

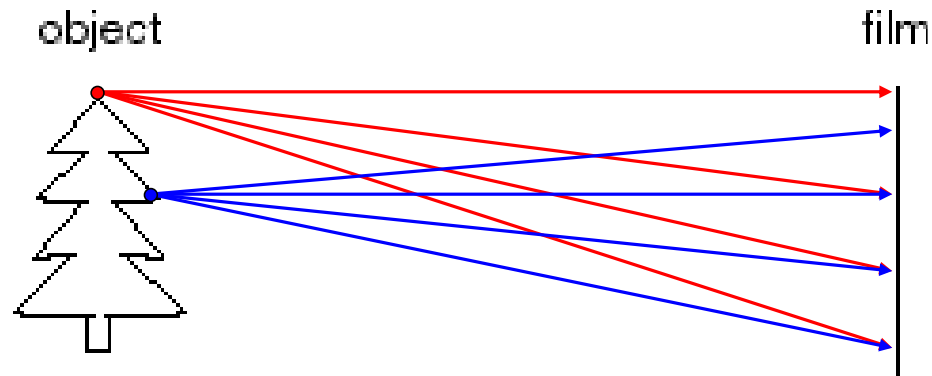
Introduction to cameras



Overview

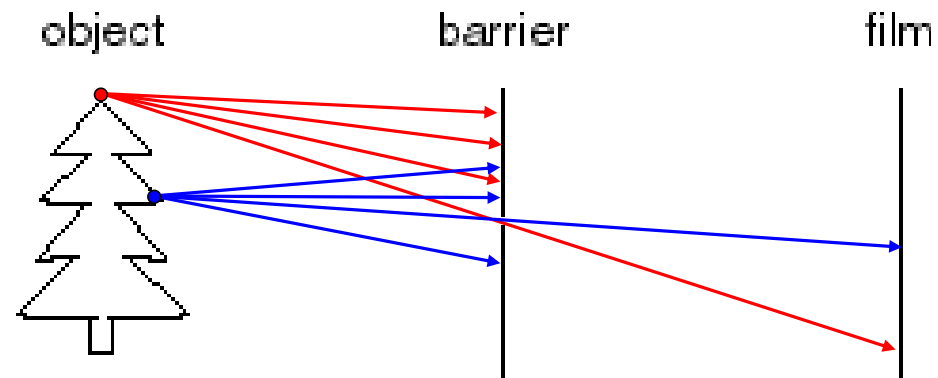
- Pinhole projection
- Lenses
- Field of view, focal length
- Marginal distortion
- Lens distortions

Let's design a camera



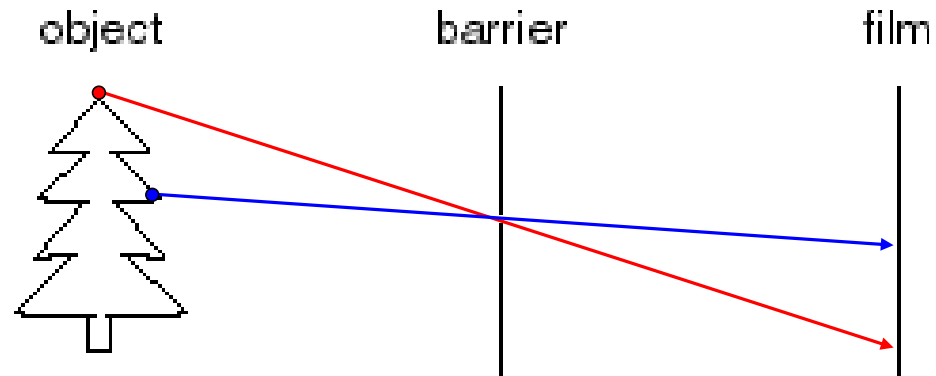
Idea 1: put a piece of film in front of an object
Do we get a reasonable image?

Pinhole camera



Add a barrier to block off most of the rays

Pinhole camera



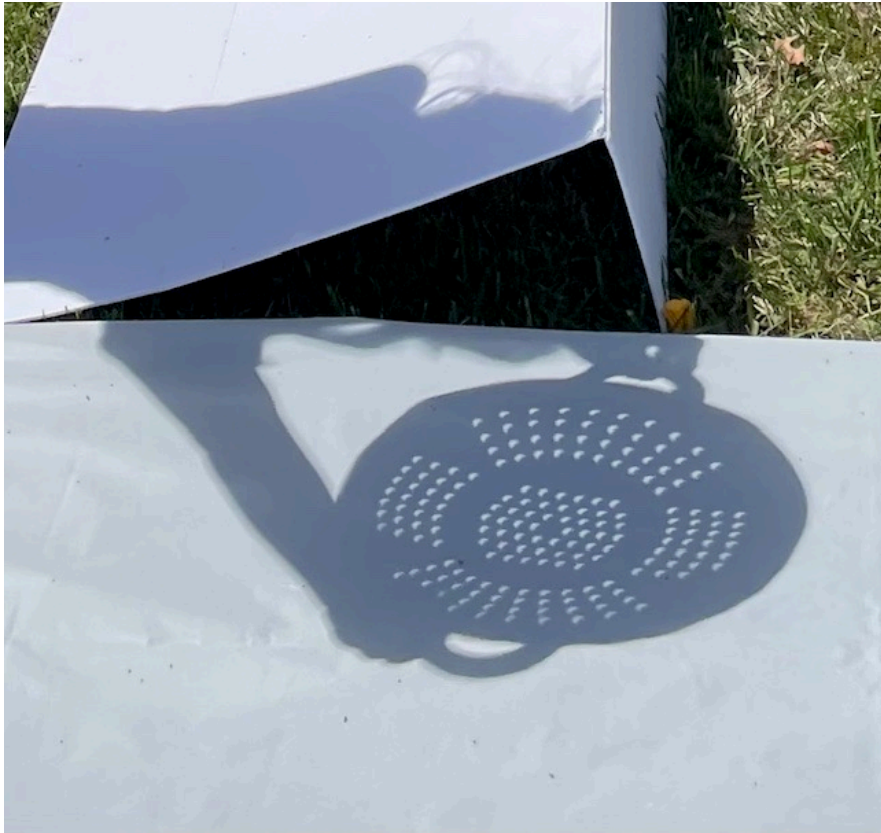
- Captures **pencil of rays** – all rays through a single point: **aperture, center of projection, optical center, focal point, camera center**
- The image is formed on the **image plane**

Pinhole cameras are everywhere



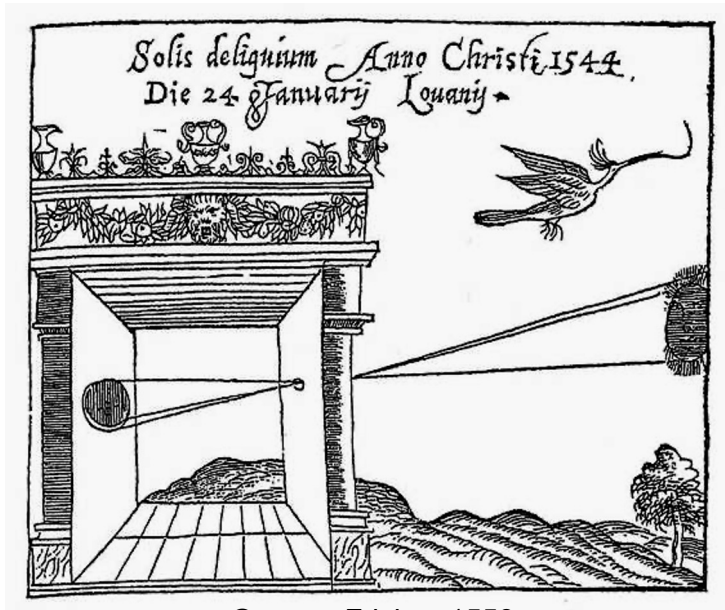
My photo during the COVID year (2020)

Pinhole cameras are everywhere



My photos during the April 2024 total eclipse

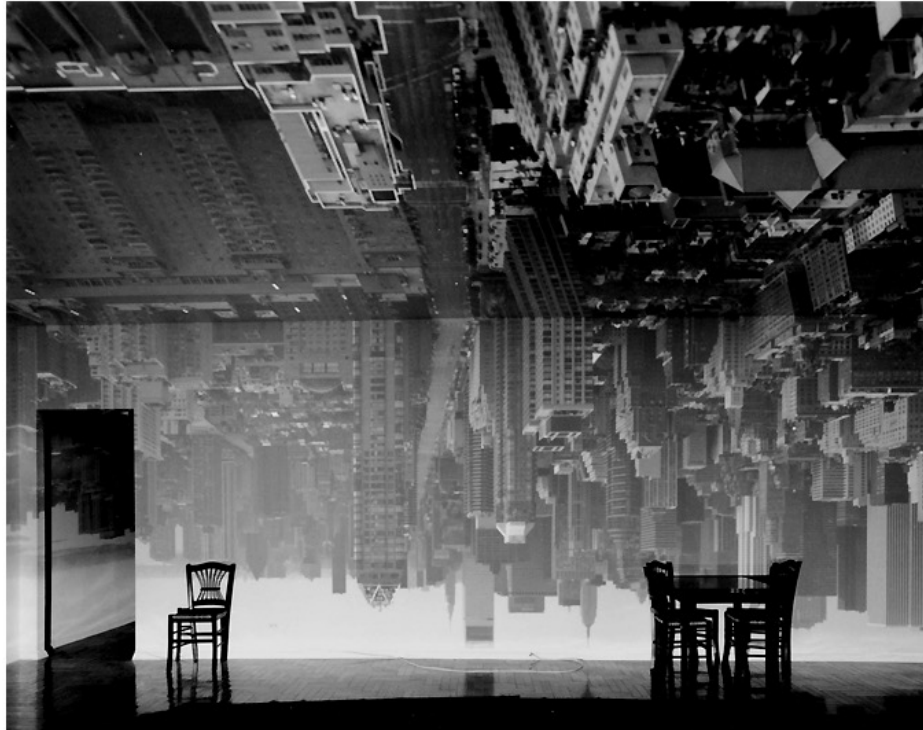
Camera obscura



Gemma Frisius, 1558

- Basic principle known to Mozi (470-390 BCE), Aristotle (384-322 BCE)
- Drawing aid for artists: described by Leonardo da Vinci (1452-1519)

Turning a room into a camera obscura



Abelardo Morell, Camera Obscura Image of
Manhattan View Looking South in Large
Room, 1996

<https://www.abelardomorell.net/camera-obscura>

After scouting rooms and reserving one for at least a day, Morell masks the windows except for the aperture. He controls three elements: the size of the hole, with a smaller one yielding a sharper but dimmer image; the length of the exposure, usually eight hours; and the distance from the hole to the surface on which the outside image falls and which he will photograph. He used 4 x 5 and 8 x 10 view cameras and lenses ranging from 75 to 150 mm.

After he's done inside, it gets harder. "I leave the room and I am constantly checking the weather, I'm hoping the maid reads my note not to come in, I'm worrying that the sun will hit the plastic masking and it will fall down, or that I didn't trigger the lens."

From *Grand Images Through a Tiny Opening*, **Photo District News**, February 2005

Turning a room into a camera obscura

My hotel room,
contrast enhanced.



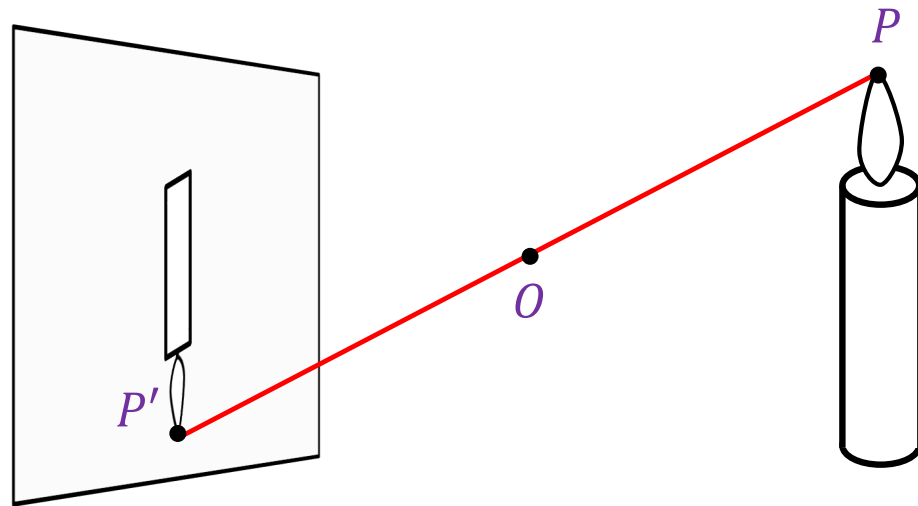
The view from my window



Accidental pinholes produce images that are
unnoticed or misinterpreted as shadows

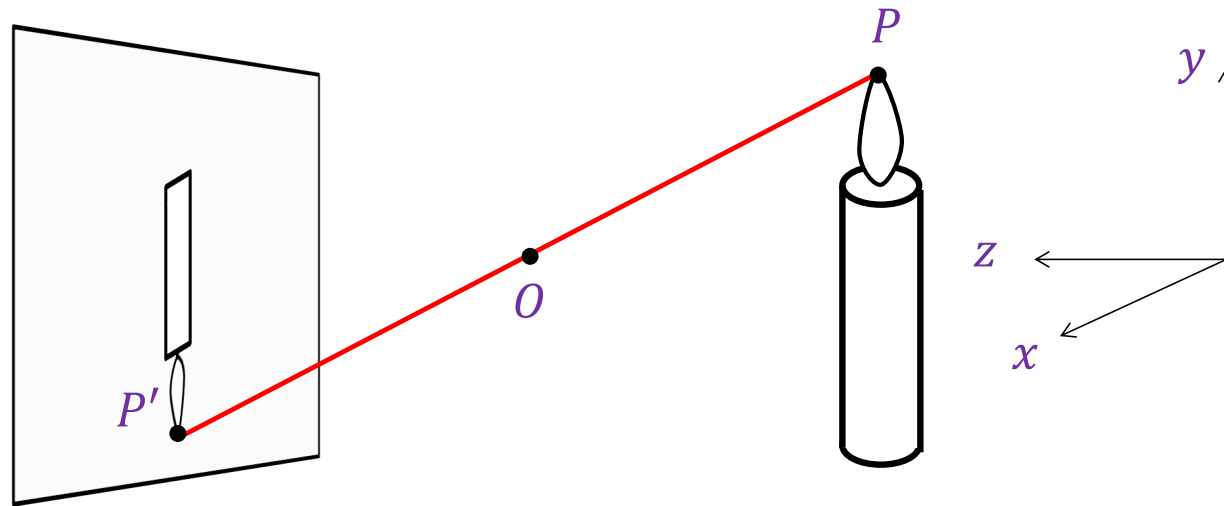
A. Torralba and W. Freeman. [Accidental Pinhole and Pinspeck Cameras](#). CVPR 2012

Modeling projection



- How do we find the projection P' of a scene point P ?
 - Form the **visual ray** connecting P to the camera center O and find where it intersects the image plane
- All scene points that lie on this visual ray have the same projection in the image
- Are there scene points for which this projection is undefined?

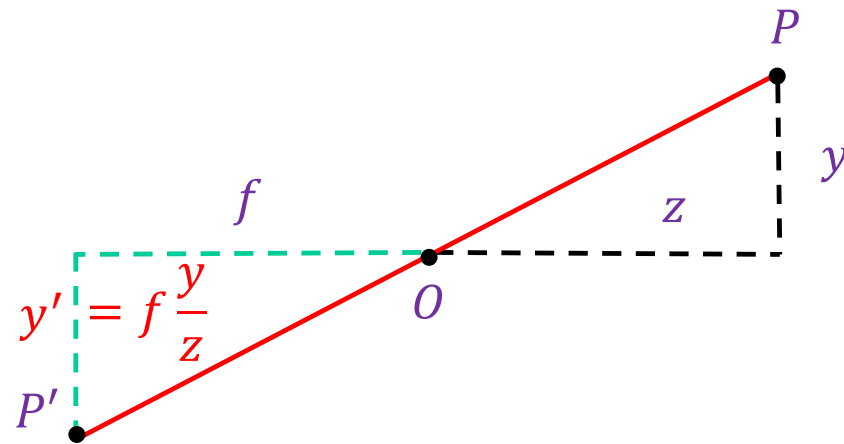
Modeling projection



Canonical coordinate system

- The optical center (O) is at the origin
- The z axis is the *optical axis* perpendicular to the image plane
- The xy plane is parallel to the image plane, x and y axes are horizontal and vertical directions of the image plane

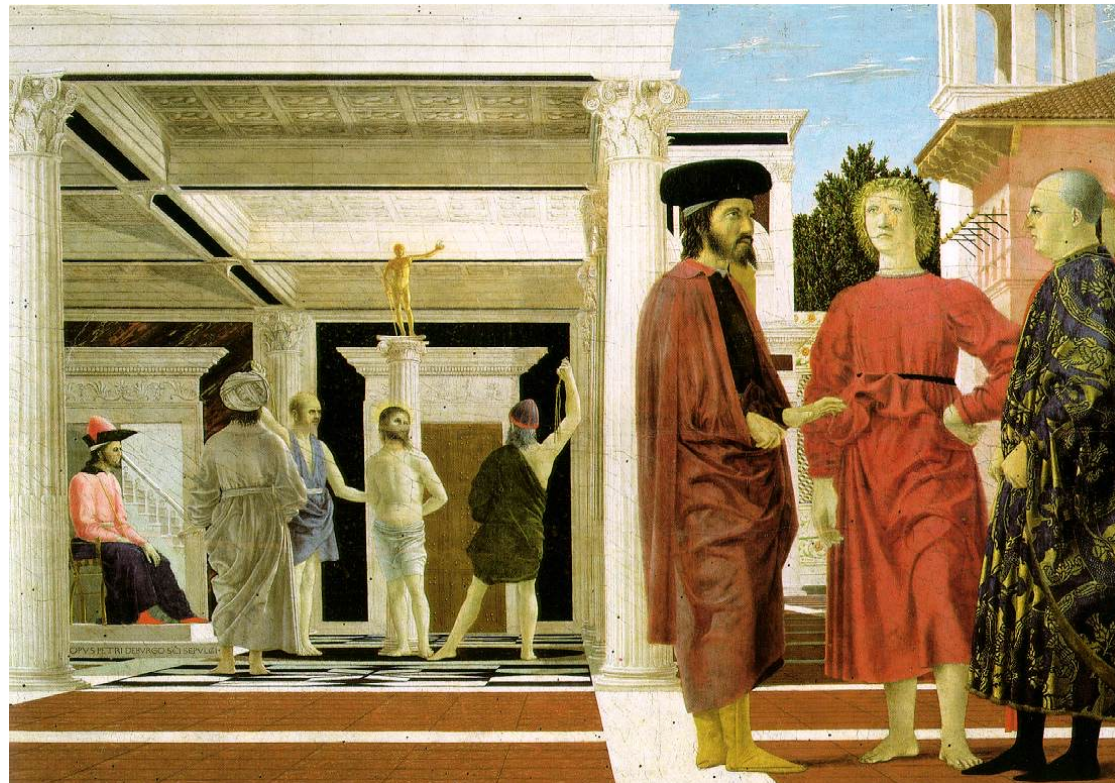
Deriving projected coordinates



$$(x, y, z) \rightarrow \left(f \frac{x}{z}, f \frac{y}{z} \right)$$

Properties of projection

- Real-world sizes (lengths) are *not* preserved in projection
 - What other properties are/are not preserved?



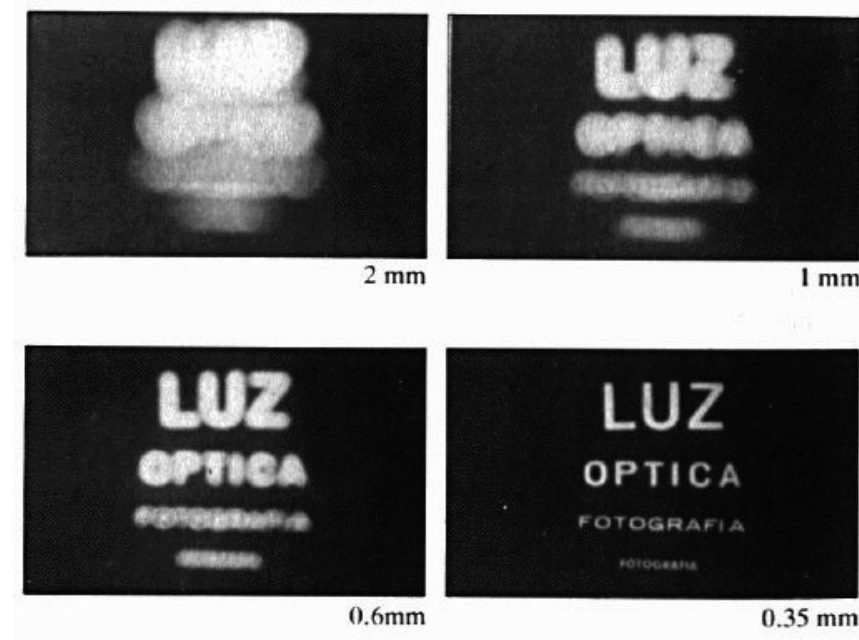
Piero della Francesca, *Flagellation of Christ*, 1455-1460

Home-made pinhole camera



Source: [P. Debevec](#) via A. Efros

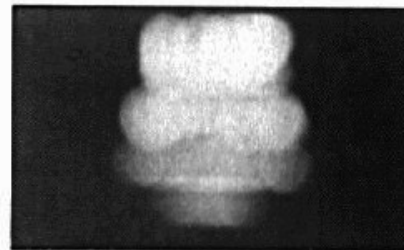
Shrinking the aperture



Why not make the aperture as small as possible?

- Less light gets through
- Diffraction!

Shrinking the aperture



2 mm



1 mm



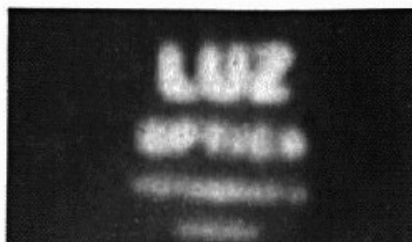
0.6 mm



0.35 mm



0.15 mm

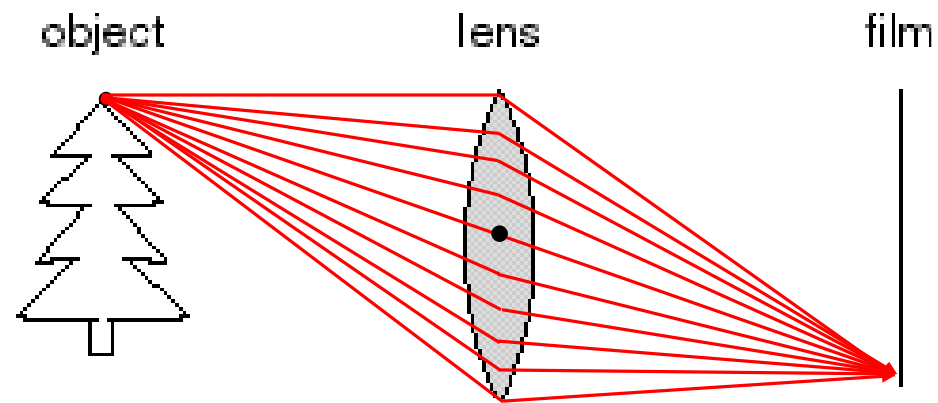


0.07 mm

Overview

- Pinhole projection
- Lenses

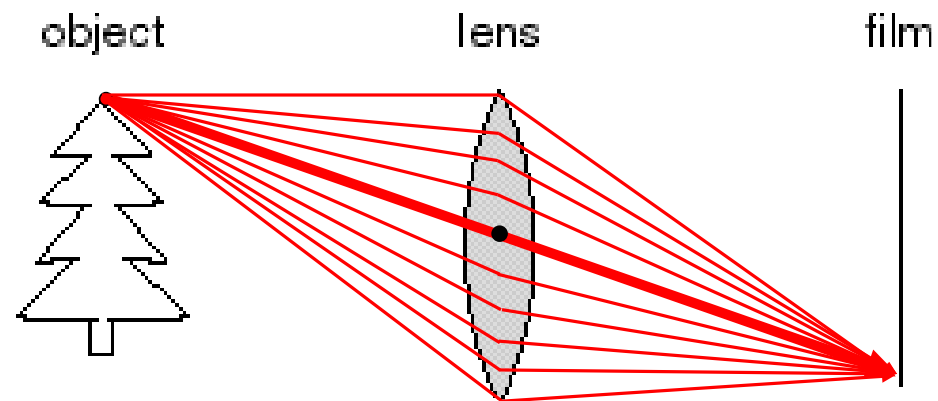
Adding a lens



A lens focuses light onto the film

- Thin lens model:

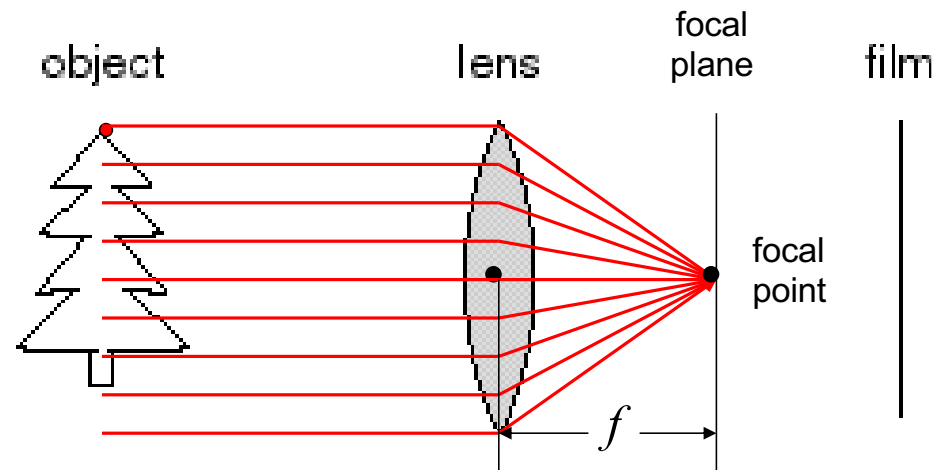
Adding a lens



A lens focuses light onto the film

- Thin lens model:
 - Rays passing through the center are not deviated (pinhole projection model still holds)

Adding a lens

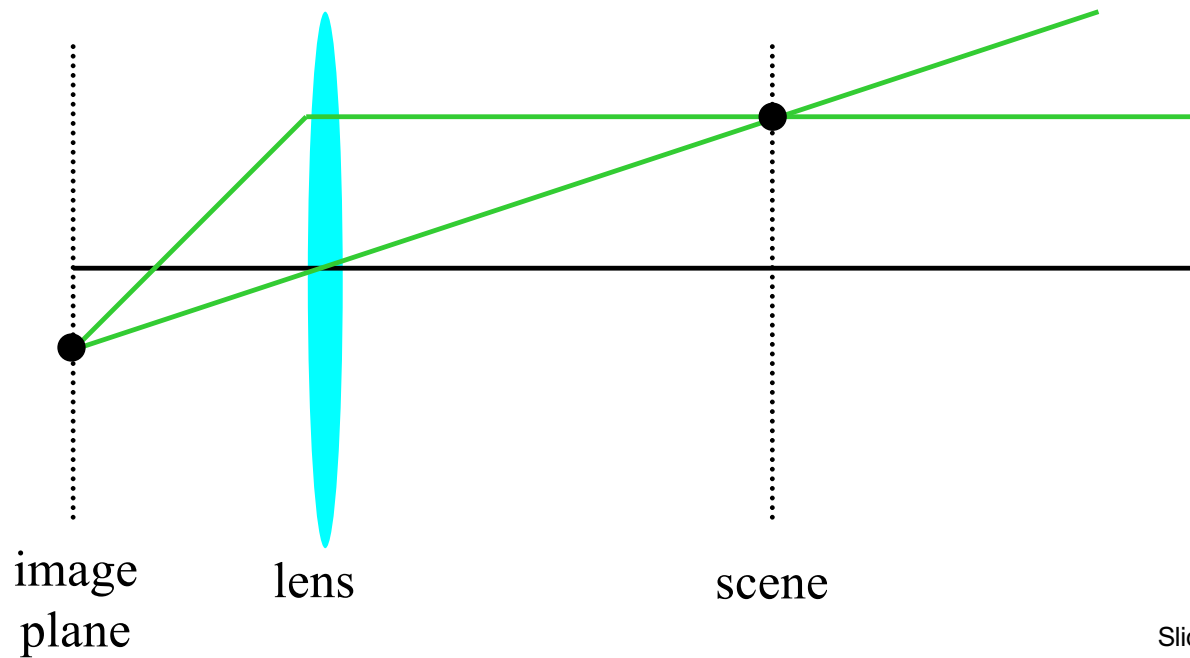


A lens focuses light onto the film

- Thin lens model:
 - Rays passing through the center are not deviated (pinhole projection model still holds)
 - All rays parallel to the optical axis pass through the *focal point*
 - All parallel rays converge to points on the *focal plane*

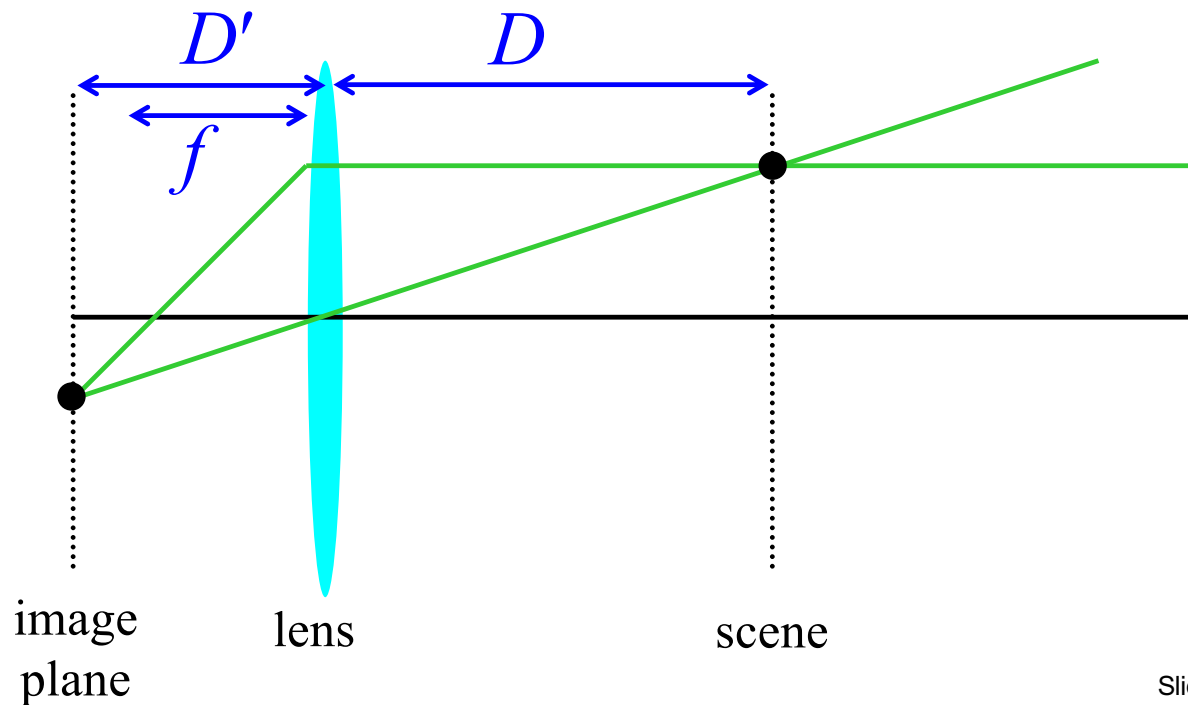
Thin lens formula

- Where does the lens focus the rays coming from a given point in the scene?



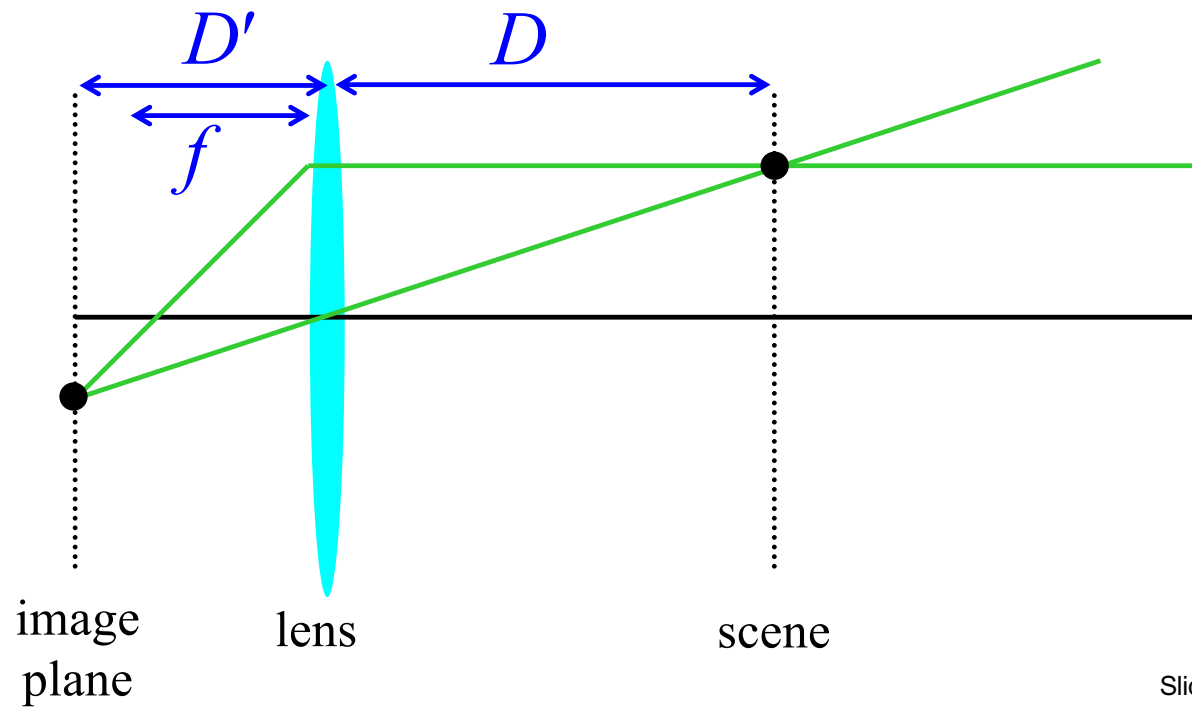
Thin lens formula

- What is the relation between the focal length (f), the distance of the object from the optical center (D), and the distance at which the object will be in focus (D')?



Thin lens formula

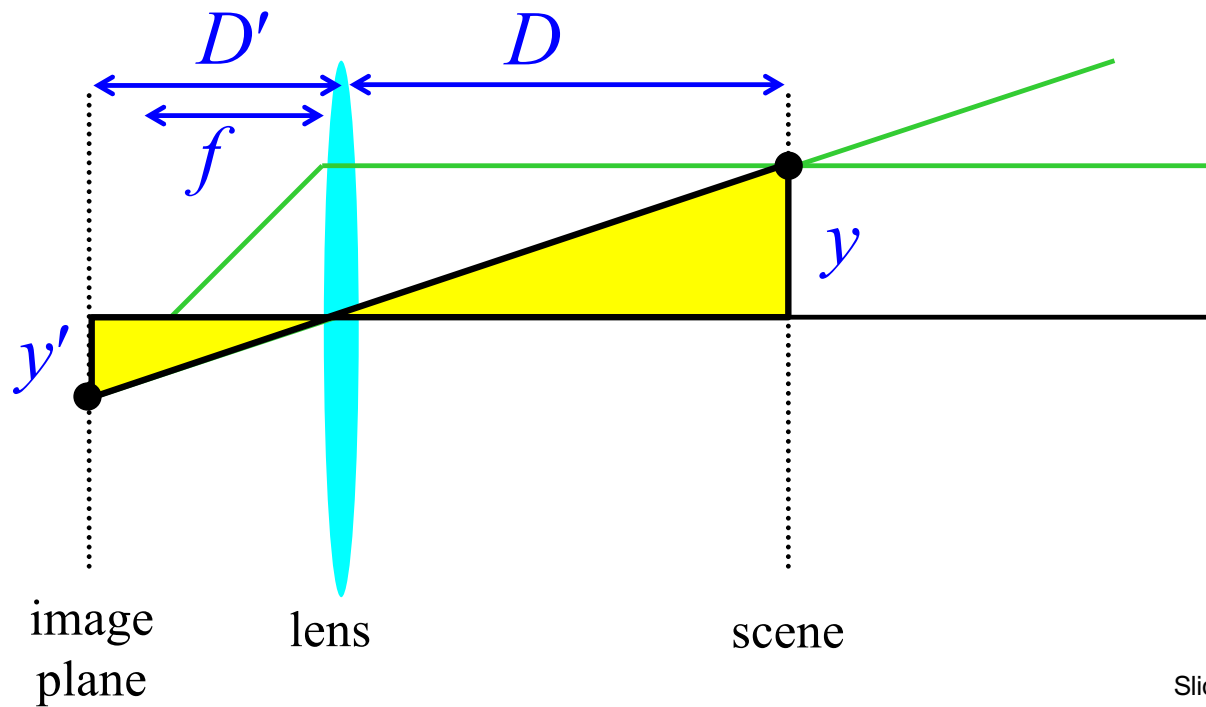
Similar triangles everywhere!



Thin lens formula

Similar triangles everywhere!

$$y'/y = D'/D$$

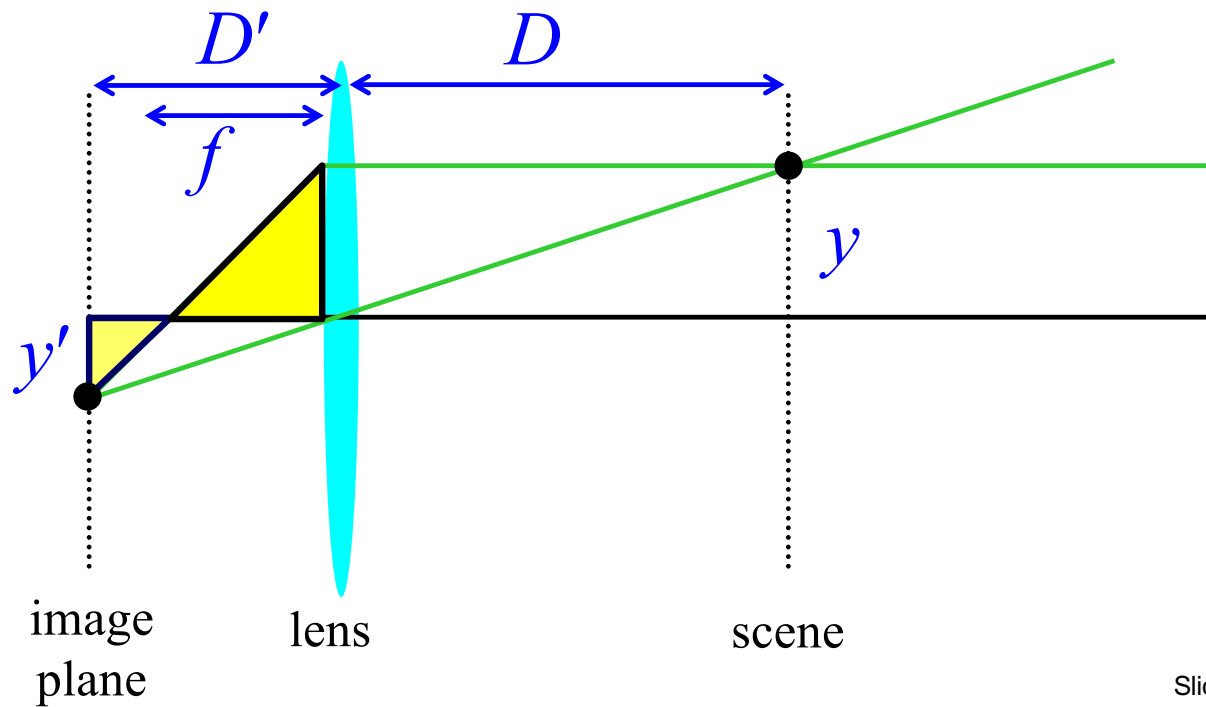


Thin lens formula

Similar triangles everywhere!

$$y'/y = D'/D$$

$$y'/y = (D' - f)/f$$

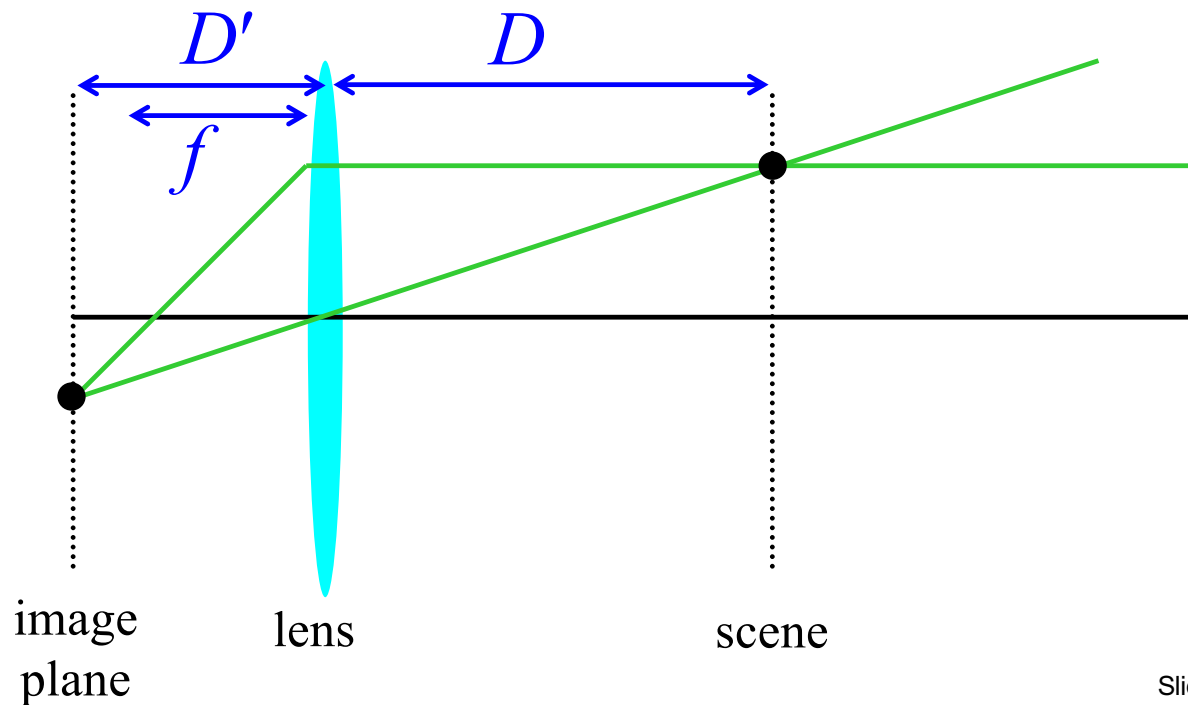


Thin lens formula

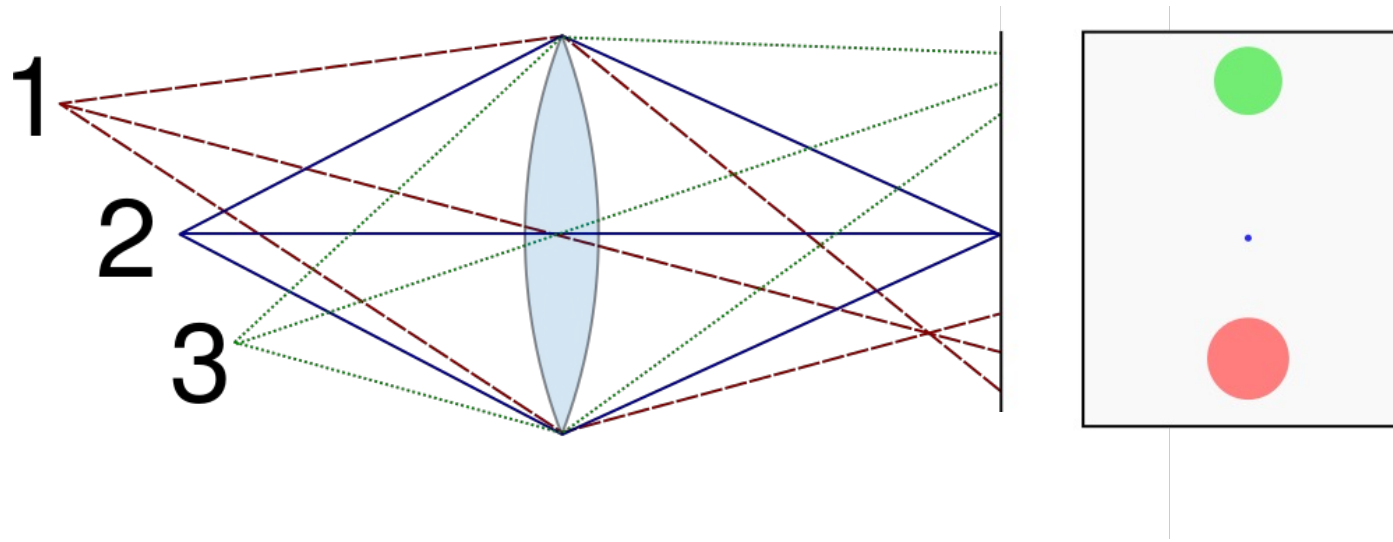
$$\frac{1}{D'} + \frac{1}{D} = \frac{1}{f}$$

Any point satisfying the thin lens equation is in focus.

What happens when D is very large?



Depth of field



- For a fixed focal length and image plane, there is a specific distance at which objects are “in focus”
 - Other points project to a “circle of confusion” in the image

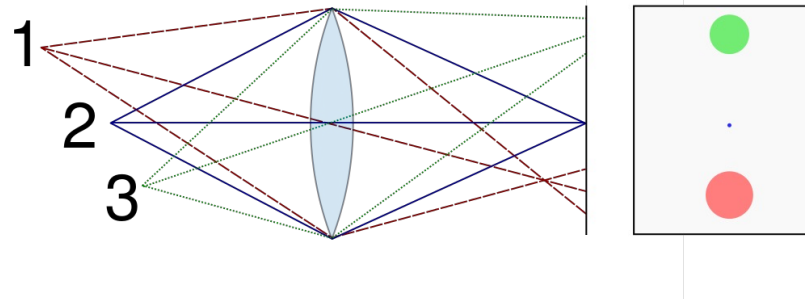
Depth of field

- Depth of field is the distance between the nearest and farthest objects in a scene that appear acceptably sharp in an image ([Wikipedia](#))



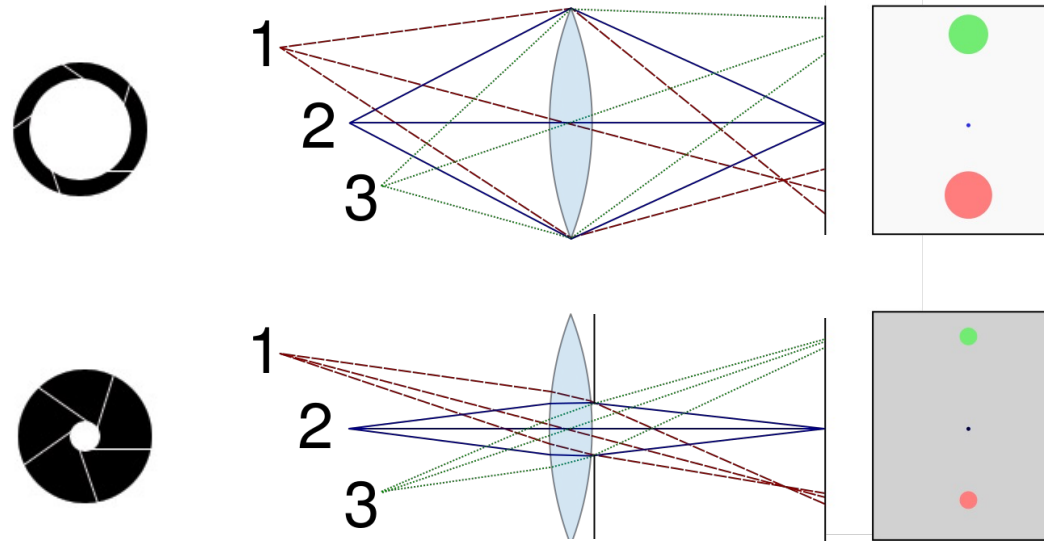
[Image source](#)
(via A. Efros)

Controlling depth of field



[Figure source](#)

Controlling depth of field



Changing the *aperture* size affects depth of field

- A smaller aperture increases the range in which the object is approximately in focus
- But small aperture reduces amount of light – need to increase *exposure*

[Figure source](#)

Varying the aperture



Large aperture = small DOF



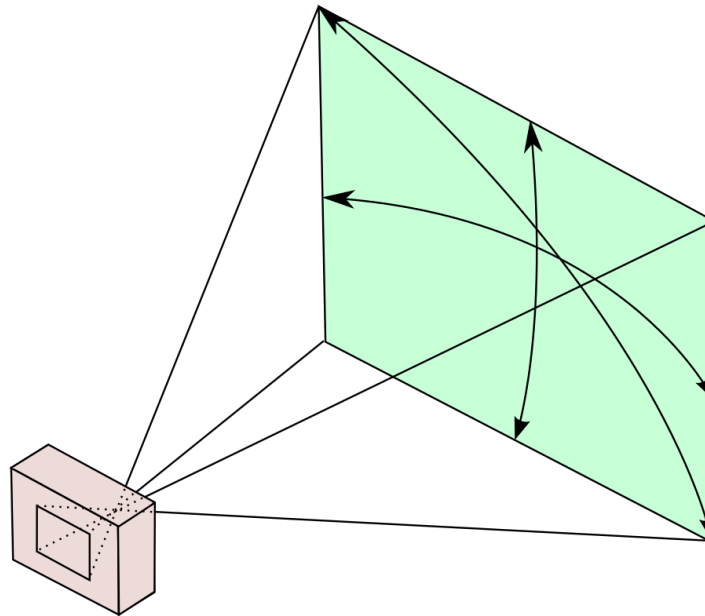
Small aperture = large DOF

Overview

- Pinhole projection
- Lenses
- Field of view, focal length

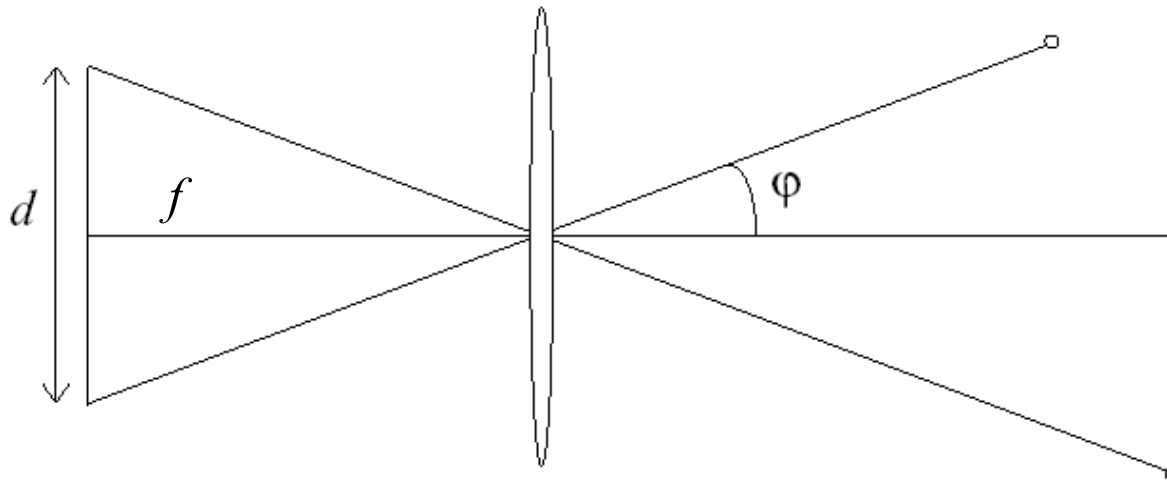
Field of view

- The field of view is the angular extent of the world observed by the camera ([Wikipedia](#))
- What determines the FOV?



Field of view

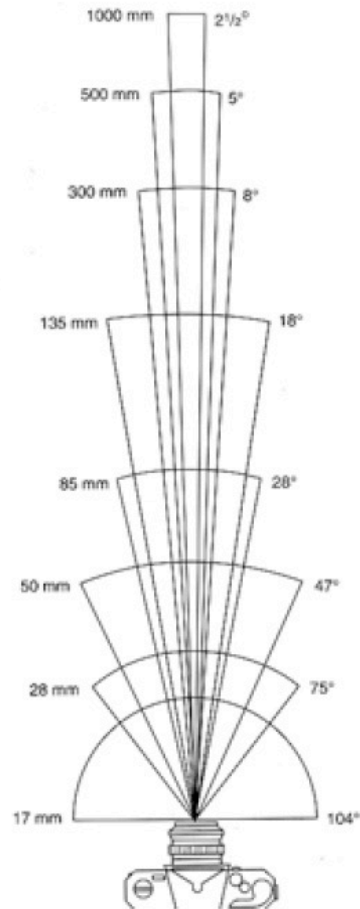
- The field of view is the angular extent of the world observed by the camera ([Wikipedia](#))
- What determines the FOV?
 - Focal length (f), length of the sensor (d):



$$\varphi = \tan^{-1} \frac{d}{2f}$$

- Larger focal length = smaller FOV

Field of view



17mm



28mm



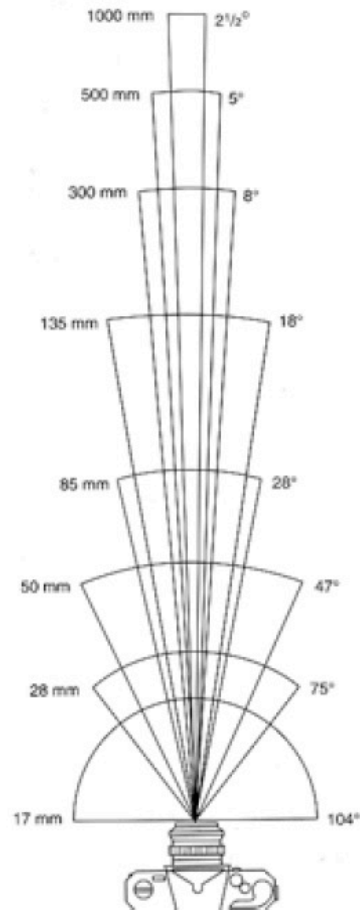
50mm



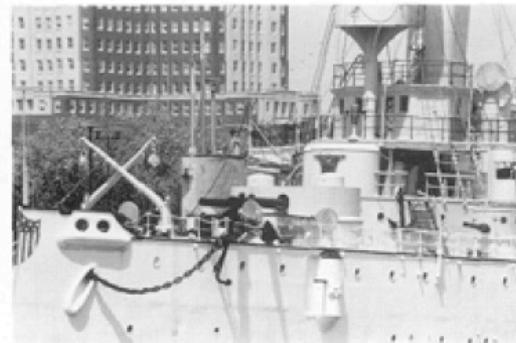
85mm

Slide by A. Efros

Field of view



135mm



300mm



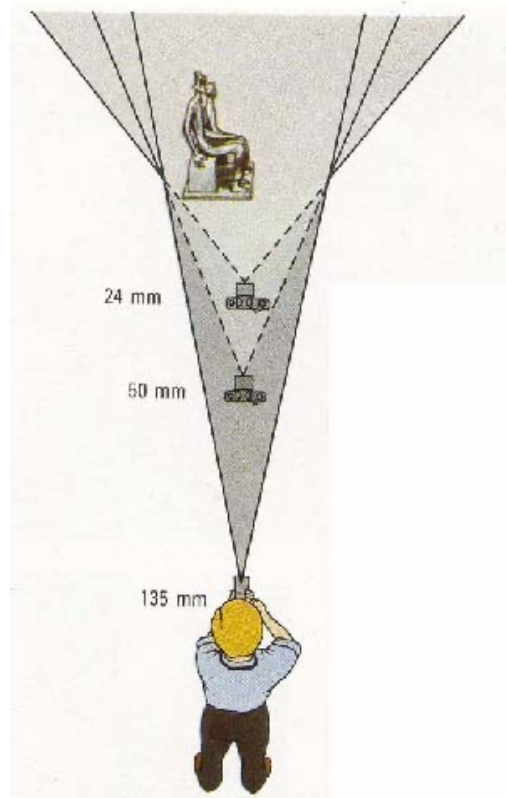
500mm



1000mm

Slide by A. Efros

Field of view / focal length



Large FOV, small f
Camera close to car



Small FOV, large f
Camera far from the car

Sources: A. Efros, F. Durand

Same effect for faces



wide-angle



standard

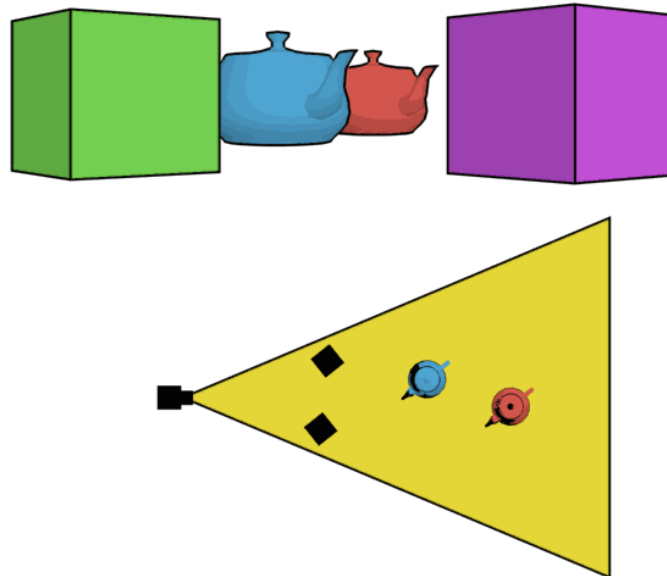


telephoto

Source: F. Durand

The dolly zoom

- Continuously adjusting the focal length while the camera moves away from (or towards) the subject



http://en.wikipedia.org/wiki/Dolly_zoom

The dolly zoom

- Continuously adjusting the focal length while the camera moves away from (or towards) the subject
- “The Vertigo shot”



[Example of dolly zoom from *Goodfellas*](#) (YouTube)

[Example of dolly zoom from *La Haine*](#) (YouTube)

My “dolly zoom”



My “dolly zoom”



Choice of lens and viewpoint: A COVID-era illustration



[Source](#)

Overview

- Pinhole projection
- Lenses
- Field of view, focal length
- Marginal distortion

Marginal distortion

- In wide-angle photos, objects on the periphery “look wrong”

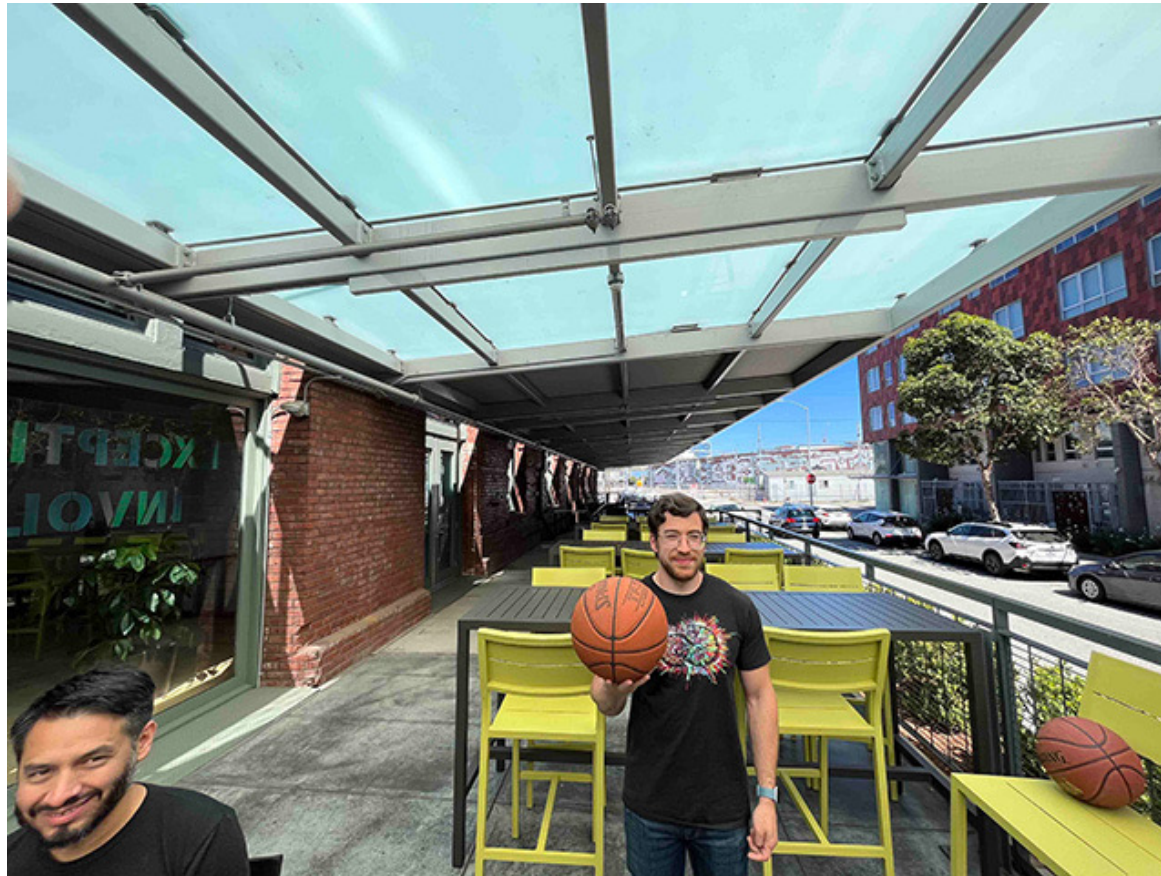


Image source:
[A. Hertzmann](#)

Marginal distortion

- What is the shape of the projection of a sphere?

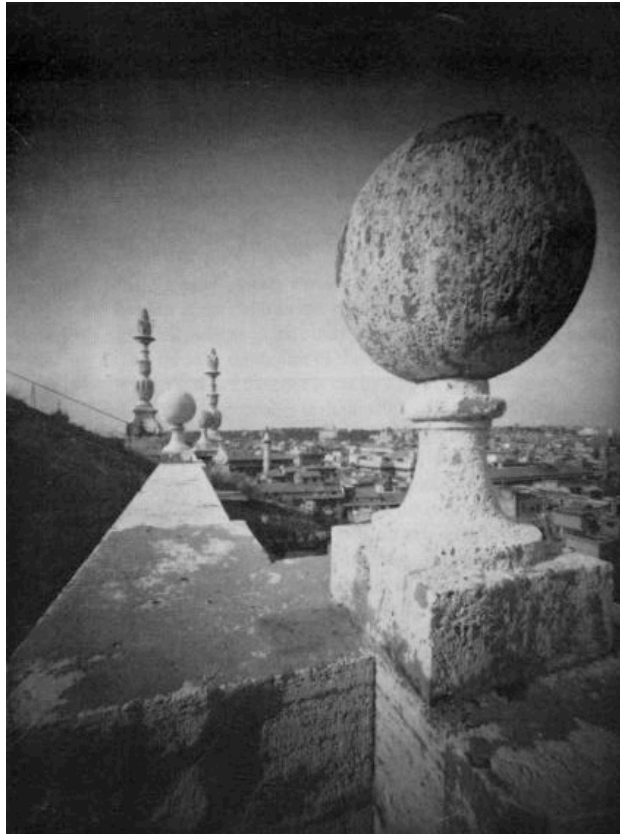
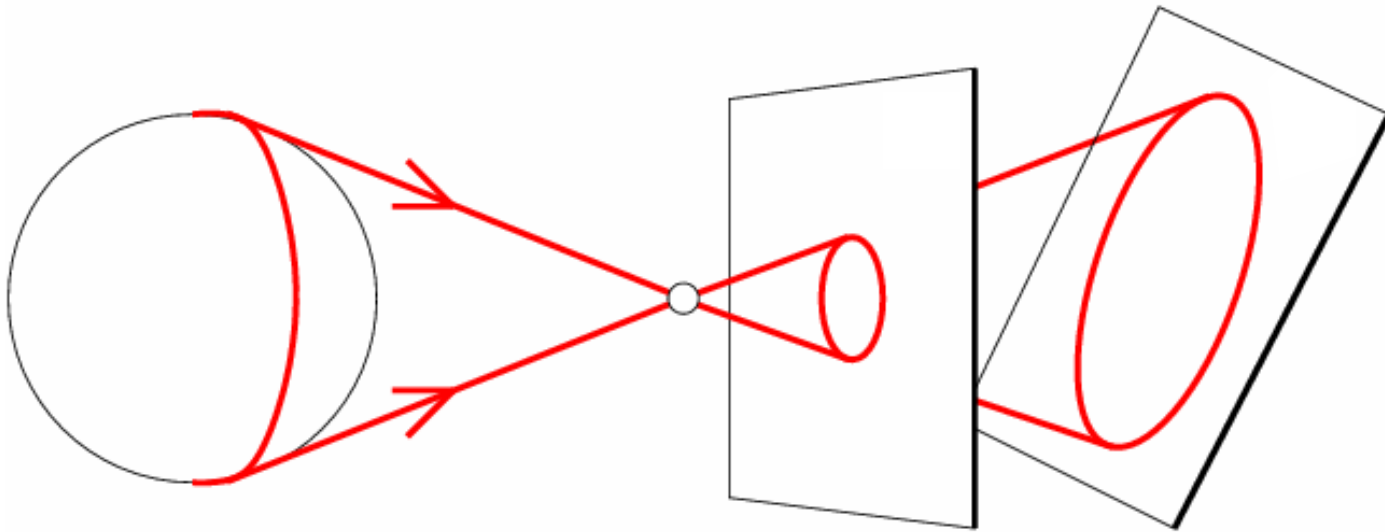


Image source: F. Durand

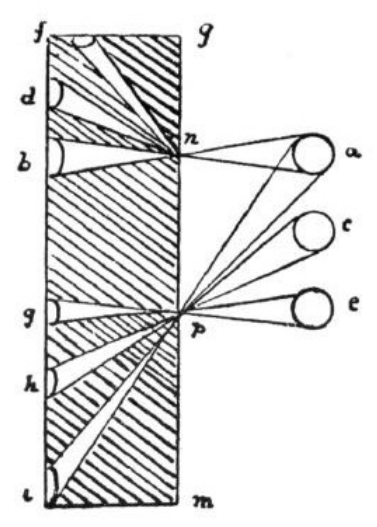
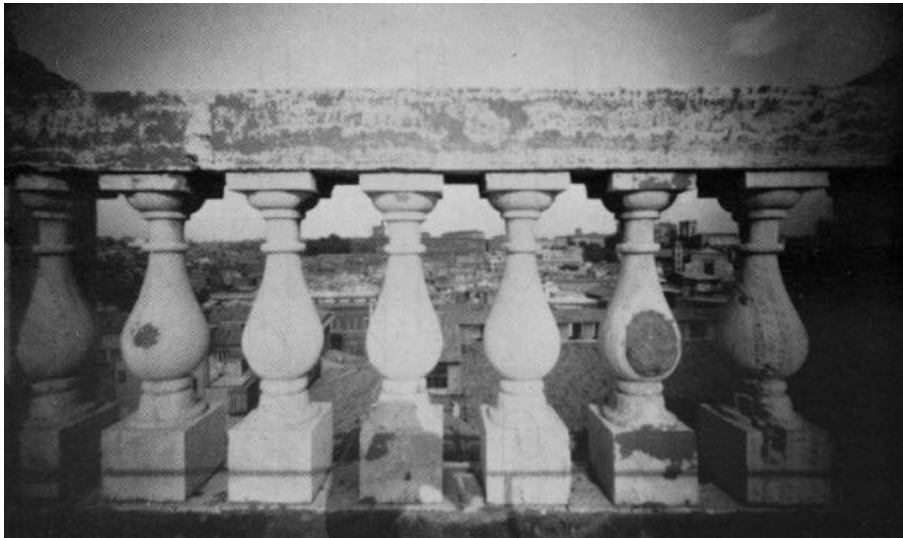
Marginal distortion

- What is the shape of the projection of a sphere?



Marginal distortion

- Are the widths of the projected columns equal?
 - The exterior columns are wider
 - This is not an optical illusion, and is not due to lens flaws
 - Phenomenon pointed out by Leonardo Da Vinci



Source: F. Durand

Marginal distortion

- Which way are these people facing?

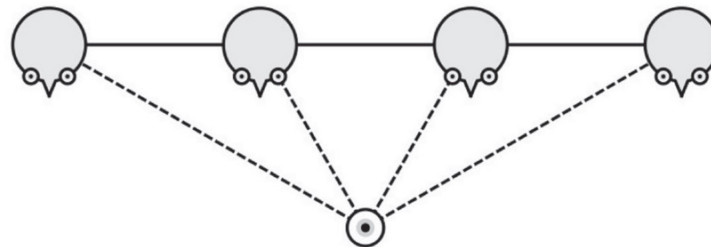


Image source: [Koenderink et al.](#) via [A. Hertzmann](#)

Perspective and art



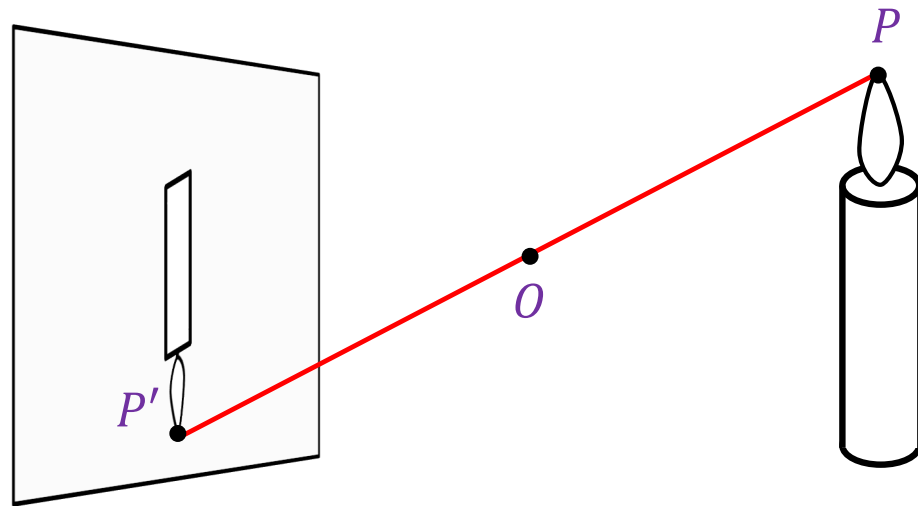
Raphael, [The School of Athens](#), 1509-1511

Perspective and art

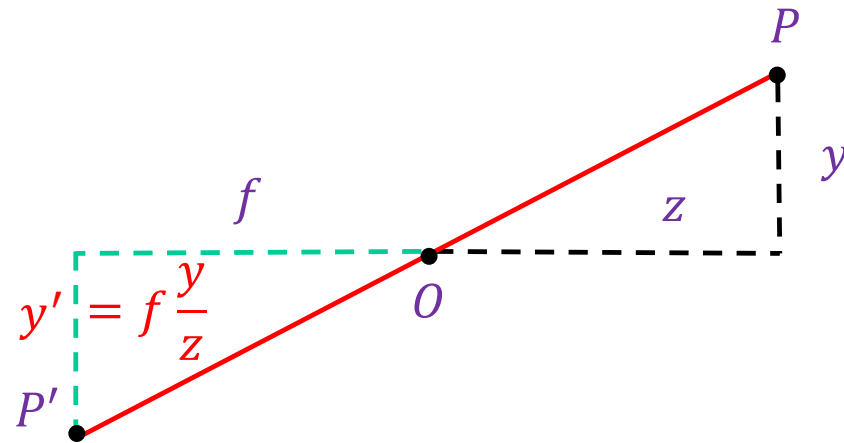
- “Large scenes with many faces are common in art... But, in the entire history of painting, I am unaware of any face depicted with the marginal distortions dictated by linear perspective.”

A. Hertzmann. [Toward a theory of perspective perception in pictures](#). Journal of Vision, 2024
[Blog post](#)

Review: Pinhole projection

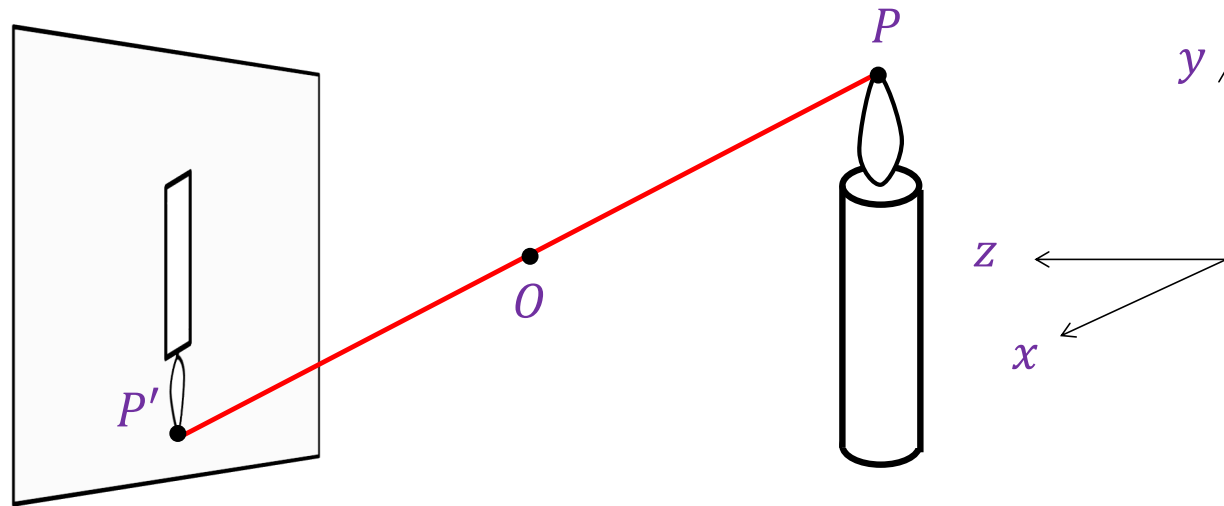


Review: Pinhole projection



$$(x, y, z) \rightarrow \left(f \frac{x}{z}, f \frac{y}{z} \right)$$

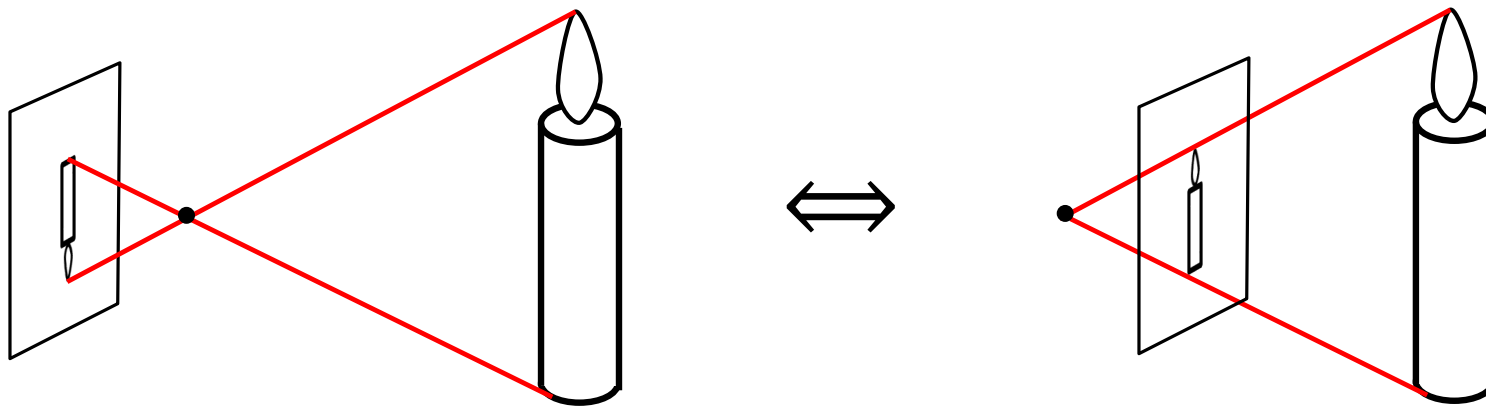
Review: Pinhole projection



Canonical coordinate system

- The optical center (O) is at the origin
- The z axis is the *optical axis* perpendicular to the image plane
- The xy plane is parallel to the image plane, x and y axes are horizontal and vertical directions of the image plane

Review: Pinhole projection



Note: instead of dealing with an image that is upside down, most of the time we will pretend that the image plane is *in front* of the camera center

Review: Field of view

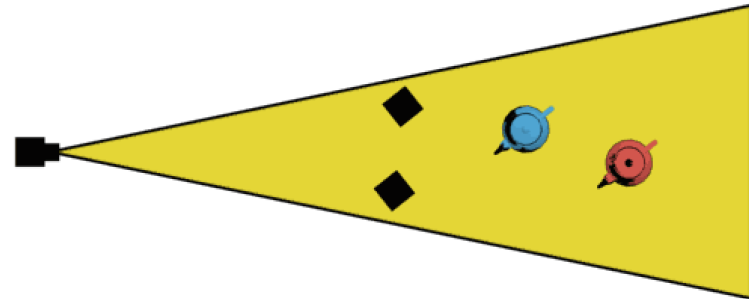
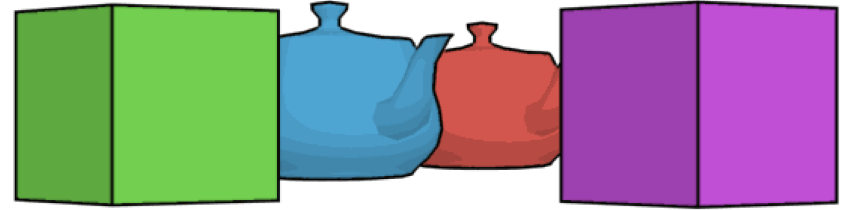
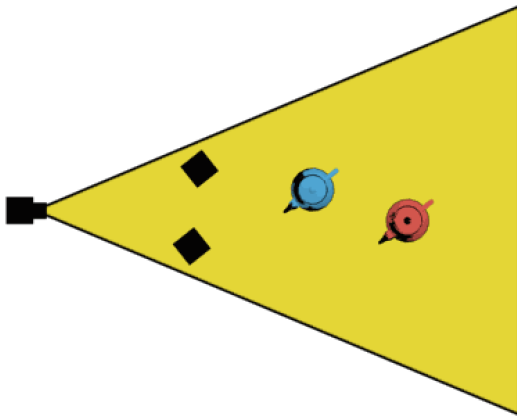
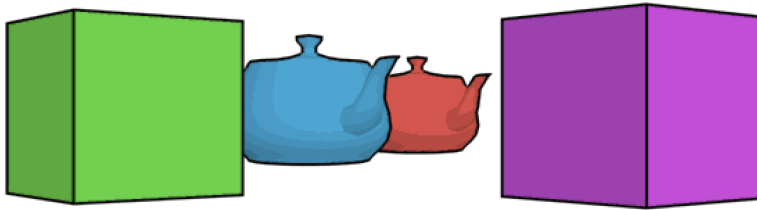
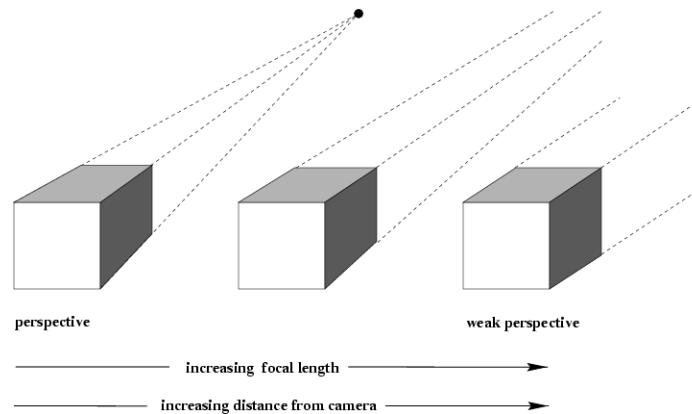


Figure source: [Wikipedia](https://en.wikipedia.org/wiki/Field_of_view)

Orthographic or parallel projection

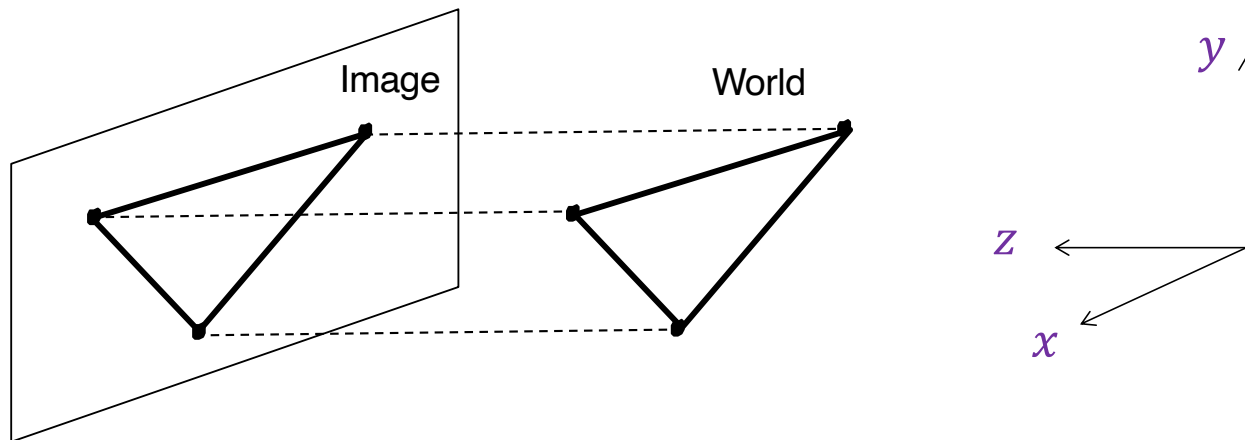
- What happens if we walk infinitely far away and zoom infinitely far in?



Source: Hartley & Zisserman

Orthographic or parallel projection

- Special case of perspective projection
 - Distance from center of projection to image plane is infinite
 - Projection equation: simply drop the z coordinate!



Orthographic or parallel projection

- Special case of perspective projection
 - Distance from center of projection to image plane is infinite
 - Projection equation: simply drop the z coordinate!



SimCity 2000

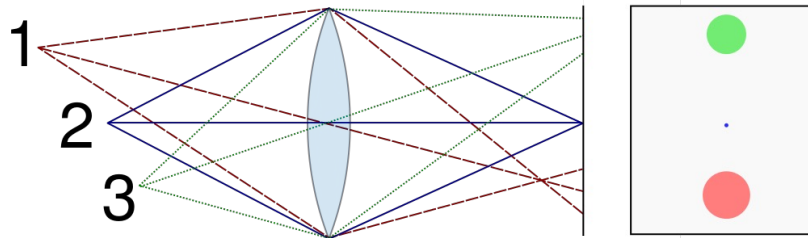


12th century Chinese scroll
(via [A. Hertzmann](#))

Review: Cameras with lenses

Review: Cameras with lenses

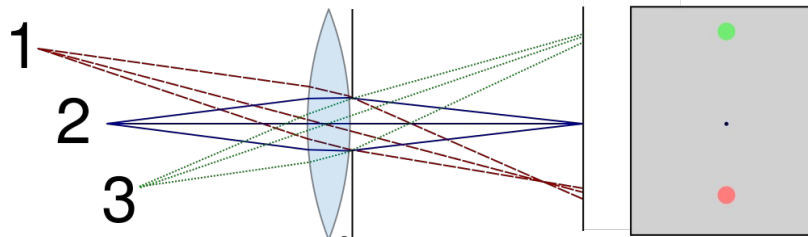
Large aperture



Small DOF



Small aperture



Large DOF

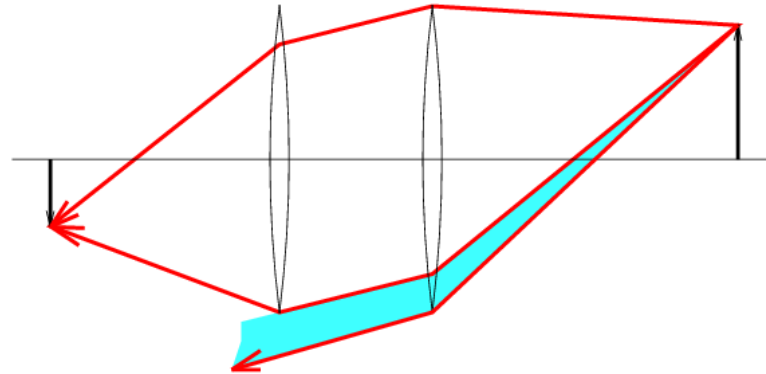


Overview

- Pinhole projection
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- Marginal distortion
- Lens distortions

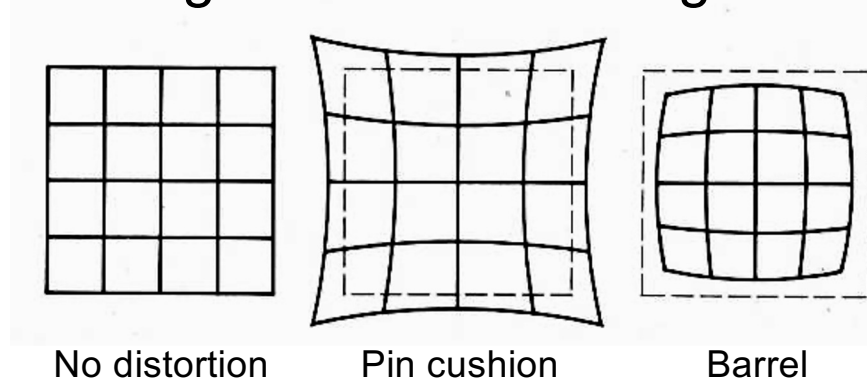


Vignetting



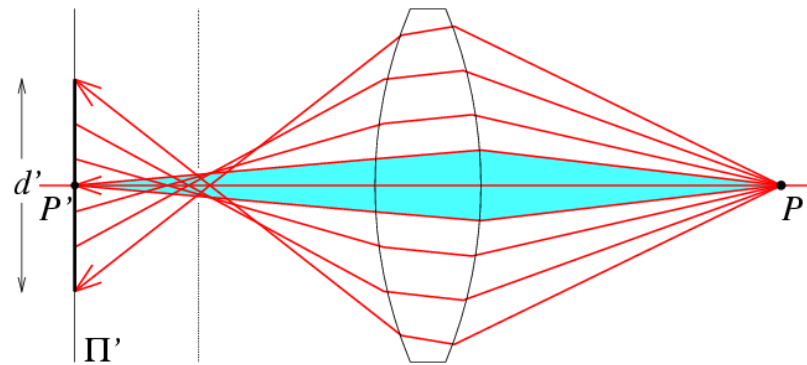
Radial distortion

- Caused by imperfect lenses
- Distortion is stronger towards the edges of the photo



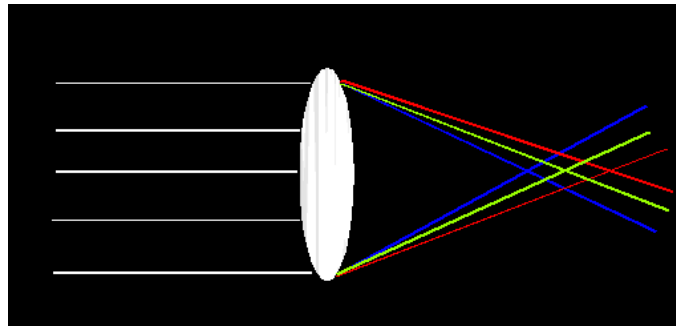
Spherical aberration

- Spherical lenses don't focus light perfectly
- Rays farther from the optical axis focus closer



Lens flaws: Chromatic aberration

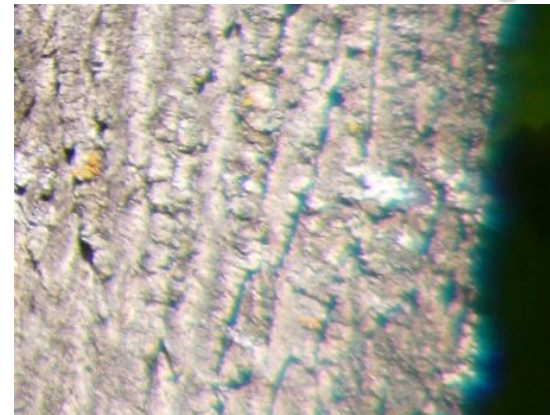
- Lens has different refractive indices for different wavelengths: causes color fringing



Near Lens Center



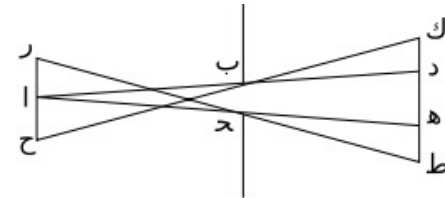
Near Lens Outer Edge



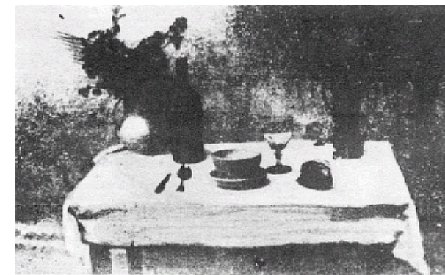
Historic milestones

- **Pinhole model:** Mozi (470-390 BCE), Aristotle (384-322 BCE)
- **Principles of optics (including lenses):** Alhacen (965-1039 CE)
- **Camera obscura:** Leonardo da Vinci (1452-1519), Johann Zahn (1631-1707)
- **First photo:** Joseph Nicephore Niepce (1822)
- **Daguerreotypes** (1839)
- **Photographic film** (Eastman, 1889)
- **Cinema** (Lumière Brothers, 1895)
- **Color Photography** (Lumière Brothers, 1908)
- **Television** (Baird, Farnsworth, Zworykin, 1920s)
- **First consumer camera with CCD**
Sony Mavica (1981)
- **First fully digital camera:** Kodak DCS100 (1990)

https://en.wikipedia.org/wiki/History_of_photography



Alhacen's notes



Niepce, "La Table Servie," 1822



Old television camera

First digitally scanned photograph

- NIST (1957), 176x176 pixels



<http://listverse.com/history/top-10-incredible-early-firsts-in-photography/>