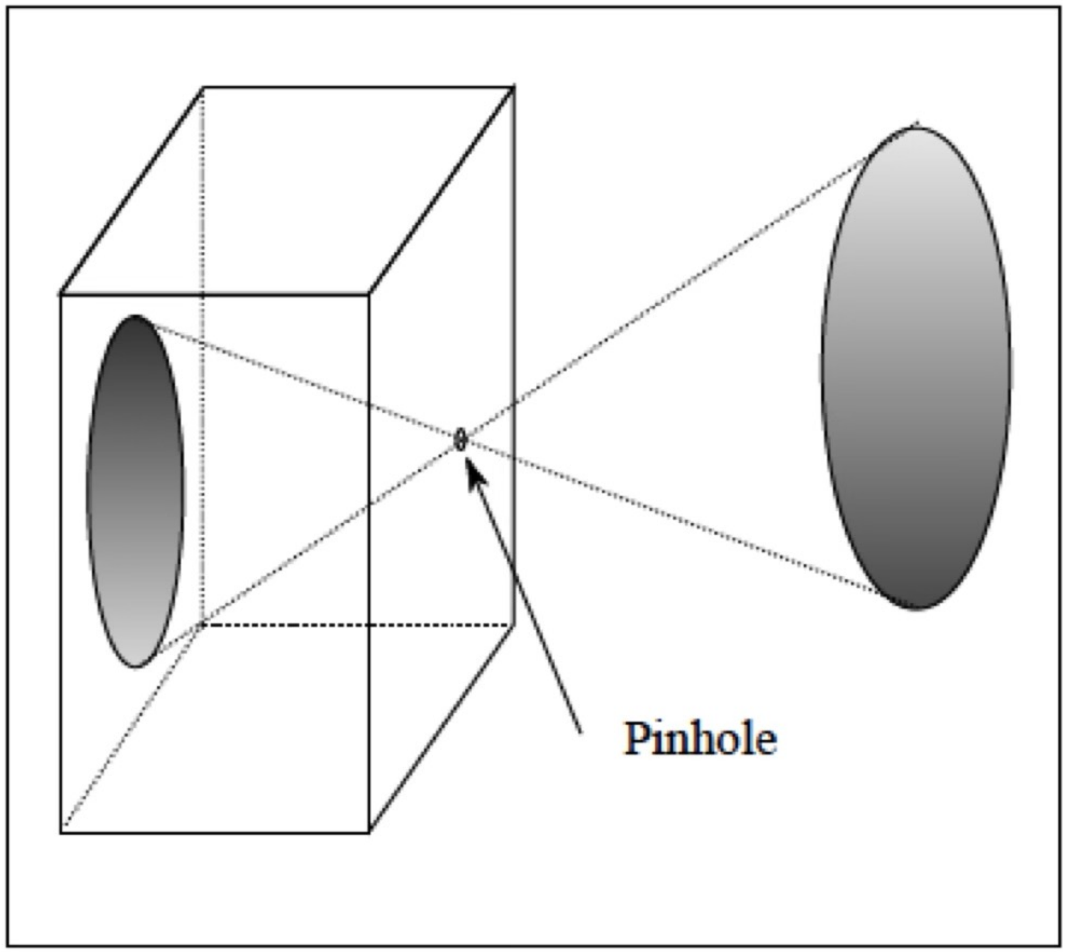
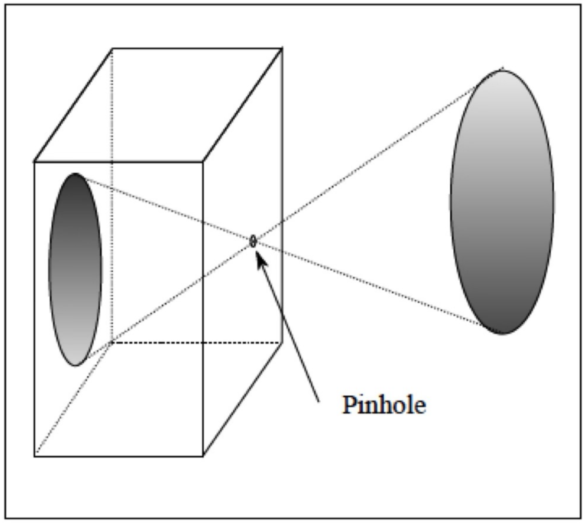
Introduction to cameras

Pinhole camera

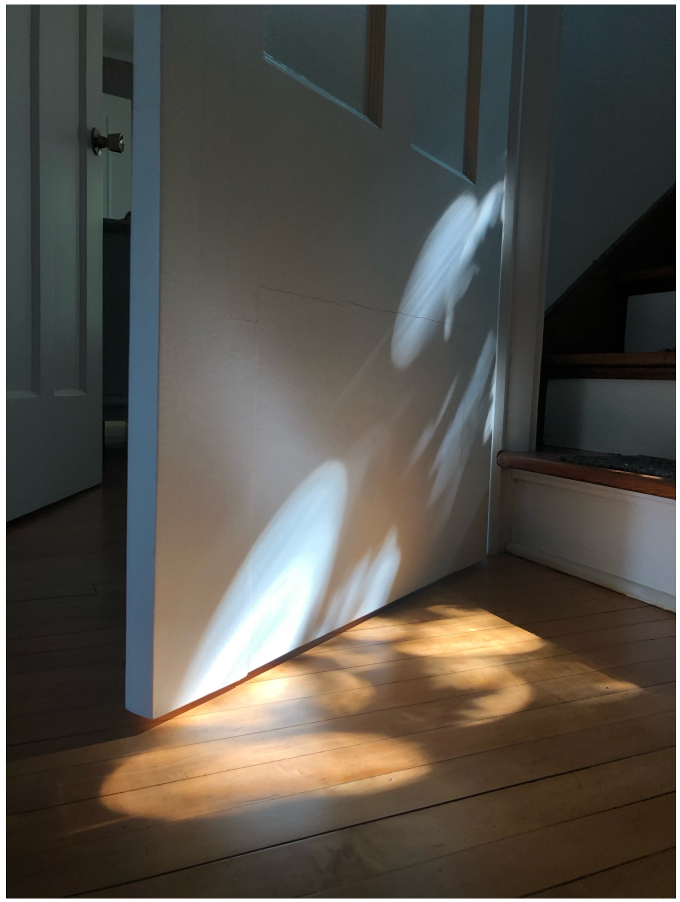


Pinhole camera



- Captures **pencil of rays** – all rays through a single point: **aperture, center of projection, optical center, focal point, camera center, pinhole**
- The image is formed on the **image plane**
- It is **upside down** (but that doesn't matter)

Accidental pinhole cameras are everywhere



Accidental pinhole cameras are everywhere

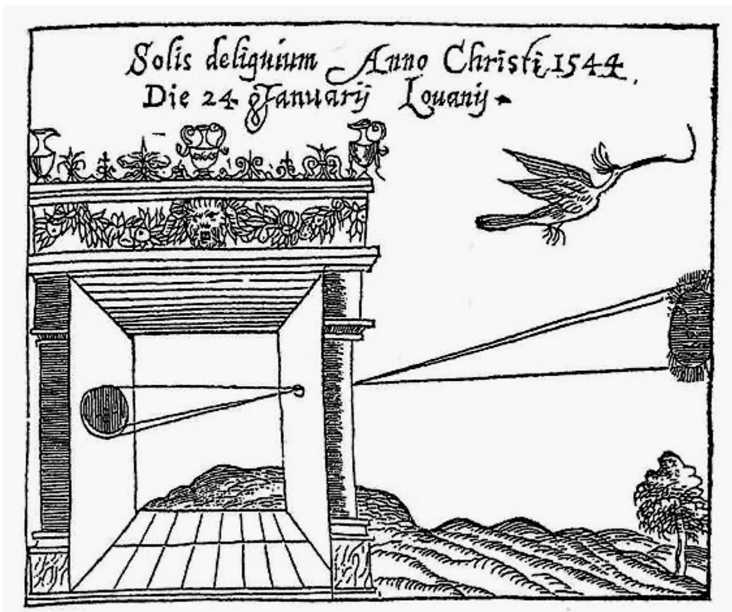
Tree shadow during a solar eclipse

photo credit: Nils van der Burg

http://www.physicstogo.org/index.cfm

Slide by Steve Seitz

Camera obscura

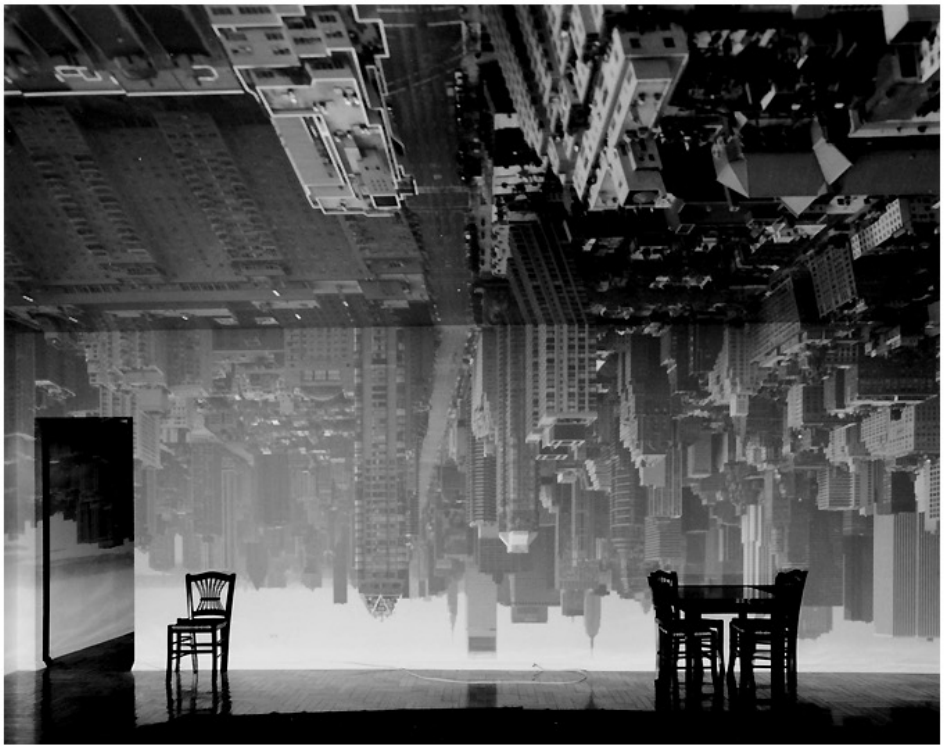


Gemma Frisius, 1558

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

Source: A. Efros

Turning a room into a camera obscura



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

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.

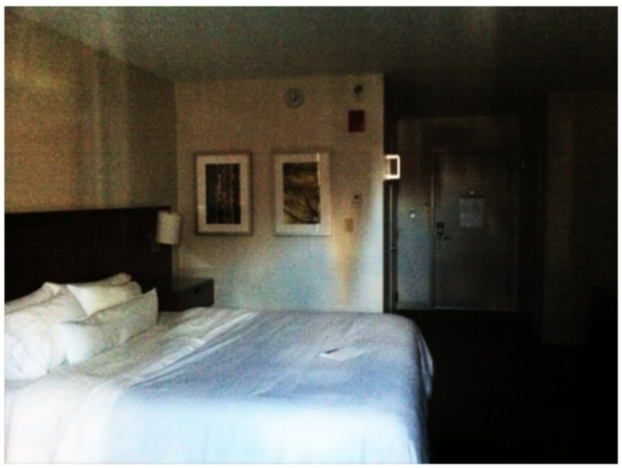
After he's done inside, it gets harder. "I leave the room and I am constantly checking the weather, I'm hoping the maid reads my note not to come in, I'm worrying that the sun will hit the plastic masking and it will fall down, or that I didn't trigger the lens."

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

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

Turning a room into a camera obscura

My hotel room, contrast enhanced.

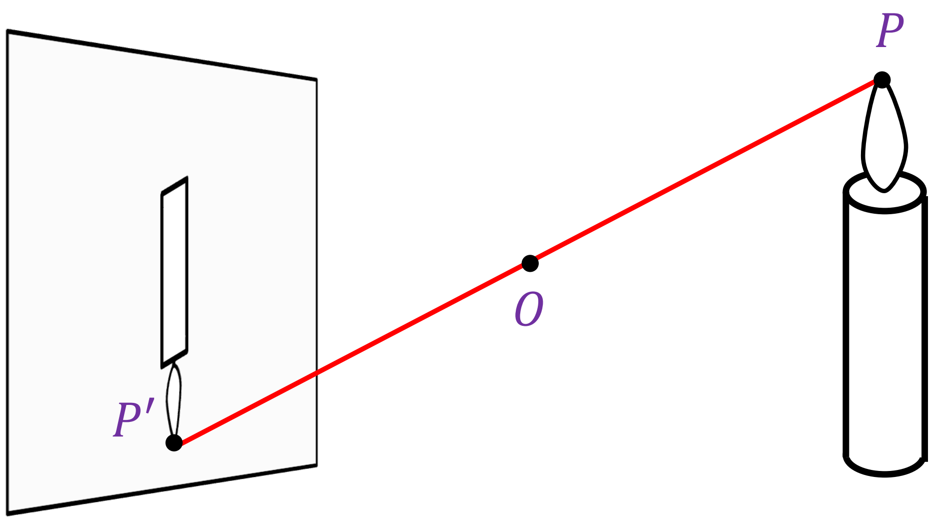


The view from my window

Accidental pinholes produce images that are unnoticed or misinterpreted as shadows

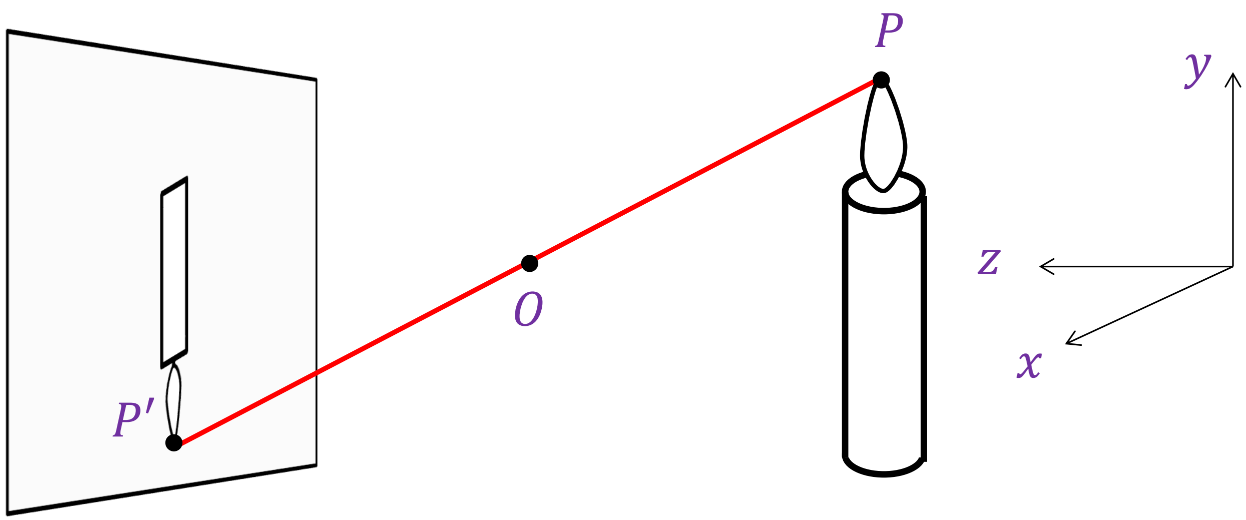
A. Torralba and W. Freeman, [Accidental Pinhole and Pinspeck Cameras](), CVPR 2012

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?

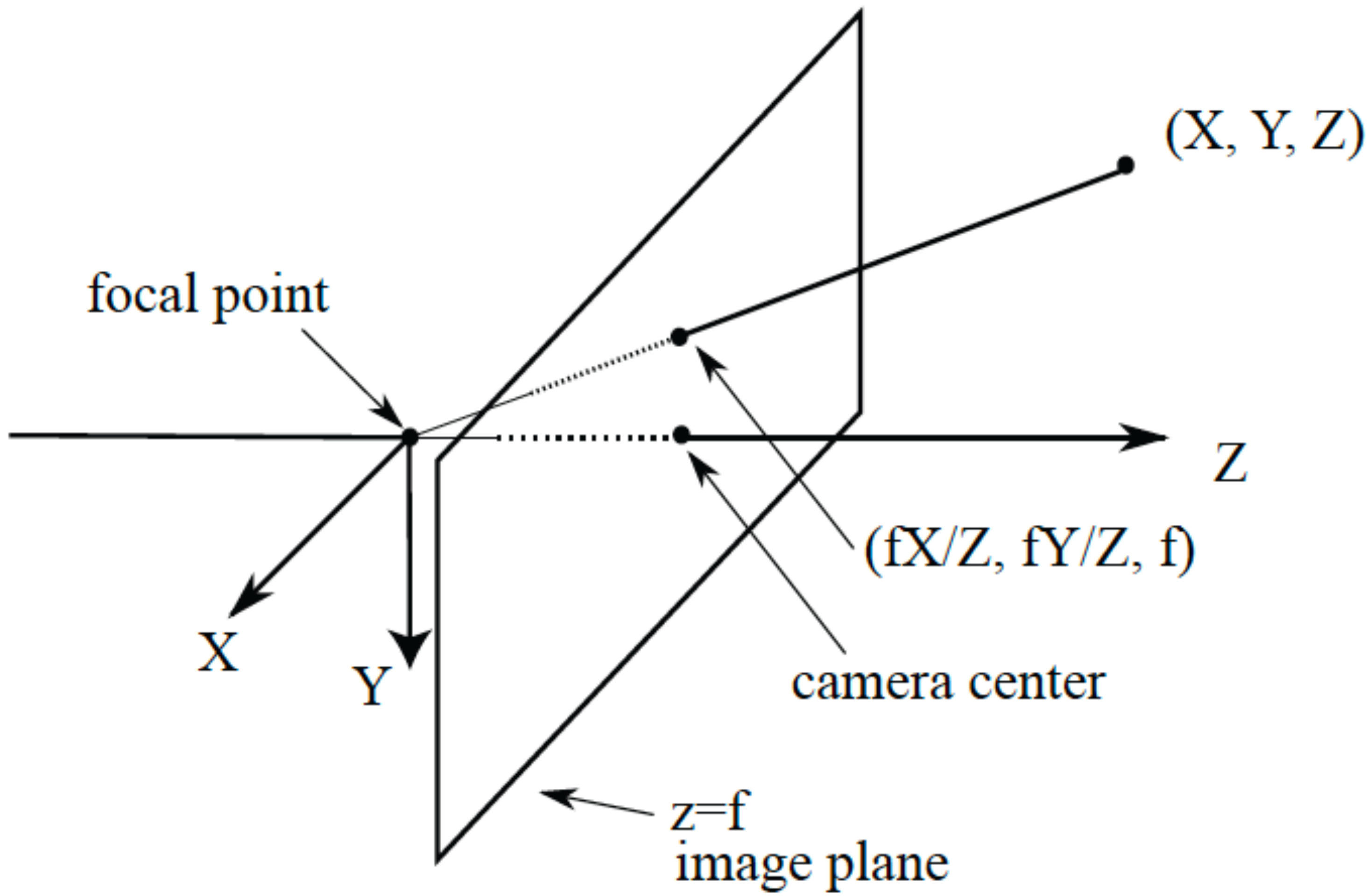
Modeling projection



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

Abstraction with right handed coordinate system



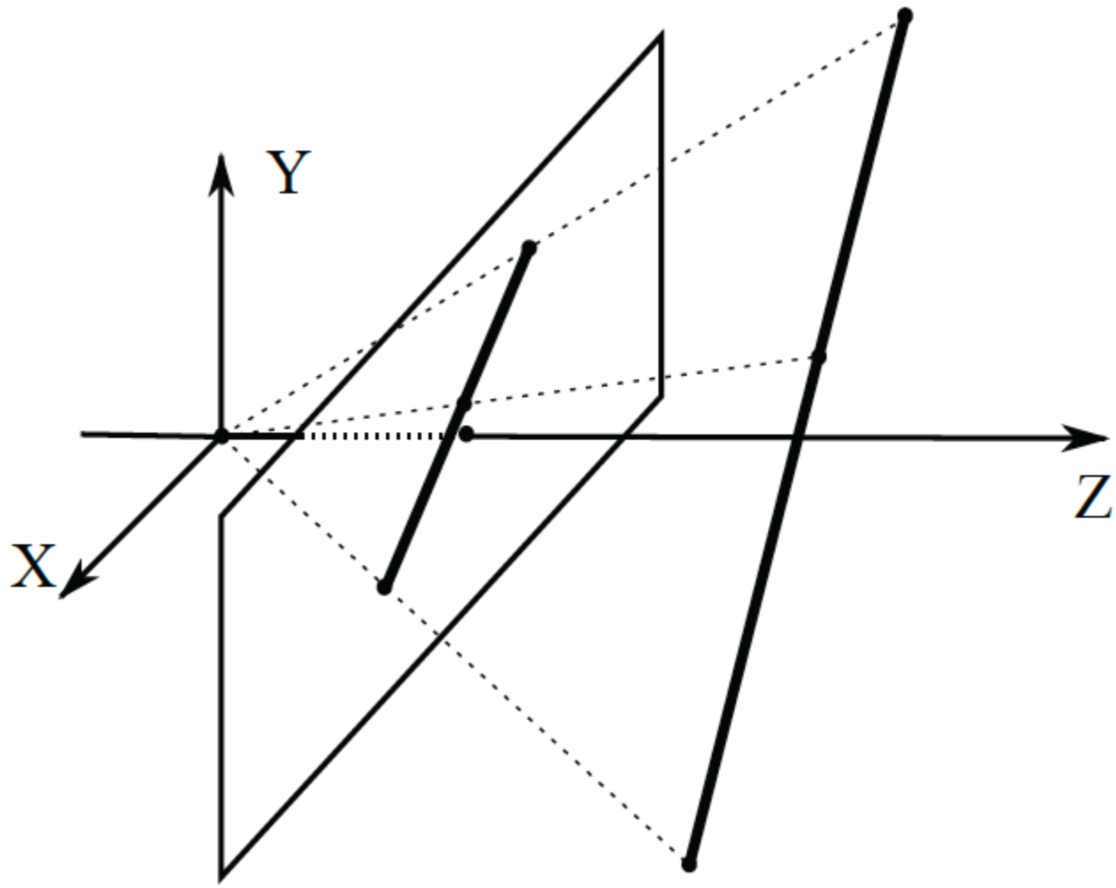
Perspective effects

2.1.2 Perspective Effects

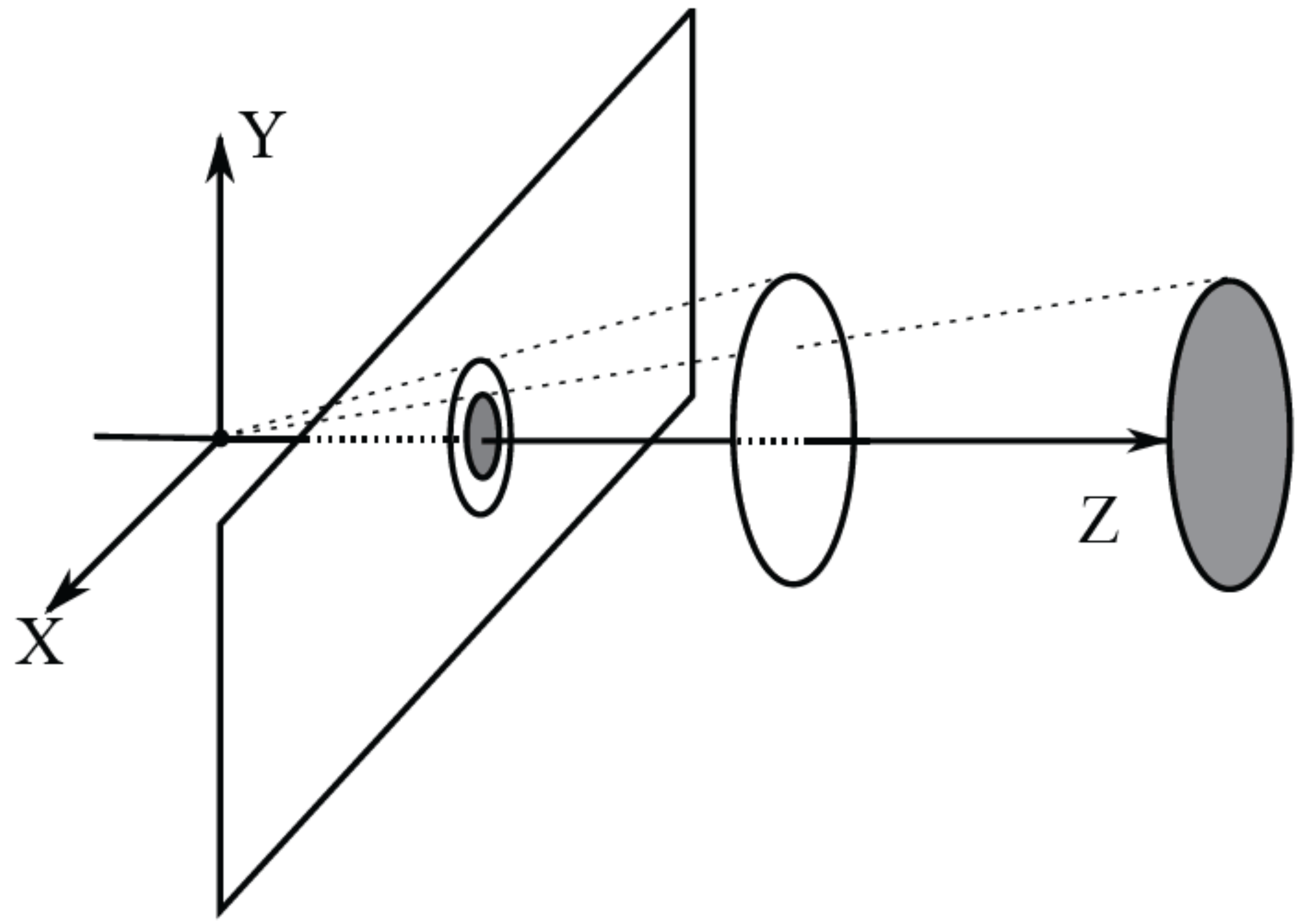
Perspective projection has a number of important properties, summarized as:

- lines project to lines;
- more distant objects are smaller;
- lines that are parallel in 3D meet in the image;
- planes have horizons;
- planes image as half-planes.

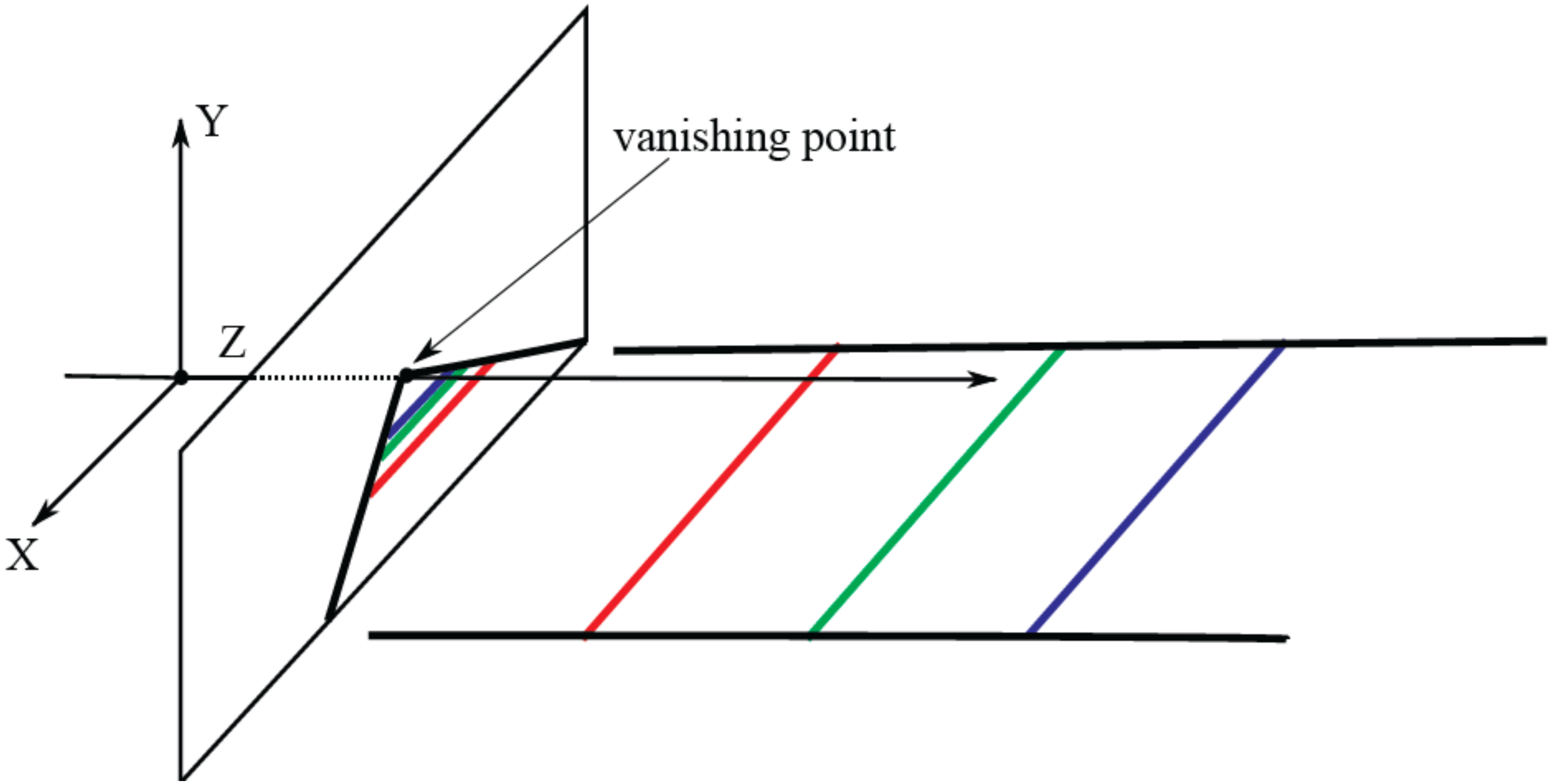
Lines -> lines



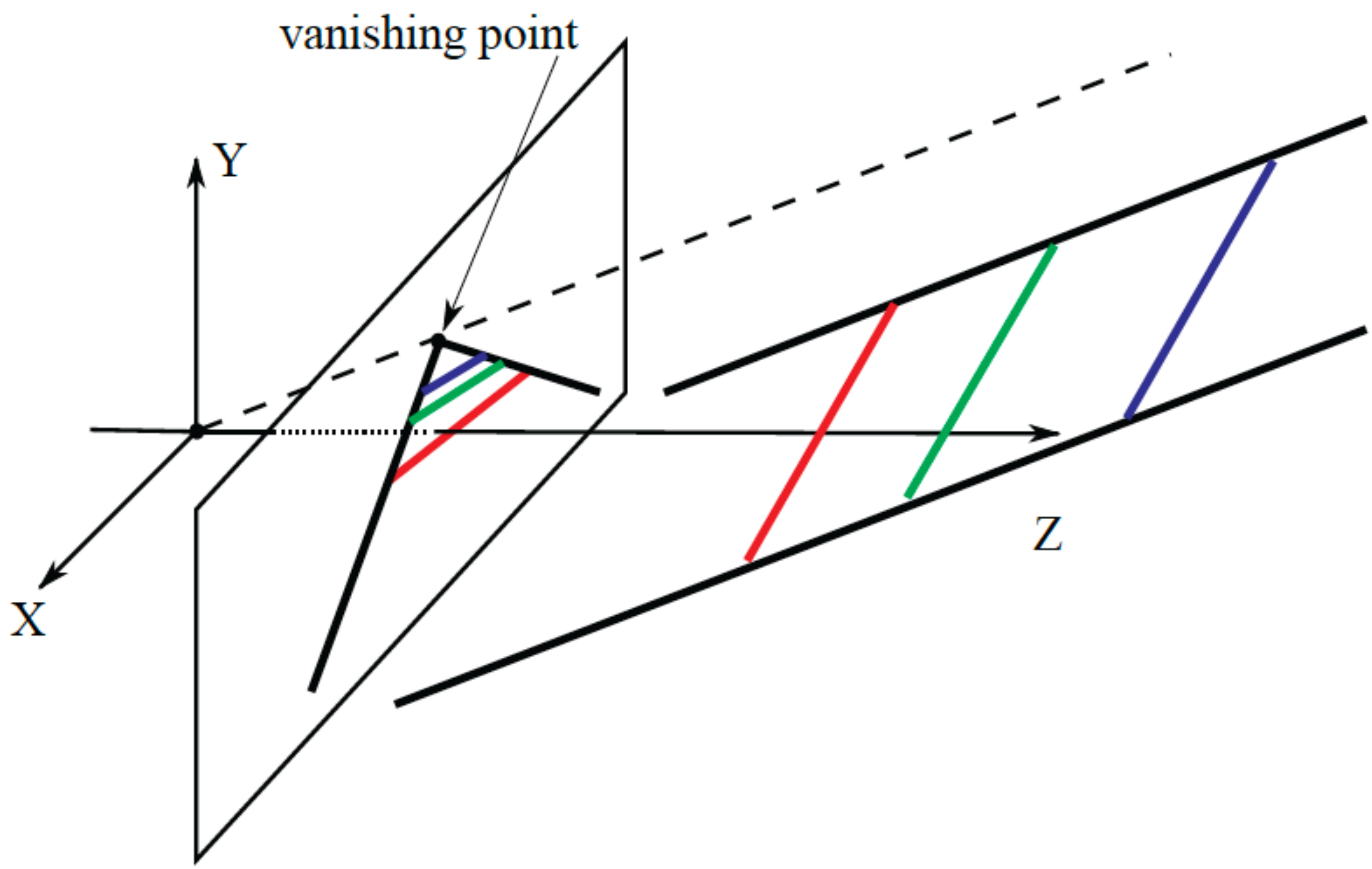
More distant objects are smaller



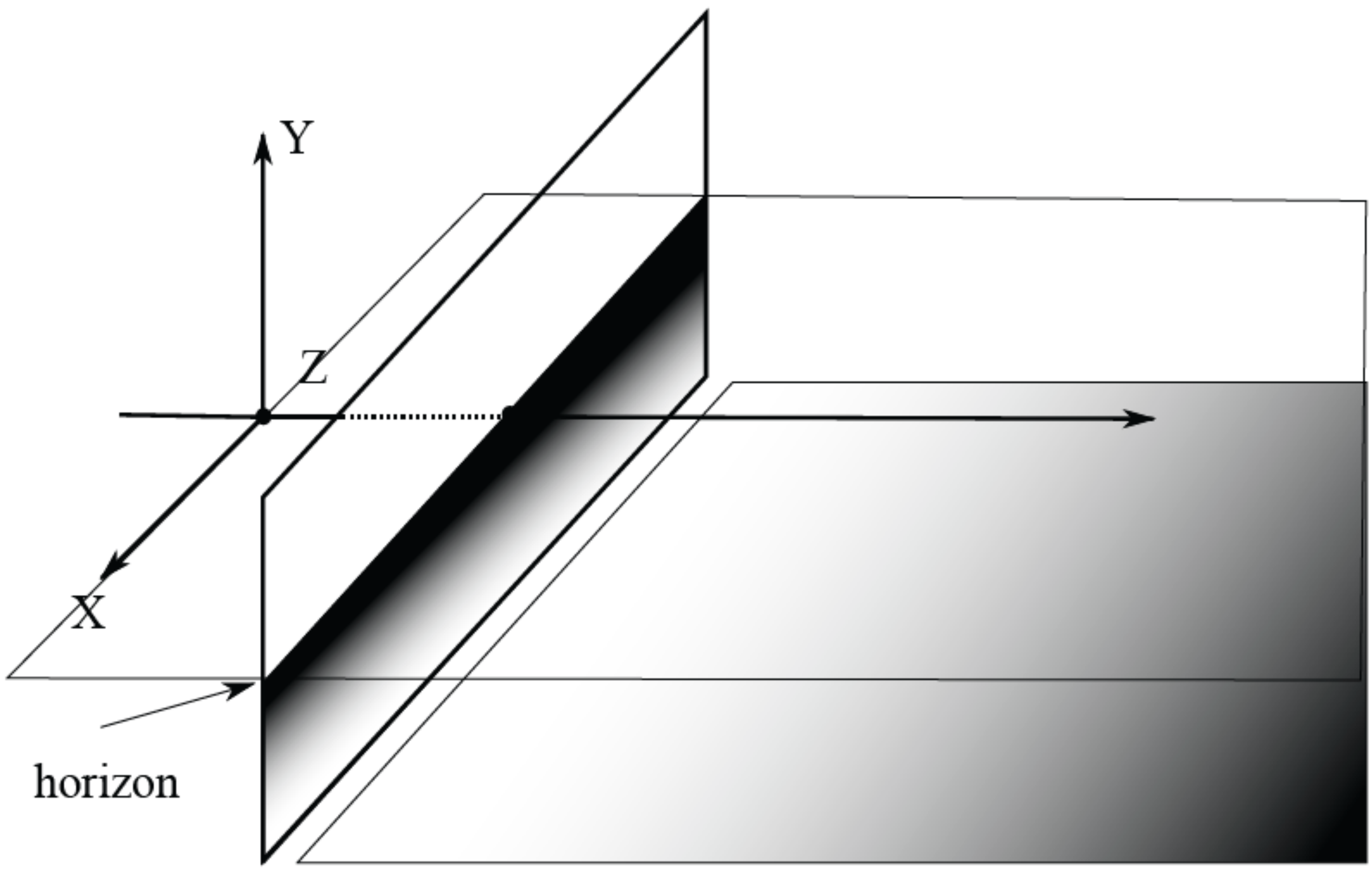
Lines that are parallel in 3D meet in the image



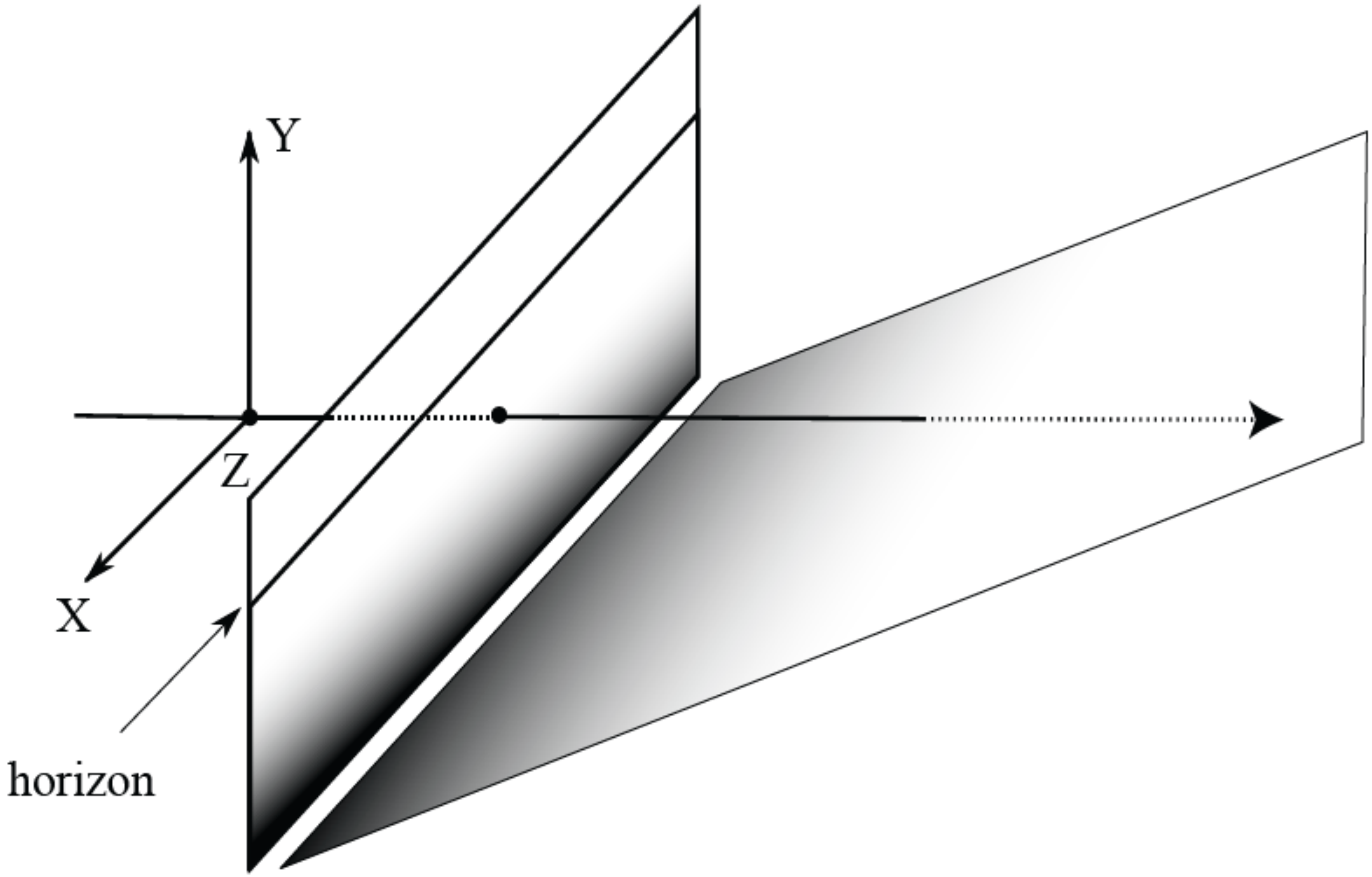
Lines that are parallel in 3D meet in the image



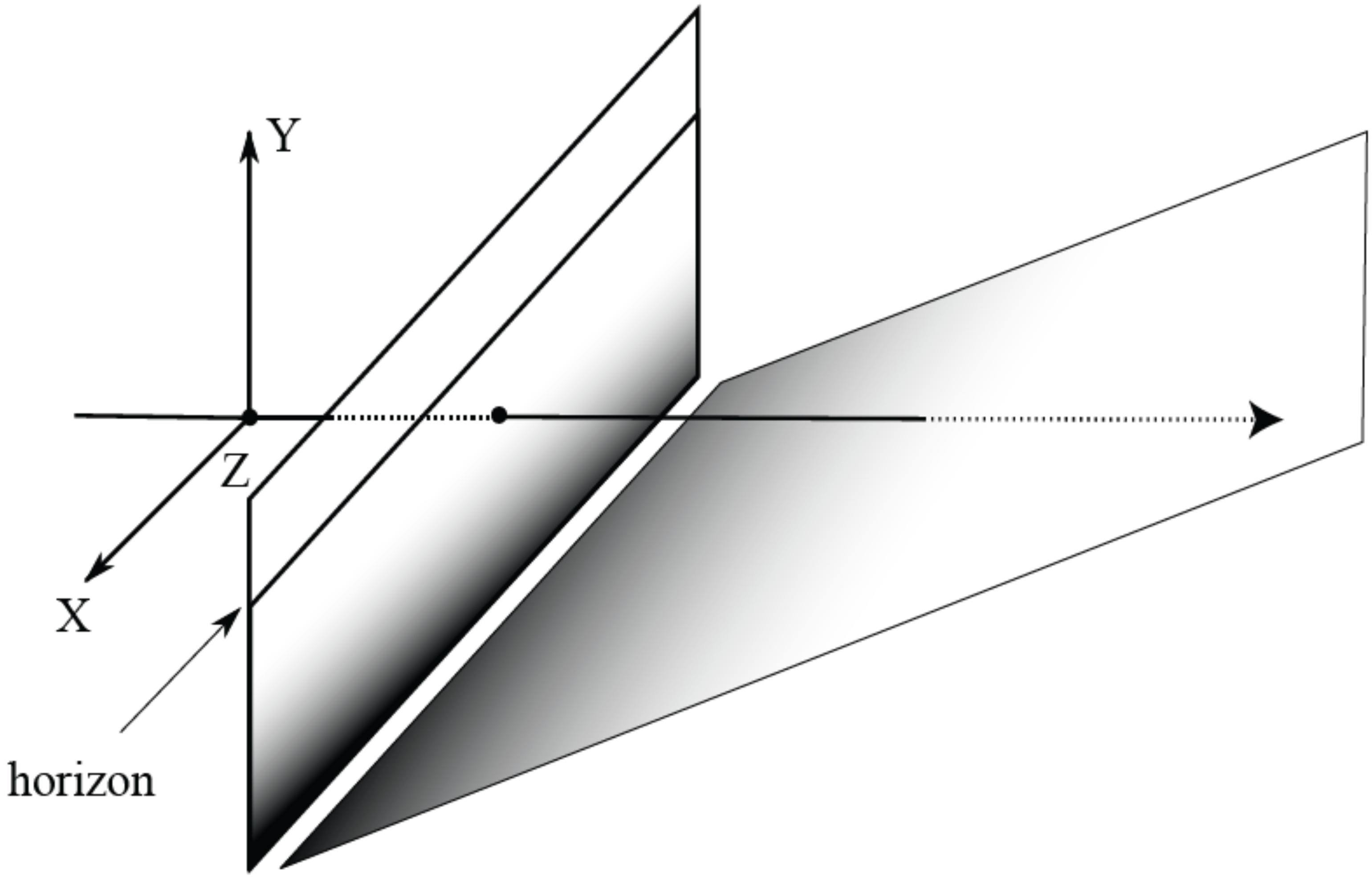
Planes have horizons



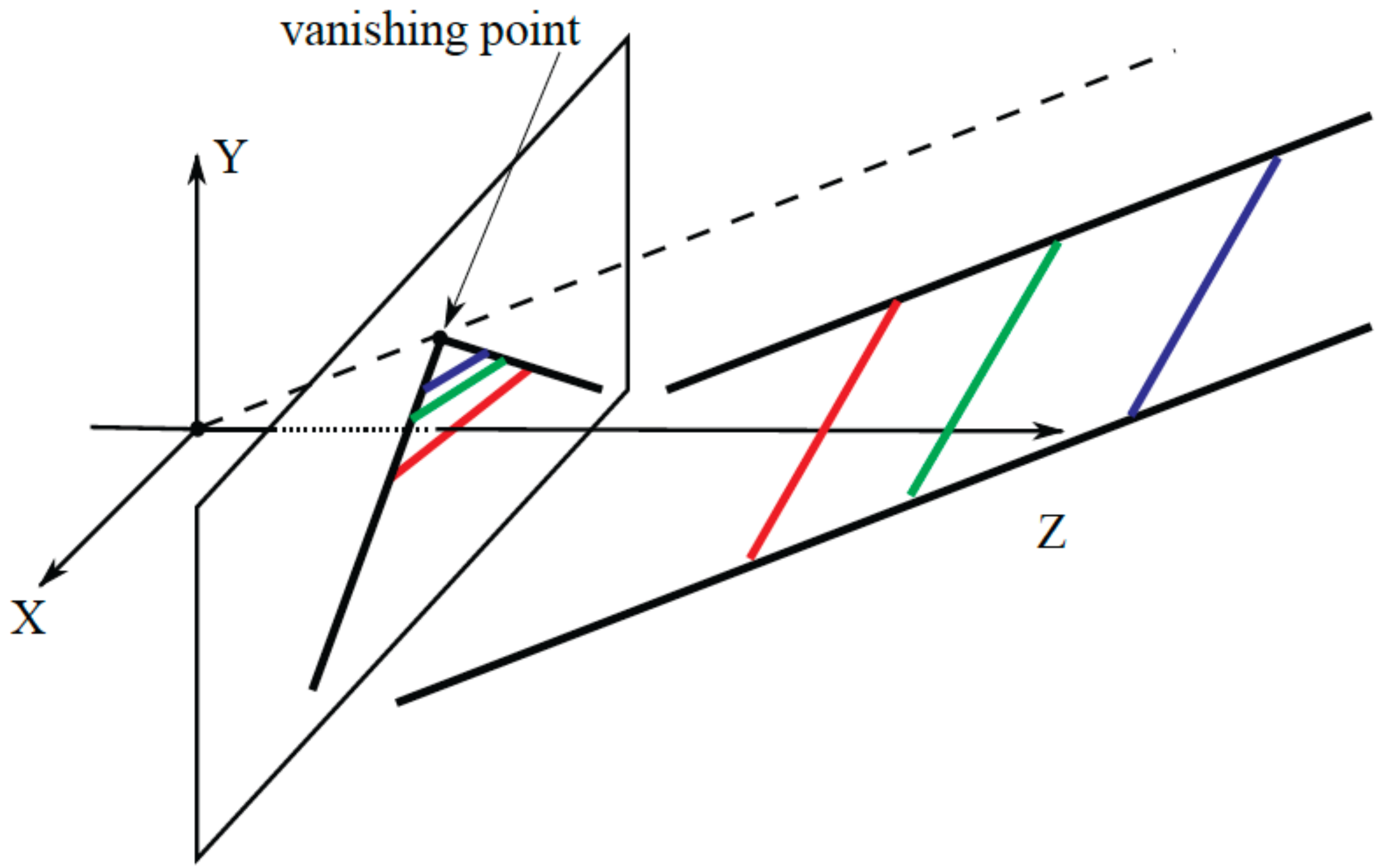
Planes have horizons



On a plane, closer to horizon is further away



Shapes are foreshortened



Spot the property!

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

Scaled orthographic projection

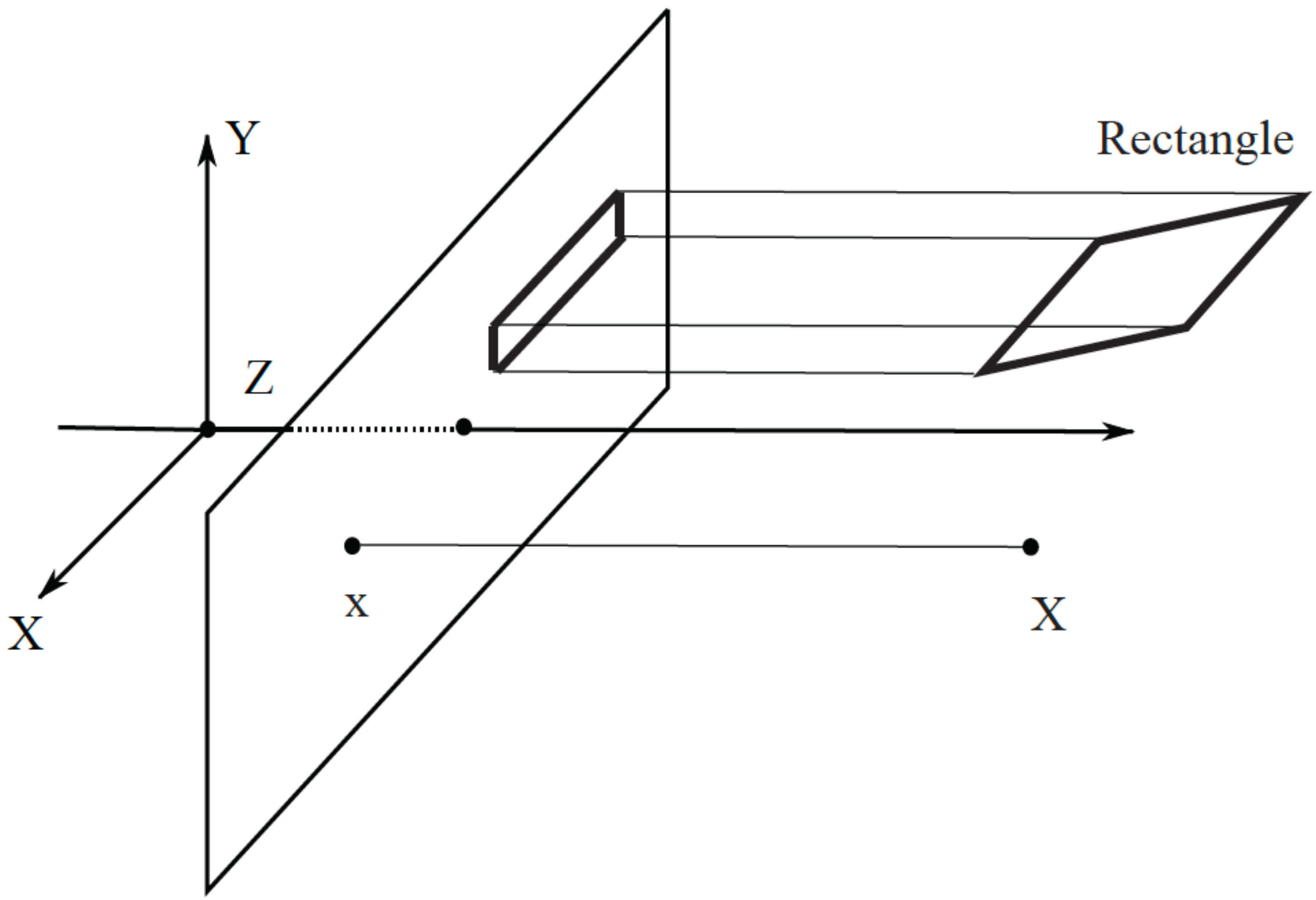
Under some circumstances, perspective projection can be simplified. Assume the camera views a set of points which are close to one another compared with the distance to the camera. Write $\mathbf{X}_i = (X_i, Y_i, Z_i)$ for the i'th point, and assume that $Z_i = Z(1+\epsilon_i)$, where ϵ_i is quite small. In this case, the distance to the set of points is much larger than the *relief* of the points, which is the distance from nearest to furthest point. The i'th point projects to $(fX_i/Z_i, fY_i/Z_i)$, which is approximately $(f(X_i/Z)(1-\epsilon_i), f(Y_i/Z)(1-\epsilon_i))$. Ignoring ϵ_i because it is small, we have the projection model

$$(X, Y, Z) \to (f/Z)(X, Y) = s(X, Y).$$

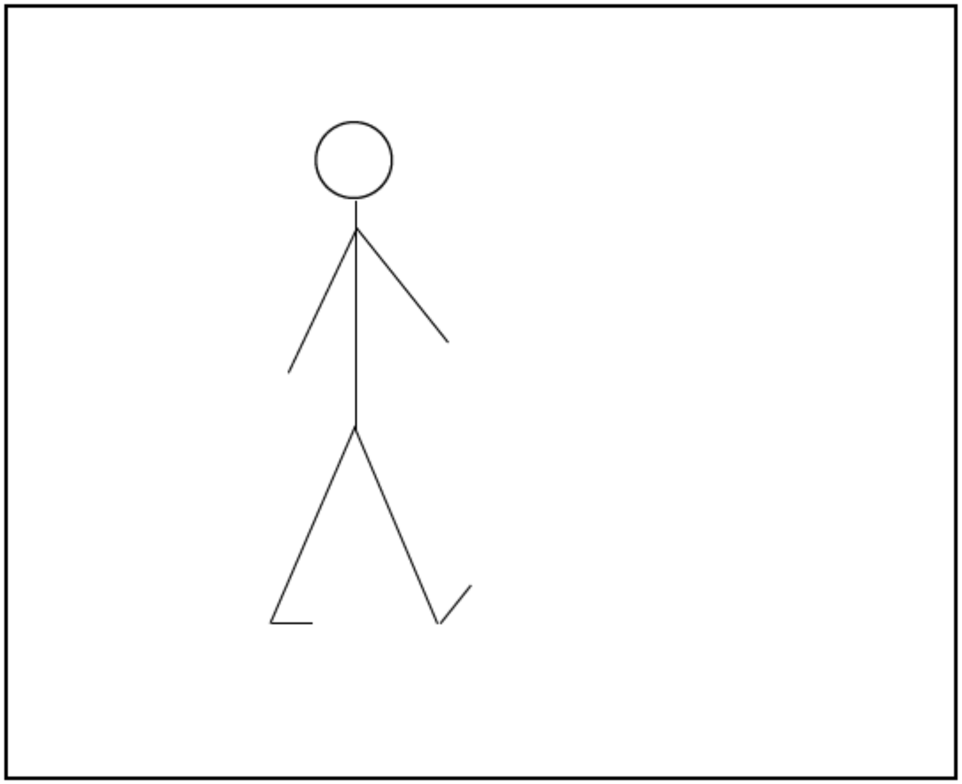
This model is usually known as *scaled orthograpic projection*. A geometric view of this model is that points in 3D "slide" down rays perpendicular to the image plane

to form their image (Figure 26.8). It is an exercise to show that parallel lines do not have vanishing points and that planes do not have horizons in scaled orthographic cameras. However, scaled orthographic cameras *do* foreshorten shapes, as Figure 26.8 and the exercises show.

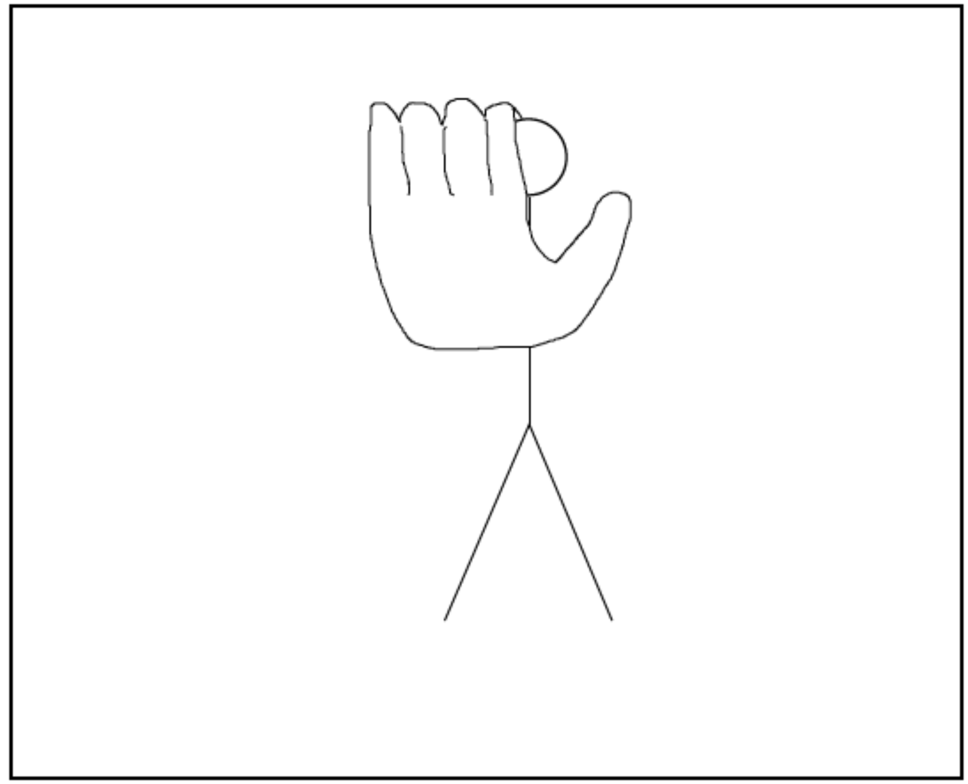
Scaled orthographic projection



Scaled orthographic projection in pictures of people



Likely SOP



Clearly perspective

Why cameras have lenses

The pinhole is small, so relatively little light gets in (dark image)

Bigger pinhole -> brighter but fuzzier image

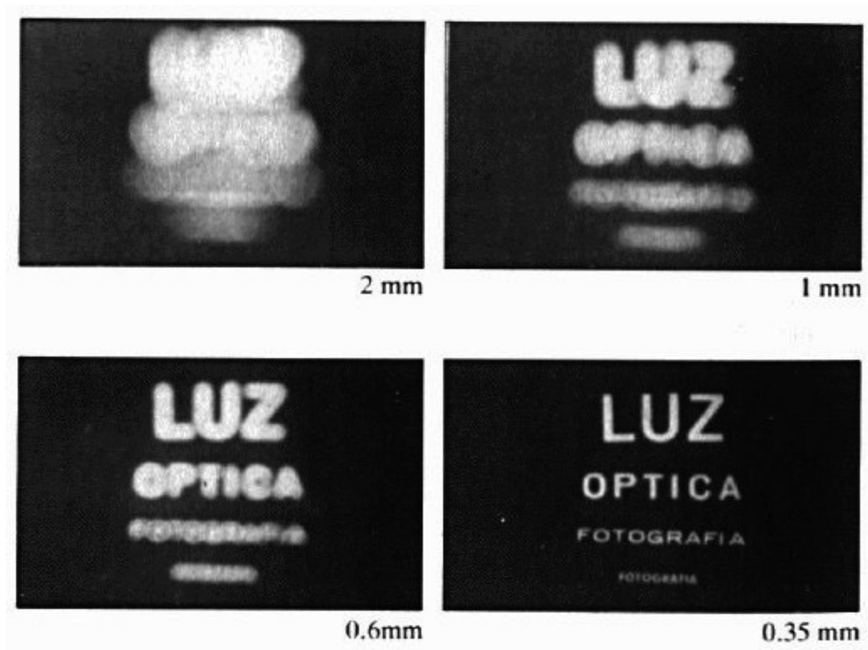
A lens system collects more light, but discourages fuzziness

Home-made pinhole camera

What is wrong with this image?

Source: P. Debevec via A. Efros

Shrinking the aperture

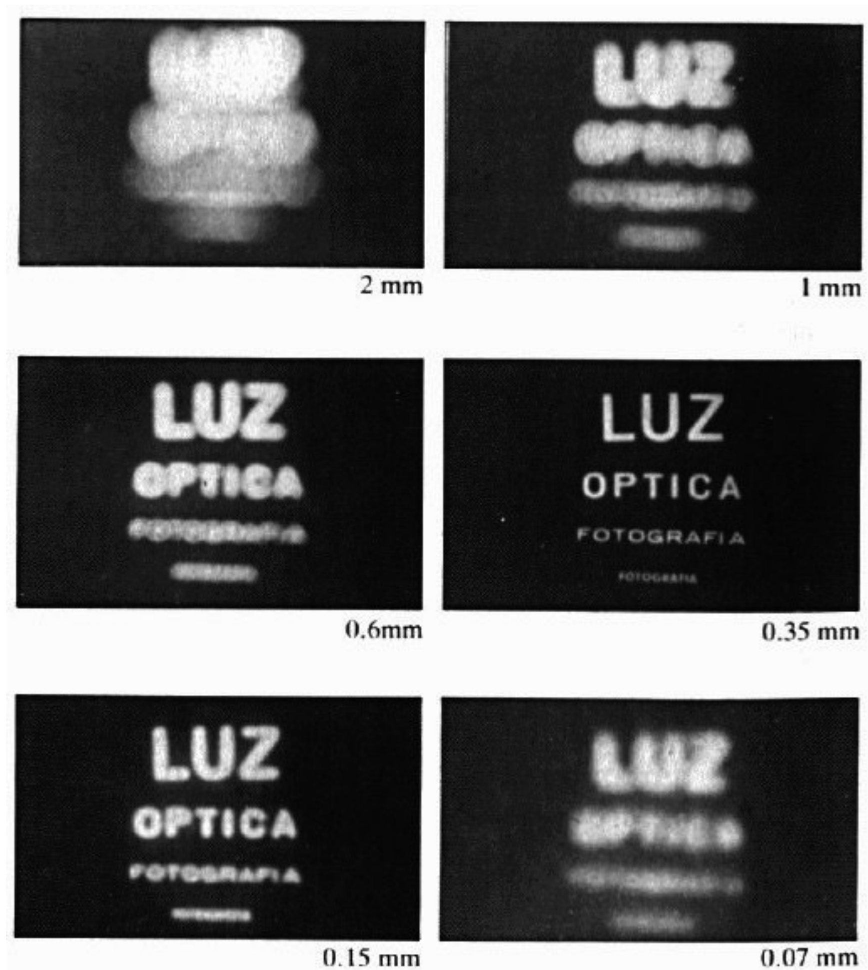


Why not make the aperture as small as possible?

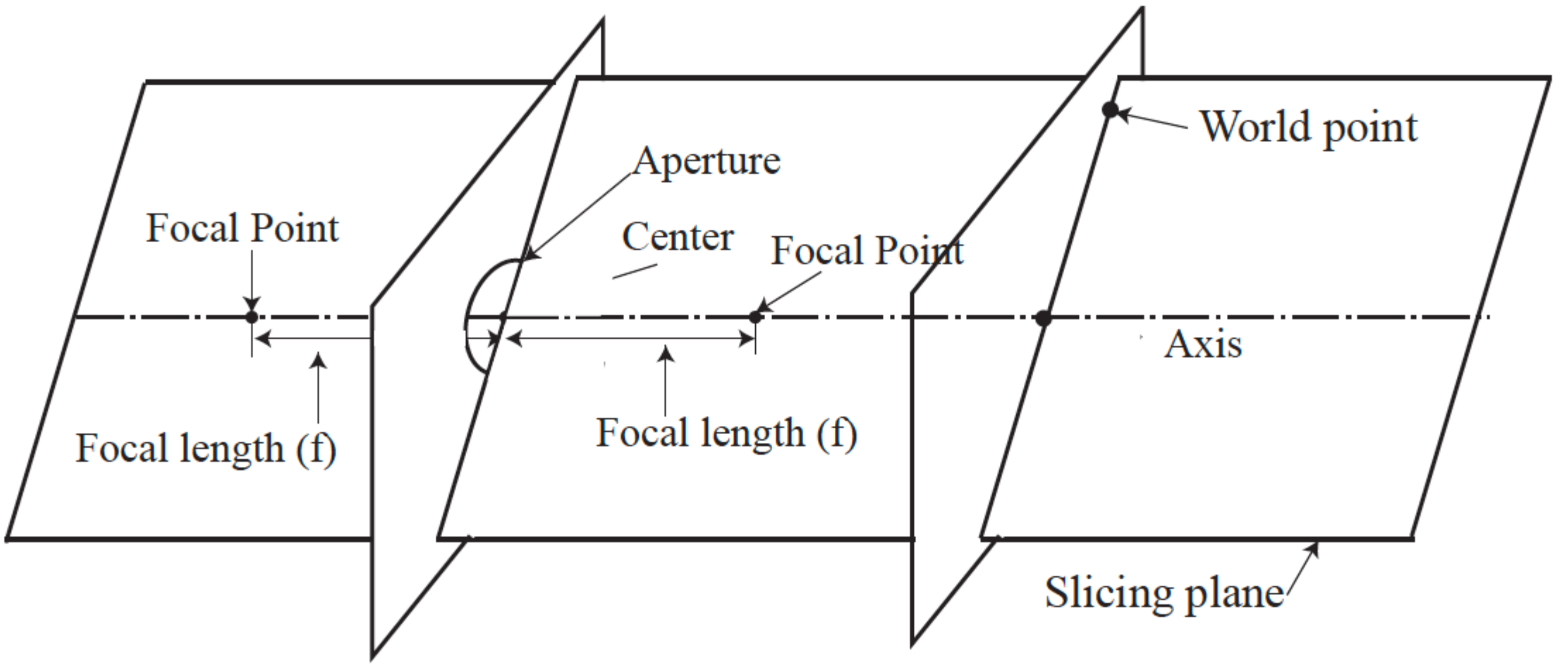
- Less light gets through
- Diffraction!

Slide by Steve Seitz

Shrinking the aperture



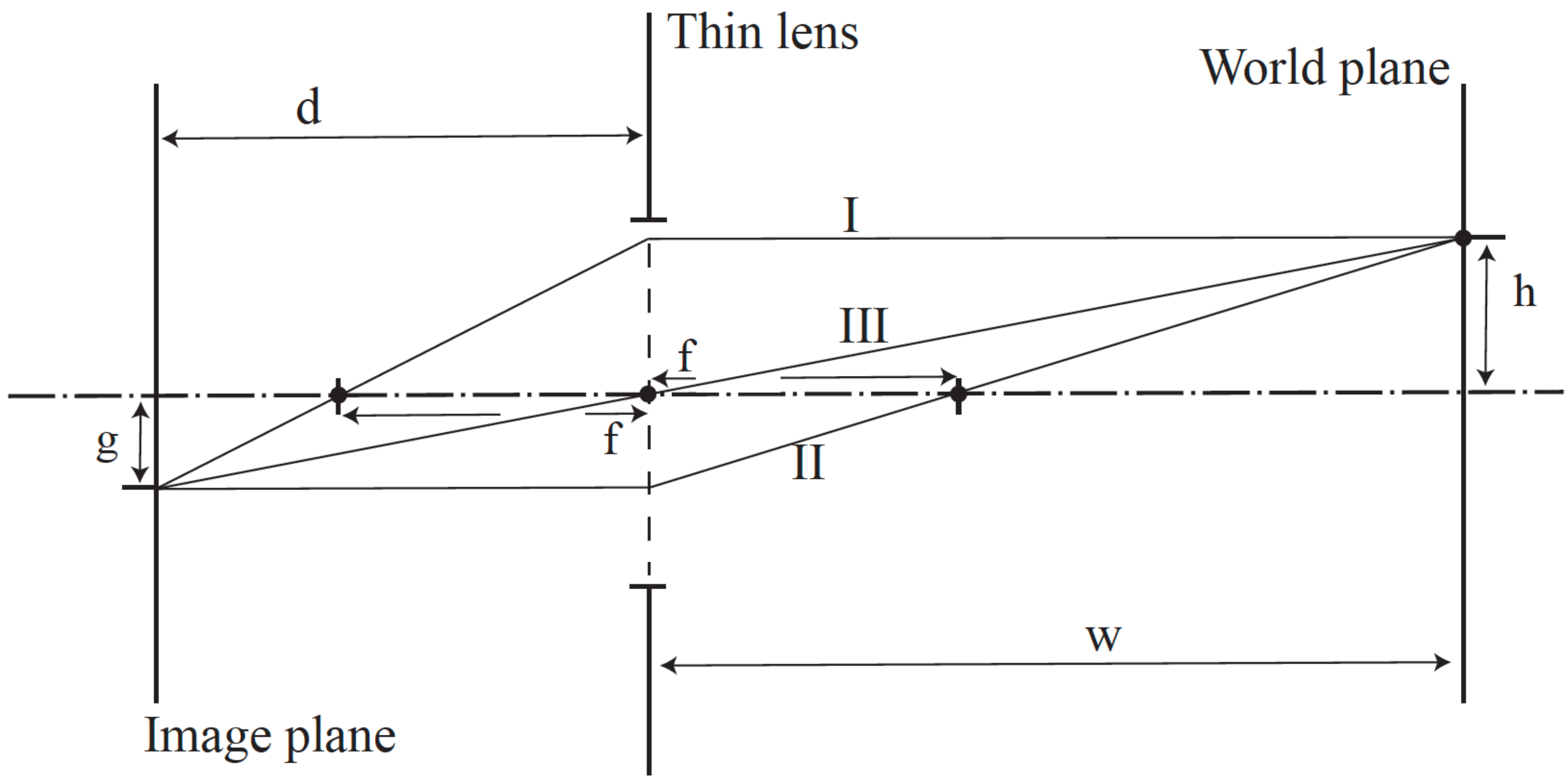
Lens model – rotational symmetry



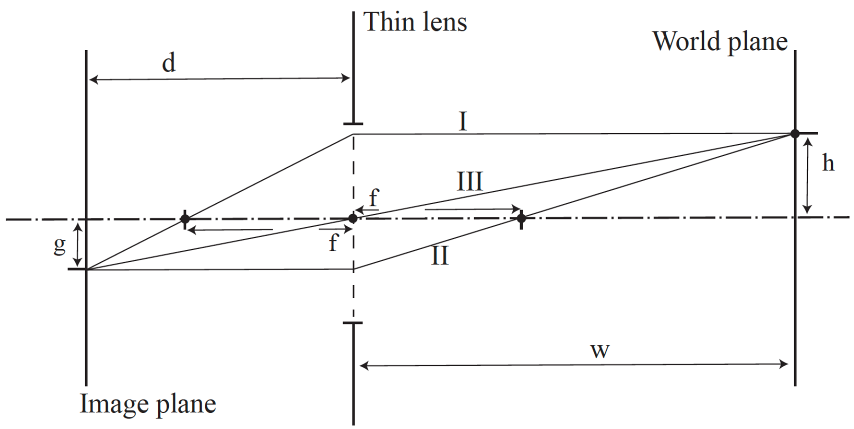
A lens focuses light onto the film

- Thin lens model:

A thin lens, 2D drawing



A thin lens, 2D drawing

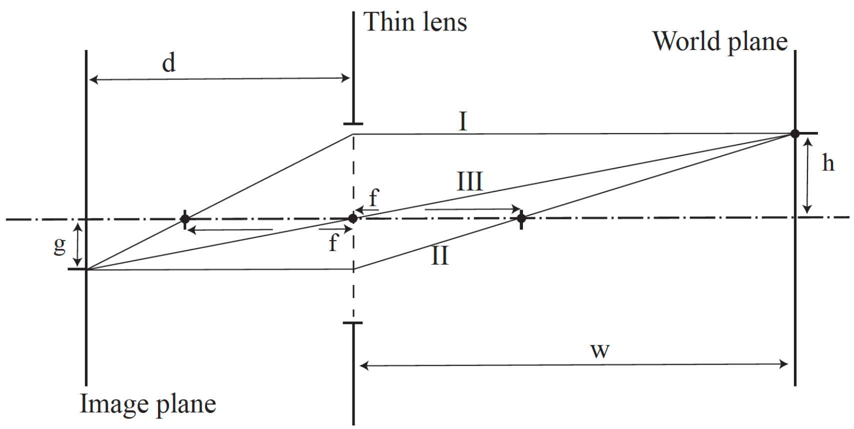


Properties:

- Ray arriving perp to lens plane passes through fp (I)
- Ray arriving through fp leaves perp to lens (II)
- Ray through lens center is unrefracted (III)

You can show: $1/f=1/w+1/d$

A thin lens, 2D drawing

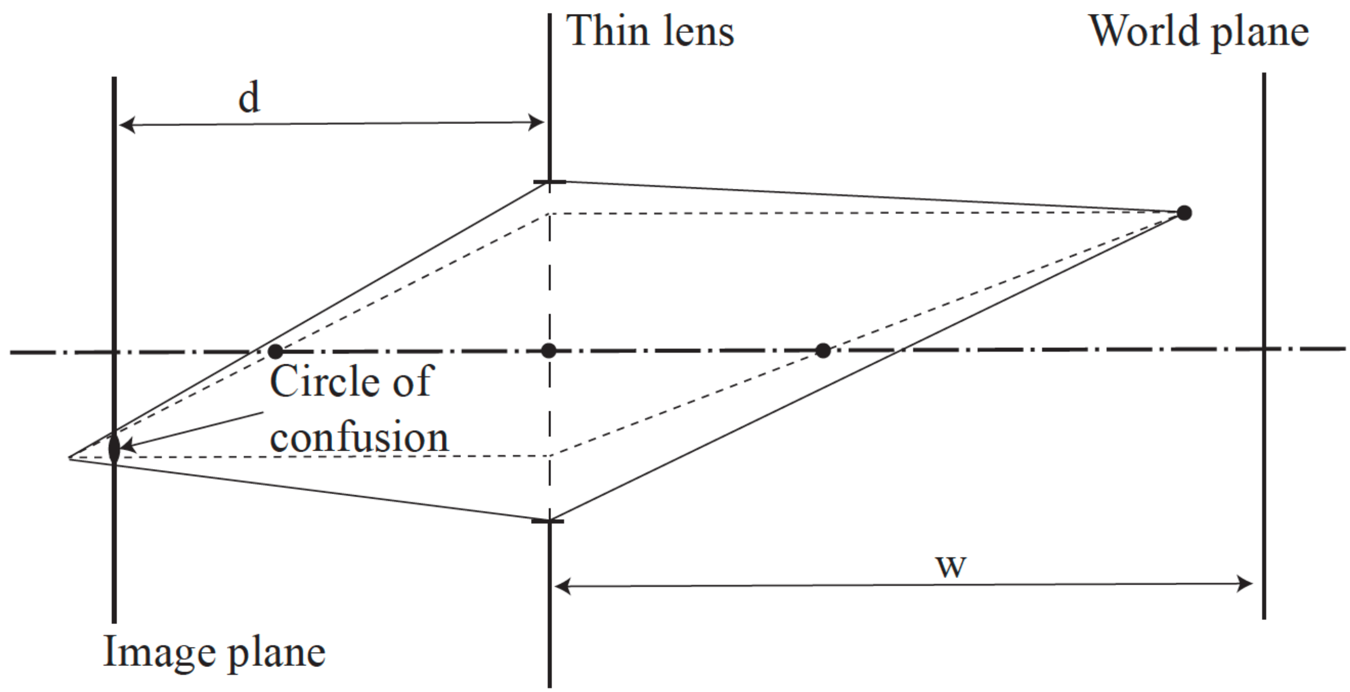


Properties:

Previous slide identifies where rays leaving a world point focus

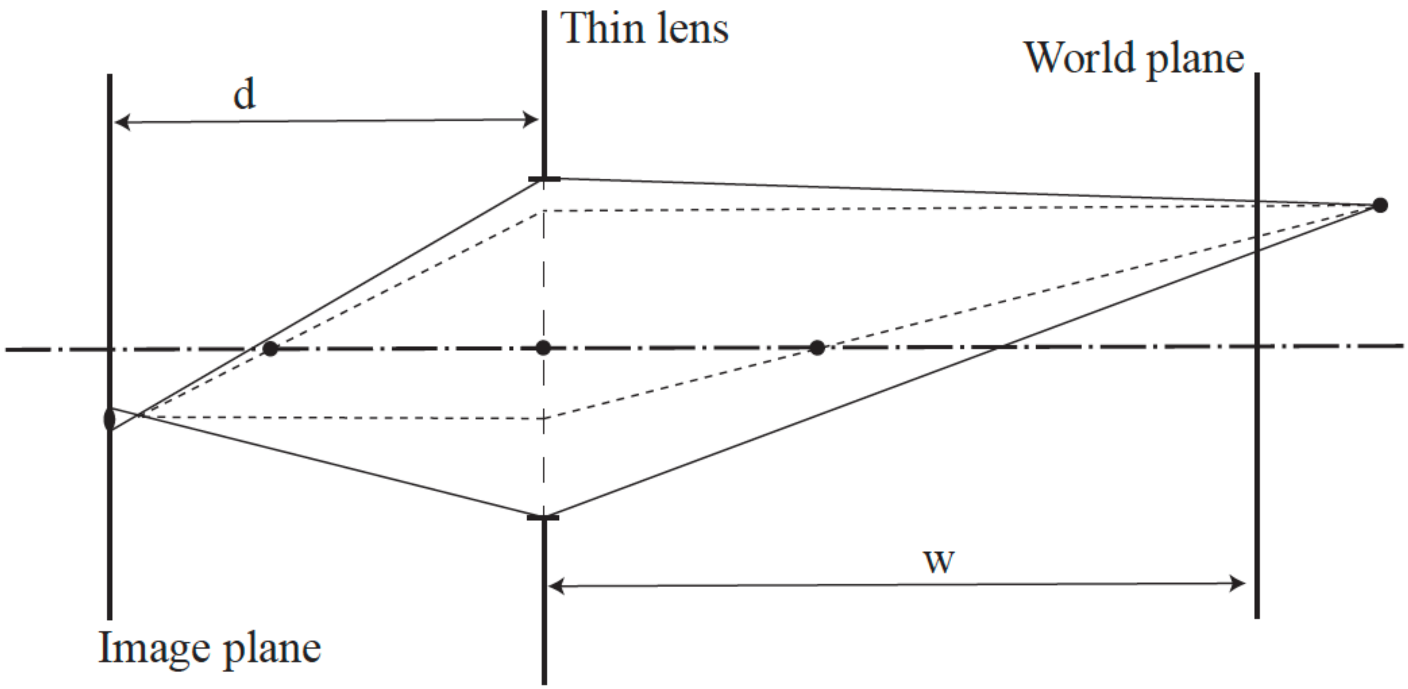
All other rays leaving world point and arriving at lens aperture focus on same point

A thin lens – world point too close



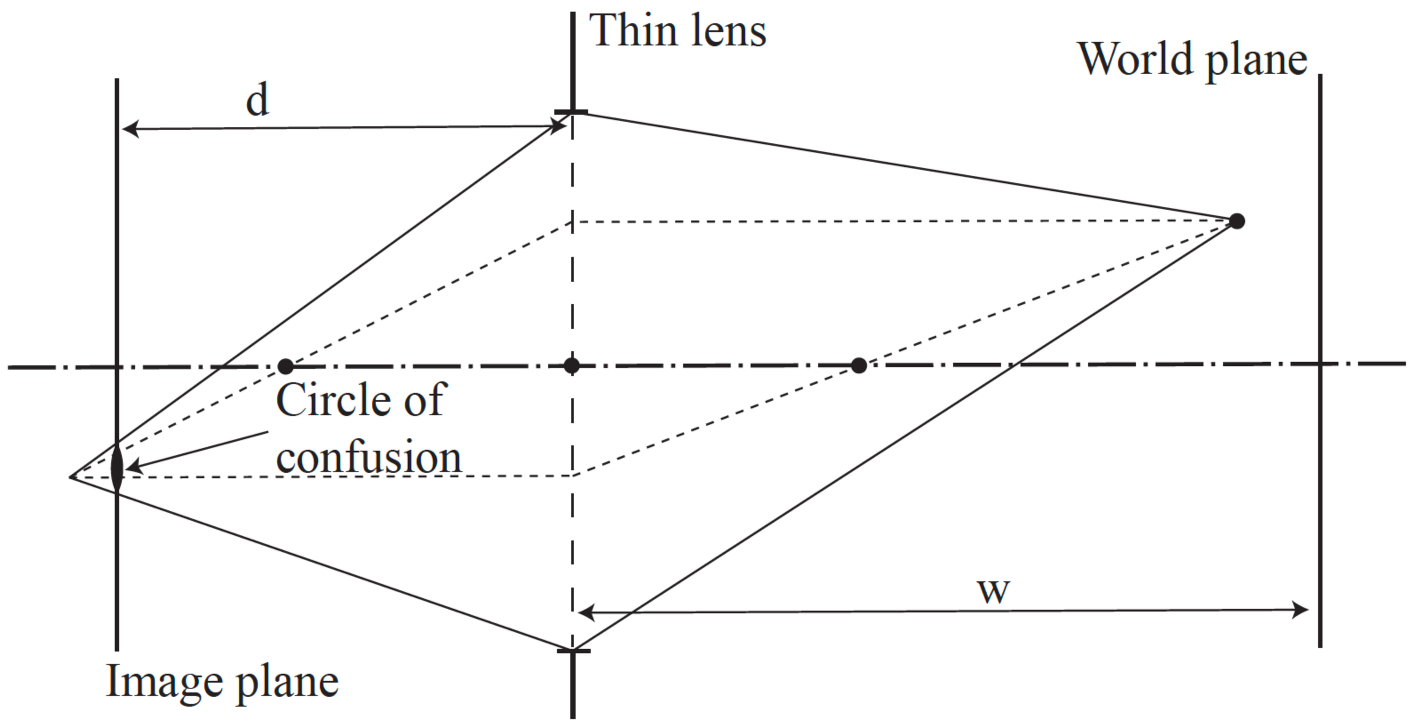
Rays focus slightly behind image plane, constructing a circle of confusion on image plane

A thin lens – world point too far



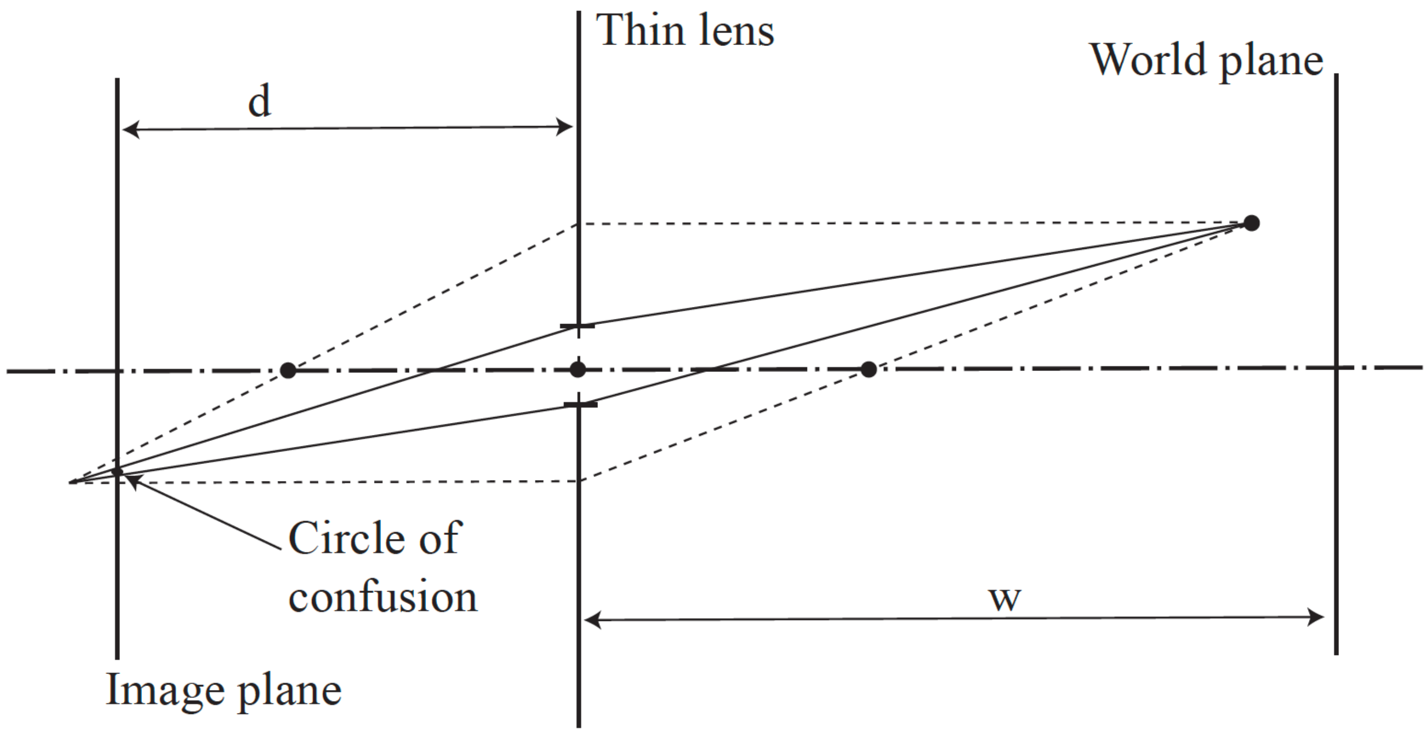
Rays focus slightly in front of image plane, constructing a circle of confusion on image plane

The aperture of the lens



Bigger aperture -> bigger circle of confusion for point at fixed location

The aperture of the lens



Smaller aperture -> Smaller circle of confusion for point at fixed locati

The aperture of the lens

Smaller aperture -> Smaller circle of confusion for point at fixed location

Bigger aperture -> bigger circle of confusion for point at fixed location

Depth of field:

range of depths around focal plane where circle of confusion < threshold

(i.e. points in focus)

Alternatively:

Bigger aperture: collects more light but smaller depth of field

Smaller aperture: collects less light, but larger depth of field

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)

Varying the aperture

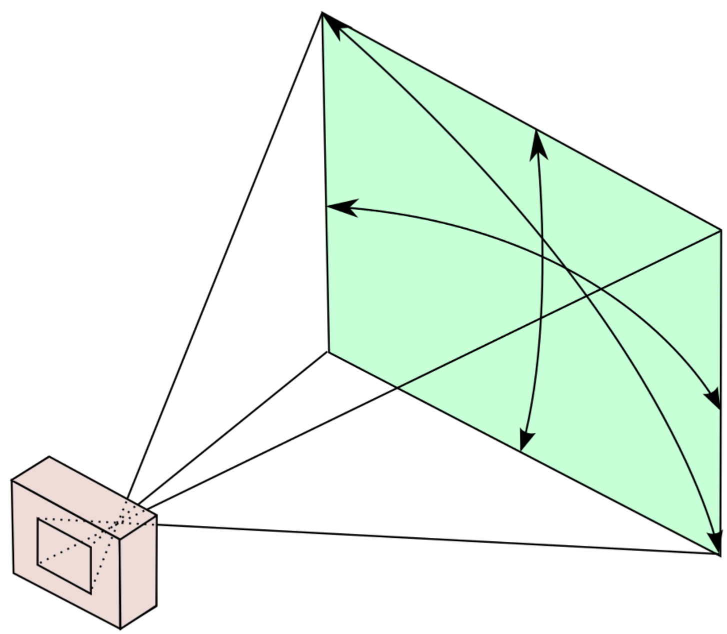
Large aperture = small DOF

Small aperture = large DOF

Slide by A. Efros

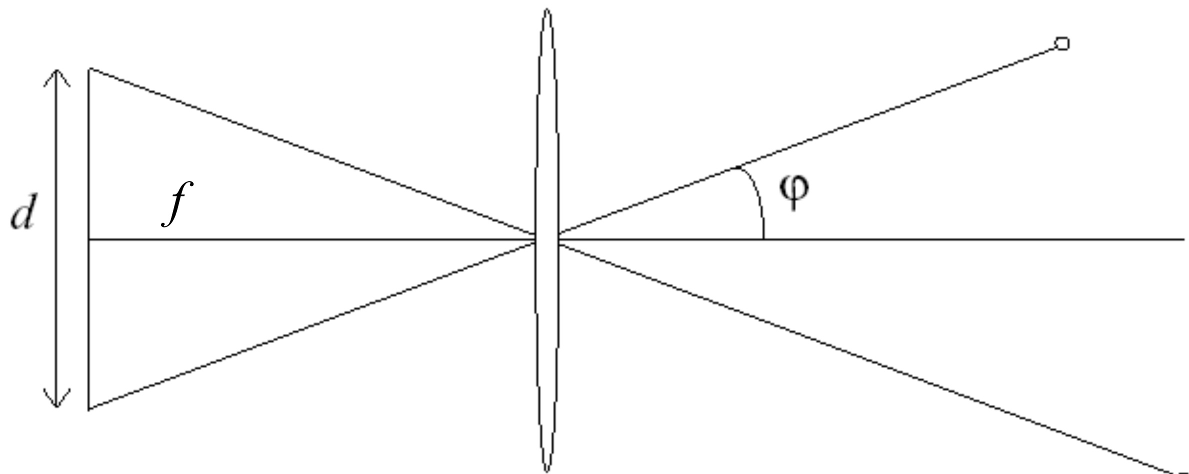
Field of view

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



Field of view

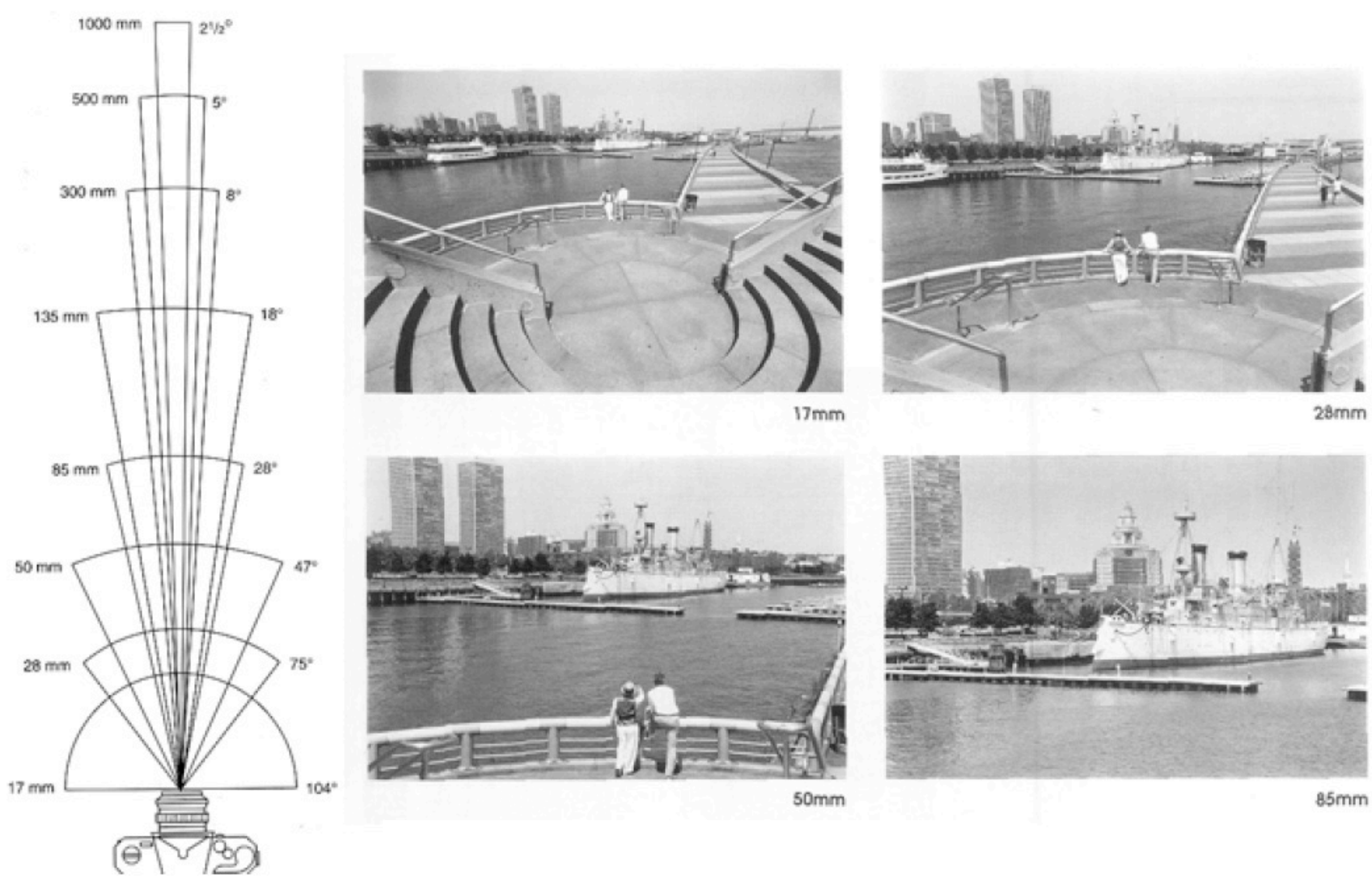
- The field of view is the angular extent of the world observed by the camera (Wikipedia)
- What determines the FOV?
  - Focal length (f), length of the sensor (d):



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

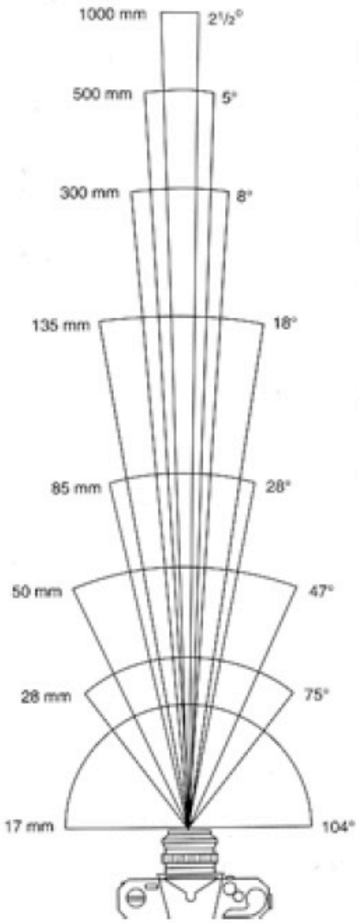
  - Larger focal length = smaller FOV

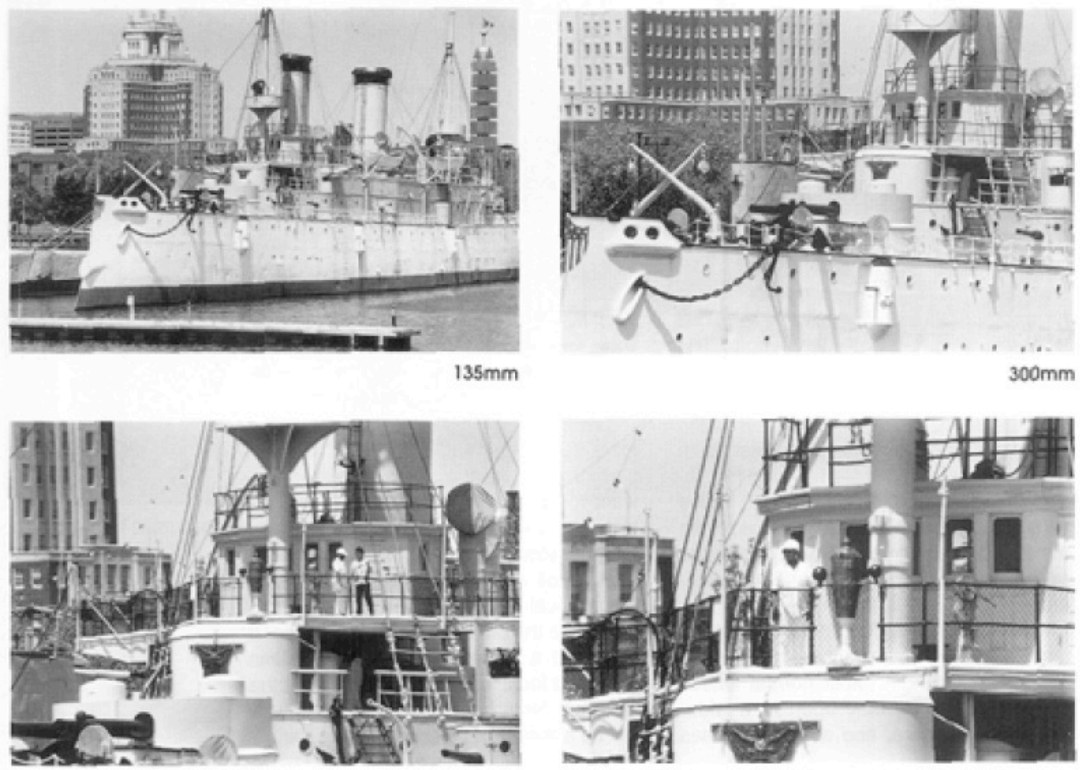
Field of view



Slide by A. Efros

Field of view



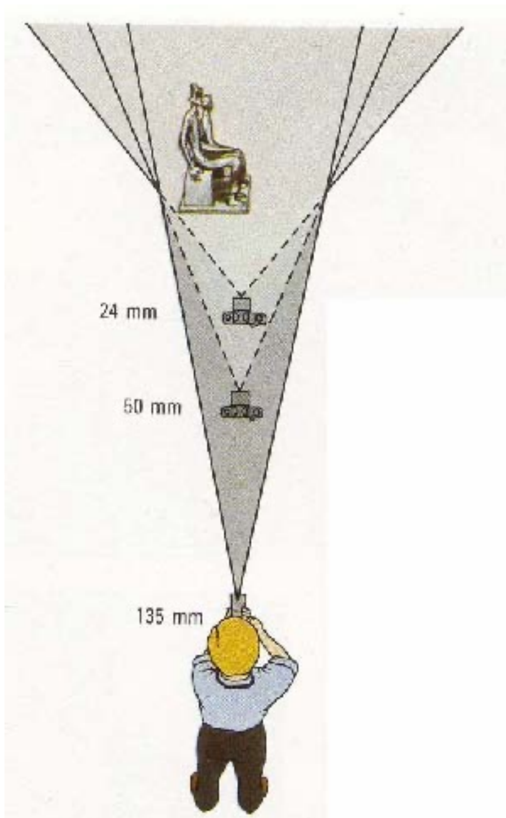


135mm

300mm

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

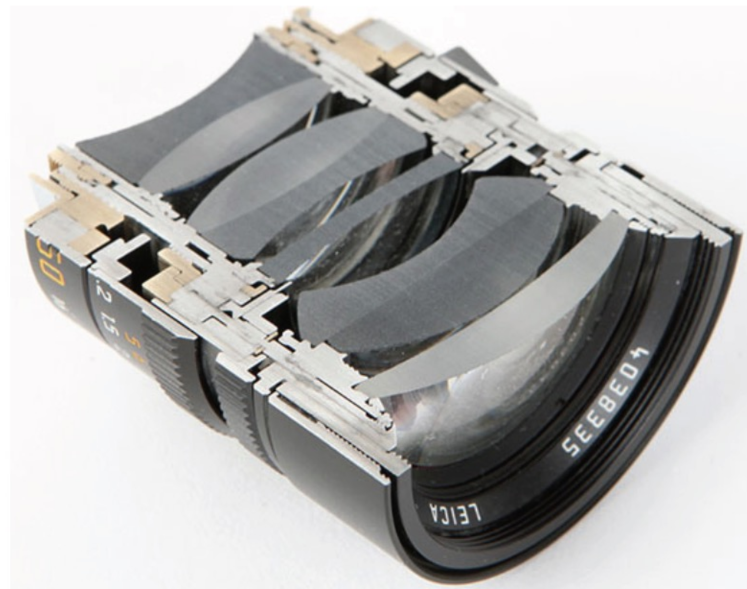
wide-angle

standard

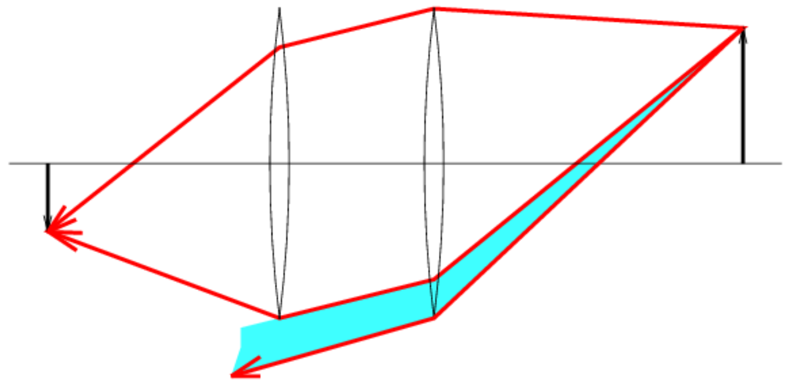
telephoto

Source: F. Durand

Real lenses

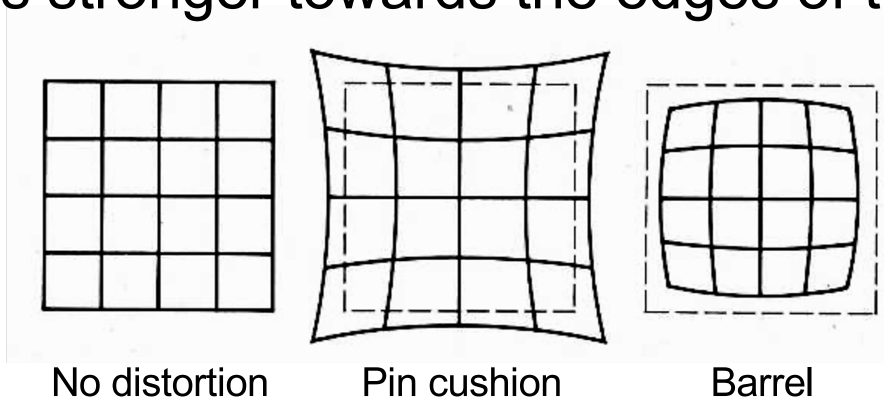


Lens flaws: Vignetting



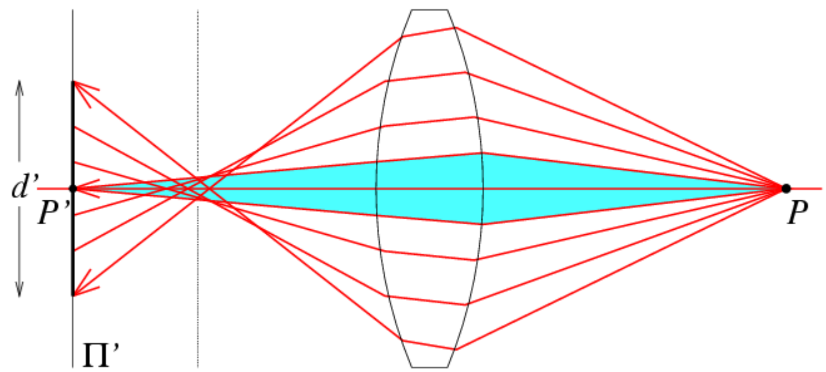
Lens flaws: Radial distortion

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



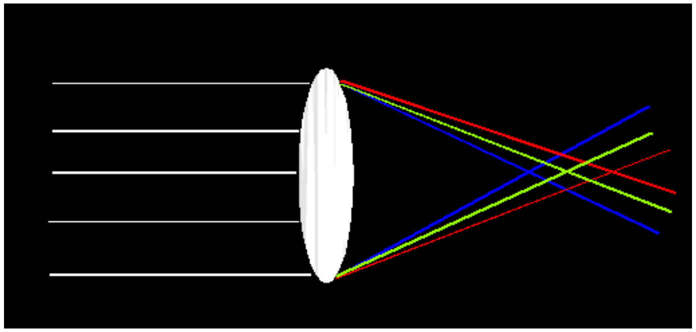
Lens flaws: Spherical aberration

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



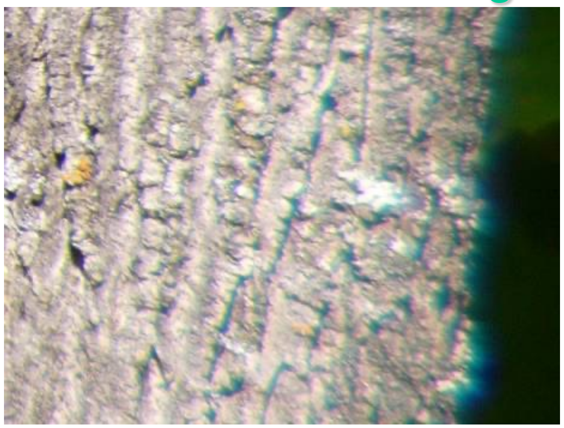
Lens flaws: Chromatic aberration

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

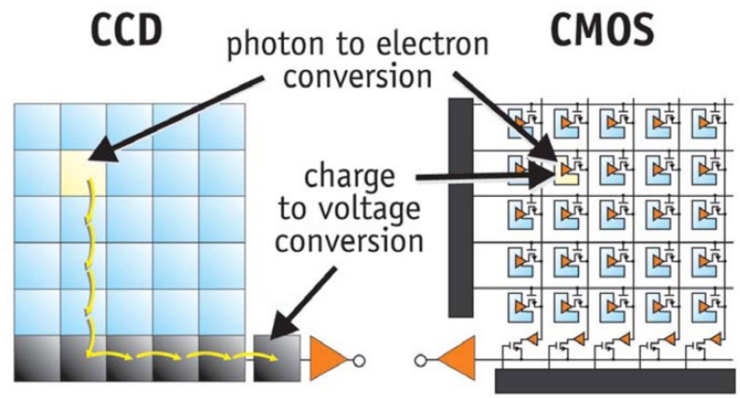


Near Lens Center

Near Lens Outer Edge



Digital camera sensors



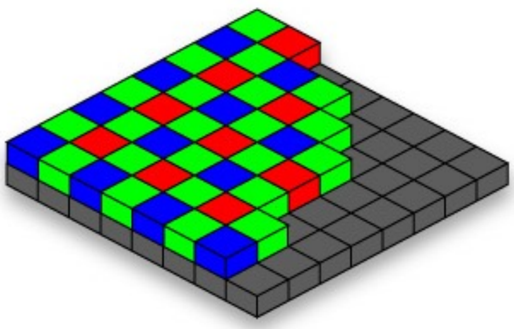
CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node. CMOS imagers convert charge to voltage inside each pixel.

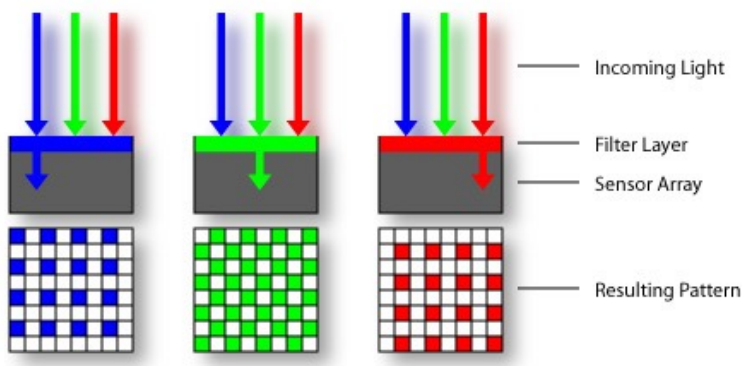
- Each cell in a sensor array is a light-sensitive diode that converts photons to electrons
  - Dominant in the past: **Charge Coupled Device (CCD)**
  - Dominant now: **Complementary Metal Oxide Semiconductor (CMOS)**

http://electronics360.globalspec.com/article/9464/ccd-vs-cmos-the-shift-in-image-sensor-technology

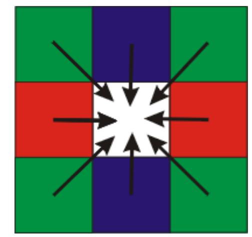
Color filter arrays

Bayer grid (1976)

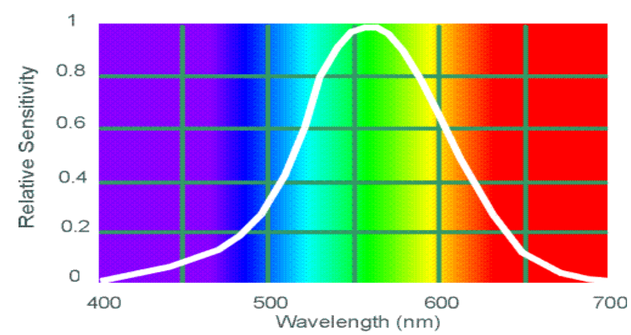




Demosaicing:
Estimation of missing components from neighboring values



Why more green?

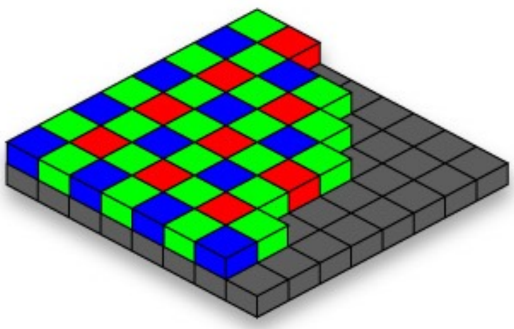


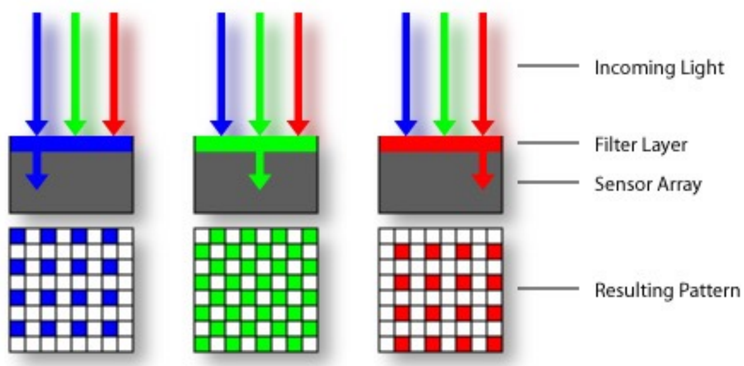
Human Luminance Sensitivity Function

Source: Steve Seitz

Color filter arrays

Bayer grid (1976)





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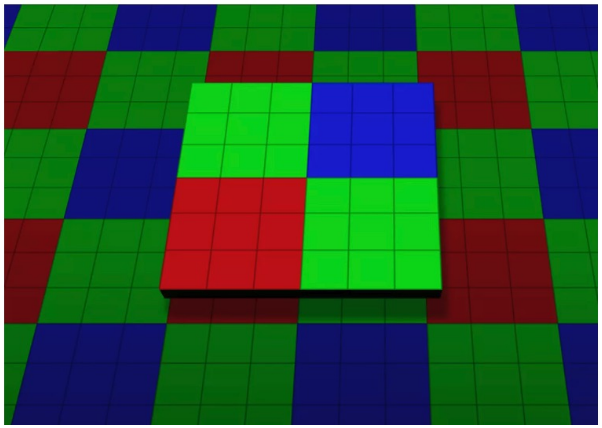


Recent cameraphone technology: pixel binning

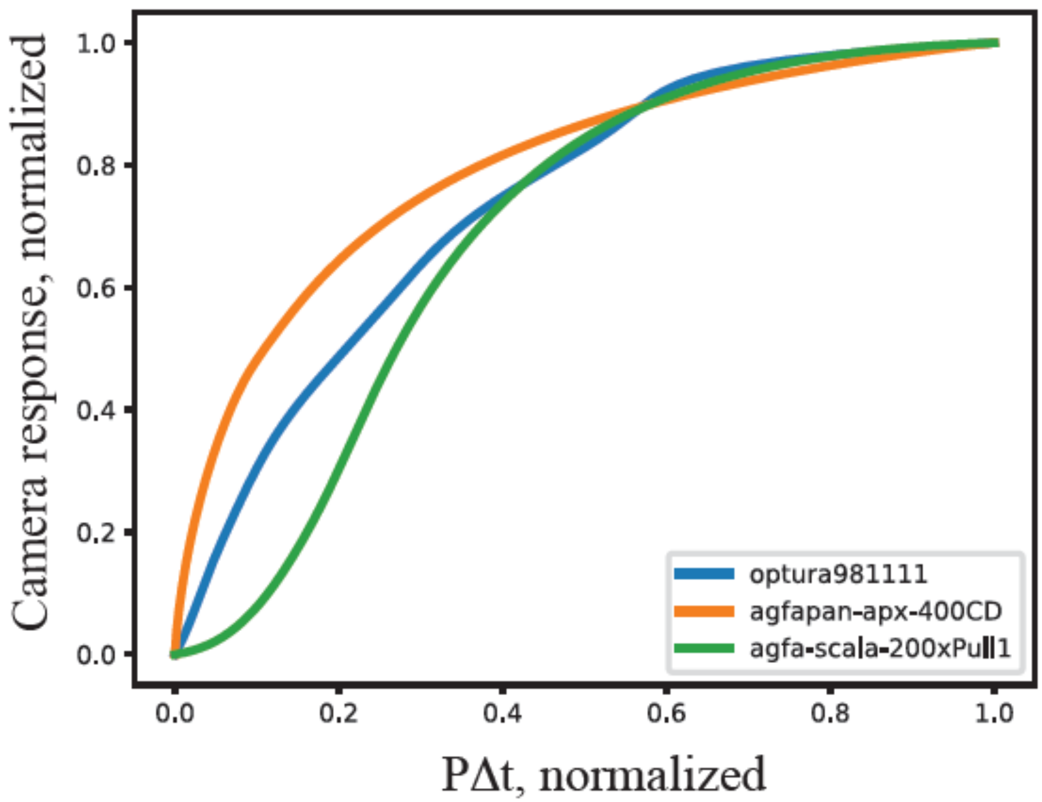
Camera response functions

Camera sensors are almost always linear BUT
image dynamic range is too big for 8 bits

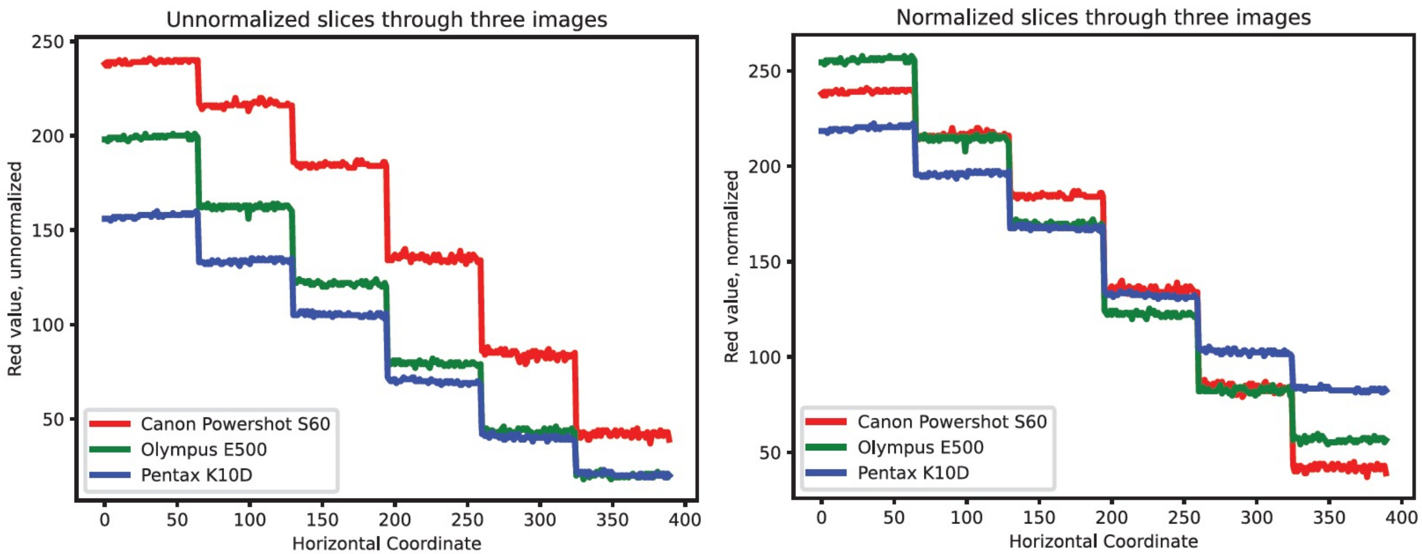
Typical cameras apply a non-linearity before or during digitization – the camera response function

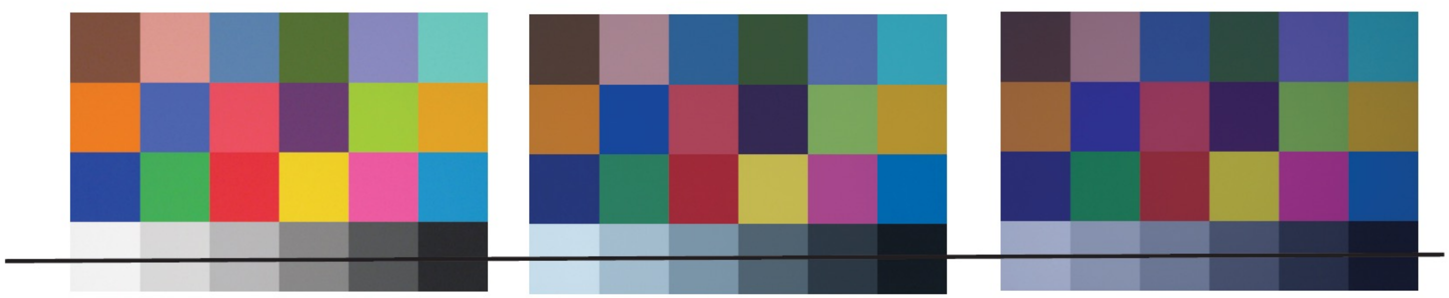
This varies from camera to camera

Camera response functions



Camera response functions – simulated images





Canon Powershot S60 Olympus E500 Pentax K10D

Misc. digital camera artifacts

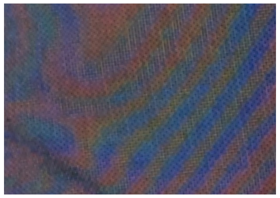
Noise
- low light is where you most notice noise
- light sensitivity (ISO) / noise tradeoff
- stuck pixels

In-camera processing
- oversharpening can produce halos

Compression
- JPEG artifacts, blocking

Blooming
- CCD charge overflowing into neighboring pixels

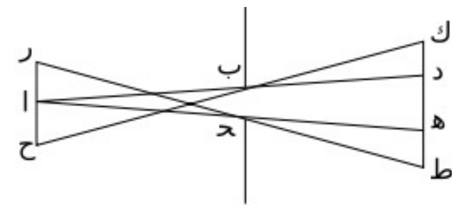
Color artifacts
- Color moire
- Purple fringing from microlenses



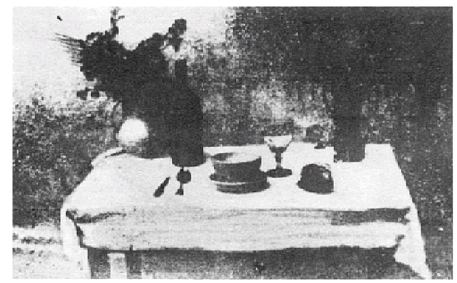
Historic milestones

- **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)
- **Daguerréotypes** (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

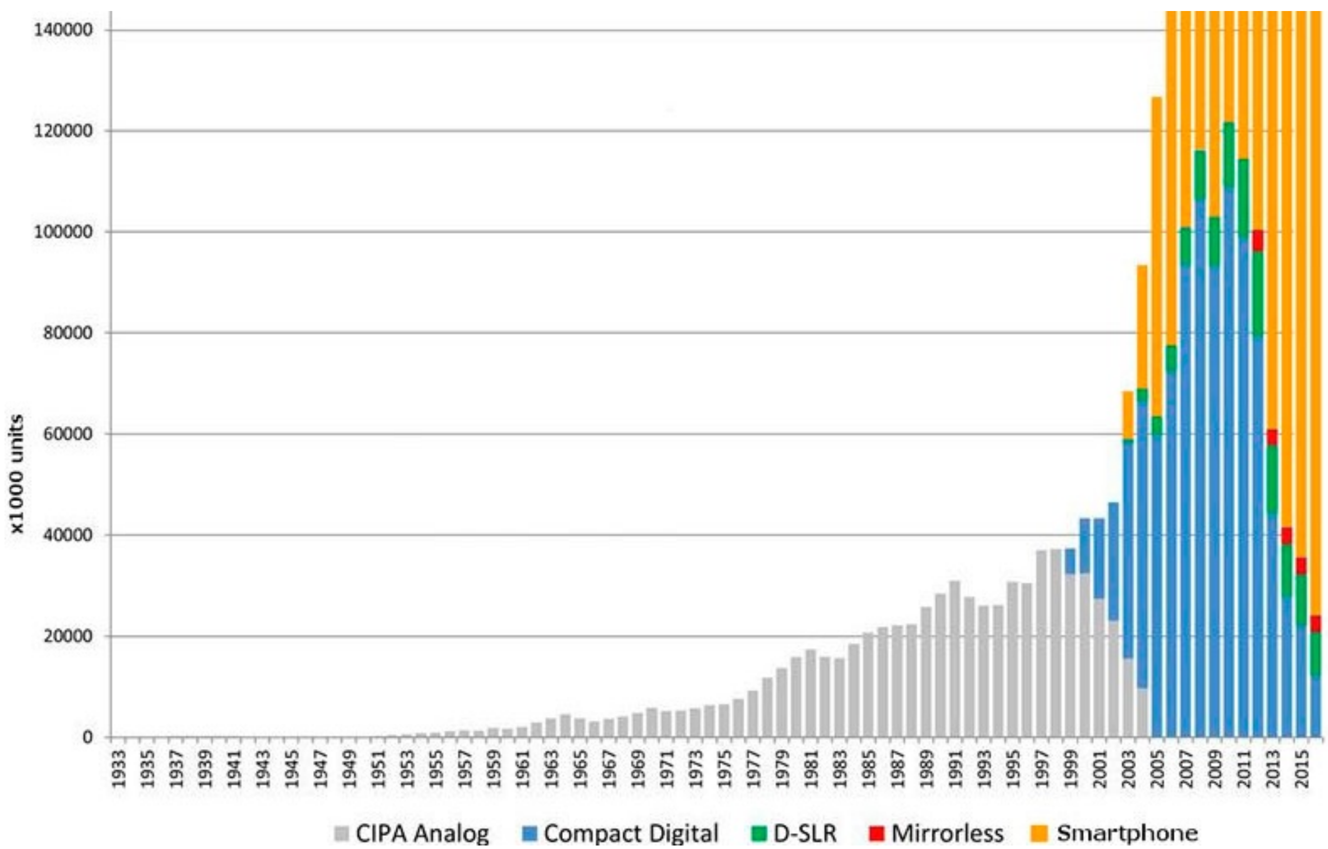

Old television camera

First digitally scanned photograph

- NIST (1957), 176x176 pixels

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

Camera sales over time



Source

Camera sales over time

The full chart…

[Source]