Image formation

Subhransu Maji

CMPSCI 670: Computer Vision

September 13, 2016

Administrivia and survey results

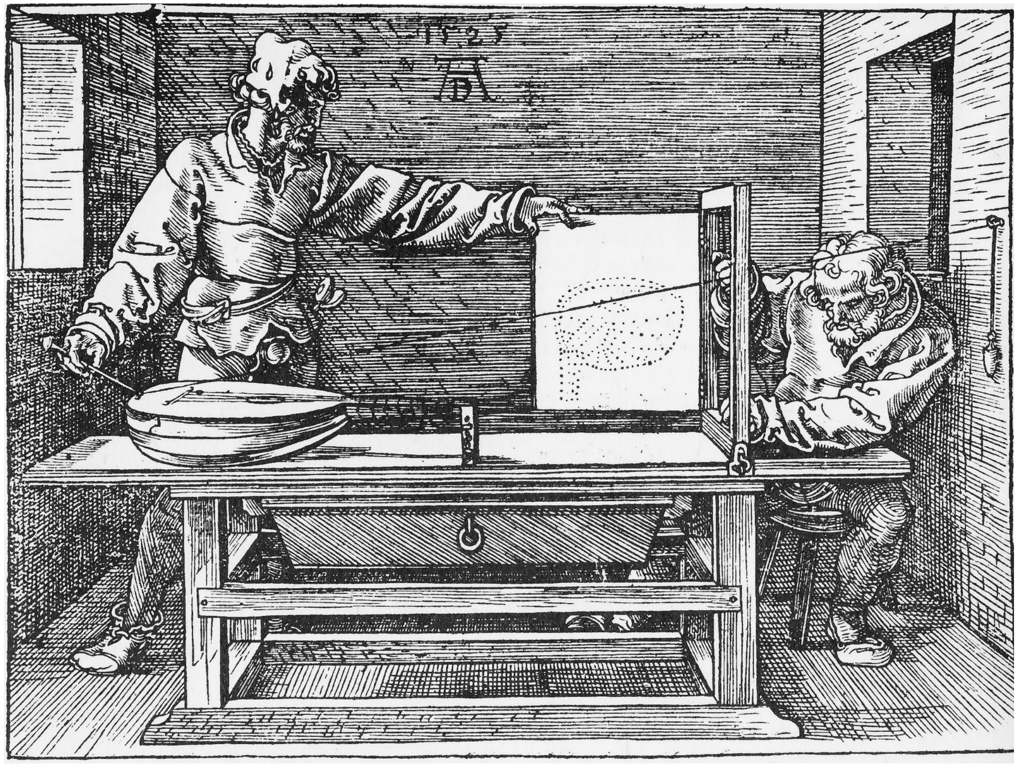
- Topics:
  - deep learning, CNNs, machine learning, AI
  - **Applications:** self driving cars, face detection/recognition, etc
  - robotics, calibration, structure from motion
  - graphics, text/natural language processing, speech,
- Goals:
  - Learn fundamentals of CV/ML/image processing
  - Do a supercool project
  - Get an awesome industry job (e.g., space exploration @ NASA)
- **Programming:** 7.5 - 8.5, **Math:** 6.5 - 7.5

- **Spire:** waitlisted students? there are a few more open slots
- Resources for vector algebra and probability added to the webpage

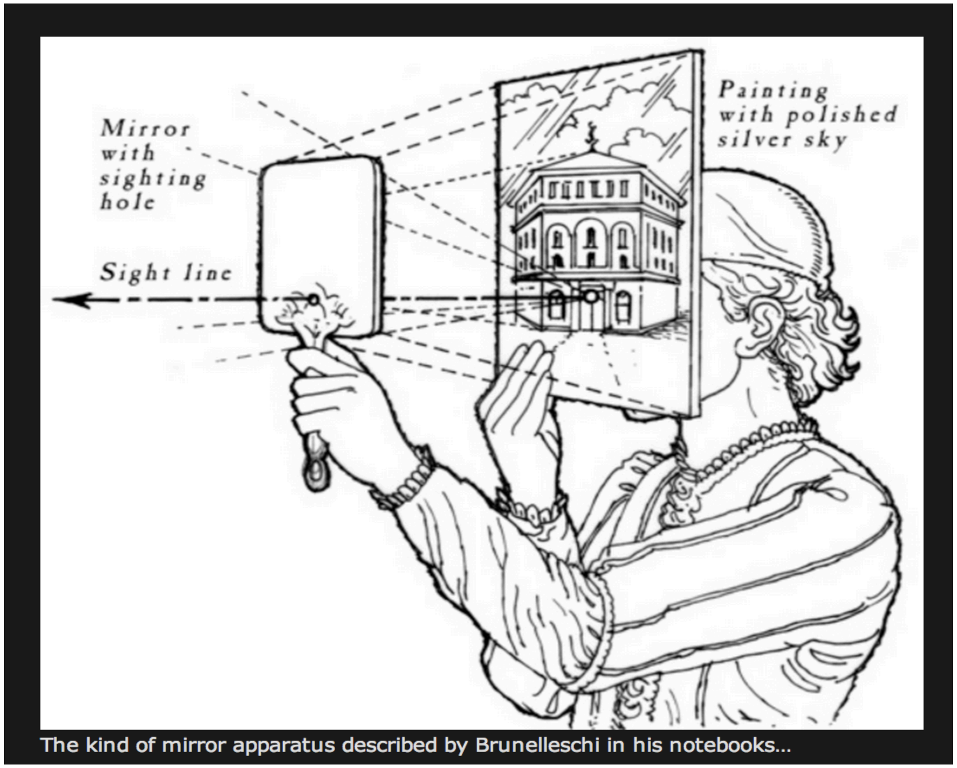
Overview of the next two lectures

- The pinhole projection model
  - qualitative properties
- Cameras with lenses
  - Depth of focus
  - Field of view
  - Lens aberrations
- Digital cameras
  - Sensors
  - Colors
  - Artifacts
- Computational photography
  - Novel sensors and cameras

Cameras

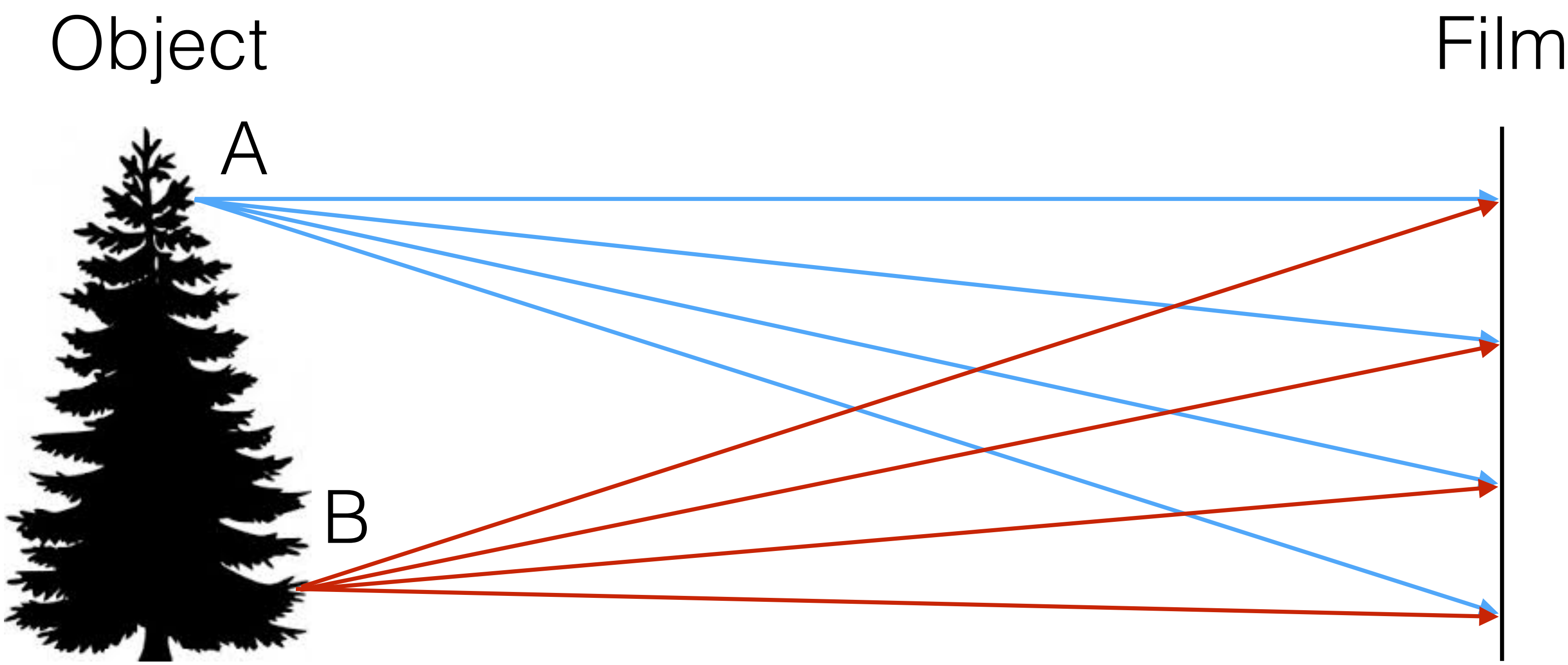


Albrecht Dürer early 1500s



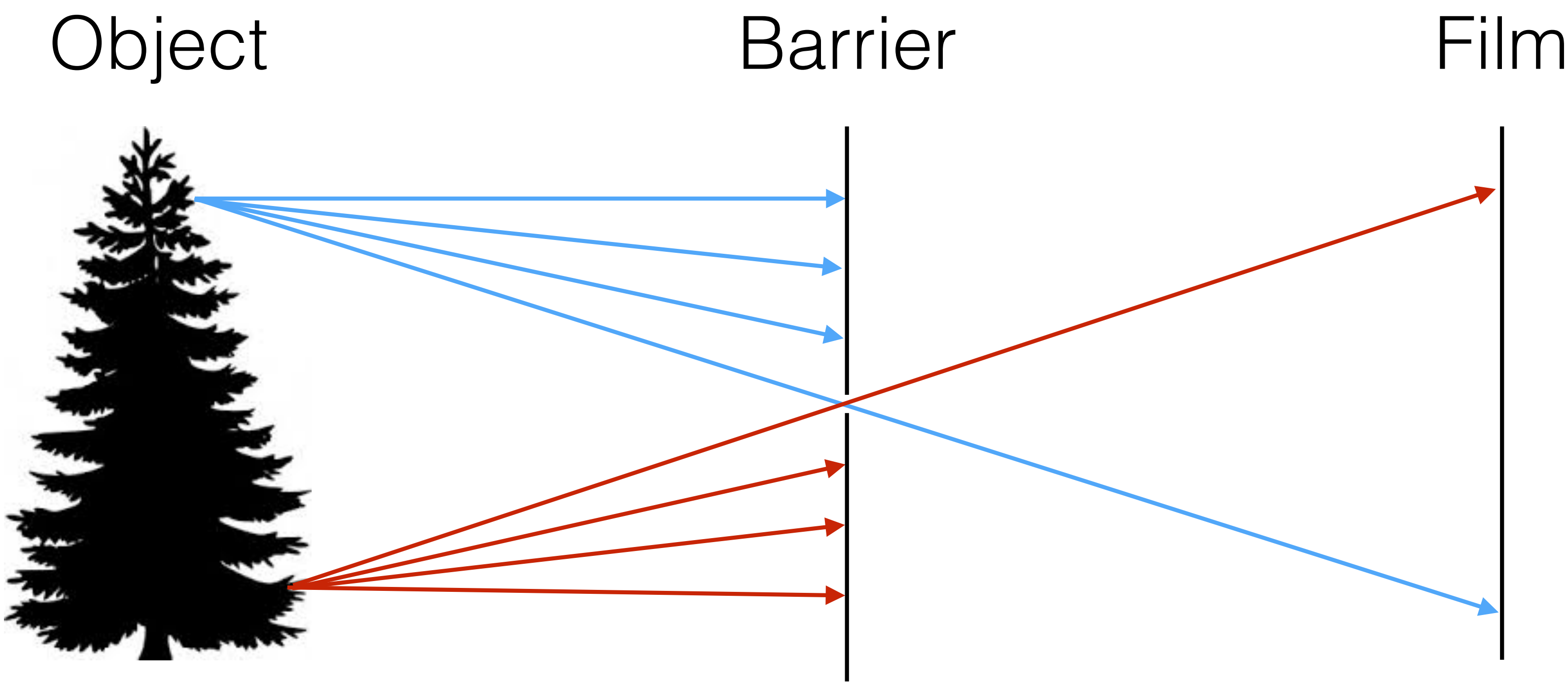
Brunelleschi, early 1400s

Lets design a camera



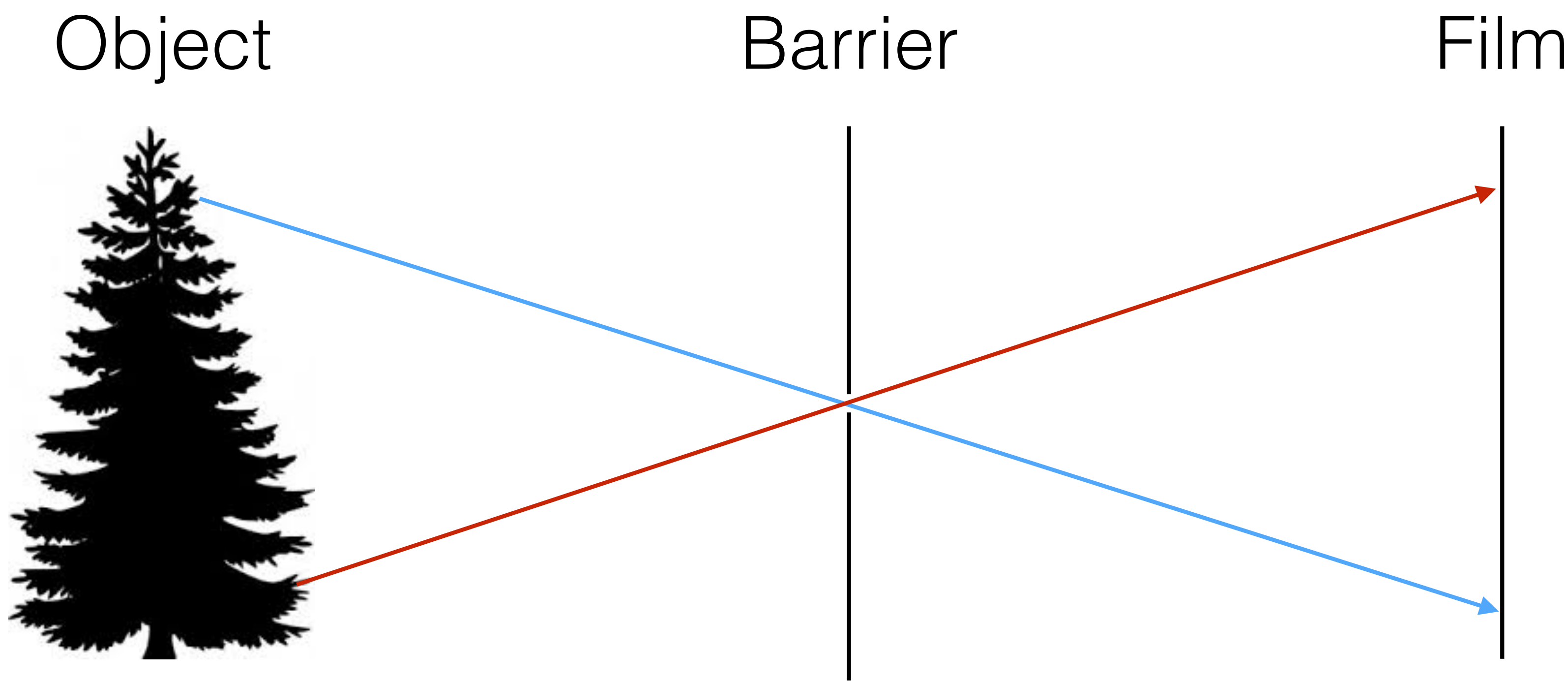
Idea 1: Lets put a film in front of an object
Do we get a reasonable image?

Pinhole camera



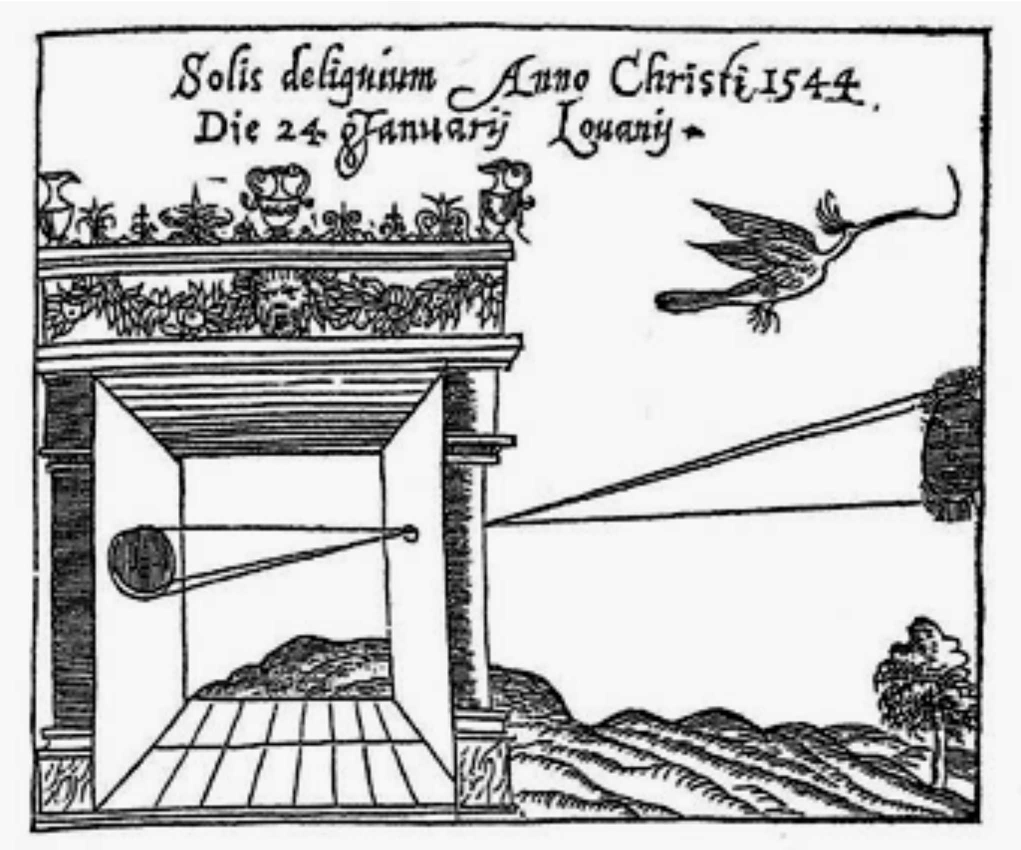
Add a barrier to block of most rays

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 obscure" 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

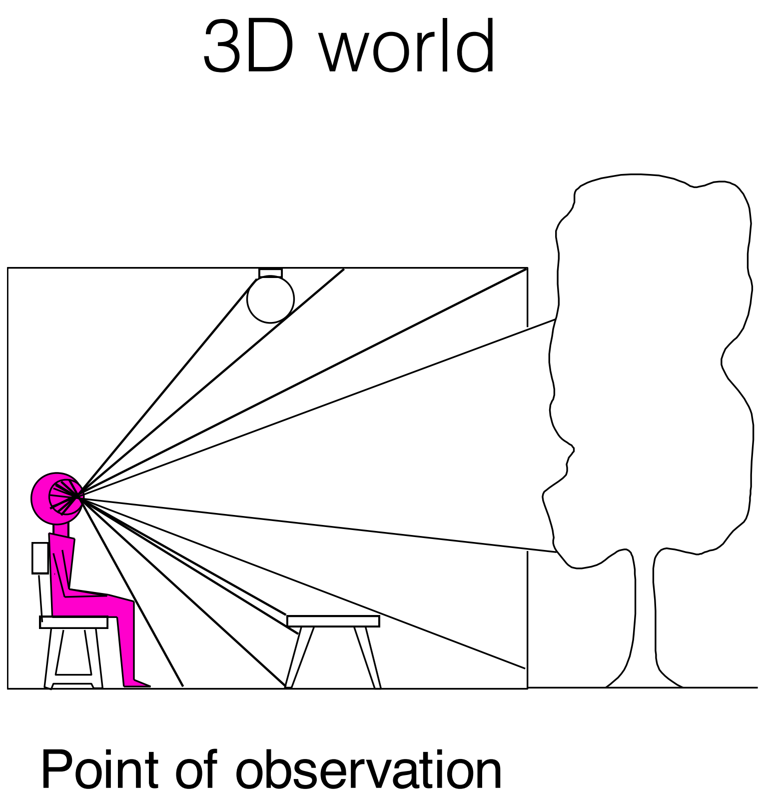
Accidental pinholes produce images that are unnoticed or misinterpreted as shadows

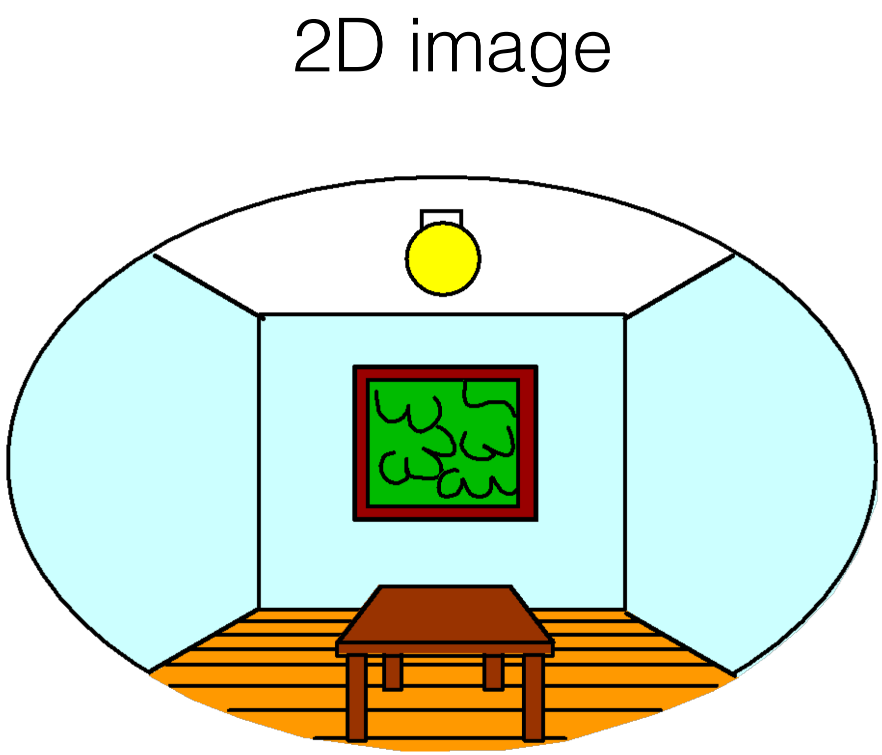
A. Torralba and W. Freeman, **Accidental Pinhole and Pinspeck Cameras**, CVPR 2012

Home-made pinhole camera

http://www.pauldebevec.com/Pinhole

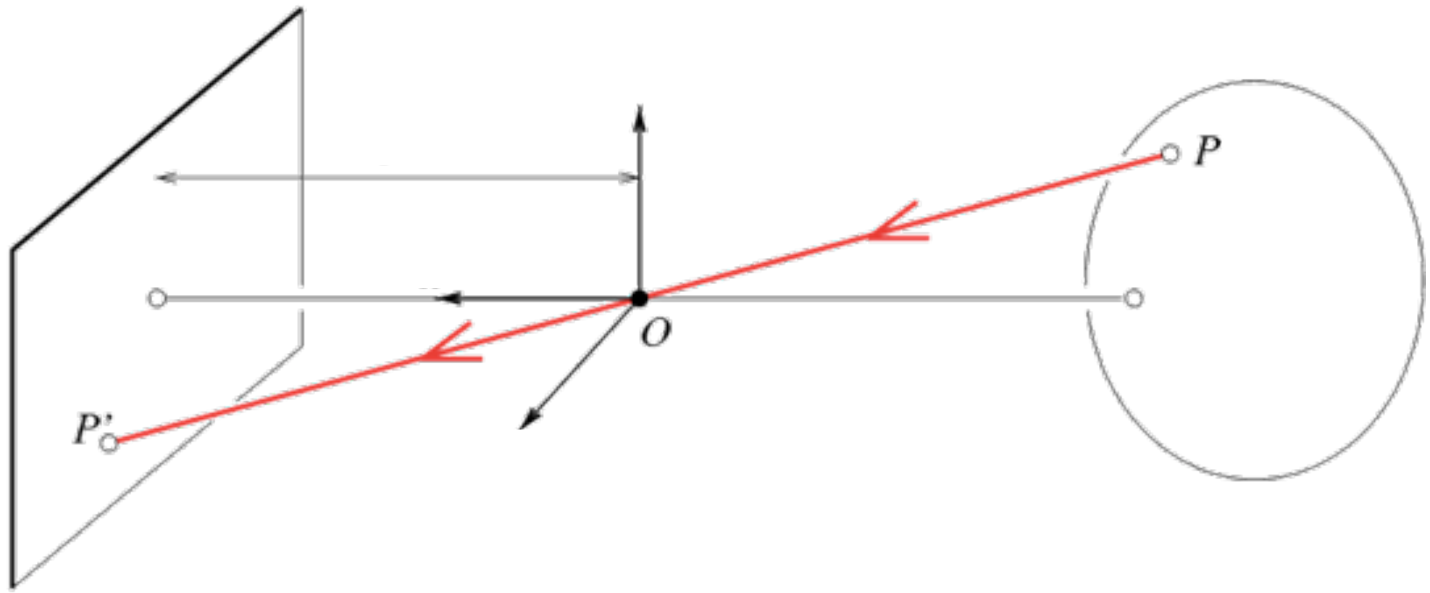
Dimensionality reduction: 3D to 2D





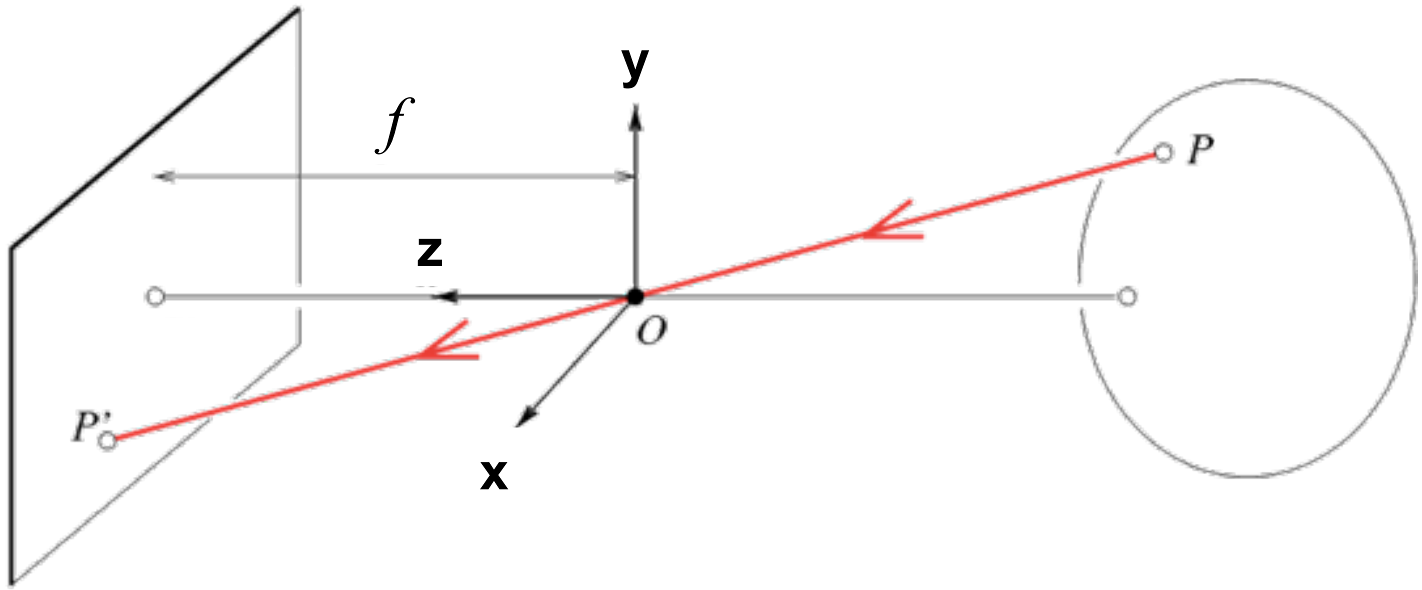
- **What is preserved?**
  - Straight lines, incidence
- **What is not preserved?**
  - Angles, lengths

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
  - Are there points for which this projection is not defined?

Modeling projection

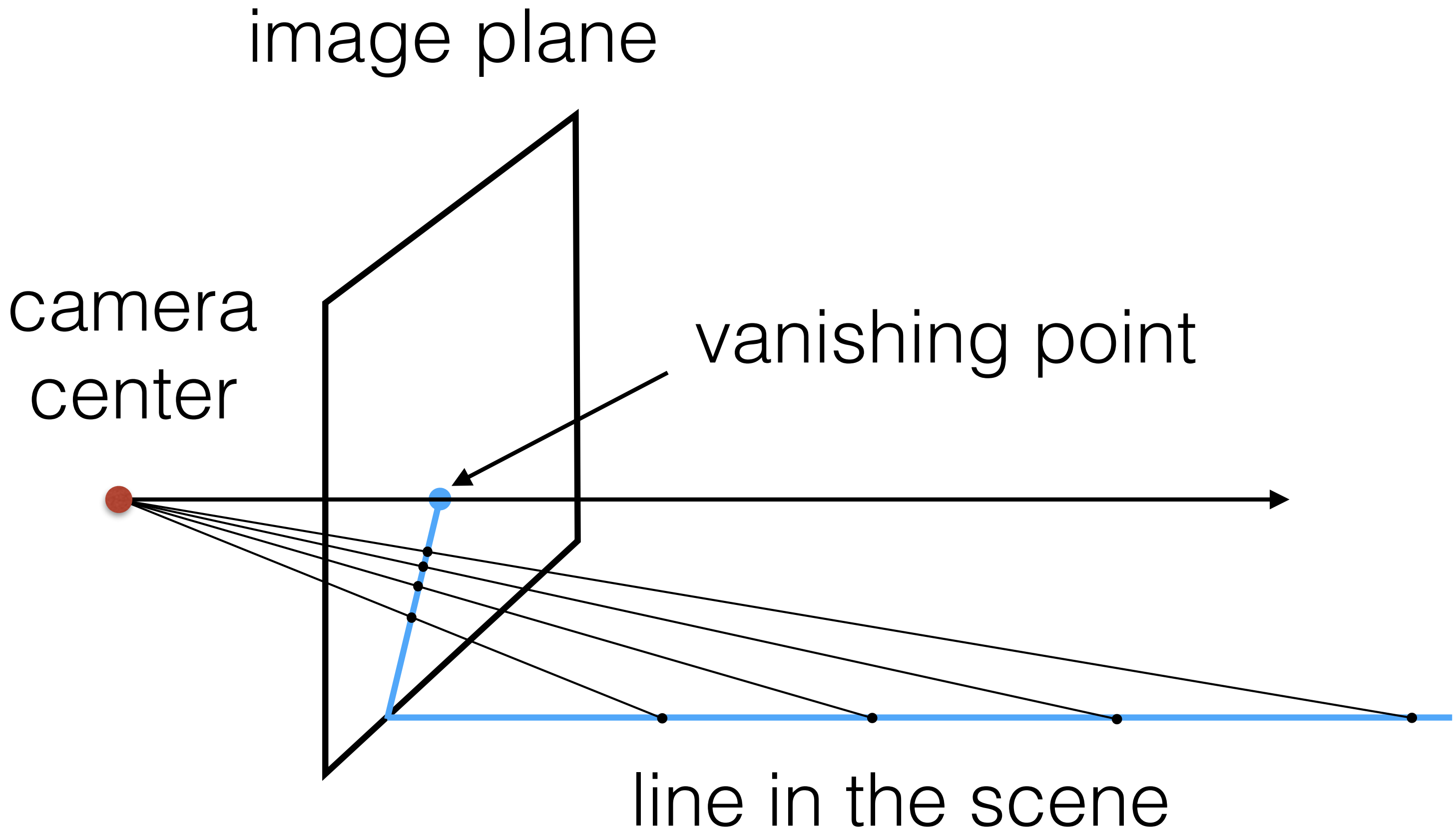


- **The coordinate system**
  - The optical center (***O***) is at the origin
  - The image plane is parallel to the xy-plane (perpendicular to the z axis)
- **Projection equations**
  - Derive using similar triangles

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

Slide by Steve Seitz

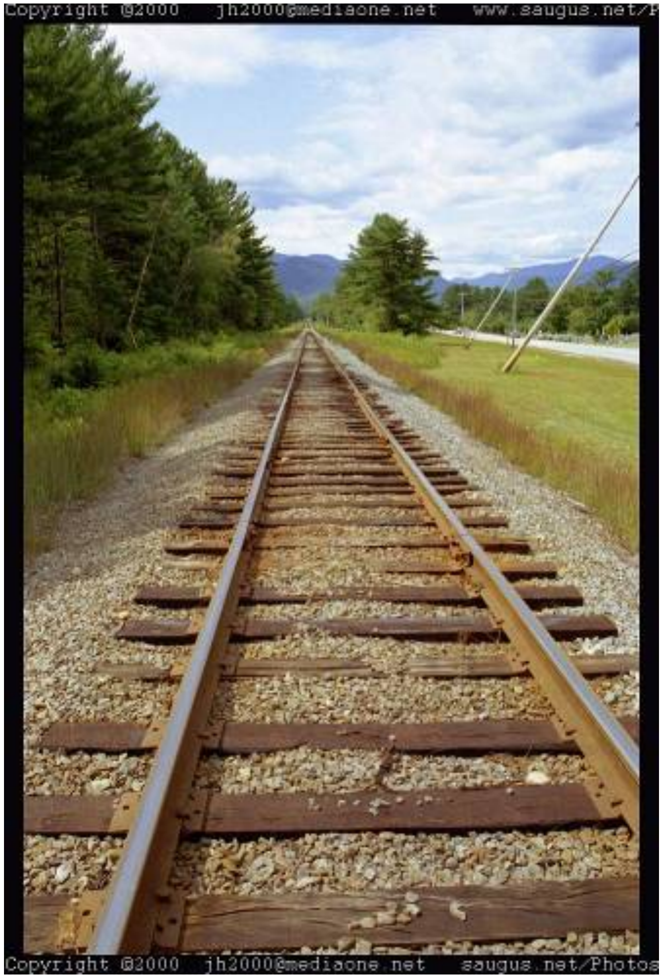
Projection of a line



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

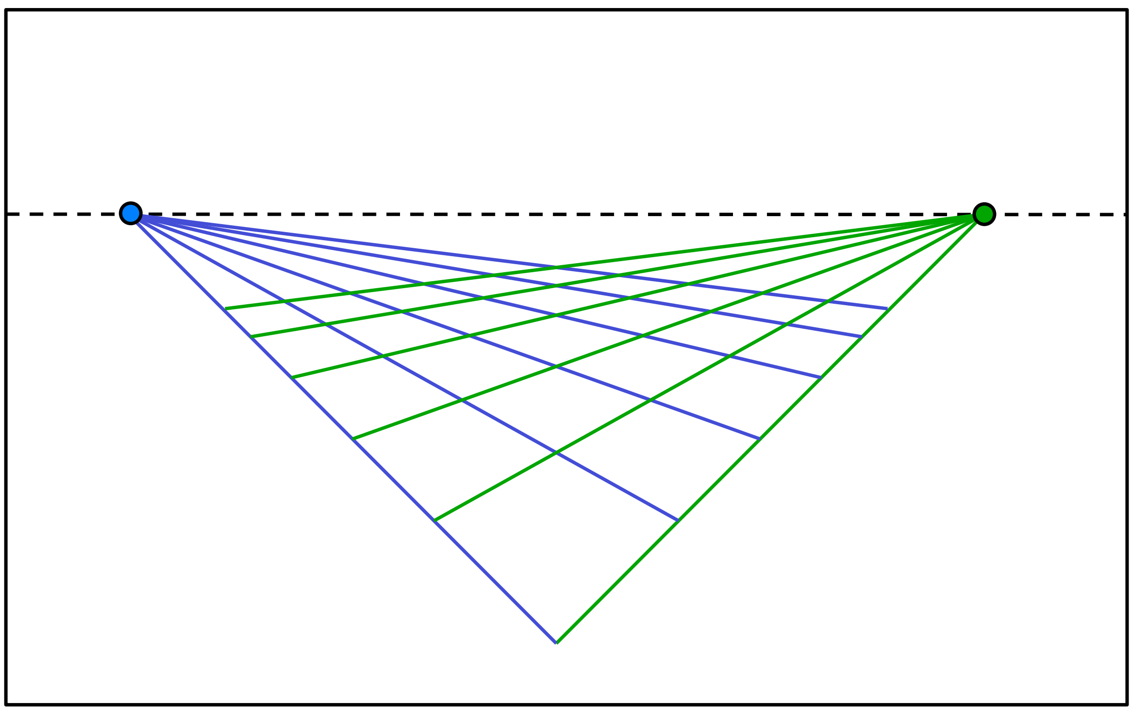
Vanishing points

- 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

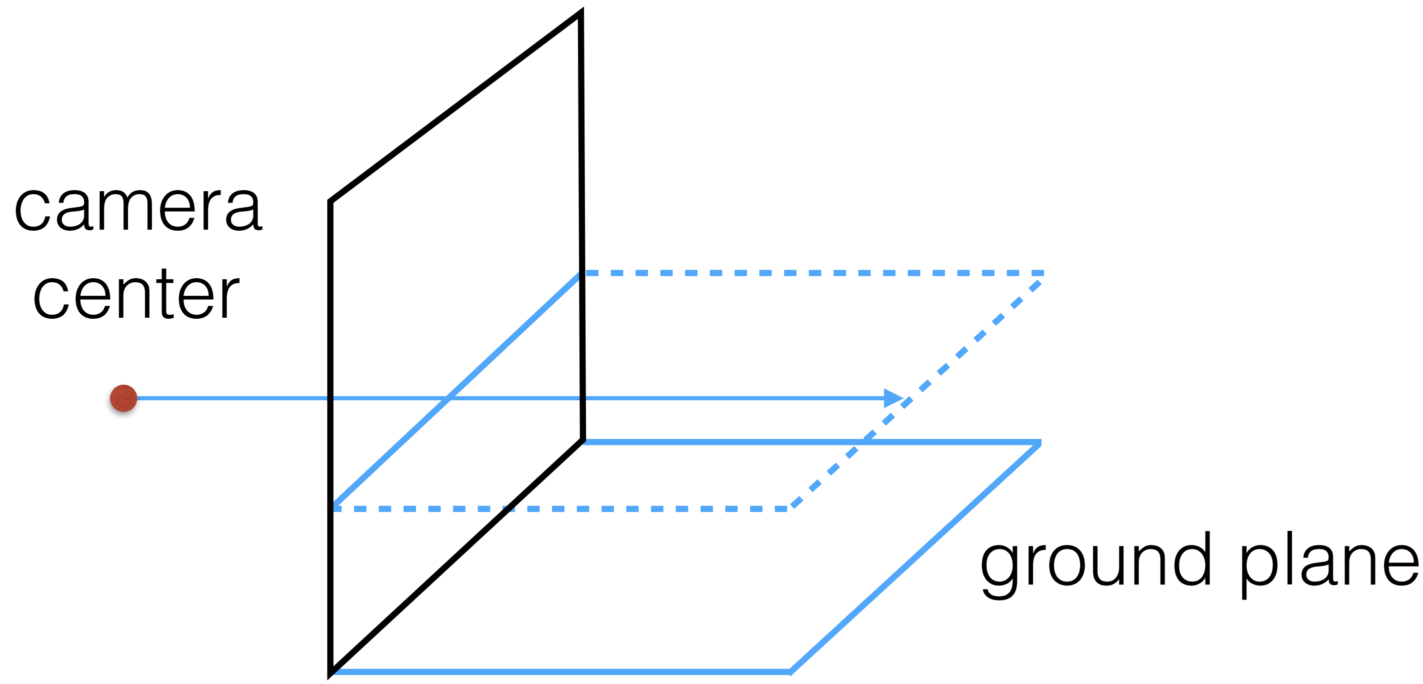


Vanishing points

- 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 about the vanishing point of a plane?



The horizon

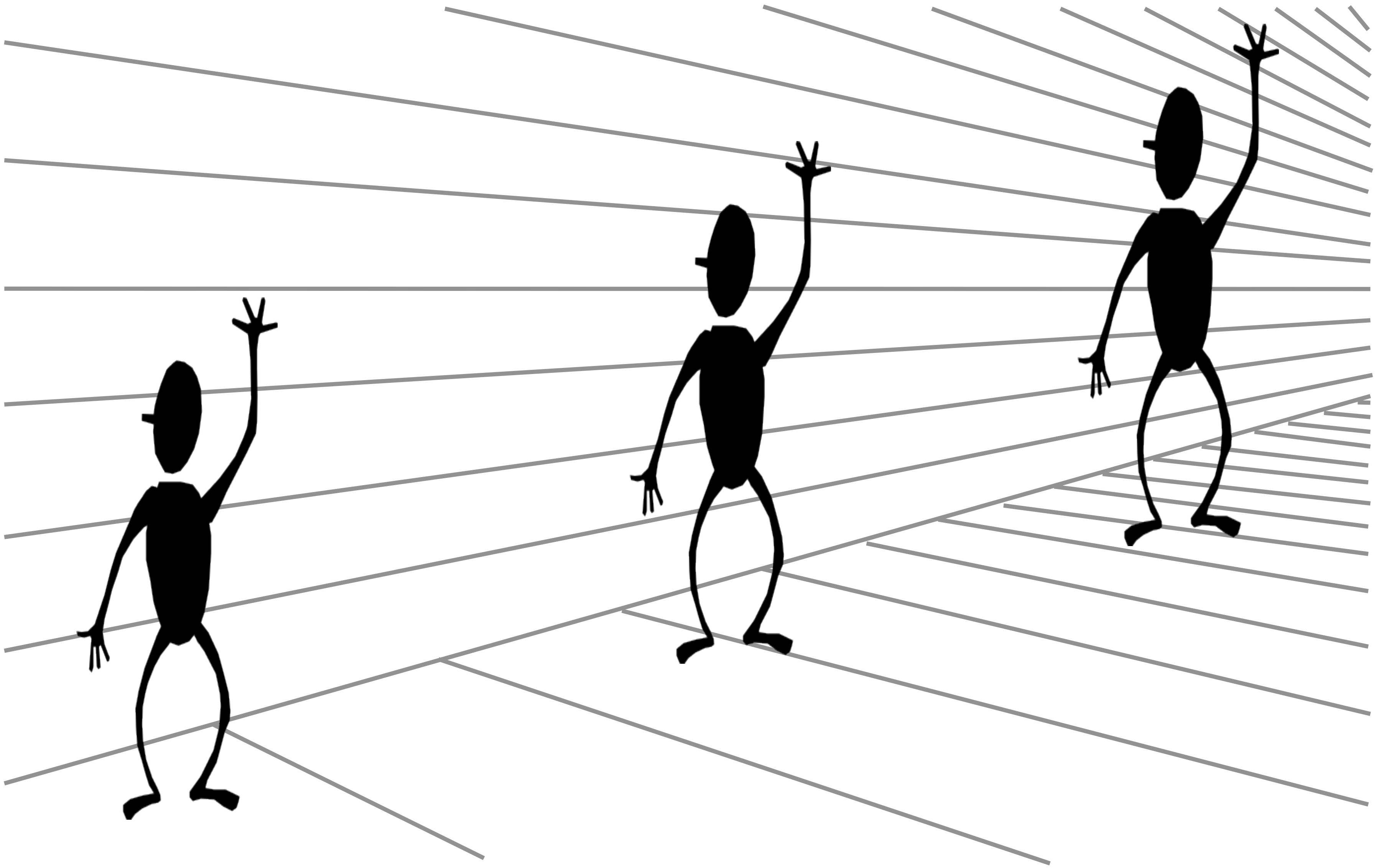


- Vanishing line of the ground plane
  - All points at the same height of the camera project to the horizon
  - Points above the camera project above the horizon
  - Provides a way of comparing heights of objects

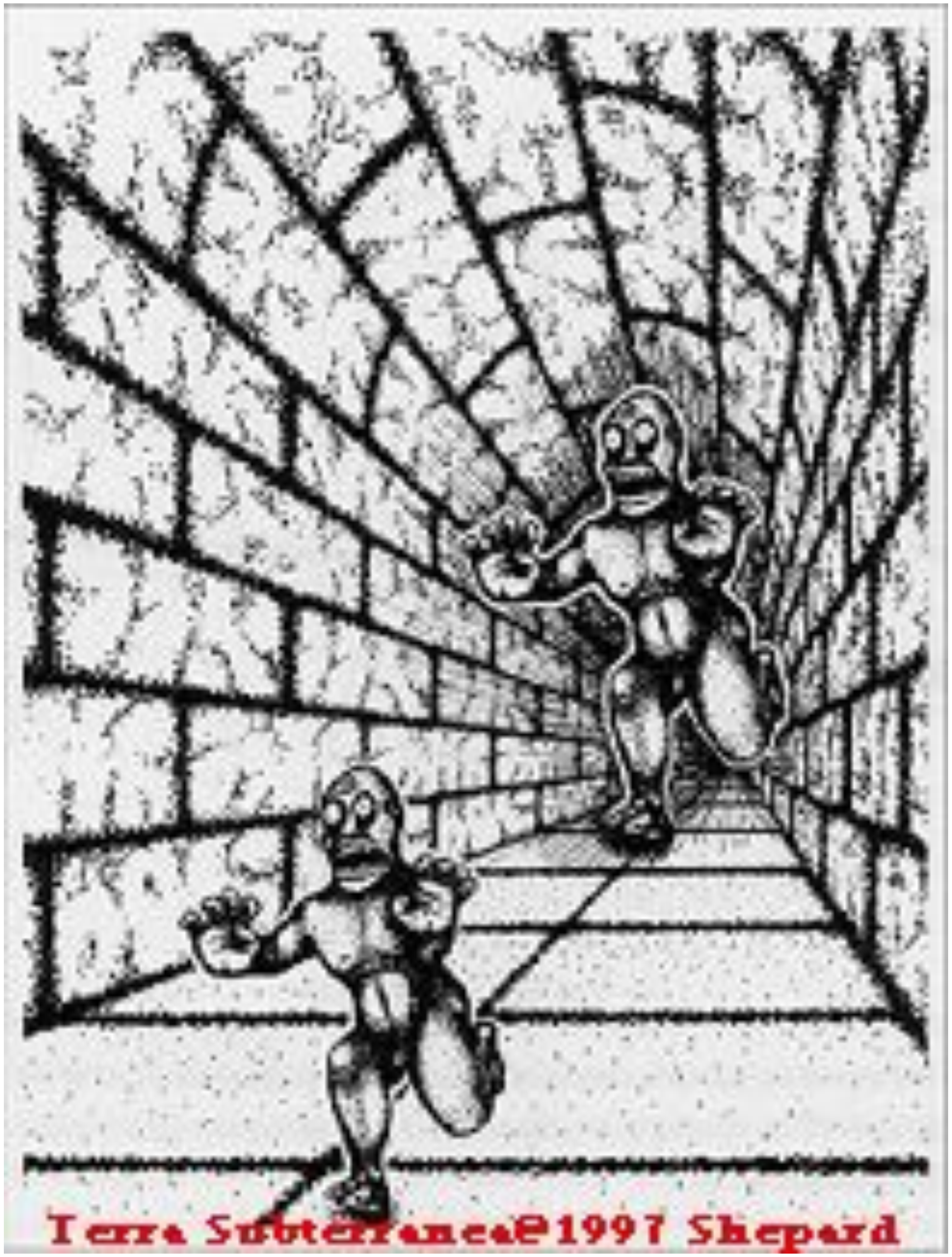
The horizon

Is the person above or below the viewer?

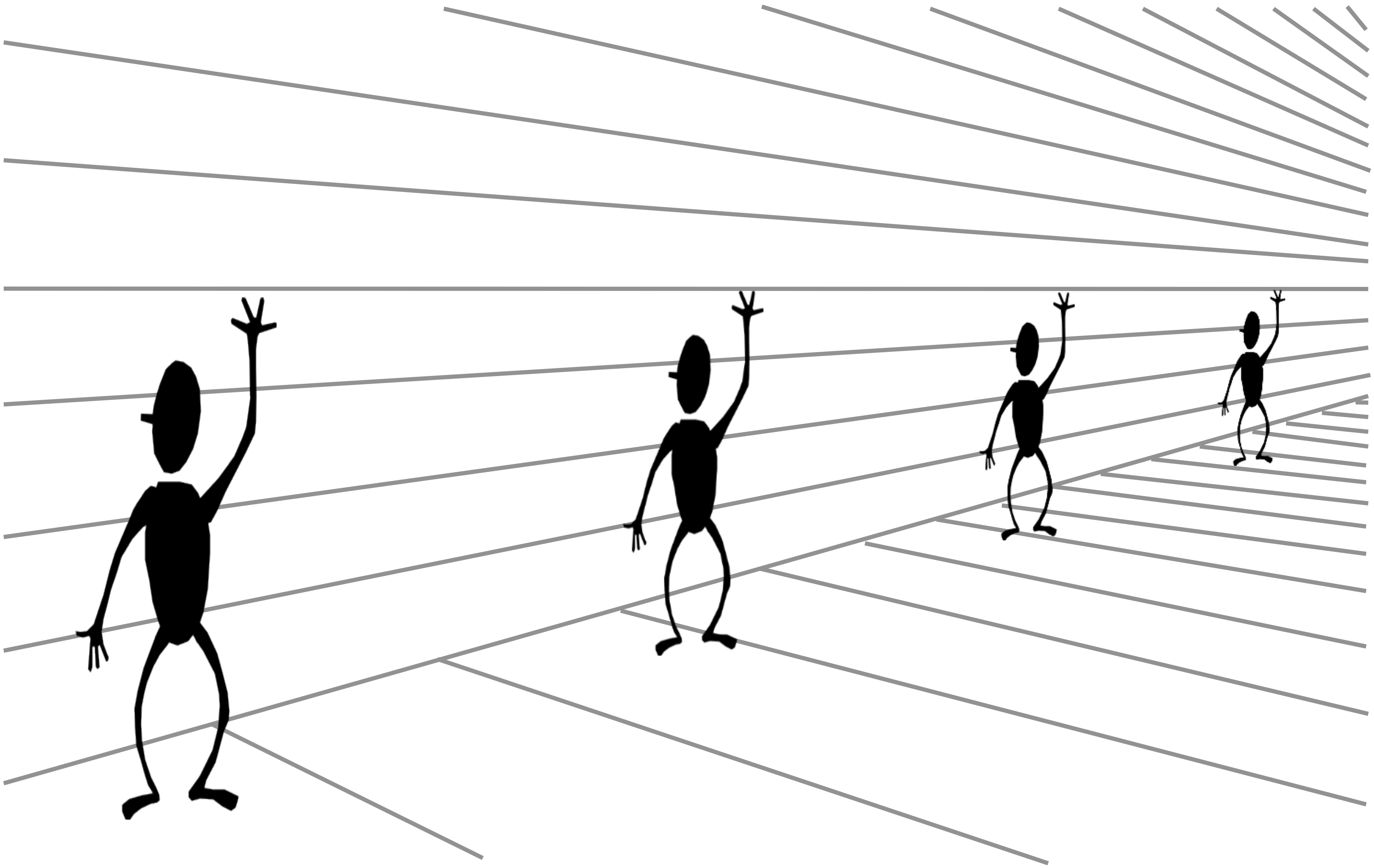
Perspective cues



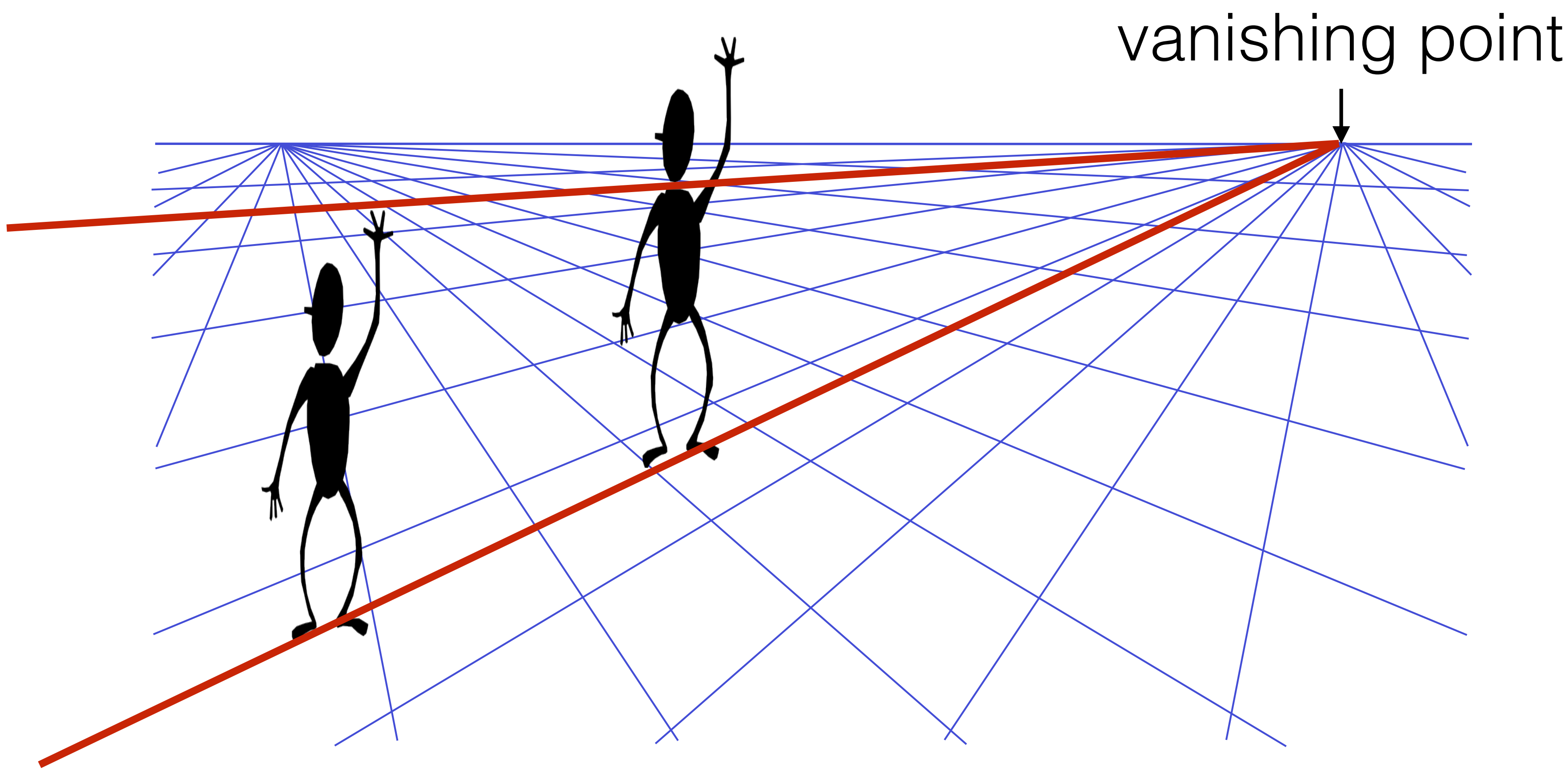
Perspective cues



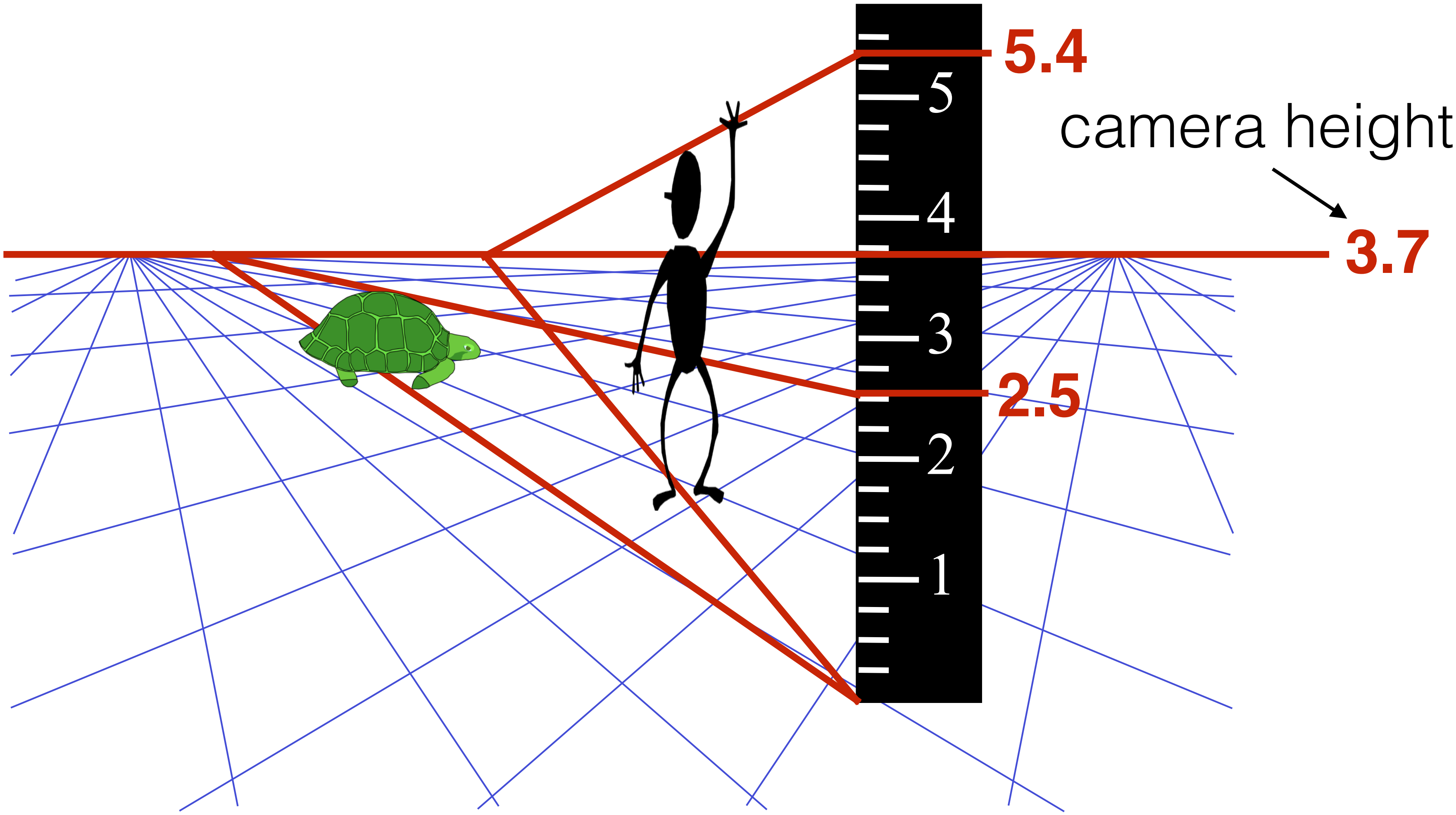
Perspective cues



Comparing heights

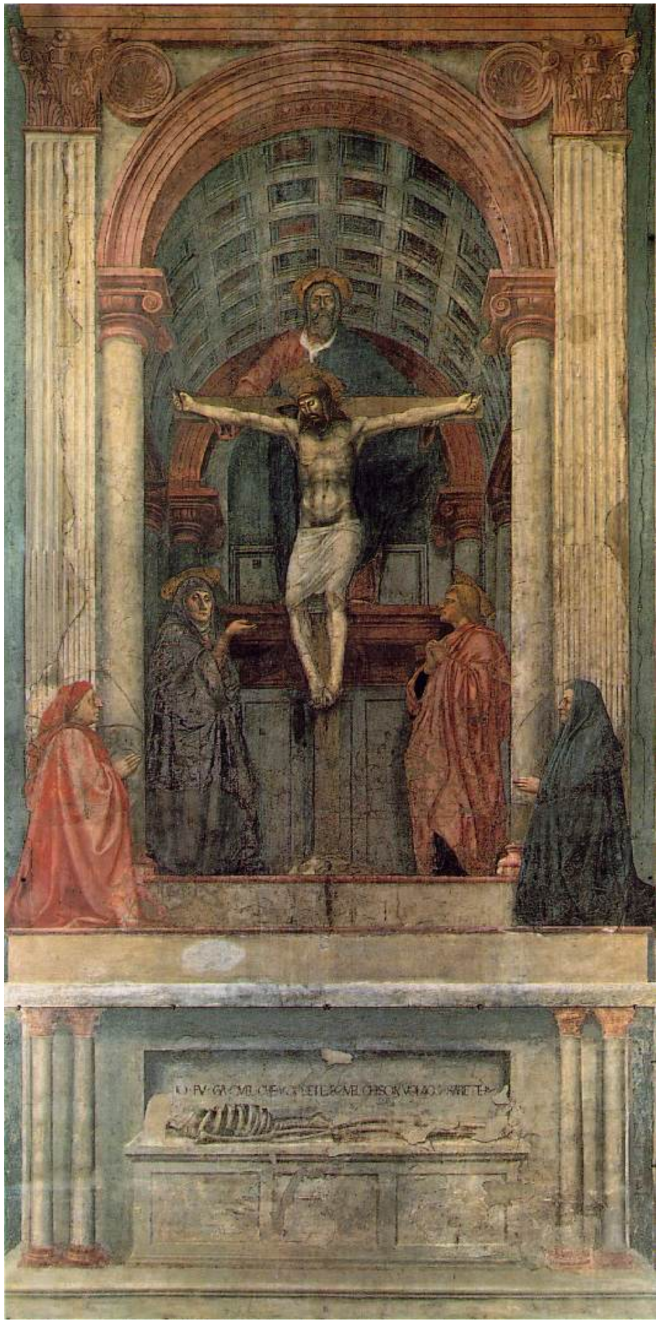


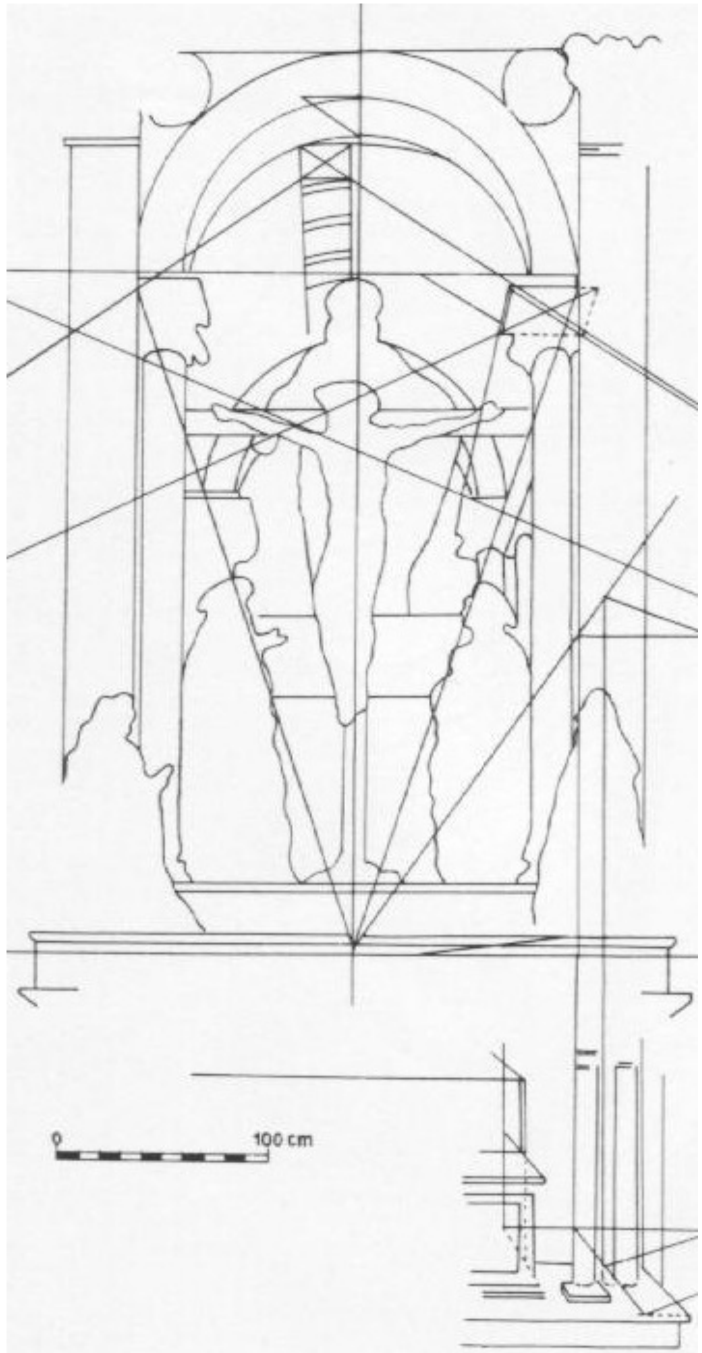
Measuring heights



What is the height of the camera?

Perspective in art





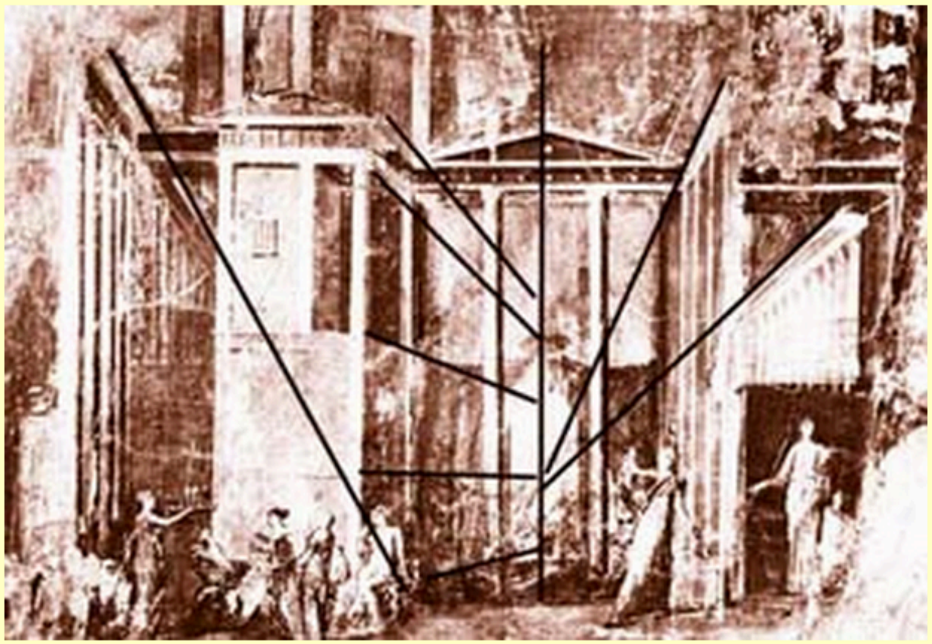
Masaccio, *Trinity*, Santa Maria Novella, Florence, 1425-28

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:

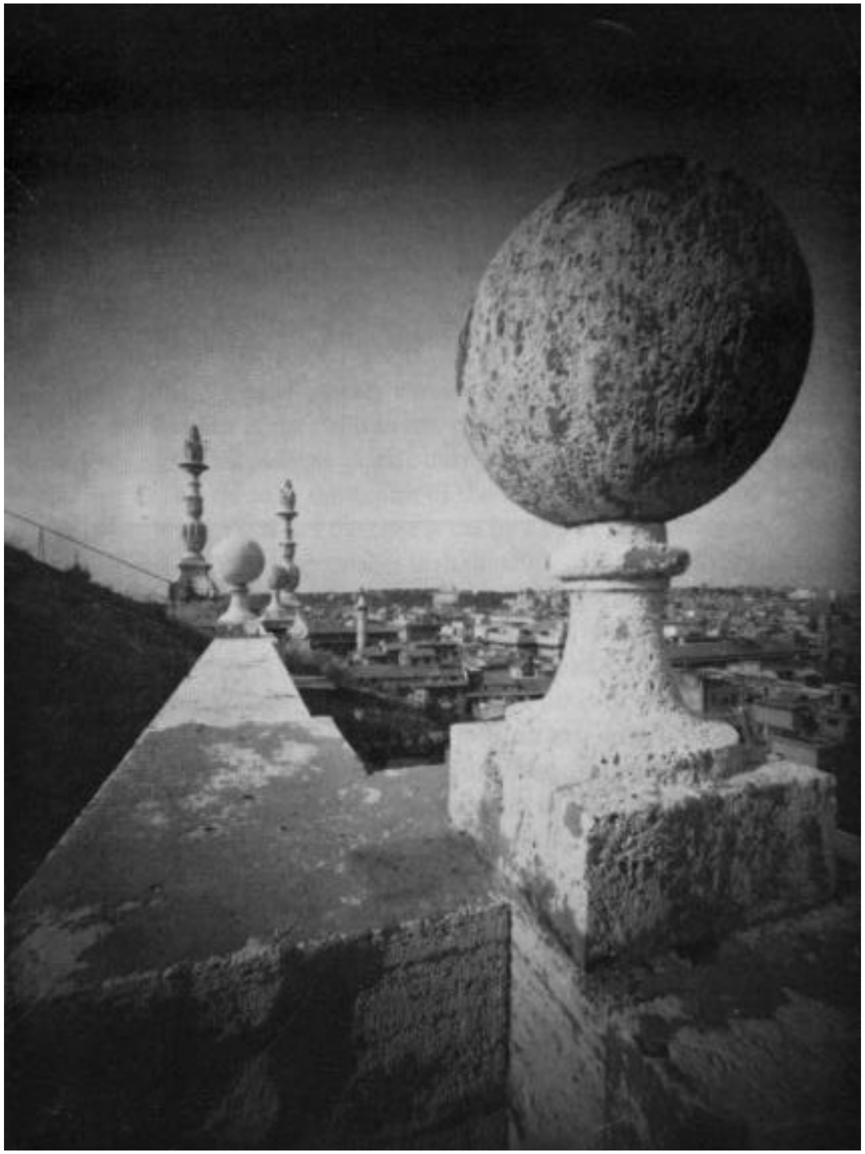


From ottobwiersma.nl

Also some Greek examples,
So apparently pre-renaissance…

Perspective distortion

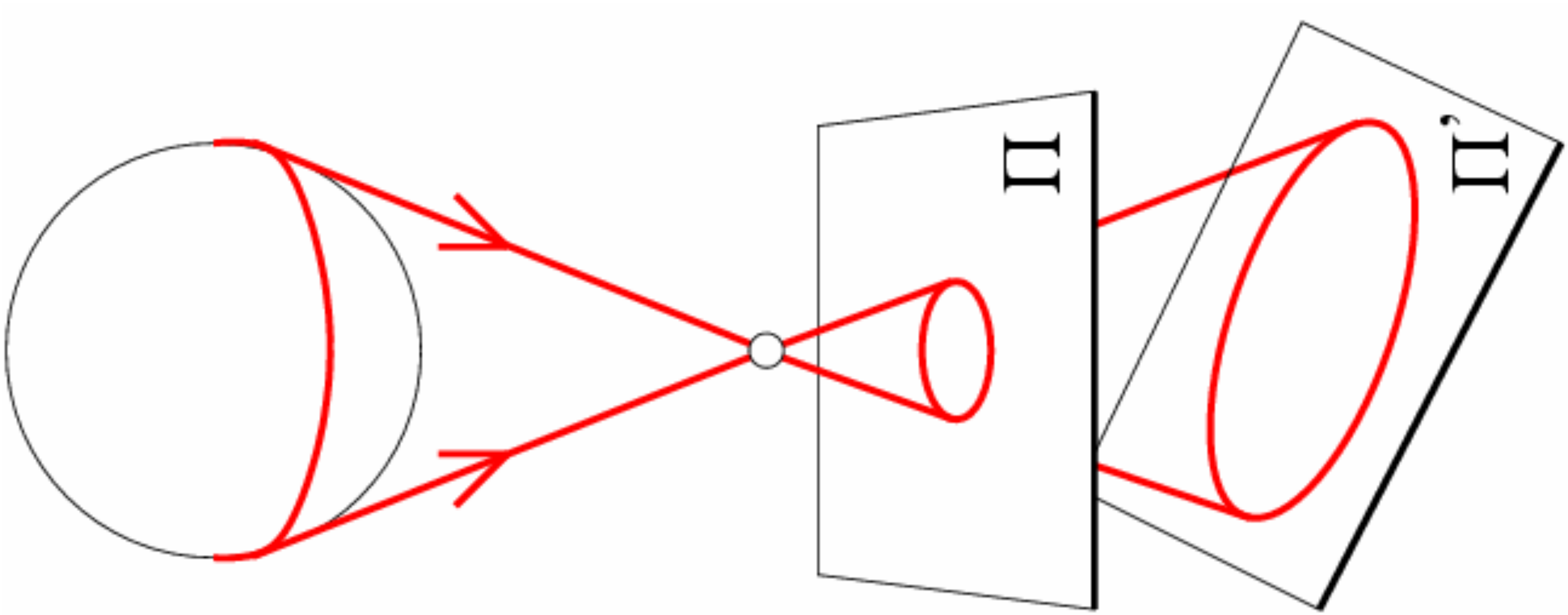
- What does a sphere project to?



M. H. Pirenne

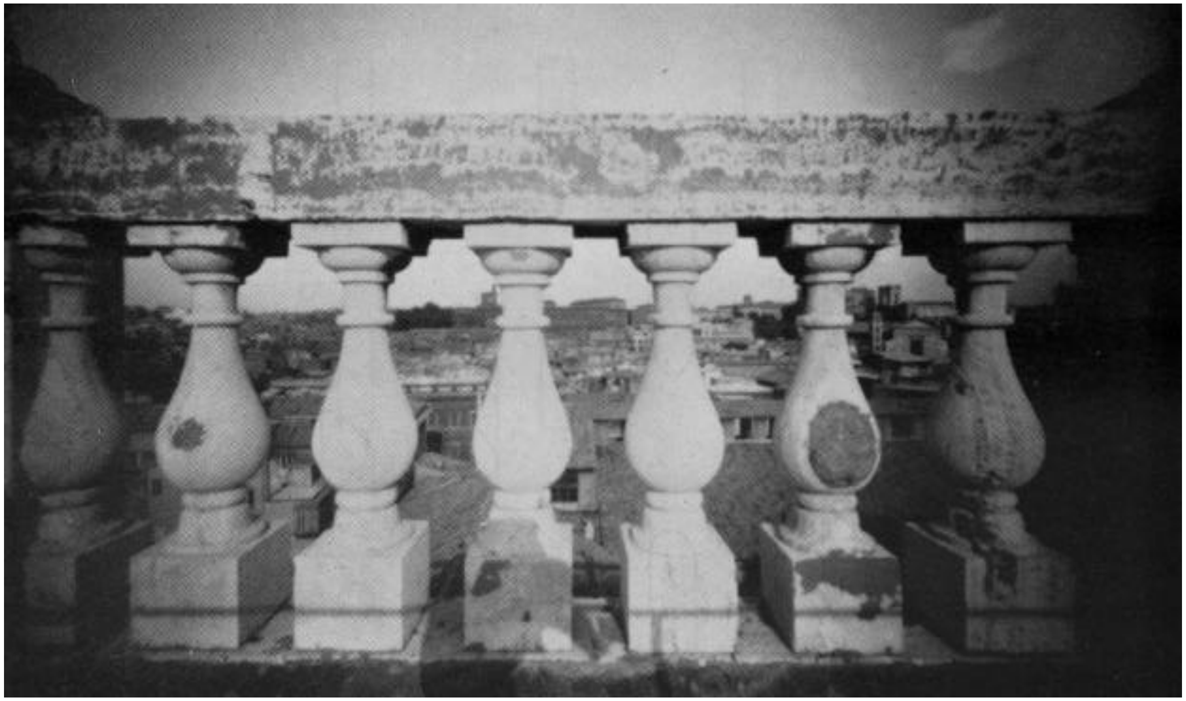
Perspective distortion

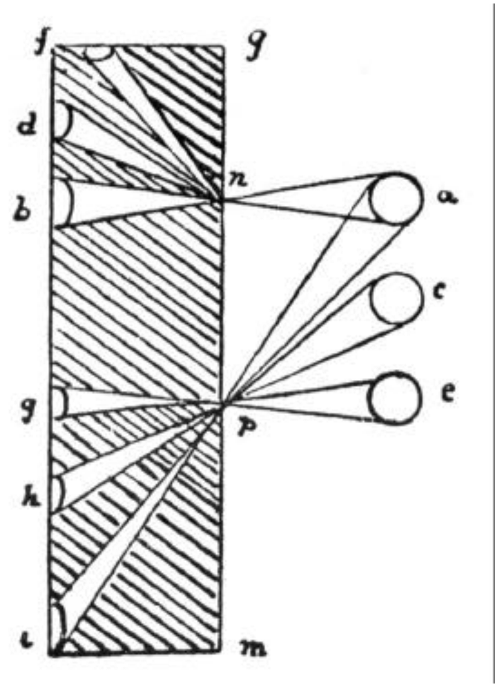
- What does a sphere project to?



Perspective distortion

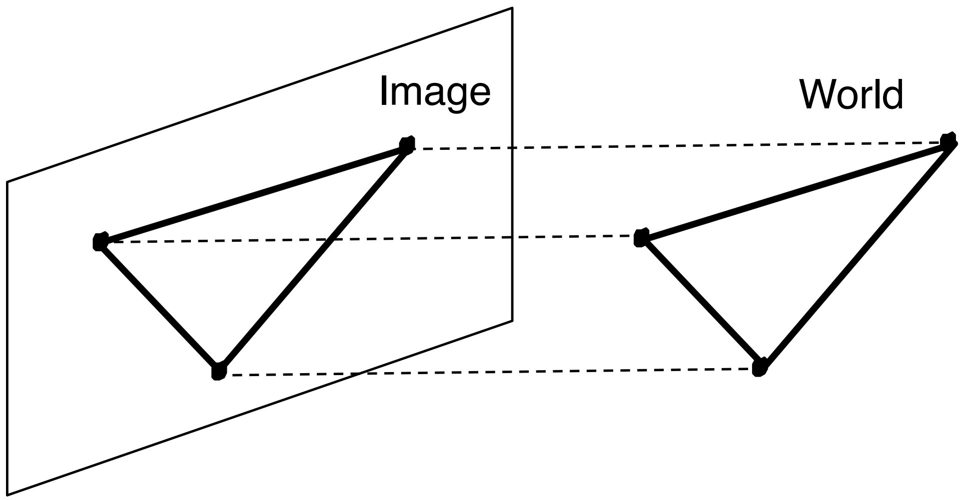
- The exterior looks bigger
- The distortion is not due to lens flaws
- Problem pointed out by Da Vinci





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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  - Qualitative properties
- Cameras with lenses
  - Depth of focus
  - Field of view
  - Lens aberrations
- Digital cameras
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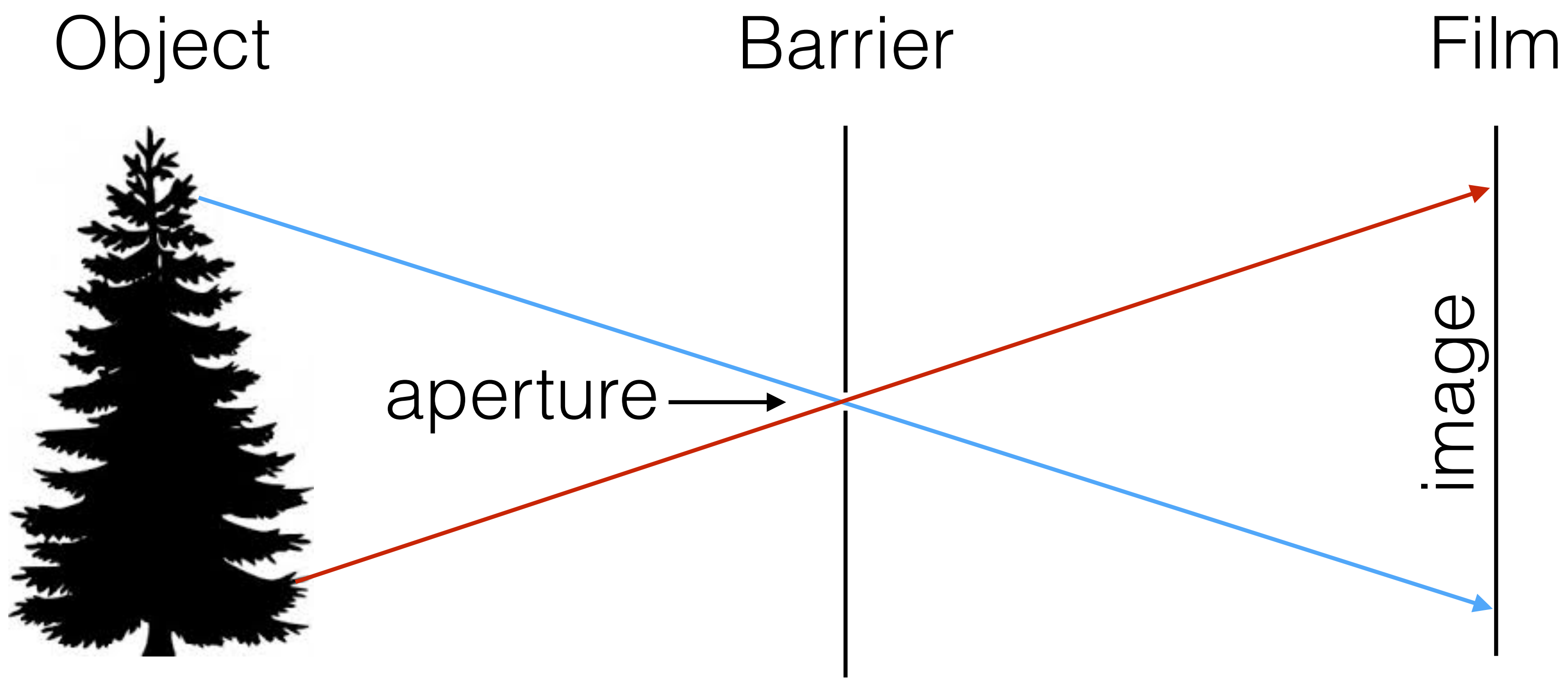
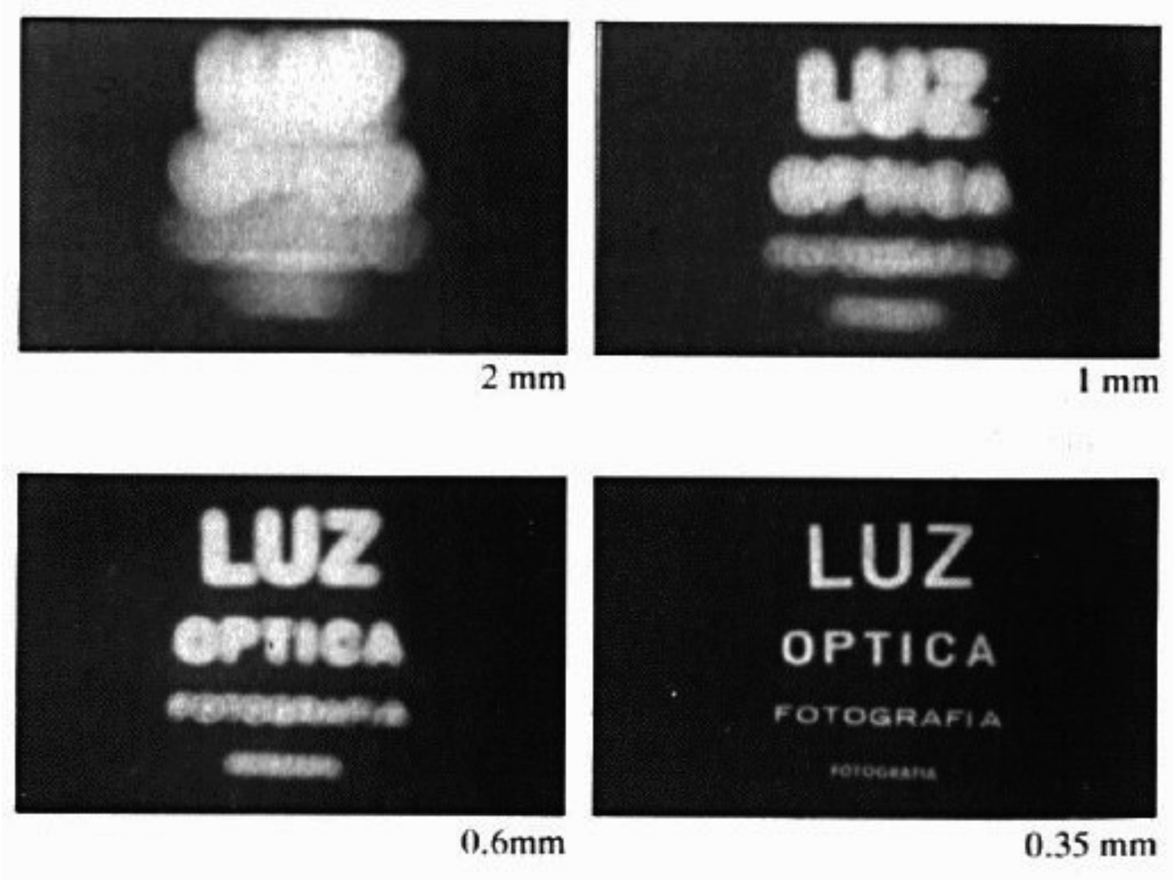
- Novel cameras
  - Computational photography

Pinhole camera



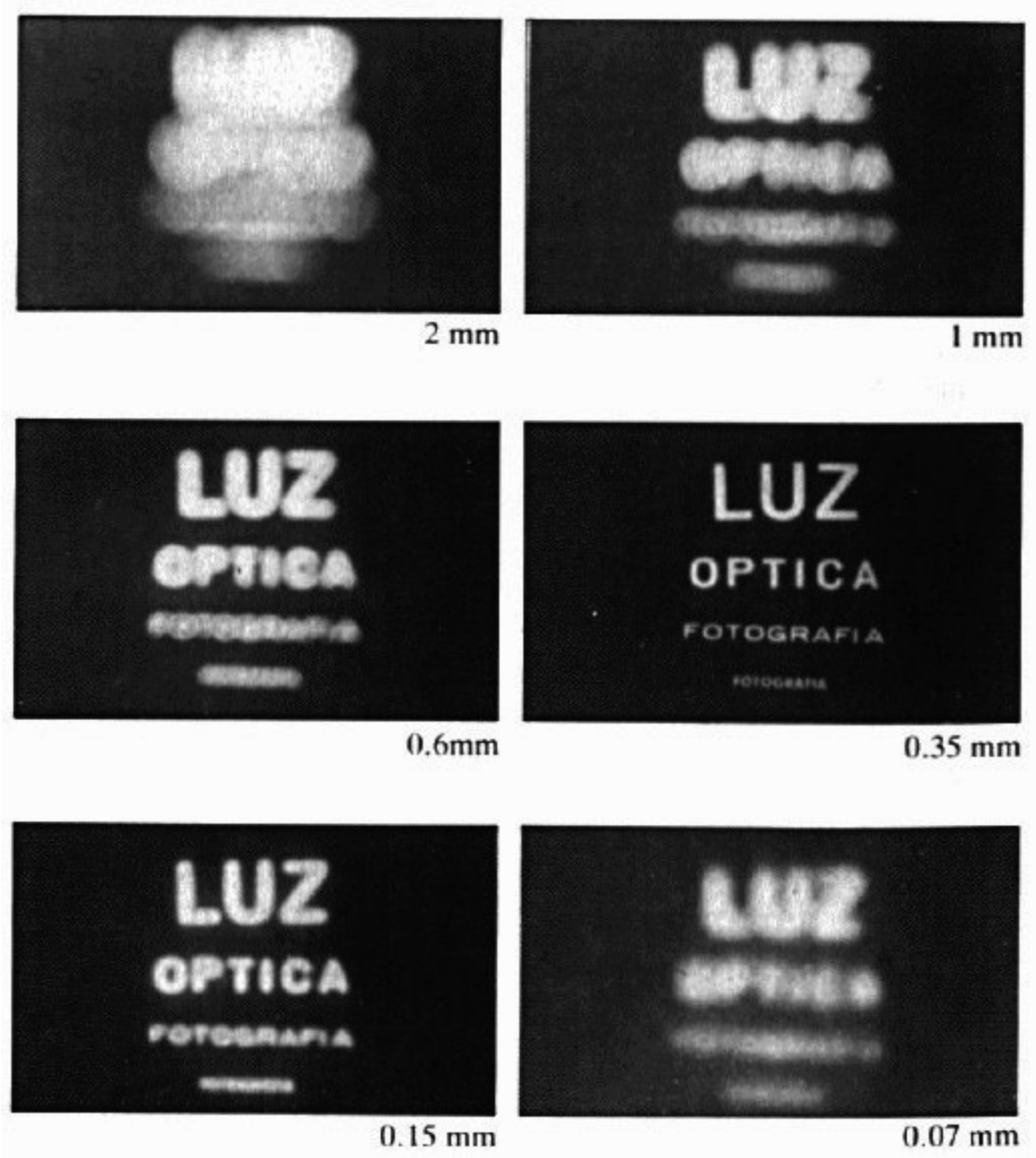
- Captures **pencil of rays** - all rays through a single point: **aperture, center of projection, focal point, camera center**
- The image is formed on the **image plane**

Shrinking the aperture



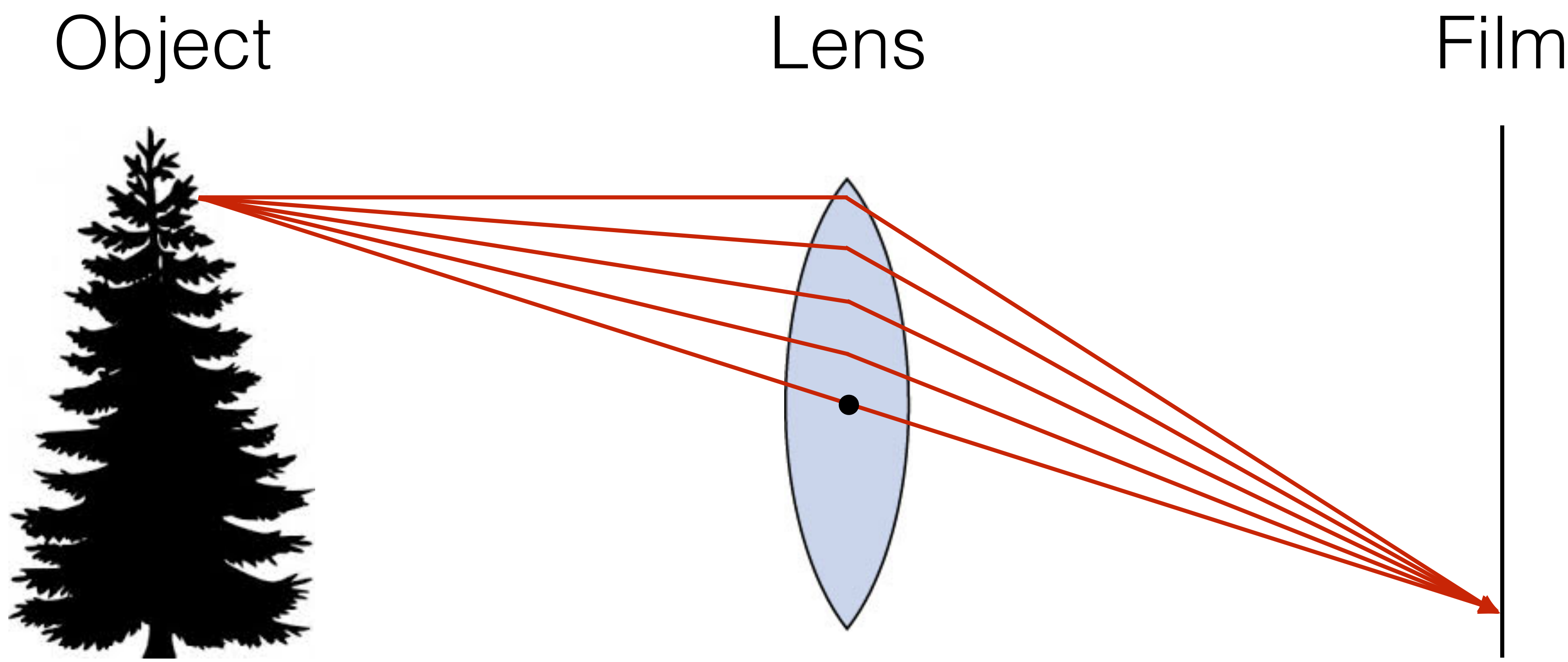
- Why not make the aperture as small as possible?
  - Less light gets through
  - Diffraction effects

Shrinking the aperture



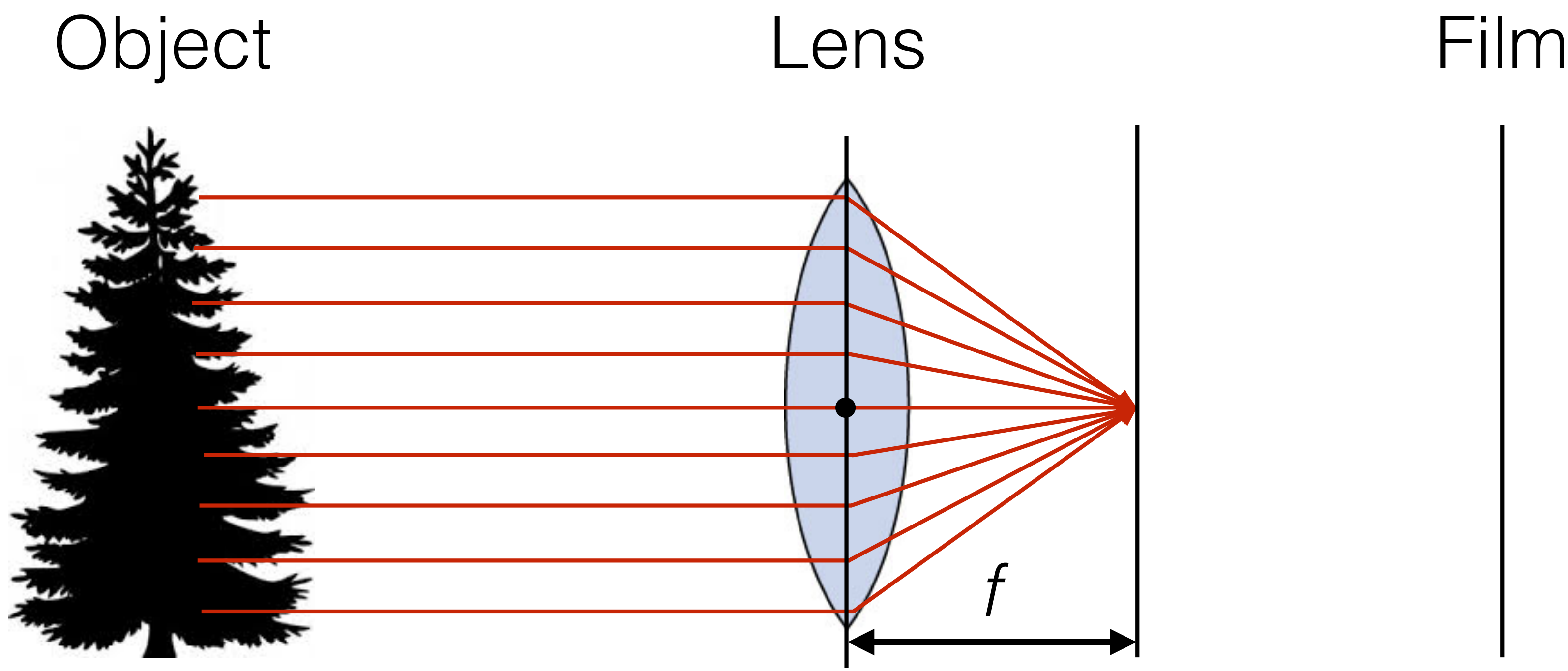
Slide by Steve Seitz

Adding a lens



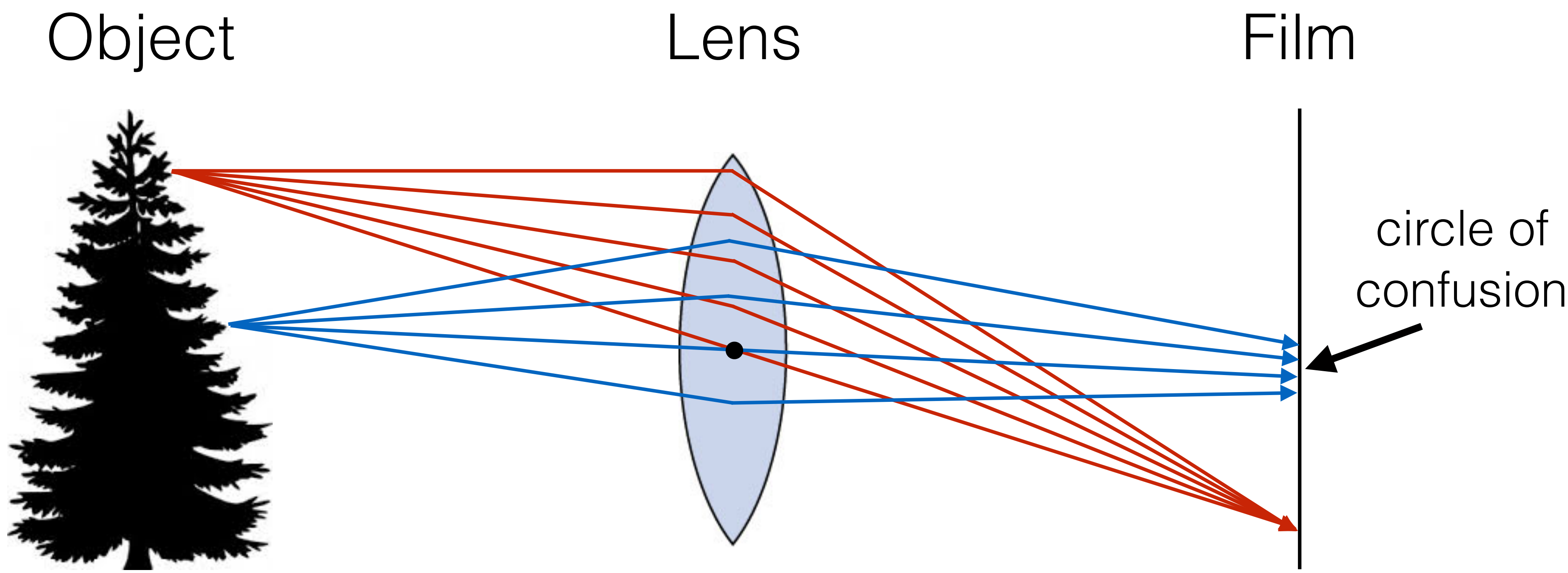
- A lens focuses light on to the film
  - **Thin lens model:**
    - Rays passing through the center are not deviated (pinhole projection model still holds)

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*

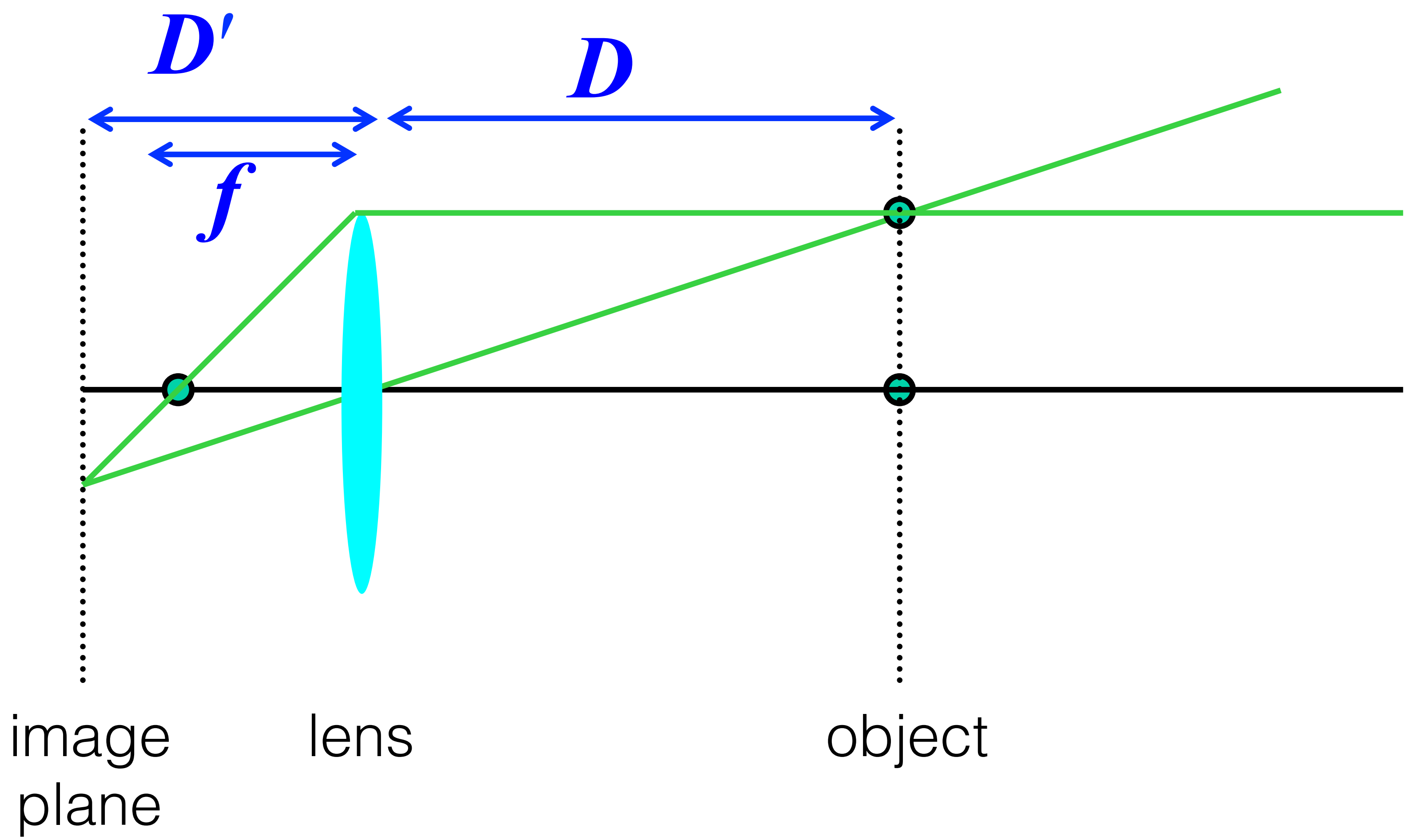
Adding a lens



- 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

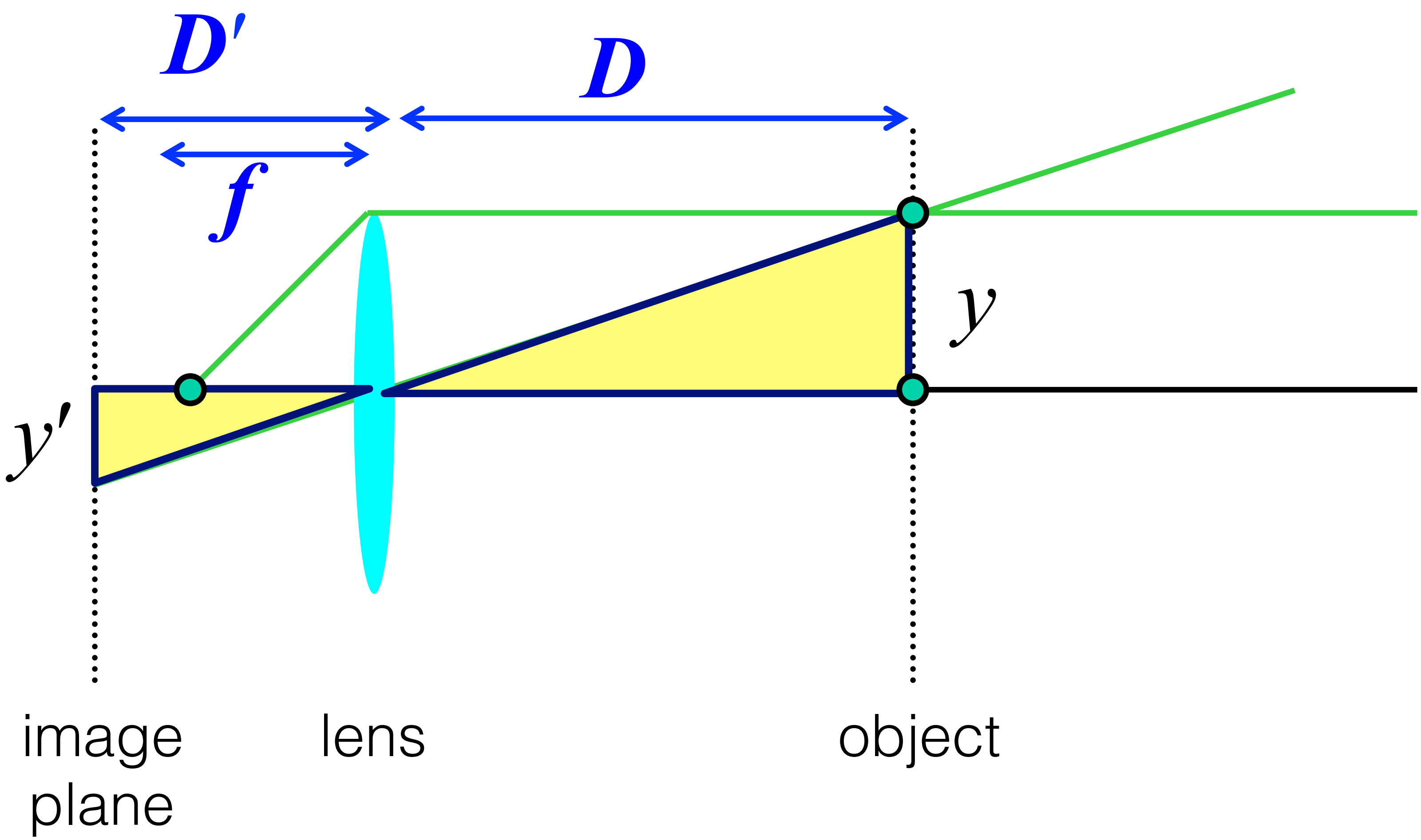
- What is the relation between the focal length (*f*), the distance of the object from the optical center (*D*) and the distance at which the object will be in focus (*D'*)?



Thin lens formula

- Similar triangles everywhere!

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

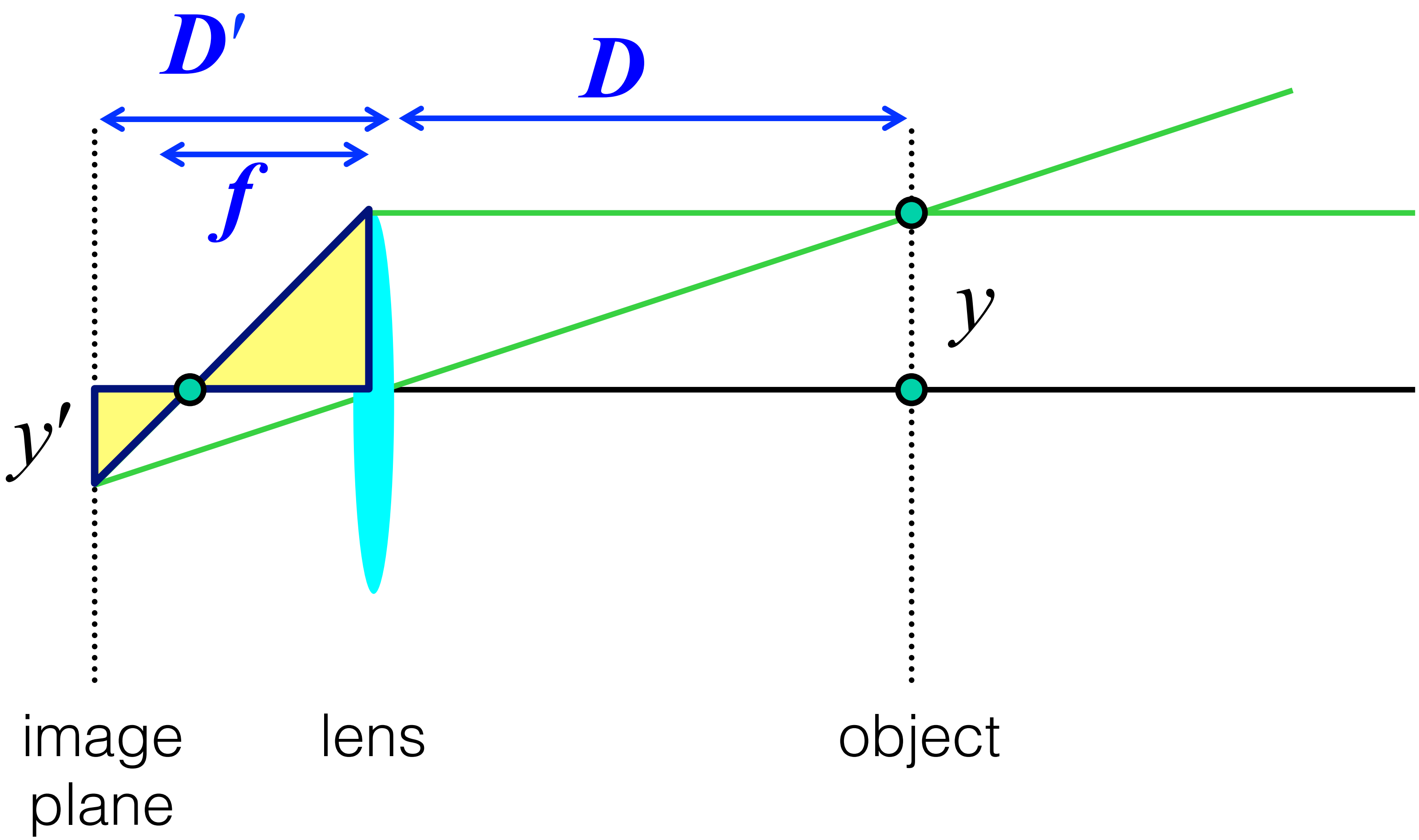


Thin lens formula

- Similar triangles everywhere!

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

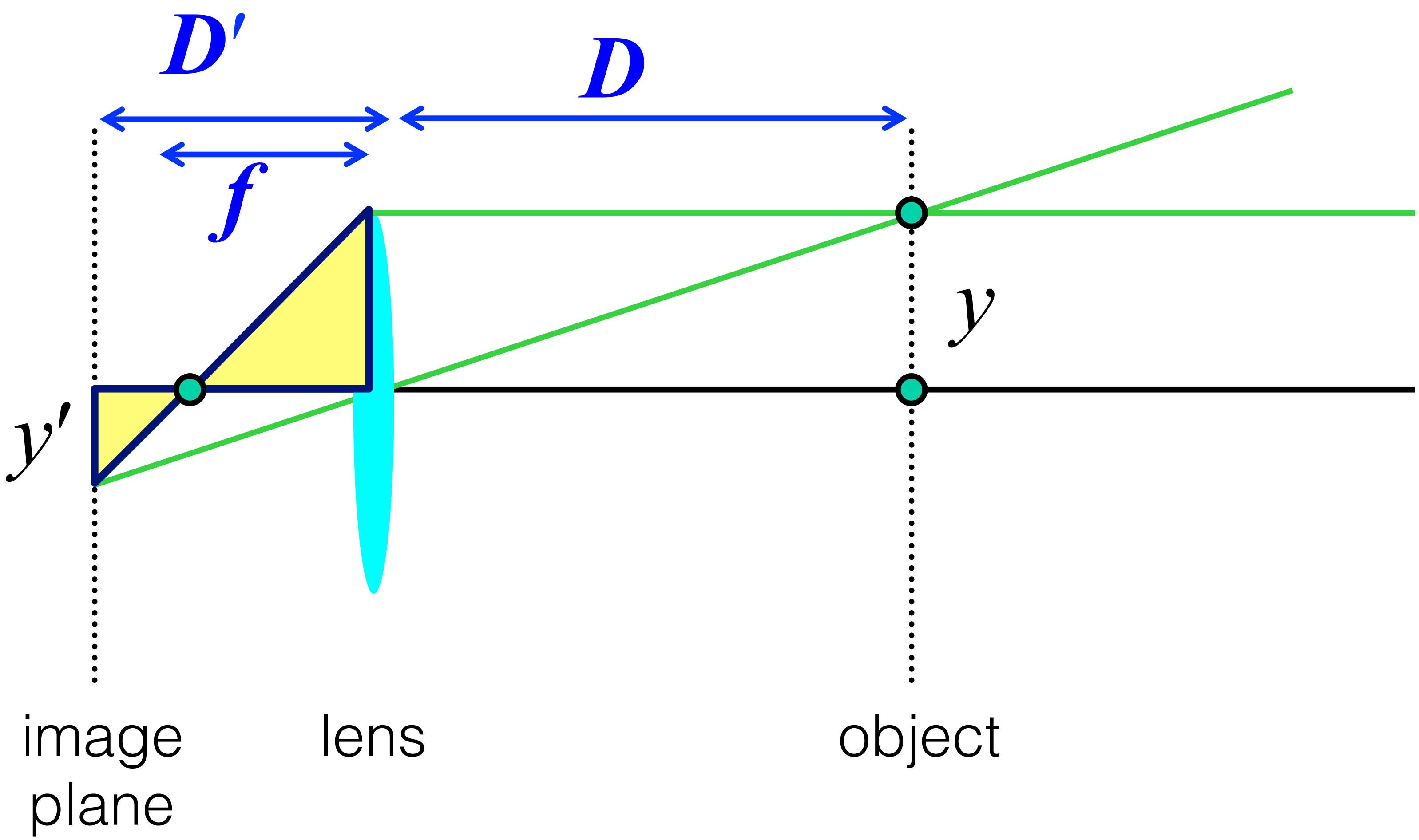
$$y'/y = (D'-f)/f$$



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

http://www.cambridgeincolour.com/tutorials/depth-of-field.htm

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

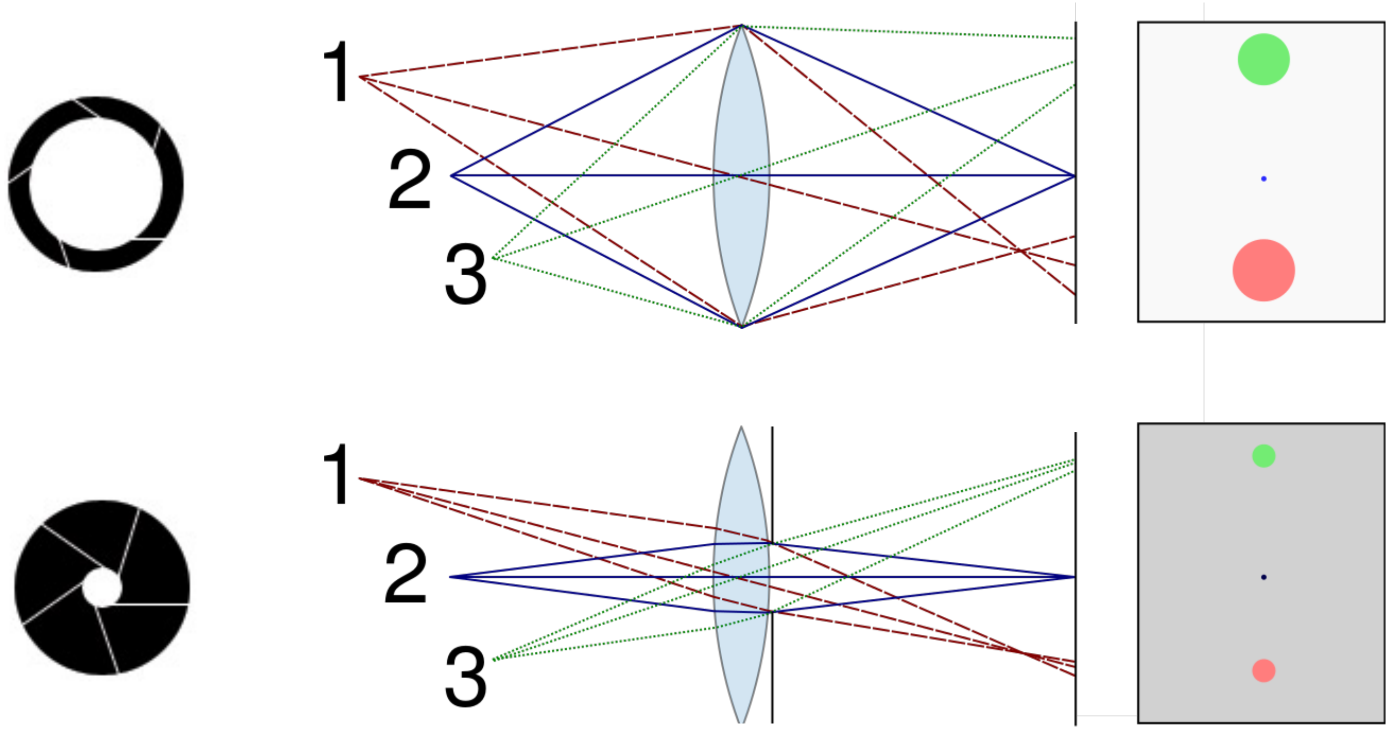
Slide by A.Efros

Varying the aperture

Large aperture = small DOF

Small aperture = large DOF

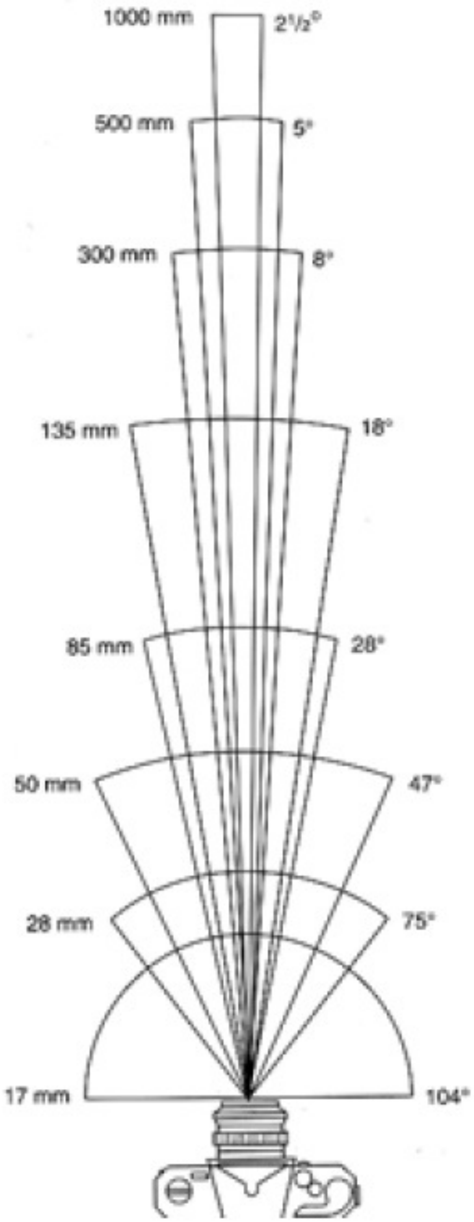
Controlling depth of field

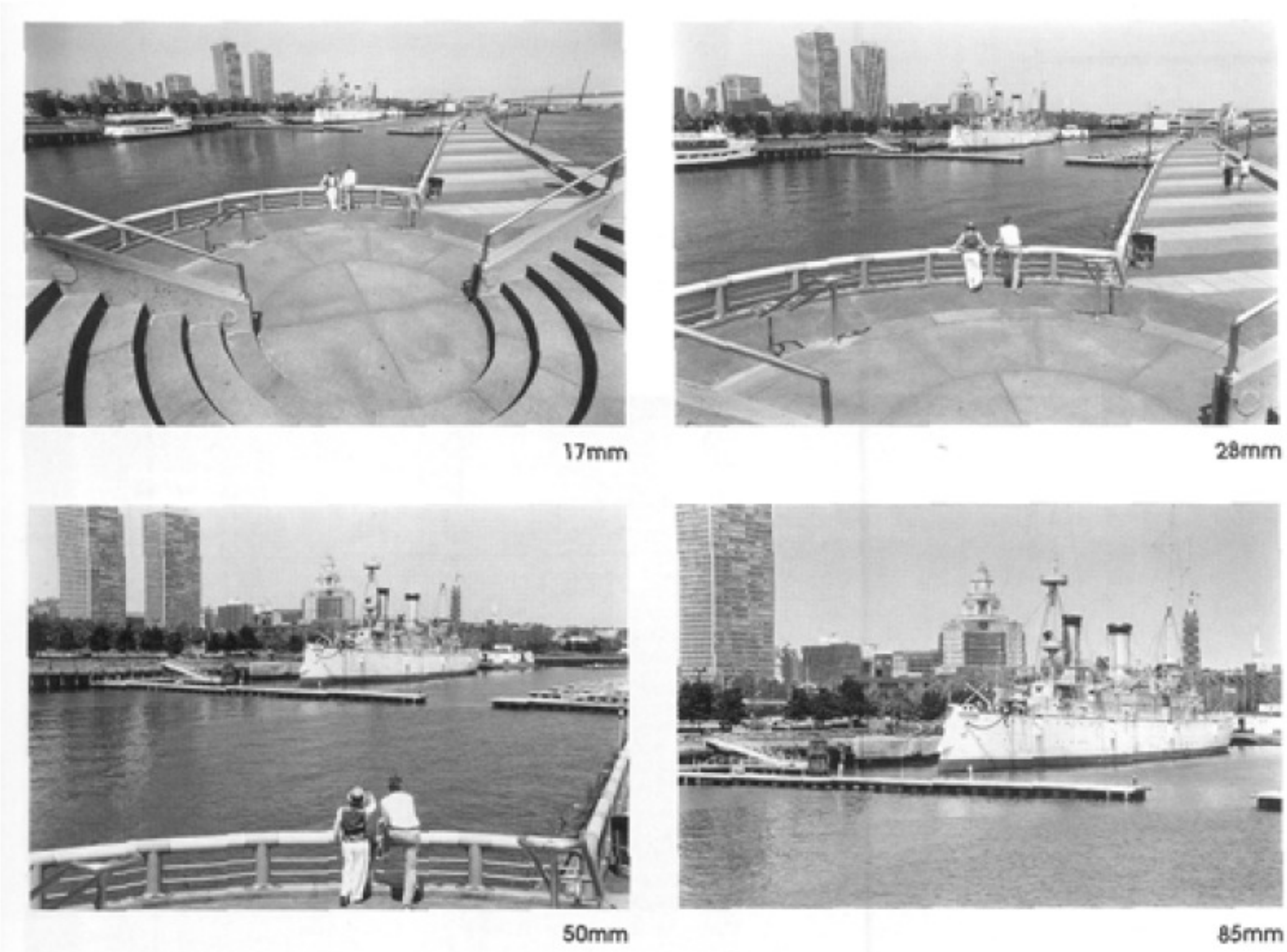


- Changing the aperture size affects the depth of field
  - A smaller aperture increases the range in which the object is approximately in focus
  - But small aperture reduces the amount of light — need to increase the exposure for contrast
  - Pinhole camera has an infinite depth of field

image credit Wikipedia

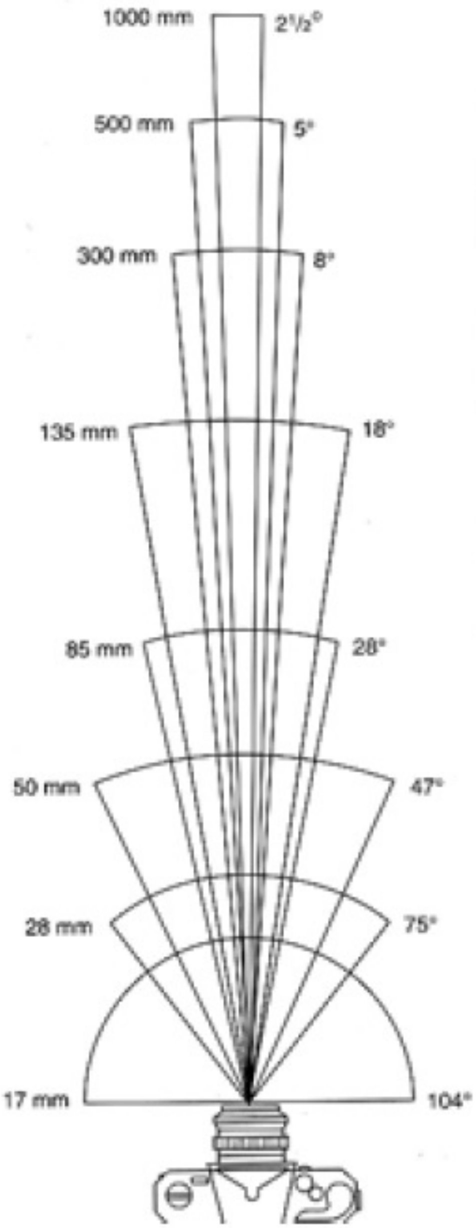
Field of view

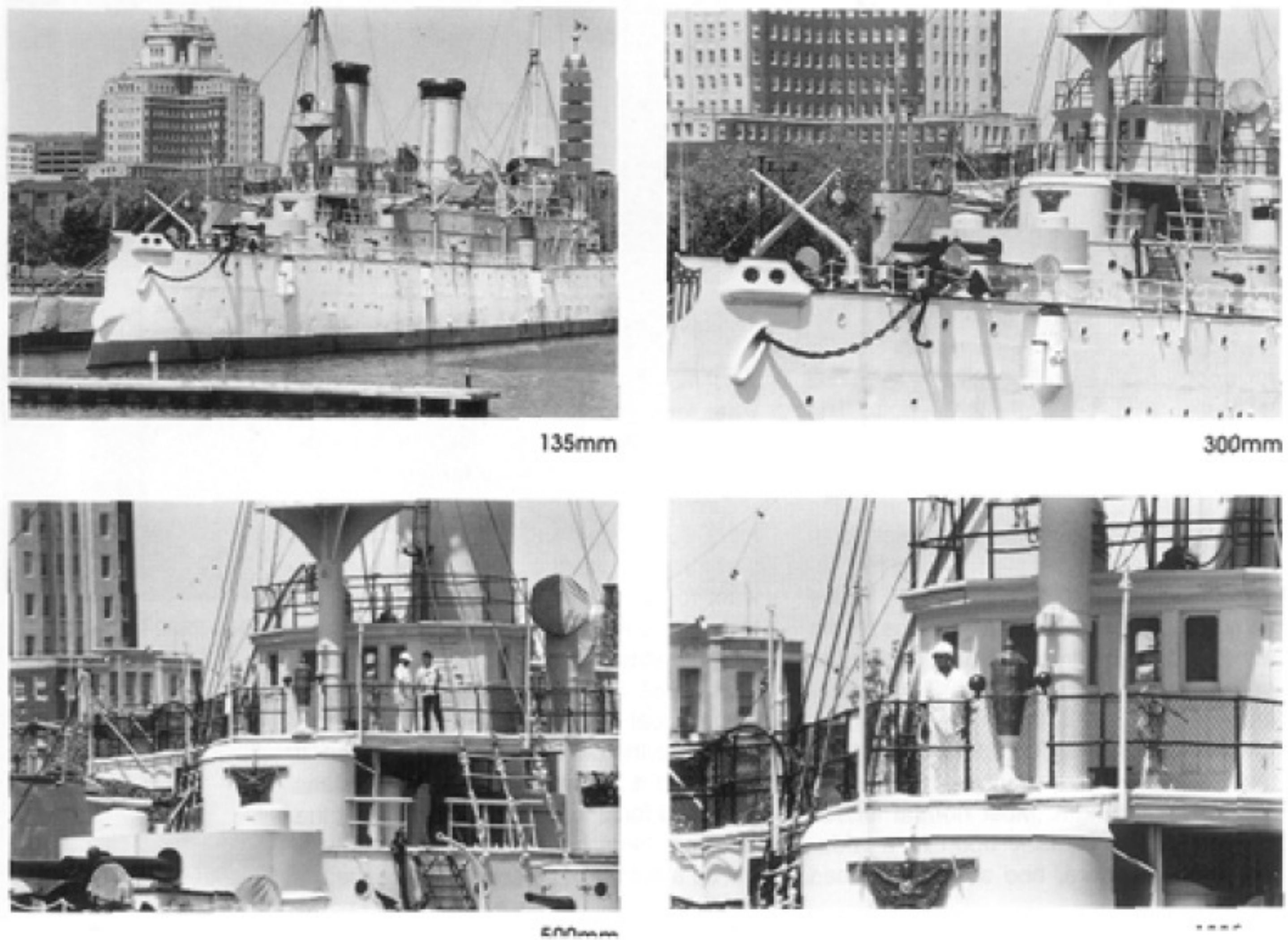




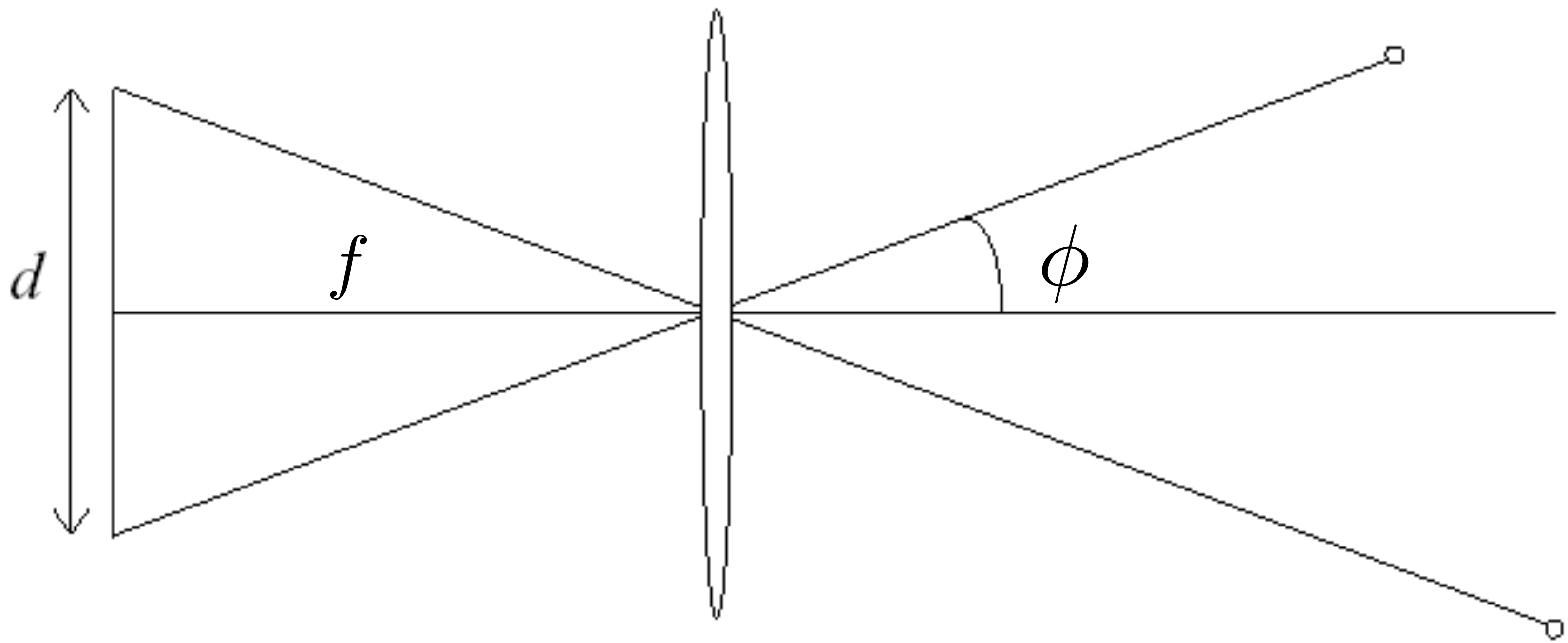
Slide by A.Efros

Field of view





Field of view

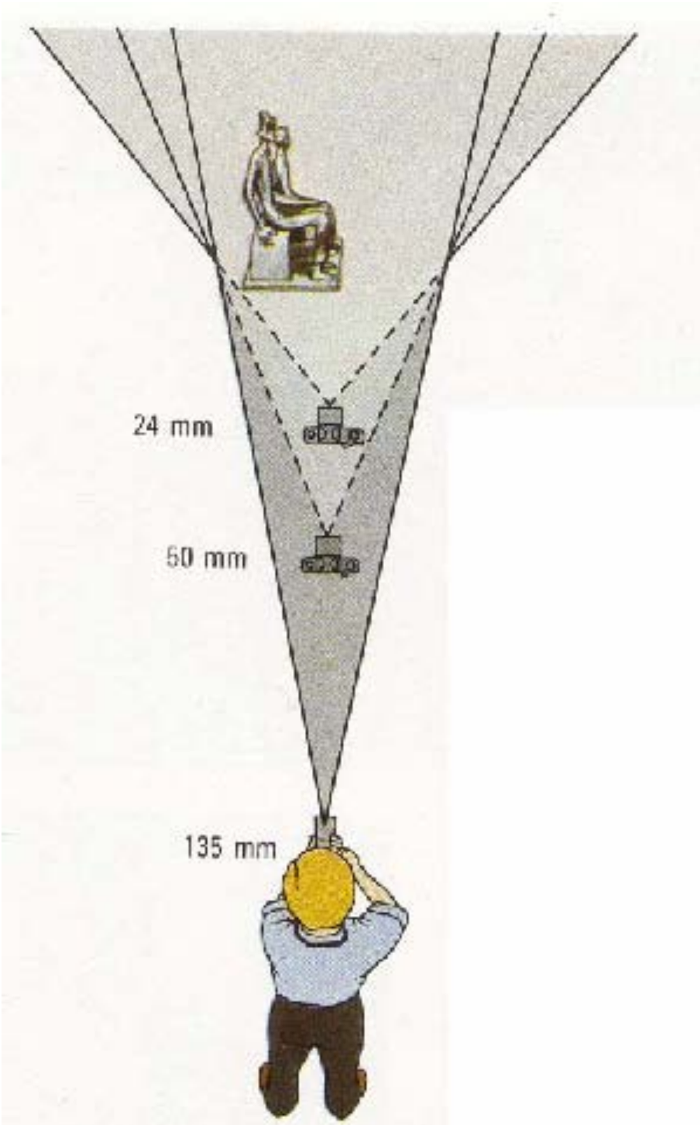


- Field of view (FOV) depends on the focal length and the size of the camera retina

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

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

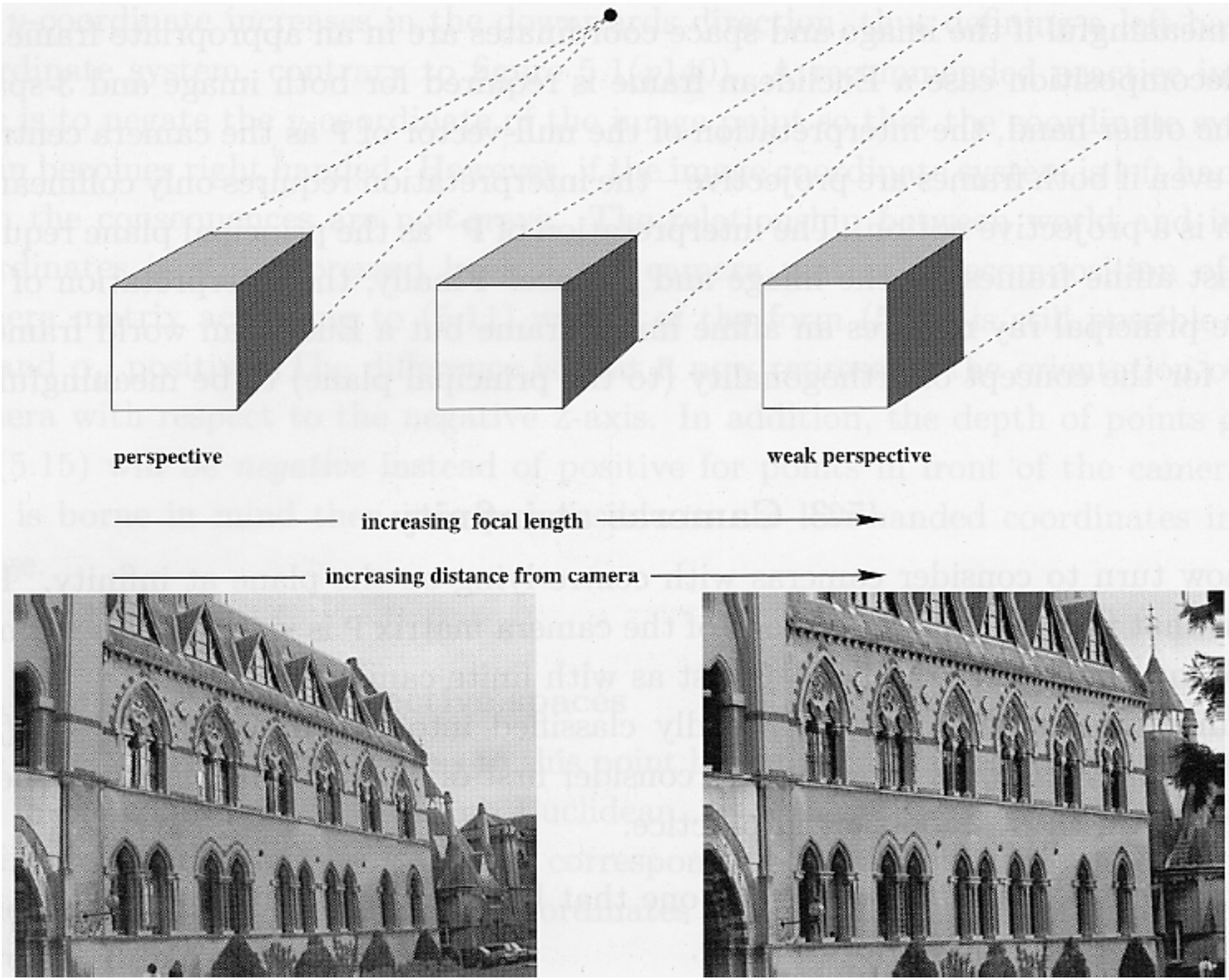
wide-angle
(short focus)

standard

telephoto
(long focus)

Slide by F.Durand

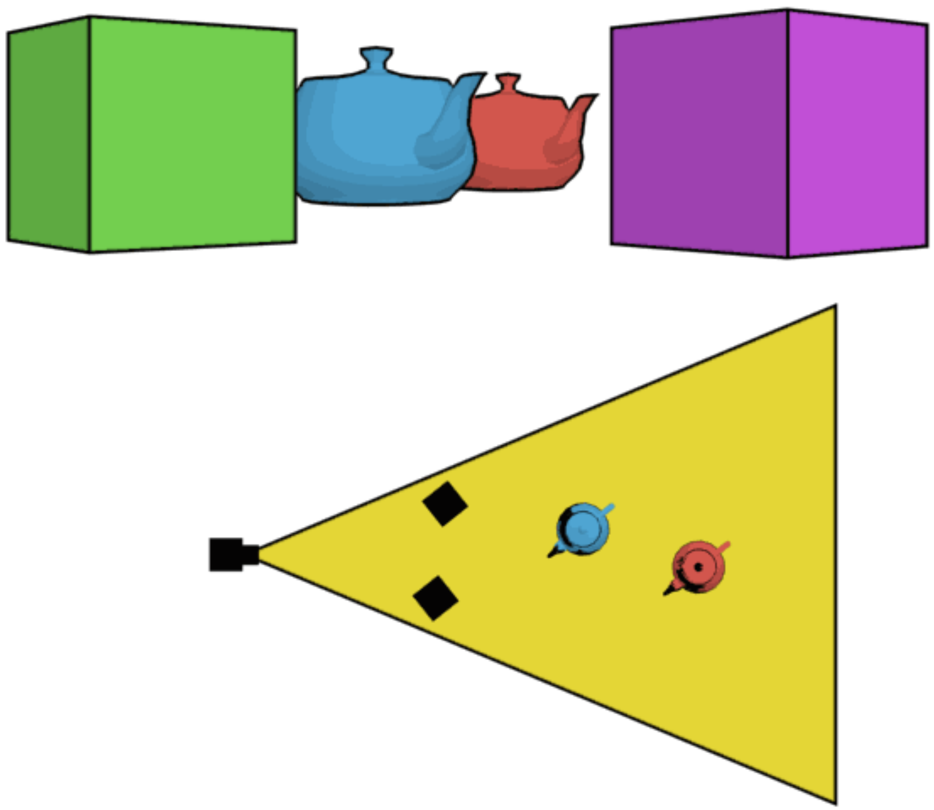
Approximating an orthographic camera



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

Image formation …

Subhransu Maji

CMPSCI 670: Computer Vision

September 13, 2016

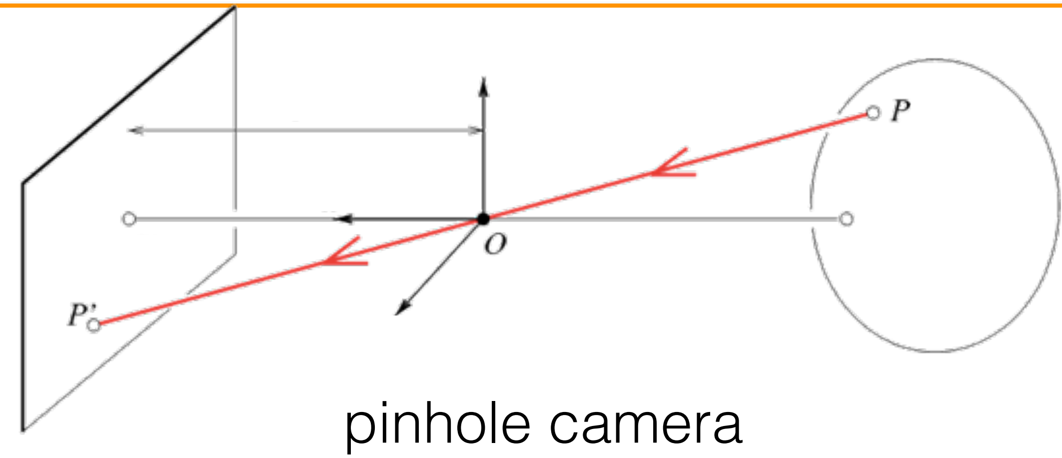
Administrivia

- Homework 01 posted
  - Due Sept 15, 1pm (That's this Thursday before class)
  - Submissions as pdf via Moodle only
    - Any combination of Latex, Word, print + scan, etc.
- Mini-project 1 posted
  - Due Sept 29

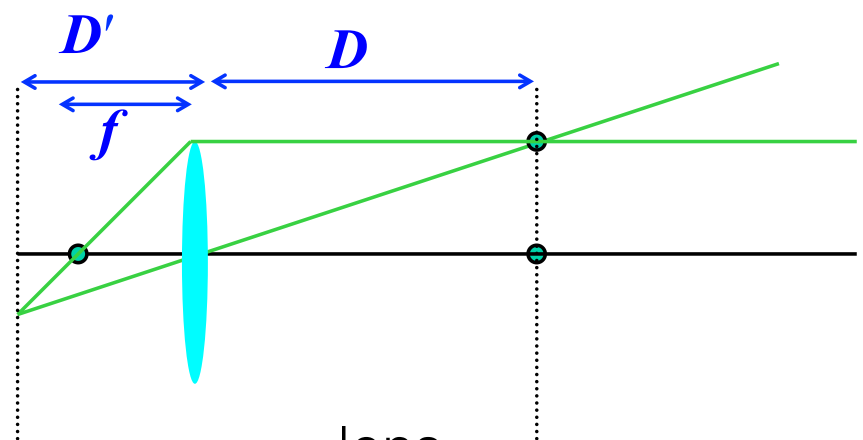
- Sign up on Piazza for announcements
  - I'll use this as the primary place for announcements
- Lecture slides and materials are posted on webpage
- TA office hours:
  - Wednesday 3-4PM, Location: CS 245
- Waitlisted students?
  - Definitely talk to me after class (OH: Today, 2:30 - 3:30pm, CS 274)

Recap of the last lecture

- The pinhole projection model
  - Qualitative properties
- Cameras with lenses
  - Depth of focus
  - Field of view
  - Lens aberrations
- Digital cameras
  - Sensors
  - Colors
  - Artifacts
- Computational photography
  - Novel sensors and cameras



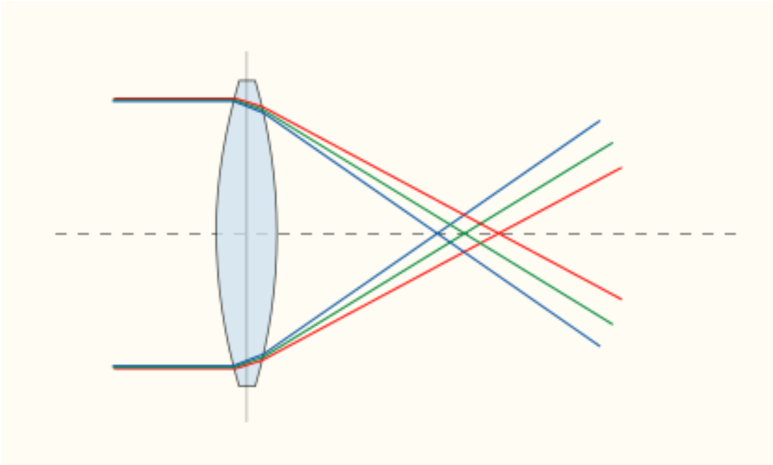
pinhole camera



lens

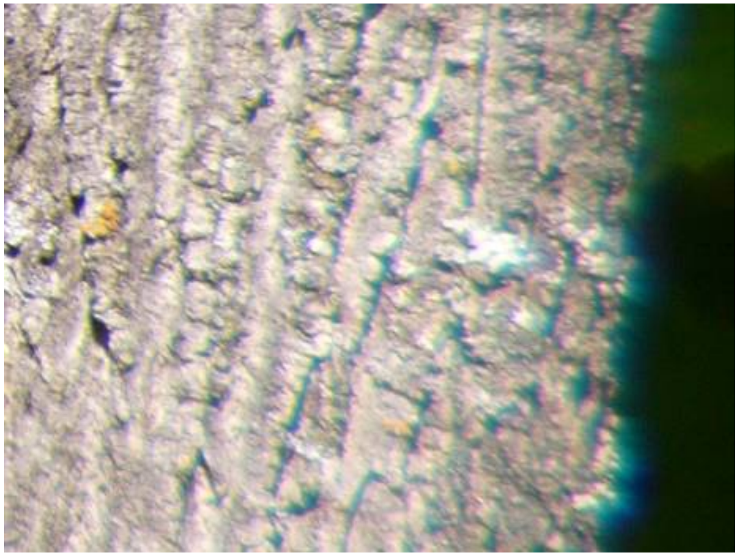
Lens flaws: Chromatic aberration

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



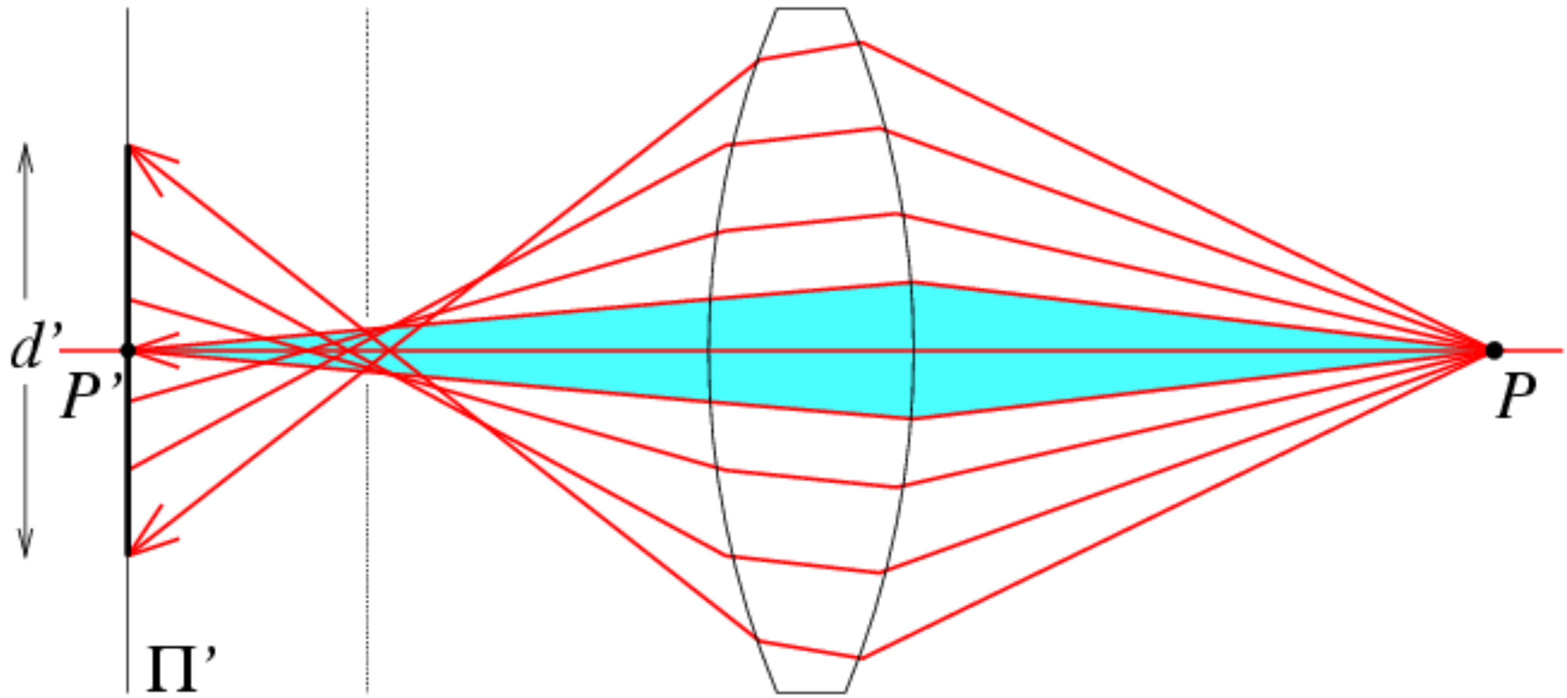
near lens center

near lens outer



Lens flaws: Spherical aberration

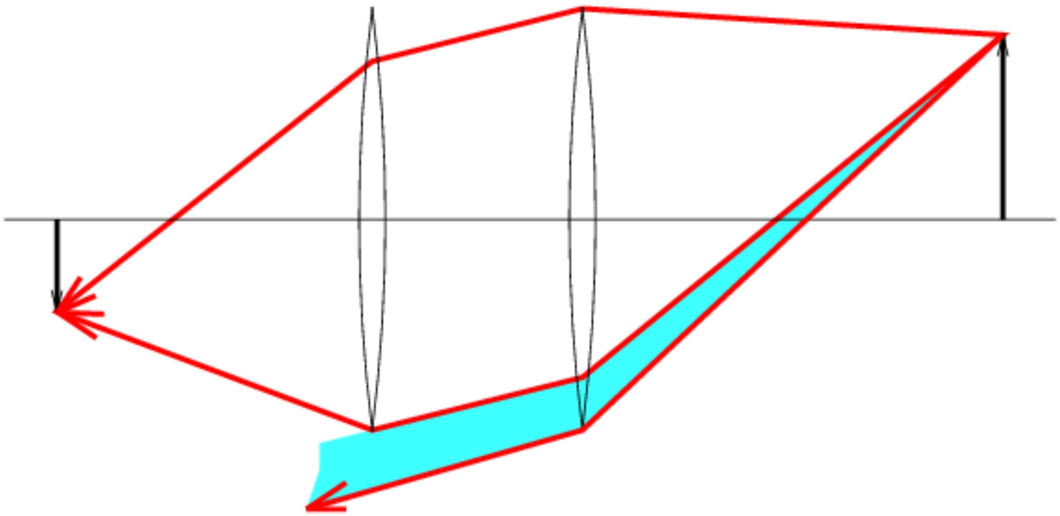
- Spherical lenses don't focus light perfectly (thin lens model)
  - Rays farther from the optical axis are focussed closer



objects lack sharpness

Lens flaws: Vignetting

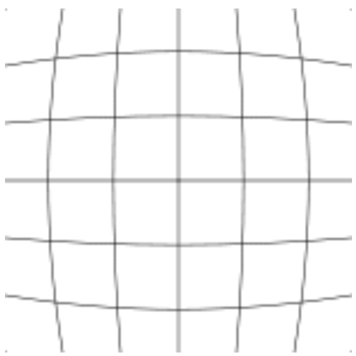
- Reduction of image brightness in the periphery



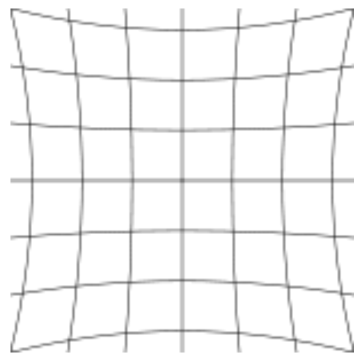
Not all rays reach the sensor

Lens flaws: Radial distortion

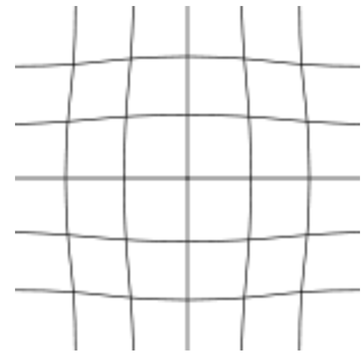
- Caused by asymmetry of lenses
- Deviations are most noticeable near the periphery



barrel distortion



pincushion distortion



mustache distortion

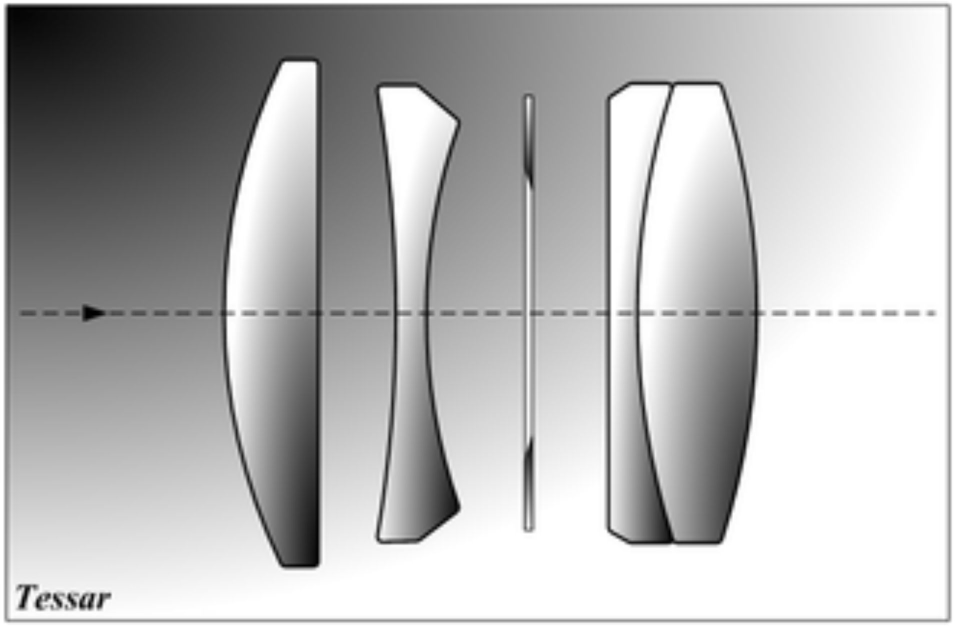
http://clanegesselphotography.blogspot.com/

http://parkingandyou.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

Overview

- The pinhole projection model
  - qualitative properties
- Cameras with lenses
  - Depth of focus
  - Field of view
  - Lens aberrations
- Digital cameras
  - Sensors
  - Colors
  - Artifacts
- Novel cameras
  - Computational photography

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

© 2002 HowStuffWorks

Early color photography

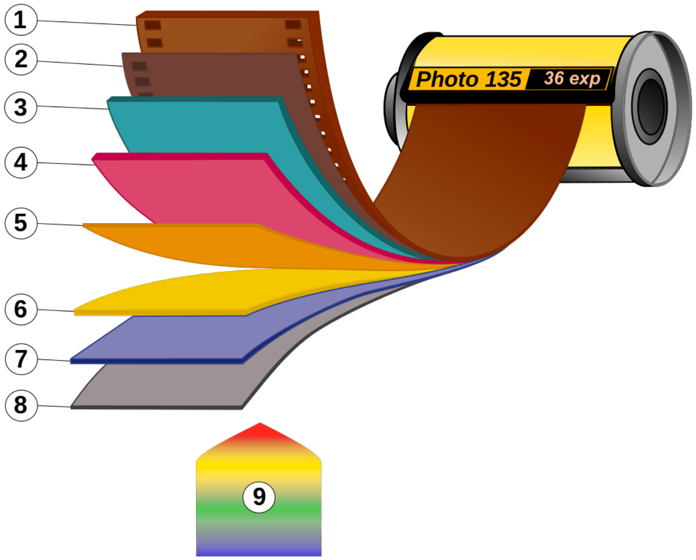
- Sergey Prokudin-Gorskii (1863-1944)
- Photographs of the Russian empire (1909-1916)

Only problem!

Homework 1: fix this by aligning the channels

Measuring light: color films

- **Color photographic film** — many layers of dyes and light sensitive materials to capture light of different frequencies simultaneously
  - Kodak pioneered color films for making paper prints
- Simultaneous measurement solves the alignment problem
  - But needs complex film design and development process



Digital images

- Color images are commonly represented using 3 channels [R, G, B]
  - The color of each pixel is given by the (r,g,b) value

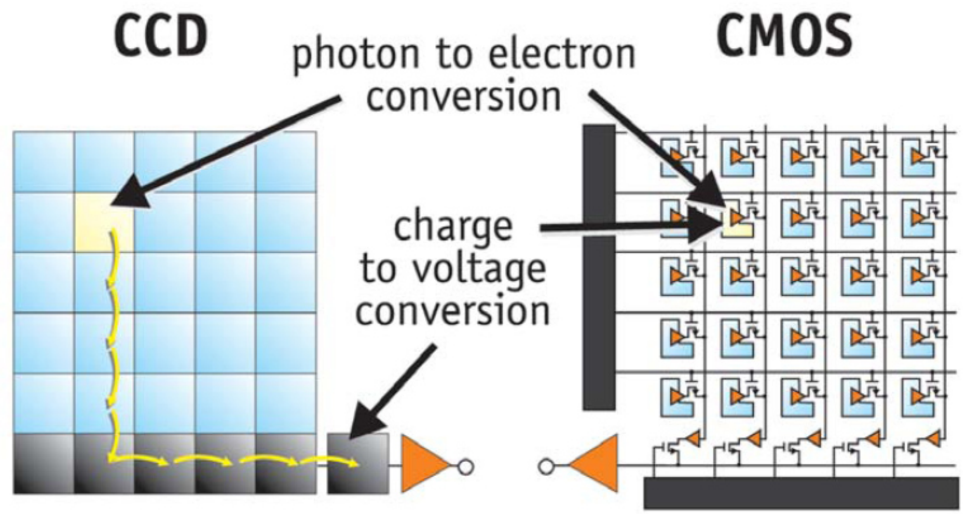
```
>> im = imread('jelly.jpg');
>> whos im
  Name         Size                Bytes  Class    Attributes

  im         428x570x3            731880  uint8

>> imshow(im);
>> imshow(im(:,:,1));
>> imshow(im(:,:,2));
>> imshow(im(:,:,3));
```

red

green

blue

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.

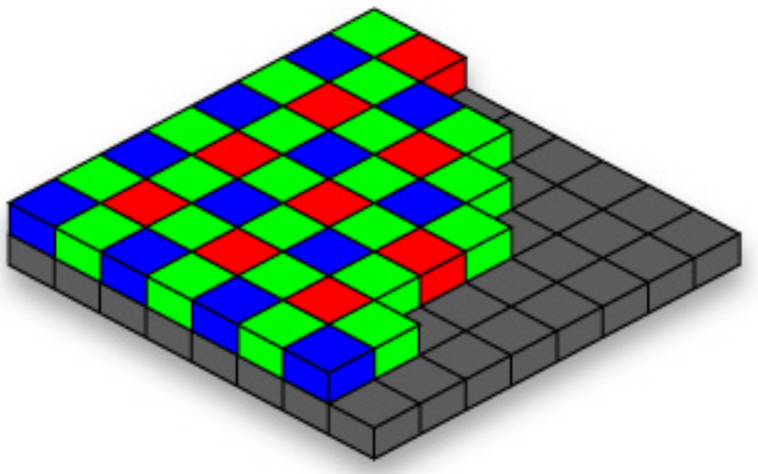
- A digital camera replaces the film with a sensor array
  - Each cell in the array is a light-sensitive diode that converts photons to electrons
  - Two common types of sensor arrays
    - Charge Coupled Device (CCD)
    - Complementary Metal Oxide Semiconductor (CMOS)

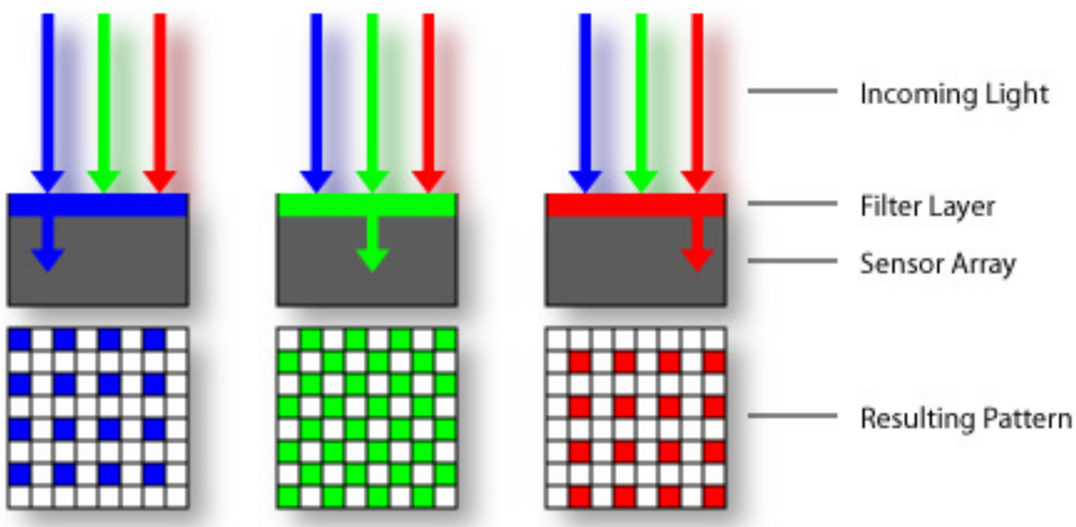
http://electronics.howstuffworks.com/digital-camera.htm

Color sensing in the camera

Color filter array

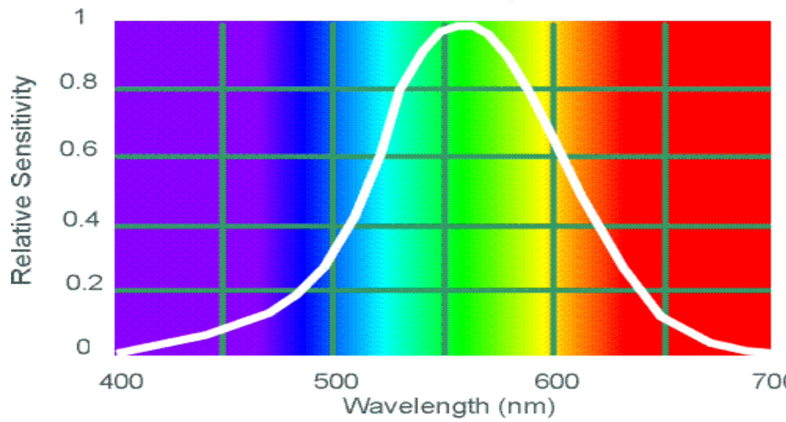
Bayer grid





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

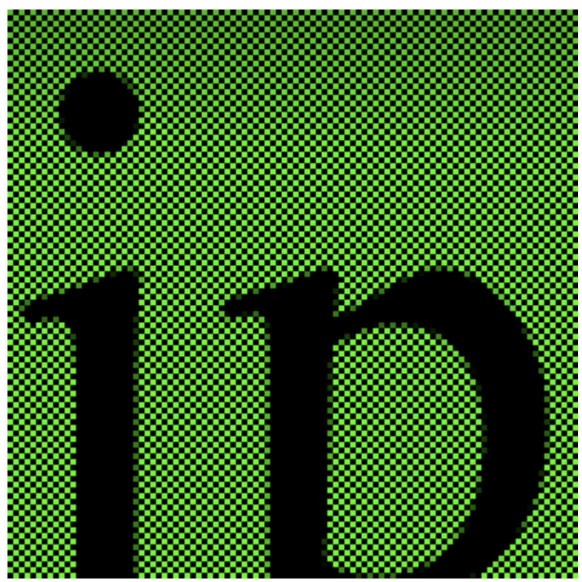
Why more green?



Human luminance sensitivity function

Demosaicing

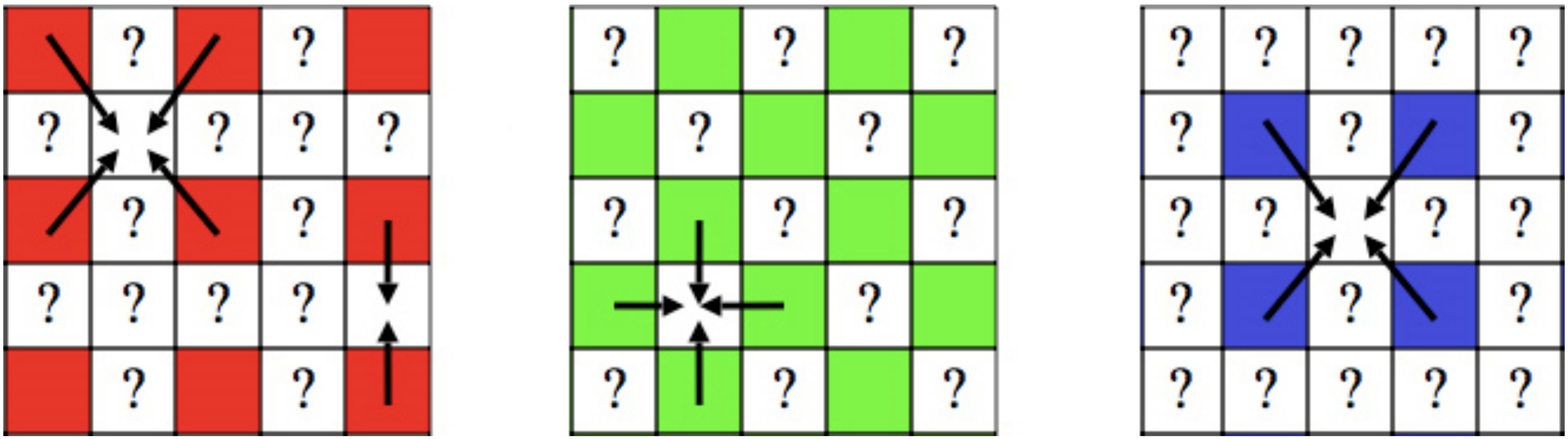
Red



Green

Blue

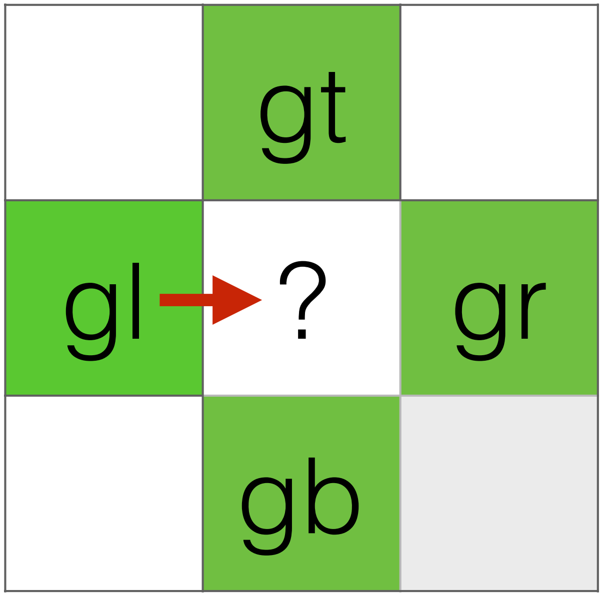
Demosaicing



- **Problem:** guess the values of ? in each of the three channels

- Why is this even possible?

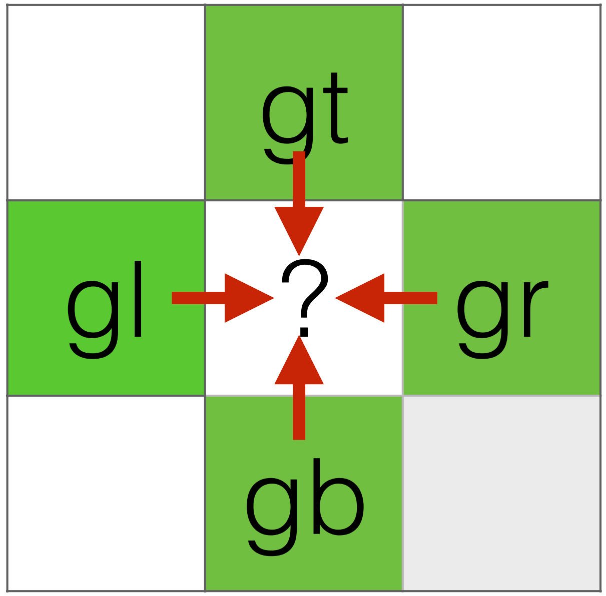
Interpolation



nearest neighbor

copy one of your neighbors

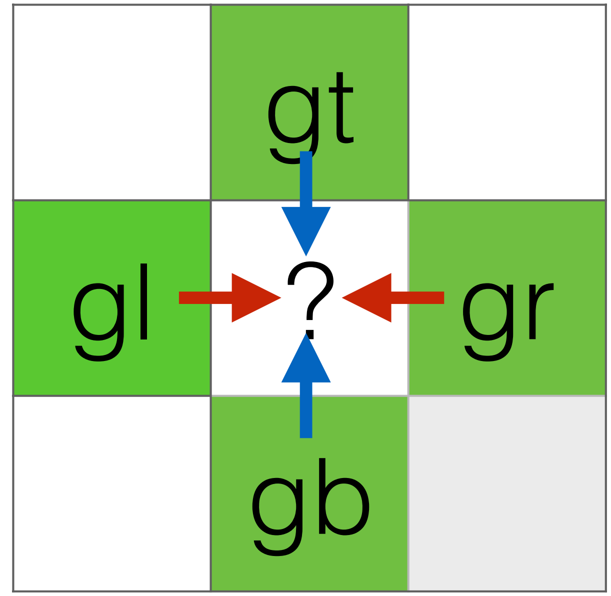
? ← gl



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

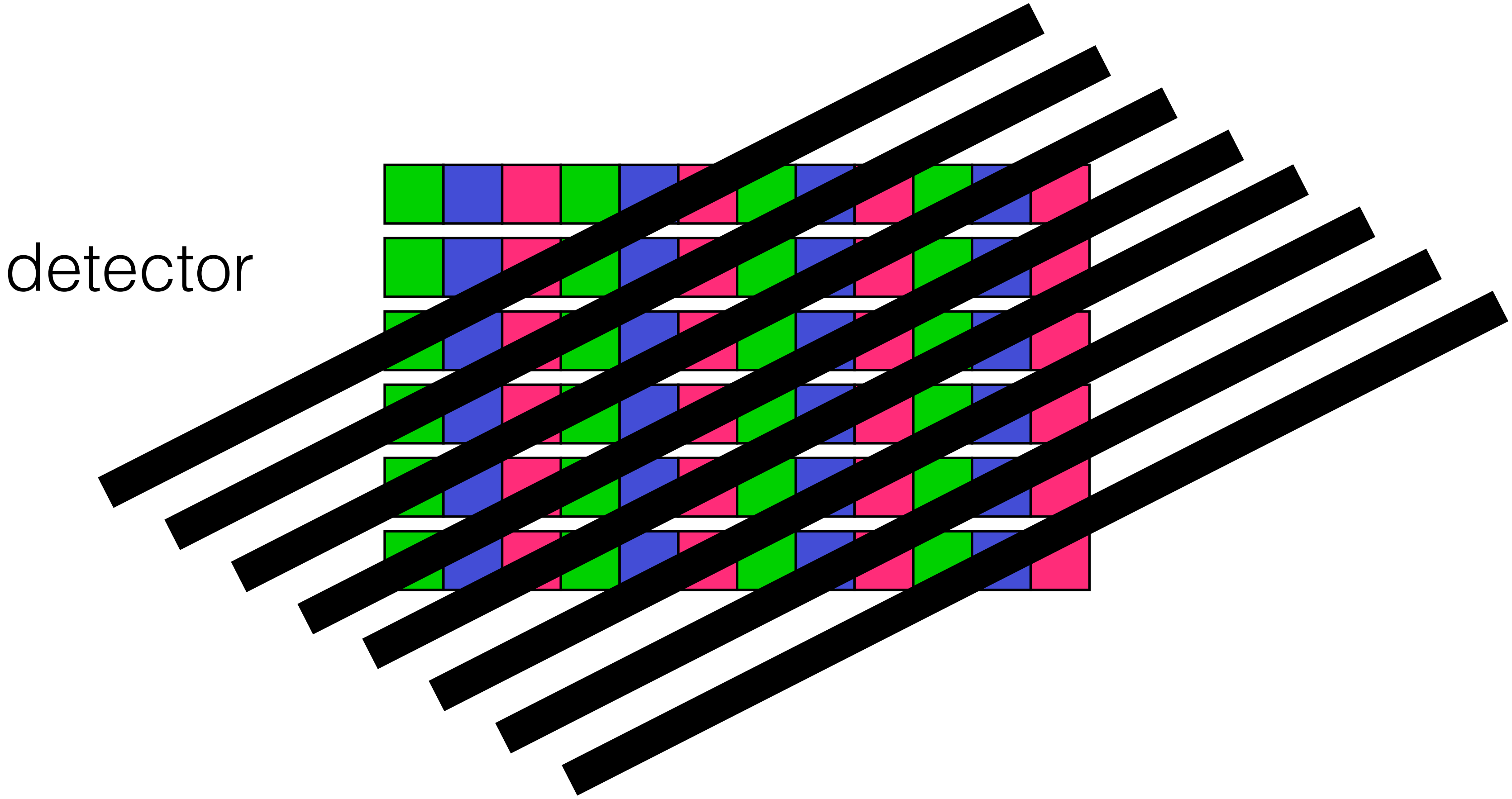
Similarly for the blue and red channels

Homework 1: implement this

Problem with demosaicing: color moiré

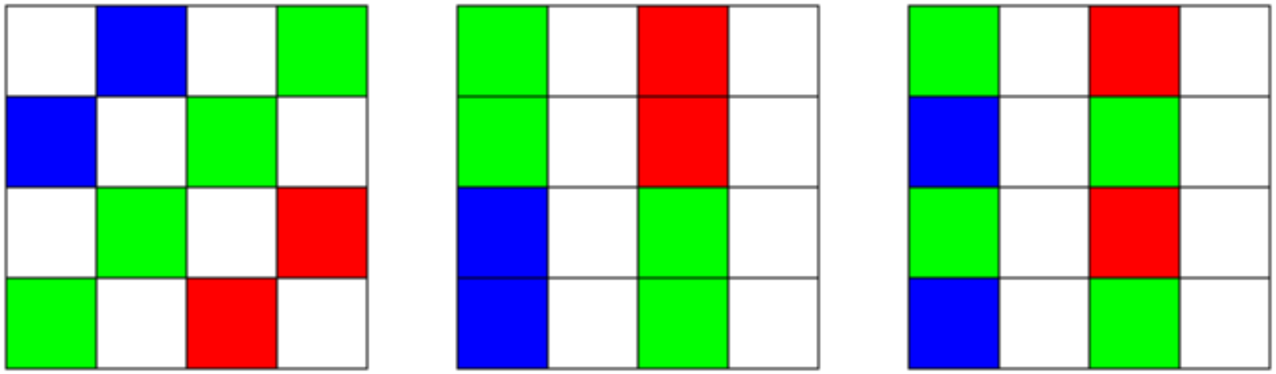
Slide by F.Durand

The cause of color moiré

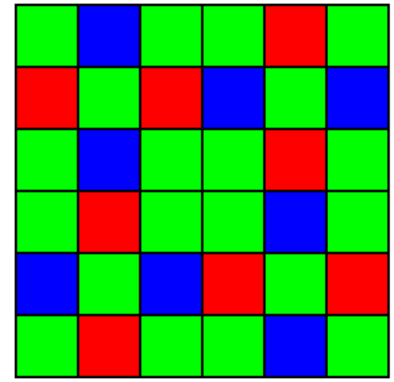


Fine black and white detail in the image scene
is misinterpreted as color information

Alternatives to Bayer filter



Three new Kodak RGBW filter patterns

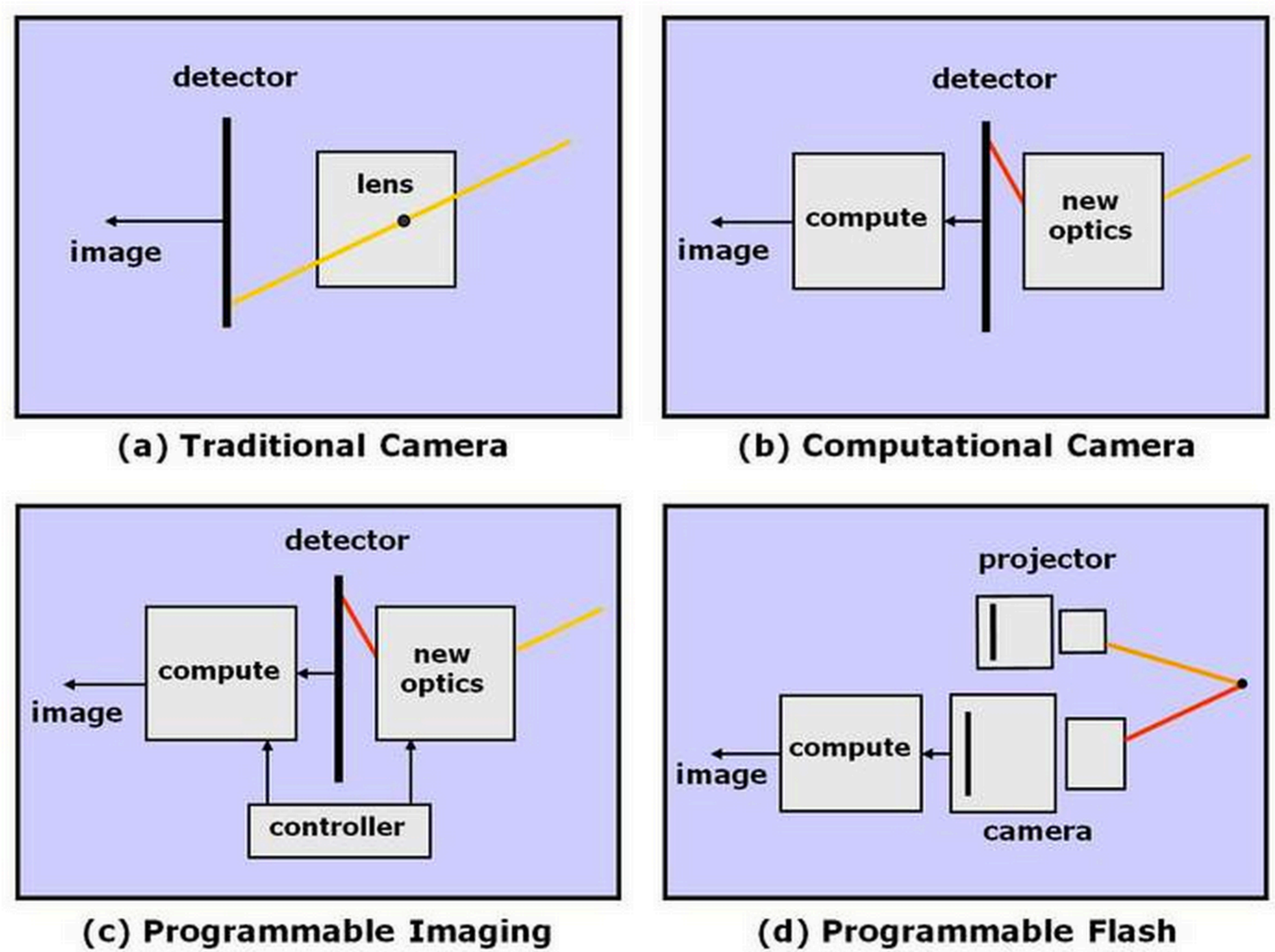


Fujifilm "X-Trans" filter

- White or “panchromatic” cells allow lights across all wavelengths
  - Better light efficiency
- How would you go about picking the best one?

Source: https://en.wikipedia.org/wiki/Bayer_filter

Computational cameras



S.K. Nayar http://www1.cs.columbia.edu/CAVE/projects/what_is/

Computational color photography

- **Goal:** Design a sampling pattern + interpolation algorithm that archives the best color reconstruction

- Sampling patterns
  - Given a nxn filter array we have $4^{(nxn)}$ possible choices
    - ➡ More choices if we allow different color filters
  - Some patterns are obviously bad for reconstruction

- Interpolation algorithms
  - Can’t easily enumerate this space
  - Non trivial algorithms for interpolation

Rethinking Color Cameras

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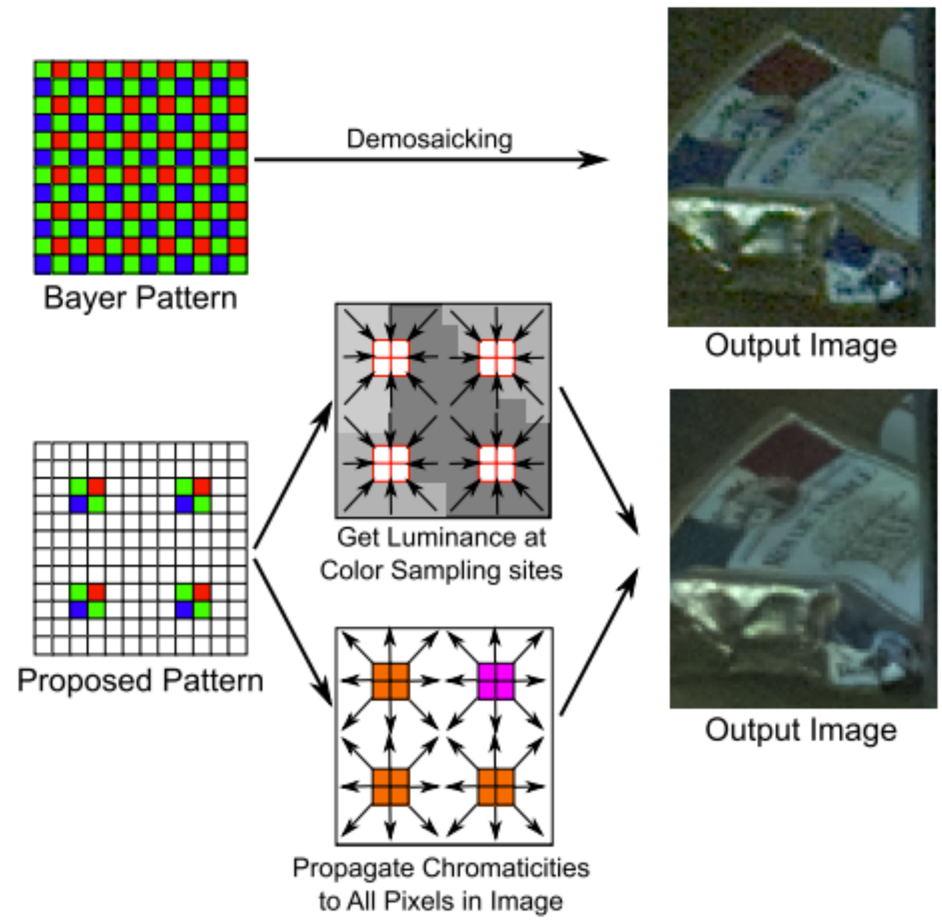
Abstract

Digital color cameras make sub-sampled measurements of color at alternating pixel locations, and then "demosaick" these measurements to create full color images by up-sampling. This allows traditional cameras with restricted processing hardware to produce color images from a single shot, but it requires blocking a majority of the incident light and is prone to aliasing artifacts. In this paper, we introduce a computational approach to color photography, where the sampling pattern and reconstruction process are co-designed to enhance sharpness and photographic speed. The pattern is made predominantly panchromatic, thus avoiding excessive loss of light and aliasing of high spatial-frequency intensity variations. Color is sampled at a very sparse set of locations and then propagated throughout the image with guidance from the un-aliased luminance channel. Experimental results show that this approach often leads to significant reductions in noise and aliasing arti-



linearly interpolate color value using intensity-based affinities

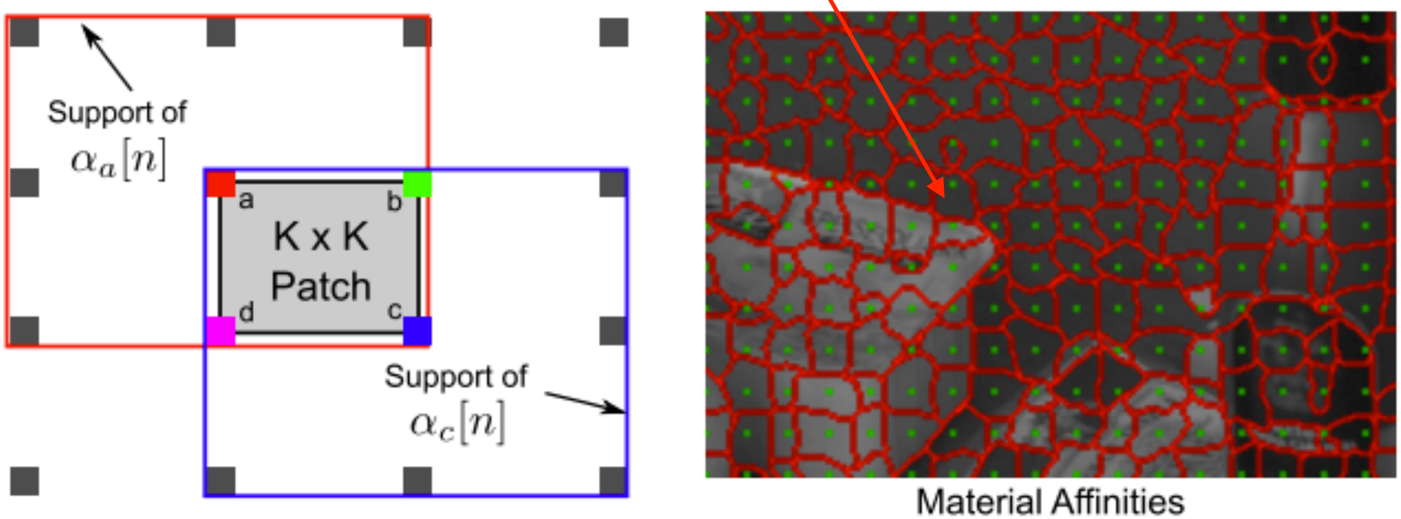
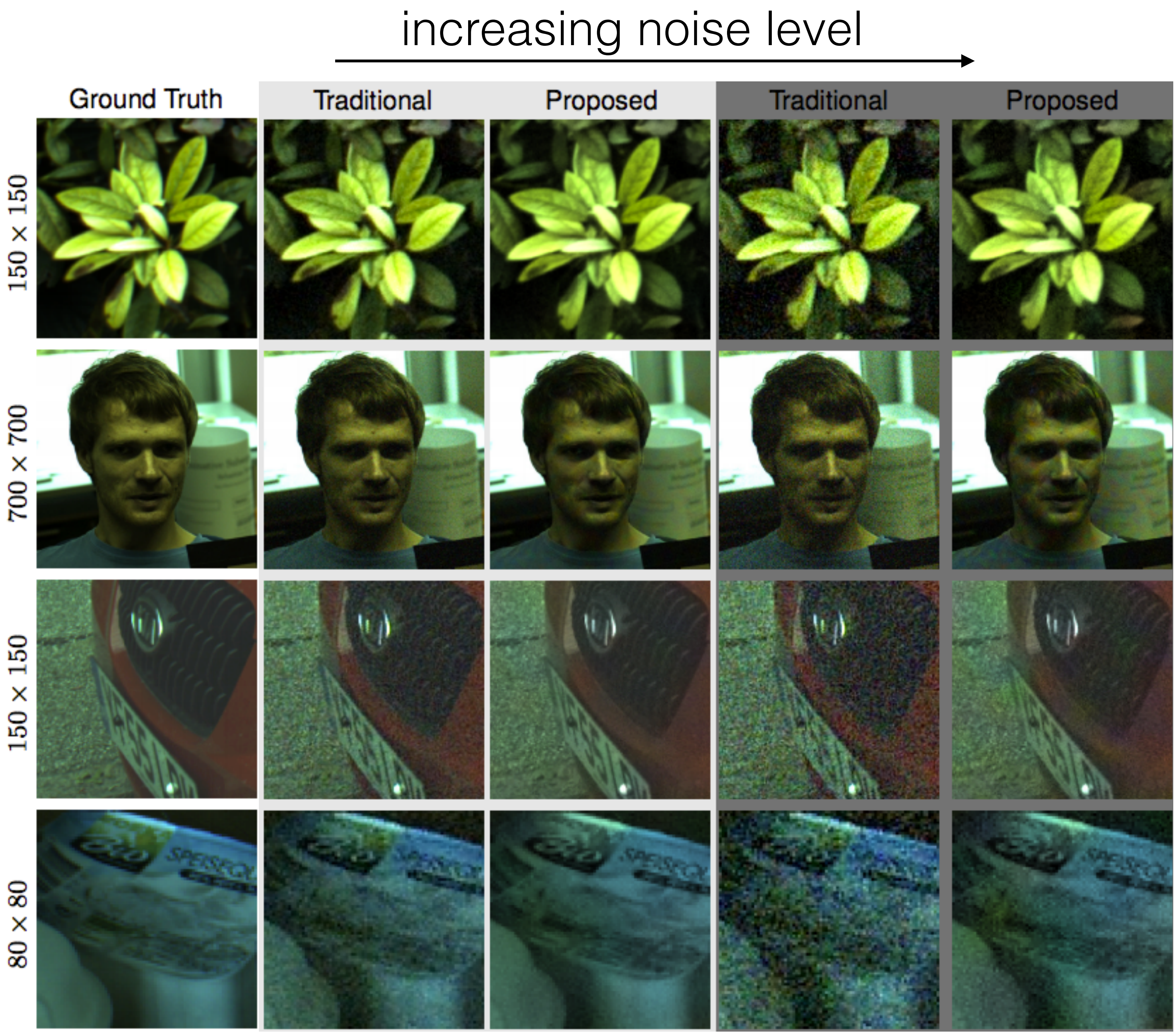


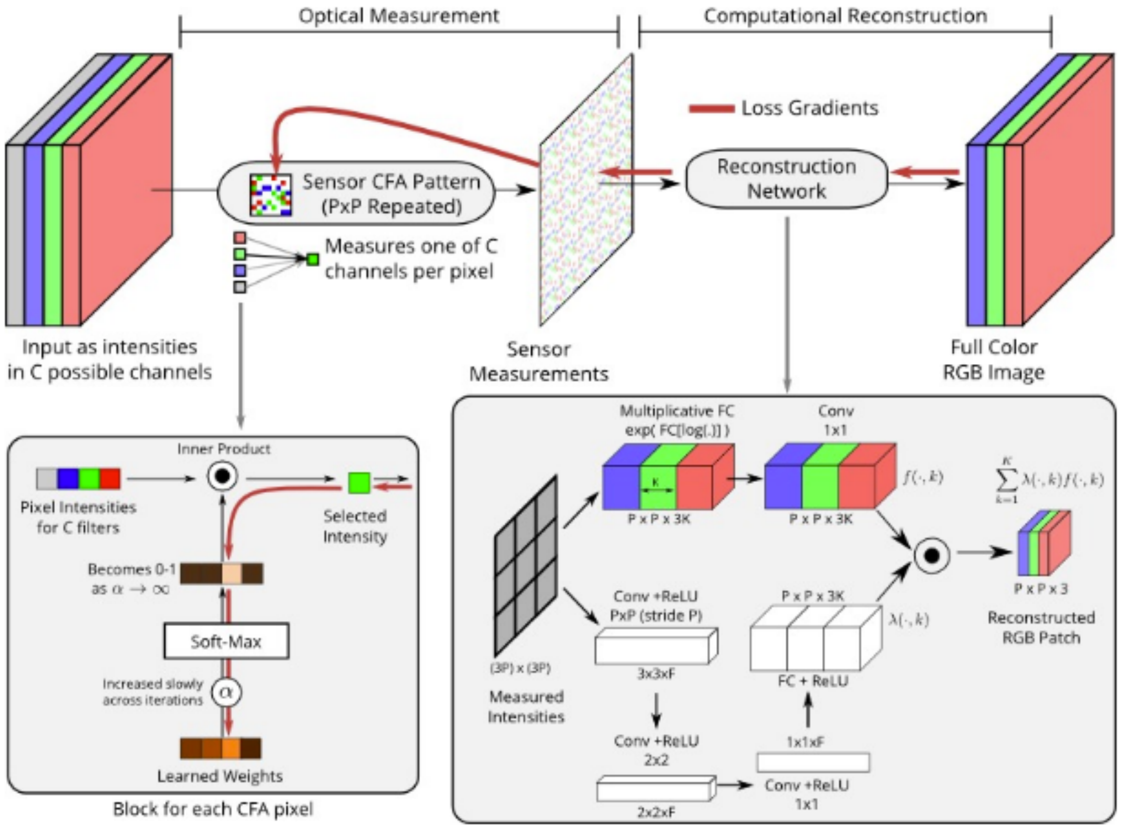
Figure 2. Propagating chromaticity with material affinities. *Left*: Chromaticities at pixels within each $K \times K$ patch are computed as convex combinations of chromaticities measured by the Bayer blocks at its corners. The combination weights are determined by four affinity maps $\alpha_j[n]$, one from each corner Bayer block j, that encode luminance edge information. *Right*: Affinity map showing regions of pixels with highest affinity to each block (marked in green), super-imposed on the corresponding luminance image.


increasing noise level
Ground Truth
Traditional
Proposed
Traditional
Proposed
150 × 150
700 × 700
150 × 150
80 × 80

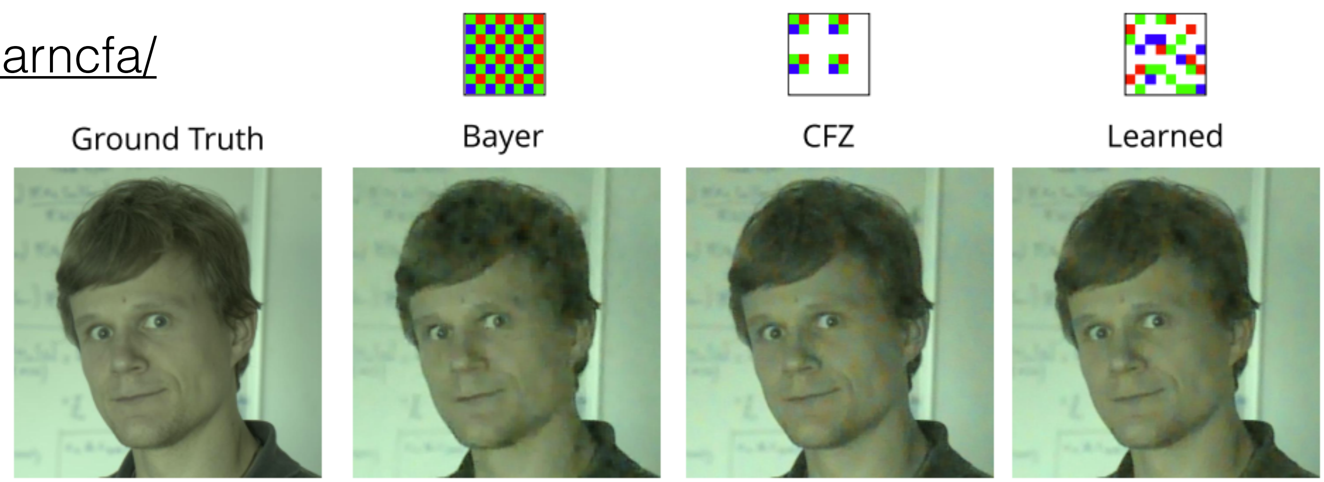
Learning Sensor Multiplexing Design through Back-propagation

Ayan Chakrabarti

To appear at NIPS'16

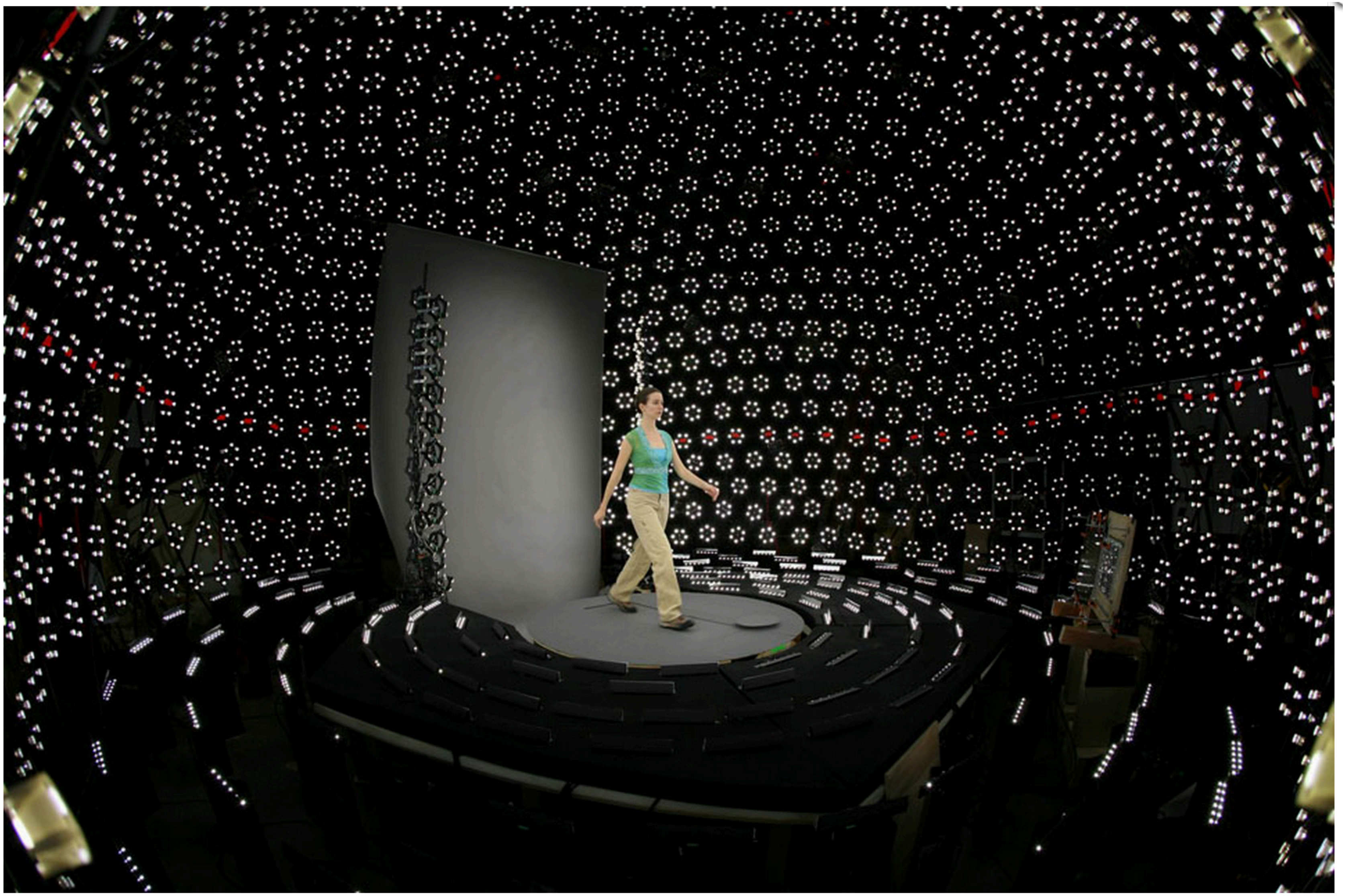


http://ttic.uchicago.edu/~ayanc/learncfa/



Light Stage 6

- Sample over time, lighting, viewing direction, pose

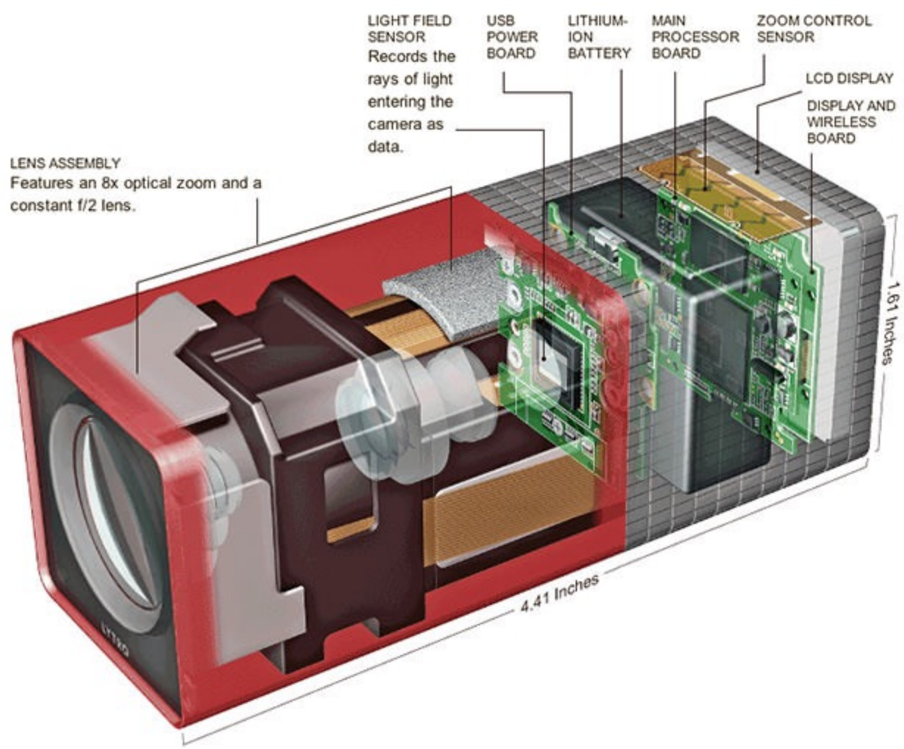


inside Light Stage 6

Paul Debevec's group at USC-ICT http://ict.usc.edu/prototypes/light-stages/

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



More readings and thoughts

- **History of optics**, Wikipedia
- A. Torralba and W. Freeman, **Accidental Pinhole and Pinspeck Cameras**, CVPR 2012
- DIY **http://www.pauldebevec.com/Pinhole**
- In MATLAB, compute the projection of a sphere using the perspective model and visualize the distortions
- Light stages over time **http://gl.ict.usc.edu/LightStages**
- Sergey Prokudin-Gorskii photographic collection at the Library of Congress **http://www.loc.gov/exhibits/empire/index.html**
- Richard Szeliski's book, Sections 2.2.3 - 2.3.2