Lecture 10: Stereo

Tuesday, Oct 2

Grad student extension ideas for problem set 2

- Implement textons approach for texture recognition [Leung & Malik]
  - Possible data sources: Vistex, Curet databases
- Build a shape-based object detector using the generalized Hough transform
- Clustering approach to video shot boundary detection
- Build a deformable contour tracker

Exam

- Next Tuesday, Oct 9, in class
- Bring one handwritten 8.5 x 11”, one-sided sheet with any notes
- Closed book/laptop/calculator

Review all material covered so far

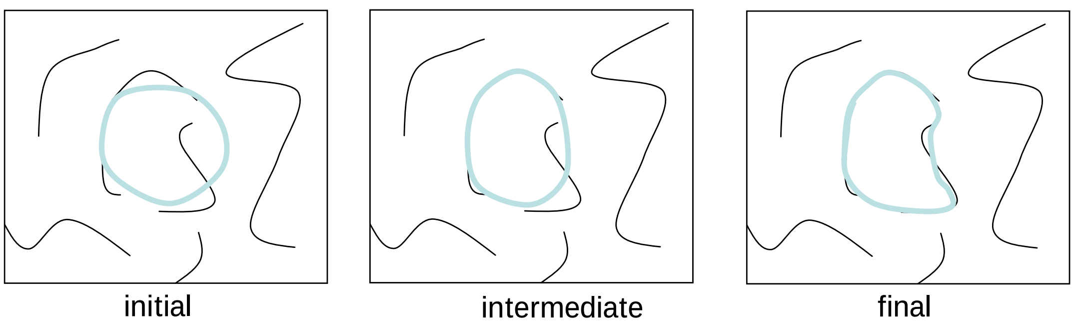
- Image formation
  - Perspective, orthographic projection properties, equations, effects
  - Pinhole cameras
  - Thin lens
  - Field of view, depth of field
- Color
  - BRDF
  - Spectral power distribution
  - Color mixing
  - Color matching
  - Color spaces
  - Human perception
- Binary image analysis
  - Histograms and thresholding
  - Connected components
  - Morphological operators
  - Region properties and invariance
  - Distance transform, Chamfer distance
- Filters
  - Application/effects of
  - Convolution properties
  - Noise models
  - Mean, median, Gaussian, derivative filters
  - Separability
- Edges, pyramids, sampling
  - Image gradients
  - Effects of noise
  - Derivative of Gaussian, Laplacian filters
  - Canny edge detection
  - Corner detection
  - Sampling and aliasing
  - Pyramids – construction and applications
- Texture
  - Analysis vs. synthesis
  - Representations
- Grouping
  - Gestalt principles
  - Clustering: agglomerative, k-means, mean shift, graph-based
  - Graphs and affinity matrices
- Fitting
  - Hough transform
  - Generalized Hough transform
  - Least squares
  - Incremental line fitting, k-means
  - Robust fitting: RANSAC, M-estimators
  - Deformable contours, energy functions
- Stereo vision

Outline

- Brief review of deformable contours
- Fundamentals of stereo vision
- Epipolar geometry

Last time: deformable contours

a.k.a. active contours, snakes



Snake energy function

The total energy of the current snake defined as

$$E_{total} = E_{in} + E_{ex}$$

Internal energy encourages smoothness or any particular shape

External energy encourages curve onto image structures (e.g. image edges)

Internal energy incorporates **prior knowledge** about object boundary, which allows a boundary to be extracted even if some image data is missing

We will want to iteratively *minimize* this energy for a good fit between the deformable contour and the target shape in the image

Discrete energy terms

- If the curve is represented by *n* points

$$v_i = (x_i, y_i) \qquad i = 0 \;\cdots\; n-1$$

$$\frac{dv}{ds} \approx \frac{v_{i+1} - v_i}{2} \qquad \frac{d^2v}{ds^2} \approx (v_{i+1} - v_i) - (v_i - v_{i-1}) = v_{i+1} - 2v_i + v_{i-1}$$

$$E_{in} = \sum_{i=0}^{n-1} \boxed{\alpha |v_{i+1} - v_i|^2} + \boxed{\beta |v_{i+1} - 2v_i + v_{i-1}|^2}$$

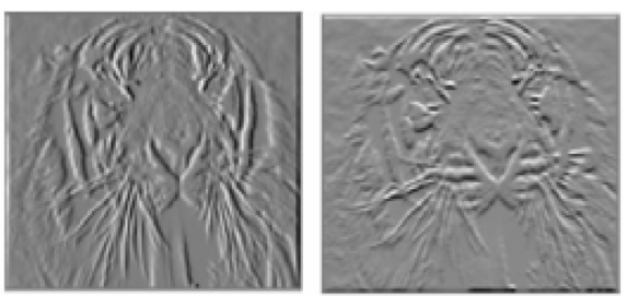
Elasticity,
Tension;
Want to favor close points

Stiffness
Curvature;
Want to favor smoothly shaped curve (not corners)

Discrete energy terms

- An external energy term for a (discrete) snake based on image edge

$$E_{ex} = -\sum_{i=0}^{n-1} |G_x(x_i, y_i)|^2 + |G_y(x_i, y_i)|^2$$

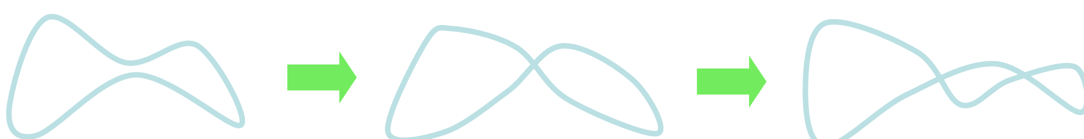


Energy minimization

- Many algorithms proposed to fit deformable contours
  - Greedy search
  - Gradient descent
  - Dynamic programming (for 2d snakes)

Problems with snakes

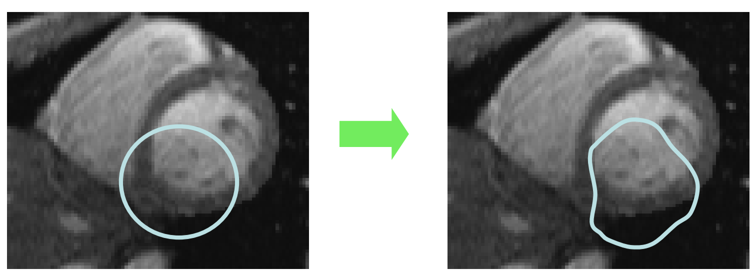
- Depends on number and spacing of control points
- Snake may oversmooth the boundary
- Not trivial to prevent curve self intersecting



- Cannot follow topological changes of objects

Problems with snakes

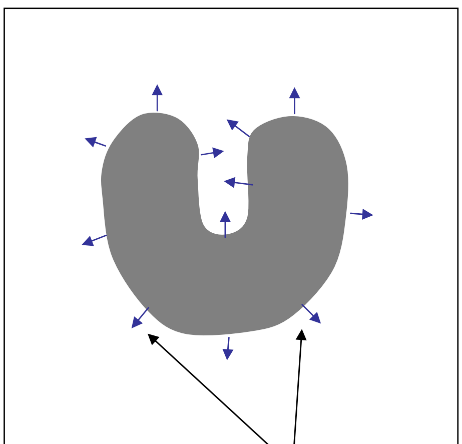
- May be sensitive to initialization, get stuck in local minimum



- Accuracy (and computation time) depends on the convergence criteria used in the energy minimization technique

Problems with snakes

- External energy: snake does not really “see” object boundaries in the image unless it gets very close to it.



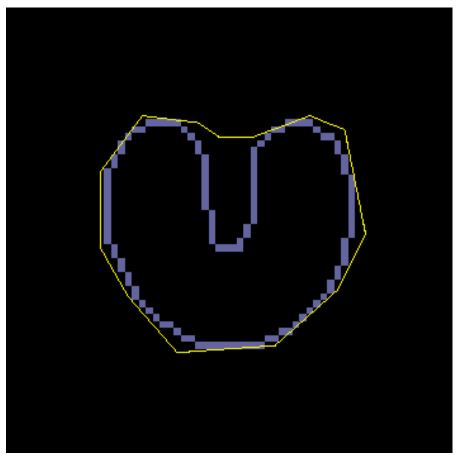
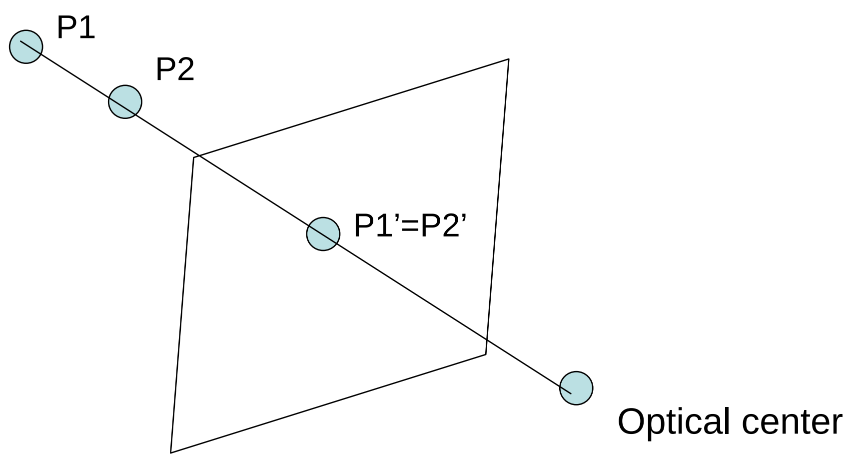


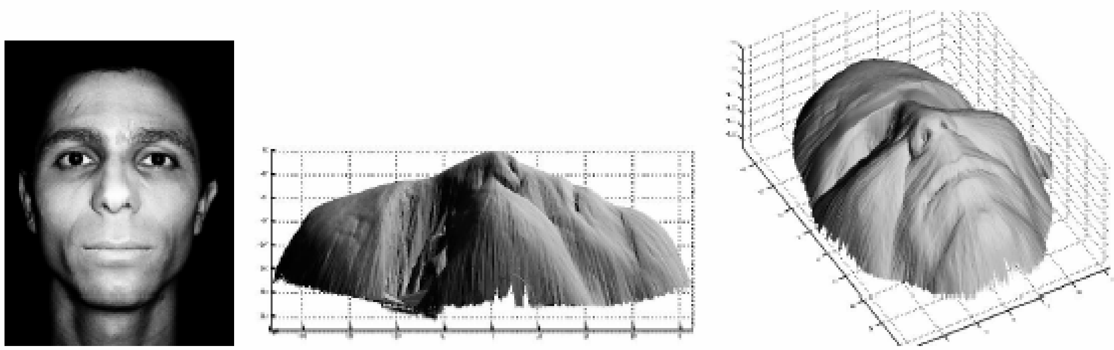
image gradients ∇I
are large only directly on the boundary

Depth unavailable in single views



What cues can indicate 3d shape?

Shading

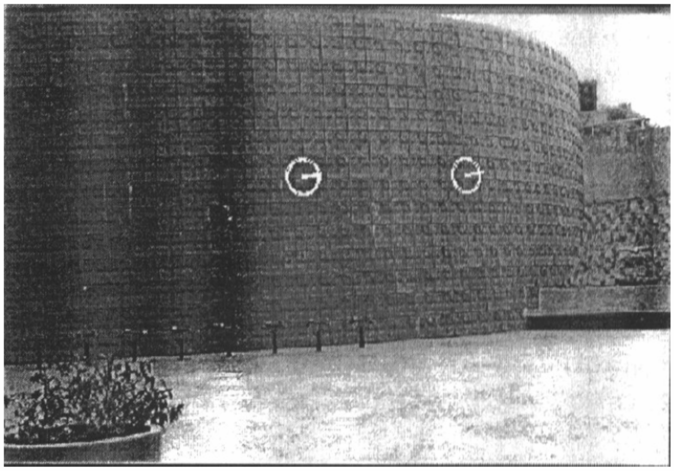

a) b) c)

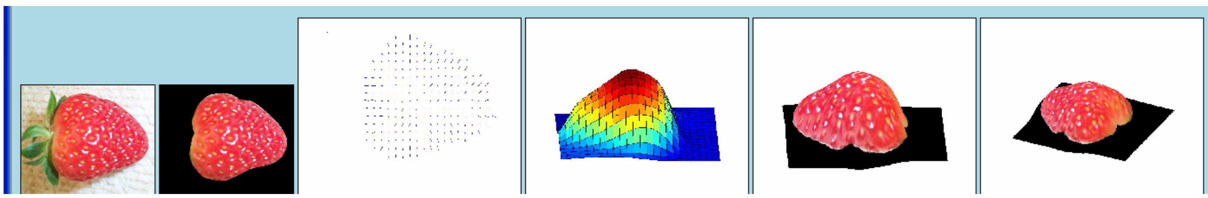
[Figure from Prados & Faugeras 2006]

Focus/Defocus

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

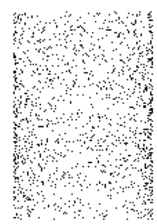
Texture





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

Motion



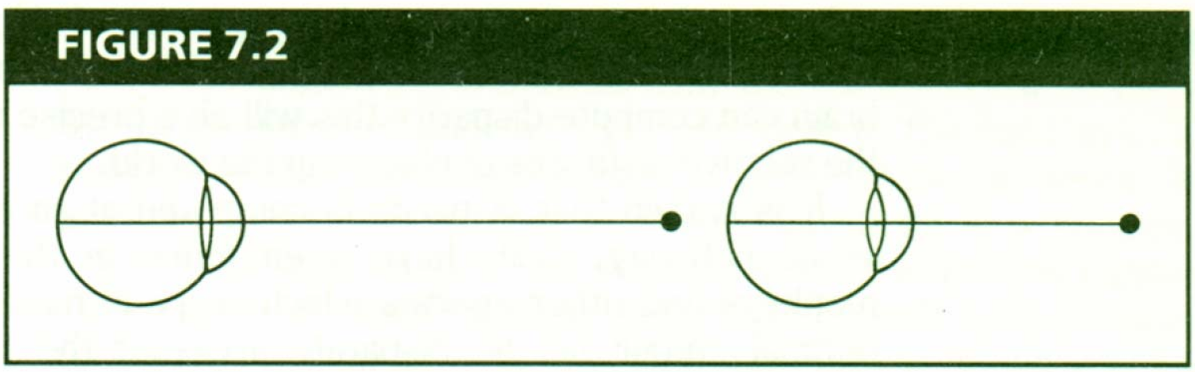
Figures from L. Zhang

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

Estimating scene shape

- Shape from X: Shading, Texture, Focus, Motion…
- Stereo:
  - shape from motion between two views
  - infer 3d shape of scene from two (multiple) images from different viewpoints

Accommodation and focus

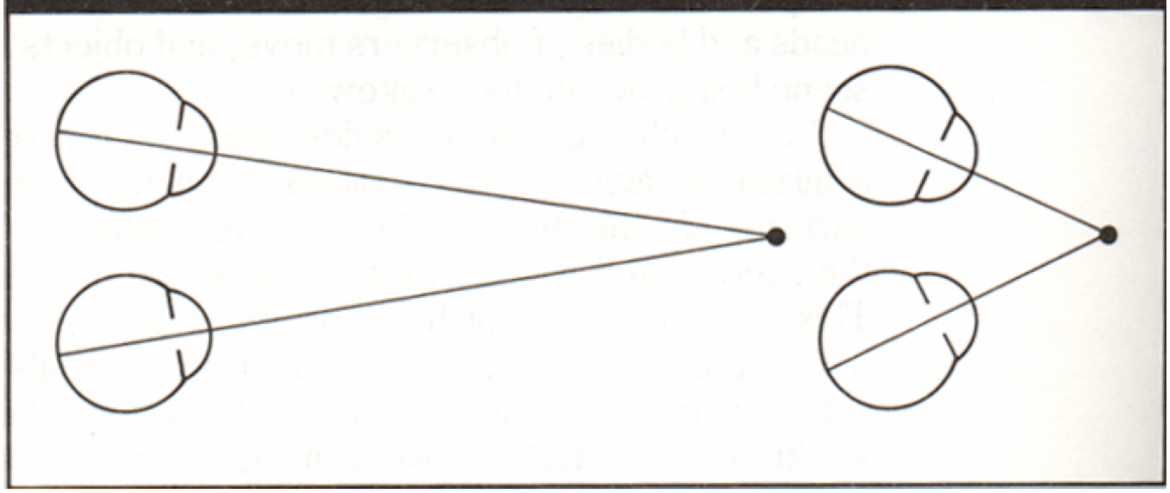


From Bruce and Green, Visual Perception,
Physiology, Psychology and Ecology

The lens modifies the image focus by adjusting its focal length.

Fixation, convergence

FIGURE 7.1



From Bruce and Green, Visual Perception,
Physiology, Psychology and Ecology

Fixation, convergence

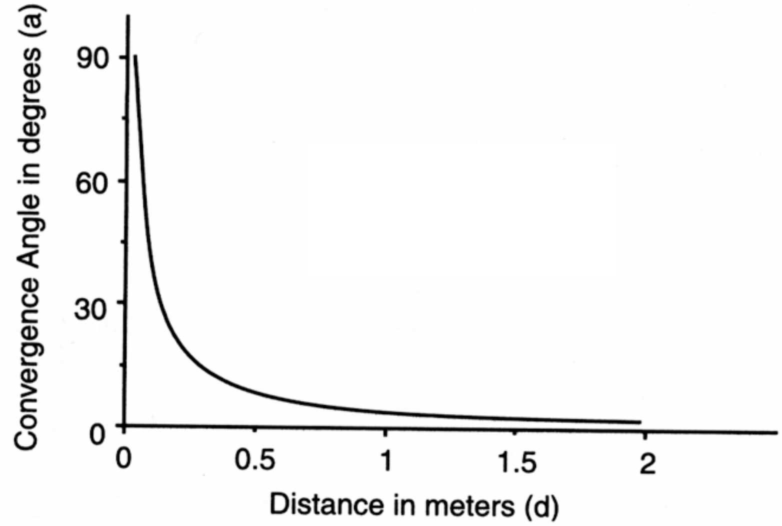
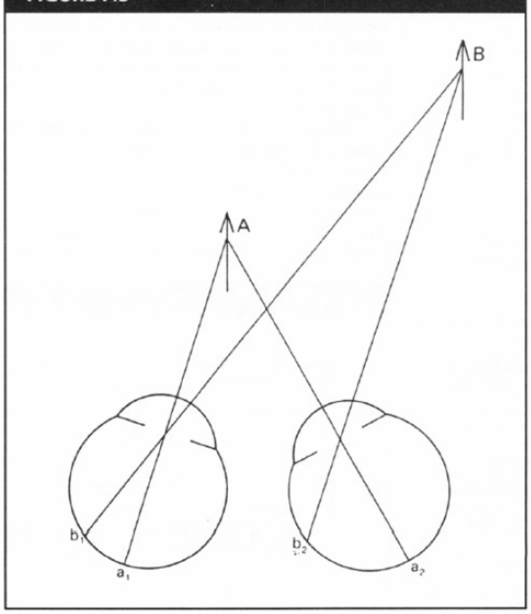


Figure 5.2.3 Convergence as a function of distance. The angle of convergence changes rapidly with distances up to a meter or two but very little after that.

From Palmer, “Vision Science”, MIT Press

Human stereopsis: disparity

FIGURE 7.3

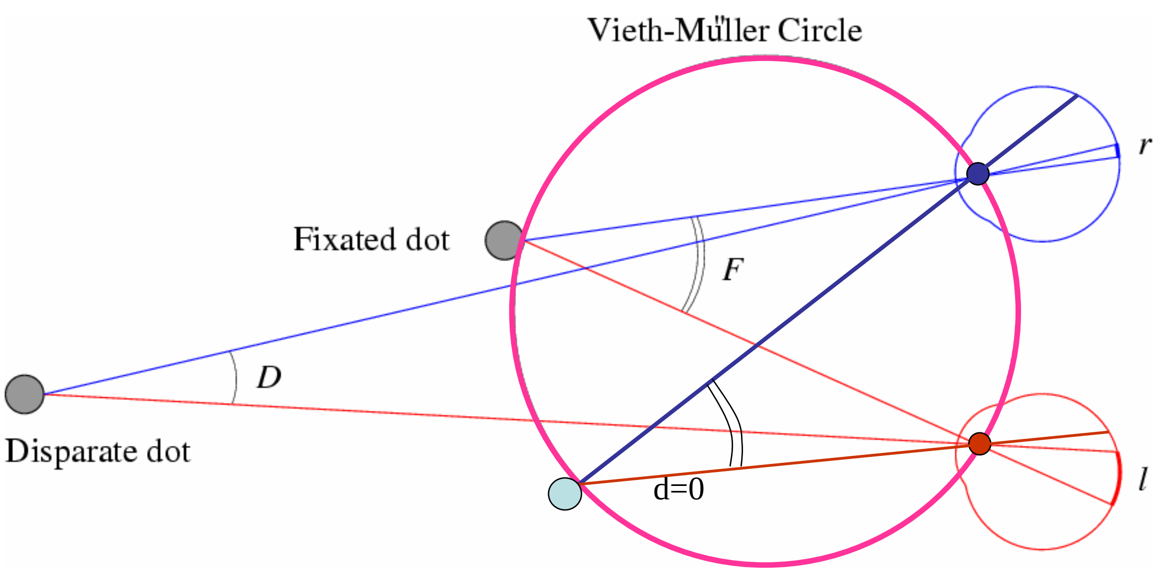


From Bruce and Green, Visual Perception, Physiology, Psychology and Ecology

Disparity occurs when eyes verge on one object; others appear at different visual angles

Adapted from David Forsyth, UC Berkeley

Human stereopsis: disparity



Disparity: *d* = *r*-*l* = *D*-*F*.

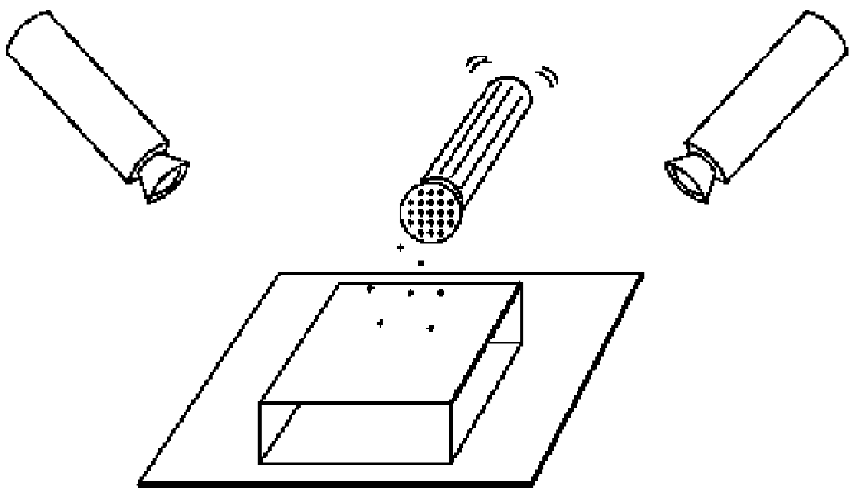
Adapted from M. Pollefeys

Random dot stereograms

- Julesz 1960: Do we identify local brightness patterns before fusion (monocular process) or after (binocular)?

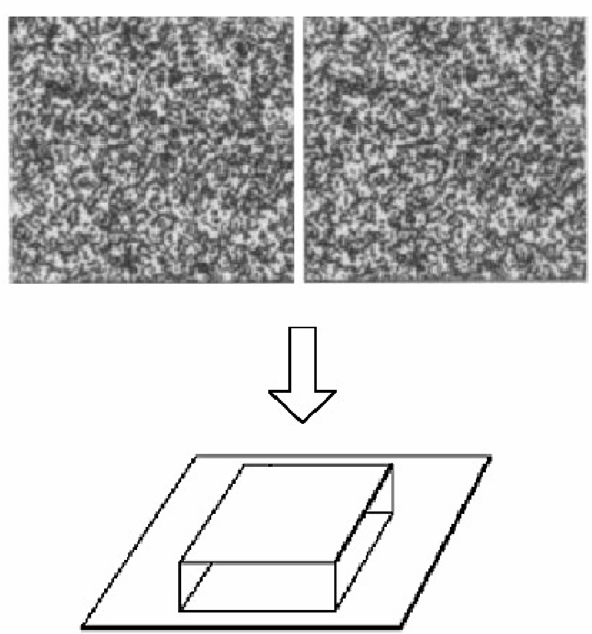
- To test: pair of synthetic images obtained by randomly spraying black dots on white objects

Random dot stereograms



Forsyth & Ponce

Random dot stereograms



Random dot stereograms

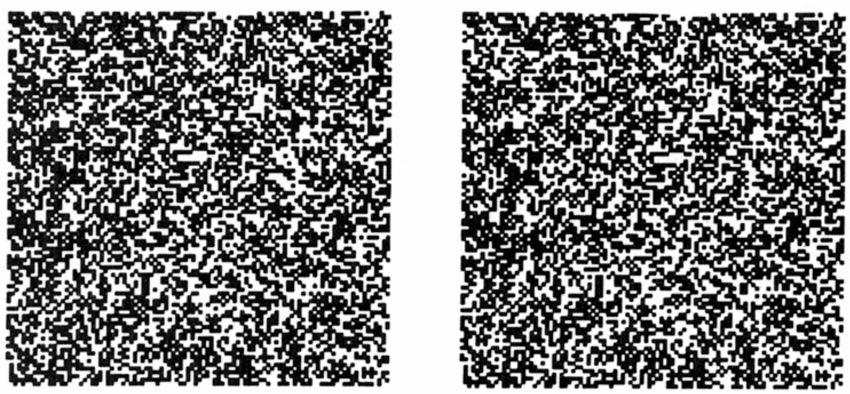


Figure 5.3.8 A random dot stereogram. These two images are derived from a single array of randomly placed squares by laterally displacing a region of them as described in the text. When they are viewed with crossed disparity (by crossing the eyes) so that the right eye's view of the left image is combined with the left eye's view of the right image, a square will be perceived to float above the page. (See pages 210–211 for instructions on fusing stereograms.)

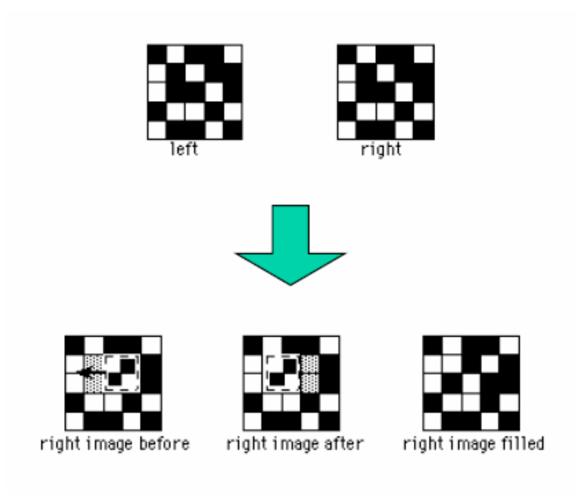
From Palmer, "Vision Science", MIT Press

Random dot stereograms

- When viewed monocularly, they appear random; when viewed stereoscopically, see 3d structure.

- Conclusion: human binocular fusion not directly associated with the physical retinas; must involve the central nervous system
- Imaginary "*cyclopean retina*" that combines the left and right image stimuli as a single unit

Generating a random dot stereogram



http://www.wellesley.edu/CS/LiDPC/OnParallaxis/Braunl.paper20.html

Autostereograms

Exploit disparity as depth cue using single image

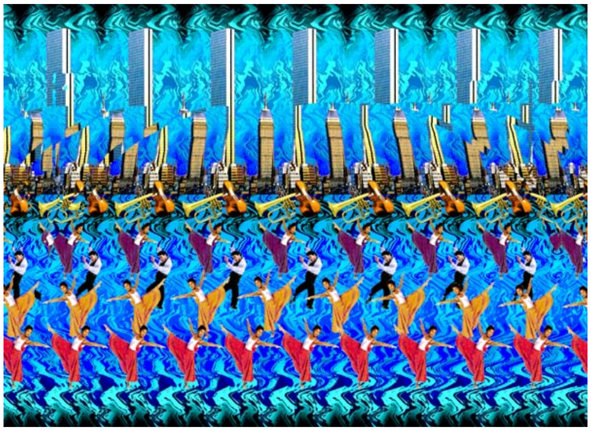
(Single image random dot stereogram, Single image stereogram)

Images from magiceye.com

Autostereograms

Images from magiceye.com

Autostereograms



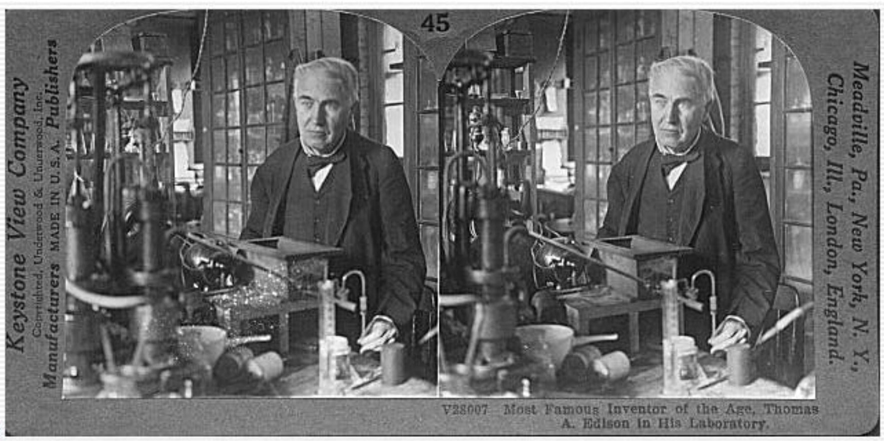
Images from magiceye.com

Stereo photography and stereo viewers

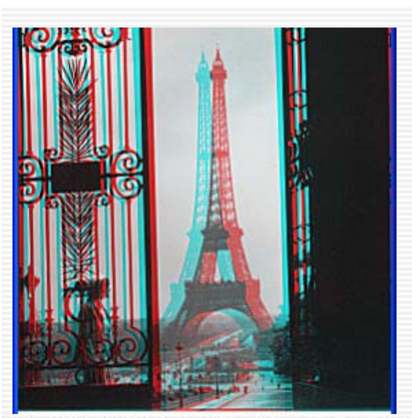
Take two pictures of the same subject from two slightly different viewpoints and display so that each eye sees only one of the images.

Invented by Sir Charles Wheatstone, 1838

Image courtesy of fisher-price.com



http://www.johnsonshawmuseum.org

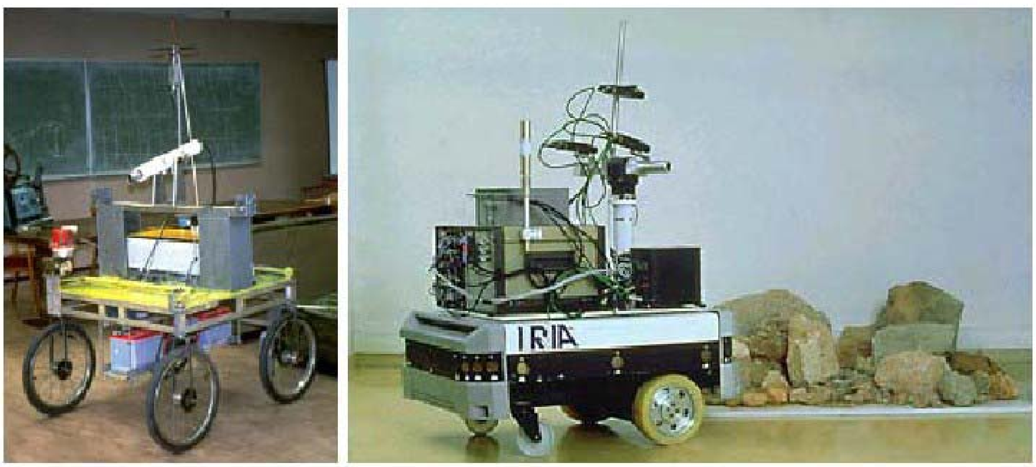


http://www.johnsonshawmuseum.org

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

http://www.well.com/~jimg/stereo/stereo_list.html

Stereo in machine vision systems



Left : The Stanford cart sports a single camera moving in discrete increments along a straight line and providing multiple snapshots of outdoor scenes
Right : The INRIA mobile robot uses three cameras to map its environment

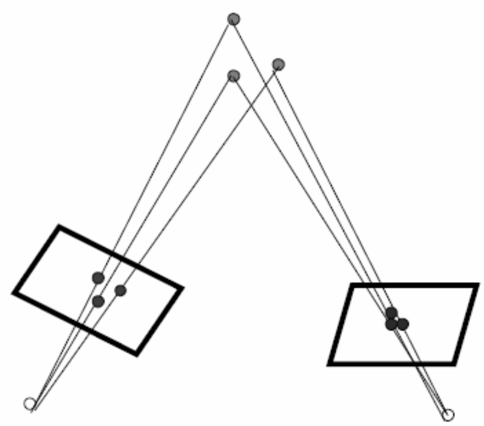
Stereo

- Main issues
  - Geometry: what information is available, how do the camera views relate?
  - Correspondences: what feature in view 1 corresponds to feature in view 2?
  - Triangulation, reconstruction: inference in presence of noise

Multi-view geometry

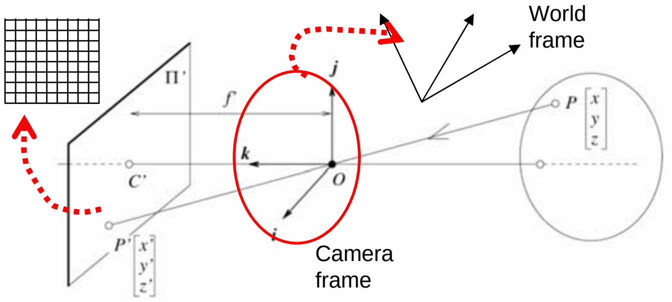
Relate

- 3-D points
- Camera centers
- Camera orientation
- Camera intrinsics



Slide credit: T. Darrell

Camera parameters



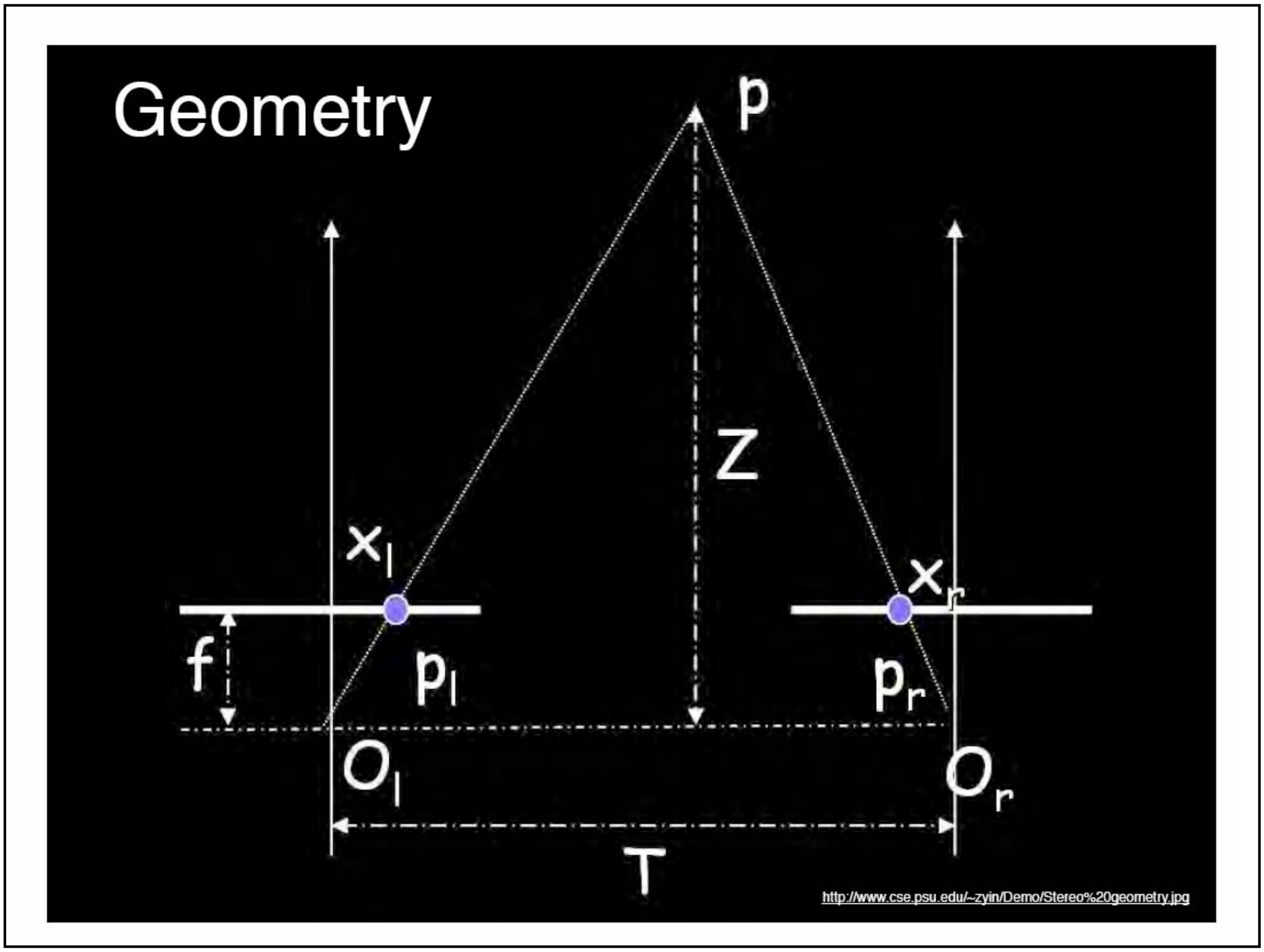
Extrinsic:
Camera frame ←→ Reference frame

Intrinsic:
Image coordinates relative to camera ←→ Pixel coordinates

- *Extrinsic* params: rotation matrix and translation vector
- *Intrinsic* params: focal length, pixel sizes (mm), image center point, radial distortion parameters

Geometry for a simple stereo system

- First, assuming parallel optical axes, known camera parameters:



Geometry
p
Z
x_l
x_r
f
p_l
p_r
O_l
O_r
T
http://www.cse.psu.edu/~zyin/Demo/Stereo%20geometry.jpg

Geometry for a simple stereo system

- Parameters in this case:
  - Camera centers (Ol, Or)
  - Focal length (f)
  - Baseline (T)

Geometry for a simple stereo system

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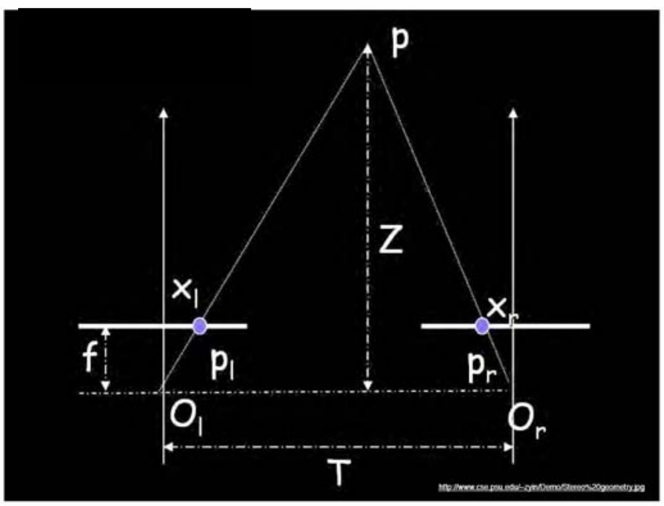
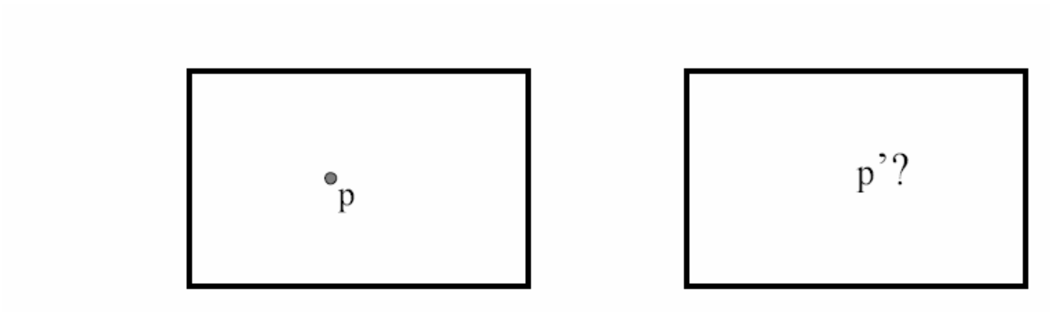


Similar triangles (pl, P, pr) and (Ol, P, Or)

$$\frac{T + xl - xr}{Z - f} = \frac{T}{Z}$$

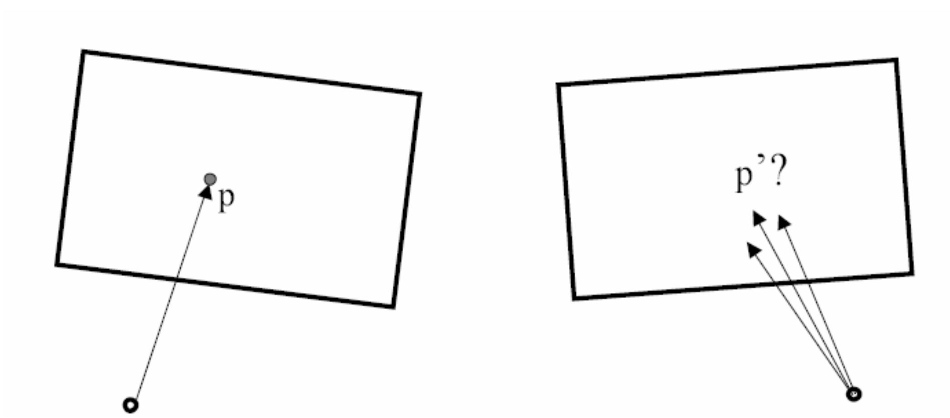
Z = f T/d
where d = xr – xl

Stereo constraints



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

Stereo constraints



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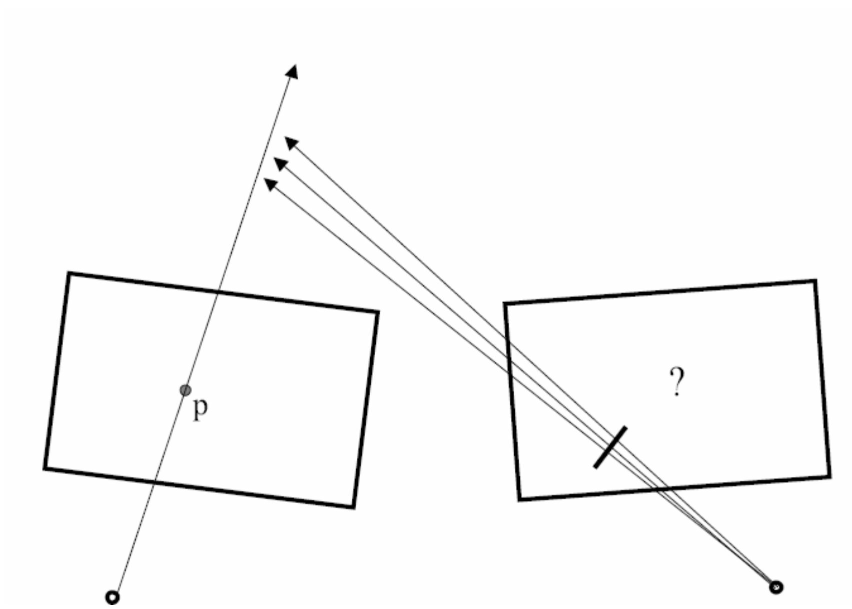
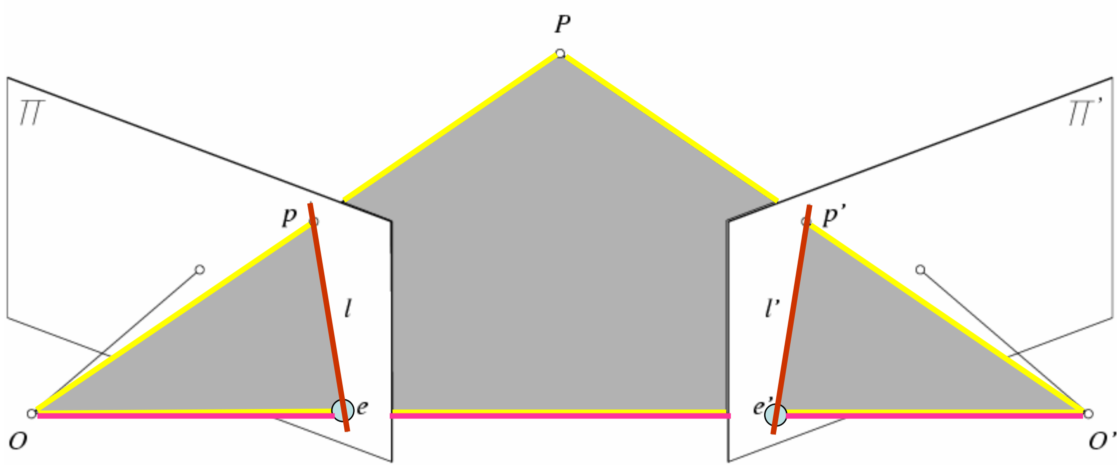
Stereo constraints



Epipolar geometry

Now the optical axes are not necessarily parallel.



• Epipolar Plane

• Baseline

• Epipoles

• Epipolar Lines

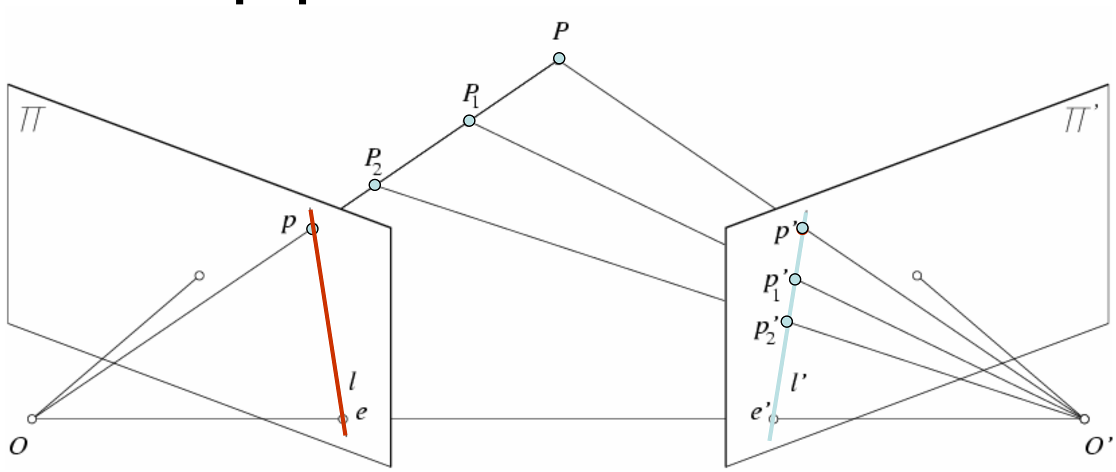
Adapted from M. Pollefeys, UNC

Epipolar geometry

- Baseline: line joining the camera centers
- Epipole: point of intersection of baseline with the image plane
- Epipolar plane: plane containing baseline
- Epipolar line: intersection of epipolar plane with the image plane

- All epipolar lines intersect at the epipole
- An epipolar plane intersects the left and right image planes in epipolar lines

Epipolar constraint

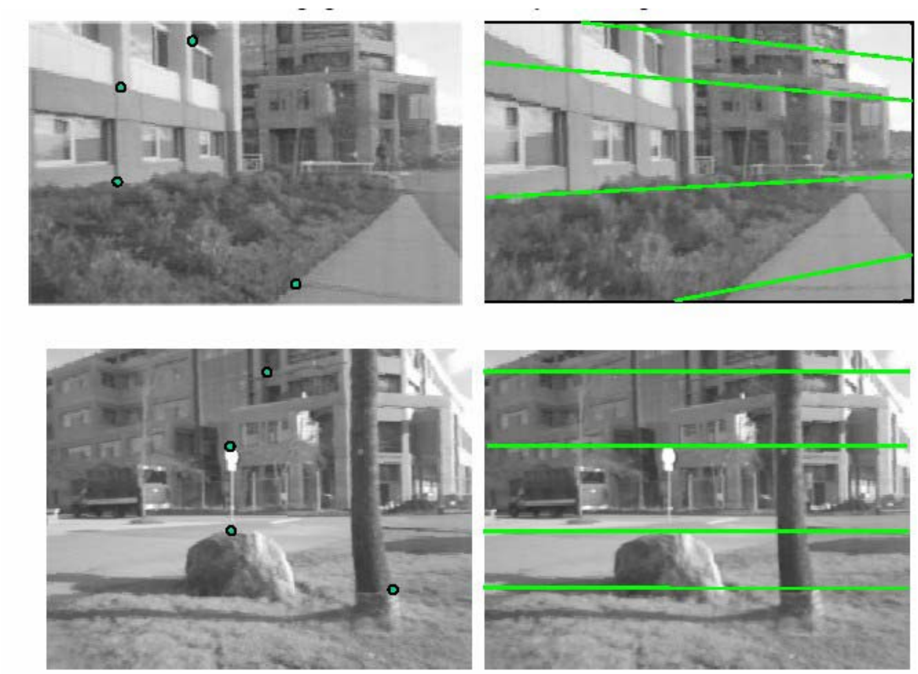


- Potential matches for *p* have to lie on the corresponding epipolar line *l'*.

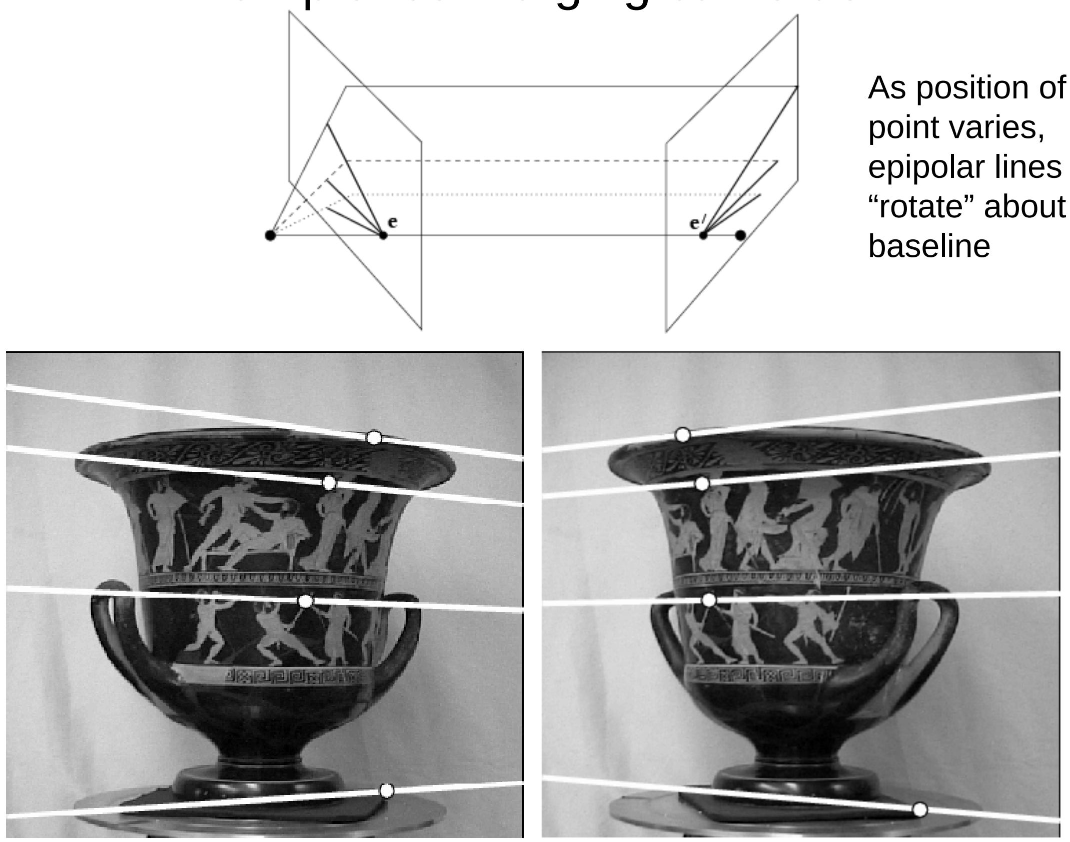
- Potential matches for *p'* have to lie on the corresponding epipolar line *l*.

Slide credit: M. Pollefeys

Epipolar constraint example



Example: converging cameras



As position of 3d point varies, epipolar lines "rotate" about the baseline

Figure from Hartley & Zisserman

Example: motion parallel with image plane

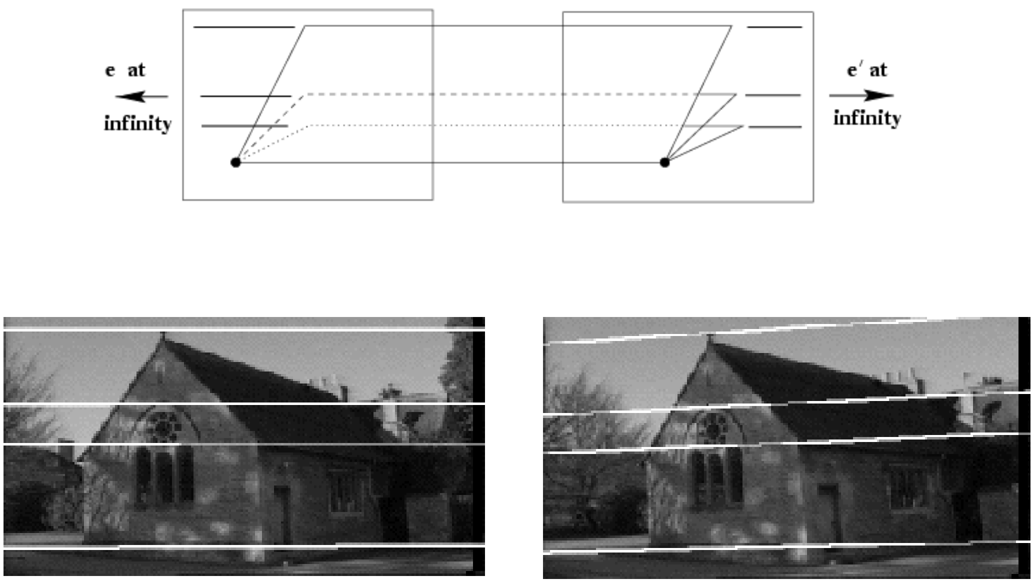
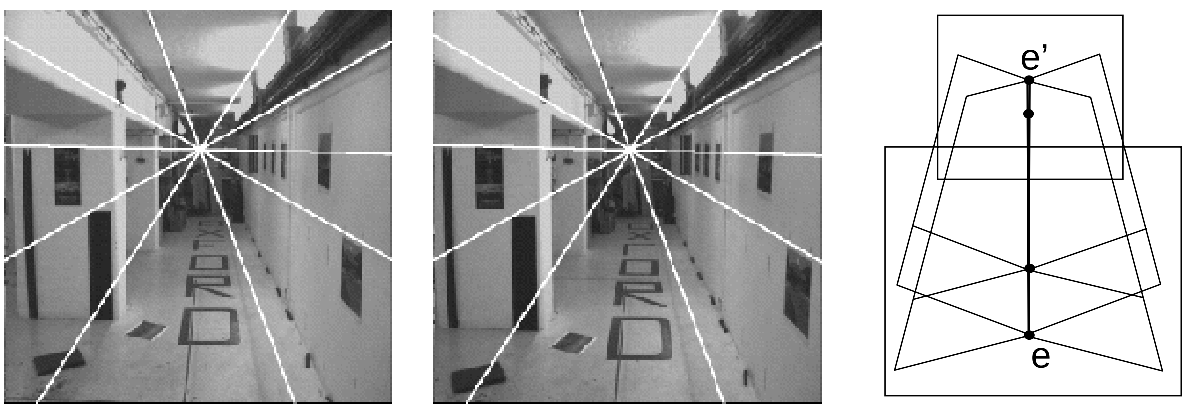


Figure from Hartley & Zisserman

Example: forward motion

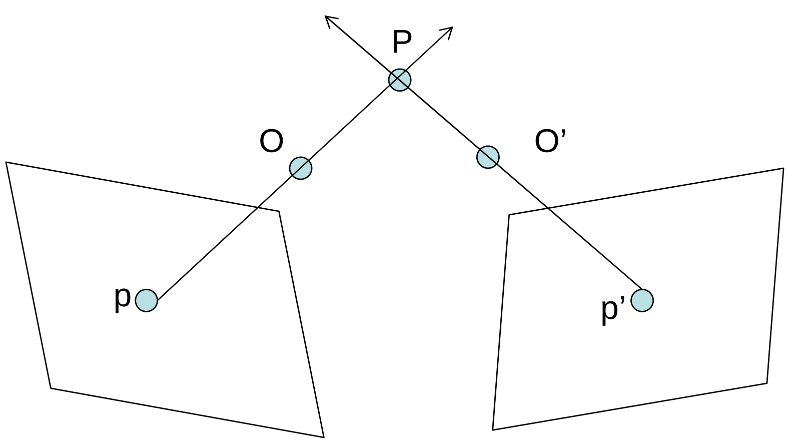


Epipole has same coordinates in both images.
Points move along lines radiating from e: “Focus of expansion”

Figure from Hartley & Zisserman

Reconstruction by triangulation

- Assuming intrinsic and extrinsic parameters are known, compute 3d location of point P from projections p and p':
- Intersect rays R = Op and R' = O'p'.



Reconstruction by triangulation

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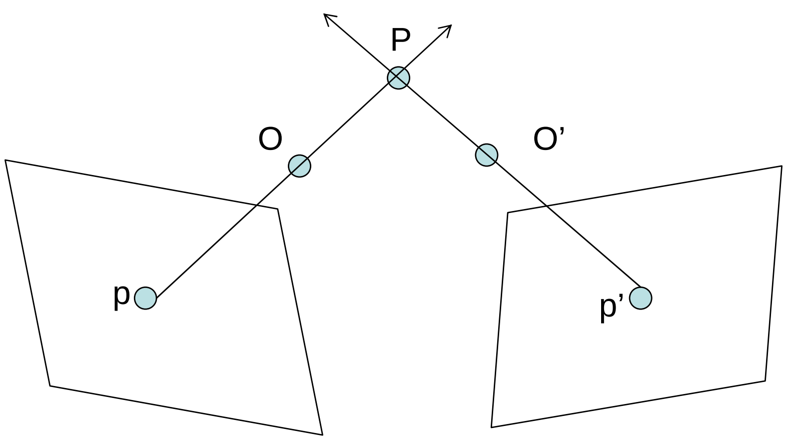
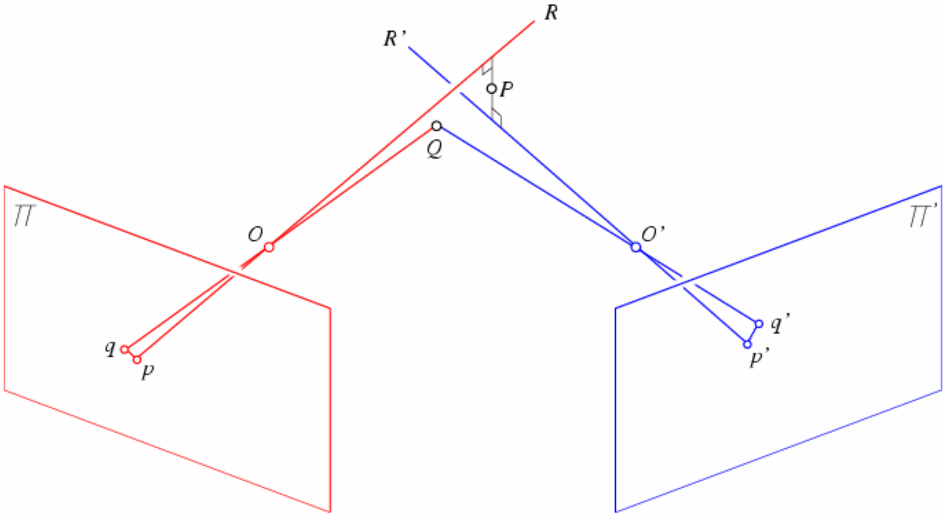


But, in practice, parameters and image locations only approximately known…

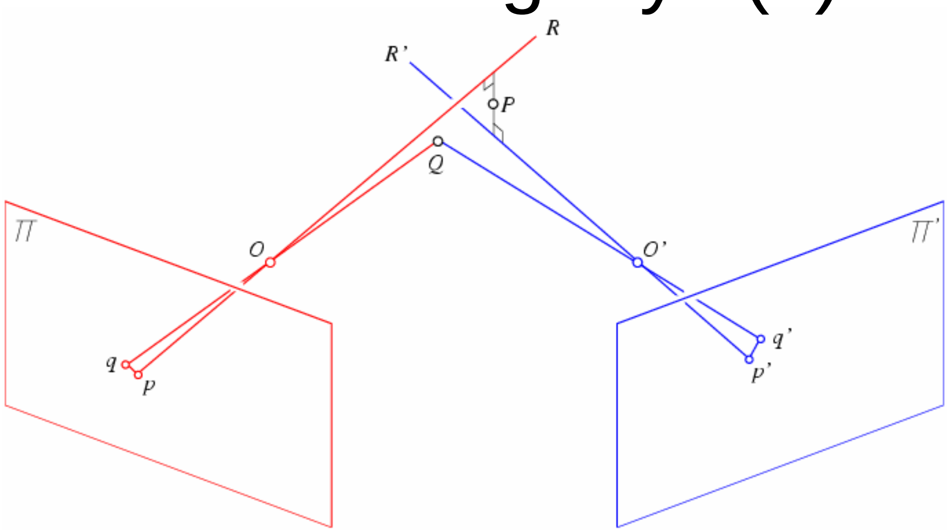
Triangulation with non-intersecting rays (1)



Construct line segment perpendicular to R and R' that intersects both rays

Midpoint of this segment is closest point to the two rays, use as P estimate of scene point

Triangulation with non-intersecting rays (2)



Estimate scene point Q as the point that minimizes summed squared distance between p and q, and p' and q' (non-linear least squares, iterative, not closed form)

Next

- 3d reconstruction
- Building stereo algorithms
  - correspondences