3D Vision and Machine Perception

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Some materials, figures, and slides (used for this course) are from textbooks, published papers, and other open lectures

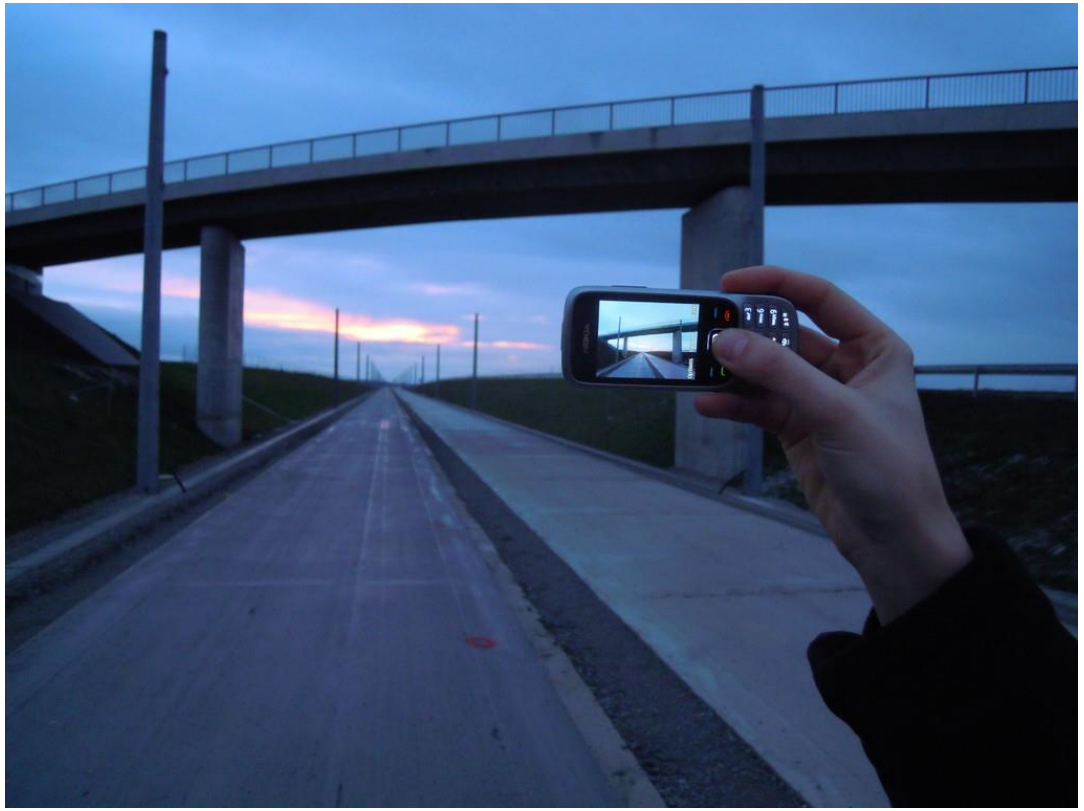
Contents

- Image (image pipeline)
- Focus, pinhole and Lens

What is an image?

- Image: projection of the 3D world onto an (2D) image plane
  - 2-dimensional patterns of brightness values
  - Formed by the projection of 3D objects

"Dürer - Man Drawing a Lute" in Geometrie (1535) by Albrecht Dürer



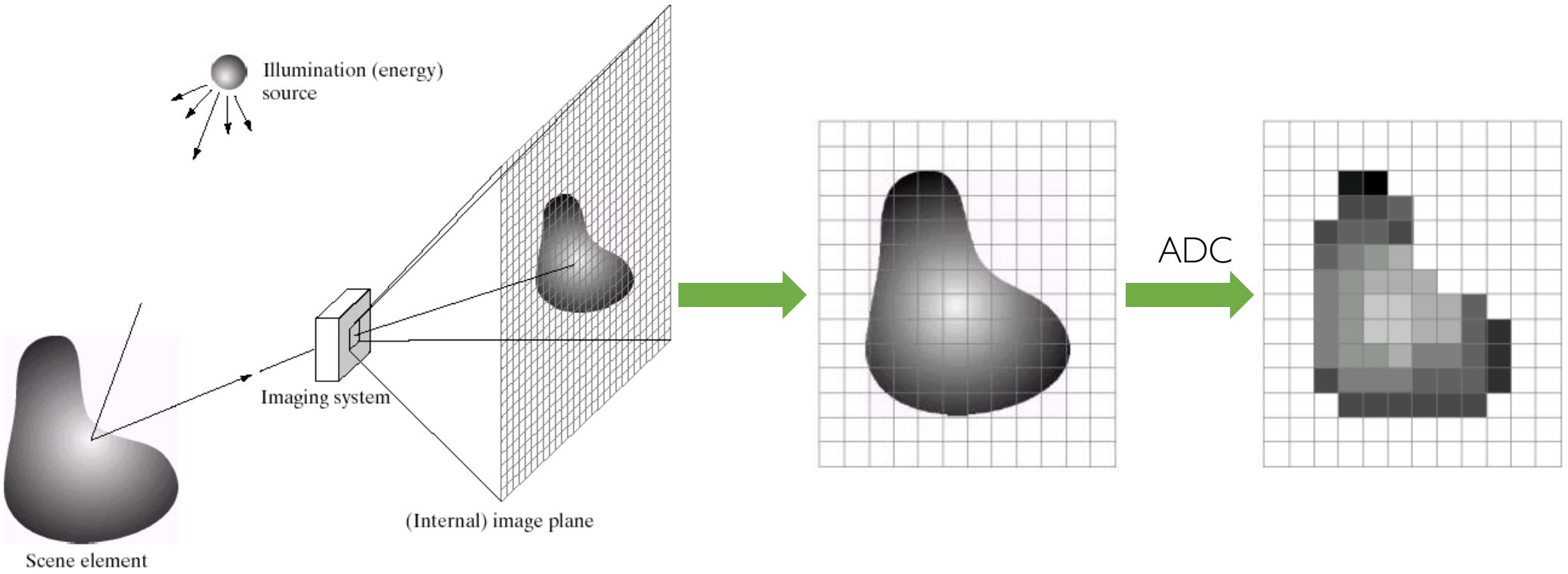
"Image created with a mobile phone" by Olaf Simons - Own work.

This is how we obtain images

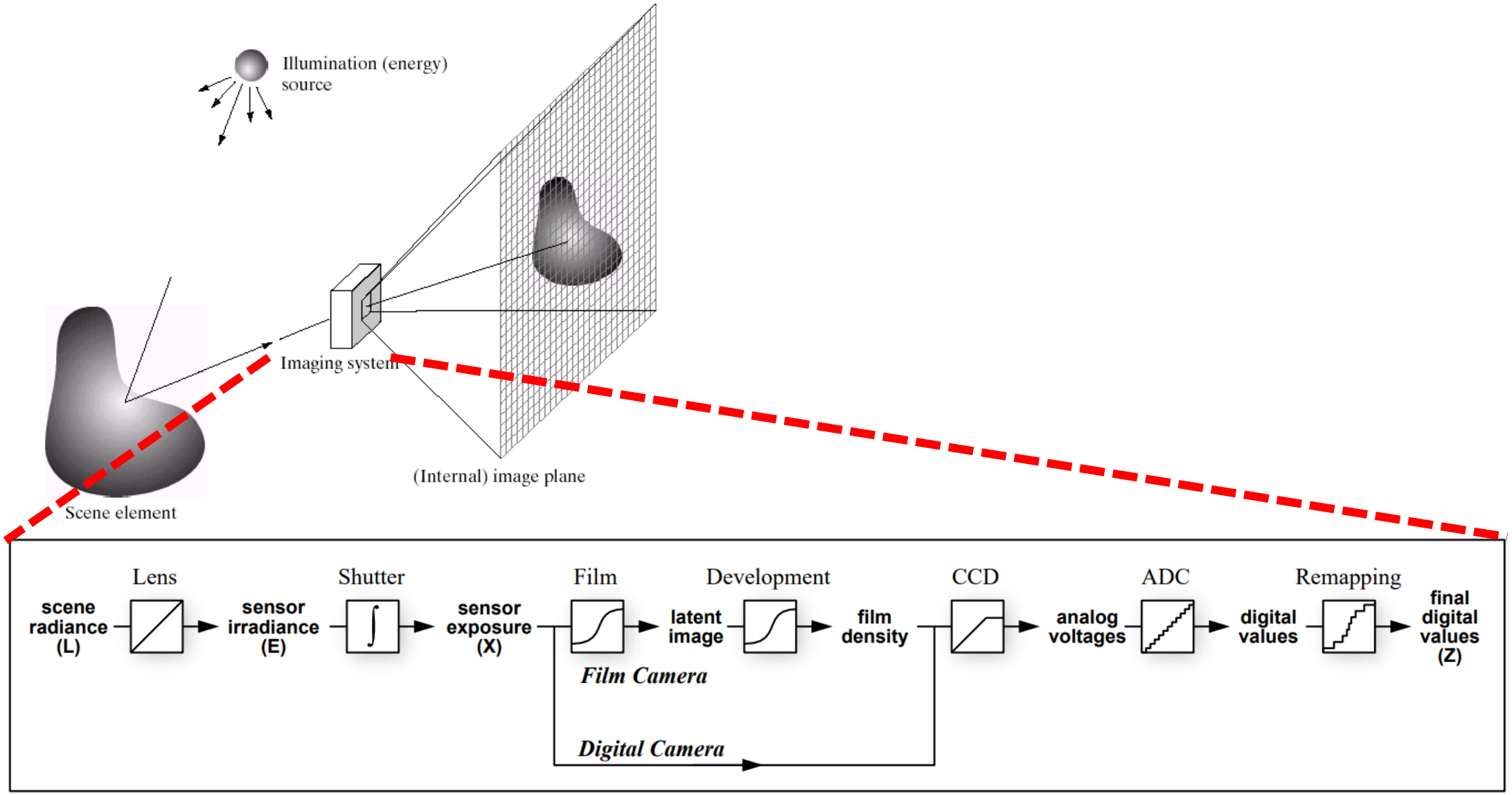
https://static.makeuseof.com/wp- content/uploads/2018/05/iphone-camera-settings-670x335.jpg

https://www.aolor.com/images/tutorial/devices/take- photos-with-iphone.jpg

Travel of a photon - Image formation



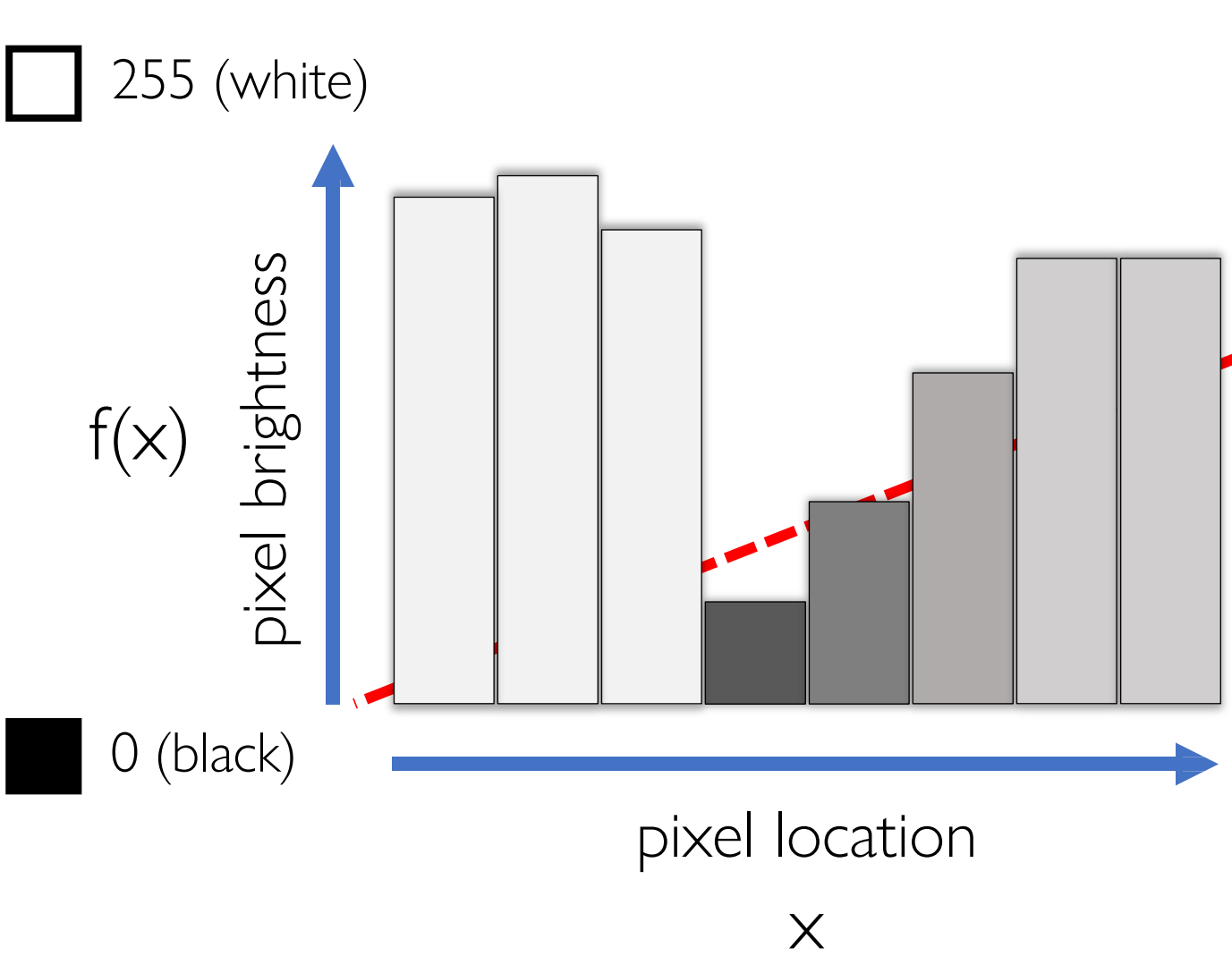
Travel of a photon - Image formation

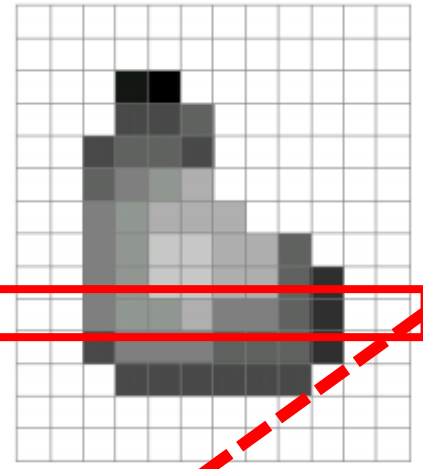


Recovering High Dynamic Range Radiance Maps from Photographs , SIGGRAPH97

Images from A. Efros

Thinking about images as functions





255	255	255	255	255	255	255	255	255
255	255	255	255	255	255	255	255	255
255	255	255	20	0	255	255	255	255
255	255	255	75	75	75	255	255	255
255	255	75	95	95	75	255	255	255
255	255	96	127	145	175	255	255	255
255	255	127	145	175	175	175	255	255
255	255	127	145	200	200	175	175	95
255	255	127	145	200	200	175	175	95
255	255	127	145	145	175	127	127	95

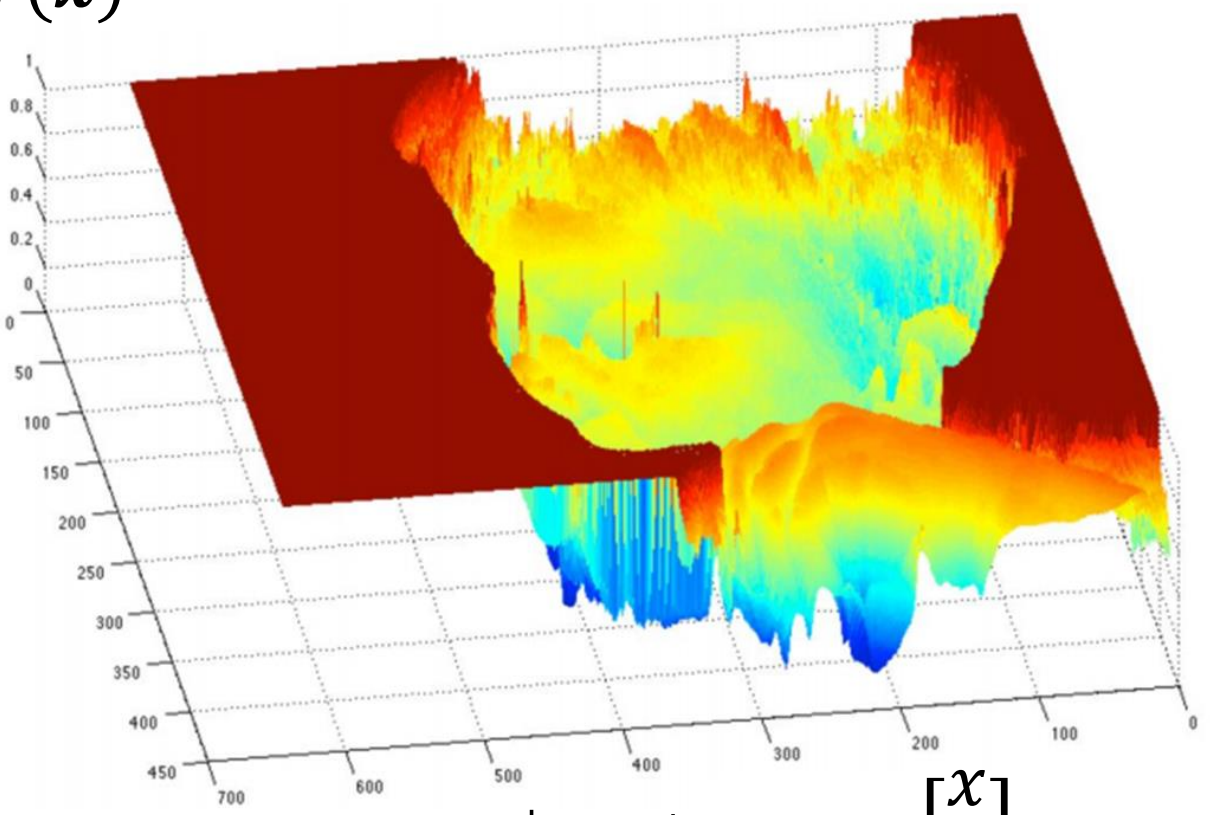
The left figure from Ioannis Gkioulekas

Thinking about images as functions

- A (grayscale) image is a 2D function

grayscale image

$f(x)$



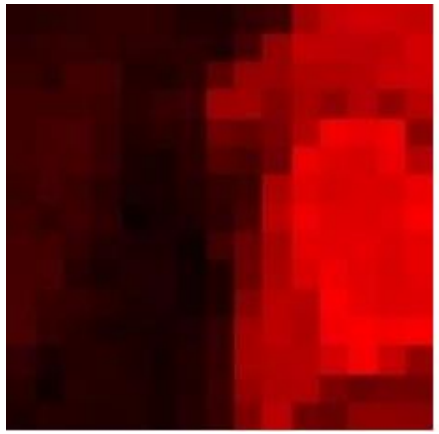
domain $x = \begin{bmatrix} x \\ y \end{bmatrix}$

What is the range of the image function f?

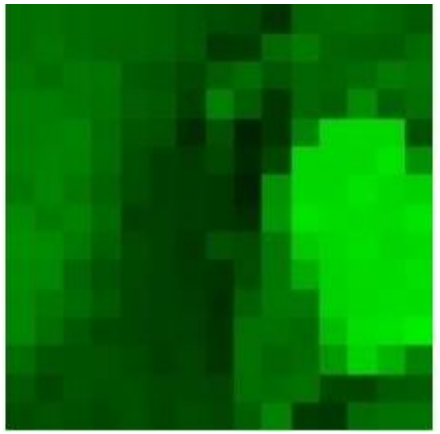
Images from Ioannis Gkioulekas

Color intensity

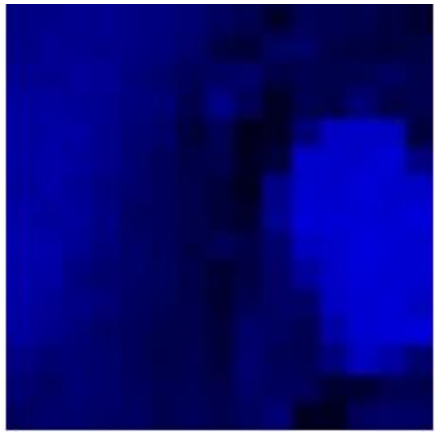
color image patch



R (red)

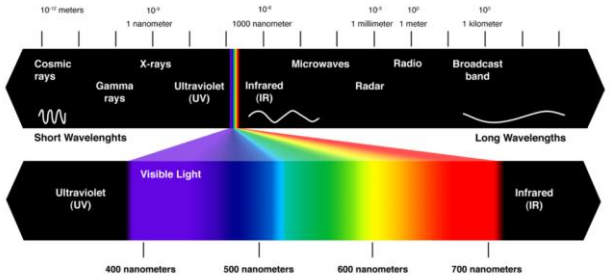


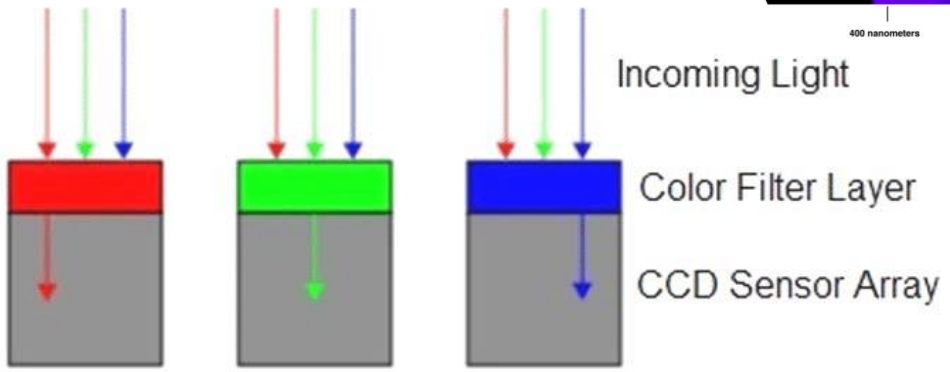
G (green)

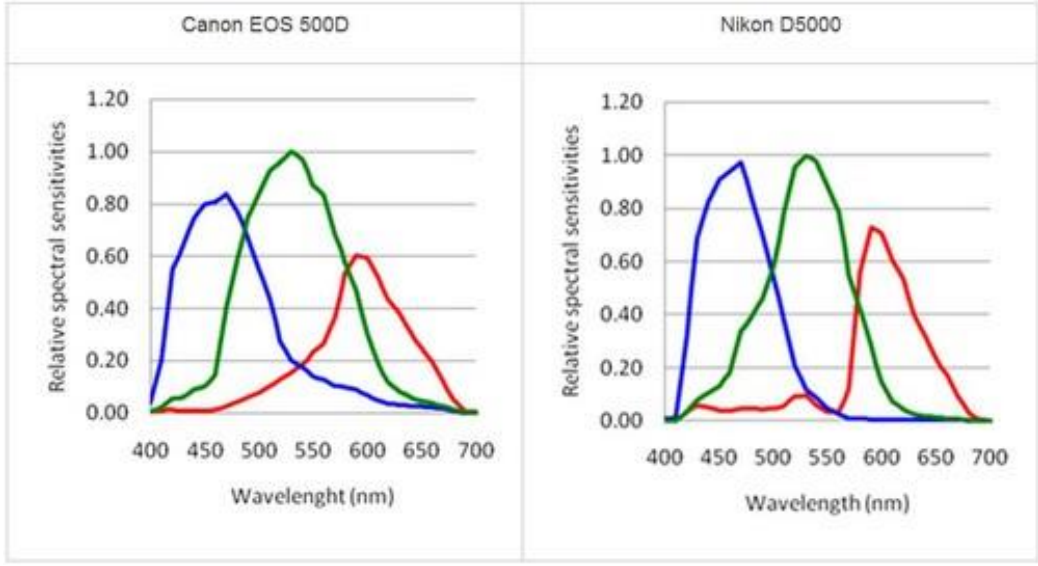


B (blue)

3D tensor: H × W × C



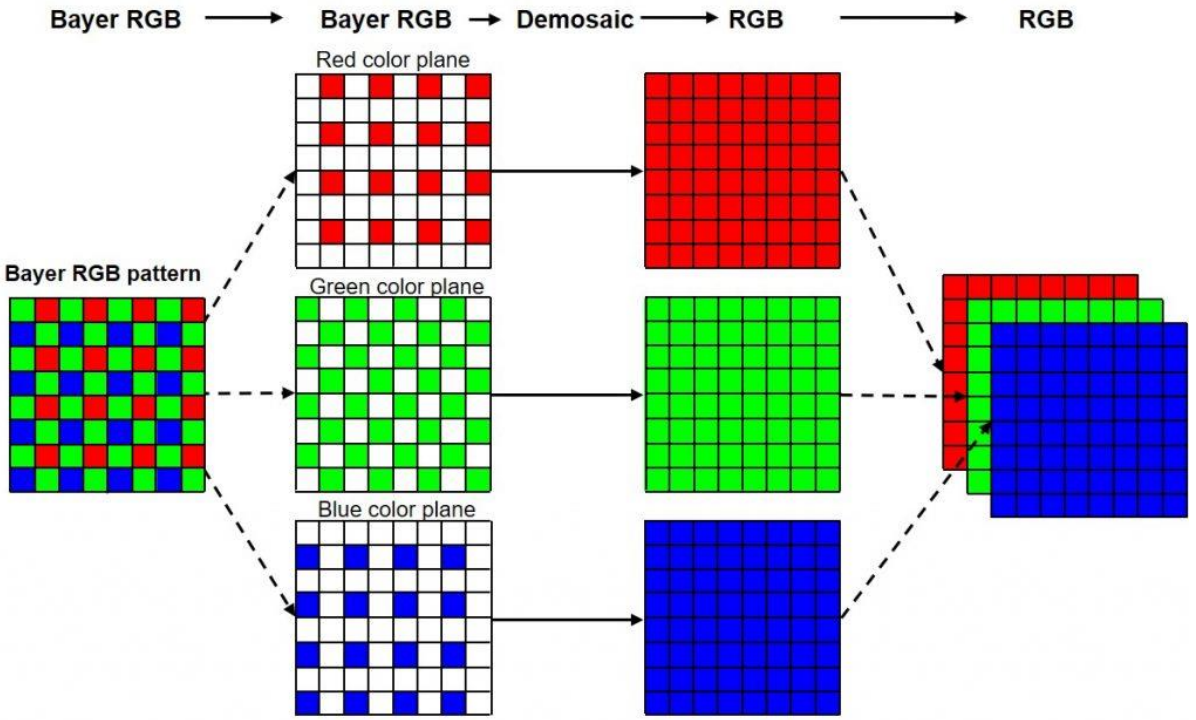




[Top] Images from Ioannis Gkioulekas
[Bottom] Images under CC license (Searched by "camera spectral response")

Bayer pattern

- Sensor placement: Bayer RGB mosaic
- Why more green?
  - We have 3 channels and square lattice don't like odd numbers
  - It's the spectrum "in the middle"
  - More important to human perception of brightness

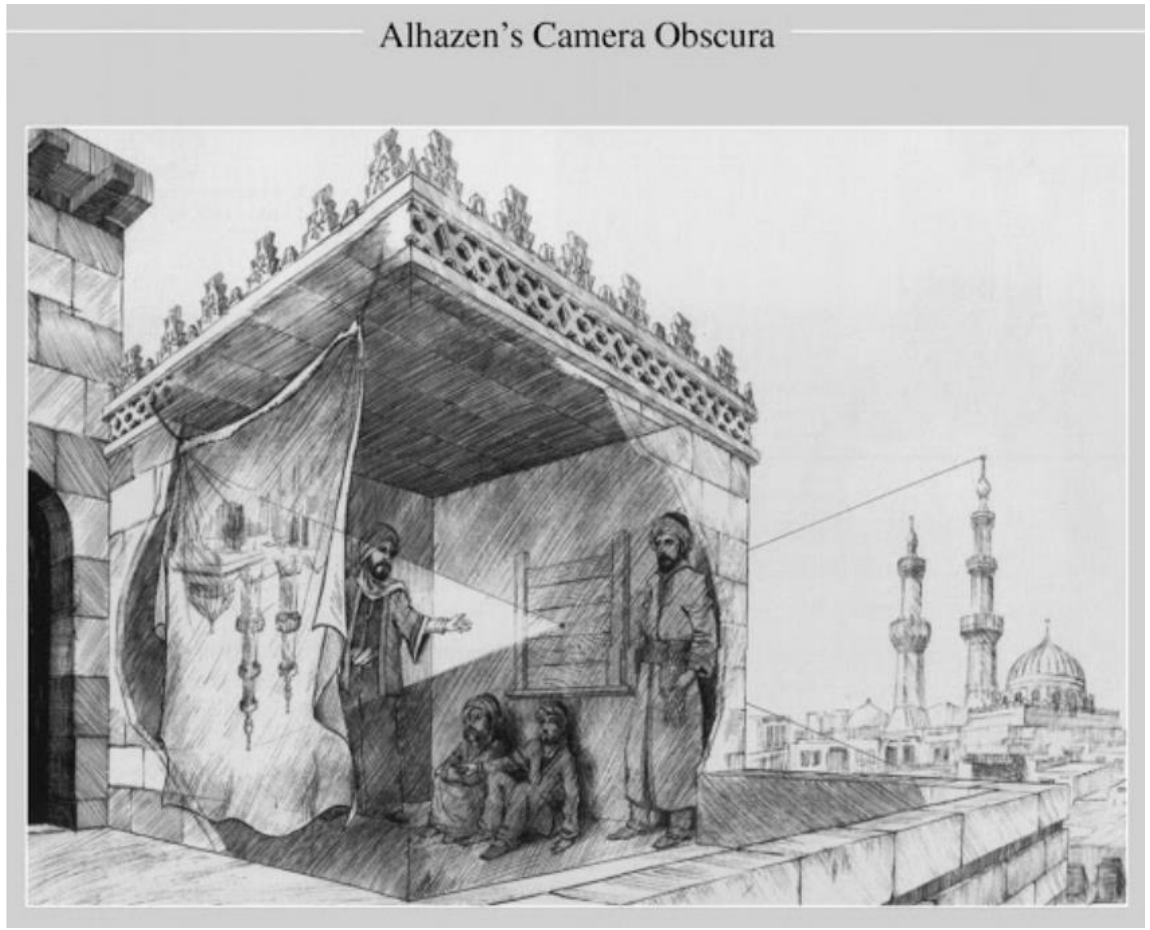


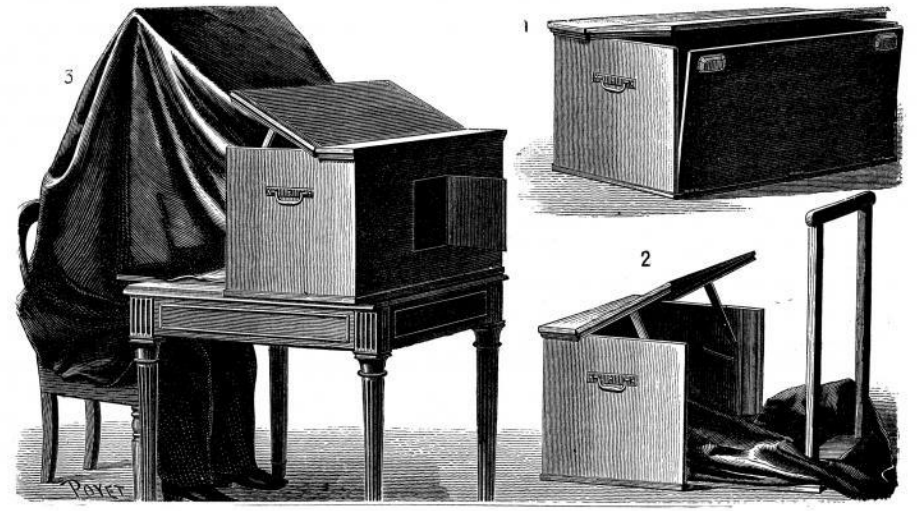
Source: https://theailearner.com/2018/10/28/bayer-filter/

Focus, Pinhole and Lens

Pinhole camera

- By Aristotle 2300 years ago (a Chinese record; 2400 years ago)





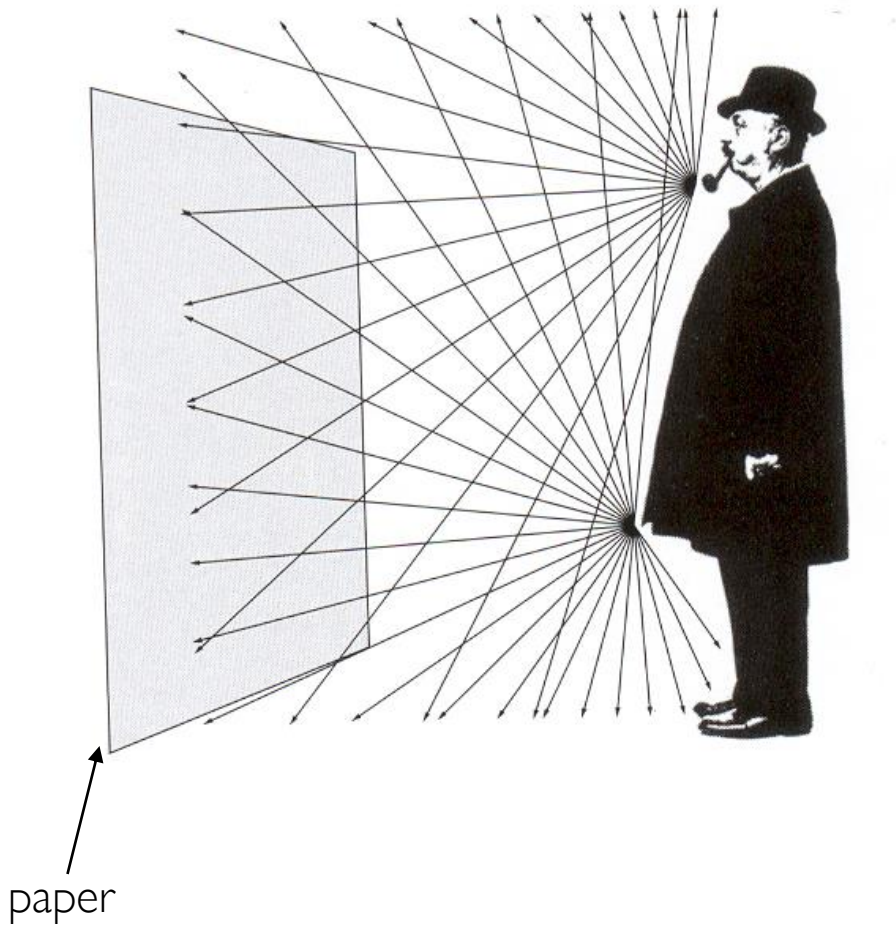
Less then 200 years ago

https://photography.lovetoknow.com/First_Camera_Invented

Images from K. J. Yoon's slide

Why is there no image on a piece of white paper?

- Light is coming from all directions!



From Photography, London et al.

Let's say we have a sensor…

digital sensor (CCD or CMOS)

… and an object we like to photograph

- What would an image taken like this look like?

real-world object

digital sensor (CCD or CMOS)

Bare-sensor imaging

real-world object

digital sensor (CCD or CMOS)

Bare-sensor imaging

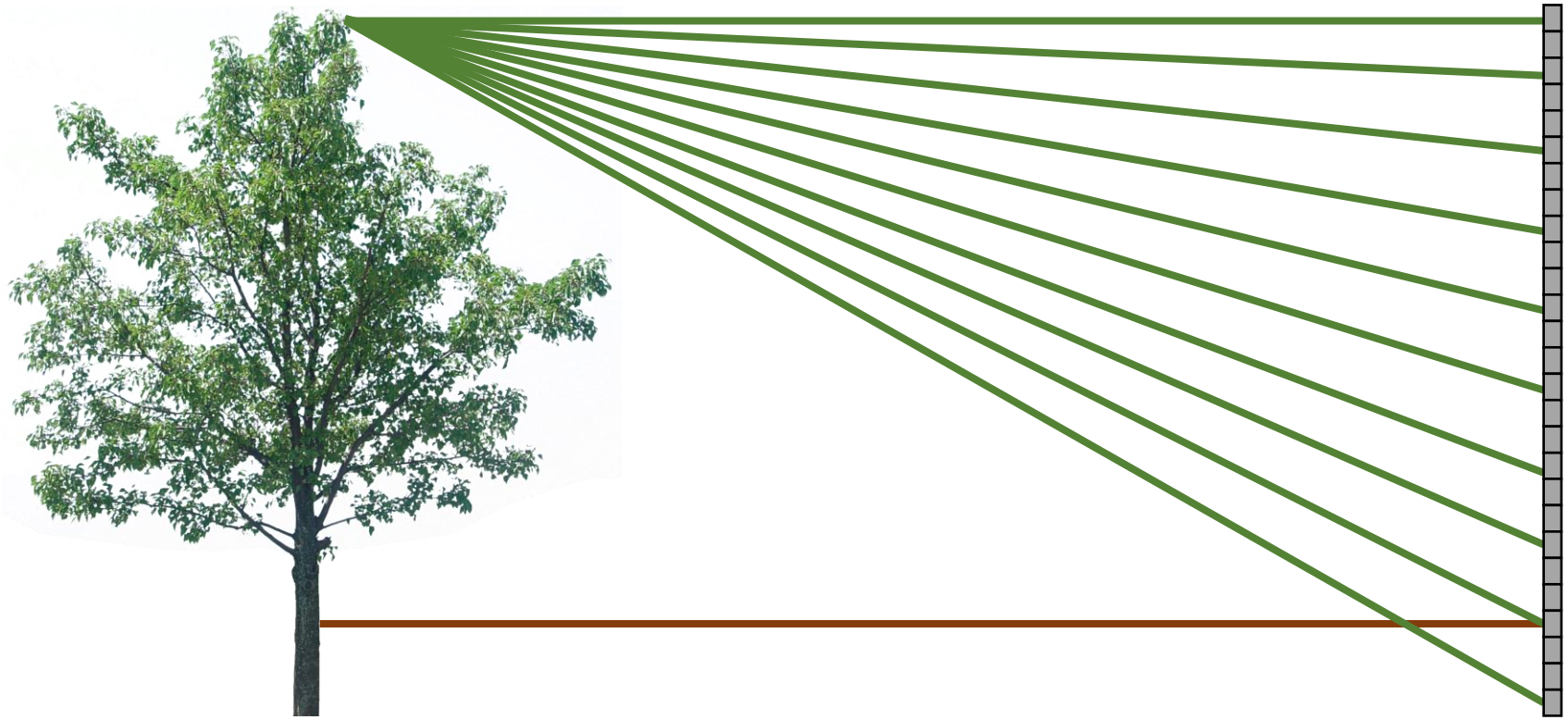
real-world object

digital sensor (CCD or CMOS)

Slide from Ioannis Gkioulekas [Lecture 16-385]

Bare-sensor imaging

real-world object

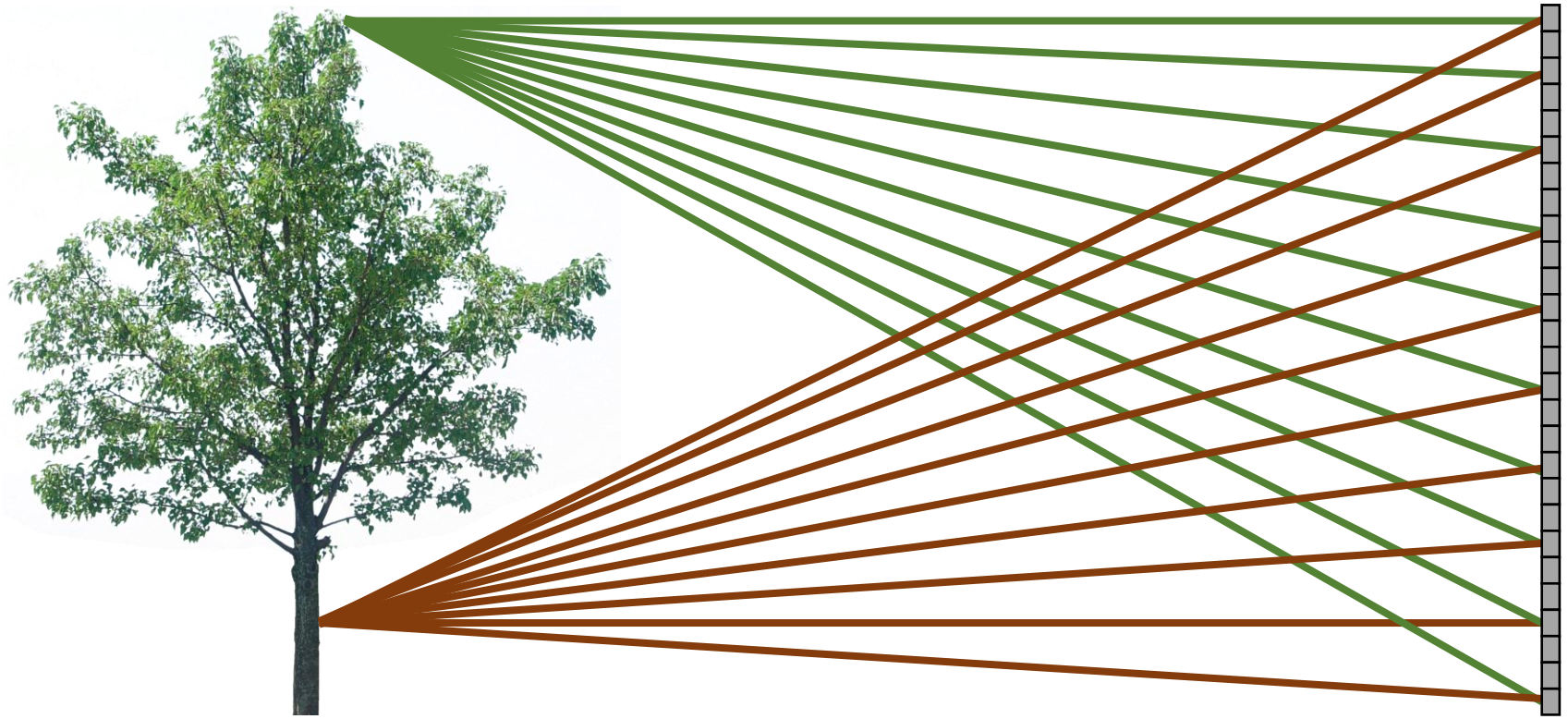


digital sensor (CCD or CMOS)

Slide from Ioannis Gkioulekas [Lecture 16-385]

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

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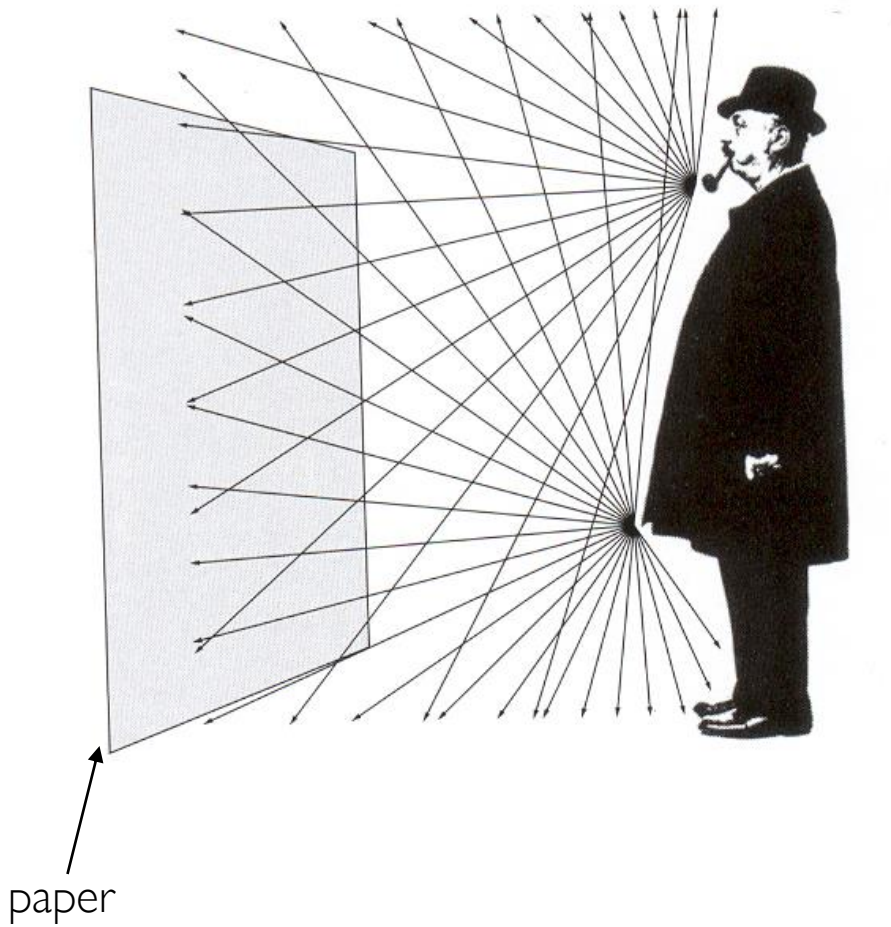
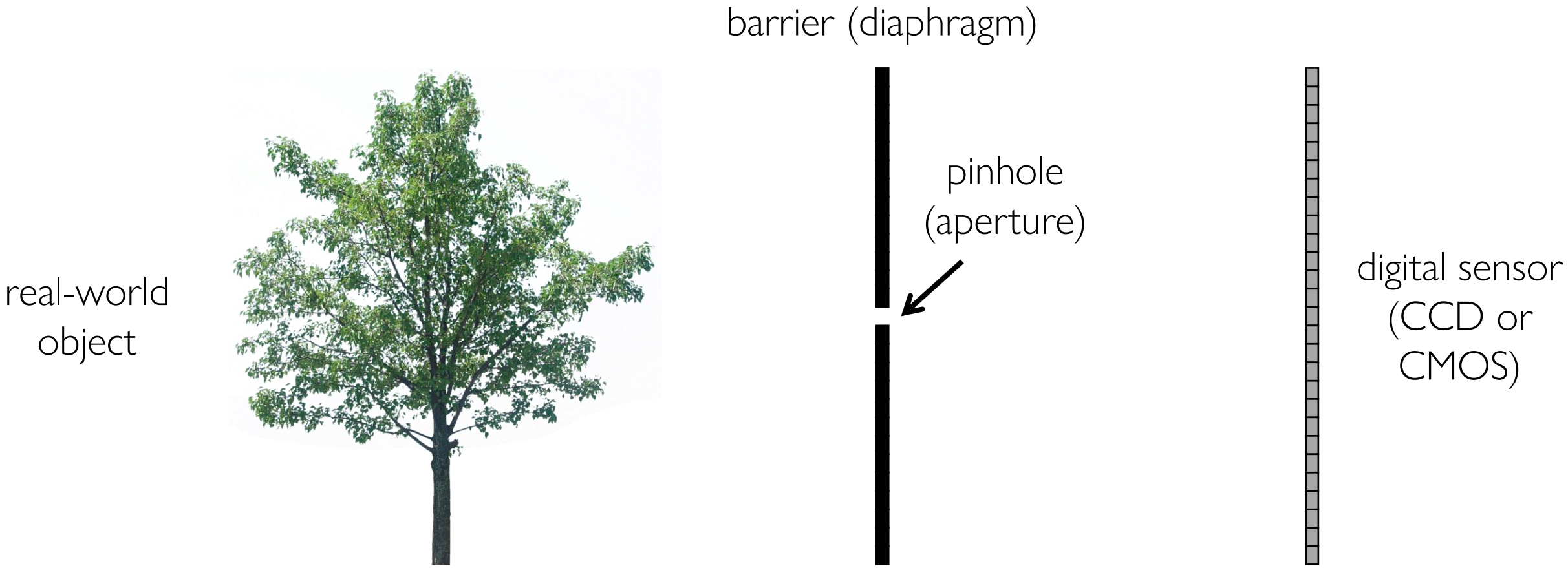


From Photography, London et al.

Let's add something to this scene

- What would an image taken like this look like?



Slide from Ioannis Gkioulekas [Lecture 16-385]

Pinhole imaging

real-world object

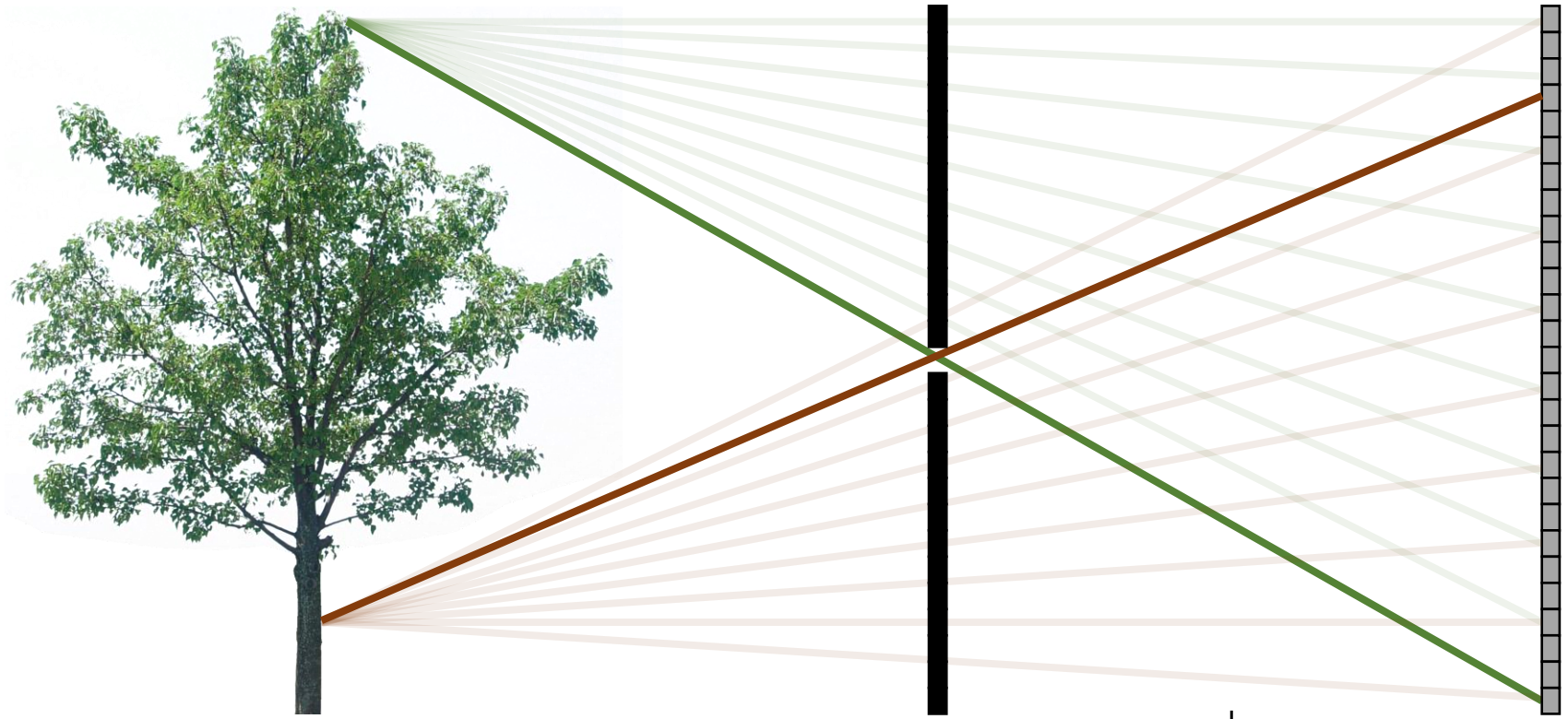
most rays are blocked

one makes it through

digital sensor (CCD or CMOS)

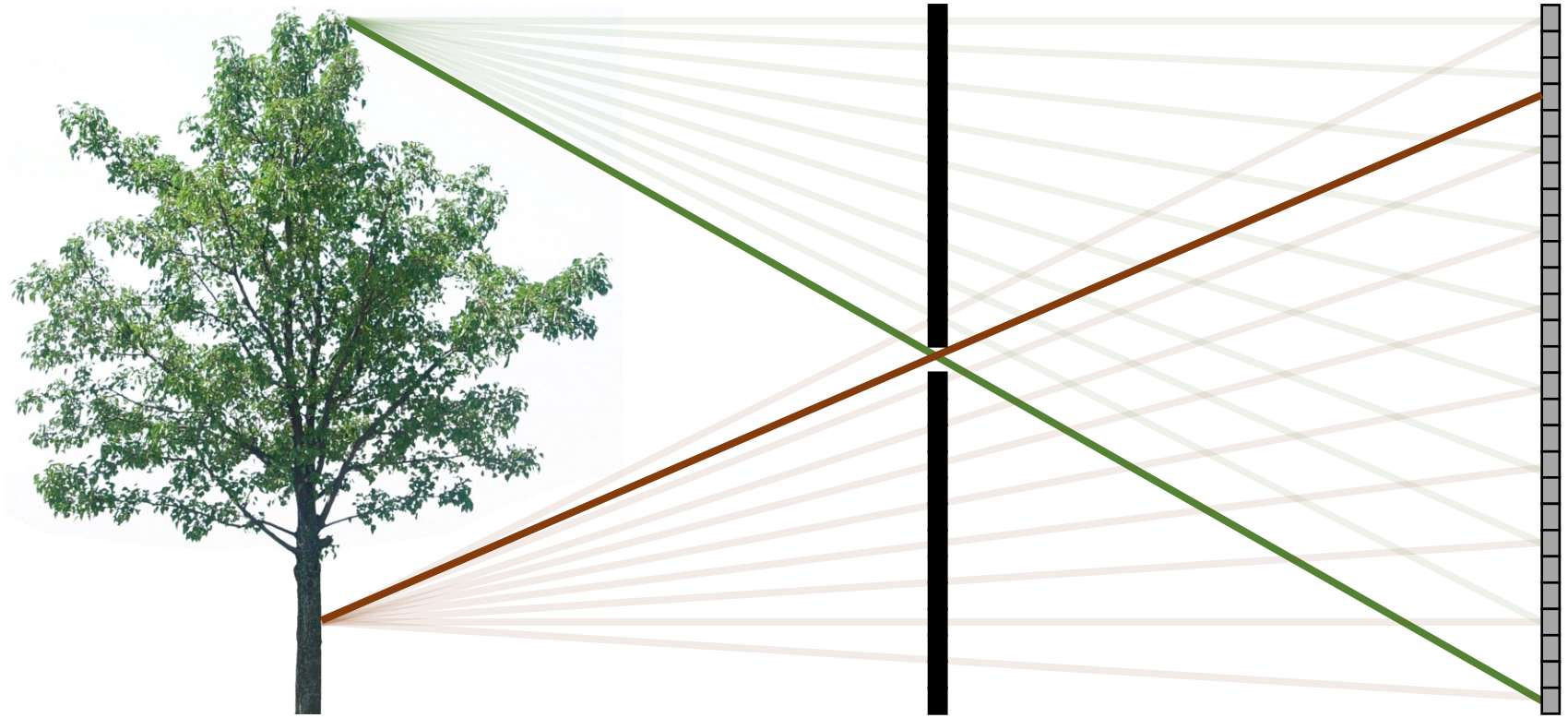
Slide from Ioannis Gkioulekas [Lecture 16-385]

Pinhole imaging



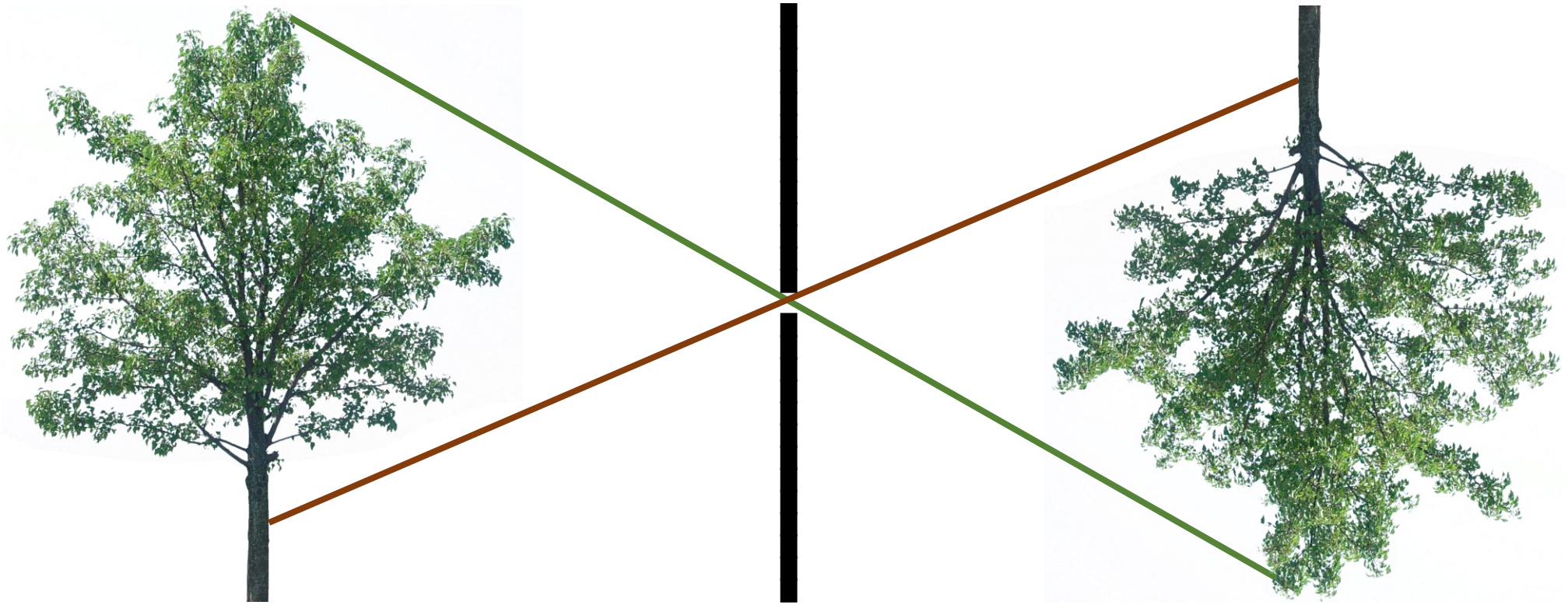
Pinhole imaging

- Each scene point contributes to only one sensor pixel
- What does the image on the sensor look like?



Pinhole imaging

real-world object



copy of real-world object (inverted and scaled)

Accidental pinhole camera

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

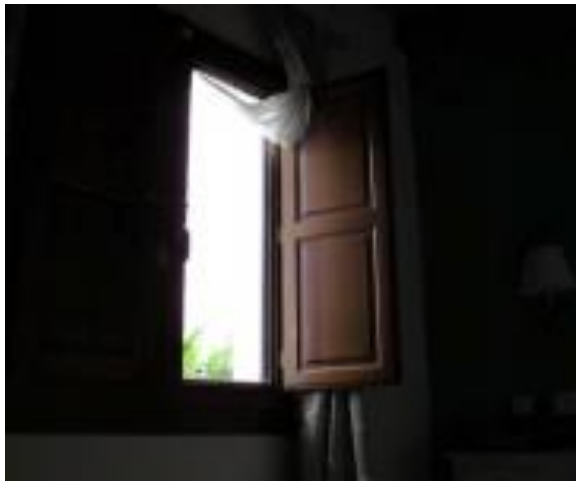
Antonio Torralba, William T. Freeman
Computer Science and Artificial Intelligence Laboratory (CSAIL)
MIT
torralba@mit.edu, billf@mit.edu

Slide from Ioannis Gkioulekas [Lecture 16-385]

What does this image say about the world outside?

Slide from Ioannis Gkioulekas [Lecture 16-385]

Accidental pinhole camera



window is an aperture

projected pattern on the wall

upside down

window with smaller gap

view outside window

Slide from Ioannis Gkioulekas [Lecture 16-385]

Slide from Ioannis Gkioulekas [Lecture 16-385]

Pinhole camera terms

real-world object

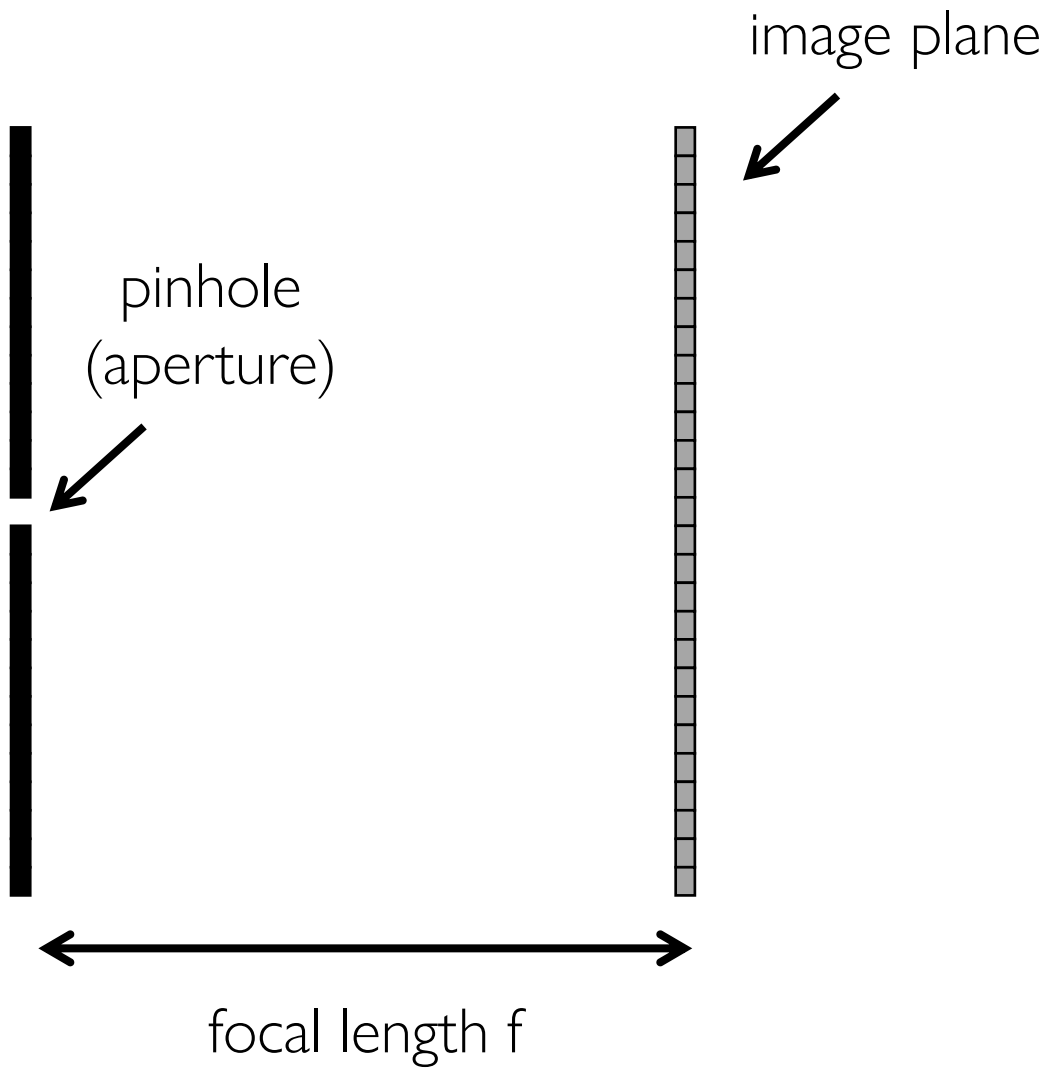
barrier (diaphragm)

pinhole (aperture)

digital sensor (CCD or CMOS)

Focal length

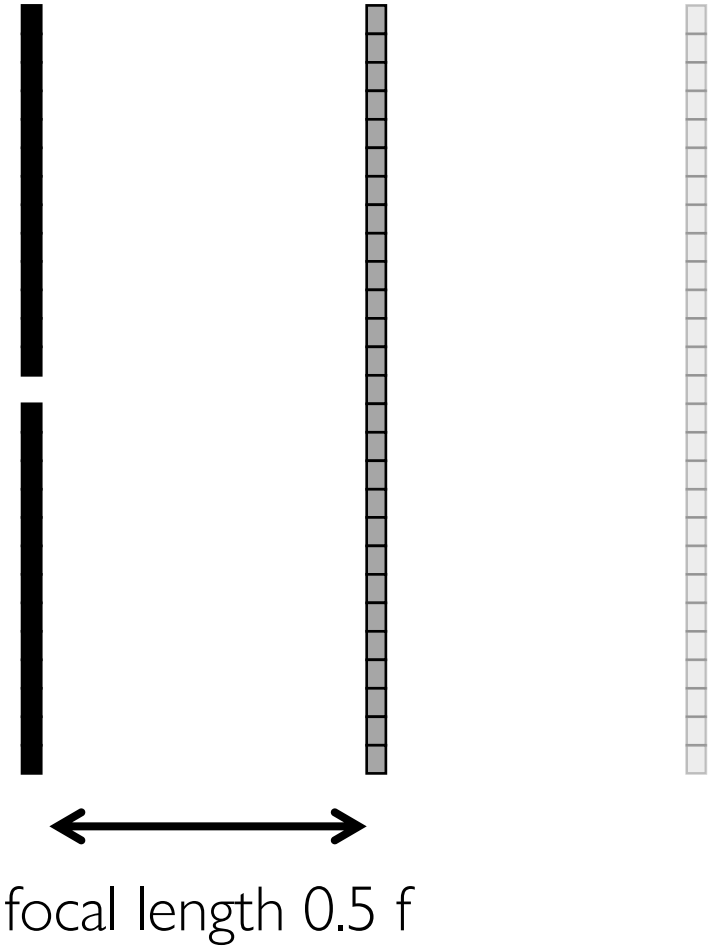
real-world object



Focal length

- What happens as we change the focal length?

real-world object

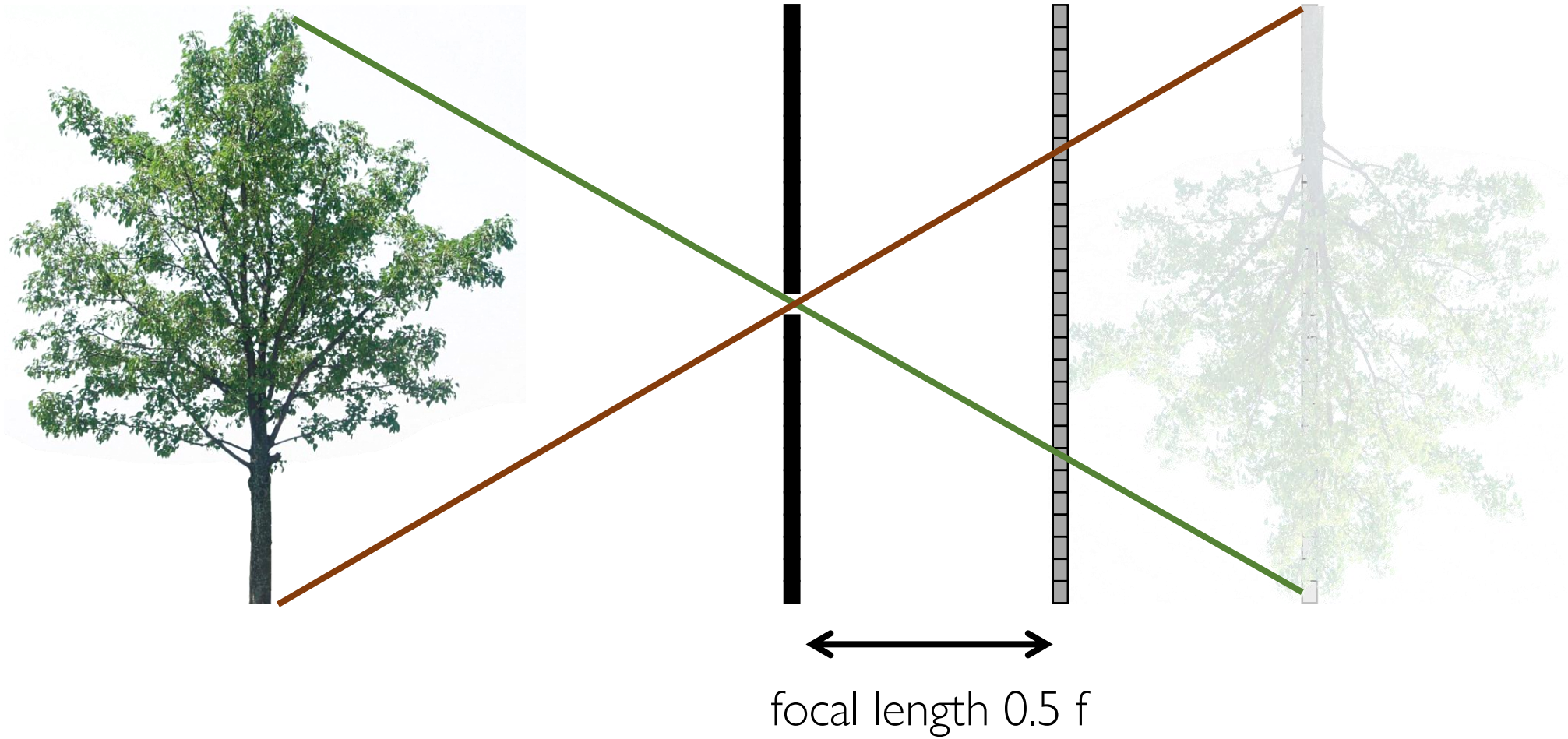


focal length 0.5 f

Focal length

- What happens as we change the focal length?

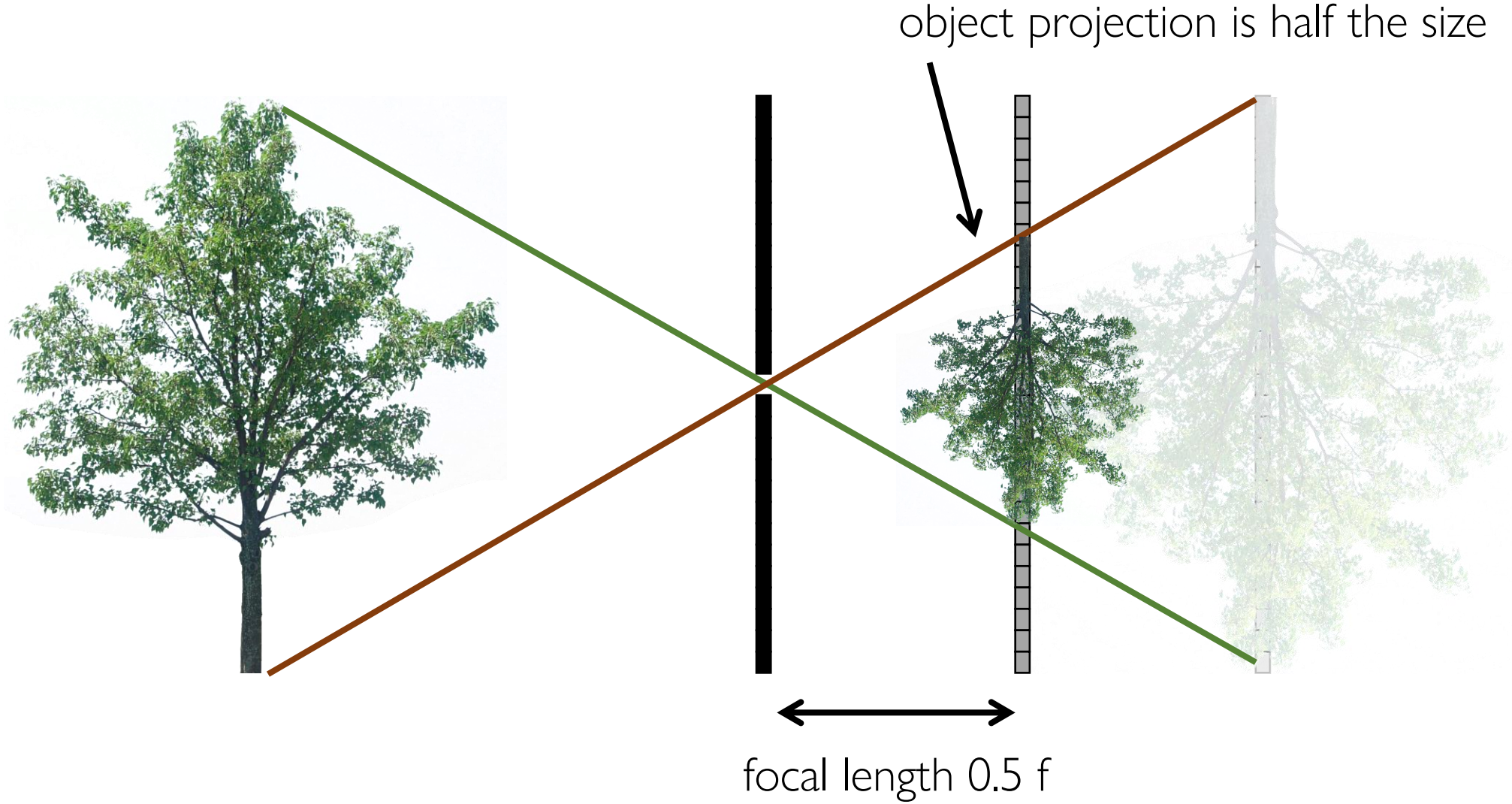
real-world object



focal length 0.5 f

Focal length

- What happens as we change the focal length?

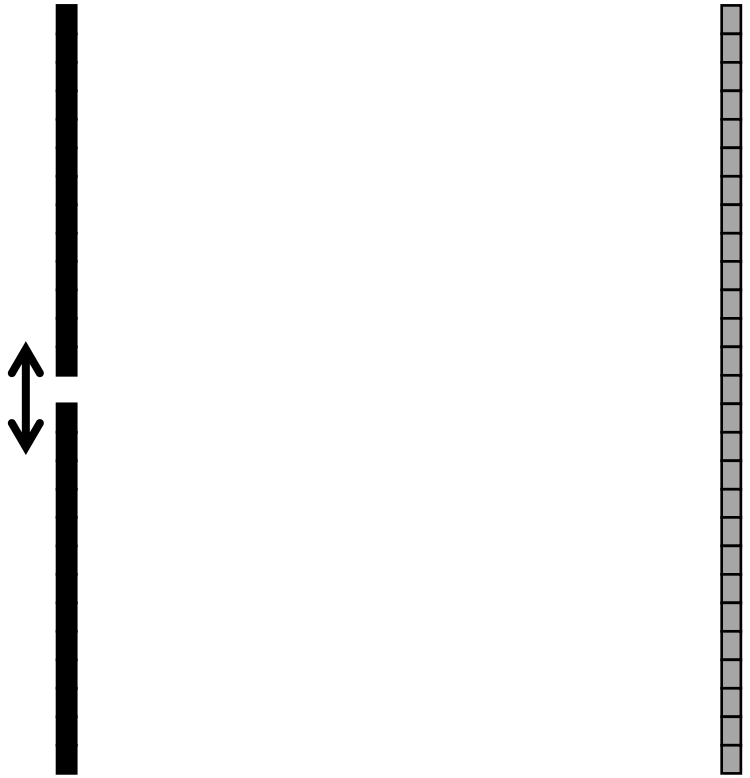


Pinhole size

- Ideal pinhole has infinitesimally small size
  - In practice that is impossible.

real-world object

pinhole diameter



Slide from Ioannis Gkioulekas [Lecture 16-385]

Pinhole size

- What happens as we change the pinhole diameter?

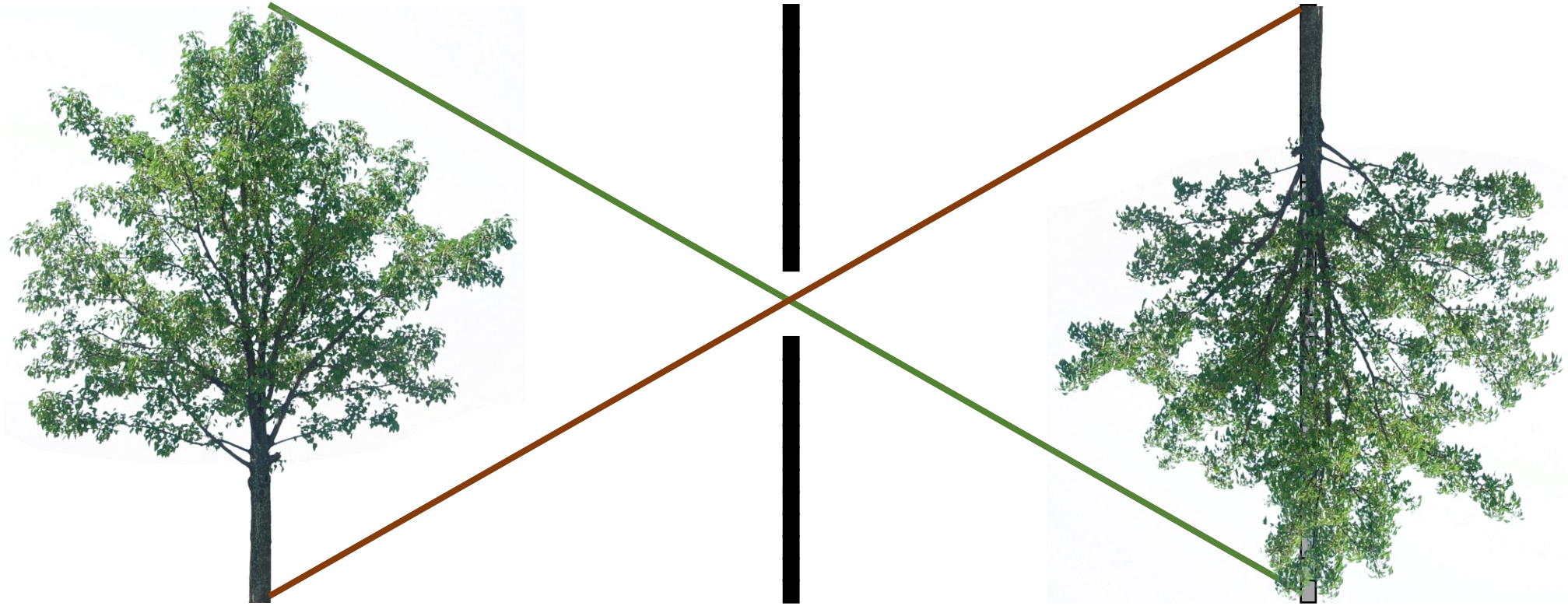
real-world object

pinhole diameter

Pinhole size

- What happens as we change the pinhole diameter?

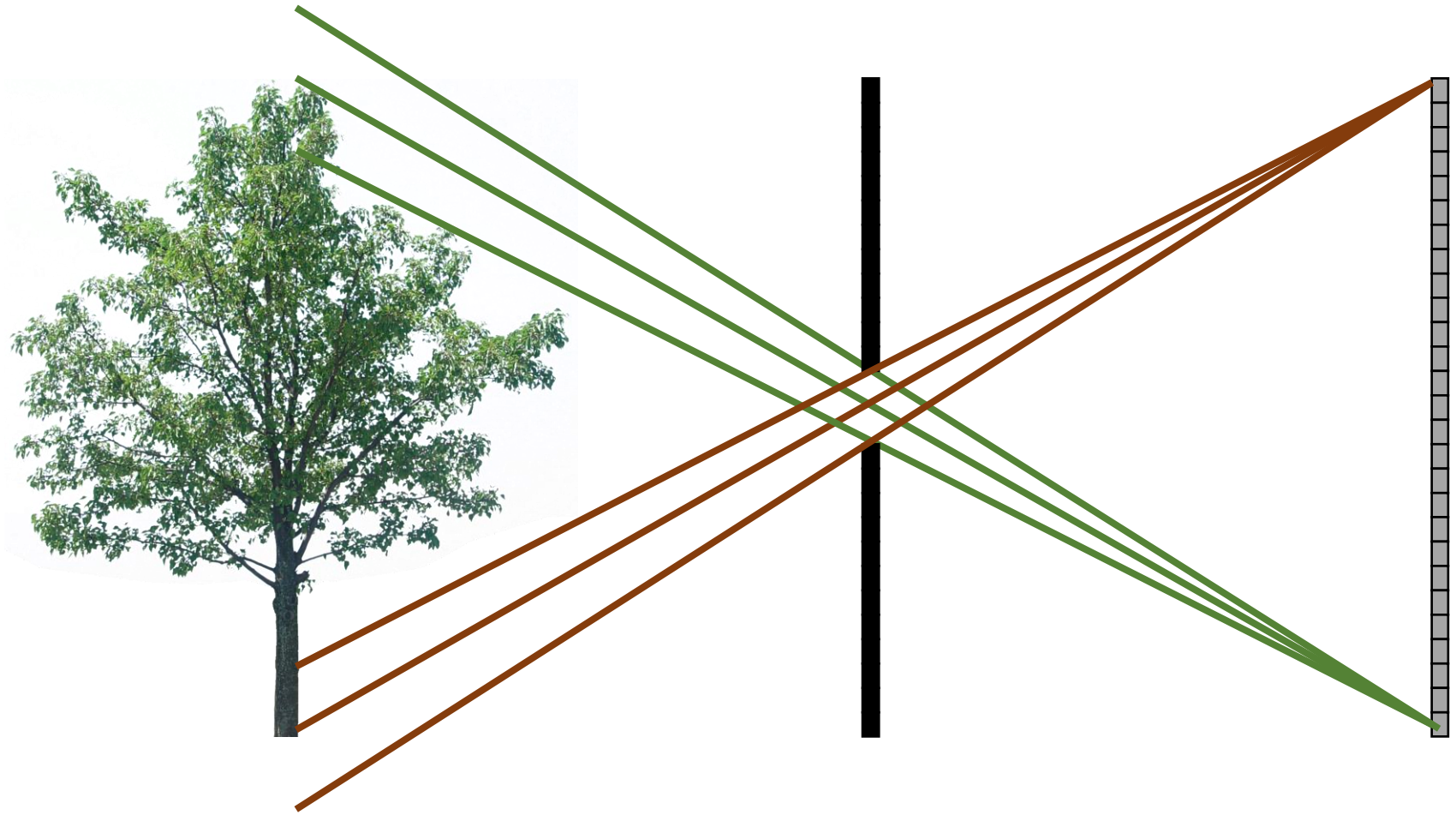
real-world object



Pinhole size

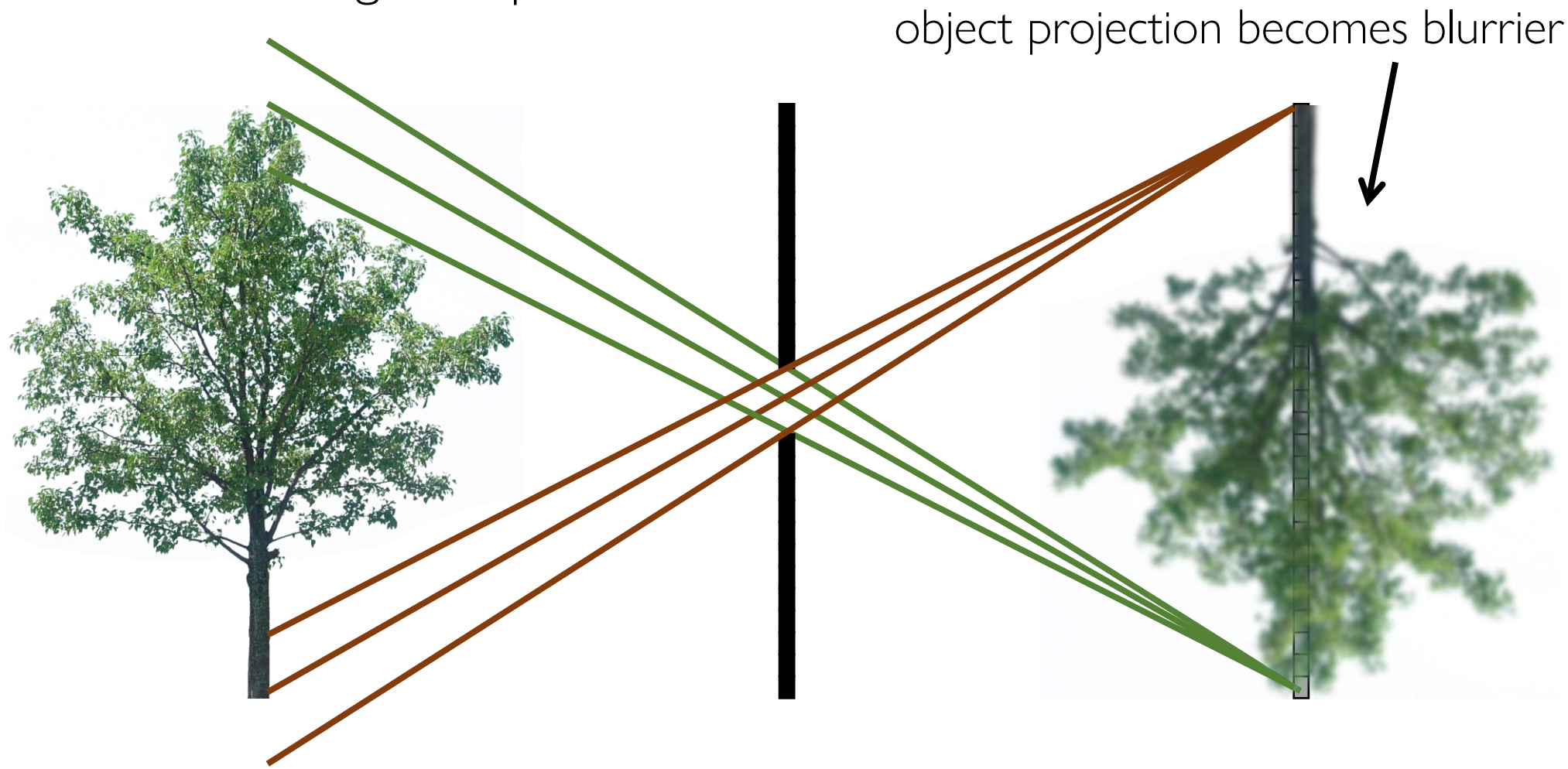
- What happens as we change the pinhole diameter?

real-world object



Pinhole size

- What happens as we change the pinhole diameter?



Light efficiency of pinhole camera

Exposure 4 seconds

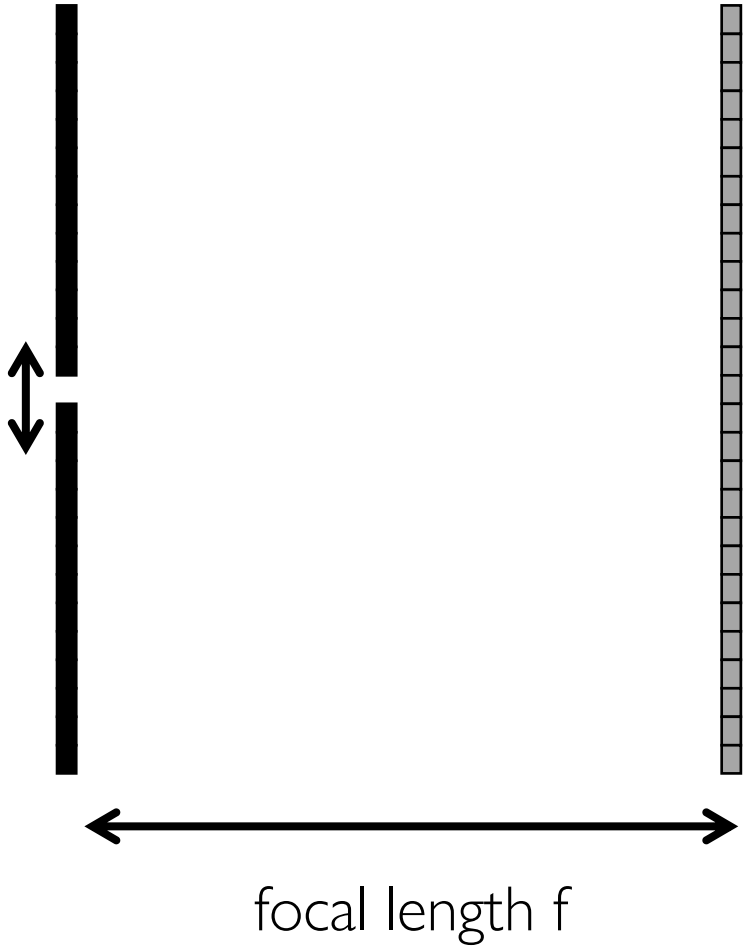
Exposure 96 minutes

Slide by S. Narasimhan`

What about light efficiency?

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

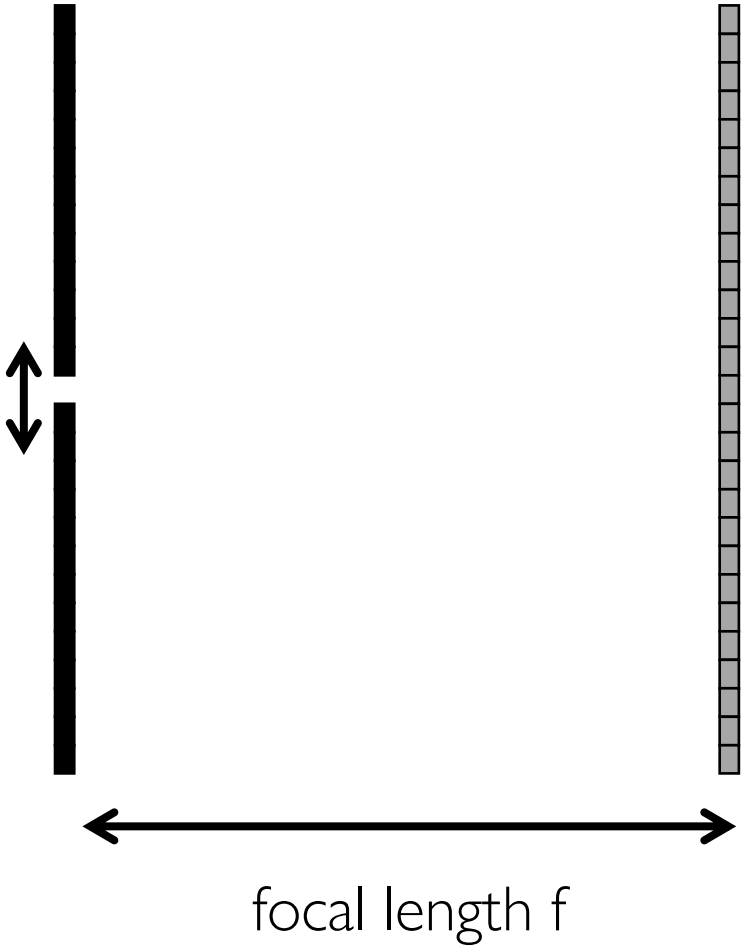
real-world object



What about light efficiency?

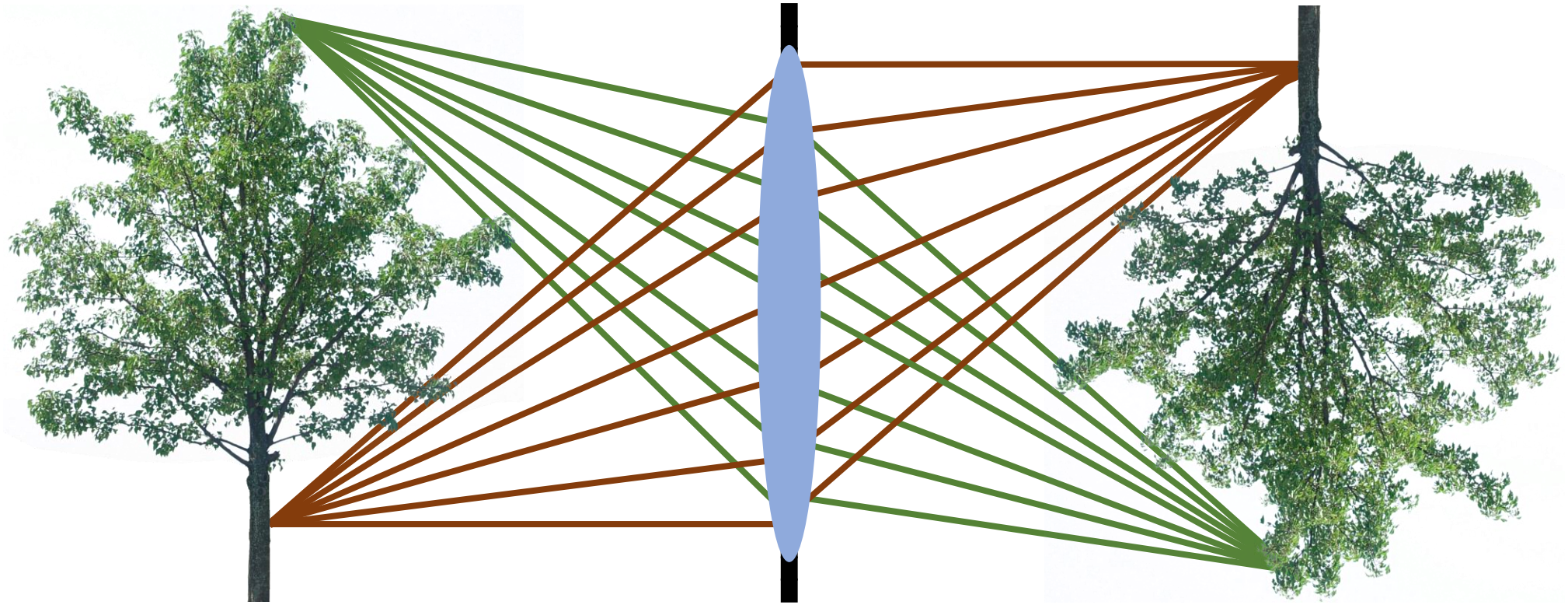
- 2x pinhole diameter → 4x light
- 2x focal length → ¼x light

real-world object



The lens camera

- Lenses map "bundles" of rays from points on the scene to the sensor.
- How does this mapping work exactly?



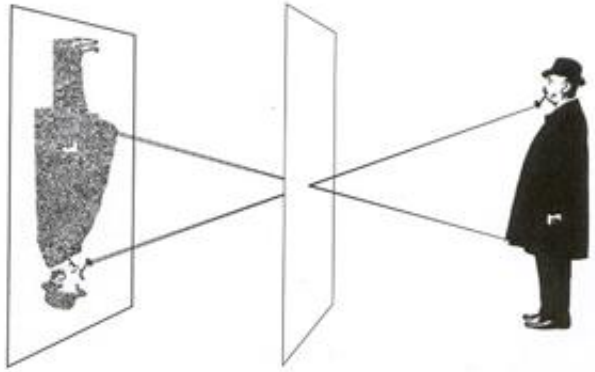
Why not pinhole? - Lens

- Two important things to observe.
  - Lens allows to capture a sharper image.
  - Lens allows a much faster exposure.

Pinhole camera (6 sec.)

Photograph made with small pinhole

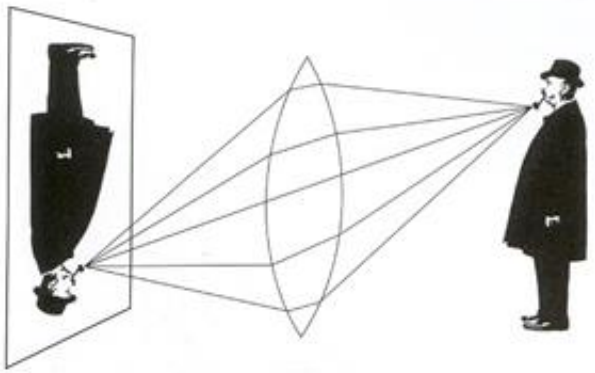
To make this picture, the lens of a camera was replaced with a thin metal disk pierced by a tiny pinhole, *equivalent in size to an aperture of f/182. Only a few rays of light from each point on the subject got through the tiny opening, producing a soft but acceptably clear photograph. Because of the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



Lens camera (1/100 sec.)

Photograph made with lens

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



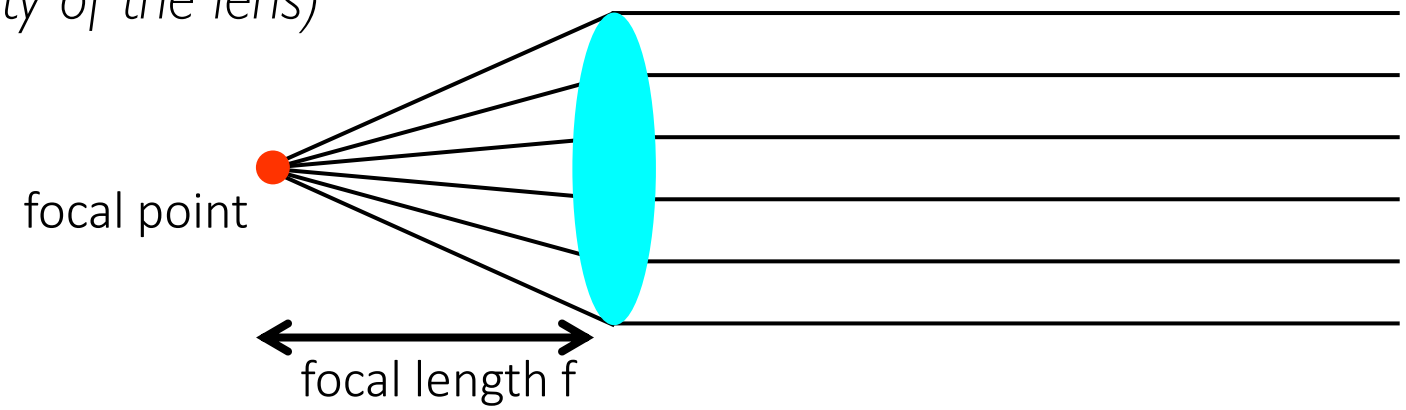
The lens opening was much bigger than the pinhole, letting in far more light, but it focused the rays from each point on the subject precisely so that they were sharp on the film.

From Photography, London et al.

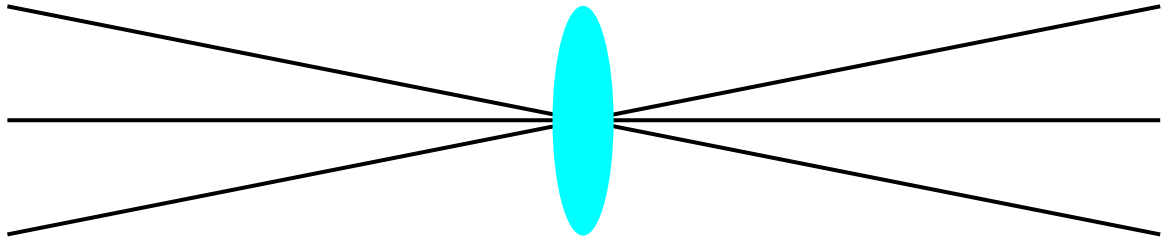
Thin lens optics

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

  (f is a property of the lens)

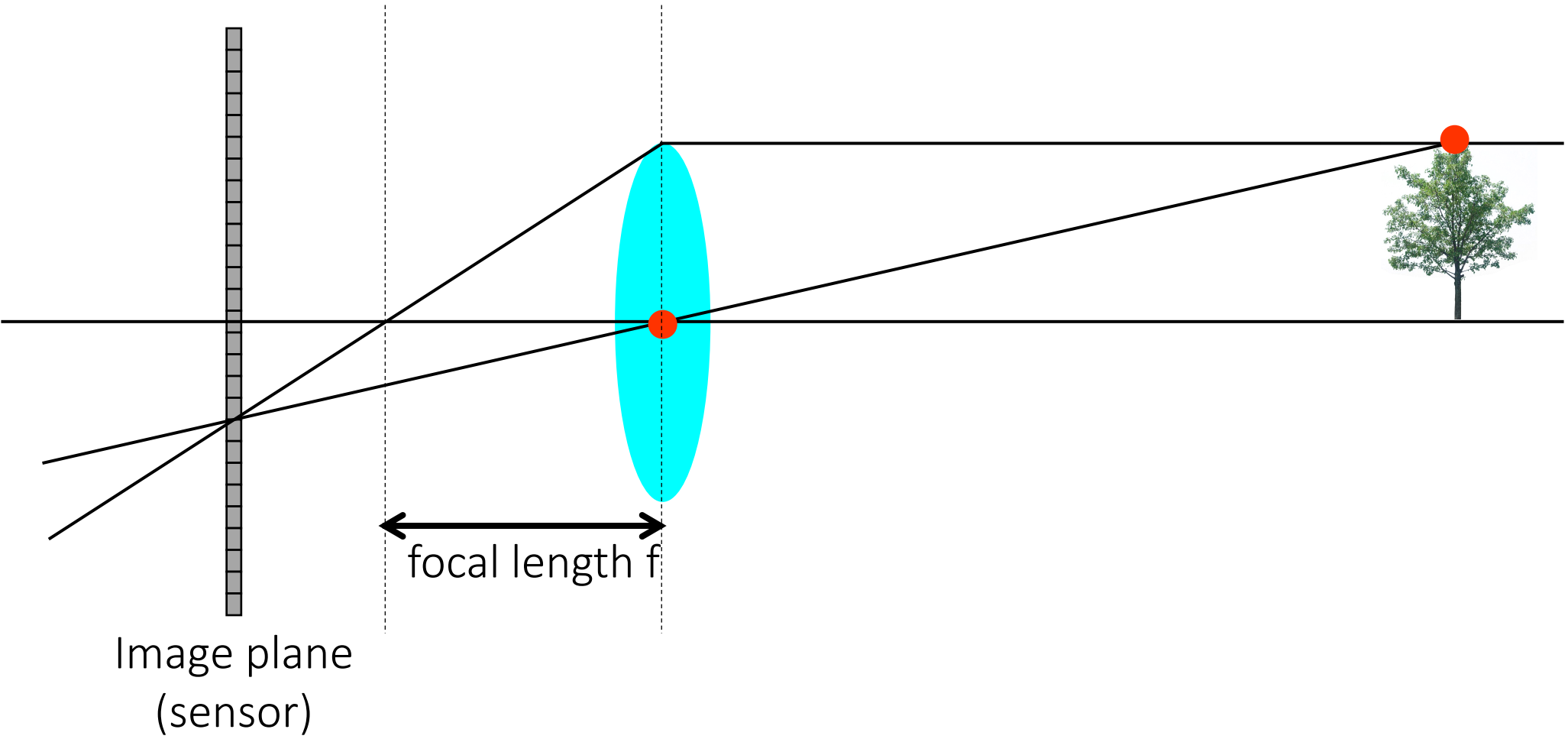


- All rays going through the center are not deviated
  - Hence same perspective as pinhole

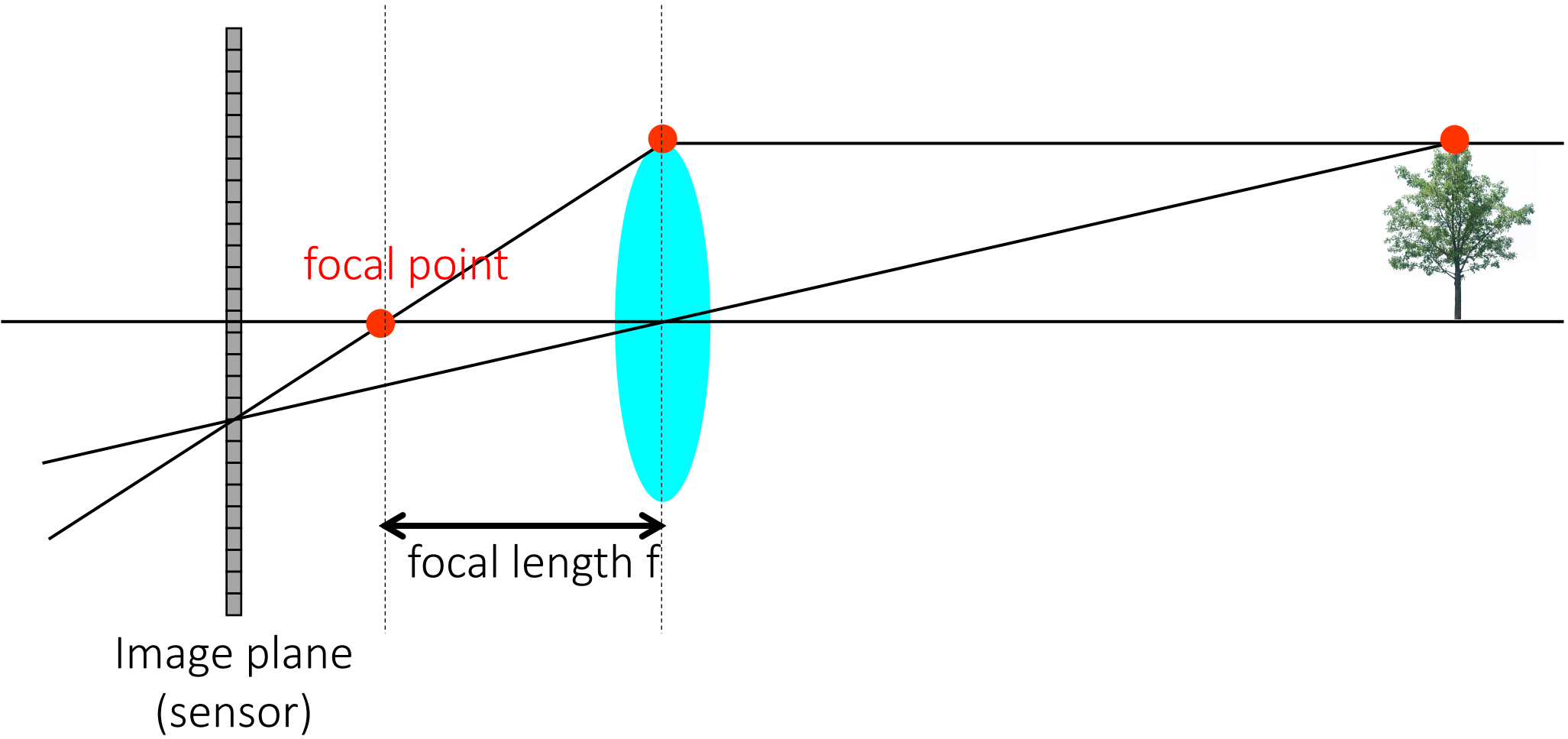


- Also, rays' behaviors are symmetric

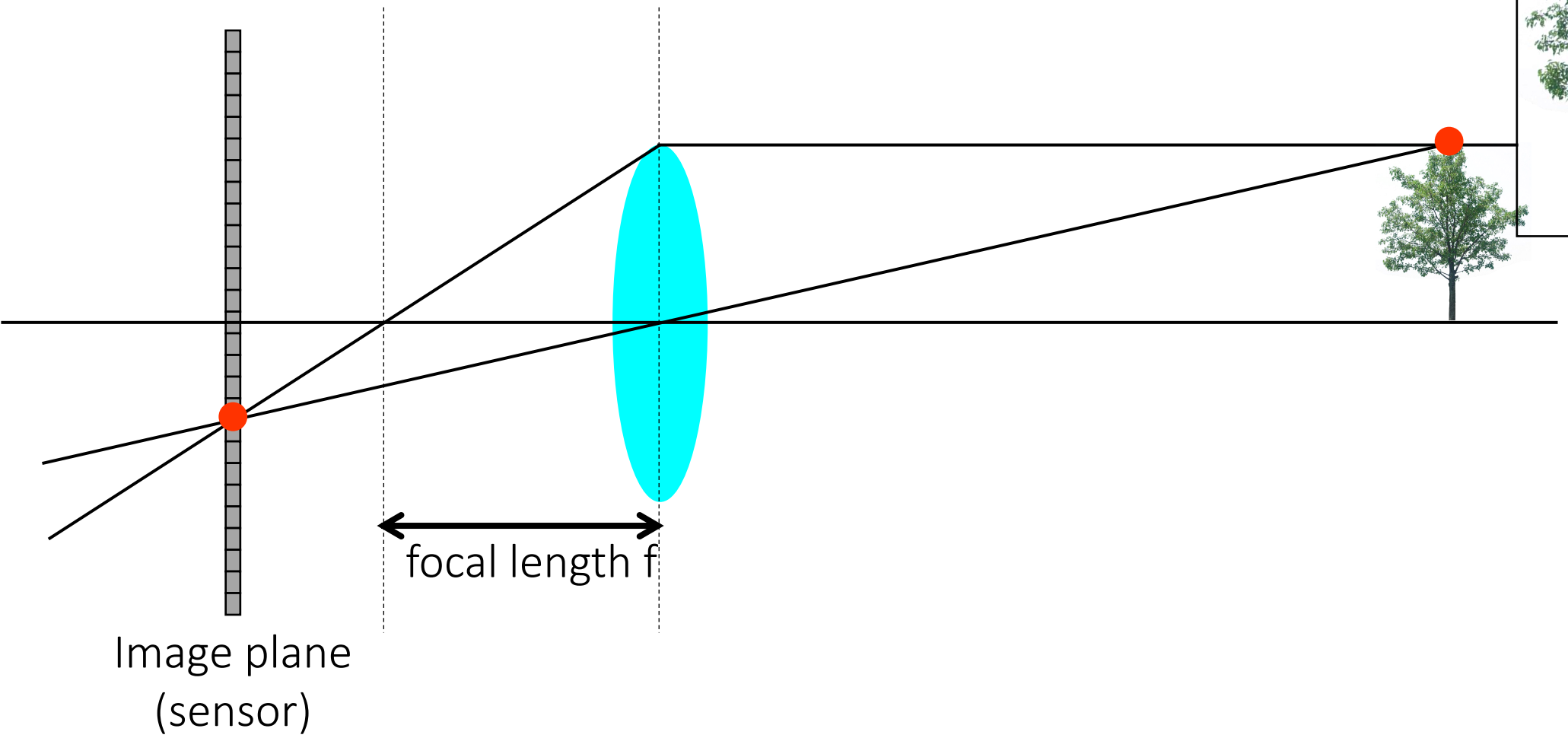
Thin lens optics - Lens focus

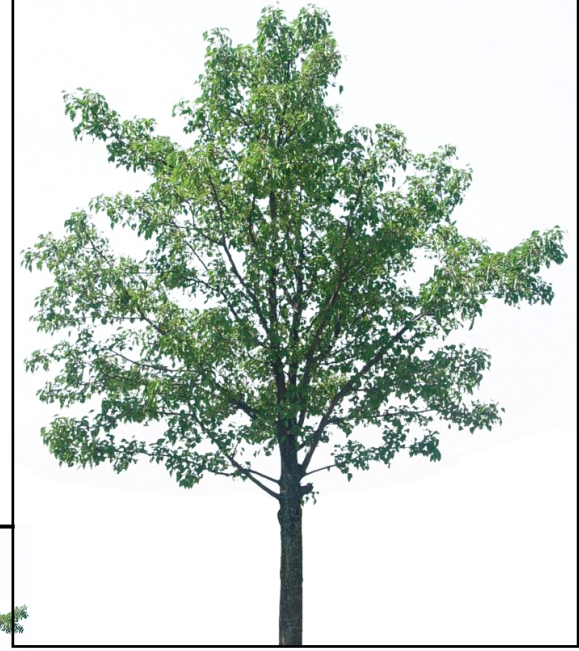


Thin lens optics - Lens focus



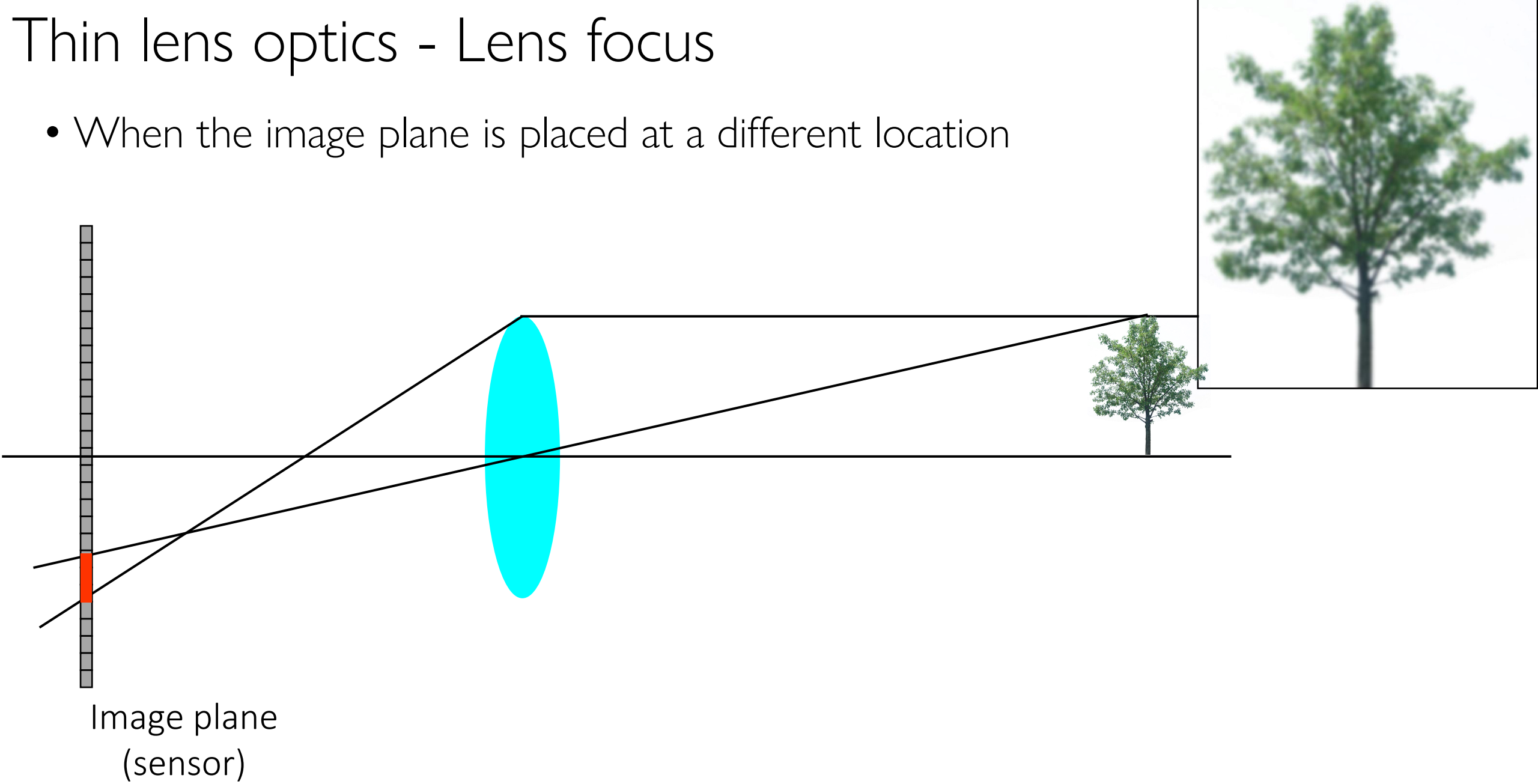
Thin lens optics - Lens focus





Thin lens optics - Lens focus

- When the image plane is placed at a different location



Thin lens optics - Lens focus

- When the image plane is placed at a different location

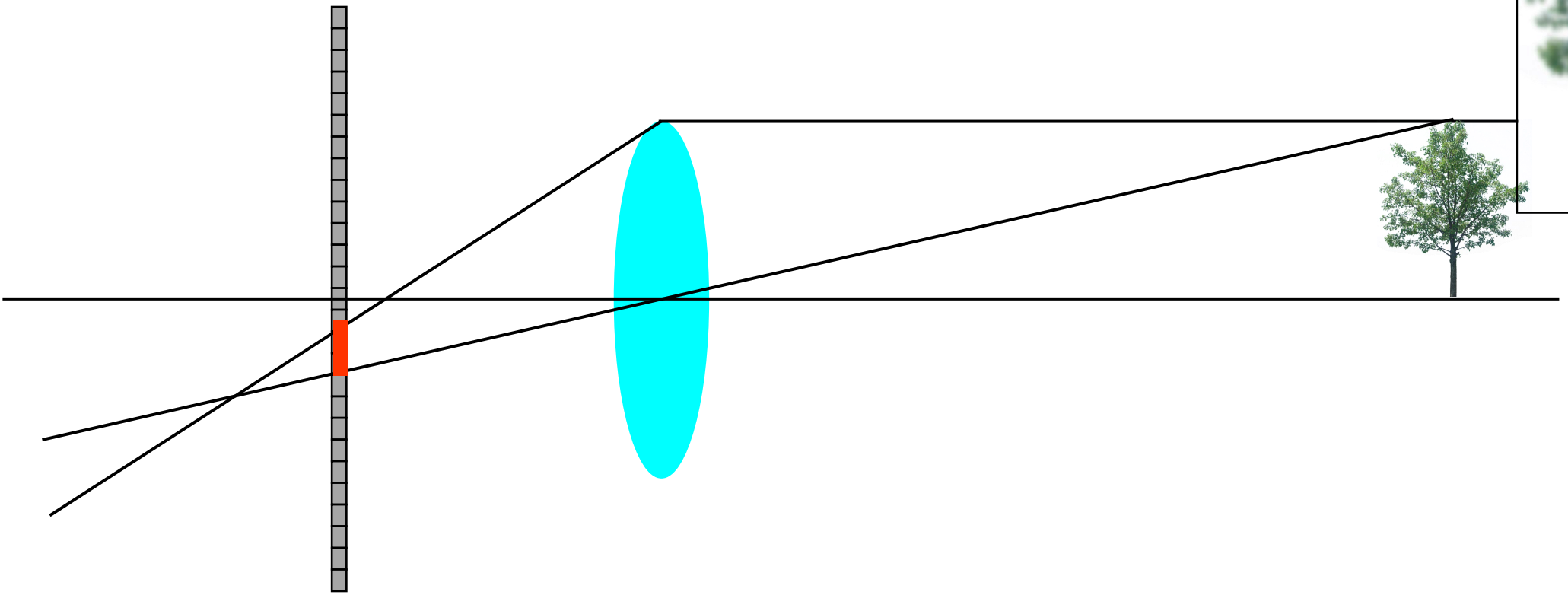
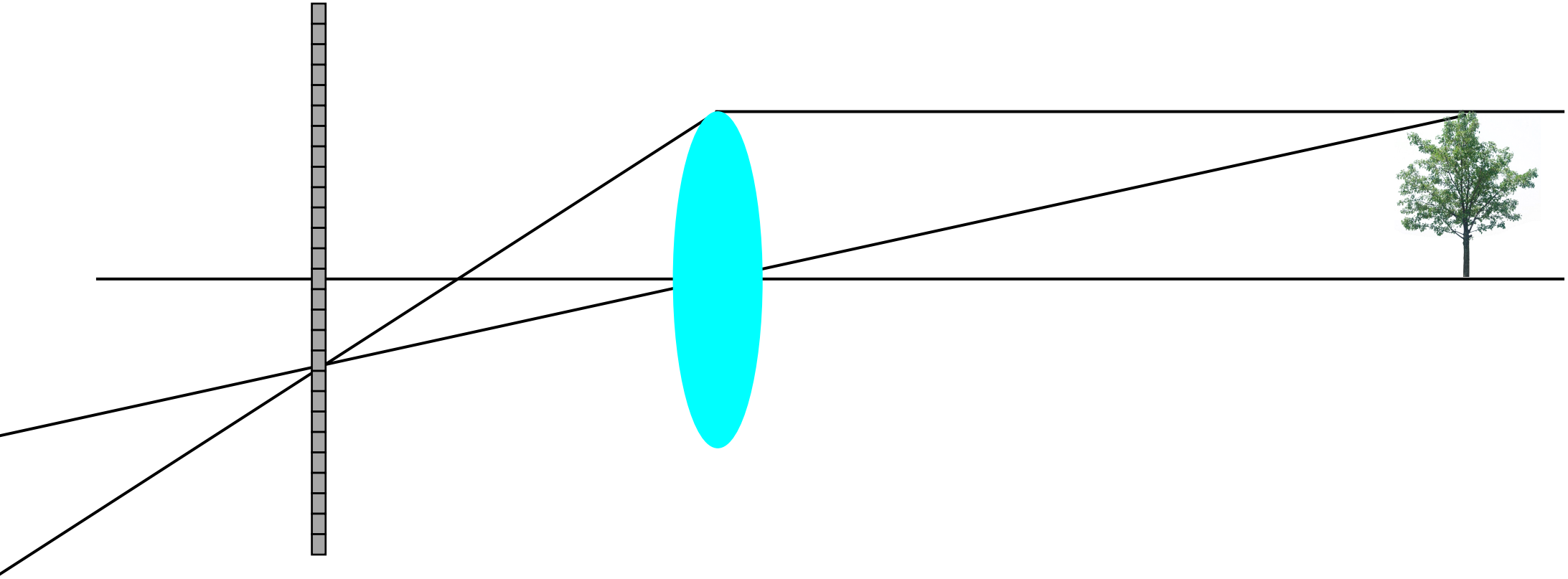


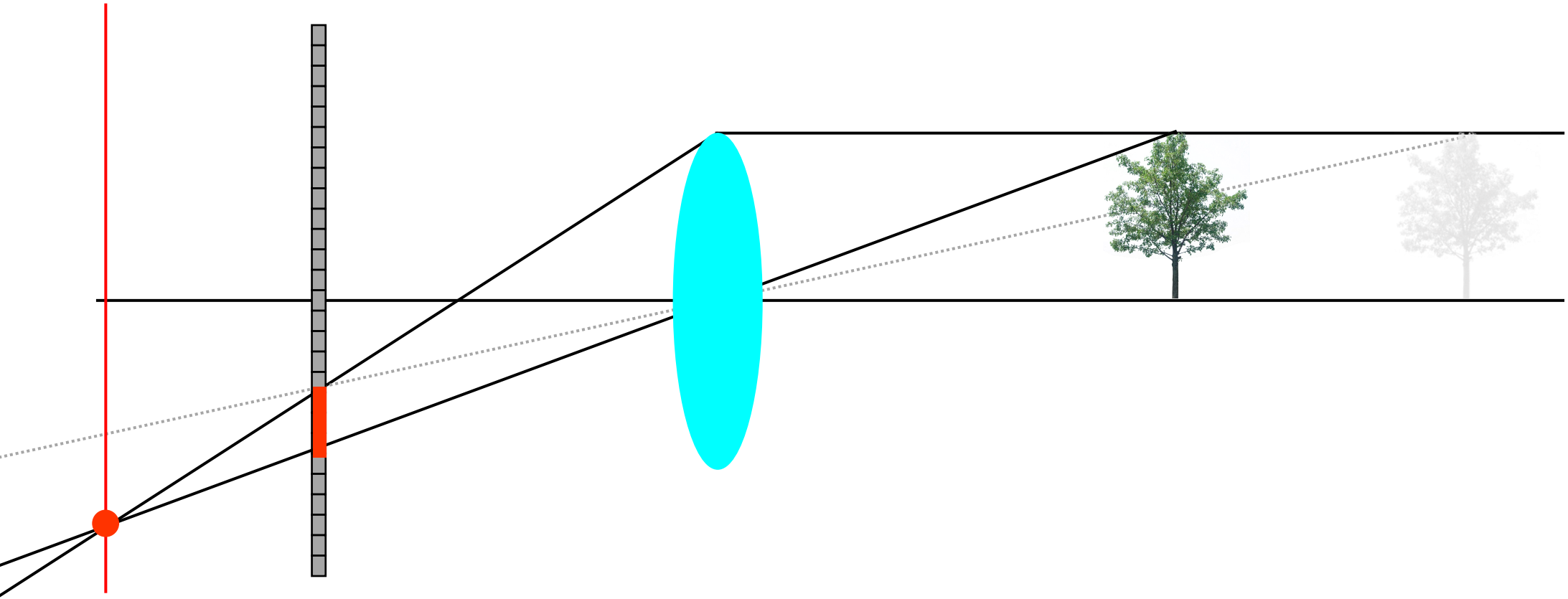
Image plane
(sensor)

Thin lens optics - Lens focus



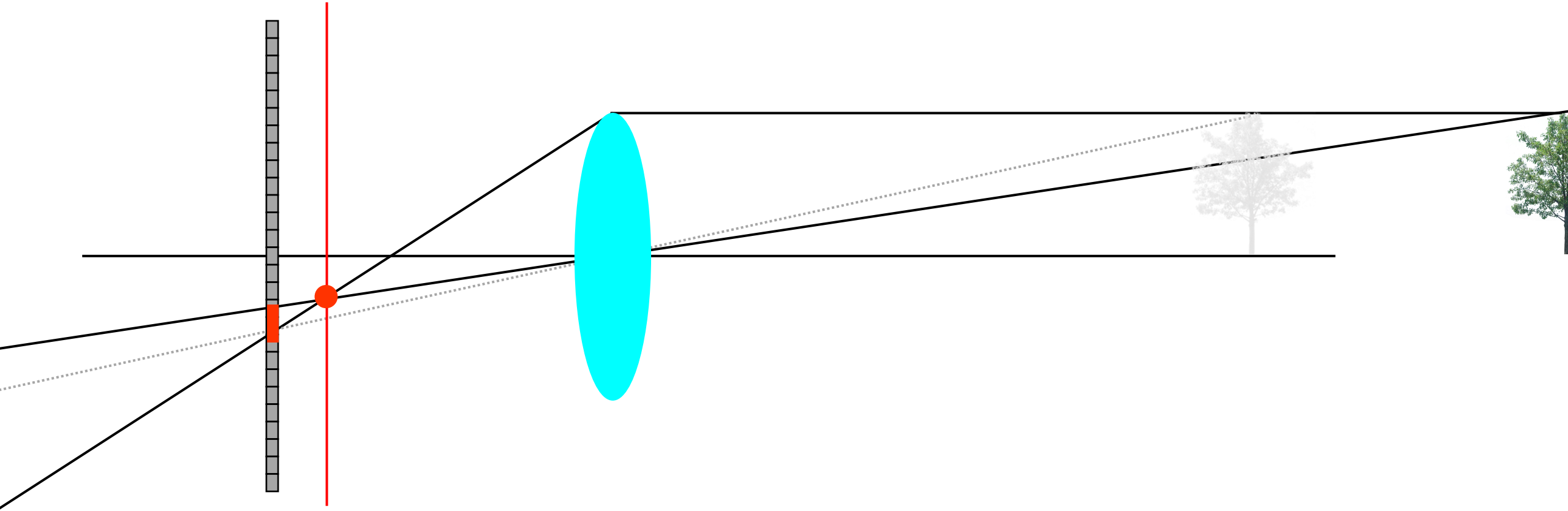
Thin lens optics - Lens focus

- When the object is placed at a different location

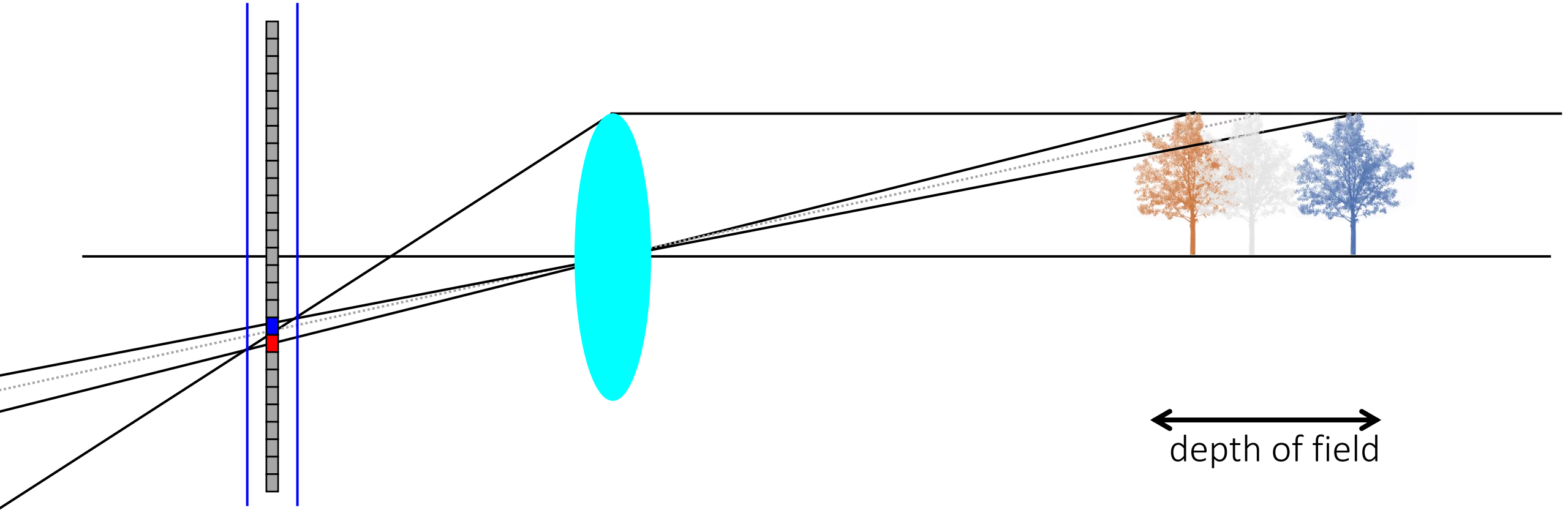


Thin lens optics - Lens focus

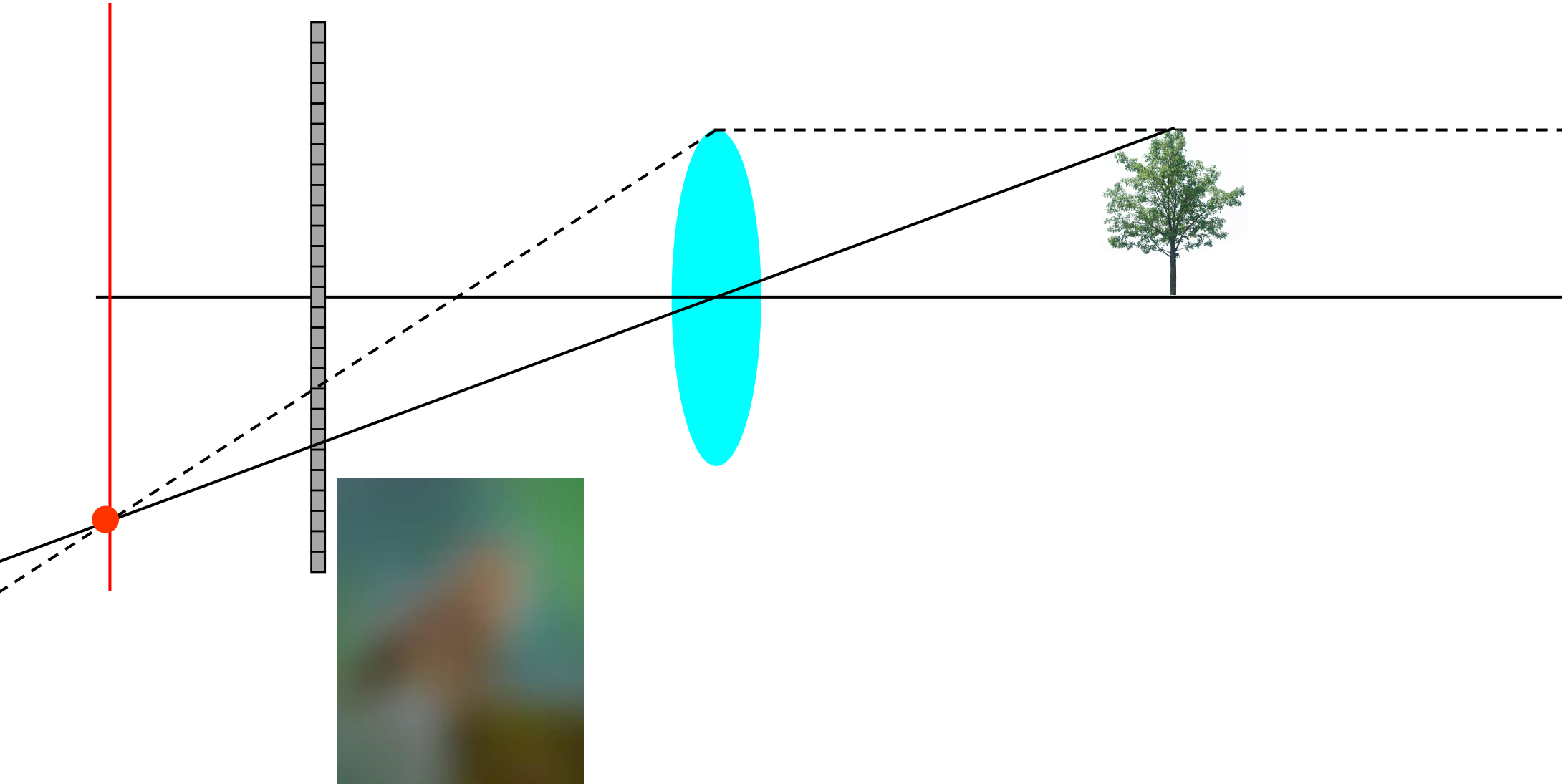
- When the object is placed at a different location



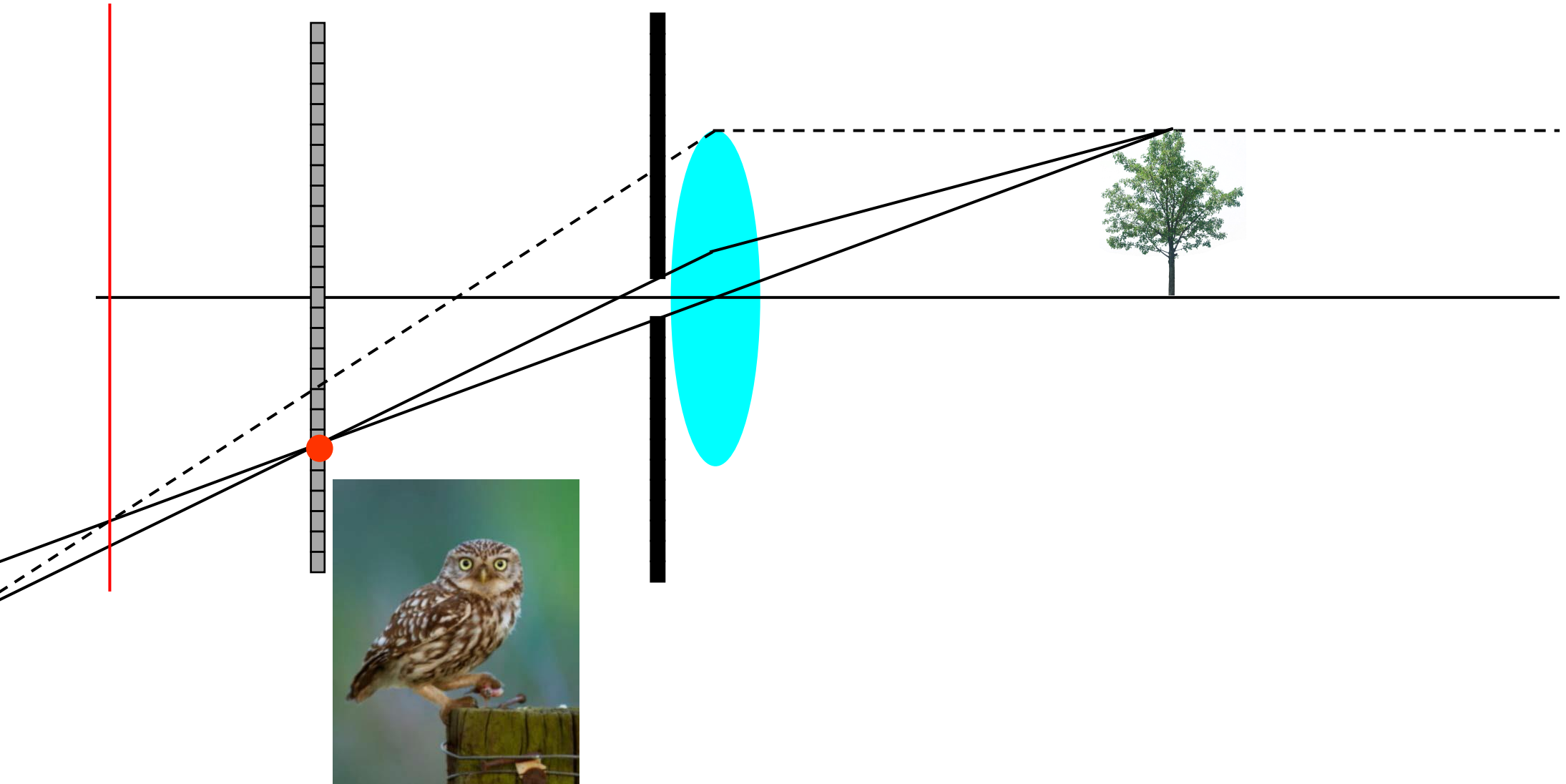
Thin lens optics - Focus tolerance



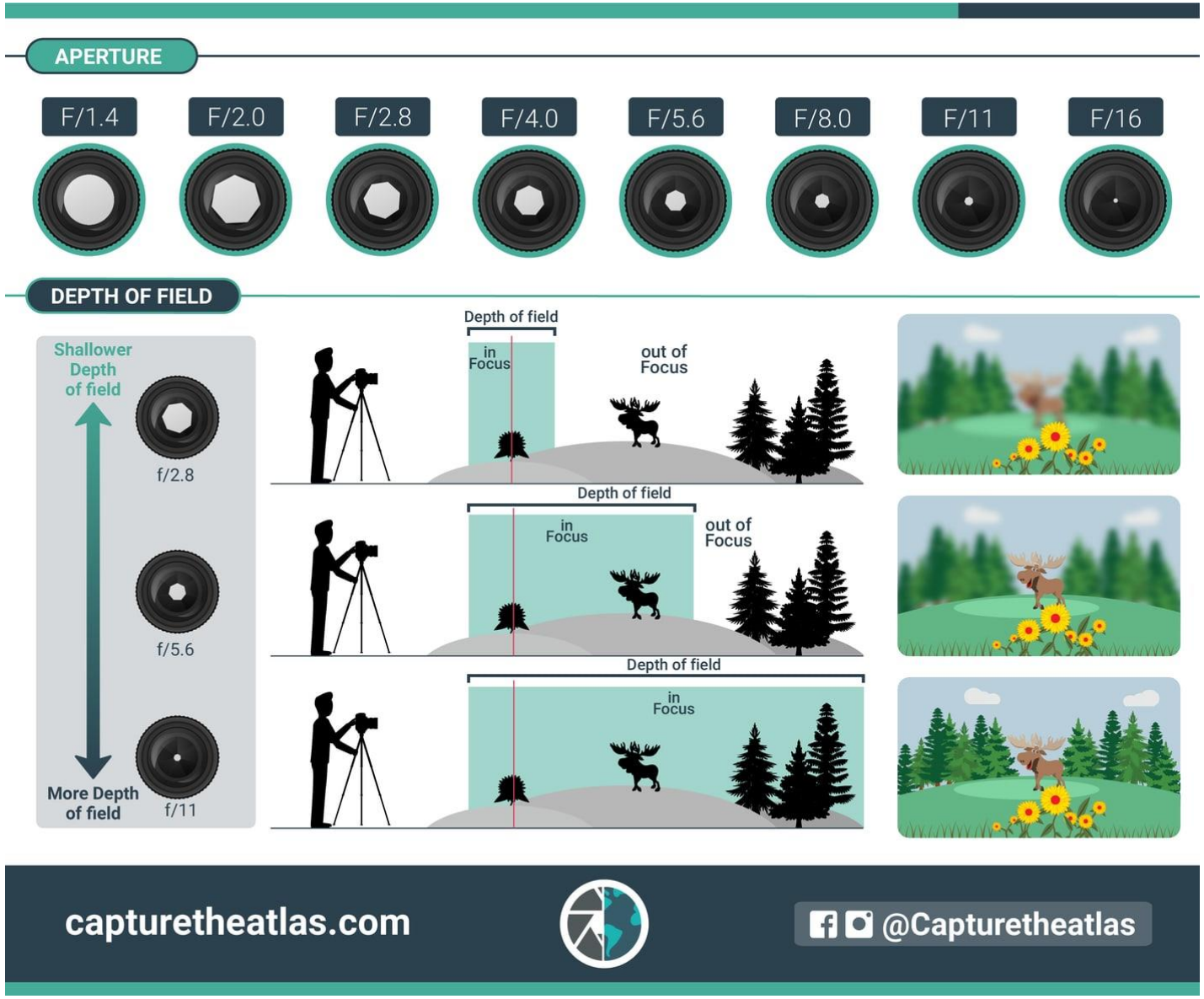
Thin lens optics - Aperture



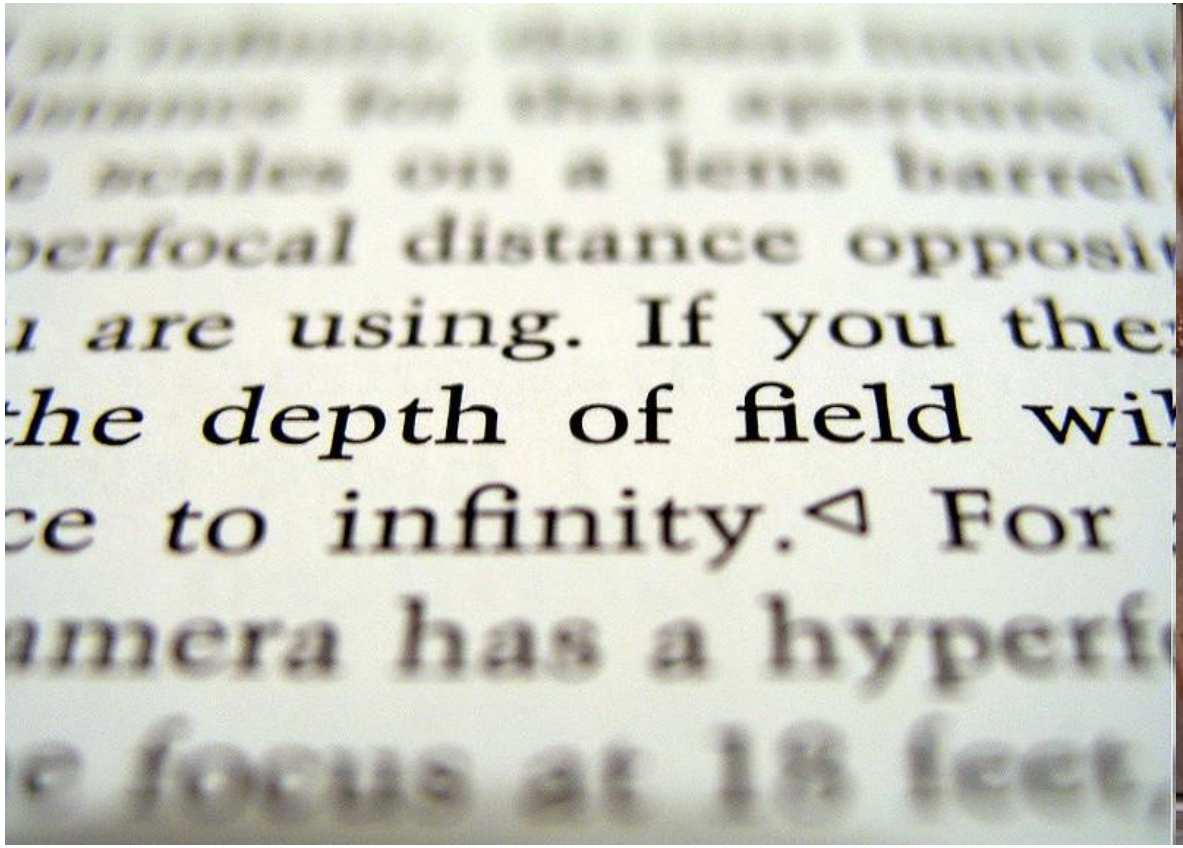
Thin lens optics - Aperture



Thin lens optics – Aperture vs. depth of field



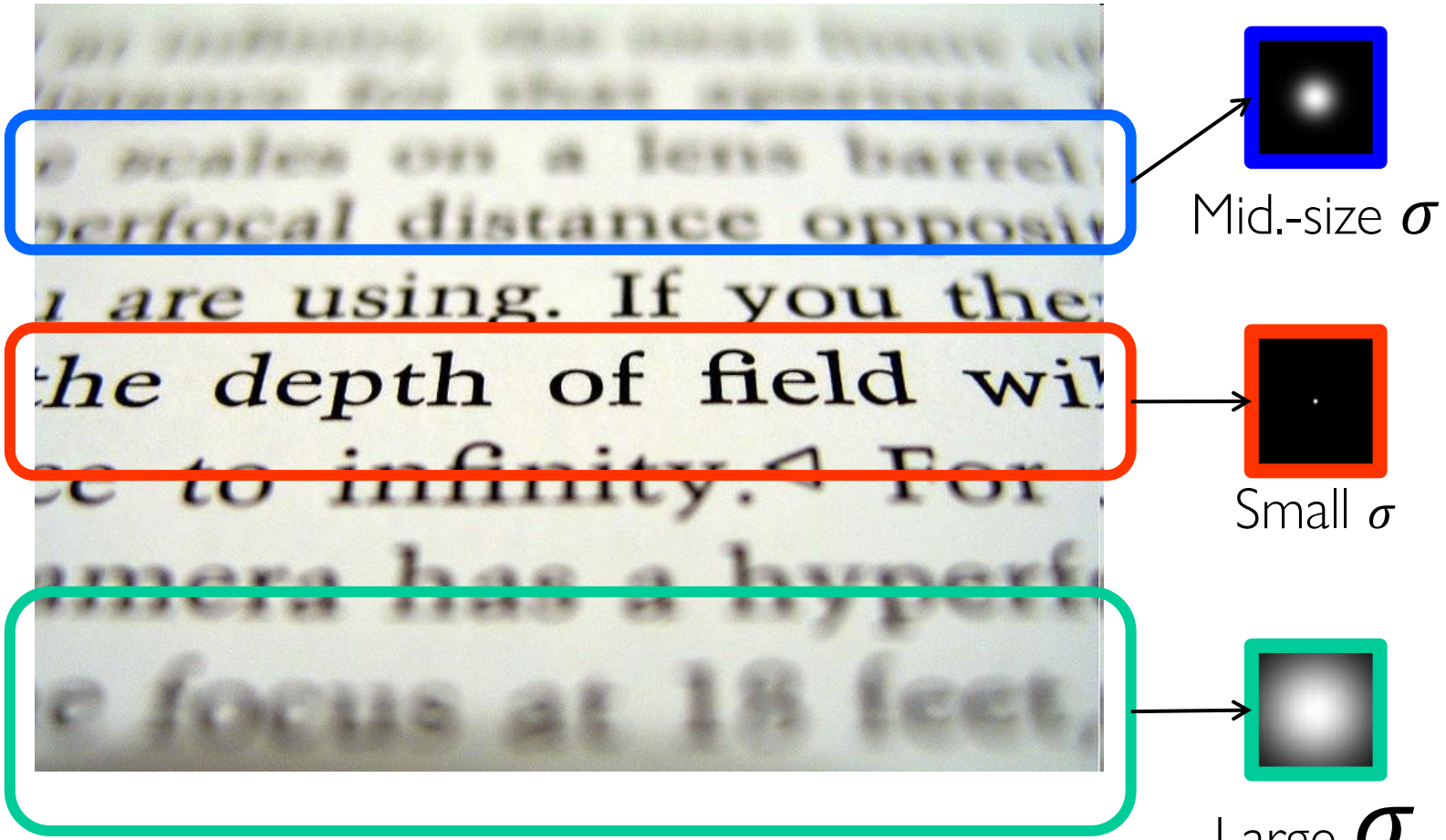
Depth of field



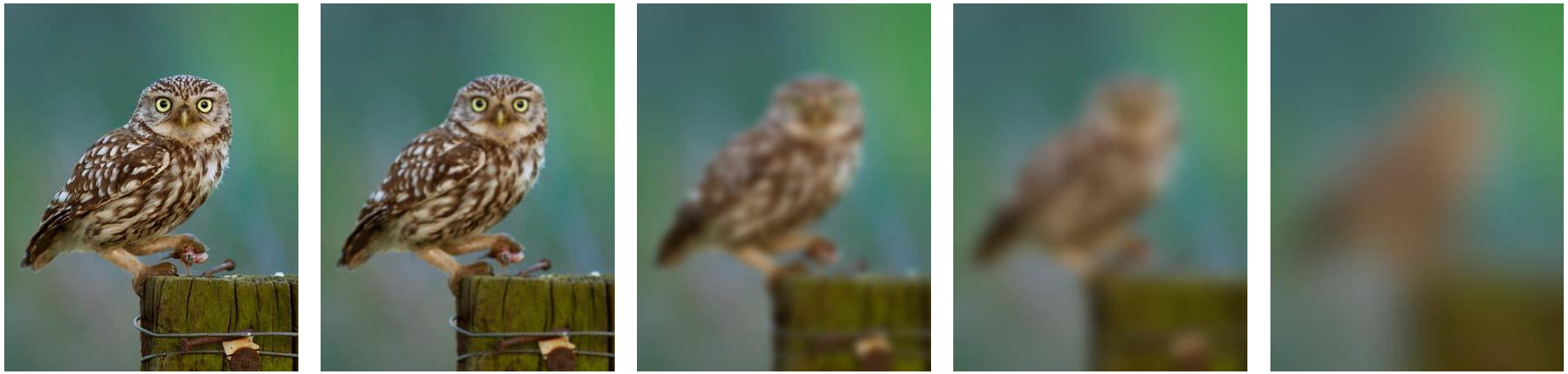
[Right] Image from K. J. Yoon's slide

Depth of field

- Approximate optics blur by linear Gaussian filters



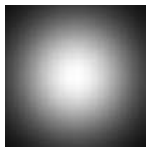
Gaussian filters



σ = 1 pixel

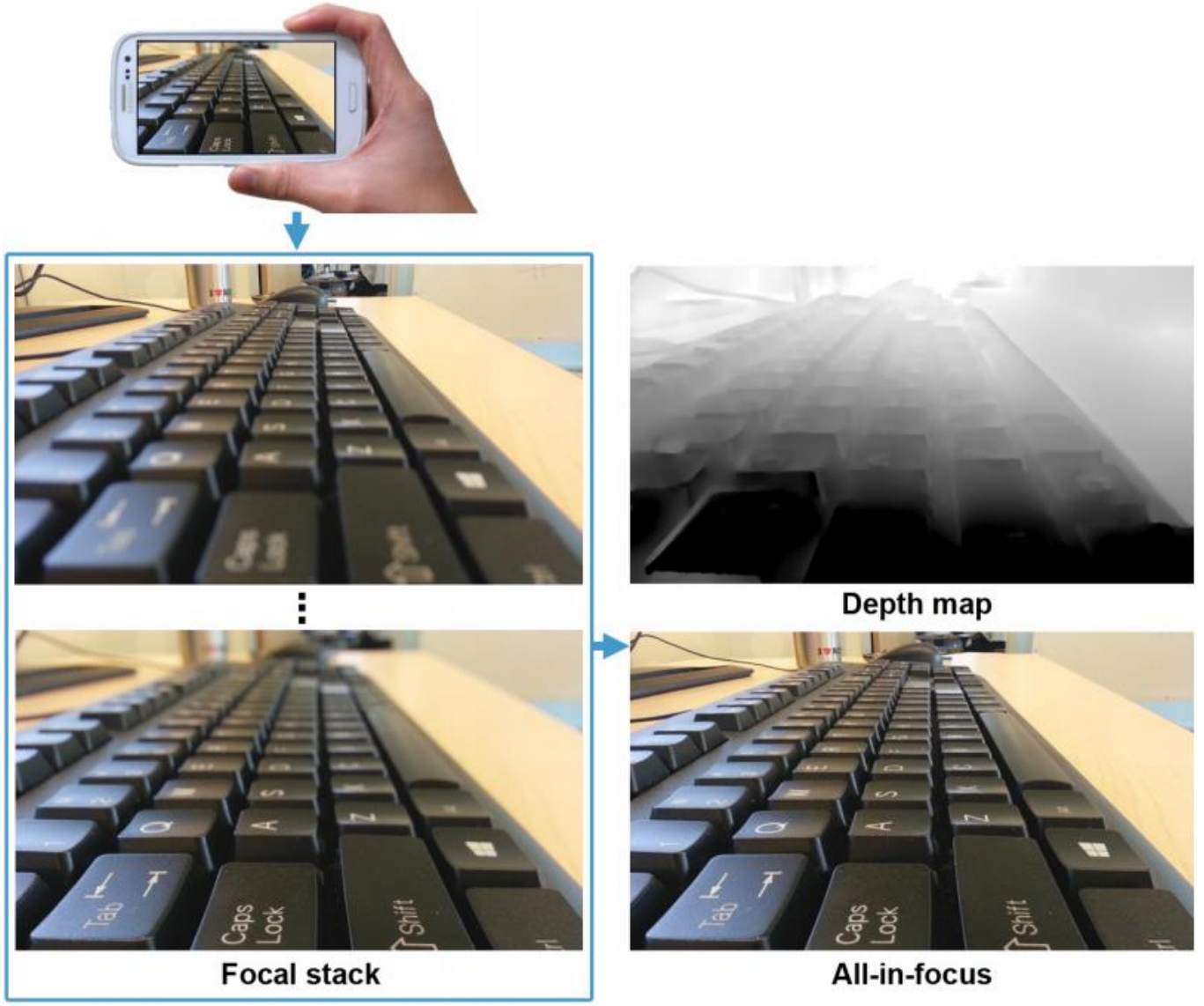
σ = 5 pixels

σ = 10 pixels



σ = 30 pixels

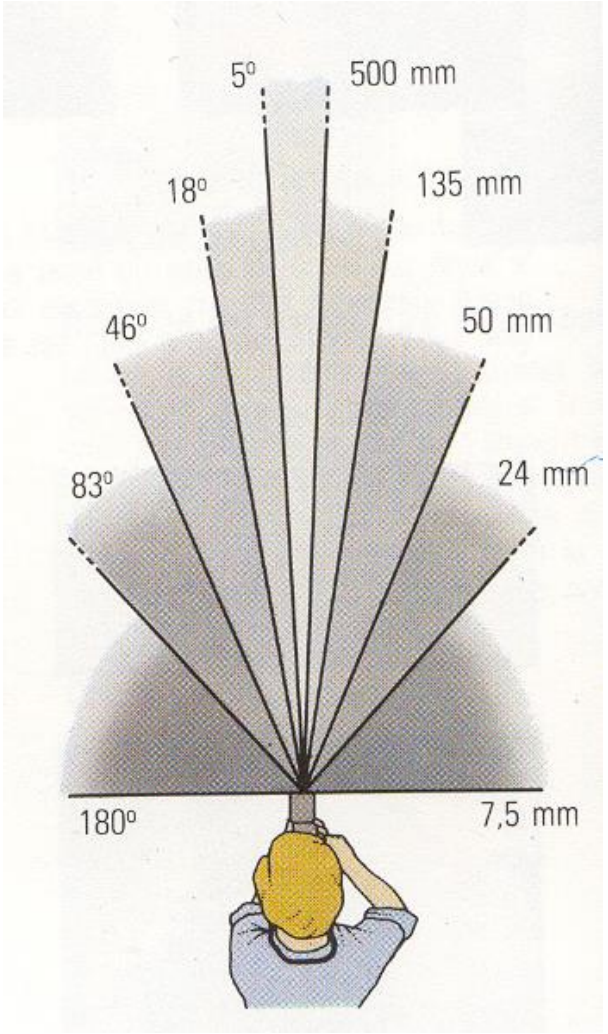
Depth from focus



Suwajanakorn et al., Depth from Focus with Your Mobile Phone , CVPR 2015.

Field of view

FoV vs. focal length



Four images using 28, 35, 50 and 72mm equivalent zoom lengths, portrait format, to illustrate angles of view.

images from Wikipedia http://en.wikipedia.org/wiki/Field_of_view_(image_processing)