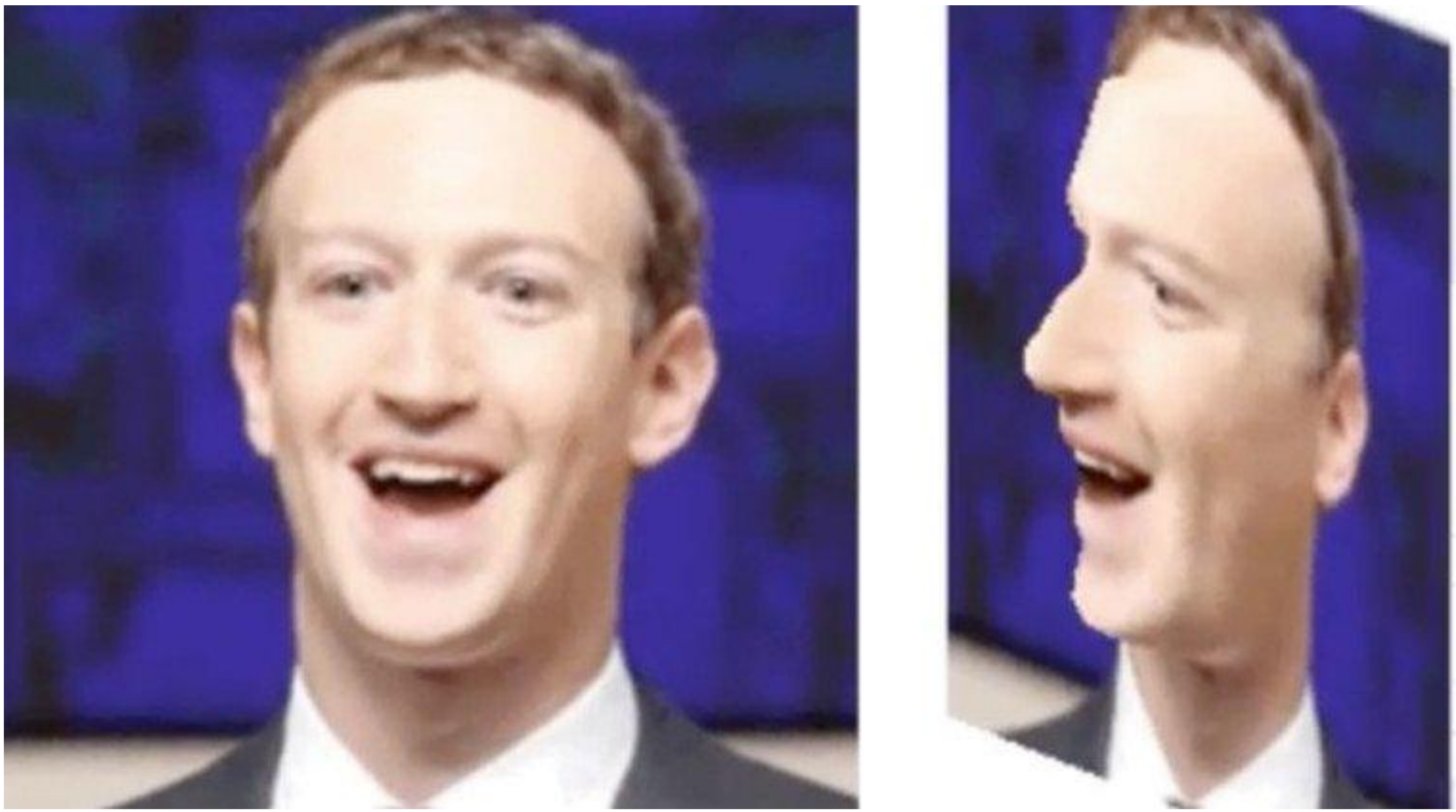
CSCE 448/748 - Computational Photography

Stereo

Nima Kalantari

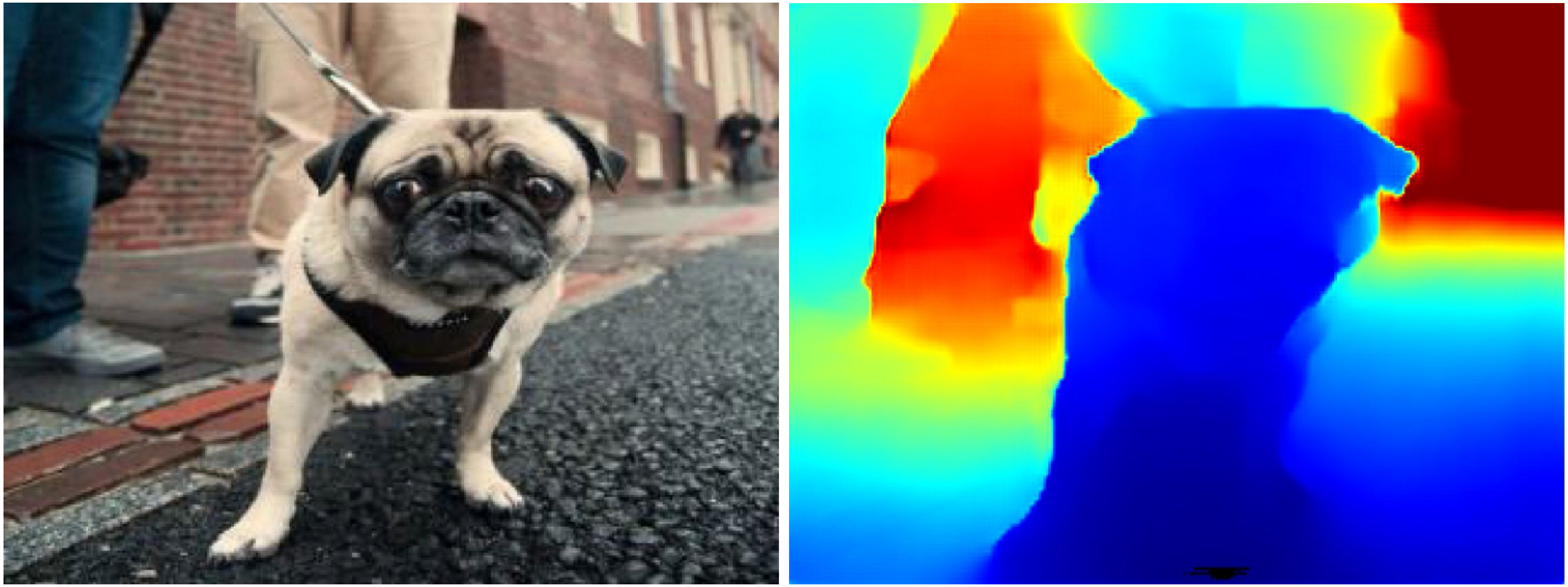
Many slides from Steve Seitz

Depth of a scene



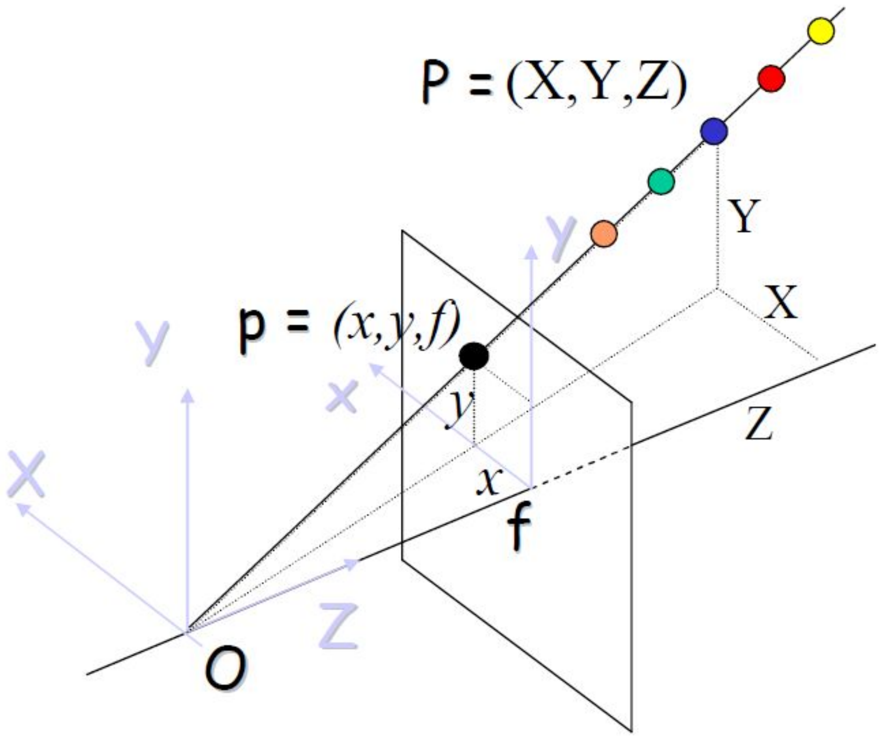
Credit: PetaPixel

Depth of a scene



Credit: Li & Snavely

Depth ambiguity



$$x = f\,\frac{X}{Z} = f\,\frac{kX}{kZ}$$

$$y = f\,\frac{Y}{Z} = f\,\frac{kY}{kZ}$$

Fundamental Ambiguity:
Any point on the ray OP has image p

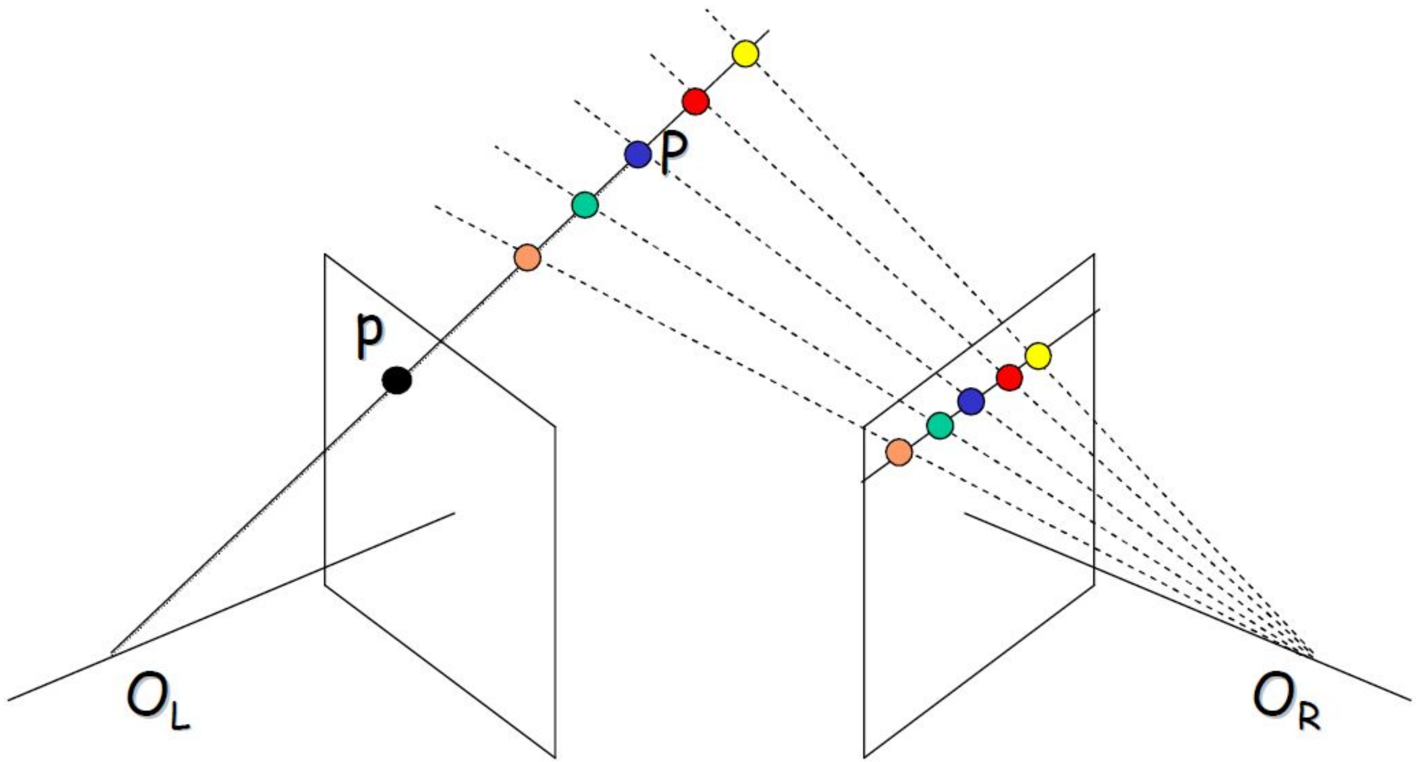
Depth ambiguity

Images from Lana Lazebnik

Forced Perspective

https://www.youtube.com/watch?v=QWMFpxkGO_s

Why Stereo Vision?



A second camera can resolve the ambiguity, enabling measurement of depth via triangulation.

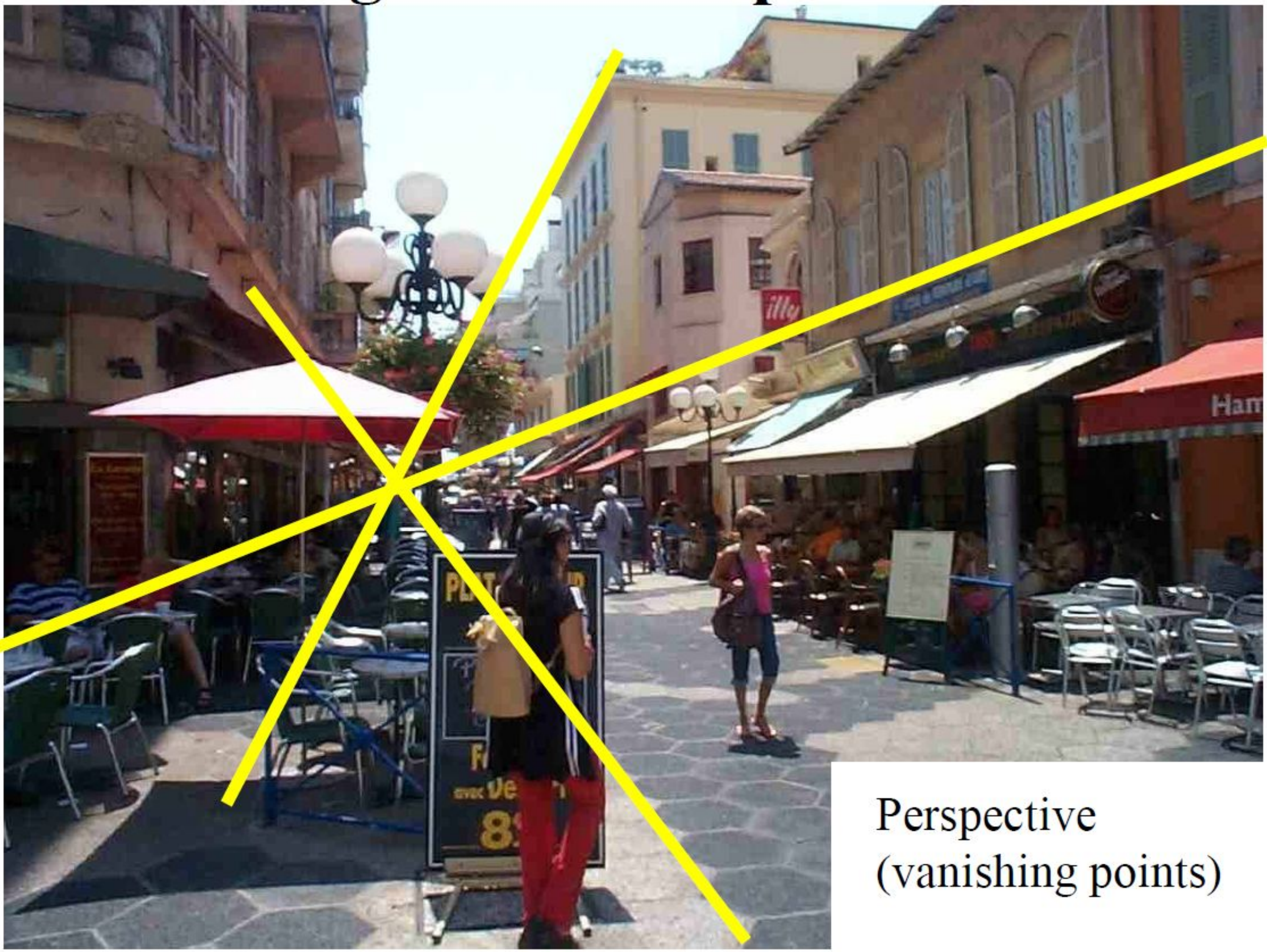
Stereo Vision

- Not that important for humans, especially at longer distances. Perhaps 10% of people are stereo blind.
- Many animals don't have much stereo overlap in their fields of view

What cues help us to perceive 3d shape and depth?

Robert Collins
CSE486, Penn State

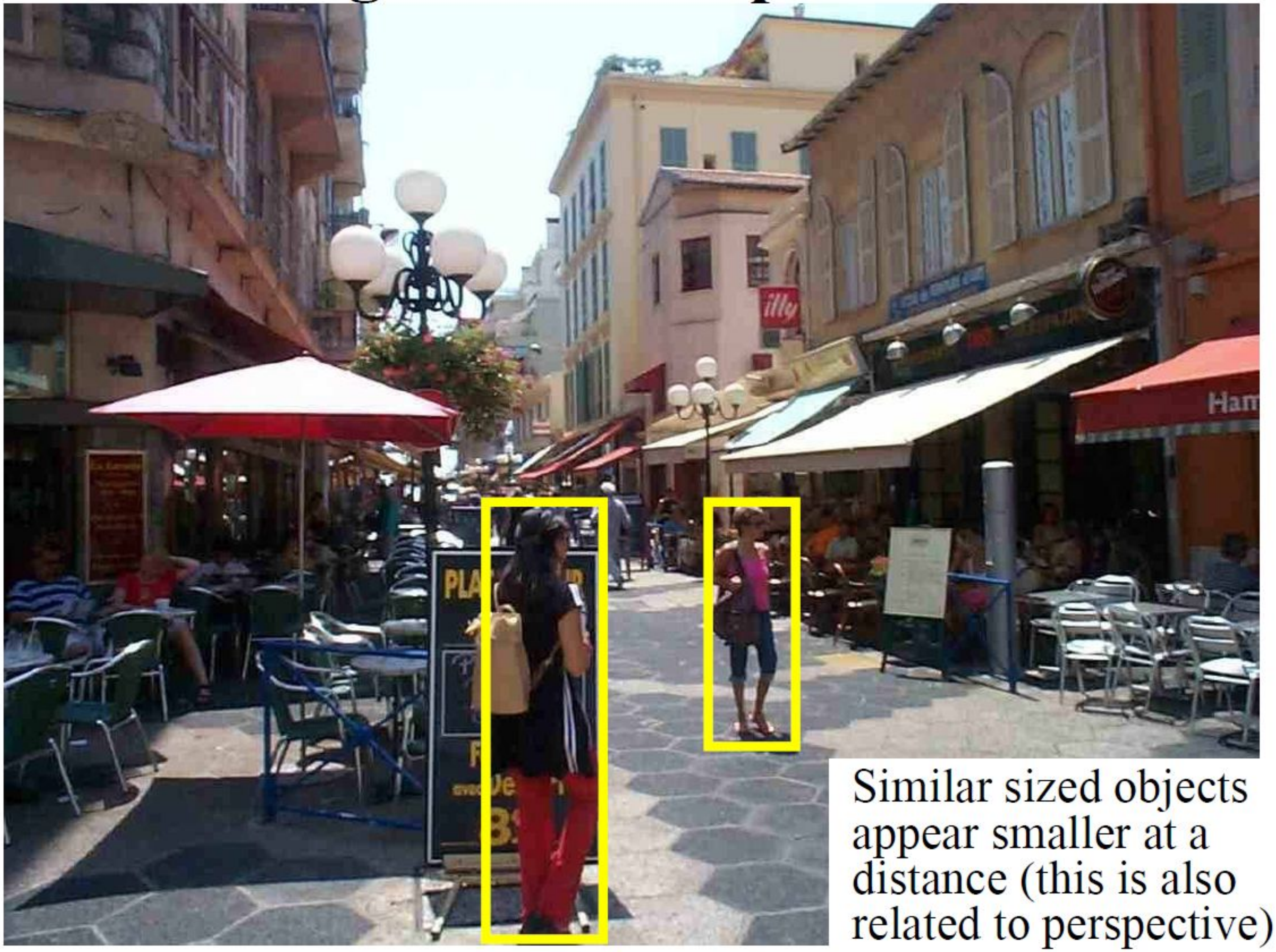
Higher-level Depth Cues



Perspective
(vanishing points)

Robert Collins
CSE486, Penn State

Higher-level Depth Cues



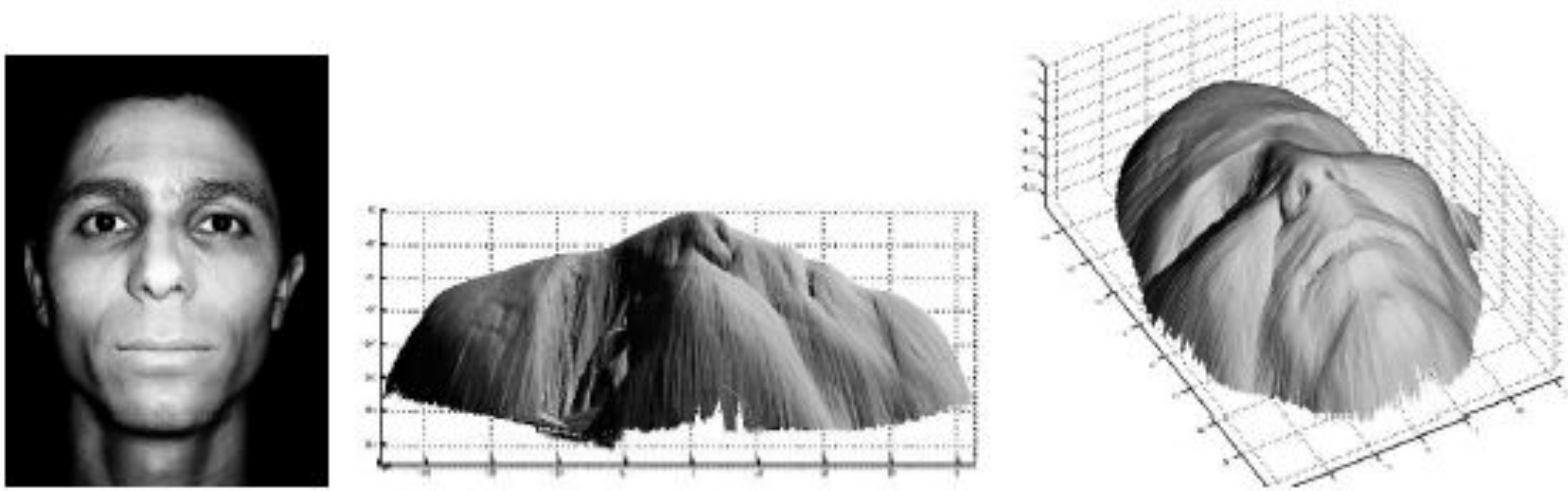
Similar sized objects appear smaller at a distance (this is also related to perspective)

Robert Collins
CSE486, Penn State

Higher-level Depth Cues

Occluded contours
(perceptual completion)

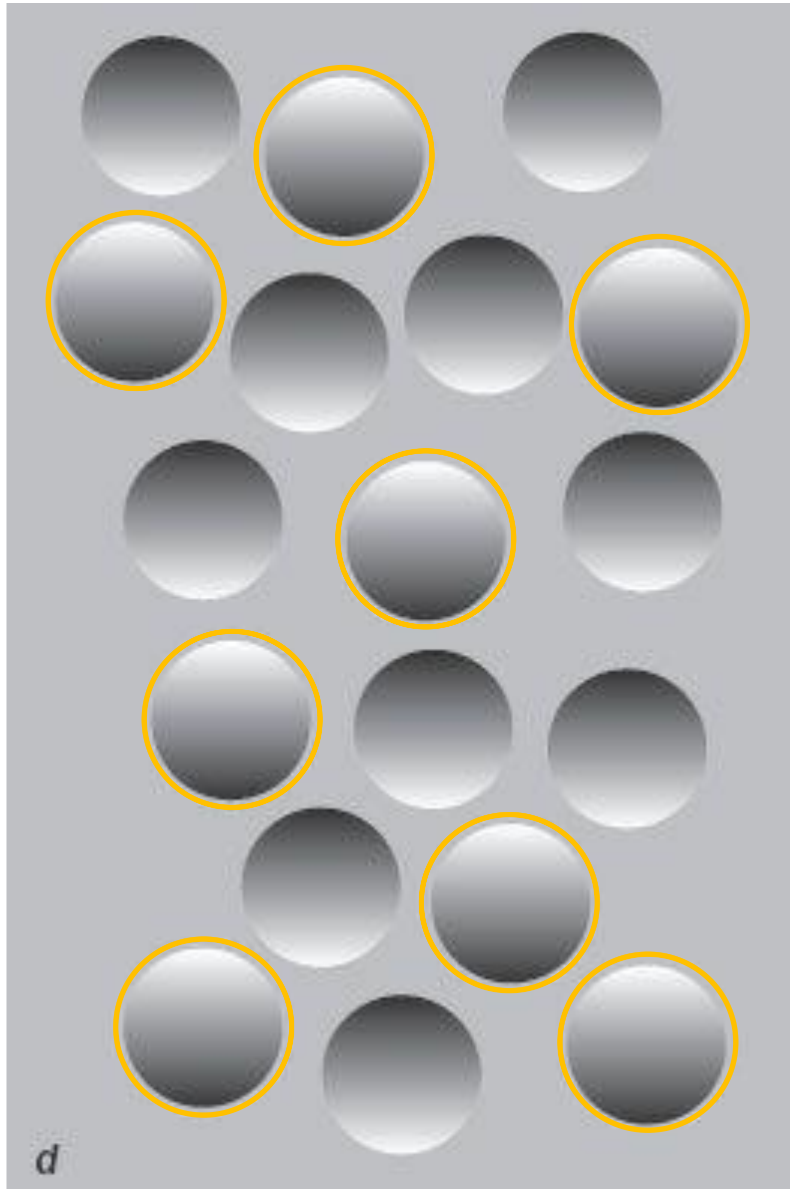
Shading



a) b) c)

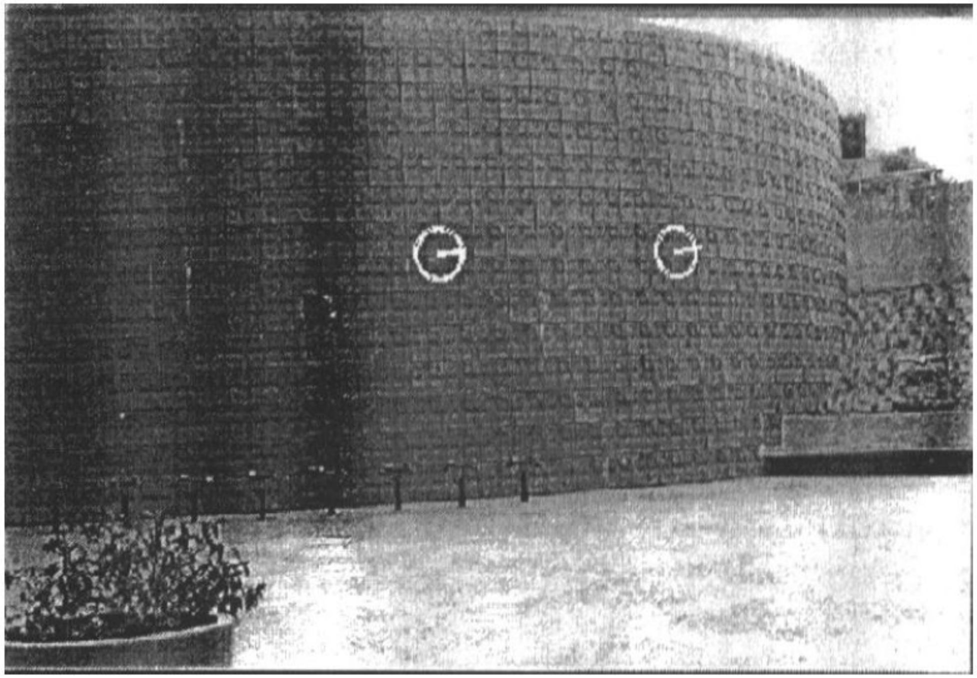
[Figure from Prados & Faugeras 2006]

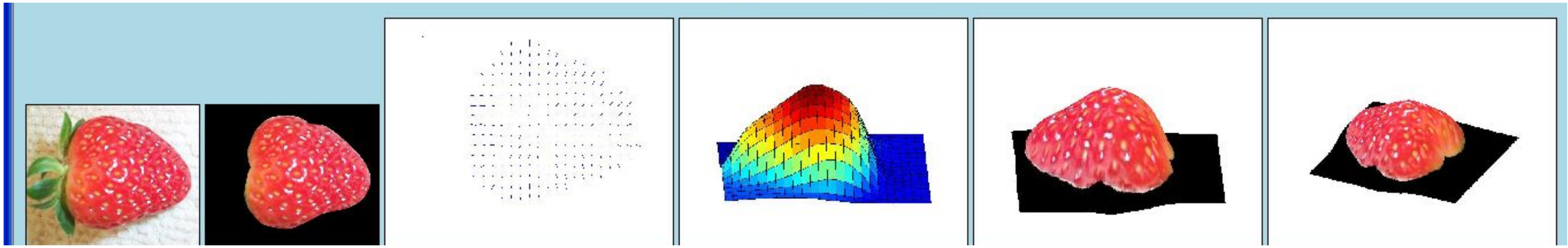
Shading



Credit: scientificamerican.com

Texture

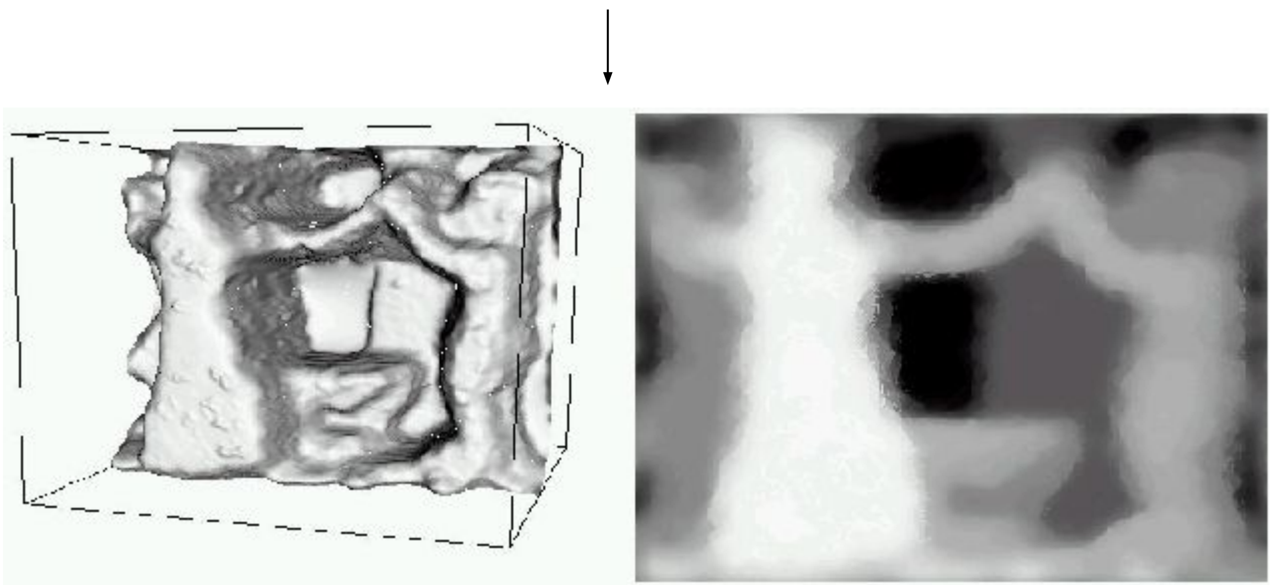




[From A.M. Loh. The recovery of 3-D structure using visual texture patterns. PhD thesis]

Focus/defocus

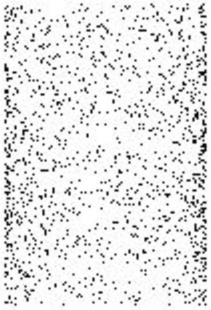
Images from same point of view, different camera parameters



3d shape / depth estimates

[figs from H. Jin and P. Favaro, 2002]

Motion



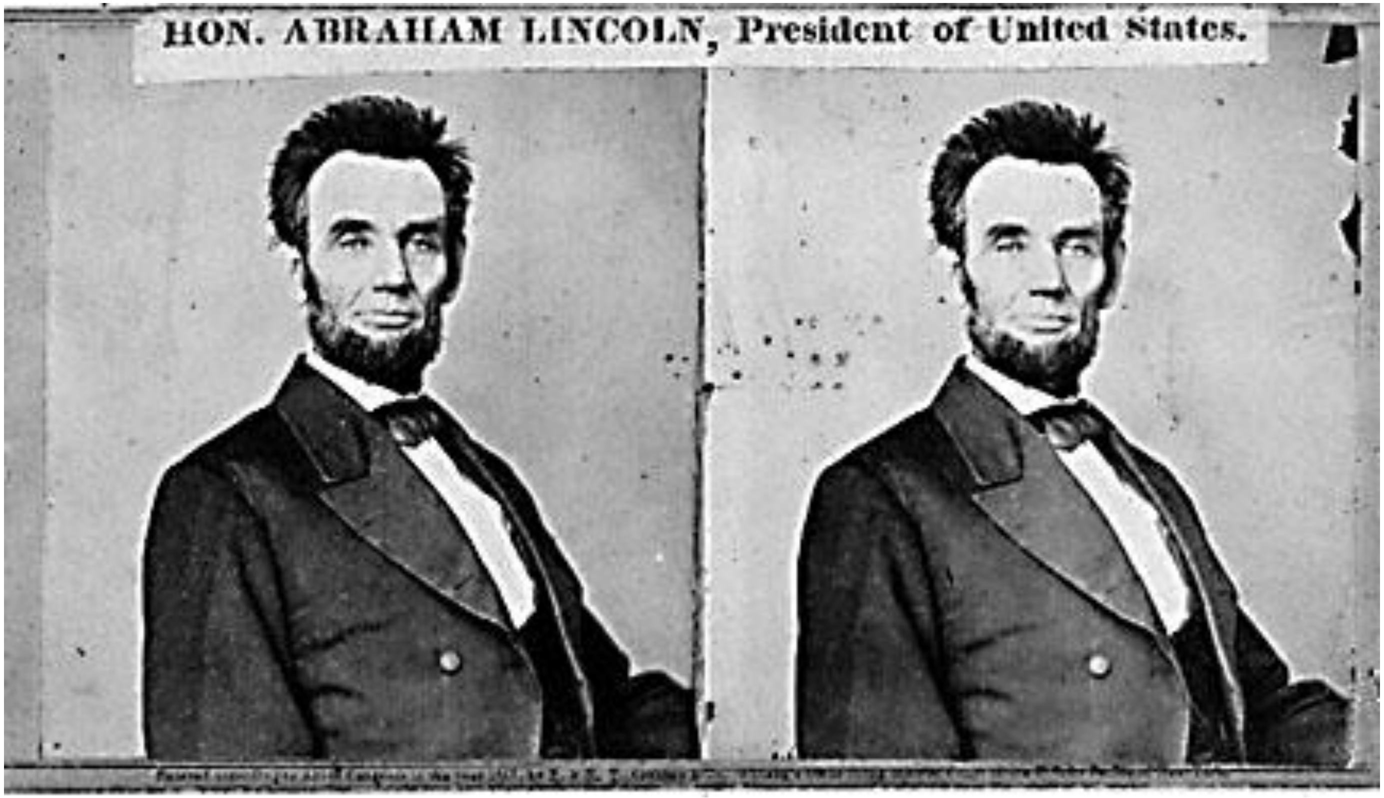
Figures from L. Zhang

http://www.brainconnection.com/teasers/?main=illusion/motion-shape

Stereo photography

Invented by Charles Wheatstone 1838

Stereo photography

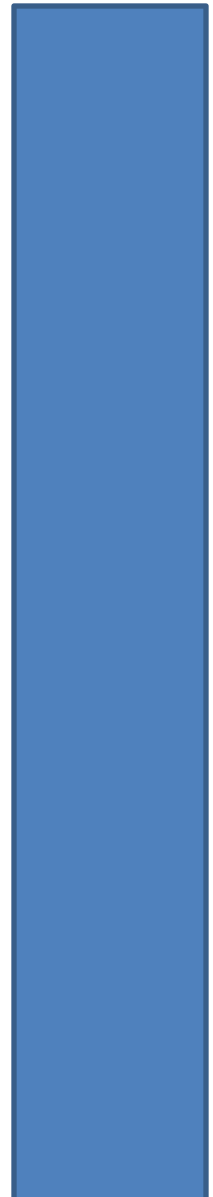


Credit: http://www.johnsonshawmuseum.org/

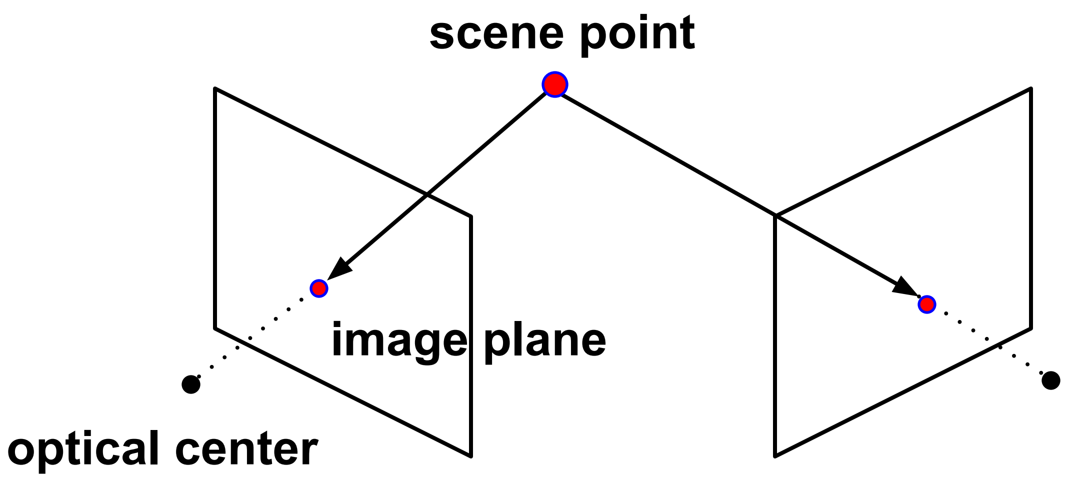
Public Library, Stereoscopic Looking Room, Chicago, by Phillips, 1923

Basic Idea

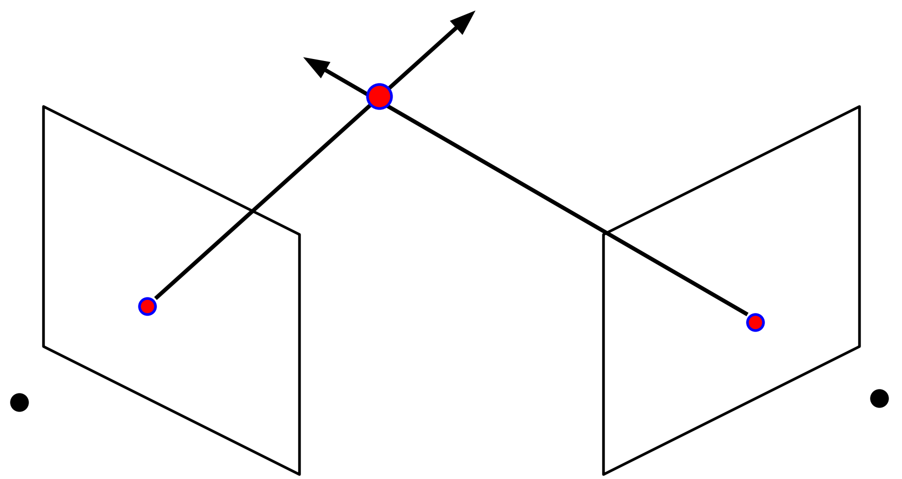
Credit: https://people.well.com/user/jimg/stereo/stereo_list.html



Stereo



Stereo

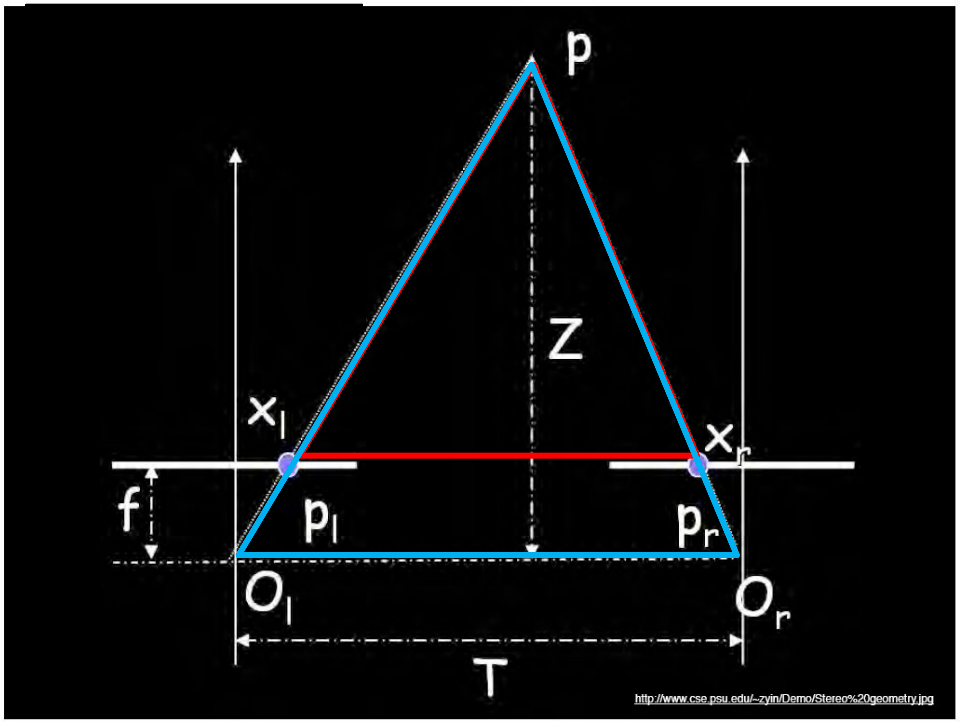


Basic Principle: Triangulation

- Gives reconstruction as intersection of two rays
- Requires
  - camera pose (calibration)
  - ***point correspondence***

Geometry for a simple stereo system

Assume parallel optical axes, known camera parameters (i.e., calibrated cameras). **What is expression for Z?**



Similar triangles (p_l, P, p_r) and (O_l, P, O_r):

$$\frac{T - x_l + x_r}{Z - f} = \frac{T}{Z}$$

$$Z = f \frac{T}{x_l - x_r}$$

disparity

Depth from disparity

image I(x,y)

Disparity map D(x,y)

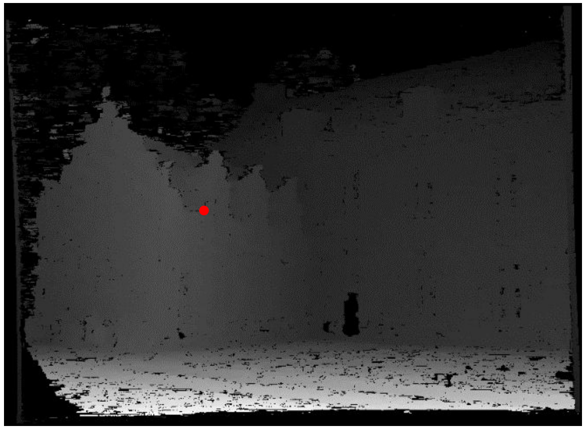


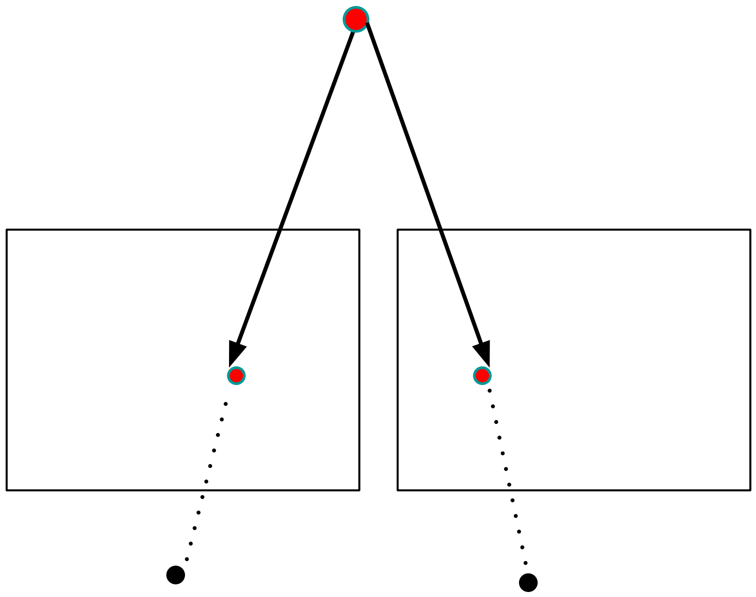
image I´(x´,y´)

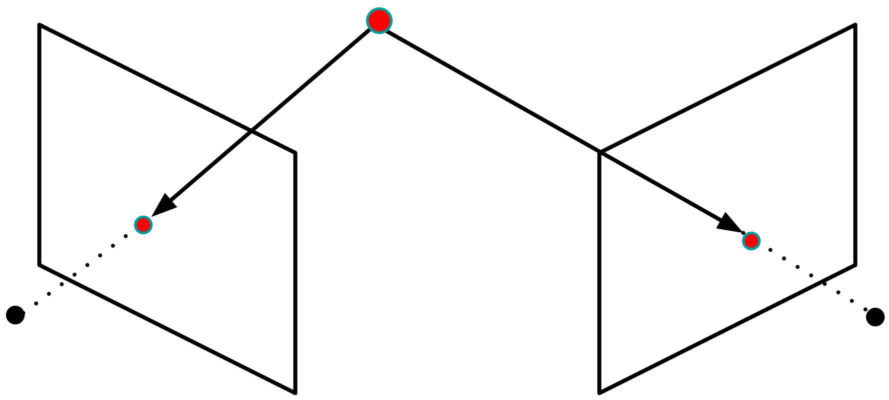
$$(x',y')=(x+D(x,y),\ y)$$

So if we could find the **corresponding points** in two images, we could **estimate relative depth**…

General case, with calibrated cameras

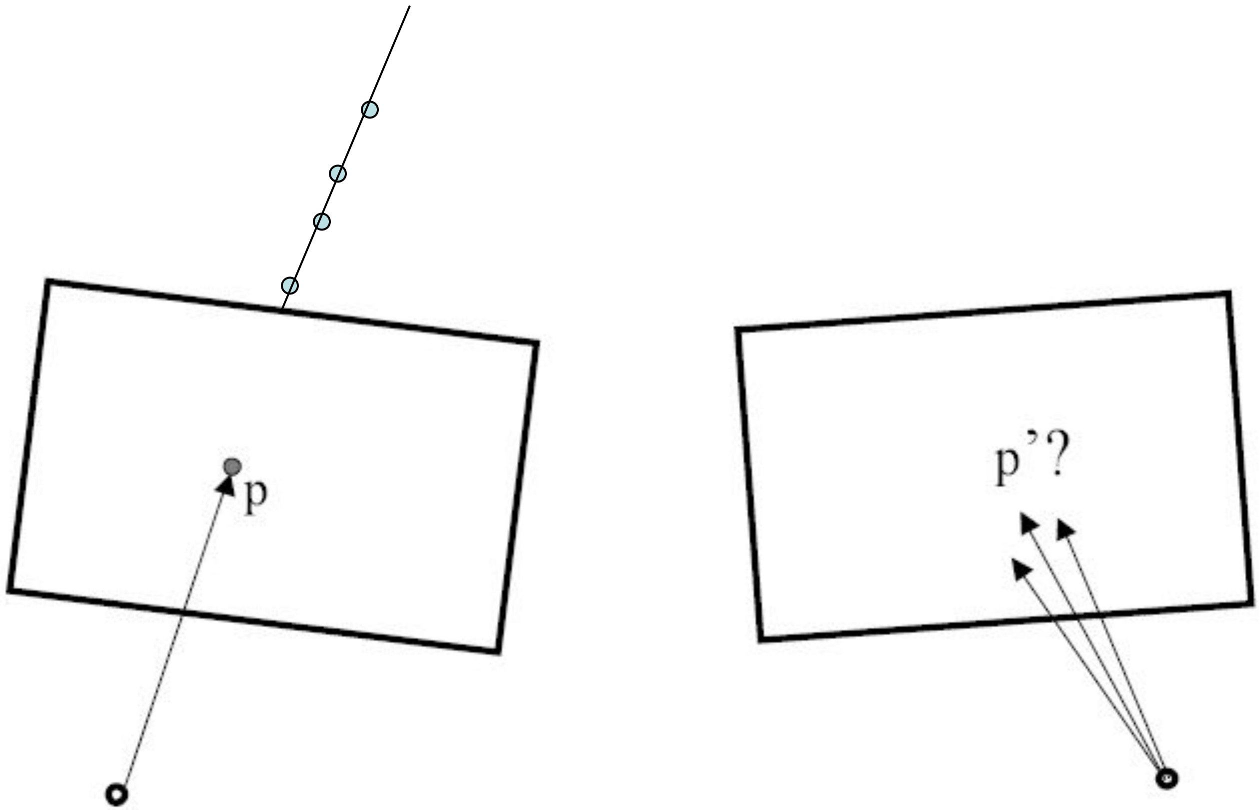
- The two cameras need not have parallel optical axes.





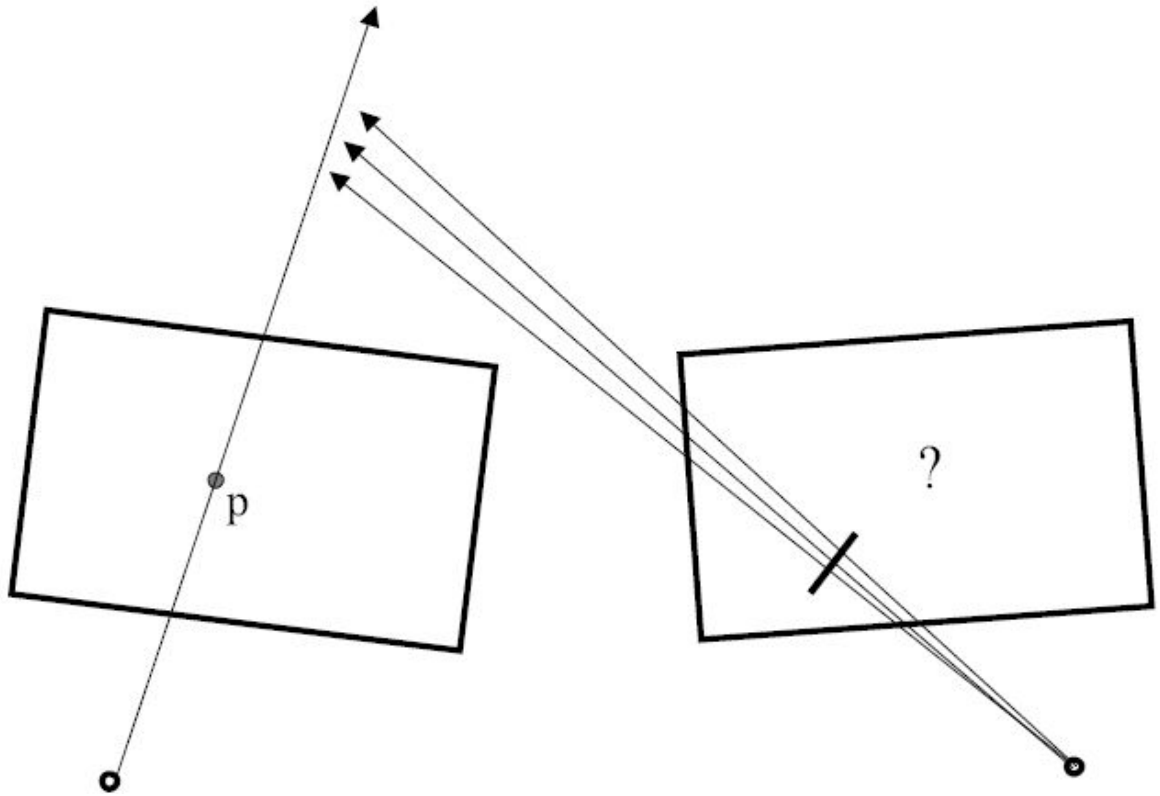
Vs.

Stereo correspondence constraints

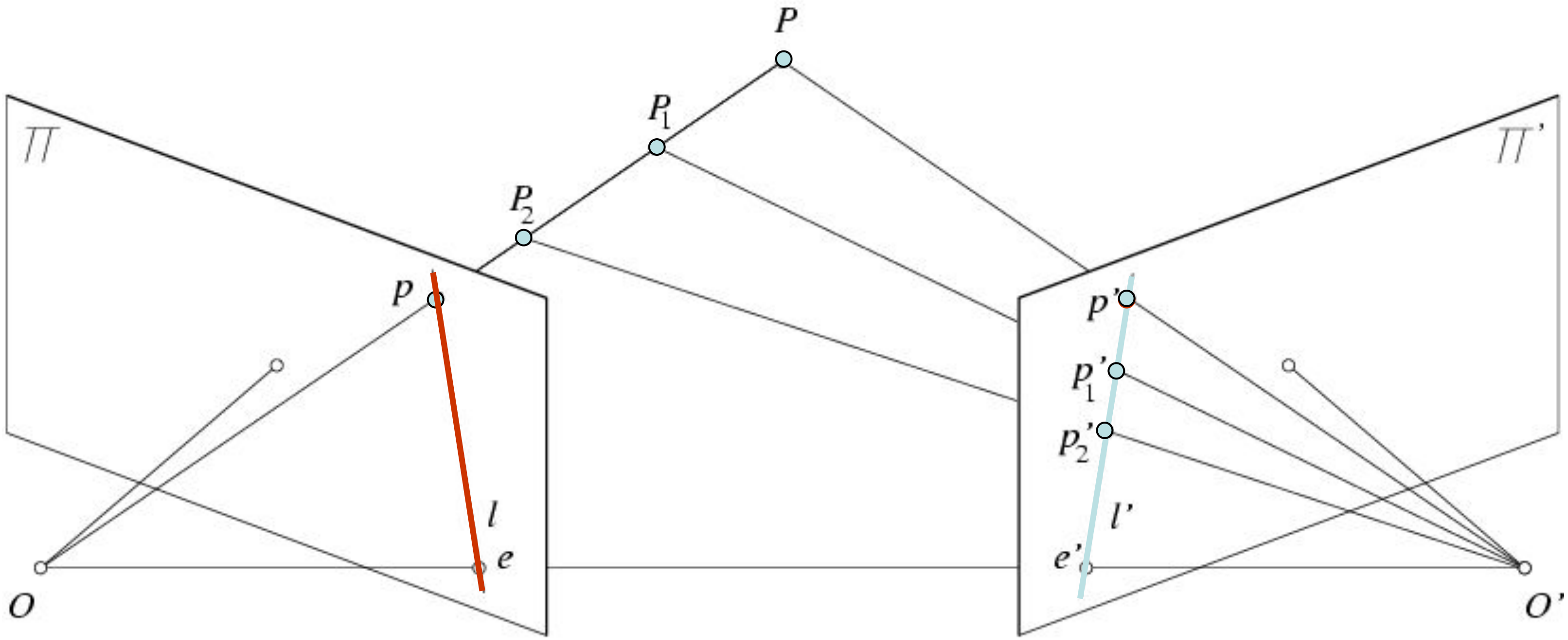


- Given p in left image, where can corresponding point p' be?

Stereo correspondence constraints



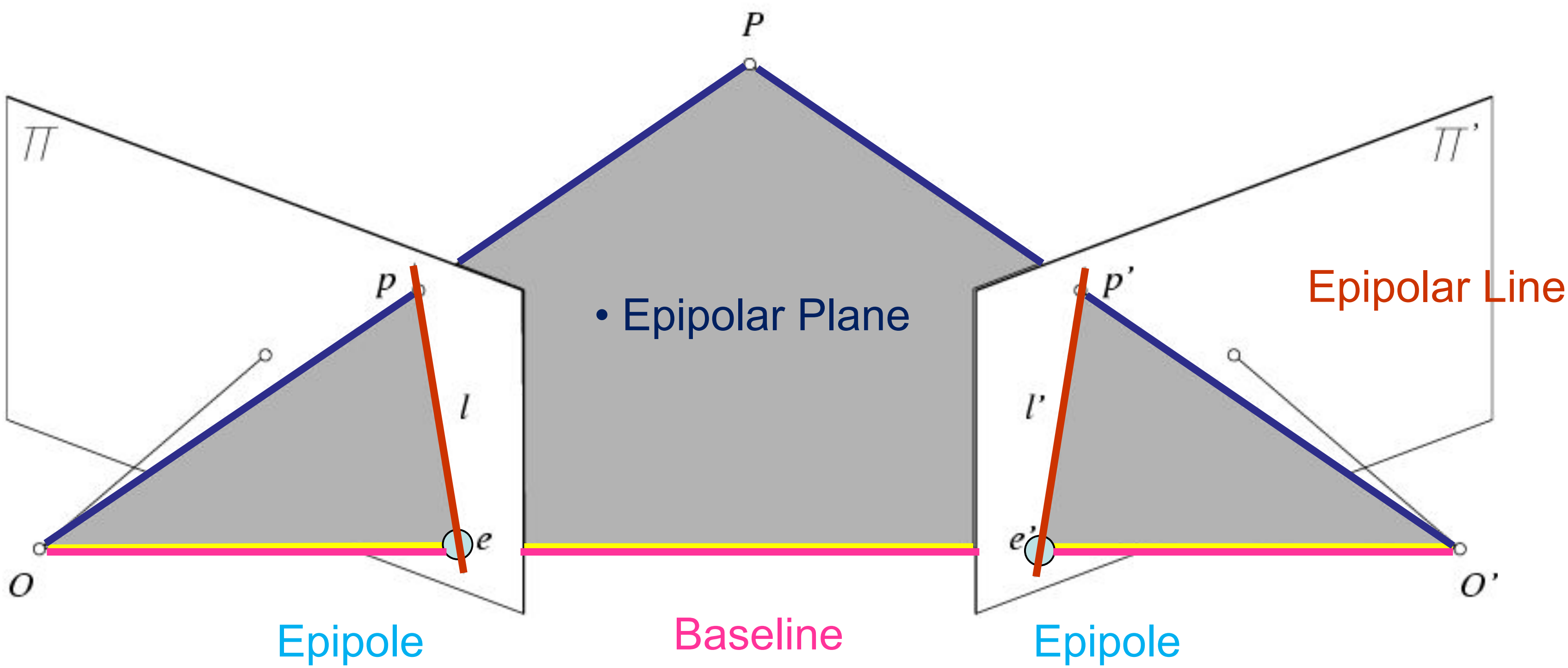
Epipolar constraint



Geometry of two views constrains where the corresponding pixel for some image point in the first view must occur in the second view.

- It must be on the line carved out by a plane connecting the world point and optical centers.

Epipolar geometry



Baseline – line joining the camera centers

Epipole – point of intersection of baseline with image plane

Epipolar plane – plane containing baseline and world point

Epipolar line – intersection of epipolar plane with image plane

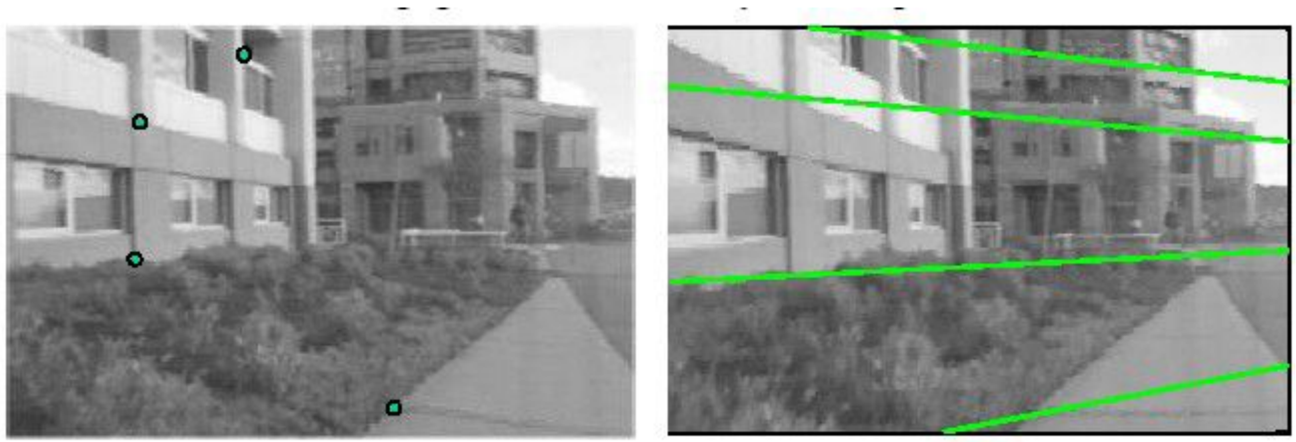
http://www.ai.sri.com/~luong/research/Meta3DViewer/EpipolarGeo.html

Epipolar constraint

This is useful because it reduces the correspondence problem to a 1D search along an epipolar line.

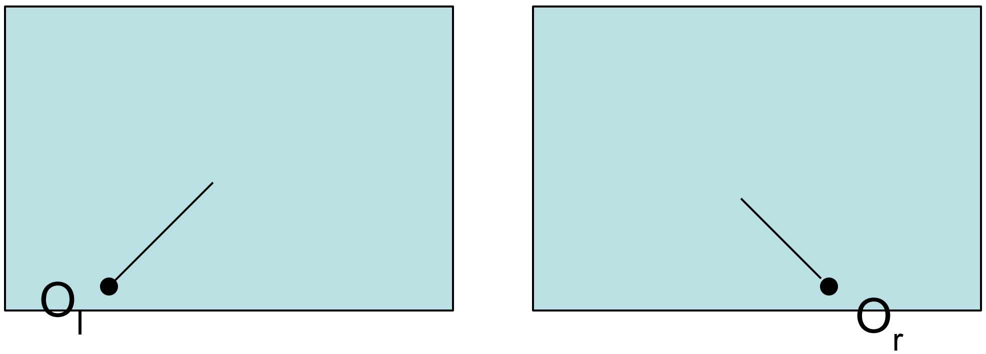
Image from Andrew Zisserman

Example

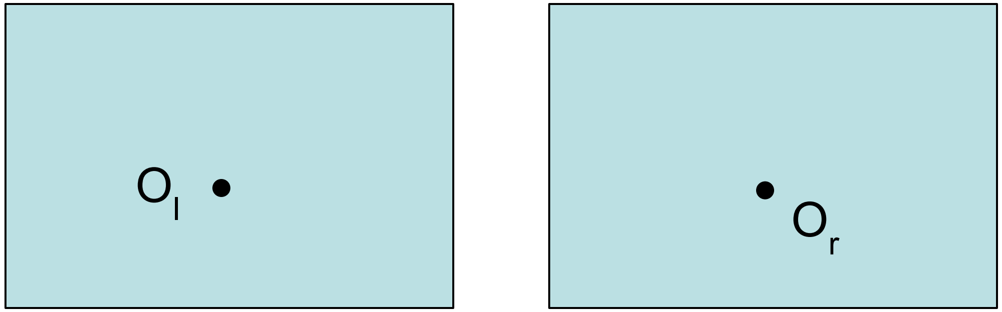


What do the epipolar lines look like?

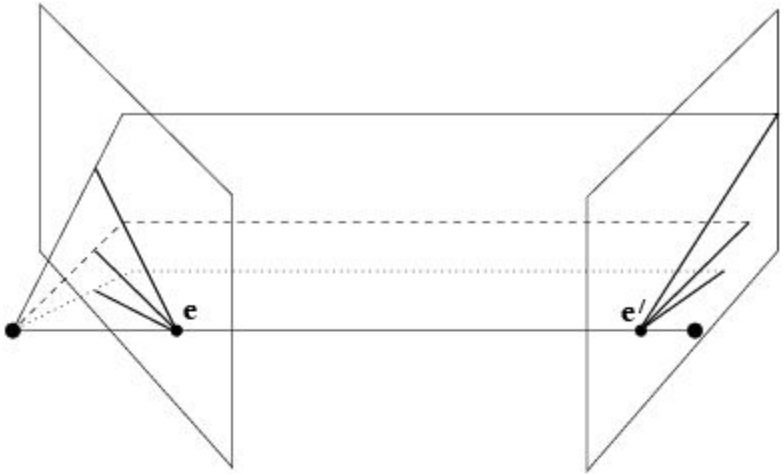
1.



2.



Example: converging cameras



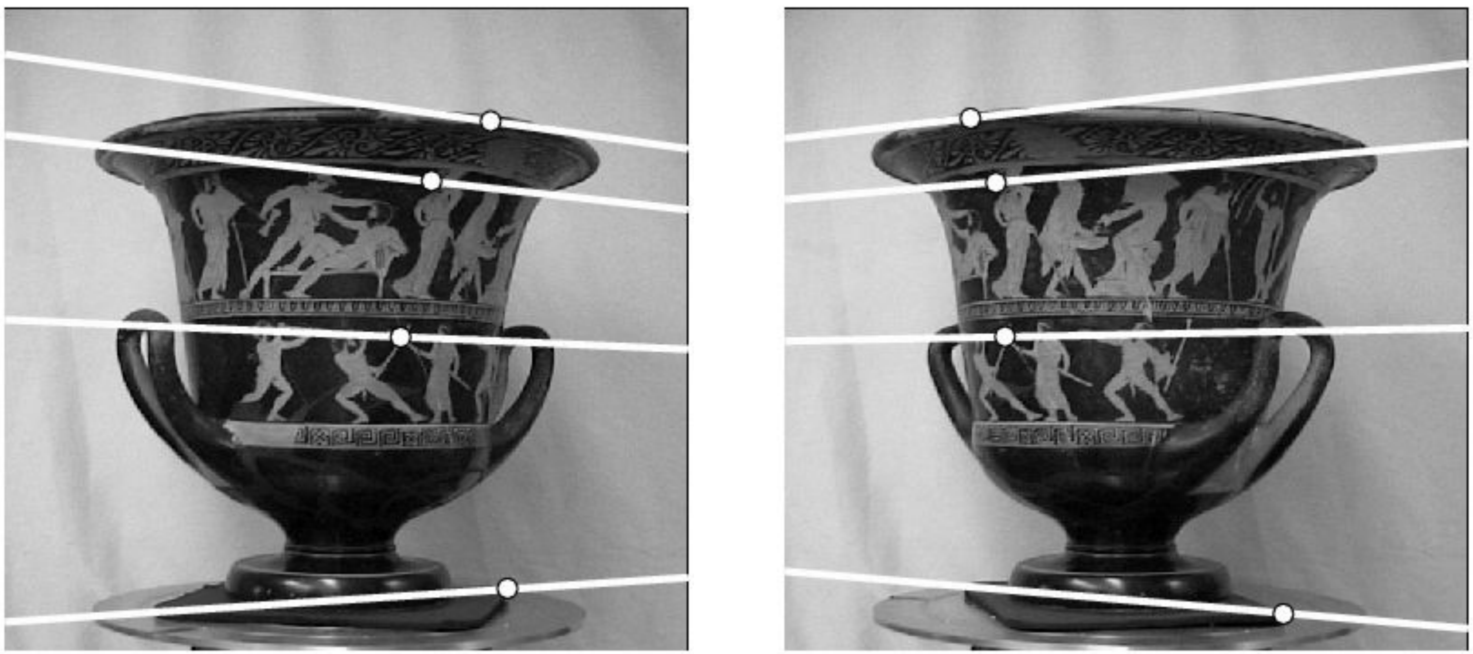
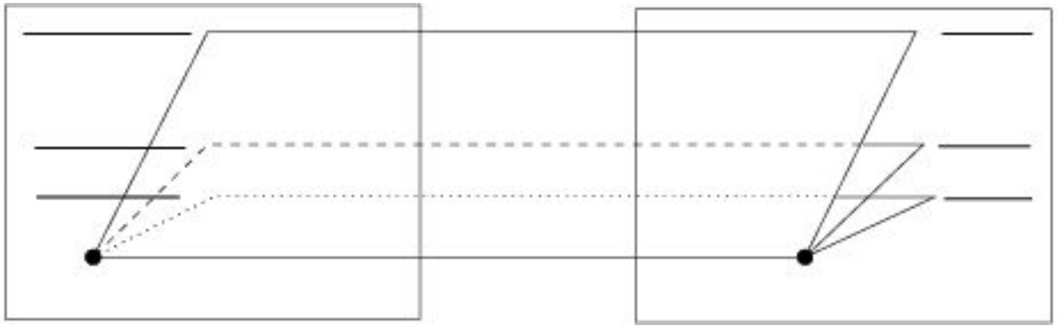


Figure from Hartley & Zisserman

Example: parallel cameras



Where are the epipoles?

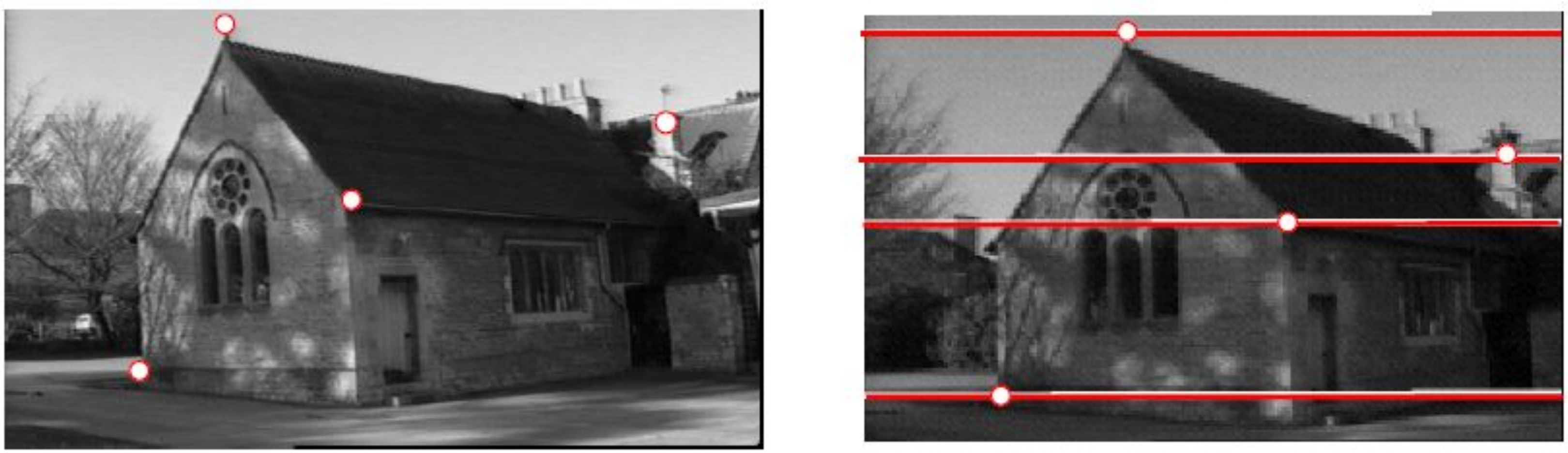
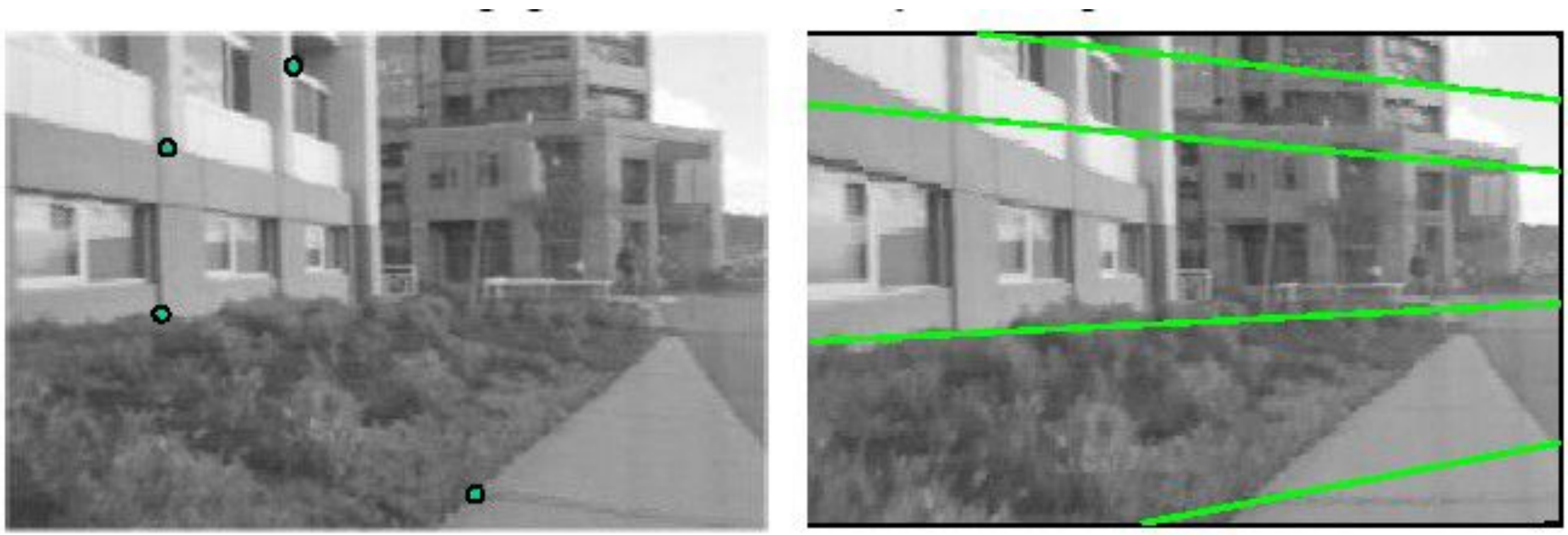


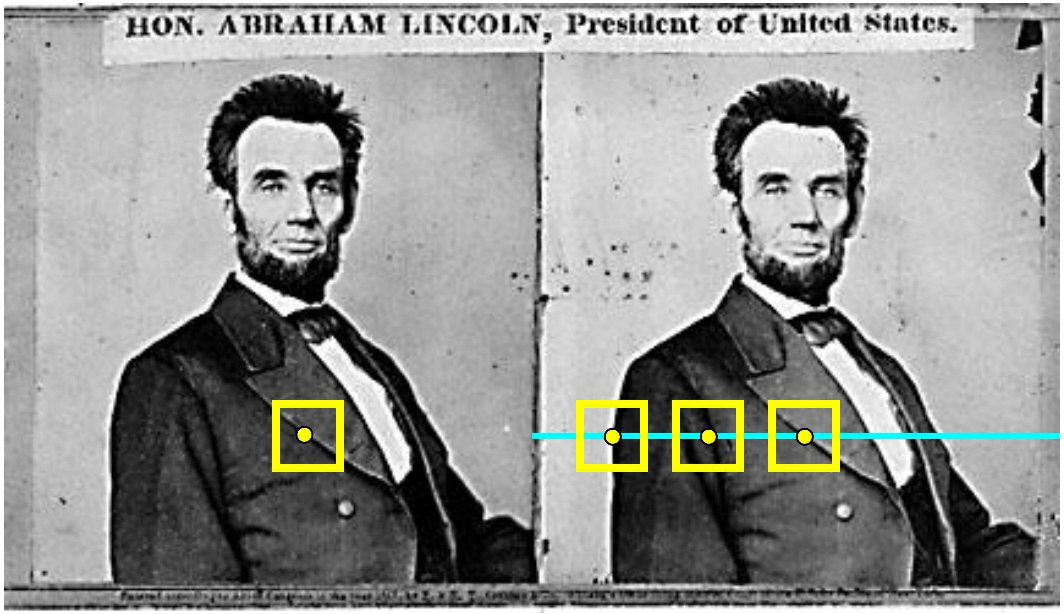
Figure from Hartley & Zisserman

The correspondence problem

Epipolar geometry constrains our search, but we still have a difficult correspondence problem.

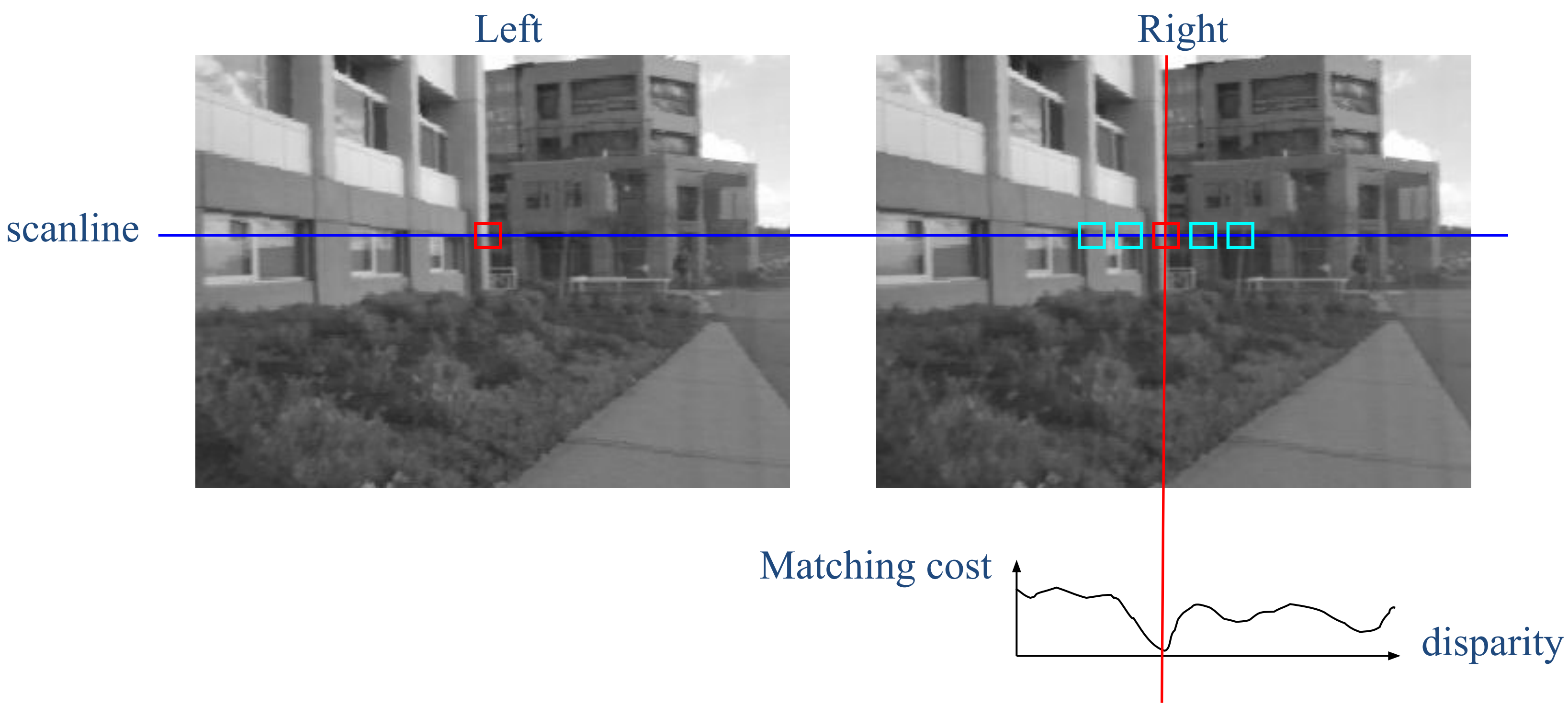


Basic stereo matching algorithm



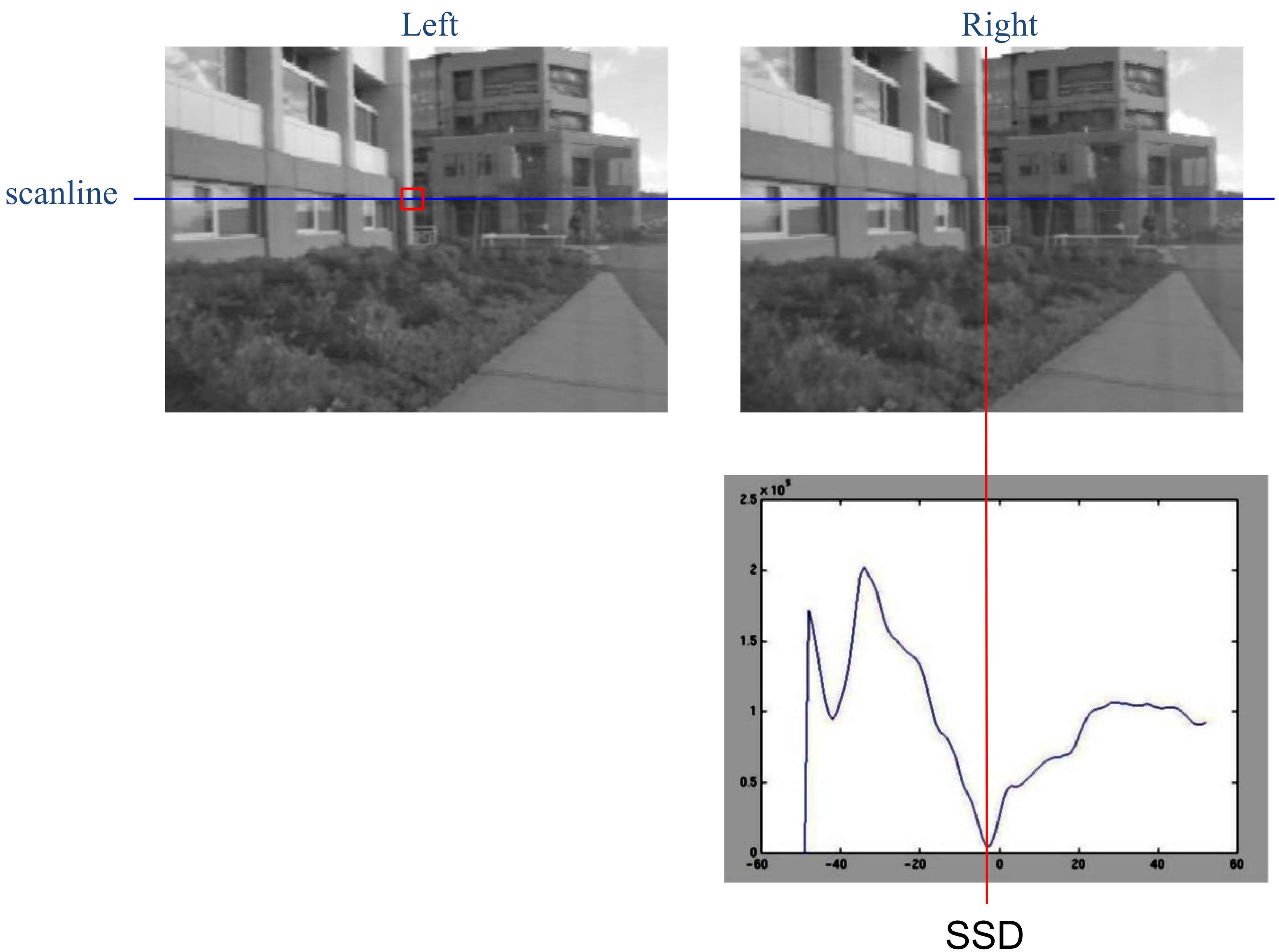
- For each pixel x in the first image
  - Find corresponding epipolar scanline in the right image
  - Examine all pixels on the scanline and pick the best match x'
  - Compute disparity x-x' and set depth(x) = fB/(x-x')

Correspondence search

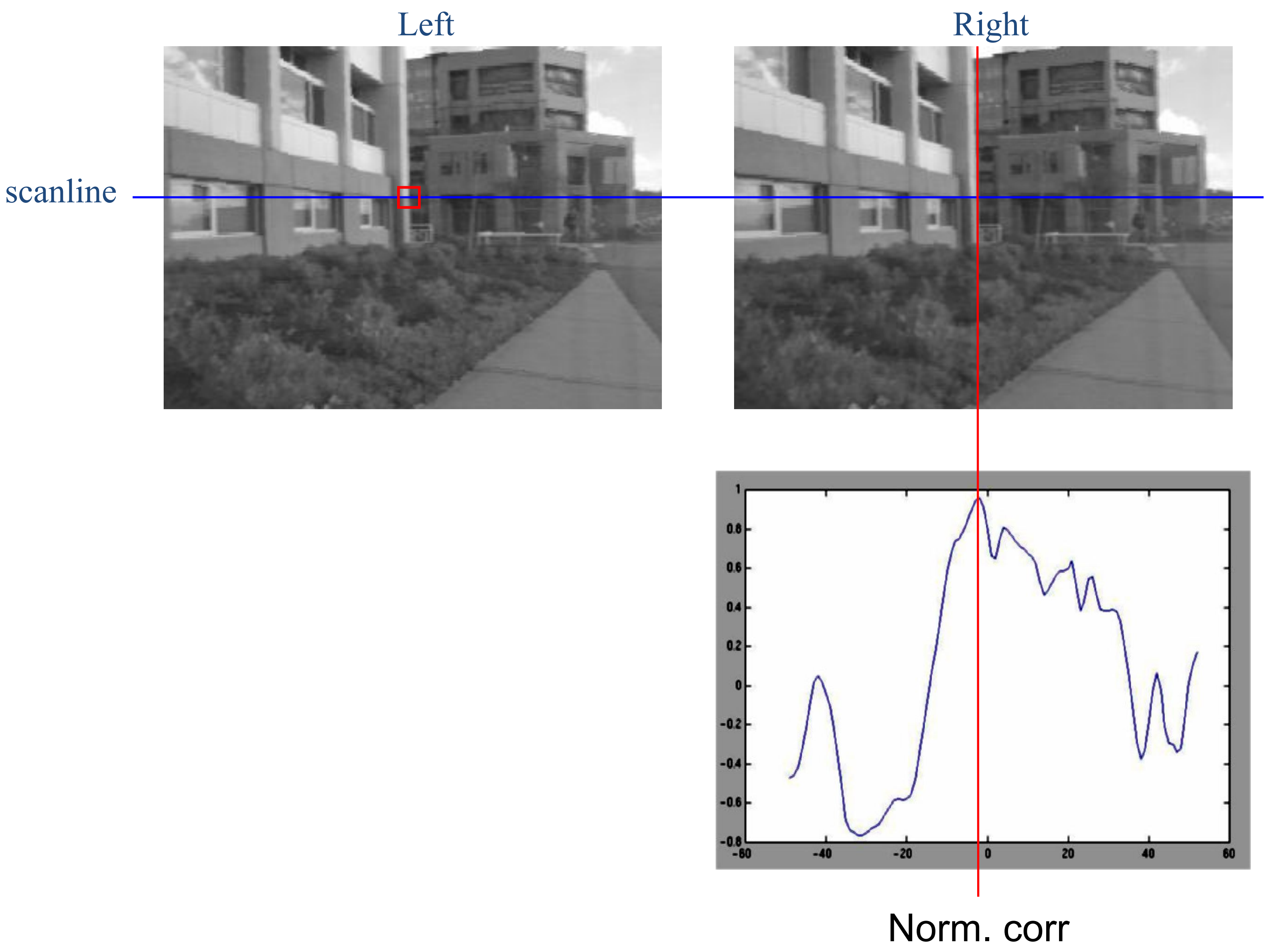


- Slide a window along the right scanline and compare contents of that window with the reference window in the left image
- Matching cost: SSD or normalized correlation

Correspondence search



Correspondence search

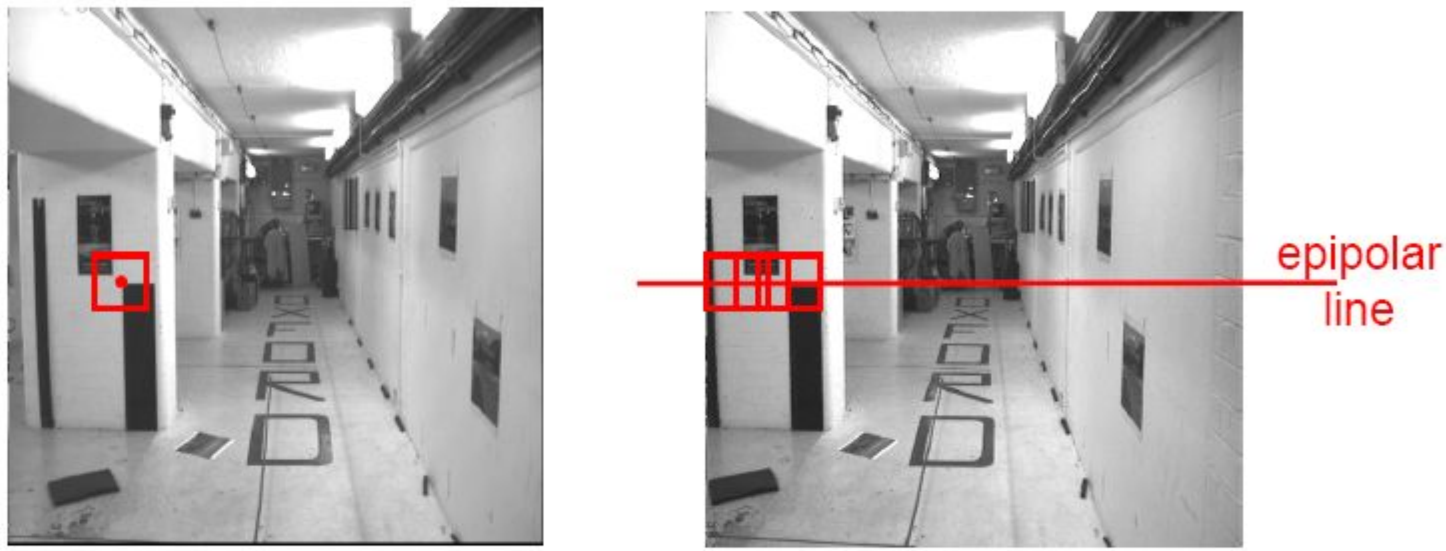


Correspondence problem

Parallel camera example: epipolar lines are corresponding image scanlines

Source: Andrew Zisserman

Correspondence problem



Neighborhoods of corresponding points are similar in intensity patterns.

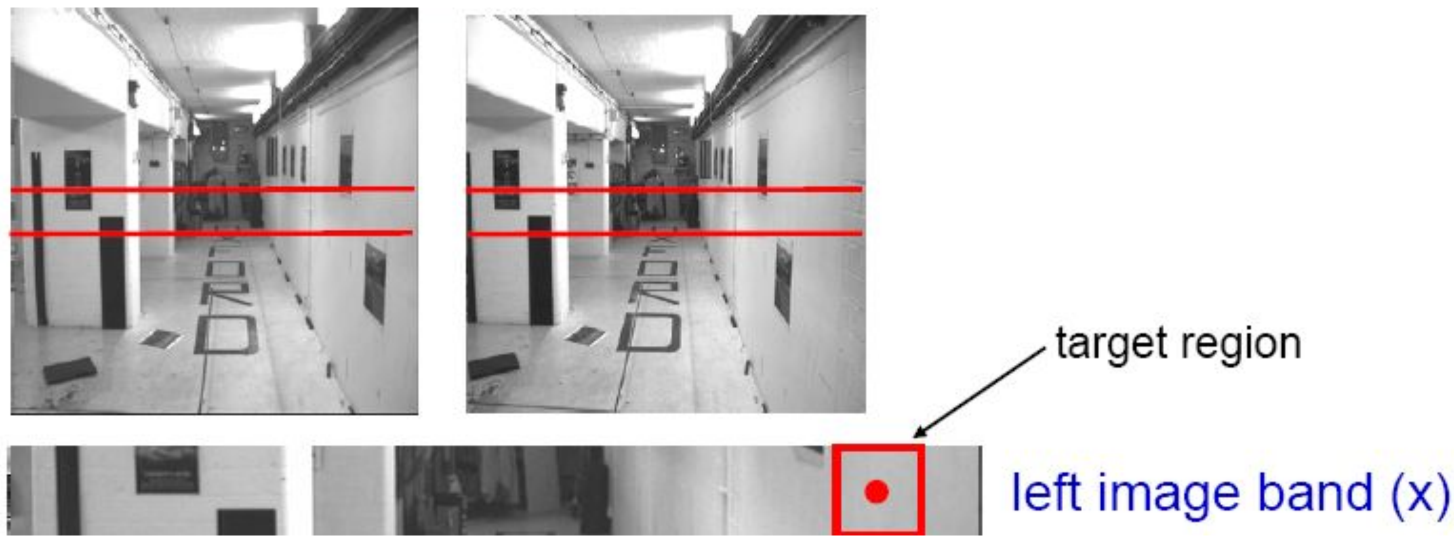
Source: Andrew Zisserman

Correlation-based window matching

left image band (x)

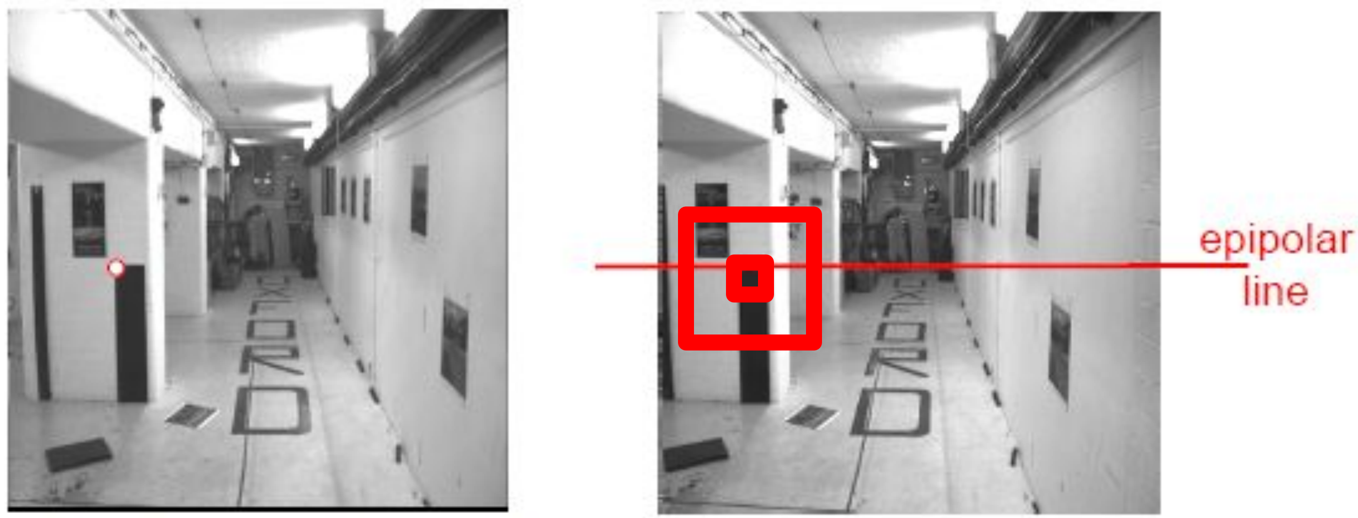
Source: Andrew Zisserman

Textureless regions



Source: Andrew Zisserman

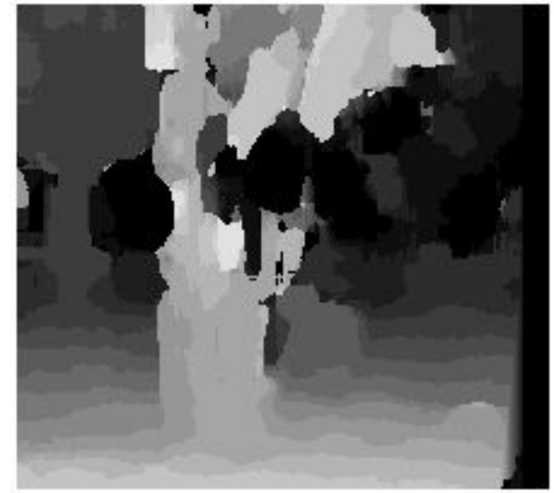
Effect of window size



Source: Andrew Zisserman

Effect of window size

W = 3



W = 20

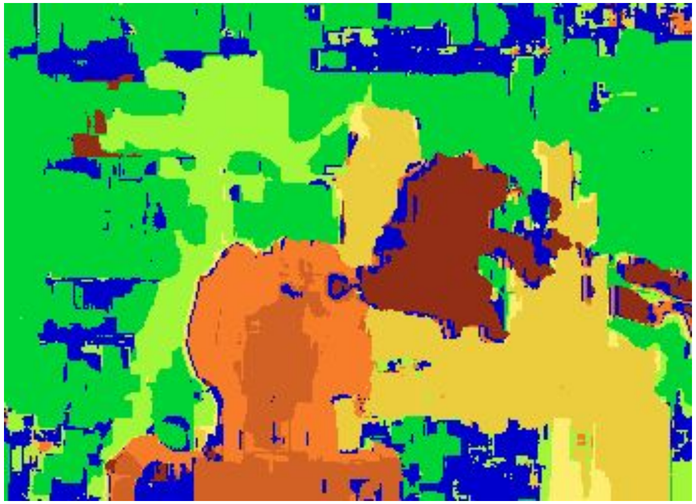
- Smaller window
  - \+ More detail
  - – More noise

- Larger window
  - \+ Smoother disparity maps
  - – Less detail

Results with window search

Data

Window-based matching



Ground truth