
DTU

Lazaros Nalpantidis

Stereo Vision

some slides borrowed or adapted from:

- *Noah Snavely*
- *Aaron Bobick*
- *Antonio Torralba*

Outline

- What is Stereo Vision?

- Stereo/Epipolar Geometry
- Rectified Stereo Case
- Depth from Stereo Matches
- Correspondence Problem
  - **Dense** vs Sparse Correspondence
  - **Local** vs Global Correspondence
  - (Dis)-Similarity Measures

- Summary

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What is Stereo Vision?

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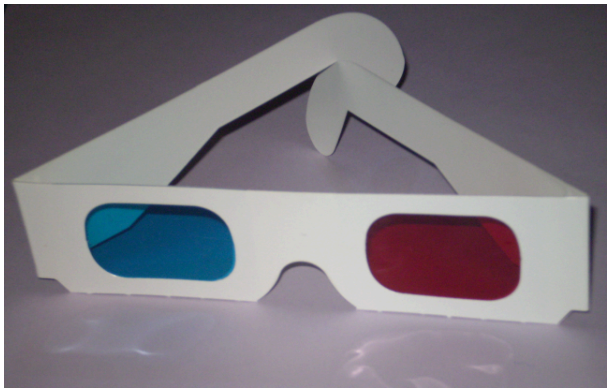
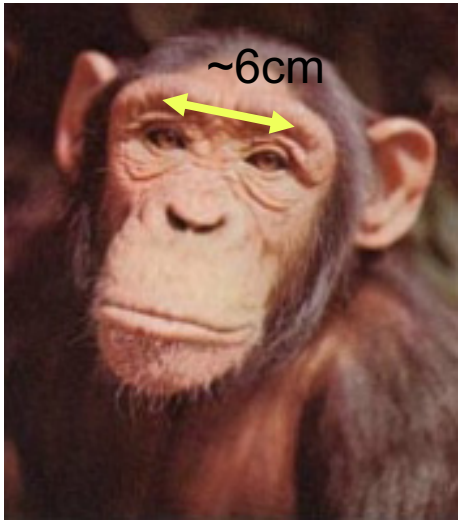
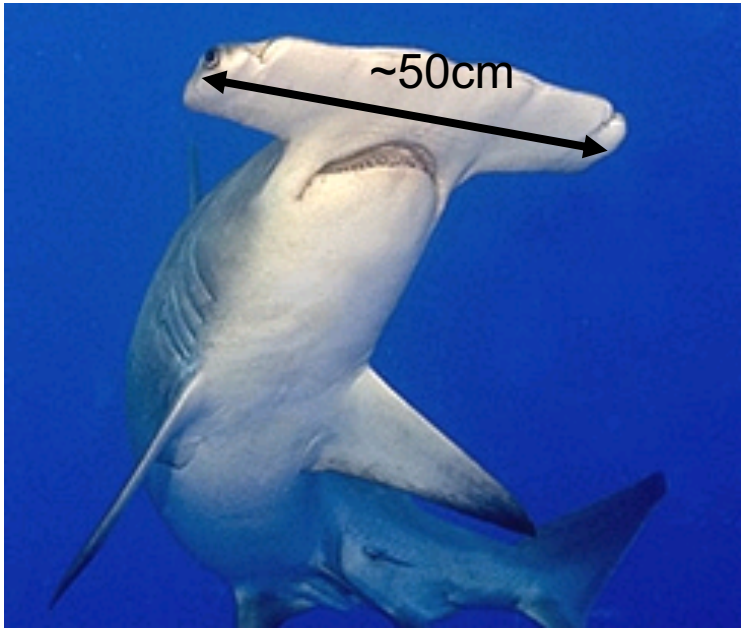
- 3D cinema
- 3D television
- …



Adapted from W. T. Freeman, P. Isola, A. Torralba

What is Stereo Vision?





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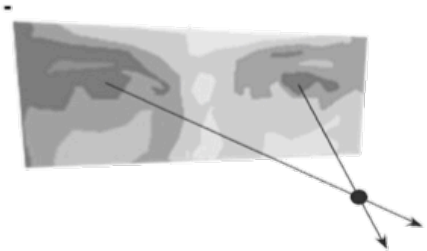
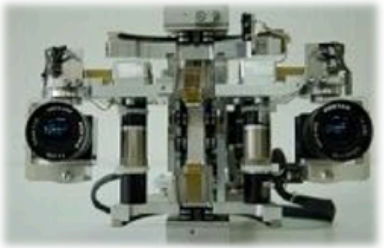
What is Stereo Vision?

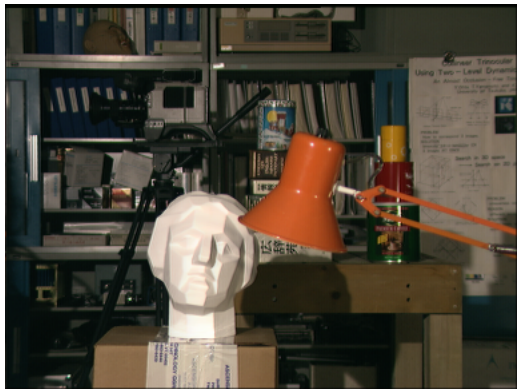
”… the mind perceives an object of three-dimensions by means of the two dissimilar pictures projected by it on the two retinae…”

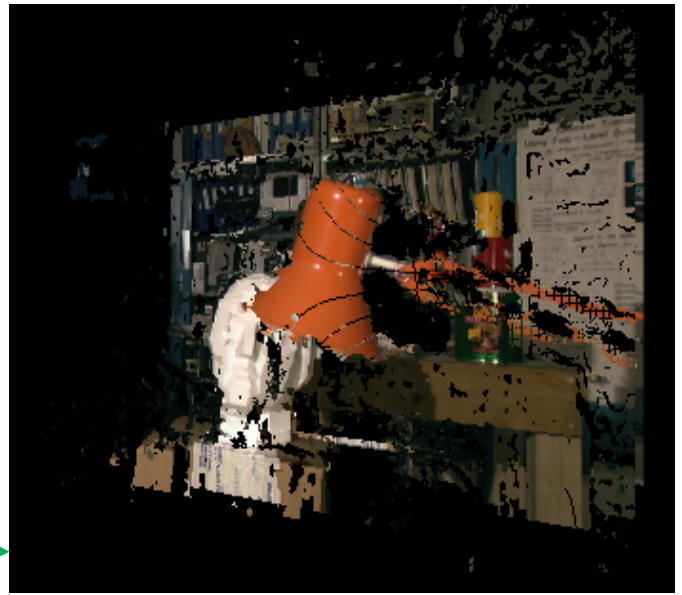
Sir Charles Wheatstone, 1838





Stereo Vision Computation





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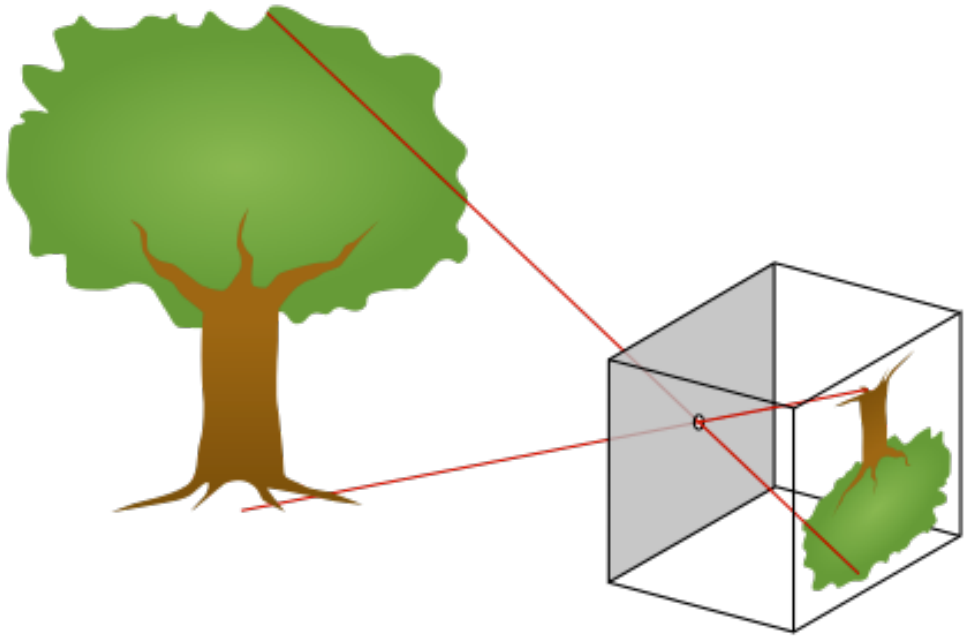
Camera Model

- Pinhole model



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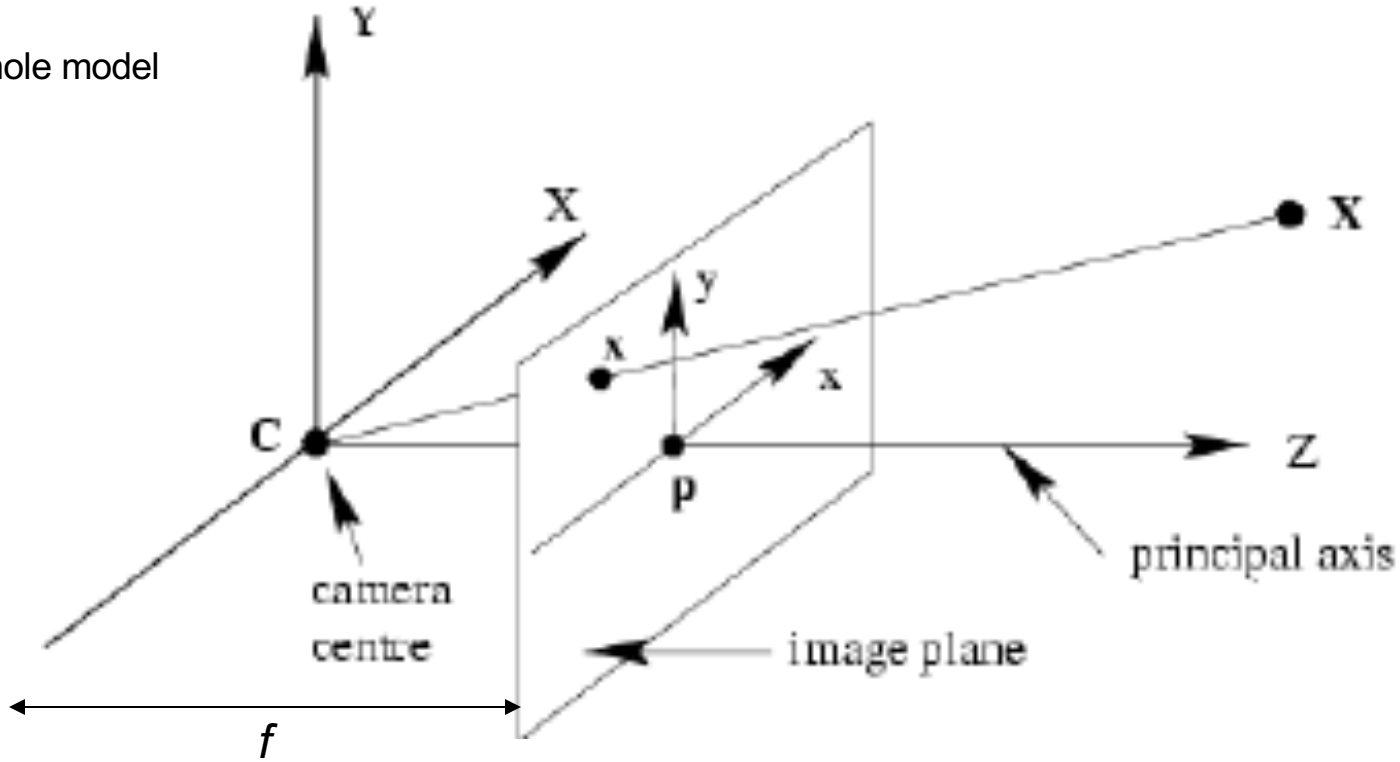
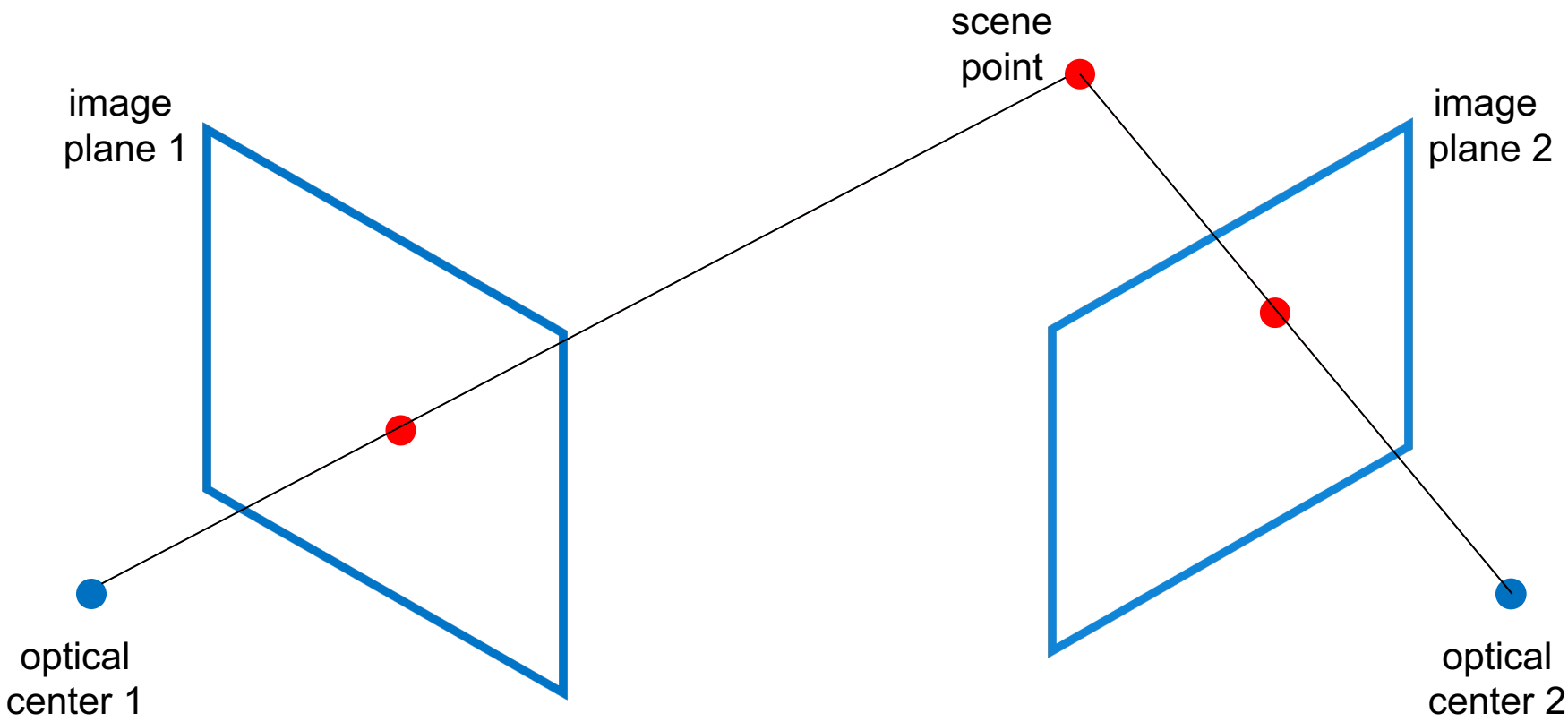


Epipolar Geometry



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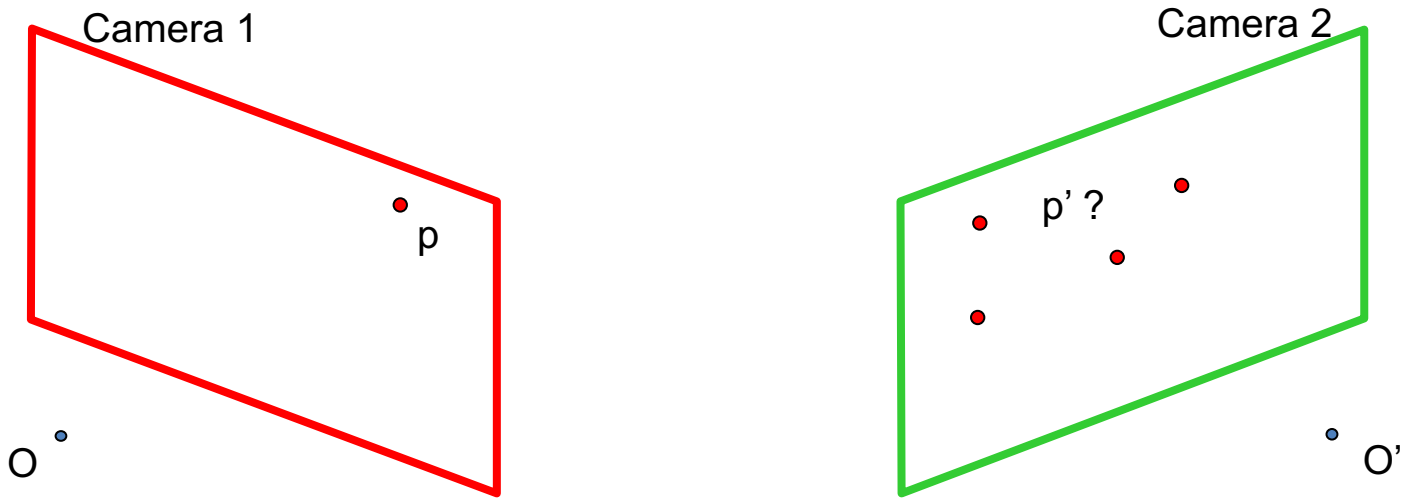
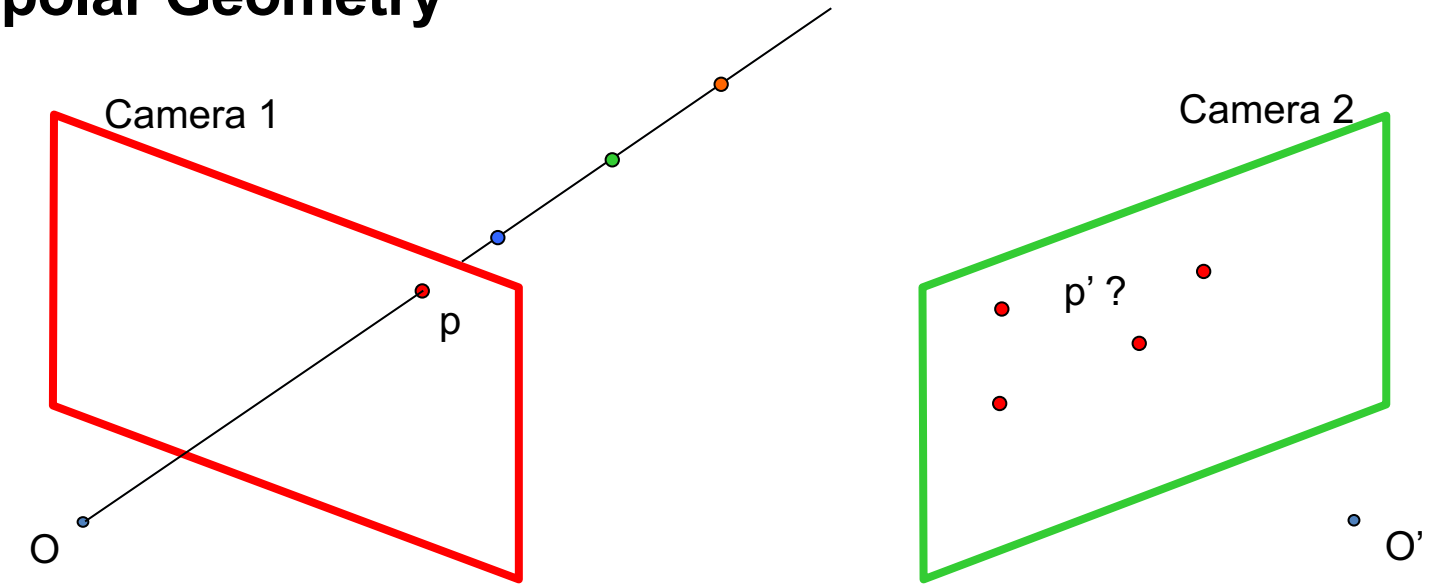


If we see a point in camera 1, are there any constraints on where we will find it on camera 2?

Epipolar Geometry



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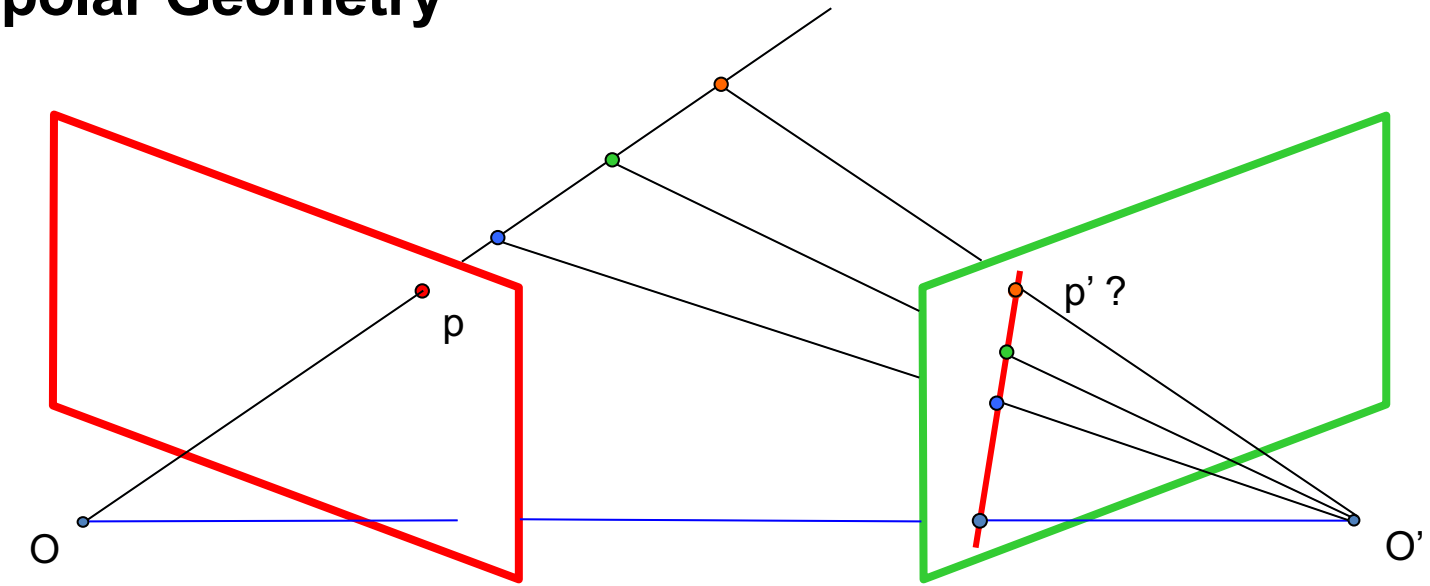

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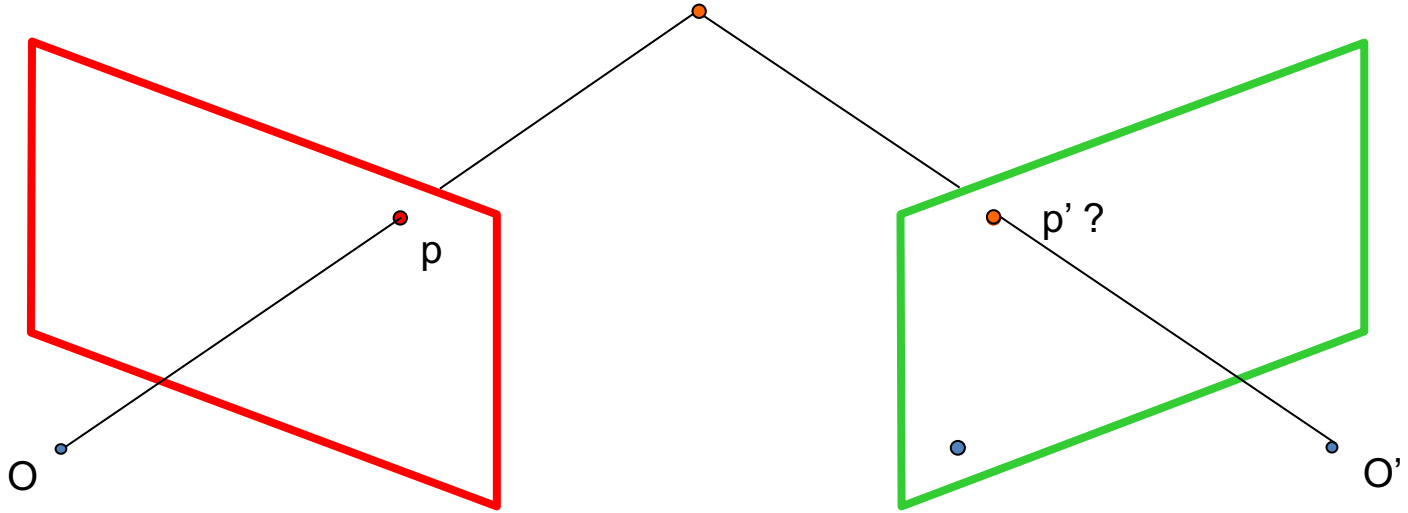
Epipolar Geometry



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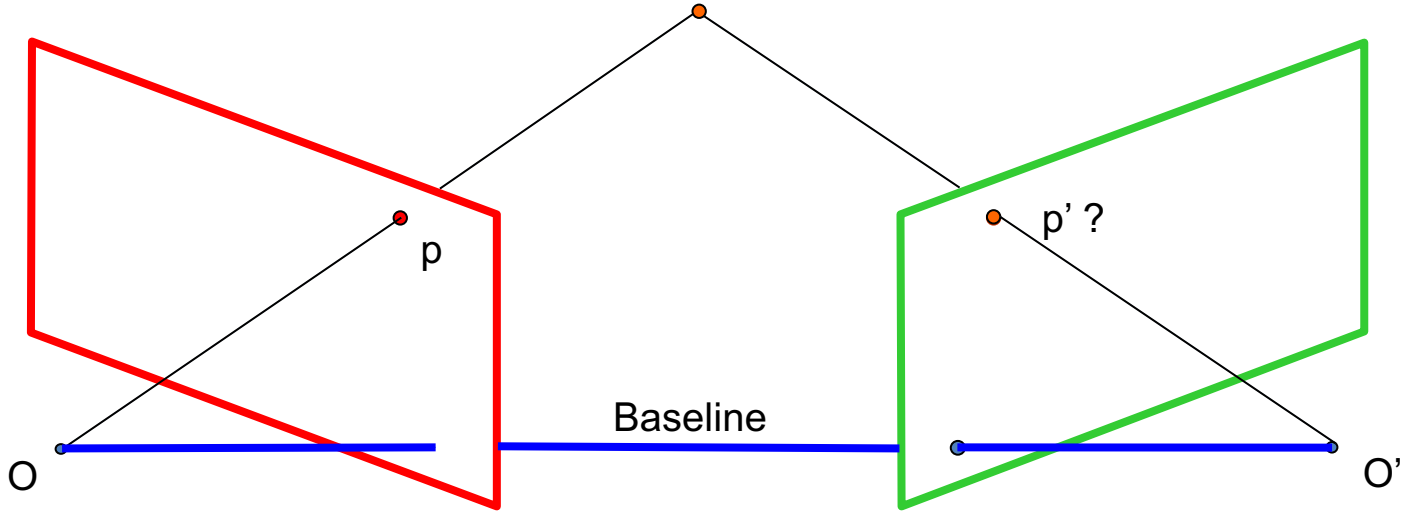
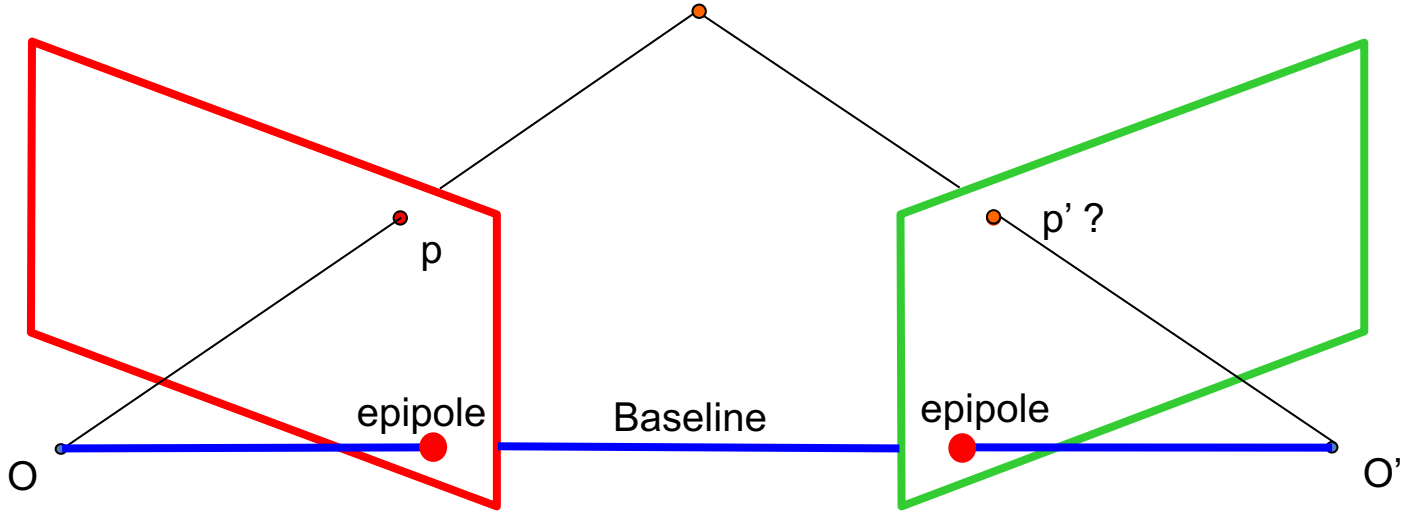


Baseline: the line connecting the two camera centers

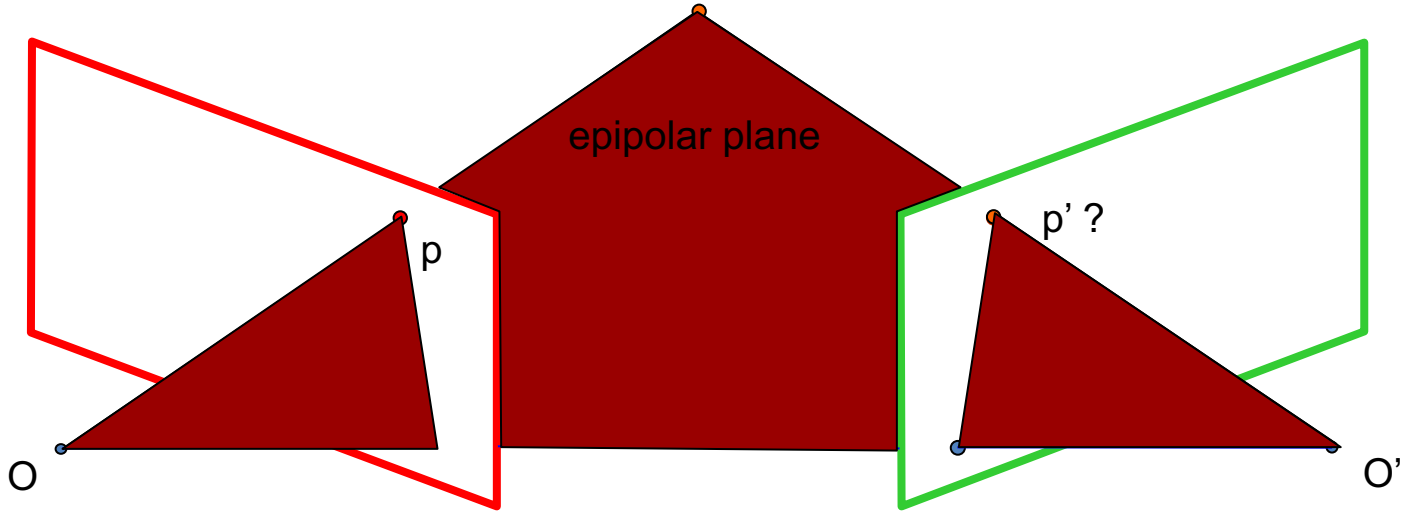
Epipolar Geometry



Baseline: the line connecting the two camera centers

Epipole: point of intersection of *baseline* with the image plane

Epipolar Geometry

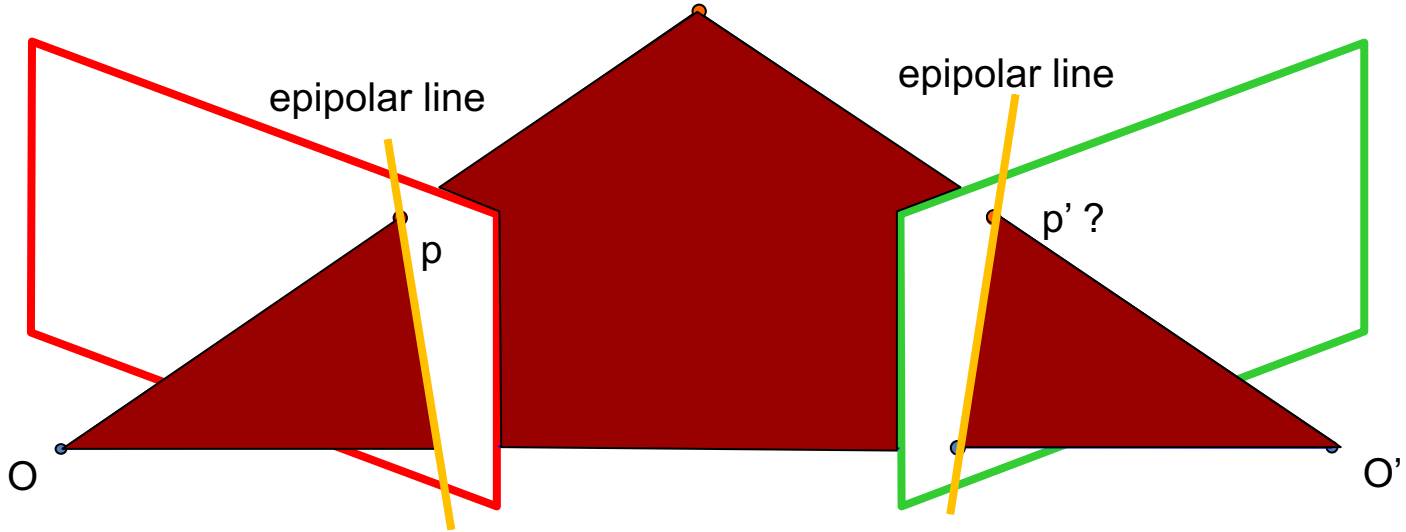


Baseline: the line connecting the two camera centers

Epipole: point of intersection of *baseline* with the image plane

Epipolar plane: the plane that contains the two camera centers and a 3D point in the world

Epipolar Geometry



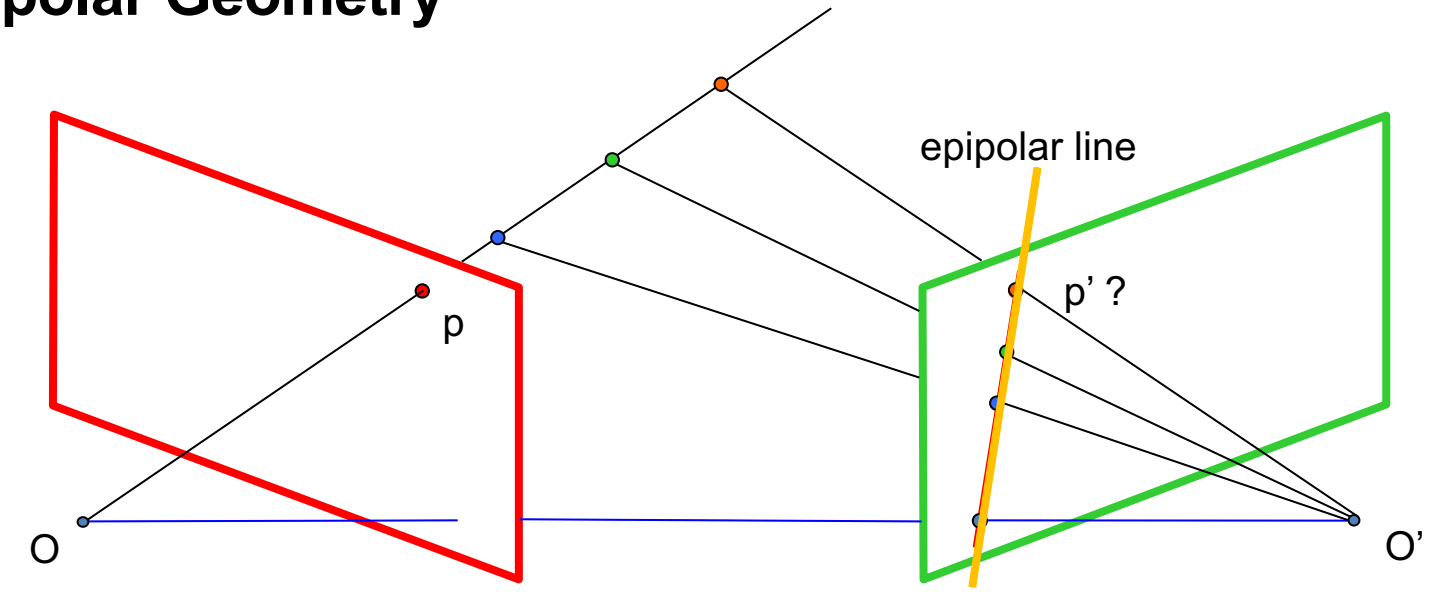
Baseline: the line connecting the two camera centers

Epipole: point of intersection of *baseline* with the image plane

Epipolar plane: the plane that contains the two camera centers and a 3D point in the world

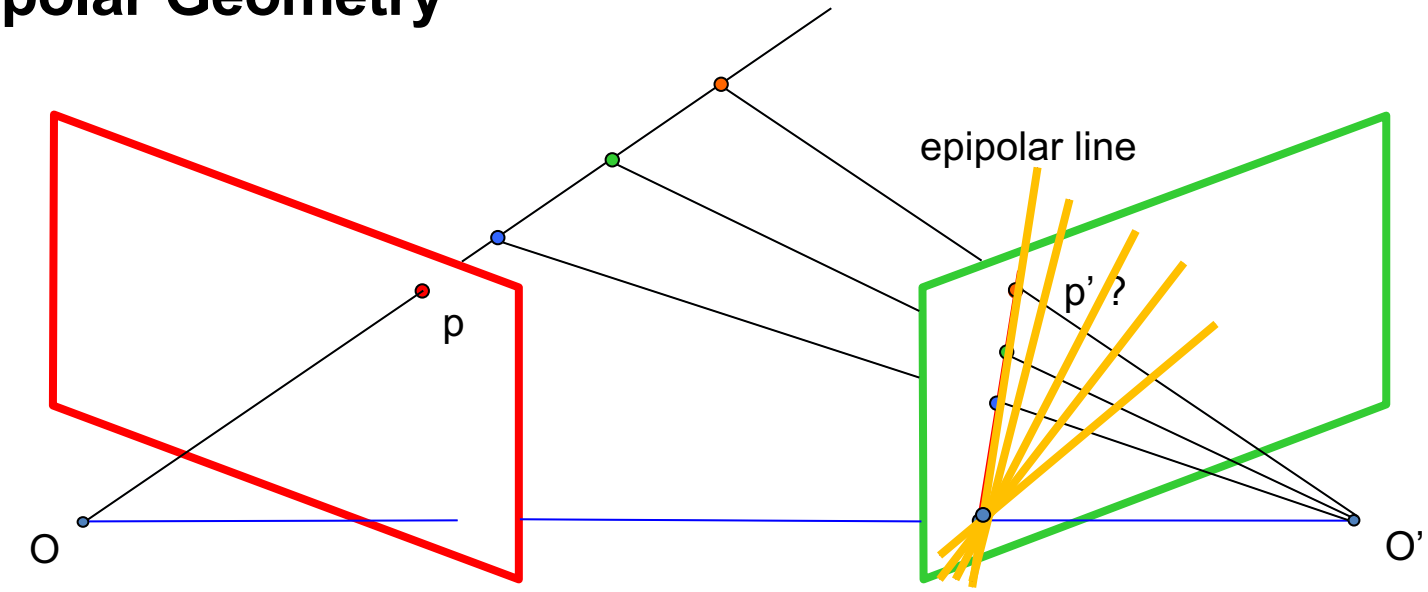
Epipolar line: intersection of the *epipolar plane* with each image plane

Epipolar Geometry



- We can search for matches across epipolar lines.
  - Search space for correspondences reduces to a 1D problem!

Epipolar Geometry



- We can search for matches across epipolar lines
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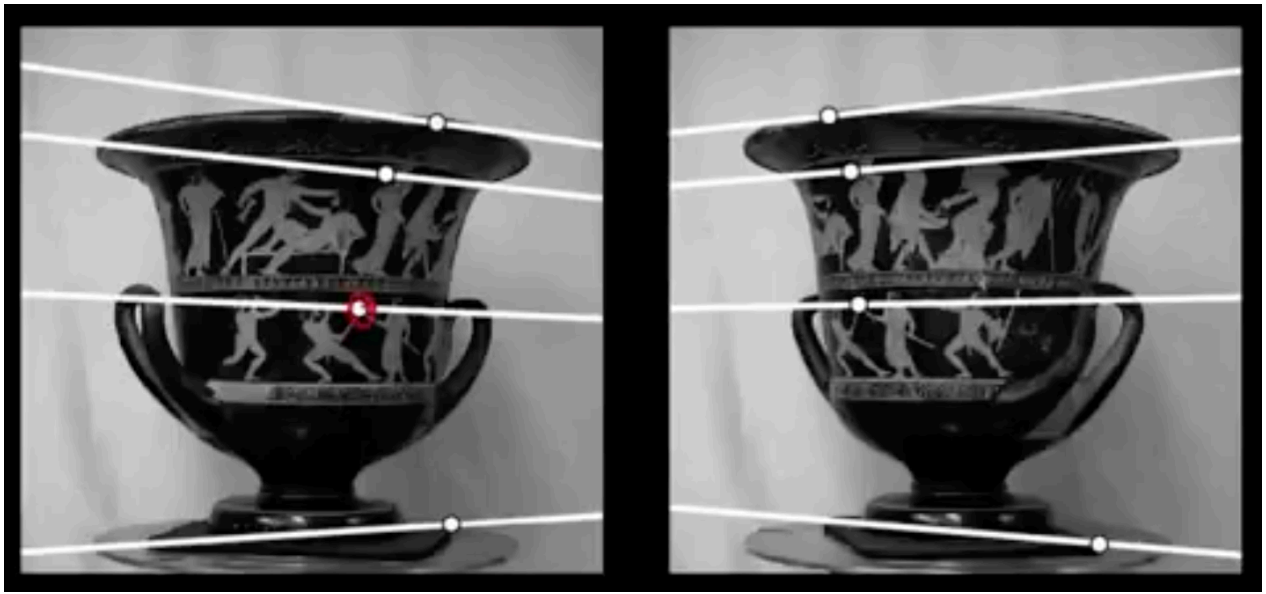
- All epipolar lines intersect at the epipoles

Epipolar Geometry



- We can search for matches across epipolar lines
  - Search space for correspondences reduces to a 1D problem!
- All epipolar lines intersect at the epipoles
  - **Where are the epipoles in this case?**

Figure from Hartley & Zisserman

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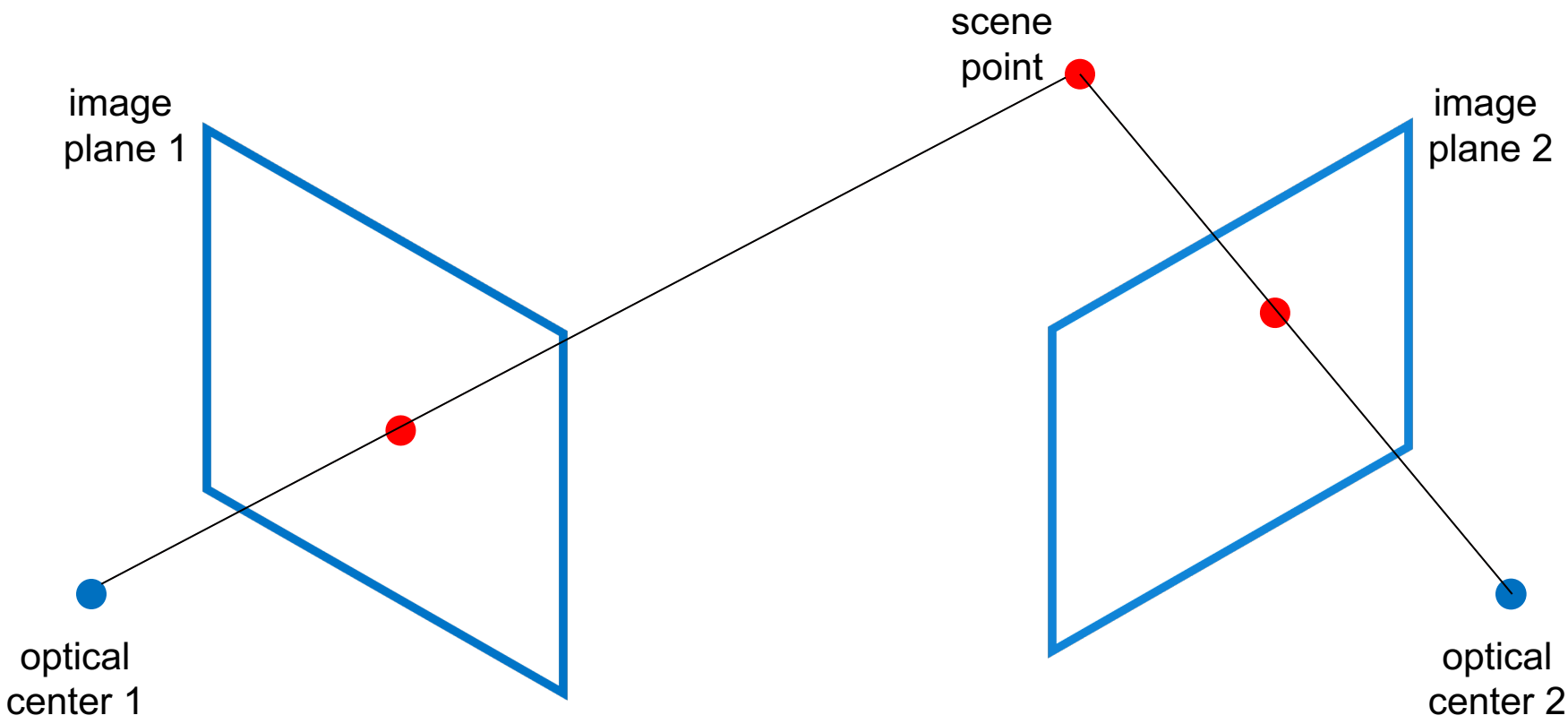
Rectified Stereo – a simpler case



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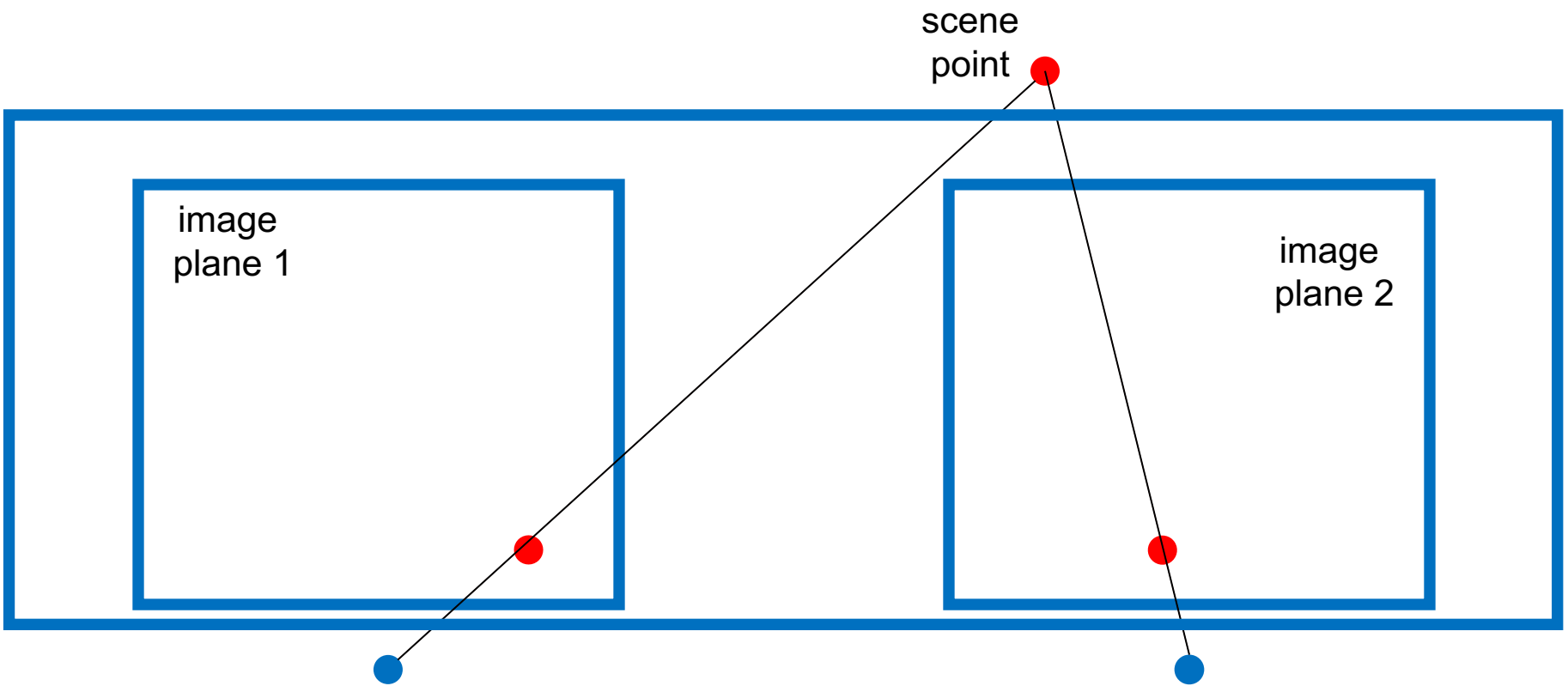
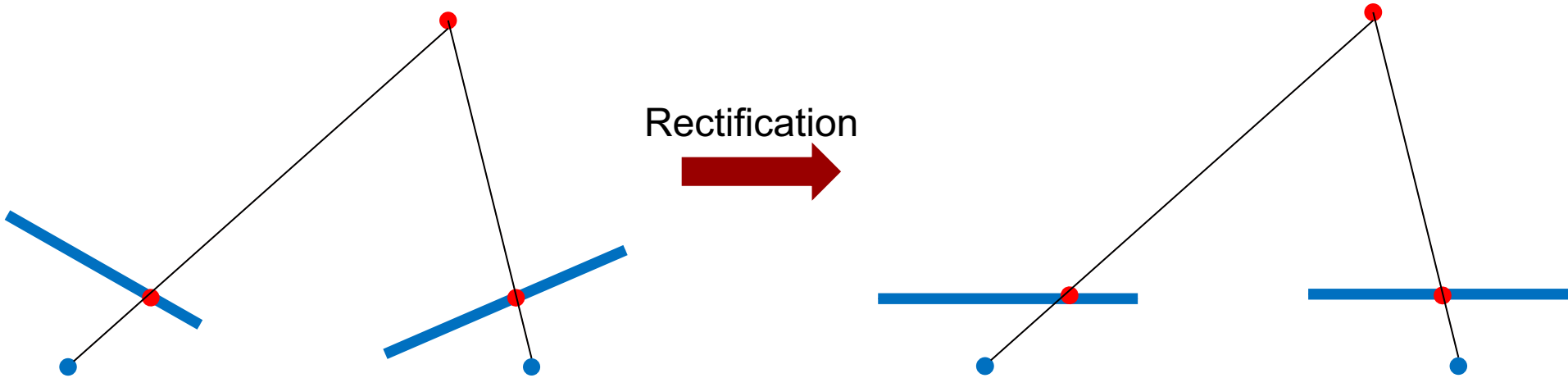


Rectified Stereo – a simpler case

- Rectification:
  - The initial images are reprojected on a common plane that is parallel to the baseline B joining the optical centers of the initial images.
  - Epipolar lines become parallel (and under certain conditions they become also horizontal)



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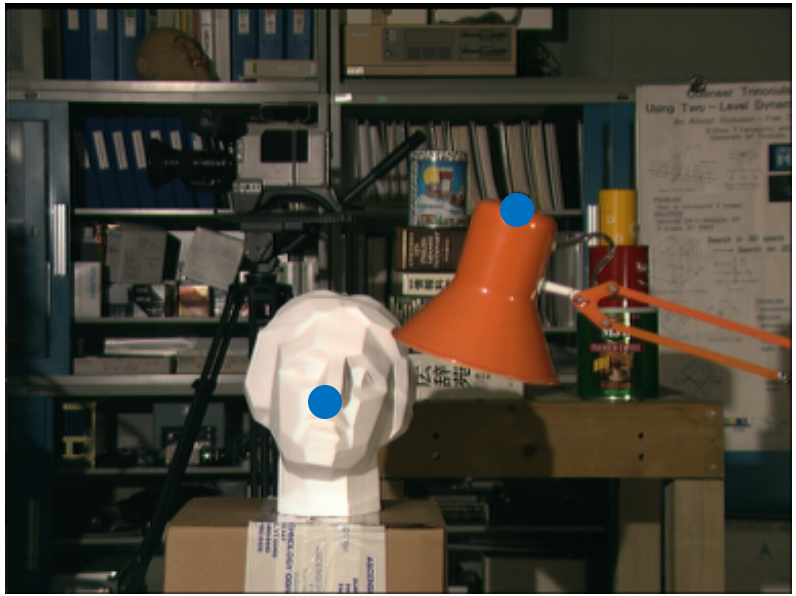

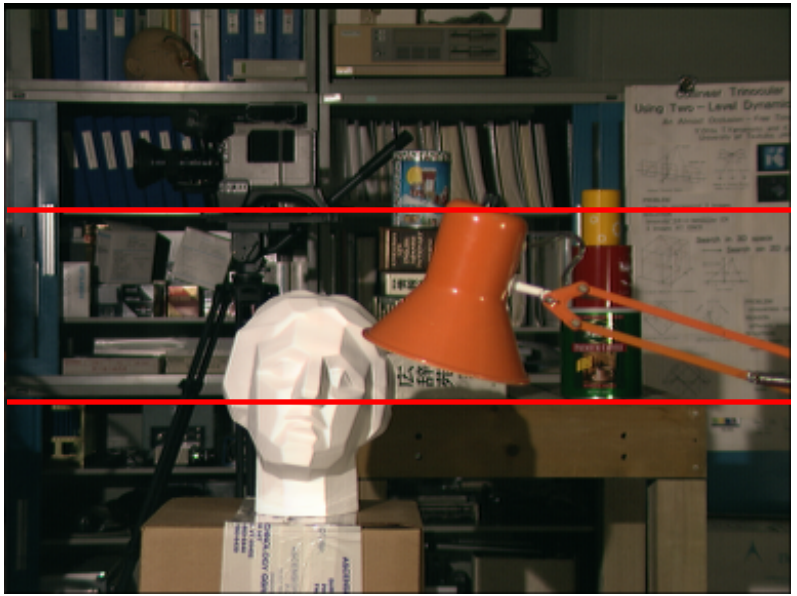

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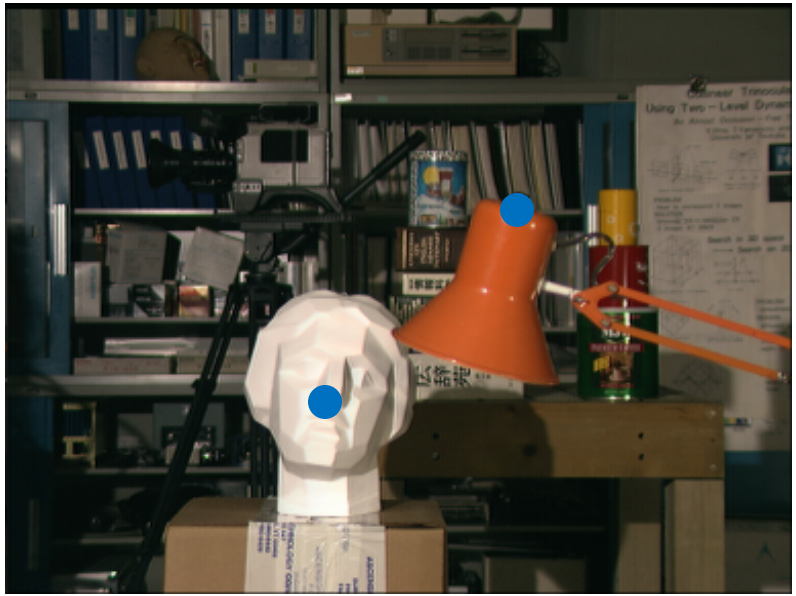

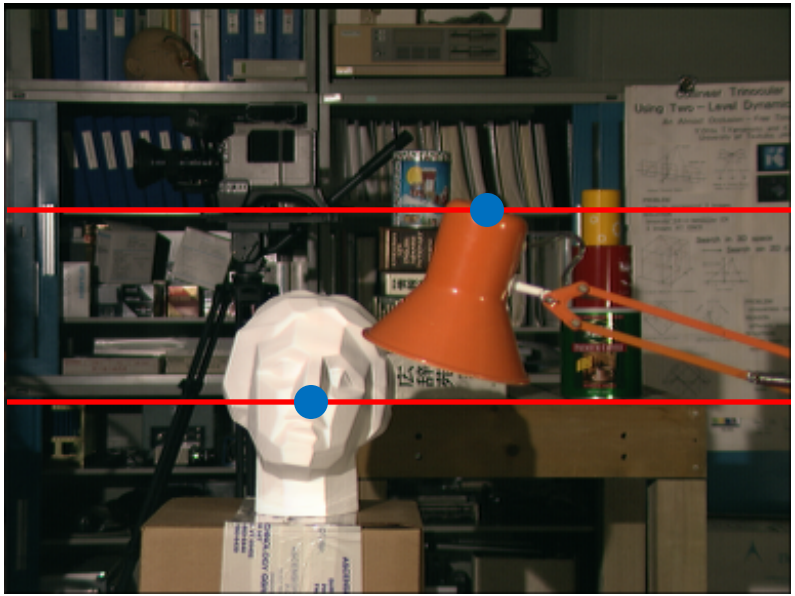

- “All epipolar lines intersect at the epipoles”
  - **Where are the epipoles in this case?**

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Depth from Stereo Matches

- Let us assume (for now!!) that:
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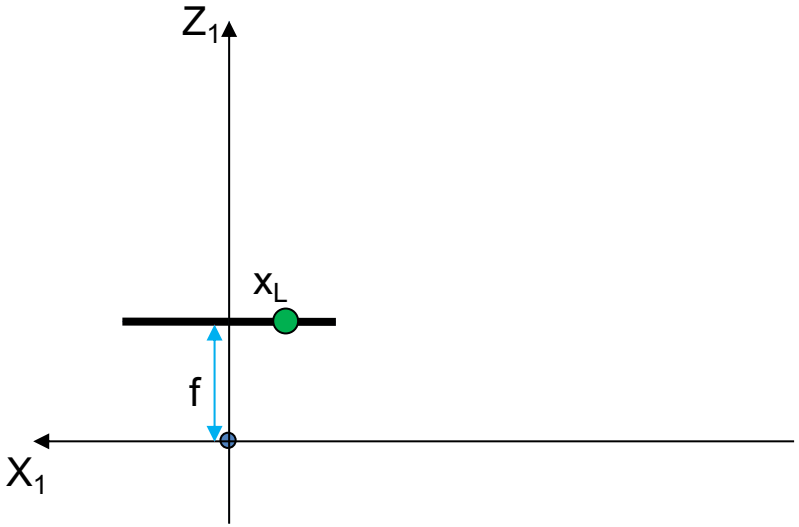
Depth from Stereo Matches



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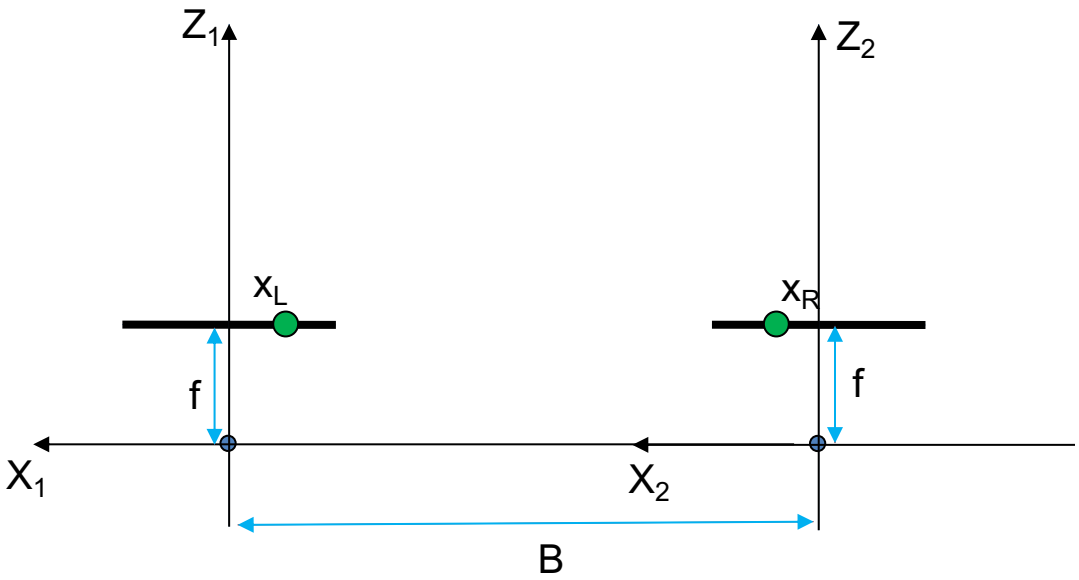

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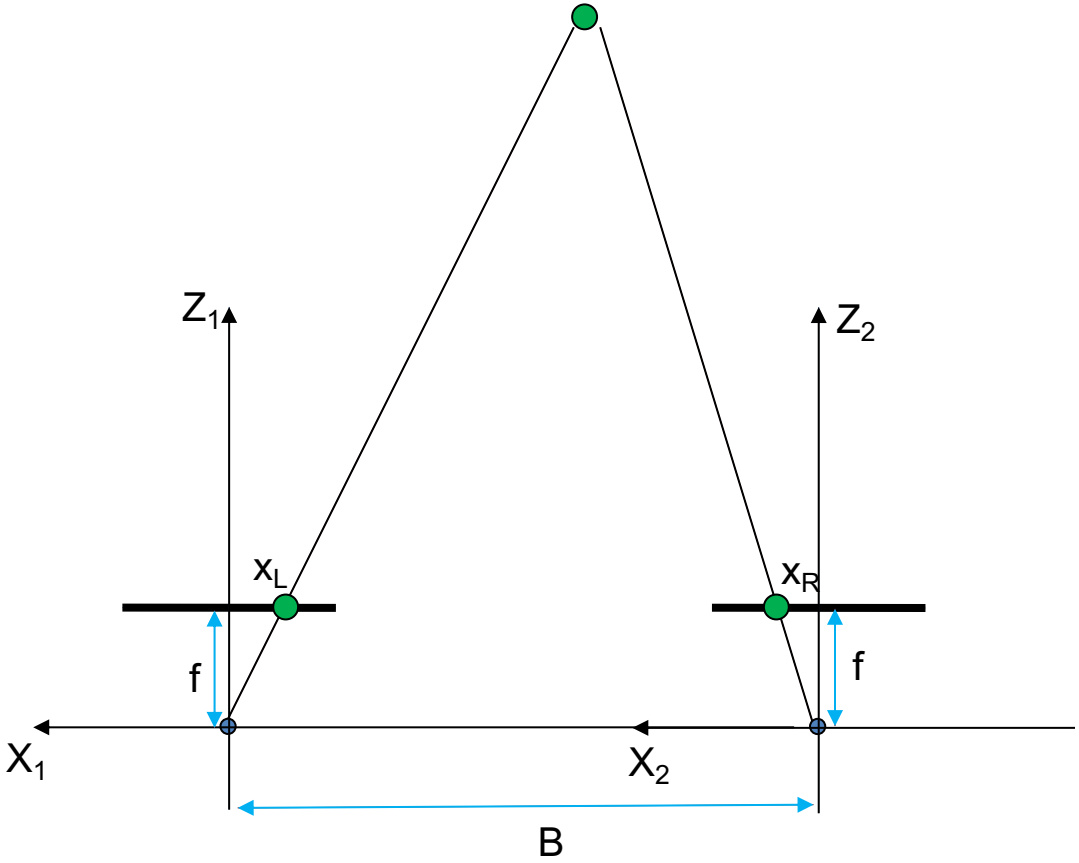

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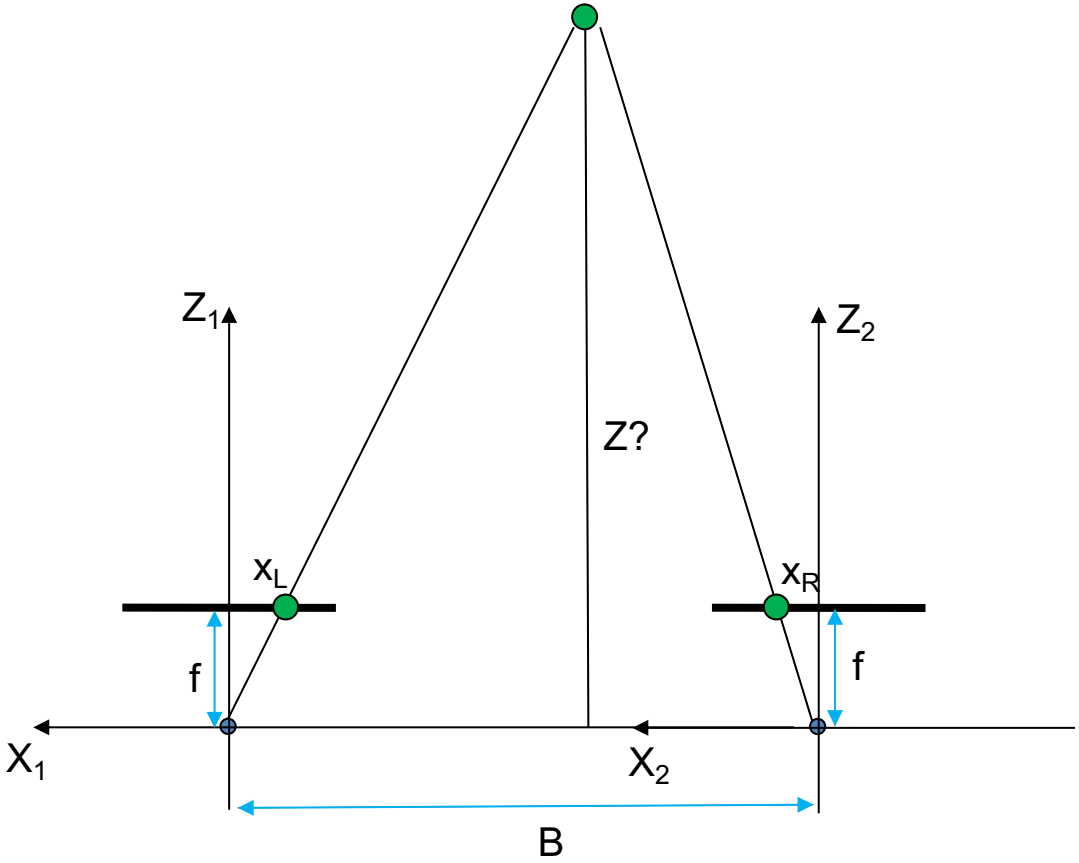

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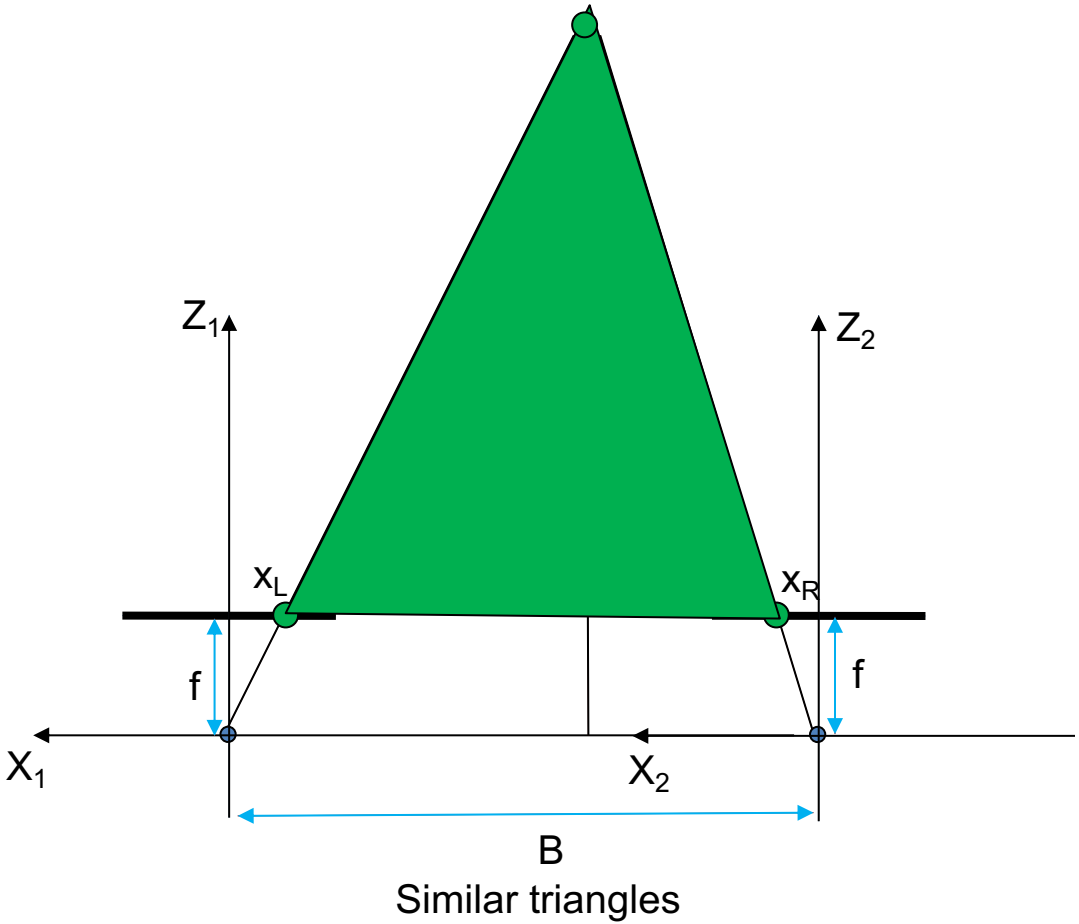
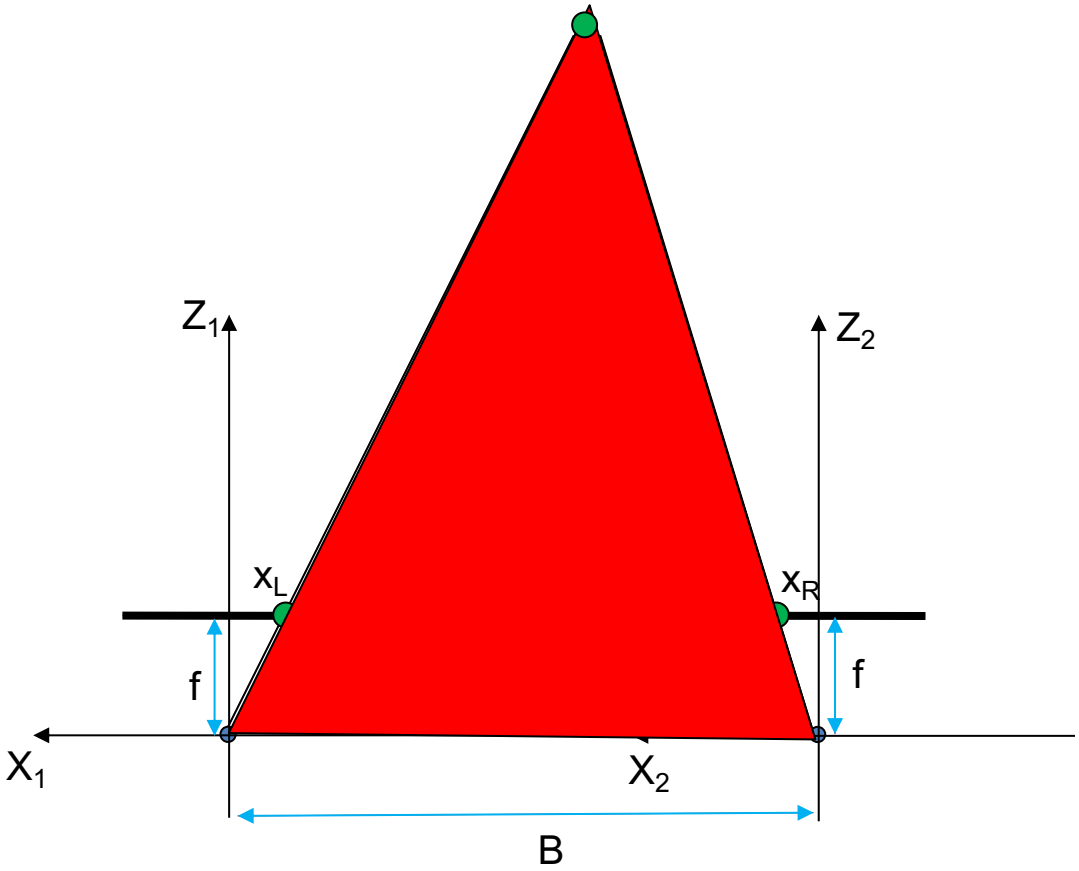


Similar triangles

Depth from Stereo Matches



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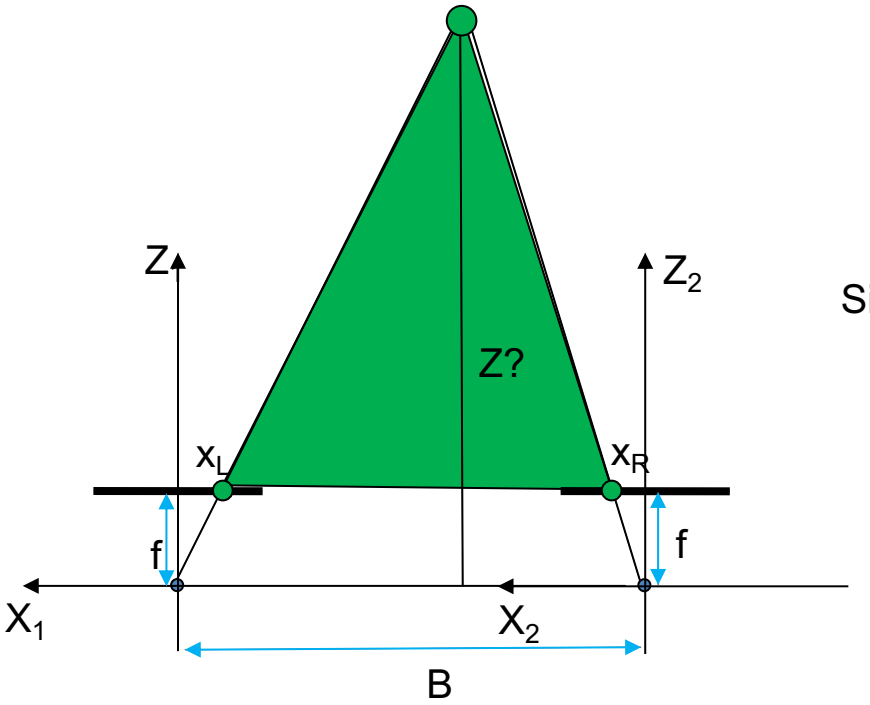
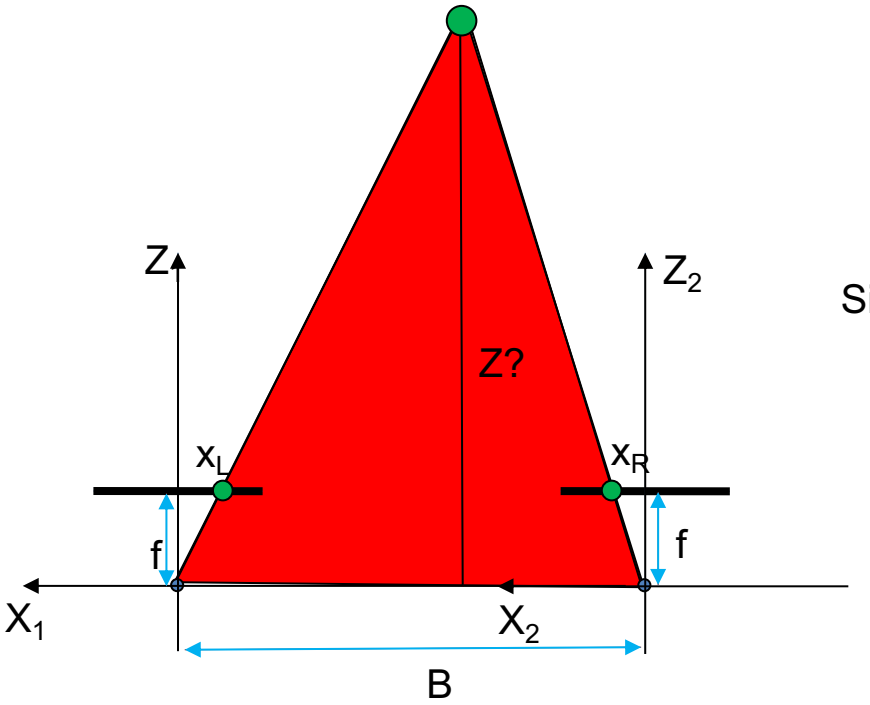


Similar triangles:

$$\frac{B+X_L-X_R}{Z-f} =$$

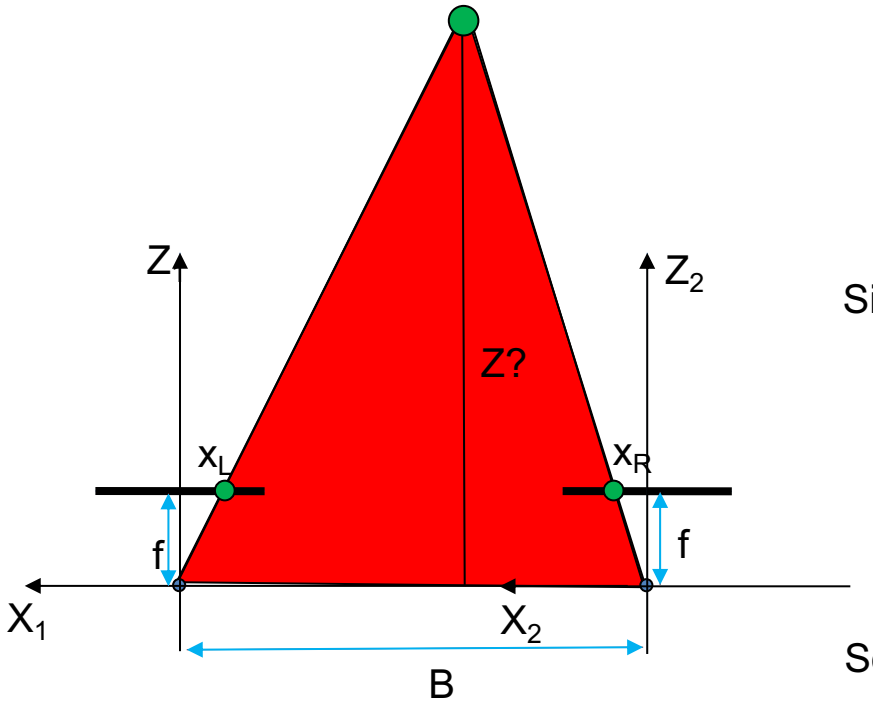
Depth from Stereo Matches



Similar triangles:

$$\frac{B+X_L-X_R}{Z-f} = \frac{B}{Z}$$

Depth from Stereo Matches



Similar triangles:

$$\frac{B+X_L-X_R}{Z-f} = \frac{B}{Z}$$

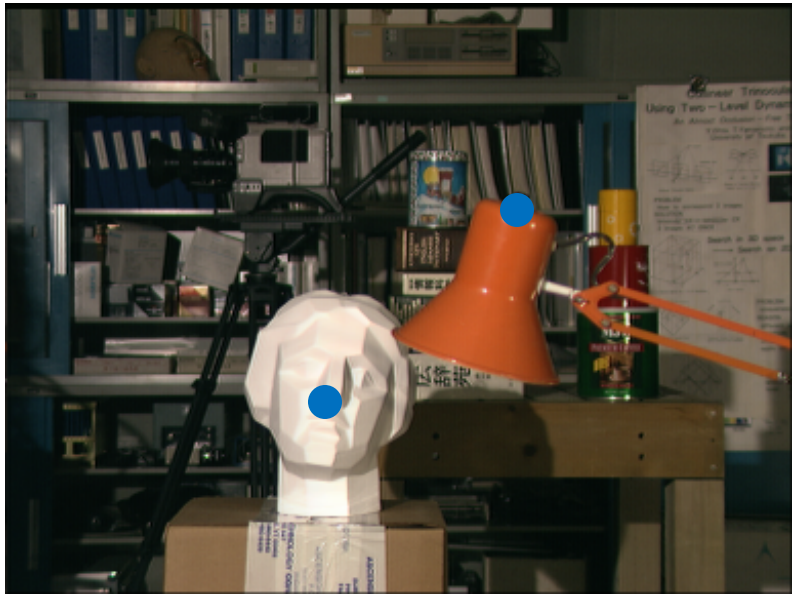
Solving for Z:

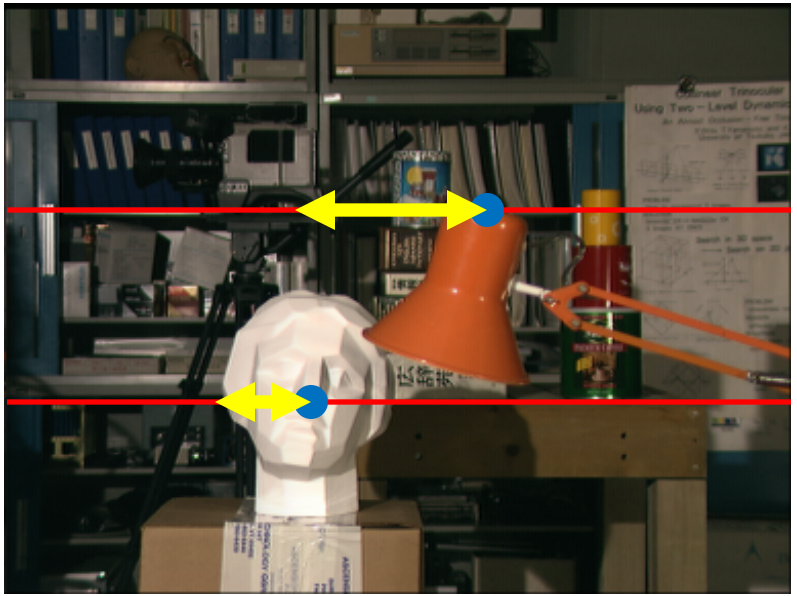
$$Z = f\,\frac{B}{X_L - X_R}$$

Disparity

Adapted from W. T. Freeman, P. Isola, A. Torralba

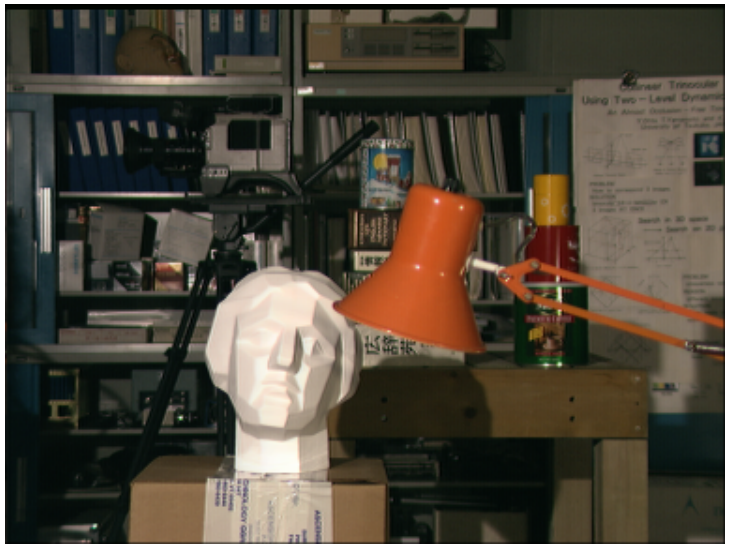
Depth from Stereo Matches





Depth from Stereo Matches

Reference Image



Disparity Map

$$Z = f \frac{B}{X_L - X_R}$$

Disparity

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Correspondence Problem

- We have assumed (up to now!!) that:
  - we can check the points along the epipolar line and
  - we can find the point (on the right image) that is **most similar** to our reference point (in the left image), i.e. we can **solve the correspondence problem**!

- *How can we indeed match corresponding pixels between the two stereo images?*

Correspondence Problem

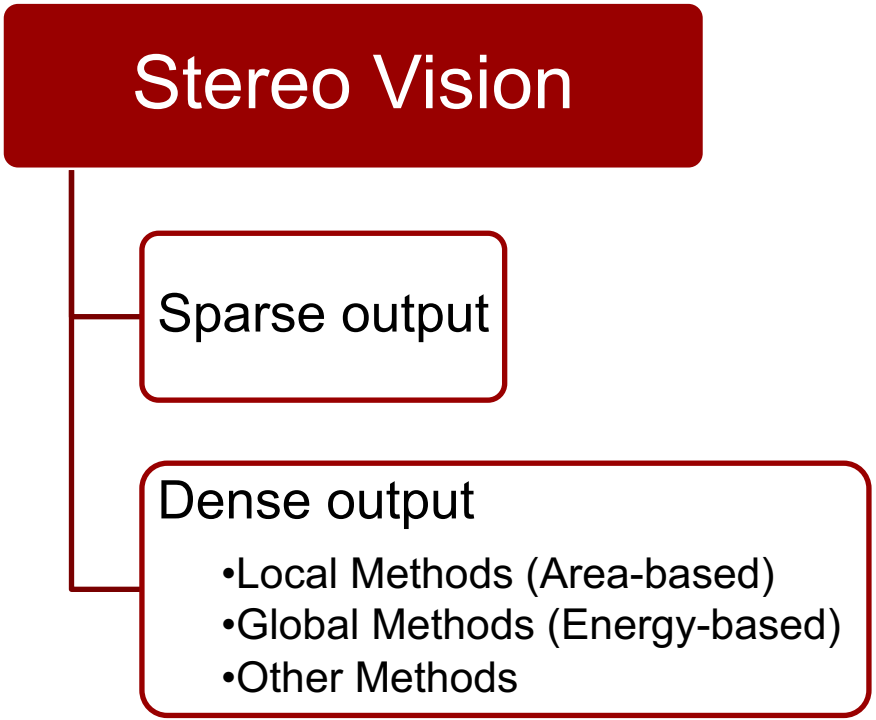
- Beyond the hard constraint of epipolar geometry, there are “soft” constraints to help identify corresponding points
  - Similarity
  - Uniqueness
  - Ordering
  - Disparity gradient is limited

Correspondence Problem

- To find matches in the image pair, we will assume
  - Most scene points visible from both views
  - Image regions for the matches are similar in appearance

Correspondence Problem

- It depends!
  - Do we need **dense** or **sparse** stereo matching?



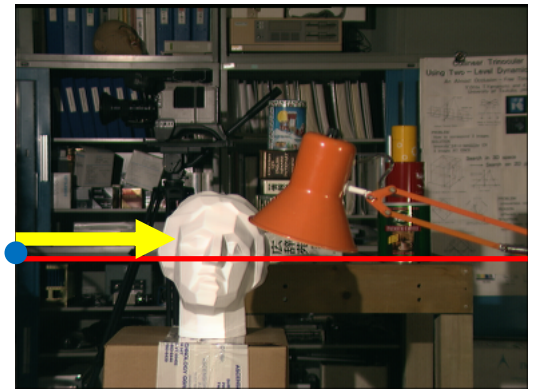
Sparse Stereo Correspondence

- Extract features (e.g. SIFT, SURF, Harris,…) and match them!

  – Pros?
  – Cons?

Dense Stereo Correspondence : Local Methods

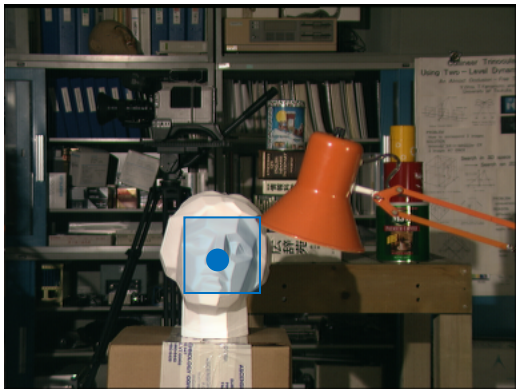
- Try to find correspondences for all the pixels of the reference image.
- For each epipolar line
  - For each pixel in the left image
    - Compare with every pixel on same epipolar line in right image
    - Choose the pixel that maximizes a similarity metric (or minimizes a dissimilarity metric!).

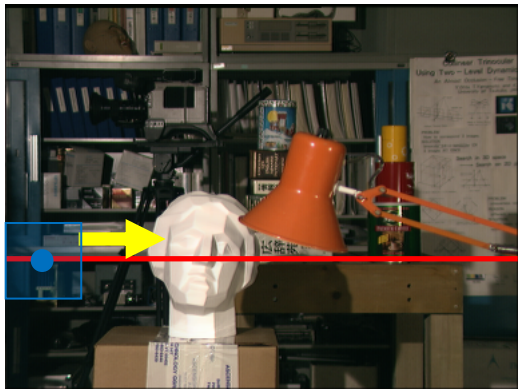


Dense Stereo Correspondence

- Try to find correspondences for all the pixels of the reference image.
- For each epipolar line
  - For each pixel in the left image
    - Compare with every pixel on same epipolar line in right image
    - Choose the pixel that maximizes a similarity metric (or minimizes a dissimilarity metric!).

- Improvement: don't match individual pixels, but rather match windows!





Stereo Correspondence Metrics

- Sum of Absolute Differences (SAD)

$$SAD(x, y, d) = \sum_{x,y \in W} |I_l(x, y) - I_r(x, y - d)|$$

- Sum of Squared Differences (SSD)

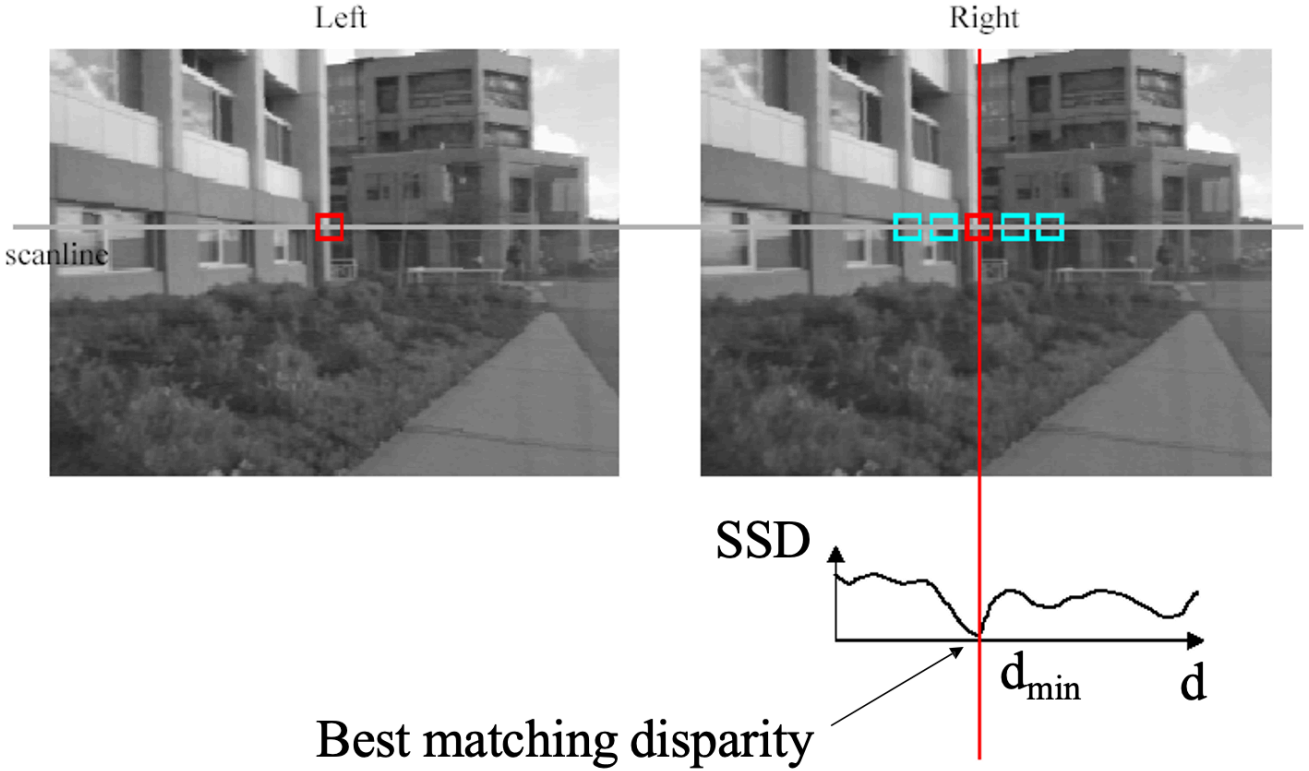
$$SSD(x, y, d) = \sum_{x,y \in W} (I_l(x, y) - I_r(x, y - d))^2$$

- Normalized Cross-Correlation

$$NCC(x, y, d) = \frac{\sum_{x,y \in W} I_l(x, y) \cdot I_r(x, y - d)}{\sqrt{\sum_{x,y \in W} I_l^2(x, y) \cdot \sum_{x,y \in W} I_r^2(x, y - d)}}$$

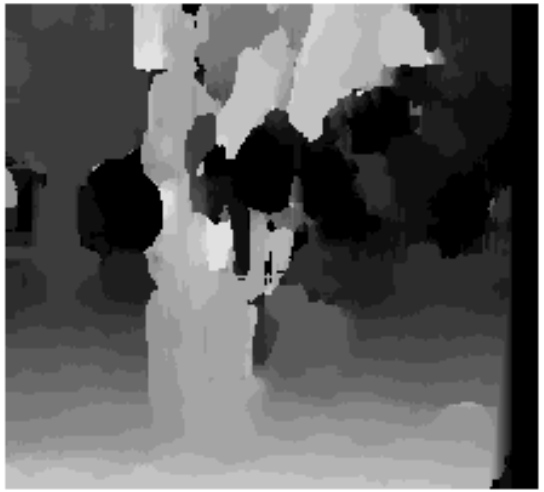
- …many many more!!!

Stereo Correspondence Metrics: SSD



Stereo Correspondence Metrics: SSD on various windows

W = 3



W = 20

- Small vs Big windows
- What are their Pros and Cons?

Figure from Li Zhang

Stereo Correspondence Metrics: Good/Bad areas

- In this stereo image pair:
  - what would be good areas to match?
  - where would you expect to face problems and why?

Figure from Hartley & Zisserman

Global Stereo Correspondence

- Up to this point, the disparity of each pixel was determined only by the information of the pixel itself and its neighborhood.
  – Thus, those methods are called ”local” or “area-based” methods.

- Example: Result of a **local** SSD algorithm with W=21:

Global Stereo Correspondence

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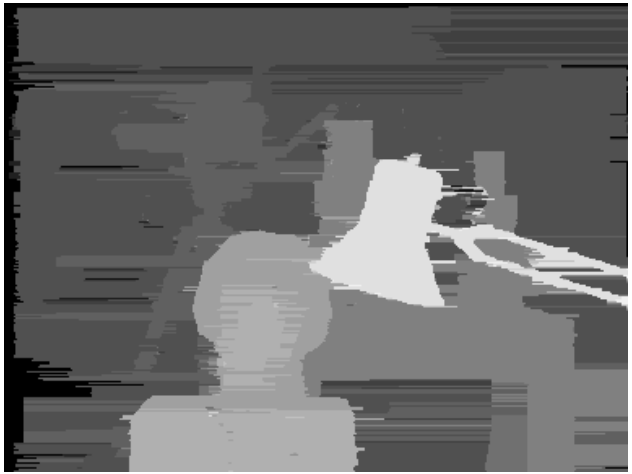
- Global methods find better solutions in expense of more computations
  – Optimize jointly the disparity values of all the pixels of each scanline (e.g. Dynamic Programming)



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  - Optimize jointly the disparity values of all the pixels of the image (e.g. graph cuts)

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  - Optimize jointly the disparity values of all the pixels of the image (e.g. graph cuts)

    - *In global algorithms, stereo correspondence is formulated as an energy function minimization problem, consisting of data and smoothness terms.*

Outline

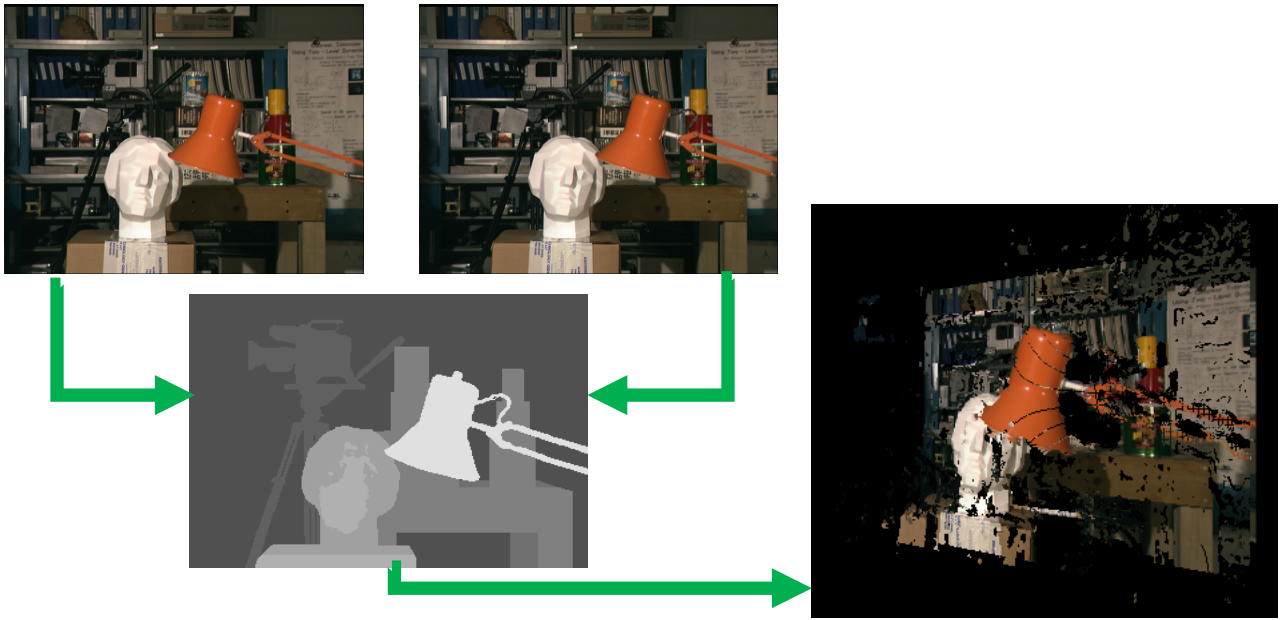
- What is Stereo Vision?

- Stereo/Epipolar Geometry
- Rectified Stereo Case
- Depth from Stereo Matches
- Correspondence Problem
  - **Dense** vs Sparse Correspondence
  - **Local** vs Global Correspondence
  - (Dis)-Similarity Measures

- Summary

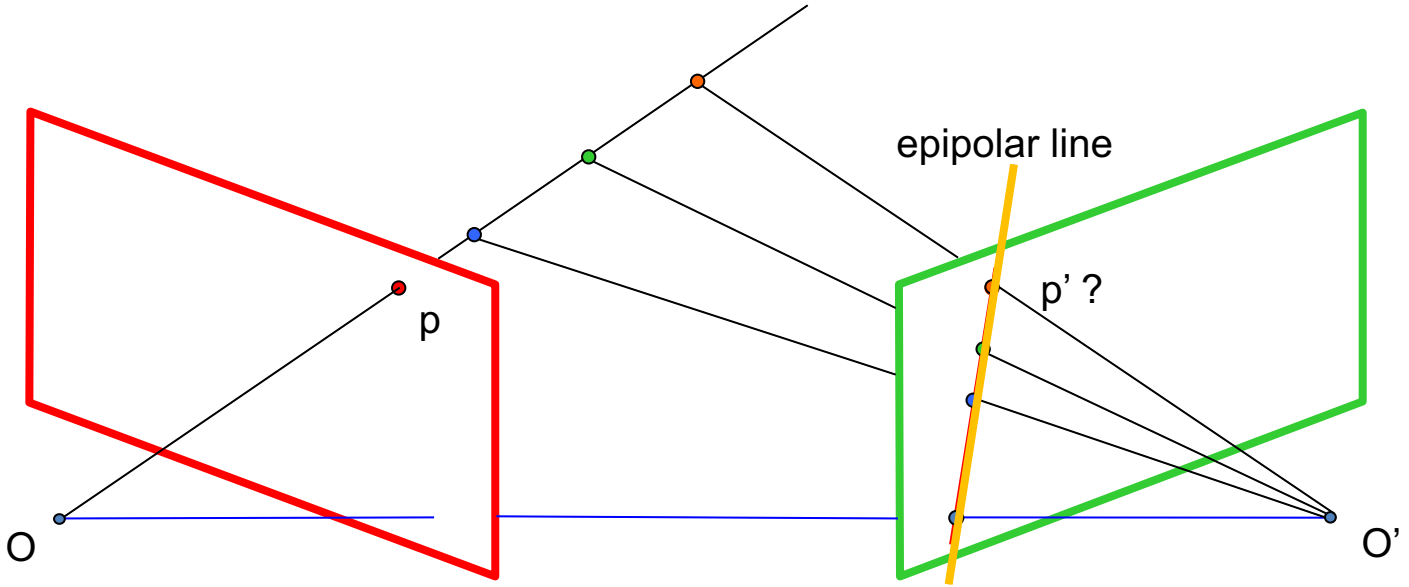
Summary

- We discussed about what Stereo Vision is.



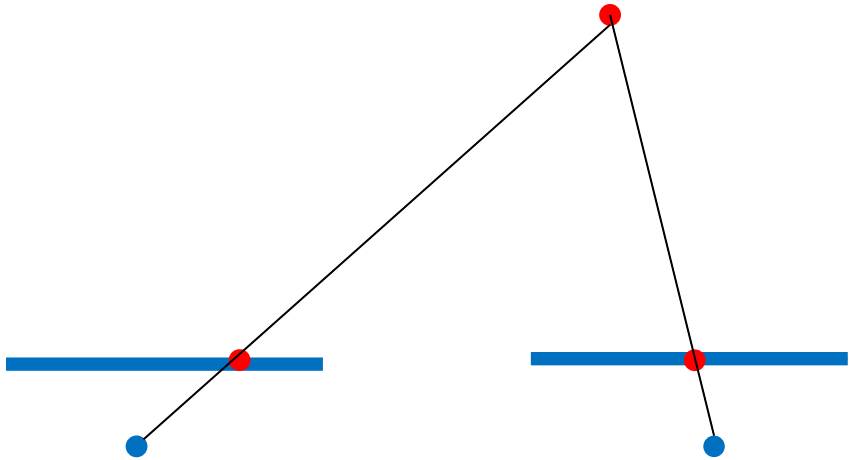
Summary

- We discussed about what Stereo Vision is.
- We learned about :
  – Stereo/Epipolar Geometry



Summary

- We discussed about what Stereo Vision is.
- We learned about :
  - Stereo/Epipolar Geometry
  - Rectified Stereo Case



Summary

- We discussed about what Stereo Vision is.
- We learned about :
  - Stereo/Epipolar Geometry
  - Rectified Stereo Case
  - Depth from Stereo Matches

Reference Image

Disparity Map

$$Z = f \frac{B}{X_L - X_R}$$

Disparity

Summary

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  - Stereo/Epipolar Geometry
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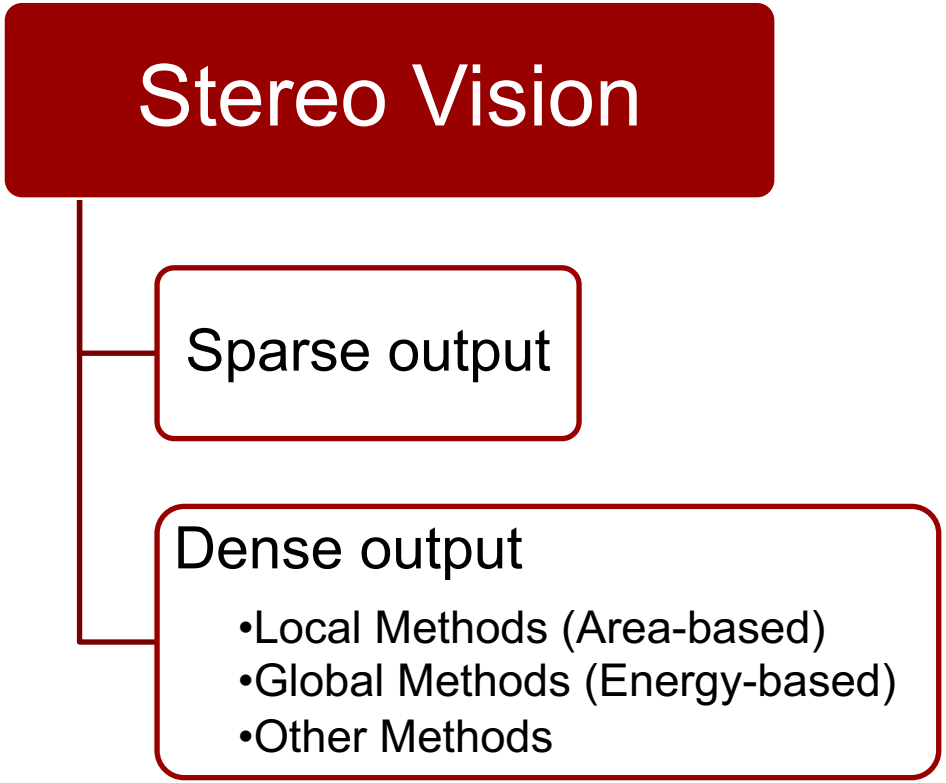

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