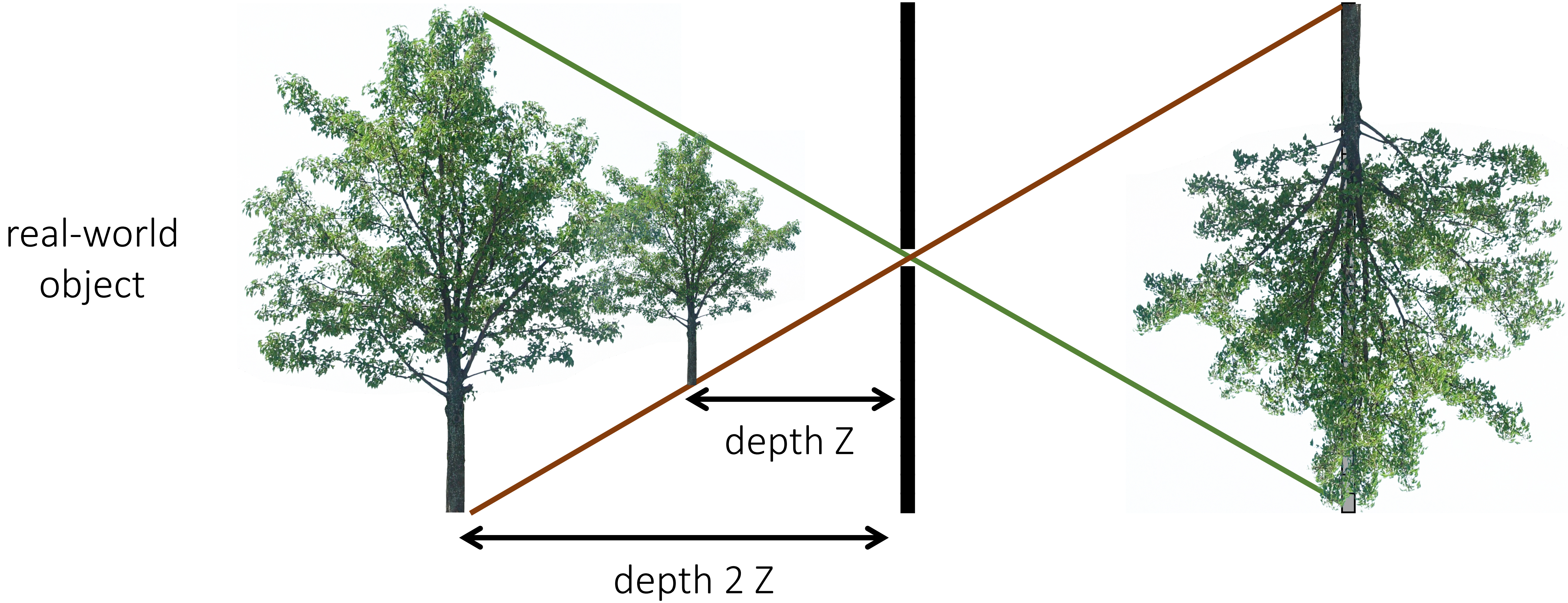
When you turn the focus ring to bring lens further-away from the sensor:
1. The in-focus distance decreases (you need to get closer to object).
2. The field of view decreases (you see a smaller part of the object).
3. The magnification increases (same part of the object is bigger on sensor).

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).

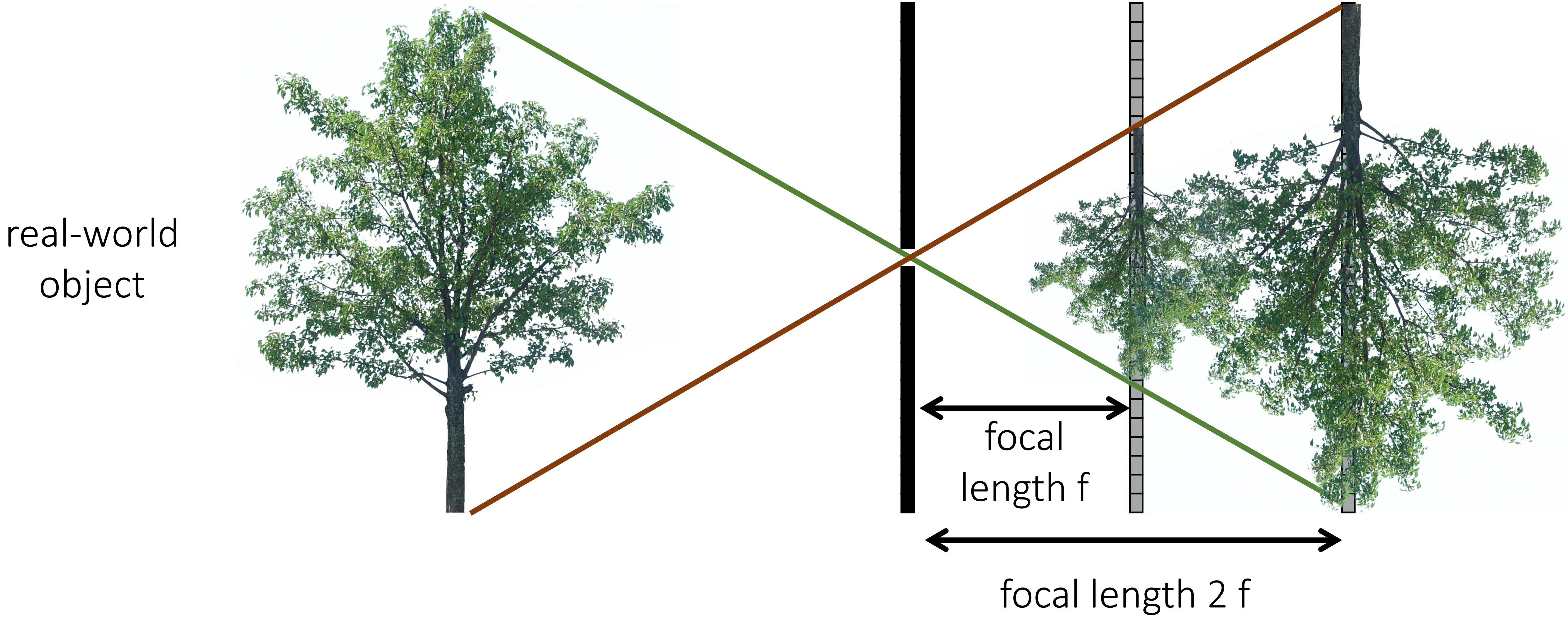
We can use both focus and zoom to cancel out their effects.

Magnification depends on depth

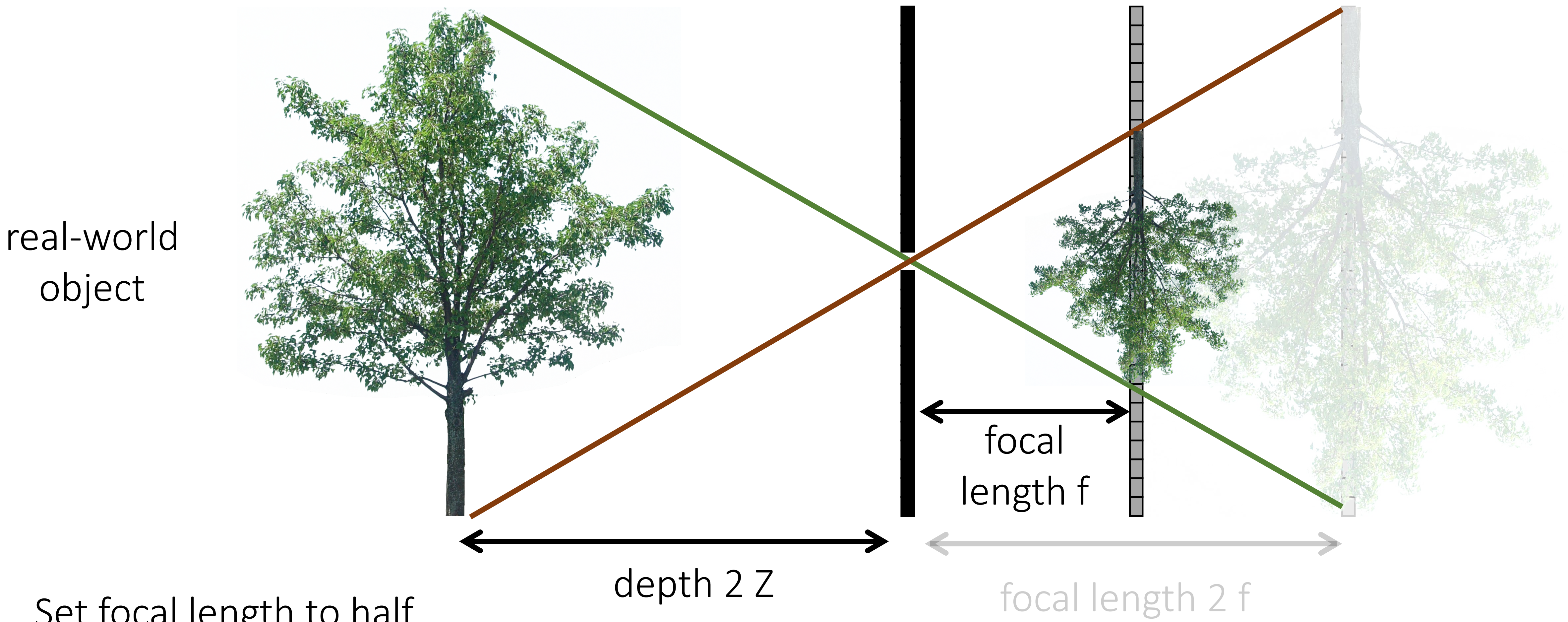
What happens as we change the focal length?



Magnification depends on focal length



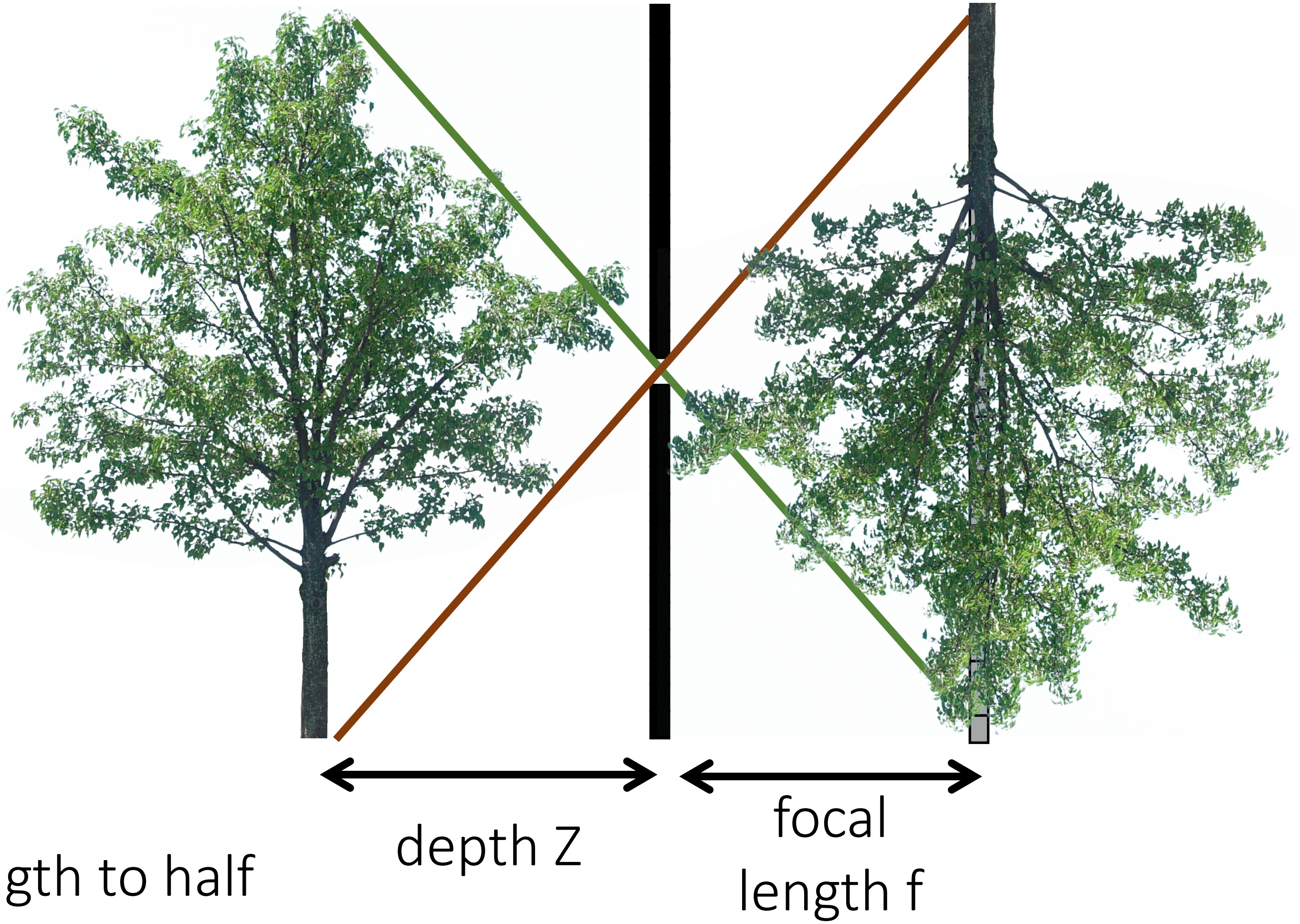
What if...



1. Set focal length to half

What if...

real-world object



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

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

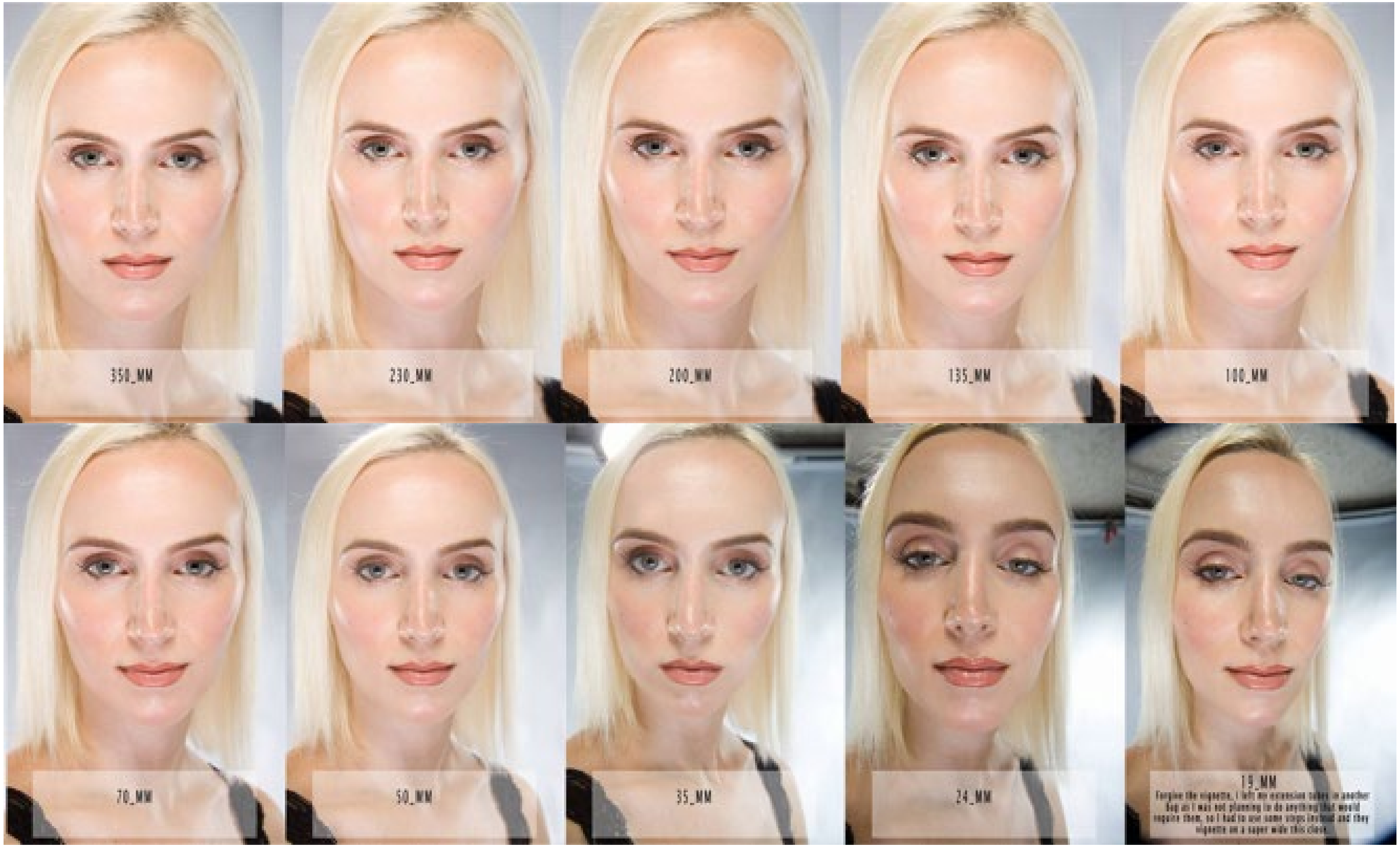
Perspective distortion

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

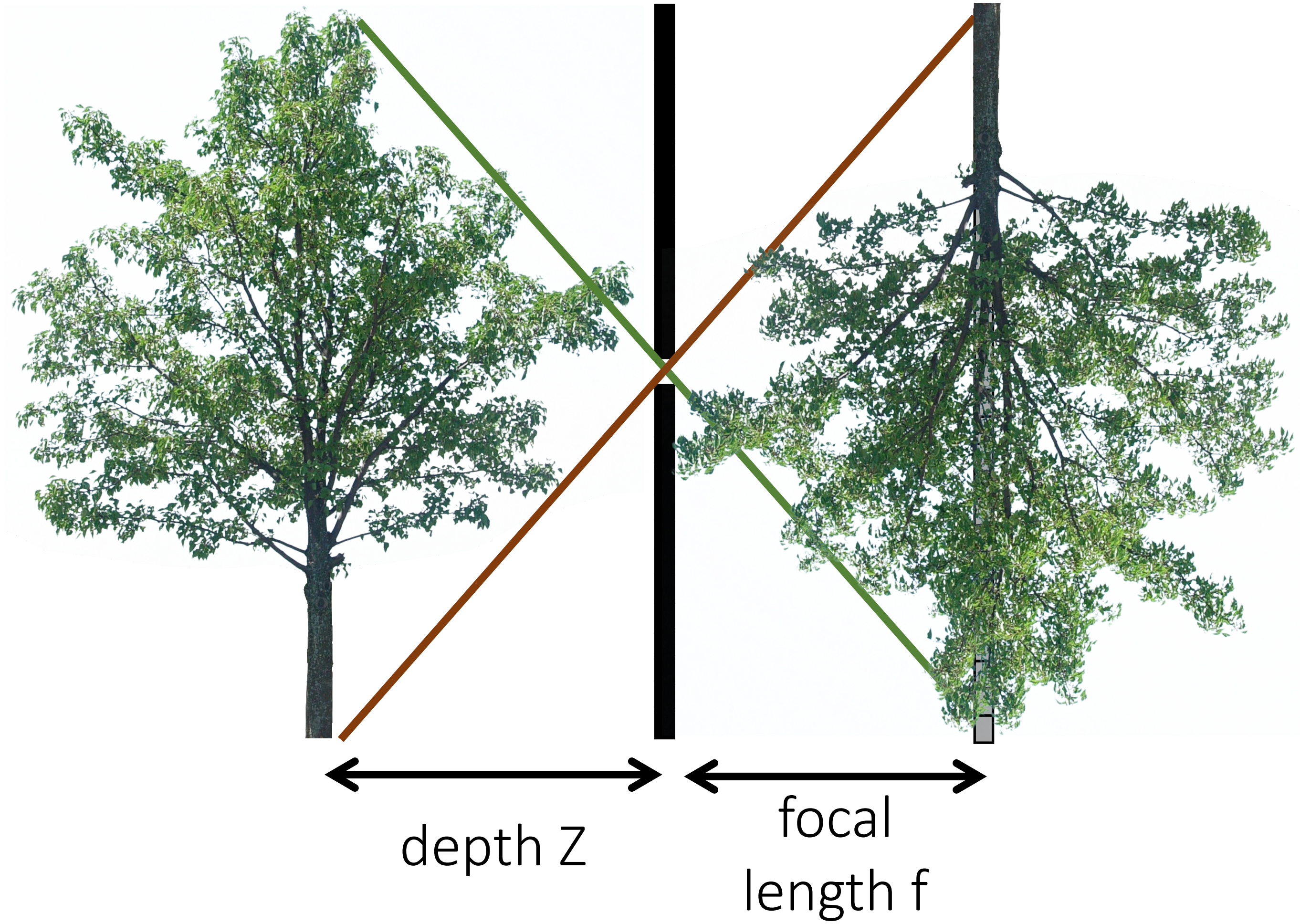
- also known as “dolly zoom”

Vertigo effect

How would you create this effect?

Orthographic camera and telecentric lenses

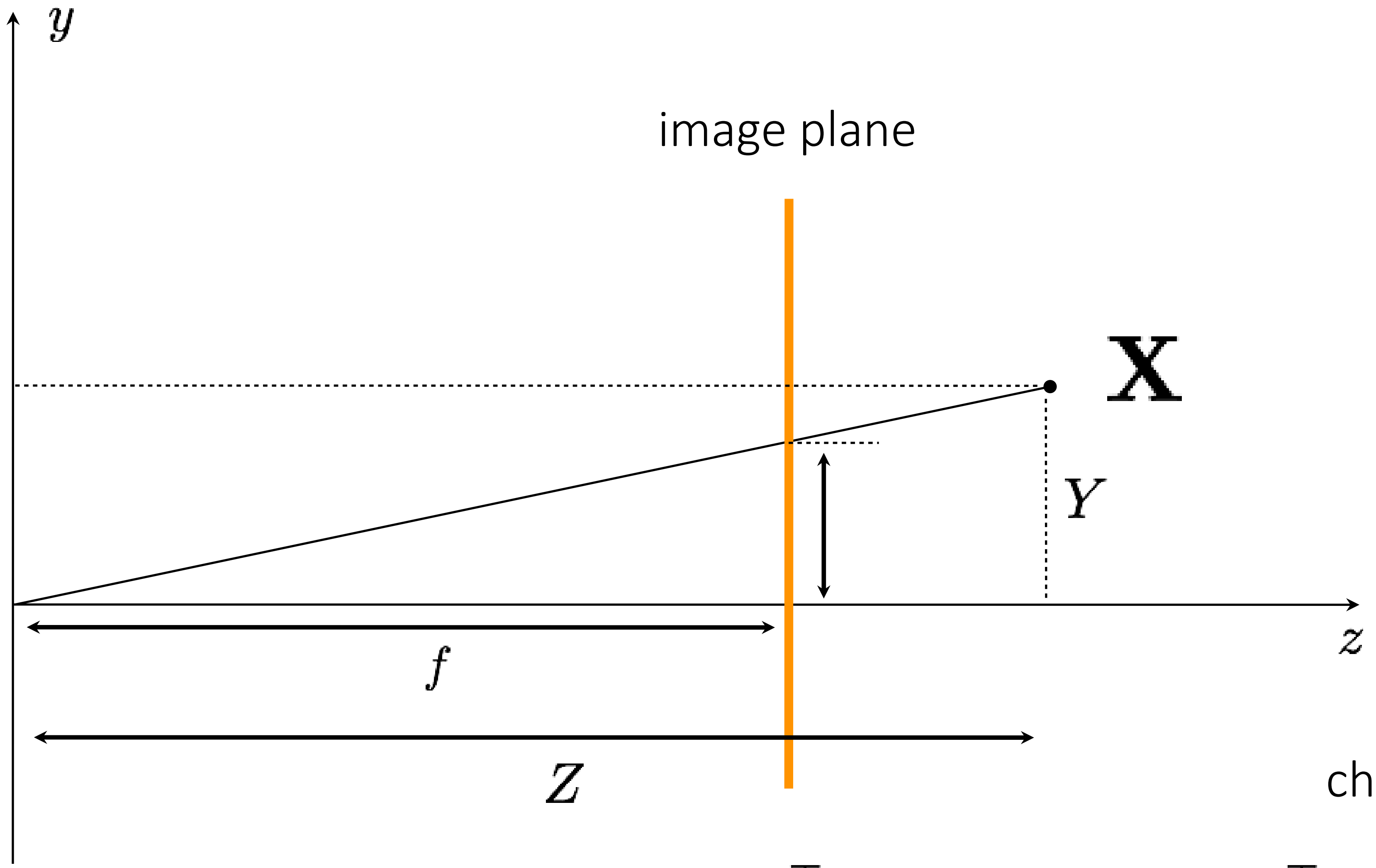
What if…



Continue increasing Z and f while maintaining same magnification?

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

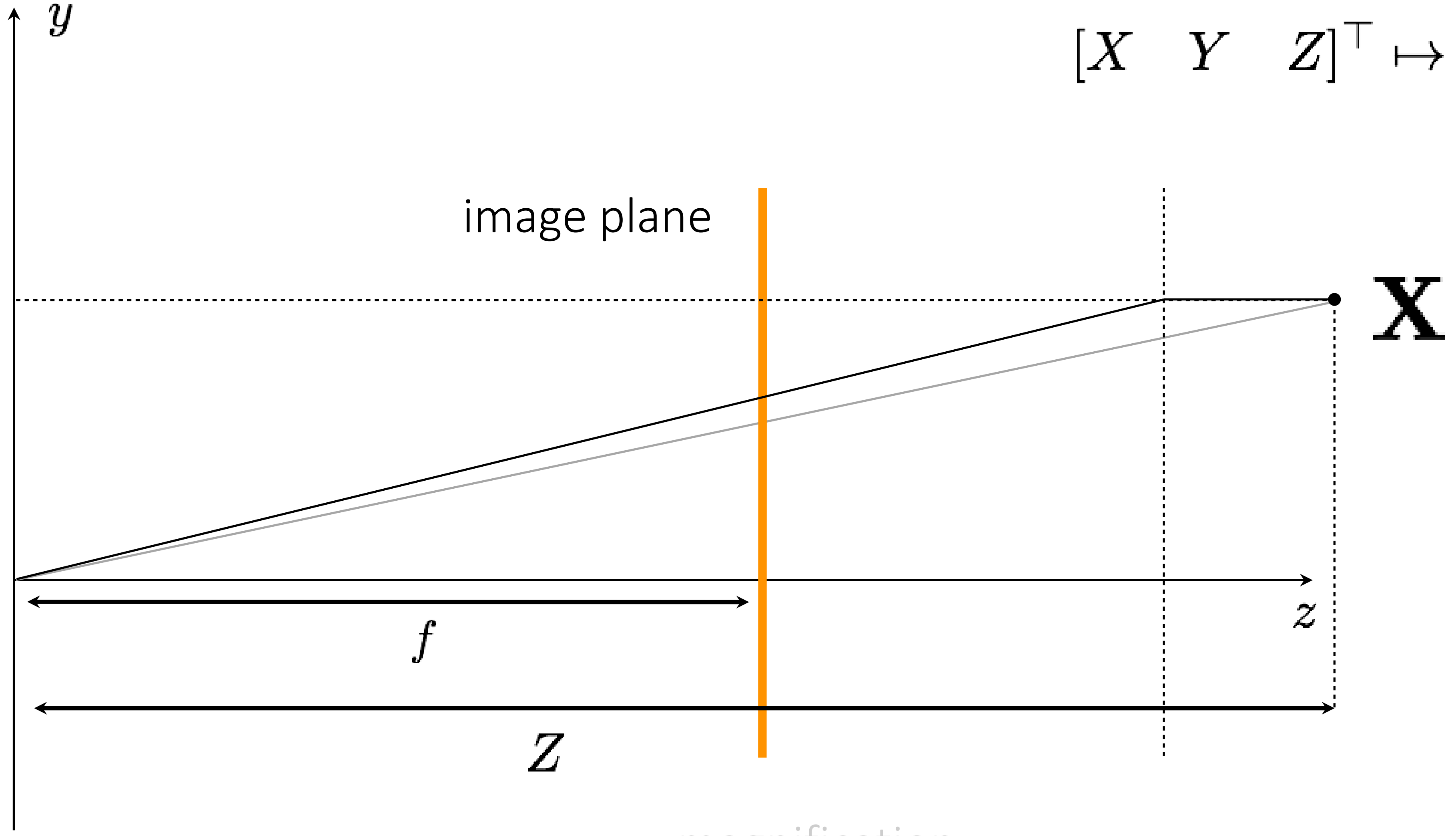
The 2D view of the (rearranged) pinhole camera



magnification changes with depth

$$[X \quad Y \quad Z]^\top \mapsto [fX/Z \quad fY/Z]^\top$$

Orthographic vs pinhole camera



$[X \quad Y \quad Z]^\top \mapsto [fX \quad fY]^\top$

magnification does not change with depth

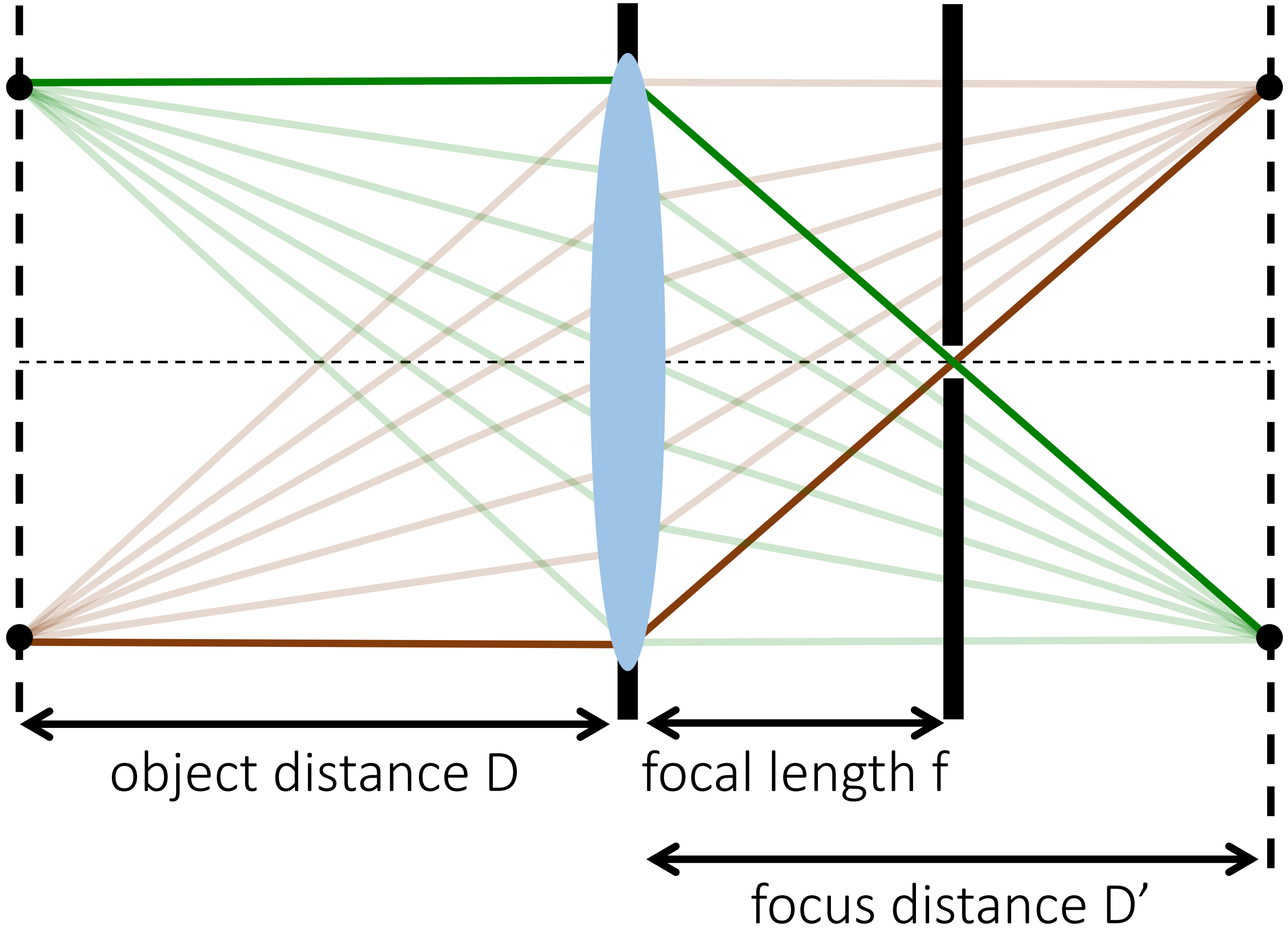
magnification changes with depth

$[X \quad Y \quad Z]^\top \mapsto [fX/Z \quad fY/Z]^\top$

How can we implement such a camera with lenses?

Telecentric lens

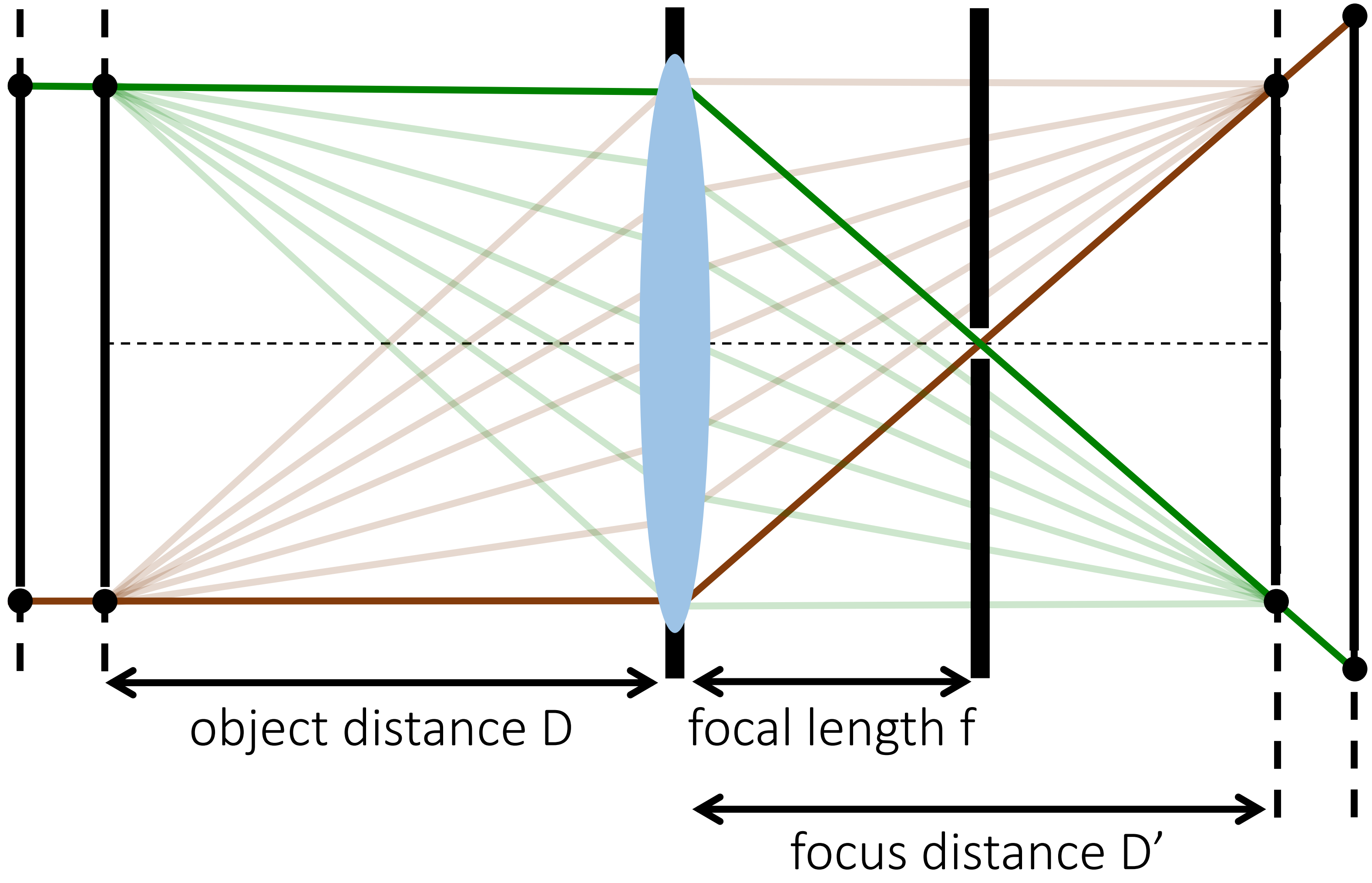
Place a pinhole at focal length, so that only rays parallel to primary ray pass through.



Telecentric lens

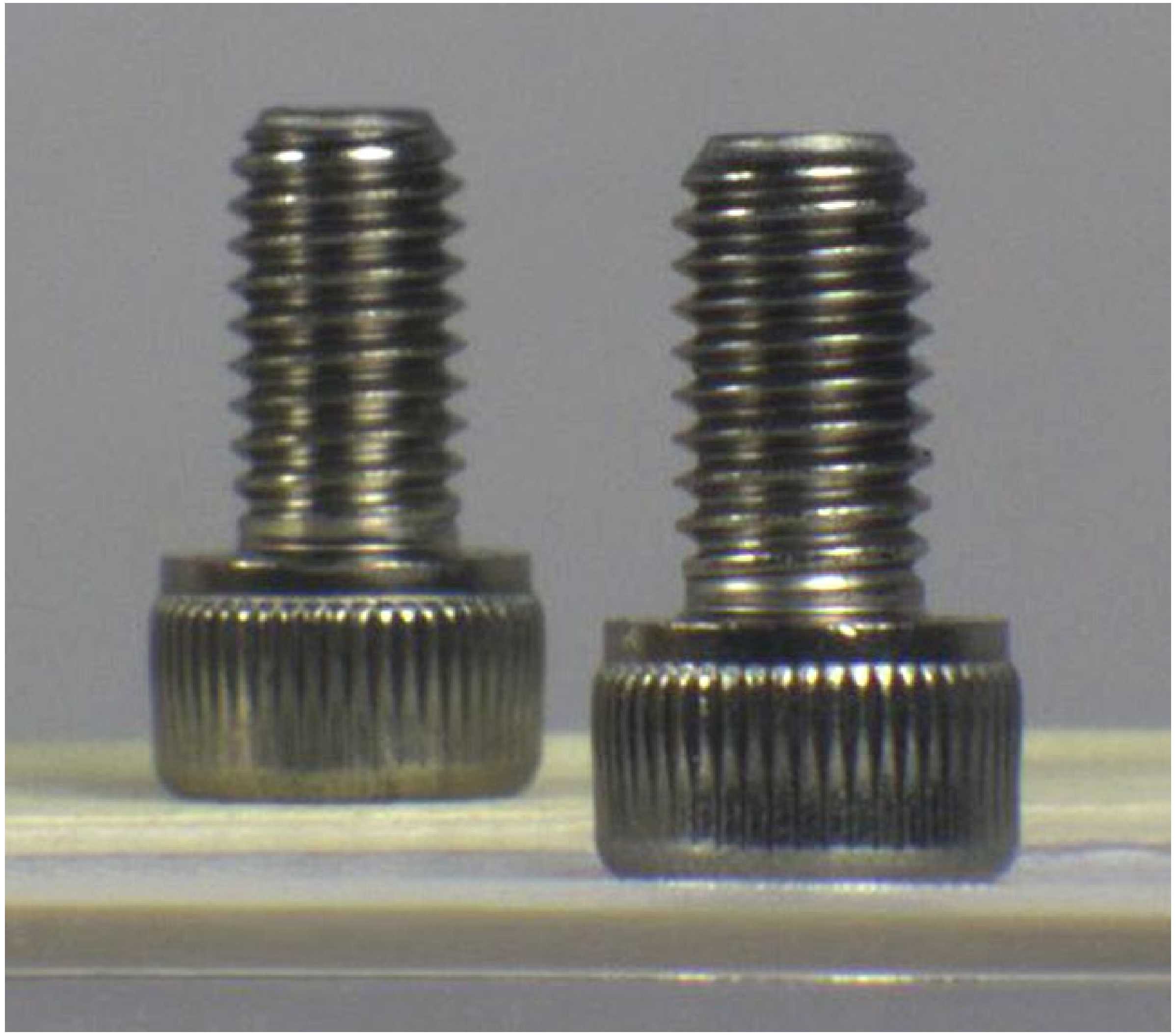
Place a pinhole at focal length, so that only rays parallel to primary ray pass through.

Magnification independent of object depth.

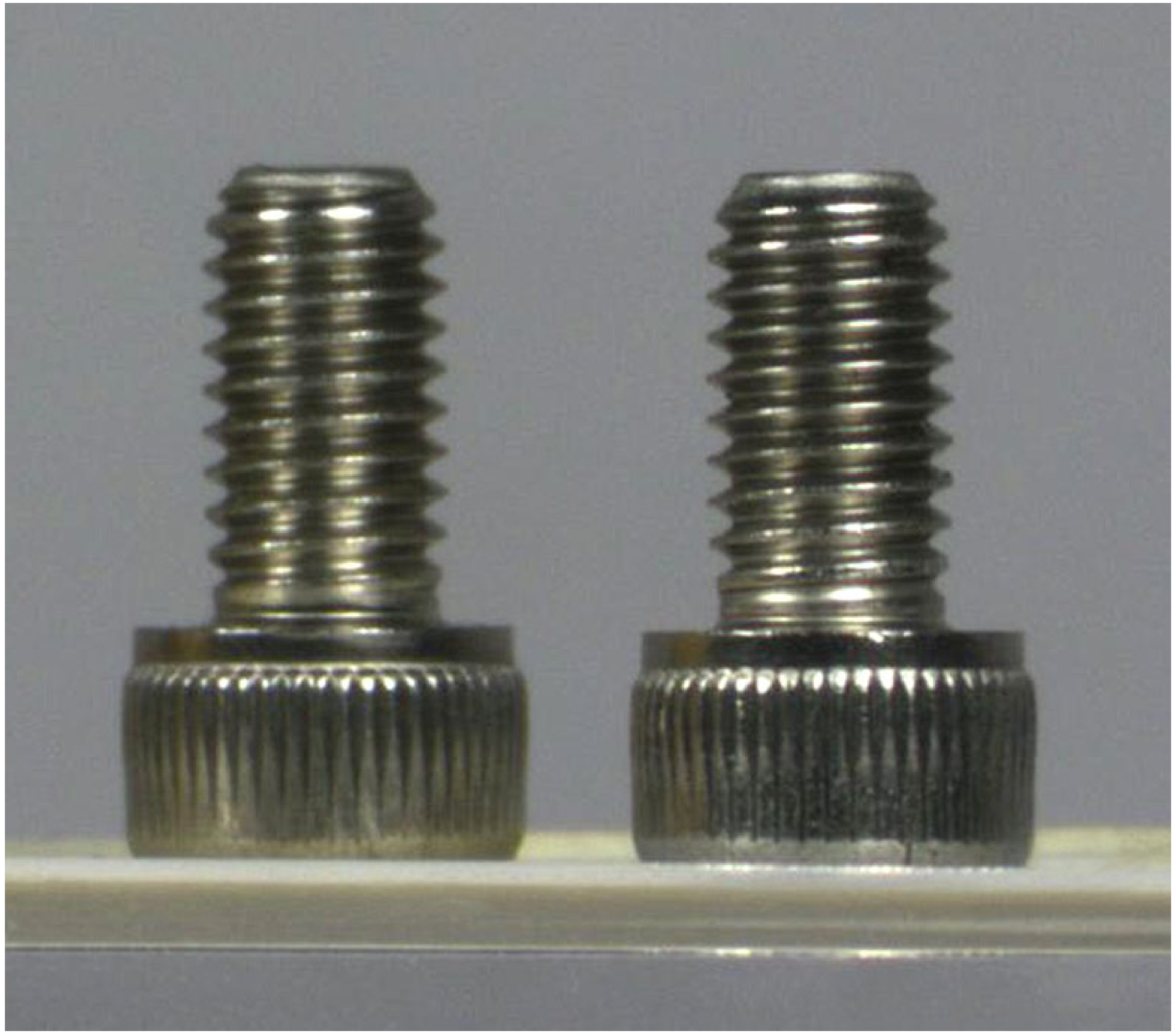


Magnification depends only on sensor-lens distance.

Regular vs telecentric lens



regular lens



telecentric lens

References

Basic reading:

- Szeliski textbook, Section 2.1.5, 2.2.3.
- Pedrotti, Pedrotti, and Pedrotti, Introduction to Optics.
  Chapters 2 and 3 have a detailed overview of basic geometric optics and lenses.

Additional reading:

- Hartley and Zisserman, "Multiple View Geometry in Computer Vision," Cambridge University Press 2004.
  Chapter 6 of this book is a very thorough treatment of camera models.
- Goodman, "Introduction to Fourier Optics," W.H. Freeman 2004.
  The standard reference on Fourier optics, chapter 4 covers aperture diffraction.
- Ray, "Applied Photographic Optics," Focal Press 2002.
  A great book covering everything about photographic optics.
- Torralba and Freeman, "Accidental Pinhole and Pinspeck Cameras," CVPR 2012.
  The eponymous paper discussed in the slides.