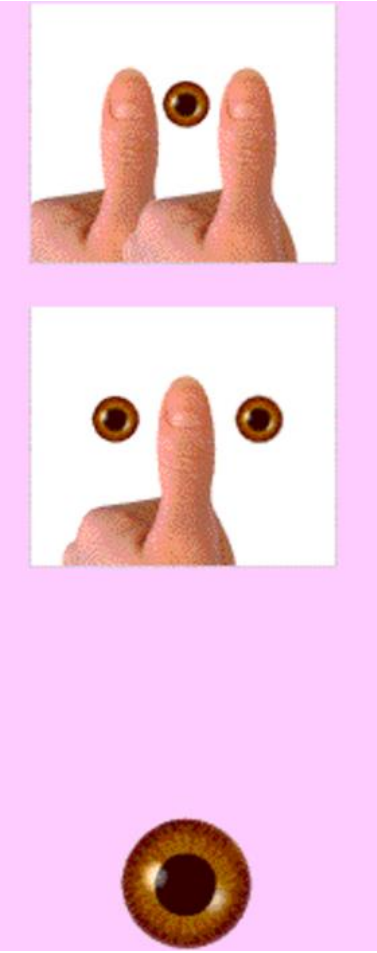
Stereo Vision - Check



http://www.vision3d.com/frame.html

Stereo Vision – Daily Life

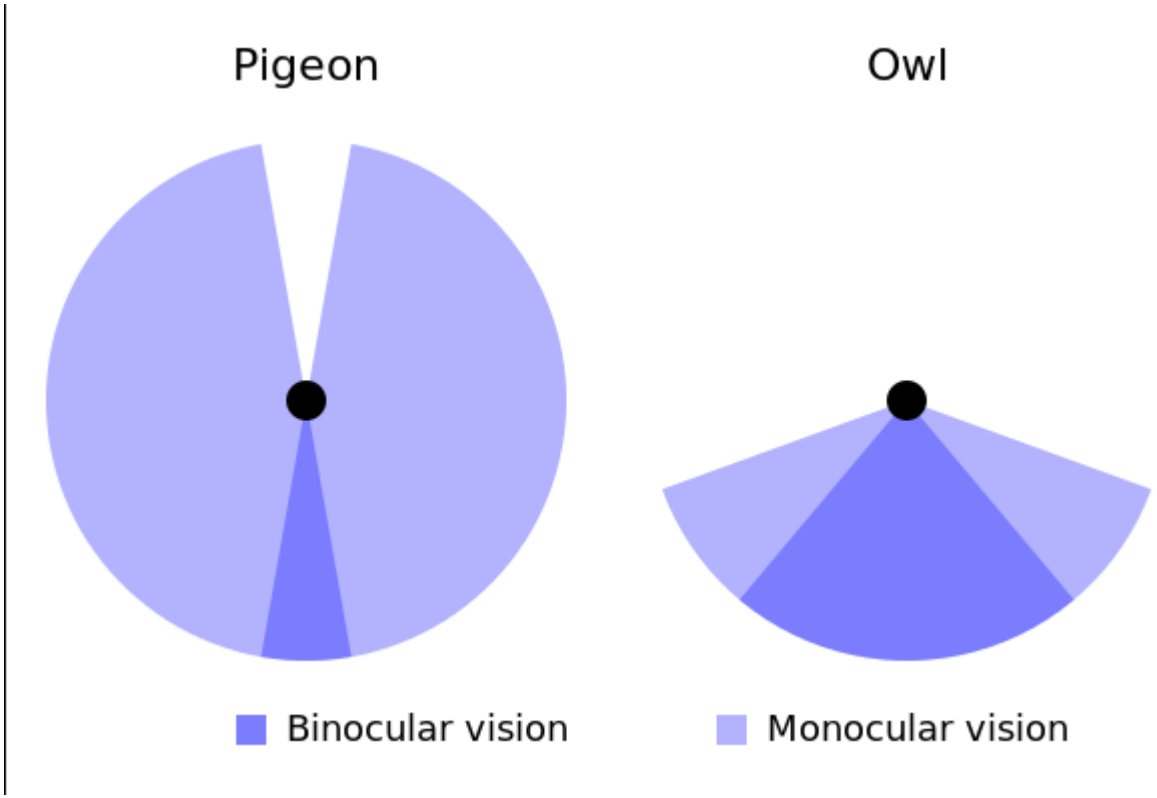
Key application – To perceive depth

- Throwing, catching or hitting a ball
- Driving and parking a car
- Planning and building a three-dimensional object
- Threading a needle and sewing and many more….

http://www.vision3d.com/

Stereo Vision – Animals

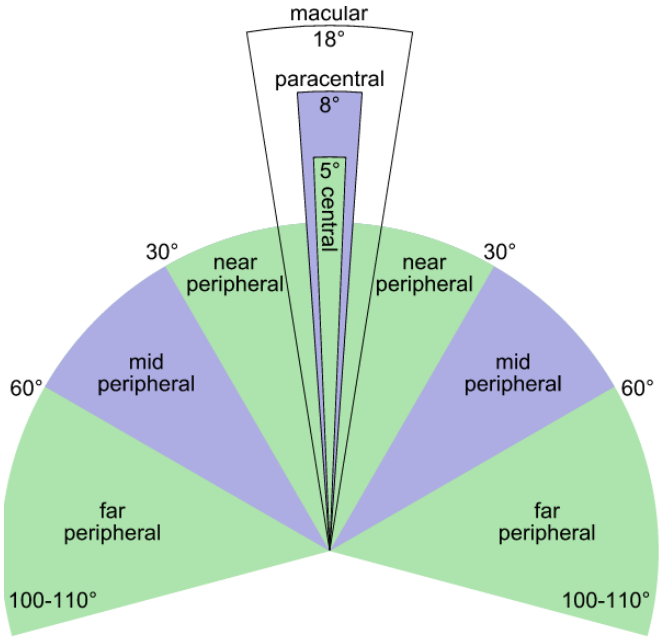
Not all life forms evolved with a priority of depth perception



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

Human Vision

The resolution of retina is highest at fovea, giving great macular vision and not so great peripheral vision



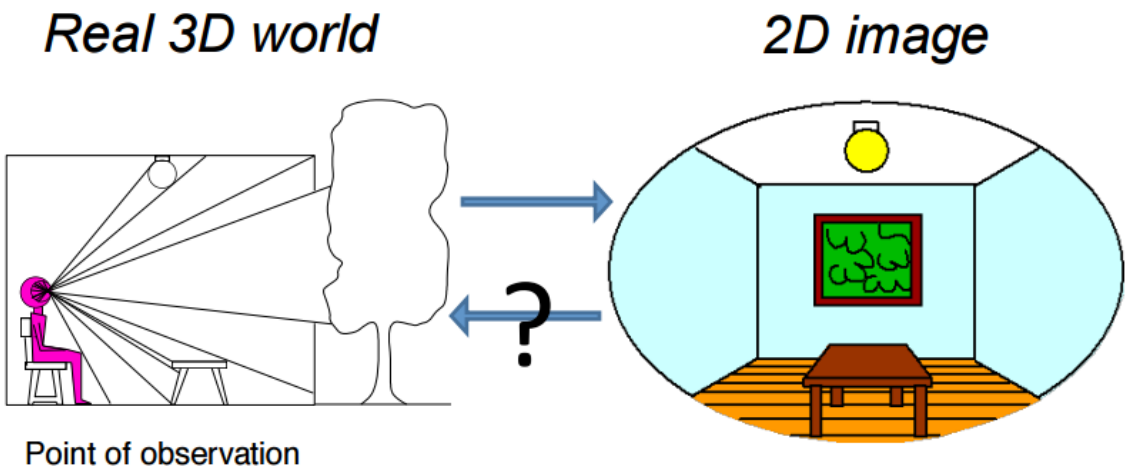
https://www.youtube.com/watch?v=xNSgmm9FX2s

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

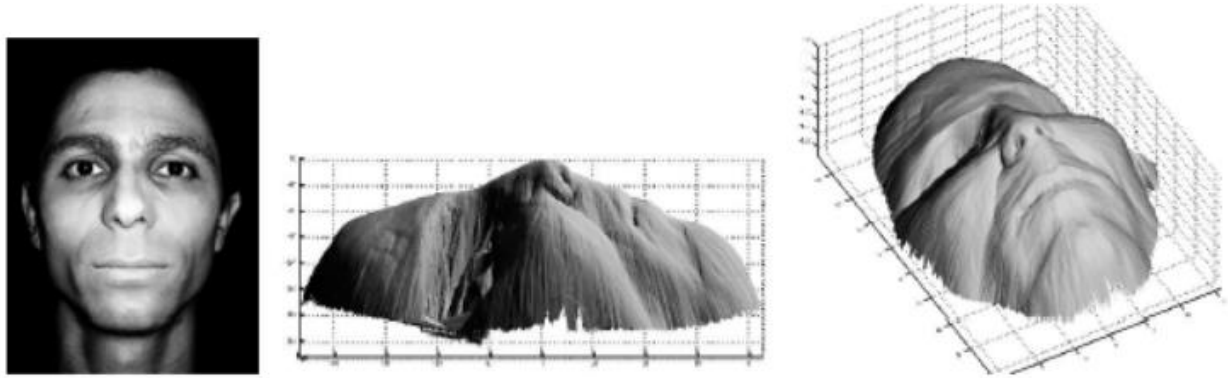
Depth Perception

Only through Stereo Vision?

- How can we automatically compute 3D geometry from images?
  - What cues in the image provide 3D information?



Visual Cues for 3D - Shading



[Figure from Prados & Faugeras 2006]

Visual Cues for 3D

- Shading
- Texture

The Visual Cliff, by William Vandivert, 1960

Slide credit: J. Hayes

Visual Cues for 3D

- Shading
- Texture
- Focus

From *The Art of Photography*, Canon

Slide credit: J. Hayes

Visual Cues for 3D

- Shading
- Texture
- Focus
- Motion

Slide credit: J. Hayes

Visual Cues for 3D

- Shading
- Texture
- Focus
- Motion

- Others:
  - Highlights
  - Shadows
  - Silhouettes
  - Inter-reflections
  - Symmetry
  - Light Polarization
  - ...

Shape From X

- X = shading, texture, focus, motion, ...
- We'll focus on the motion cue

Slide credit: J. Hayes

Can structure of entire scene be recovered from a single view?

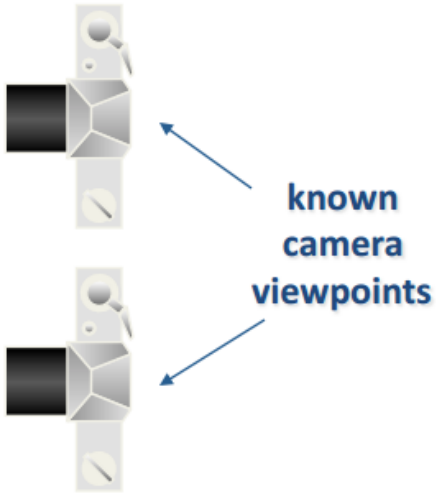
Intrinsic ambiguity of the mapping from 3D to image (2D)

Courtesy slide S. Lazebnik

Slide source: S. Savarese.

Stereo Reconstruction

- The Stereo Problem
  - Shape from two (or more) images
  - Biological motivation



Slide credit: J. Hayes

Stereo Photography and Stereo Viewers

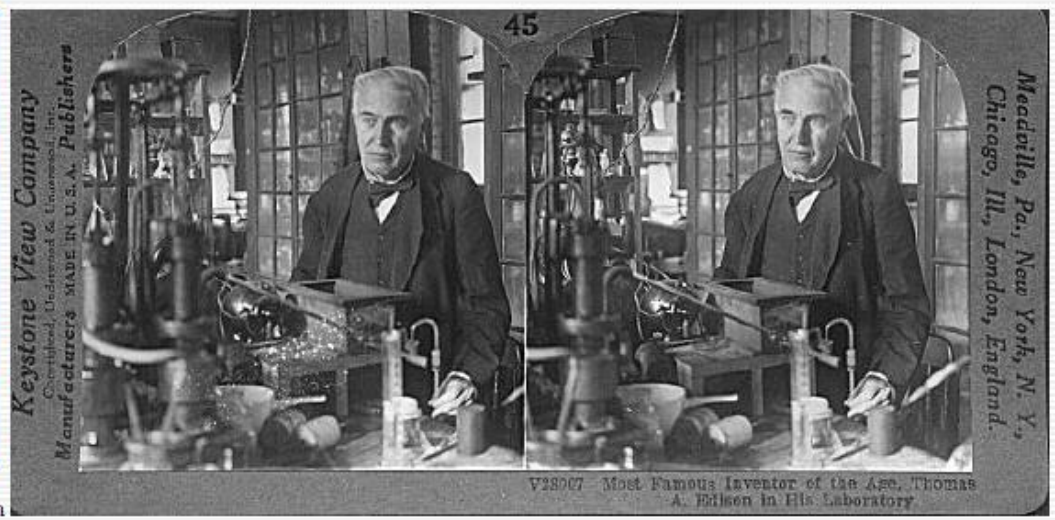
Take two pictures of the same subject from two slightly different viewpoints and display so that each eye sees only one of the images.

Invented by Sir Charles Wheatstone, 1838

Image courtesy of fisher-price.com

Slide source: K. Grauman.

Stereo Photography and Stereo Viewers

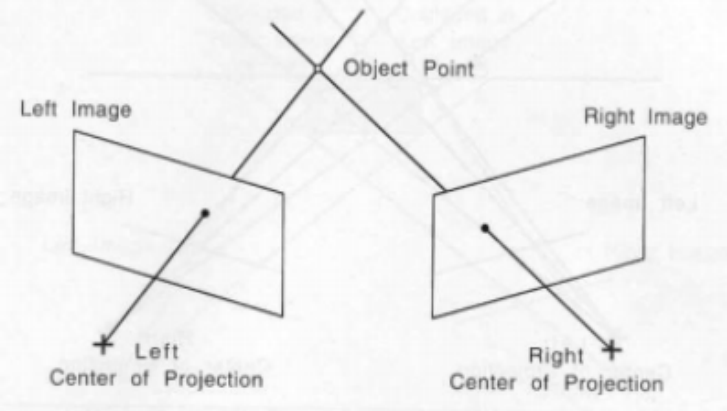


http://www.johnsonshawmuseum.org

Slide source: K. Grauman.

Triangulation

- The 3D location of point in space is restricted to straight line that passes through center of projection and the projection of the object point on image plane
- Stereo Vision determines the position of a point in space by finding the intersection of the two lines passing through center of projection and the projection of object point on image planes



Core Problems in Stereo

- **Correspondence:** Given a point in one image, how can I find the corresponding point x' in another one ?

- **Camera geometry:** Given corresponding points in two images, find camera matrices, position and pose.

- **Scene geometry:** Find coordinates of 3D point from its projection into 2 or multiple images.

Slide source: S. Savarese.

Core Problems in Stereo

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Slide source: S. Savarese.

Stereo Correspondence Problem

- We have two images taken from cameras with different intrinsic (focal length, resolution) and extrinsic (distance between cameras and orientation change) parameters

- How do we match a point in the first image to a point in the second? How can we constrain our search?

Depth Map Estimation

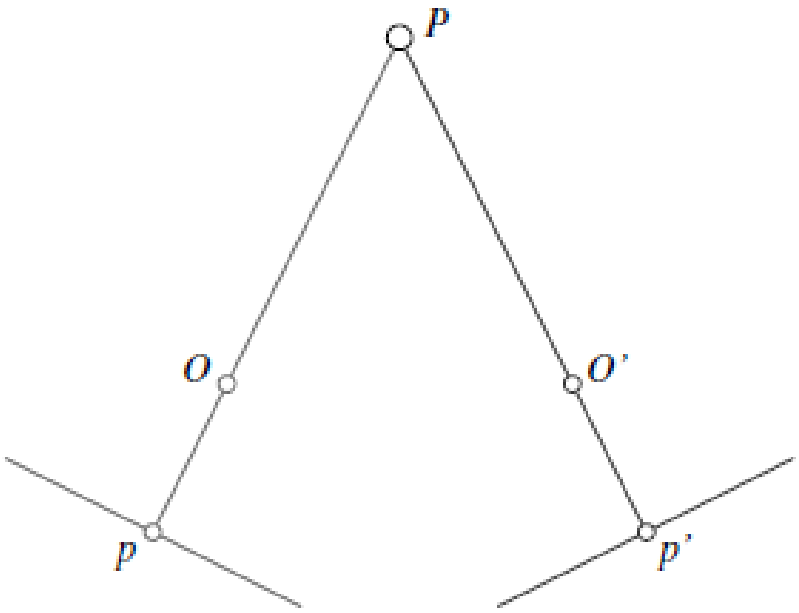
image 1

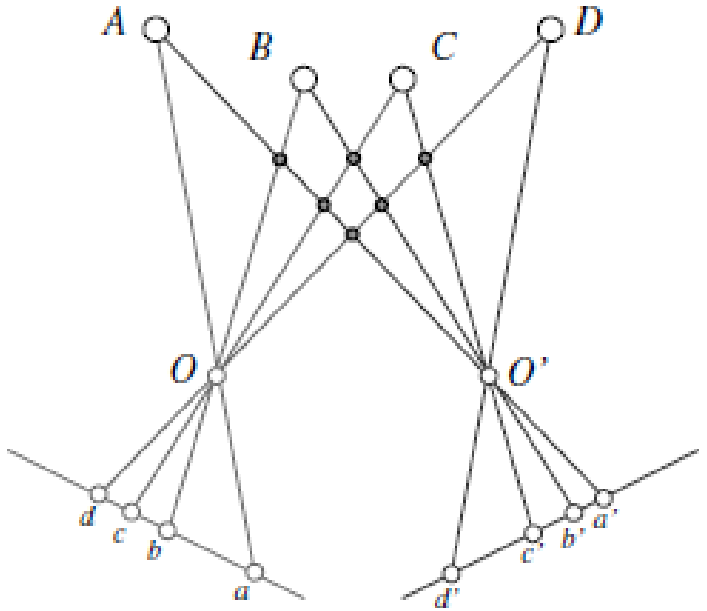
image 2

Dense depth map

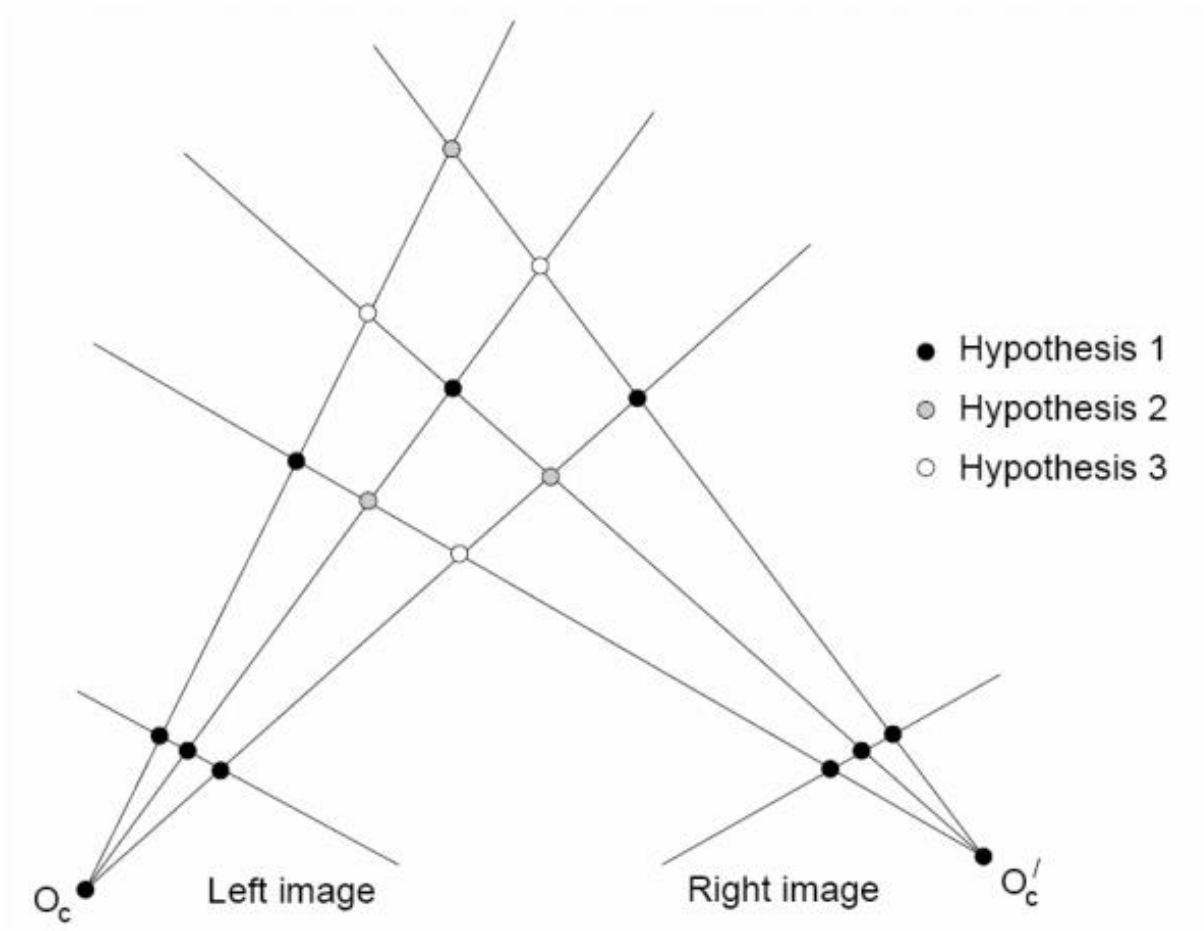
Given a calibrated binocular stereo pair, can we fuse it to produce a depth image?

Binocular Vision - Ambiguity

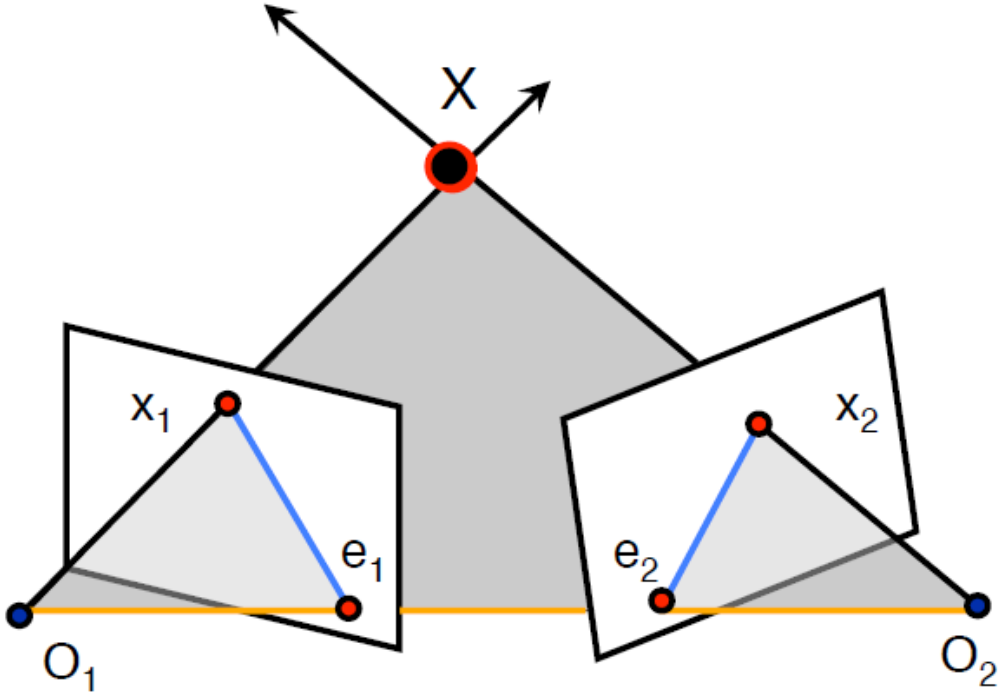




Binocular Vision – How to verify?



Epipolar Geometry



- Epipolar Plane
- Baseline
- Epipolar Lines

- Epipoles e_1, e_2

  = intersections of baseline with image planes
  = projections of the other camera center
  = vanishing points of camera motion direction

Slide source: S. Savarese.

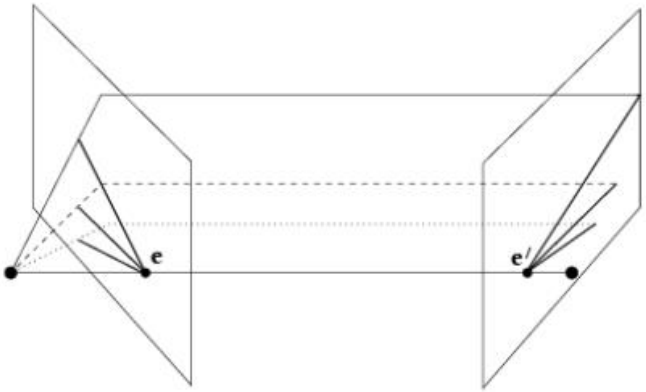
Epipolar Geometry Terms

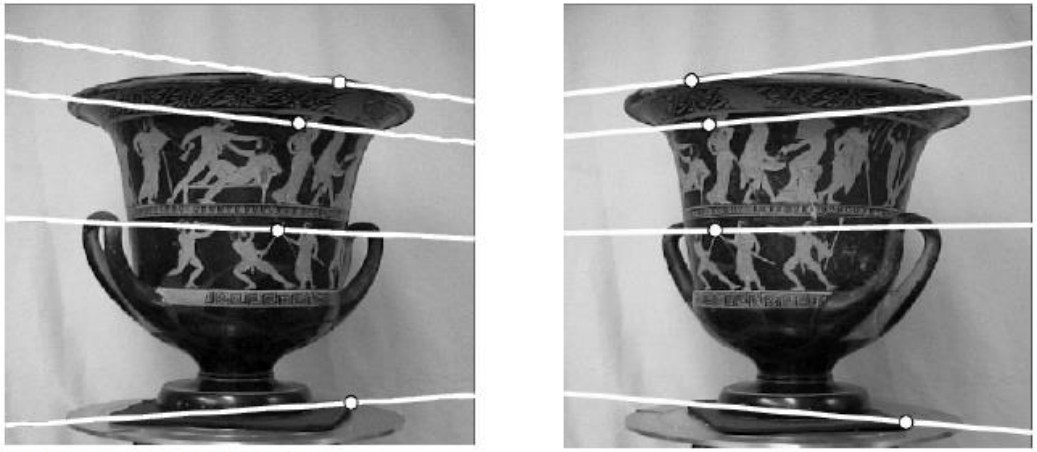
- **Baseline**: line joining the camera centers
- **Epipole**: point of intersection of baseline with the image plane
- **Epipolar plane**: plane containing baseline and world point
- **Epipolar line**: intersection of epipolar plane with the image plane

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

Slide source: K. Grauman.

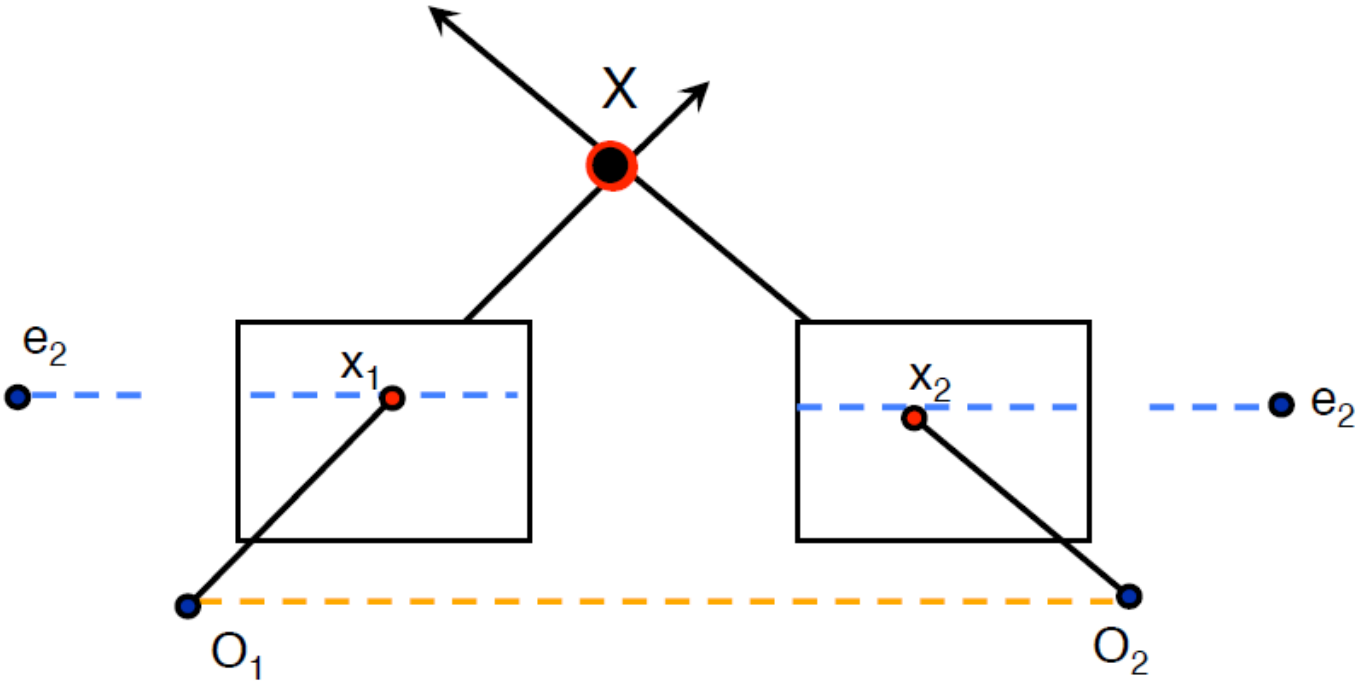
Example





Slide source: S. Savarese, K. Grauman; Figure from Hartley and Zisserman.

What if the Image planes are parallel?

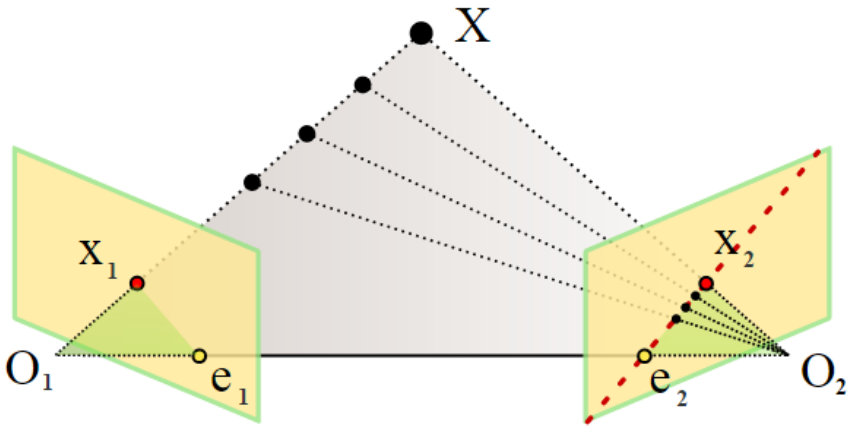


- Baseline intersects the image plane at infinity
- Epipoles are at infinity
- Epipolar lines are parallel to x axis

Slide source: S. Savarese.

How is Epipolar Geometry useful for Stereo Vision?

To reduce the correspondence search problem of features from 2D (Whole image) to 1D (A single line)



Epipolar Constraint – Point corresponds to a ray

We try to estimate the position of X based on x and x'. From Geometry

- Potential matches for x have to lie on the corresponding line l'.
- Potential matches for x' have to lie on the corresponding line l.

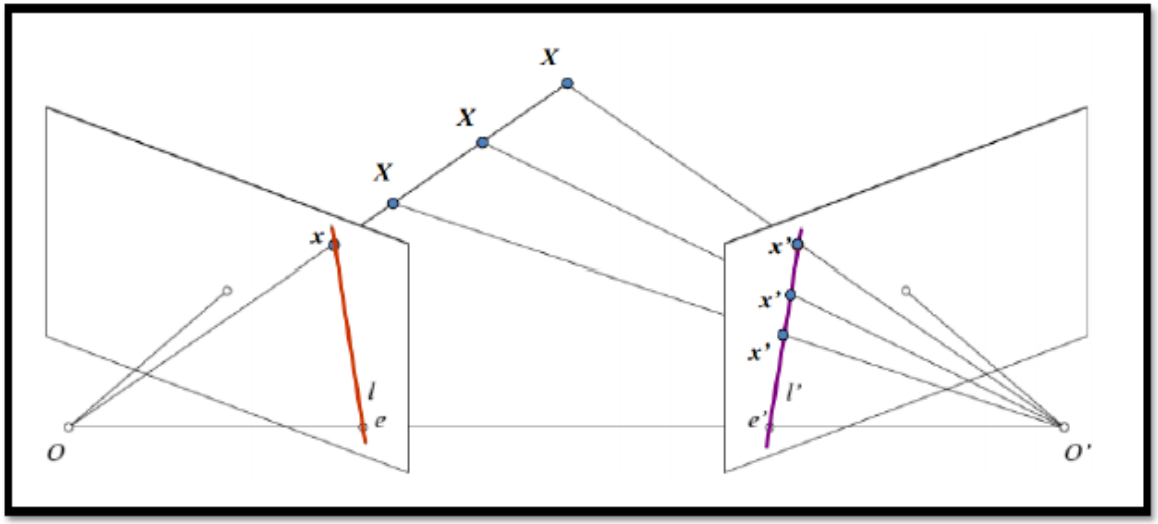


Image Rectification

- Arbitrary arrangement of cameras results in image planes that are not parallel.
- Complicated Epipolar representation and correspondence search. How to make it simpler?

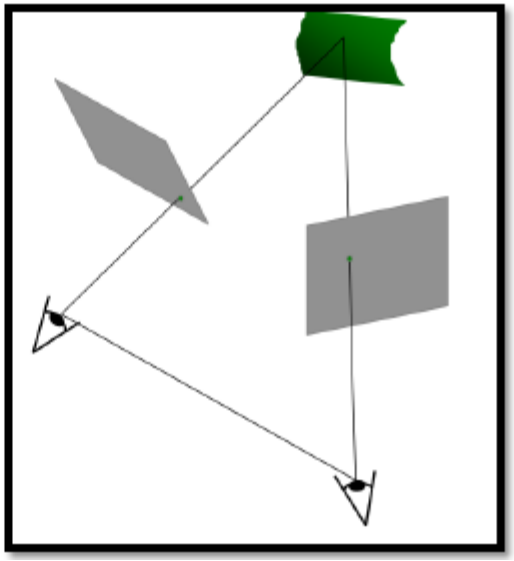
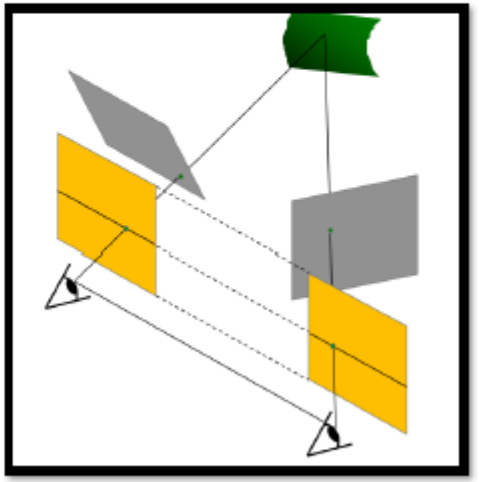


Image Rectification

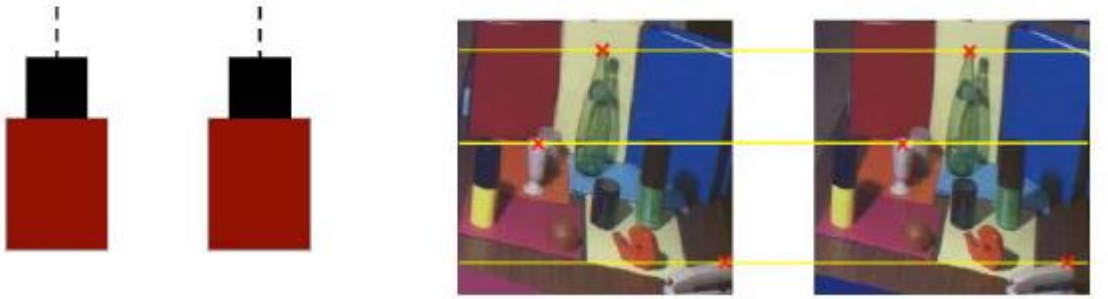
- Re-project image planes onto a common plane parallel to the line between optical centers
- Pixel search would be horizontal after this transformation



- C. Loop and Z. Zhang. Computing Rectifying Homographies for Stereo Vision. IEEE Conf. Computer Vision and Pattern Recognition, 1999

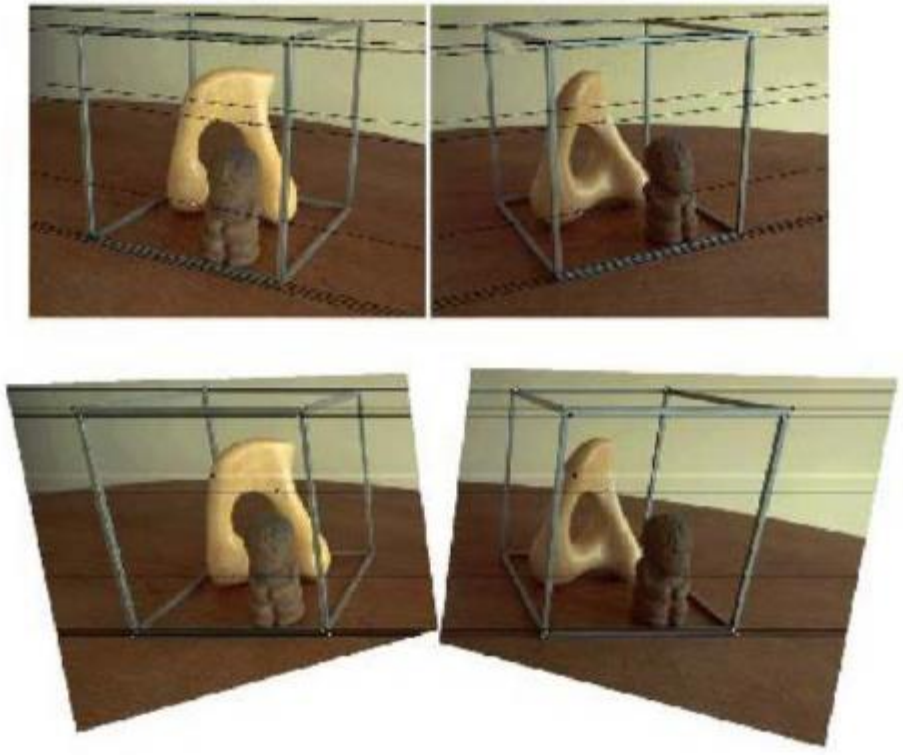
Image Rectification - Example

Original stereo pair



Stereo pair in standard form

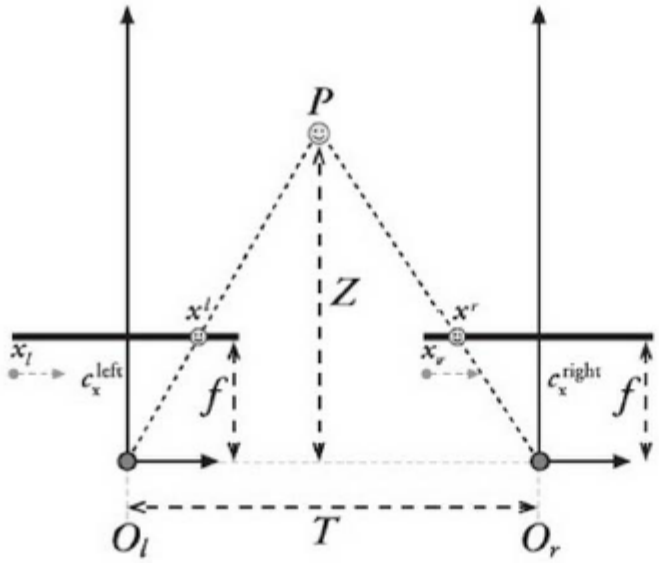
Image Rectification – by Projective Transformation



Disparity

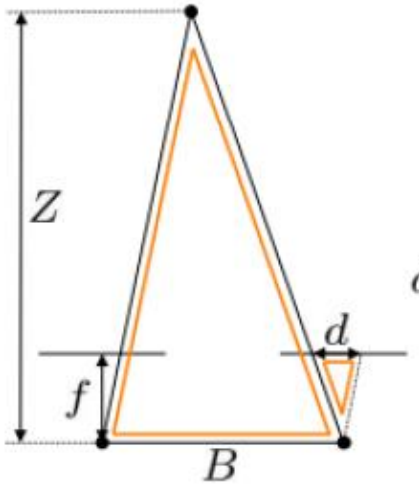
Disparity is defined as the difference in the location of a feature point between the right and left images

Disparity high for closer objects and low for distant objects



$$d = x^l - x^r$$

Depth from Disparity

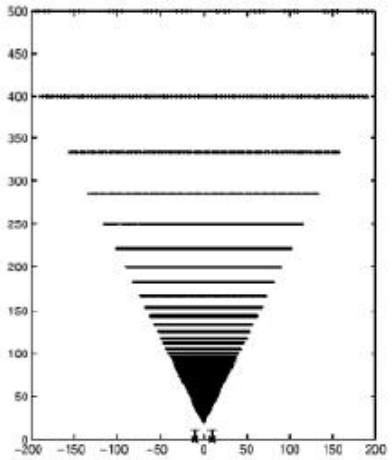


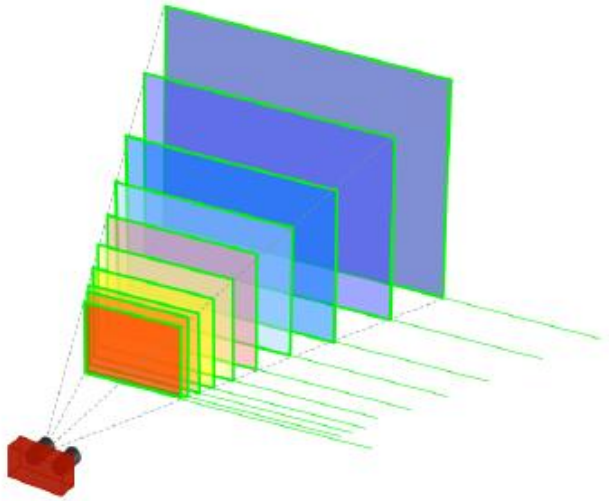
$$\frac{B}{Z} = \frac{d}{f}$$

$$d = \frac{Bf}{Z}$$

B – Baseline
Z – Depth
d – Disparity
f – focal length

Depth Resolution from Disparity

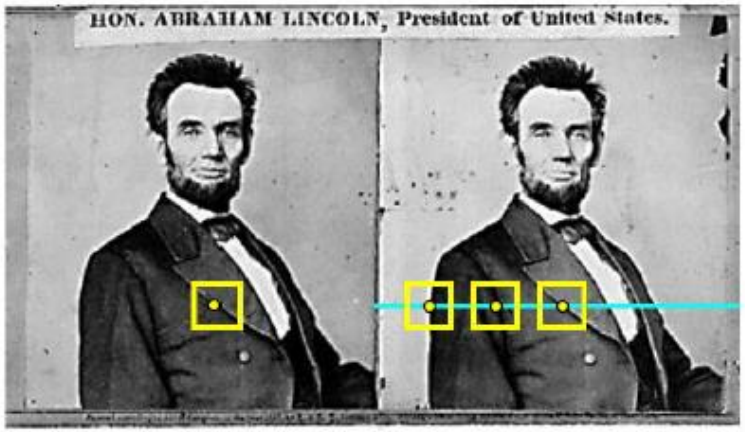




$$\frac{dd}{dZ} = \frac{Bf}{Z^2}$$

$$\Delta Z = \frac{Z^2}{Bf}\Delta d$$

Basic Stereo Matching Algorithm



- Perform Stereo Rectification
- 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'

Basic Stereo Matching Algorithm

```
for x=1:w,
  for y=1:h,
    bestdist=inf;
    for i=-dr:0,
      if (dist(pix(x,y),pix(x+i,y))<bestdist)
         d(x,y)=i; best=sim(pix(x,y),pix(x+i,y)); end
    end
  end
end
```

Basic Stereo Matching Algorithm

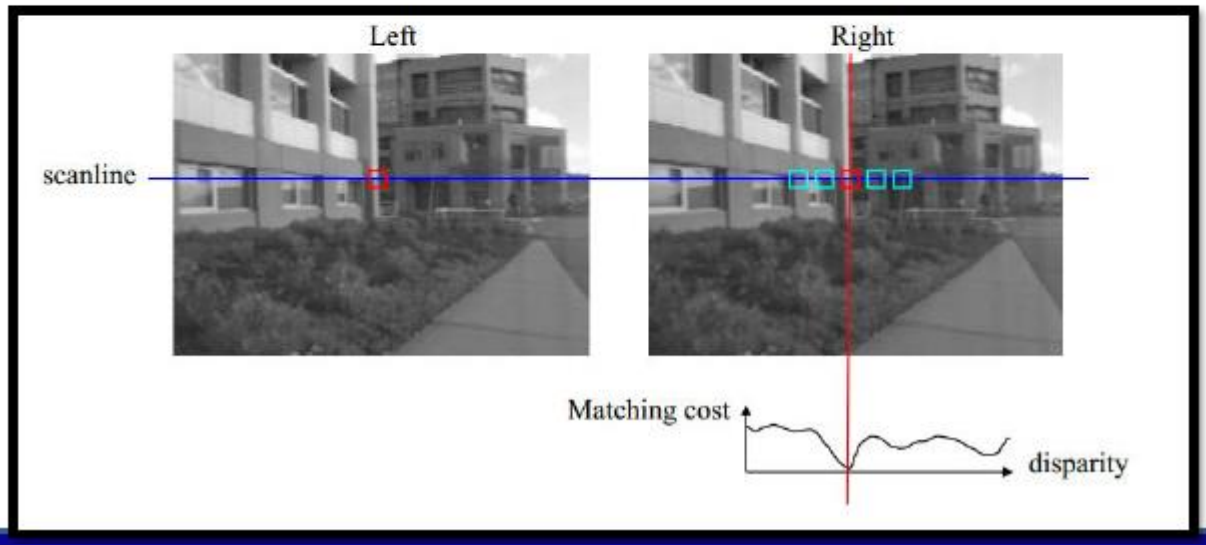
Let's make some assumptions to simplify the matching problem

1. Baseline is relatively small(compared to the depth of scene points)
2. Most scene points are visible in both views
3. Also, matching regions are similar in appearance

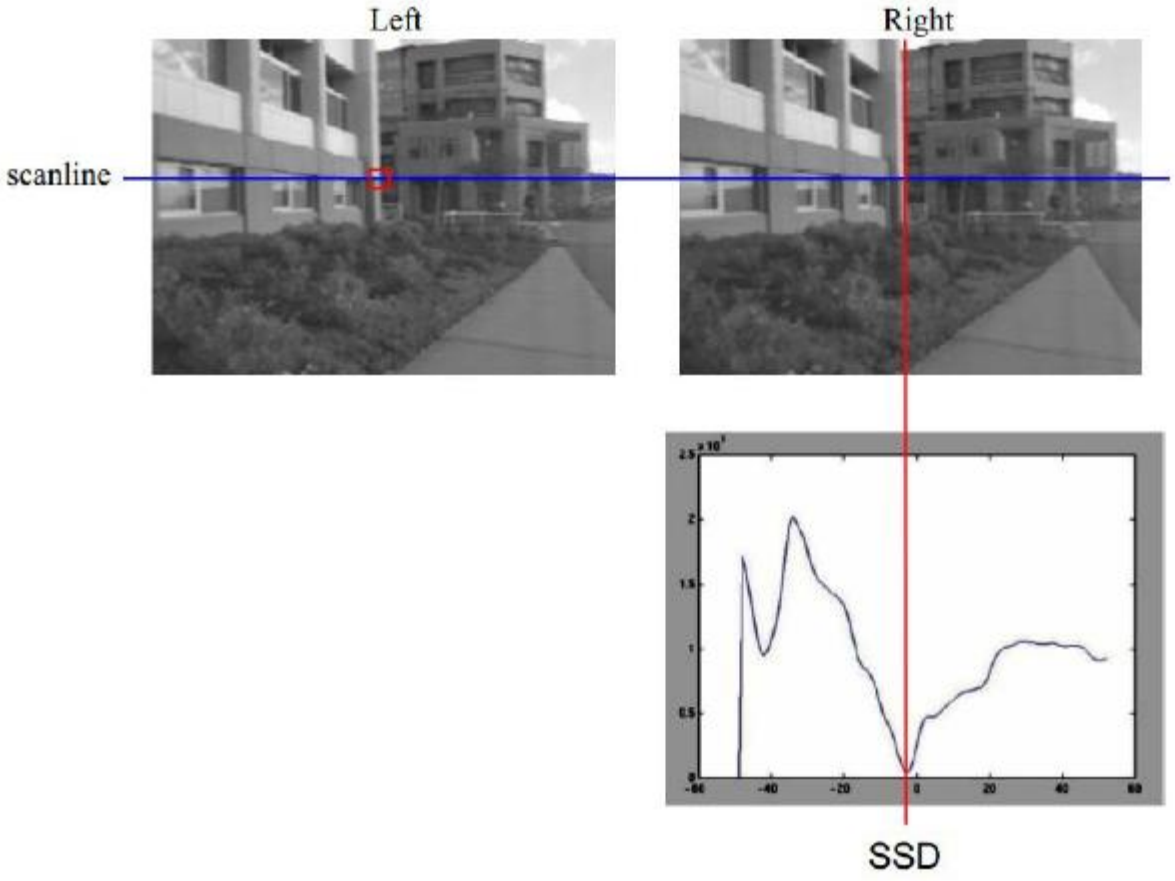
Correspondence with Similarity Constraint

- Slide a window along the right scanline and compare contents of that window with the reference window in the left image

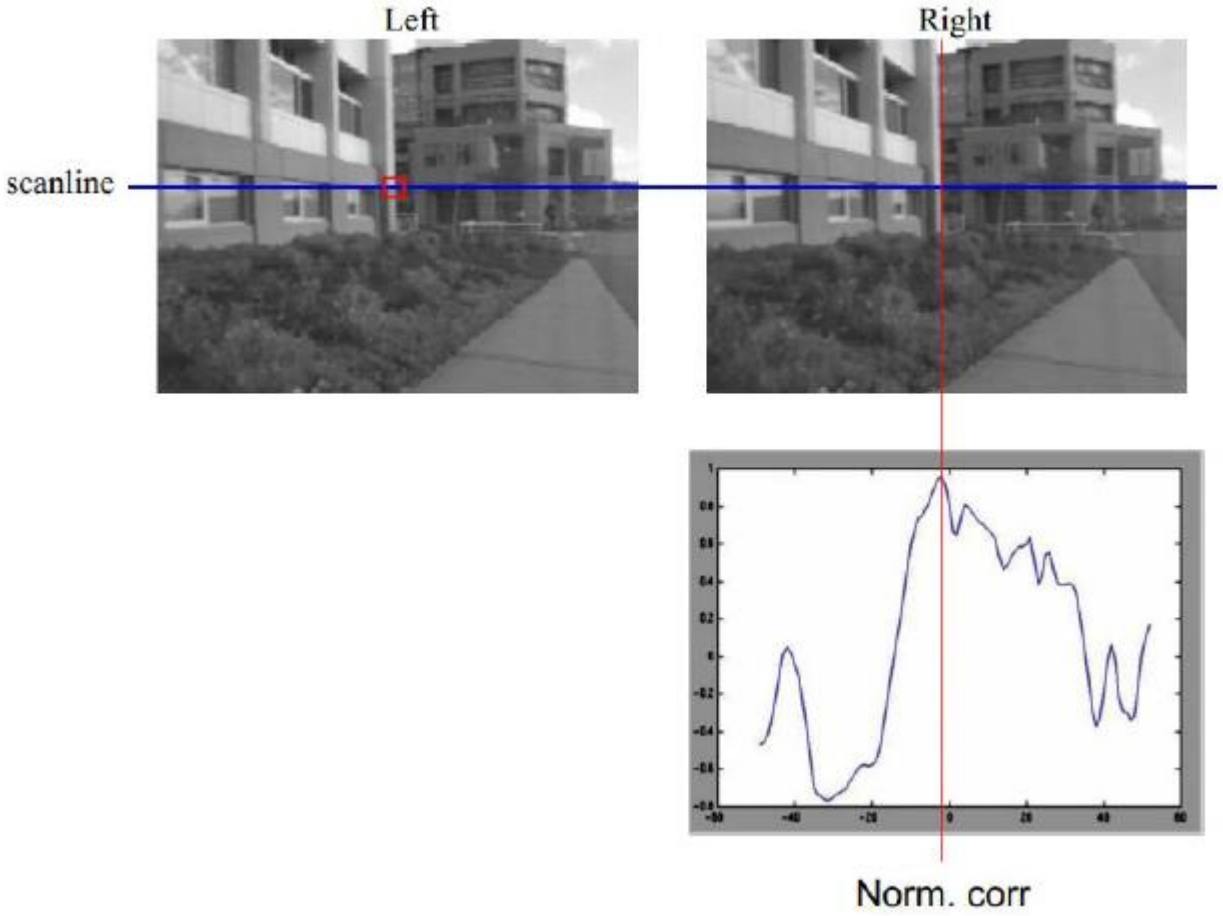
- Matching cost: SSD or normalized correlation



Correspondence with SSD



Correspondence with NCC

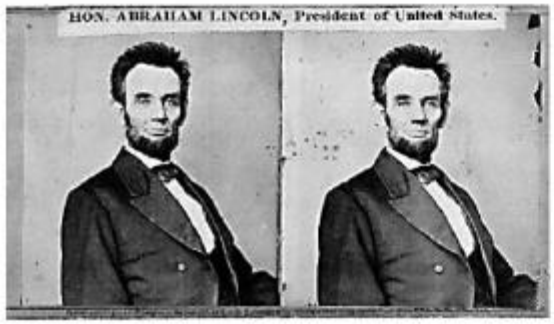


Correspondence with NCC

- Smaller Window Size – More detail, But More Noise
- Large Window Size – Smooth disparity map, but less detail

W = 3 W = 20

Similarity Constraint Failure



Textureless surfaces

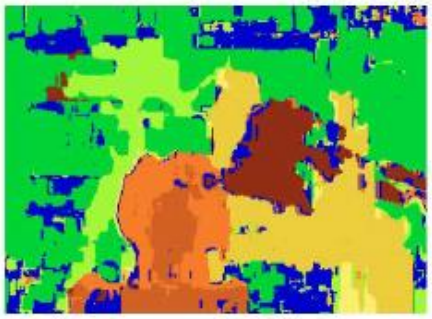
Occlusions, repetition

Non-Lambertian surfaces, specularities

Results with Window Search

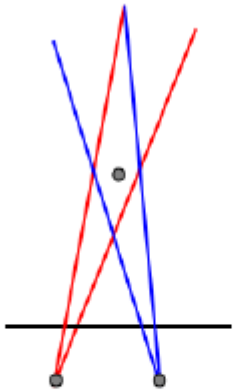
Data

Window-based matching

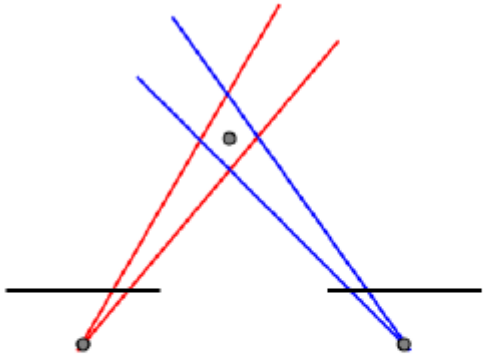


Ground truth

Role of Baseline



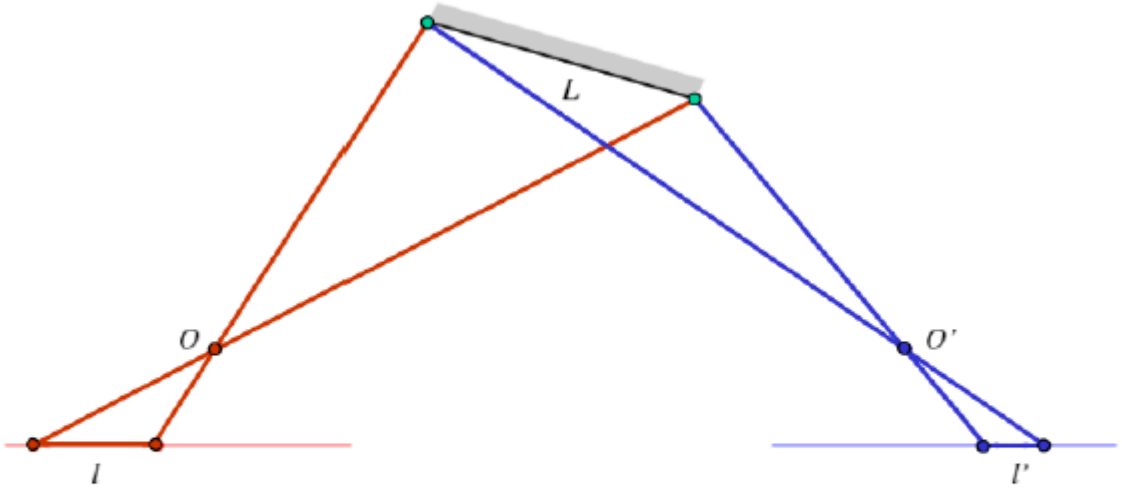
Small Baseline



Large Baseline

Small baseline: large depth error
Large baseline: difficult search problem

Role of Baseline



- Matching with fixed-size windows will fail!
- Possible solution: adaptively vary window size

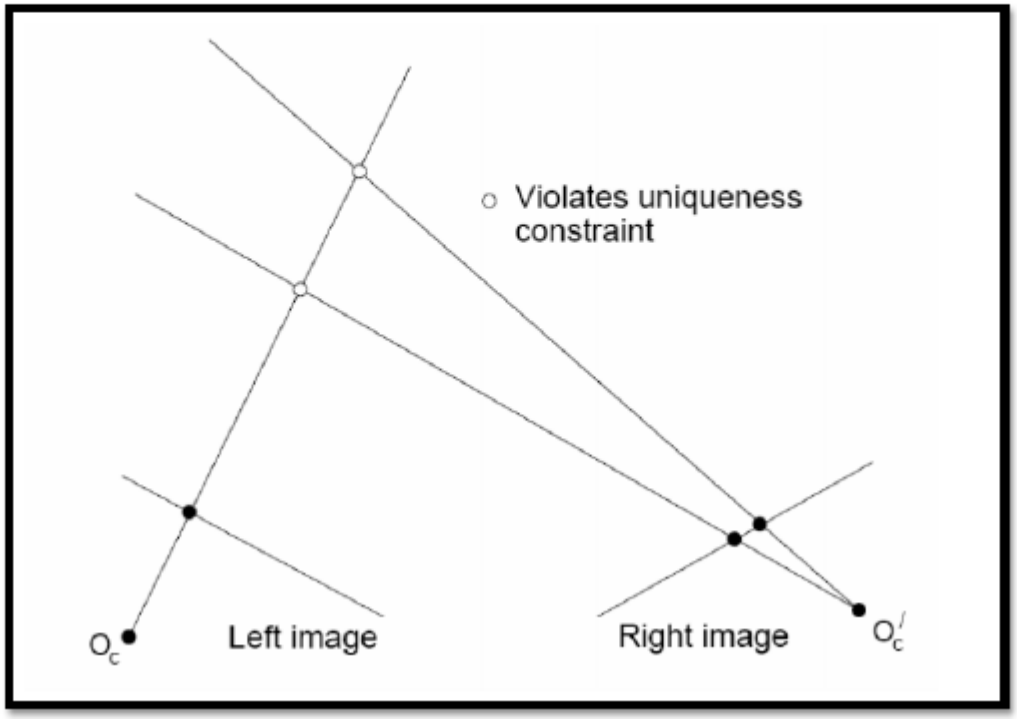
Can we improve Window based matching?

- The similarity constraint is **local** (each reference window is matched independently)
- Need to enforce **non-local** correspondence constraints

We can improve by imposing few global constraints while estimating disparity

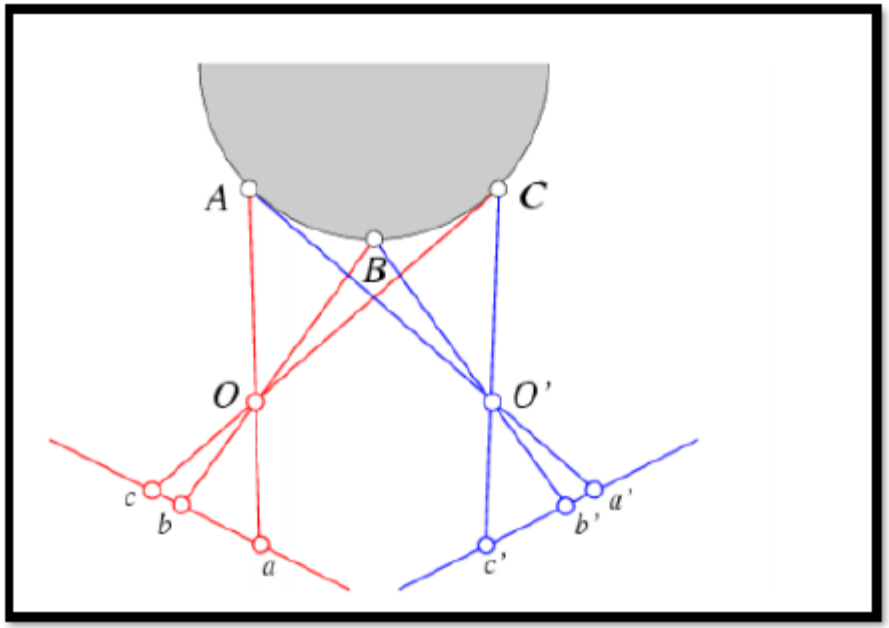
Uniqueness Constraint

- Uniqueness - For any point in one image, there should be at most one matching point in the other image



Ordering Constraint

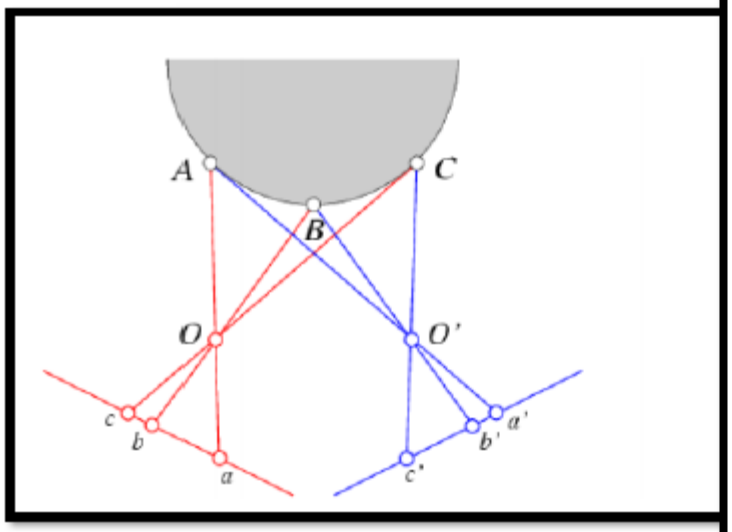
- Ordering - Corresponding points should be in the same order in both the images

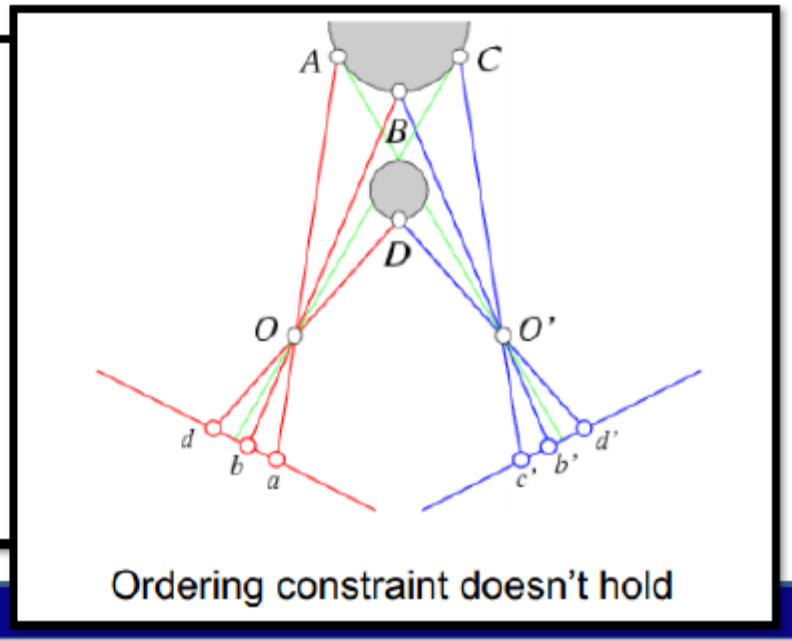


Can this fail?

Ordering Constraint

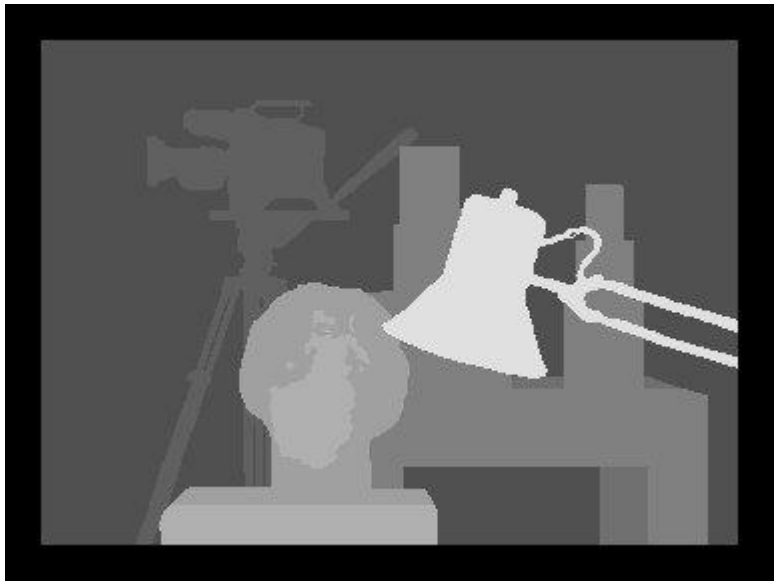
- Ordering - Corresponding points should be in the same order in both the images. Does not always hold true. For instance, if we have a smaller object in front of large object, the images violate ordering constraint



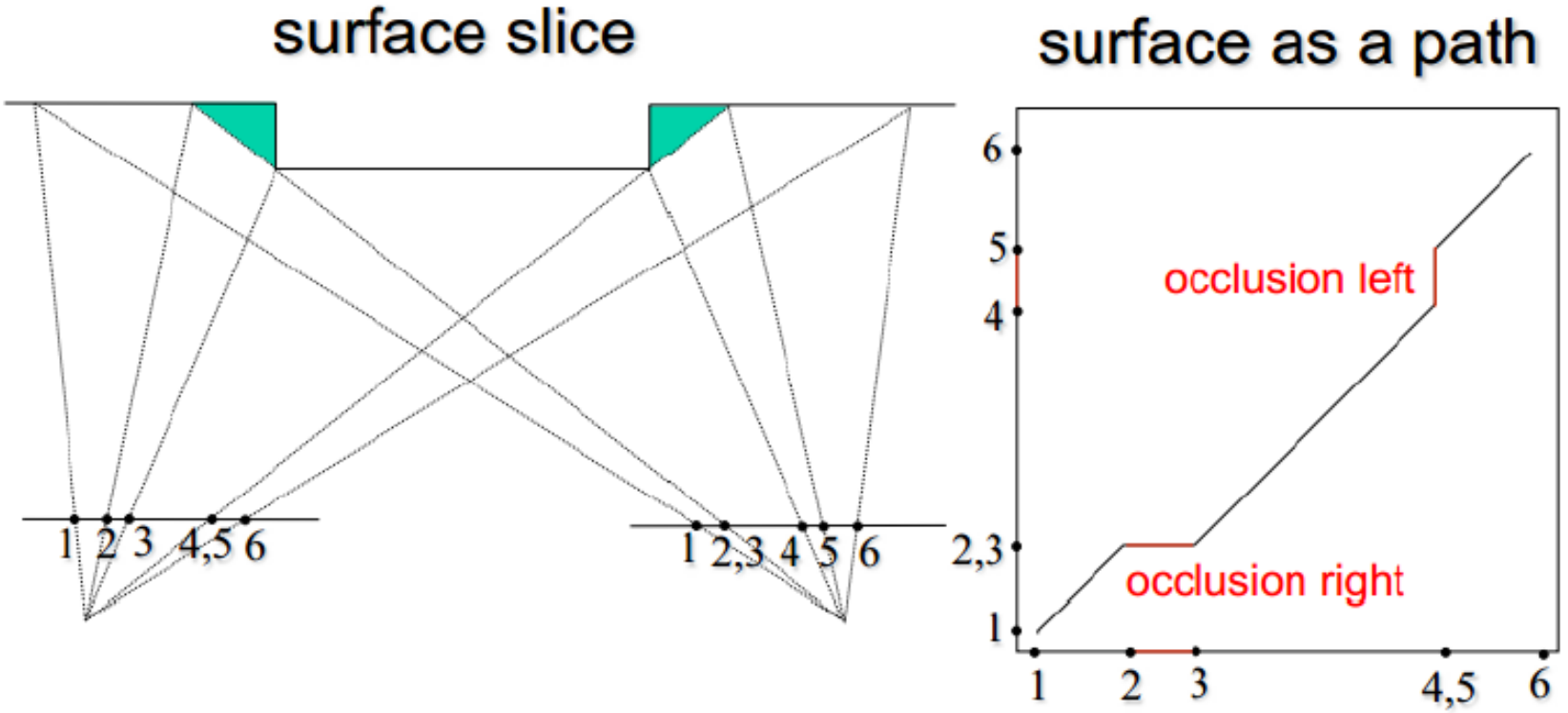


Smoothness Constraint

The change in disparity is smooth unless encountered with depth discontinuities

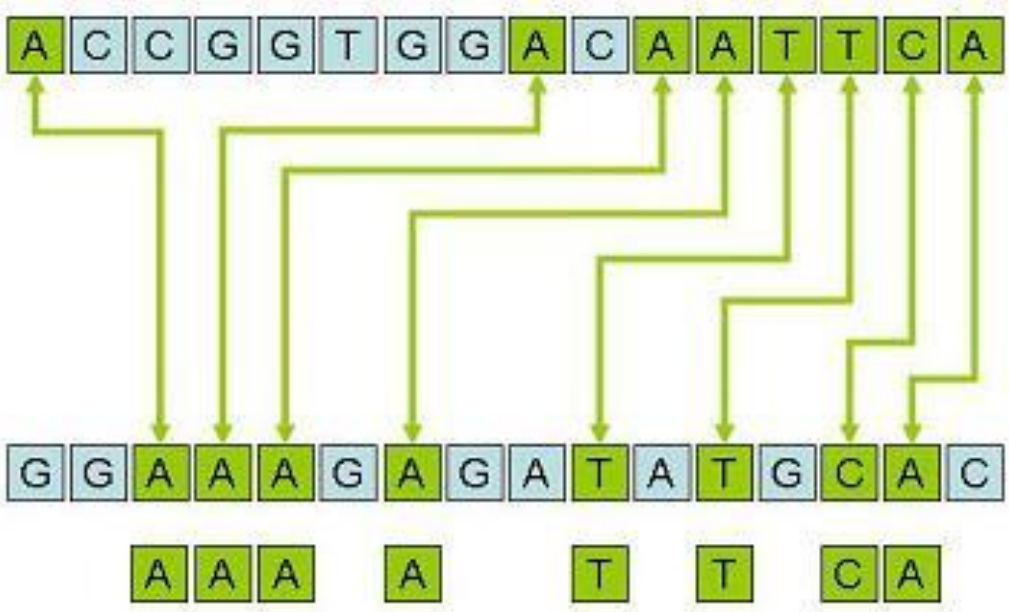


Surface as a Path

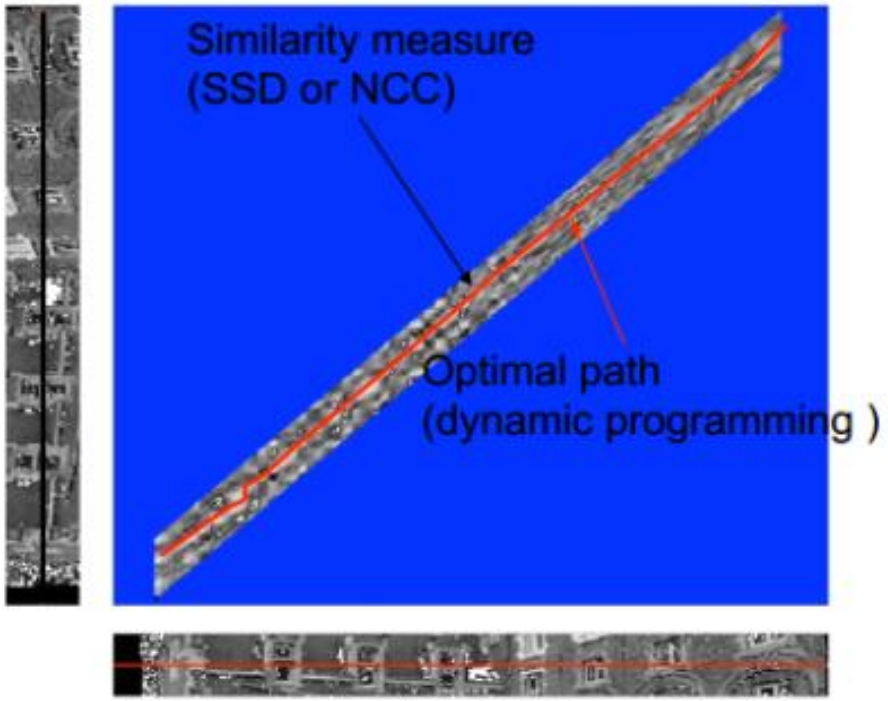


Stereo Matching as Longest Common Subsequence Problem

Dynamic Programming!



Stereo Matching with Constraints



Constraints
- epipolar
- ordering
- uniqueness
- disparity limit

(Cox et al. CVGIP'96; Koch'96; Falkenhagen´97;
Van Meerbergen,Vergauwen,Pollefeys,VanGool IJCV'02)