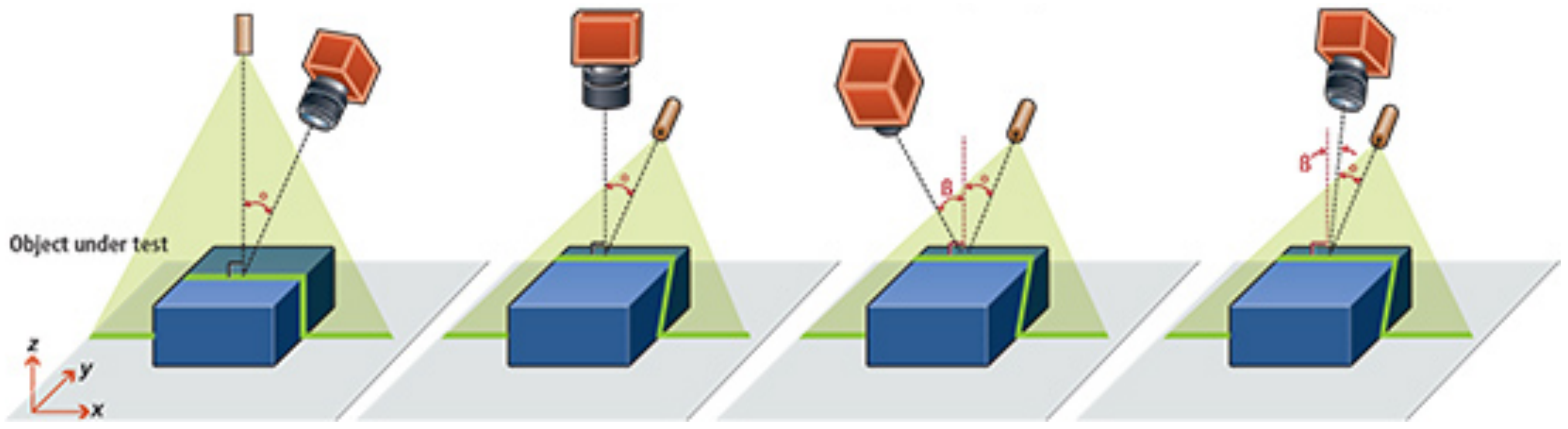
THE UNIVERSITY OF BRITISH COLUMBIA

CPSC 425: Computer Vision



Lecture 2: Image Formation

(slide credits / thanks to **Bob Woodham, Jim Little** and **Fred Tung**)

This Lecture

Topics:

- Image Formation
- Cameras and Lenses
- Projection

Readings:

- **Today's** Lecture: Szeliski Chapter 2, Forsyth & Ponce (2nd ed.) 1.1.1 — 1.1.3
- **Next** Lecture: Forsyth & Ponce (2nd ed.) 4.1, 4.5

What is **Computer Vision**?

Compute vision, broadly speaking, is a research field aimed to enable computers to **process and interpret visual data**, as sighted humans can.

Image (or video)

Sensing Device

Interpreting Device

Image Credit: https://www.flickr.com/photos/flamephoenix1991/8376271918

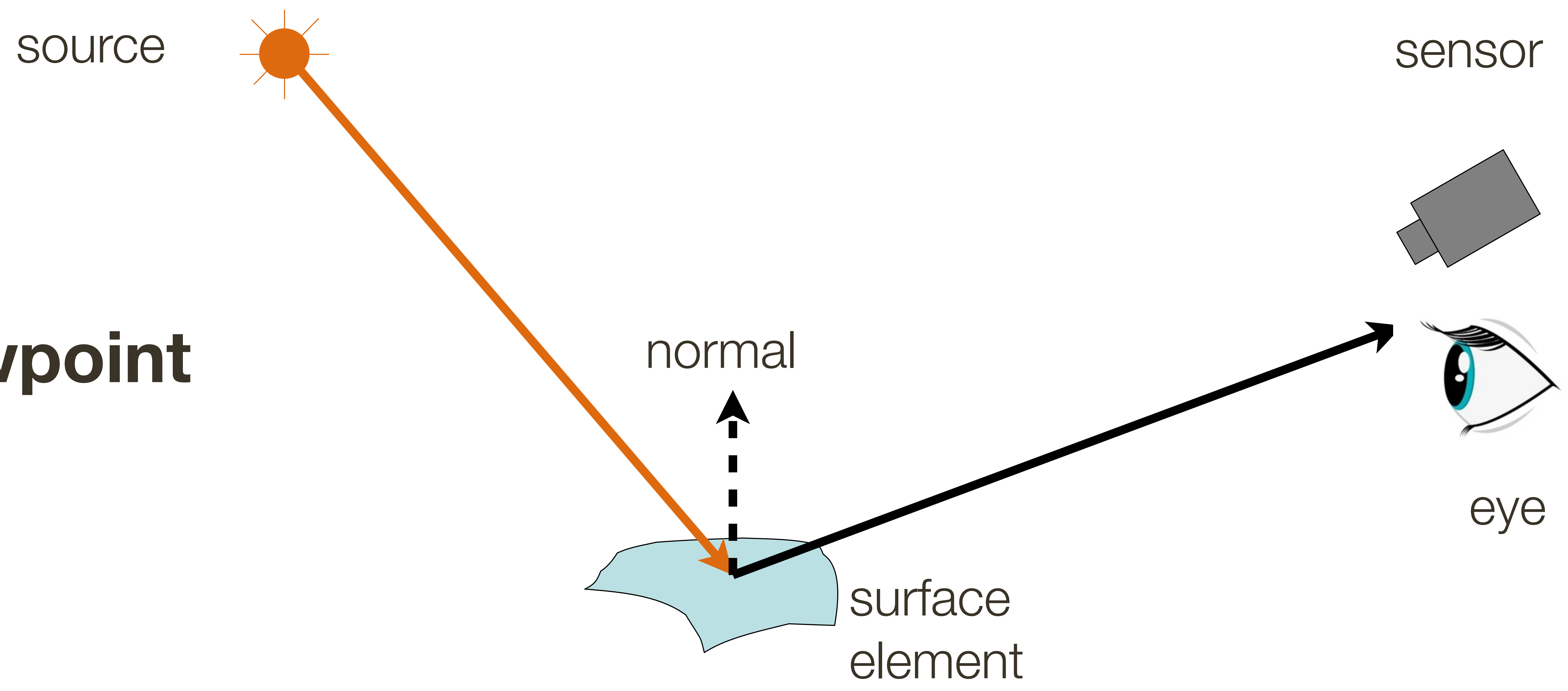
Interpretation

blue sky,
trees,
fountains,
UBC, …

Overview: Image Formation, Cameras and Lenses

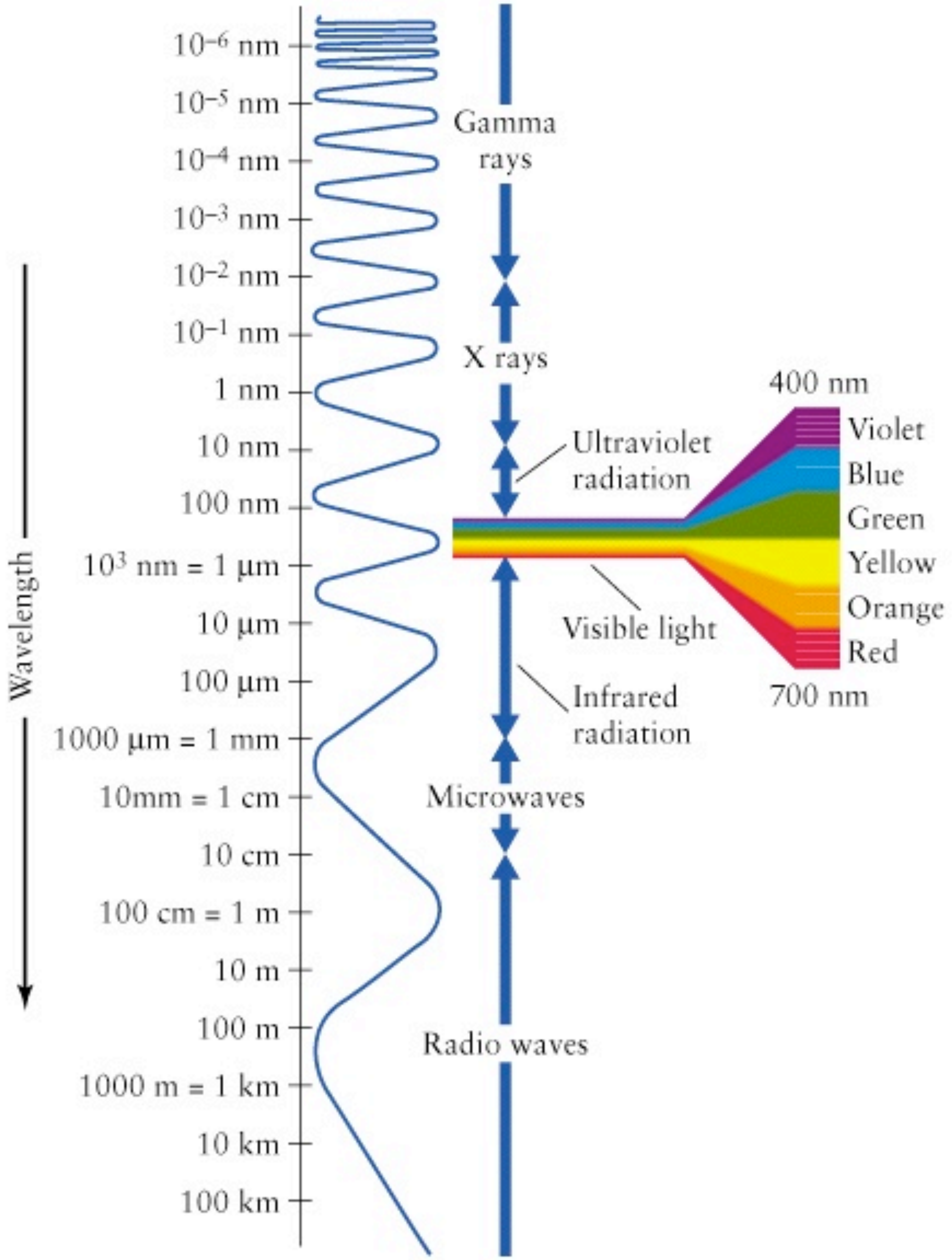
The **image formation process** that produces a particular image depends on

- **Lighting** condition
- Scene **geometry**
- **Surface** properties
- Camera **optics** and **viewpoint**



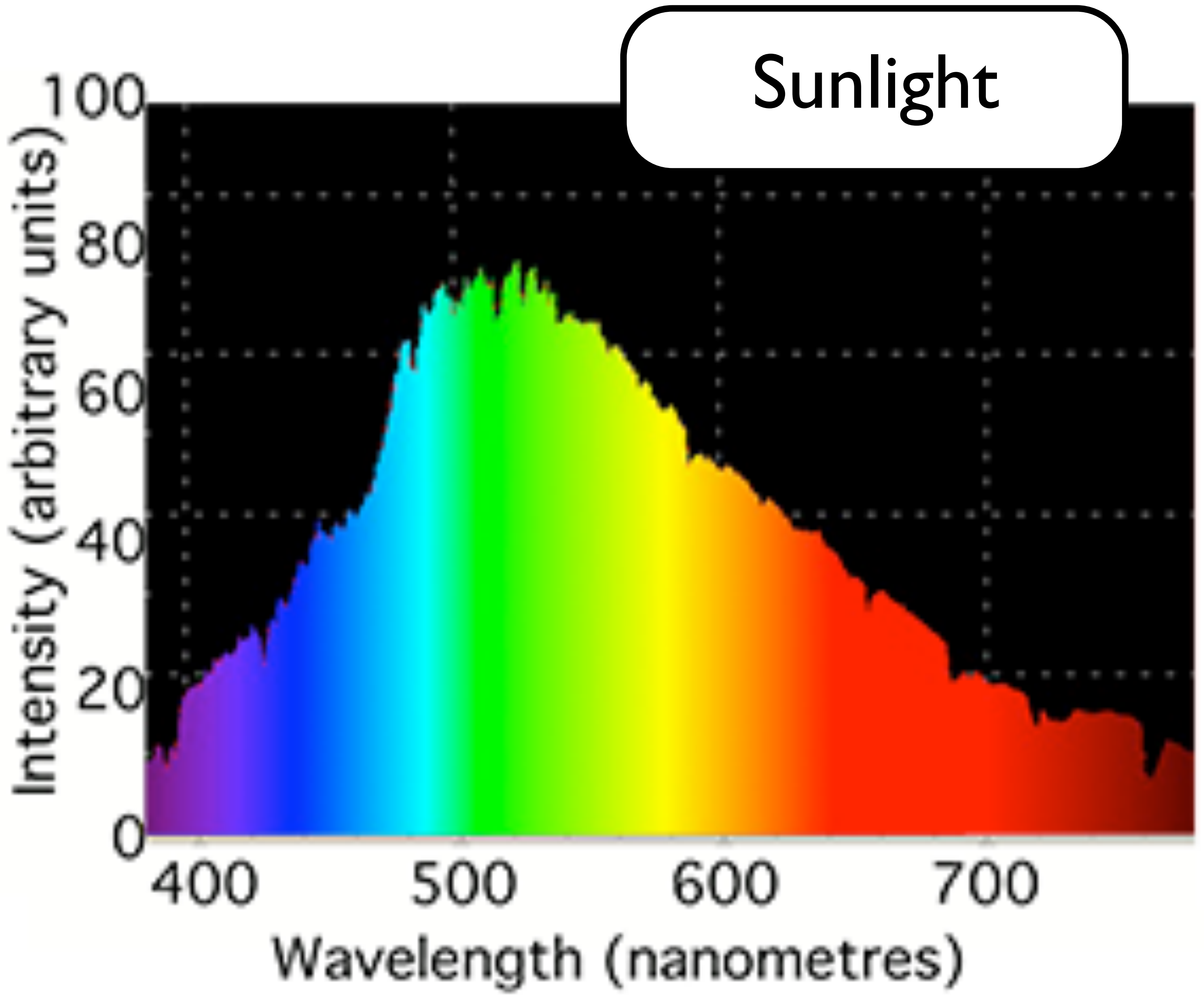
Sensor (or eye) **captures amount of light** reflected from the object

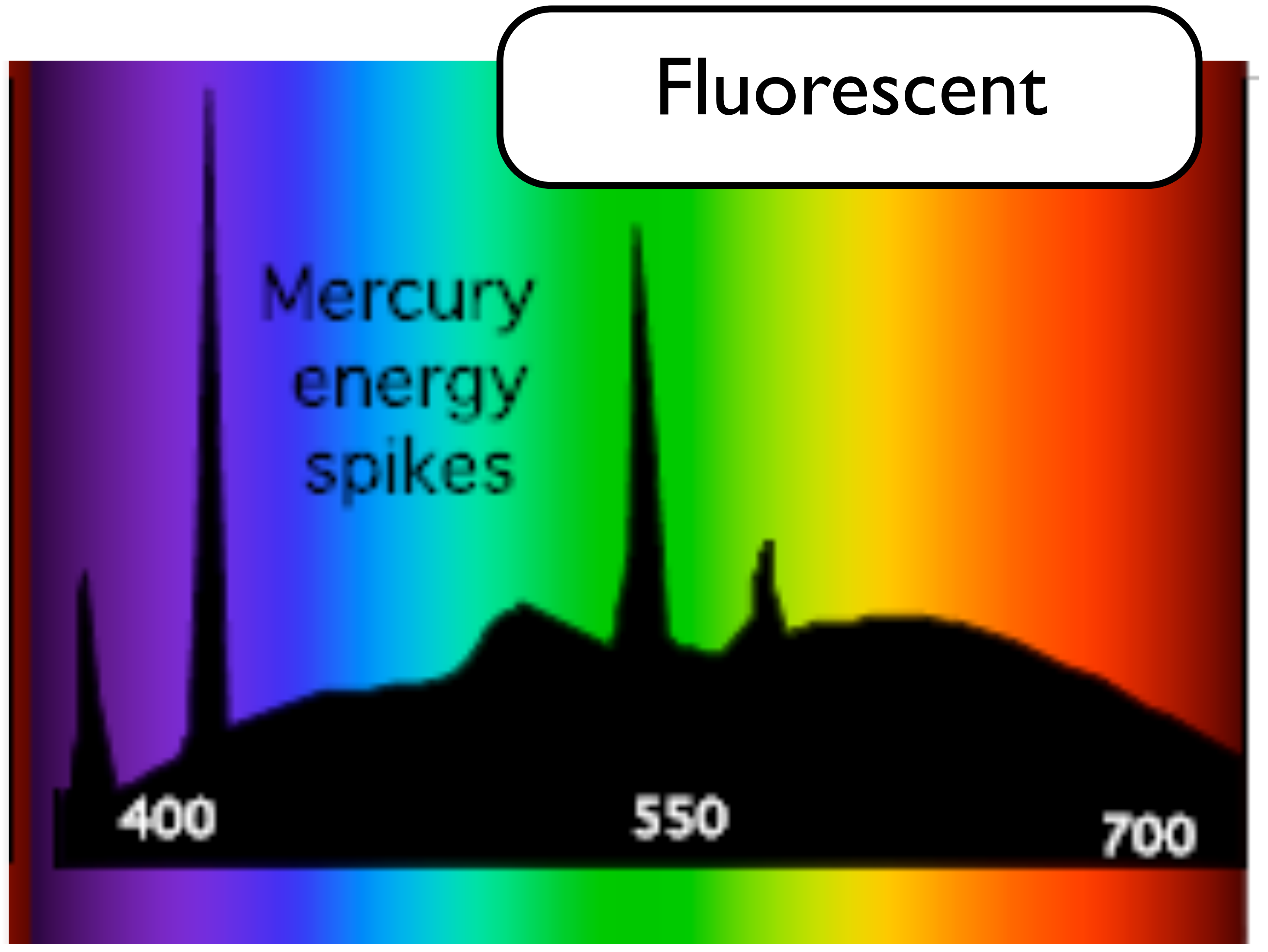
Light and Color



- Light is electromagnetic radiation in the 400-700nm band
- This is the peak in the spectrum of sunlight passing through the atmosphere
- Newton's Prism experiment showed that white light is composed of all frequencies
- Black is the absence of light!

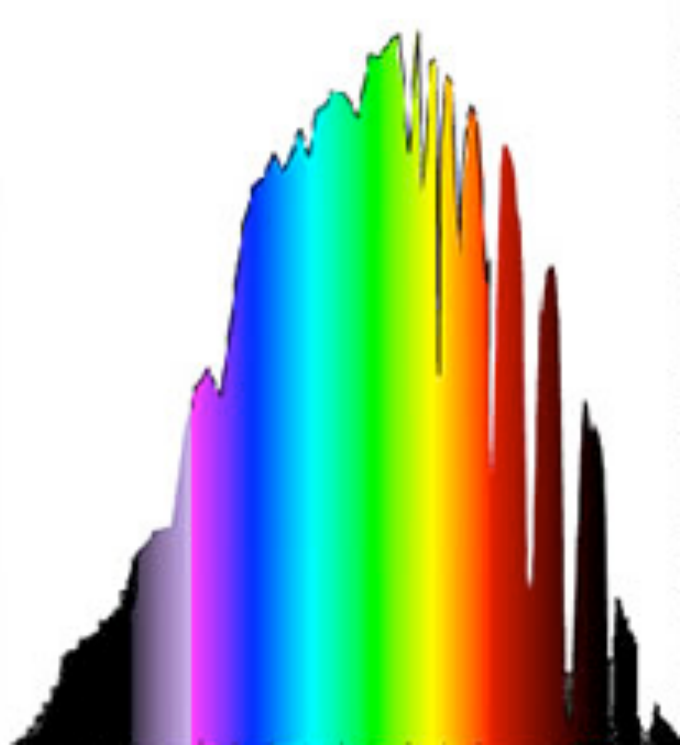
Spectral Power Distribution

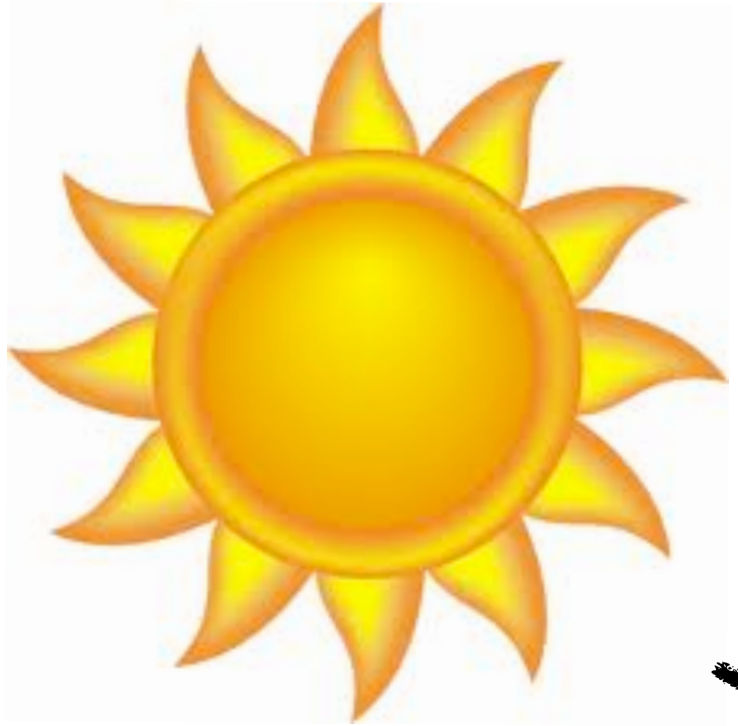




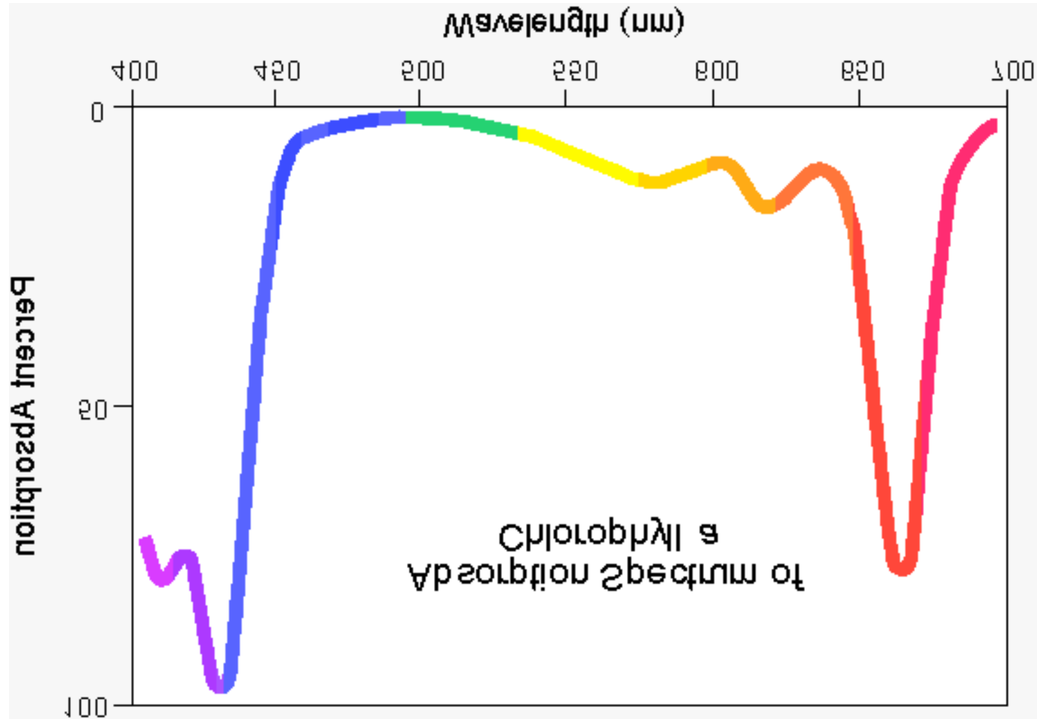
- The spectral distribution of energy in a light ray determines it's colour
- Surfaces reflect light energy according to a spectral distribution as well
- The combination of incident spectra and reflectance spectra determine the light colour

Spectral Reflectance Example





$E(\lambda)$



$S(\lambda)$

$E(\lambda)S(\lambda)$

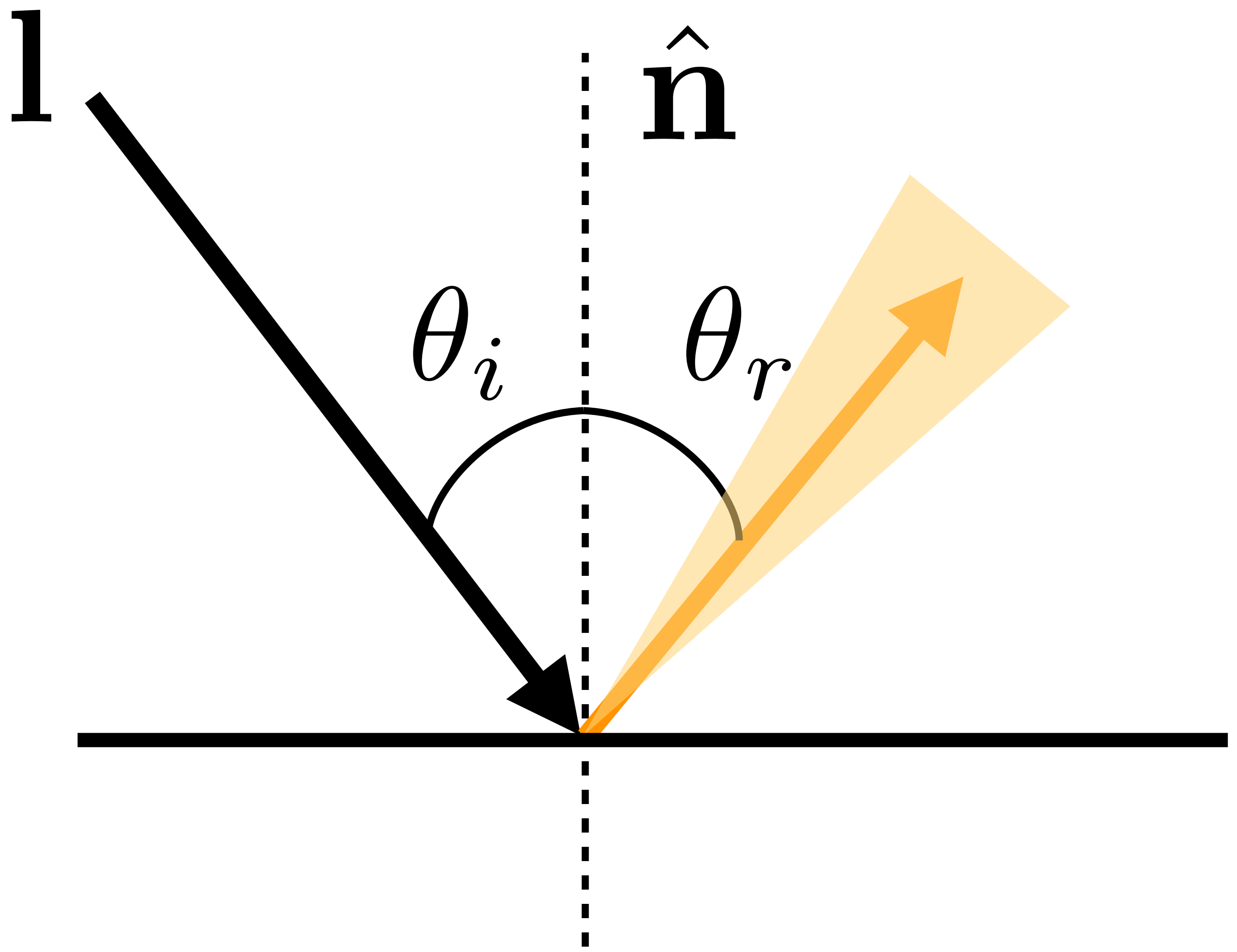
Surface Reflectance

- Reflected intensity also depends on geometry: surface orientation, viewer position, shadows, etc.

It also depends on surface properties, e.g., diffuse or specular

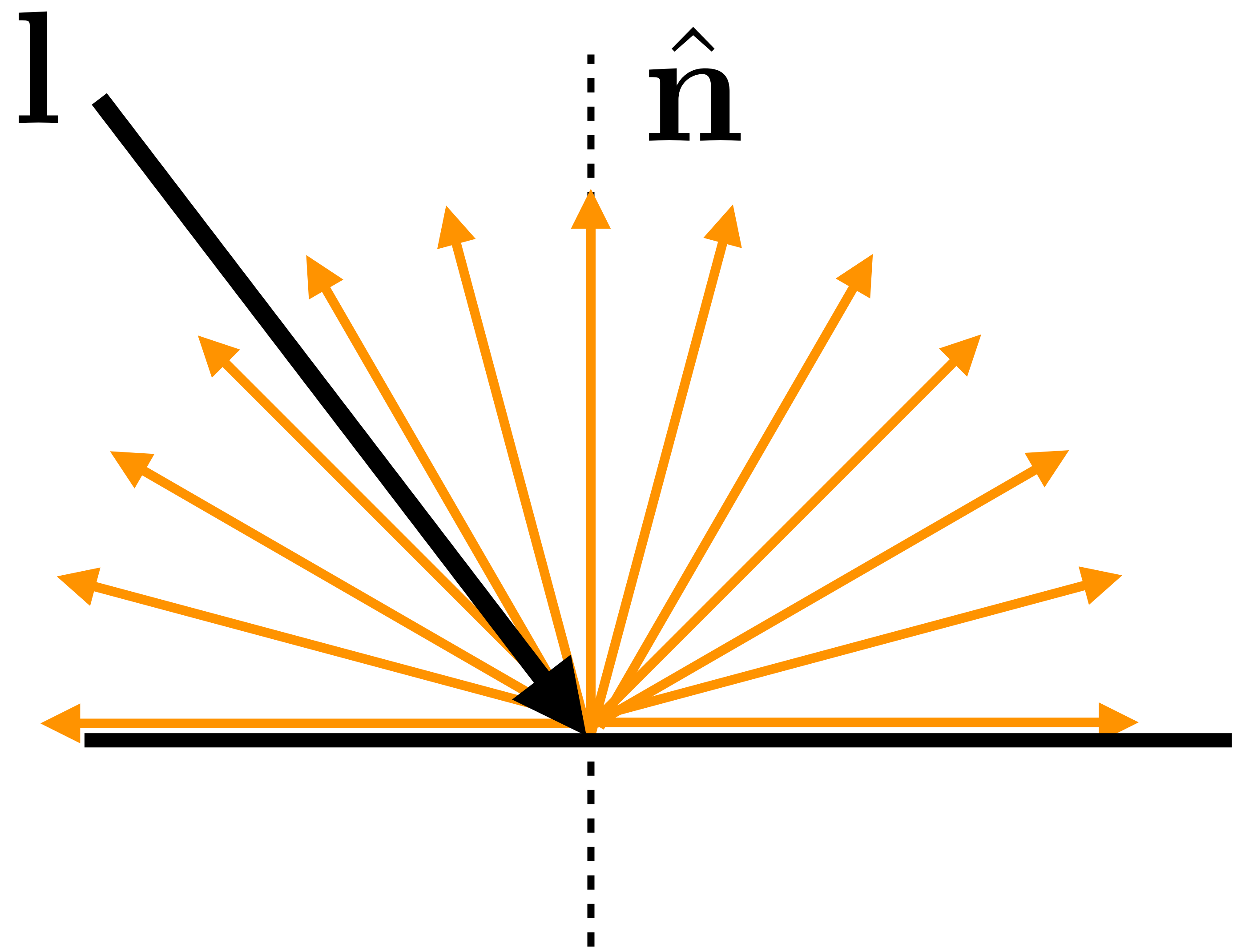
Diffuse and Specular Reflection

- A pure mirror reflects light along a line symmetrical about the surface normal
- A pure diffuse surface scatters light equally in all directions



Pure Mirror Reflection

$$\theta_i = \theta_r$$

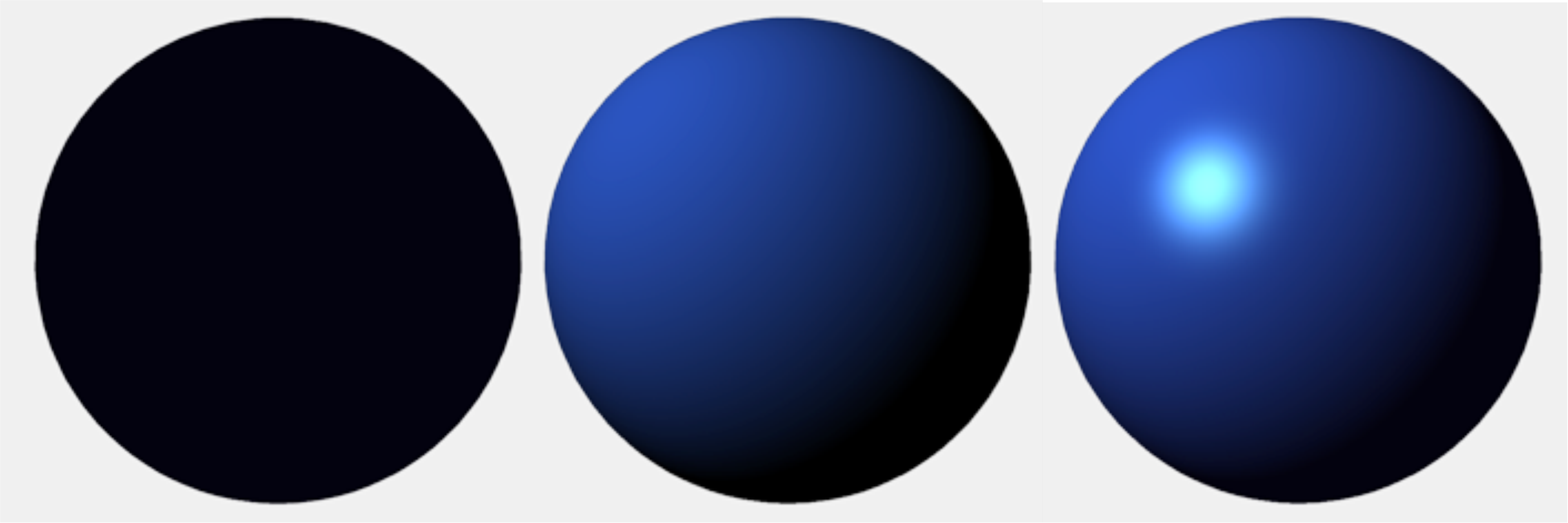


Lambertian Reflection
(Diffuse)

Specular surfaces directly reflect over a small angle

Diffuse and Specular Reflection

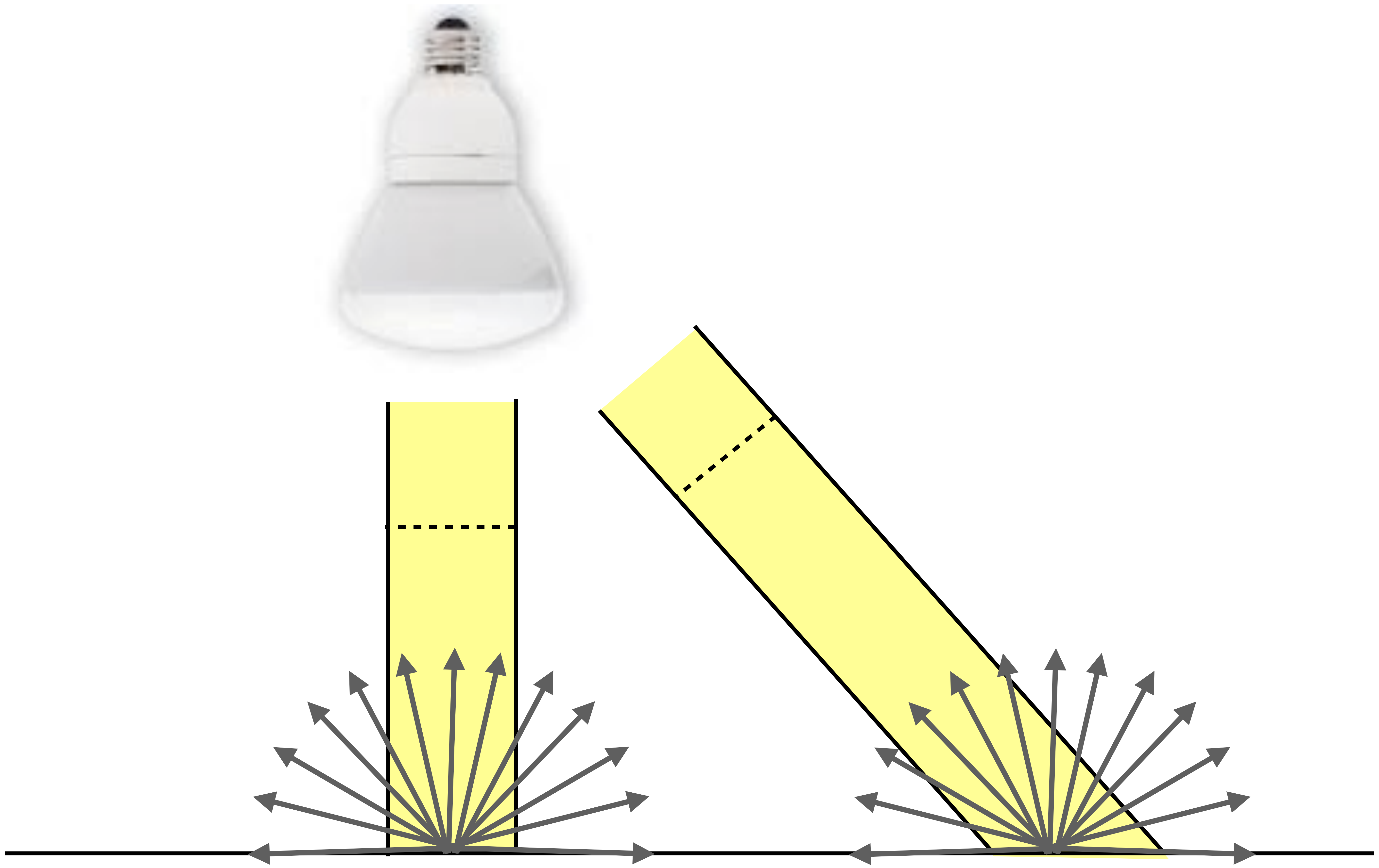
- A sphere lit with ambient, +diffuse, +specular reflectance



Ambient +Diffuse +Specular

Diffuse Reflection

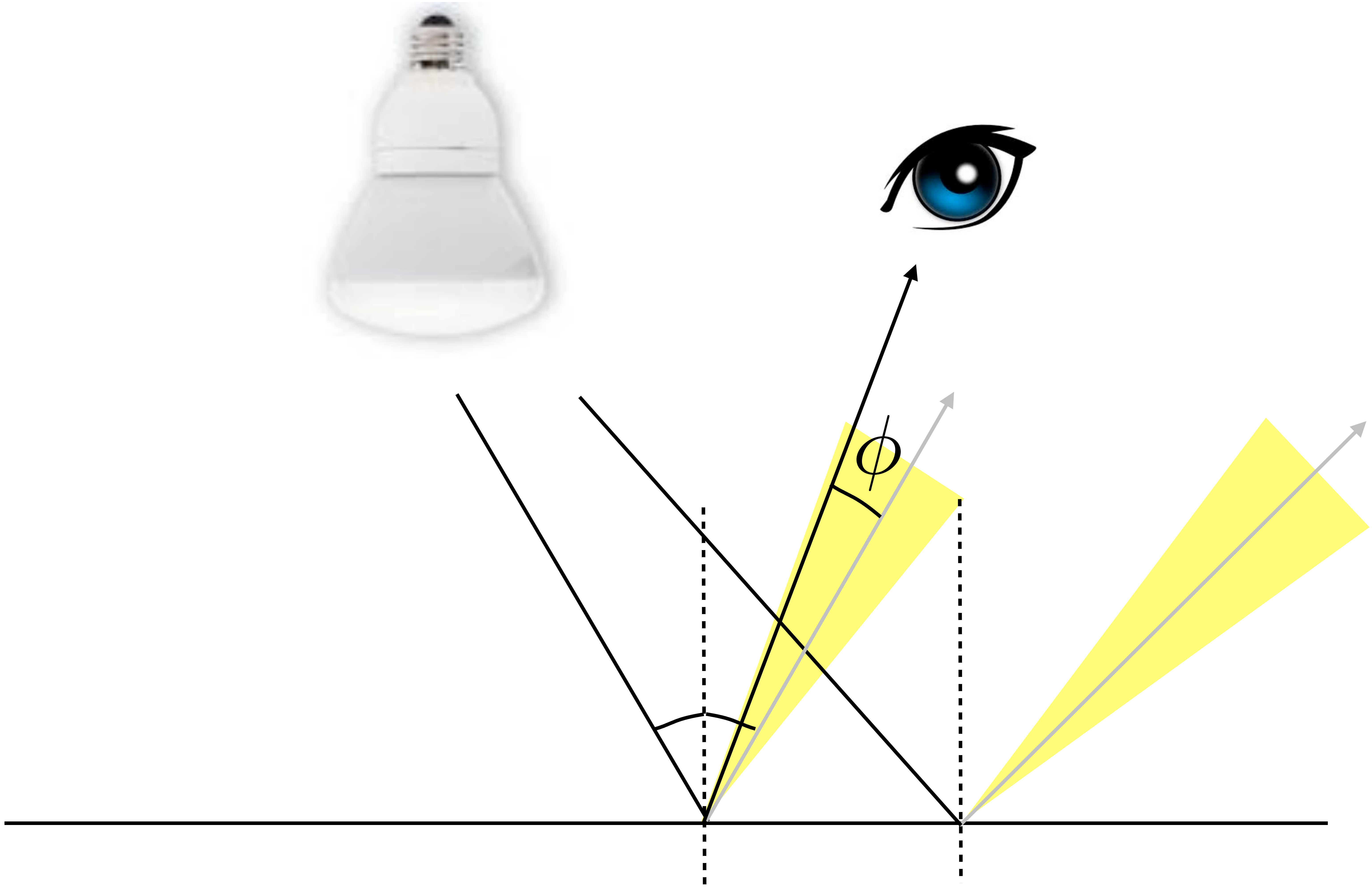
- Light is reflected equally in all directions (Lambertian surface)
- But the amount of light reaching unit surface area depends on the angle between the light and the surface...

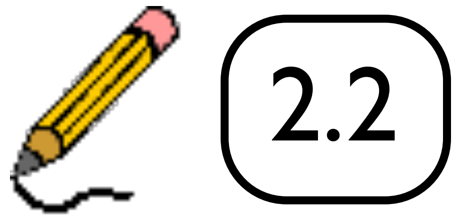


2.1

Specular Reflection

- Light reflected strongly around the mirror reflection direction
- Intensity depends on viewer position

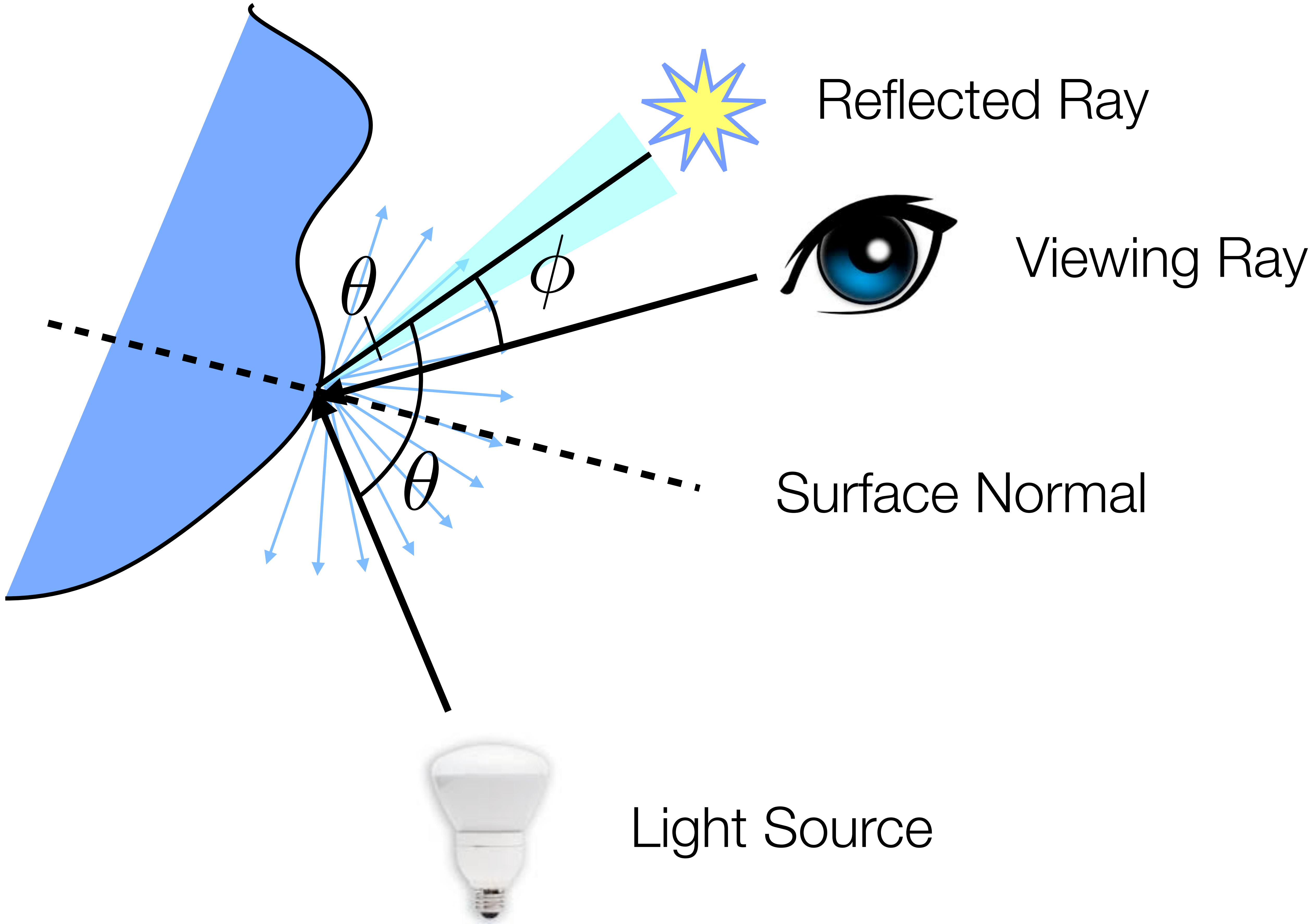




Phong Illumination Model

- Includes ambient, diffuse and specular reflection

$$\boxed{I = k_a i_a + k_d i_d \cos\theta + k_s i_s \cos^\alpha \phi}$$



Reflectance in Vision

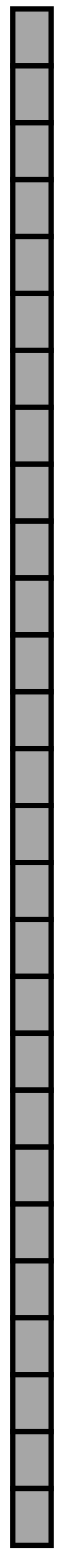
Cameras

Old school **film** camera

Digital CCD/CMOS camera

Let's say we have a **sensor** ...

Digital CCD/CMOS camera

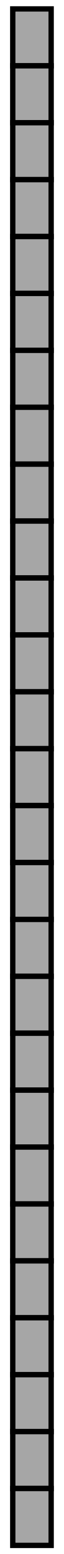


Slide Credit: Ioannis (Yannis) Gkioulekas (CMU)

… and the **object** we would like to photograph

What would an image taken like this look like?

real-world object

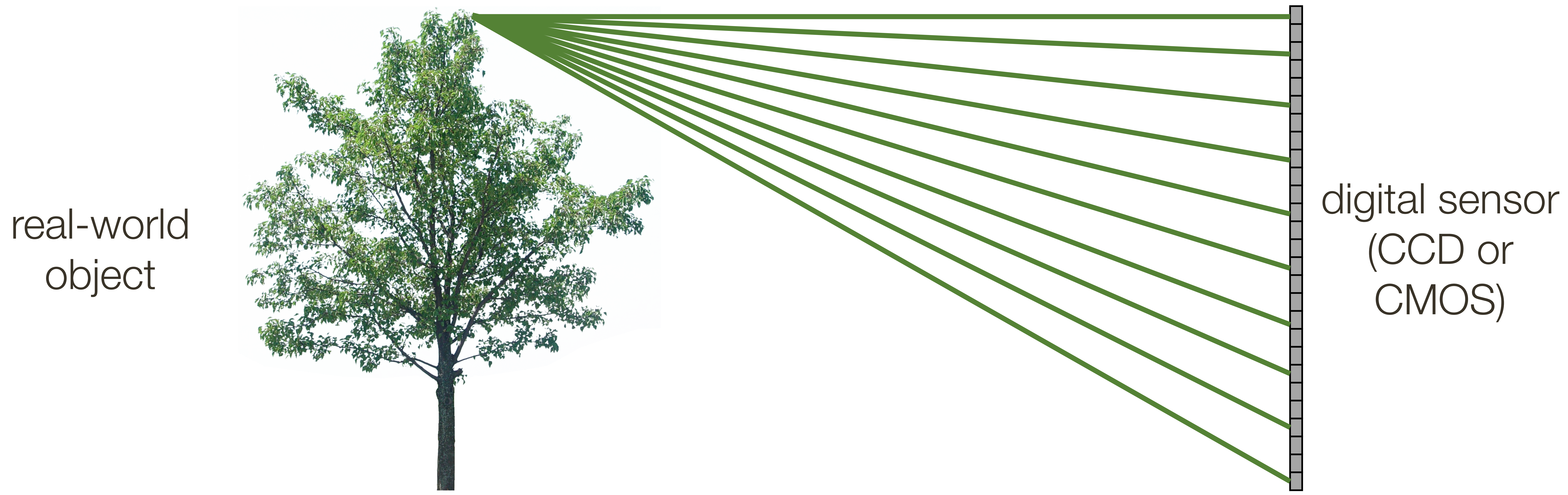


digital sensor (CCD or CMOS)

Bare-sensor imaging

Slide Credit: Ioannis (Yannis) Gkioulekas (CMU)

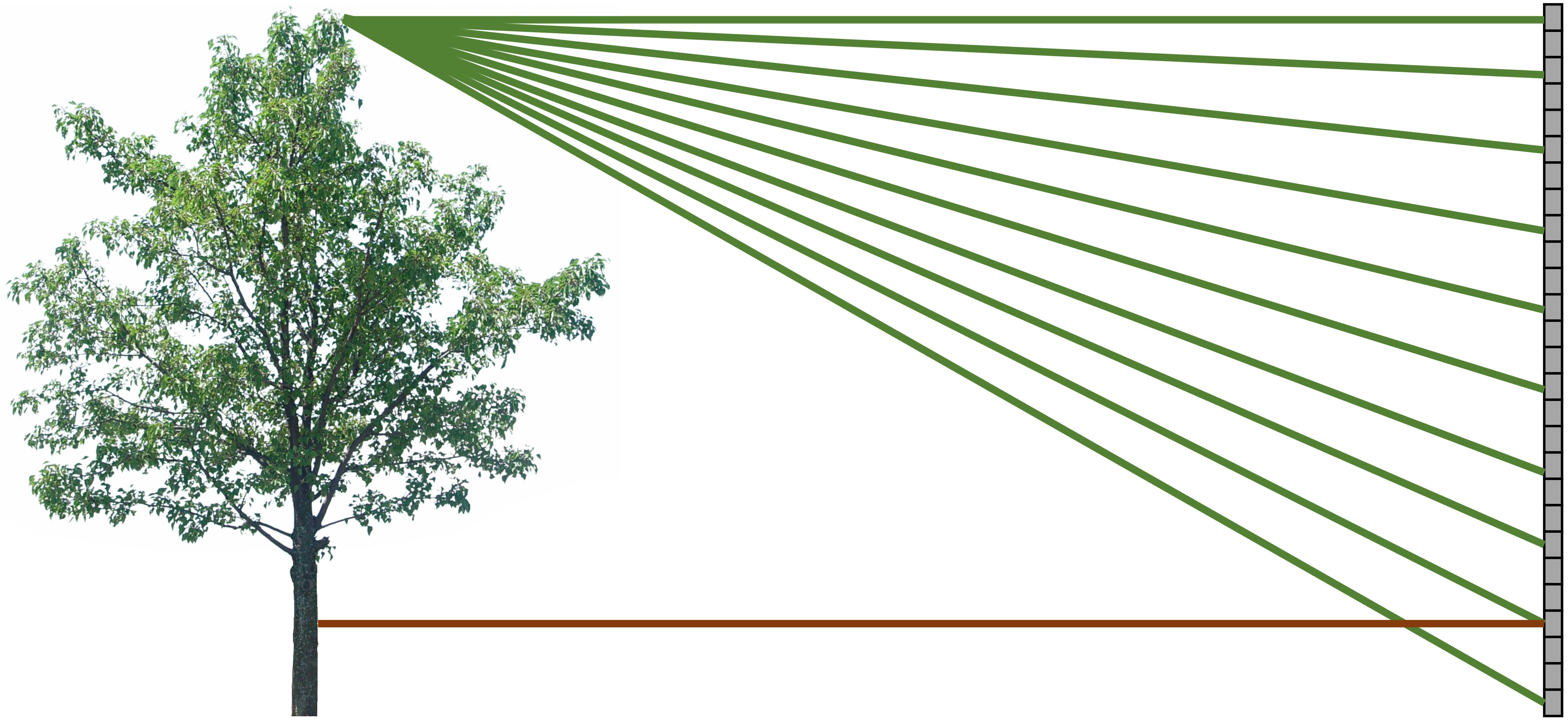
Bare-sensor imaging



Slide Credit: Ioannis (Yannis) Gkioulekas (CMU)

Bare-sensor imaging

real-world object

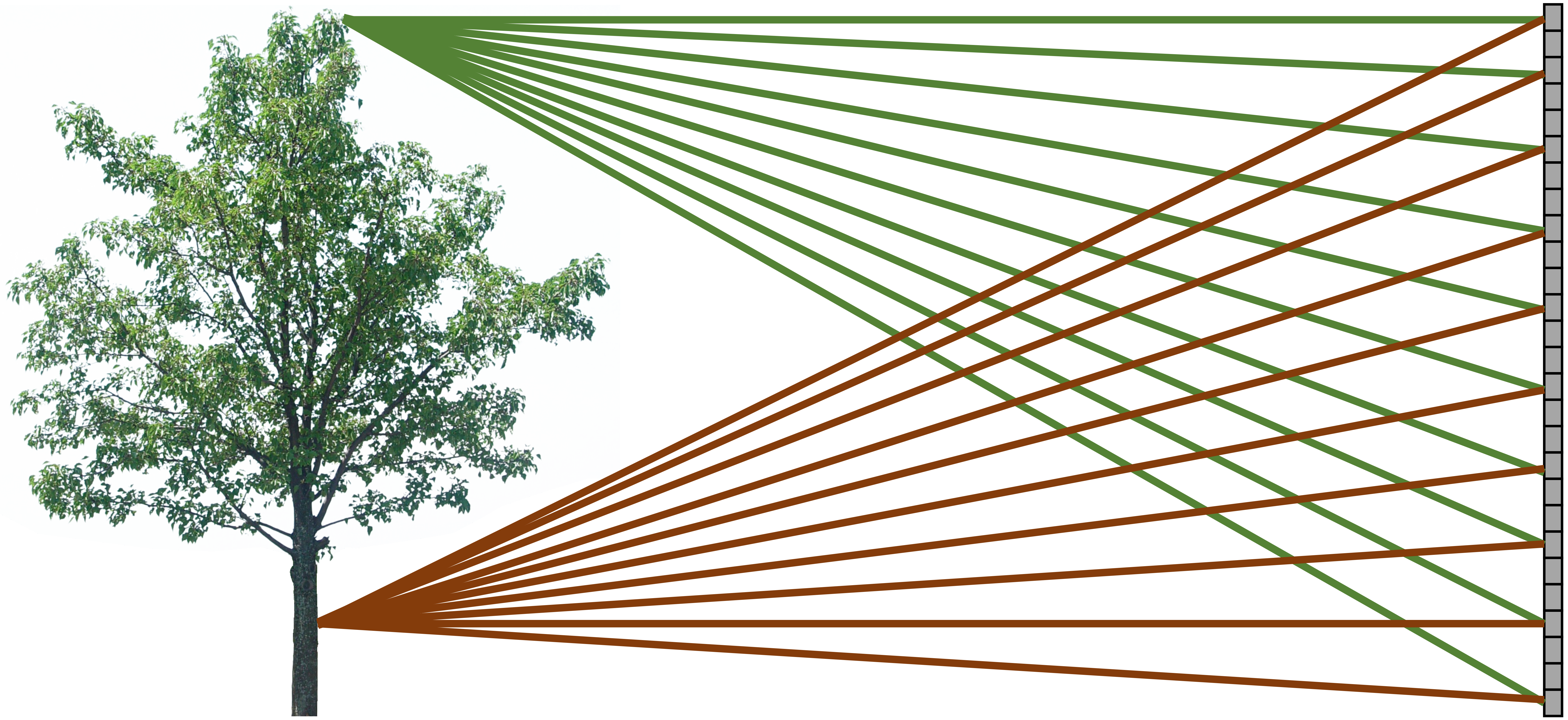


digital sensor (CCD or CMOS)

Slide Credit: Ioannis (Yannis) Gkioulekas (CMU)

Bare-sensor imaging

real-world object



digital sensor (CCD or CMOS)

All scene points contribute to all sensor pixels

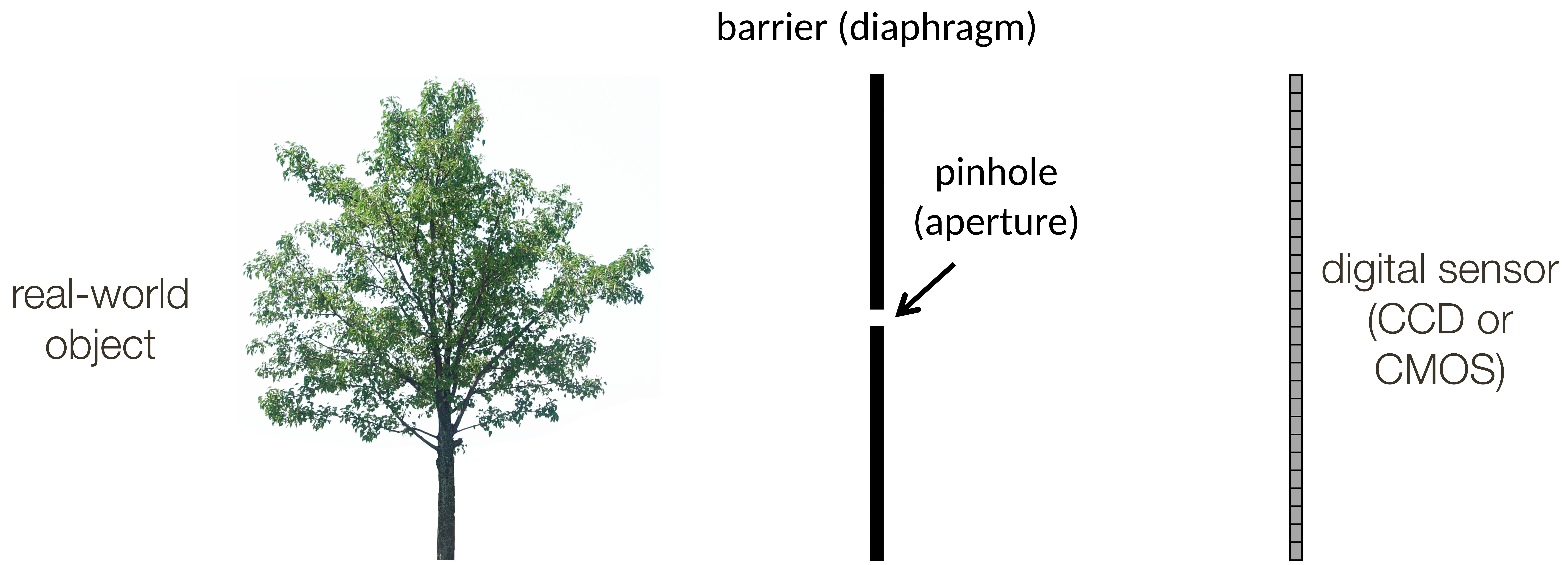
Slide Credit: Ioannis (Yannis) Gkioulekas (CMU)

Bare-sensor imaging

All scene points contribute to all sensor pixels

Slide Credit: Ioannis (Yannis) Gkioulekas (CMU)

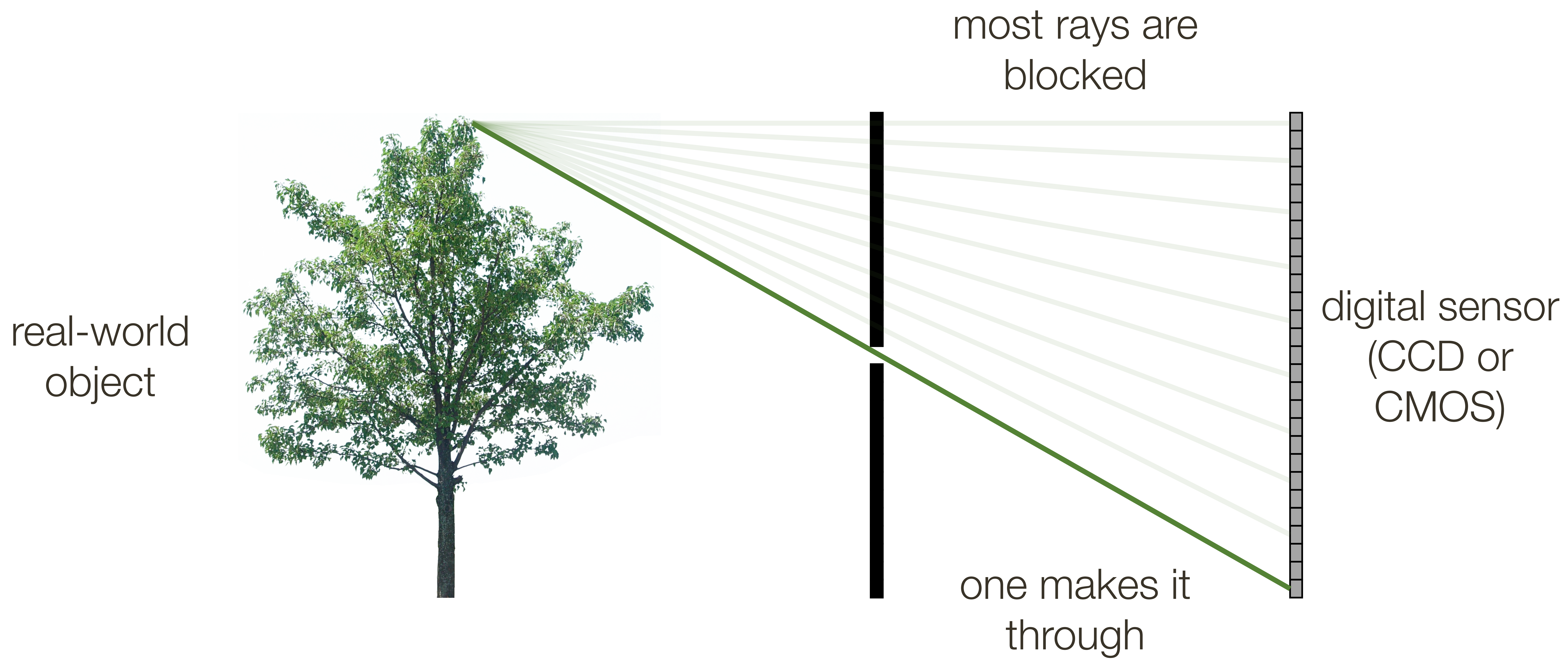
Pinhole Camera



What would an image taken like this look like?

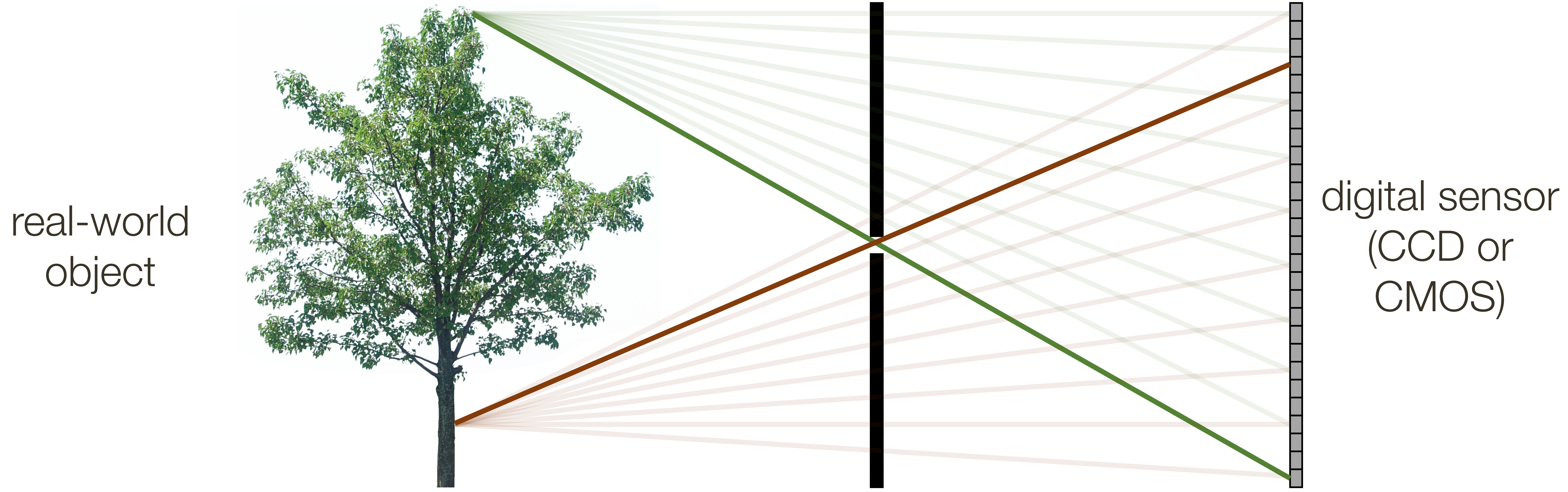
Slide Credit: Ioannis (Yannis) Gkioulekas (CMU)

Pinhole Camera



Slide Credit: Ioannis (Yannis) Gkioulekas (CMU)

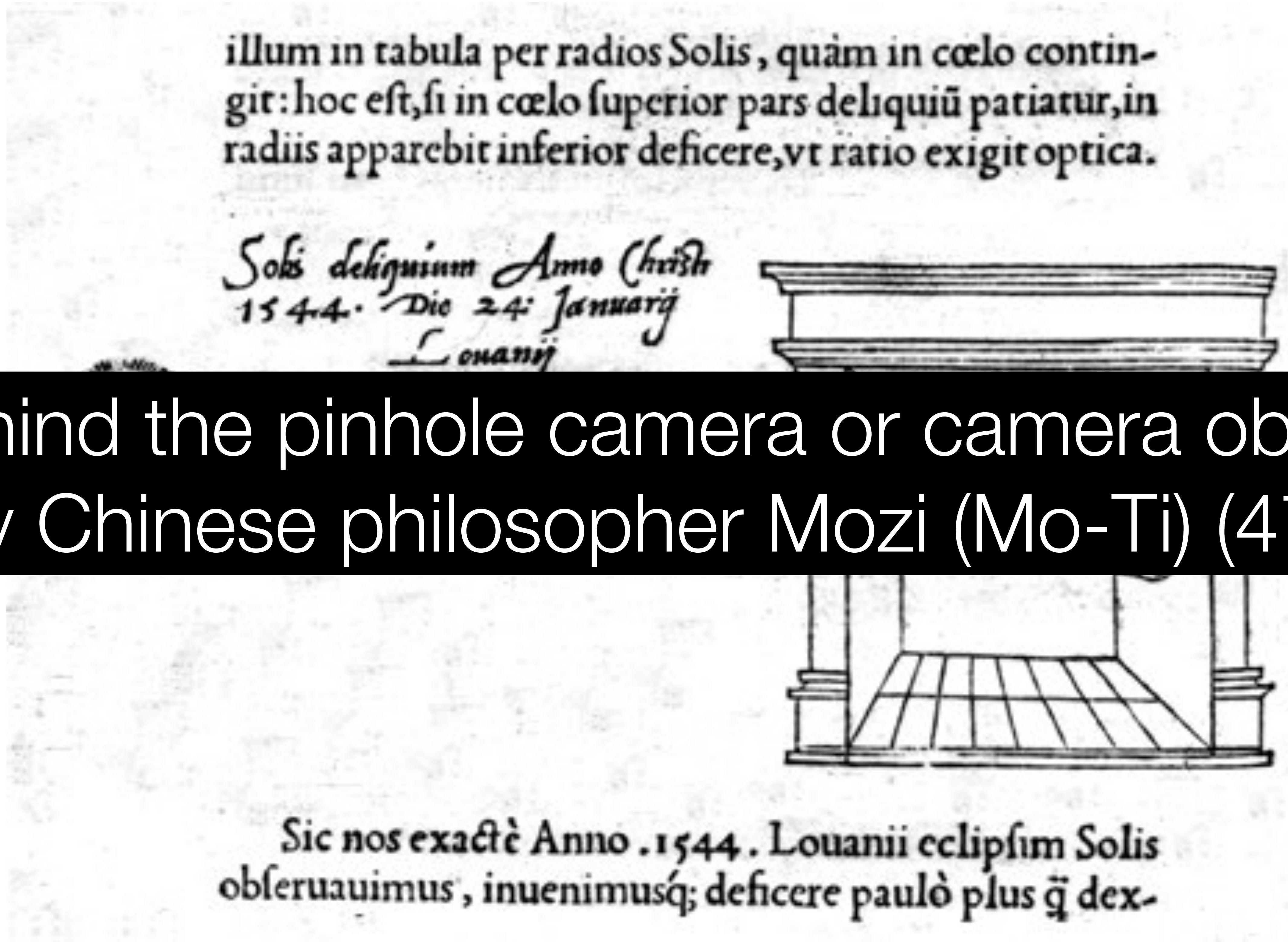
Pinhole Camera



Each scene point contributes to only one sensor pixel

Slide Credit: Ioannis (Yannis) Gkioulekas (CMU)

Camera Obscura (latin for “dark chamber”)



illum in tabula per radios Solis, quàm in cœlo contin-
git: hoc eſt, ſi in cœlo ſuperior pars deliquiũ patiatur, in
radiis apparebit inferior deficere, vt ratio exigit optica.

Sic nos exactè Anno .1544. Louanii eclipſim Solis
obſeruauimus, inuenimuſq; deficere paulò plus q̄ dex-

principles behind the pinhole camera or camera obscura were first mentioned by Chinese philosopher Mozi (Mo-Ti) (470 to 390 BCE)

Reinerus Gemma-Frisius observed an eclipse of the sun at Louvain on January 24, 1544. He used this illustration in his book, “De Radio Astronomica et Geometrica,” 1545. It is thought to be the first published illustration of a camera obscura.

Credit: John H., Hammond, “Th Camera Obscure, A Chronicle”

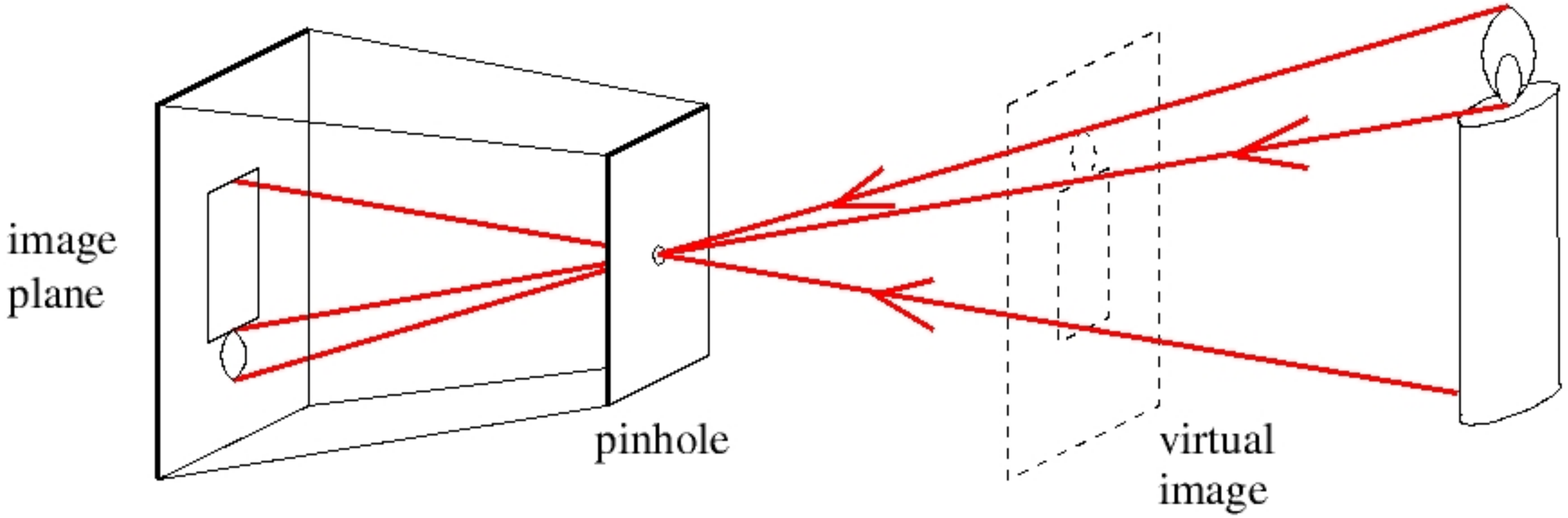
First **Photograph** on Record

La table servie

Credit: Nicéphore Niepce, 1822

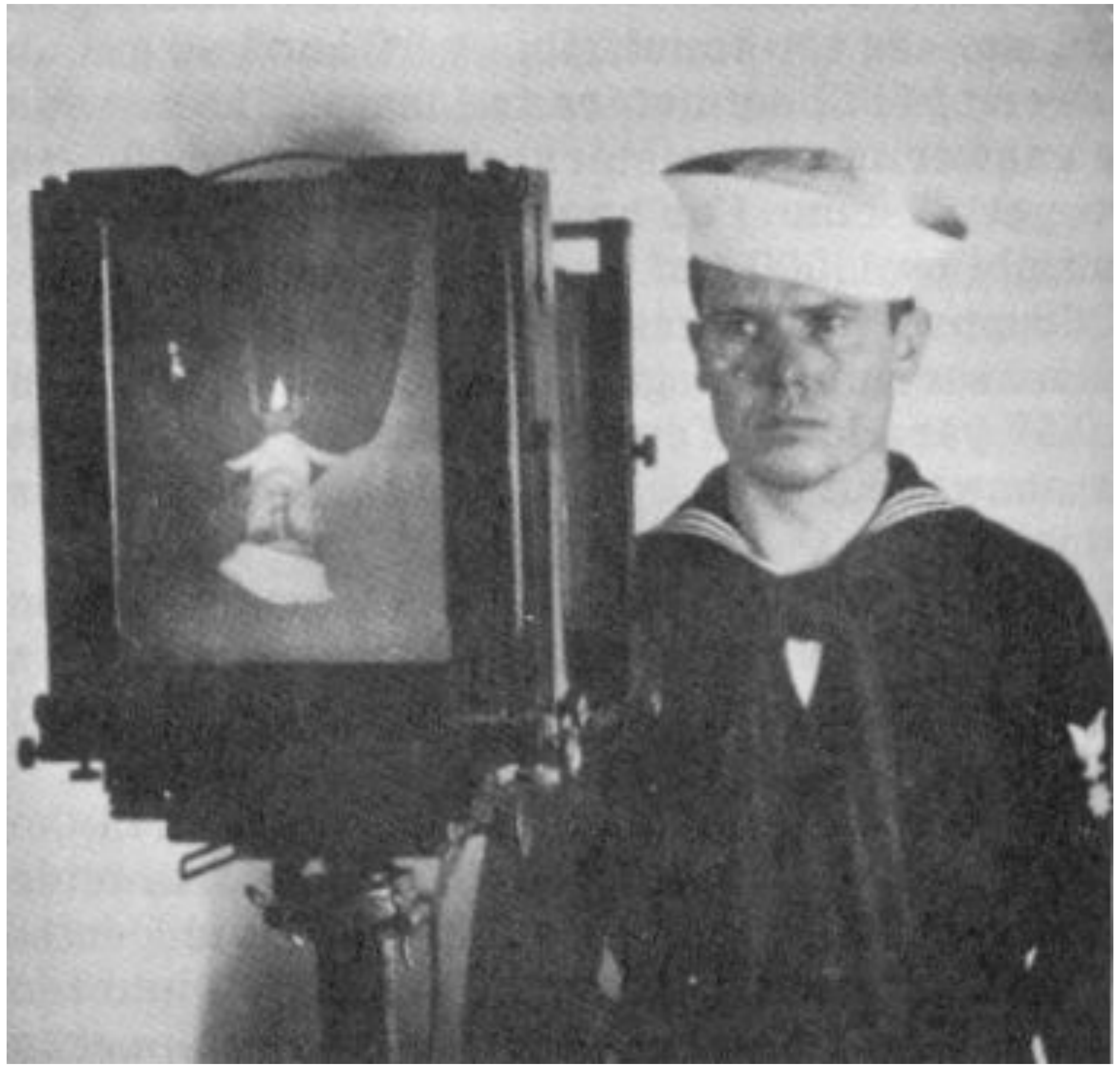
Pinhole Camera

A pinhole camera is a box with a small hall (**aperture**) in it



Forsyth & Ponce (2nd ed.) Figure 1.2

Image **Formation**



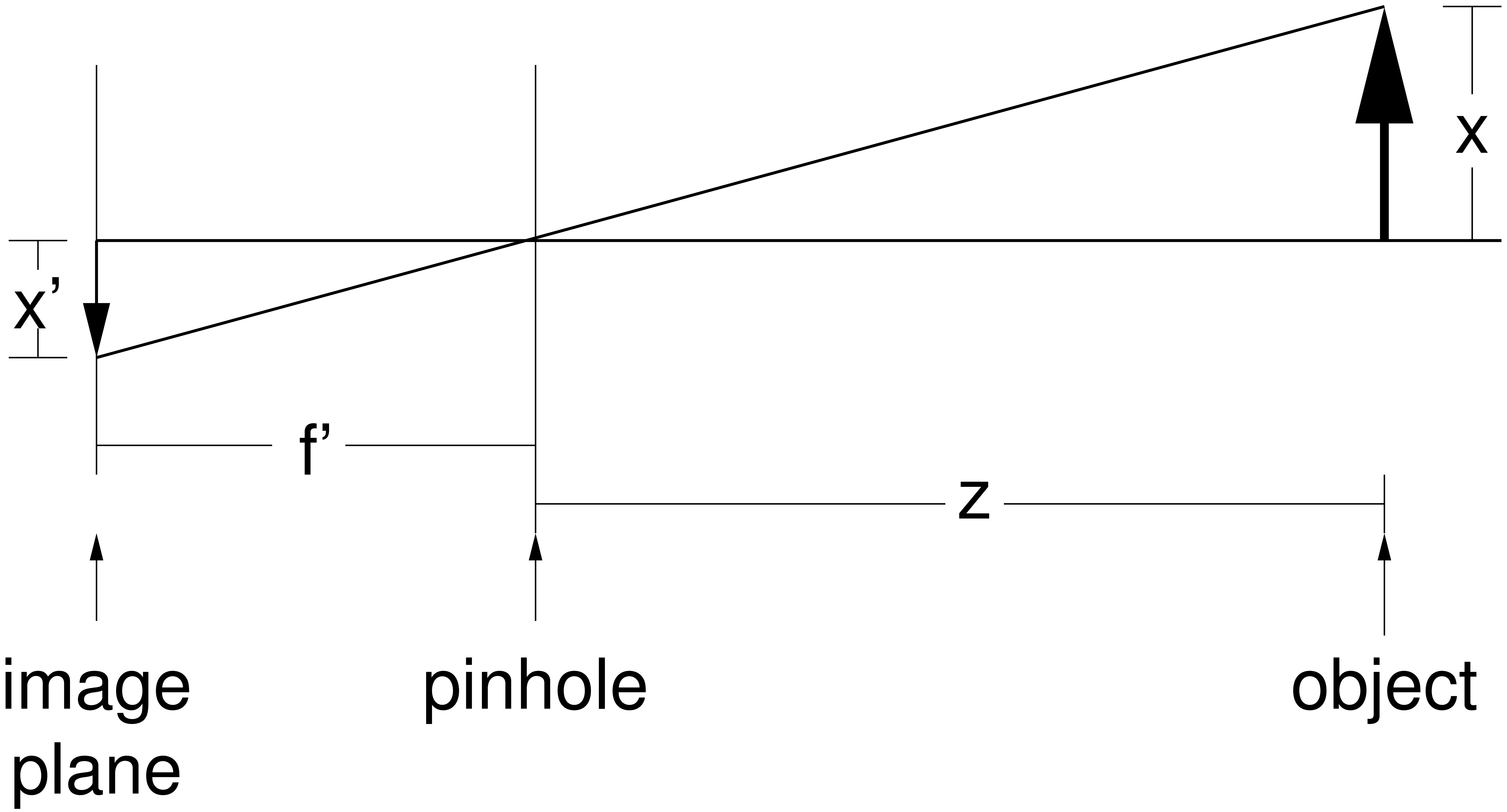
Forsyth & Ponce (2nd ed.) Figure 1.1

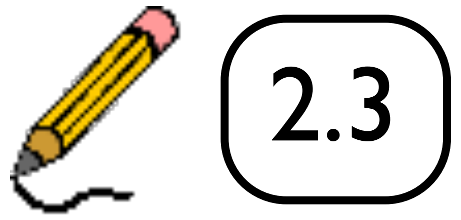
Credit: US Navy, Basic Optics and Optical Instruments. Dover, 1969

Accidental Pinhole Camera

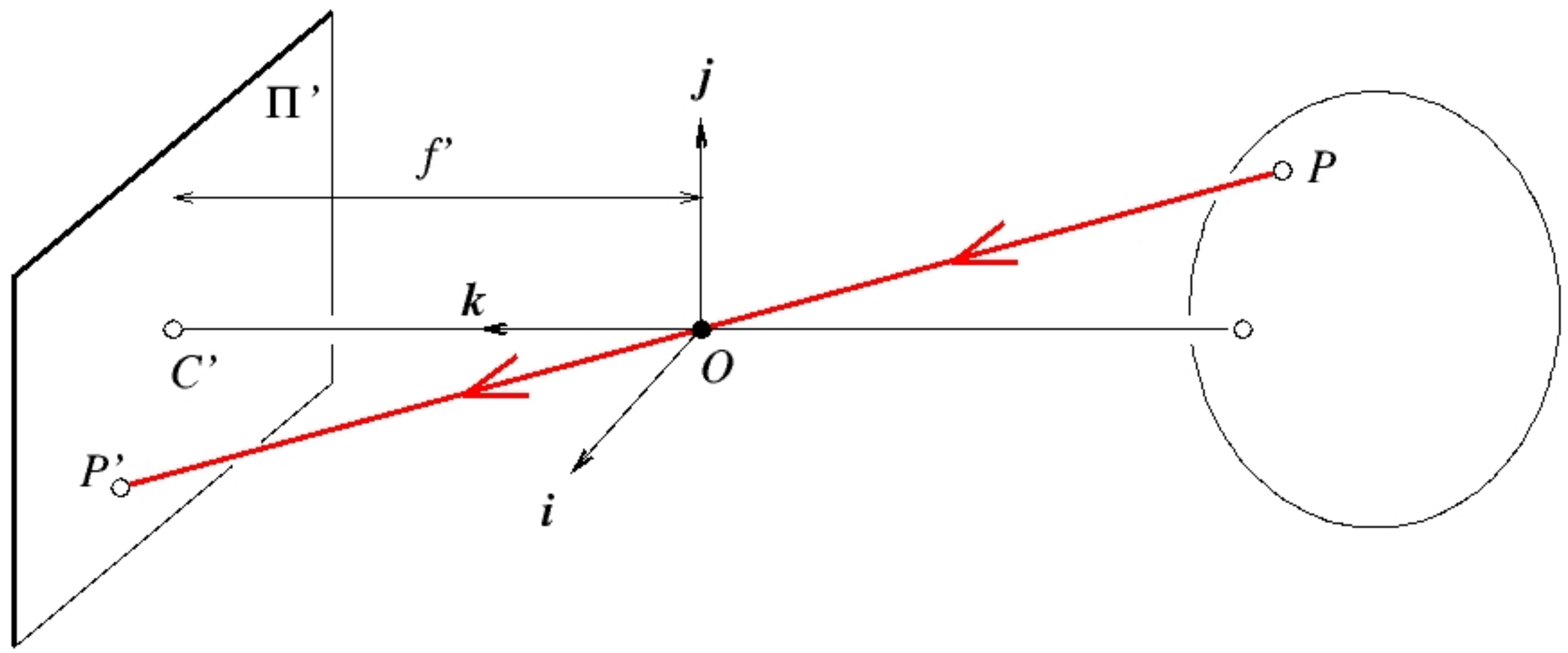
Image Credit: Ioannis (Yannis) Gkioulekas (CMU)

Pinhole Camera





Perspective Projection



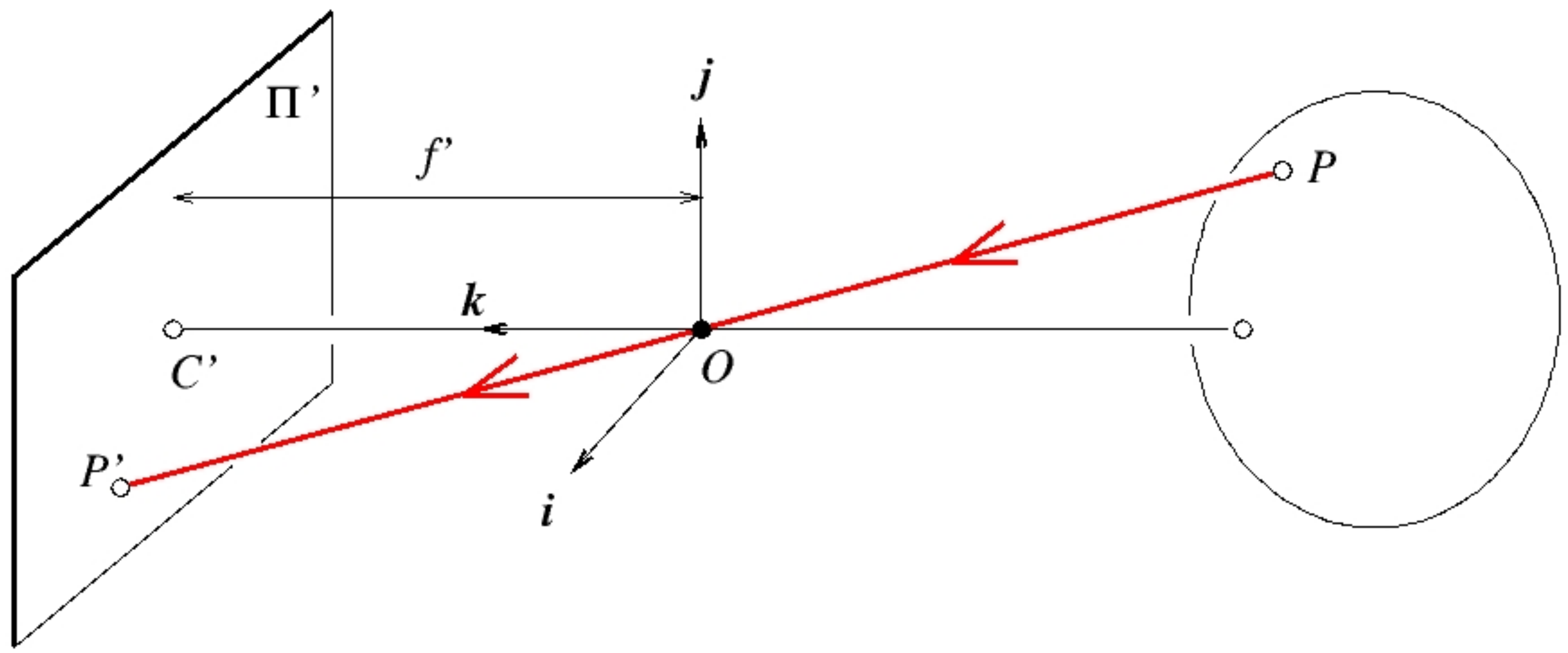
3D object point

Forsyth & Ponce (1st ed.) Figure 1.4

$$P = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$ projects to 2D image point $$P' = \begin{bmatrix} x' \\ y' \end{bmatrix}$$ where

$$\boxed{\begin{aligned} x' &= f' \frac{x}{z} \\ y' &= f' \frac{y}{z} \end{aligned}}$$

Perspective Projection: Matrix Form



Forsyth & Ponce (1st ed.) Figure 1.4

Camera Matrix

$$\mathbf{C} = \begin{bmatrix} f' & 0 & 0 & 0 \\ 0 & f' & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

3D object point

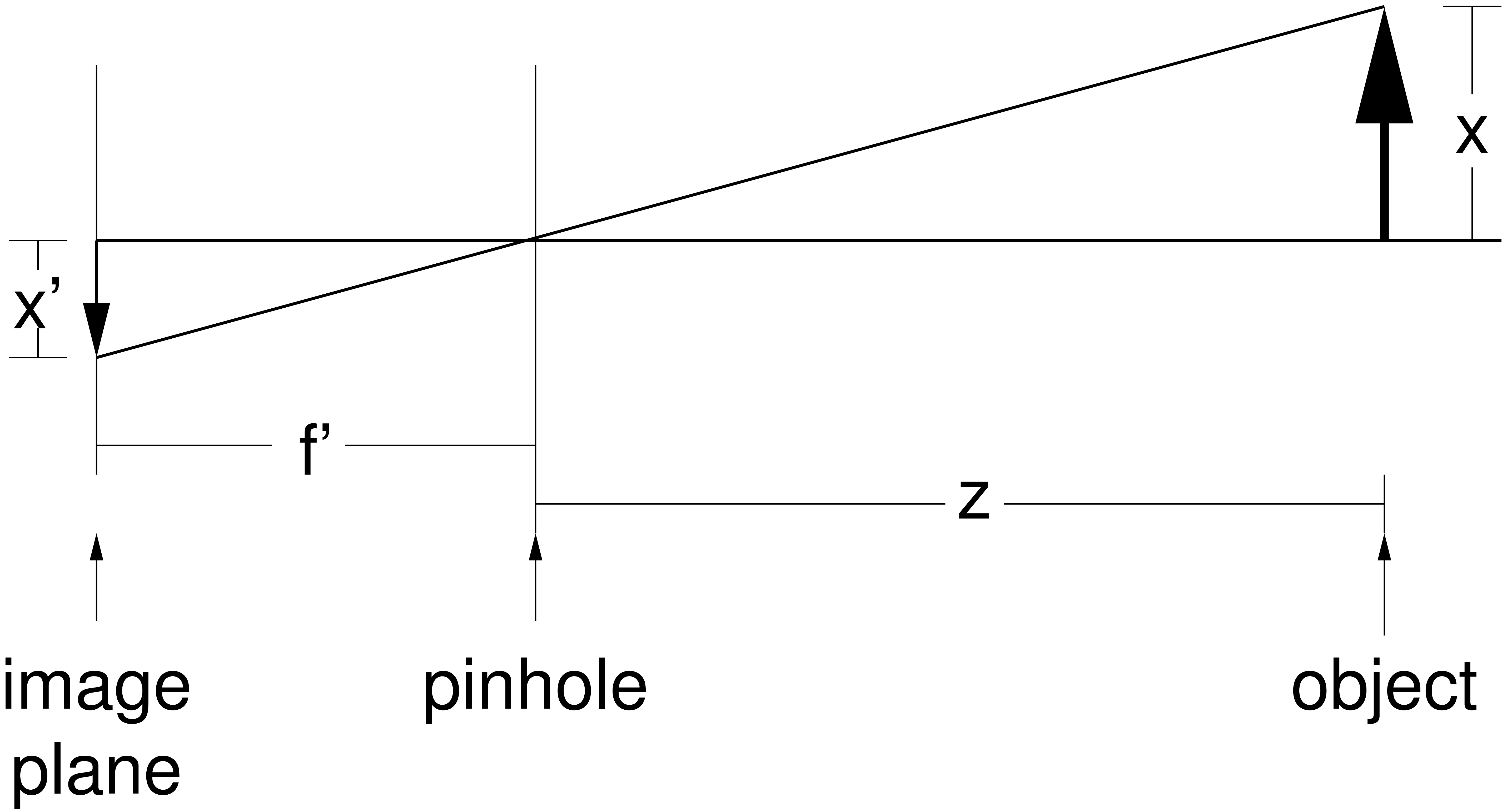
$$P = \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$ projects to 2D image point $$P' = \begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix}$$ where $$\boxed{\text{s}P' = \mathbf{C}P}$$

(s is a scale factor)

2.4

Pinhole Camera

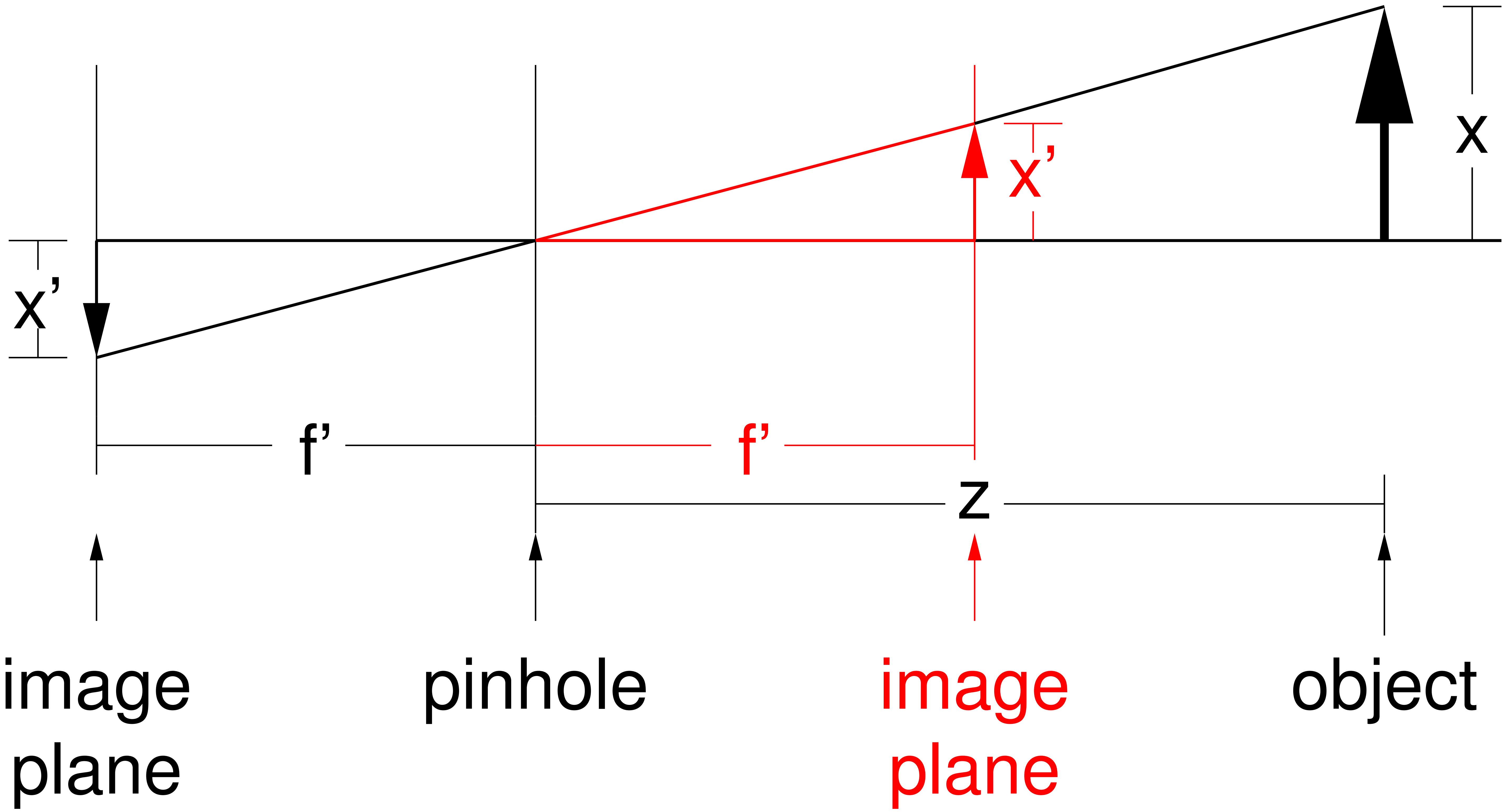
f' is the **focal length** of the camera



Note: In a pinhole camera we can adjust the focal length, all this will do is change the **size** of the resulting image

Pinhole Camera

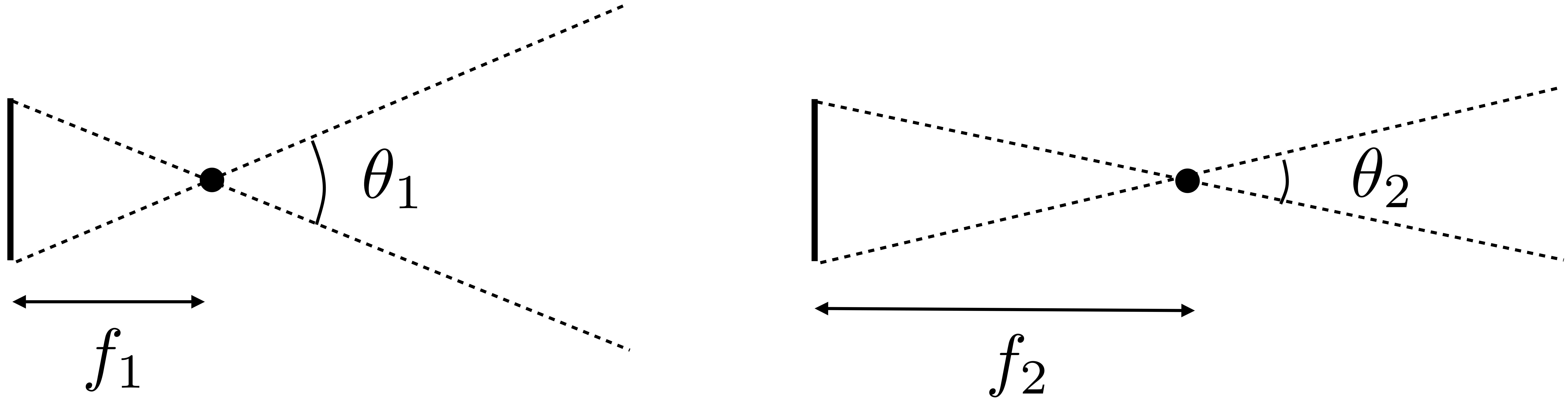
It is convenient to think of the **image plane** being in front of the pinhole



What happens if object moves towards the camera? Away from the camera?

Focal Length

- For a fixed sensor size, focal length determines the field of view (fov)



2.5 **Q:** What is the field of view of a full frame (35mm) camera with a 50mm lens? 100mm lens?

Focal Length

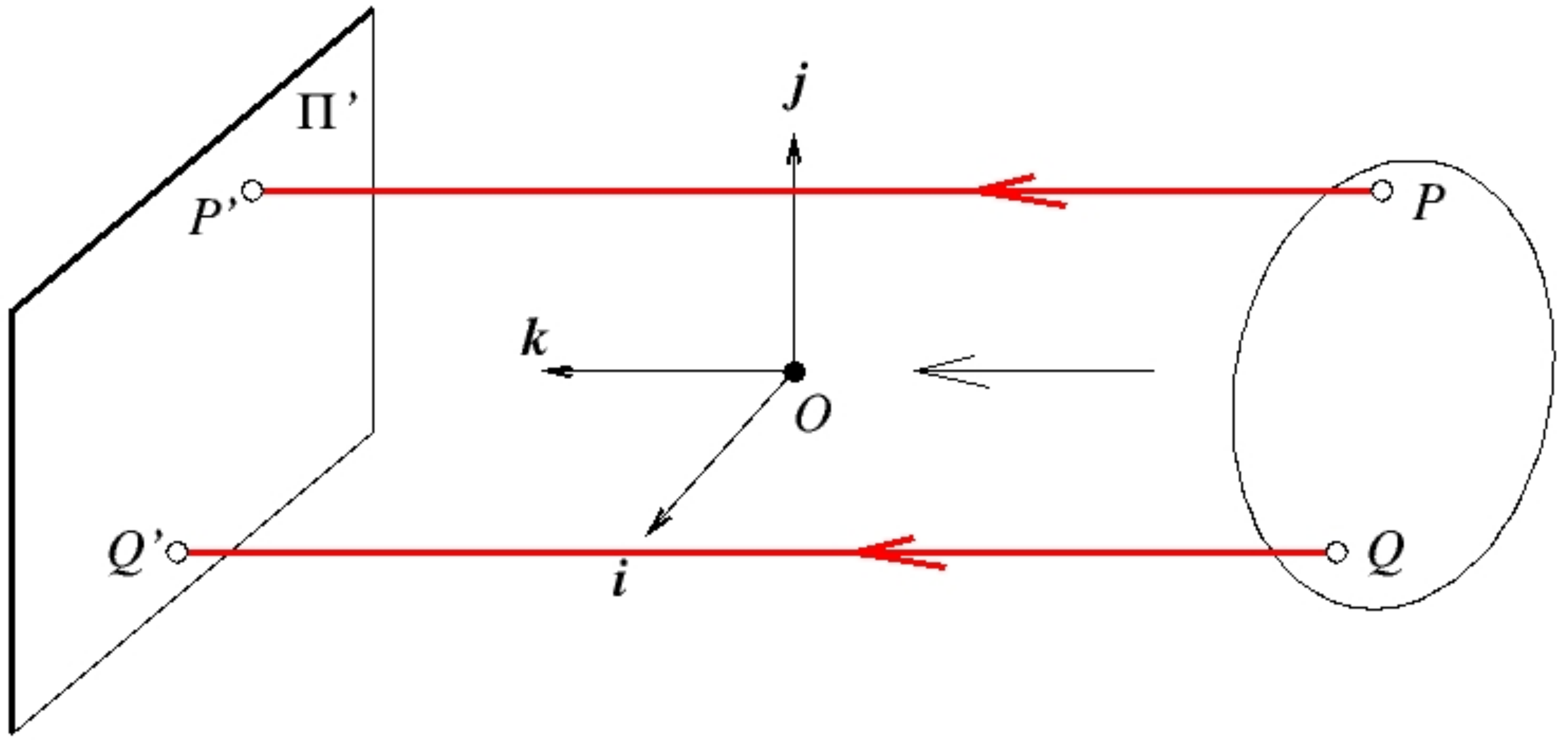
28 mm

35 mm

50 mm

70 mm

Orthographic Projection

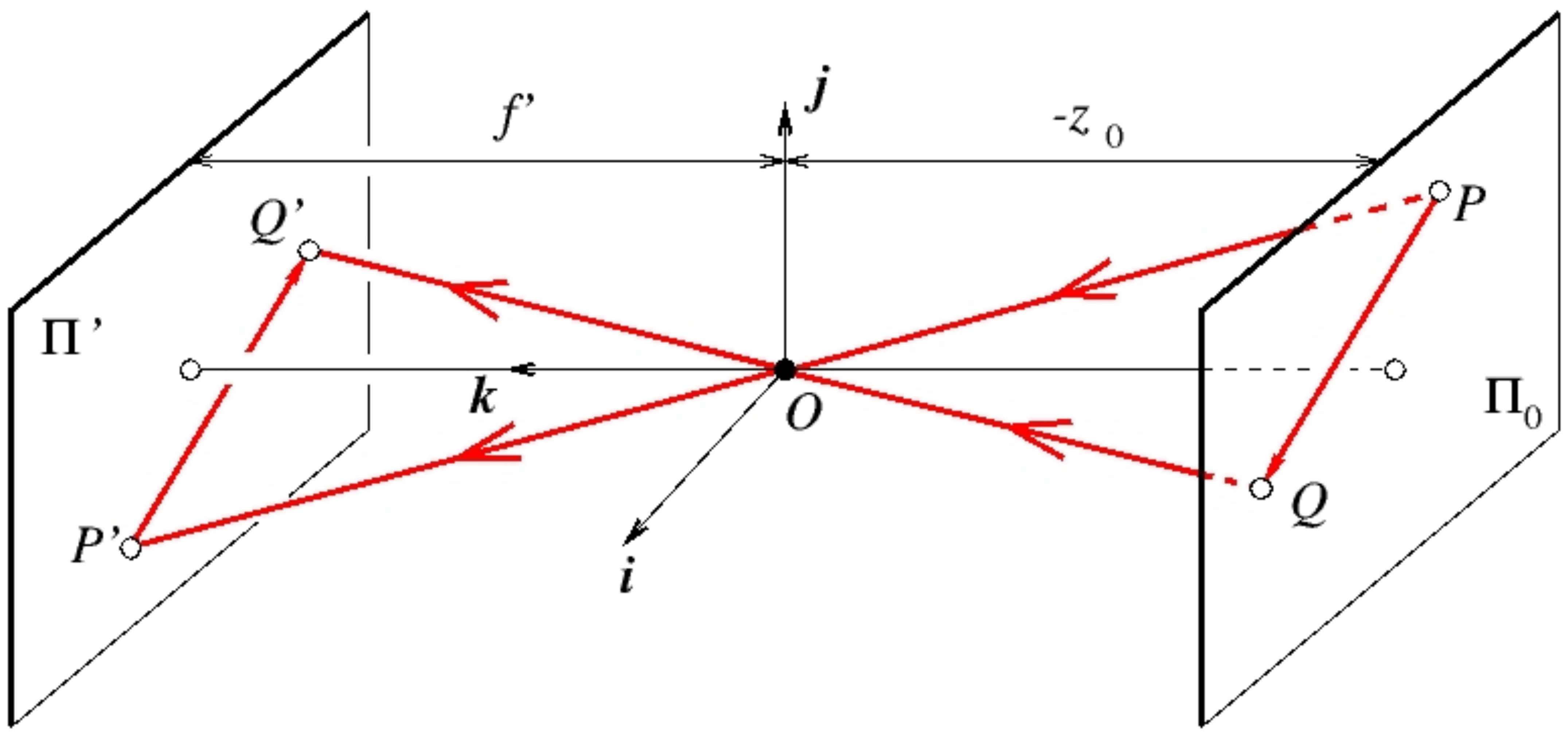


Forsyth & Ponce (1st ed.) Figure 1.6

3D object point $P = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$ projects to 2D image point $P' = \begin{bmatrix} x' \\ y' \end{bmatrix}$

where $\boxed{\begin{aligned} x' &= x \\ y' &= y \end{aligned}}$

Weak Perspective



Forsyth & Ponce (1st ed.) Figure 1.5

3D object point $P = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$ in Π_0 projects to 2D image point $P' = \begin{bmatrix} x' \\ y' \end{bmatrix}$

where $\boxed{\begin{array}{rcl} x' & = & mx \\ y' & = & my \end{array}}$ and $m = \dfrac{f'}{z_0}$

Summary of **Projection Equations**

3D object point $P = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$ projects to 2D image point $P' = \begin{bmatrix} x' \\ y' \end{bmatrix}$ where

Perspective	$x' = f'\frac{x}{z}$ $y' = f'\frac{y}{z}$
Weak Perspective	$x' = m\,x$ $y' = m\,y$ $m = \frac{f'}{z_0}$
Orthographic	$x' = x$ $y' = y$

Projection Models: Pros and Cons

Weak perspective (including orthographic) has simpler mathematics

— accurate when object is small and/or distant

— useful for recognition

Perspective is more accurate for real scenes

When **maximum accuracy** is required, it is necessary to model additional details of a particular camera

— use perspective projection with additional parameters (e.g., lens distortion)

Why **Not** a Pinhole Camera?

— If pinhole is **too big** then many directions are averaged, blurring the image

— If pinhole is **too small** then diffraction becomes a factor, also blurring the image

— Generally, pinhole cameras are **dark**, because only a very small set of rays from a particular scene point hits the image plane

— Pinhole cameras are **slow**, because only a very small amount of light from a particular scene point hits the image plane per unit time

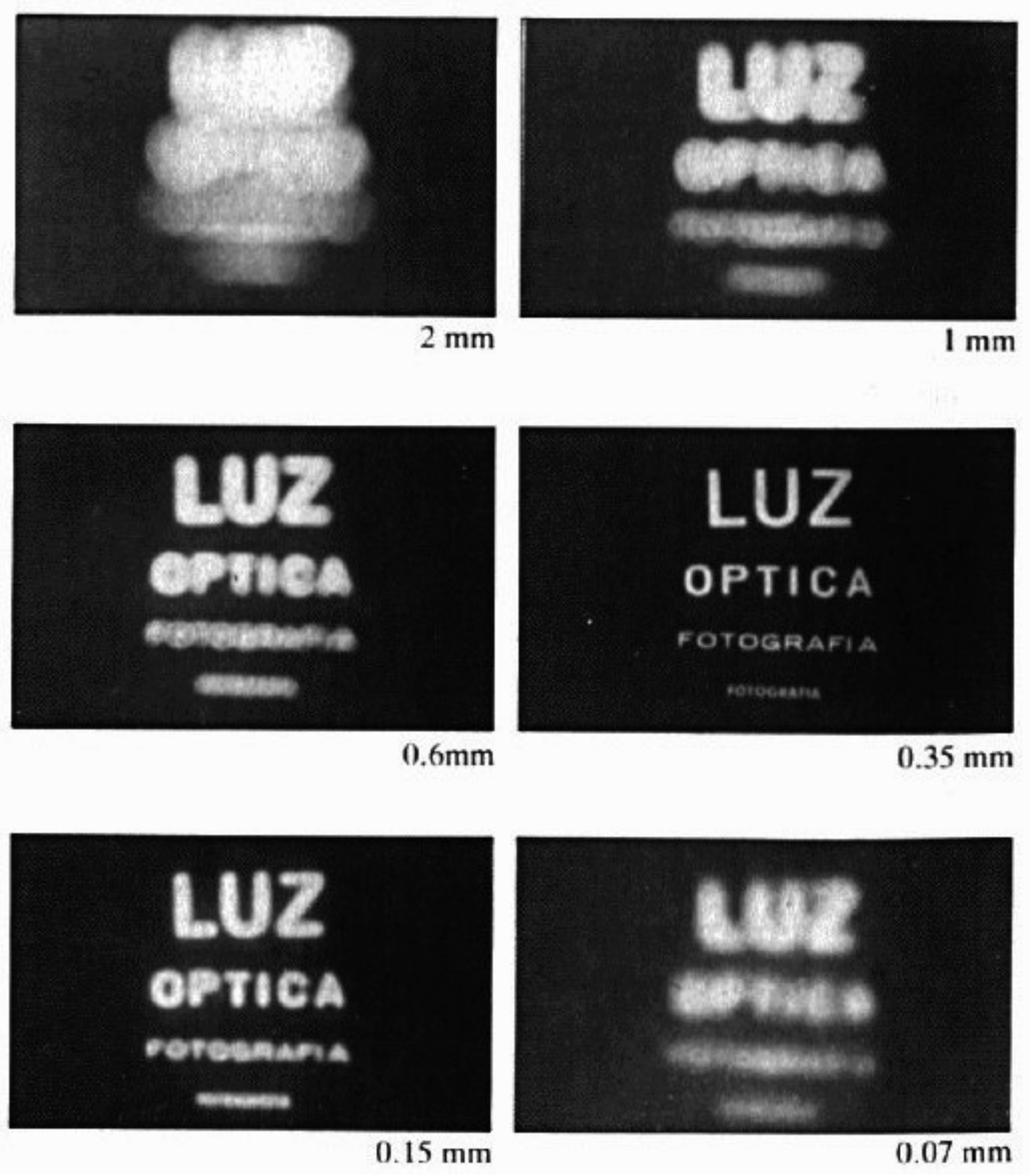
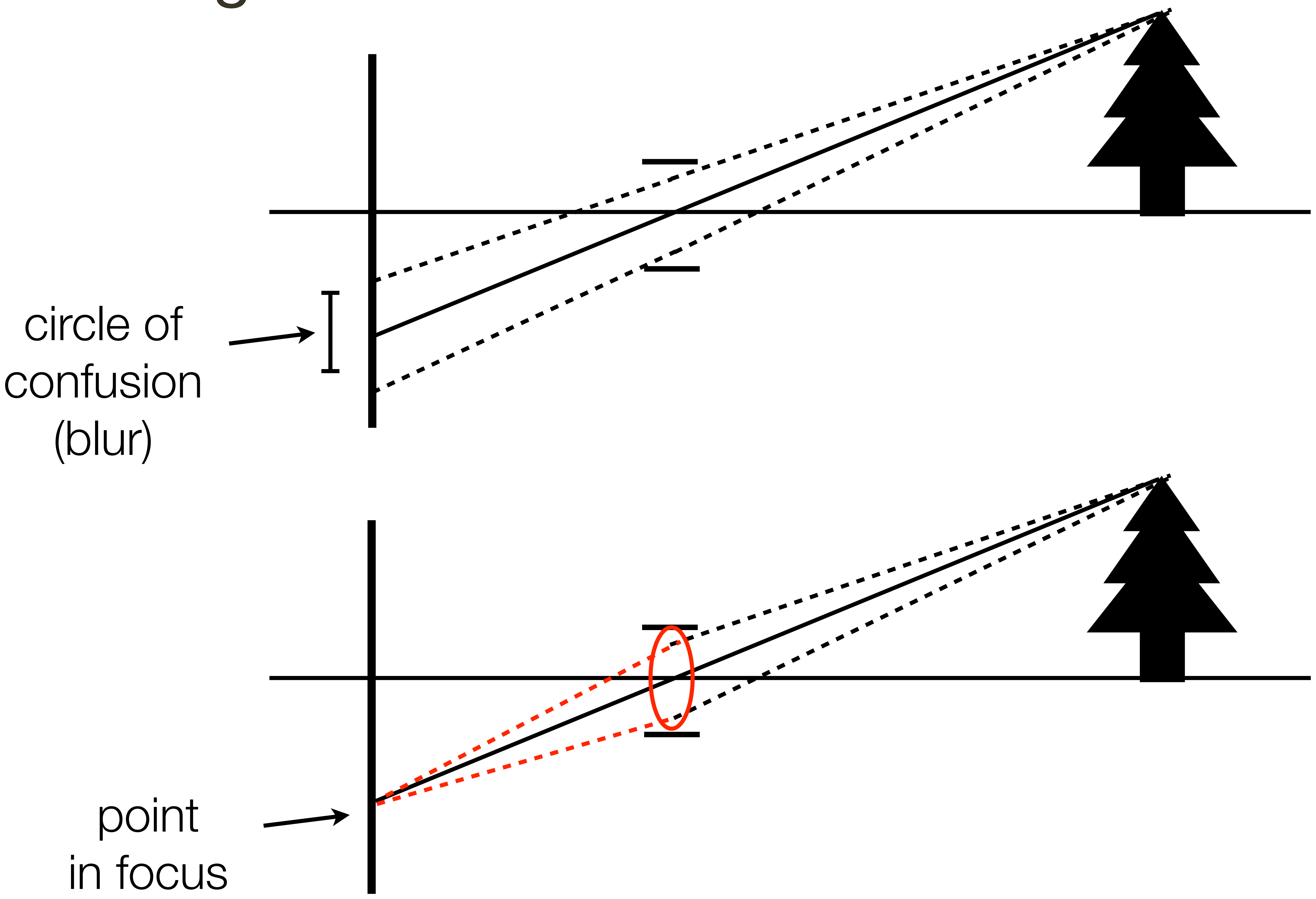


Image Credit: Credit: E. Hecht. “Optics,” Addison-Wesley, 1987

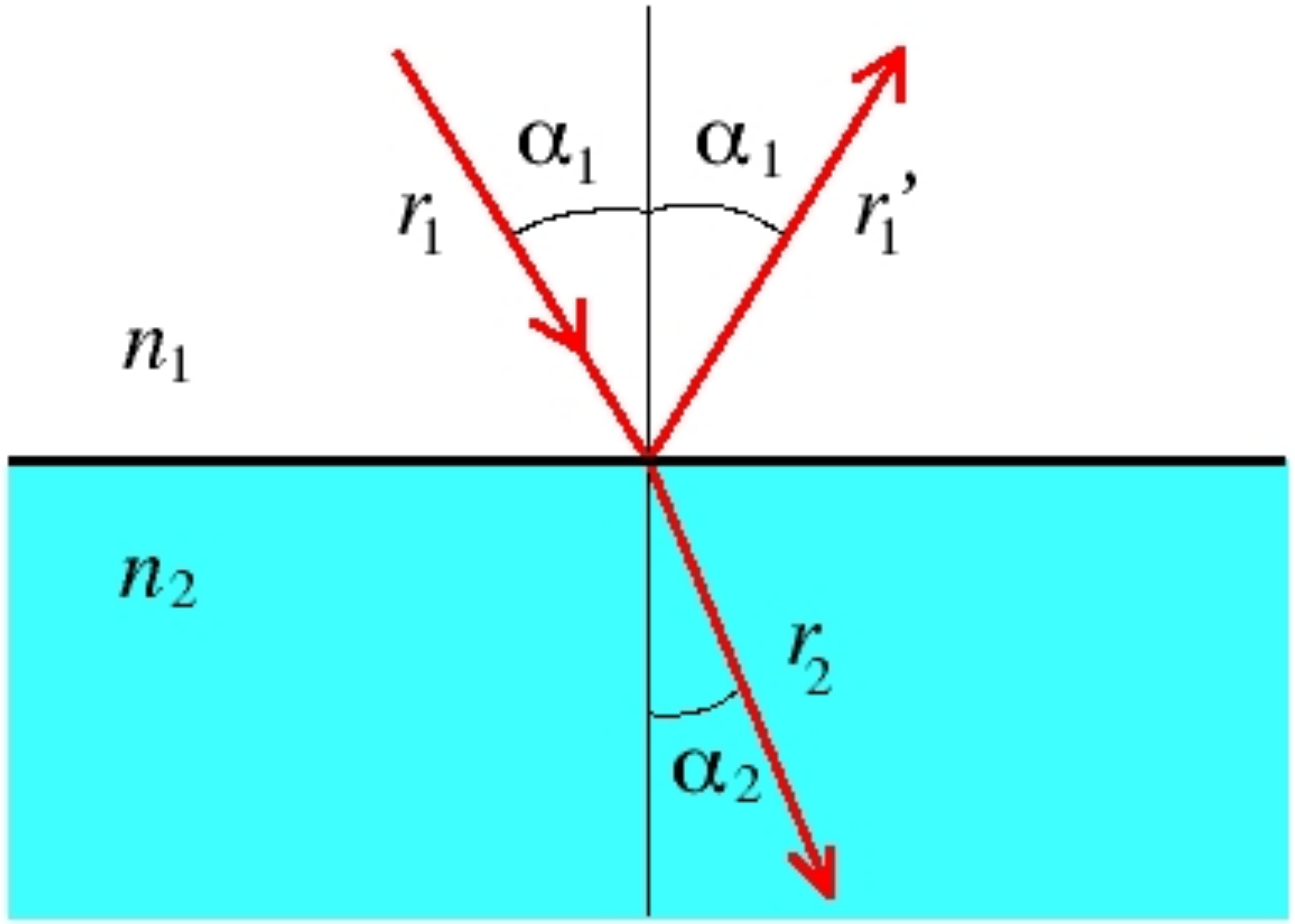
Reason for **Lenses**

- A real camera must have a finite aperture to get enough light, but this causes blur in the image



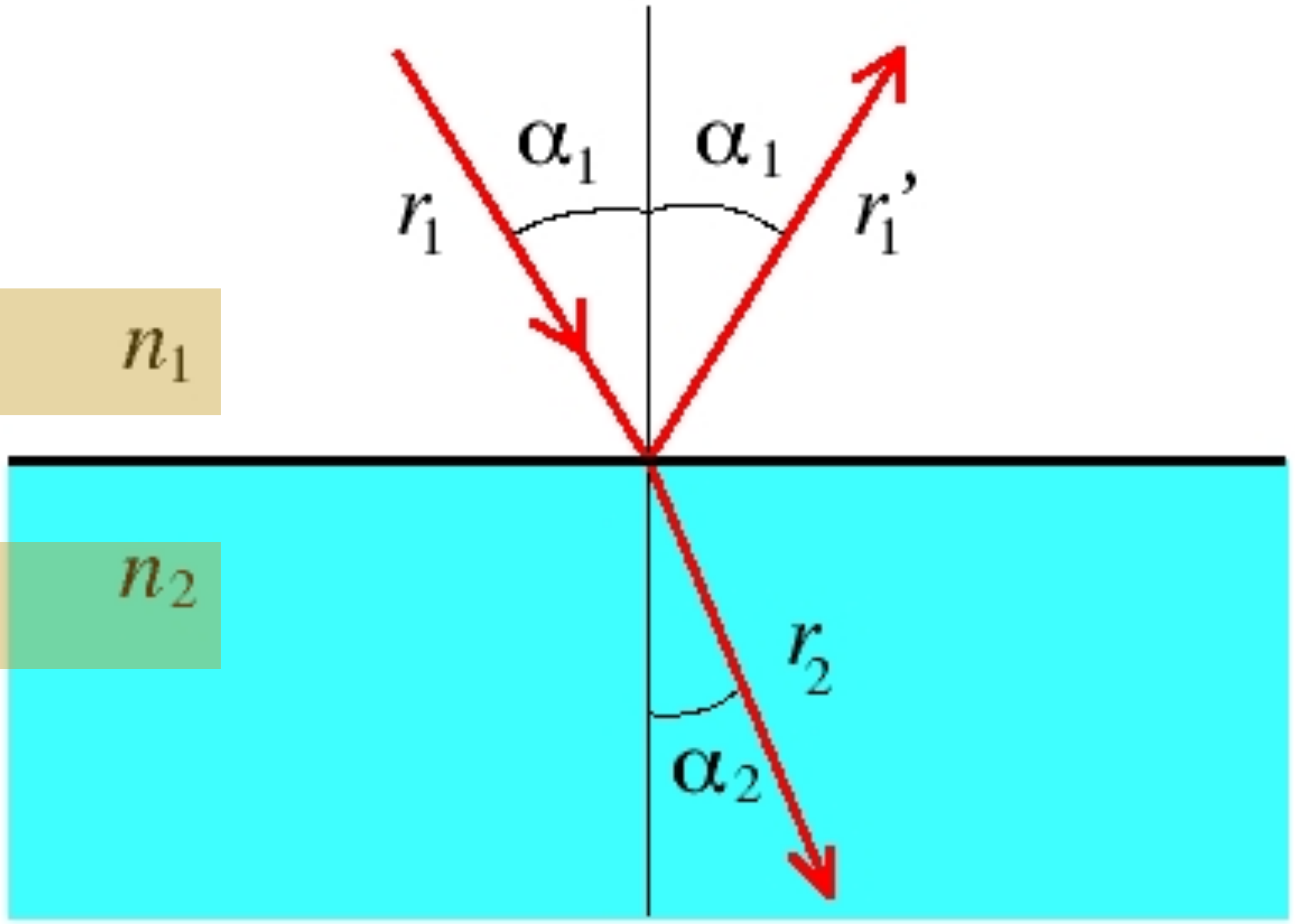
Solution: use a **lens** to focus light onto the image plane

Snell's Law



$$\boxed{n_1 \sin \alpha_1 = n_2 \sin \alpha_2}$$

Snell's Law

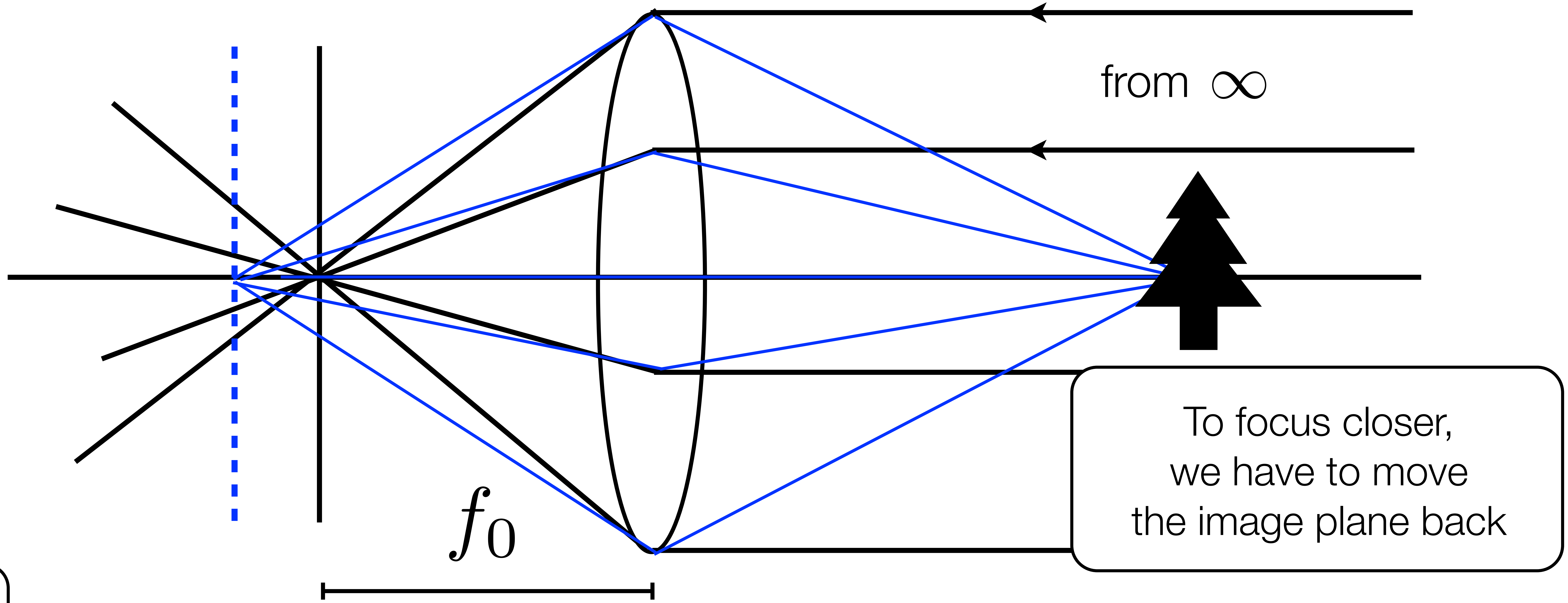


Index of **refraction**

$$\boxed{n_1 \sin \alpha_1 = n_2 \sin \alpha_2}$$

Lens Basics

- A lens focuses rays from infinity at the focal length of the lens
- Points passing through the centre of the lens are not bent



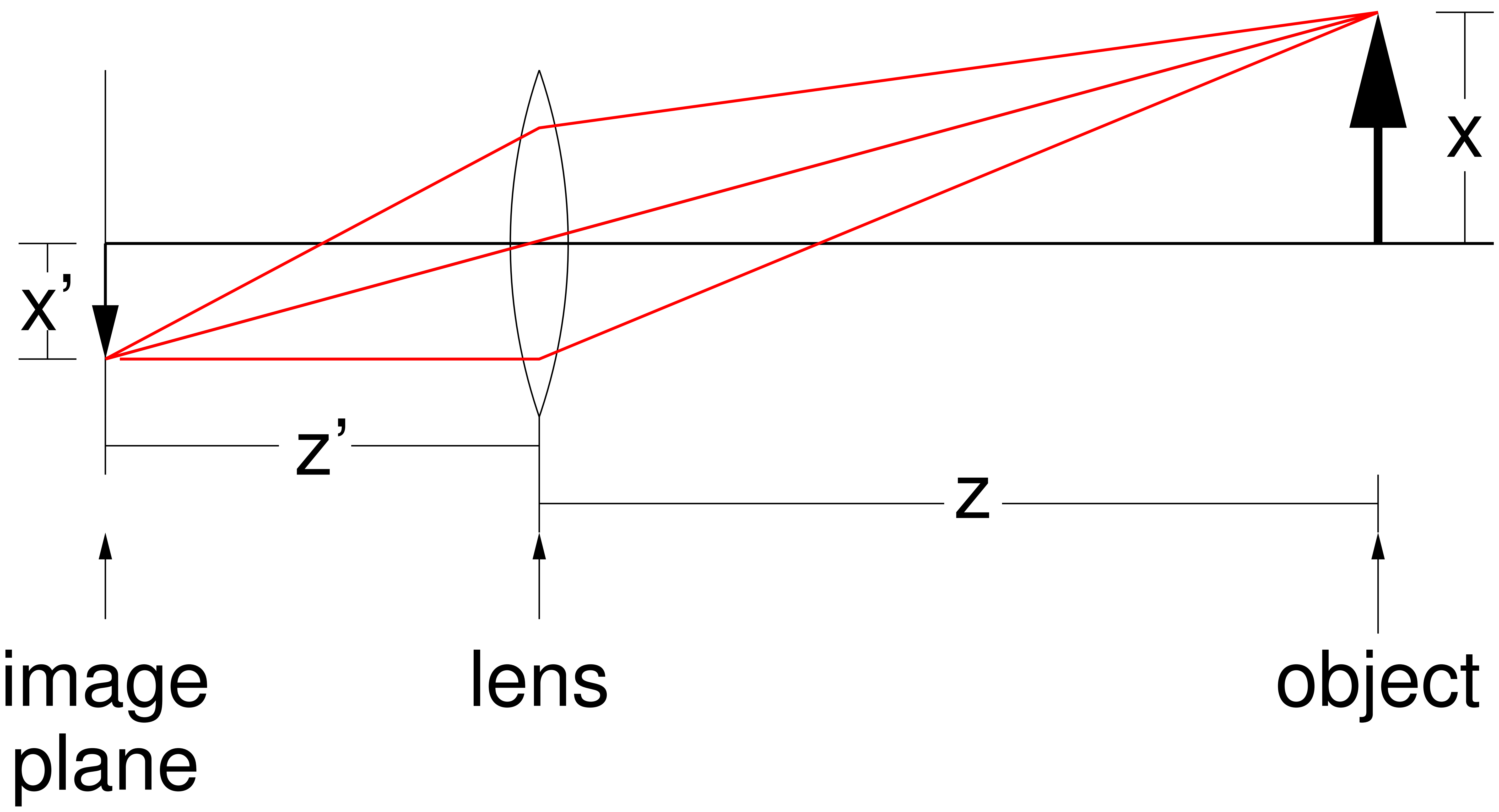
2.6

- We can use these 2 properties to find the lens equation

Lens Basics

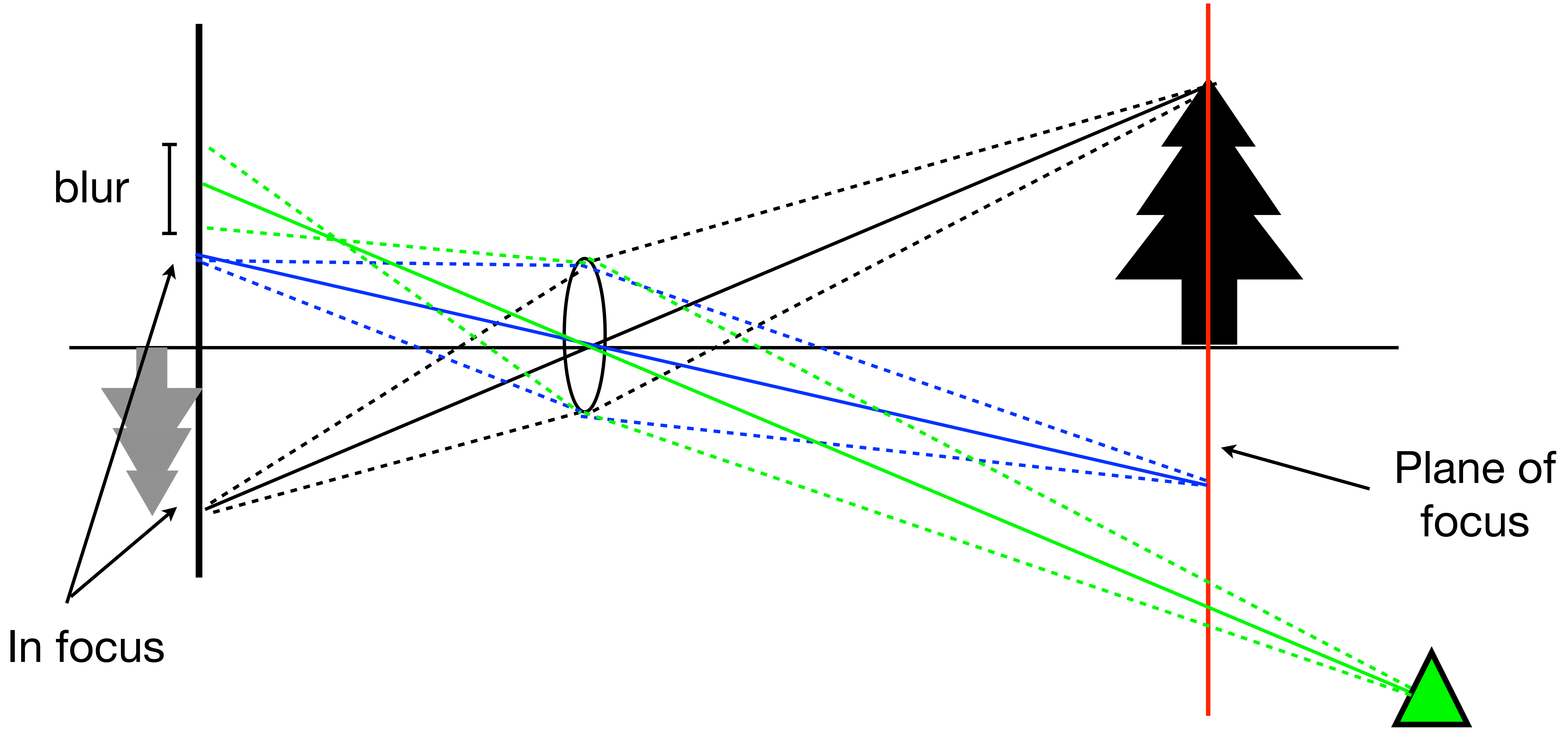
- A 50mm lens is focussed at infinity. It now moves to focus on something 5m away. How far does the lens move?

Pinhole Model **with Lens**



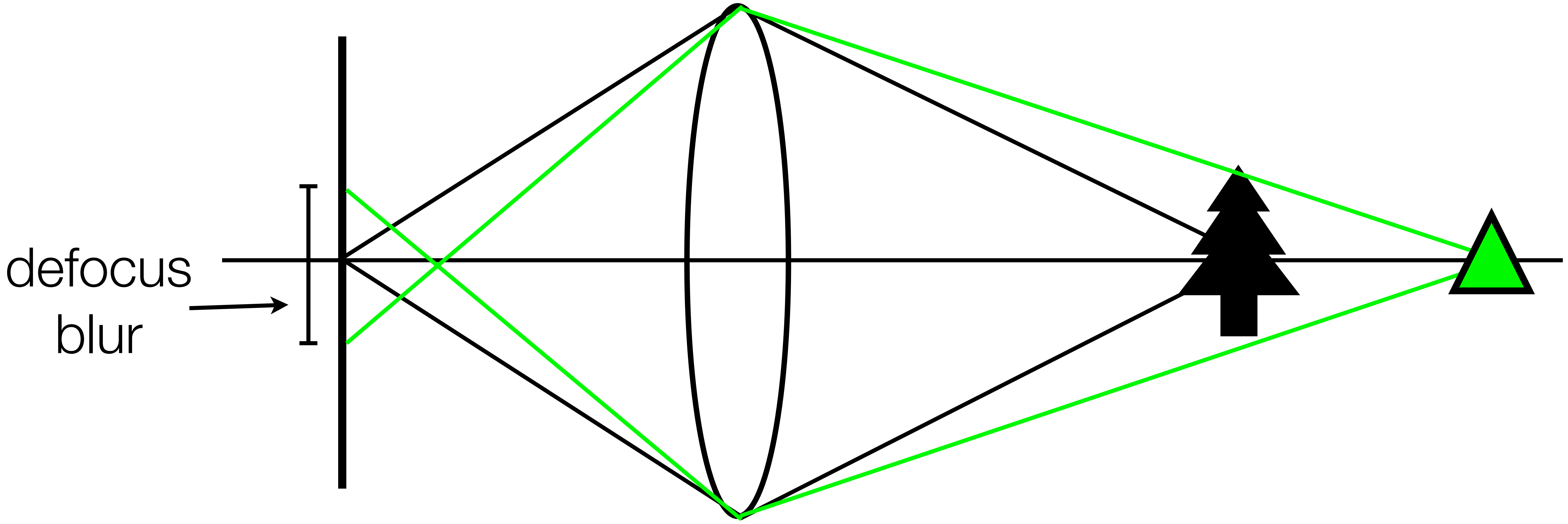
Lens Basics

- Lenses focus all rays from a plane in the world

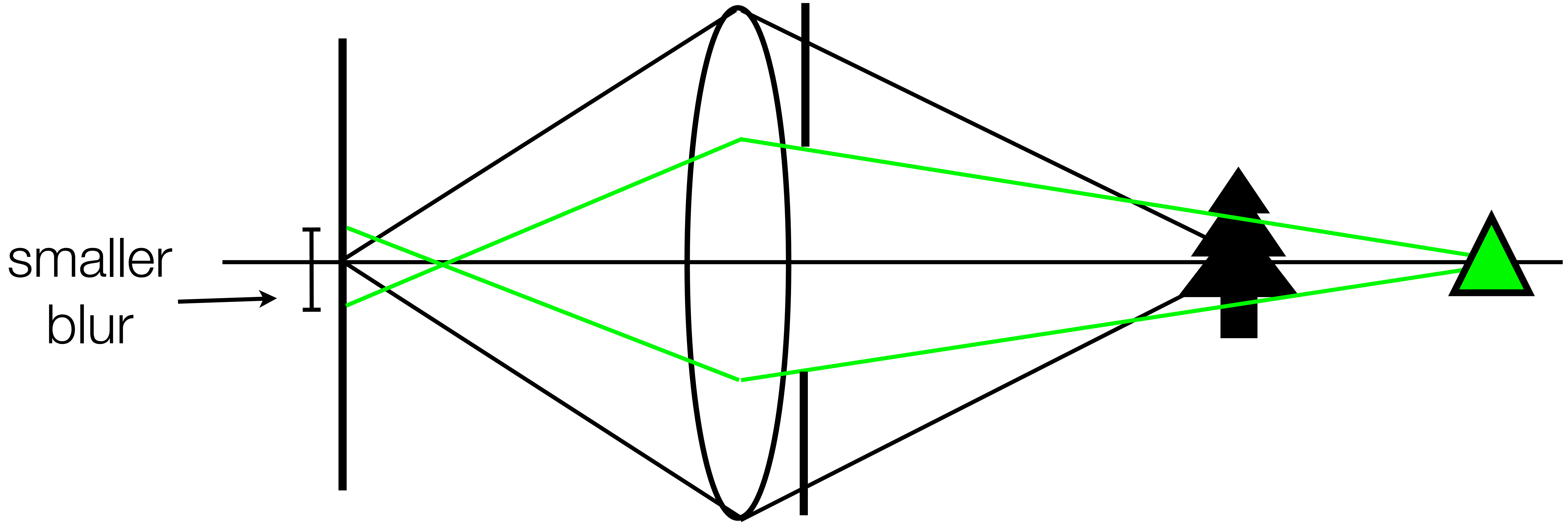


- Objects off the plane are blurred depending on distance

Effect of Aperture Size



Smaller aperture ⇒ smaller blur, larger **depth of field**



Depth of Field

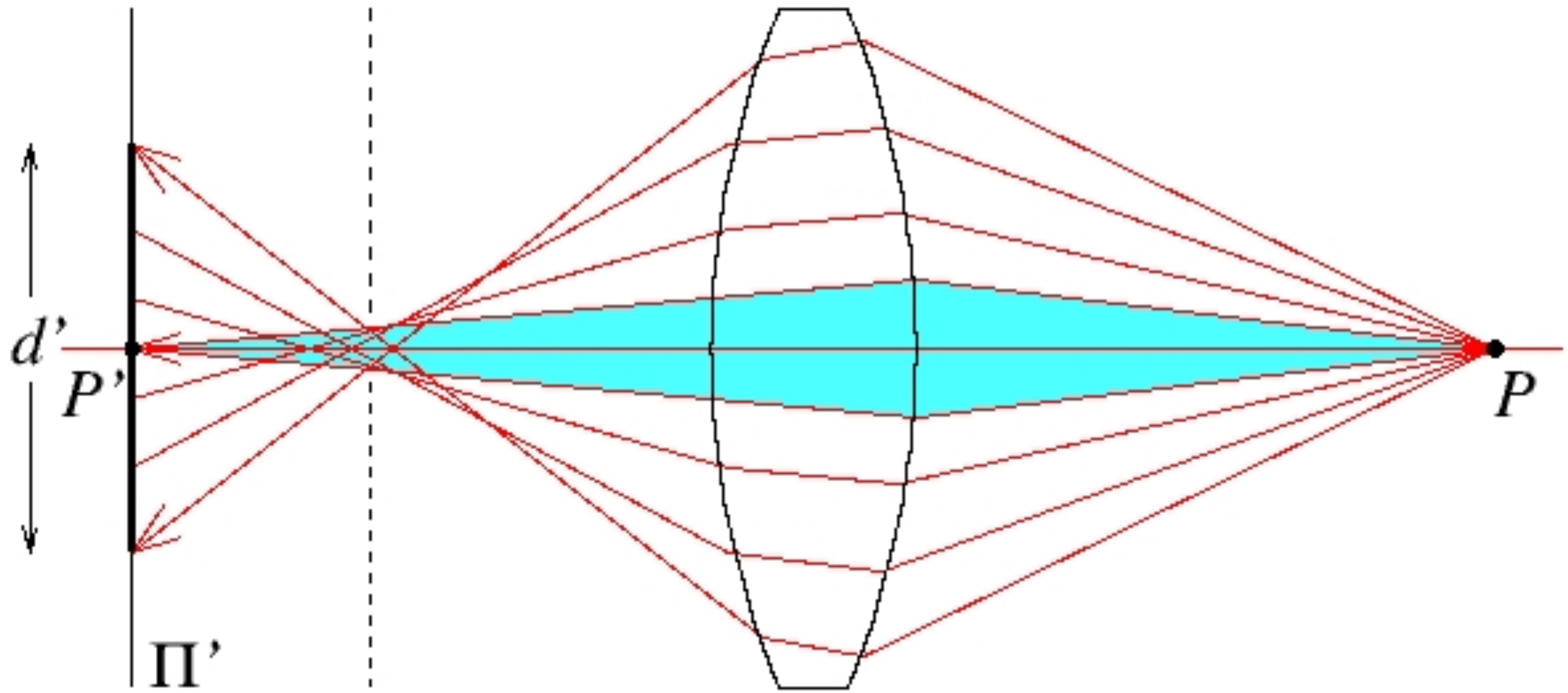
- Photographers use large apertures to give small depth of field

Aperture size = f/N, ⇒ large N = small aperture

Real Lenses

- Real Lenses have multiple stages of positive and negative elements with differing refractive indices
- This can help deal with issues such as chromatic aberration (different colours bent by different amounts), vignetting (light fall off at image edge) and sharp imaging across the zoom range

Spherical **Aberration**



Forsyth & Ponce (1st ed.) Figure 1.12a

Spherical **Aberration**

Un-aberrated image

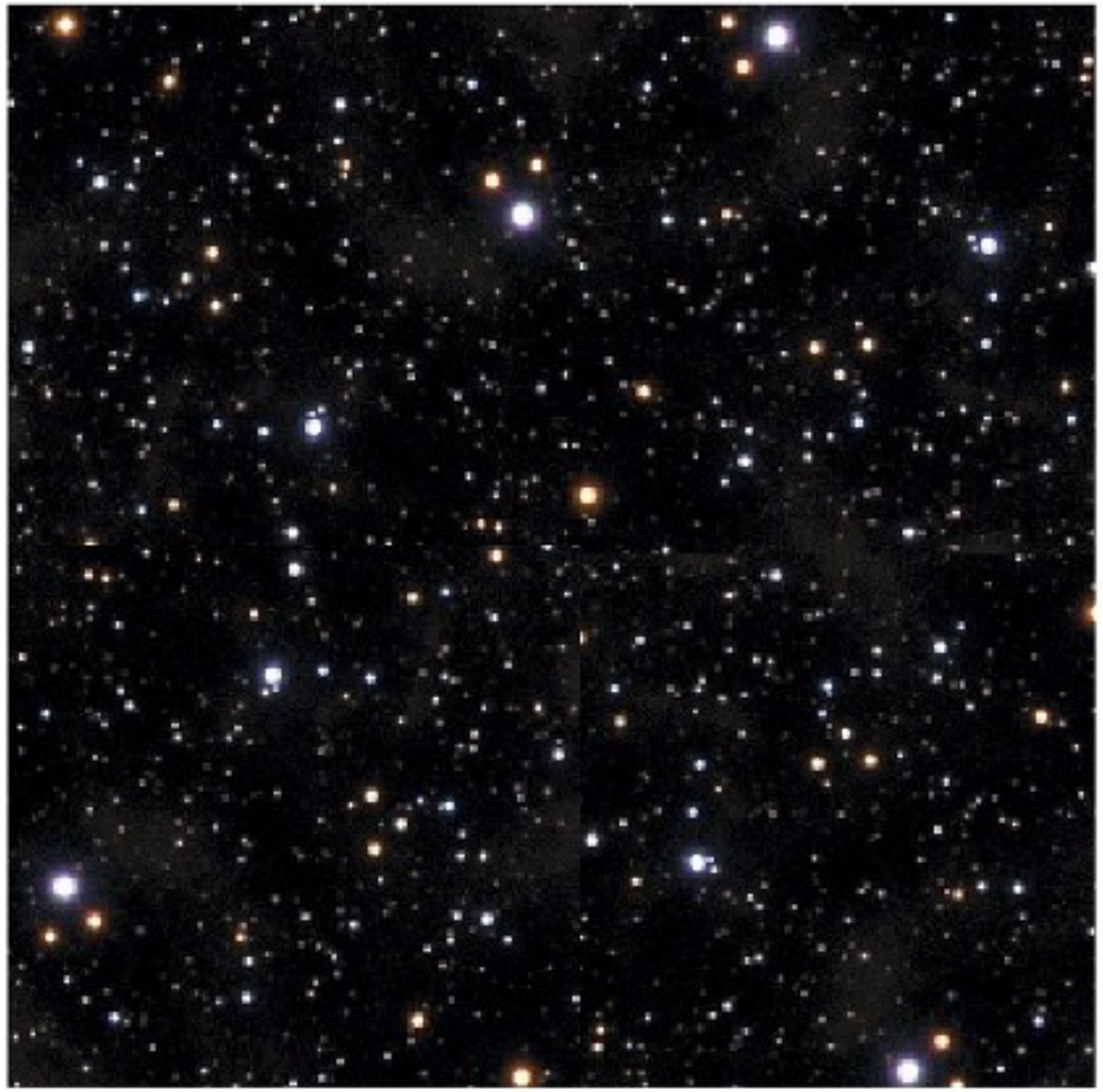
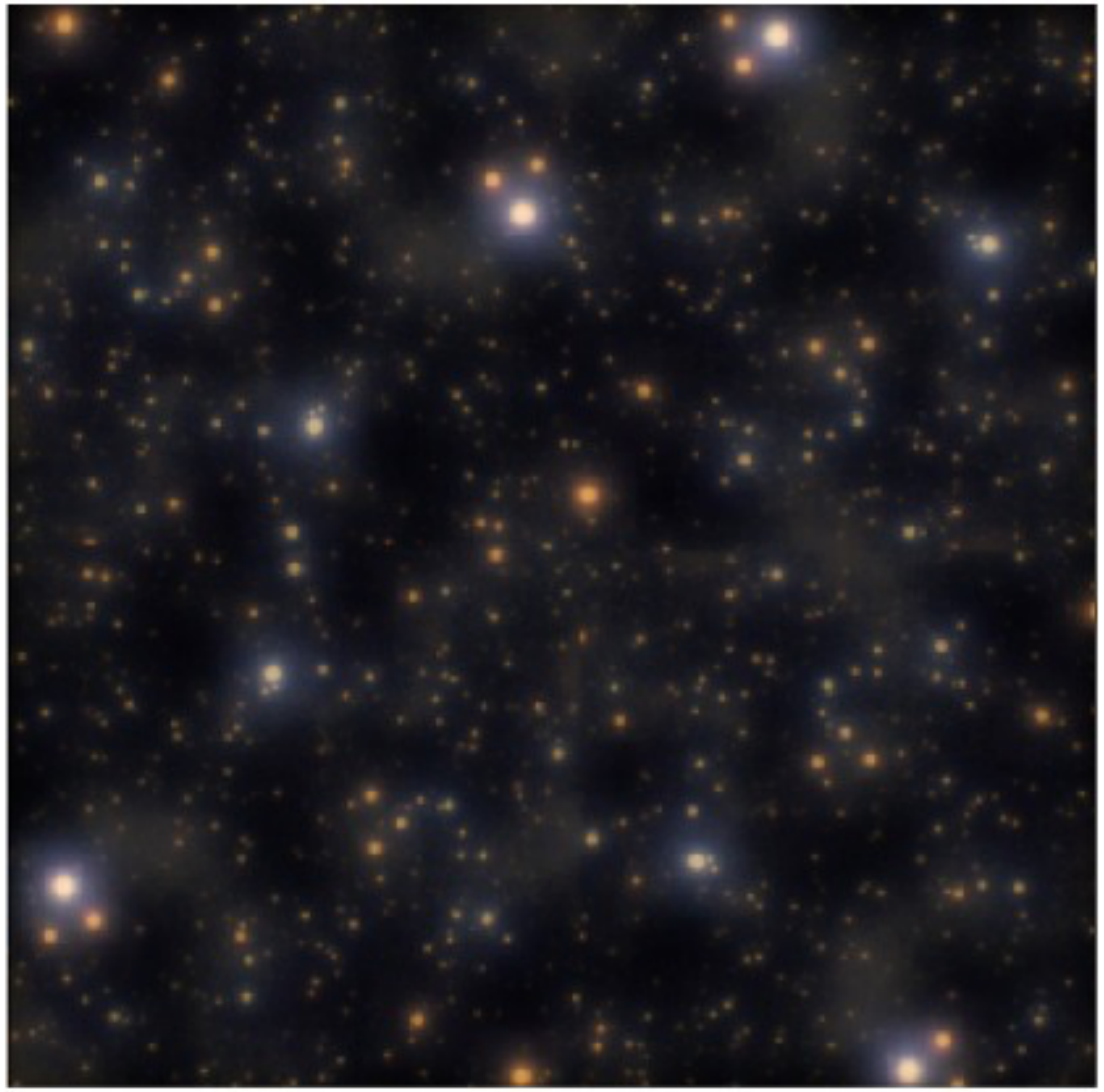
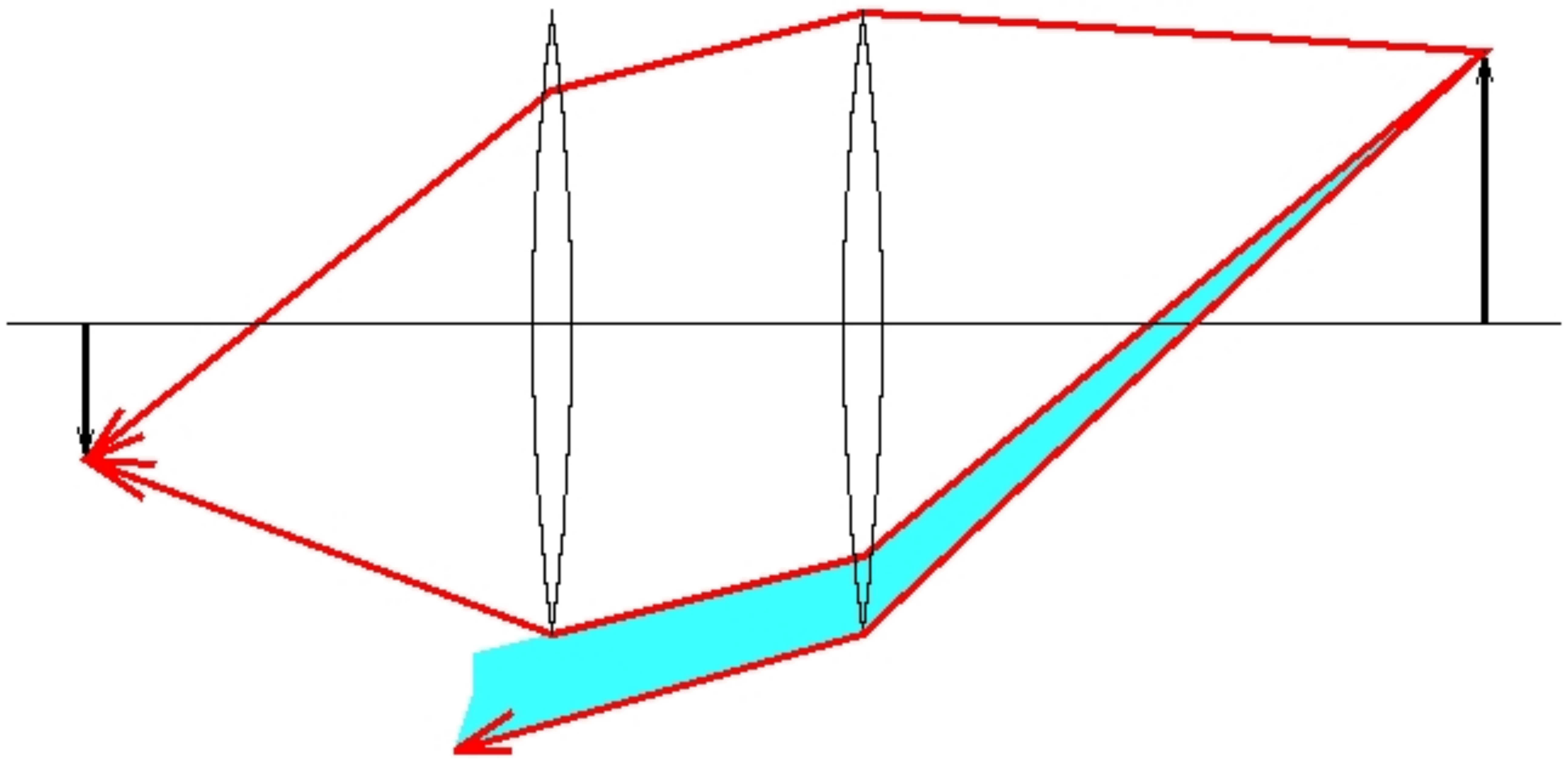


Image from lens with Spherical Aberration



Vignetting

Vignetting in a two-lens system



Forsyth & Ponce (2nd ed.) Figure 1.12

The shaded part of the beam **never reaches** the second lens

Vignetting

Image Credit: Cambridge in Colour

Chromatic **Aberration**

- Index of **refraction depends on wavelength**, λ, of light
- Light of different colours follows different paths
- Therefore, not all colours can be in equal focus

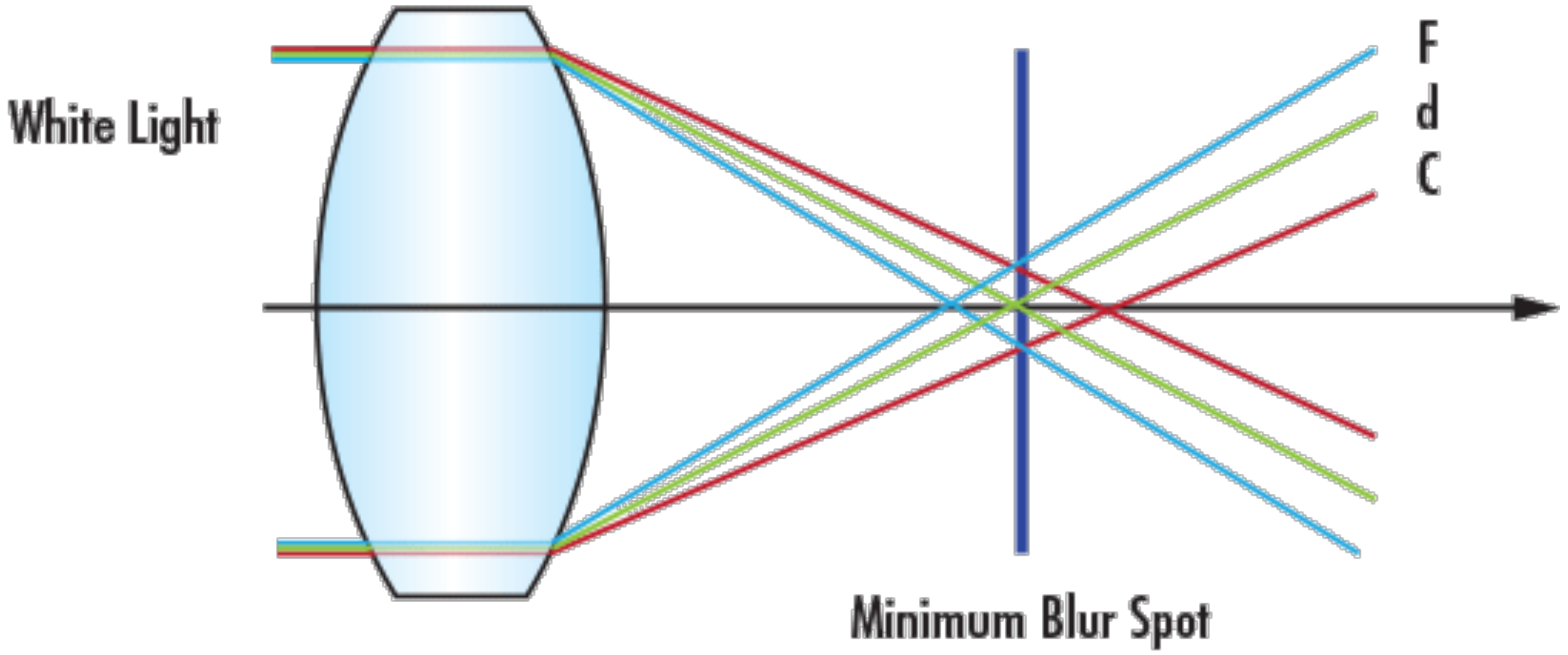


Image Credit: Trevor Darrell

Other (Possibly Significant) **Lens Effects**

Chromatic **aberration**

— Index of refraction depends on wavelength, λ, of light

— Light of different colours follows different paths

— Therefore, not all colours can be in equal focus

Scattering at the lens surface

— Some light is reflected at each lens surface

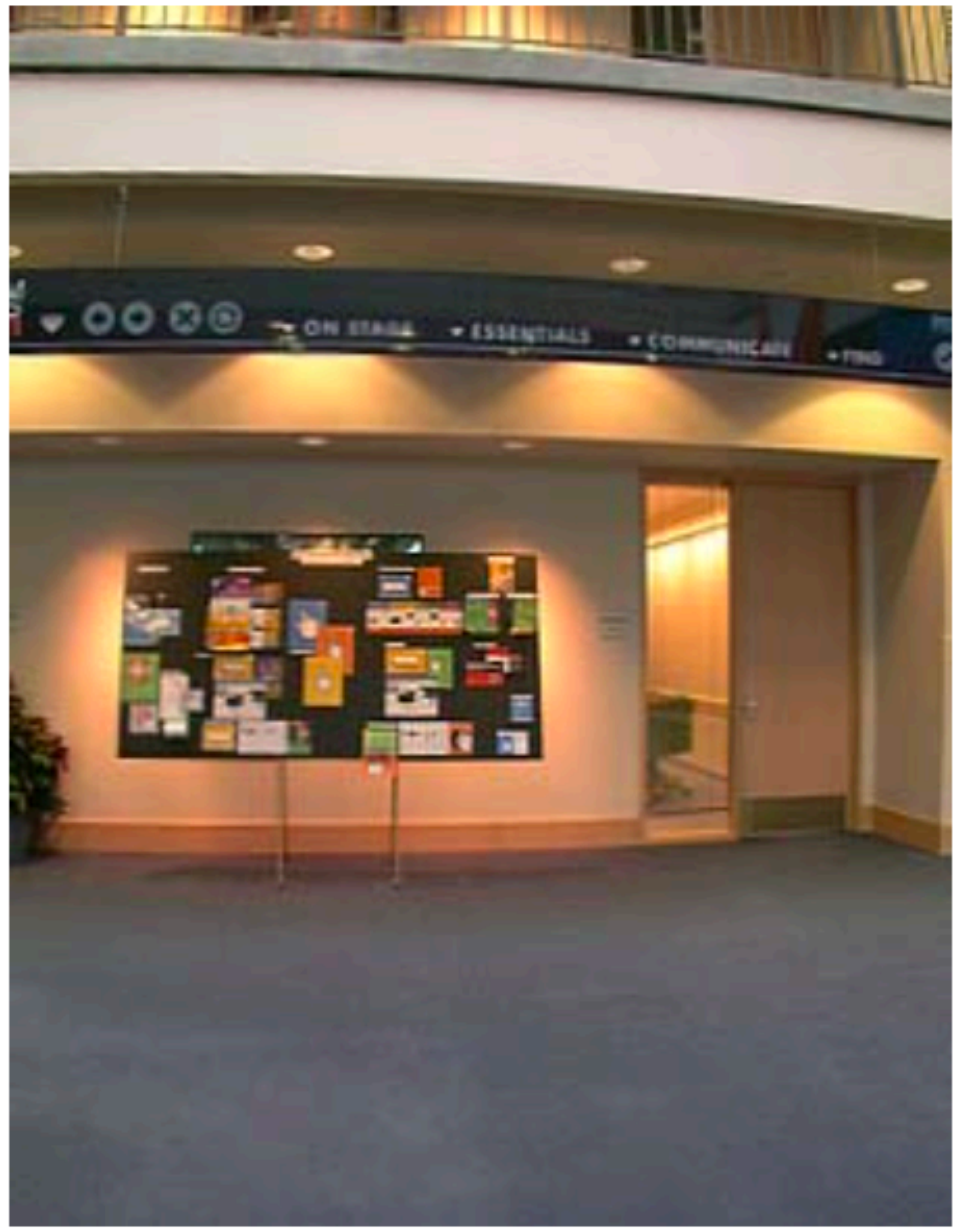
There are other **geometric phenomena/distortions**

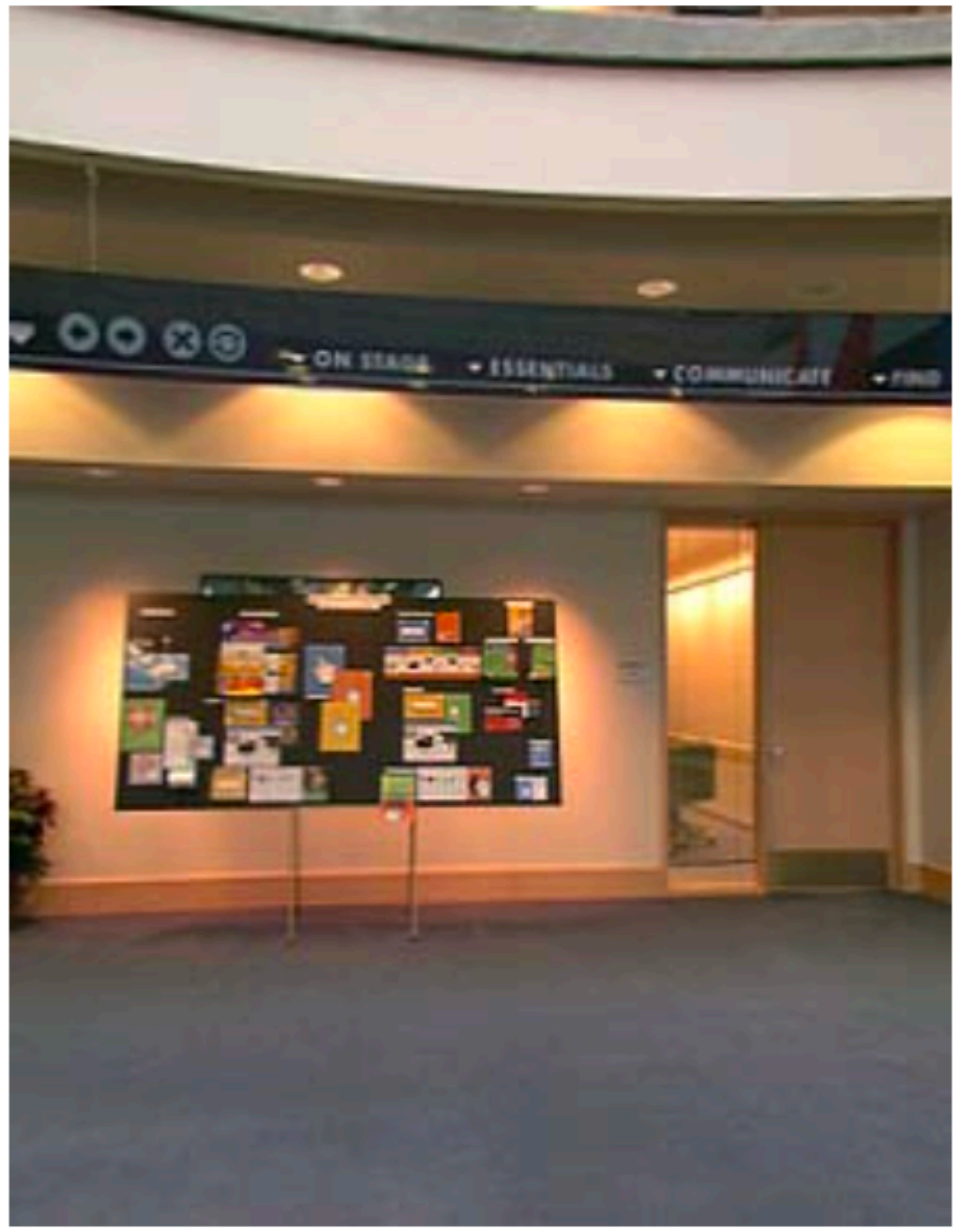
— pincushion distortion

— barrel distortion

— etc

Lens **Distortion**





Fish-eye Lens

Szeliski (1st ed.) Figure 2.13

Lines in the world are no longer lines on the image, they are curves!

Lecture **Summary**

— We discussed a “physics-based” approach to image formation. Basic abstraction is the **pinhole camera**.

— **Lenses overcome limitations** of the pinhole model while trying to preserve it as a useful abstraction

— Projection equations: **perspective**, weak perspective, orthographic

— Thin lens equation

— Some “aberrations and **distortions**” persist (e.g. spherical aberration, vignetting)

Reminders

Readings:

— **Today's** Lecture: Szeliski Chapter 2, Forsyth & Ponce (2nd ed.) 1.1.1 — 1.1.3

— **Next** Lecture: Forsyth & Ponce (2nd ed.) 4.1, 4.5

Reminders:

— Complete **Assignment 0** (ungraded) suggest by **Sept 14**

— **Web**: https://mattabrown.github.io/425

— Check out **Piazza** and **Canvas**, setup **iClicker** account