3D photography

Digital Visual Effects, Spring 2005

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2005/5/18

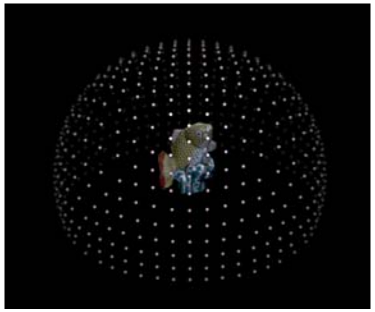
with slides by Szymon Rusinkiewicz, Richard Szeliski, Steve Seitz and Brian Curless

Announcements

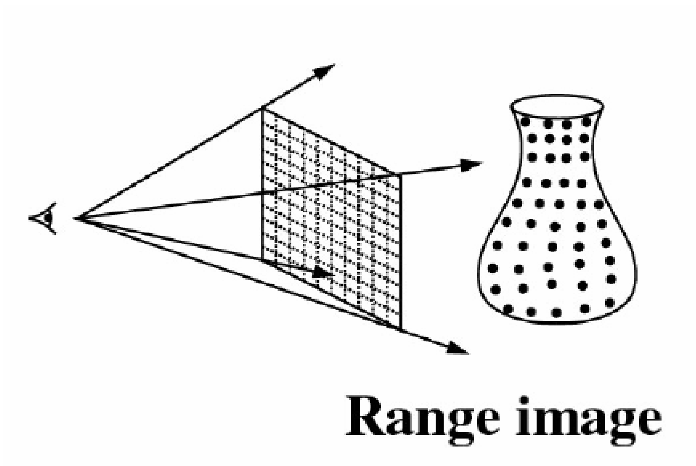
- Project #2 winning artifacts
- Project #3 is due next Tuesday
- CGCG talk on 5/23, 2:20pm, CSIE 107

3D photography

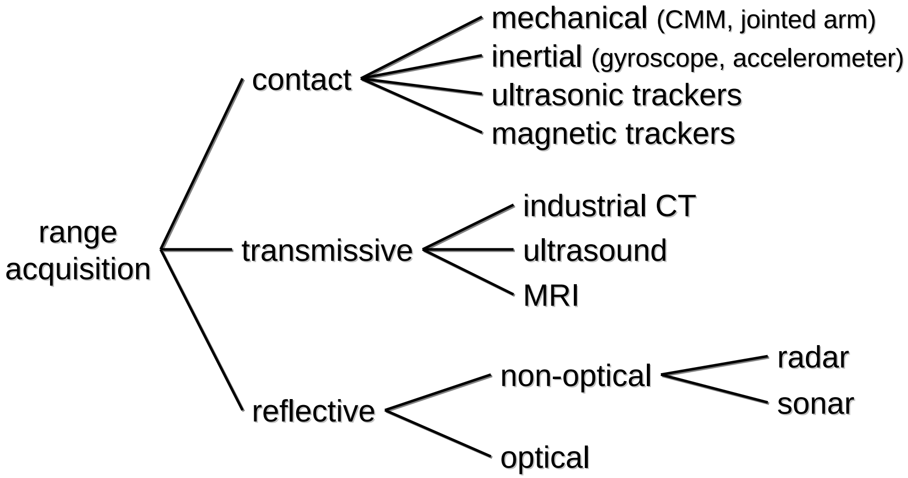
- Acquisition of geometry and material



Range acquisition



Range acquisition taxonomy

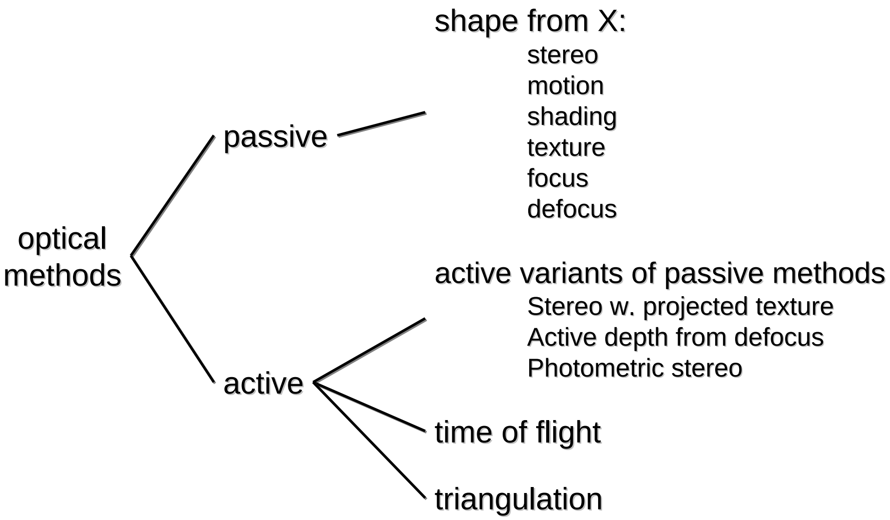


Touch Probes

- Jointed arms with angular encoders
- Return position, orientation of tip

Faro Arm – Faro Technologies, Inc.

Range acquisition taxonomy



Outline

- Passive approaches
  - Stereo
  - Multiview approach
- Active approaches
  - Triangulation
  - Shadow scanning
- Active variants of passive approaches
  - Photometric stereo
  - Example-based photometric stereo
  - Helmholtz stereo

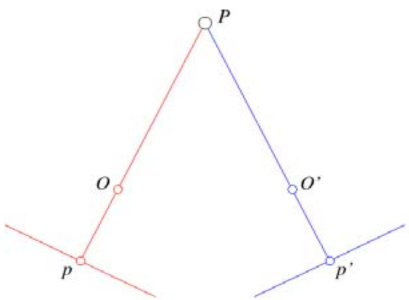
Passive approaches

Stereo

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

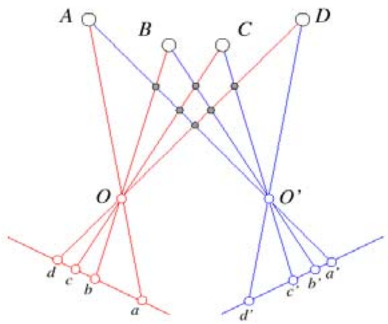
Stereo

- One distinguishable point being observed
  - The preimage can be found at the intersection of the rays from the focal points to the image points



Stereo

- Many points being observed
  - Need some method to establish correspondences



Components of stereo vision systems

- Camera calibration: previous lecture
- Image rectification: simplifies the search for correspondences
- Correspondence: which item in the left image corresponds to which item in the right image
- Reconstruction: recovers 3-D information from the 2-D correspondences

Epipolar geometry

- Epipolar constraint: corresponding points must lie on conjugate epipolar lines
  - Search for correspondences becomes a 1-D problem

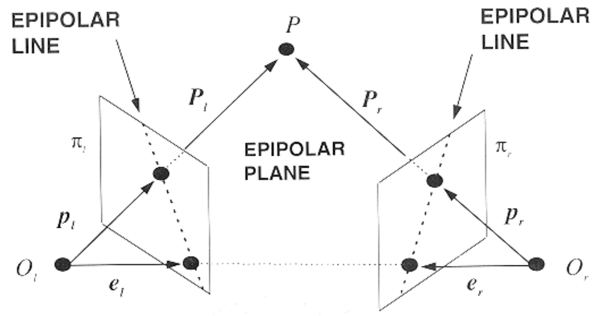
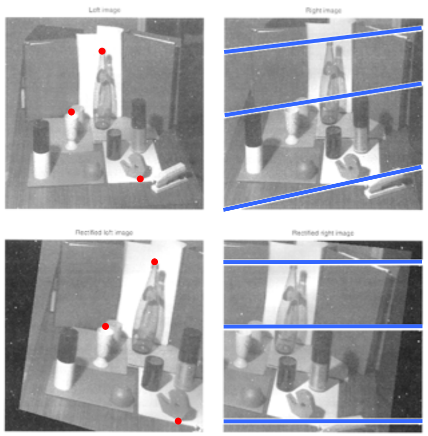


Image rectification

- Warp images such that conjugate epipolar lines become collinear and parallel to *u* axis

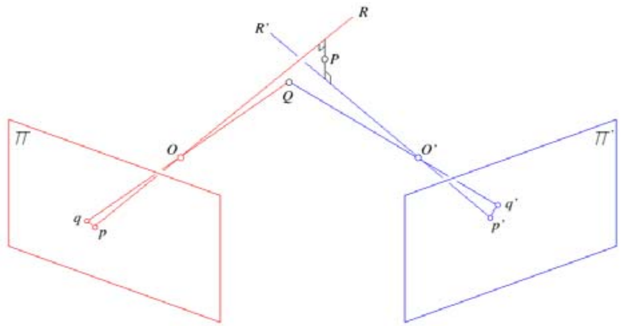


Disparity

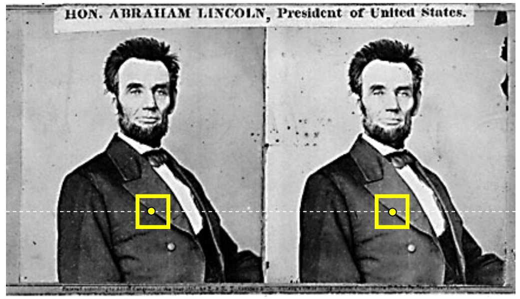
- With rectified images, disparity is just (horizontal) displacement of corresponding features in the two images
  - Disparity = 0 for distant points
  - Larger disparity for closer points
  - Depth of point proportional to 1/disparity

Reconstruction

- Geometric
  - Construct the line segment perpendicular to R and R' that intersects both rays and take its mid-point



Basic stereo algorithm



For each epipolar line

For each pixel in the left image

- compare with every pixel on same epipolar line in right image
- pick pixel with minimum match cost

Improvement: match ***windows***

Basic stereo algorithm

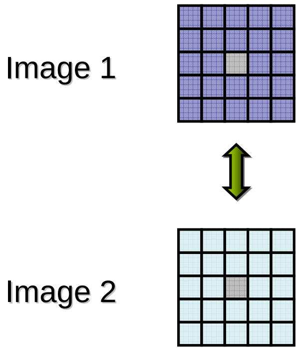
- For each pixel
  - For each disparity
    - For each pixel in window
      - Compute difference
  - Find disparity with minimum SSD

Reverse order of loops

- For each disparity
  - For each pixel
    - For each pixel in window
      - Compute difference
- Find disparity with minimum SSD at each pixel

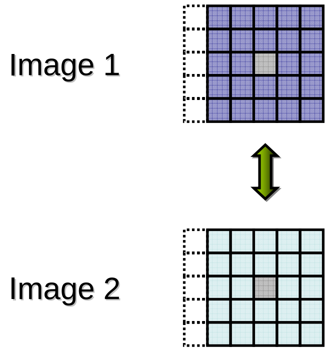
Incremental computation

- Given SSD of a window, at some disparity



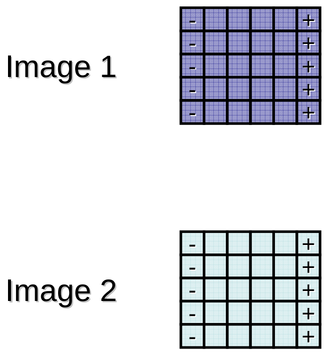
Incremental computation

- Want: SSD at next location



Incremental computation

- Subtract contributions from leftmost column, add contributions from rightmost column

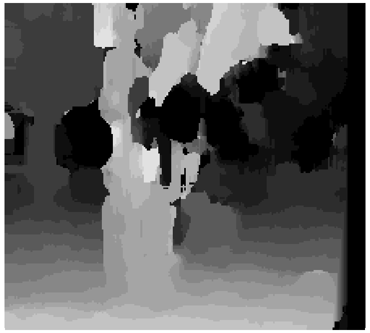


Selecting window size

- Small window: more detail, but more noise
- Large window: more robustness, less detail
- Example:

Selecting window size

3 pixel window



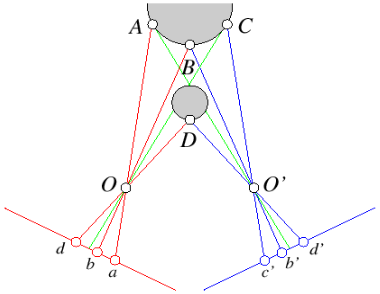
20 pixel window

Non-square windows

- Compromise: have a large window, but higher weight near the center
- Example: Gaussian
- For each disparity
  - For each pixel
    - Compute weighted SSD

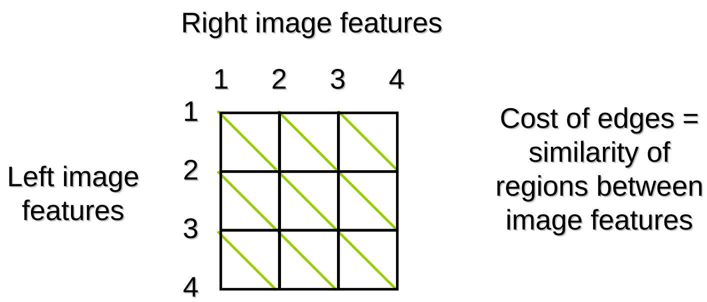
Ordering constraint

- Order of matching features usually the same in both images
- But not always: occlusion



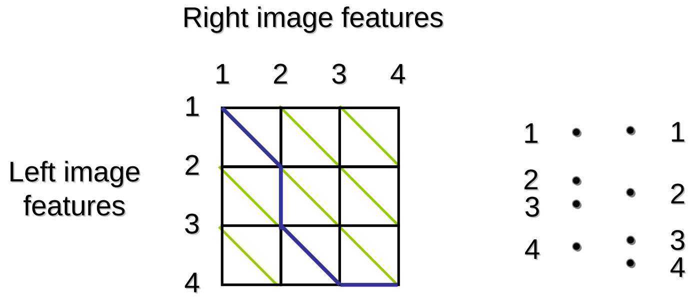
Dynamic programming

- Treat feature correspondence as graph problem



Dynamic programming

- Find min-cost path through graph



Energy minimization

- Another approach to improve quality of correspondences
- Assumption: disparities vary (mostly) smoothly
- Minimize energy function:

$$E_{data}+\lambda E_{smoothness}$$

- E_{data}: how well does disparity match data
- $E_{smoothness}$: how well does disparity match that of neighbors – regularization

Energy minimization

- If data and energy terms are nice (continuous, smooth, etc.) can try to minimize via gradient descent, etc.
- In practice, disparities only piecewise smooth
- Design smoothness function that doesn't penalize large jumps too much
  - Example: $V(\alpha,\beta)=\min(|\alpha-\beta|, K)$

Stereo as energy minimization

- Matching Cost Formulated as Energy
  - "data" term penalizing bad matches

$$D(x,y,d)=\left|\mathbf{I}(x,y)-\mathbf{J}(x+d,y)\right|$$

  - "neighborhood term" encouraging spatial smoothness

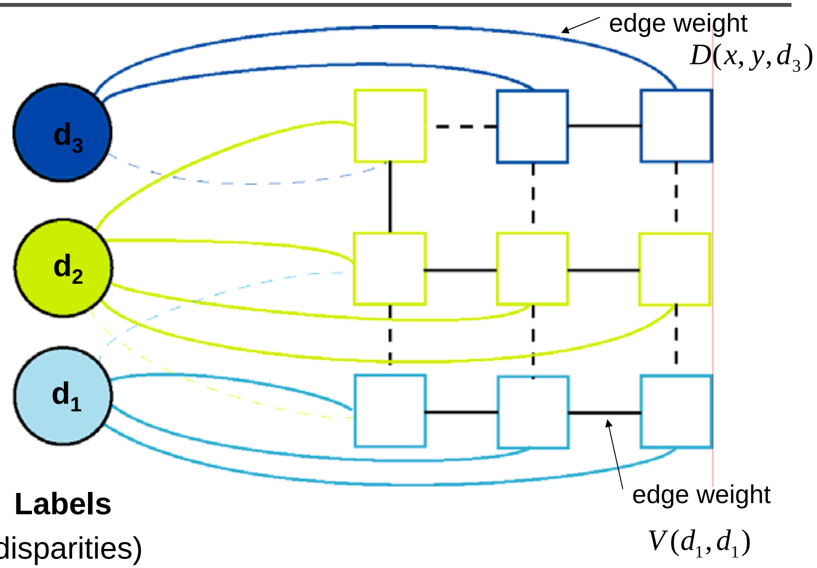
$$V(d_1,d_2)=\text{cost of adjacent pixels with labels d1 and d2}$$
$$=\left|d_1-d_2\right| \quad \text{(or something similar)}$$

$$E=\sum_{(x,y)}D(x,y,d_{x,y})+\sum_{neighbors\ (x1,y1),(x2,y2)}V(d_{x1,y1},d_{x2,y2})$$

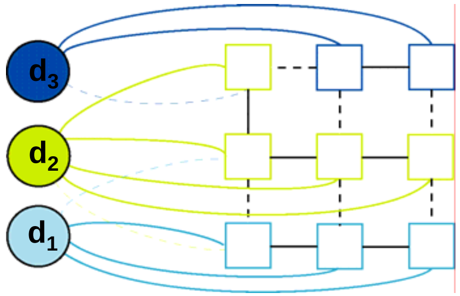
Energy minimization

- Hard to find global minima of non-smooth functions
  - Many local minima
  - Provably NP-hard
- Practical algorithms look for approximate minima (e.g., simulated annealing)

Energy minimization via graph cuts

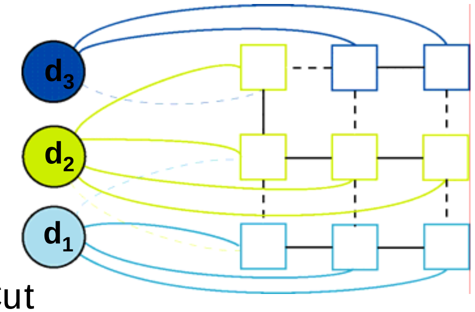


Energy minimization via graph cuts



- Graph Cost
  - Matching cost between images
  - Neighborhood matching term
  - Goal: figure out which labels are connected to which pixels

Energy minimization via graph cuts

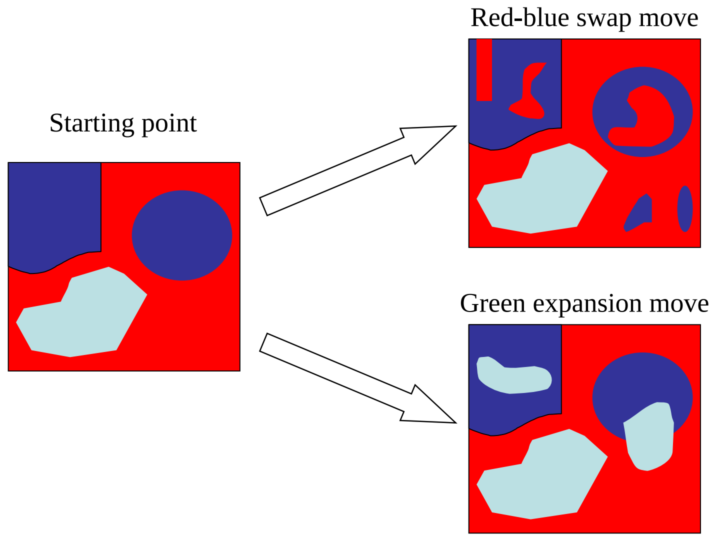


- Graph Cut
  - Delete enough edges so that
    - each pixel is (transitively) connected to exactly one label node
  - Cost of a cut: sum of deleted edge weights
  - Finding min cost cut equivalent to finding global minimum of energy function

Computing a multiway cut

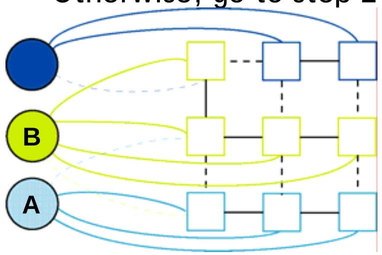
- With 2 labels: classical min-cut problem
  - Solvable by standard flow algorithms
    - polynomial time in theory, nearly linear in practice
  - More than 2 terminals: NP-hard
    [Dahlhaus *et al.*, STOC ‘92]
- Efficient approximation algorithms exist
  - Within a factor of 2 of optimal
  - Computes local minimum in a strong sense
    - even very large moves will not improve the energy
  - Yuri Boykov, Olga Veksler and Ramin Zabih, [Fast Approximate Energy Minimization via Graph Cuts](), International Conference on Computer Vision, September 1999.

Move examples

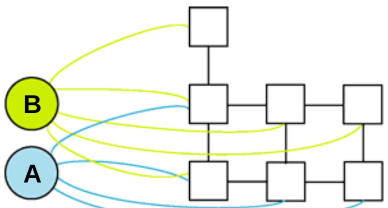


The swap move algorithm

1. Start with an arbitrary labeling
2. Cycle through every label pair *(A,B)* in some order
   2.1 Find the lowest *E* labeling within a single *AB*-swap
   2.2 Go there if it’s lower *E* than the current labeling
3. If *E* did not decrease in the cycle, we’re done
   Otherwise, go to step 2



Original graph



AB subgraph
(run min-cut on this graph)

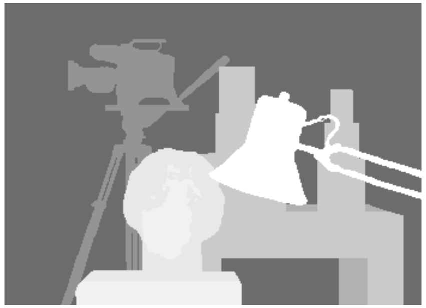
The expansion move algorithm

1. Start with an arbitrary labeling
2. Cycle through every label *A* in some order
   2.1 Find the lowest *E* labeling within a single *A*-expansion
   2.2 Go there if it’s lower *E* than the current labeling
3. If *E* did not decrease in the cycle, we’re done
   Otherwise, go to step 2

Stereo results

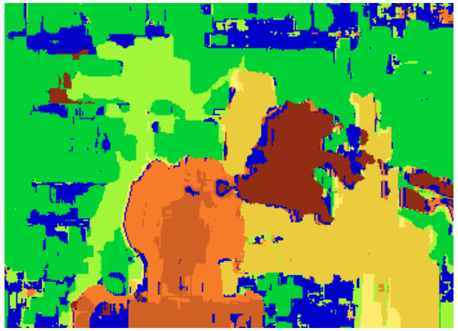
– Data from University of Tsukuba

scene



ground truth

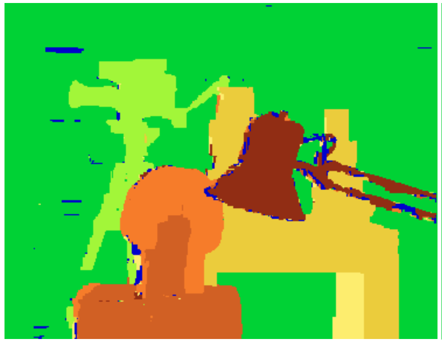
Results with window correlation



normalized correlation
(best window size)

ground truth

Results with graph cuts



graph cuts
(Potts model *E*,
expansion move algorithm)

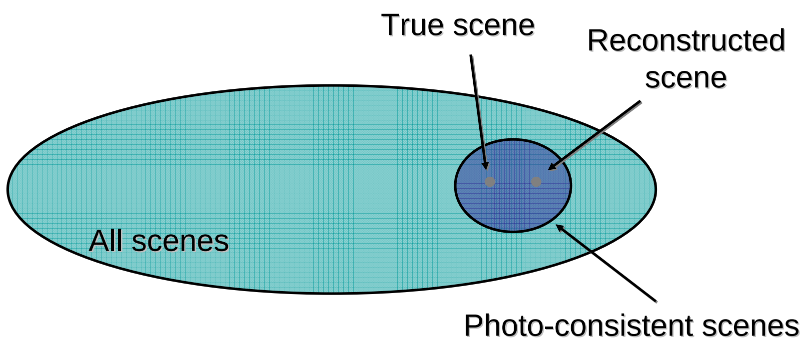
ground truth

Volumetric multiview approaches

- Goal: find a model consistent with images
- "Model-centric" (vs. image-centric)
- Typically use discretized volume (voxel grid)
- For each voxel, compute occupied / free
  (for some algorithms, also color, etc.)

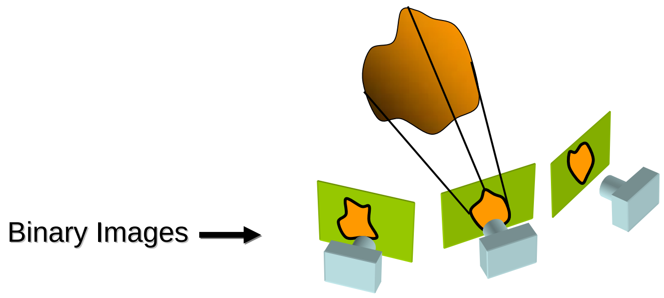
Photo consistency

- Result: not necessarily correct scene
- Many scenes produce the same images



Silhouette carving

- Find silhouettes in all images
- Exact version:
  - Back-project all silhouettes, find intersection



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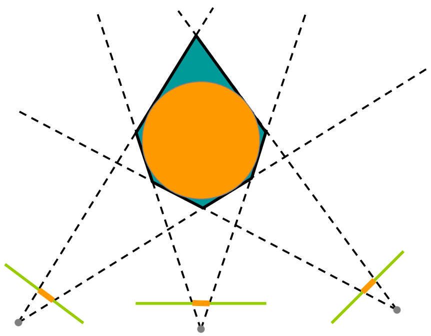


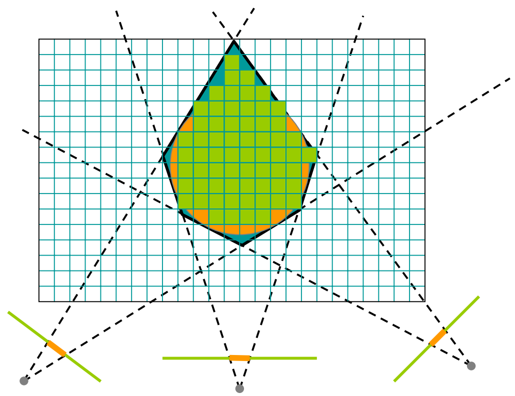
Silhouette carving

- Limit of silhouette carving is *visual hull* or *line hull*
- Complement of lines that don't intersect object
- In general not the same as object
  - Can't recover "pits" in object
- Not the same as convex hull

Silhouette carving

- Discrete version:
  - Loop over all voxels in some volume
  - If projection into images lies inside all silhouettes, mark as occupied
  - Else mark as free

Silhouette carving



Voxel coloring

- Seitz and Dyer, 1997
- In addition to free / occupied, store color at each voxel
- Explicitly accounts for occlusion

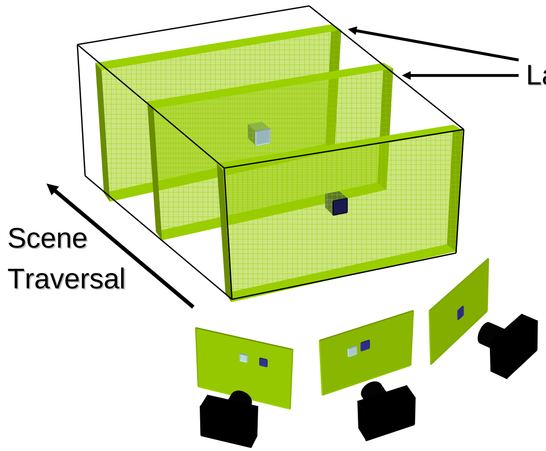
Voxel coloring

- Basic idea: sweep through a voxel grid
  - Project each voxel into each image in which it is visible
  - If colors in images agree, mark voxel with color
  - Else, mark voxel as empty
- Agreement of colors based on comparing standard deviation of colors to threshold

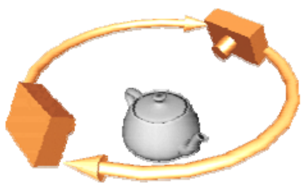
Voxel coloring and occlusion

- Problem: which voxels are visible?
- Solution: constrain camera views
  - When a voxel is considered, necessary occlusion information must be available
  - Sweep occluders before occludees
  - Constrain camera positions to allow this sweep

Voxel coloring sweep order



Voxel coloring camera positions



Inward-looking
Cameras above scene

Outward-looking
Cameras inside scene

Seitz

Image acquisition

Selected Dinosaur Images

Selected Flower Images

•Calibrated Turntable

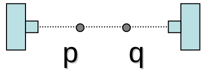
•360° rotation (21 images)

Voxel coloring results

Dinosaur Reconstruction
72 K voxels colored
7.6 M voxels tested
7 min. to compute
on a 250MHz SGI

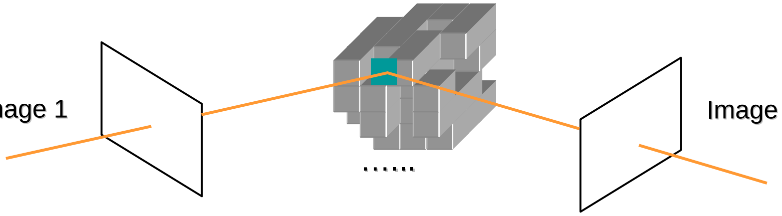
Flower Reconstruction
70 K voxels colored
7.6 M voxels tested
7 min. to compute
on a 250MHz SGI

Limitations of voxel coloring



- A view-independent depth order may not exist
- Need more powerful general-case algorithms
  - Unconstrained camera positions
  - Unconstrained scene geometry/topology

Space carving

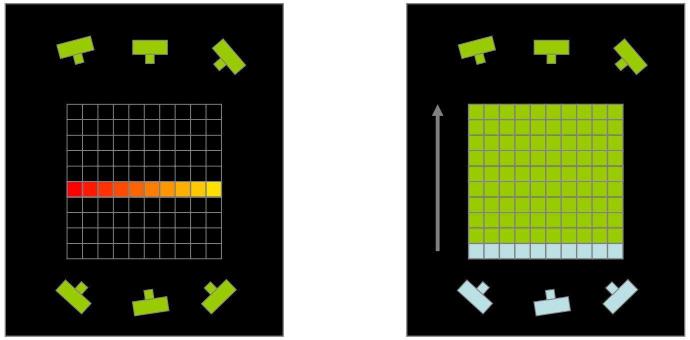


Initialize to a volume V containing the true scene
Choose a voxel on the current surface
Project to visible input images
Carve if not photo-consistent
Repeat until convergence

Multi-pass plane sweep

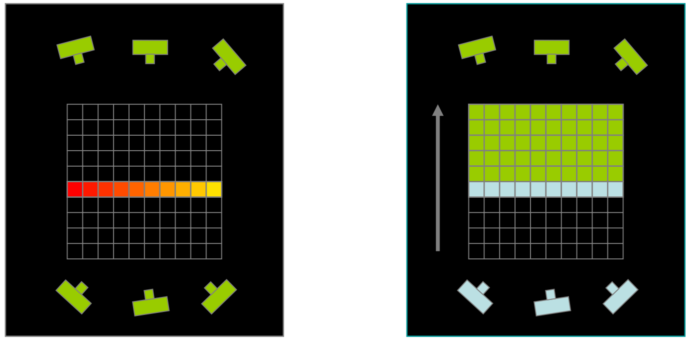
- Faster alternative:
  - Sweep plane in each of 6 principal directions
  - Consider cameras on only one side of plane
  - Repeat until convergence

Multi-pass plane sweep

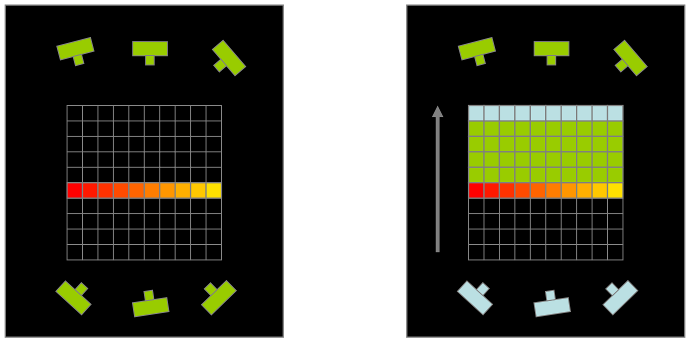


True Scene Reconstruction

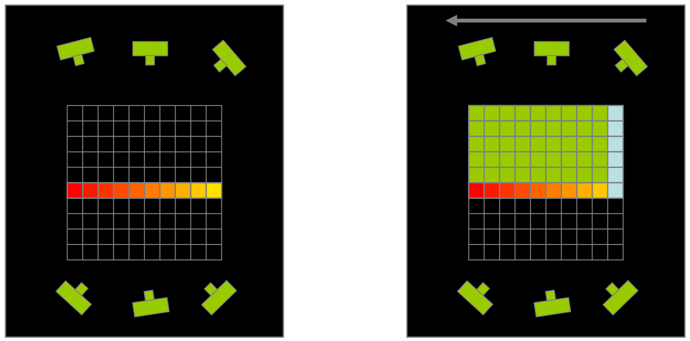
Multi-pass plane sweep



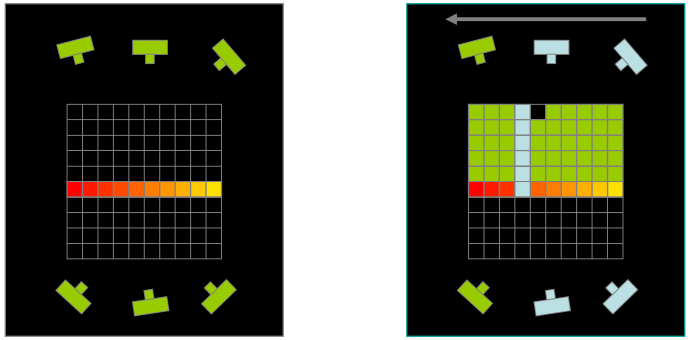
Multi-pass plane sweep



Multi-pass plane sweep



Multi-pass plane sweep



Space carving results: African violet

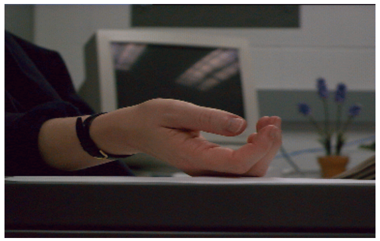
Input image (1 of 45)

Reconstruction

Reconstruction

Reconstruction

Space carving results: hand



Input image
(1 of 100)

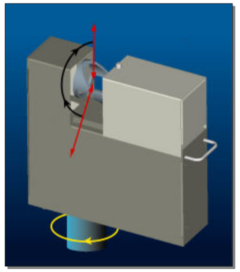
Reconstruction

Active approaches

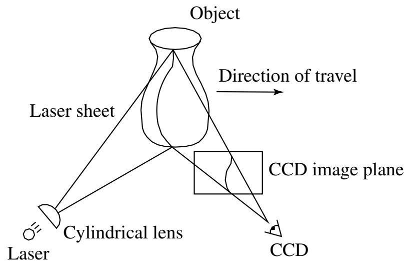
Time of flight

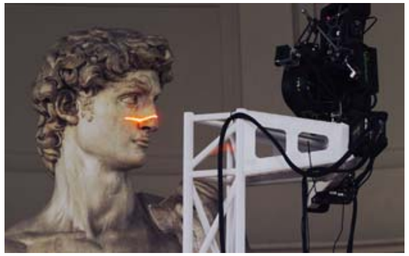
- Basic idea: send out pulse of light (usually laser), time how long it takes to return

$$r = \frac{1}{2} c \Delta t$$



Laser scanning (triangulation)

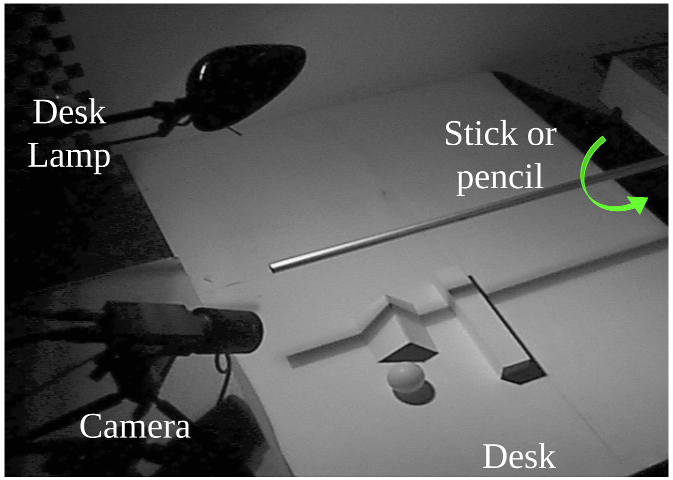




Digital Michelangelo Project
http://graphics.stanford.edu/projects/mich/

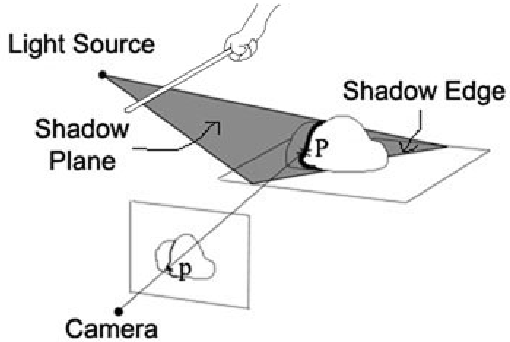
- Optical triangulation
  - Project a single stripe of laser light
  - Scan it across the surface of the object
  - This is a very precise version of structured light scanning
- Other patterns are possible

Shadow scanning



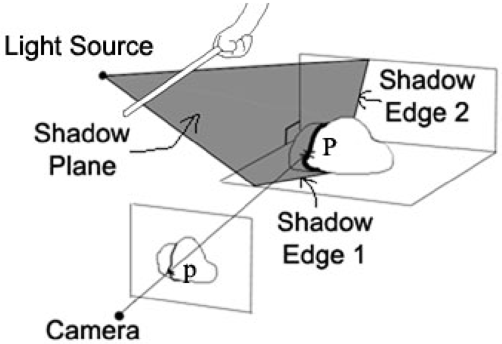
http://www.vision.caltech.edu/bouguetj/ICCV98/

Basic idea



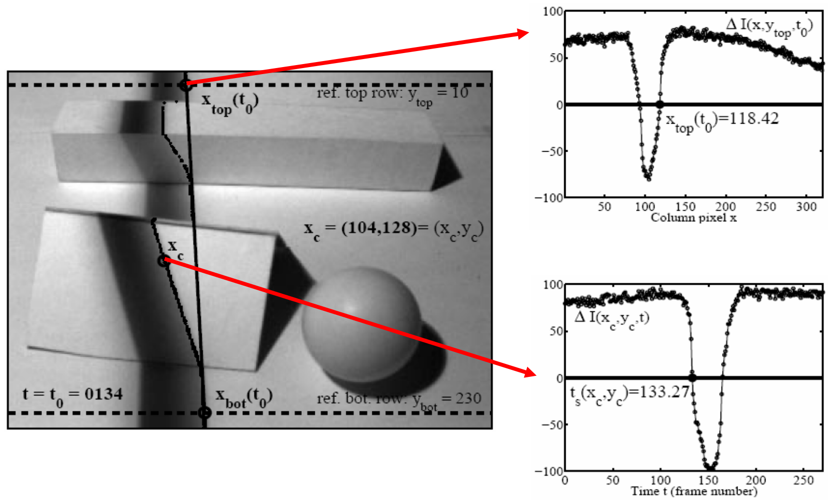
- Calibration issues:
  - where's the camera wrt. ground plane?
  - where's the shadow plane?
    - depends on light source position, shadow edge

Two Plane Version



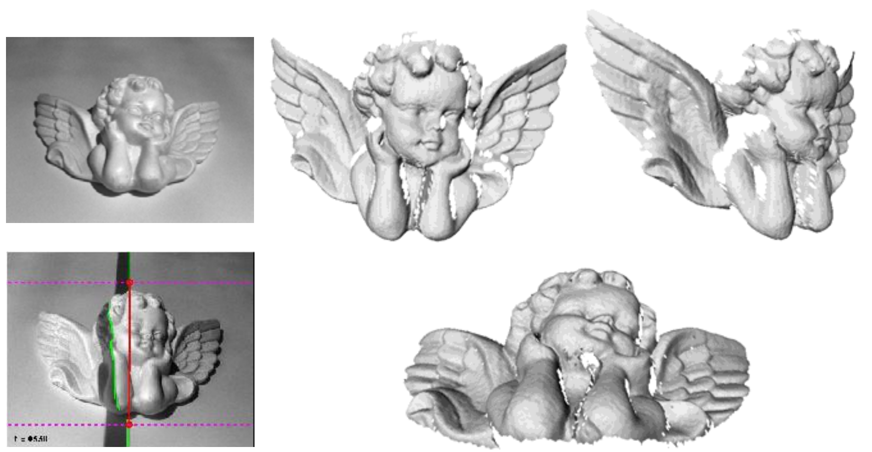
- Advantages
  – don't need to pre-calibrate the light source
  – shadow plane determined from two shadow edges

Estimating shadow lines



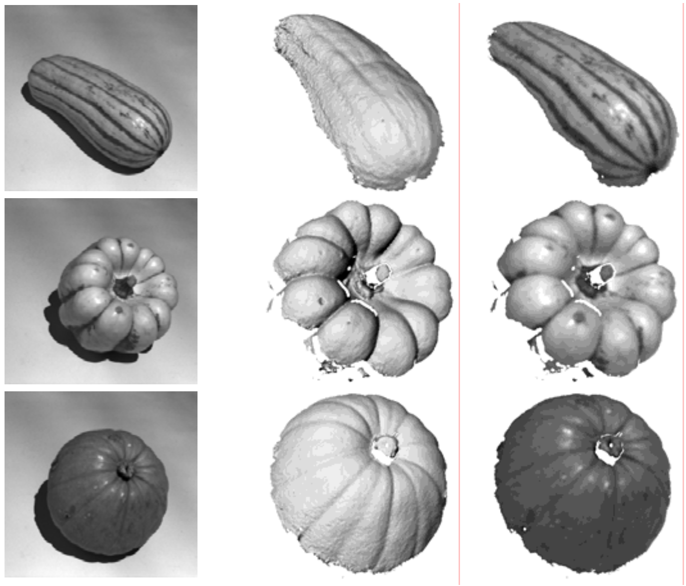
Shadow scanning in action

Results

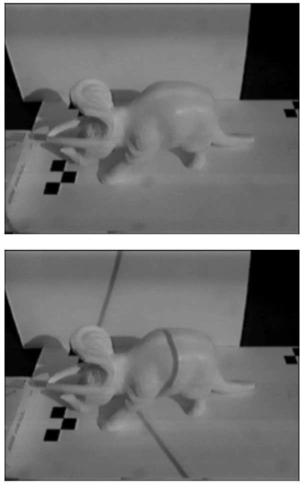


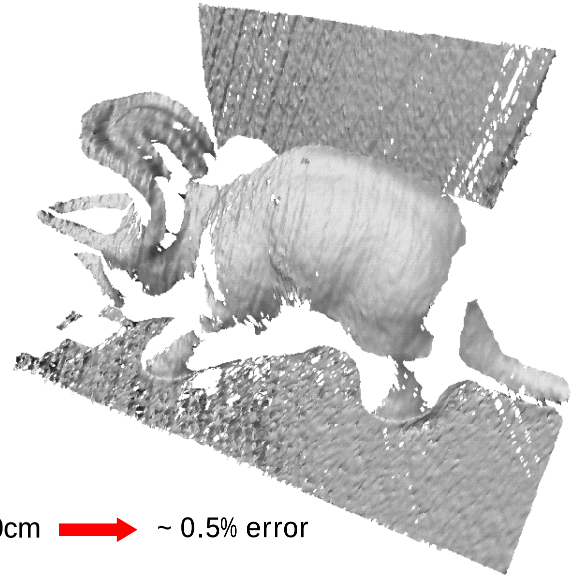
accuracy: 0.1mm over 10cm ➡ ~ 0.1% error

Textured objects



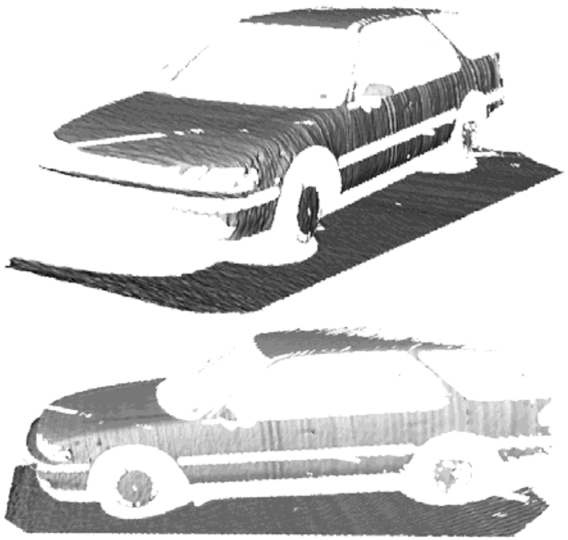
Scanning with the sun





accuracy: 1mm over 50cm → ~ 0.5% error

Scanning with the sun



accuracy: 1cm over 2m

→ ~ 0.5% error

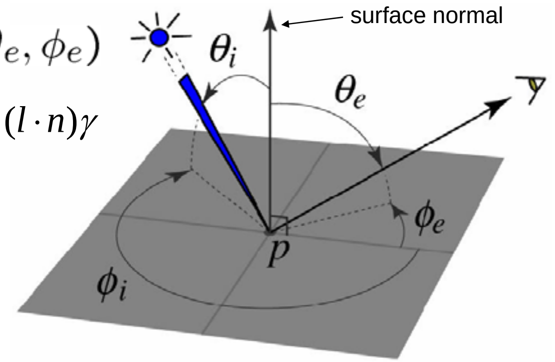
Active variants of passive approaches

The BRDF

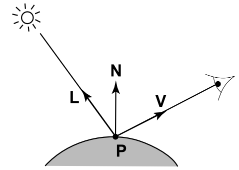
- The Bidirectional Reflection Distribution Function
  - Given an incoming ray (θ_i, ϕ_i) and outgoing ray (θ_e, ϕ_e) what proportion of the incoming light is reflected along outgoing ray?

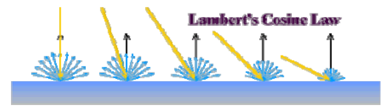
$$\rho(\theta_i, \phi_i, \theta_e, \phi_e)$$

$$I = \rho(l, v) \times (l \cdot n)\gamma$$



Diffuse reflection (Lambertian)



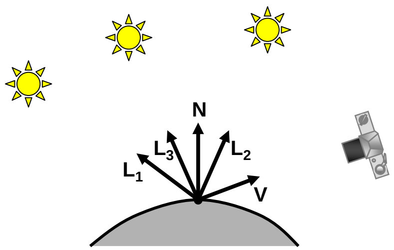


$$\rho(l, v) = k_d$$ ← **albedo**

$$I = k_d \mathbf{N} \cdot \mathbf{L}$$

Assuming that light strength is 1.

Photometric stereo



$$I_1 = k_d \mathbf{N} \cdot \mathbf{L_1}$$
$$I_2 = k_d \mathbf{N} \cdot \mathbf{L_2}$$
$$I_3 = k_d \mathbf{N} \cdot \mathbf{L_3}$$

- Can write this as a matrix equation:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = k_d \begin{bmatrix} \mathbf{L_1}^T \\ \mathbf{L_2}^T \\ \mathbf{L_3}^T \end{bmatrix} \mathbf{N}$$

Solving the equations

$$\underbrace{\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix}}_{\substack{\mathbf{I} \\ 3 \times 1}} = \underbrace{\begin{bmatrix} \mathbf{L_1}^T \\ \mathbf{L_2}^T \\ \mathbf{L_3}^T \end{bmatrix}}_{\substack{\mathbf{L} \\ 3 \times 3}} \underbrace{k_d \mathbf{N}}_{\substack{\mathbf{G} \\ 3 \times 1}}$$

$$\mathbf{G} = \mathbf{L}^{-1} \mathbf{I}$$

$$k_d = \|\mathbf{G}\|$$

$$\mathbf{N} = \frac{1}{k_d} \mathbf{G}$$

More than three lights

- Get better results by using more lights

$$\begin{bmatrix} I_1 \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} \mathbf{L_1} \\ \vdots \\ \mathbf{L_n} \end{bmatrix} k_d \mathbf{N}$$

- Least squares solution:

$$\begin{aligned} \mathbf{I} &= \mathbf{LG} \\ \mathbf{L^T I} &= \mathbf{L^T L G} \\ \mathbf{G} &= (\mathbf{L^T L})^{-1}(\mathbf{L^T I}) \end{aligned}$$

- Solve for N, k_d as before

Trick for handling shadows

- Weight each equation by the pixel brightness:

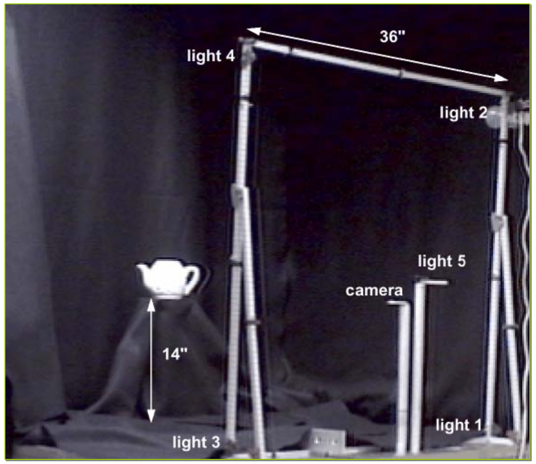
$$I_i(I_i) = I_i[k_d \mathbf{N} \cdot \mathbf{L_i}]$$

- Gives weighted least-squares matrix equation:

$$\begin{bmatrix} I_1^2 \\ \vdots \\ I_n^2 \end{bmatrix} = \begin{bmatrix} I_1 \mathbf{L_1}^T \\ \vdots \\ I_n \mathbf{L_n}^T \end{bmatrix} k_d \mathbf{N}$$

- Solve for N, k_d as before

Photometric Stereo Setup



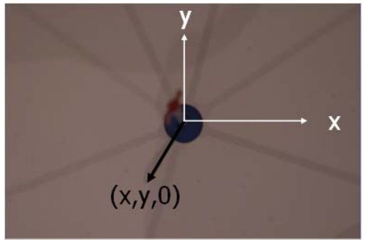
Procedure

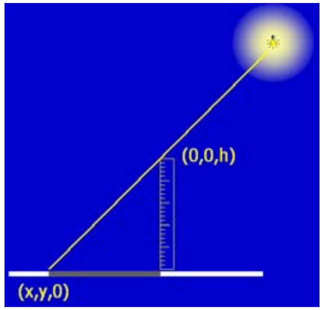
- Calibrate camera
- Calibrate light directions/intensities
- Photographing objects (HDR recommended)
- Estimate normals
- Estimate depth

Estimating light directions

- Trick: place a chrome sphere in the scene

  – the location of the highlight tells you where the light source is
- Use a ruler





Photographing objects

Normalize light intensities

Estimate normals

Depth from normals

$$(n_x, n_y, n_z) = \left(\frac{\partial z}{\partial x}, \frac{\partial z}{\partial y}, -1\right) = (p, q, -1)$$

$$E = E_{data} + E_{smooth} + E_{cons}$$

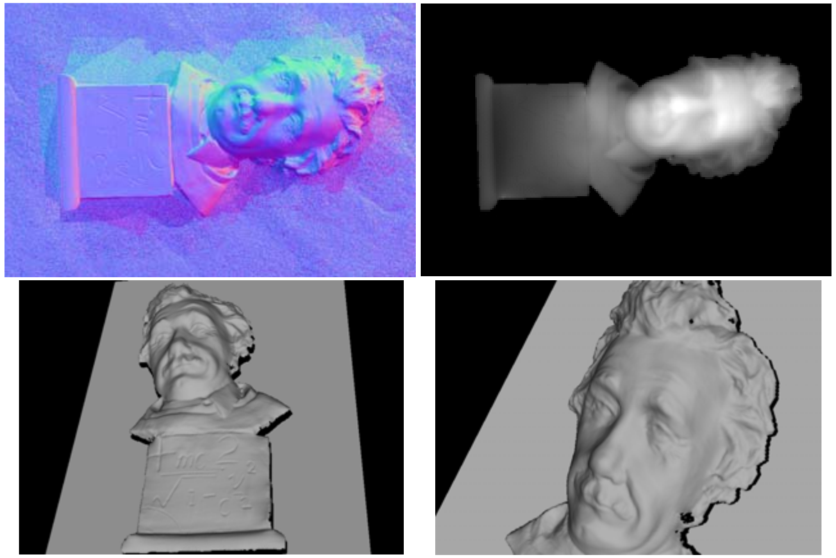
$$= \sum_{i,j} w_{data} * \left[\left(\frac{\partial z(i,j)}{\partial x} - p_{ij} \right)^2 + \left(\frac{\partial z(i,j)}{\partial y} - q_{ij} \right)^2 \right]$$

$$+ \sum_{i,j} w_{smooth} * \left[\left(\frac{\partial^2 z(i,j)}{\partial x^2} \right)^2 + 2\left(\frac{\partial^2 z(i,j)}{\partial x \partial y} \right)^2 + \left(\frac{\partial^2 z(i,j)}{\partial y^2} \right)^2 \right]$$

$$+ \sum_{(i,j)\in Cons} w_{cons} * \left(z(i,j) - c_{ij} \right)^2$$

$$E = \frac{1}{2} z^T A z - b^T z + c \quad \equiv \quad Az = b$$

Results



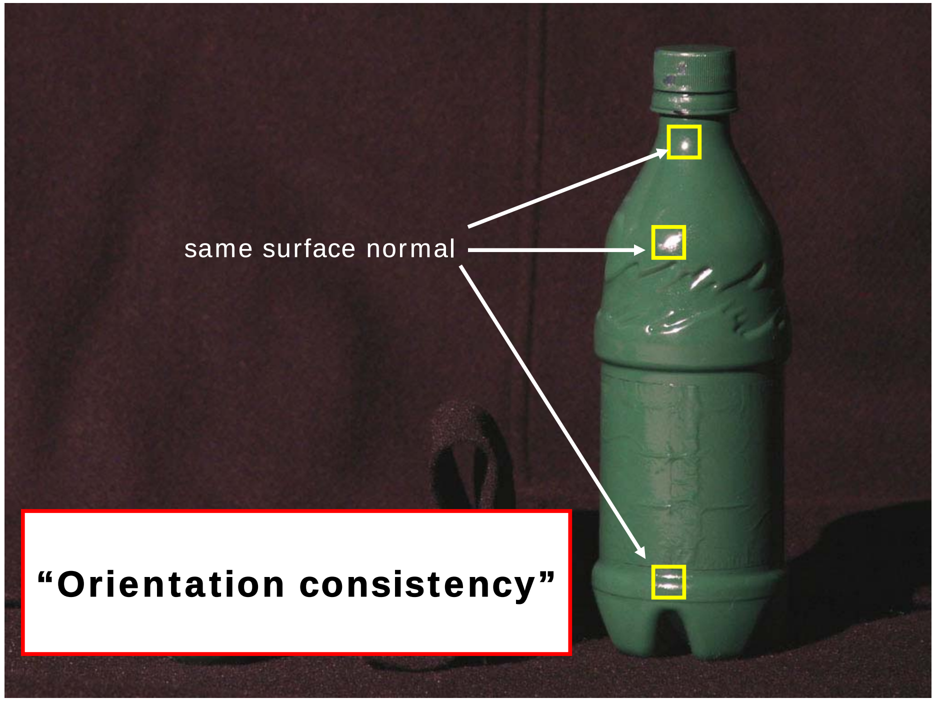
Limitations

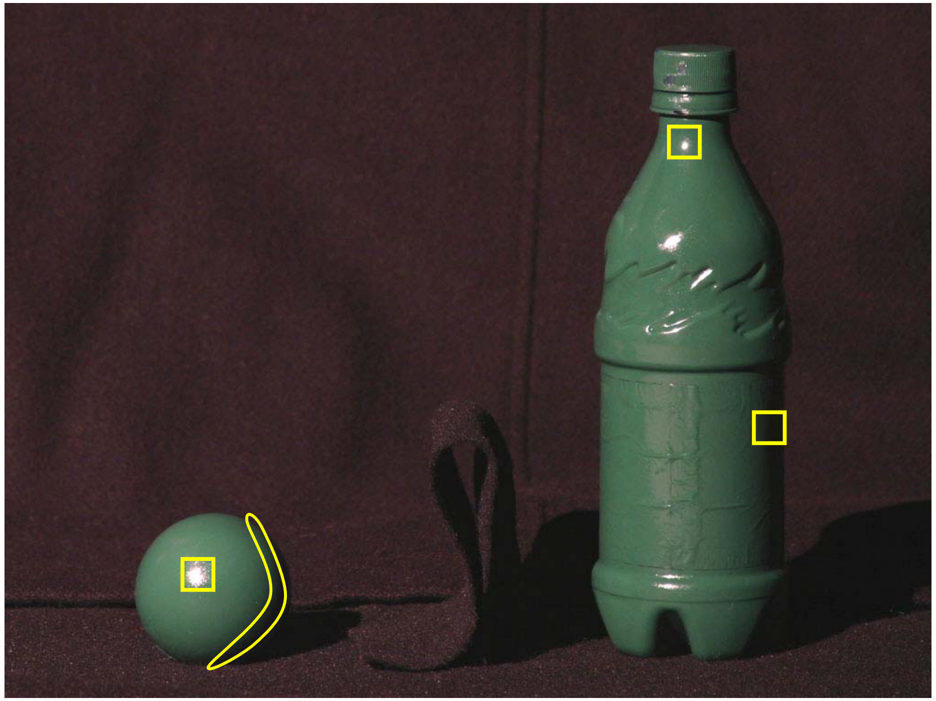
- Big problems
  - doesn't work for shiny things, semi-translucent things
  - shadows, inter-reflections
- Smaller problems
  - calibration requirements
    - measure light source directions, intensities
    - camera response function

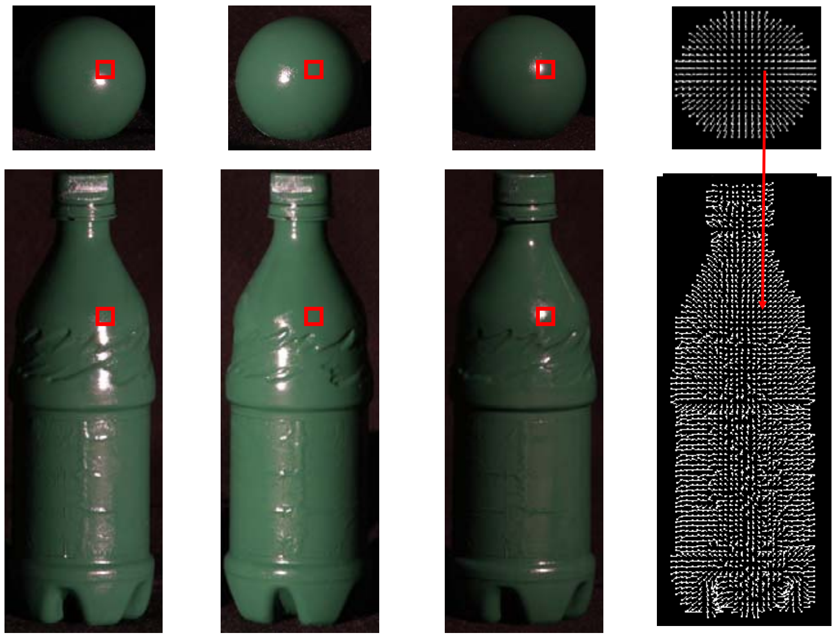
Example-based photometric stereo

- Estimate 3D shape by varying illumination, fixed camera

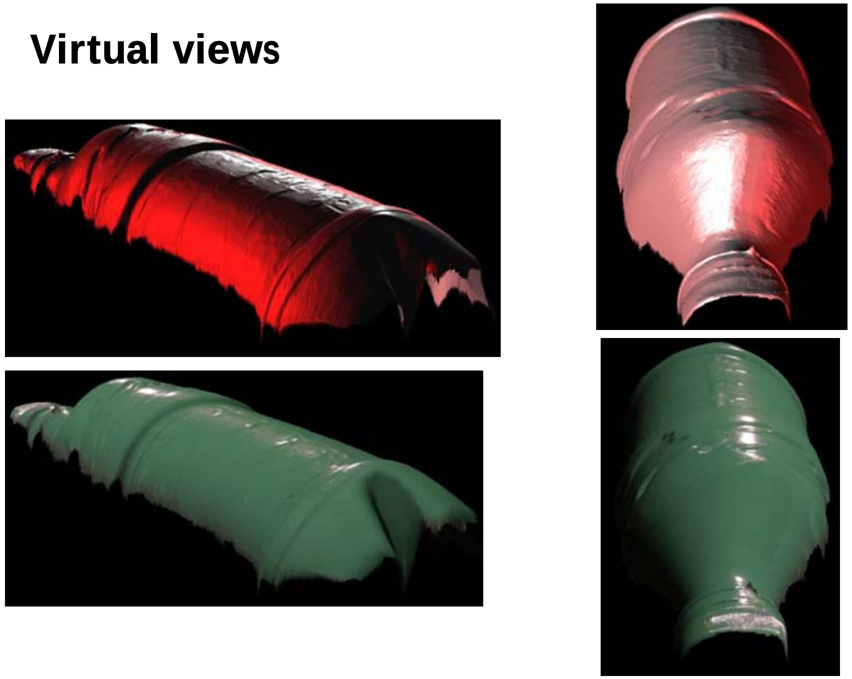
- Operating conditions
  - any opaque material
  - distant camera, lighting
  - reference object available
  - no shadows, interreflections, transparency


same surface normal
“Orientation consistency”

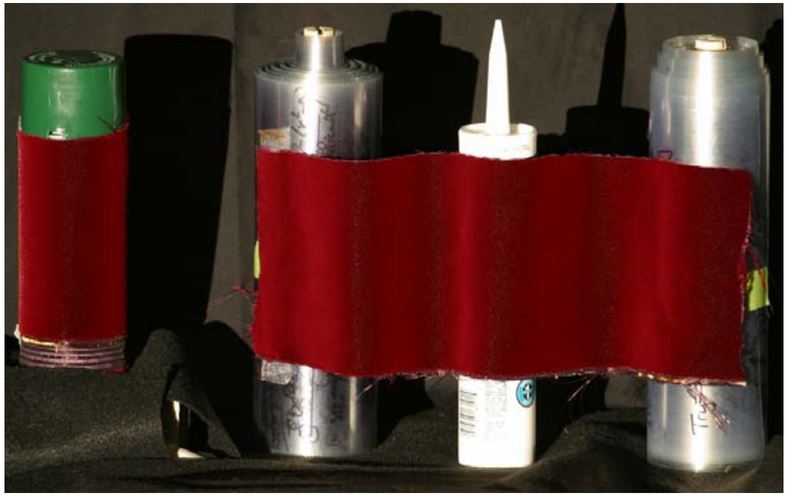




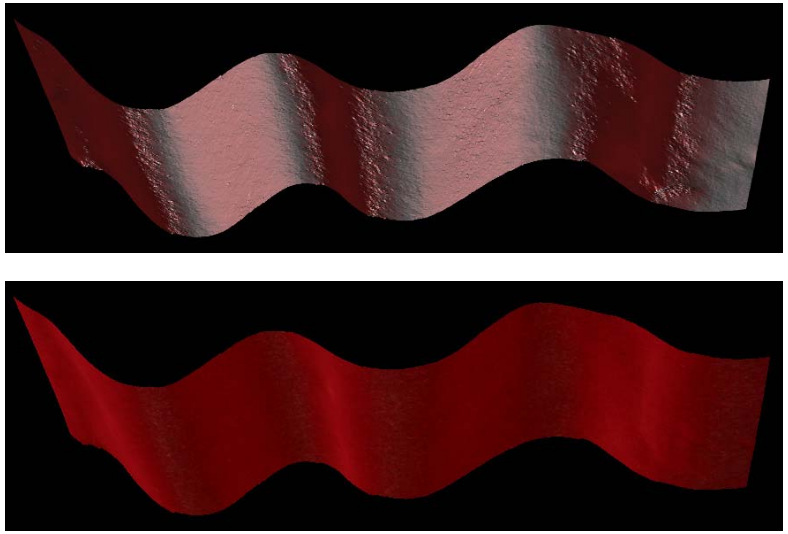
Virtual views



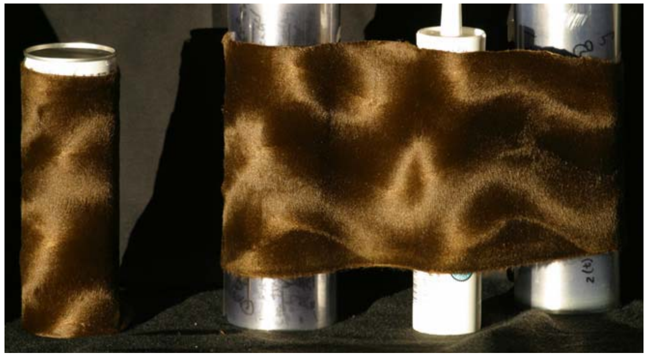
Velvet



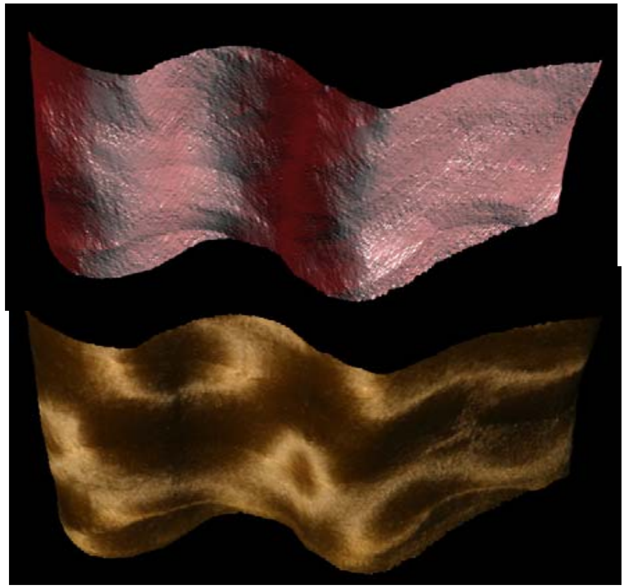
Virtual Views

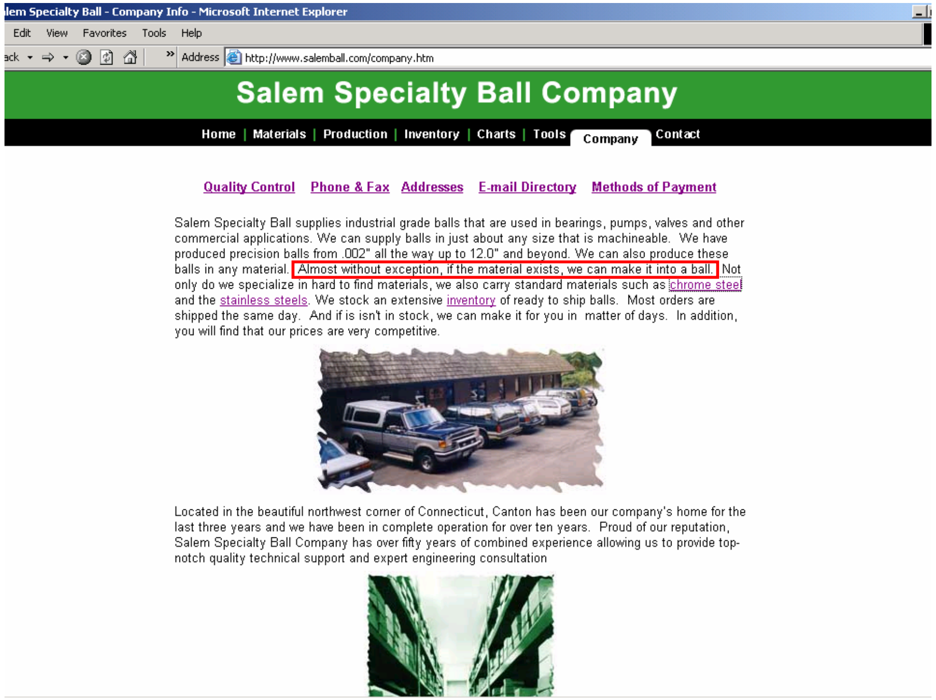


Brushed Fur



Virtual Views

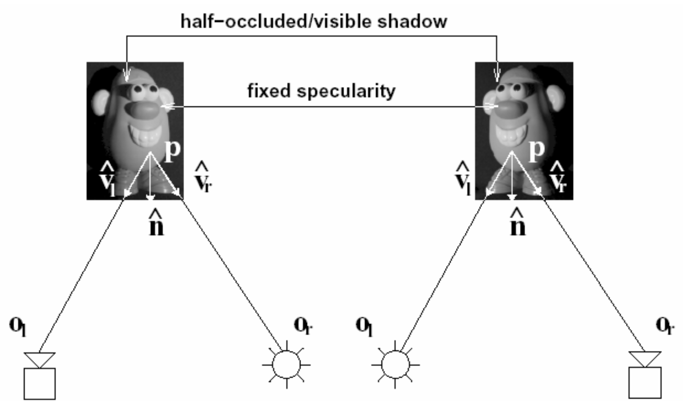




Helmholtz Stereo

- Based on Helmholtz reciprocity: surface reflectance is the same under interchange of light, viewer
- So, take pairs of observations w. viewer, light interchanged
- Ratio of the observations in a pair is independent of surface material

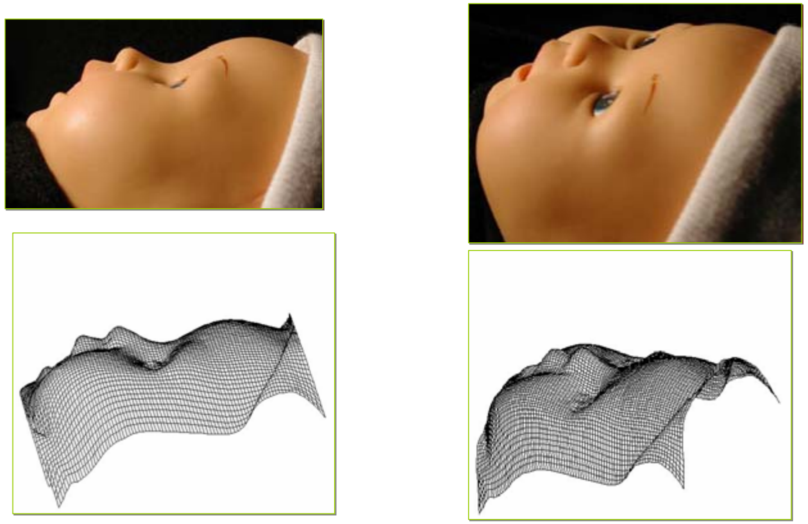
Helmholtz Stereo



$$\left(i_l \frac{\hat{v}_l}{|o_l - p|^2} - i_r \frac{\hat{v}_r}{|o_r - p|^2}\right) \cdot \hat{n} = w(d) \cdot \hat{n} = 0 \quad W(d^\star) \text{ will be rank } 2$$

Helmholtz Stereo

Helmholtz Stereo



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