SIGGRAPH 2000 Course on
3D Photography

Passive 3D Photography

Steve Seitz
Carnegie Mellon University
University of Washington
http://www.cs.cmu.edu/~seitz

Visual Cues

Shading

Merle Norman Cosmetics, Los Angeles

Visual Cues

Shading

Texture

The Visual Cliff, by William Vandivert, 1960

Visual Cues

Shading

Texture

Focus

From *The Art of Photography*, Canon

Visual Cues

Shading

Texture

Focus

Motion

Visual Cues

Shading

Texture

Focus

Motion

Others:

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

Shape From X

- X = shading, texture, focus, motion, ...

Talk Outline

Overview Leading Approaches

1. Single view modeling
2. Stereo reconstruction
3. Structure from motion

Single View Modeling

How Do Humans Do This?

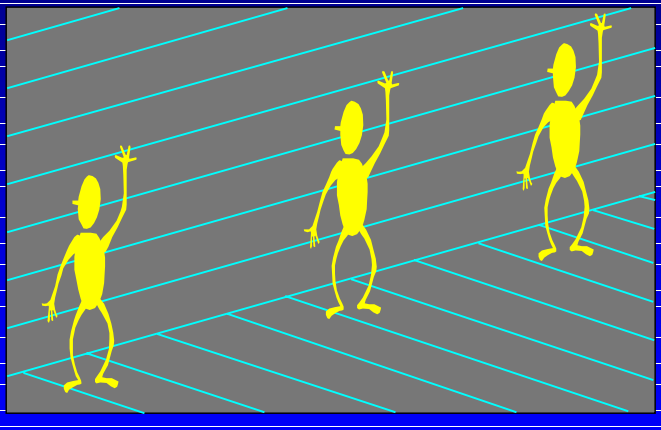
Good Guesswork Based on Priors

- **"these lines *look* parallel"**
- **"this *looks* like a cube"**
- **"this *looks* like a shadow"**

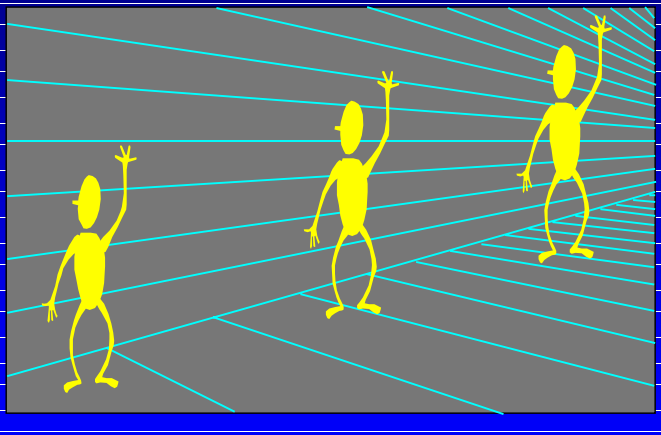
Computers Can Do This Too

- **Shape from shading** [Horn 89]
- **User-aided modeling**
  - > "Tour into the Picture" [Horry 97]
  - > "Facade" [Debevec 96]
  - > "Single View Metrology" [Criminisi 99]
- **Learning approaches**
  - > "Morphable Models" [Blanz 99]

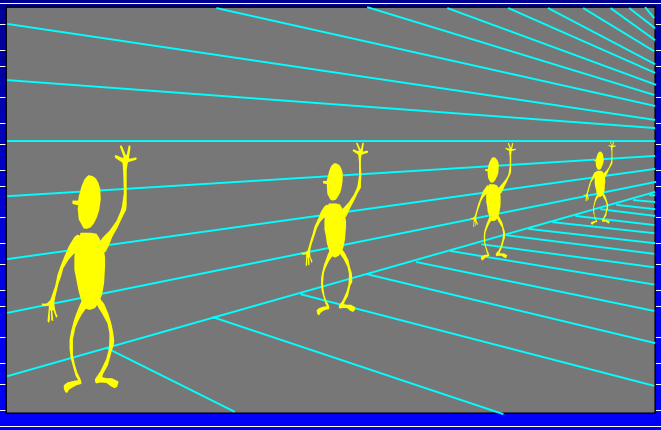
Perspective Cues



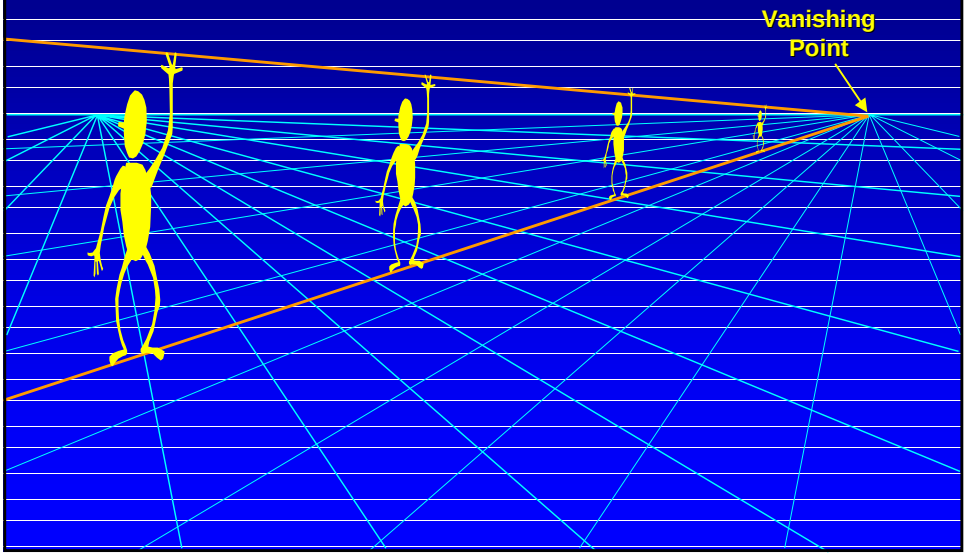
Perspective Cues



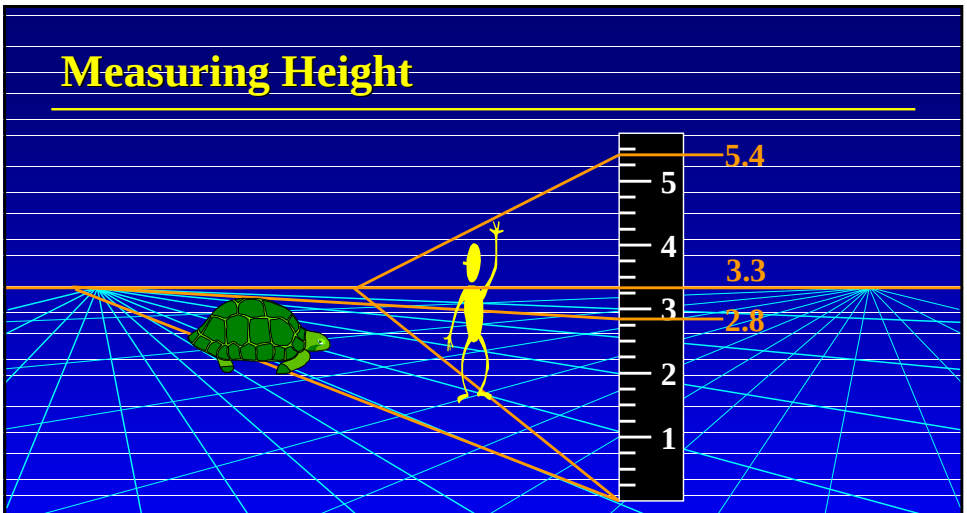
Perspective Cues



Vanishing Points



Measuring Height



Same Concepts Enable

- *Reconstructing X, Y, and Z*
- *Computing camera projection matrix*
- *Eliminating the ruler*

“Single View Metrology” [Criminisi 99]

“Single View Metrology” [Criminisi 99]

The Music Lesson, Jan Vermeer, 1662-65
Royal Collection of Her Majesty Queen Elizabeth II

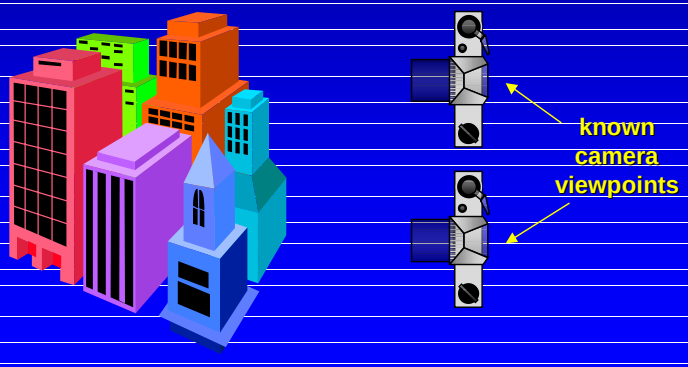
“Morphable Models” [Blanz 99]

Video

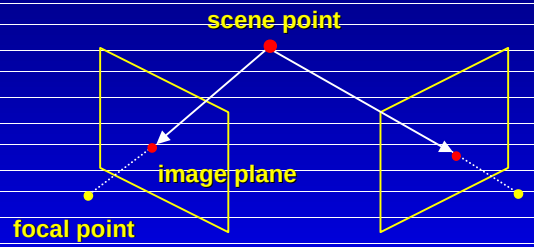
Stereo Reconstruction

The Stereo Problem

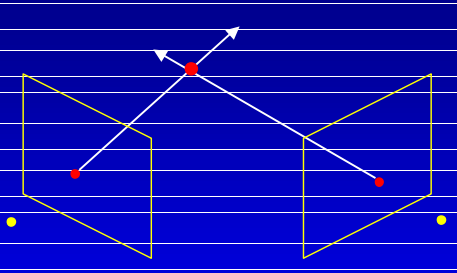
- Shape from two (or more) images
- Biological motivation



Stereo



Stereo



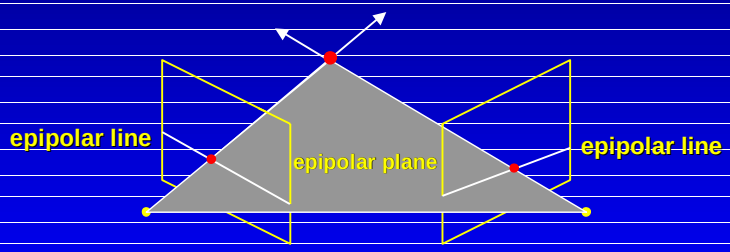
Basic Principle: Triangulation

- Gives reconstruction as intersection of two rays
- Requires ***point correspondence***

Stereo Correspondence

Determine Pixel Correspondence

- **Pairs of points that correspond to same scene point**



Epipolar Constraint

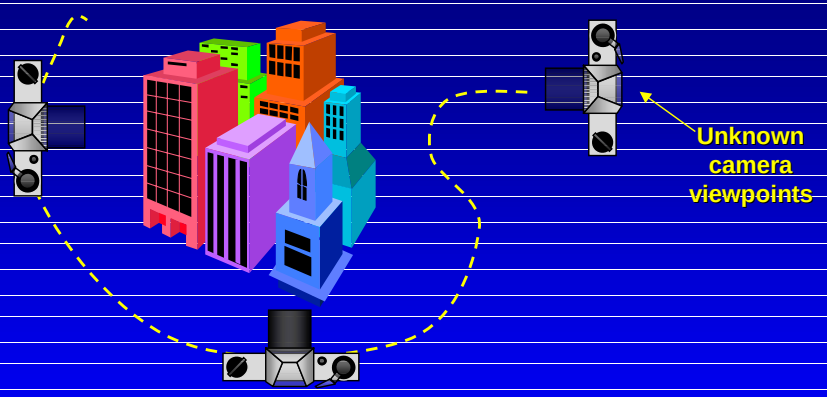
- **Reduces correspondence problem to 1D search along *conjugate epipolar lines***

Stereo Matching Algorithms

Match Pixels in Conjugate Epipolar Lines

- **Assume color of point does not change**
- **Pitfalls**
  - > specularities
  - > low-contrast regions
  - > occlusions
  - > image error
  - > camera calibration error
- **Numerous approaches**
  - > dynamic programming [Baker 81,Ohta 85]
  - > smoothness functionals
  - > more images (trinocular, N-ocular) [Okutomi 93]
  - > graph cuts [Boykov 00]

Structure from Motion



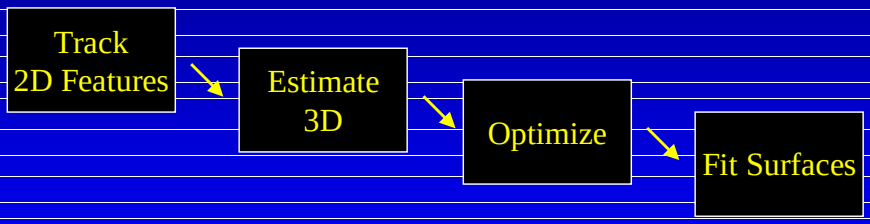
Reconstruct

- Scene geometry
- Camera motion

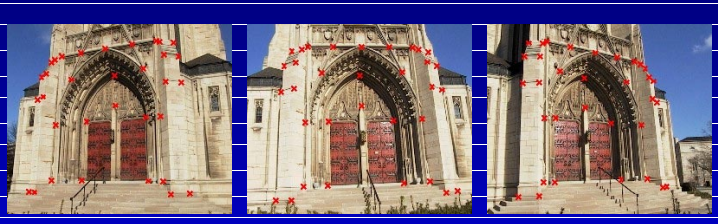
Structure from Motion

The SFM Problem

- Reconstruct scene geometry and camera motion from two or more images



Structure from Motion



Step 1: Track Features

- **Detect good features**
  > corners, line segments
- **Find correspondences between frames**
  > window-based correlation

Structure from Motion

$$\begin{bmatrix} \mathbf{I}_1 \\ \mathbf{I}_2 \\ \vdots \\ \mathbf{I}_f \end{bmatrix} = \begin{bmatrix} \mathbf{\Pi}_1 \\ \mathbf{\Pi}_2 \\ \vdots \\ \mathbf{\Pi}_f \end{bmatrix} \begin{bmatrix} \mathbf{X}_1 & \mathbf{X}_2 & \cdots & \mathbf{X}_n \end{bmatrix}$$

Images **Motion** **Structure**

Step 2: Estimate Motion and Structure

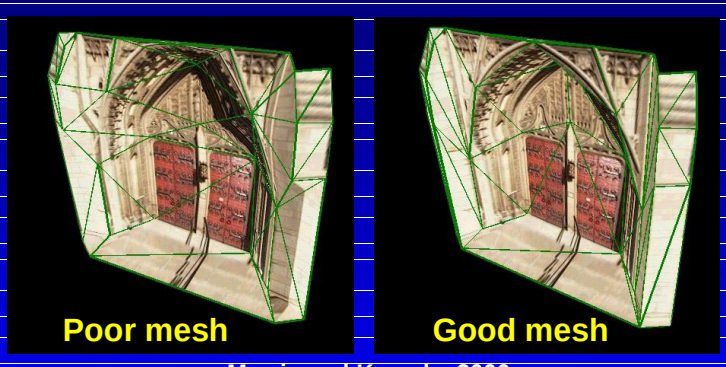
- **Orthographic projection, e.g.,** [Tomasi 92]
- **2 or 3 views at a time** [Hartley 00]

Structure from Motion

Step 3: Refine Estimates

- Nonlinear optimization over cameras and points
  > [Hartley 94]
- "Bundle adjustment" in photogrammetry

Structure from Motion



Morris and Kanade, 2000

Step 4: Recover Surfaces

- **Image-based triangulation** [Morris 00, Baillard 99]
- **Silhouettes** [Fitzgibbon 98]
- **Stereo** [Pollefeys 99]

Resources

Computer Vision Home Page

- http://www.cs.cmu.edu/afs/cs/project/cil/ftp/html/vision.html

Computer Vision Textbooks

- O. Faugeras, *Three-Dimensional Computer Vision*, MIT Press, 1993.
- E. Trucco and A. Verri, *Introductory Techniques for 3-D Computer Vision*, Prentice-Hall, 1998.
- V. S. Nalwa, *A Guided Tour of Computer Vision*, Addison-Wesley, 1993.
- R. Jain, R. Kasturi and B. G. Schunck, *Machine Vision*, McGraw-Hill, 1995.
- R. Klette, K. Schluns and A. Koschan, *Computer Vision: Three-Dimensional Data from Images*, Springer-Verlag, 1998.
- M. Sonka, V. Hlavac and R. Boyle, *Image Processing, Analysis, and Machine Vision*, Brooks/Cole Publishing, 1999.
- D. H. Ballard and C. M. Brown, *Computer Vision*, Prentice-Hall, 1982.
- B. K. P. Horn, *Robot Vision*, McGraw-Hill, 1986.
- J. Koenderink, *Solid Shape*, MIT Press, 1990.
- D. Marr, *Vision*, Freeman, 1982.

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- A. Criminisi, I. Reid, & A. Zisserman, “Single View Metrology”, ICCV 2000, pp. 434-441.
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- R. Zhang, P-S. Tsai, J. Cryer, & M. Shah, “Shape from Shading: A Survey”, IEEE Trans. on PAMI, 21(8), 1999.

Stereo

- Y. Boykov, O. Veksler, & R. Zabih, “Fast Approximate Energy Minimization via Graph Cuts”, ICCV, 1999.
- Y. Ohta & T. Kanade, "Stereo by Intra- and Inter-Scanline Search Using Dynamic Programming", IEEE Trans. on PAMI, 7(2), 1985, pp. 129-154.
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Structure from Motion

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- A.W. Fitzgibbon, G. Cross, & A. Zisserman, “Automatic 3D Model Construction for Turn-Table Sequences”, SMILE Workshop, 1998.
- R. Hartley & A. Zisserman, “Multiple View Geometry”, Cambridge Univ. Press, 2000.
- R. Hartley, “Euclidean Reconstruction from Uncalibrated Views”, In Applications of Invariance in Computer Vision, Springer-Verlag, 1994, pp. 237-256.
- D. Morris & T. Kanade, “Image-Consistent Surface Triangulation”, CVPR 00, pp. 332-338.
- M. Pollefeys, R. Koch & L. Van Gool, “Self-Calibration and Metric Reconstruction in spite of Varying and Unknown Internal Camera Parameters”, Int. J. of Computer Vision, 32(1), 1999, pp. 7-25.
- C. Tomasi & T. Kanade, ”Shape and Motion from Image Streams Under Orthography: A Factorization Method", Int. Journal of Computer Vision, 9(2), 1992, pp. 137-154.