Lenses, exposure, and (de)focus

15-463, 15-663, 15-862
Computational Photography
Fall 2017, Lecture 15

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

Course announcements

- Homework 4 is out.
  - Due October 26th.
  - Bilateral filter will take a very long time to run.
  - Final teams are on sign-up spreadsheet.
  - Drop by Yannis' office to pick up cameras any time.

- Yannis has extra office hours on Wednesday, 2-4pm.
  - You can come to ask questions about HW4 (e.g., "how do I use a DSLR camera?").
  - You can come to ask questions about final project.

- Project ideas are due on Piazza on Friday 20th.

Overview of today’s lecture

- Motivation for using lenses.
- The thin lens model.
- Real lenses and aberrations.
- Field of view.
- Lens designations.
- Exposure control.
- Lens camera and pinhole camera.
- Telecentric lenses.

Slide credits

Most of these slides were adapted from:

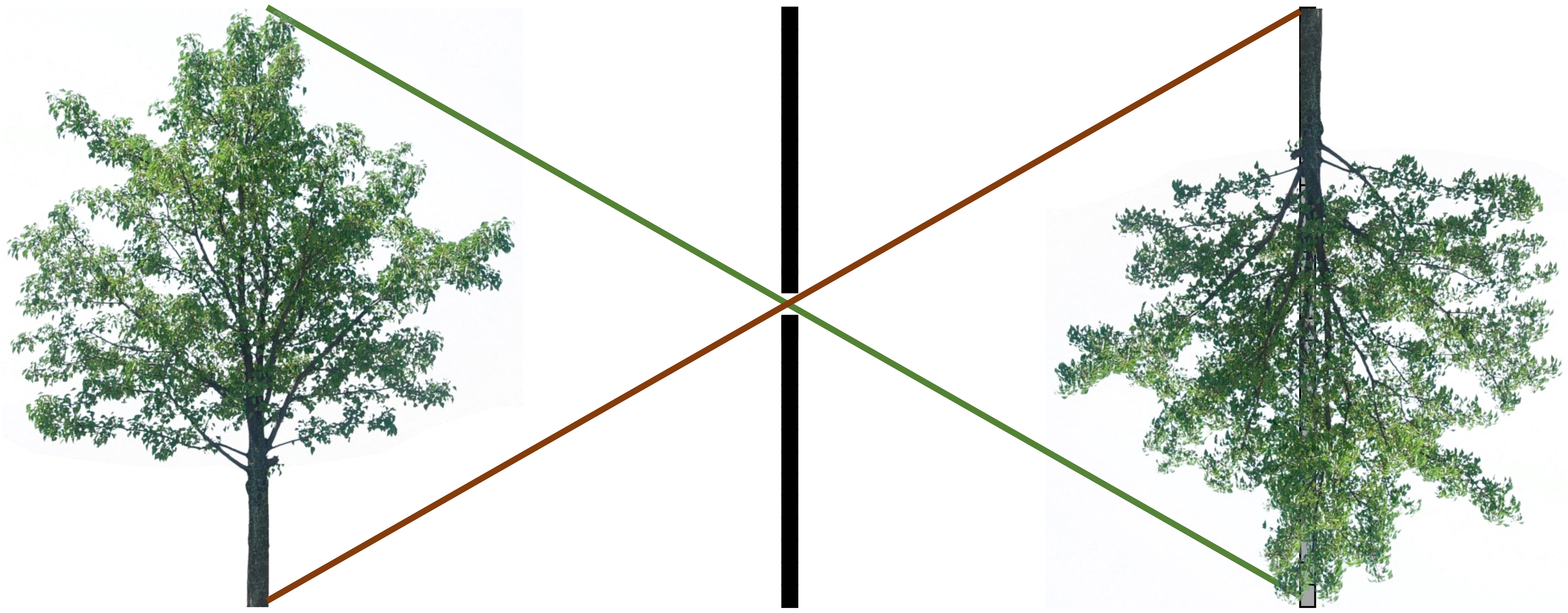
- Kris Kitani (15-463, Fall 2016).
- Fredo Durand (MIT).

Some slides borrowed from:

- Gordon Wetzstein (Stanford).

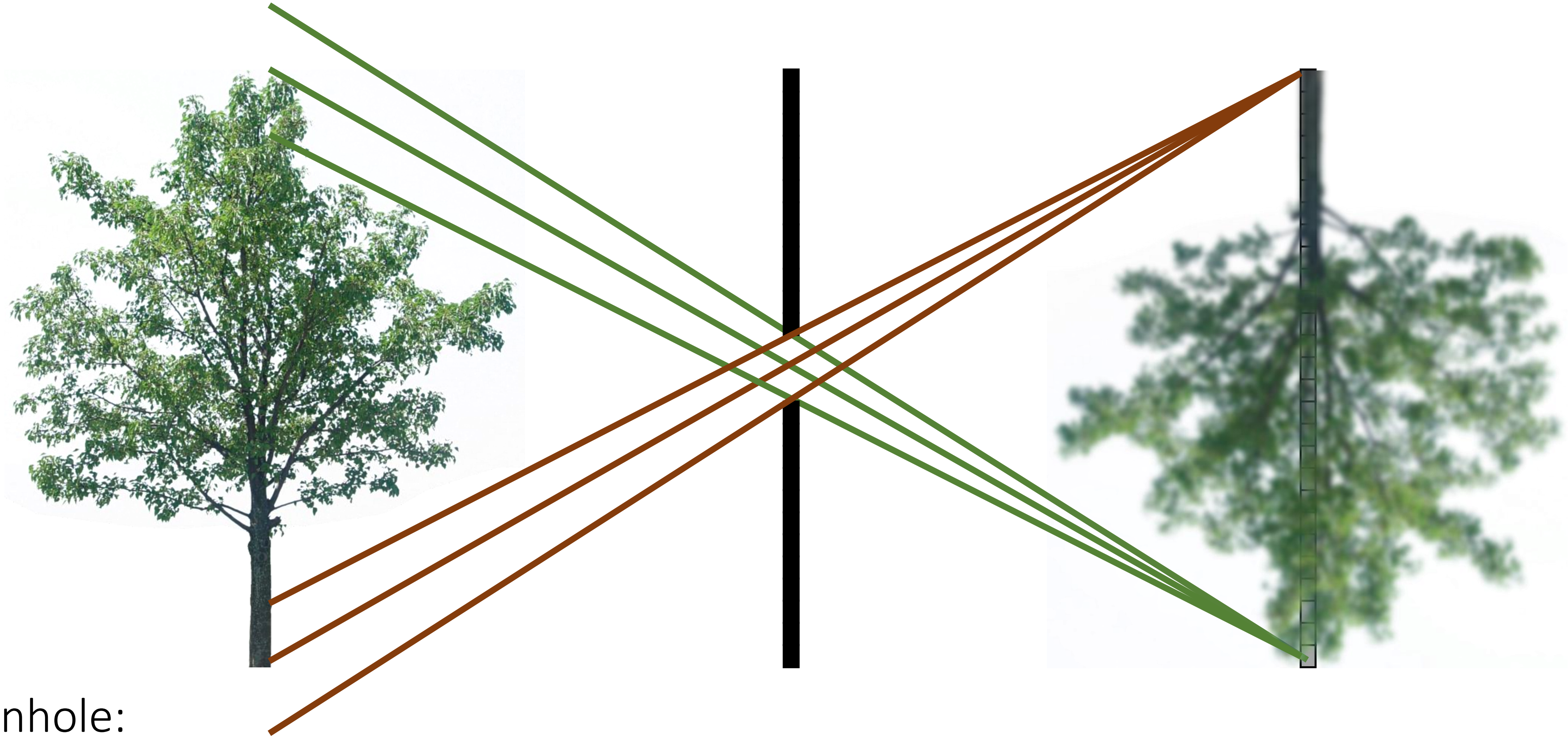
Motivation for using lenses

Pinhole camera



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

Pinhole camera

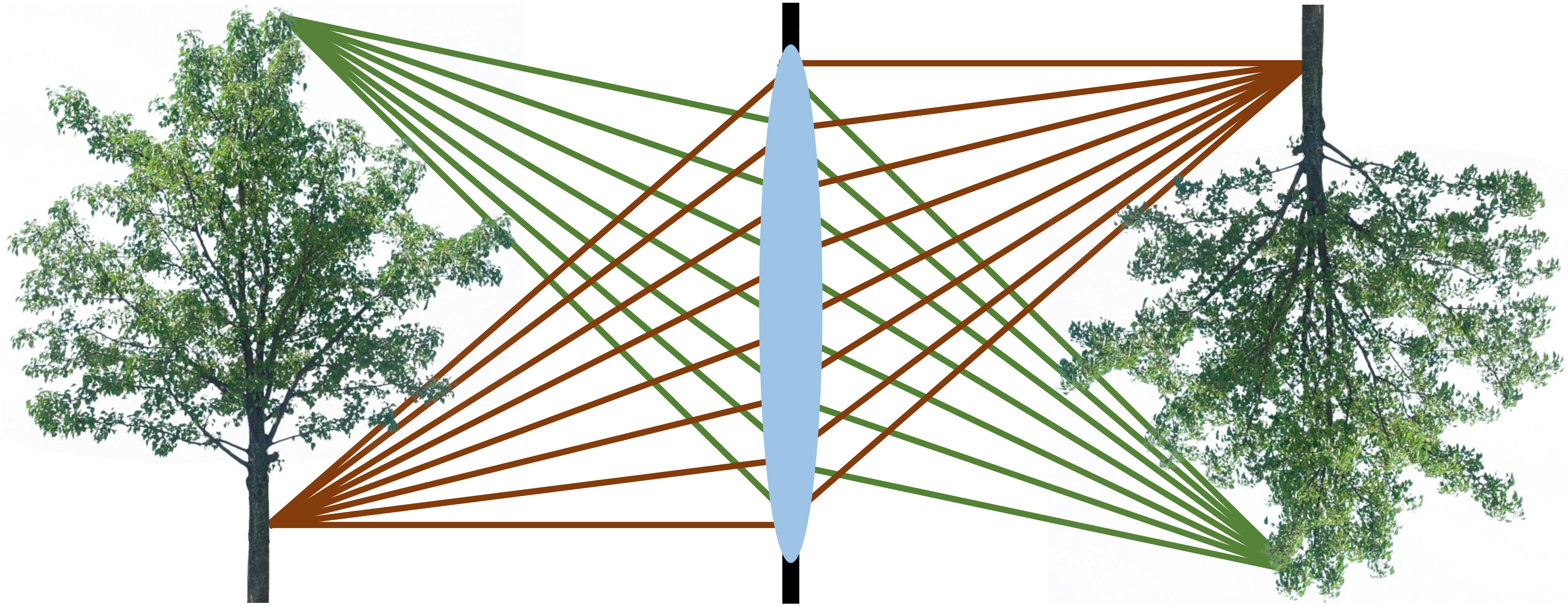


Large pinhole:

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

Can we get best of both worlds?

Almost, by using lenses



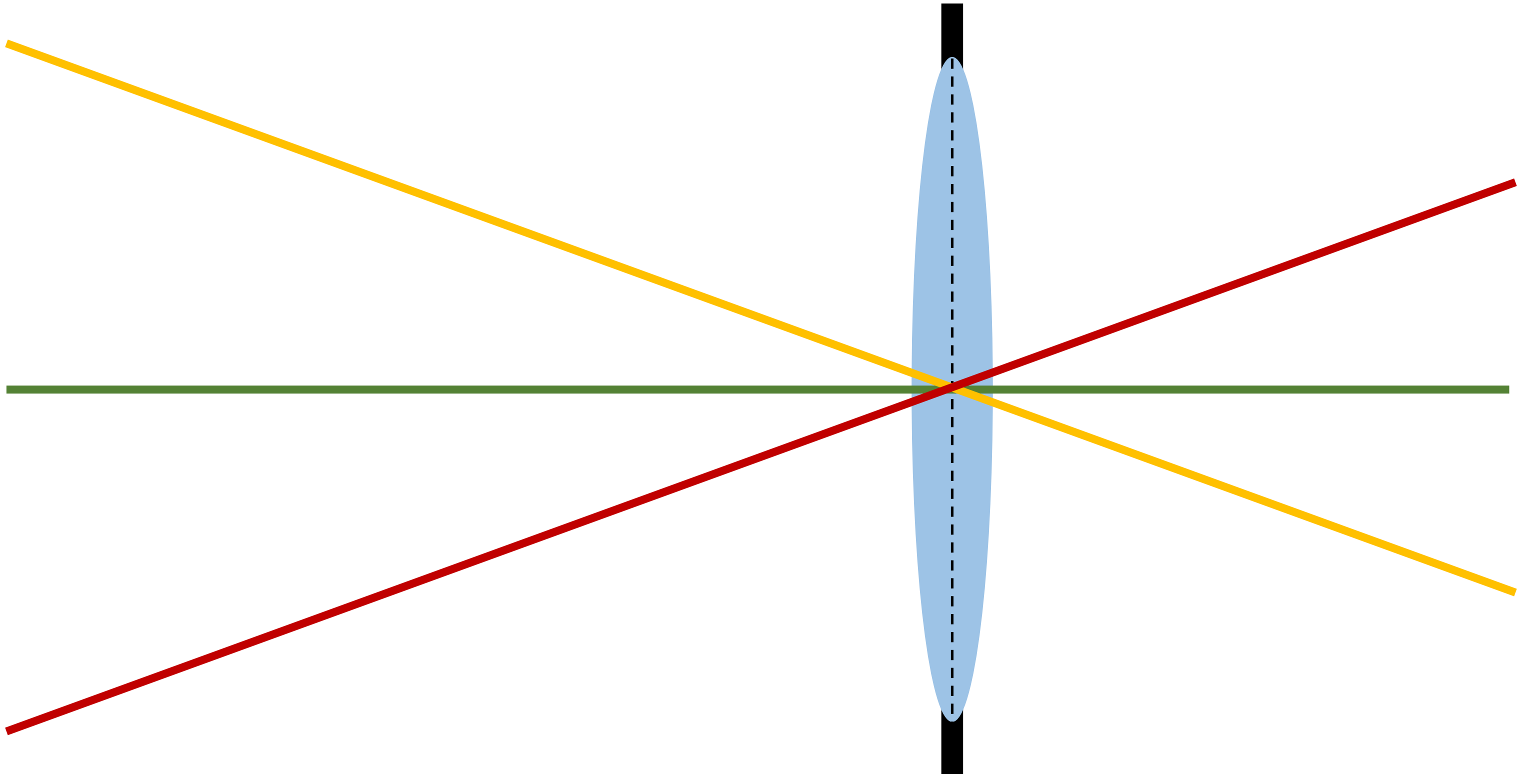
Lenses map “bundles” of rays from points on the scene to the sensor.

How does this mapping work exactly?

The thin lens model

Thin lens model

Simplification of geometric optics for well-designed lenses.



Two assumptions:

1. Rays passing through lens center are unaffected.

Thin lens model

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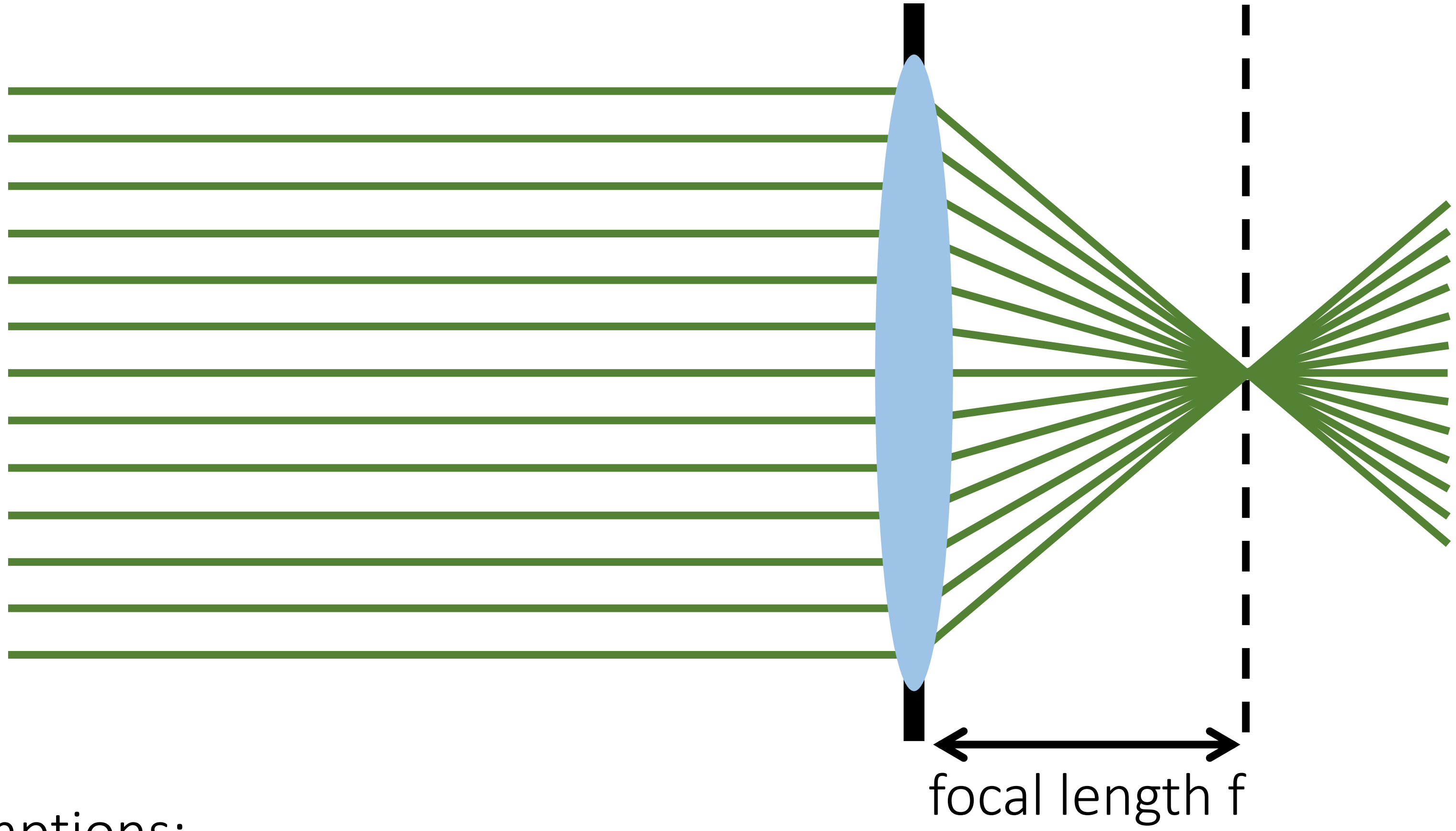

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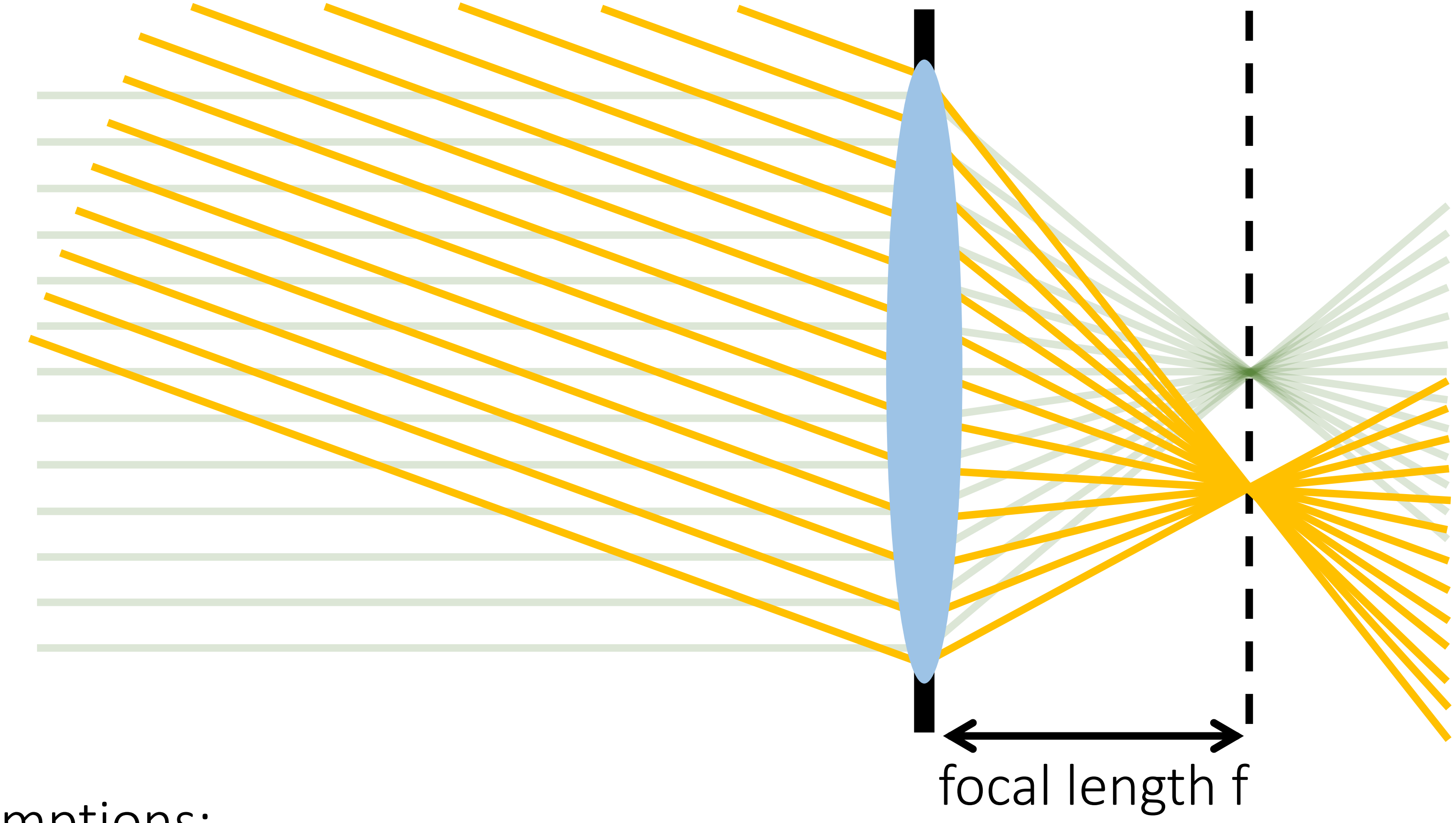

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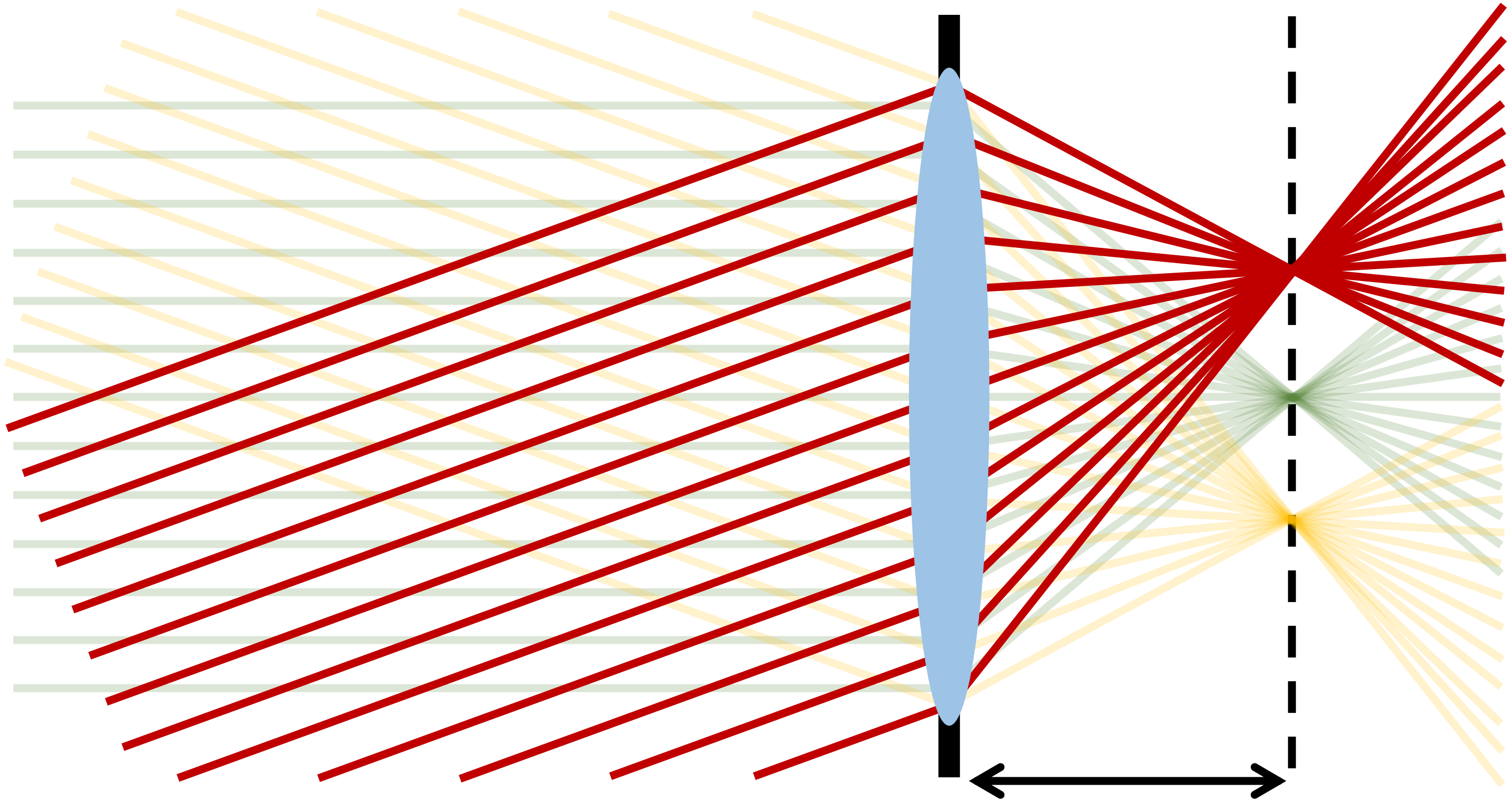

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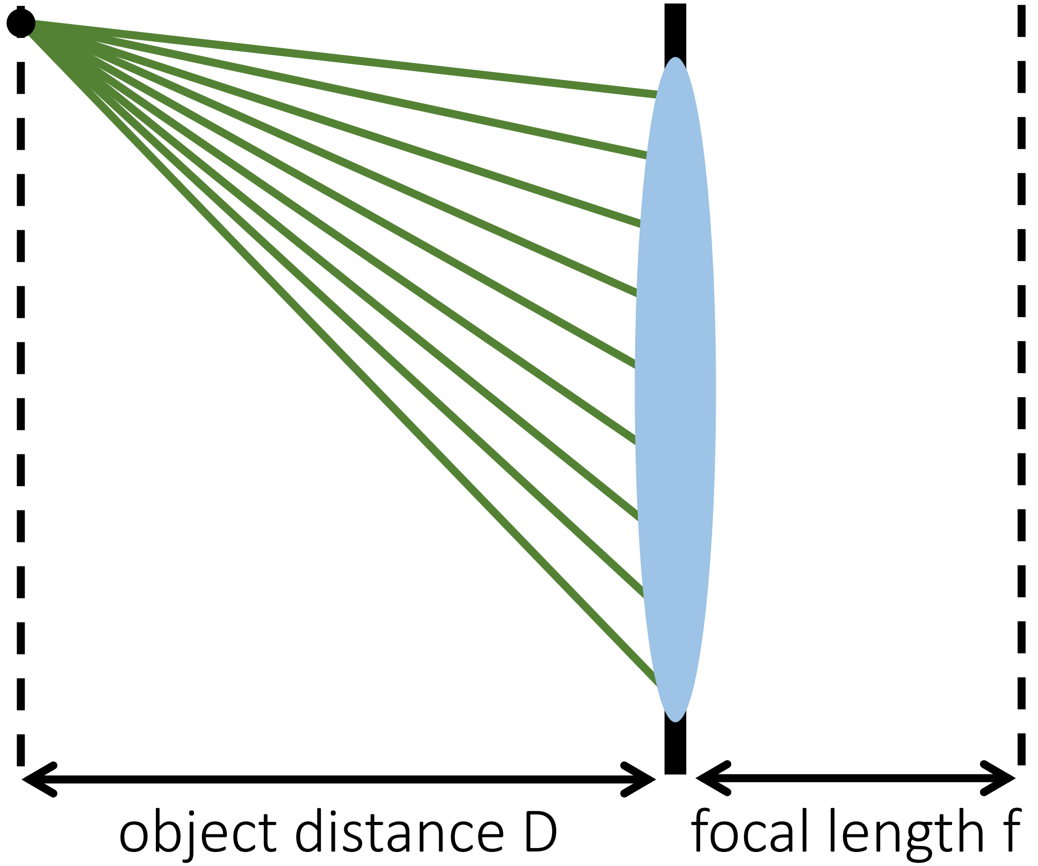
Tracing rays through a thin lens

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



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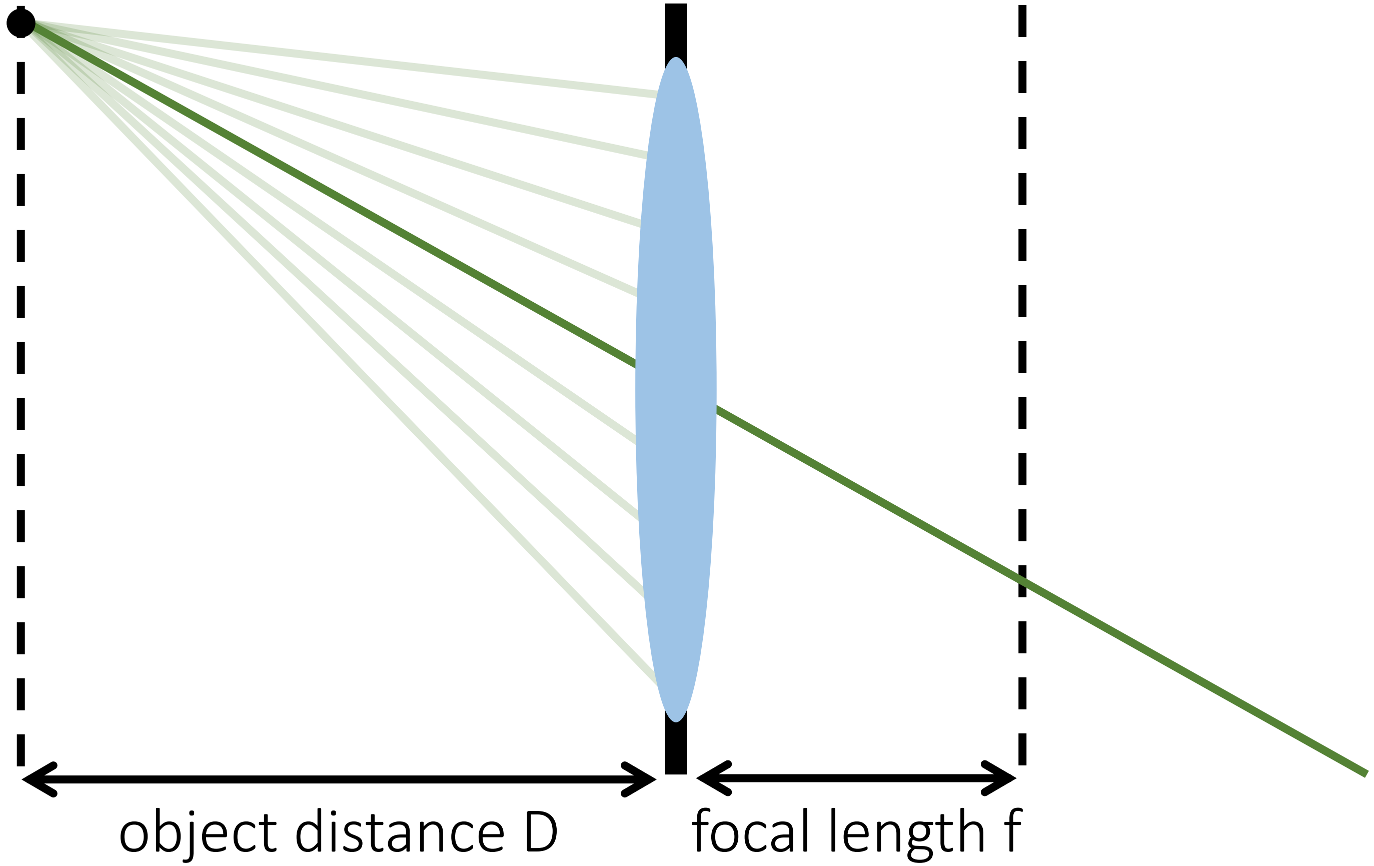

Tracing rays through a thin lens

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

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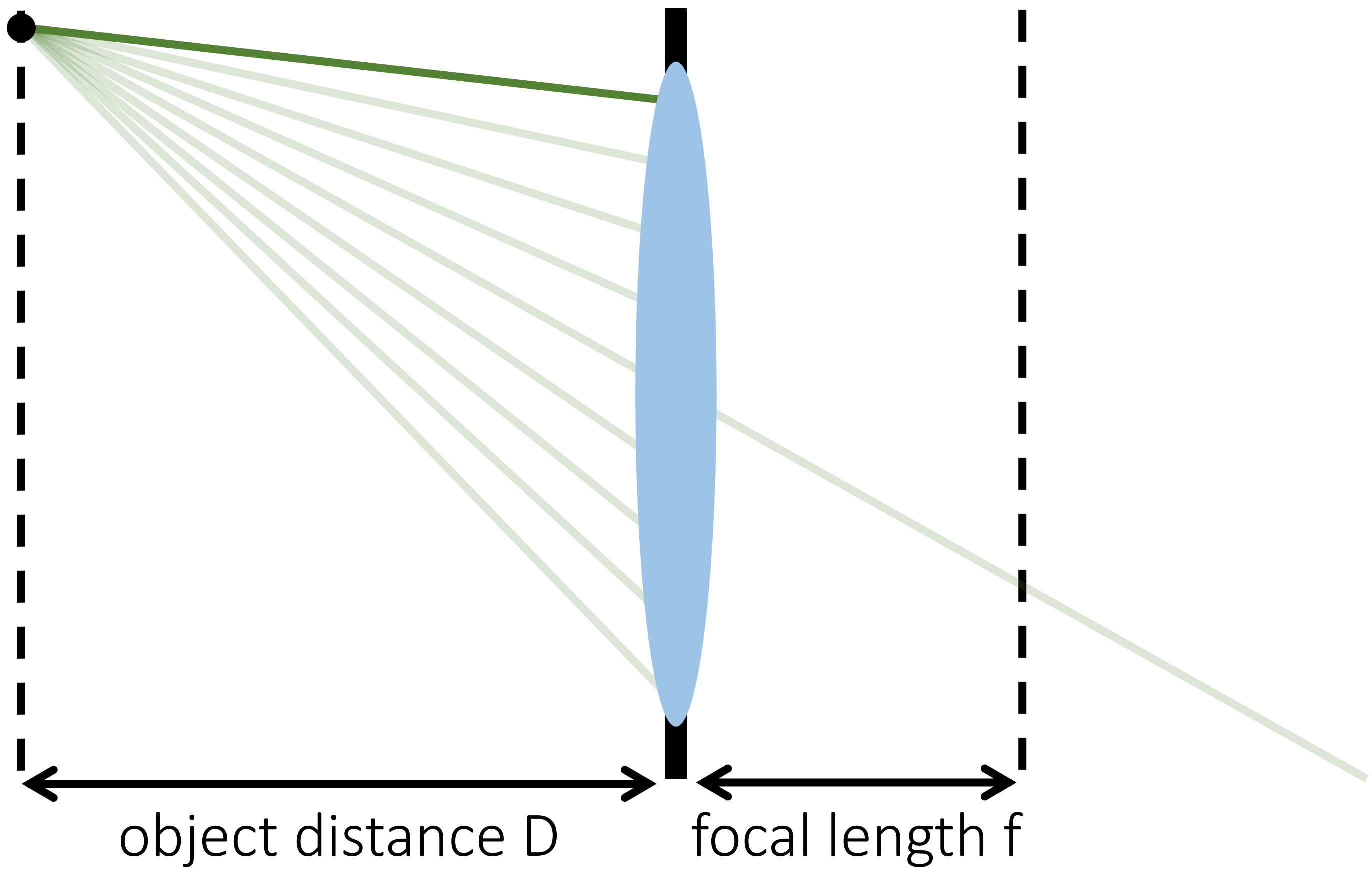
2. For all other rays:



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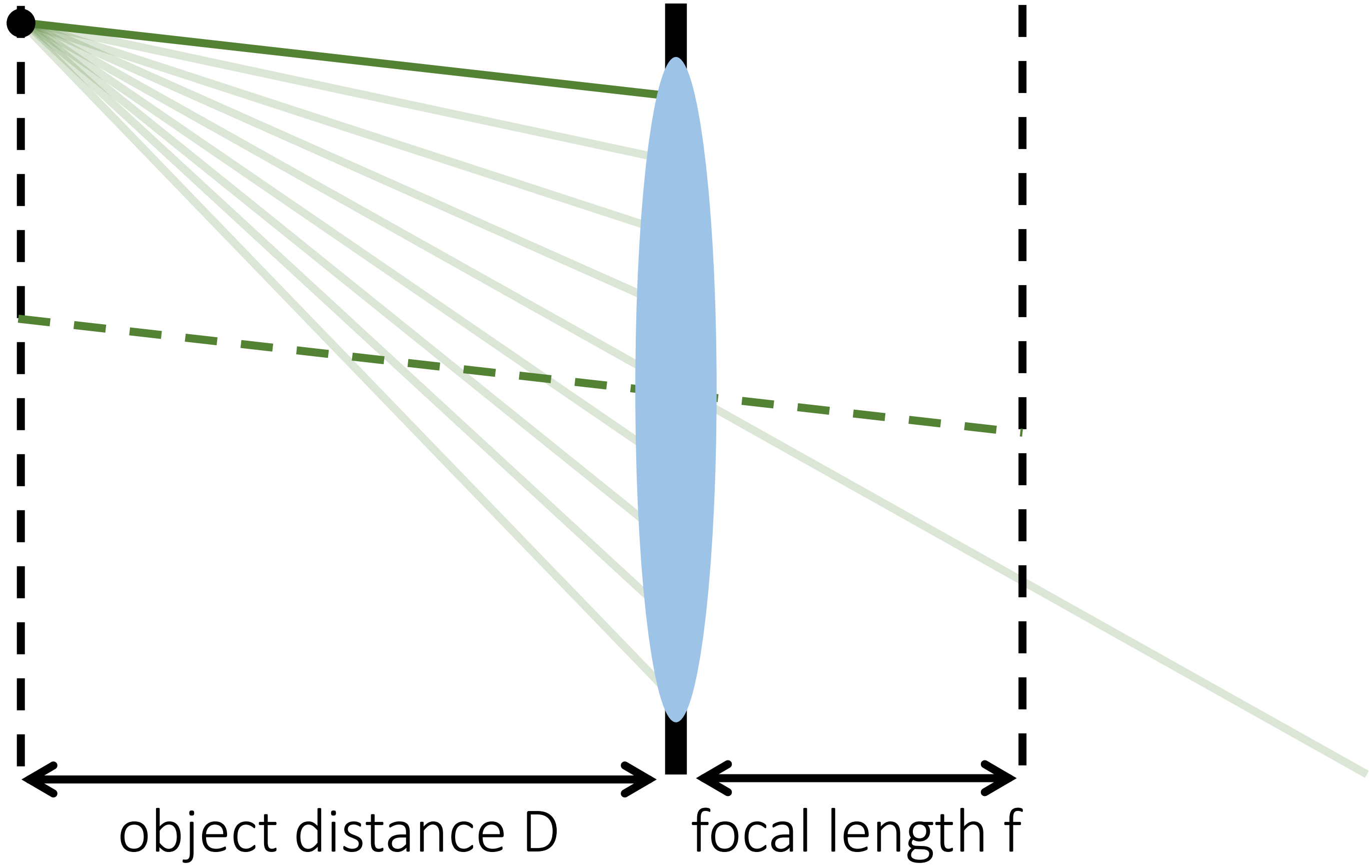

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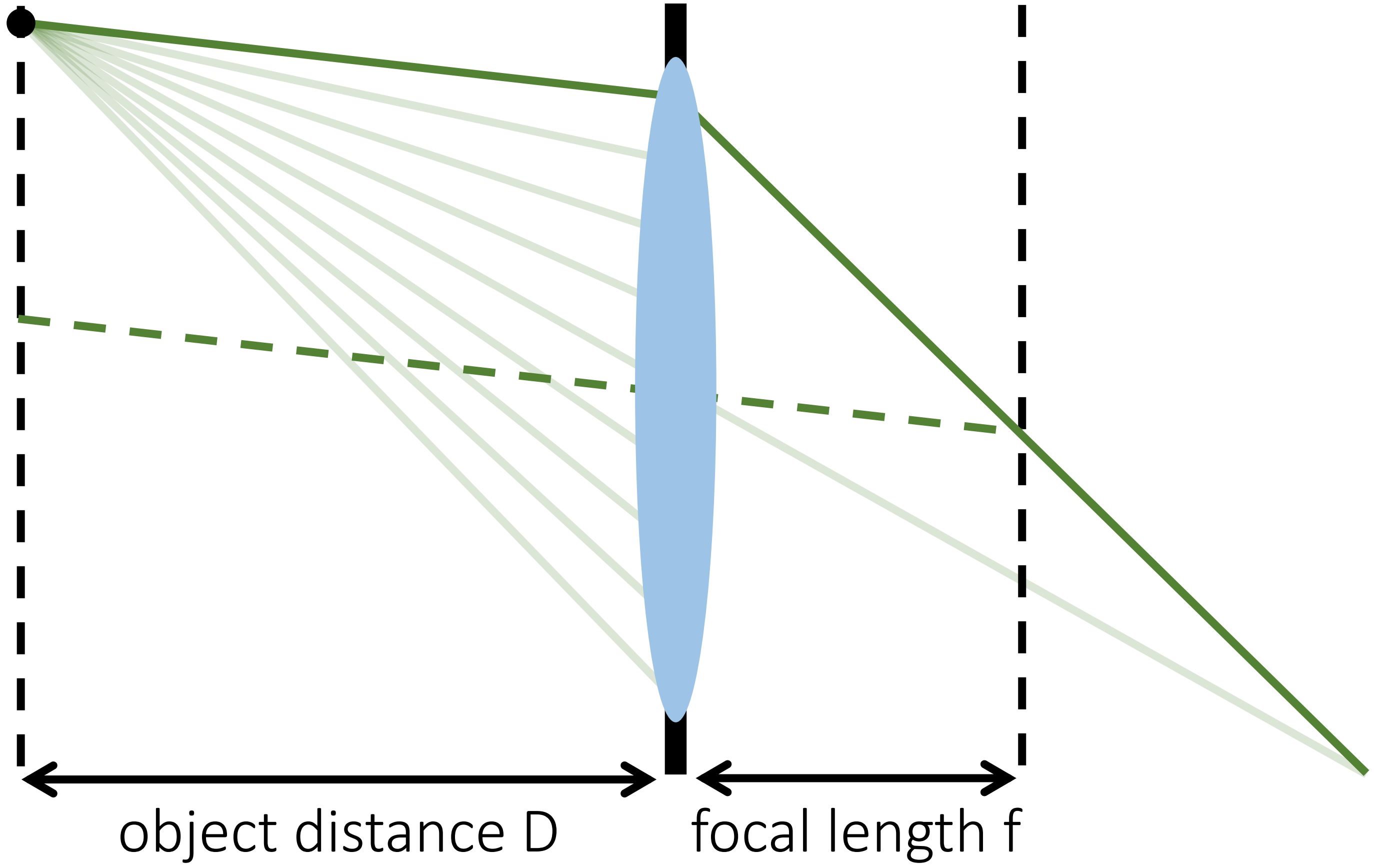

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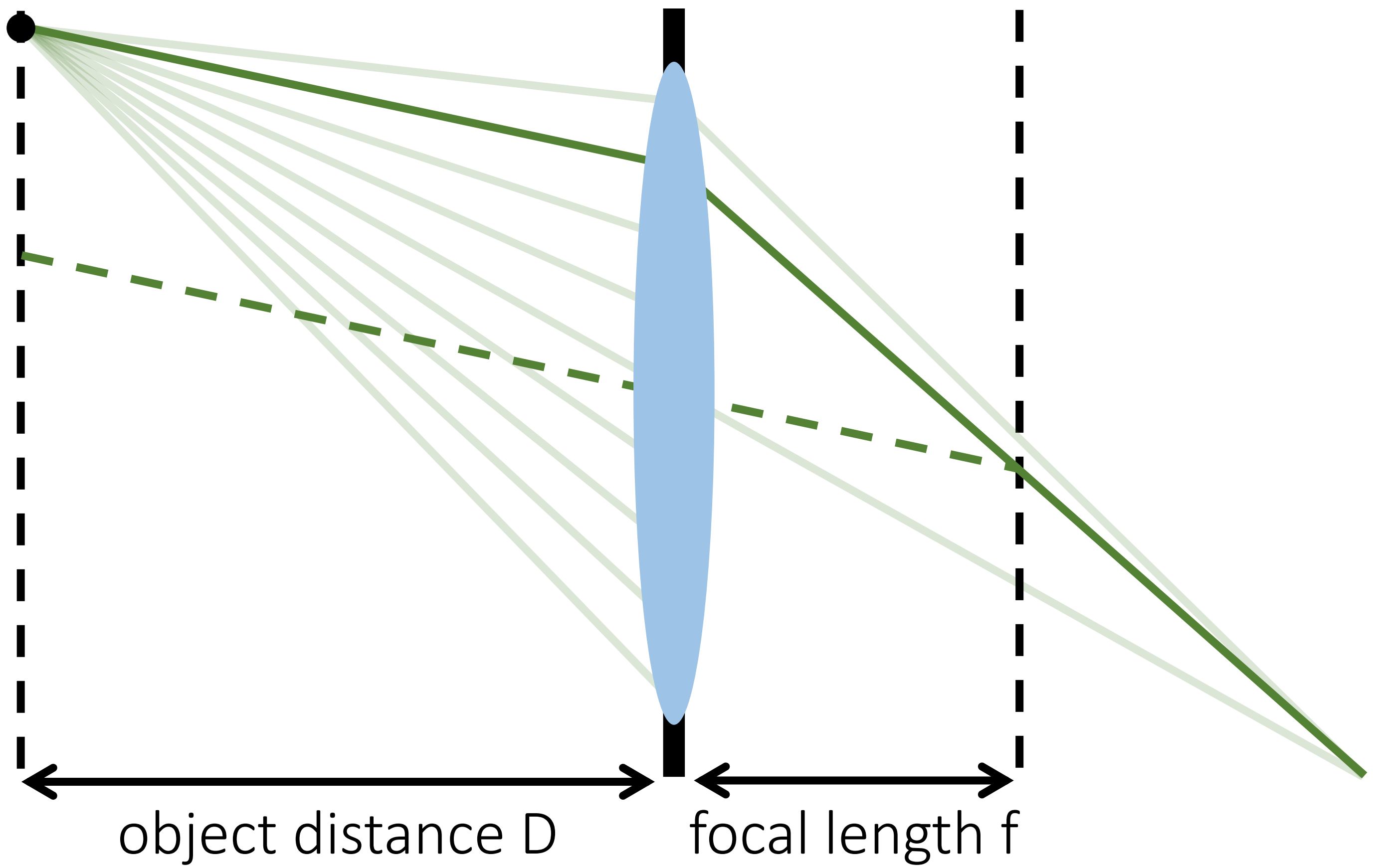

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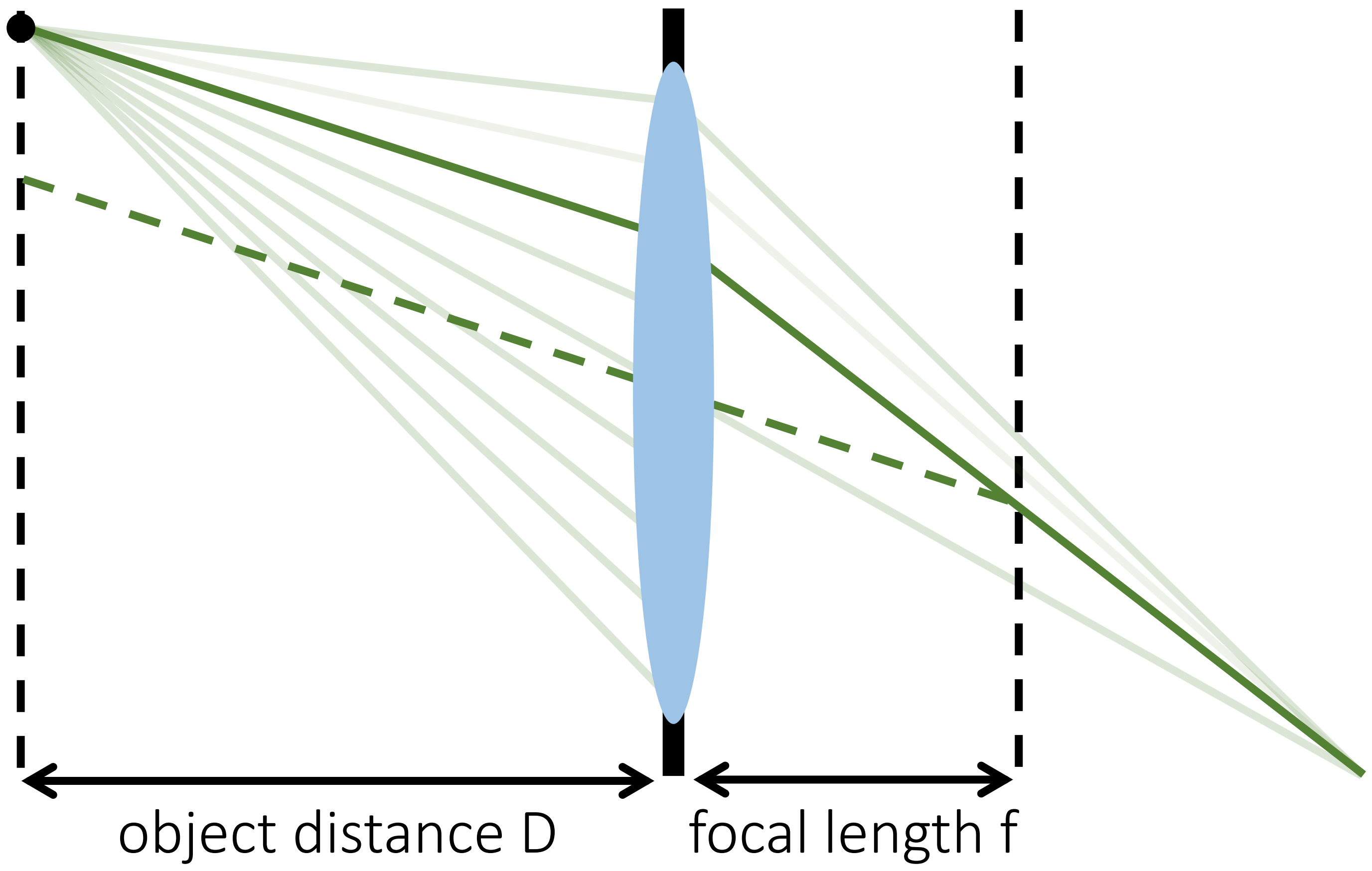

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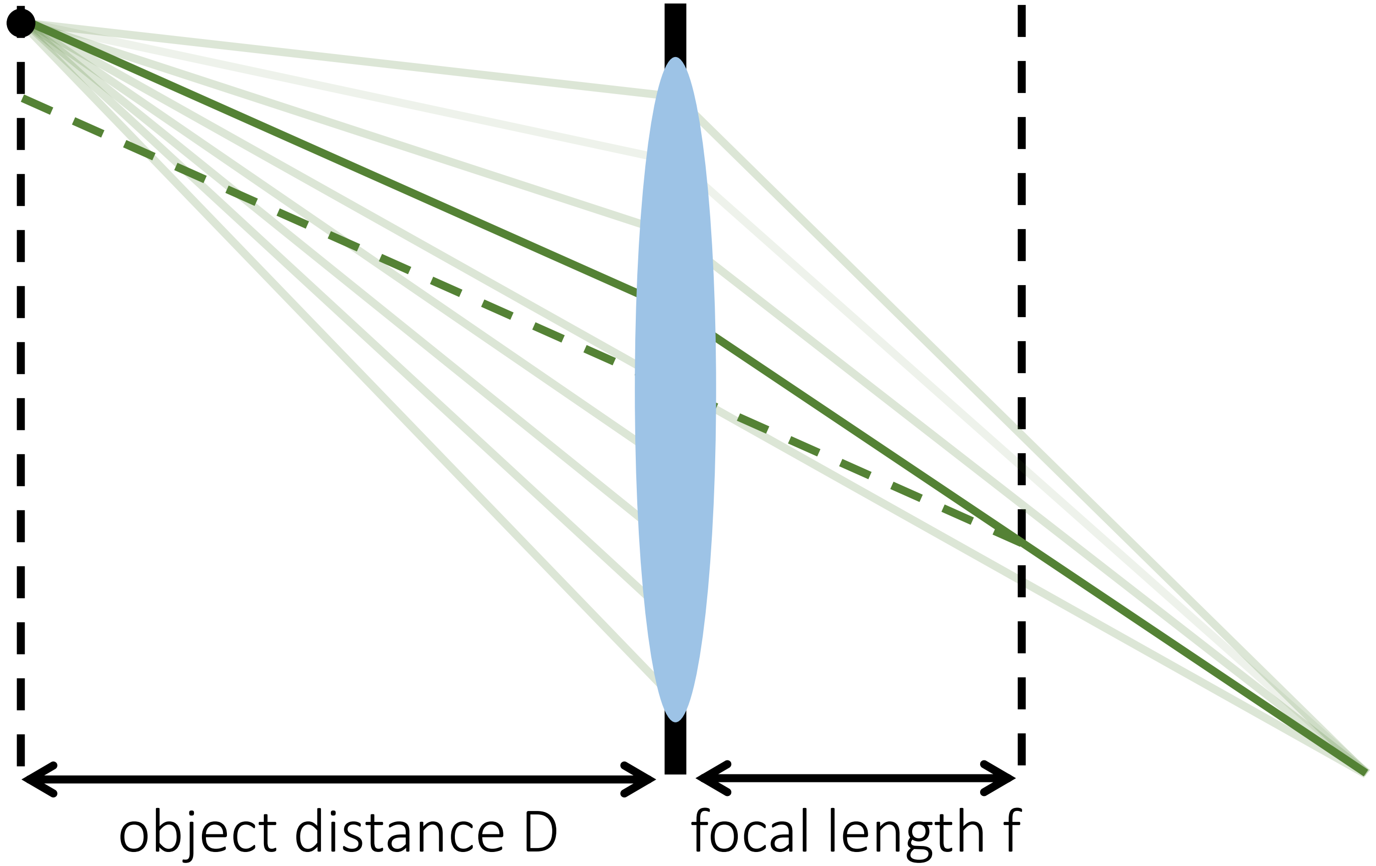

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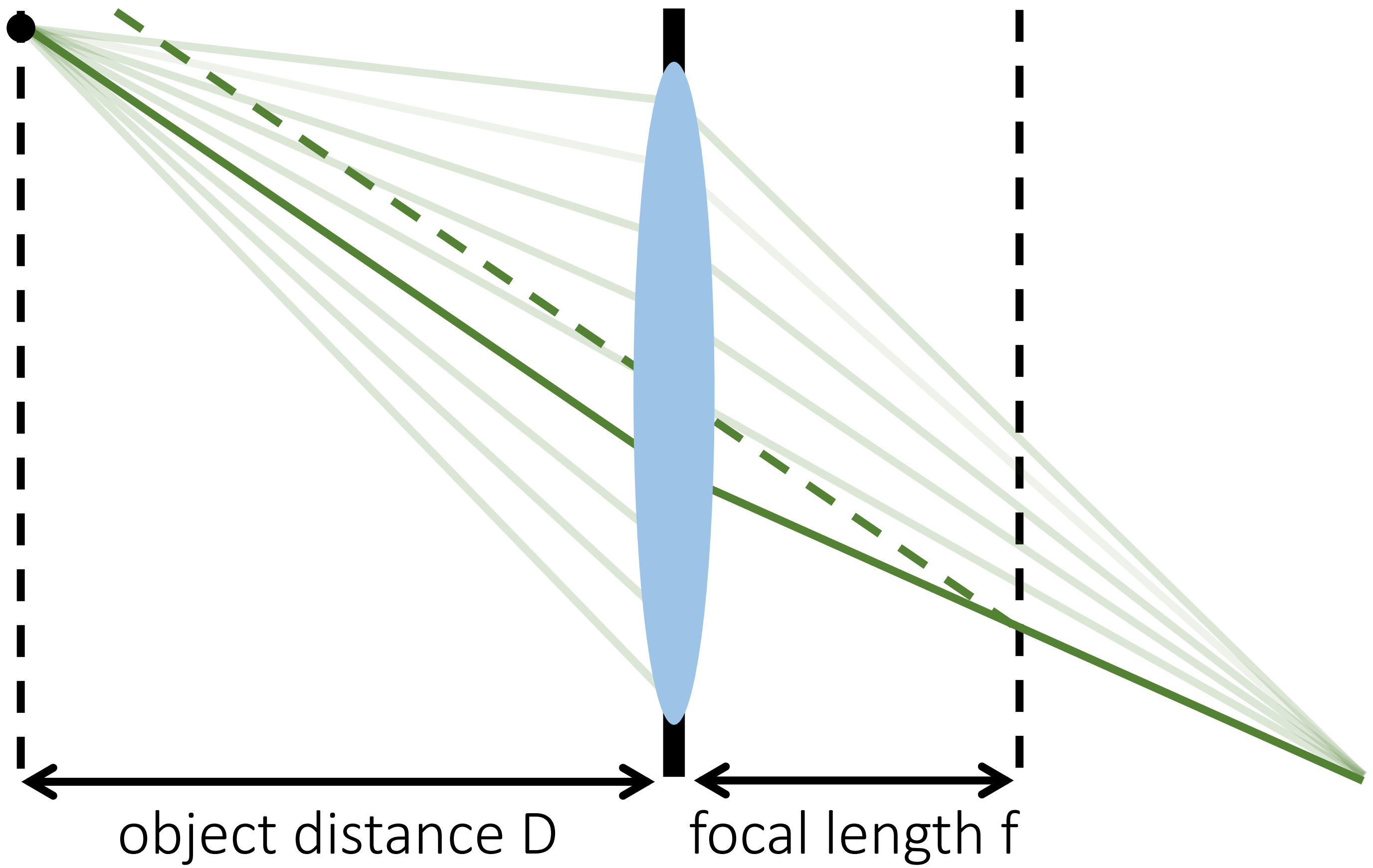

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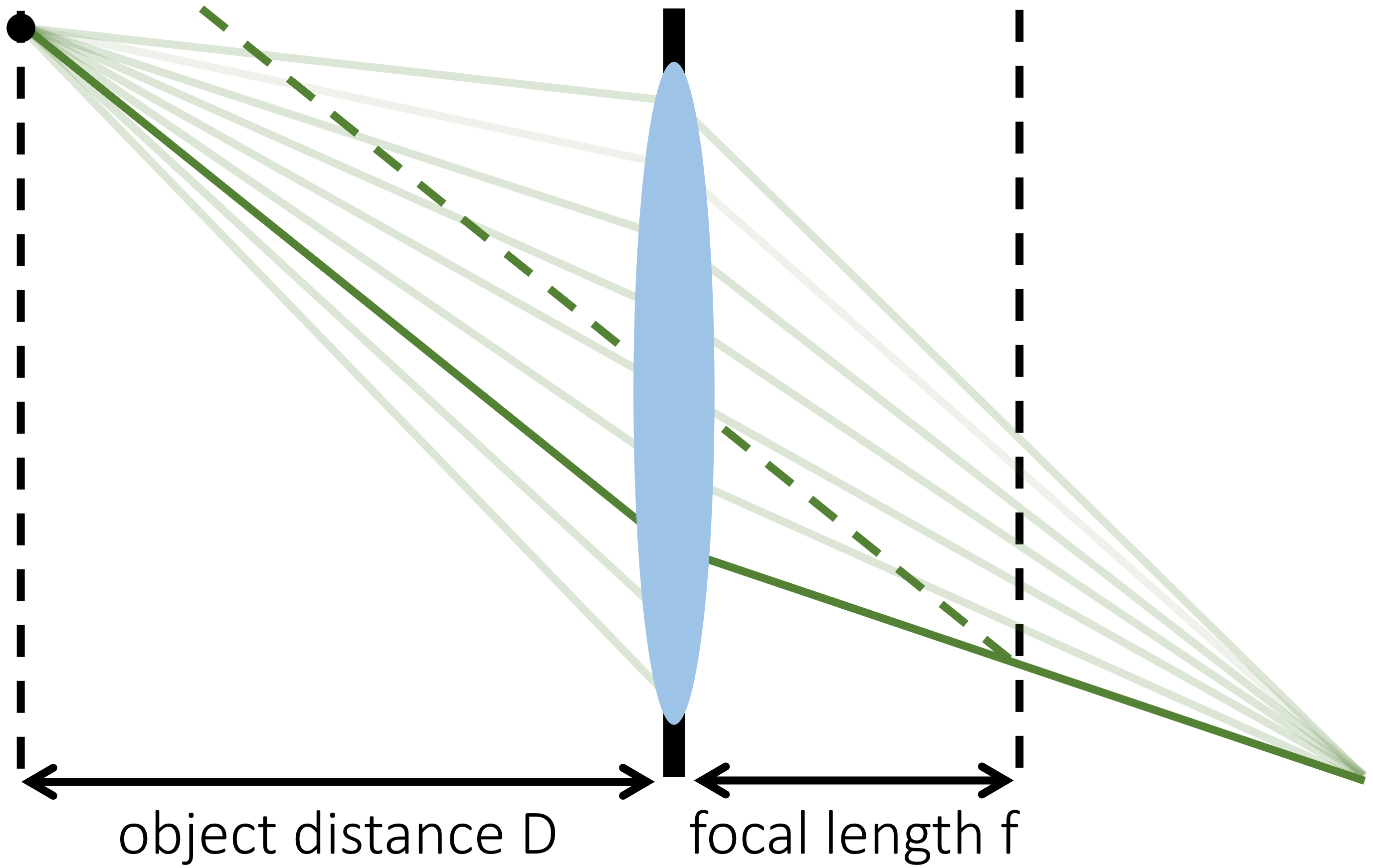

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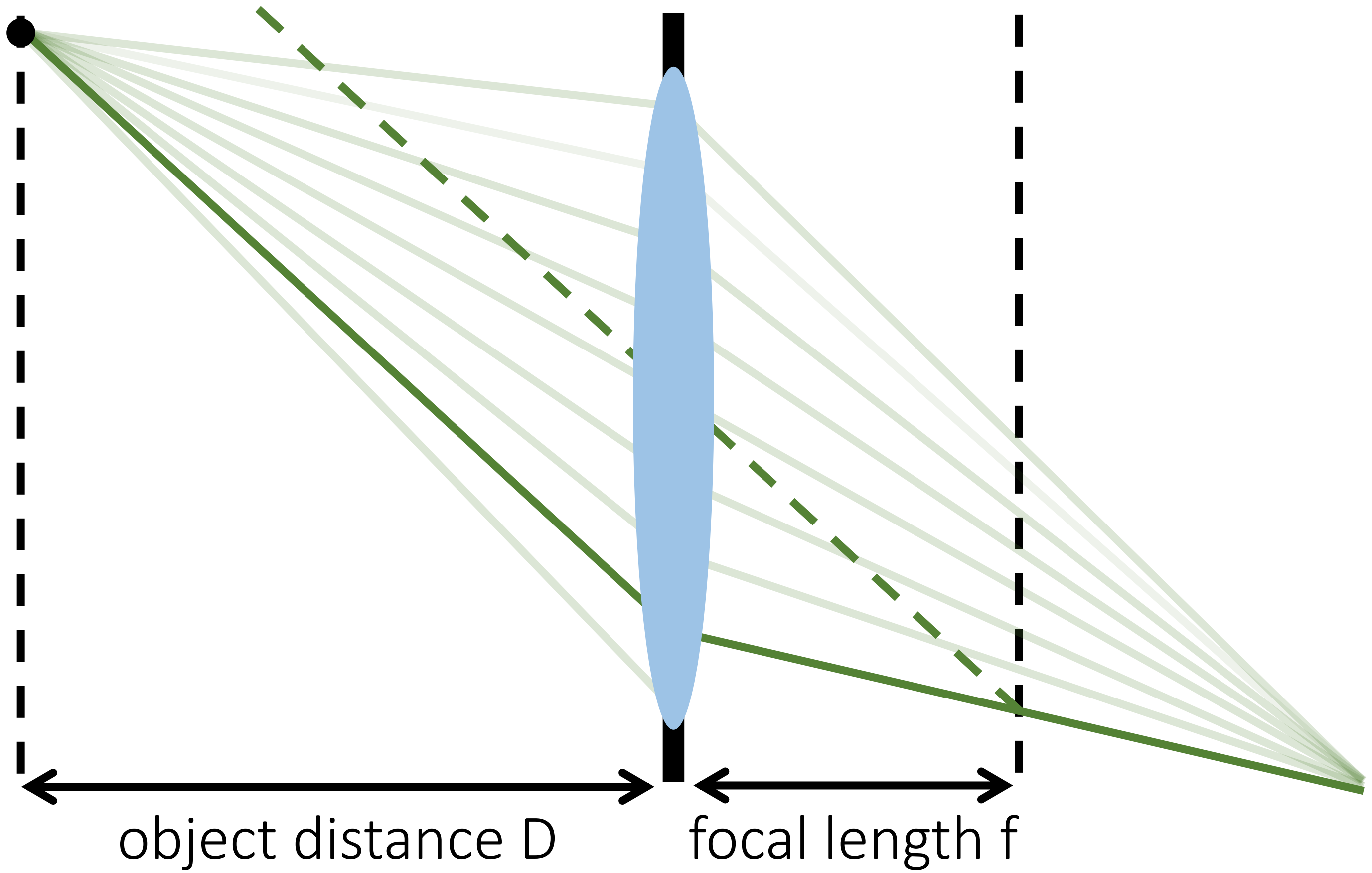

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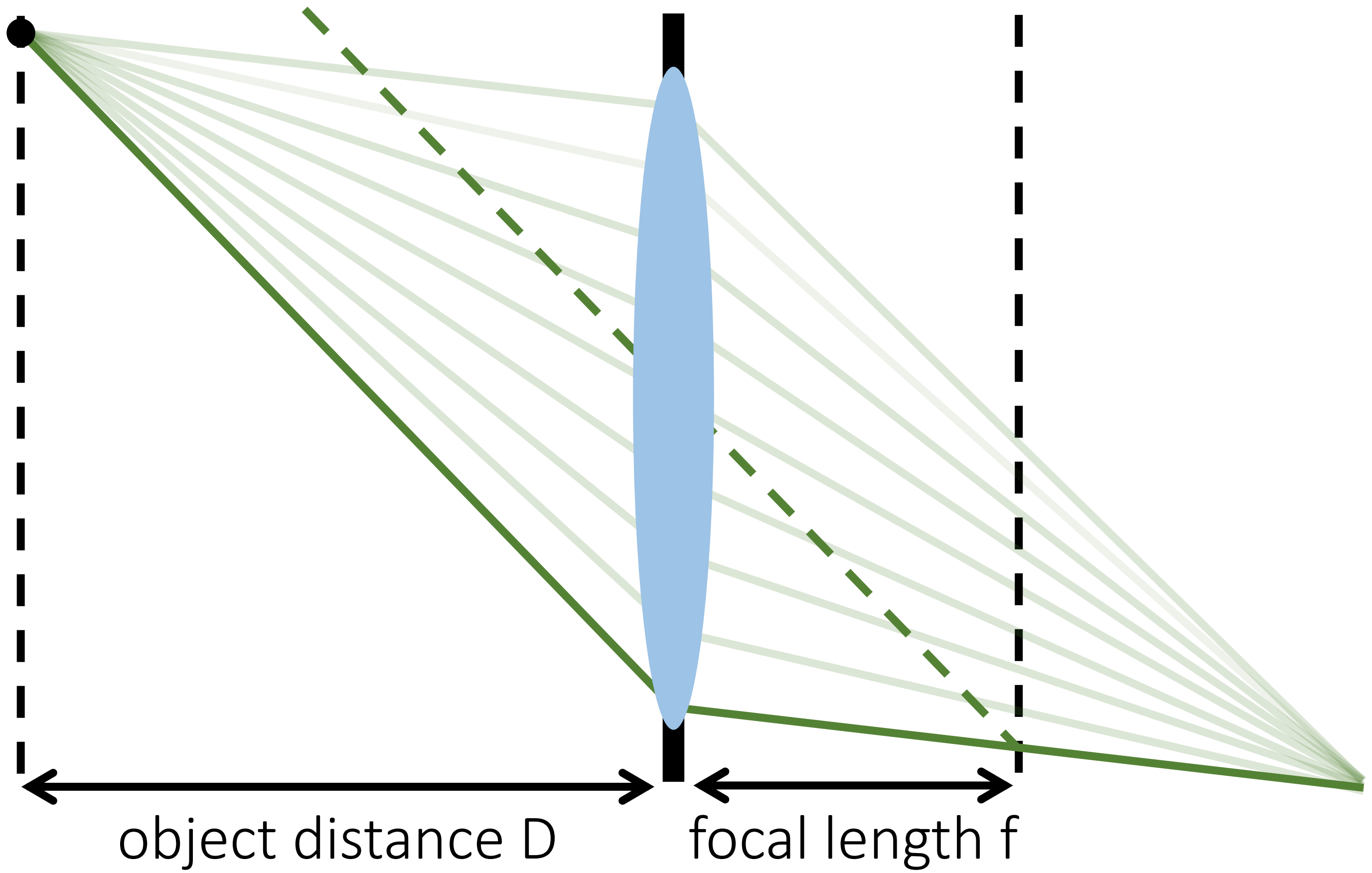

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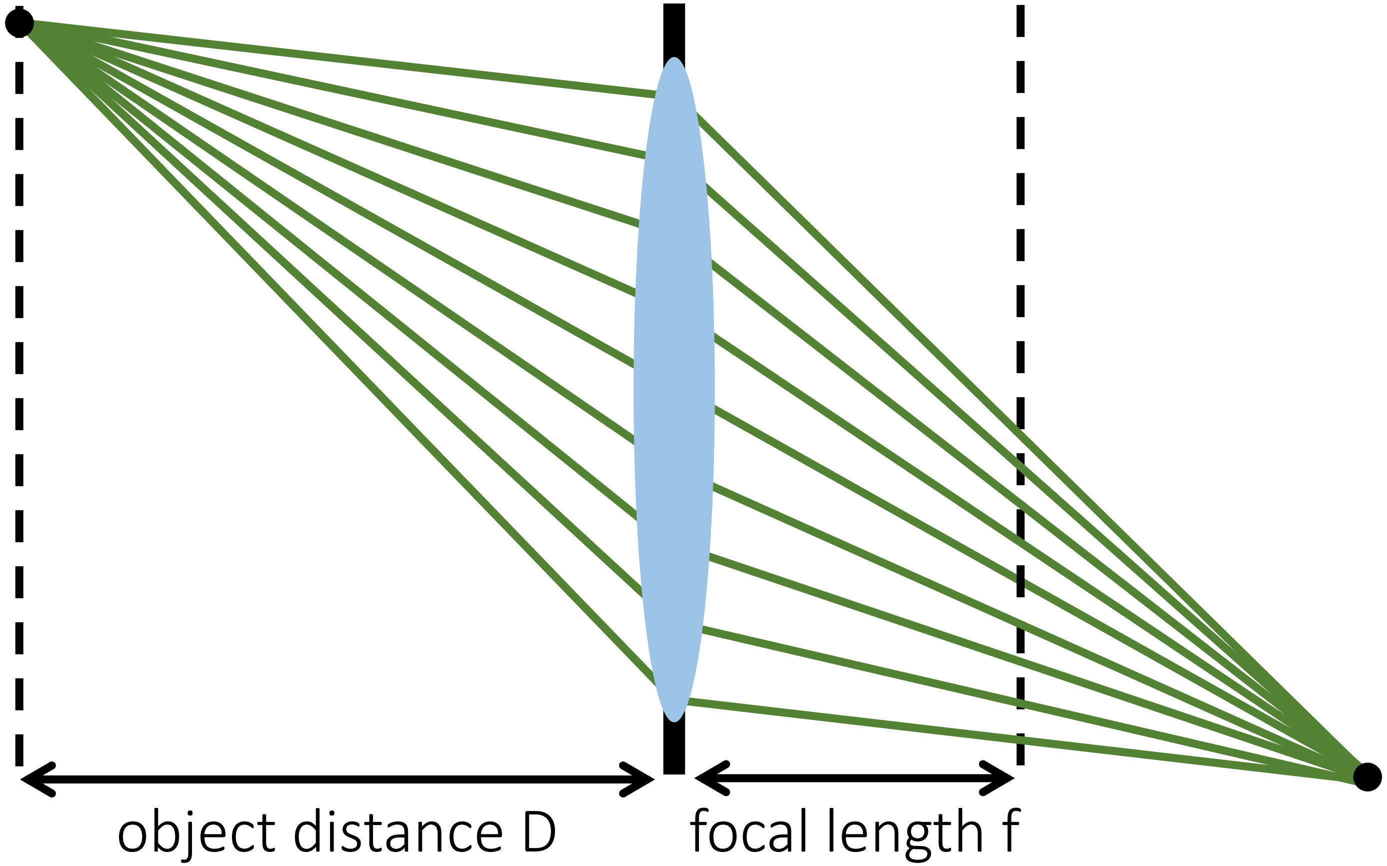

Focusing property:

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

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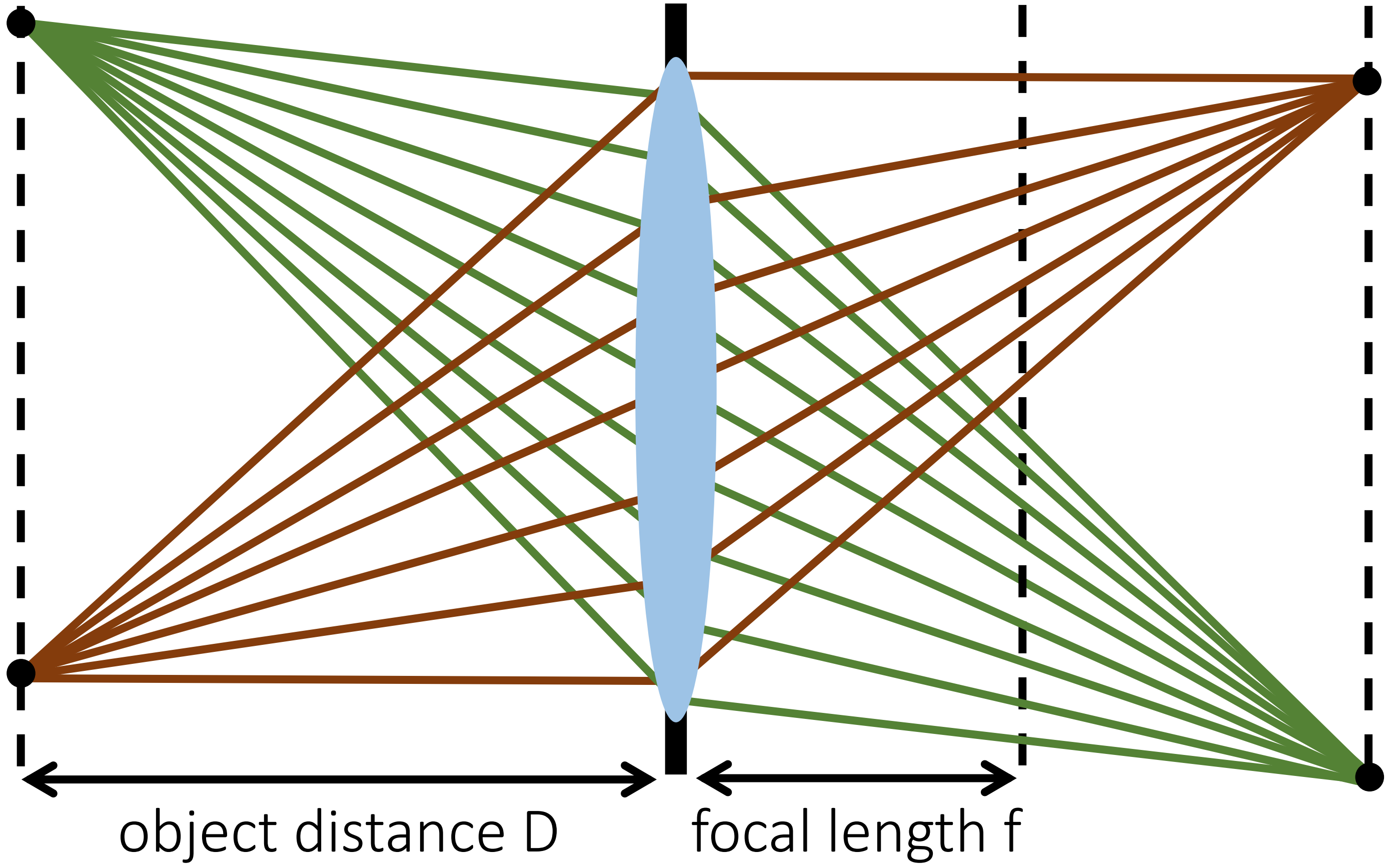
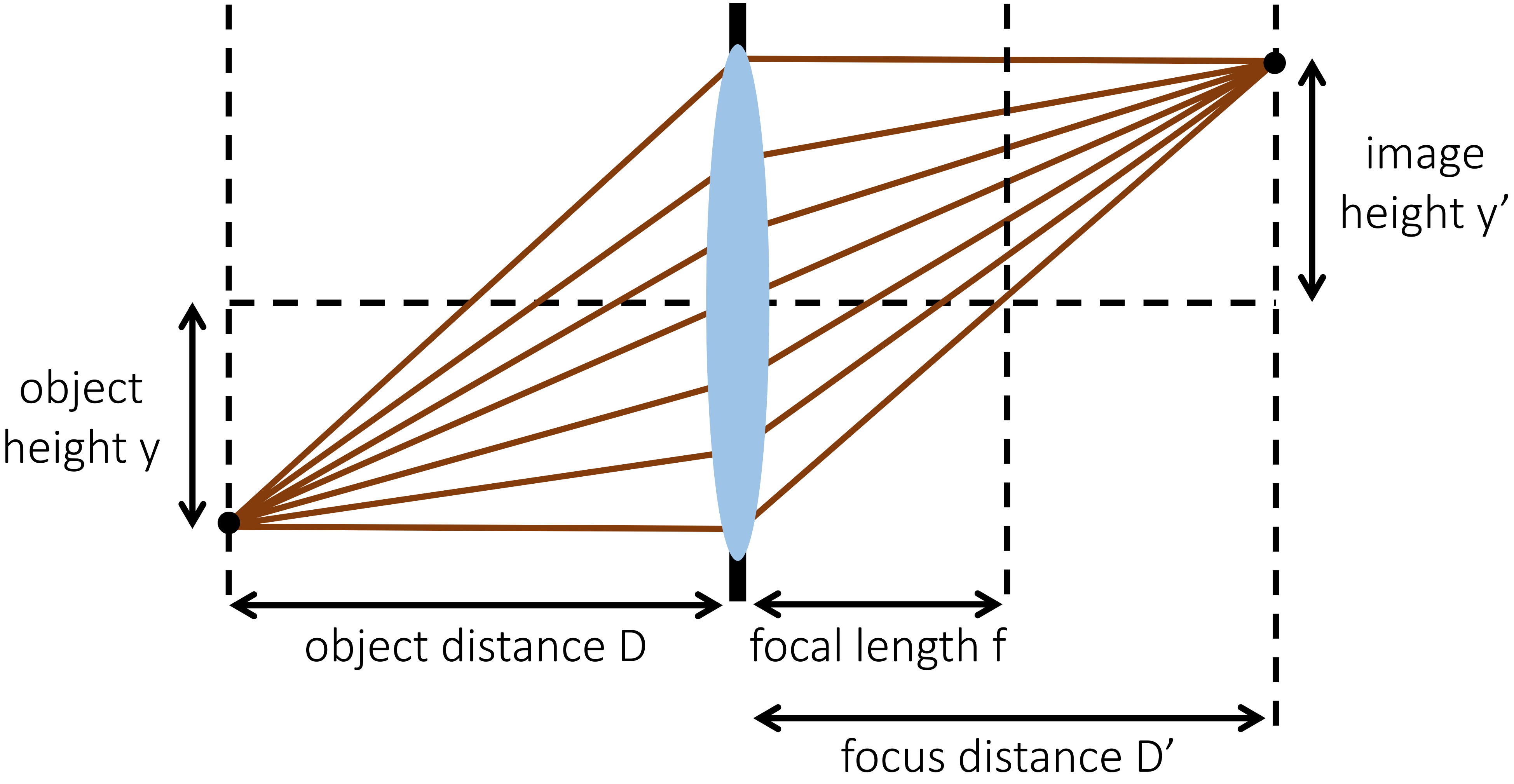


Focusing property:

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.

Thin lens formula

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



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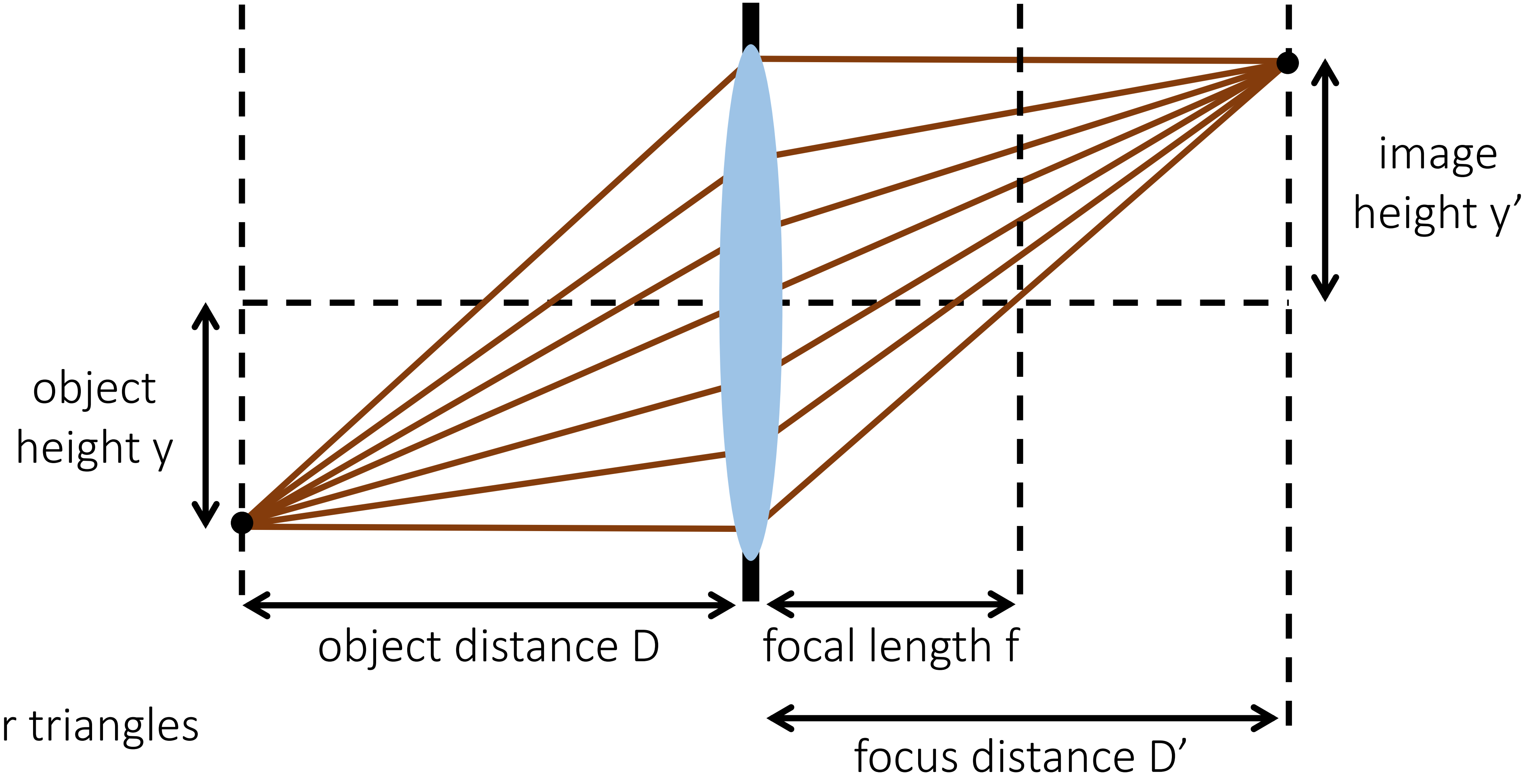
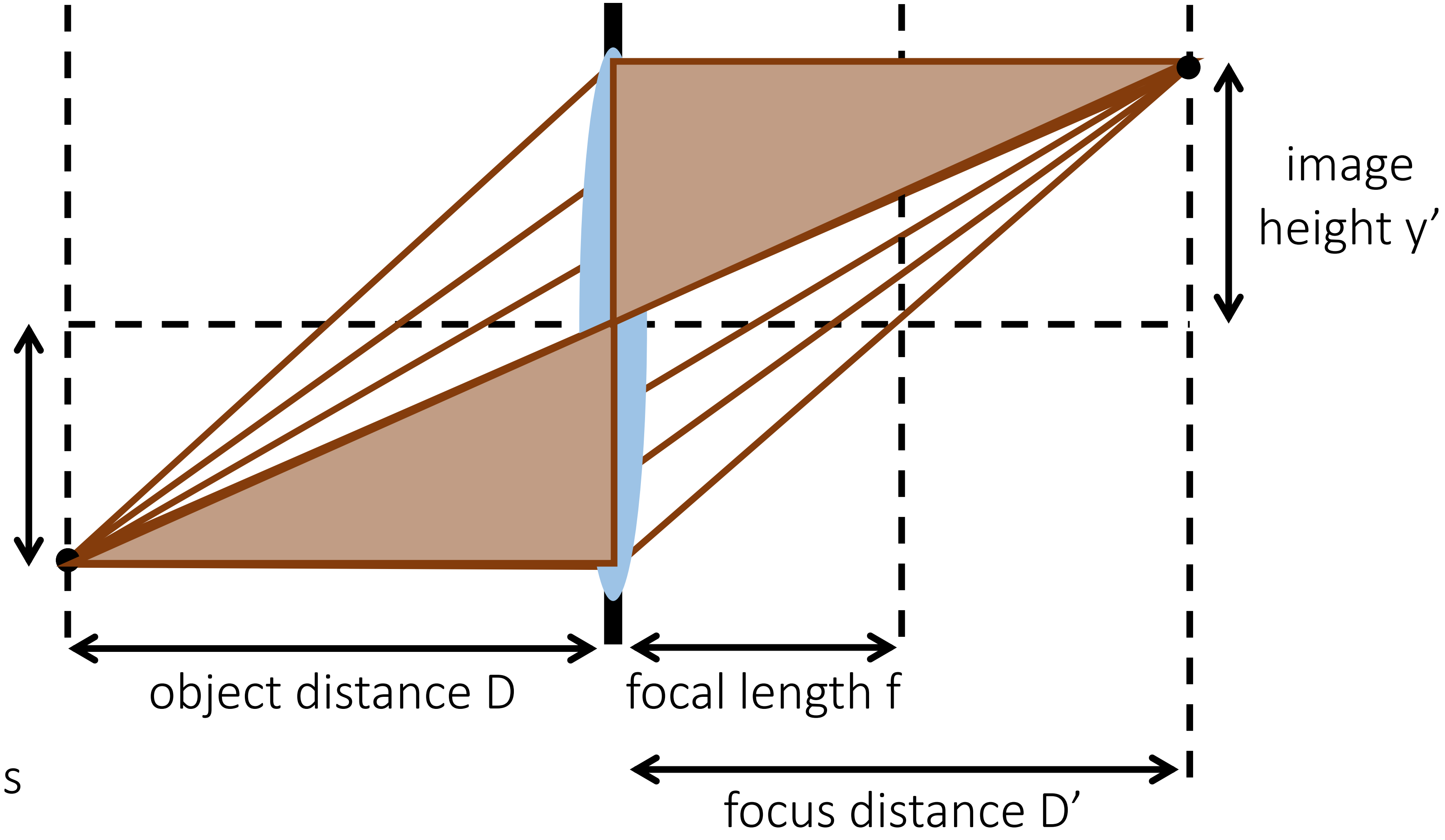


Use similar triangles

Thin lens formula

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

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



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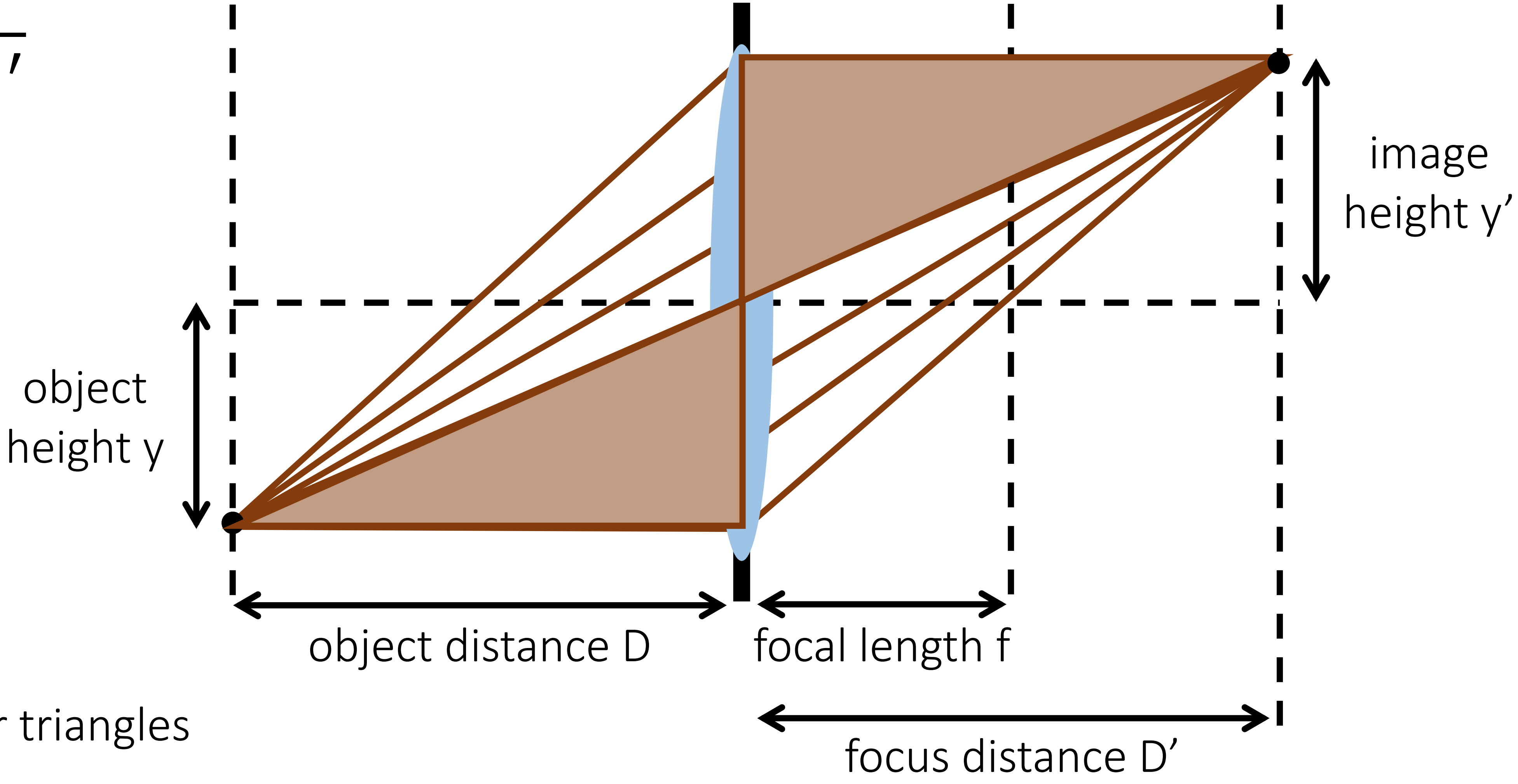

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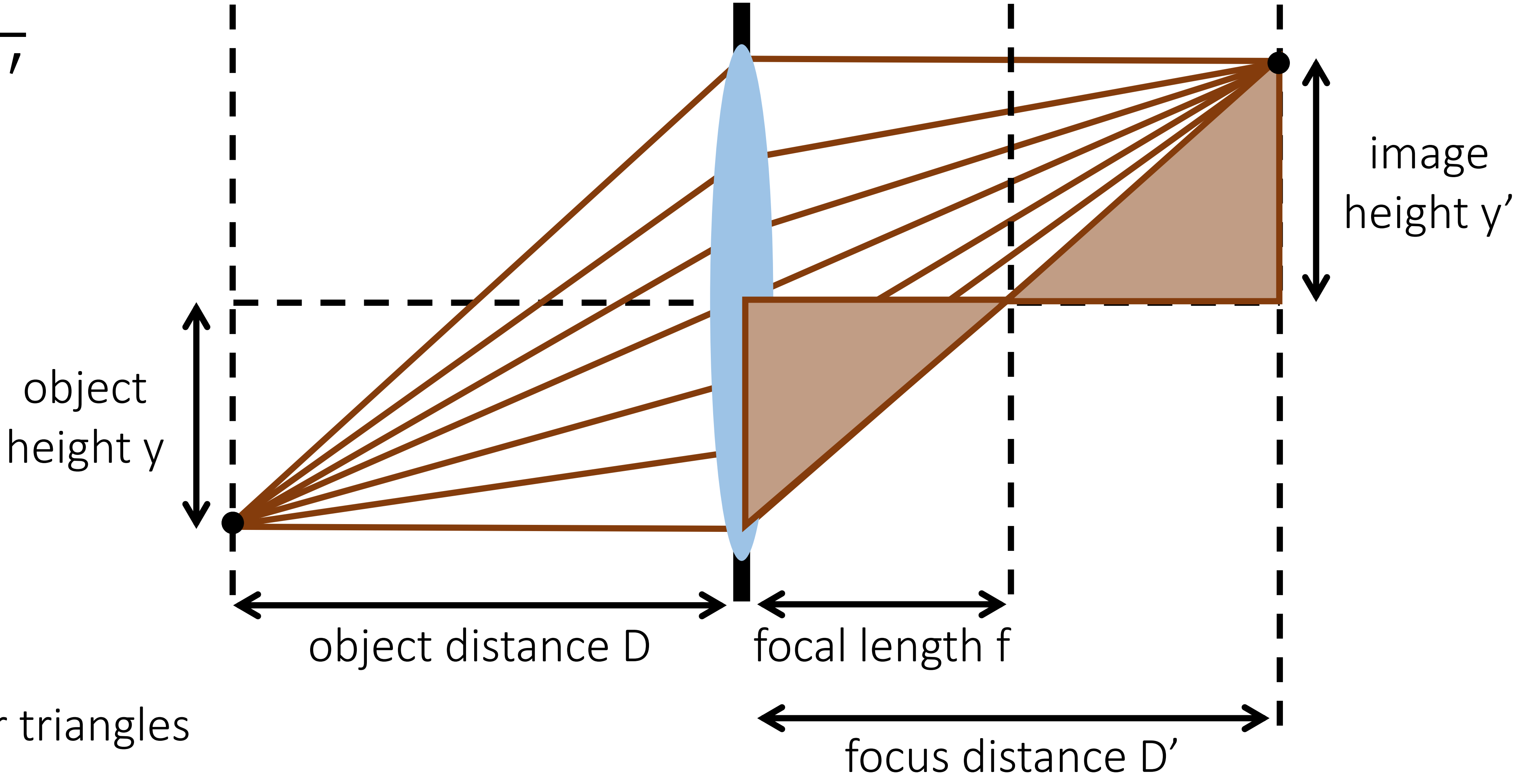

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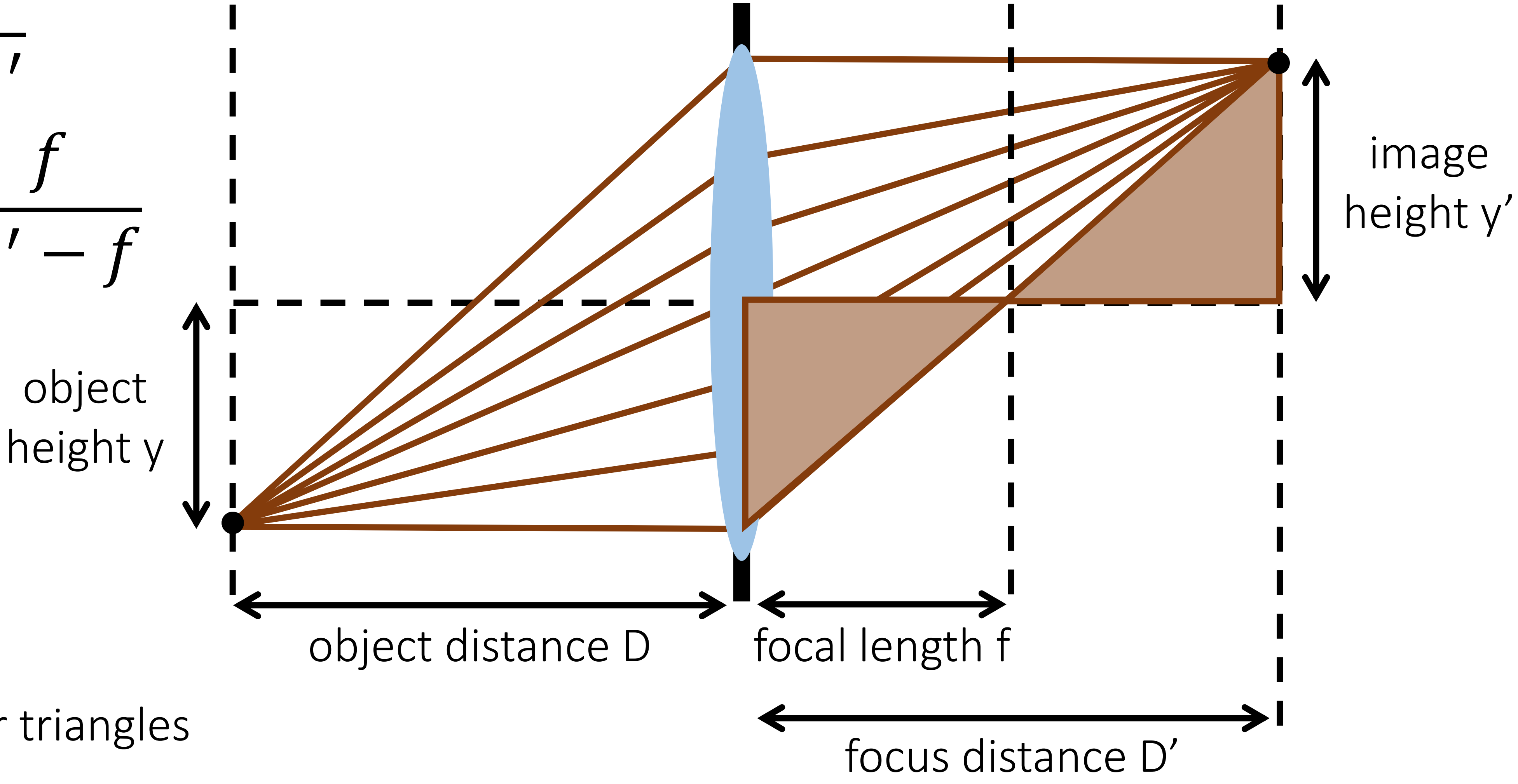
How can we relate scene-space (D, y) and image space (D’, y’) quantities?

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

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



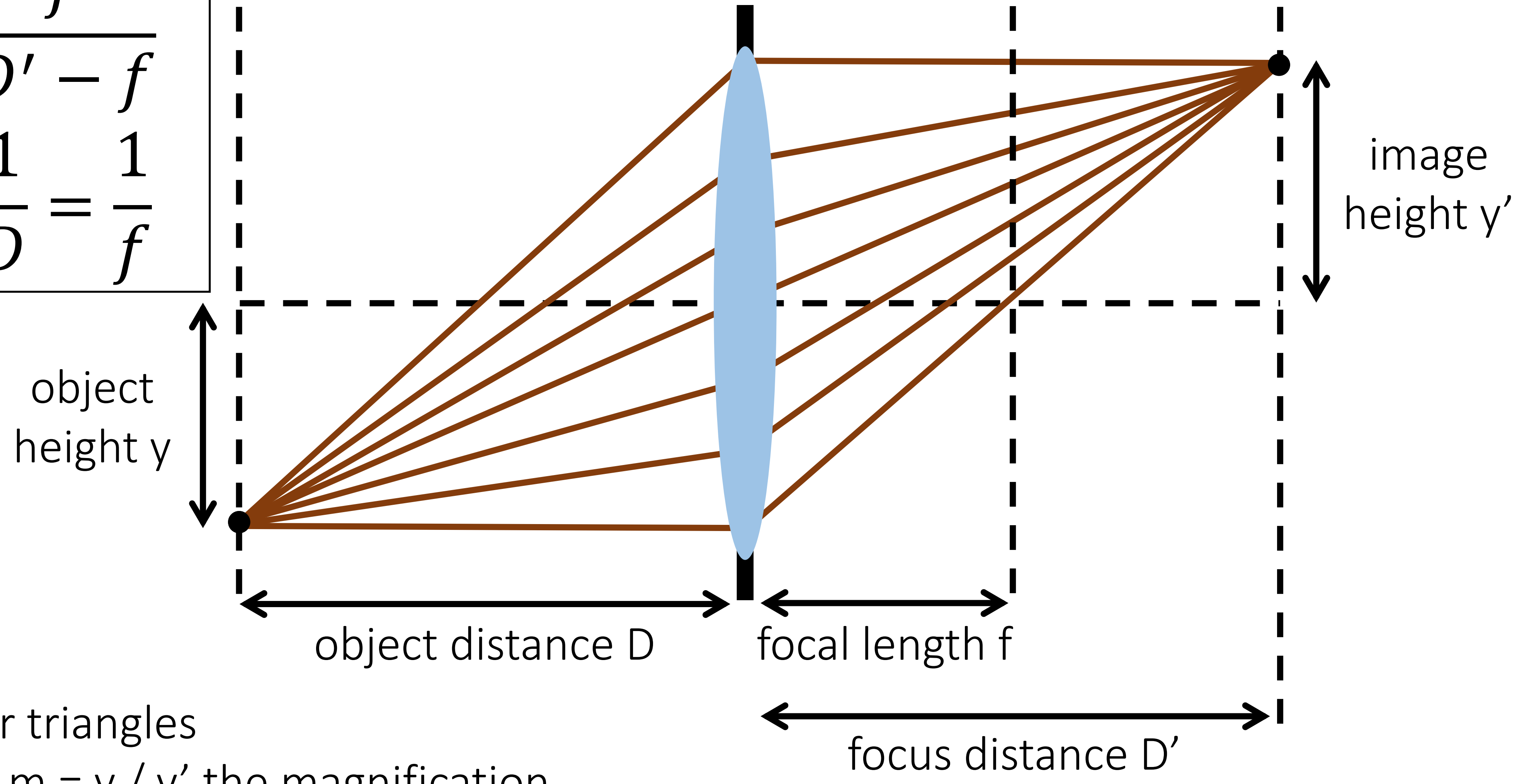
Use similar triangles

Thin 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 = ?

$$\boxed{\begin{gathered} m = \frac{f}{D' - f} \\ \frac{1}{D'} + \frac{1}{D} = \frac{1}{f} \end{gathered}}$$

Special focus distances

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

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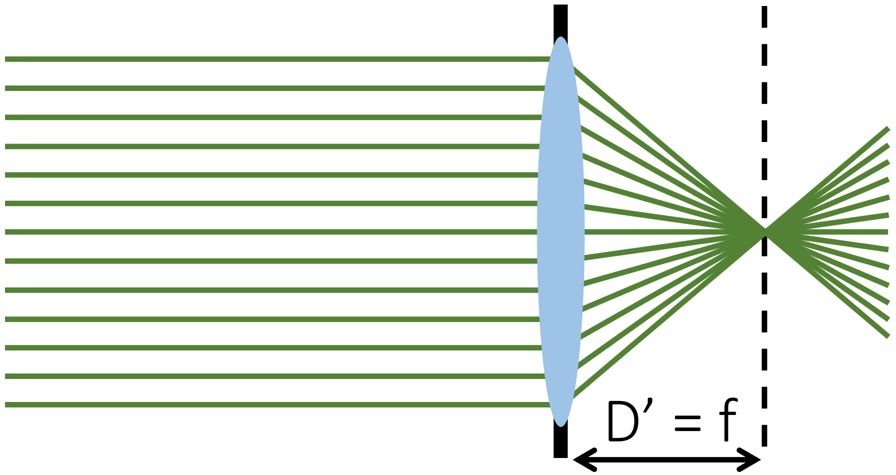
D’ = f, D = ∞, m = ∞ → infinity focus (parallel rays)



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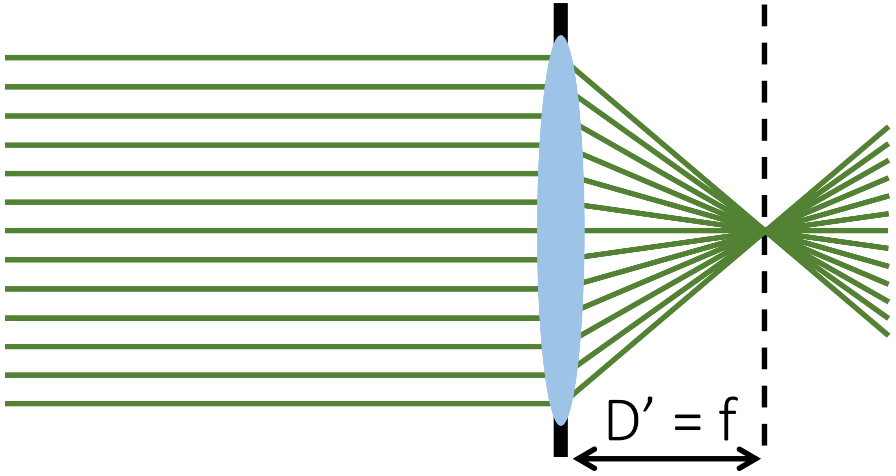
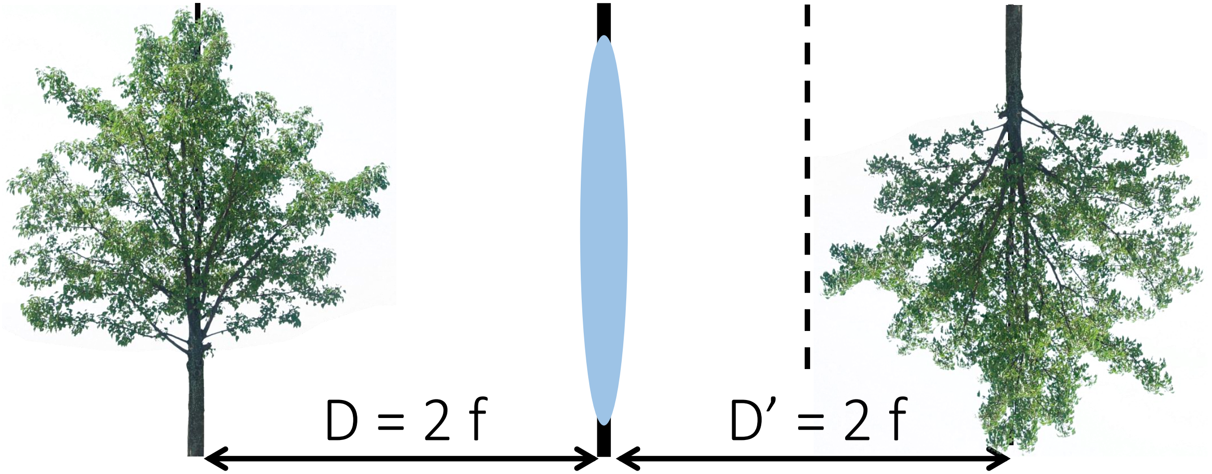
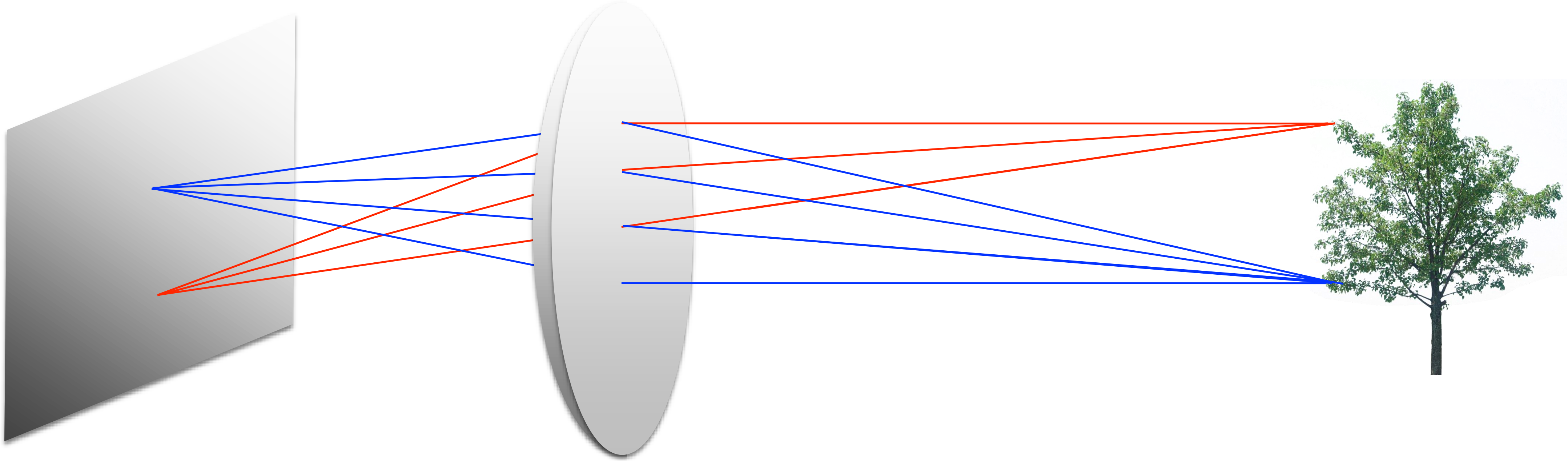


D' = D = 2 f, m = 1 → object is reproduced in real-life size



Are all our problems solved?



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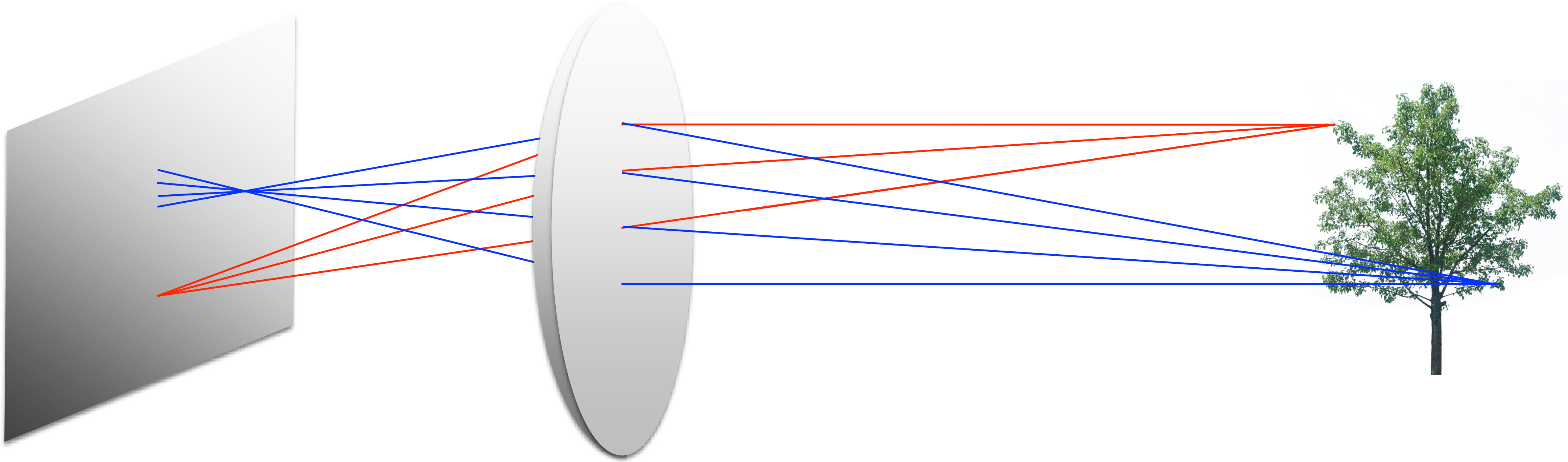

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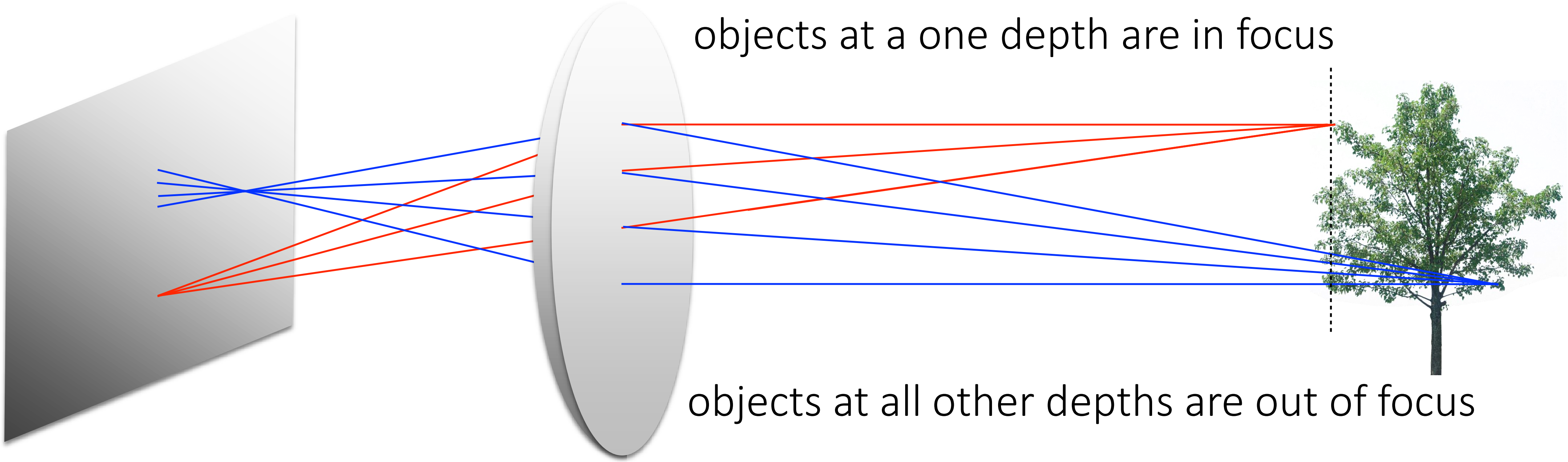

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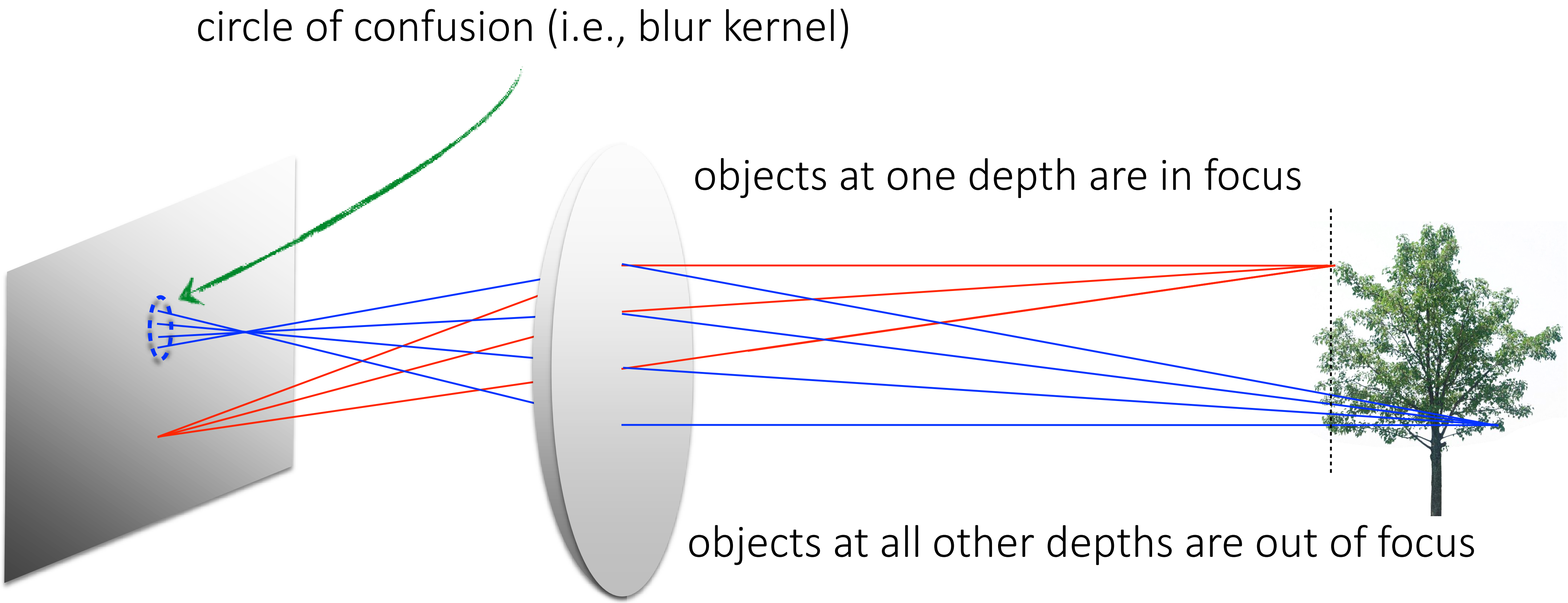
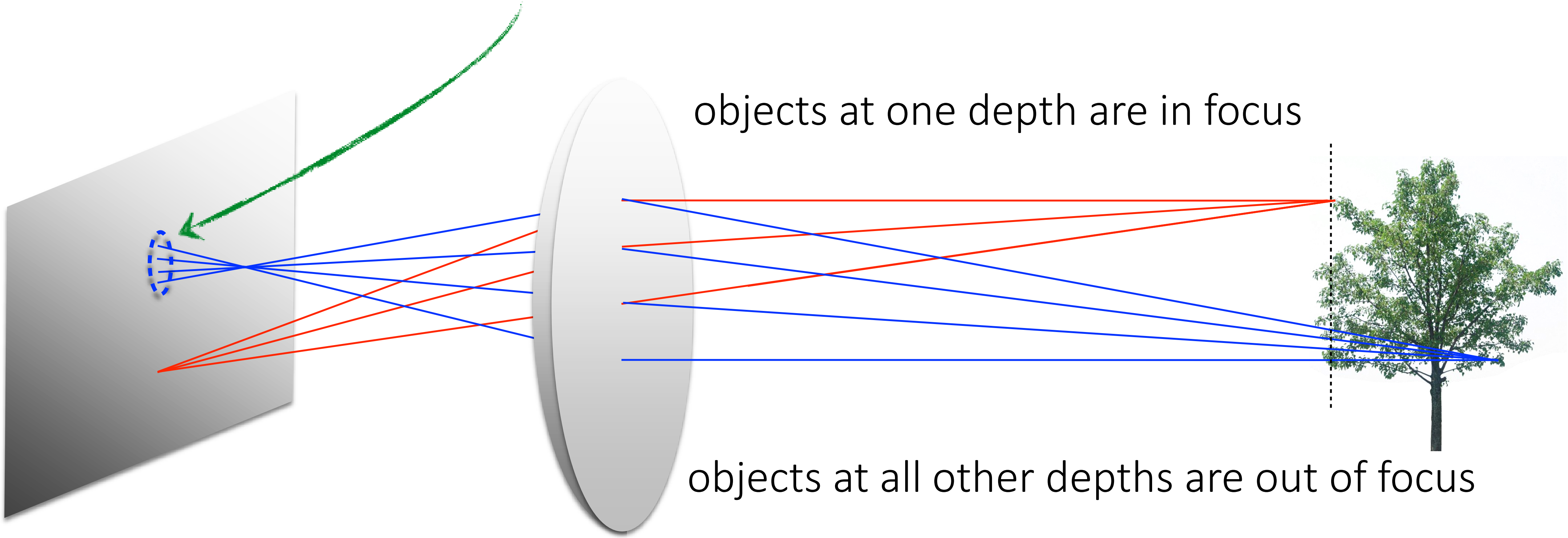


Is the circle of confusion constant?

Are all our problems solved?

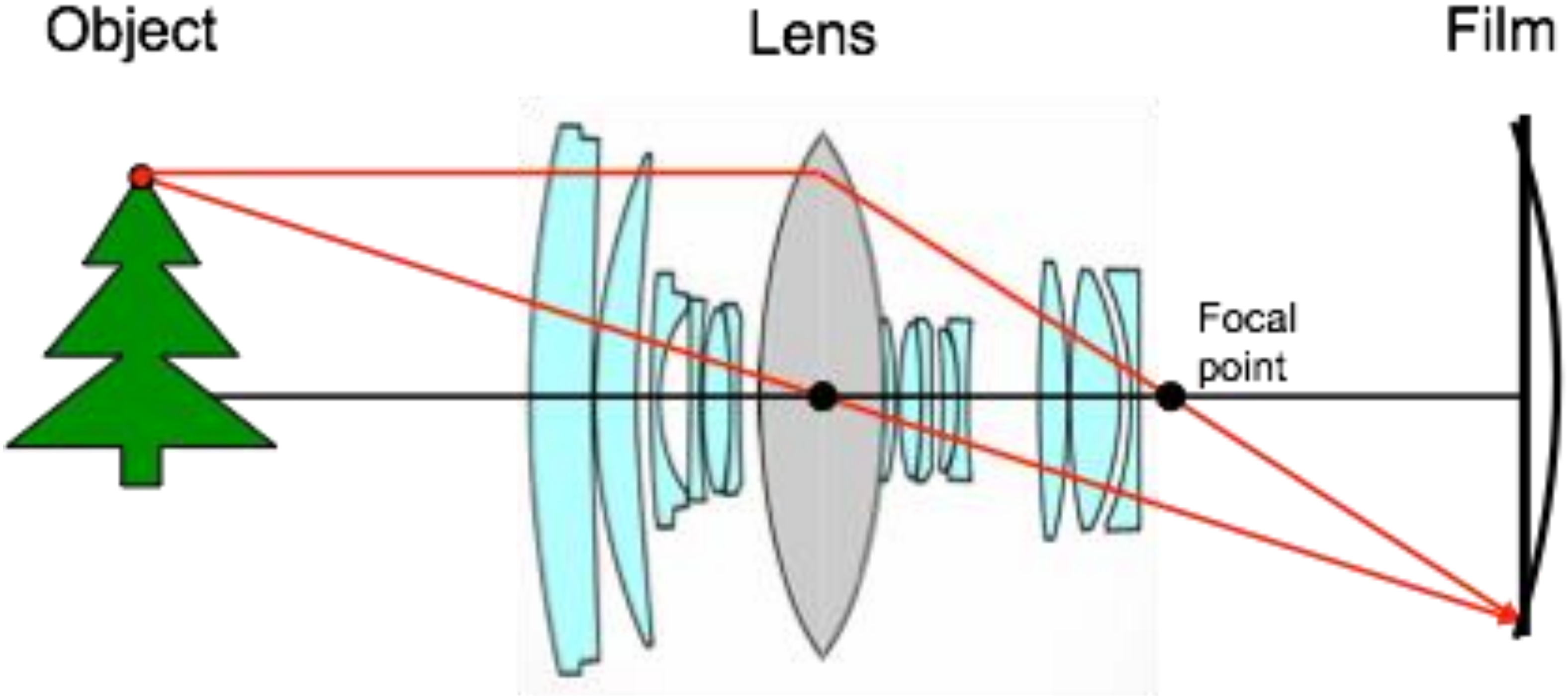


How do we change the depth where objects are in focus?

Real lenses and aberrations

Thin lenses are a fiction

The thin lens model assumes that the lens has no thickness, but this is never true…



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

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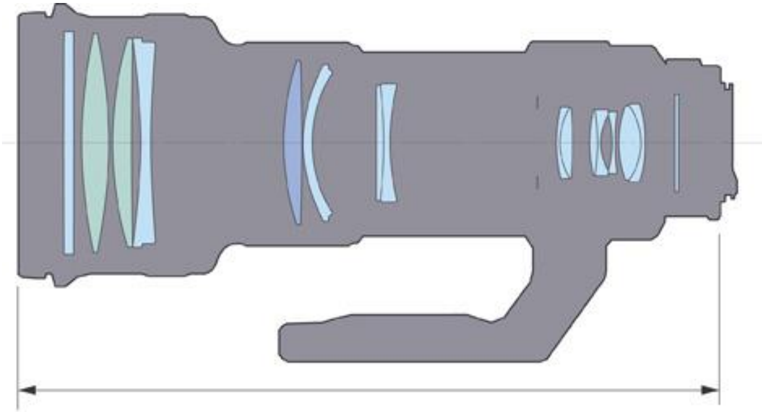

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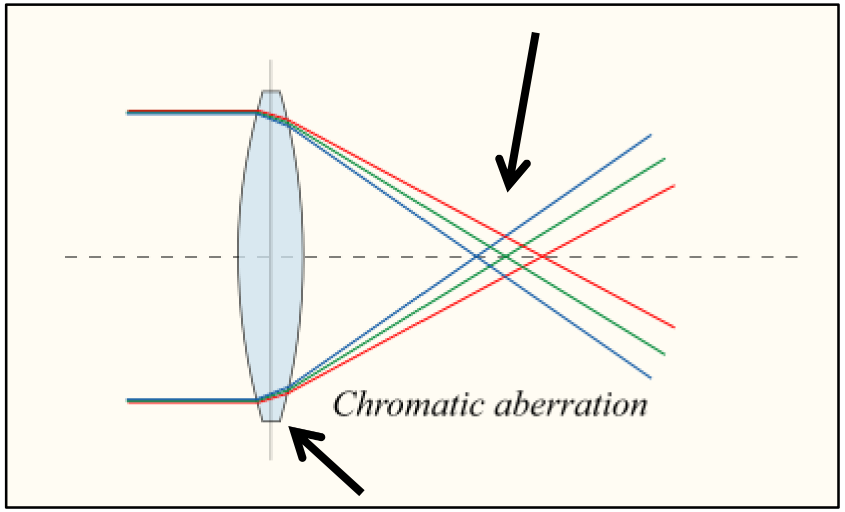
Aberrations

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

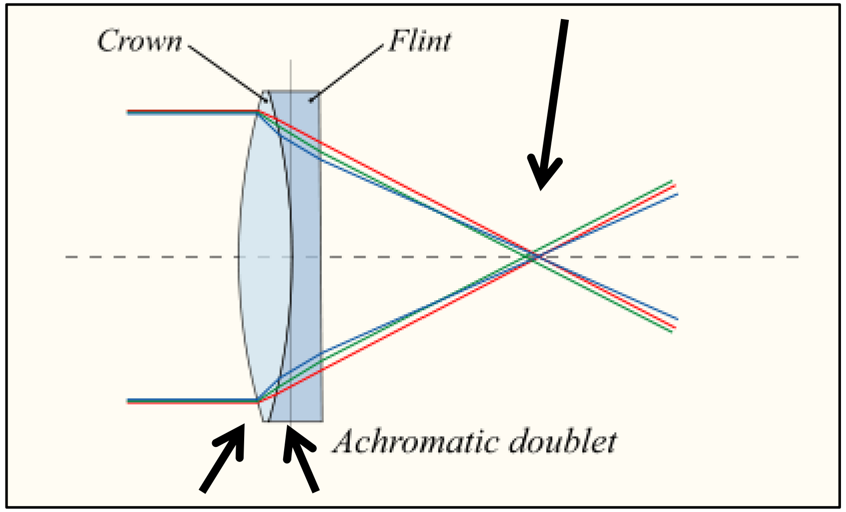
- Example: chromatic aberration.

focal length shifts with wavelength



glass has dispersion (refractive index changes with wavelength)

one lens cancels out dispersion of other



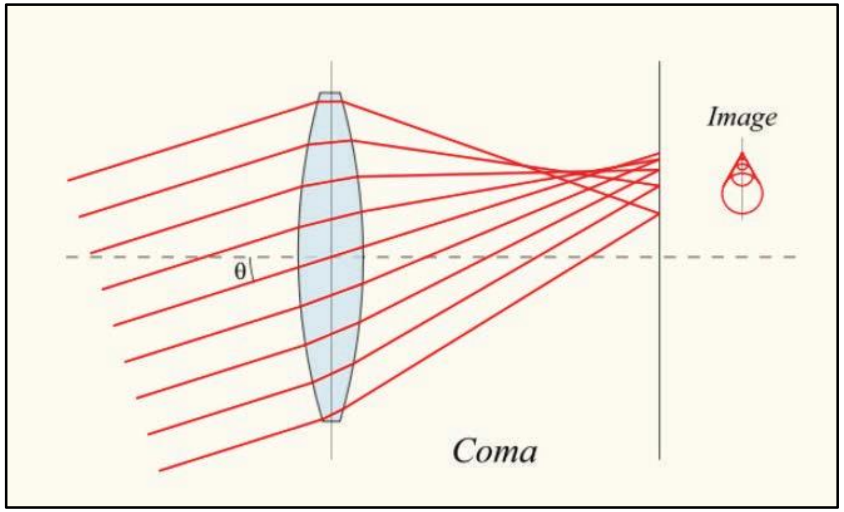
glasses of different refractive index

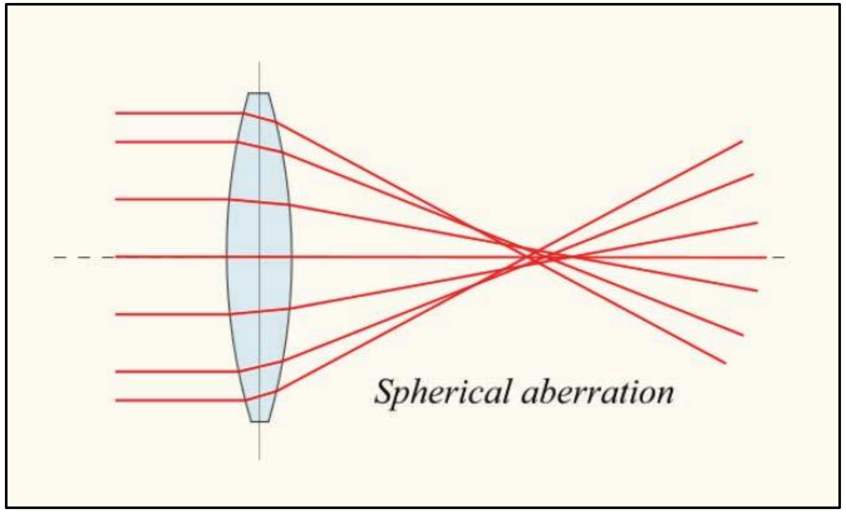
Using a doublet (two-element compound lens), we can reduce chromatic aberration.

Aberrations

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

- Example: chromatic aberration.
- Many other types (coma, spherical, astigmatism.





Why do we wear glasses?

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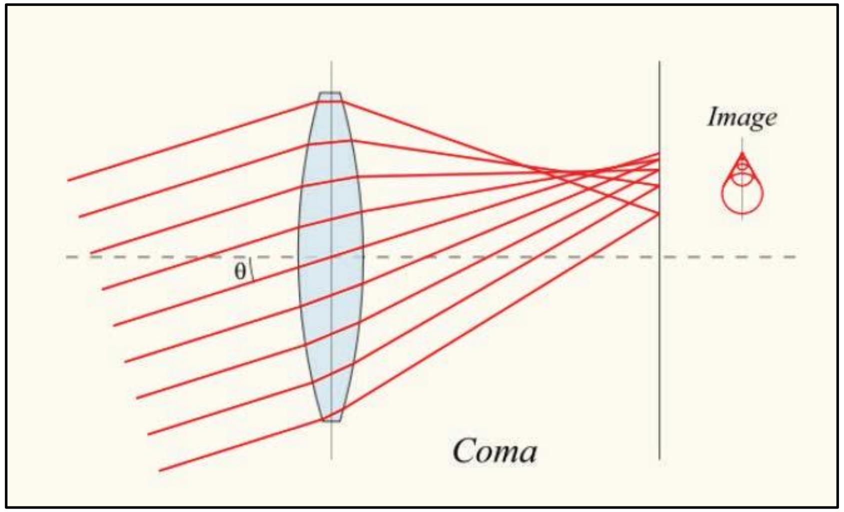
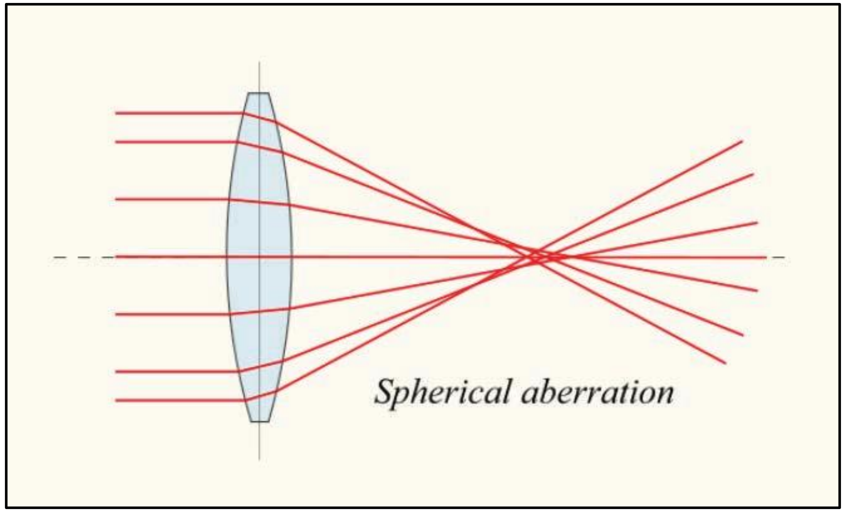
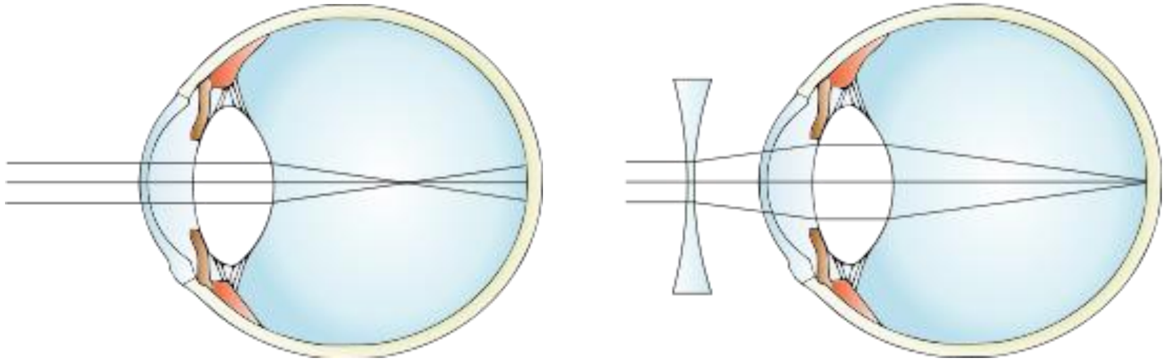




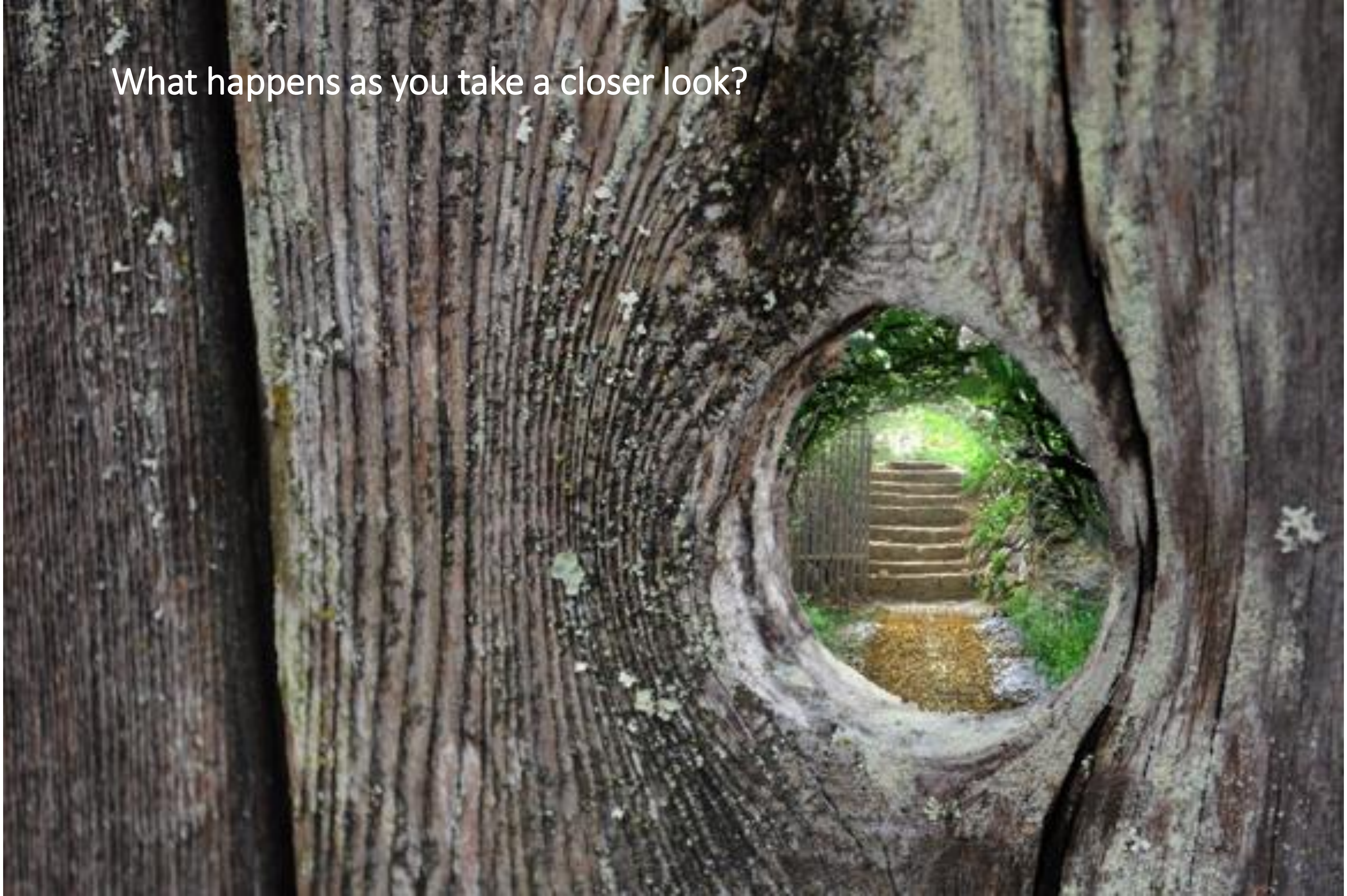
Why do we wear glasses?

- We turn our eye into a compound lens to correct aberrations!



Field of view

What happens as you take a closer look?



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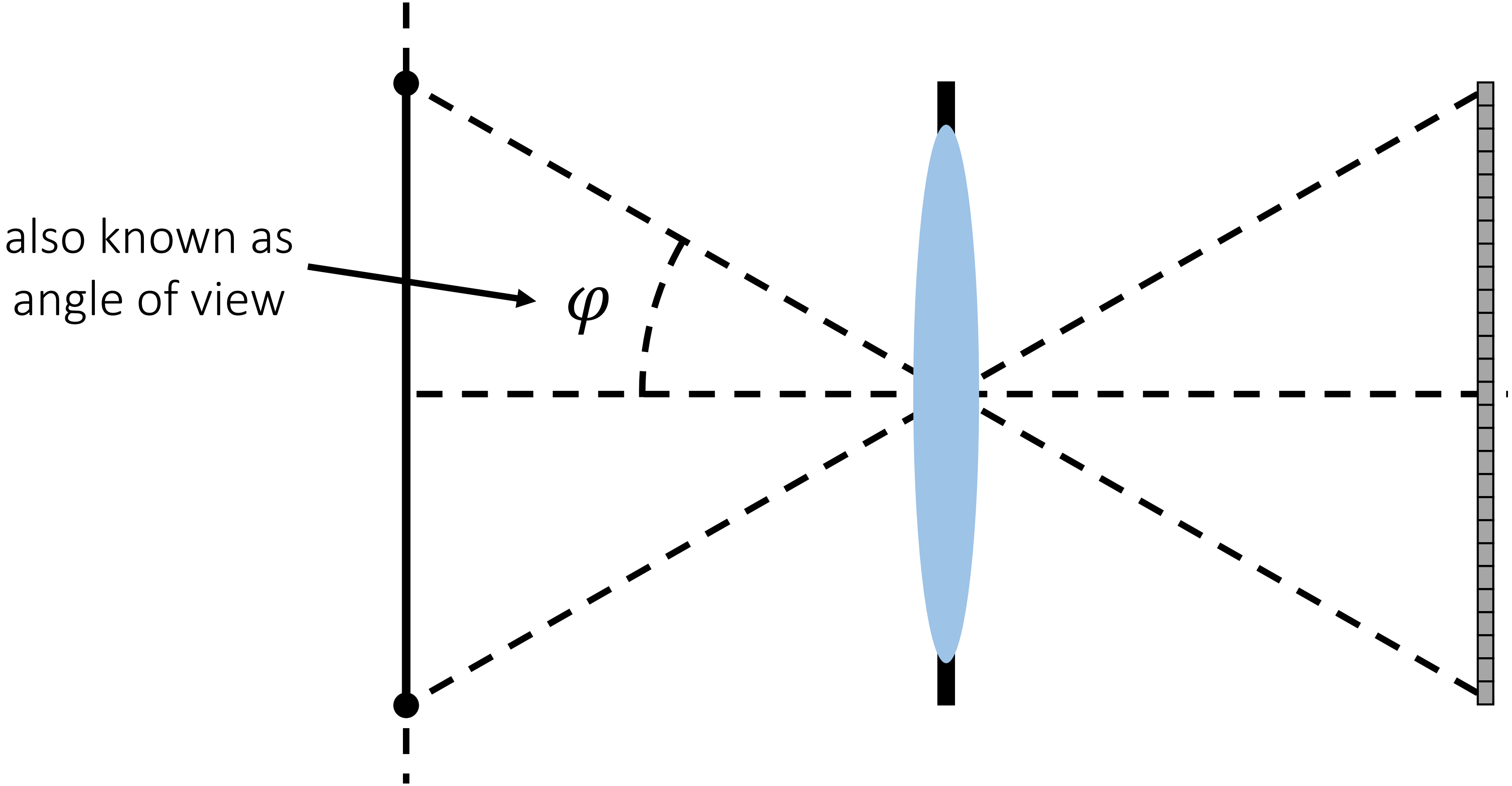

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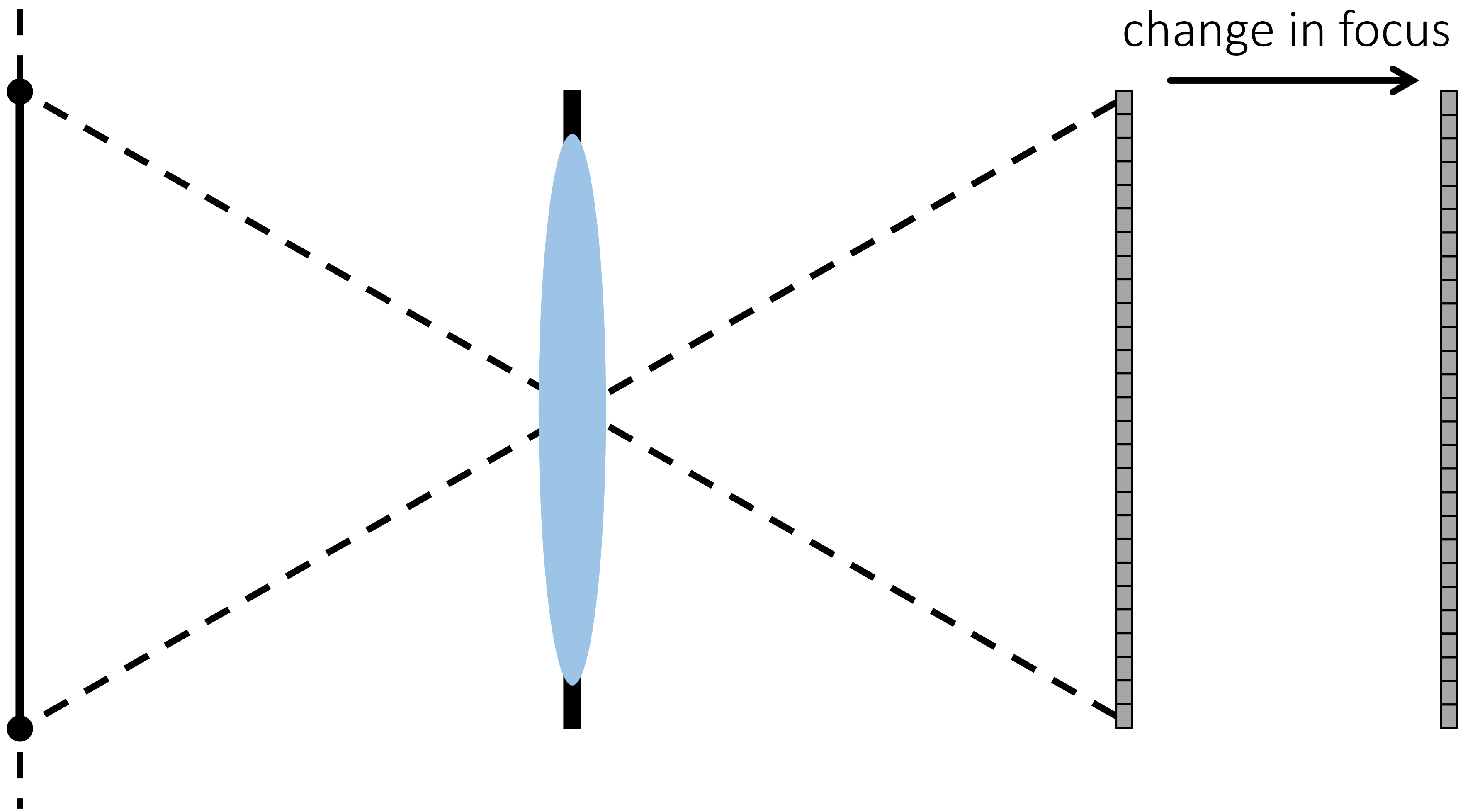
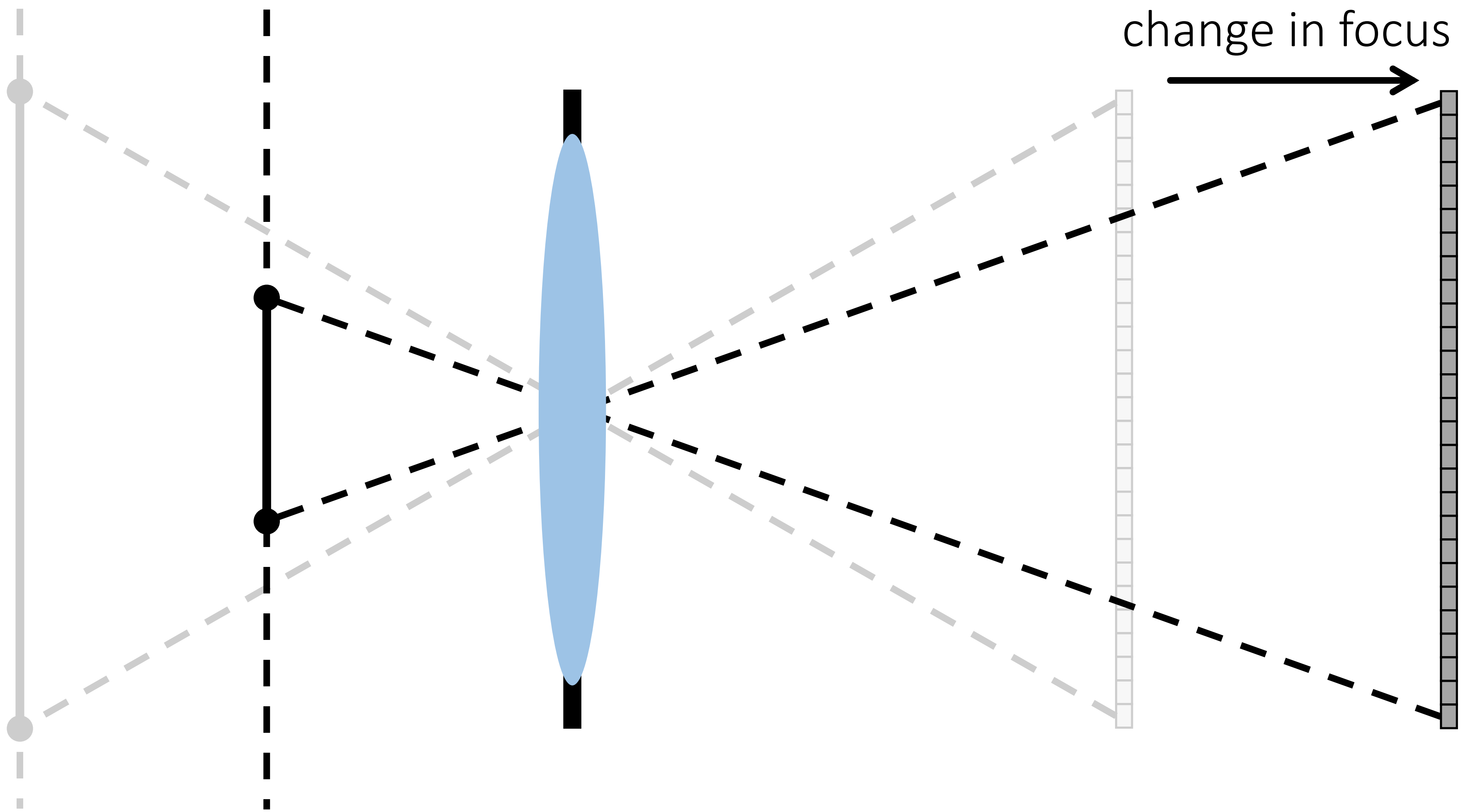


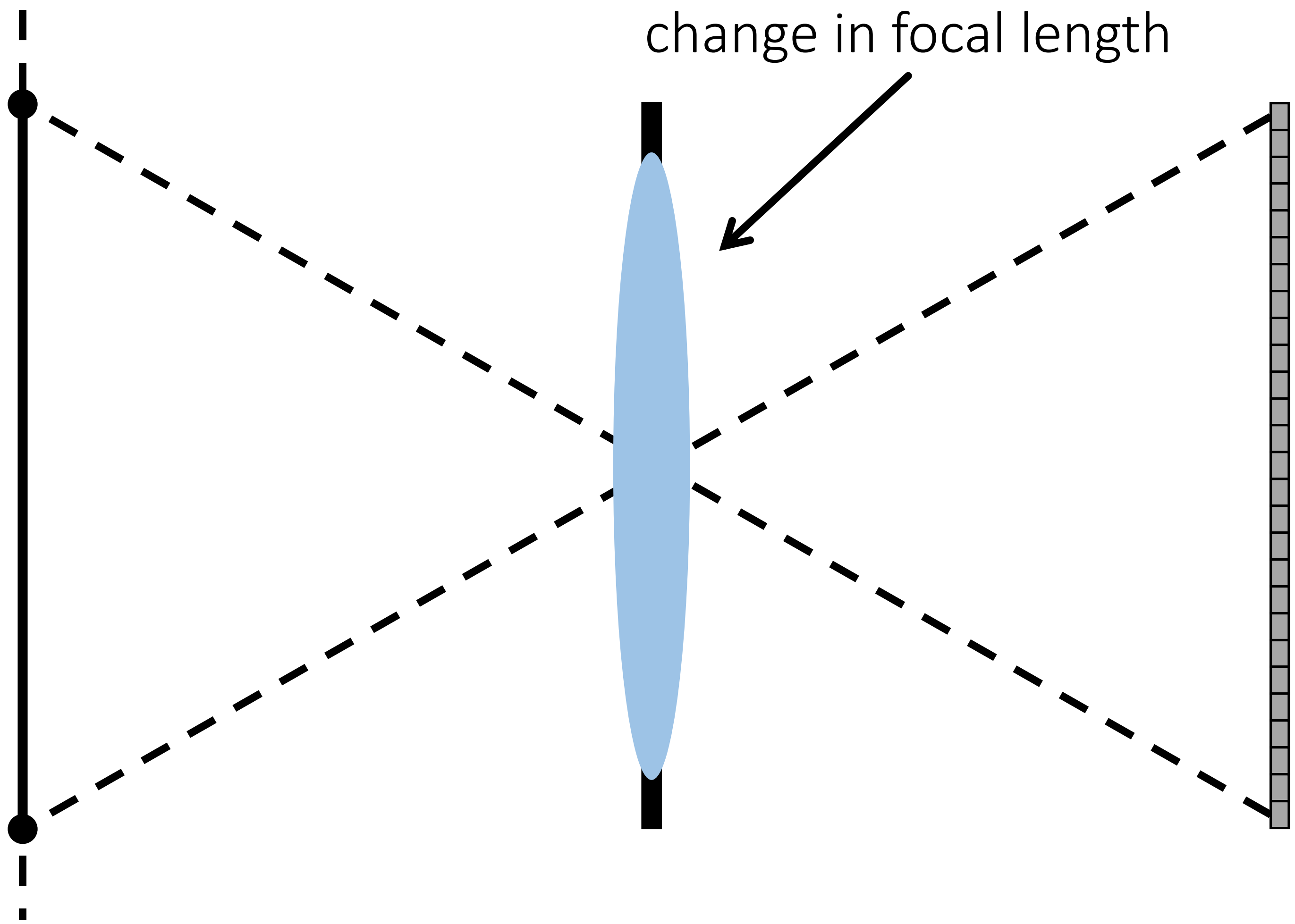
- What happens to field of view when we focus closer?

Field of view



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

Field of view

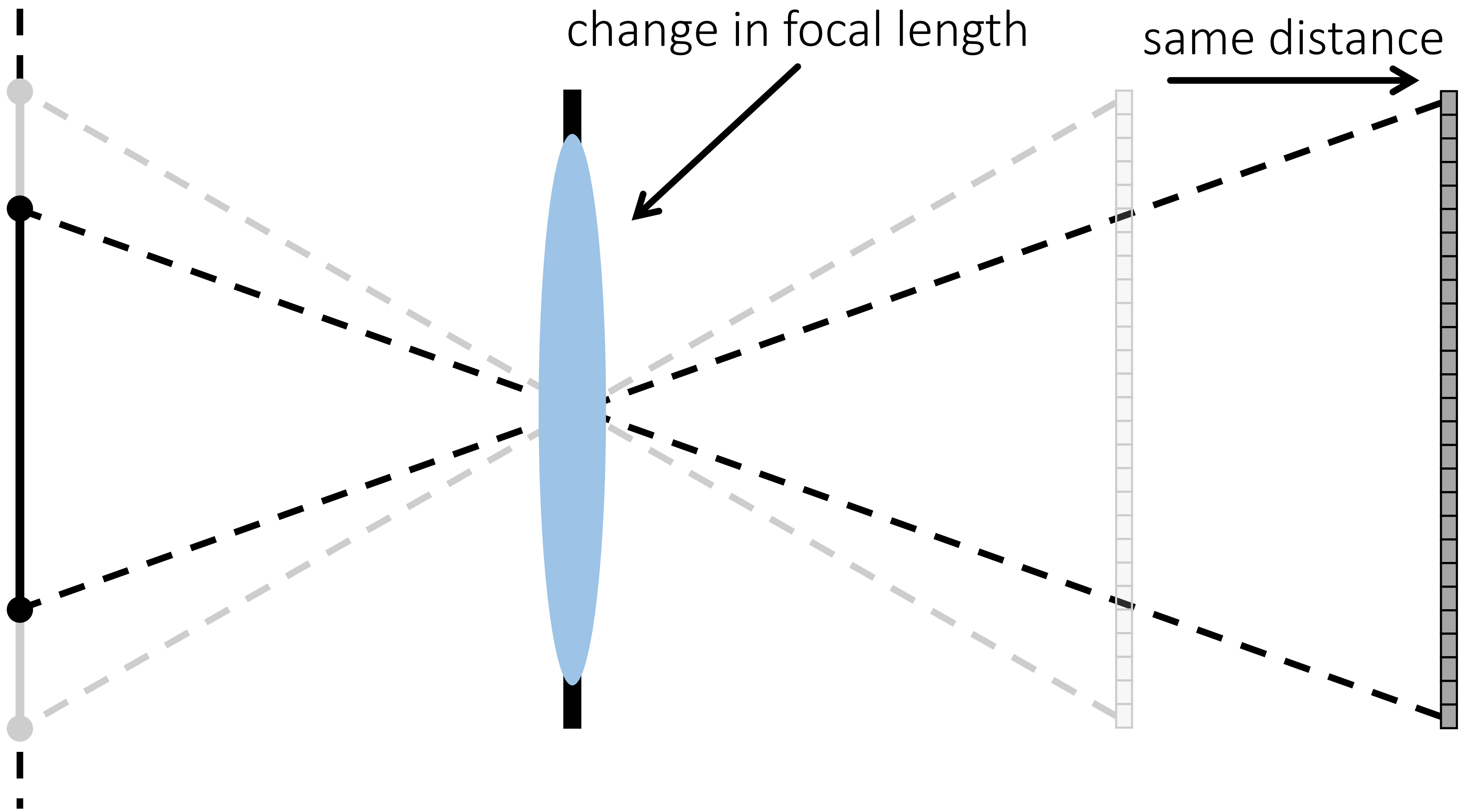


Note: “zooming” means changing focal length, which is different from refocusing

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

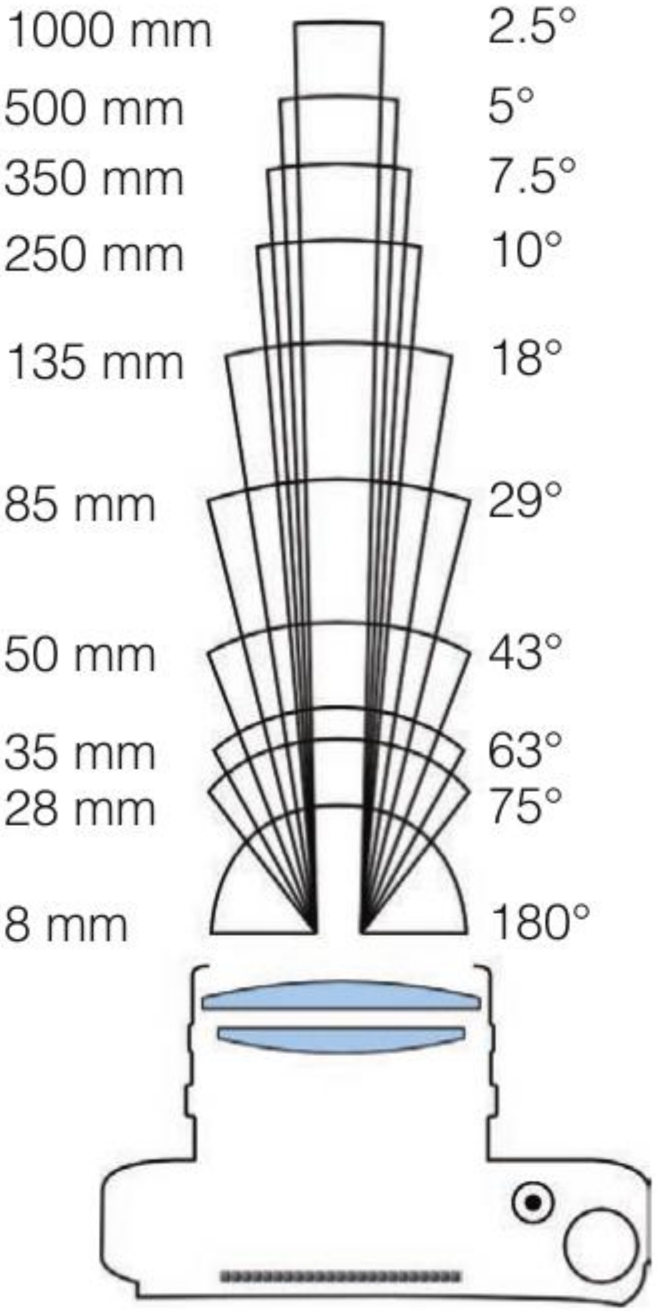
Field of view

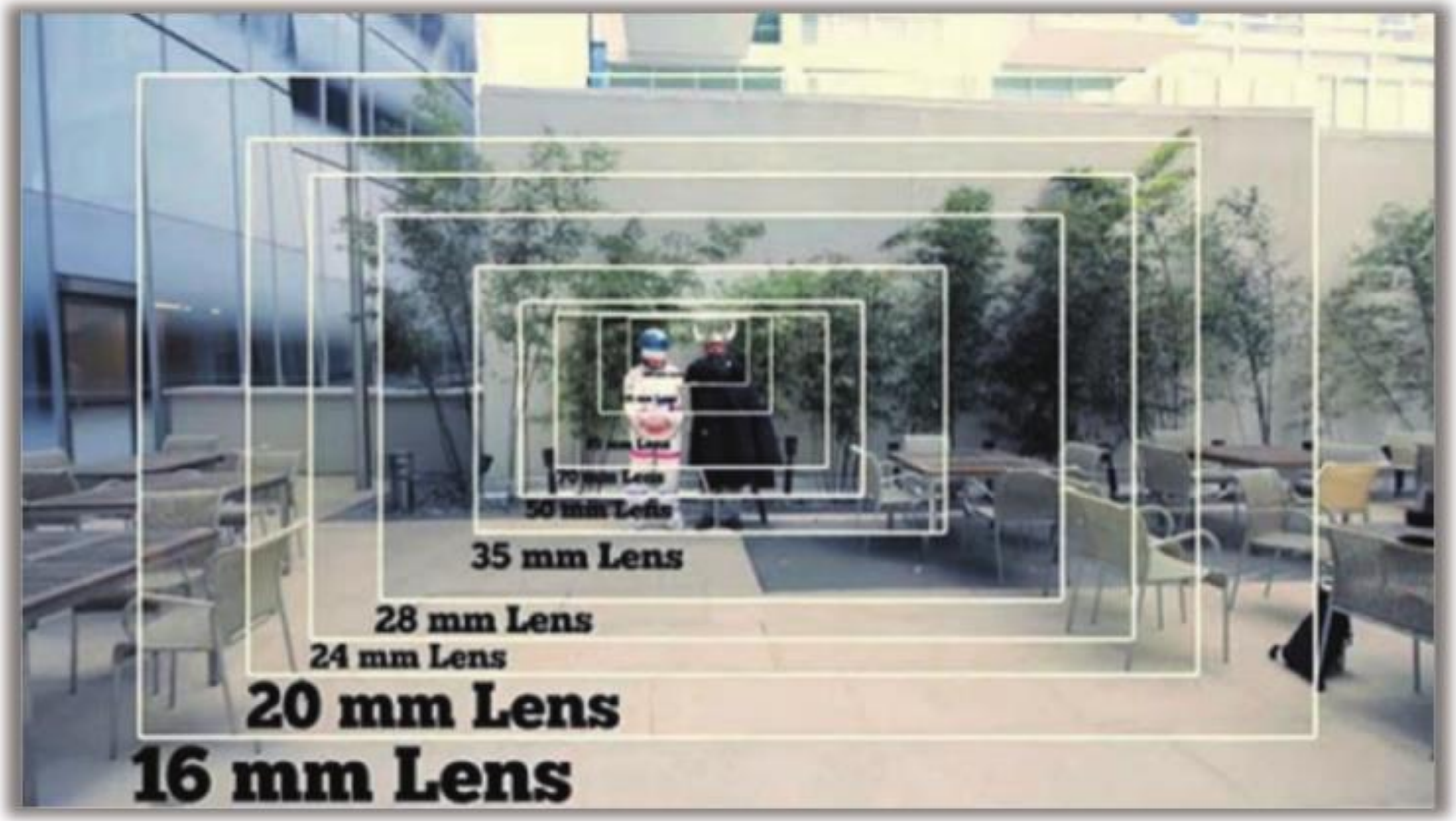
Note: “zooming” means changing focal length, which is different from refocusing



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

Field of view

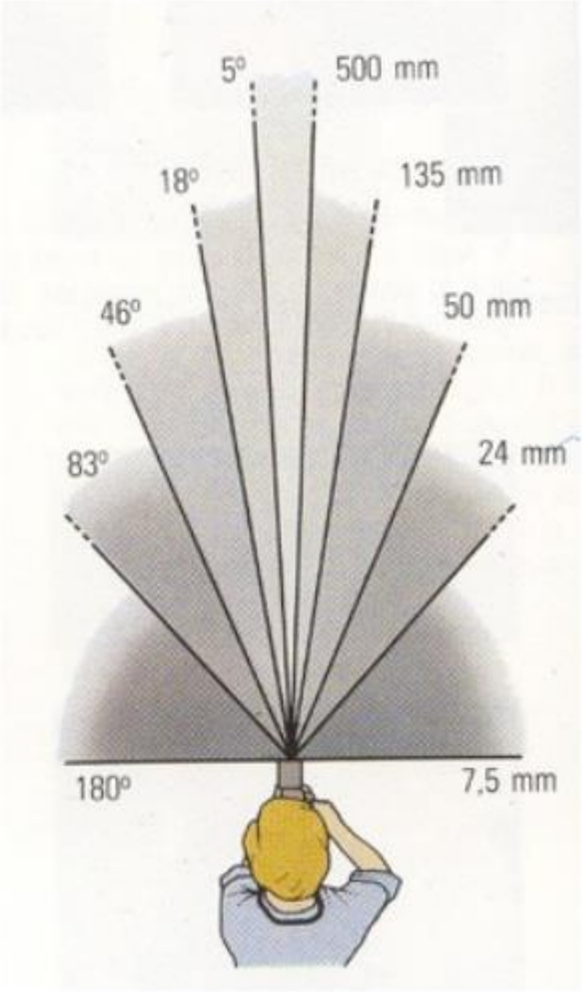




Andrew McWilliams

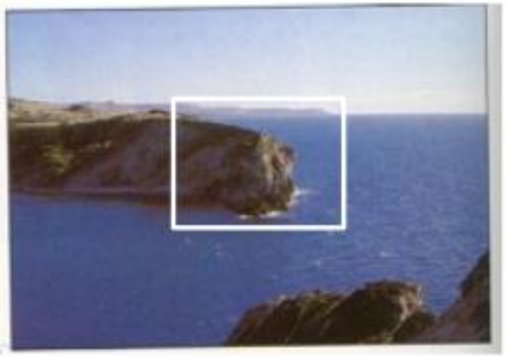
Field of view

Increasing the focal length is similar to cropping



f = ?

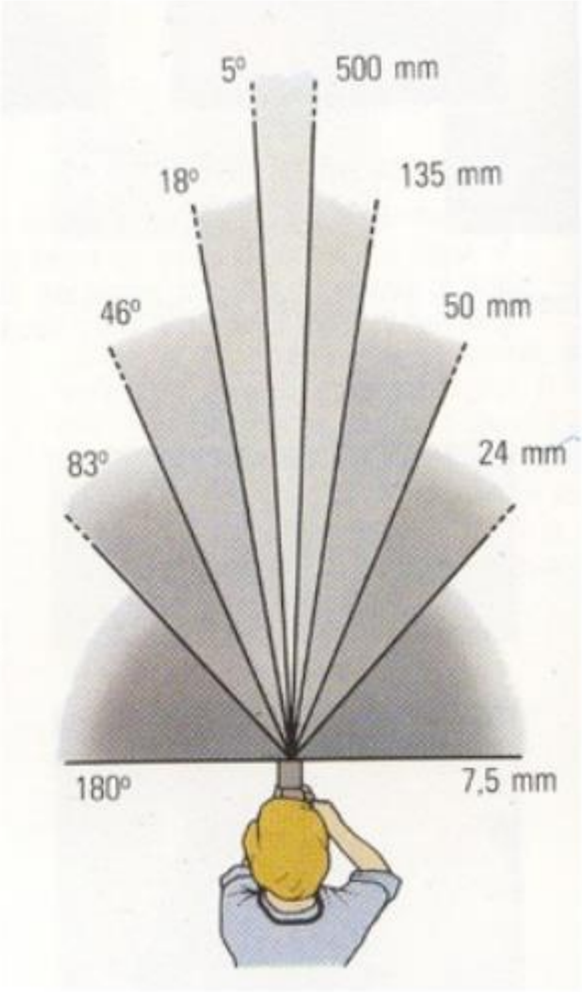
f = ?



f = ?

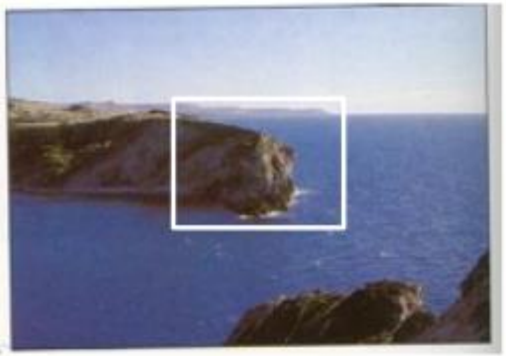
Field of view

Increasing the focal length is similar to cropping



f = 25 mm

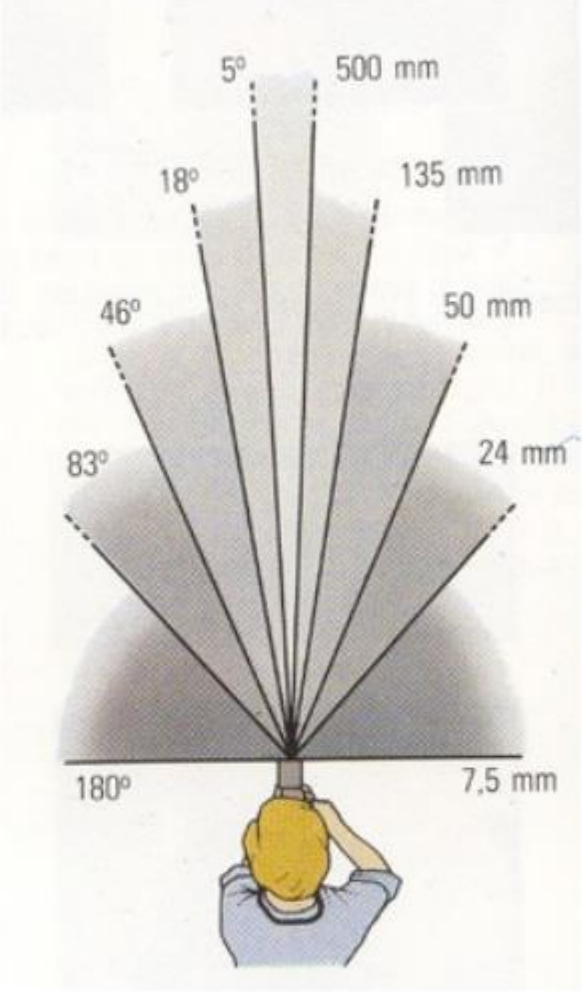
f = ?



f = ?

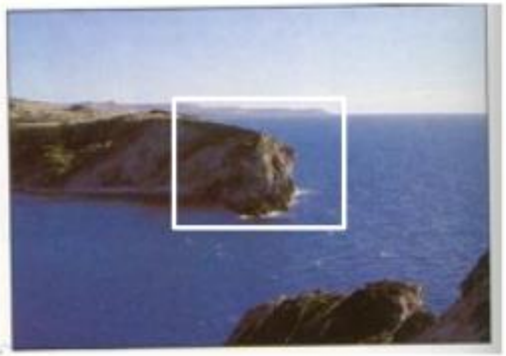
Field of view

Increasing the focal length is similar to cropping



f = 25 mm

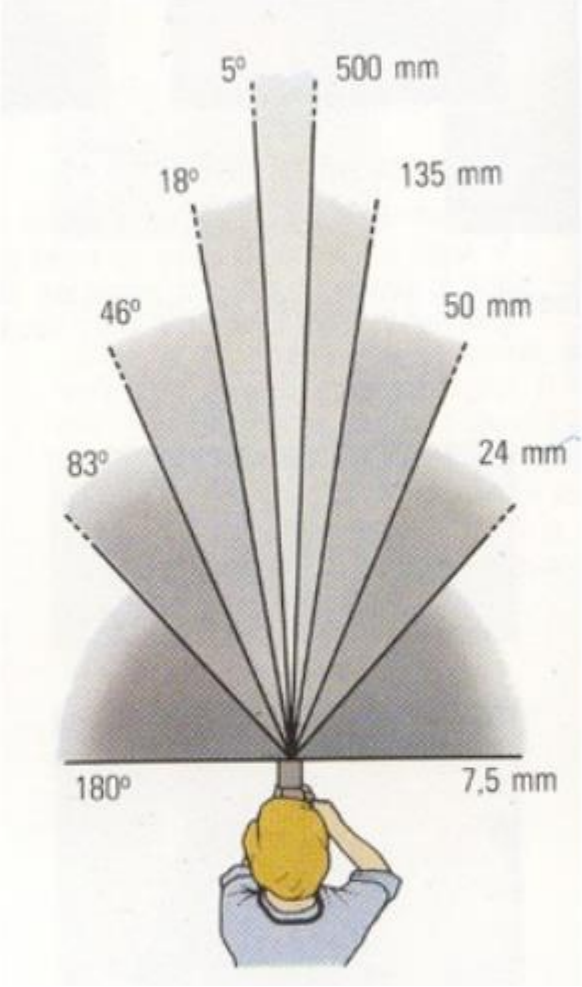
f = 50 mm



f = ?

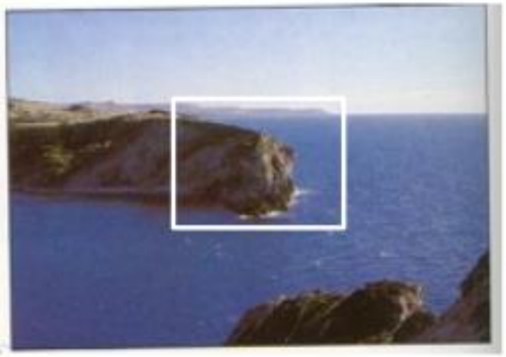
Field of view

Increasing the focal length is similar to cropping



f = 25 mm

f = 50 mm



f = 135 mm

Is this effect identical to cropping?

Perspective distortion

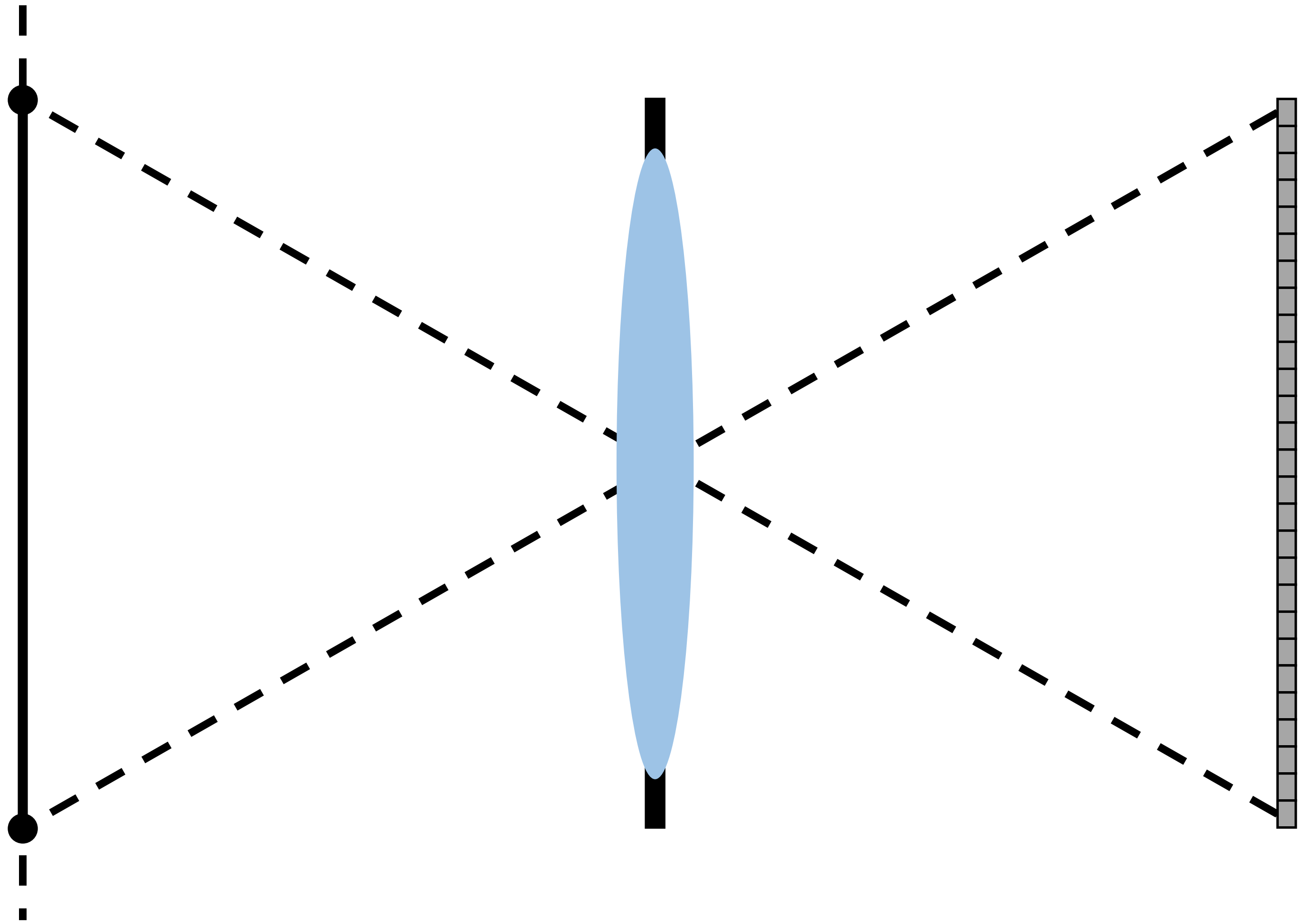
Different focal lengths introduce different perspective distortion at same magnification.

short focal length

mid focal length

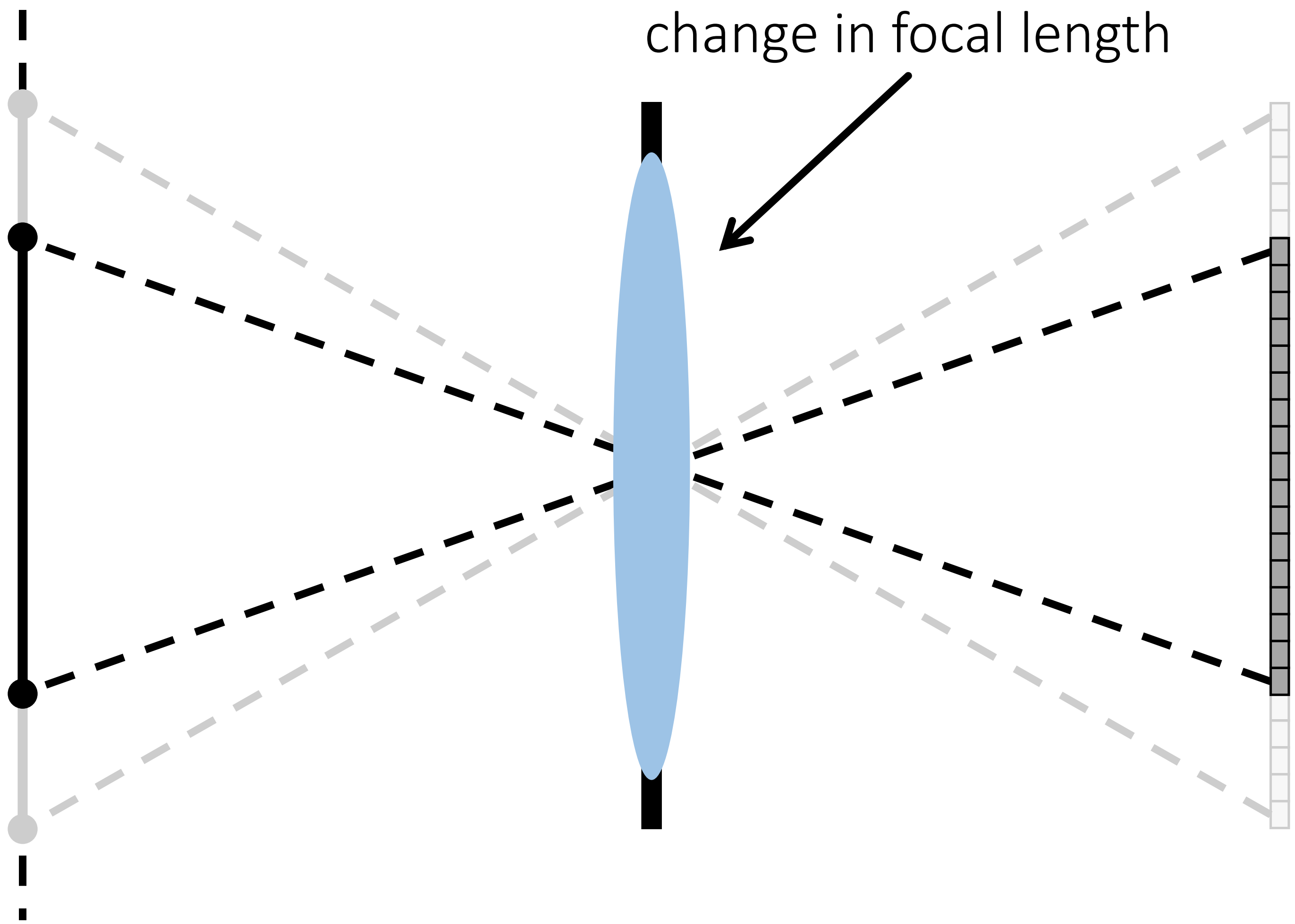
long focal length

Field of view also depends on sensor size



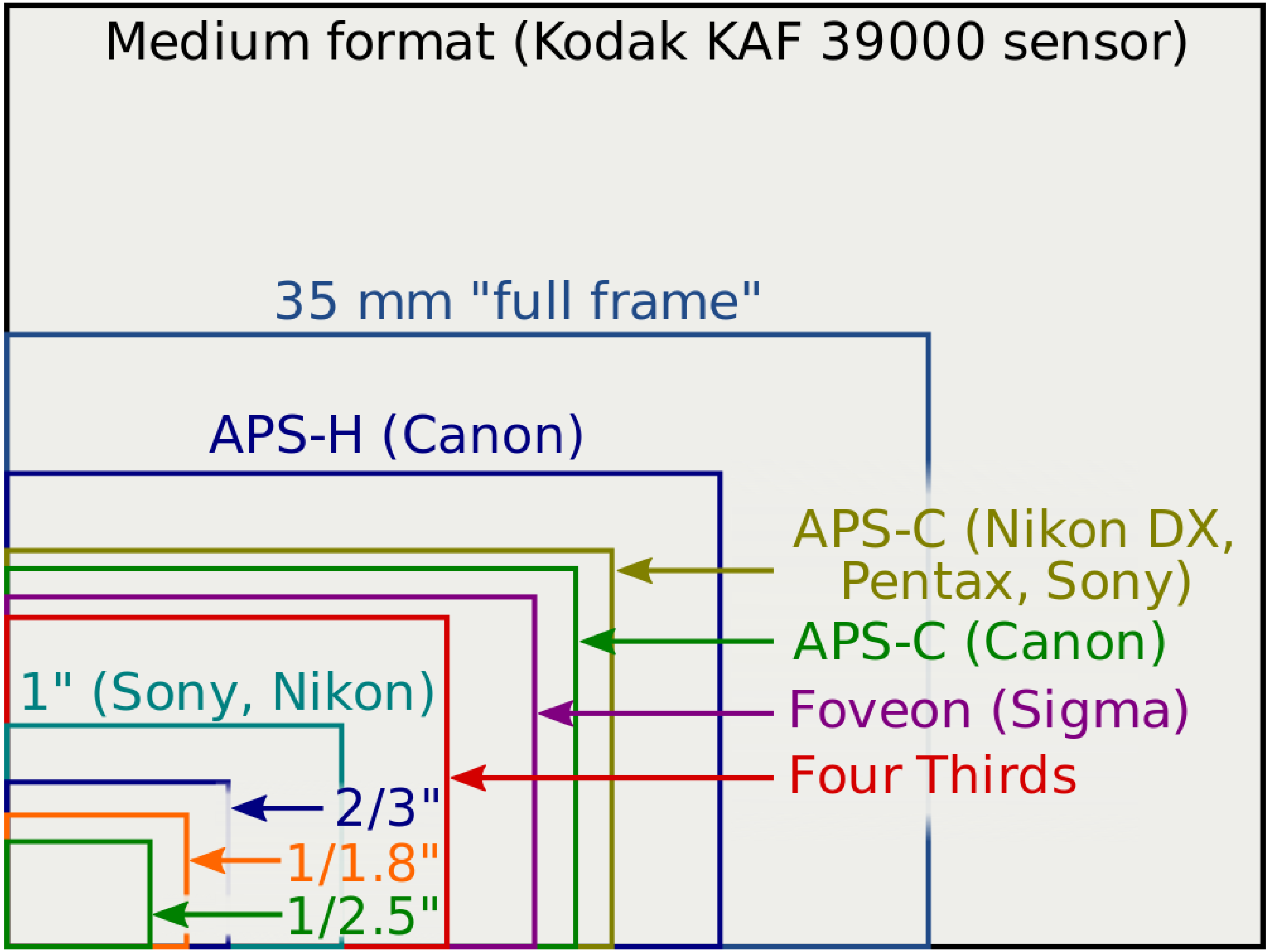
- What happens to field of view when we reduce sensor size?

Field of view also depends on sensor size



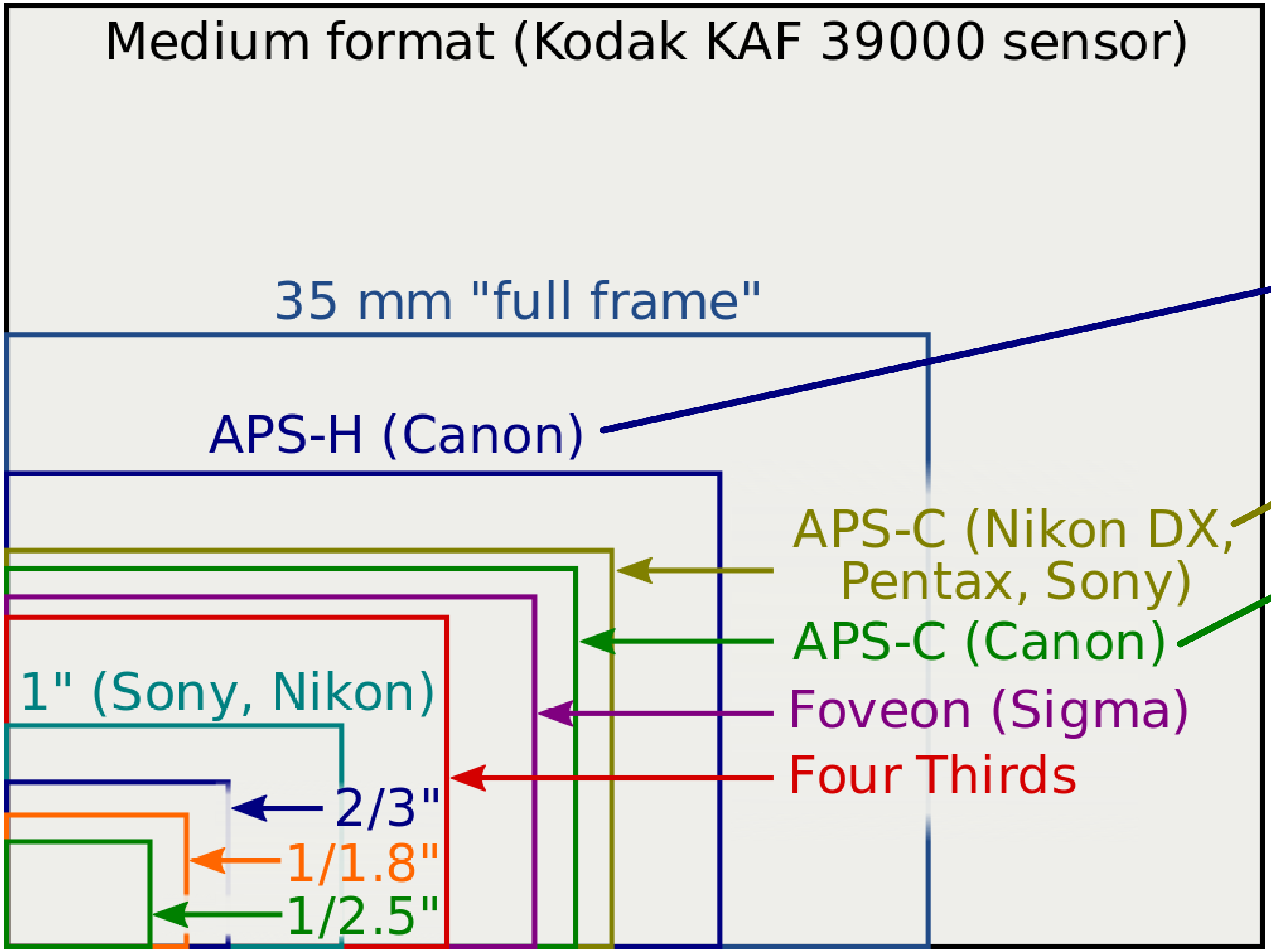
- What happens to field of view when we reduce sensor size? → It decreases.

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.

Lens designations

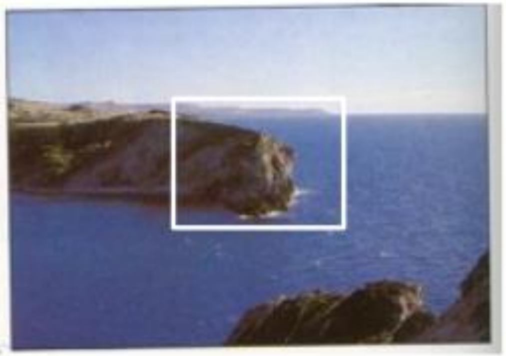
Designation based on field of view

What focal lengths go to what category depends on sensor size.

- Here we assume full frame sensor (same as 35 mm film).
- Even then, there are no well-defined ranges for each category.

wide-angle f = 25 mm

mid-range f = 50 mm



telephoto f = 135 mm

Wide-angle lenses

Lenses with focal length 35 mm or smaller.

They tend to have large and curvy frontal elements.

Wide-angle lenses

Ultra-wide lenses can get impractically wide…

Fish-eye lens: can produce (near) hemispherical field of view.

Telephoto lenses

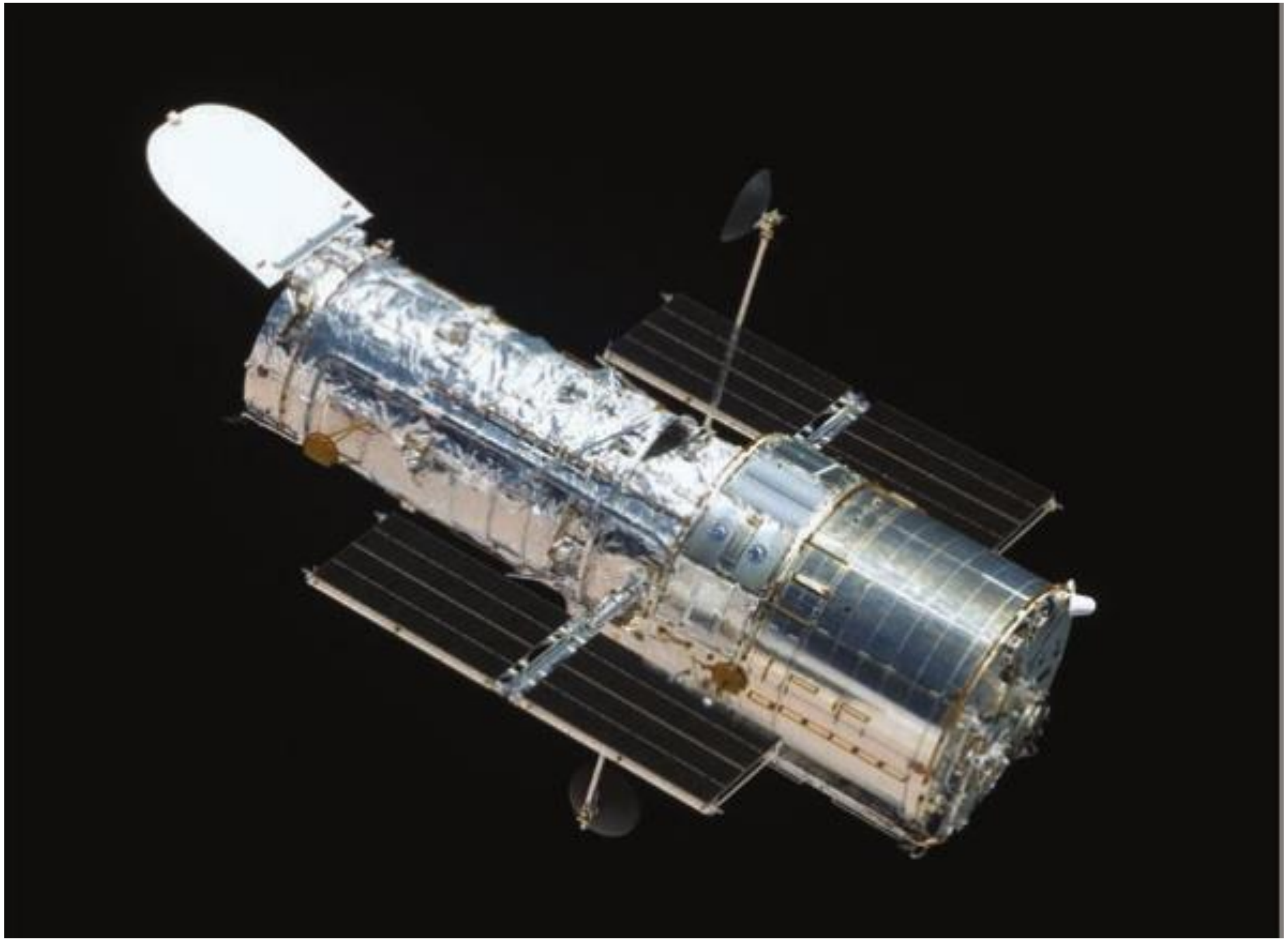
Lenses with focal length 85 mm or larger.

Technically speaking, “telephoto” refers to a specific lens design, not a focal length range. But that design is mostly useful for long focal lengths, so it has also come to mean any lens with such a focal length.

Telephotos can get very big…

Telephoto lenses

- What is this?
- What is its focal length?



Telephotos can get very big…

Prime vs zoom lenses

focus ring:
changes focus
distance

single focal
length

Prime lens: fixed focal length

available focal
length range

focus ring:
changes focus
distance

zoom ring:
changes focal
length

Zoom lens: variable focal length

Why use prime lenses and not always use the more versatile zoom lenses?

Prime vs zoom lenses

focus ring:
changes focus
distance

single focal
length

available focal
length range

focus ring:
changes focus
distance

zoom ring:
changes focal
length

Prime lens: fixed focal length

Zoom lens: variable focal length

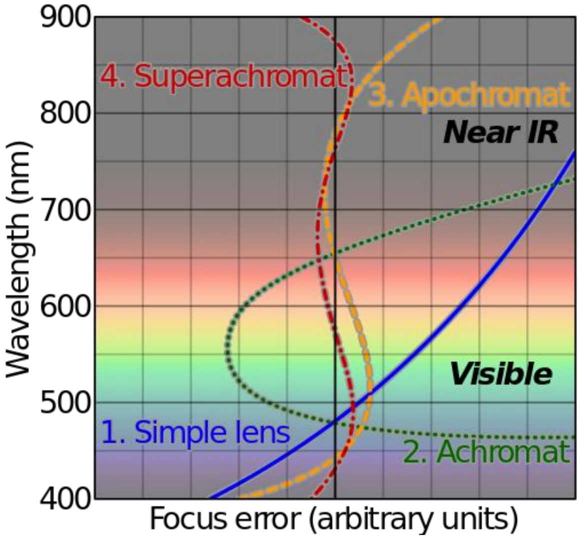
Why use prime lenses and not always use the more versatile zoom lenses?

- Zoom lenses have larger aberrations due to the need to cover multiple focal lengths.

Other kinds of lens designations

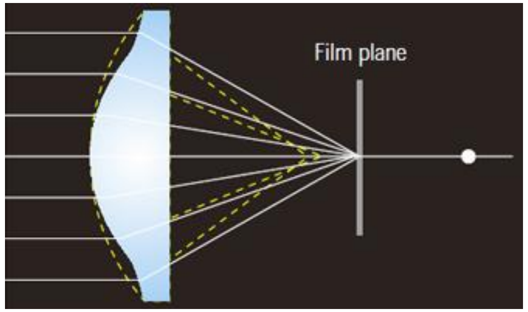
Macro lens: can achieve very large magnifications (typically at least 1:1).

- Macro photography: extremely close-up photography.



Achromatic or apochromatic lens: corrected for chromatic aberration.

- Achromatic: two wavelengths have same focus.
- Apochromatic (better): three wavelengths have same focus.

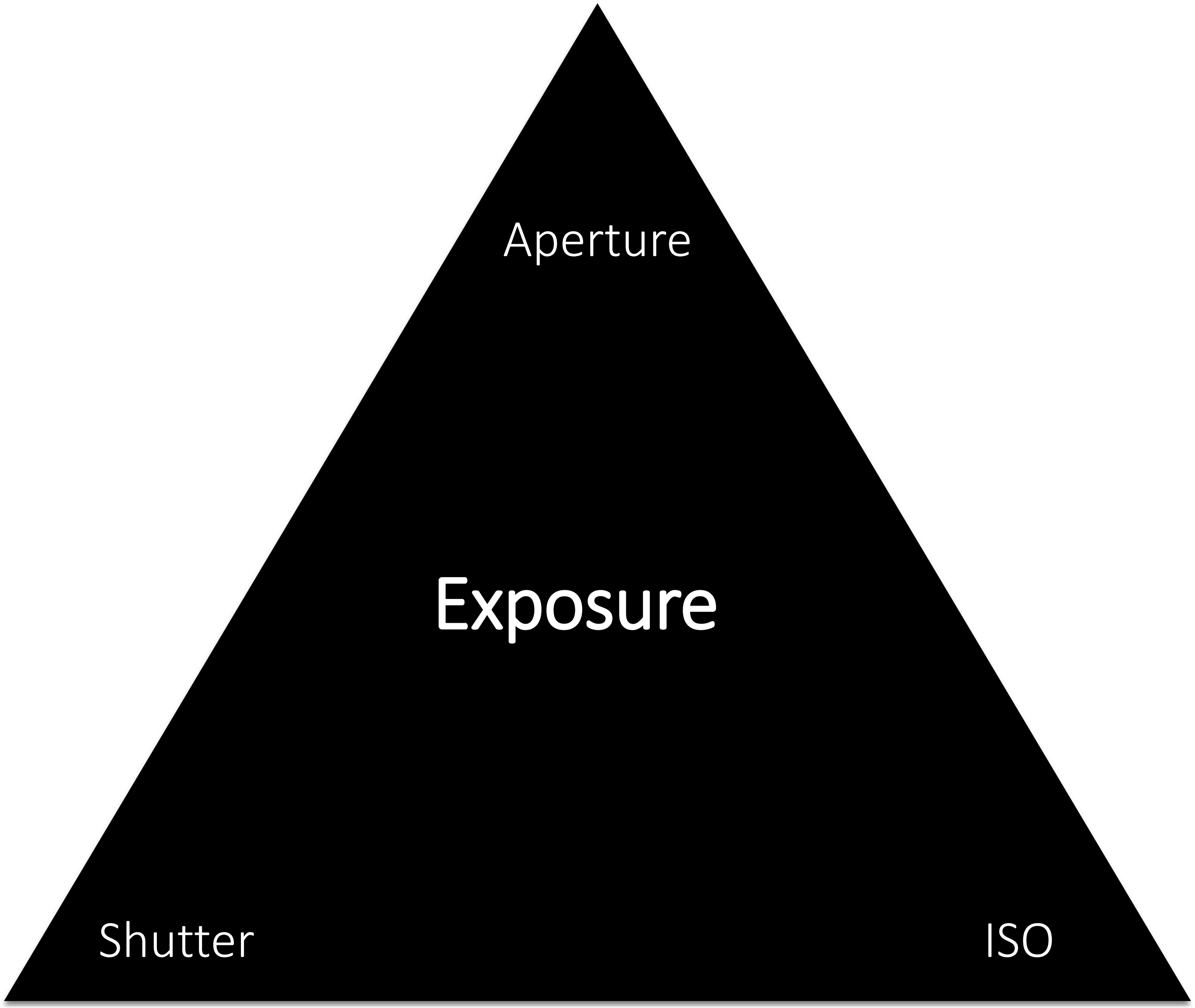


Aspherical lens: manufactured to have special (non-spherical) shape that reduces aberrations.

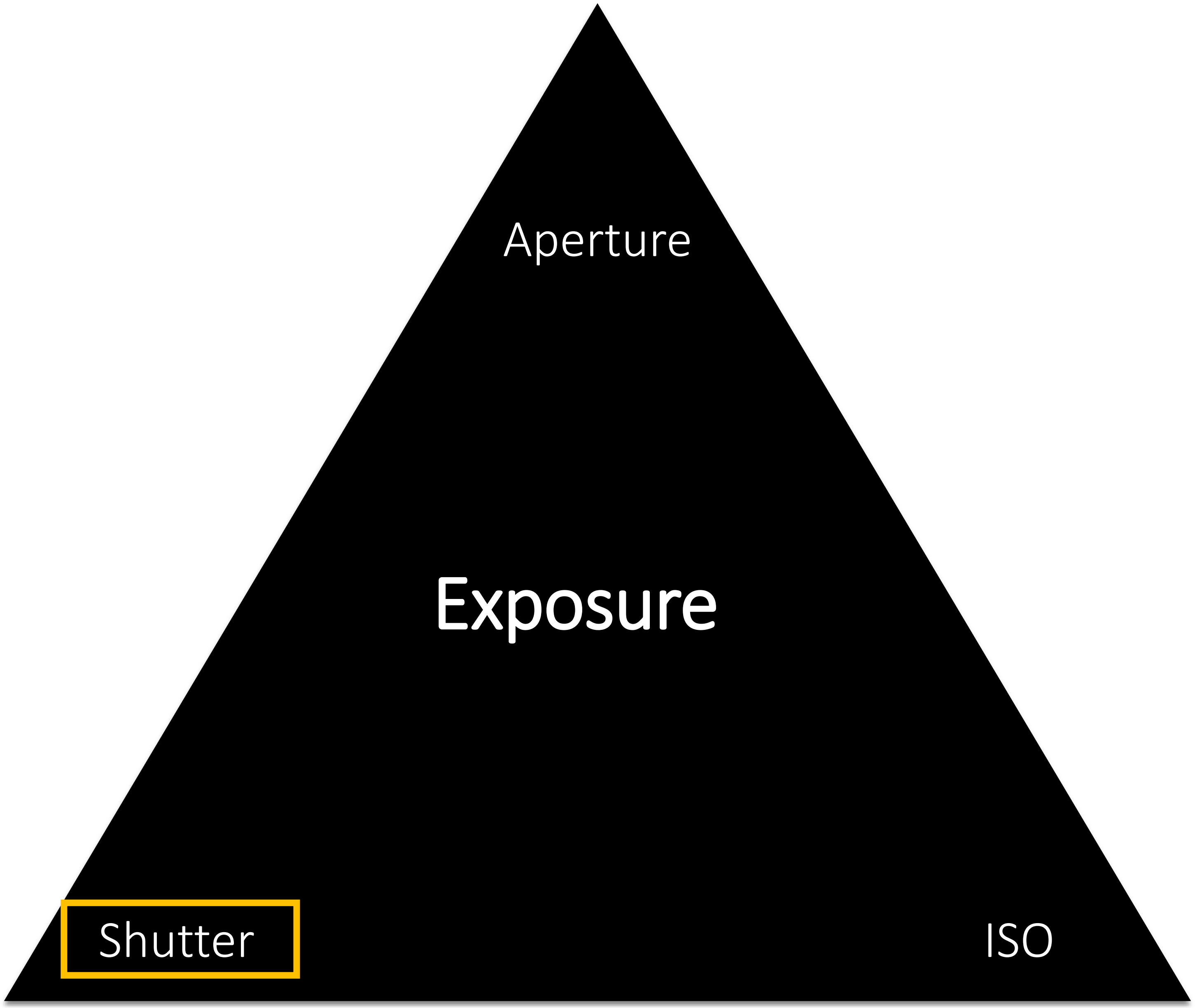
- Expensive, often only 1-2 elements in a compound lens are aspherical.

Exposure control

Exposure controls brightness of image

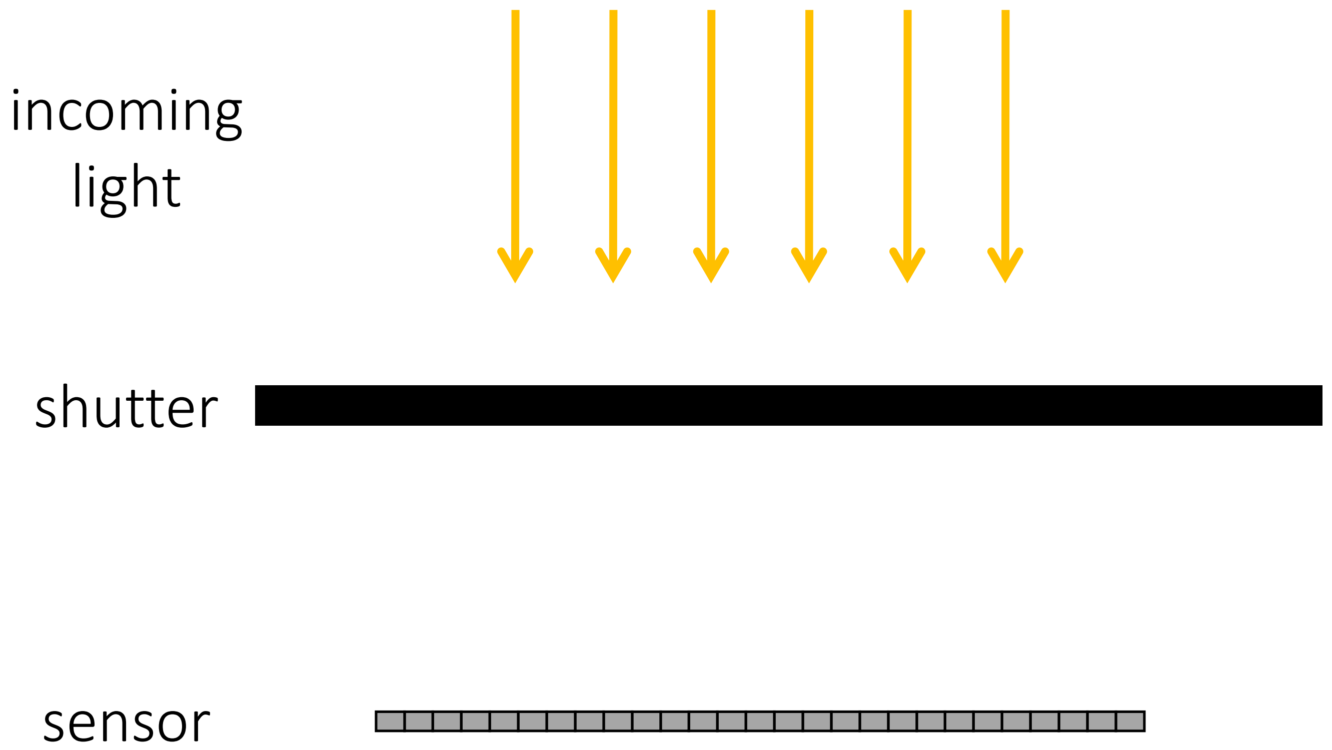


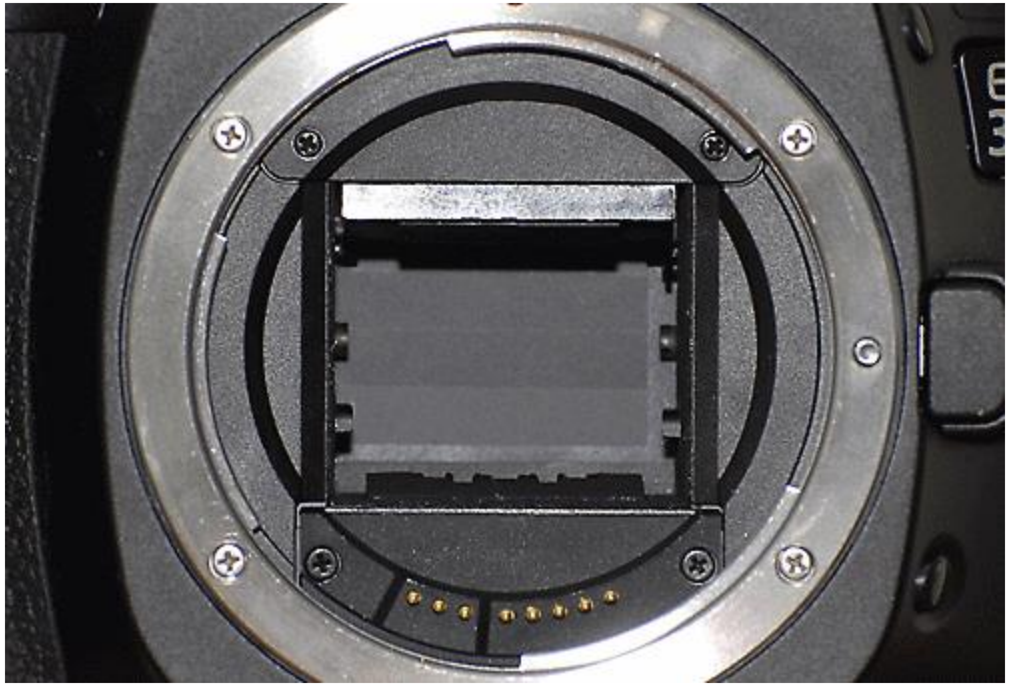
Exposure controls brightness of image



Shutter speed

Controls the **length of time** that shutter remains open.

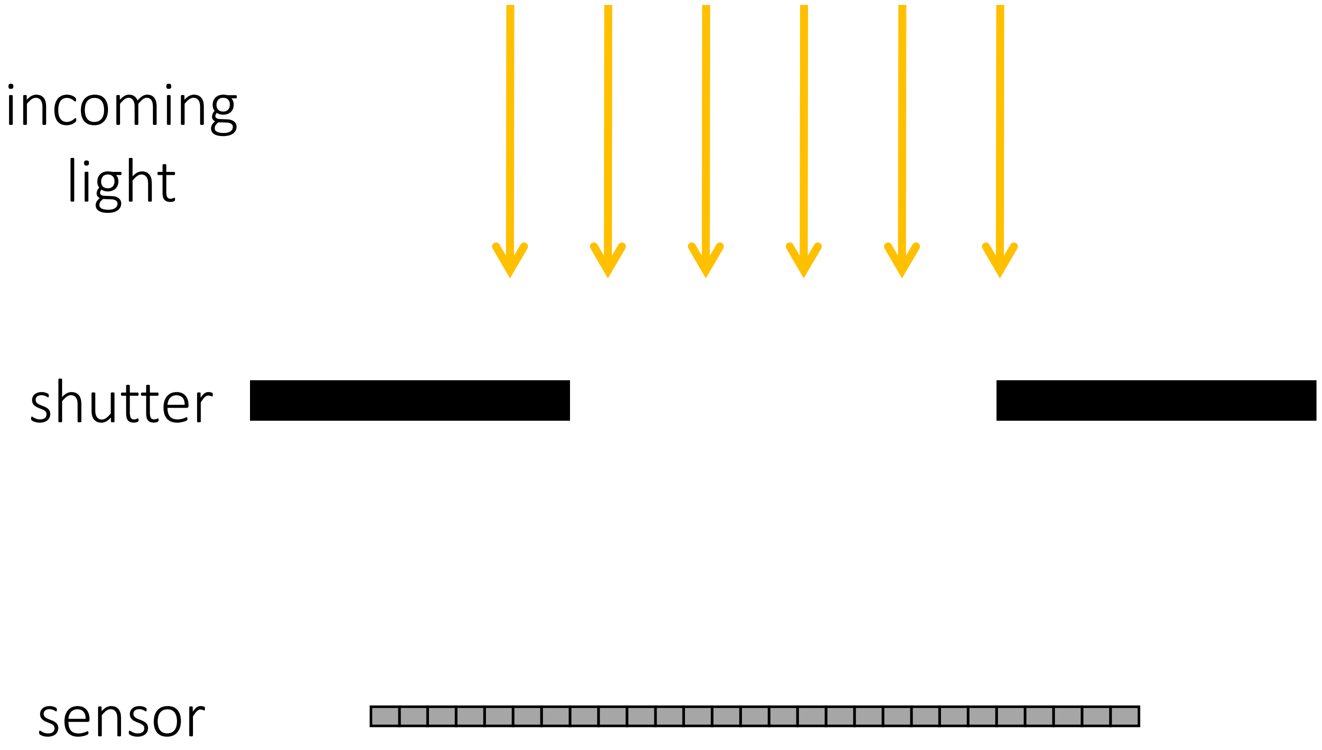


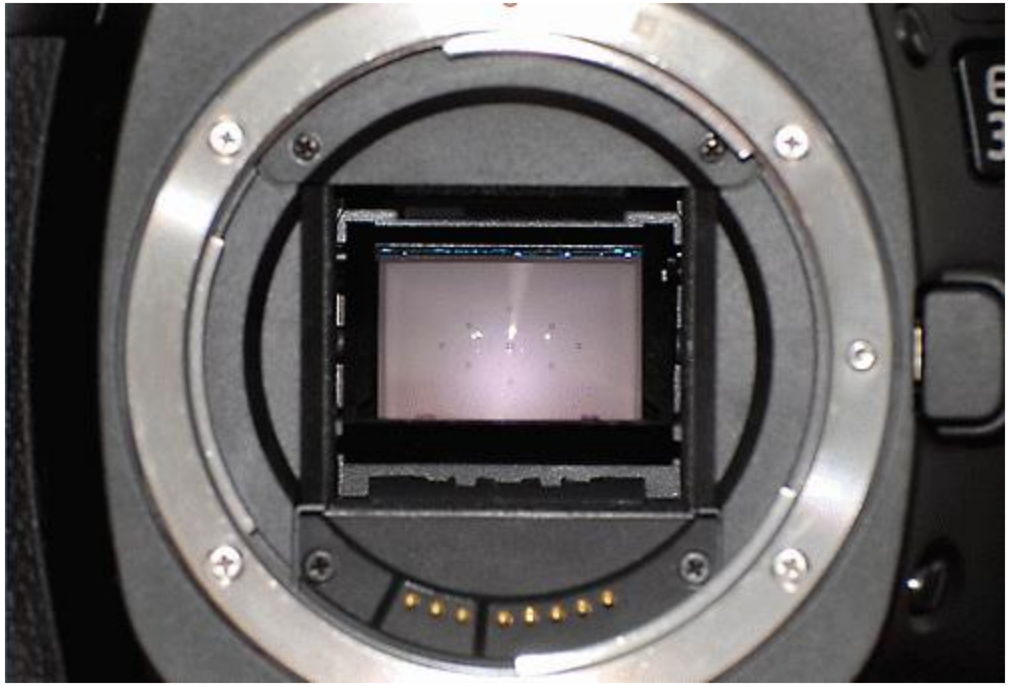


closed shutter

Shutter speed

Controls the **length of time** that shutter remains open.



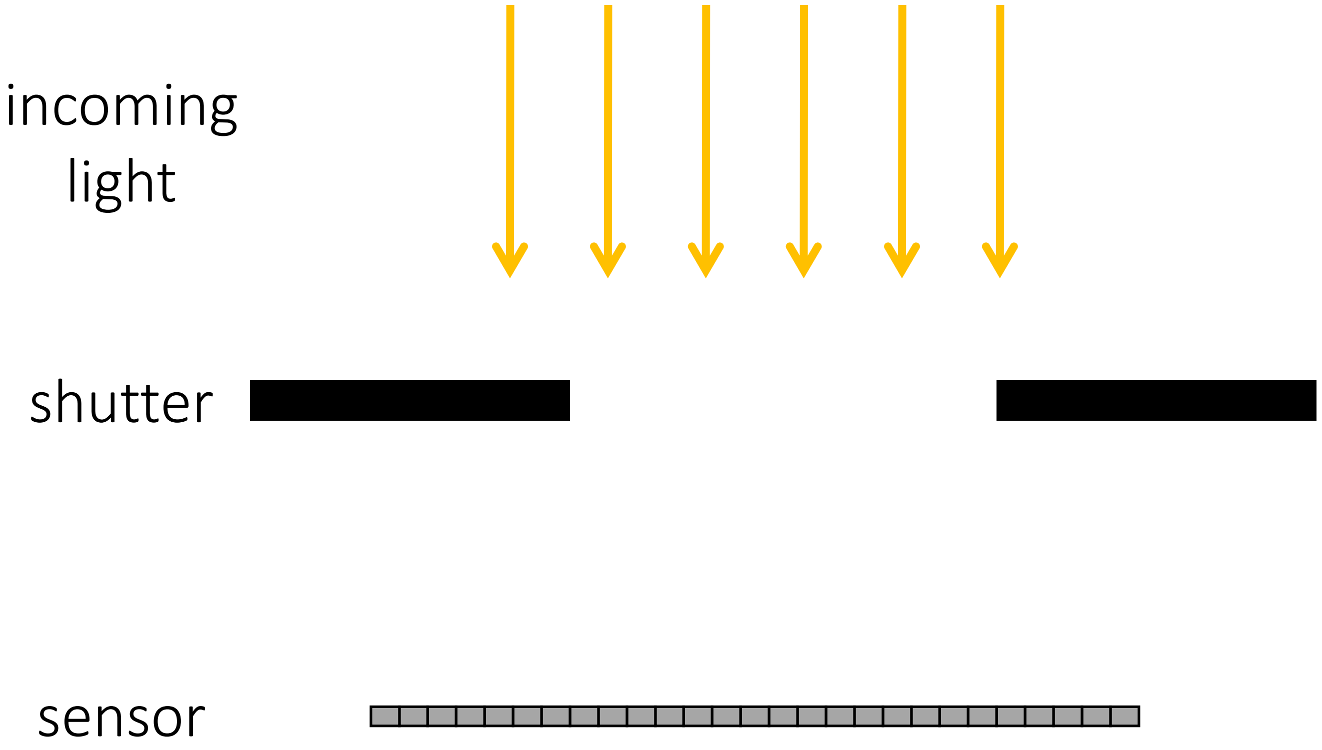


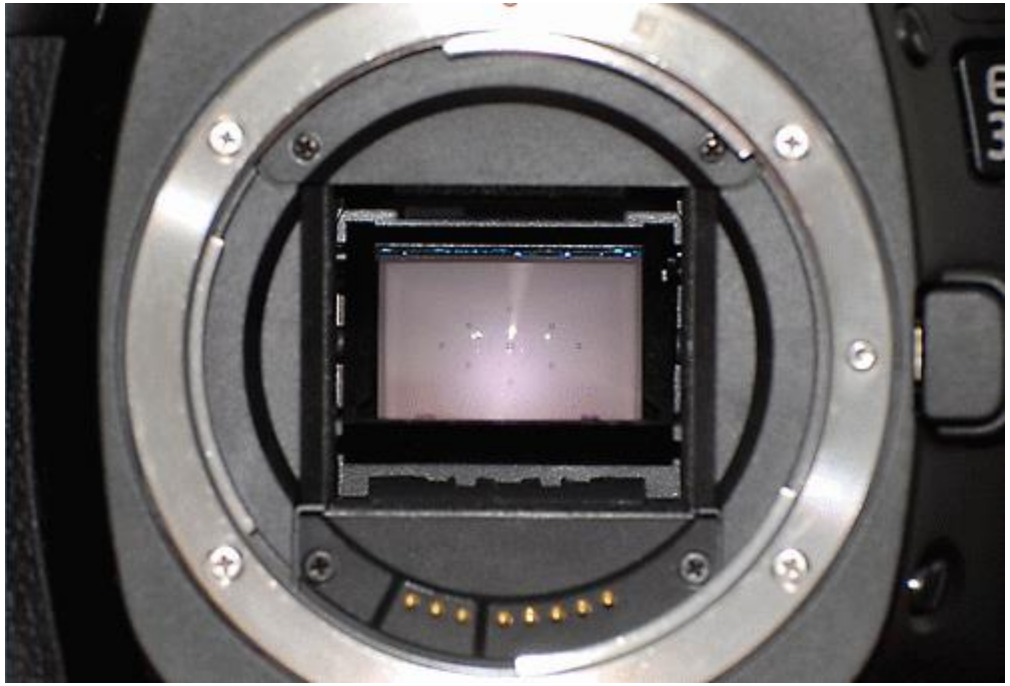
open shutter

Nikon D3s

Shutter speed

Controls the **period of time** that shutter remains open.



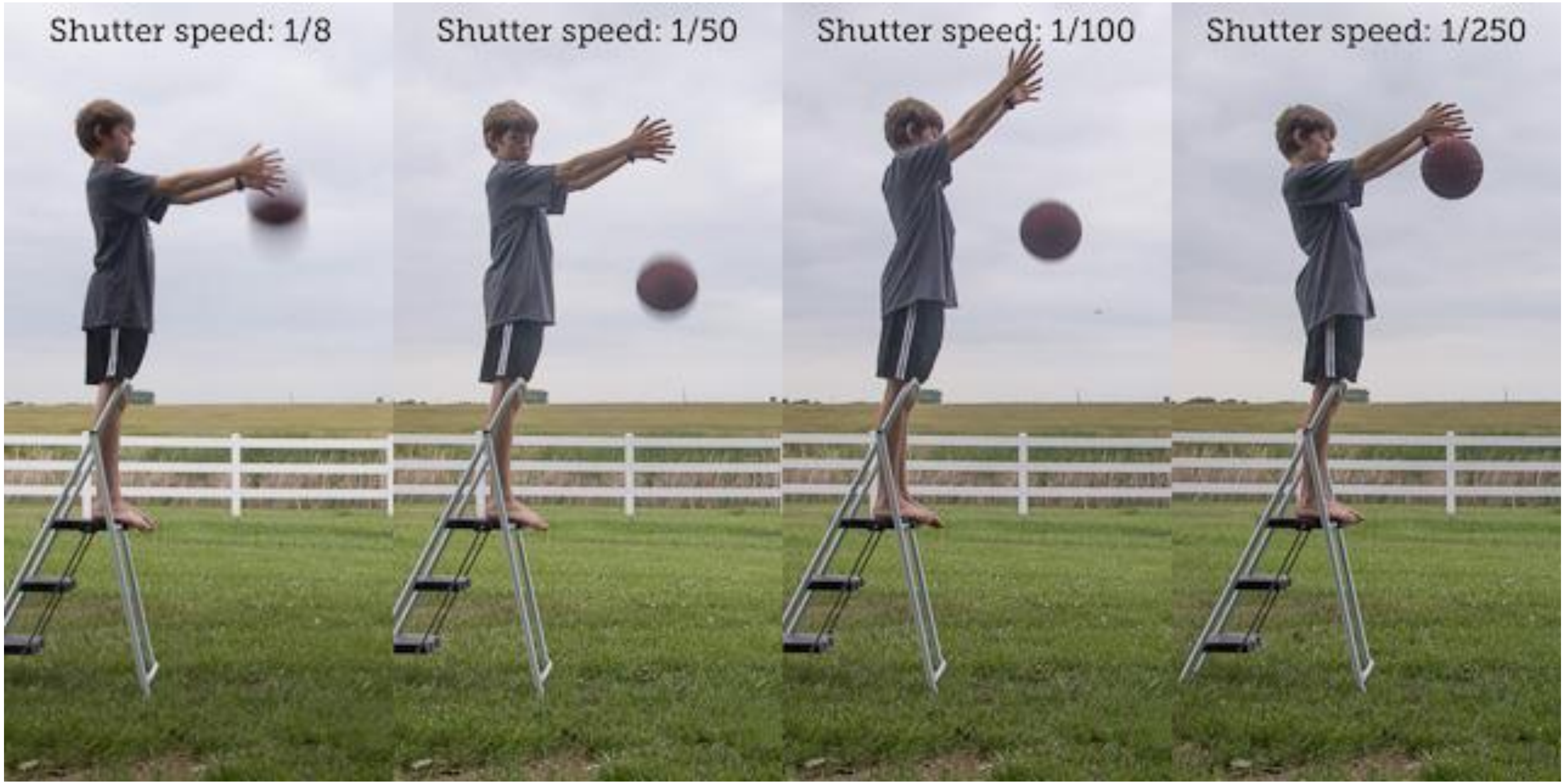


open shutter

What happens to the image as we increase shutter speed?

Side-effects of shutter speed

Moving scene elements appear blurry.

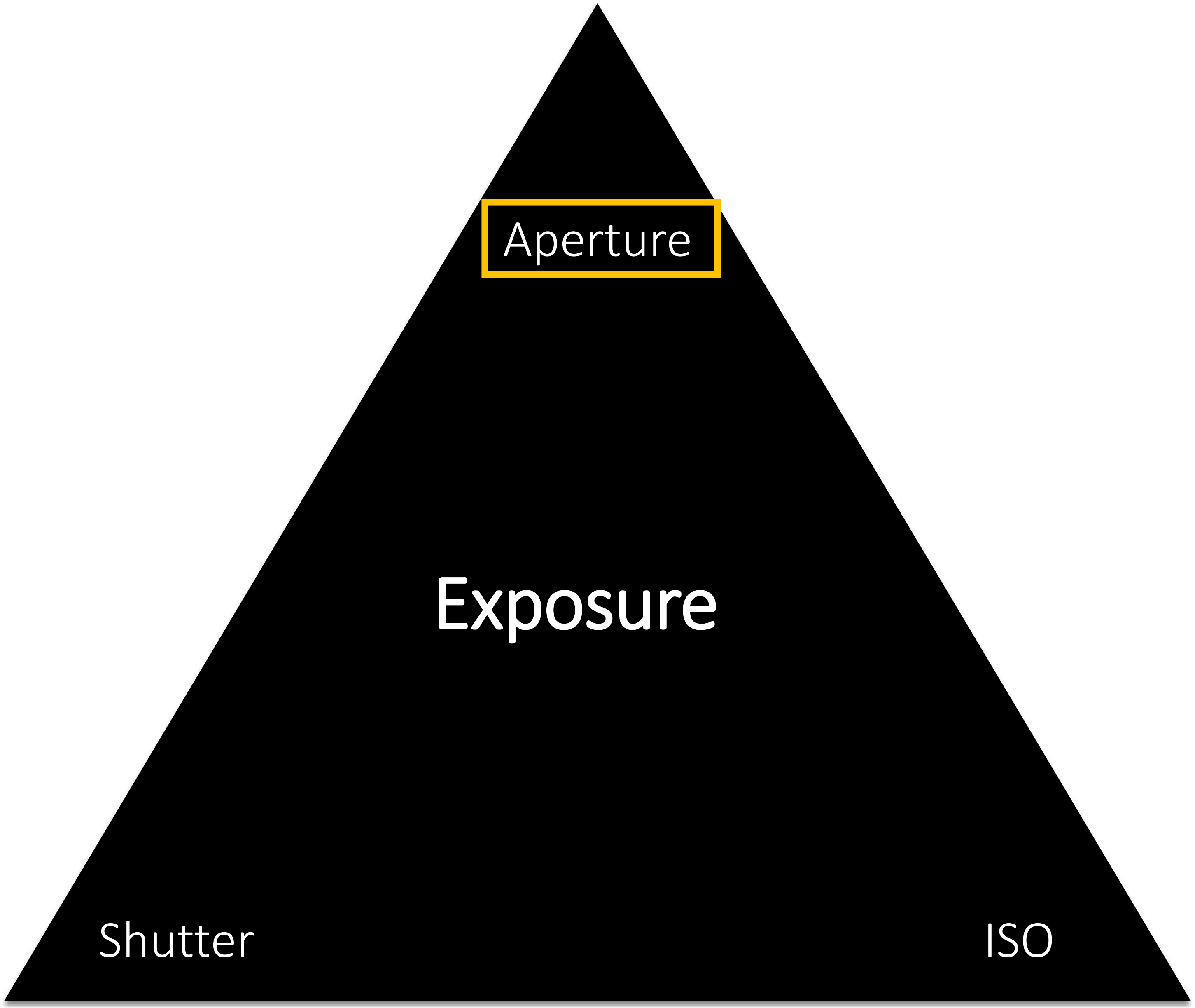


How can we “simulate” decreasing the shutter speed?

Motion deblurring

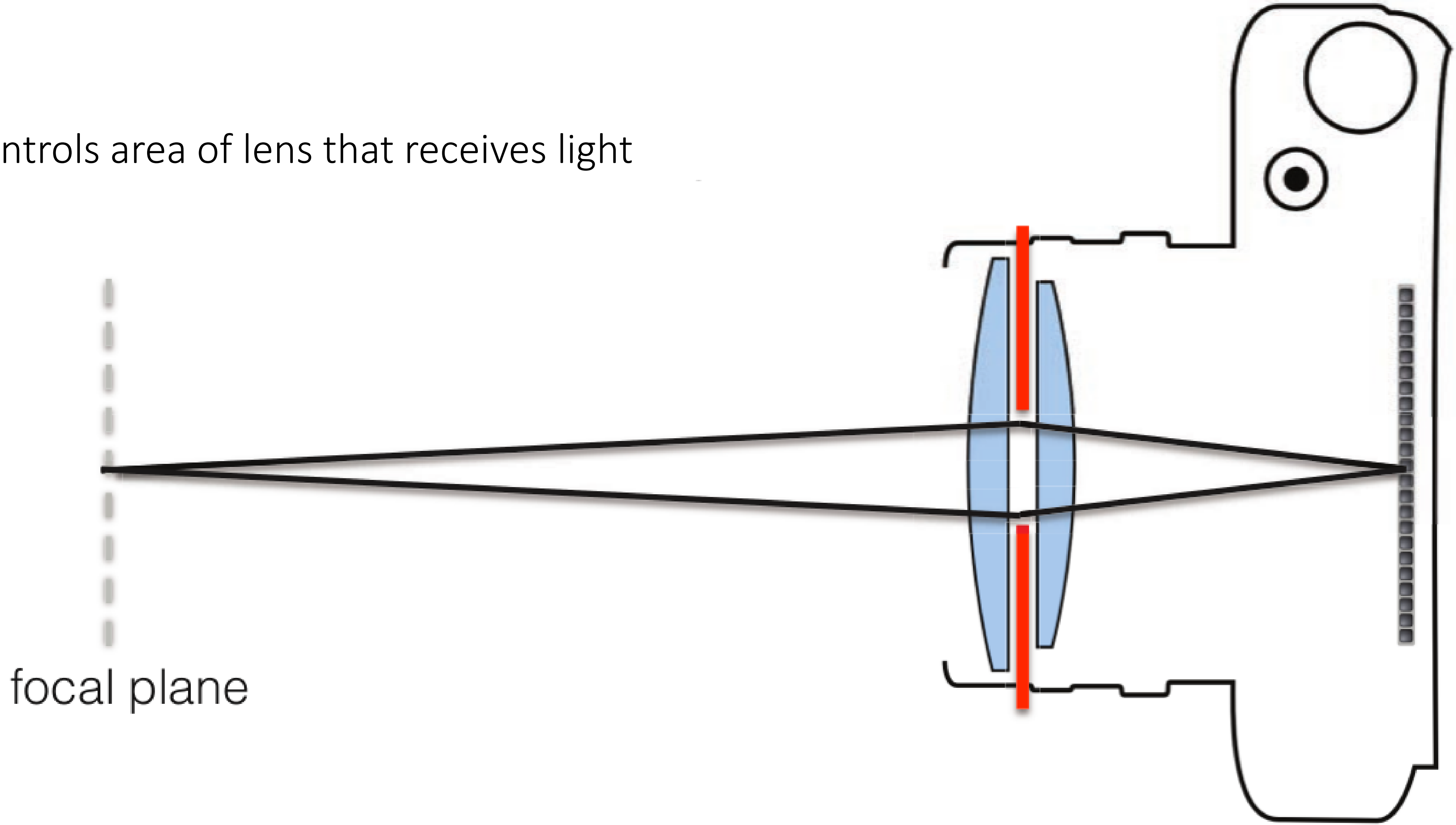
Shah et al. High-quality Motion Deblurring from a Single Image, SIGGRAPH 2008

Exposure controls brightness of image



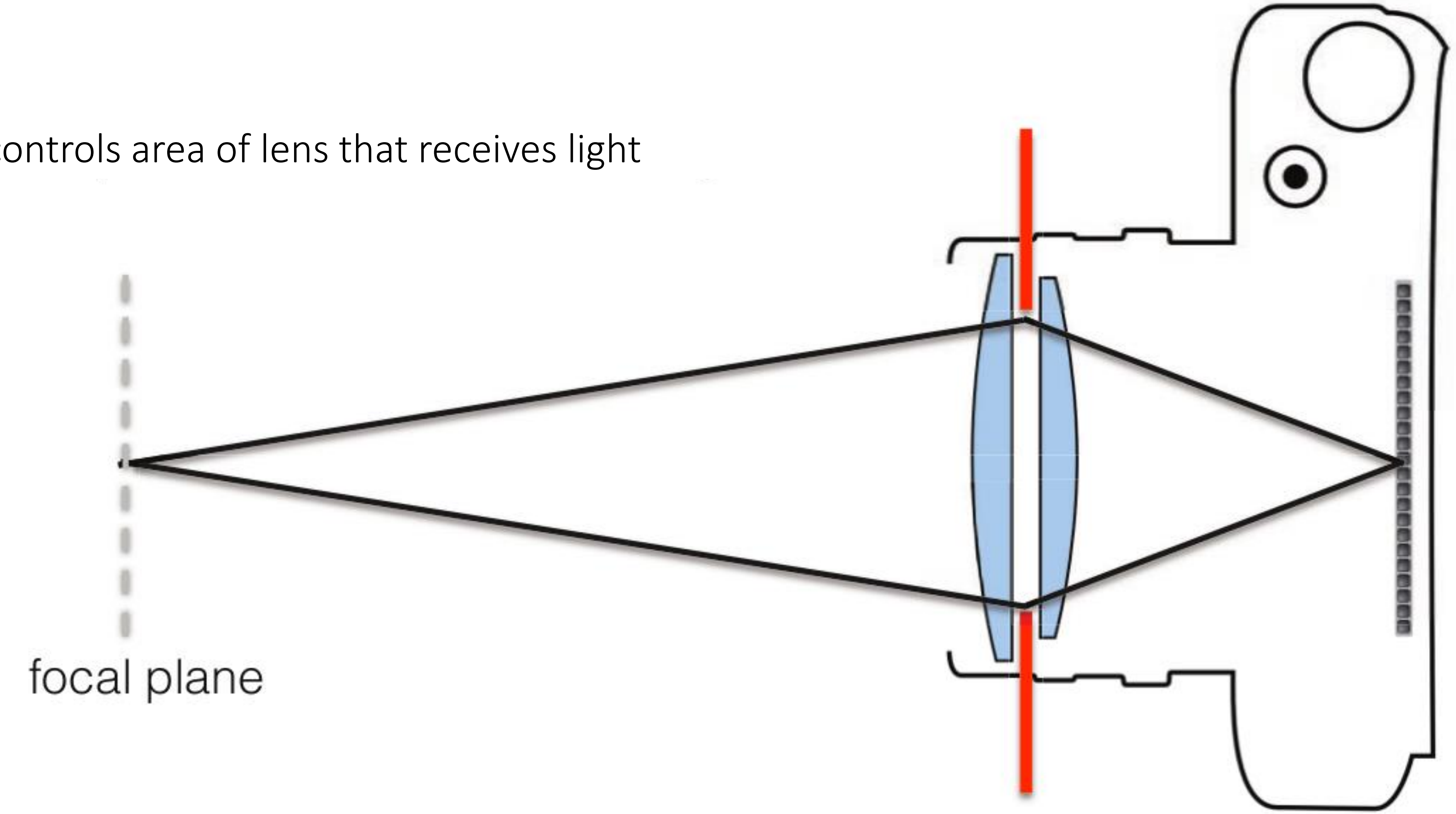
Aperture

controls area of lens that receives light



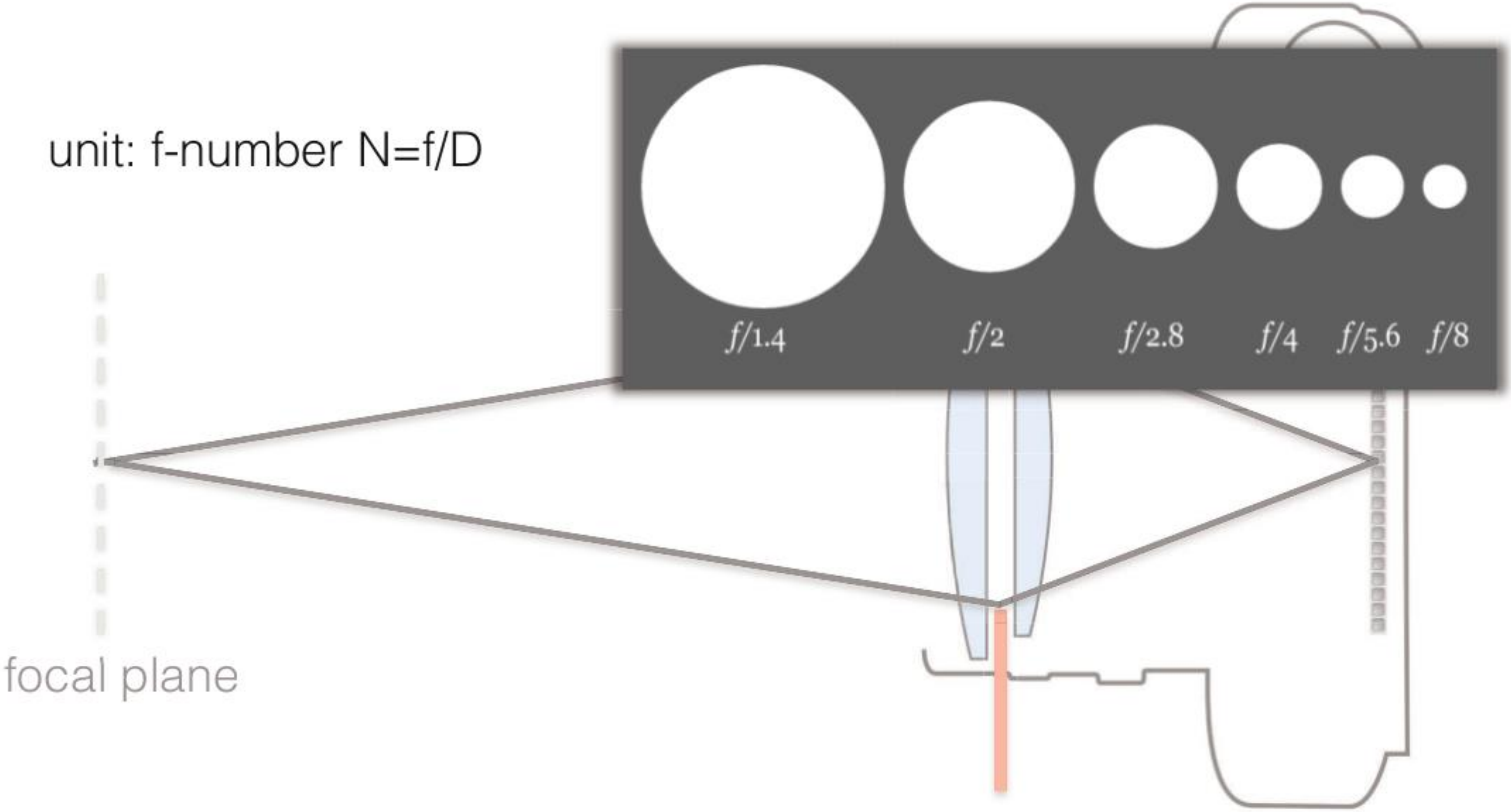
Aperture

controls area of lens that receives light



Aperture

- unit: f-number N=f/D



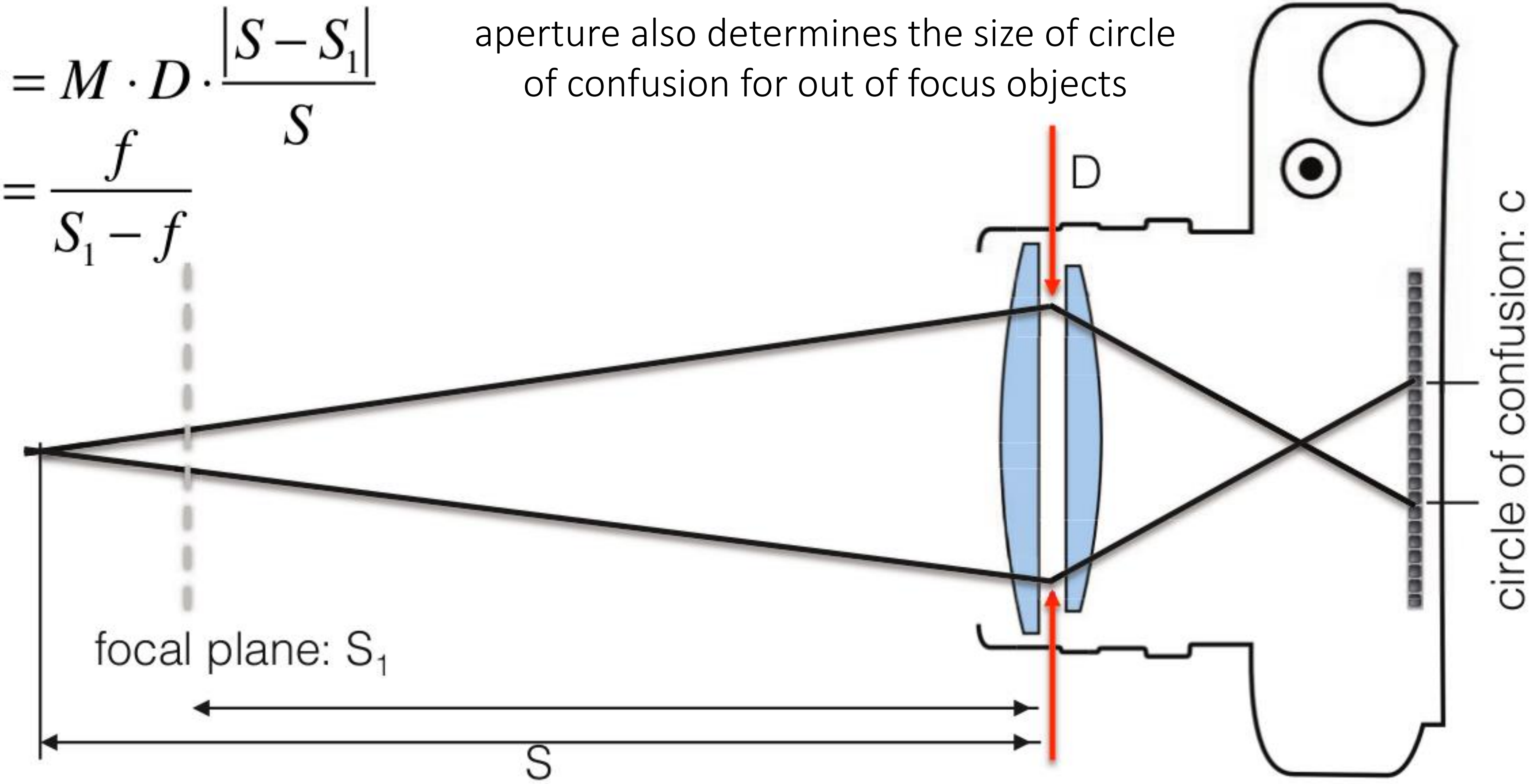
Aperture size

Circle of Confusion

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

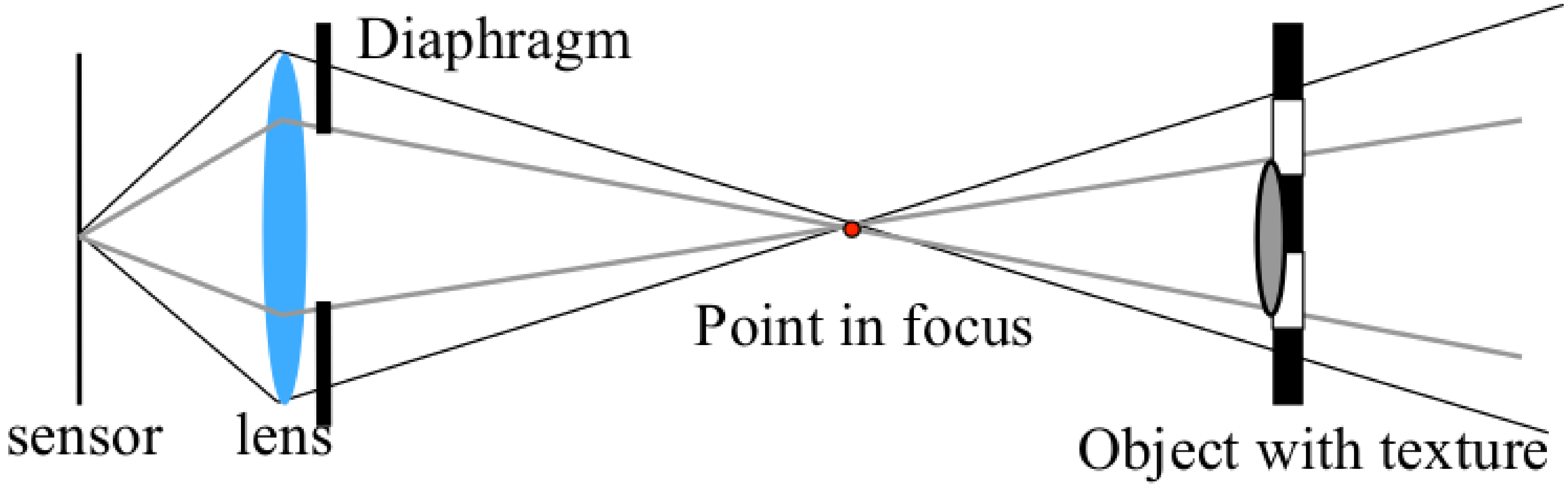
$$M = \frac{f}{S_1 - f}$$

aperture also determines the size of circle of confusion for out of focus objects



Circle of confusion

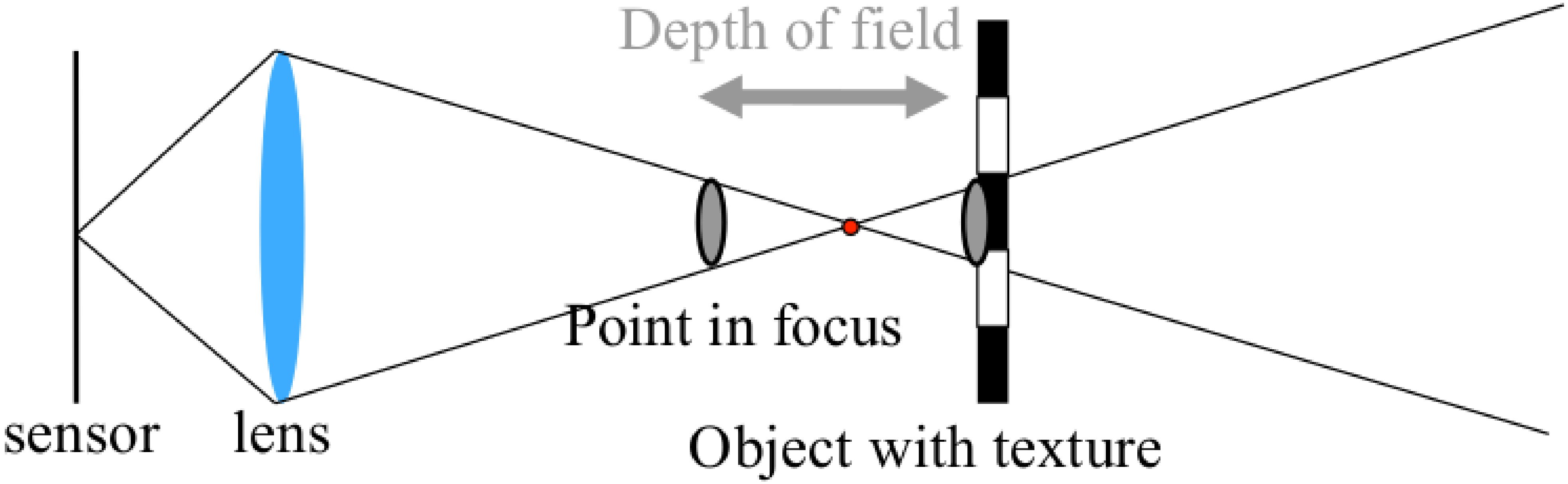
Aperture also controls size of circle of confusion for out of focus objects



Take off your glasses and squint.

Depth of field

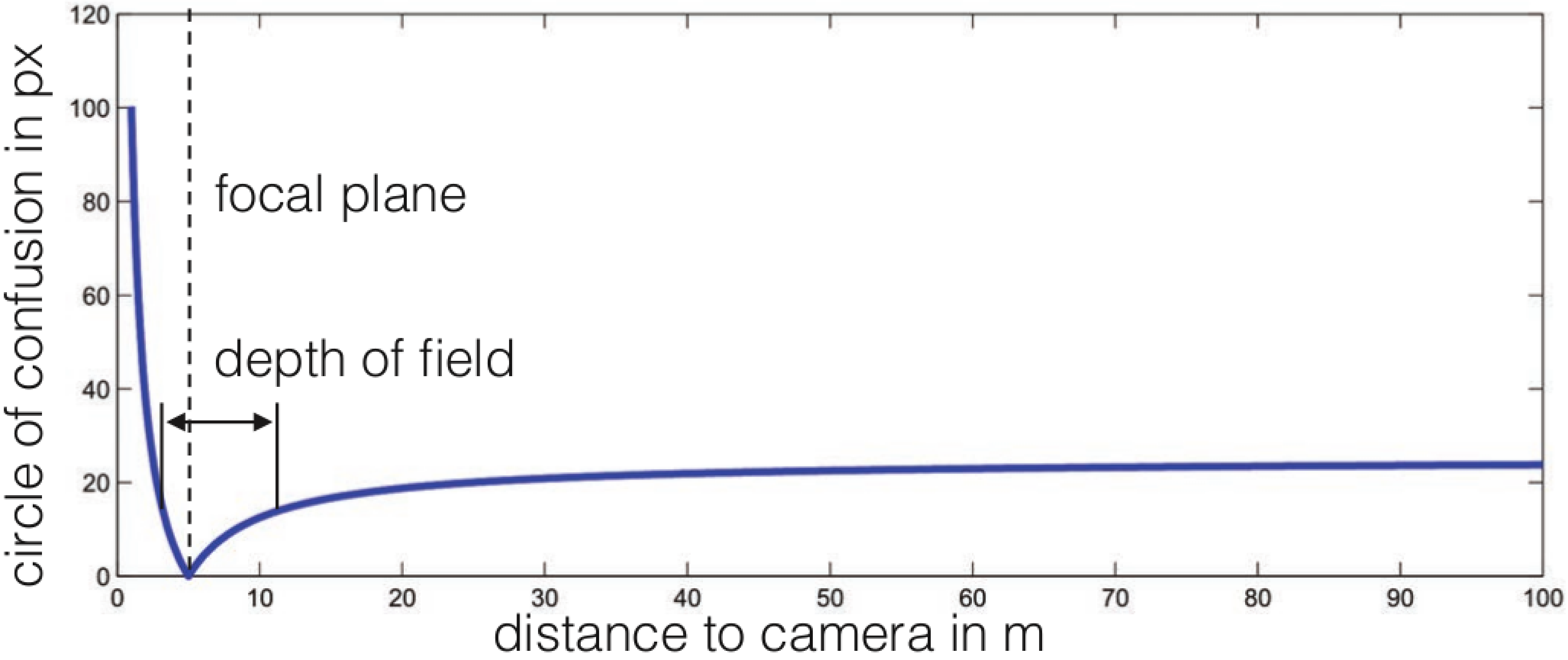
Range of depths for which the circle of confusion is “acceptable”



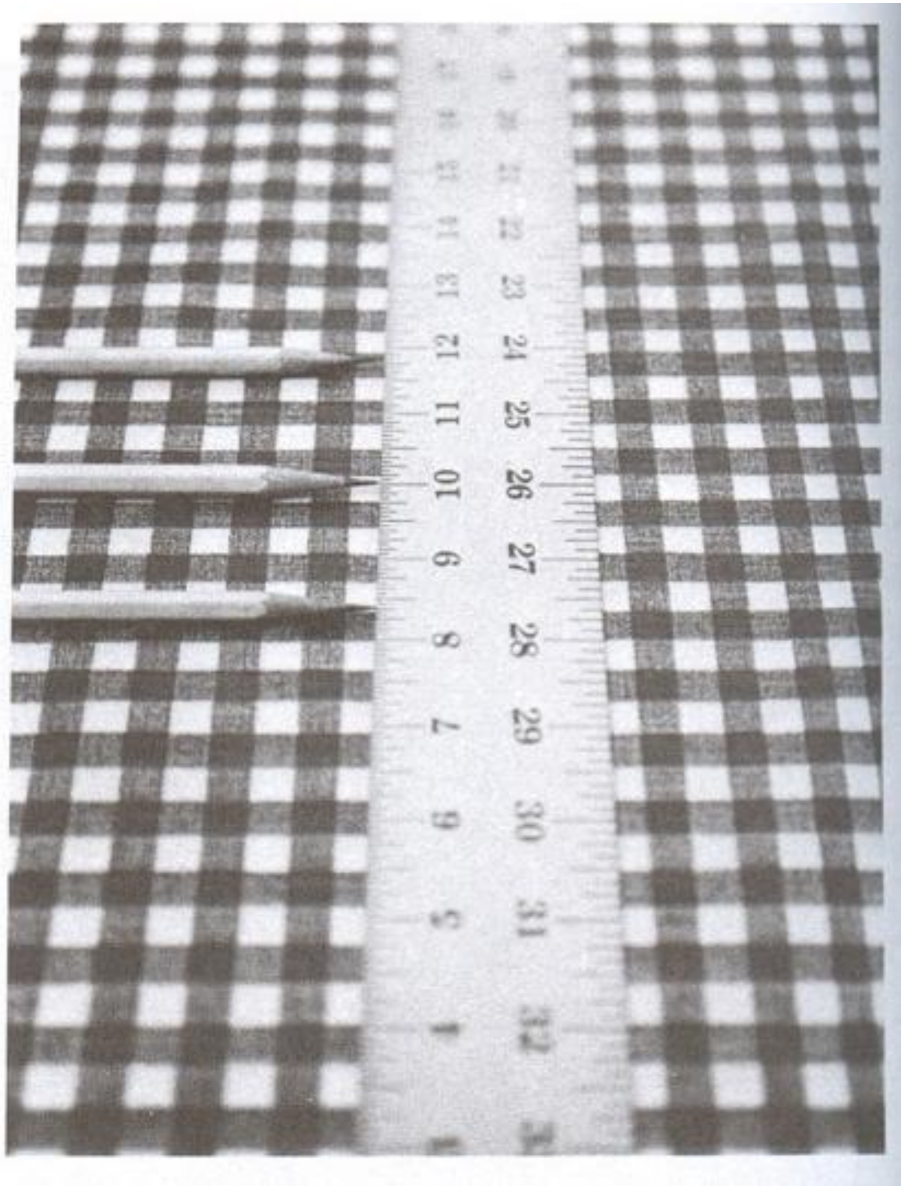
Circle of Confusion

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

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



Depth of field

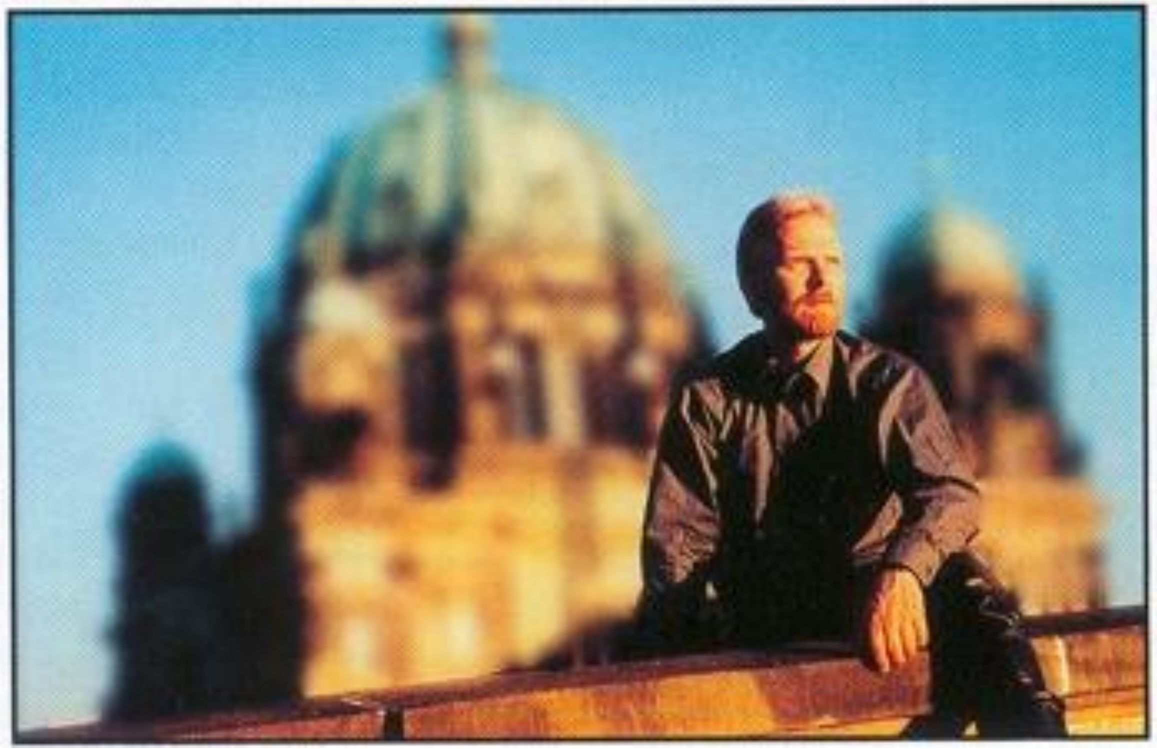


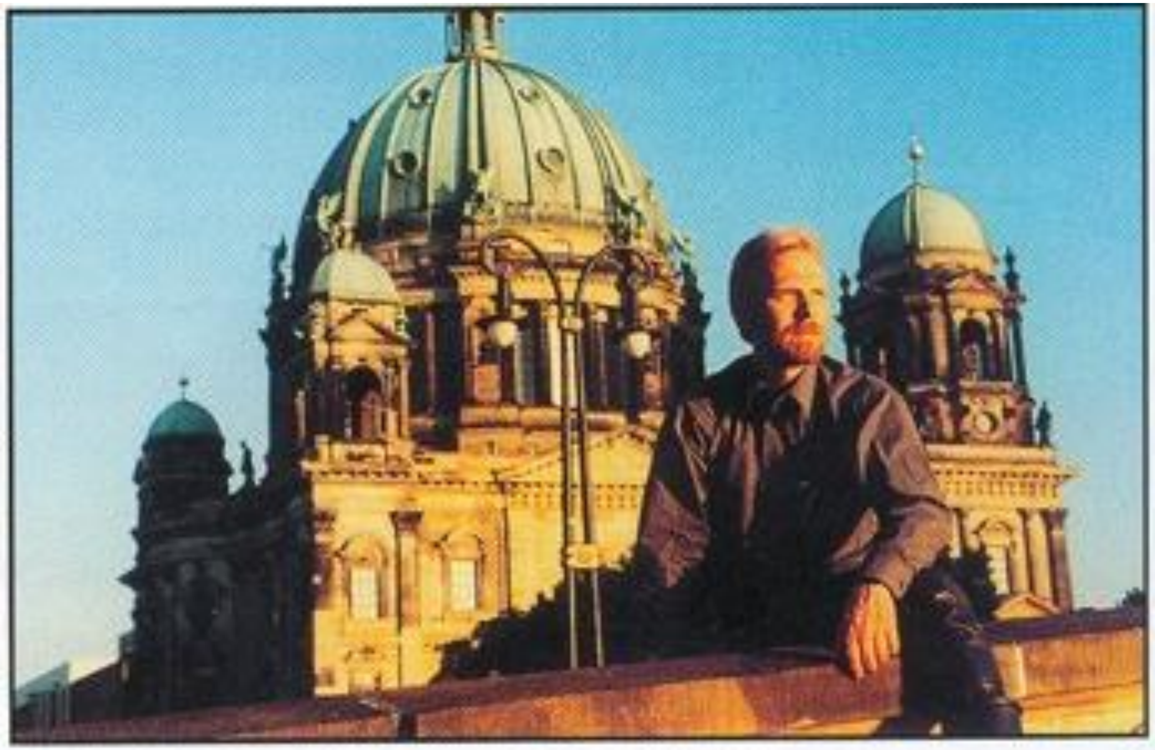
Depth of field

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

Depth of field

Sharp depth of field ("bokeh") is often desirable … and not just for campaigning reasons





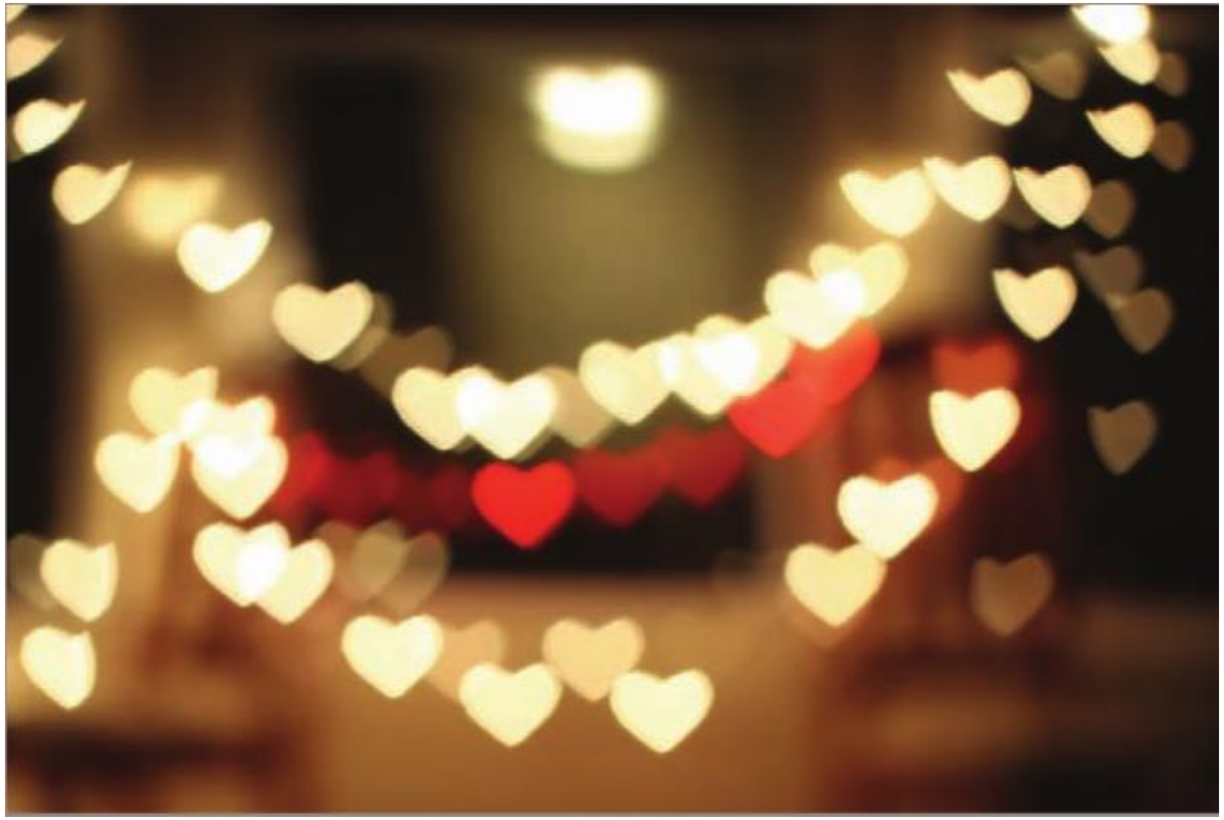
Depth of field

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

... and not just for campaigning reasons

Depth of field

Form of bokeh is determined by shape of aperture



Lens “speed”

A “fast” lens is one that has a very large max aperture.

Leica Noctilux 50mm f/0.95 (Price tag: > $10,000

Fast lenses tend to be bulky and expensive.

How can you simulate bokeh?

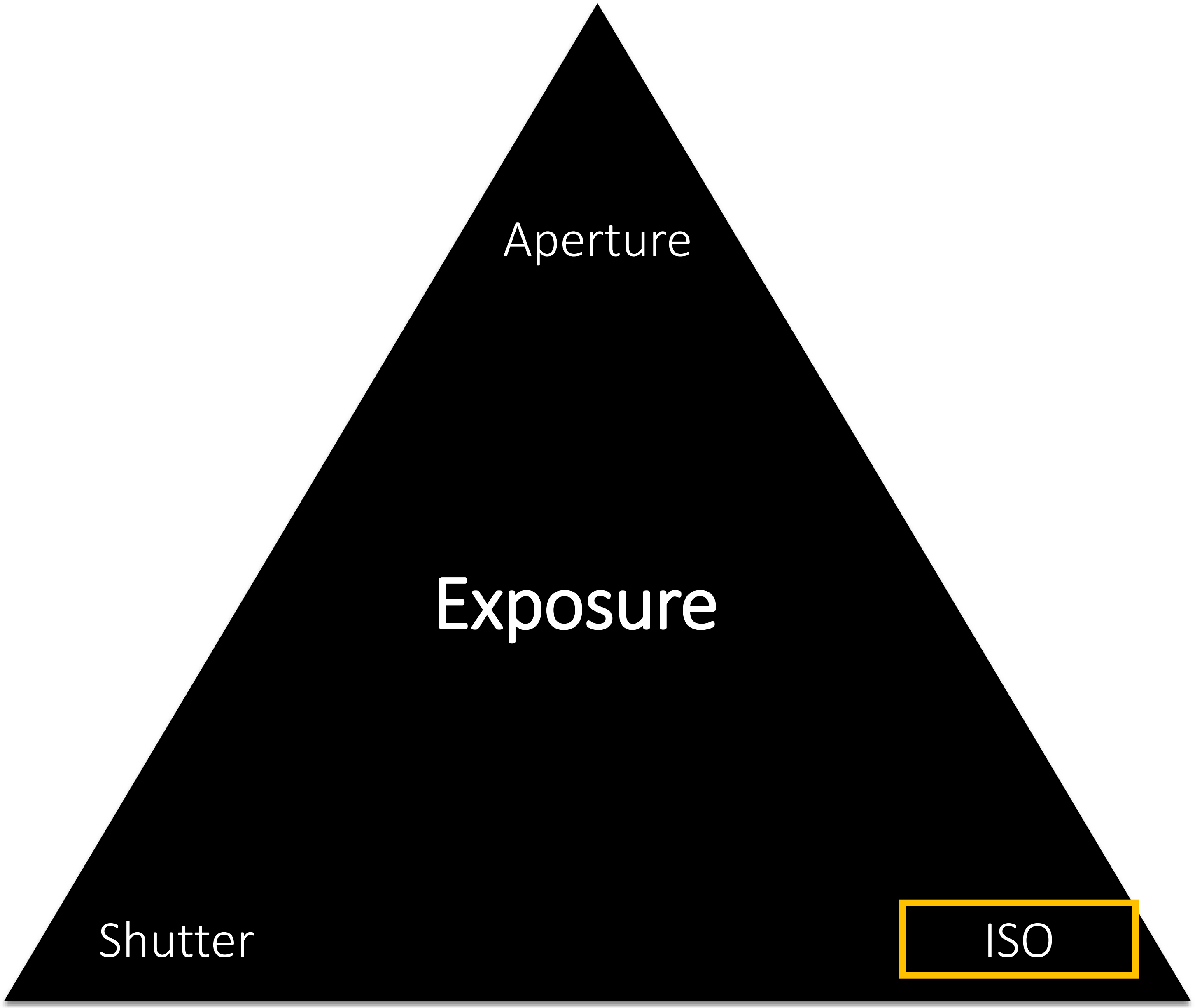
How can you simulate bokeh?

Infer per-pixel depth, then blur with depth-dependent kernel.

- Example: Google camera “lens blur” feature

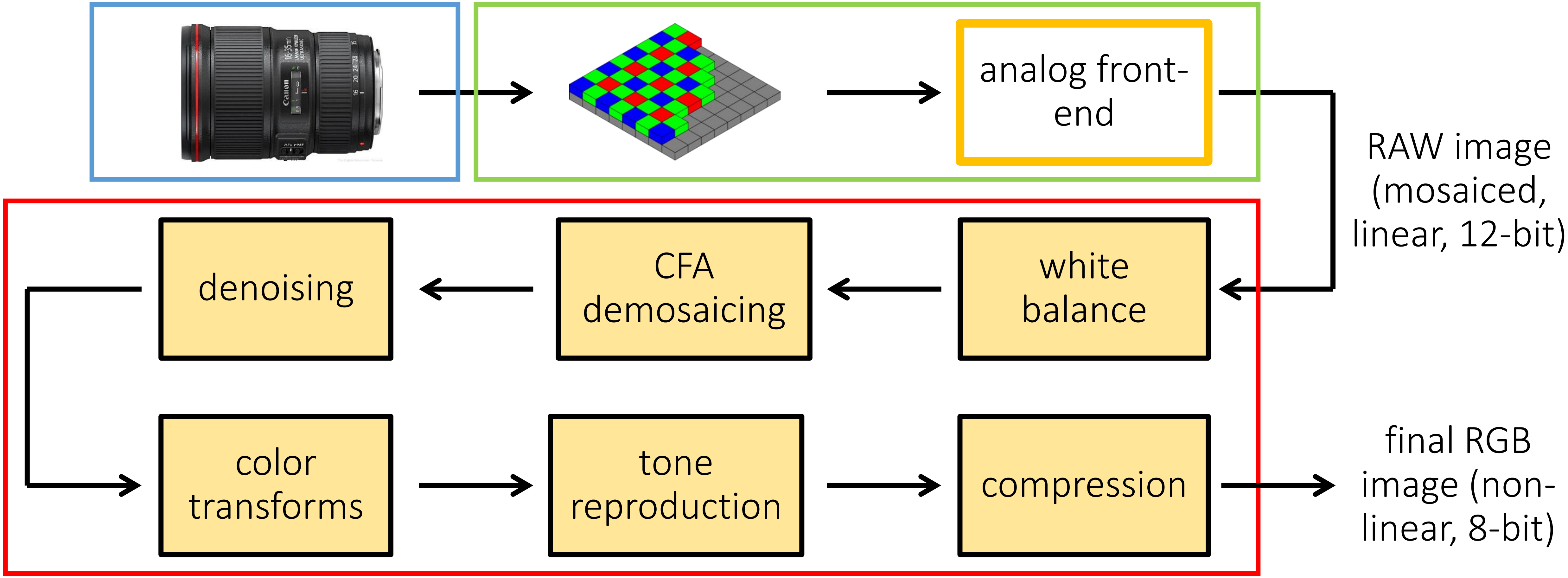
Barron et al., “Fast Bilateral-Space Stereo for Synthetic Defocus,” CVPR 2015

Exposure controls brightness of image

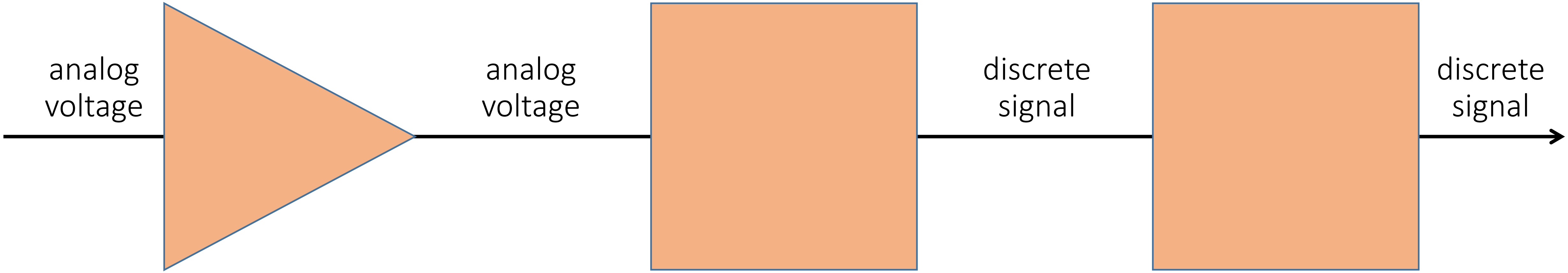


The (in-camera) image processing pipeline

The sequence of image processing operations applied by the camera's image signal processor (ISP) to convert a RAW image into a "conventional" image.



Analog front-end



<u>analog amplifier (gain)</u>:

- gets voltage in range needed by A/D converter.
- accommodates ISO settings.
- accounts for <u>vignetting</u>.

<u>analog-to-digital converter (ADC)</u>:

- depending on sensor, output has 10-16 bits.
- most often (?) 12 bits.

<u>look-up table (LUT)</u>:

- corrects non-linearities in sensor's response function (within proper exposure).
- corrects defective pixels.

"ISO" is an initialism for the International Organization for Standardization

Side-effects of increasing ISO

Image becomes very grainy because noise is amplified.

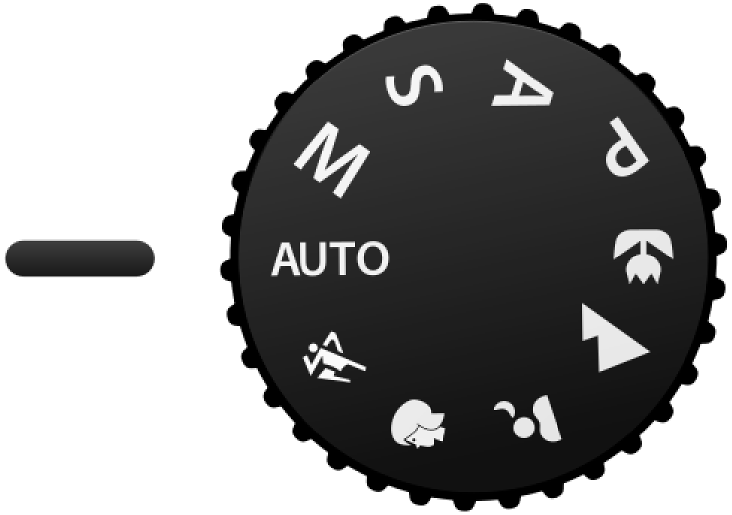
Camera modes

Aperture priority ("A"): you set aperture, camera sets everything else.
- Pros: Direct depth of field control.
- Cons: Can require impossible shutter speed (e.g. with f/1.4 for a bright scene).

Shutter speed priority ("S"): you set shutter speed, camera sets everything else.
- Pros: Direct motion blur control.
- Cons: Can require impossible aperture (e.g. when requesting a 1/1000 speed for a dark scene)

Automatic ("AUTO"): camera sets everything.
- Pros: Very fast, requires no experience.
- Cons: No control.

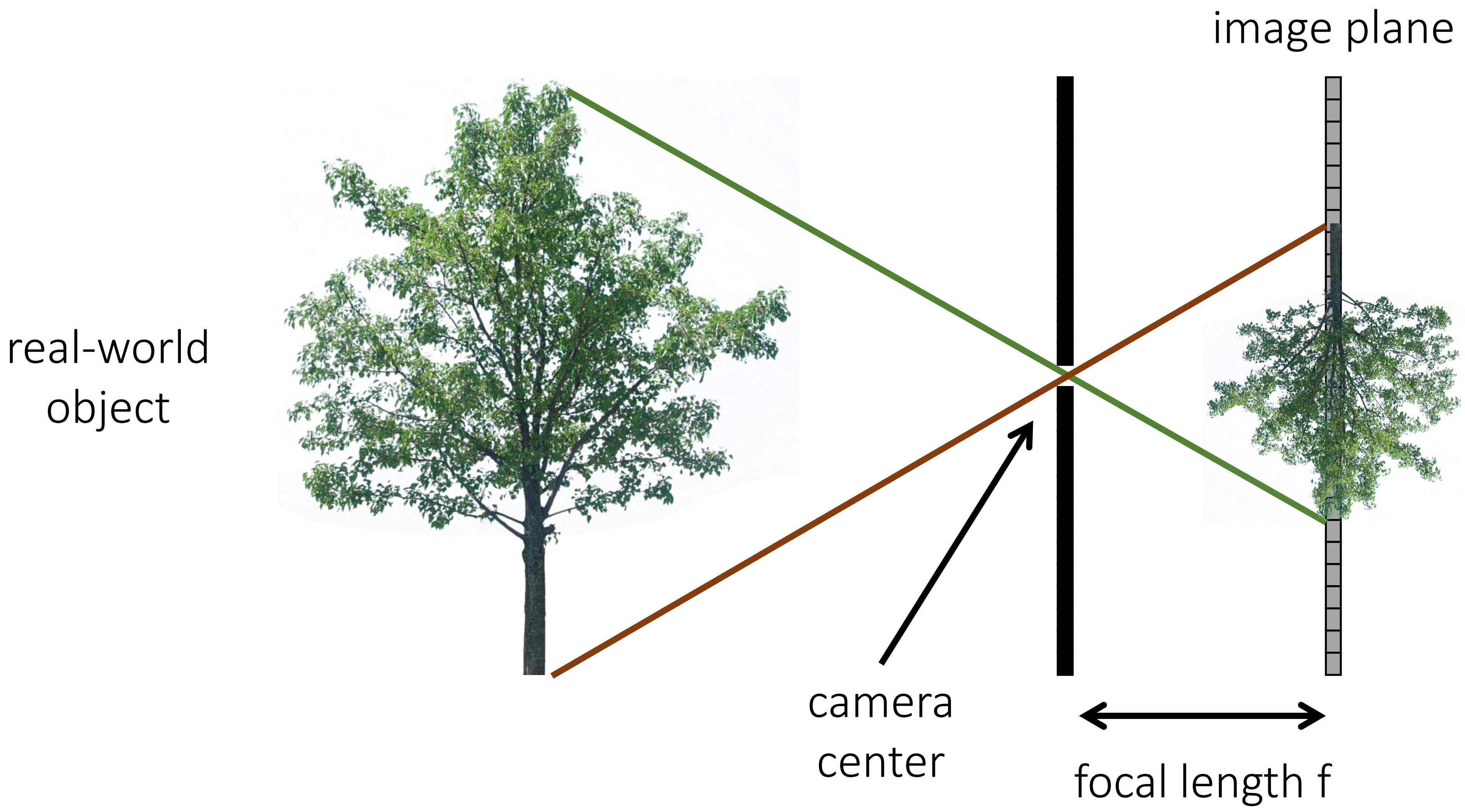
Manual ("M"): you set everything.
- Pros: Full control.
- Cons: Very slow, requires a lot of experience.



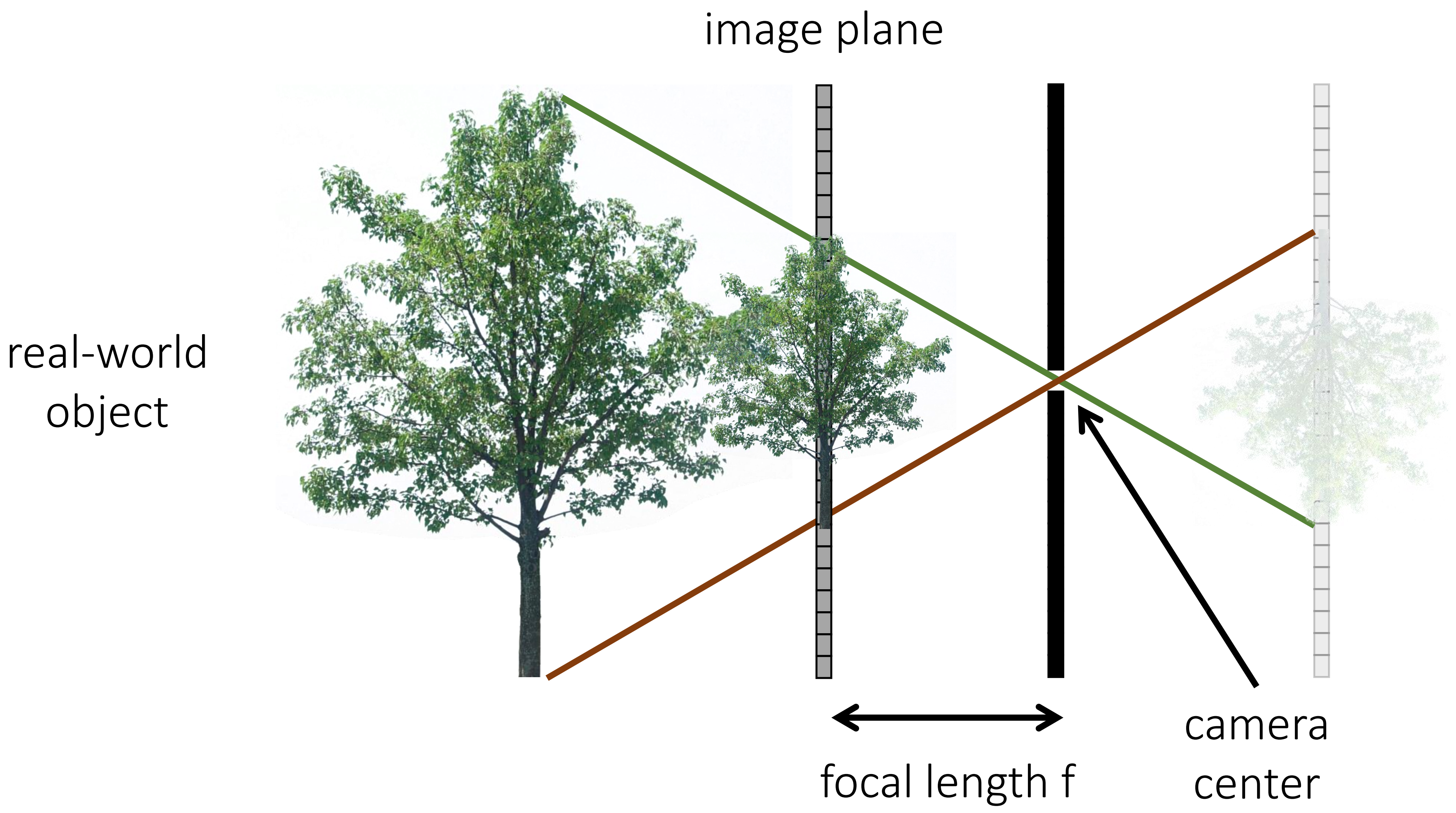
generic camera mode dial

Lens camera and pinhole camera

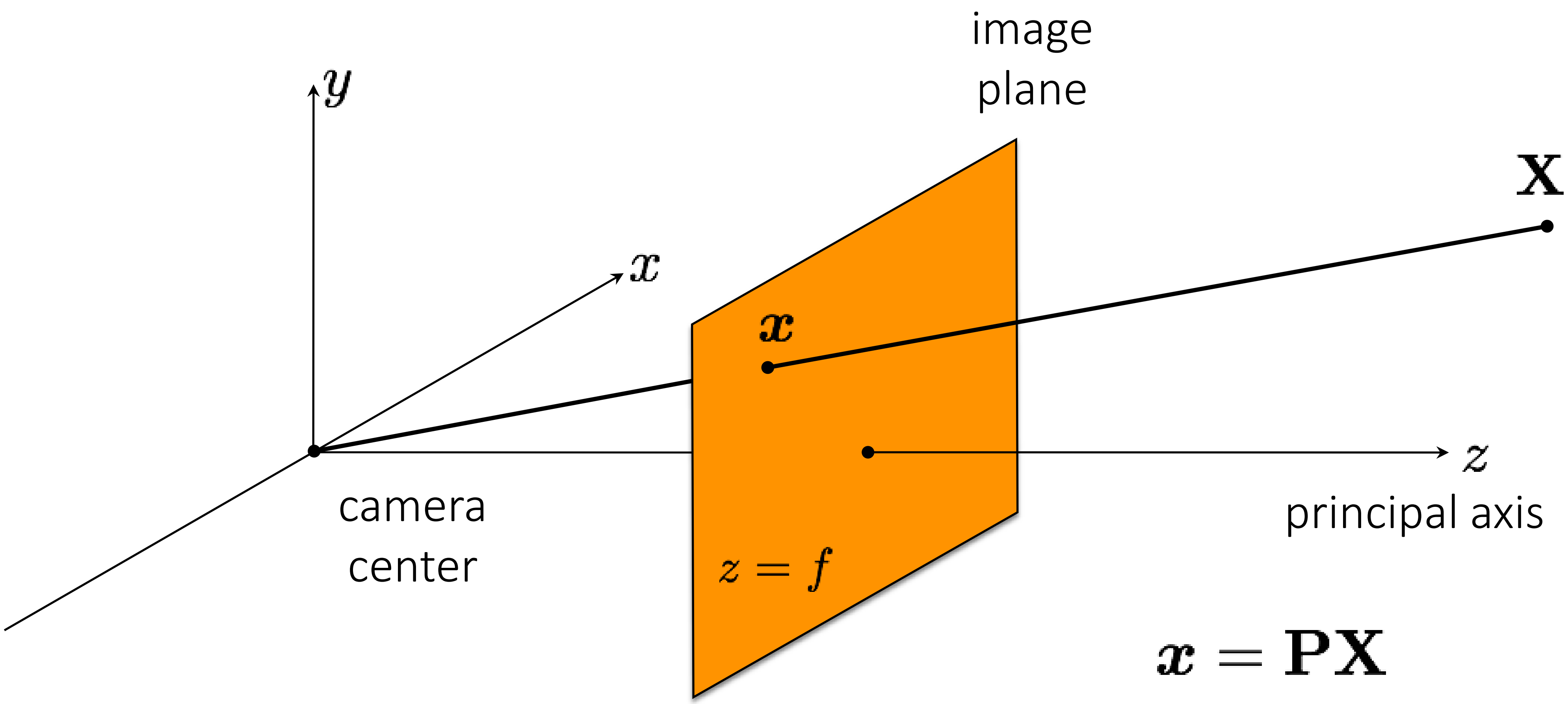
The pinhole camera



The (rearranged) pinhole camera



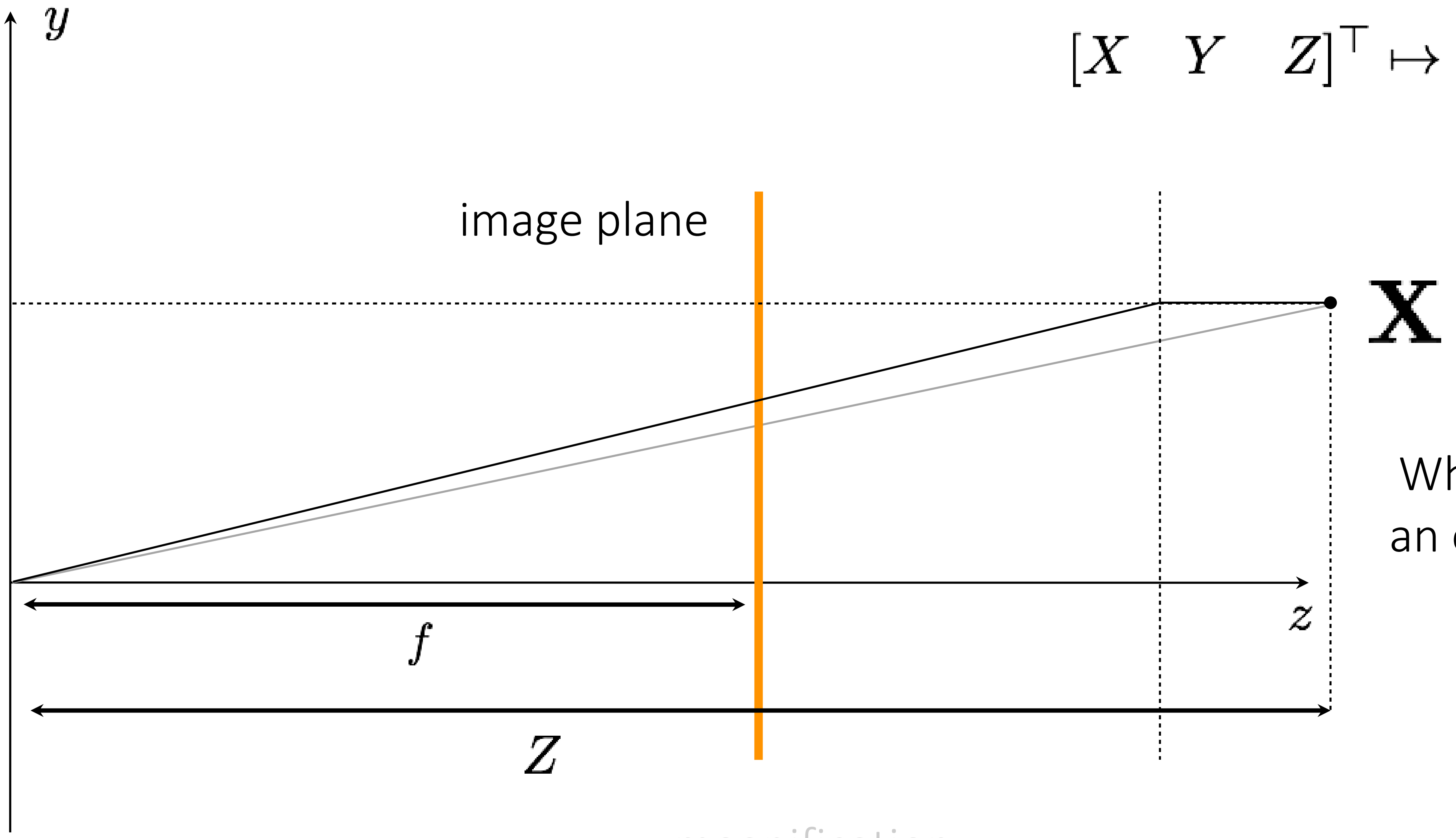
The (rearranged) pinhole camera



Is this model valid for a camera using a lens?

Telecentric lenses

Orthographic vs pinhole camera



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

magnification does not change with depth

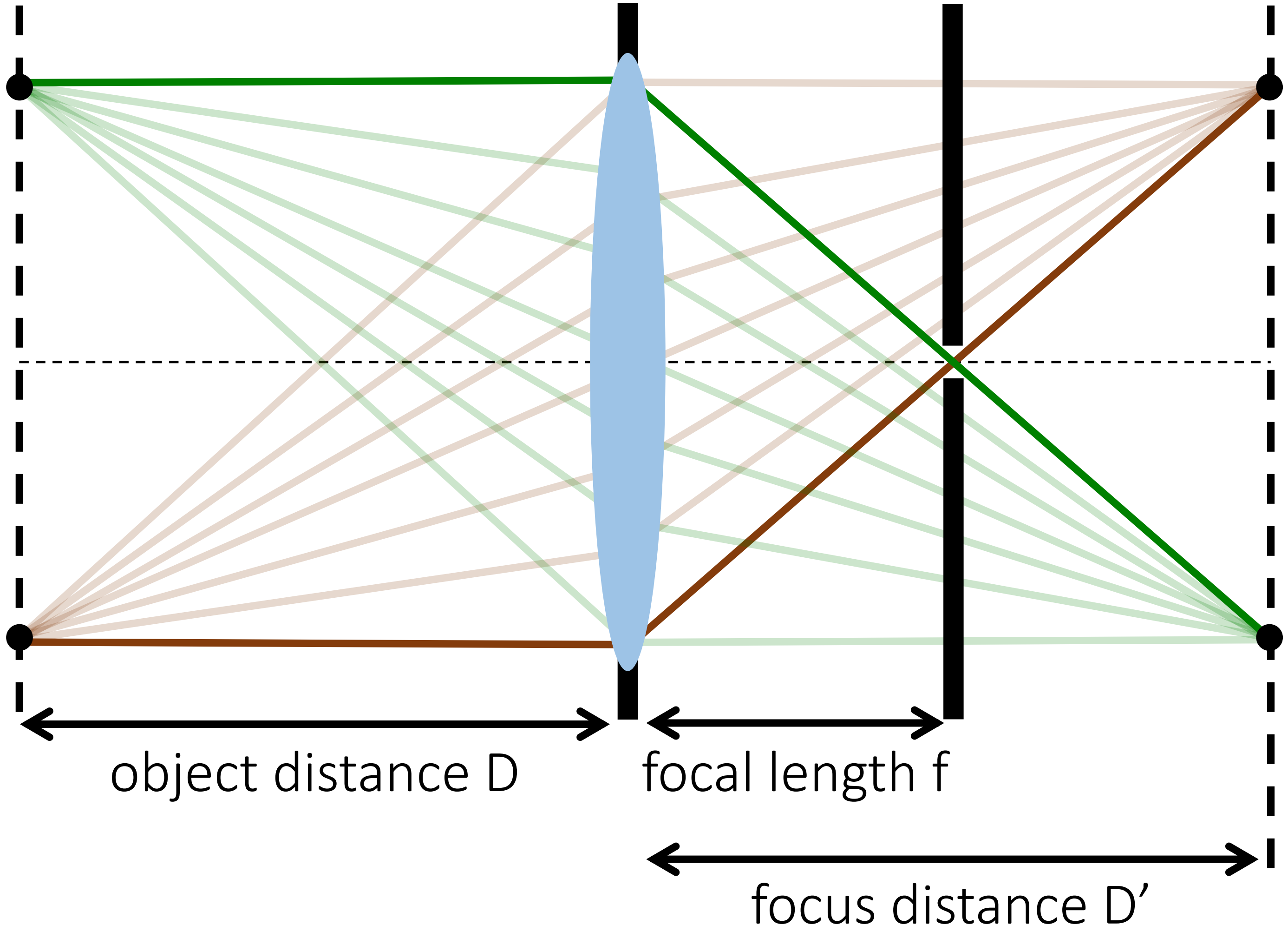
What lens do we use for an orthographic camera?

magnification changes with depth

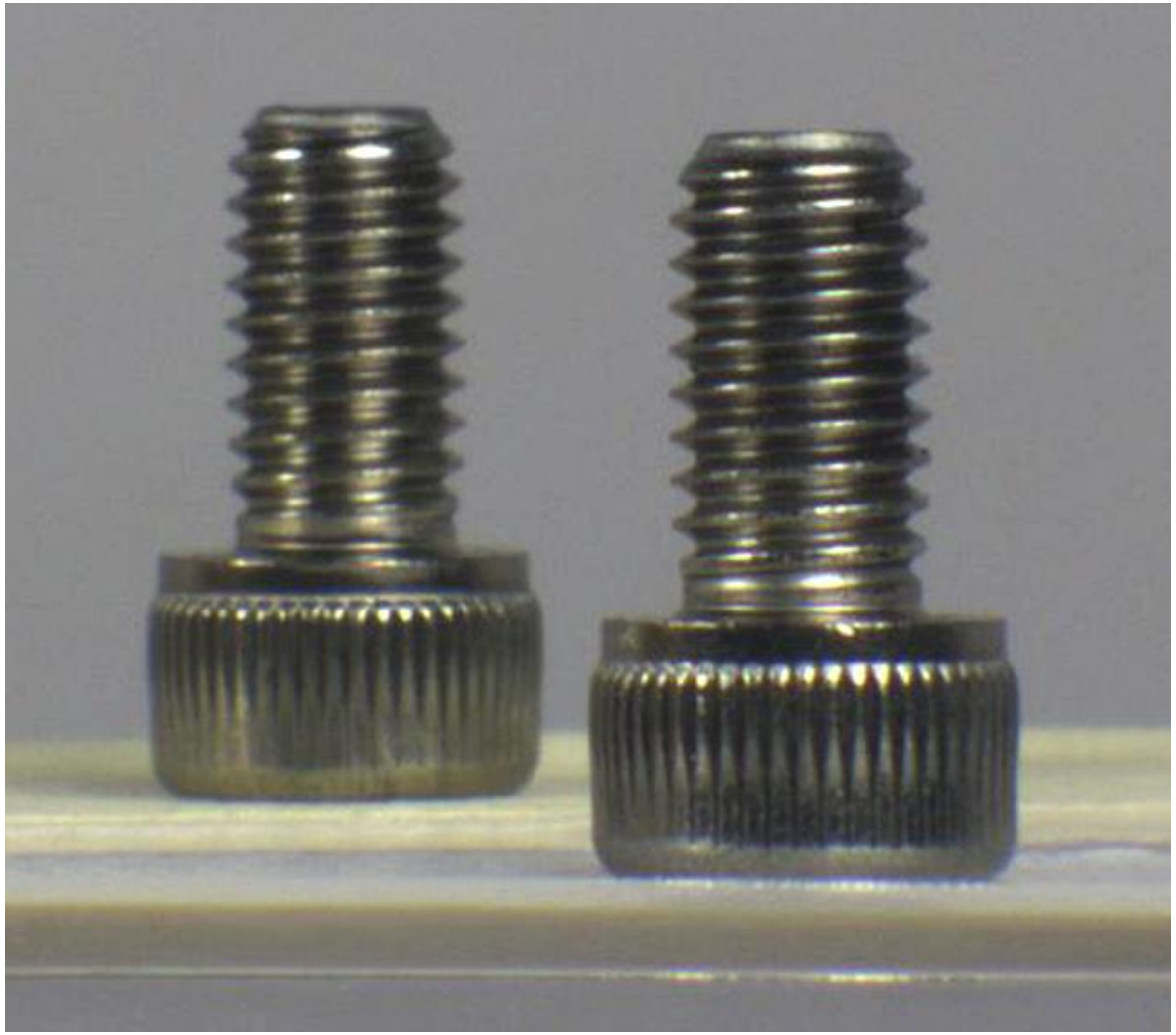
$$[X \quad Y \quad Z]^\top \mapsto [fX/Z \quad fY/Z]^\top$$

Telecentric lens

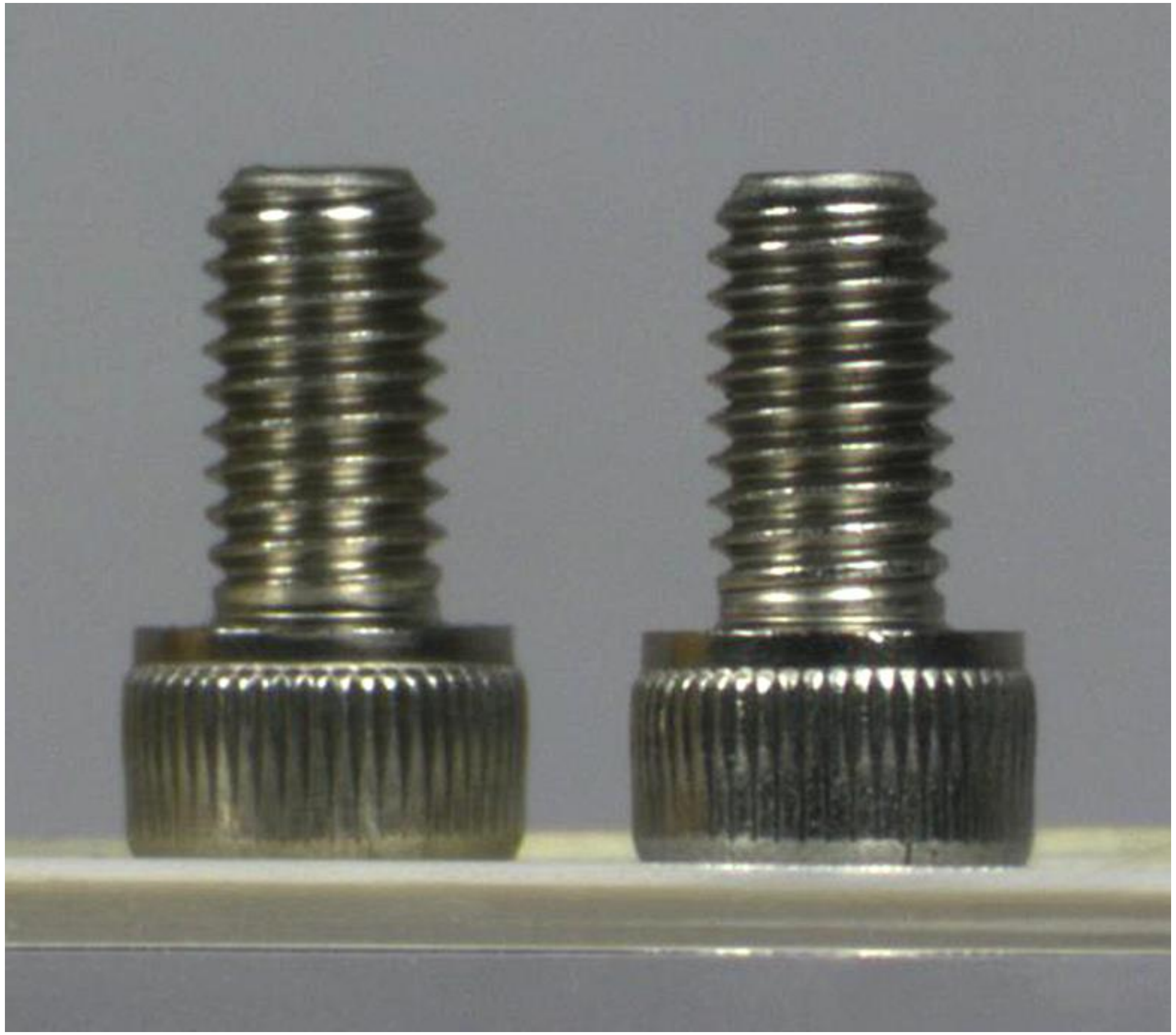
Place a pinhole at focal length, so that only rays parallel to primary ray pass through.



Regular vs telecentric lens



regular lens



telecentric lens

References

Basic reading:

- Szeliski textbook, Section 2.2.3.

Additional reading:

- London and Upton, “Photography,” Pearson 2013.
  a great book on photography, discussing in detail many of the issues addressed in this lecture.
- Ray, “Applied Photographic Optics,” Focal Press 2002.
  another nice book covering everything about photographic optics.
- Shah et al., “High-quality Motion Deblurring from a Single Image,” SIGGRAPH 2008.
- Fergus et al., “Removing Camera Shake from a Single Image,” SIGGRAPH 2006.
  two standard papers on motion deblurring for dealing with long shutter speeds.
- Barron et al., “Fast Bilateral-Space Stereo for Synthetic Defocus,” CVPR 2015.
  the lens blur paper.