Image formation

370: Intro to Computer Vision

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College of
INFORMATION AND
COMPUTER SCIENCES

UMASS
AMHERST

Overview

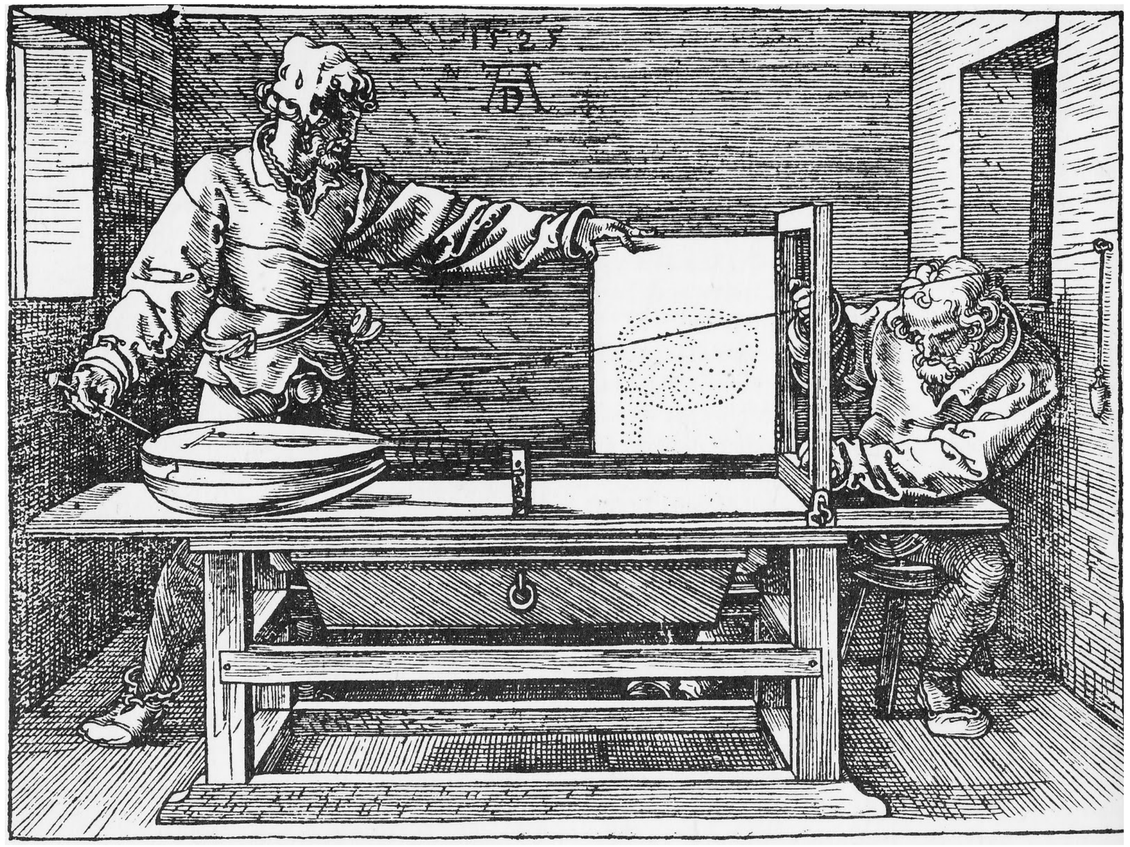
The pinhole projection model

- Qualitative properties

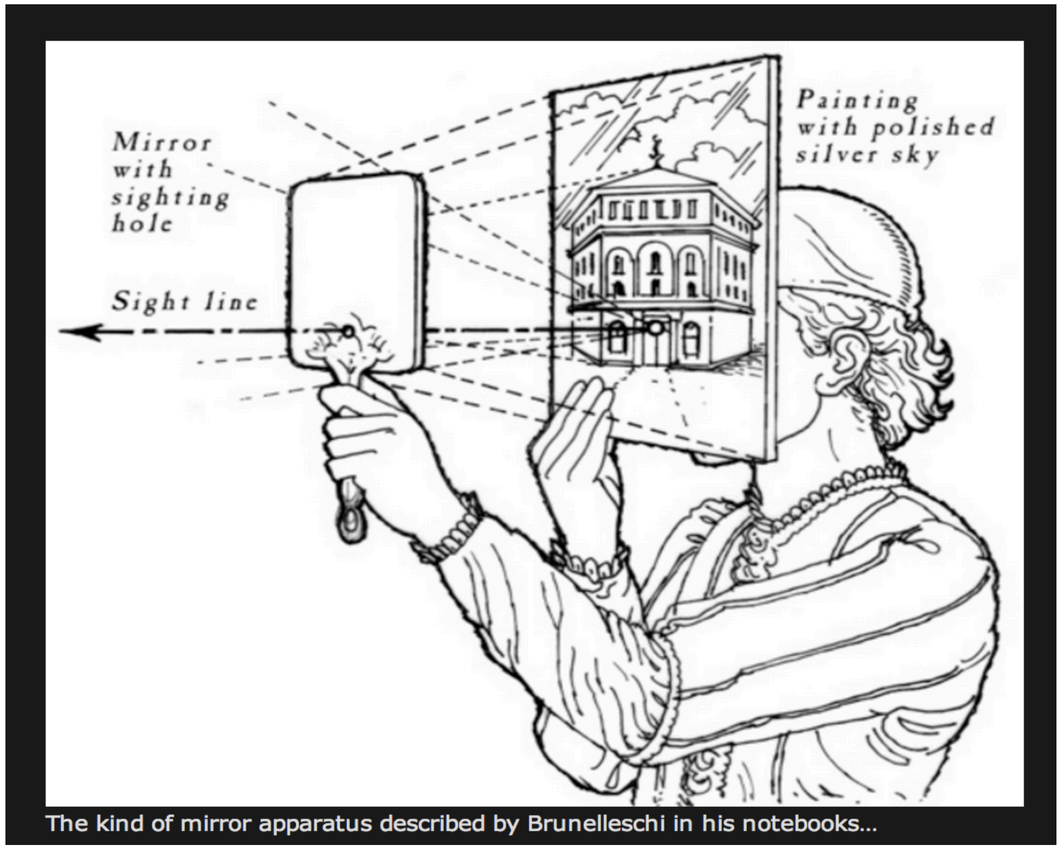
Cameras with lenses

- Depth of focus
- Field of view
- Lens aberrations

Cameras

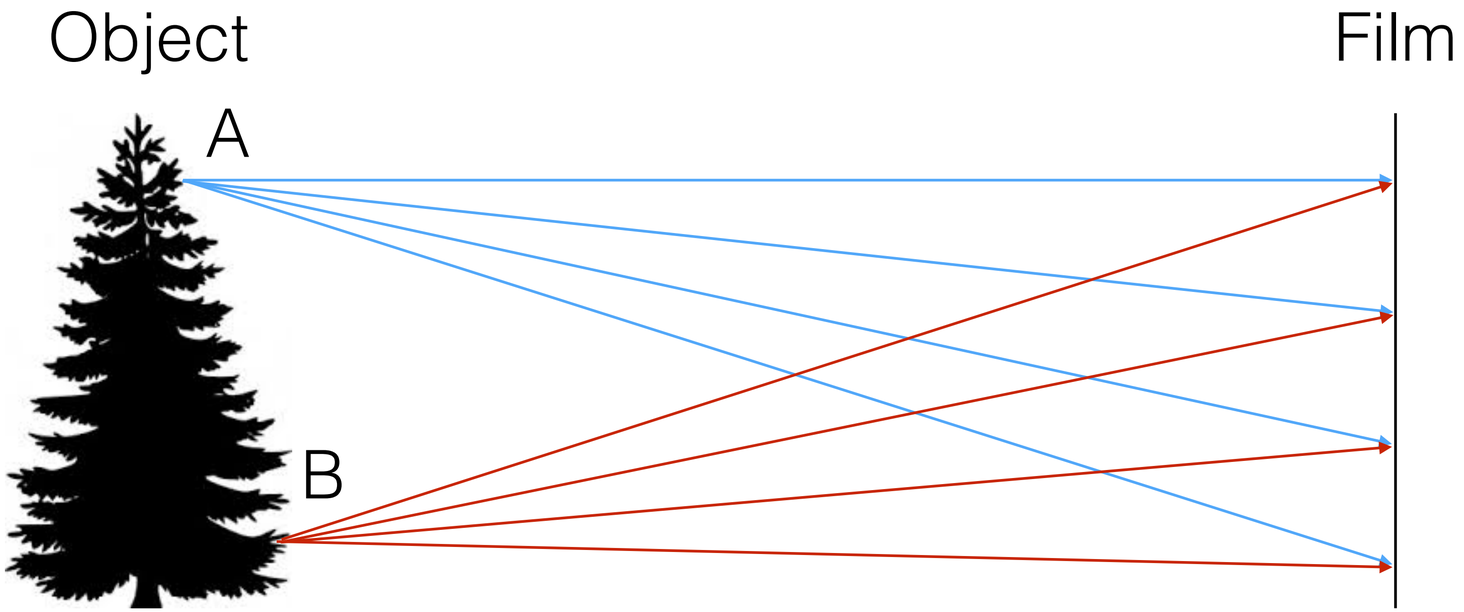


Albrecht Dürer early 1500s



Brunelleschi, early 1400s

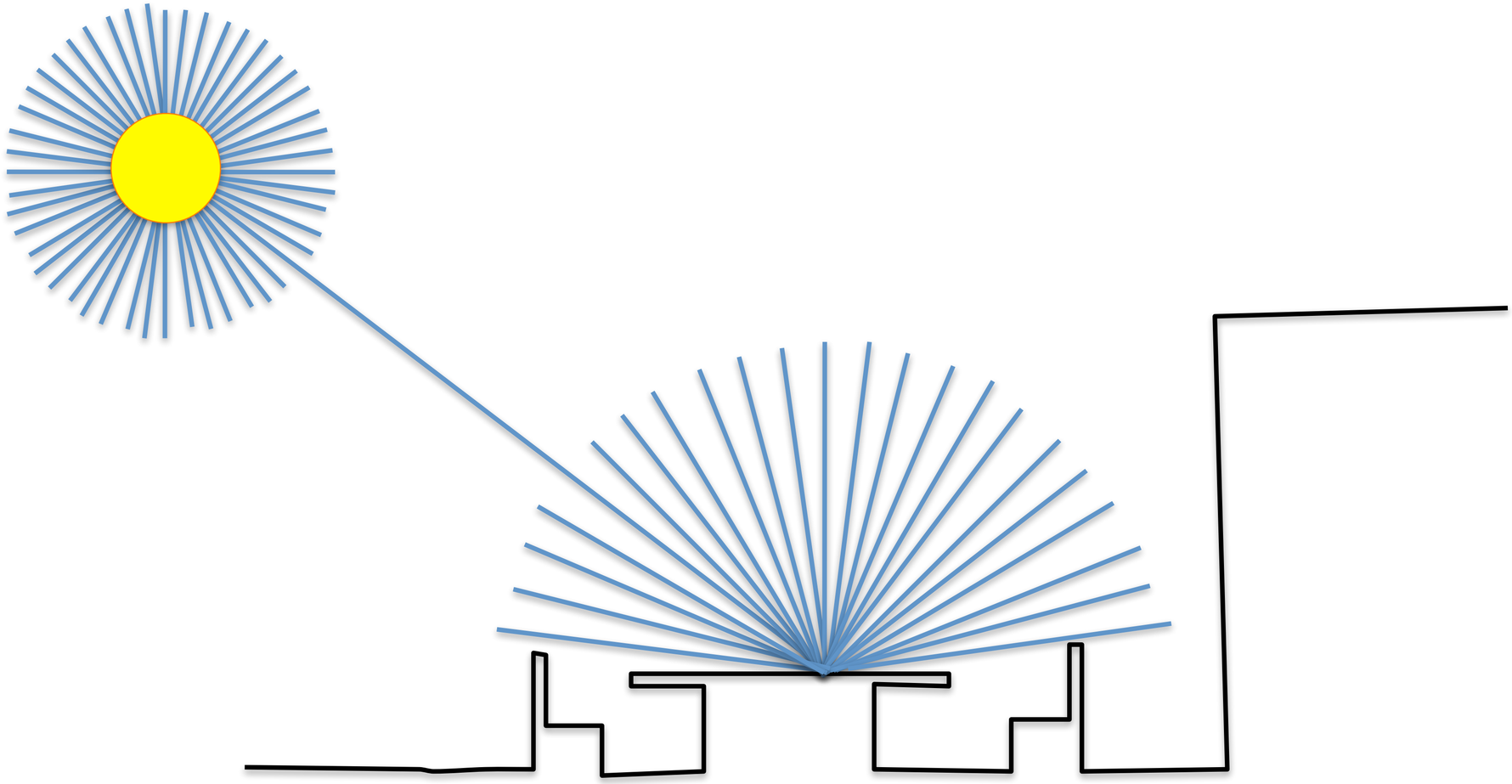
Lets design a camera



Let’s put a film in front of an object

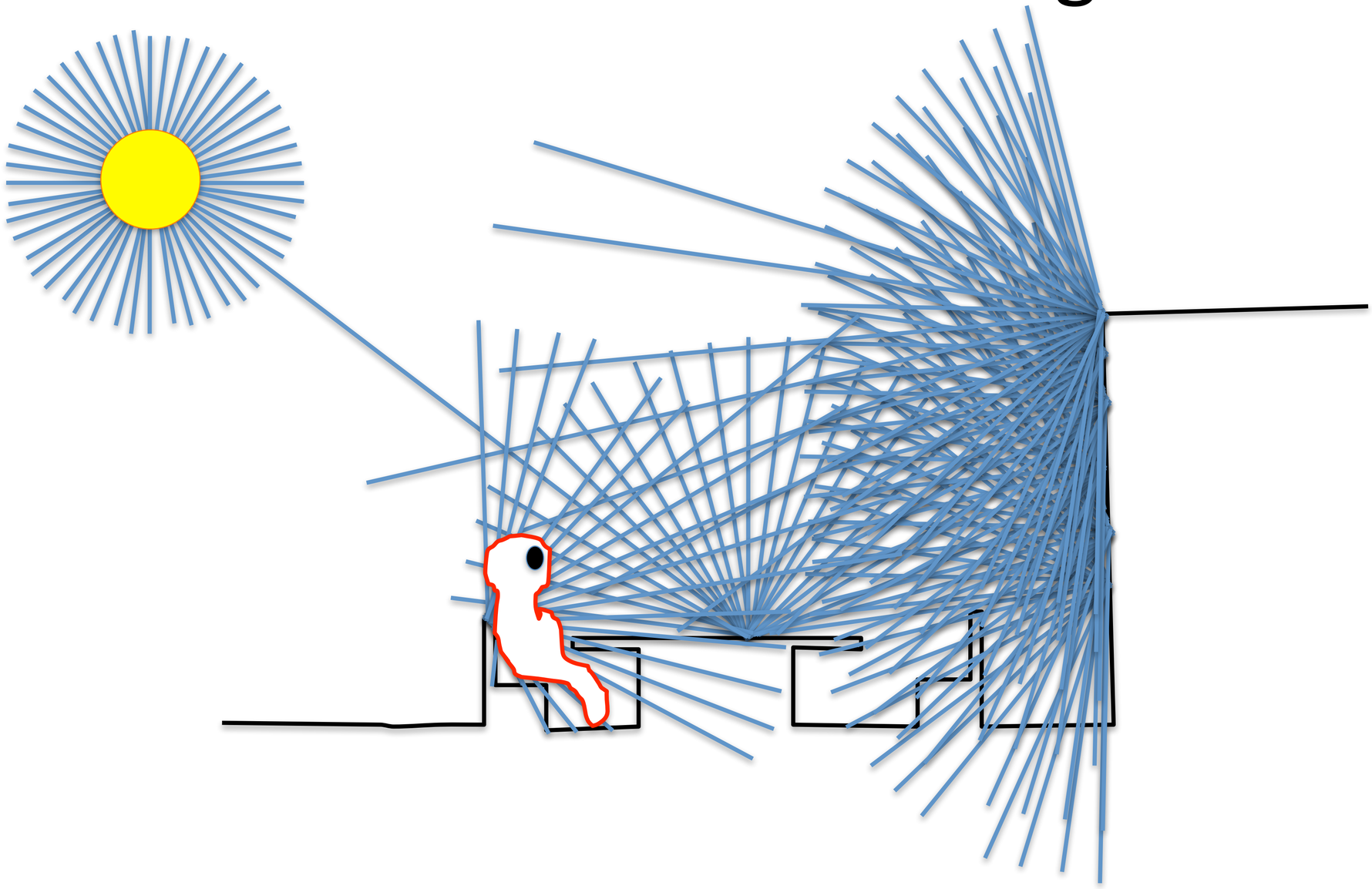
Question: What image do we expect on the film?

The structure of ambient light



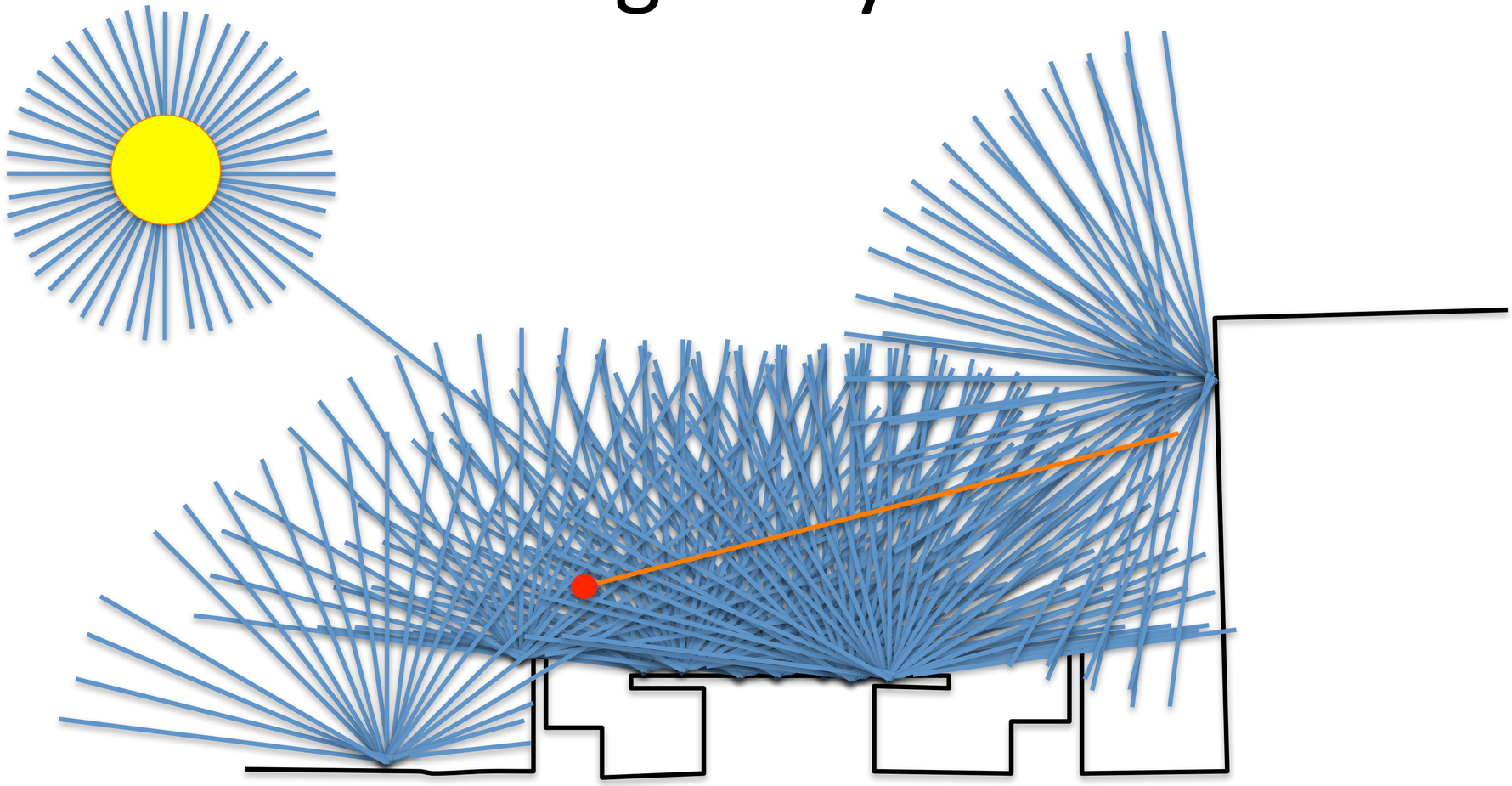
Source: Bill Freeman

The structure of ambient light



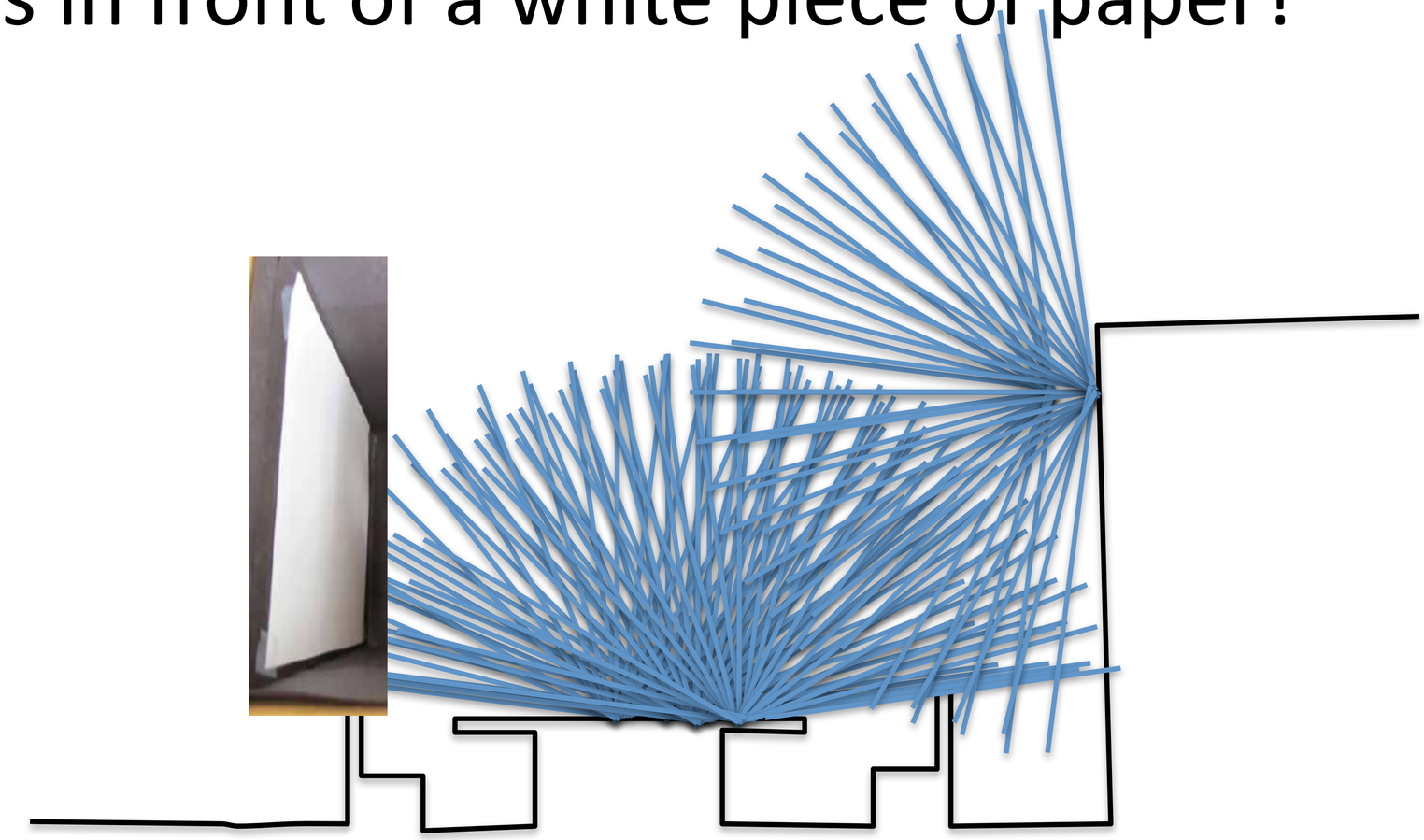
Source: Bill Freeman

All light rays



Source: Bill Freeman

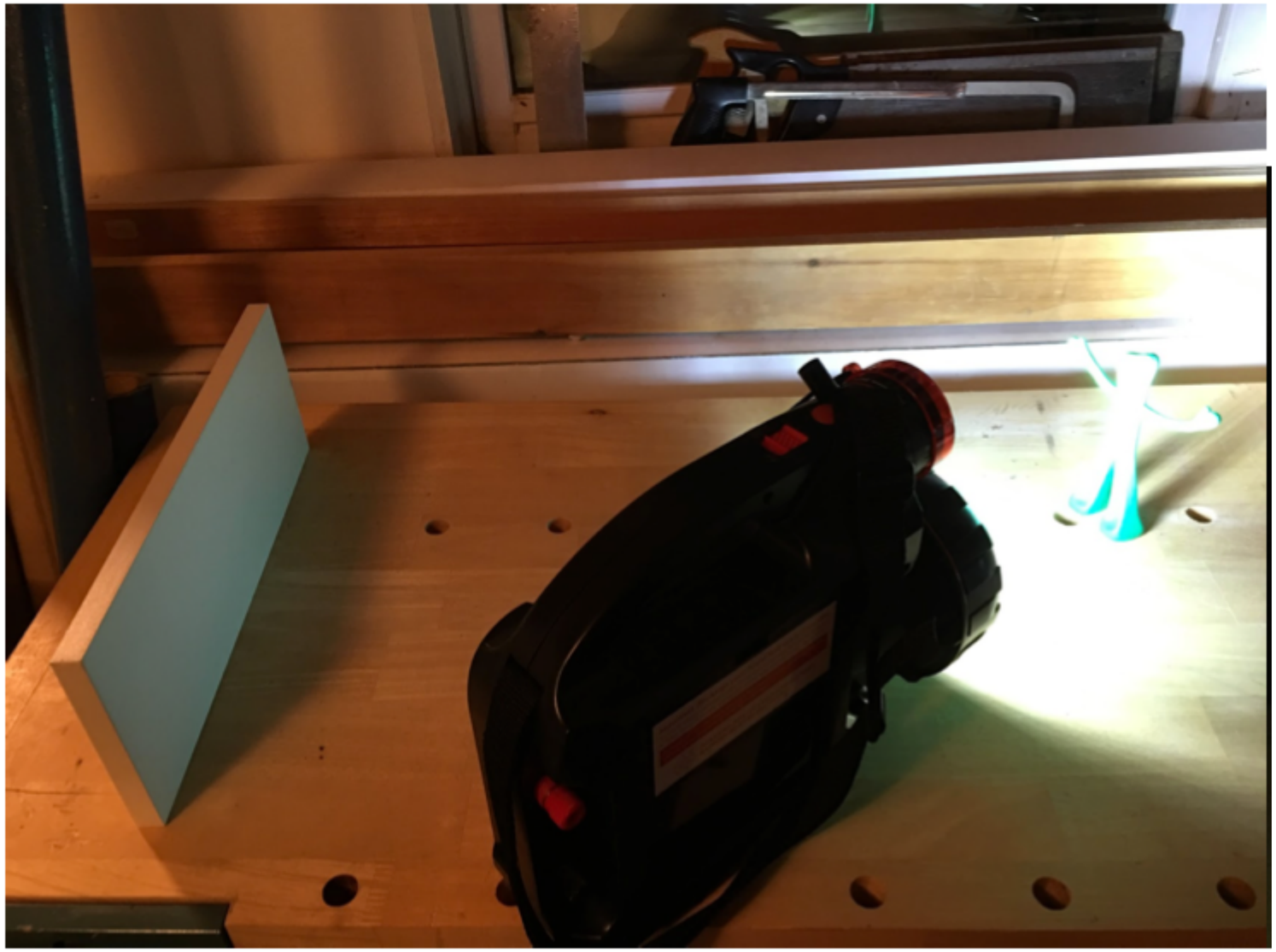
Why don’t we generate an image when an object is in front of a white piece of paper?



Why is there no picture appearing on the paper?

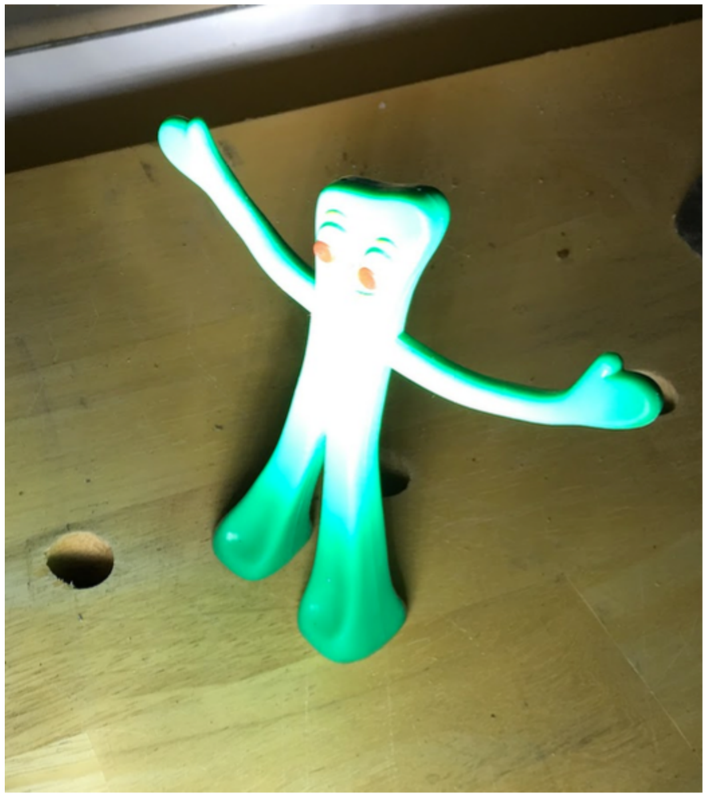
Source: Bill Freeman

Let’s check, do we get an image?



Source: Bill Freeman

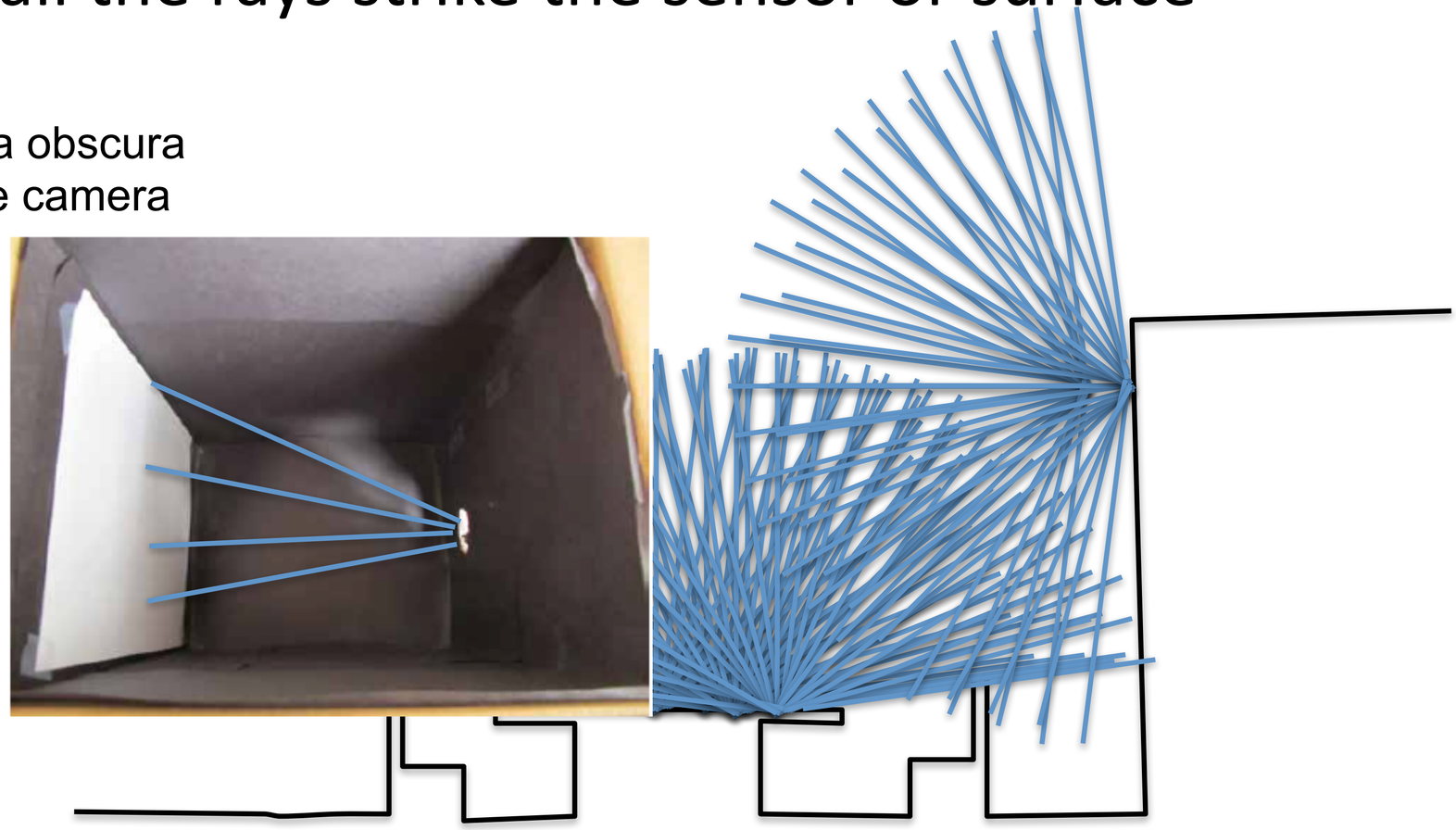
Let’s check, do we get an image? No



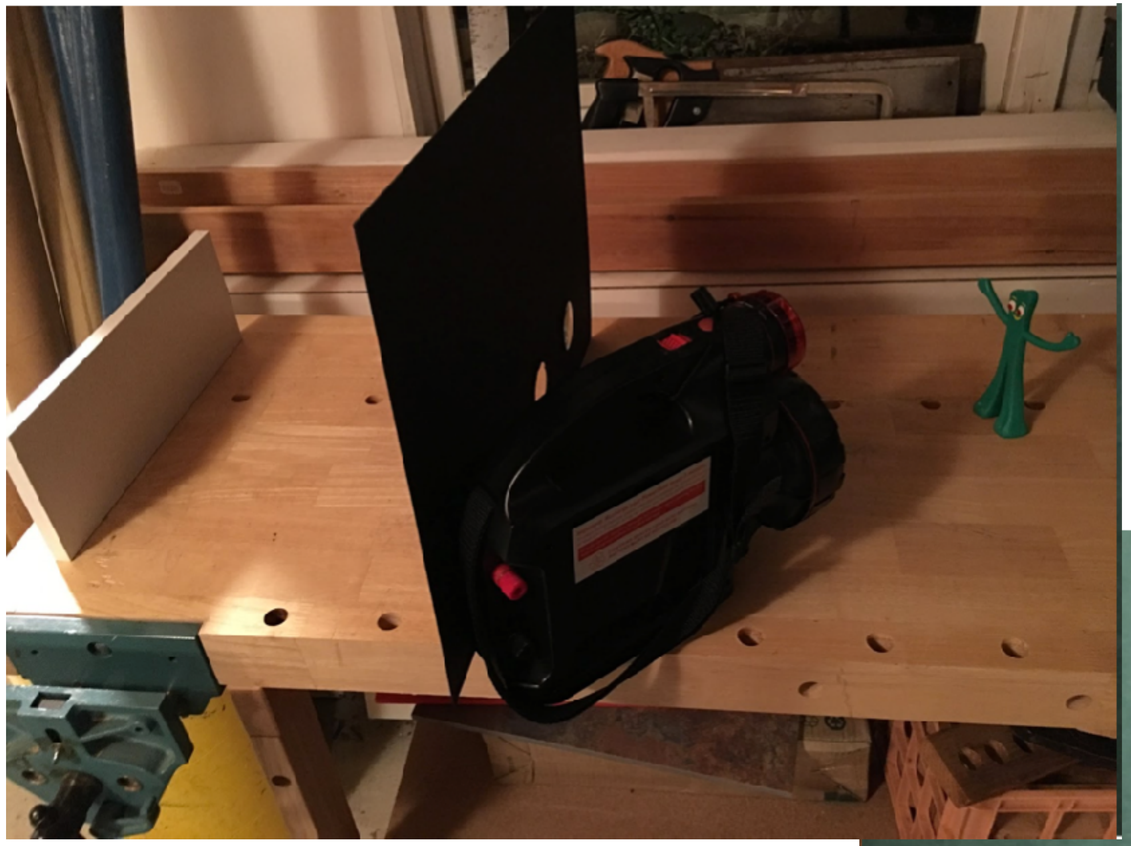
Source: Bill Freeman

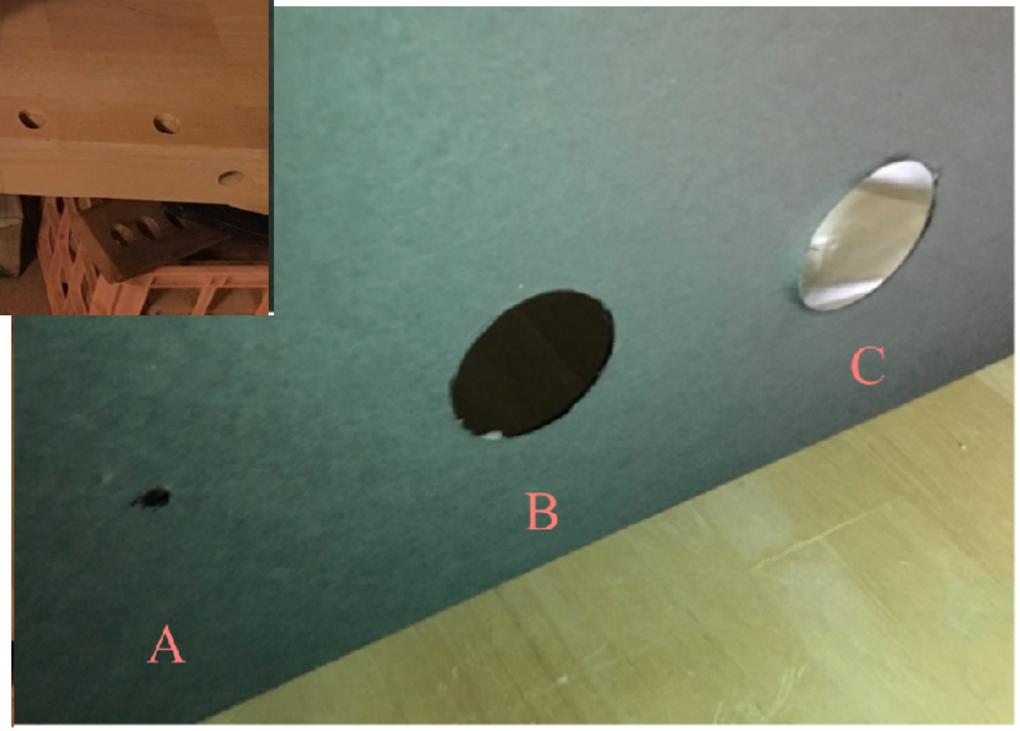
To make an image, we need to have only a subset of all the rays strike the sensor or surface

The camera obscura
The pinhole camera



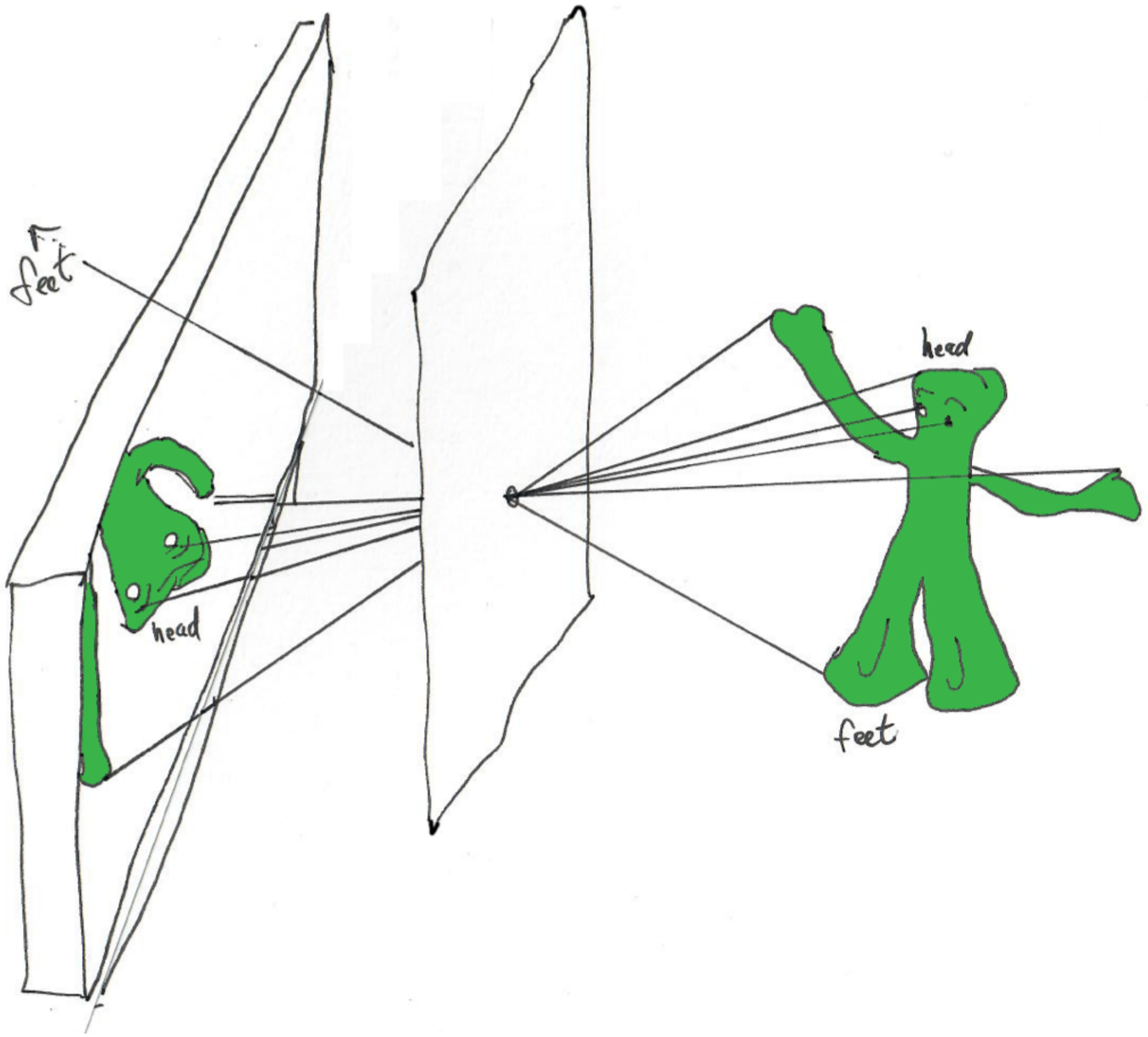
Let’s try putting different occluders in between the object and the sensing plane



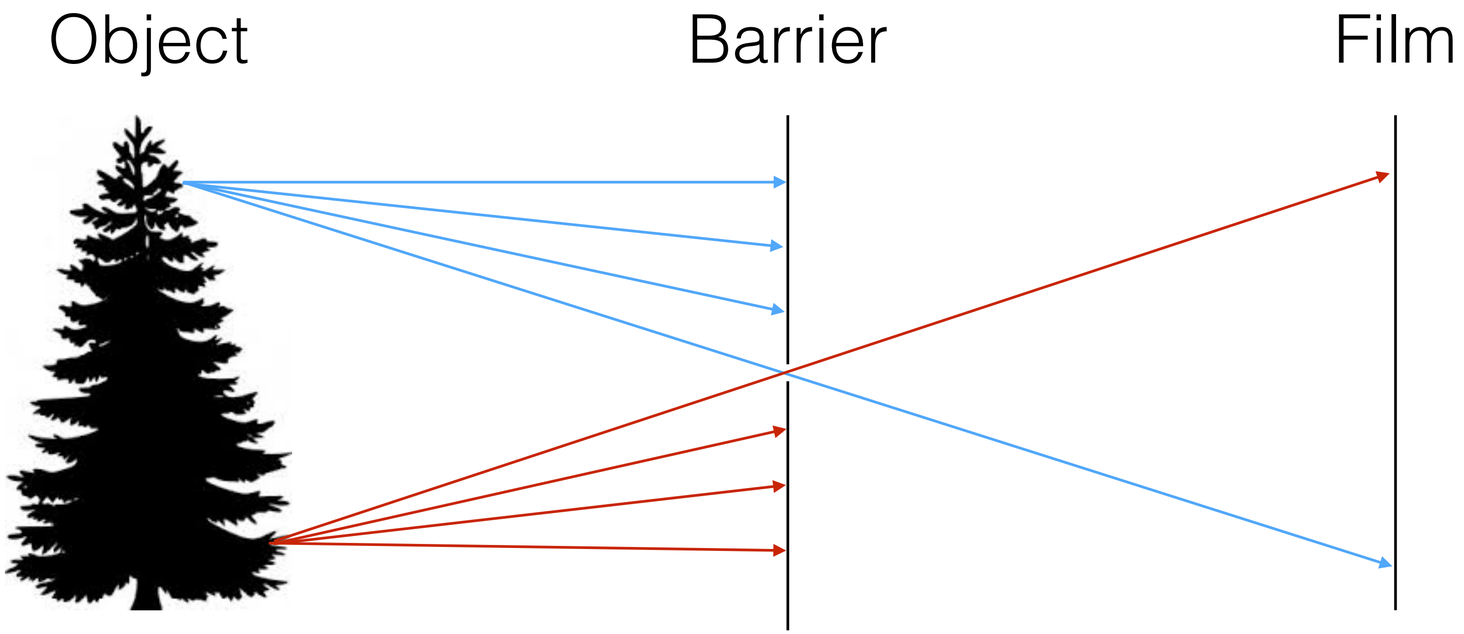


light on wall past pinhole

image is inverted

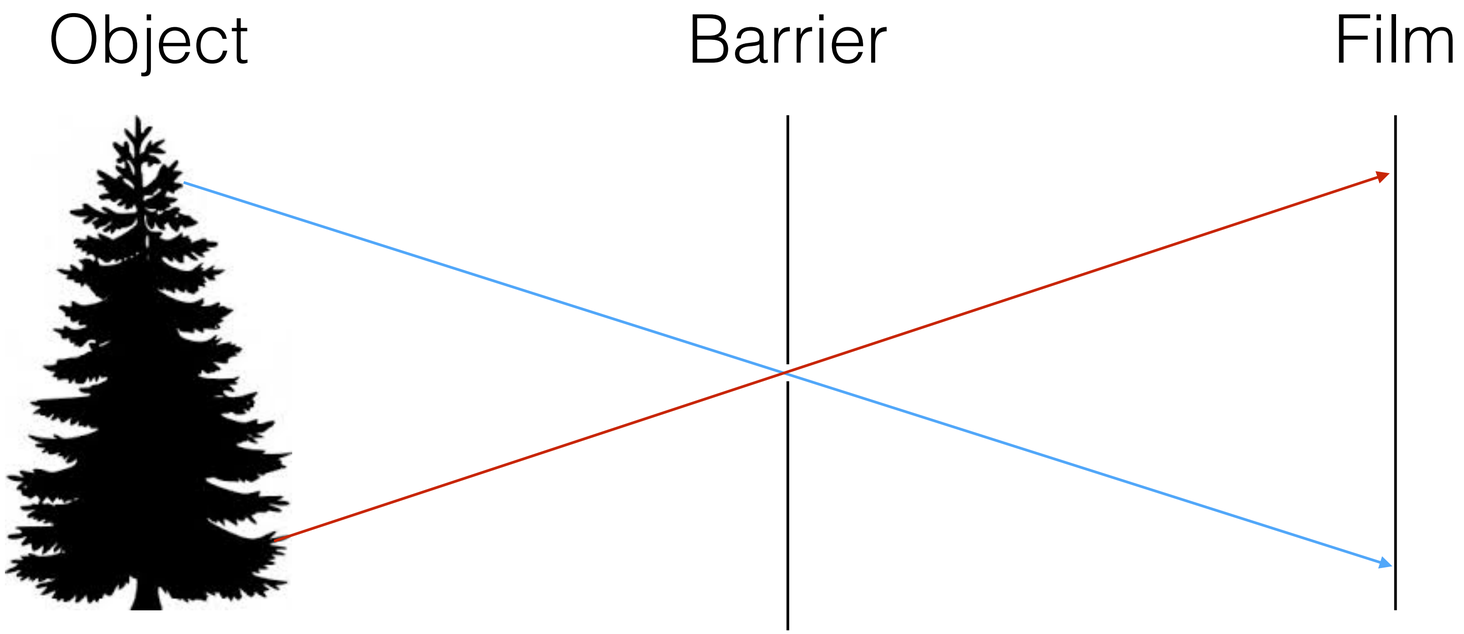


Pinhole camera



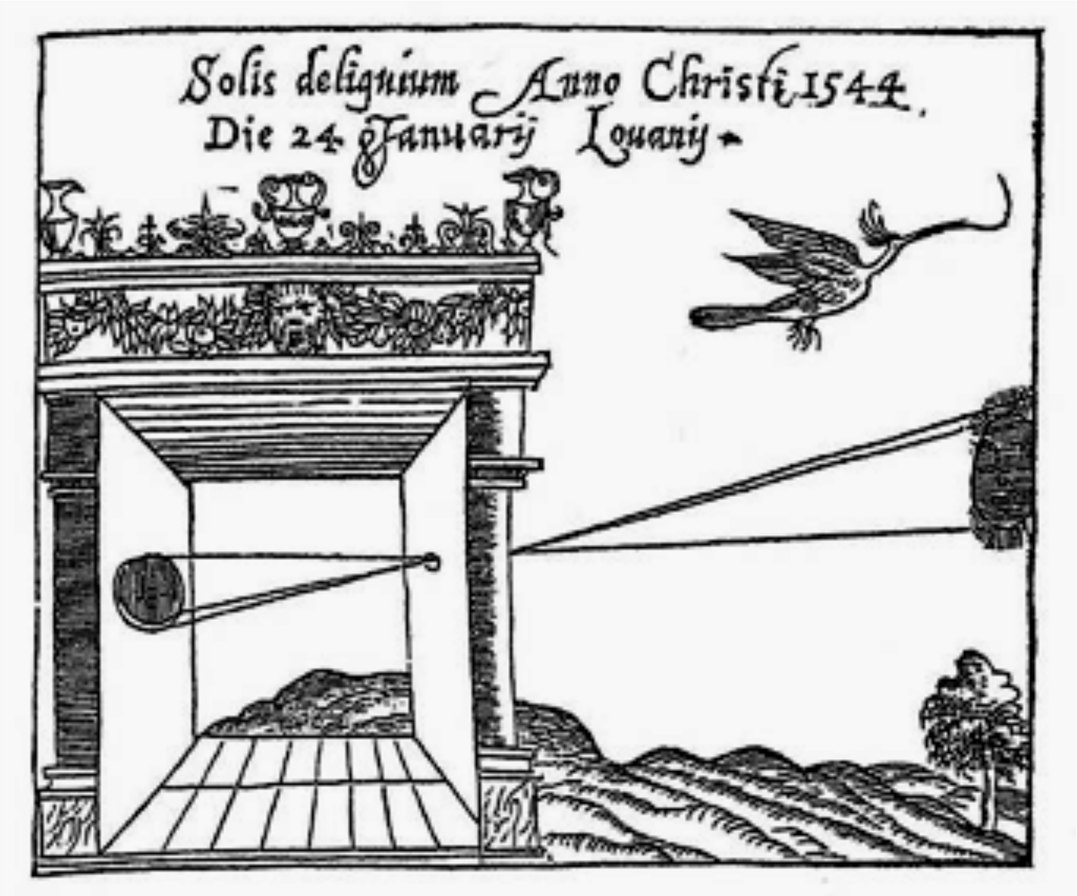
Add a barrier to block of most rays

Pinhole camera



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

Camera obscura



Gemma Frisius, 1558

Basic principle known to Mozi (470-390 BCE), Aristotle (384-322 BCE)

Drawing aids for artists: described by Leonardo Da Vinci (1452-1519 AD)

"Camera obscura" Latin for "darkened room"

Pinhole cameras are everywhere

Tree shadow during a solar eclipse
photo credit: Nils van der Burg
http://www.physicstogo.org/index.cfm

Accidental pinhole cameras

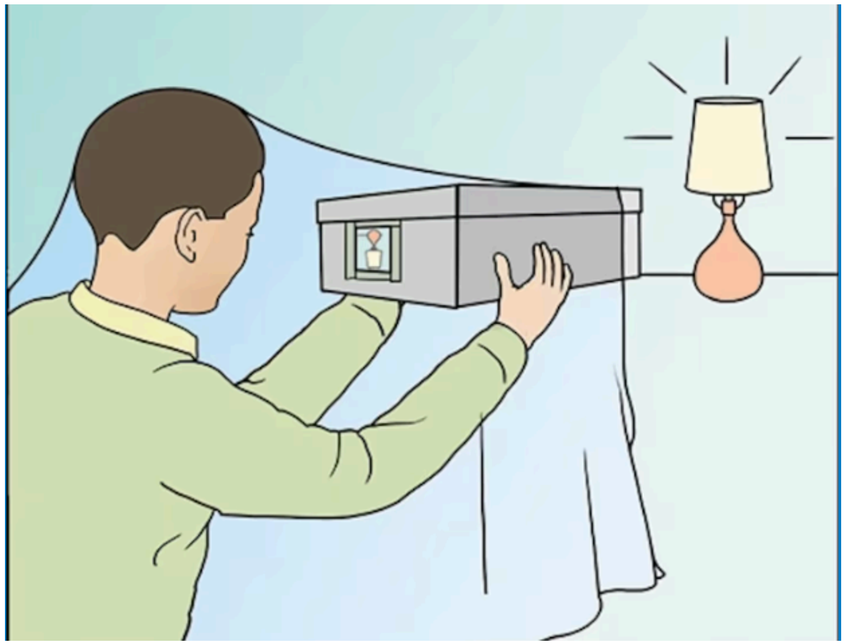
My hotel room,
contrast enhanced.

The view from my window

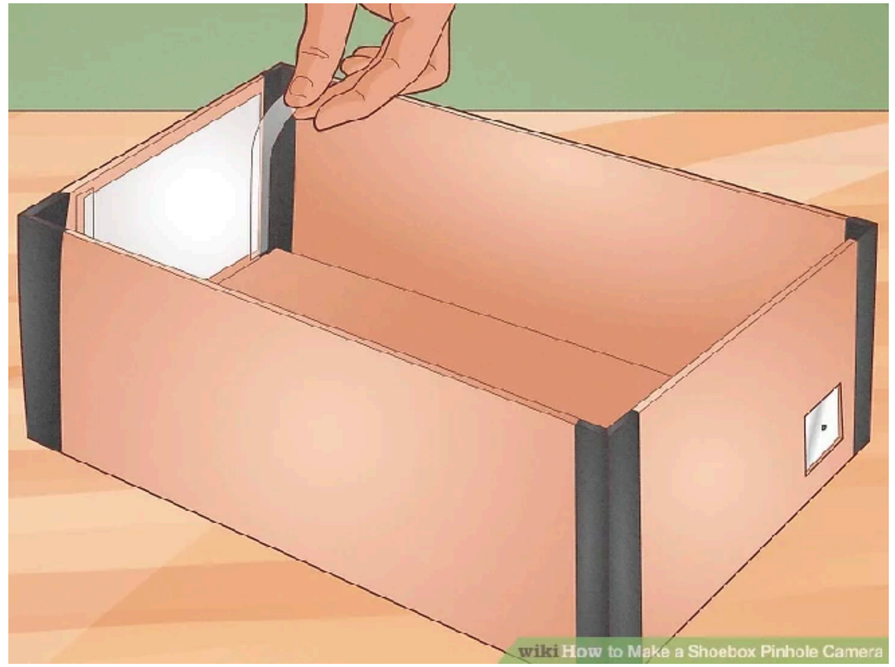
Accidental pinholes produce images that are unnoticed or misinterpreted as shadows

A. Torralba and W. Freeman, **Accidental Pinhole and Pinspeck Cameras**, CVPR 2012

Home-made pinhole camera



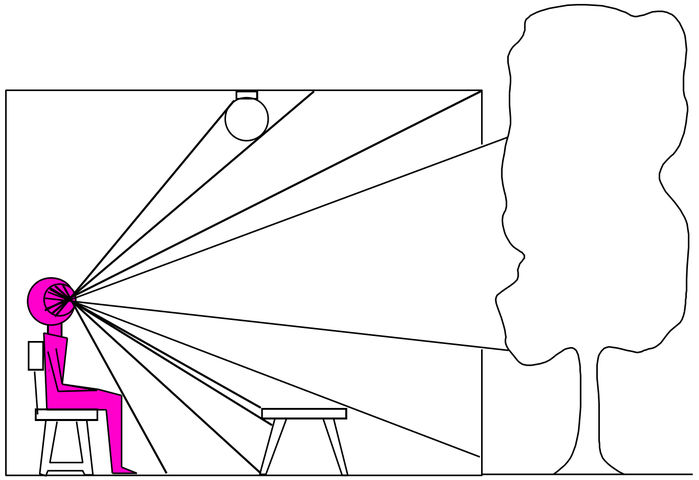
https://kids.nationalgeographic.com/books/article/pinhole-camera



https://www.wikihow.com/Make-a-Shoebox-Pinhole-Camera

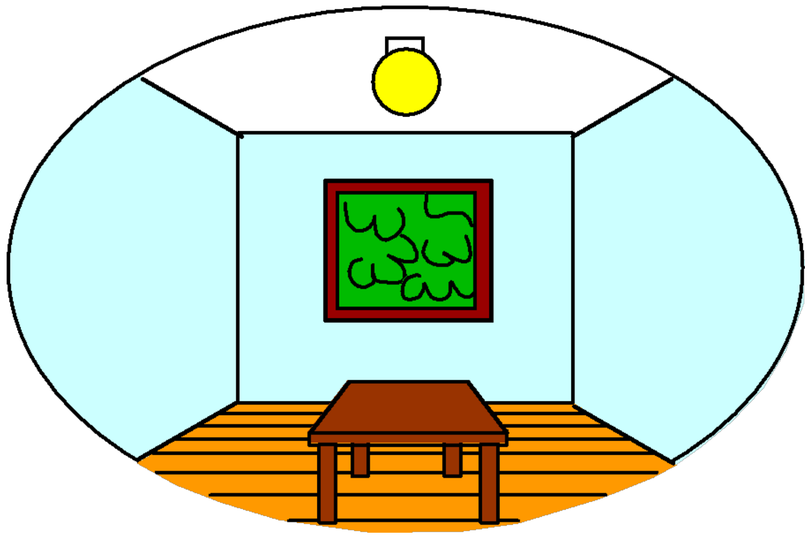
Dimensionality reduction: 3D to 2D

3D world



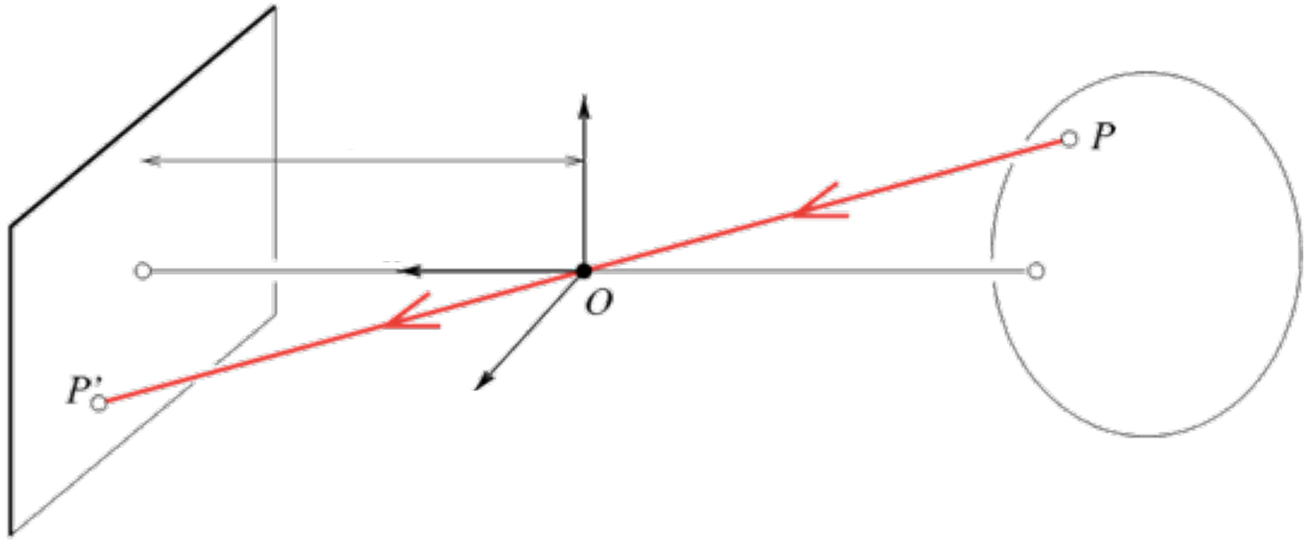
Point of observation

2D image



- **What is preserved?**
  - Straight lines, incidence
- **What is not preserved?**
  - Angles, lengths

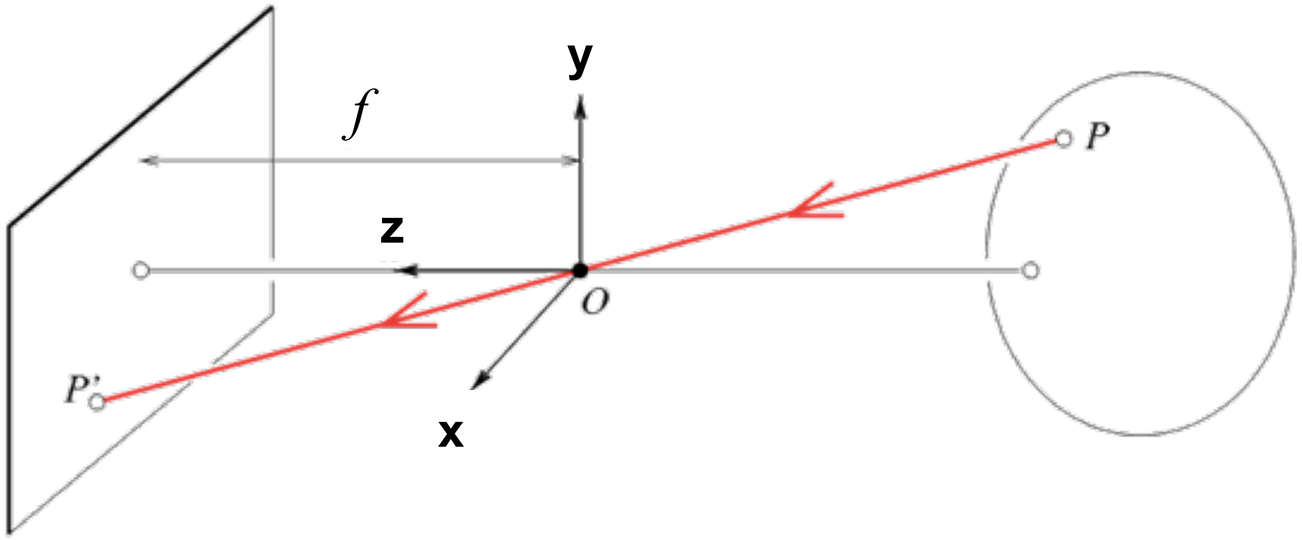
Modeling projection



To compute the projection *P'* of a scene point *P,* form a **visual ray** connection 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 on the image

Modeling projection



The coordinate system

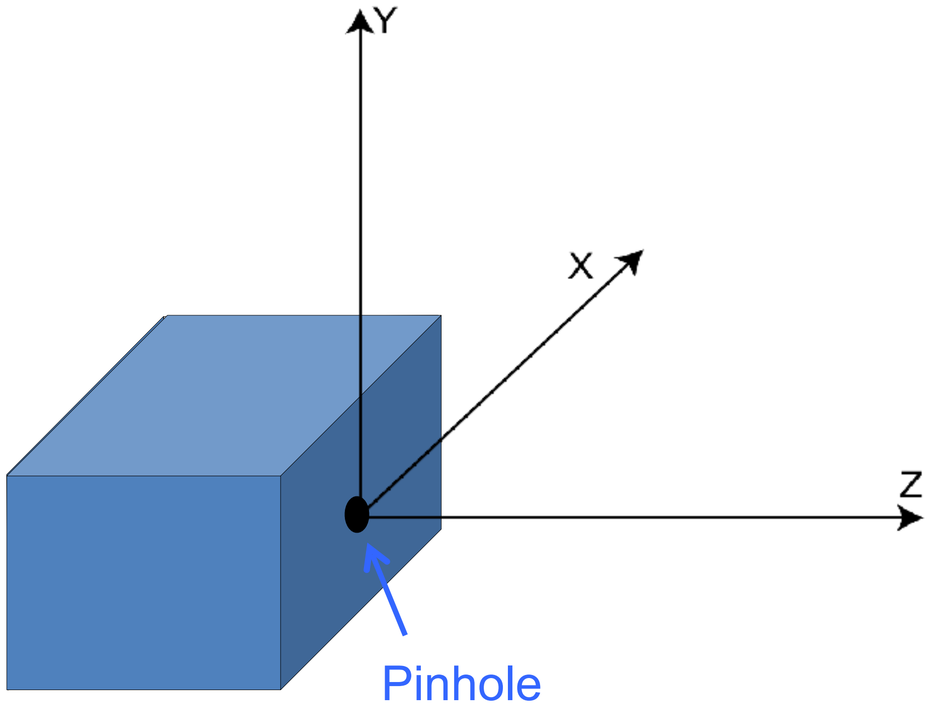
- The optical center (***O***) is at the origin
- The image plane is parallel to the xy-plane (perpendicular to the z axis)

Projection equations

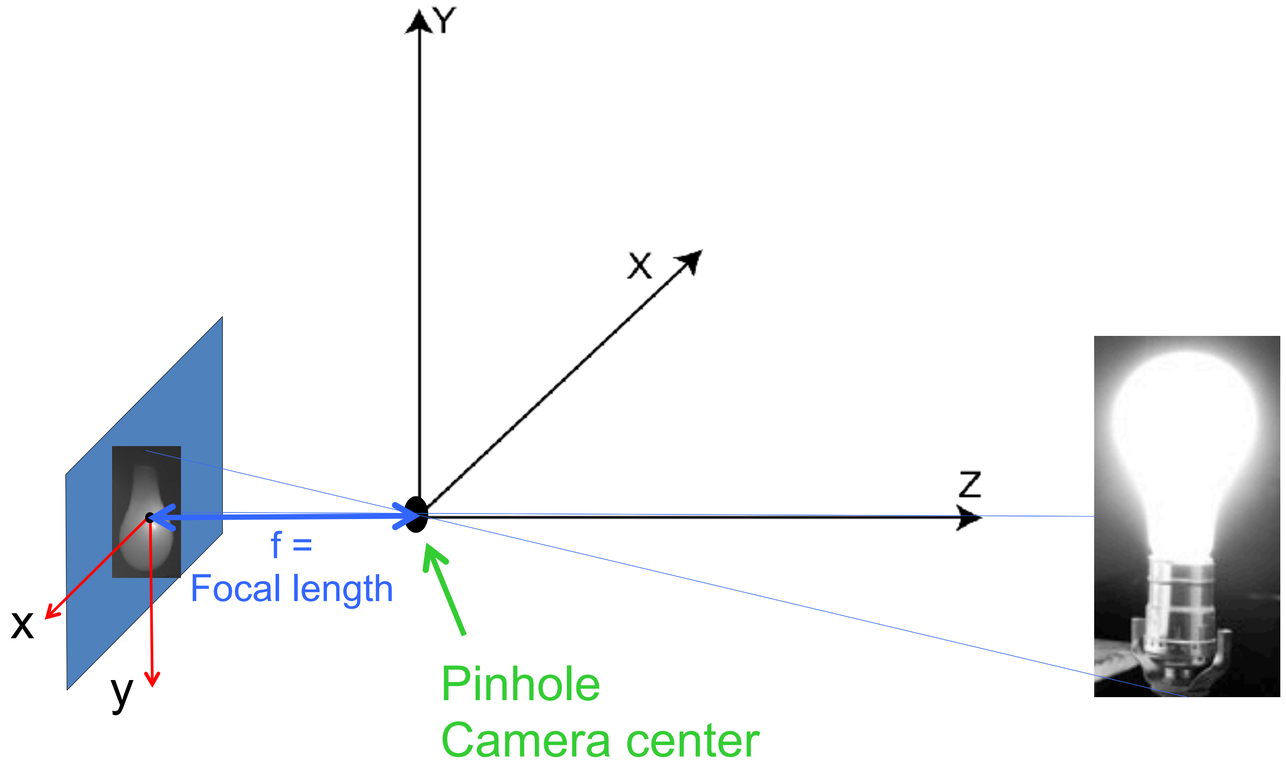
- Derive using similar triangles

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

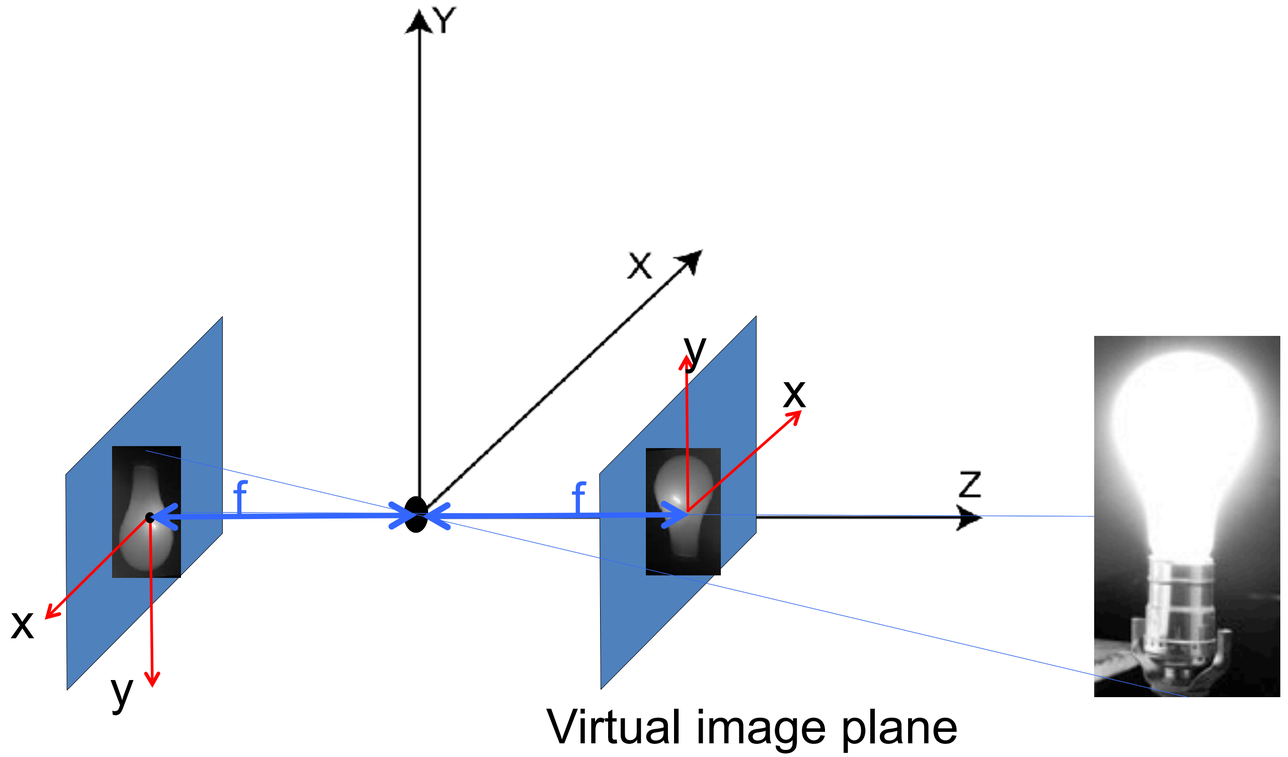
Real and virtual imaging planes



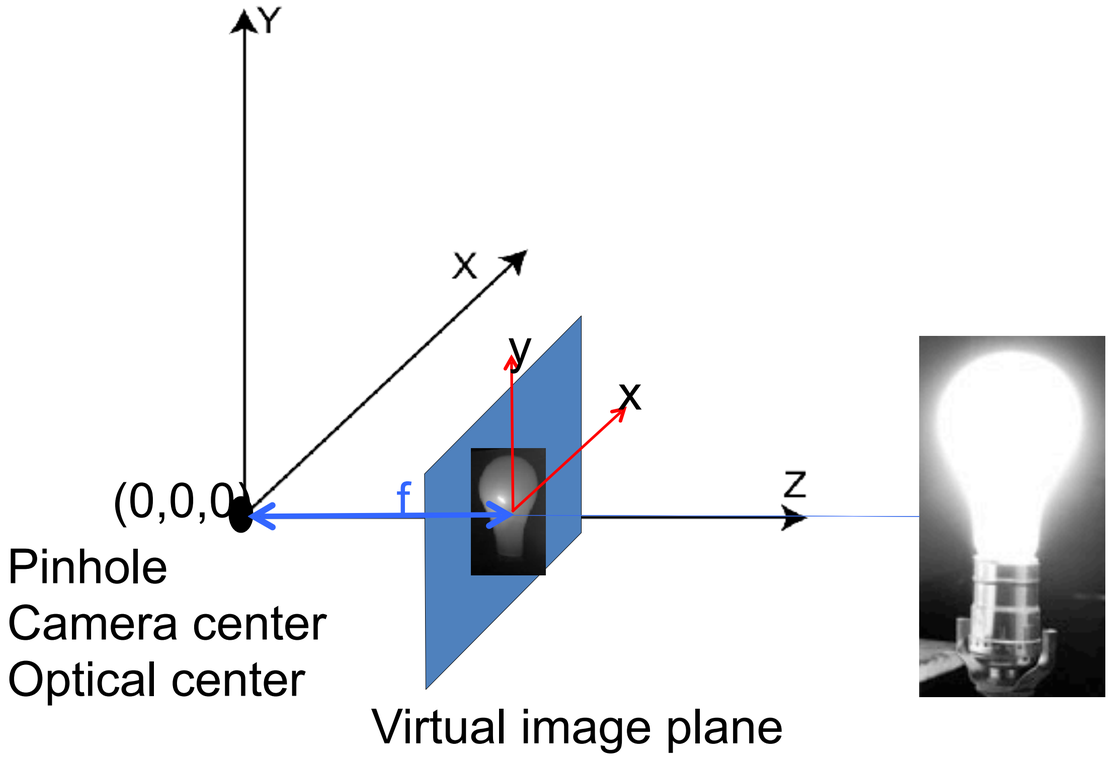
Real and virtual imaging planes



Real and virtual imaging planes



Real and virtual imaging planes



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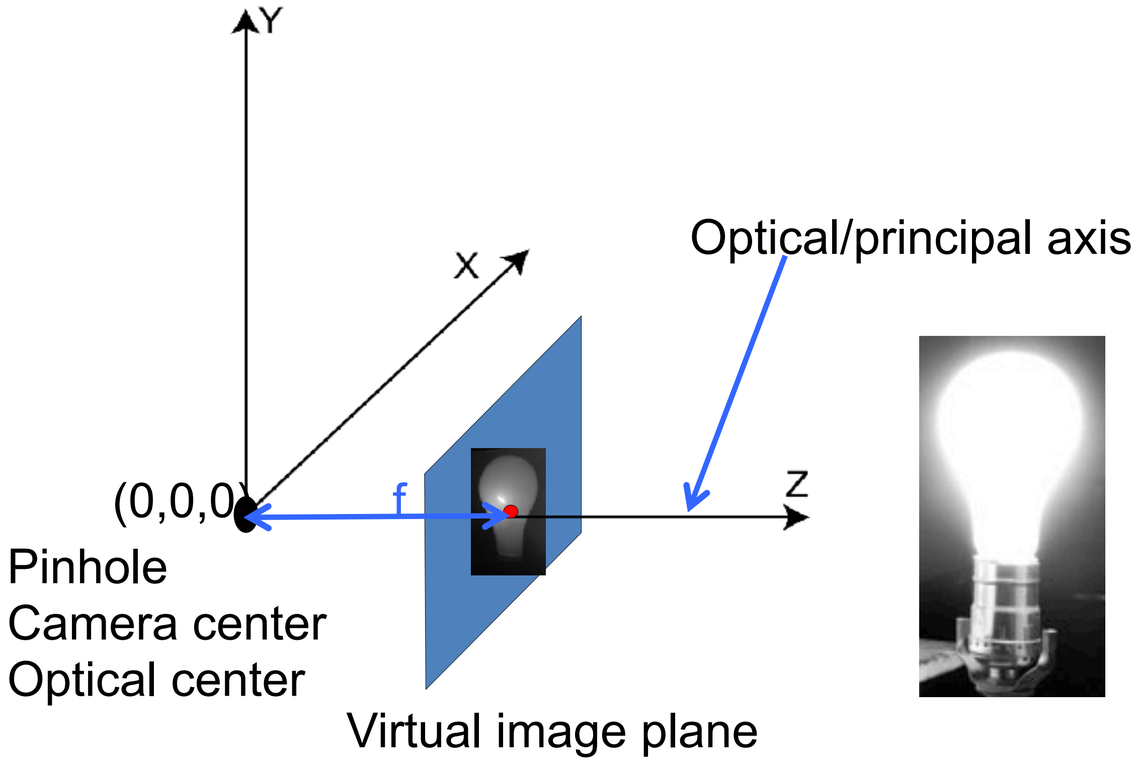
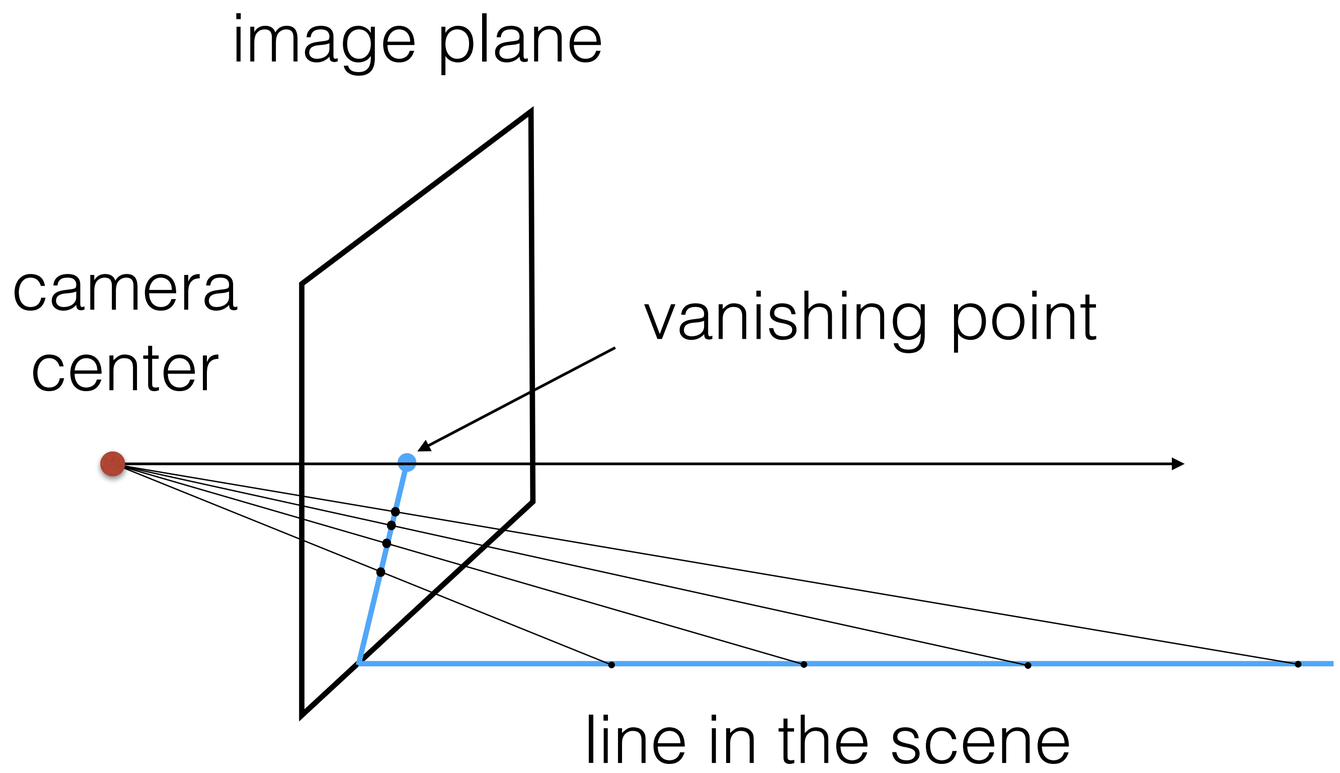


Projection of a line

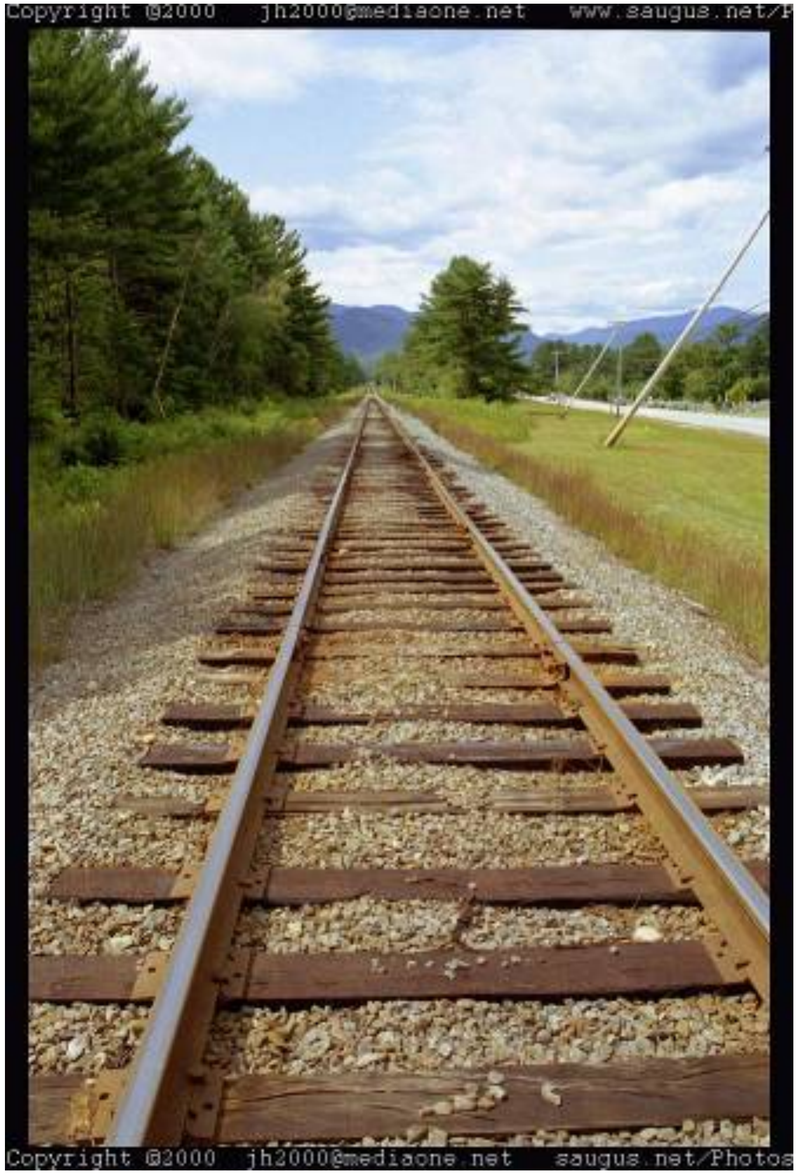


Question: What if we add another line parallel to the first one?

Vanishing points

Each direction in space has its own vanishing point

- All lines going in the that direction converge at that point
- **Exception:** directions that are parallel to the image plane

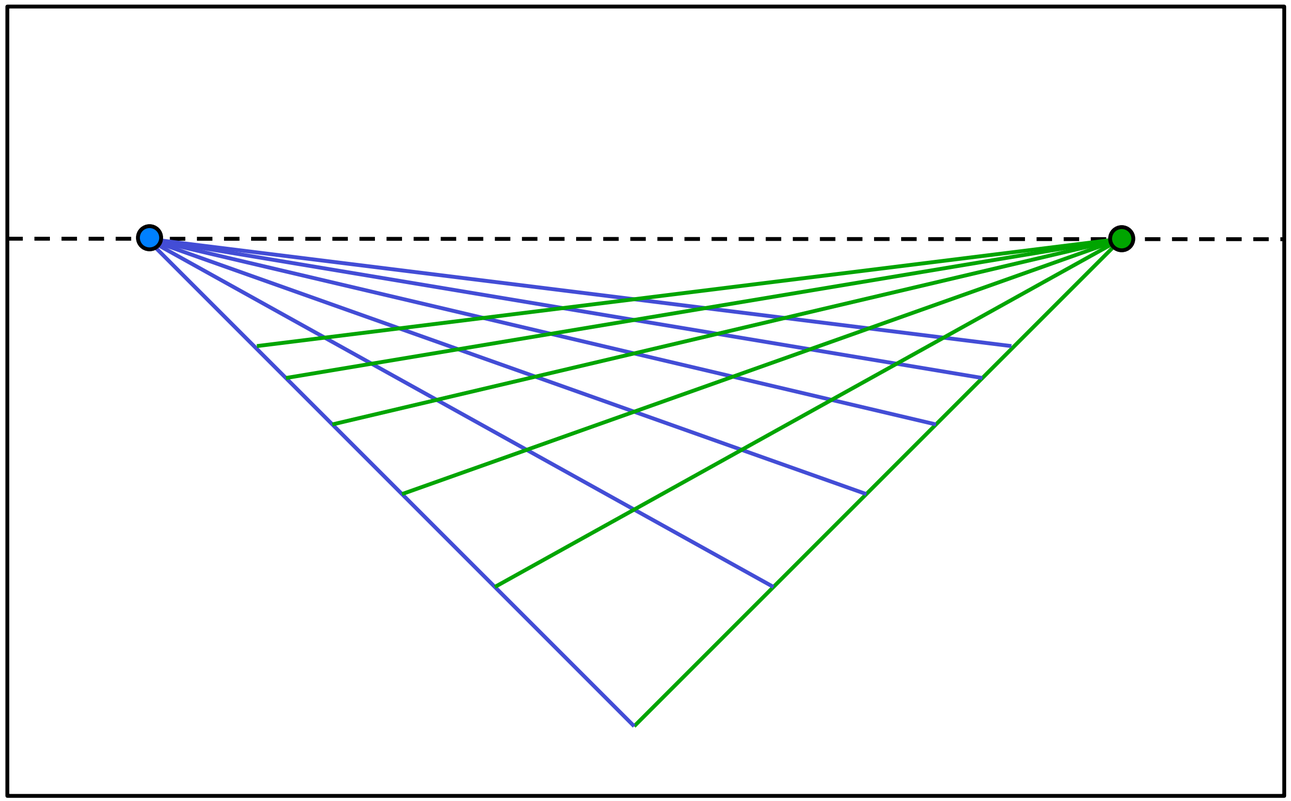


Slide by Steve Seitz

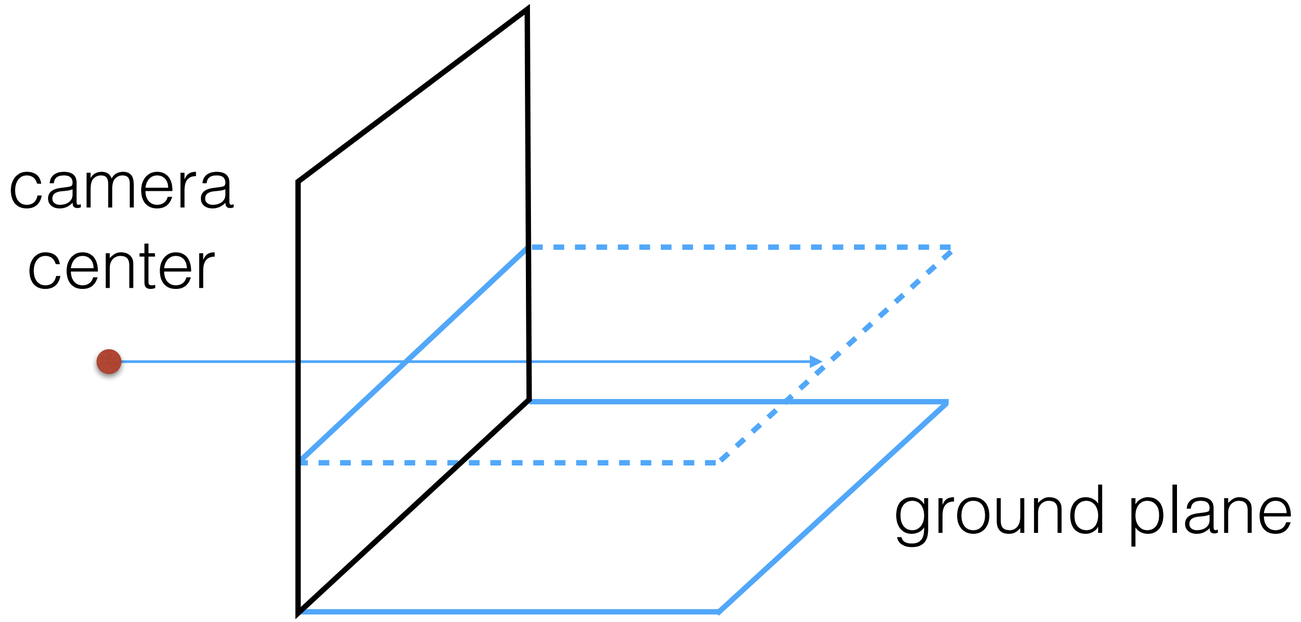
Vanishing points

Each direction in space has its own vanishing point

- All lines going in the that direction converge at that point
- **Exception:** directions that are parallel to the image plane
- **What happens to the ground plane?**



The horizon



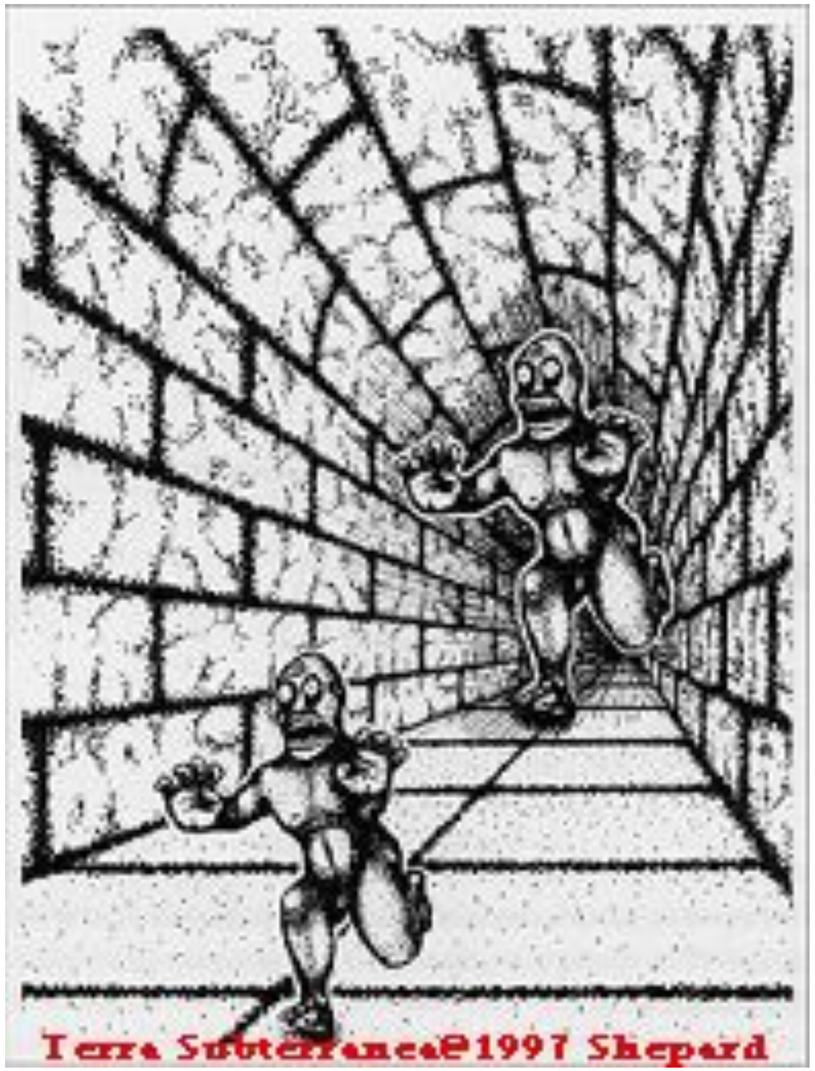
Vanishing line of the ground plane

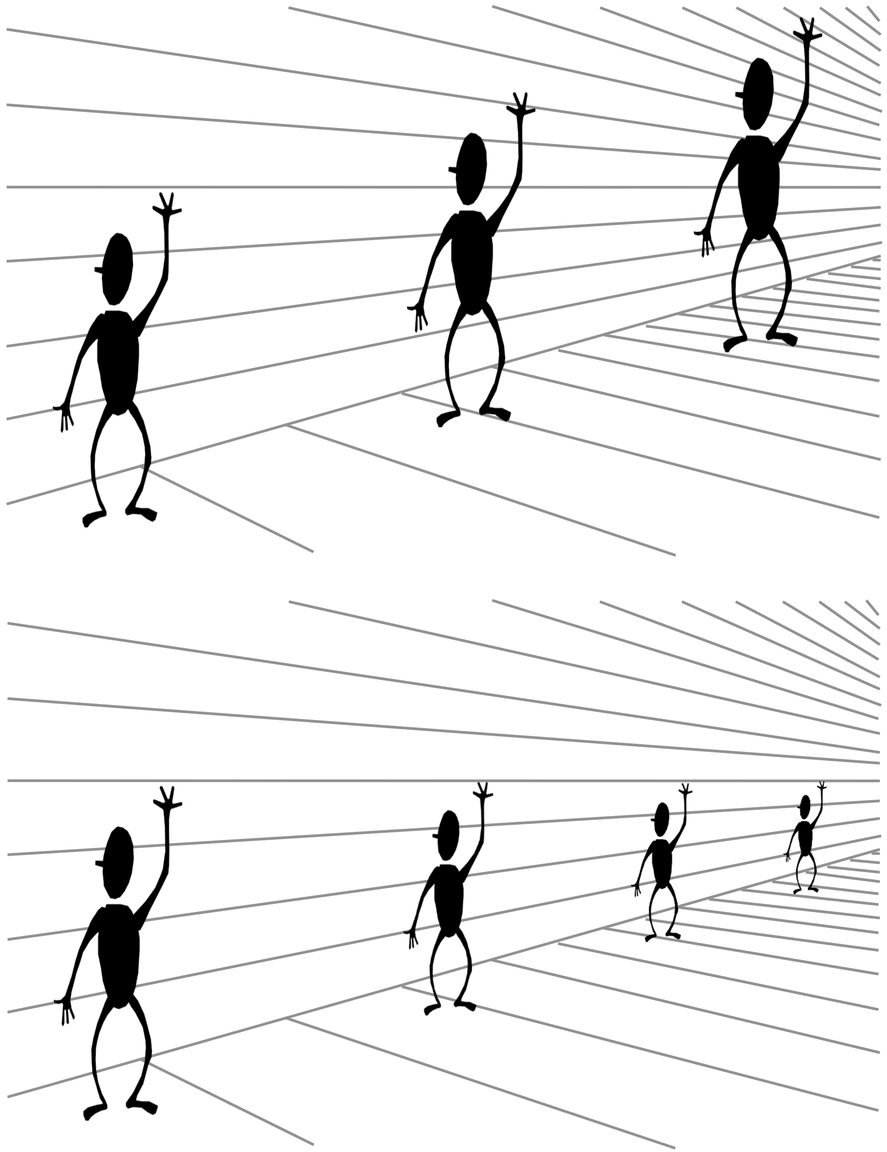
- All points at the same height of the camera project to the horizon
- Points above the camera project above the horizon
- Provides a way of comparing heights of objects

The horizon

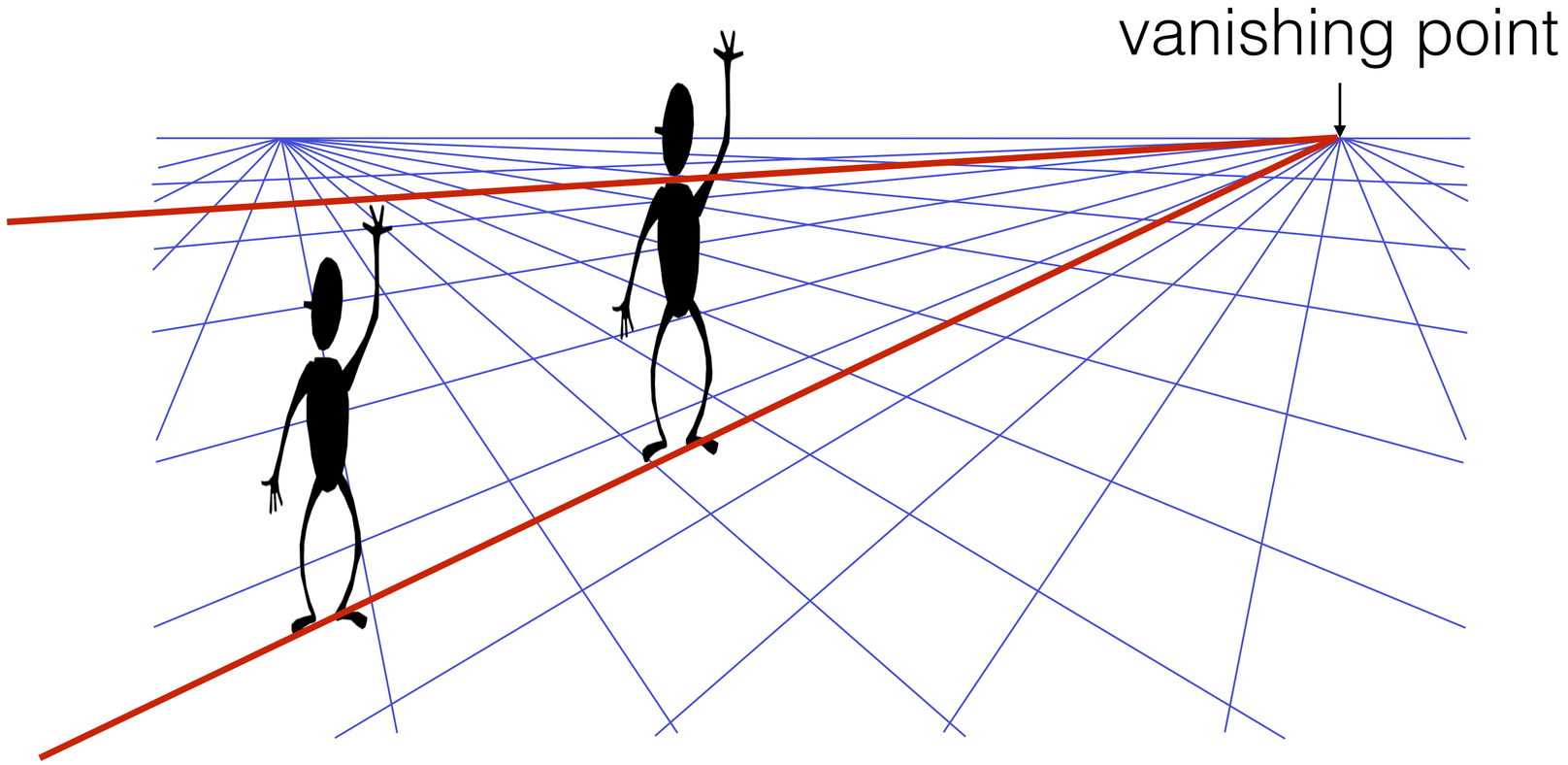
Is the person above or below the viewer?

Perspective cues

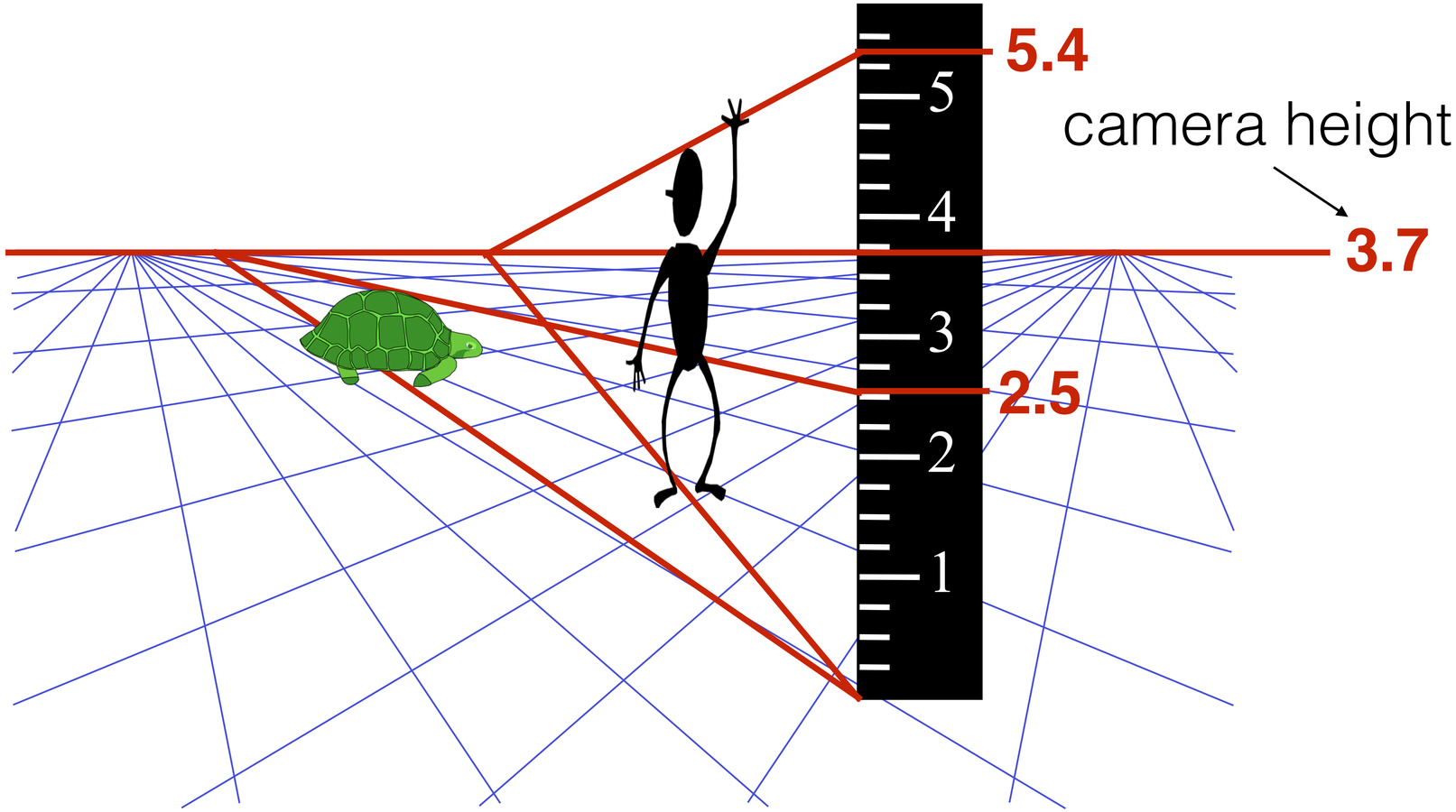




Comparing heights

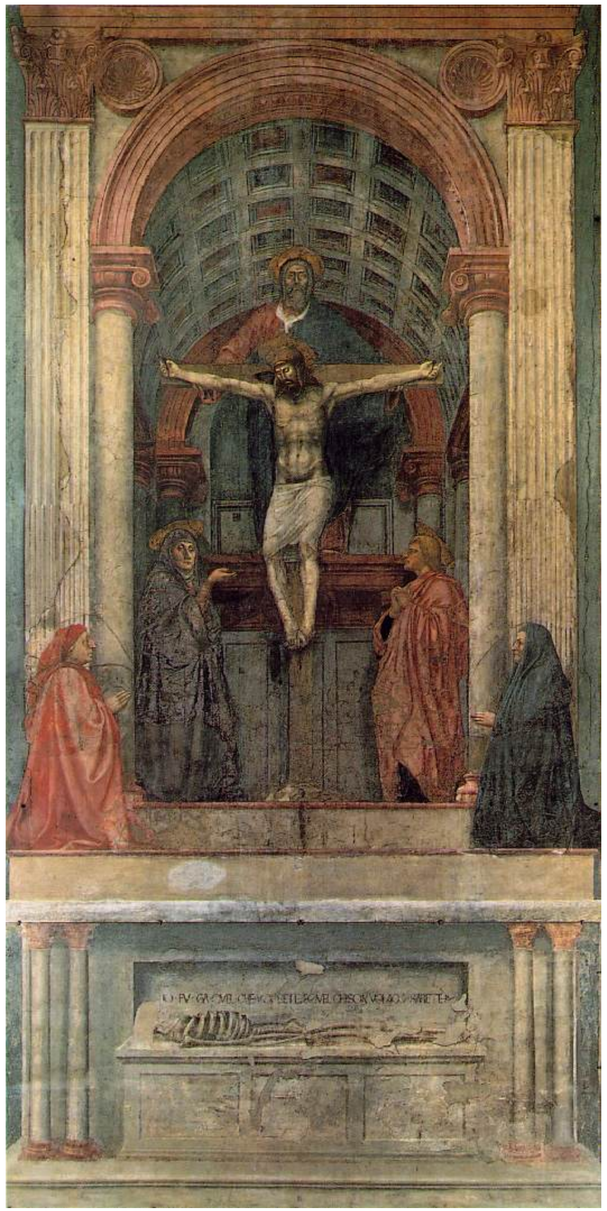


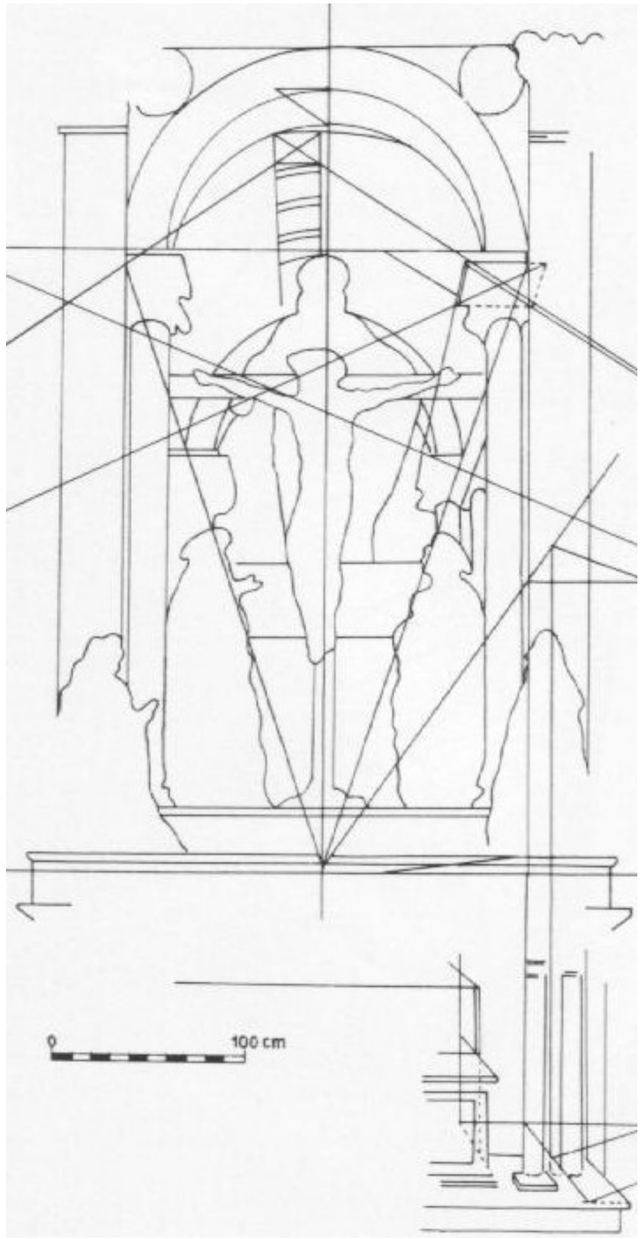
Measuring heights



What is the height of the camera?

Perspective in art





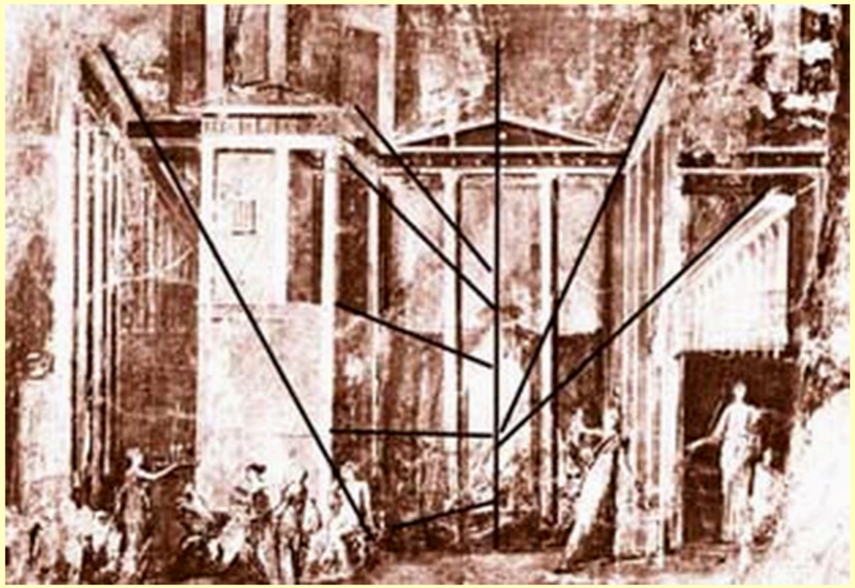
Masaccio, *Trinity*, Santa Maria Novella, Florence, 1425-28

One of the first consistent uses of perspective in Western art

Perspective in art

(At least partial) Perspective projections in art well before the Renaissance

Several Pompei wallpaintings show the fragmentary use of linear perspective:

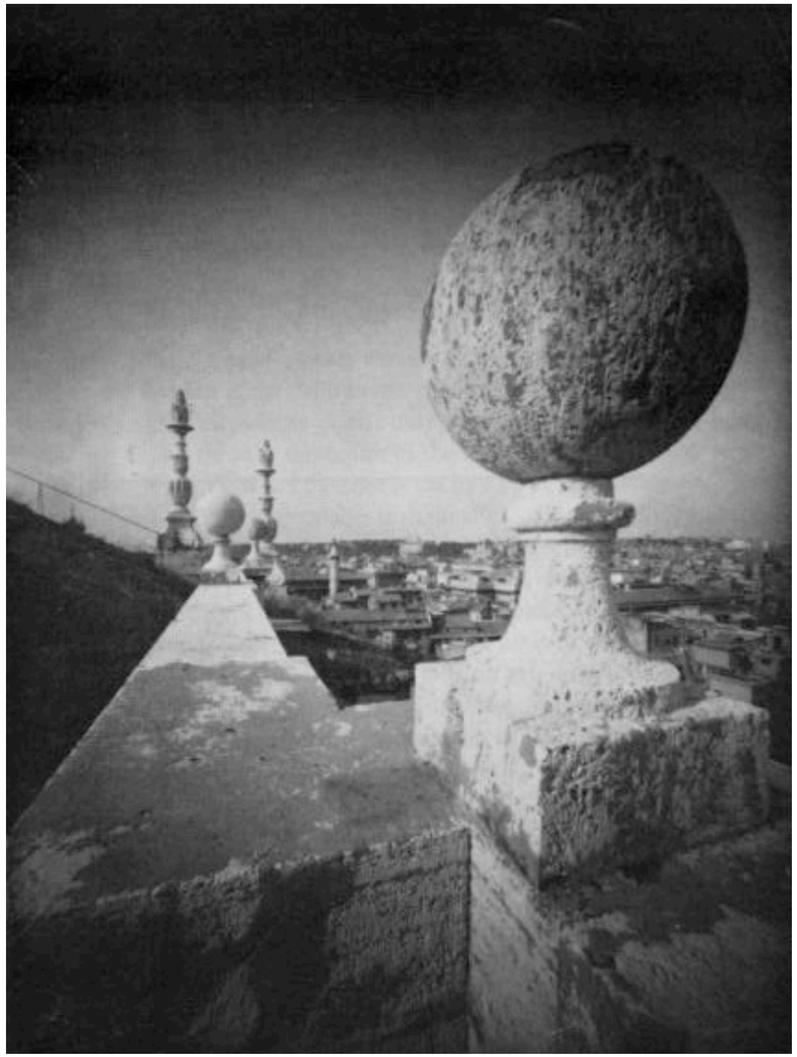


From ottobwiersma.nl

Also some Greek examples,
So apparently pre-renaissance…

Perspective distortion

What does a sphere project to?



M. H. Pirenne

Slide by Steve Seitz

Perspective distortion

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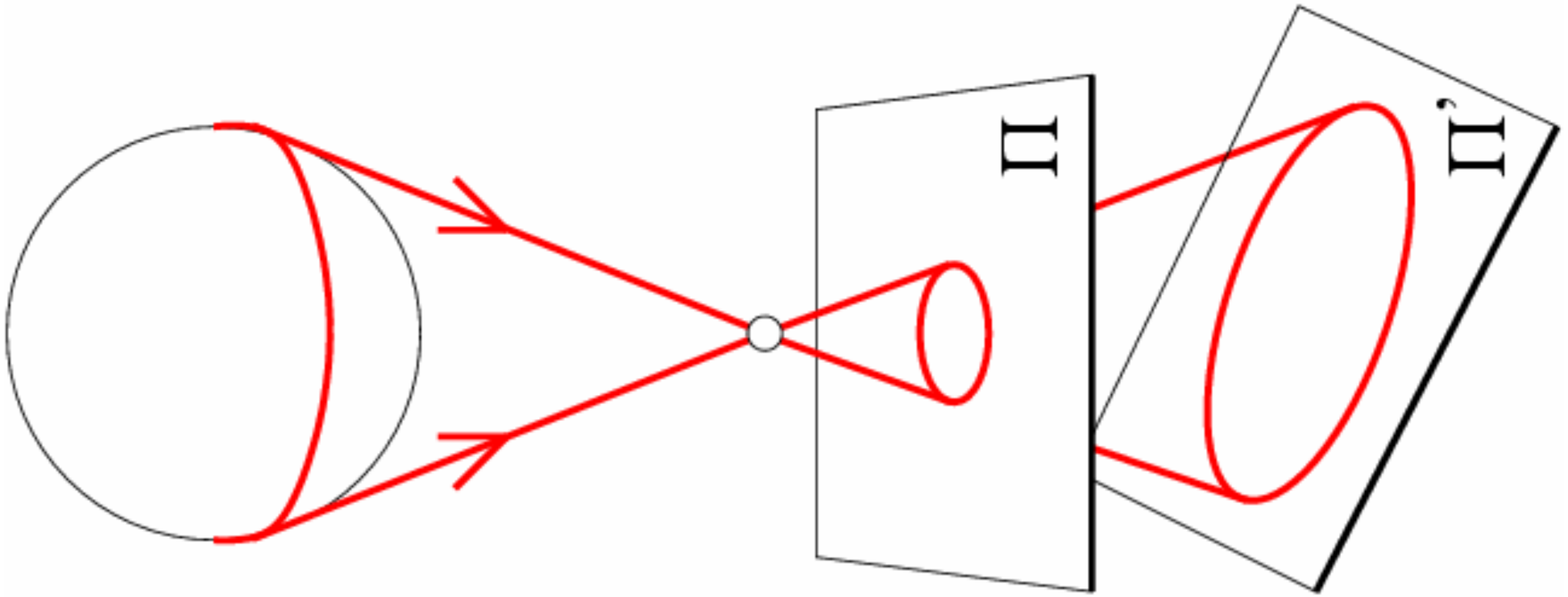
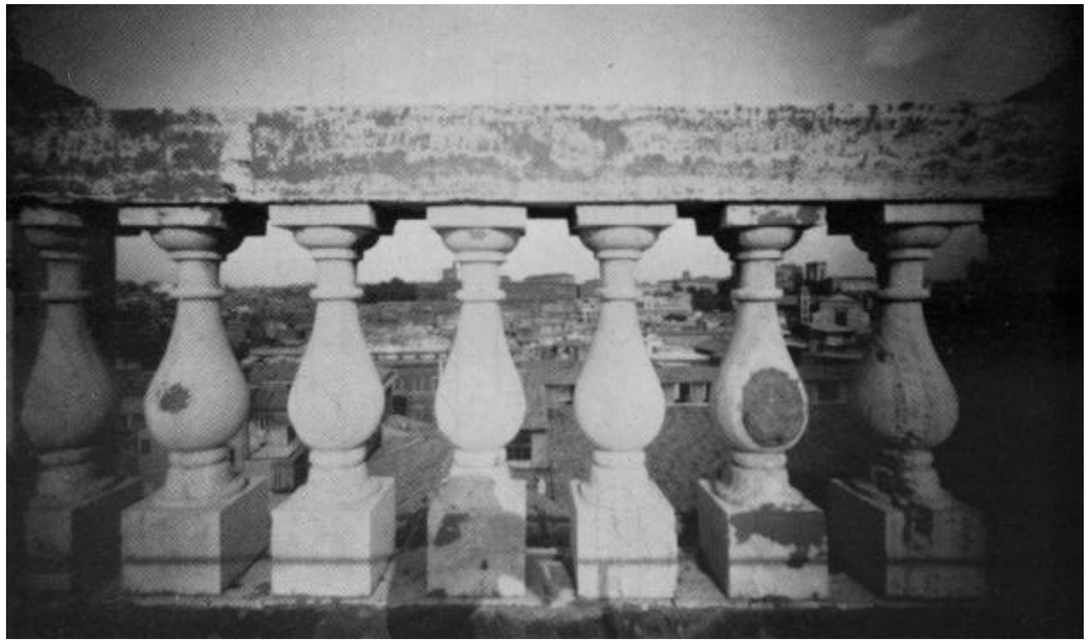


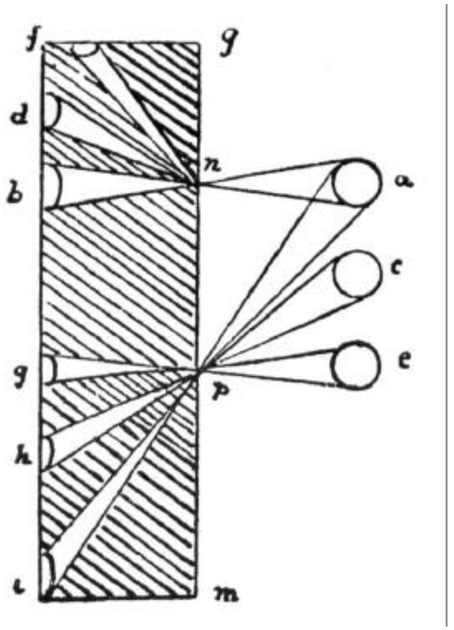
Perspective distortion

The exterior looks bigger

The distortion is not due to lens flaws

Problem pointed out by Da Vinci

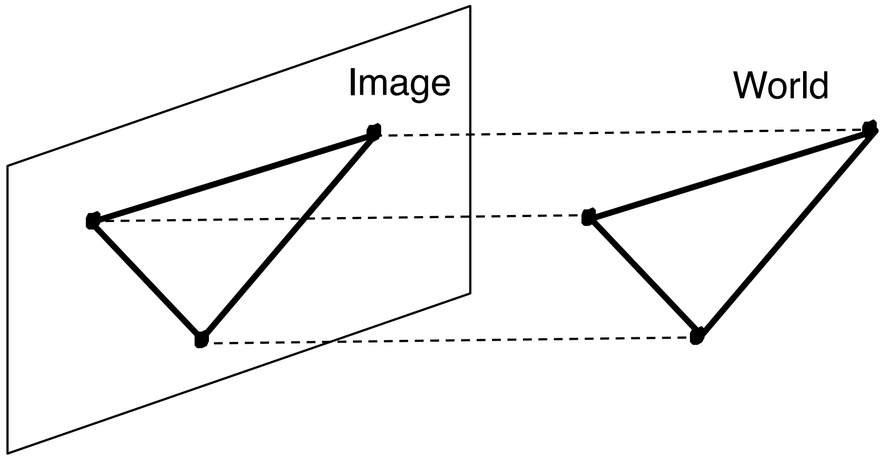




Orthographic projection

Special case of perspective projection

- Distance of the object from the image plane is infinite
- Also called the “parallel projection”



Orthographic projection

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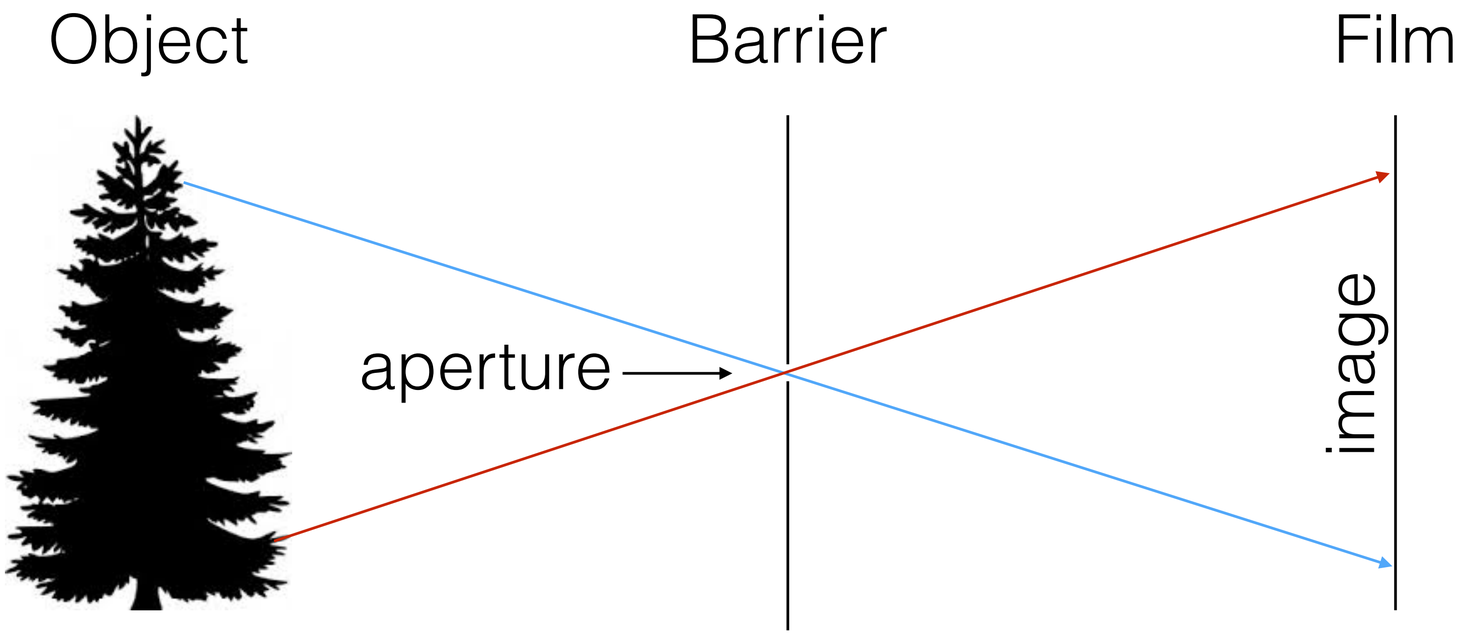
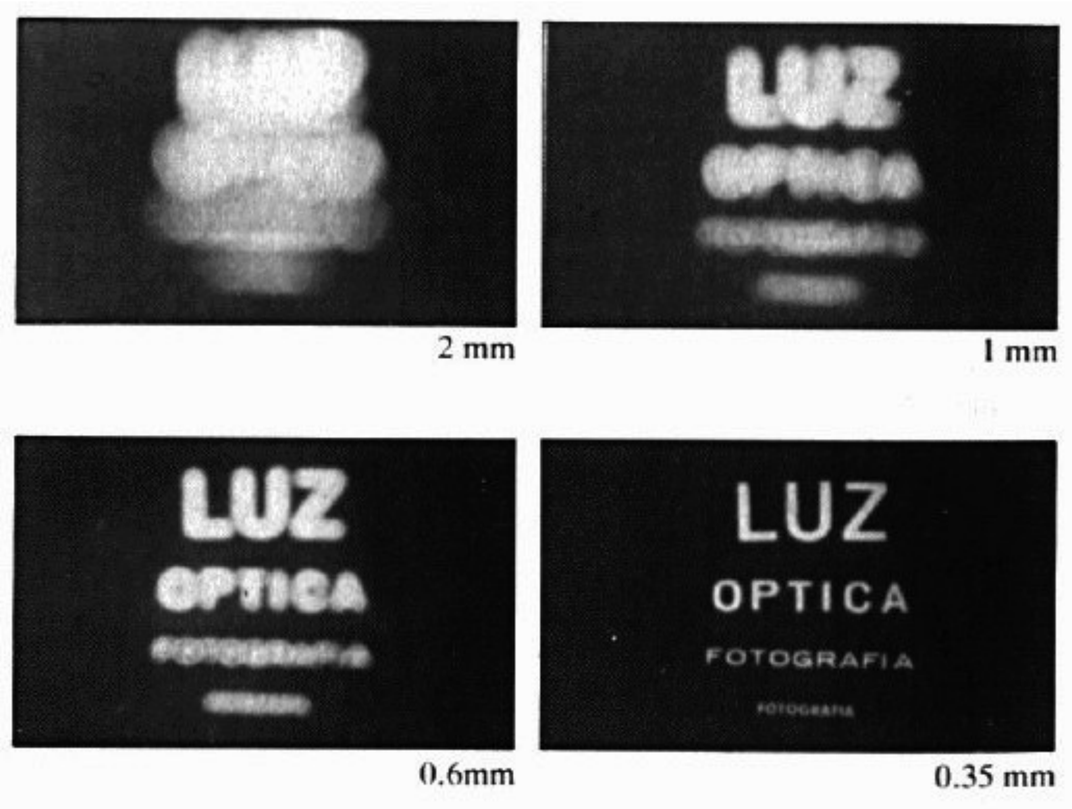
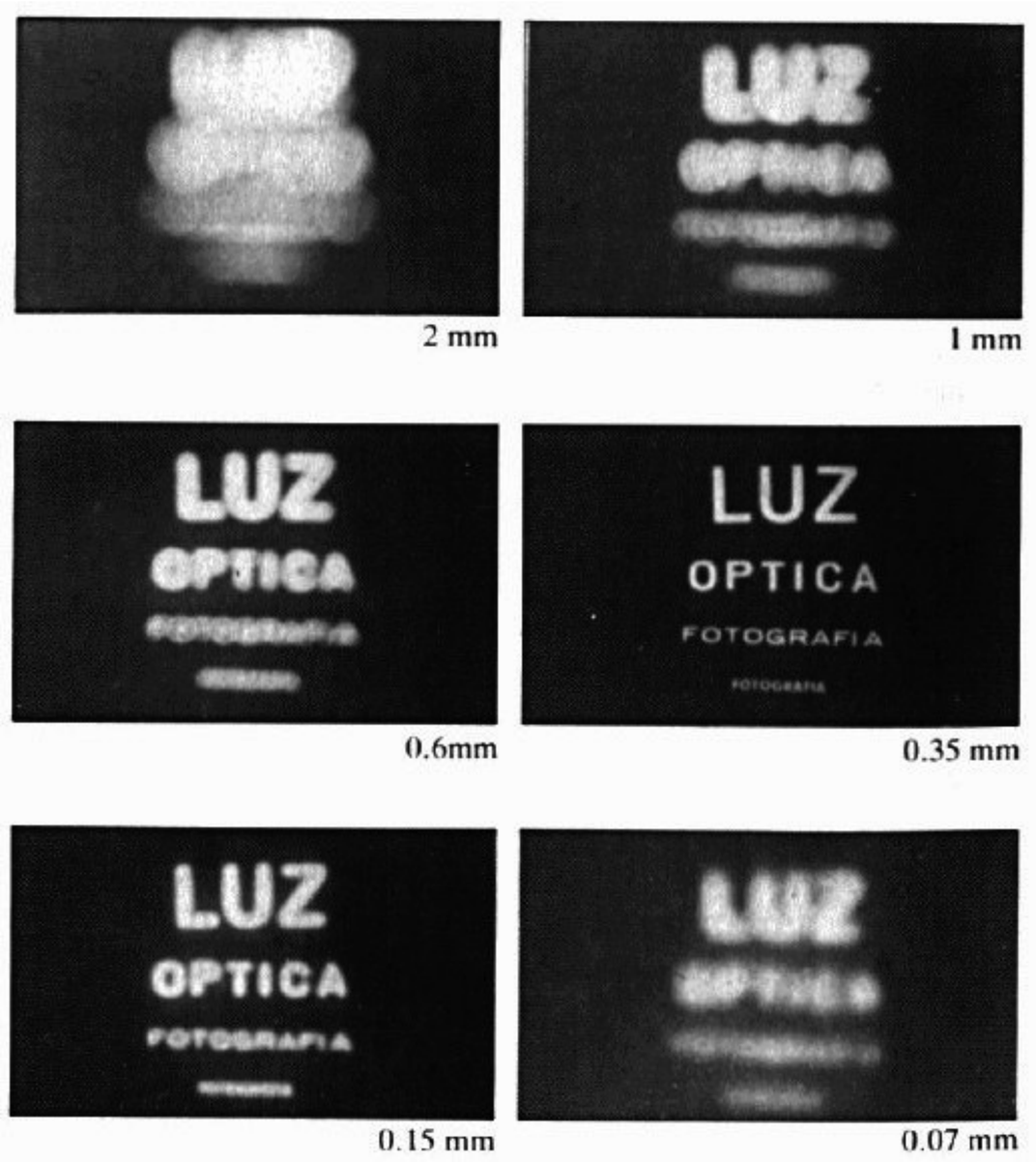
Pinhole camera



Shrinking the aperture

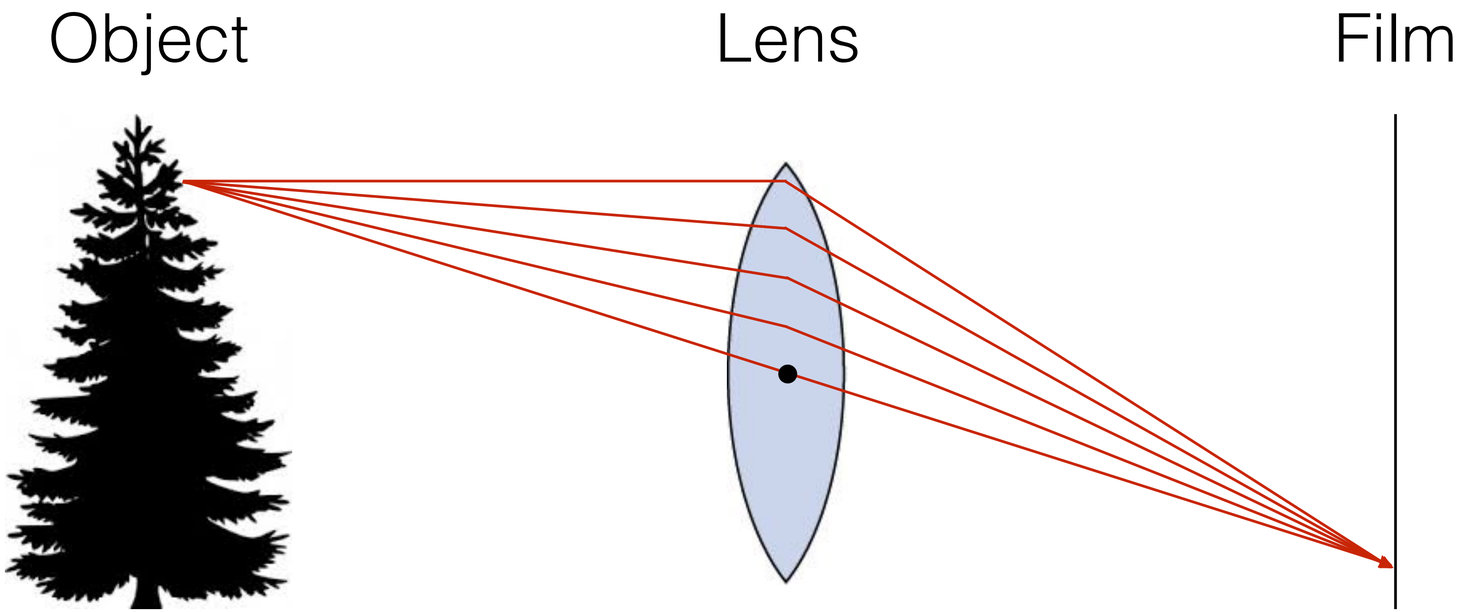


Shrinking the aperture



Slide by Steve Seitz

Adding a lens

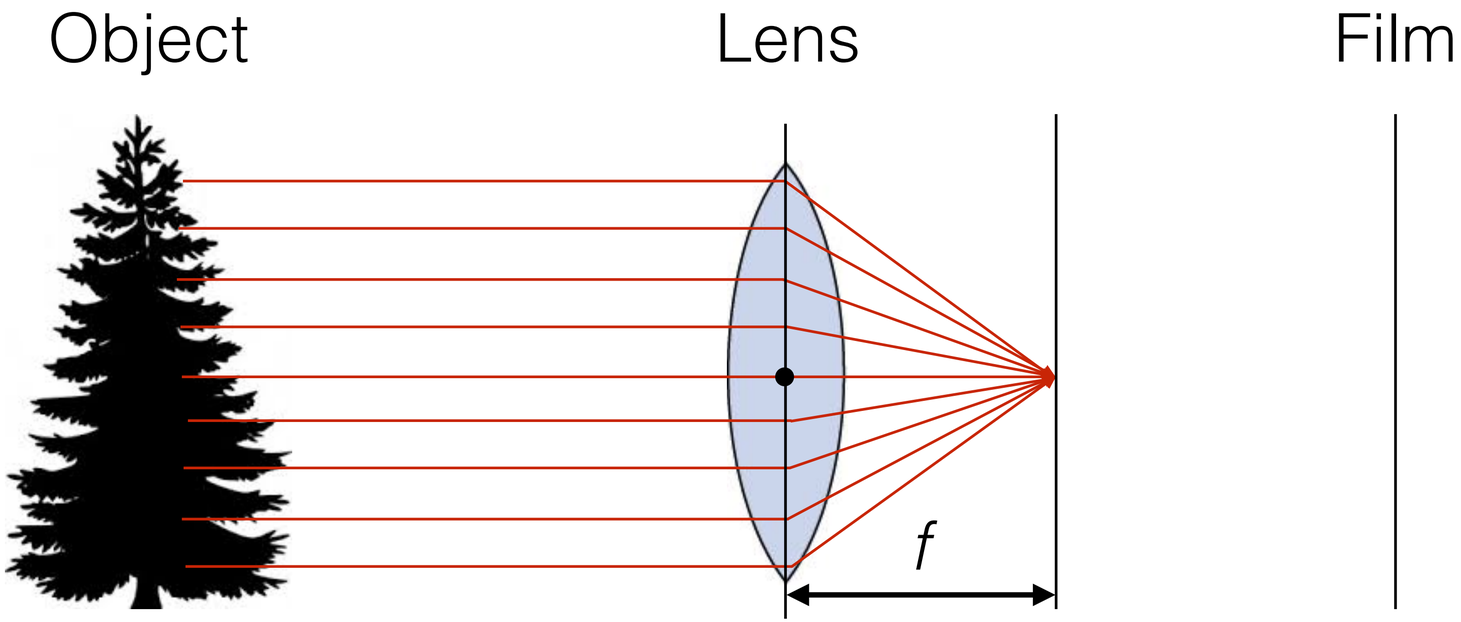


A lens focuses light on to the film

Thin lens model:

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

Adding a lens

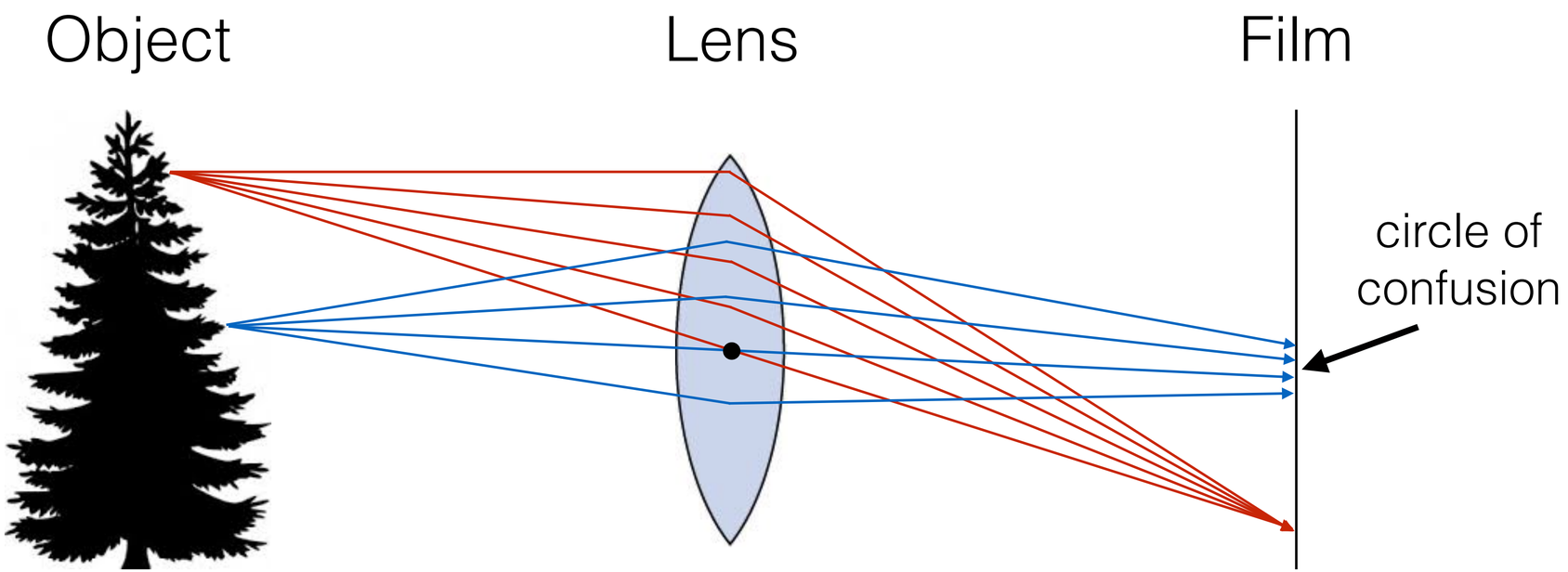


A lens focuses light on to the film

Thin lens model:

- Rays passing through the center are not deviated (pinhole projection model still holds)
- All parallel rays converge to one point on a plane located at the *focal length f*

Adding a lens

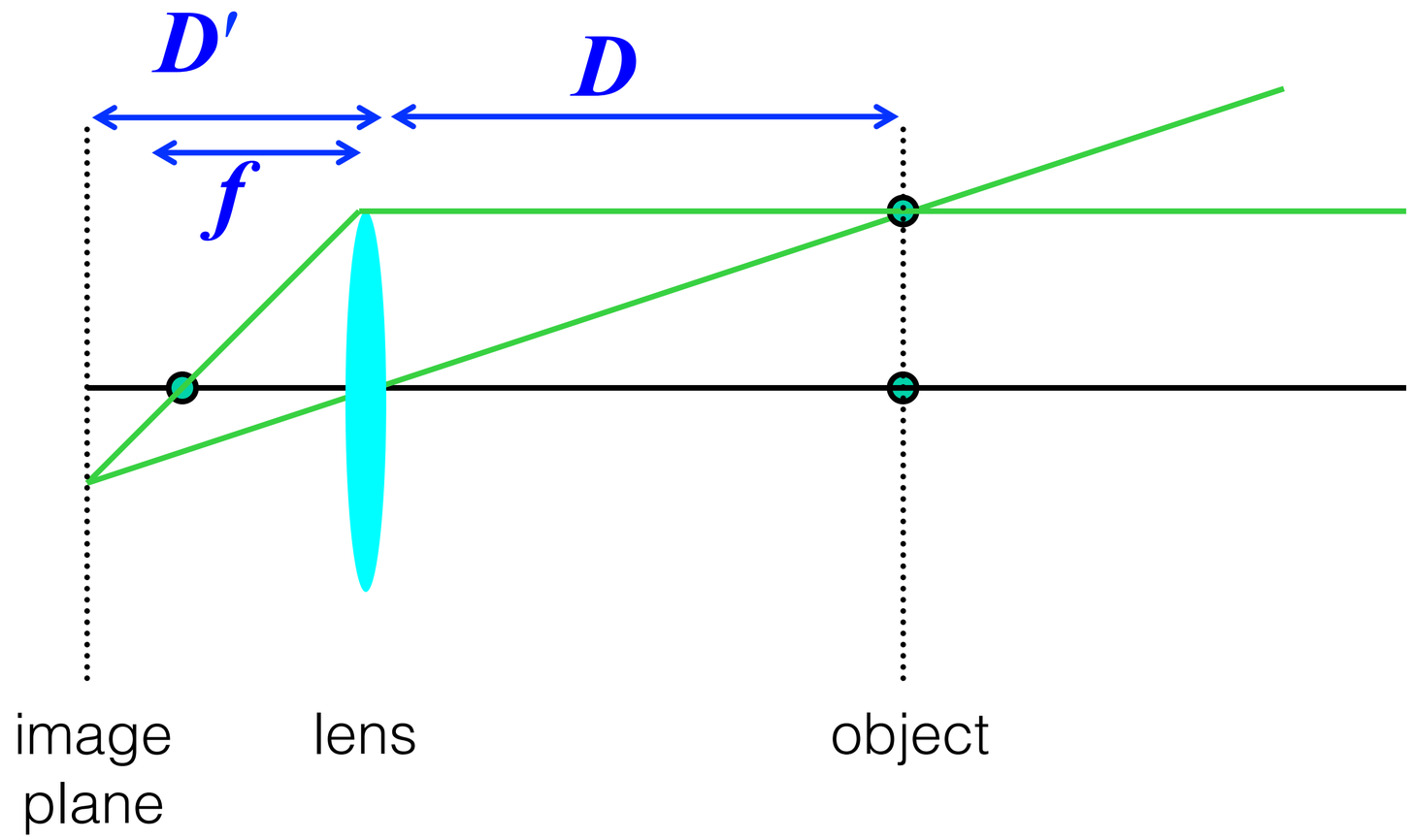


A lens focuses light on to the film

- There is a specific distance at which objects are “in focus”
- other points project on to a “circle of confusion” in the image

Thin lens formula

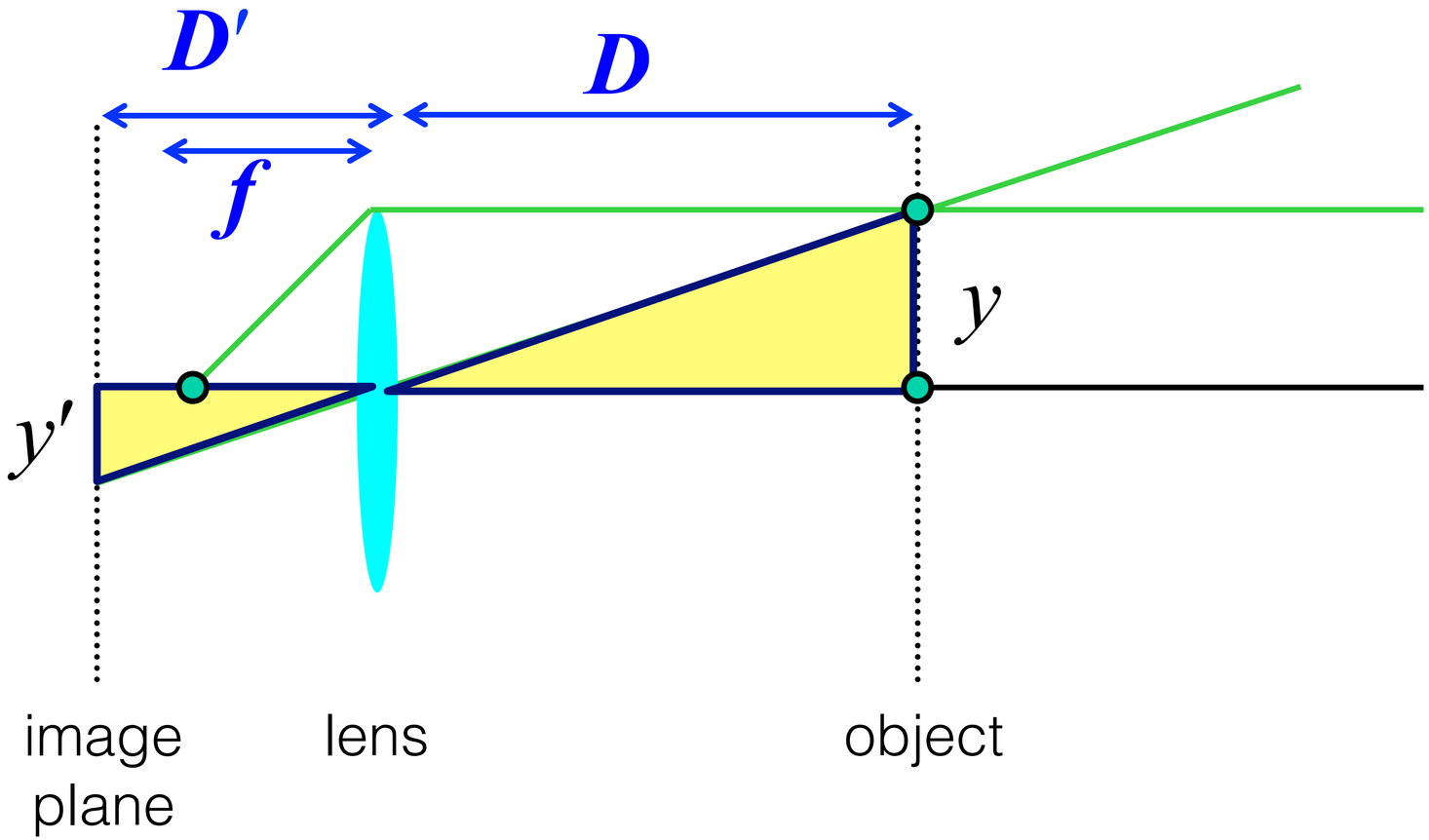
What is the relation between the focal length (f), the distance of the object from the optical center (D) and the distance at which the object will be in focus (D')?



Thin lens formula

Similar triangles everywhere!

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

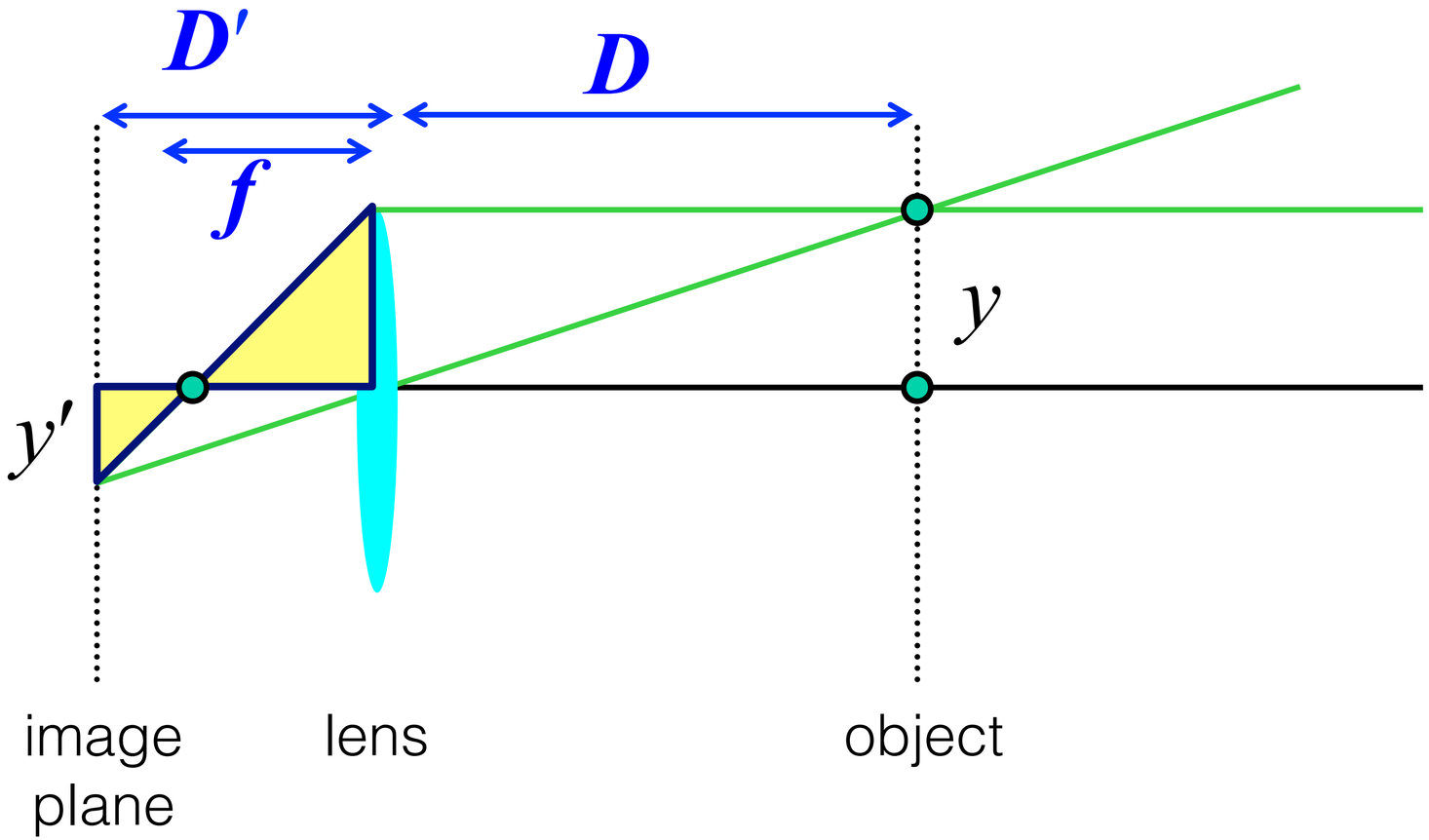


Thin lens formula

Similar triangles everywhere!

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

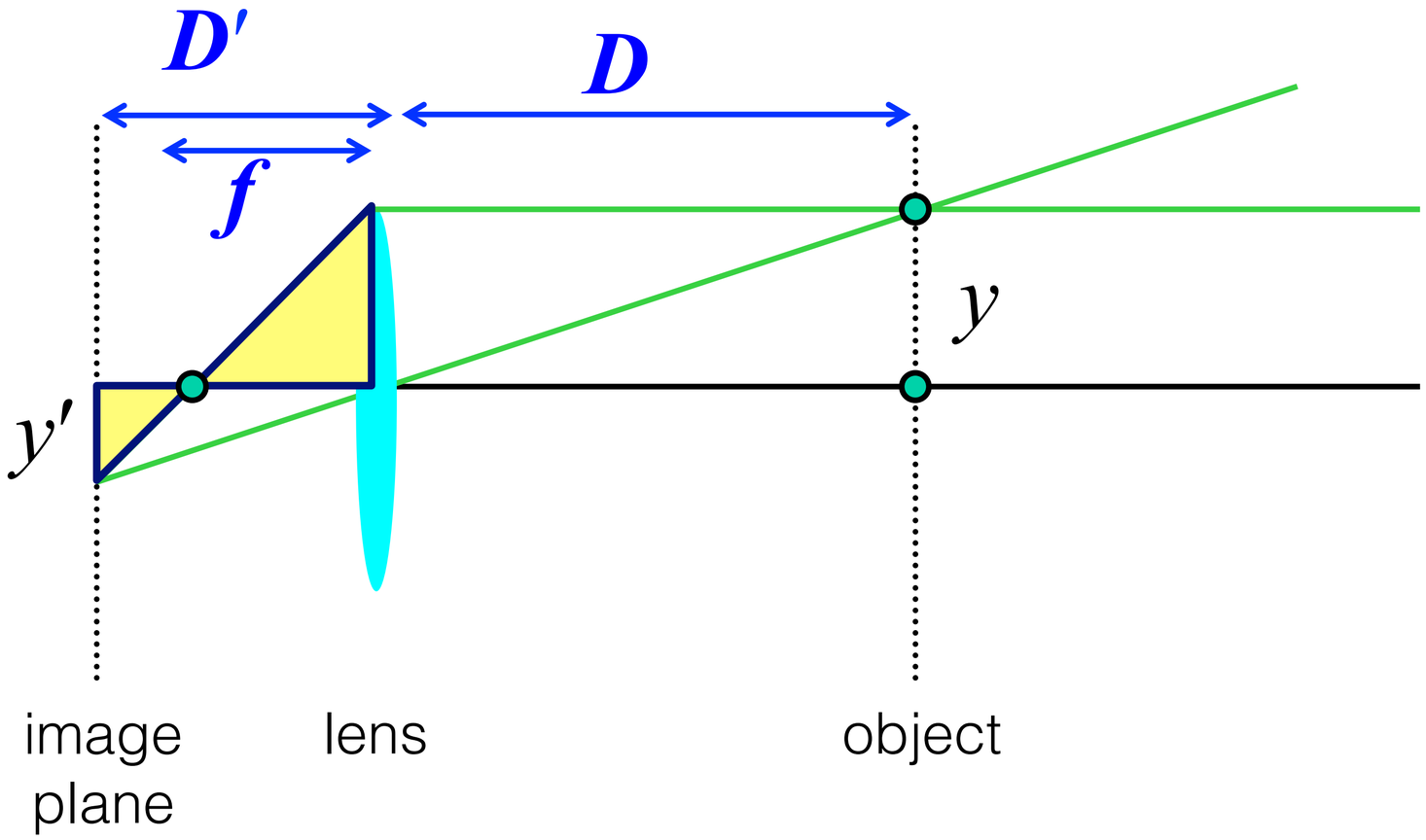
$$y'/y = (D'-f)/f$$



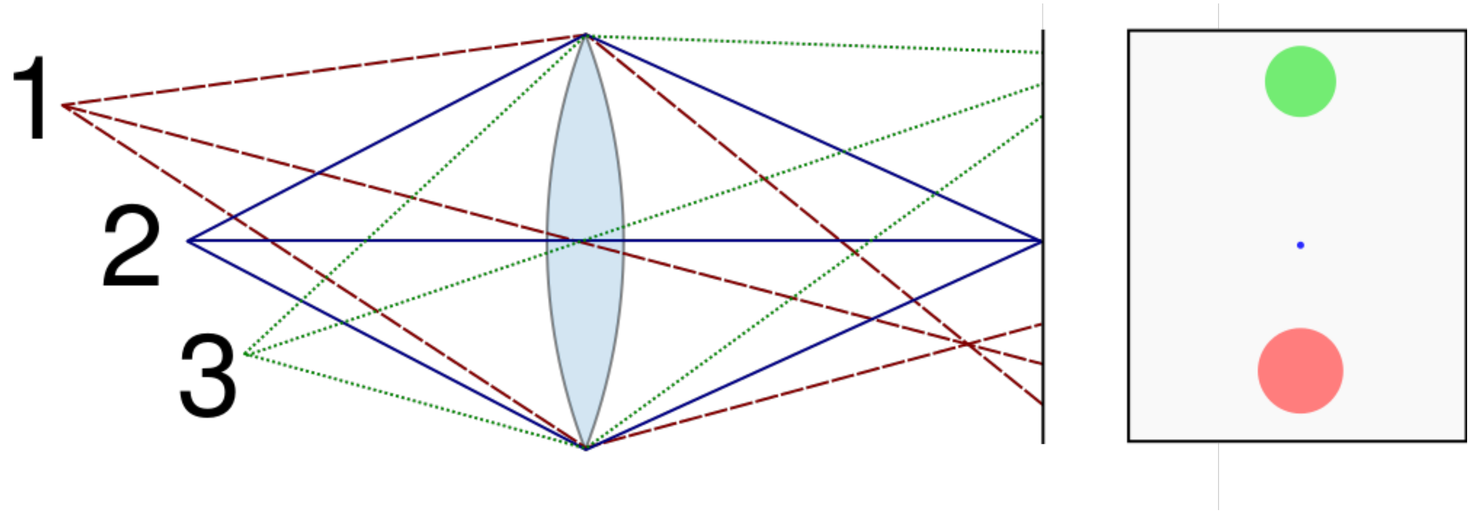
Thin lens formula

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

Any point satisfying the thin lens equation is in focus



Depth of field



DOF is the distance between the nearest and farthest objects in a scene that appear acceptably sharp in an image

image credit Wikipedia

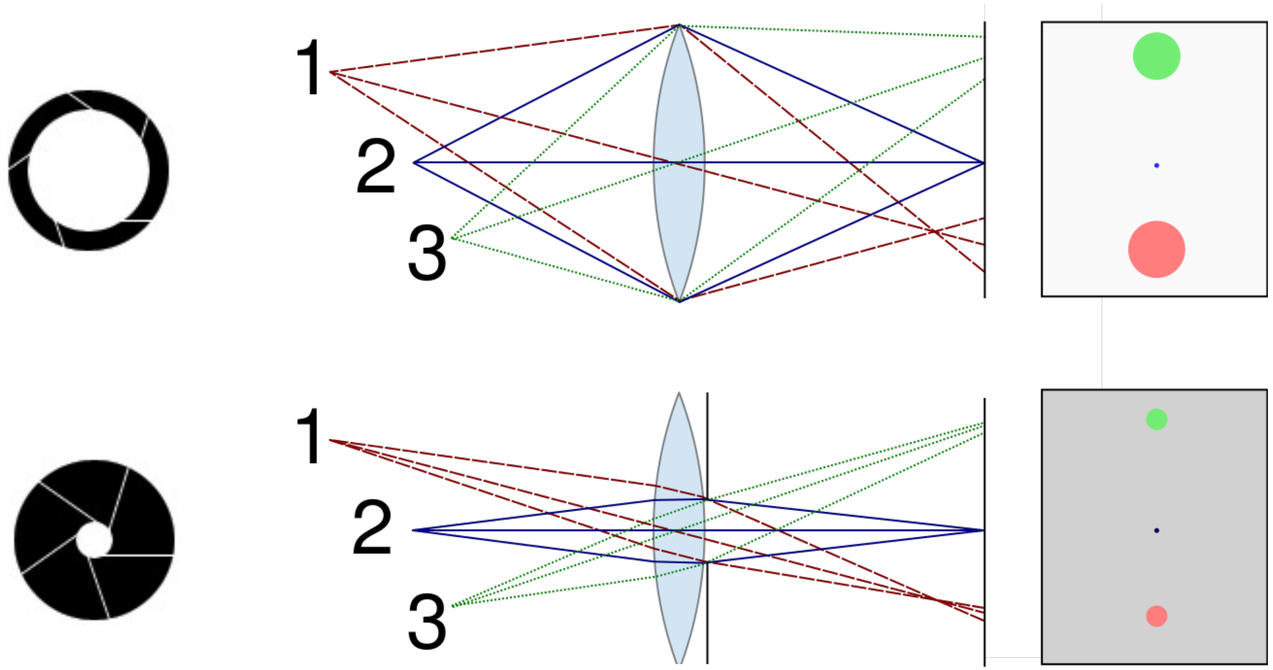
Depth of field

Narrow Depth of Field

Wide Depth of Field

Photos by Monoram

Controlling depth of field



Changing the aperture size affects the depth of field

- A smaller aperture increases the range in which the object is approximately in focus
- But small aperture reduces the amount of light — need to increase the exposure for contrast
- Pinhole camera has an infinite depth of field

image credit Wikipedia

Varying the aperture

Large aperture = small DOF

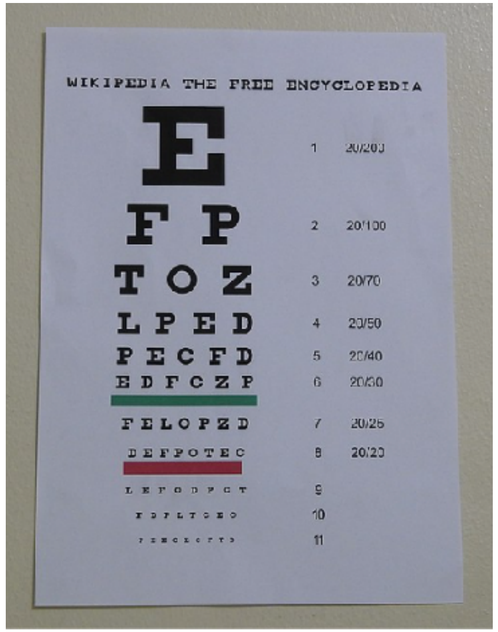
Small aperture = large DOF

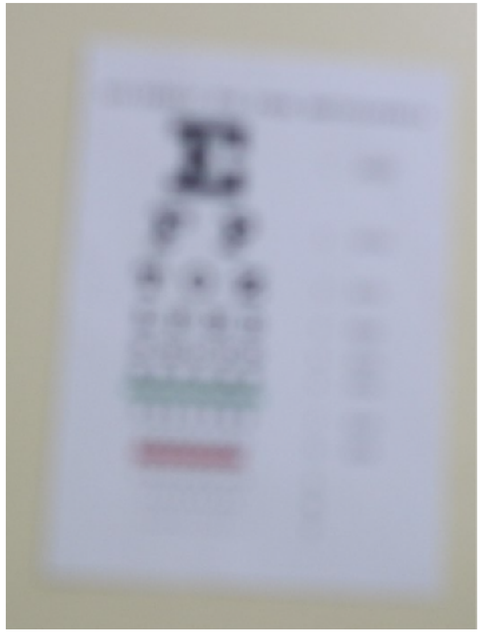
iPhone portrait mode

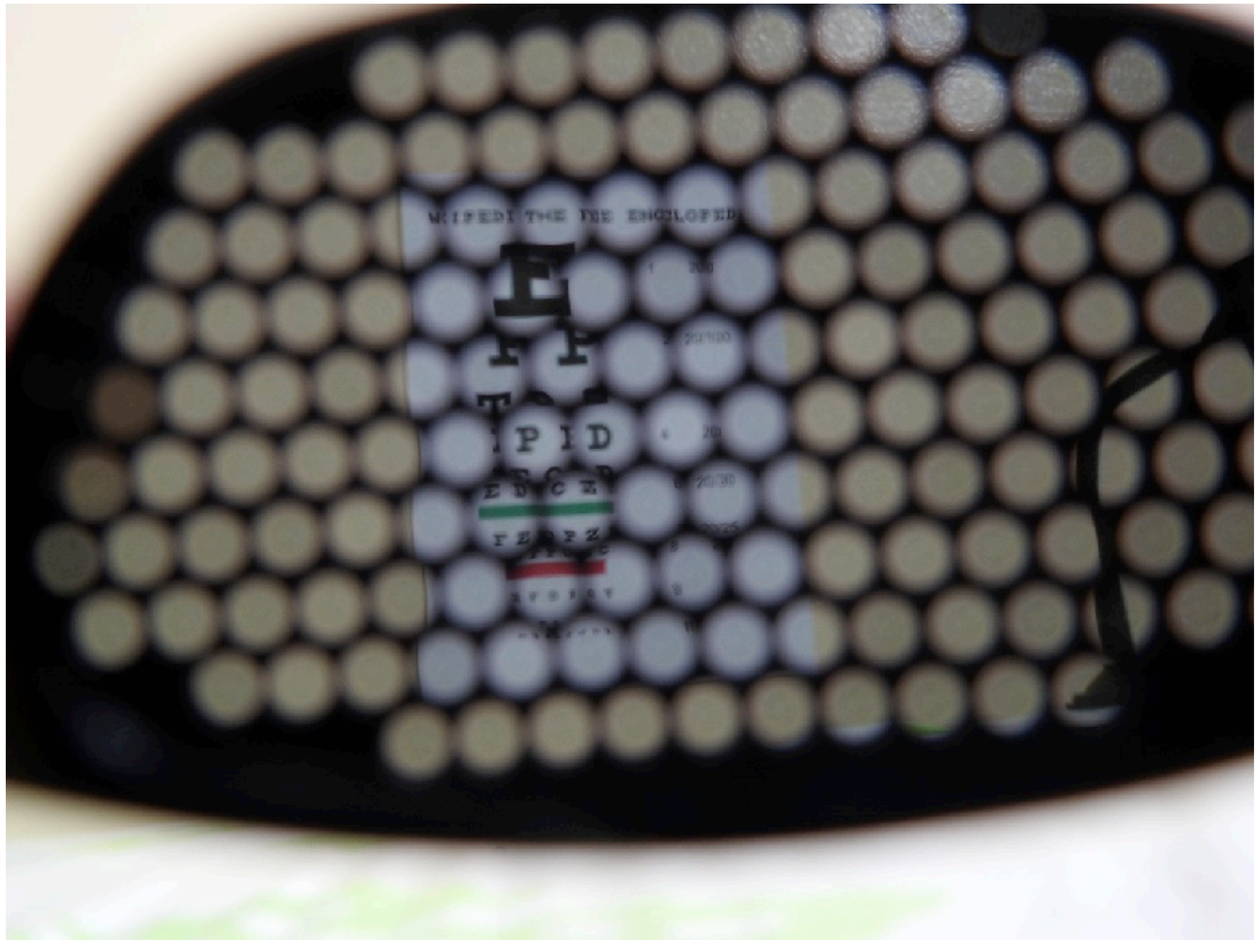
http://www.businessinsider.com/apple-iphone-portrait-mode-explained-2017-10

Pinhole glasses

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





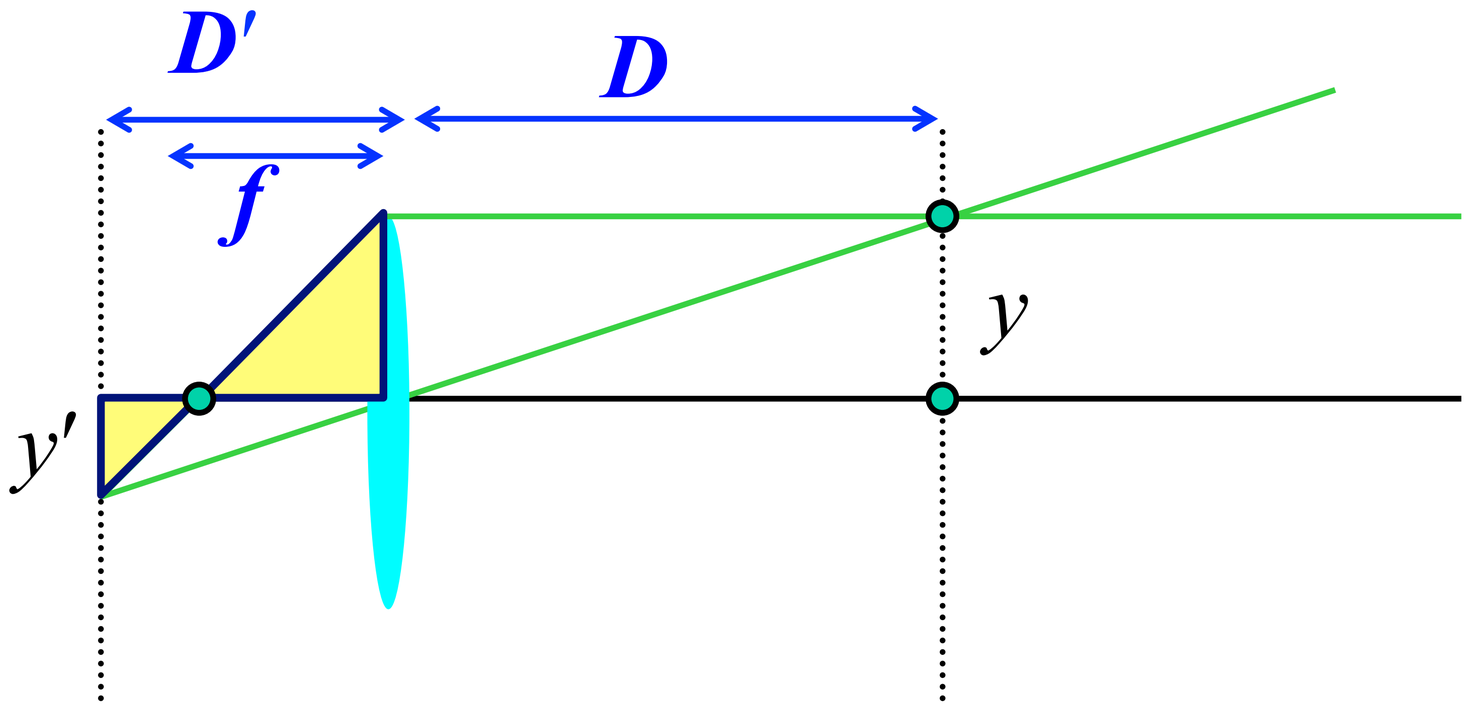


Out of focus

In focus, but darker

Controlling depth of field

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



DOF depends on the distance of the object (D) and the focal length (f) of the camera

- Objects far away have a larger depth of field
- Increasing the focal length reduces the depth of field

image credit Wikipedia

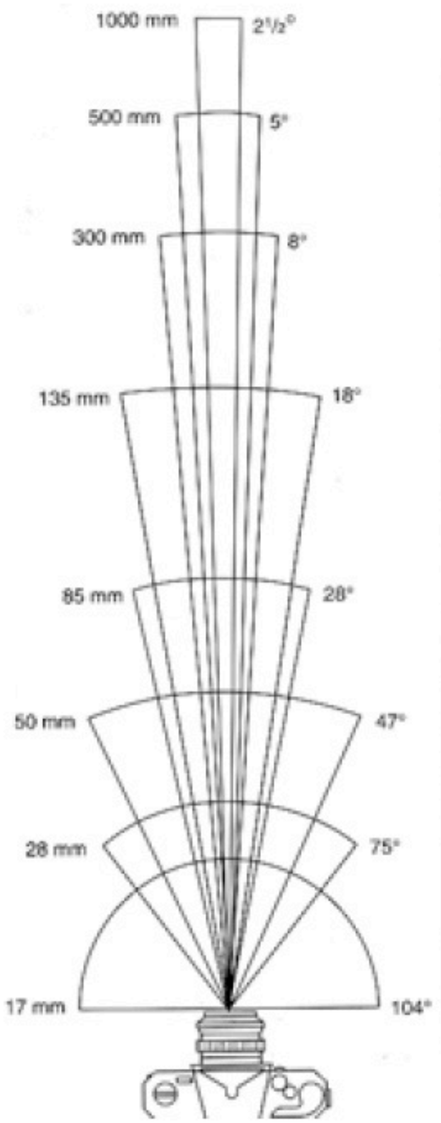
Fake miniature photography

"Jodhpur rooftops" by Paul Goyette

http://www.wallcoo.net/photography/Tilt-shift_Photography_Wallpapers_1920x1080/wallpapers/1600x900/Tallinn_old_town_1920x1080.html

http://www.wallcoo.net/photography/Tilt-shift_Photography_Wallpapers_1920x1080/wallpapers/1366x768/Tilt_Shift_Wallpaper_20_by_leiyagami.html

Field of view



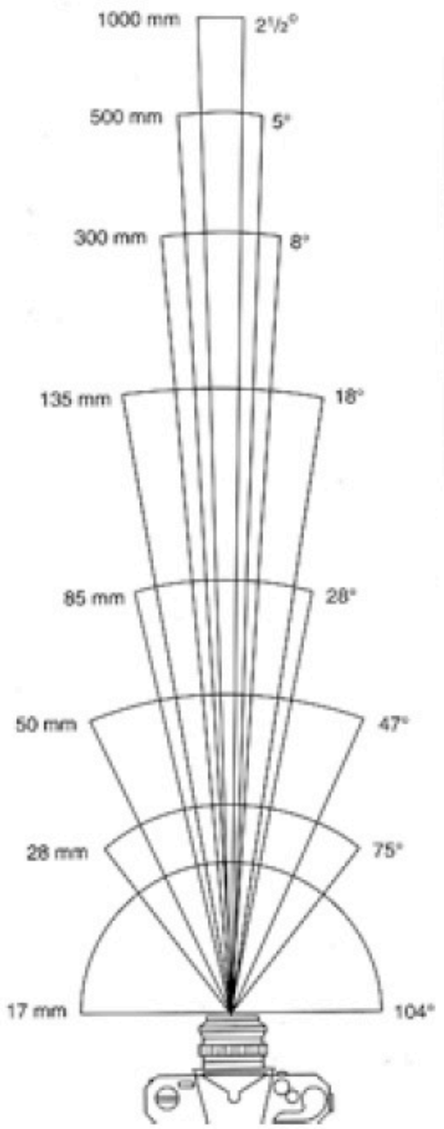
17mm

28mm

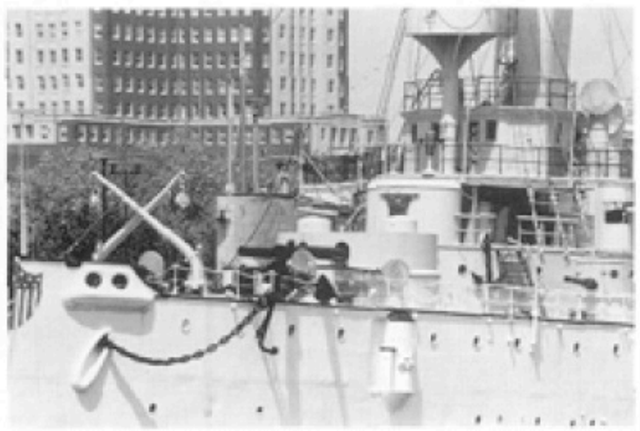
50mm

85mm

Field of view

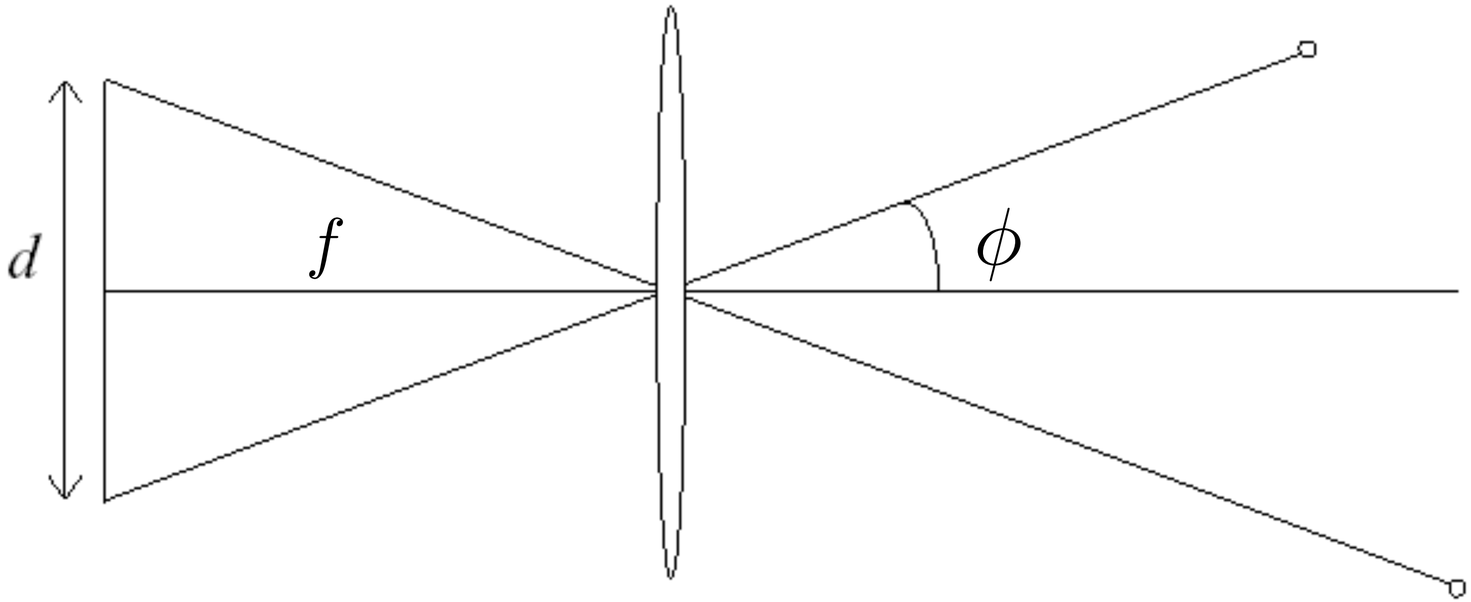


135mm



300mm

Field of view

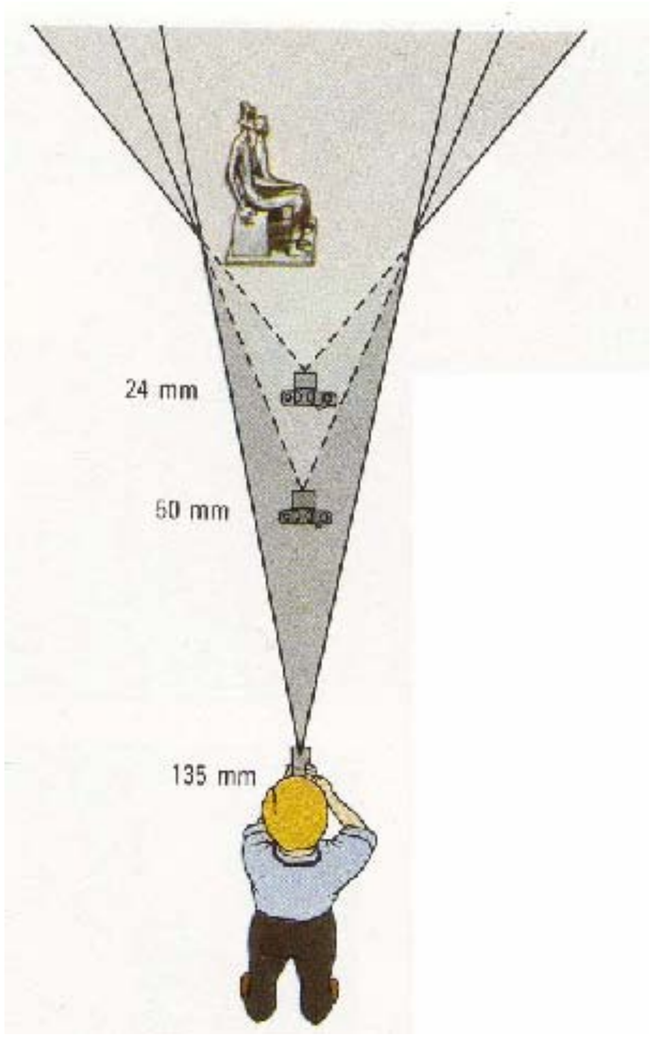


Field of view (FOV) depends on the focal length and the size of the camera retina

$$\phi = \tan^{-1}\left(\frac{d}{2f}\right)$$

Larger focal length = smaller FOV

Field of view, focal length



$$\tan(\phi) \times 2f = d$$

$$\sim (\phi) \times 2f = d$$

Large FOV, small *f* — Camera close to the car

Small FOV, large *f* — Camera far from the car

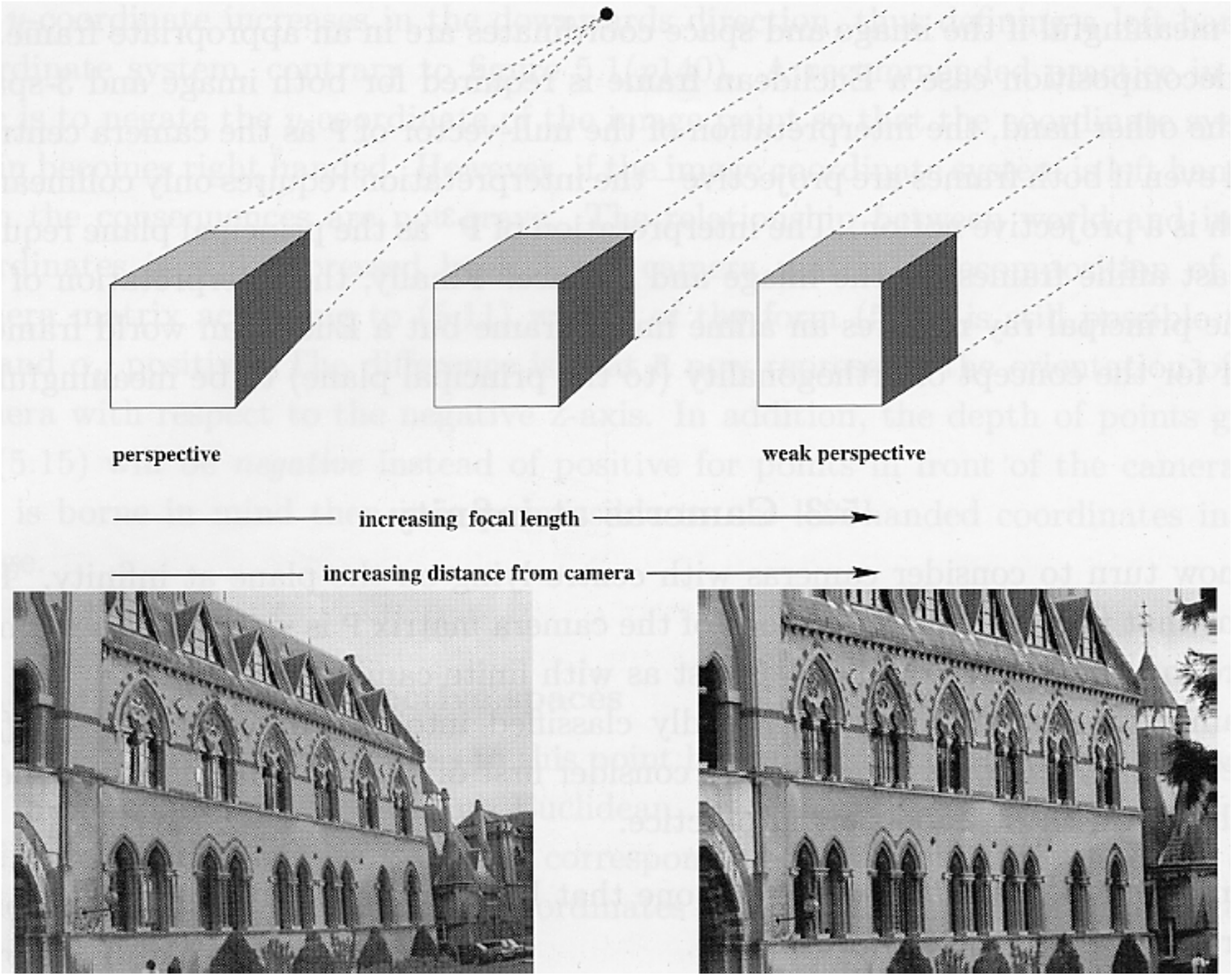
Same effect for faces

wide-angle
(short focus)

standard

telephoto
(long focus)

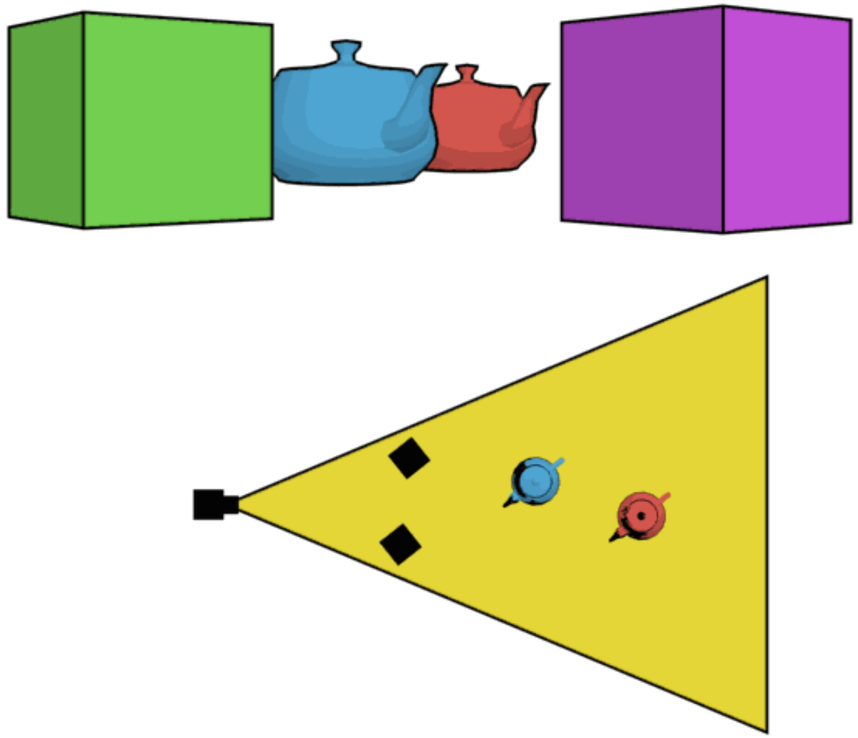
Approximating an orthographic camera



Source: Hartley & Zisserman

The dolly zoom

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

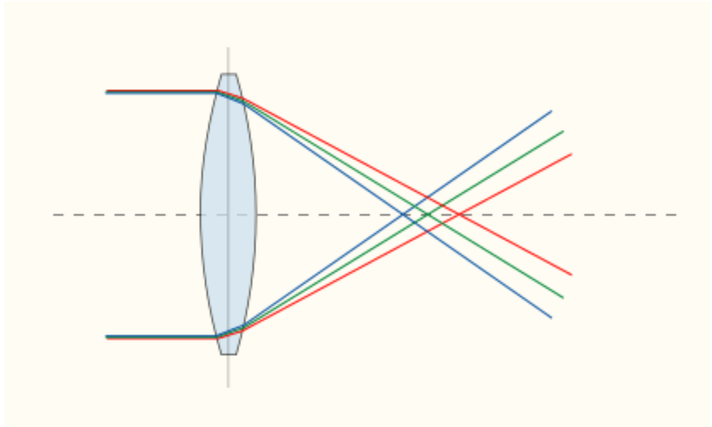
Also called as “Vertigo shot” or the “Hitchcock shot”

Example of dolly zoom from Goodfellas

Example of dolly zoom from La Haine

Lens flaws: Chromatic aberration

Lens have different refractive indices (Snell's law) for different wavelengths: causes color fringing



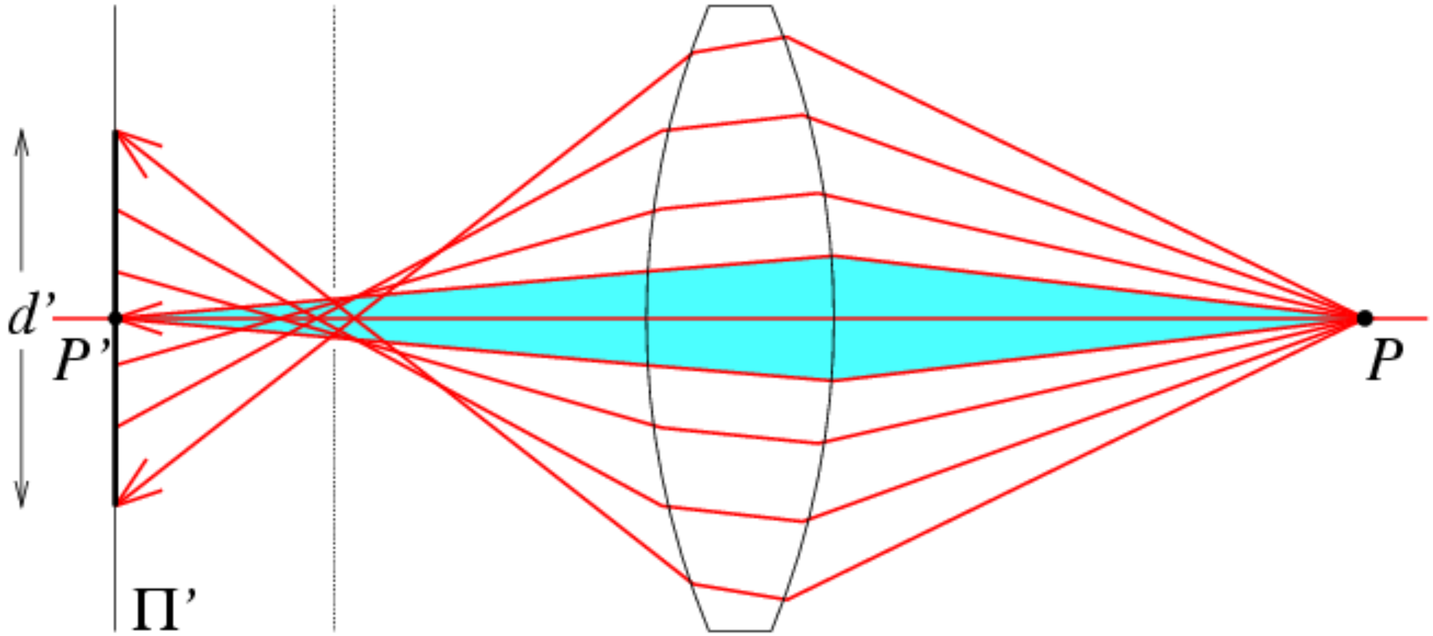
near lens center

near lens outer

Lens flaws: Spherical aberration

Spherical lenses don’t focus light perfectly (thin lens model)

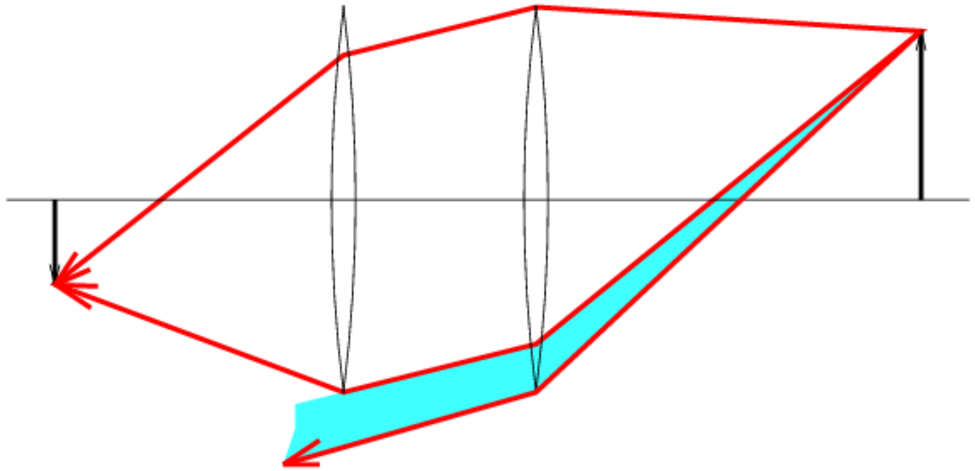
- Rays farther from the optical axis are focussed closer



objects lack sharpness

Lens flaws: Vignetting

Reduction of image brightness in the periphery

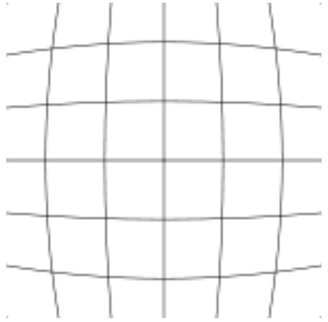


Not all rays reach the sensor

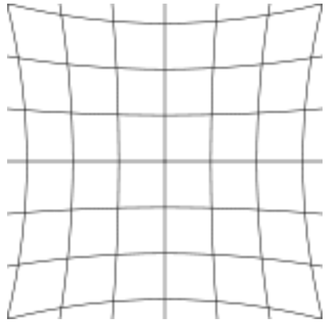
Lens flaws: Radial distortion

Caused by asymmetry of lenses

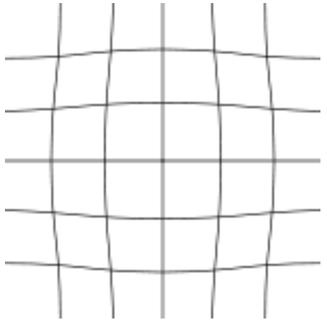
Deviations are most noticeable near the periphery



barrel distortion



pincushion distortion



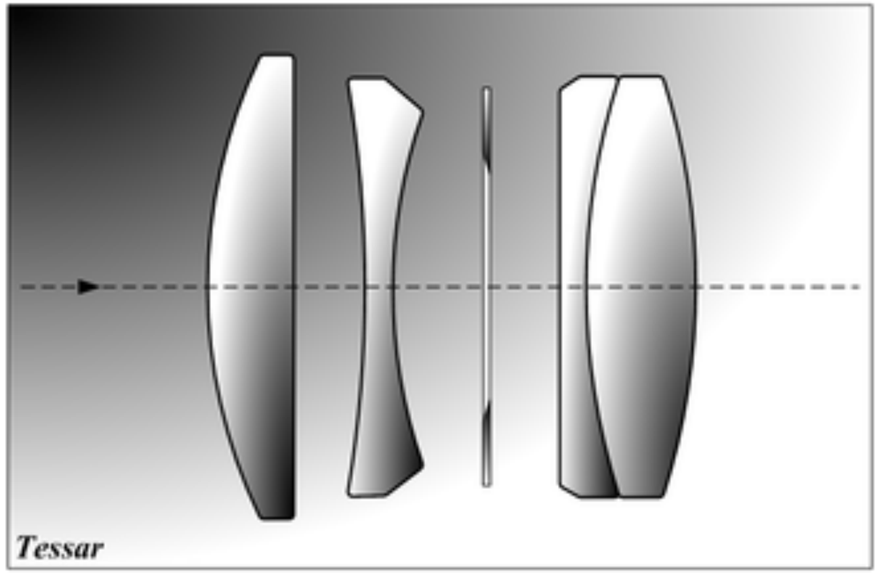
mustache distortion

http://clanegesselphotography.blogspot.com/

Real photographic lens

Many uses: cameras, telescopes, microscopes, etc

fixed focal length



Example of a prime lens - Carl Zeiss **Tessar**

adjustable zoom

Nikkor 28-200 mm zoom lens, extended to 200 mm at left and collapsed to 28 mm focal length at right.

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

Lytro camera

Light field camera: capture intensity along each direction of the light

- Traditional cameras integrate light coming from all directions

A captured light field allows you re-render an image post-hoc

- https://pictures.lytro.com/lytro/collections/41/pictures/1088670

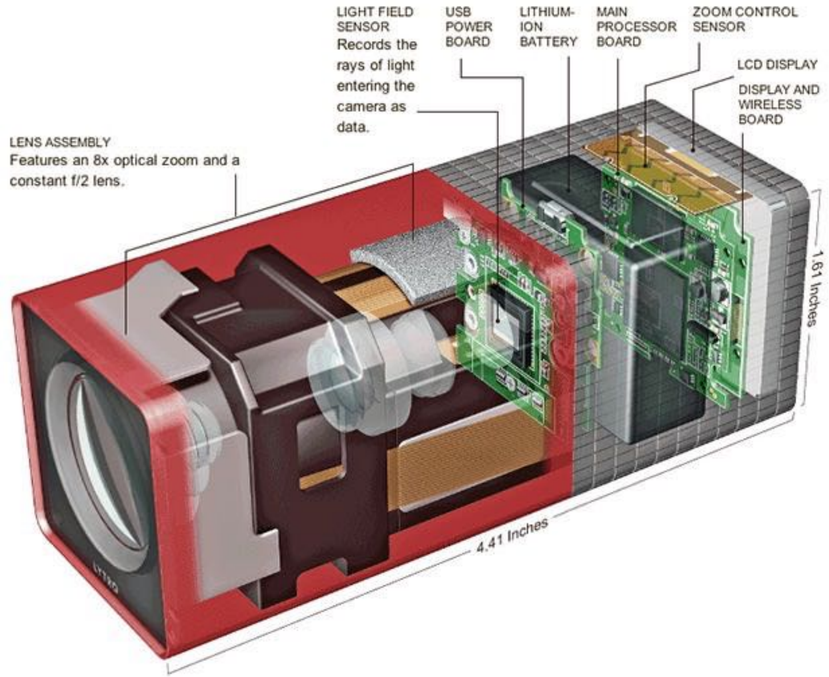
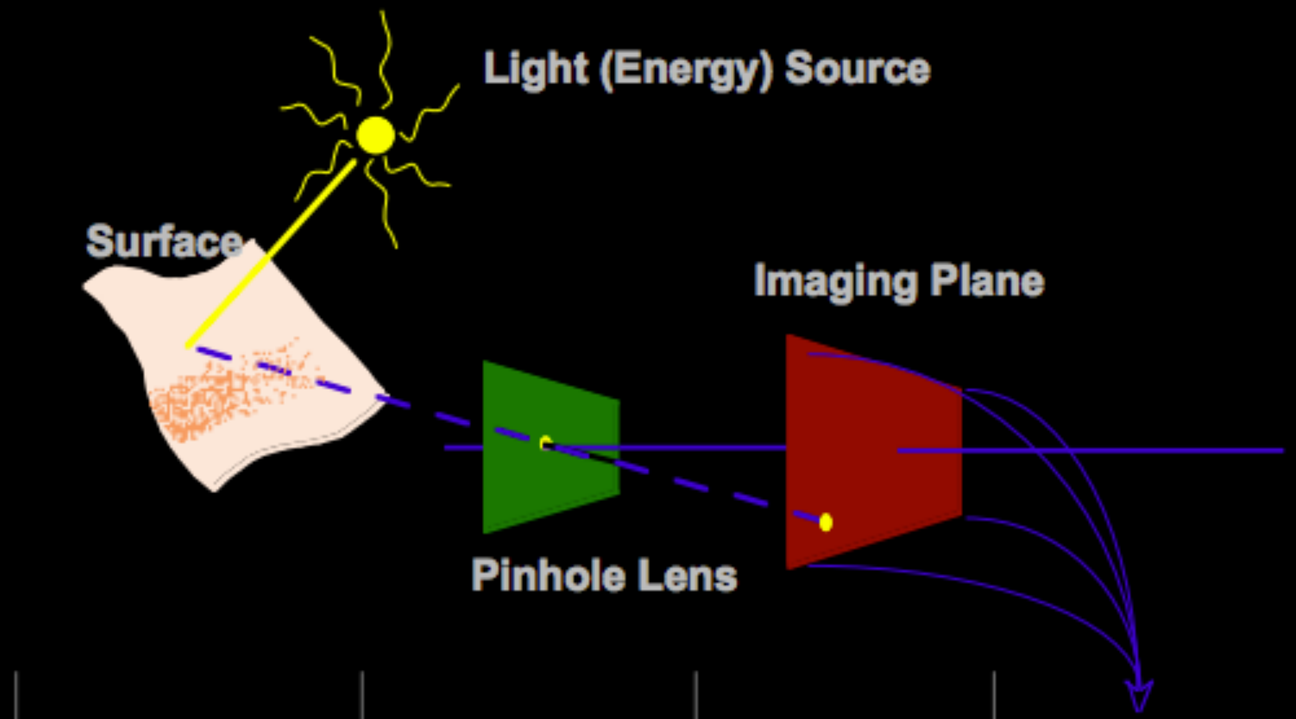


Image capture



Measuring light

Photographic film — strip of transparent plastic film base coated on one side with a gelatin emulsion containing light-sensitive materials

Creates a latent image when exposed to light for short duration

Films are then chemically developed to form a photograph

Early films/photographic plates could *only* capture intensity

An incredible story…

Sergey Prokudin-Gorsky (1912)

1909

Nicholas II of Russia

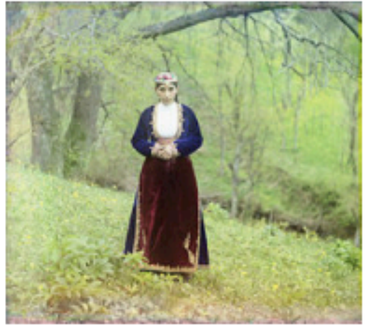
Dagestani Sunni Muslim, 1904[27][47]

Greek women and children harvesting tea in Chakvi, Georgia, circa 1905–1915

Italian woman in formal dress, posed, standing near gate, circa 1905–1915

Jewish children with their teacher in Samarkand, circa 1905–1915

Minister of the Interior, Bukhara, circa 1905–1915



Armenian woman in national costume near Artvin (then in the Russian Empire, now in Turkey), circa 1905–1915

Zindan (prison) in Bukhara, 1907

A chapel in Myatusovo, 1909

Staraya Ladoga Fortress, 1909

Staraya Ladoga Fortress, 1909

Young Russian peasant women in a rural area along the Sheksna River near the small town of Kirillov, 1909

Church of St. John the Baptist on Malyshevaya Hill; Staraya Ladoga, 1909

The St Nicholas Monastery Staraya Ladoga, 1909

General view of the city of Perm, 1910

General view of the city of Perm from Gorodskie Gorki, 1910

Razguliai, outskirts of the city of Perm, 1910

Summertime location of the exchange in the city Perm, 1910

Staro-Sibirskaia Gate in the city of Perm, 1910

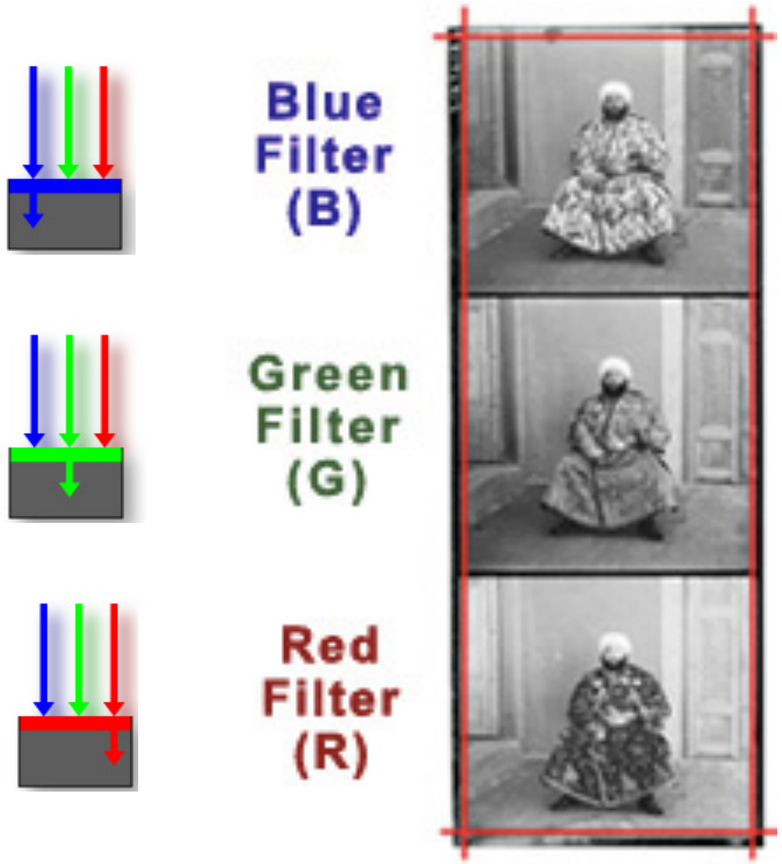
Headquarters of the Ural Railway Administration in the city of Perm, 1910

Mary Magdalene Church in the city Perm, 1910

Early color photography — three color technique

Sergey Prokudin-Gorskii (1863-1944)

Photographs of the Russian empire (1909-1916)



Only problem!

Idea for alignment

Fix one channel (say red).

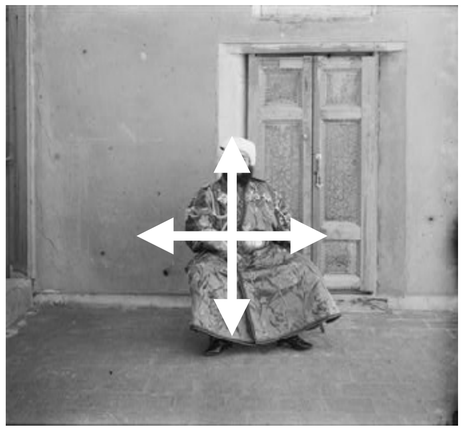
Assume that channels are only translated, i.e., no rotation, scaling, etc.

For each shift, say: $x \in (-15,15), y \in (-15,15)$

- Measure similarity
- Pick the shift that *maximizes* similarity

red

green



Repeat for the blue channel

How to measure similarity?

Measure similarity using Euclidean distance

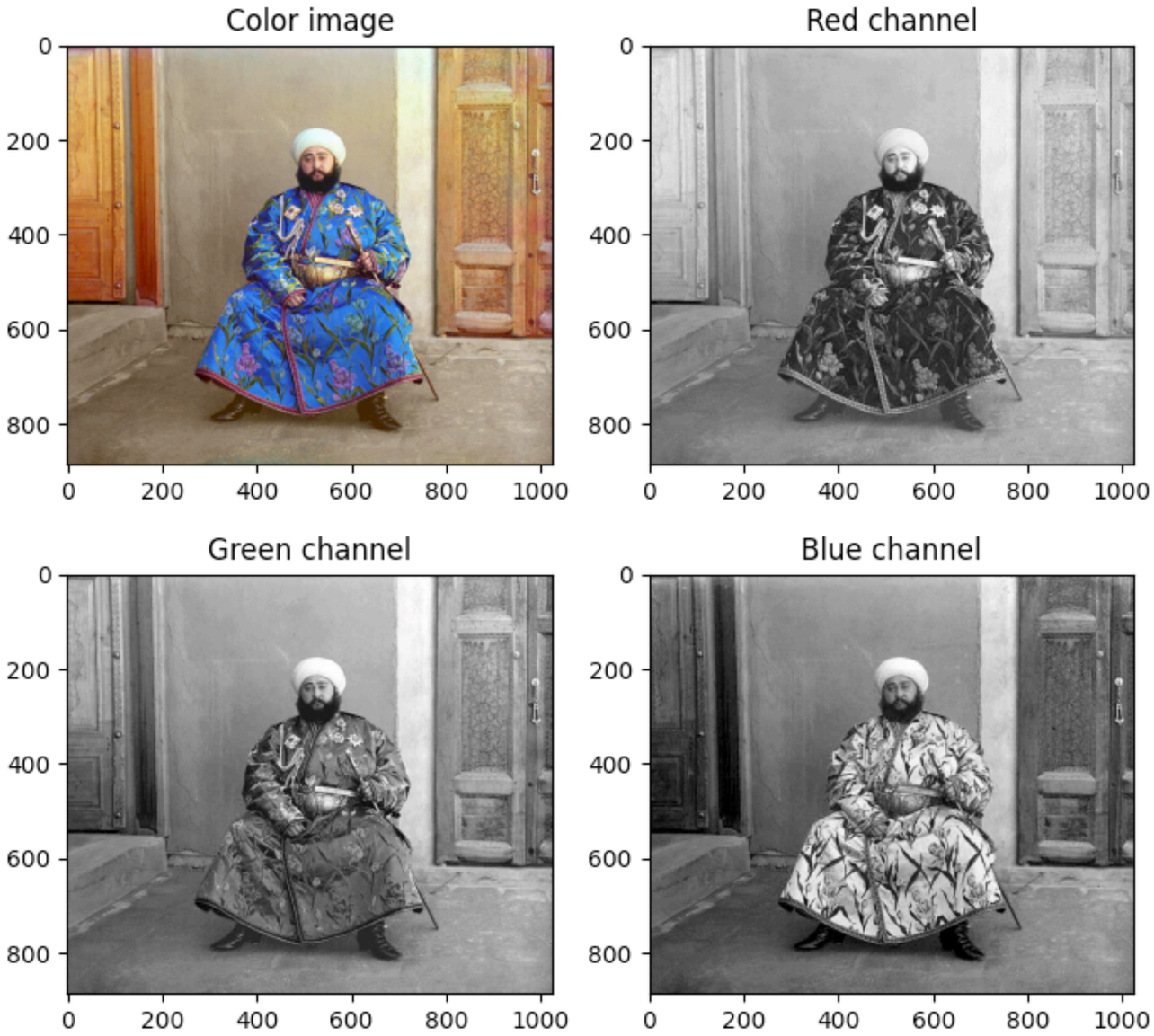
Align a central region of the images to avoid boundary artifacts

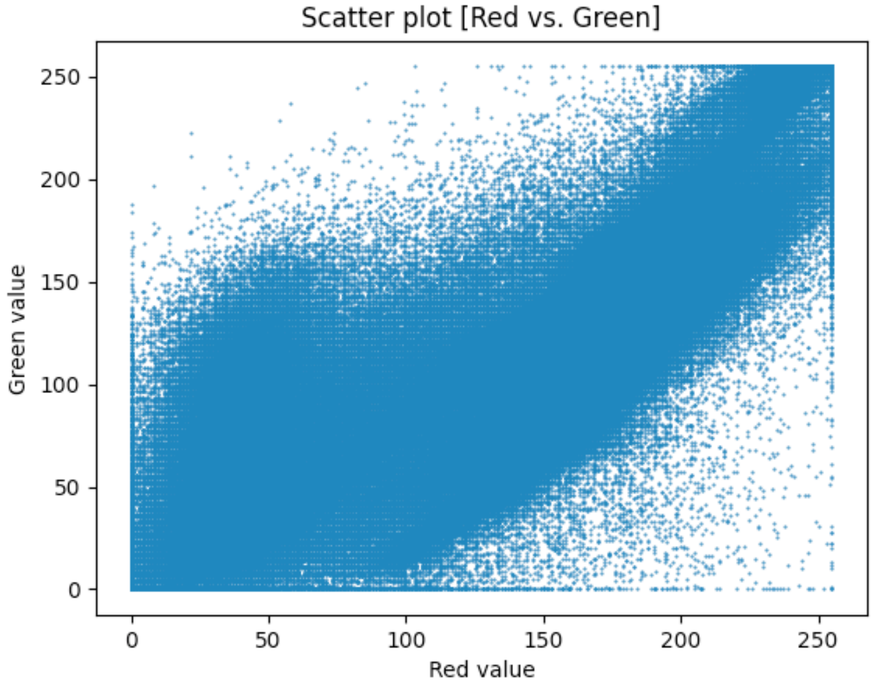
red

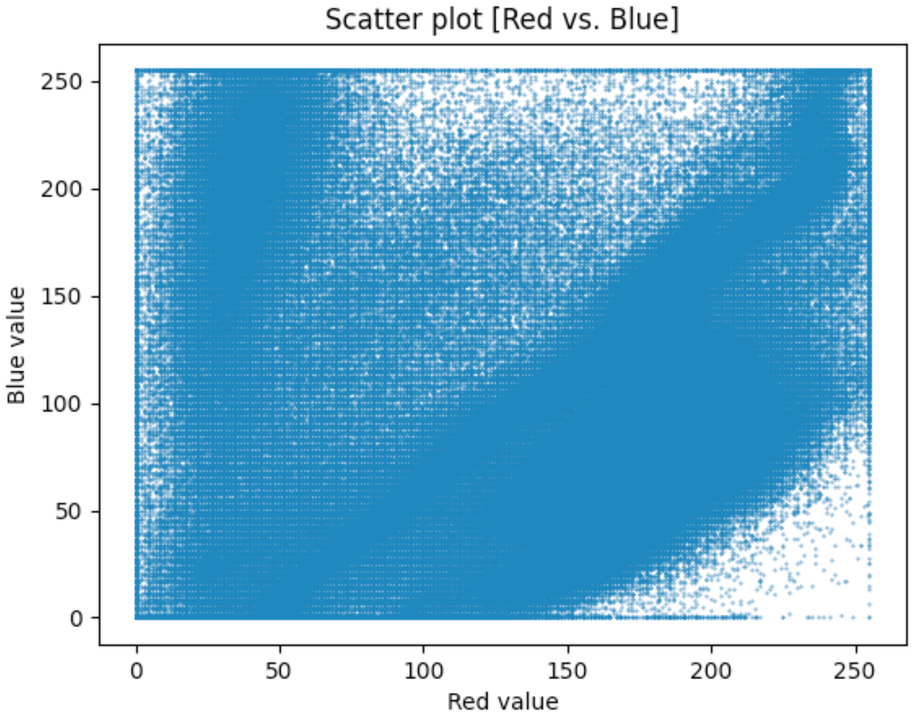
green

$$\mathrm{d}(\mathbf{p}, \mathbf{q}) = \mathrm{d}(\mathbf{q}, \mathbf{p}) = \sqrt{(q_1 - p_1)^2 + (q_2 - p_2)^2 + \cdots + (q_n - p_n)^2}$$

Why does it work?



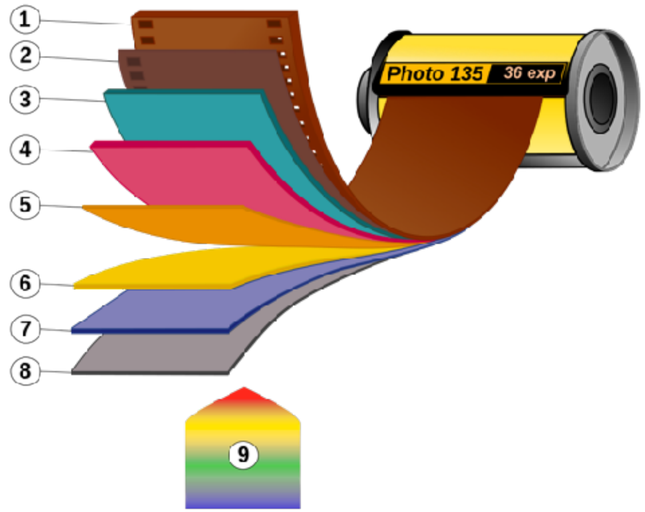




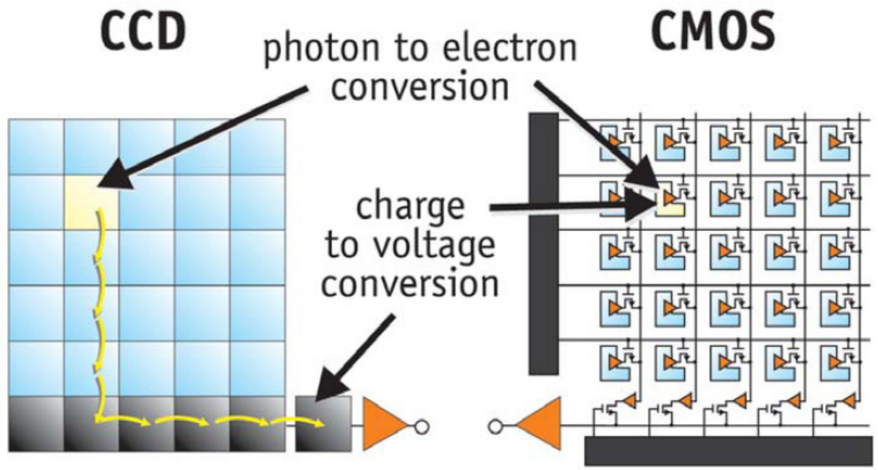
Measuring light: color films

Color photographic film — many layers of dyes and light sensitive materials to capture light of different frequencies simultaneously

- Solves the alignment problem!
- But needs complex film design and development process
- Kodak pioneered color films for making paper prints



Digital camera



CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node. CMOS imagers convert charge to voltage inside each pixel.

A digital camera replaces the film with a sensor array

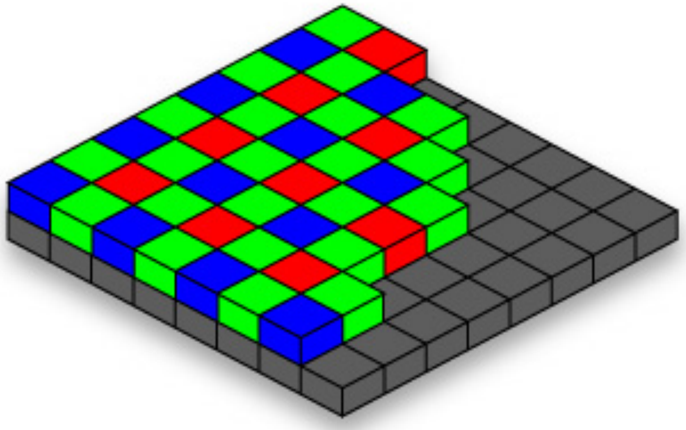
- Each cell in the array is a light-sensitive diode that converts photons to electrons
- Two common types of sensor arrays
  - Charge Coupled Device (CCD)
  - Complementary Metal Oxide Semiconductor (CMOS)

http://electronics.howstuffworks.com/digital-camera.htm

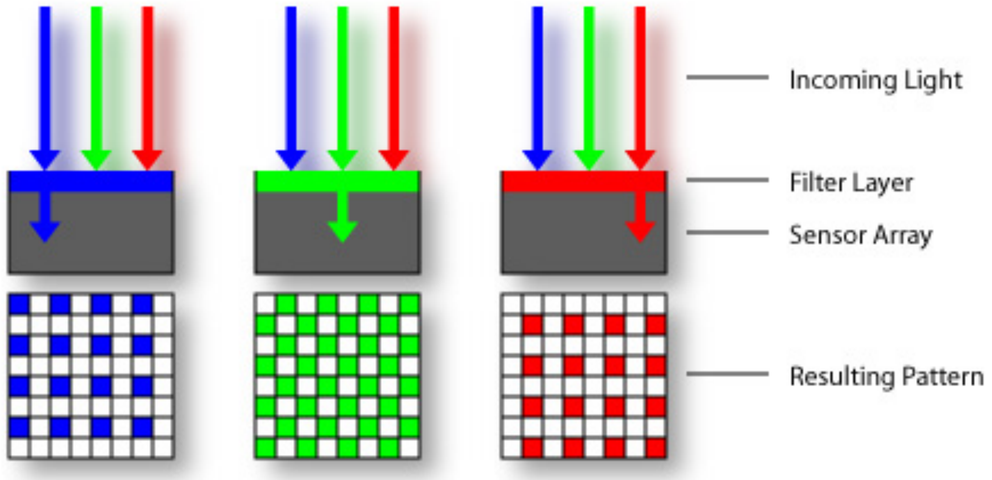
Color sensing in the camera

Color filter array

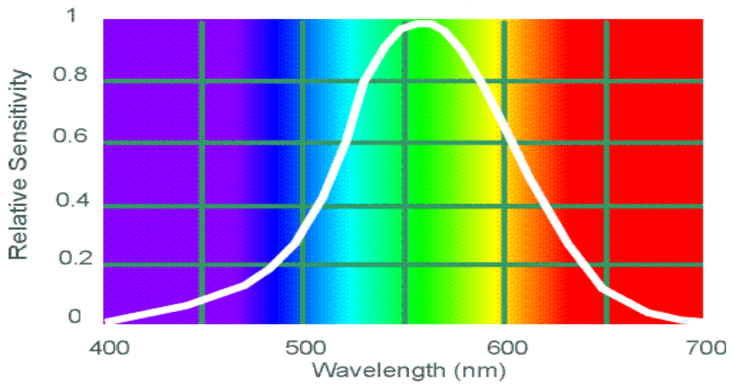
Bayer grid



Estimate missing components from neighboring values (**demosiacing**)

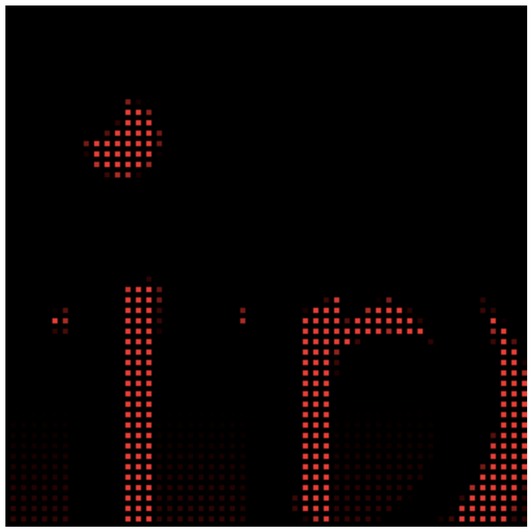


Why more green?

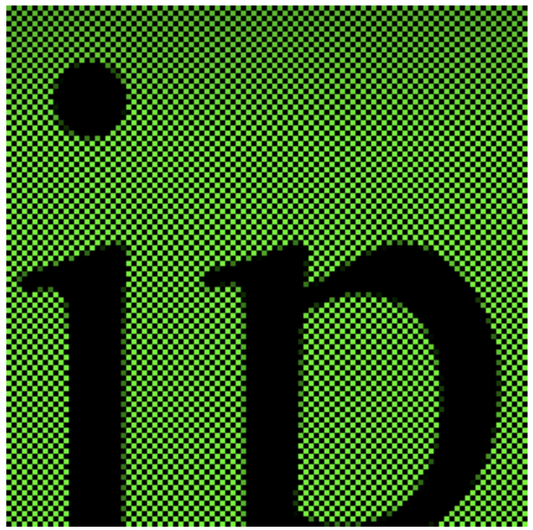


Human luminance sensitivity function

What is captured? — a moscaiced image



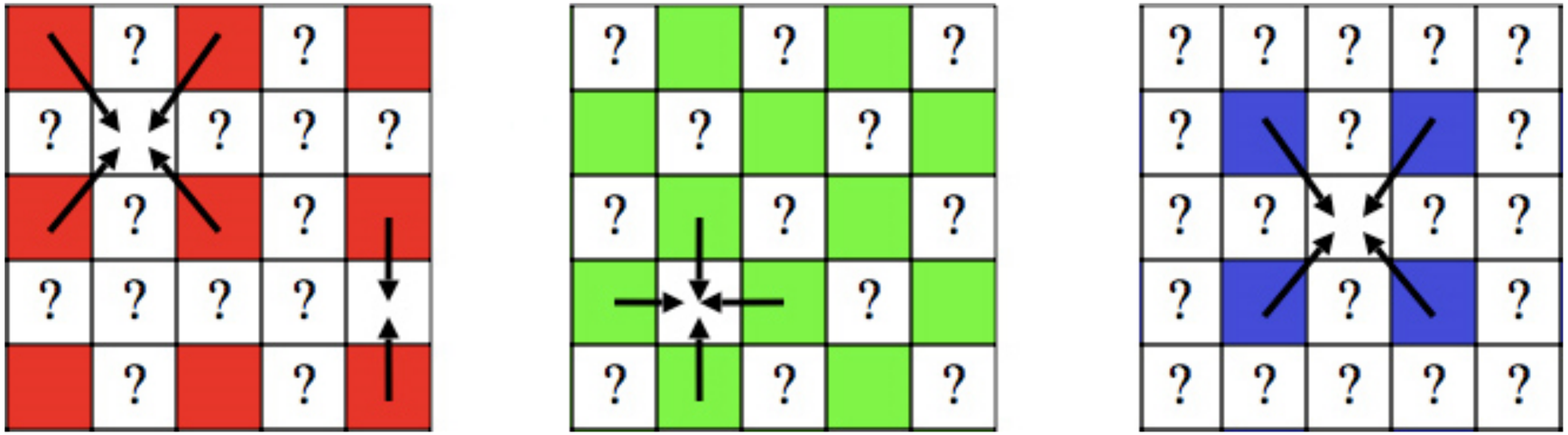
Red



Green

Blue

Demosaicing — interpolating the missing values

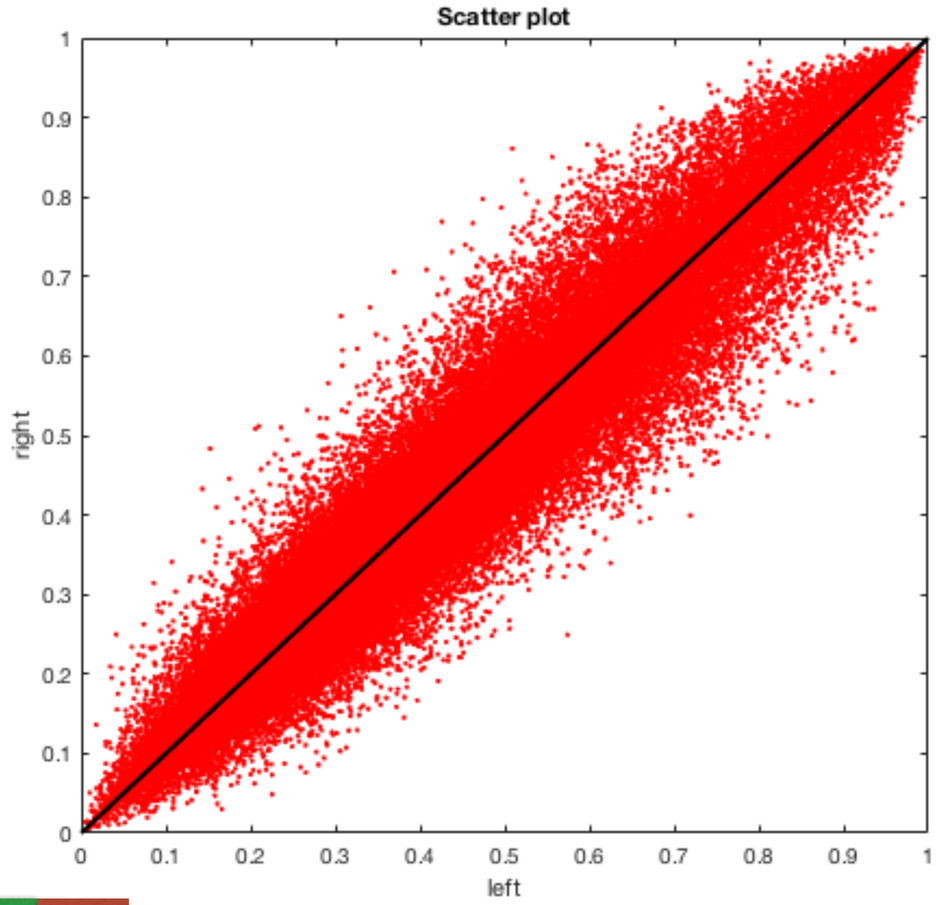


Problem: guess the values of missing pixels in each of the three channels

How?

Why is this possible?

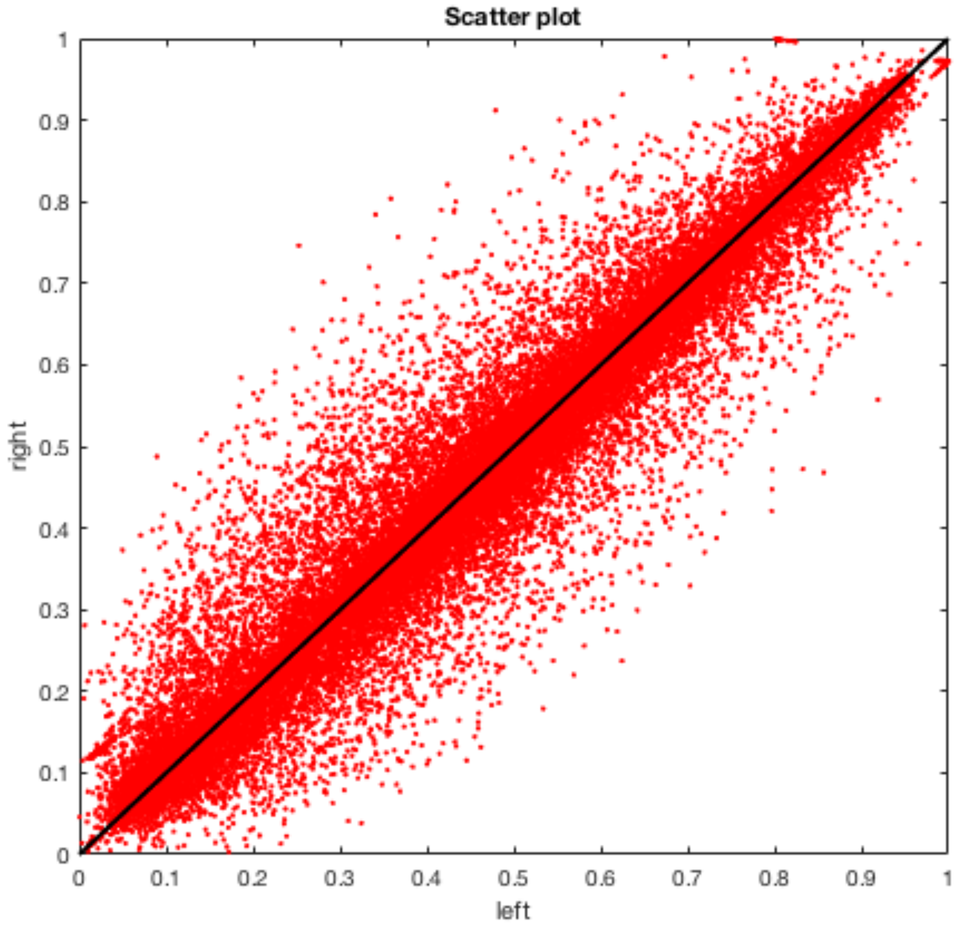
Adjacent pixel values are strongly correlated



Why is this possible?

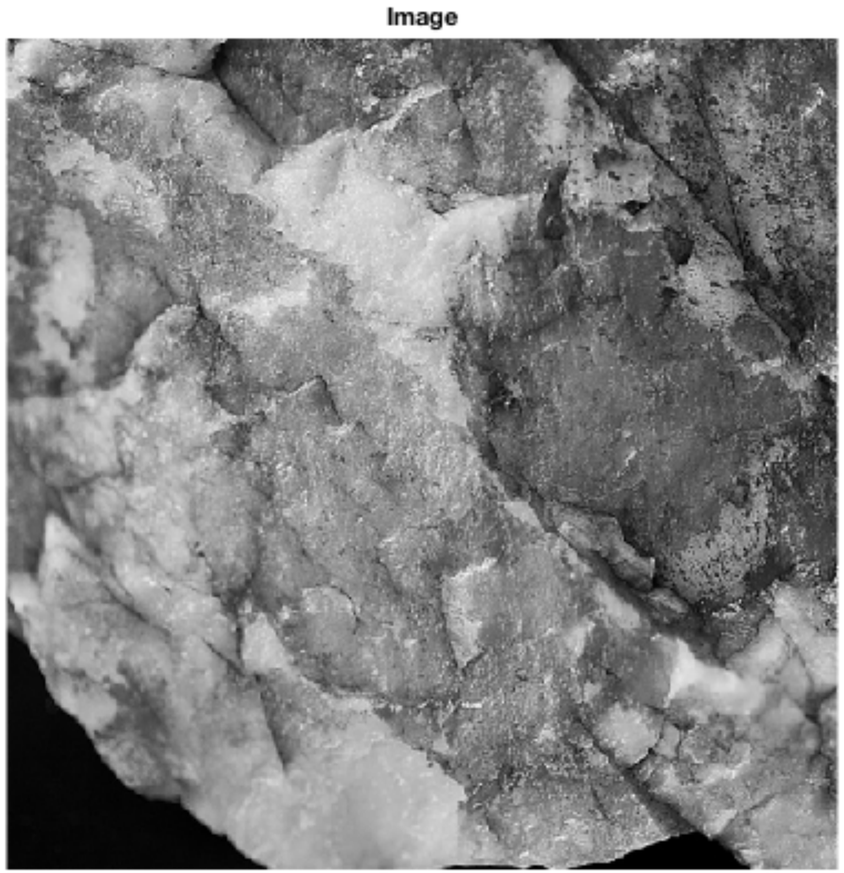
Adjacent pixel values are strongly correlated

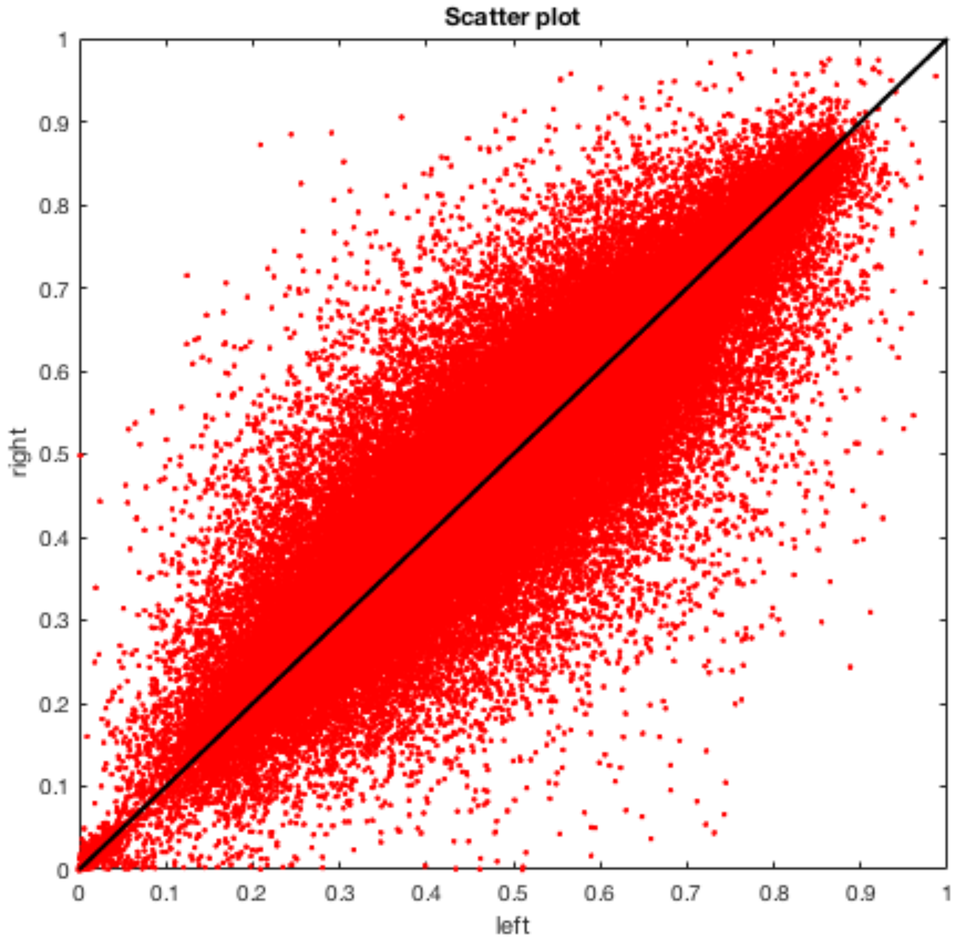
left | right



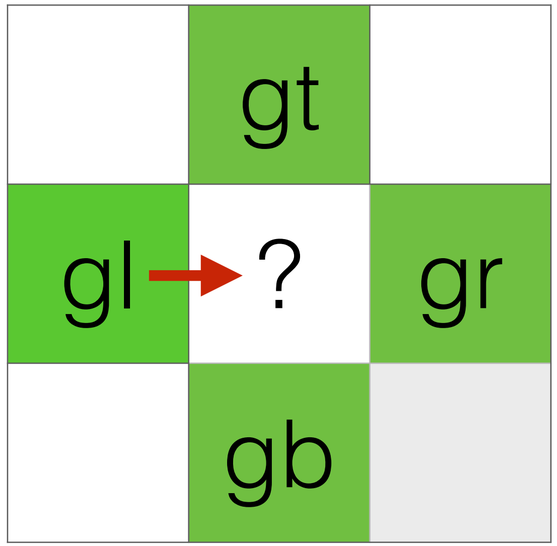
Why is this possible?

Adjacent pixel values are strongly correlated





Interpolation

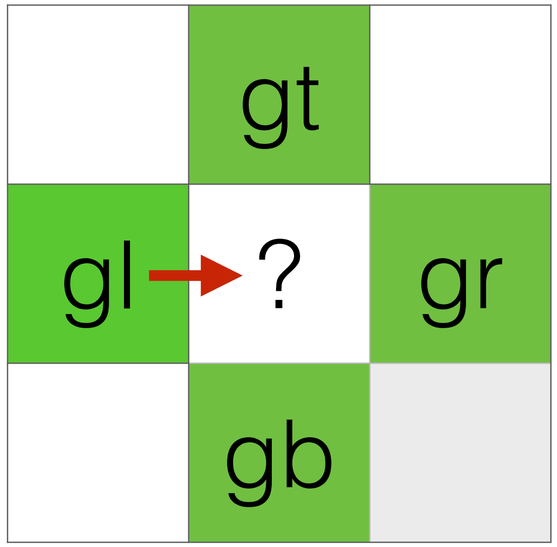


nearest neighbor

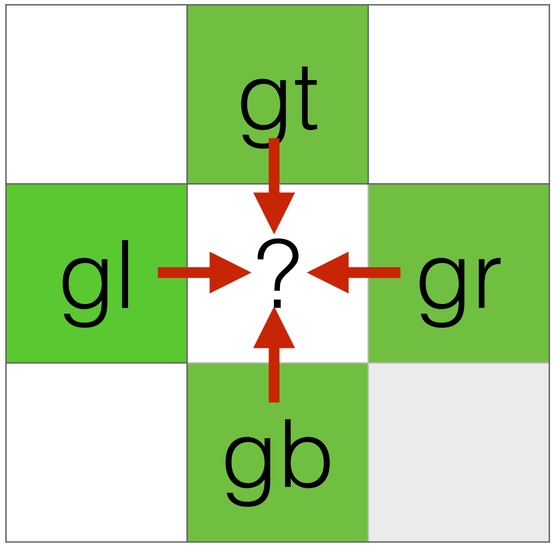
copy one of your neighbors

? ←gl

Interpolation

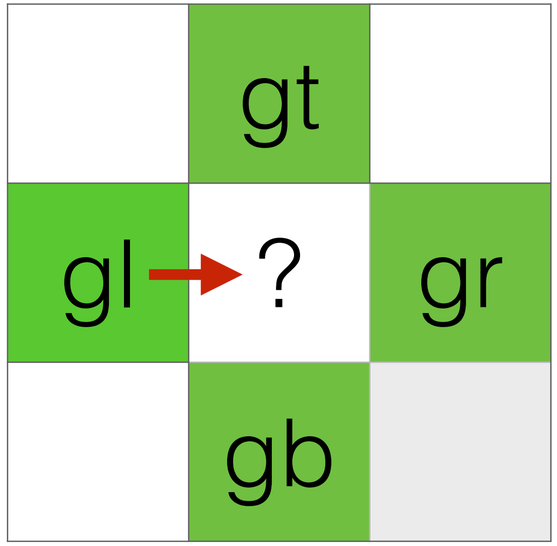


nearest neighbor
copy one of your neighbors
? ←gl

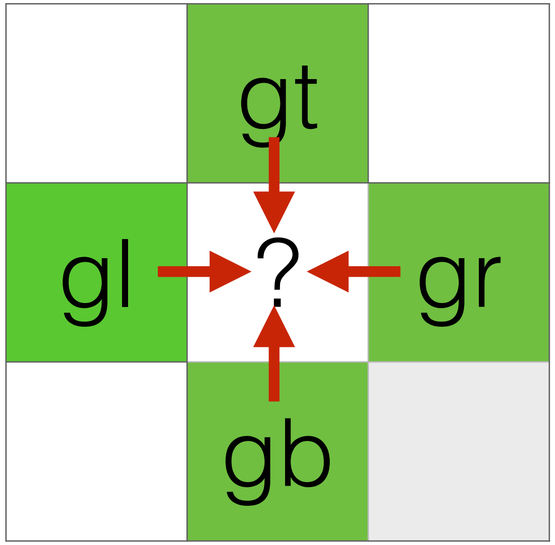


linear interpolation
average values of your neighbors
? ←(gt+gl+gr+gb)/4

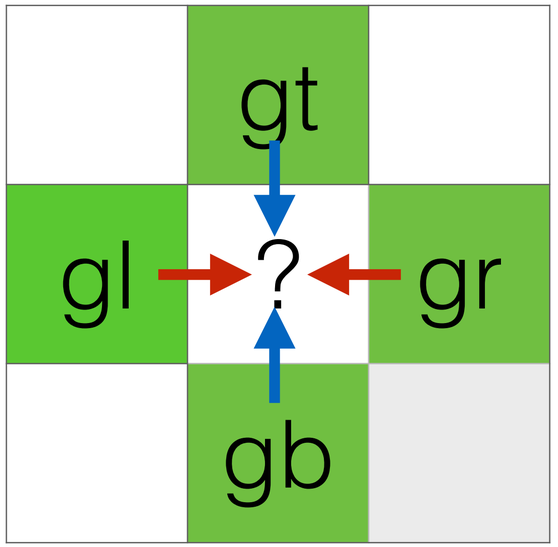
Interpolation



nearest neighbor
copy one of your neighbors
? ←gl



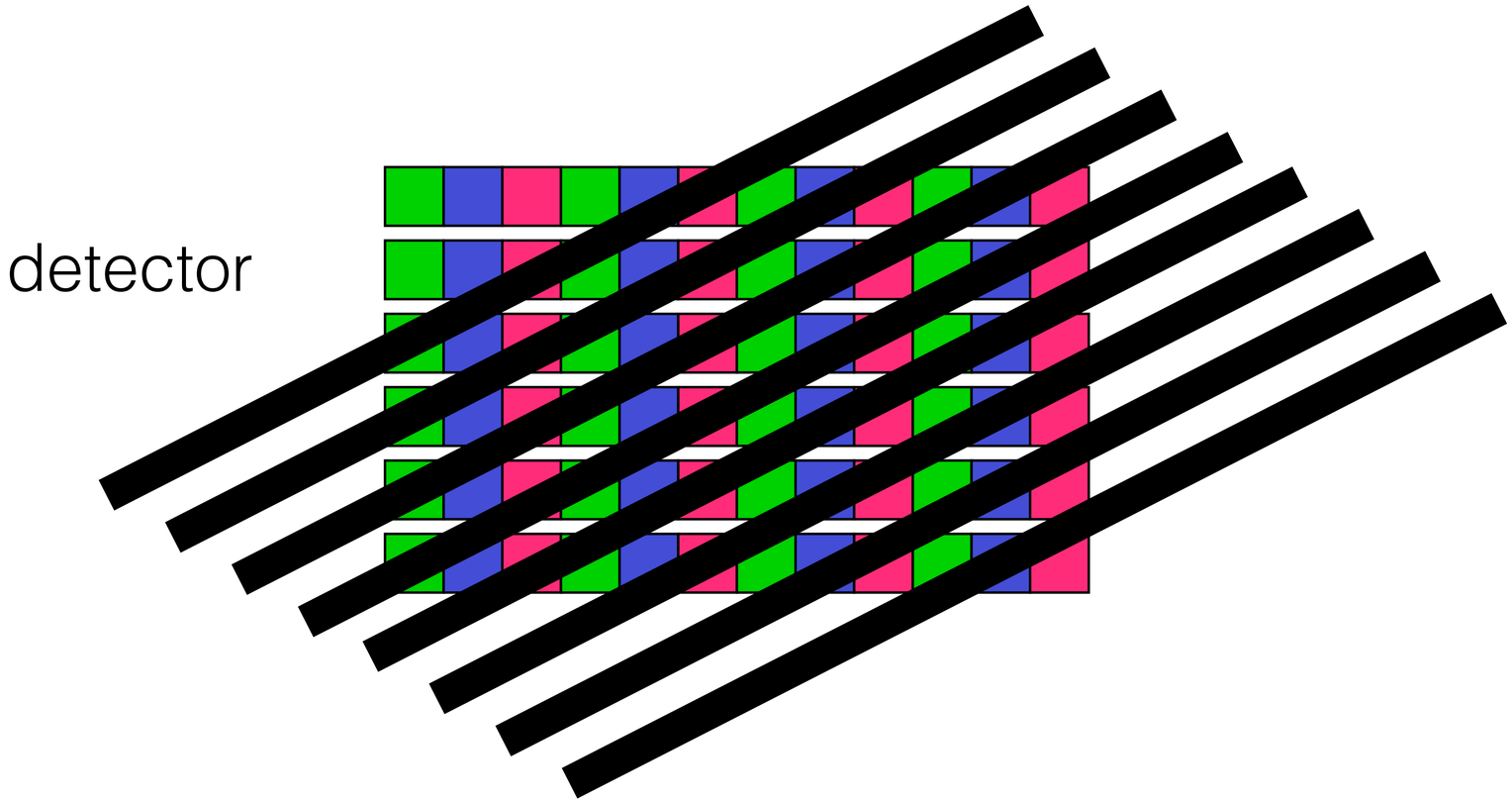
linear interpolation
average values of your neighbors
? ←(gt+gl+gr+gb)/4



adaptive gradient
average based on nbhd. structure
if |gt-gb| > |gl-gr|
? ← (gl+gr)/2
else
? ← (gt+gb)/2

Problem: color moiré

The cause of color moiré



Fine black and white detail in the image scene
is misinterpreted as color information