Image-based modeling

Digital Visual Effects, Spring 2009

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with slides by Richard Szeliski, Steve Seitz and Alexei Efros

Announcements

- Project #2 artifact voting by next Wednesday

Outline

- Models from multiple (sparse) images
  - Structure from motion
  - Facade
- Models from single images
  - Tour into pictures
  - Single view metrology
  - Other approaches

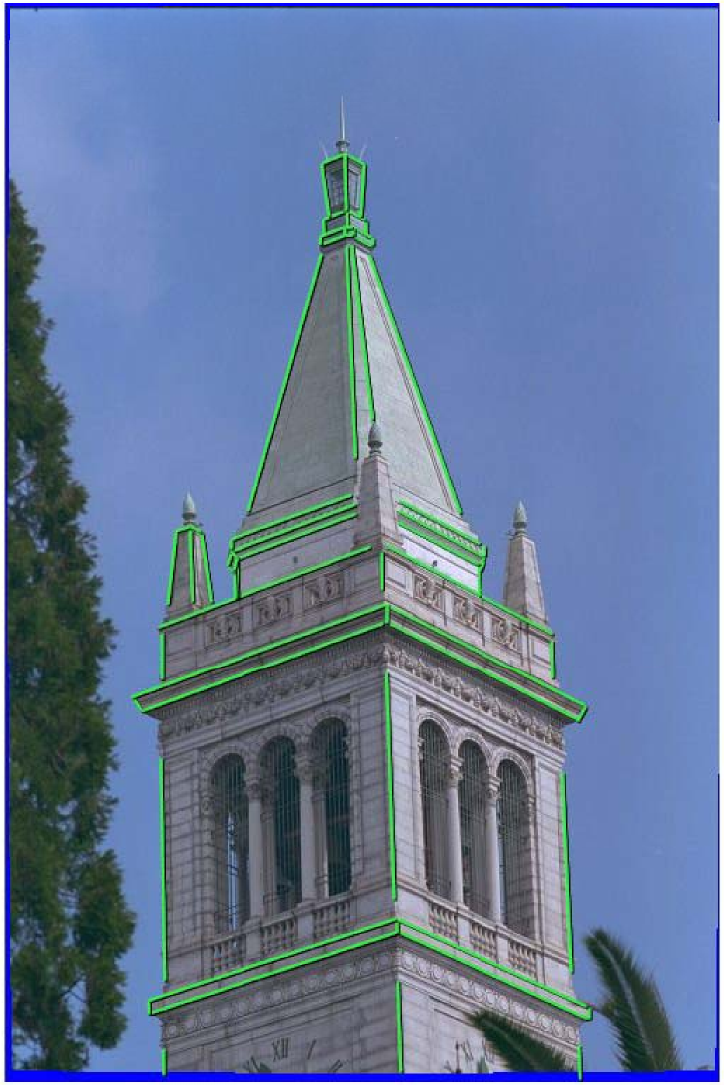
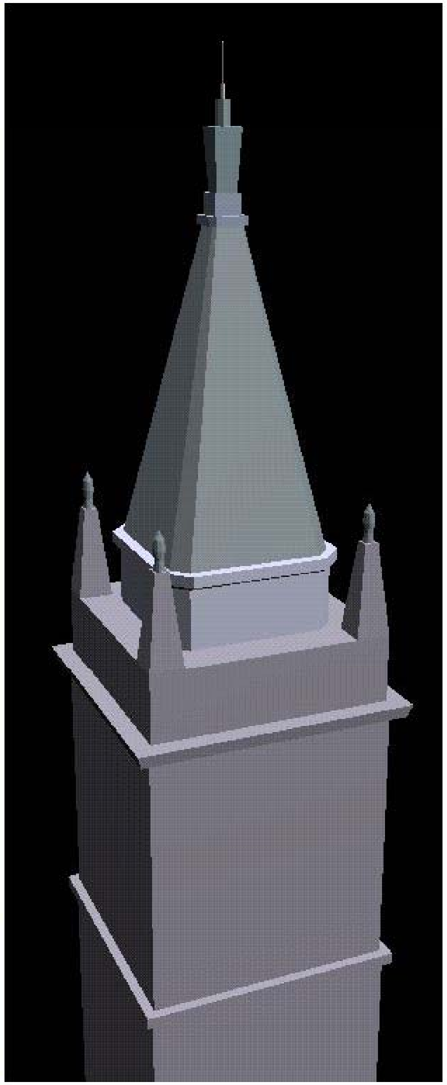
Models from multiple images (Façade, Debevec *et. al.* 1996)

Facade

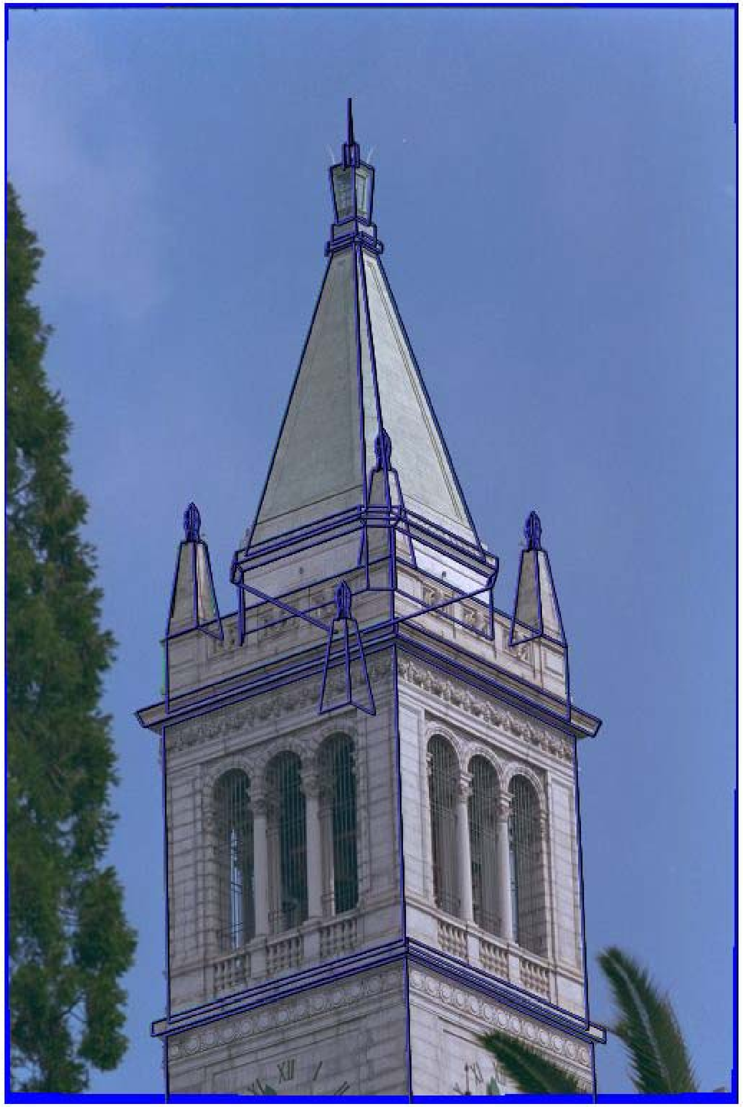
- Use a sparse set of images
- Calibrated camera (intrinsic only)
- Designed specifically for modeling architecture
- Use a set of blocks to approximate architecture

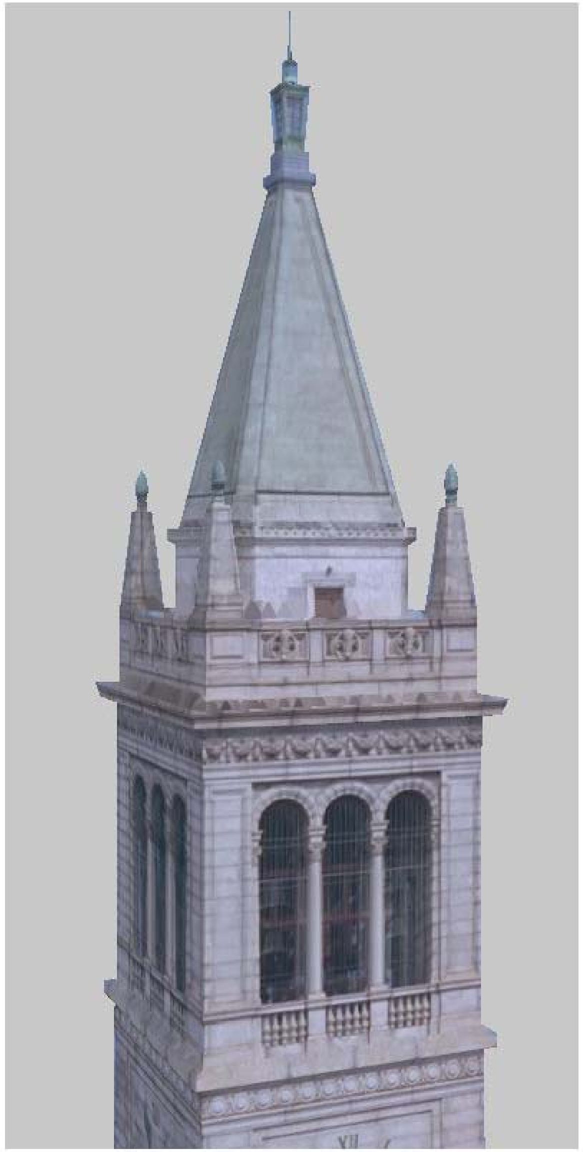
- Three components:
  - geometry reconstruction
  - texture mapping
  - model refinement

Idea

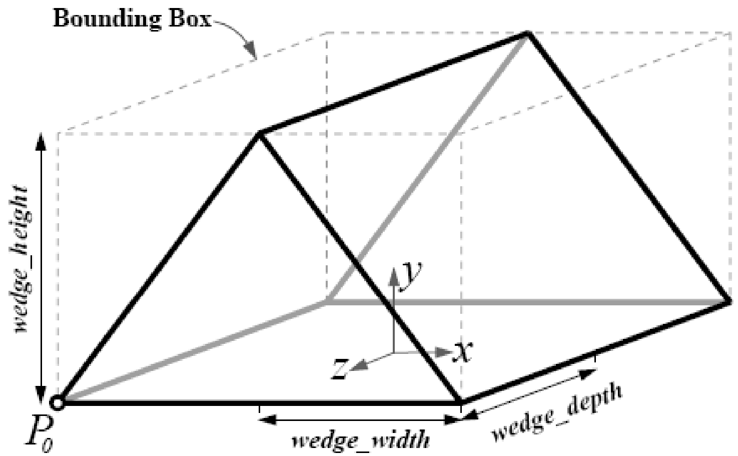
 

Idea



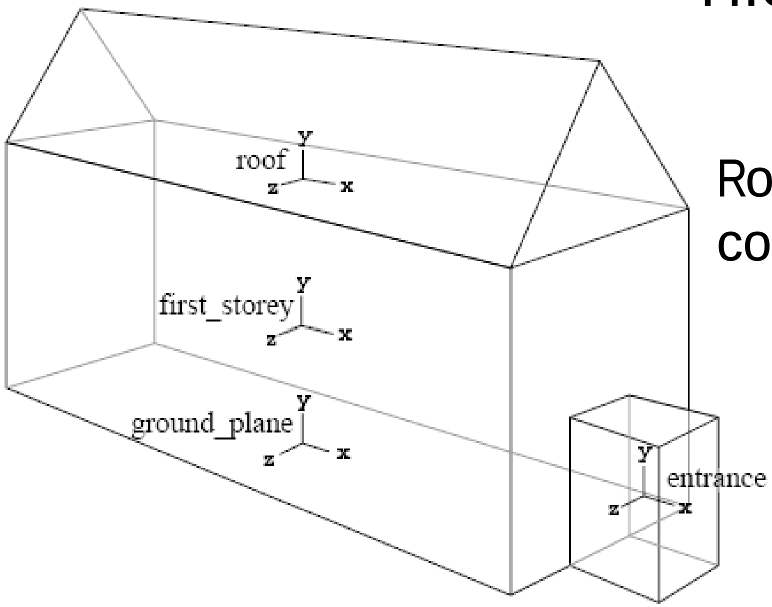


Geometric modeling

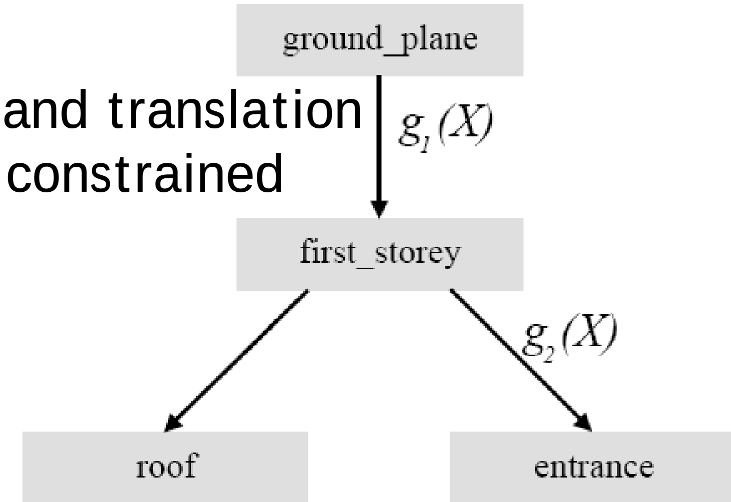


A block is a geometric primitive with a **small** set of parameters

Hierarchical modeling for a scene



Rotation and translation could be constrained



Reasons for block modeling

- Architectural scenes are well modeled by geometric primitives.
- Blocks provide a high level abstraction, easier to manage and add constraints.
- No need to infer surfaces from discrete features; blocks essentially provide prior models for architectures.
- Hierarchical block modeling effectively reduces the number of parameters for robustness and efficiency.

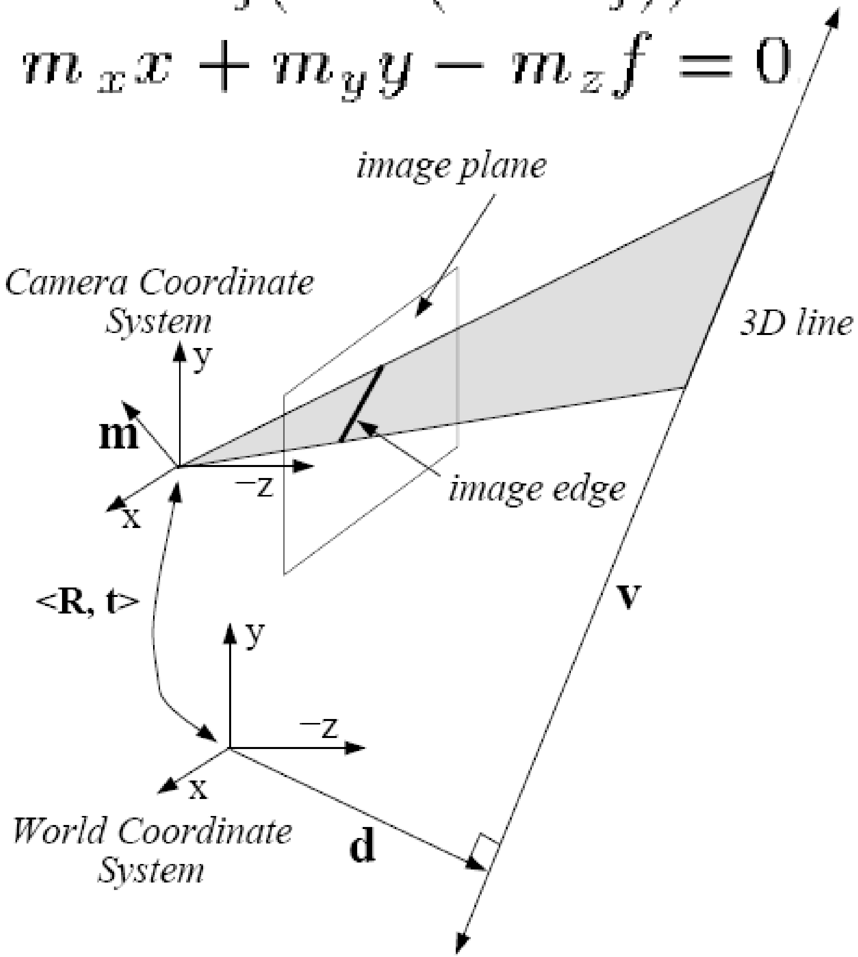
Reconstruction

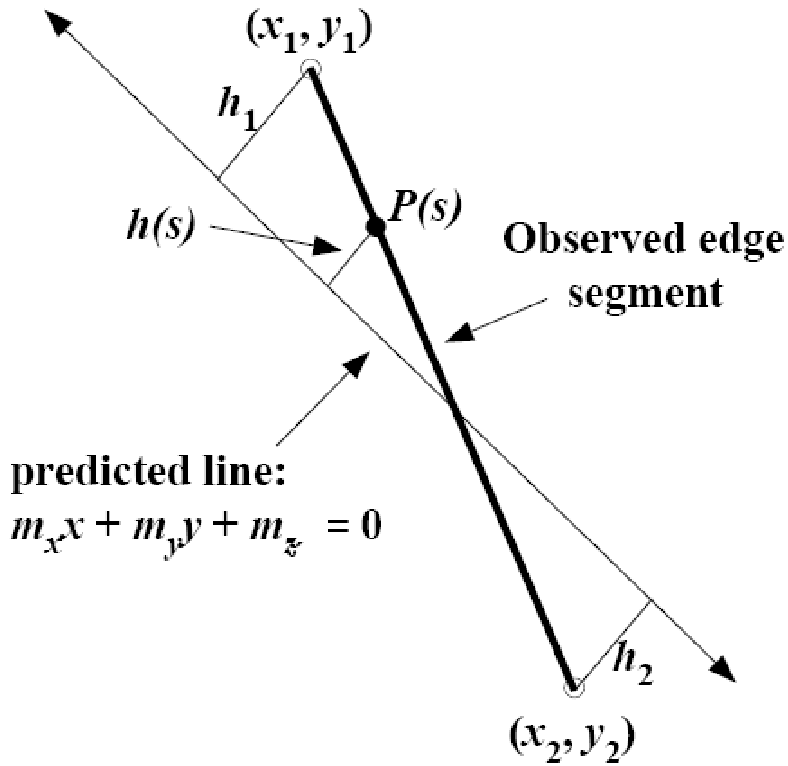
minimize $\mathcal{O} = \sum Err_i$

$$\mathbf{m} = R_j(\mathbf{v} \times (\mathbf{d} - t_j))$$

$$m_x x + m_y y - m_z f = 0$$

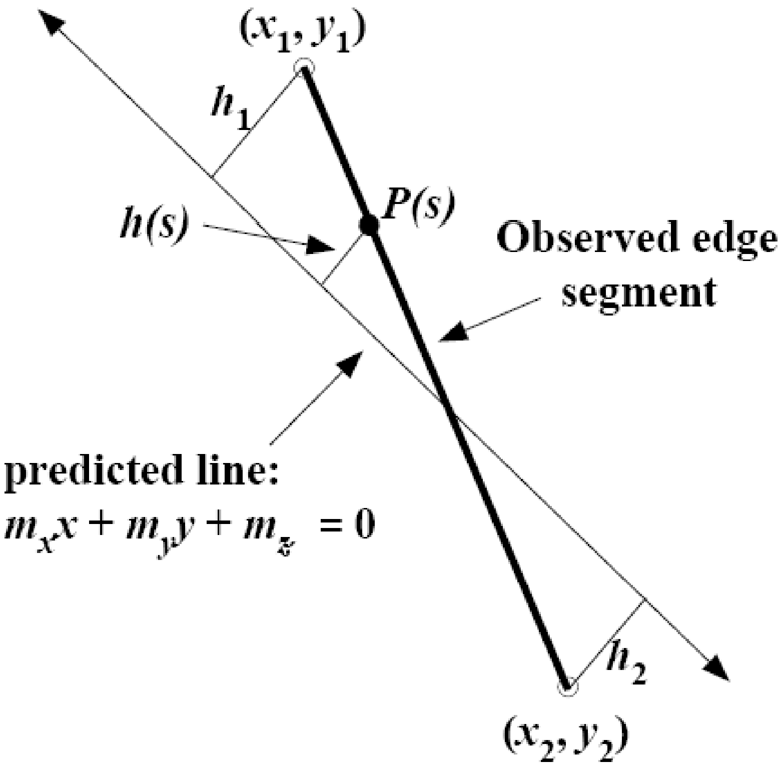
$$Err_i = \int_0^l h^2(s)ds$$





Reconstruction

$$Err_i = \int_0^l h^2(s)ds$$



$$h_1 = \frac{m_x x_1 + m_y y_1 + m_z}{\sqrt{m_x^2 + m_y^2}}$$

$$h_2 = \frac{m_x x_2 + m_y y_2 + m_z}{\sqrt{m_x^2 + m_y^2}}$$

$$h(s) = h_1 + s\frac{h_2 - h_1}{l}$$

$$Err_i = \int_0^l h^2(s)ds = \frac{l}{3}(h_1^2 + h_1 h_2 + h_2^2)$$

Reconstruction

$$Err_i = \int_0^l h^2(s)ds = \frac{l}{3}(h_1^2 + h_1 h_2 + h_2^2) = \mathbf{m}^T (A^T B A) \mathbf{m}$$

$$h_1 = \frac{m_x x_1 + m_y y_1 + m_z}{\sqrt{m_x^2 + m_y^2}}$$

$$h_2 = \frac{m_x x_2 + m_y y_2 + m_z}{\sqrt{m_x^2 + m_y^2}}$$

$$\mathbf{m} = (m_x, m_y, m_z)^T \qquad \mathbf{m} = R_j(\mathbf{v} \times (\mathbf{d} - t_j))$$

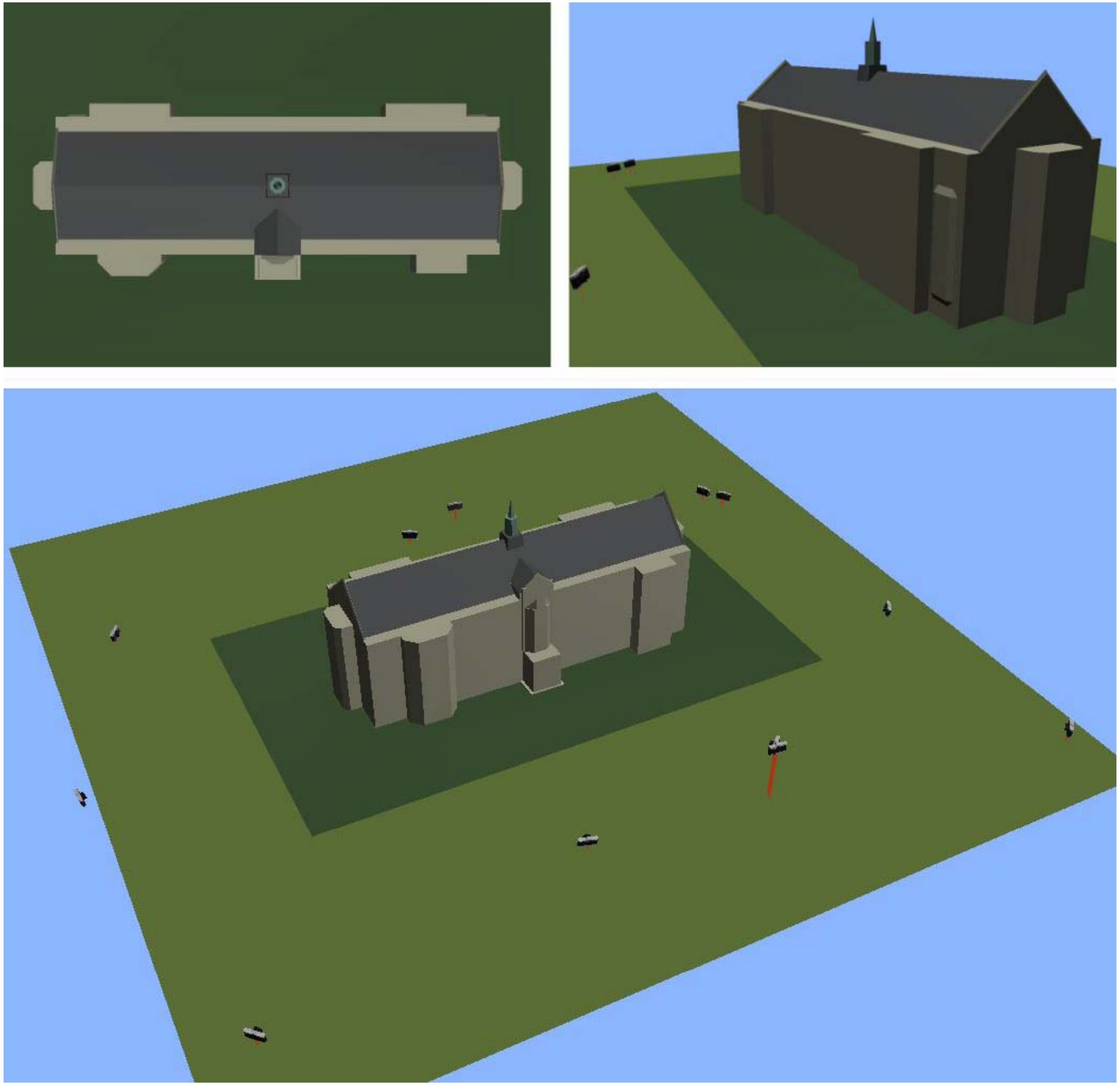
$$A = \begin{pmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \end{pmatrix}$$

$$B = \frac{l}{3(m_x^2 + m_y^2)} \begin{pmatrix} 1 & 0.5 \\ 0.5 & 1 \end{pmatrix}$$

nonlinear w.r.t.
camera and model

Results

3 of 12 photographs



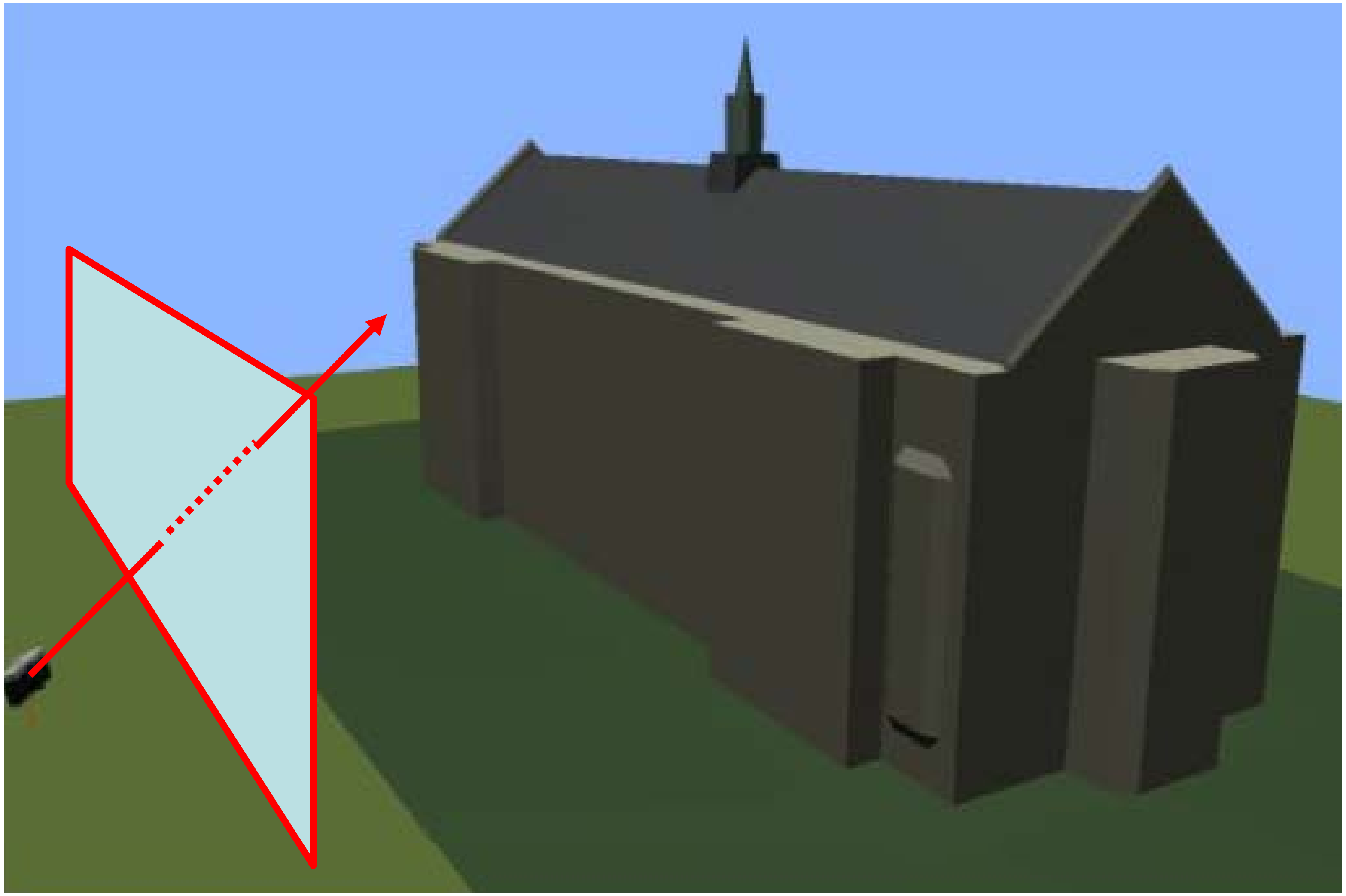
Texture mapping

Texture mapping in real world

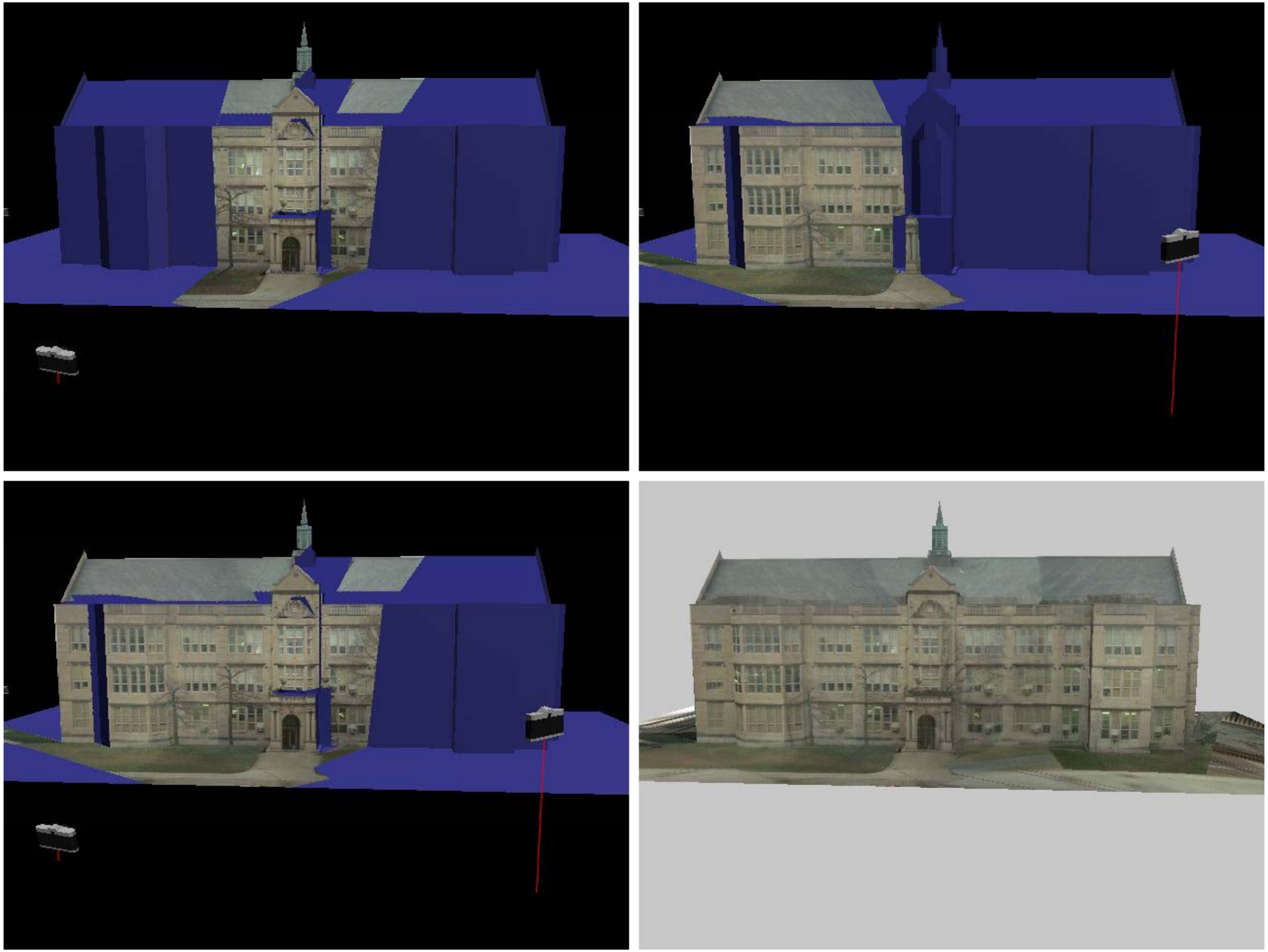
Demo movie

Michael Naimark,
San Francisco Museum
of Modern Art, 1984

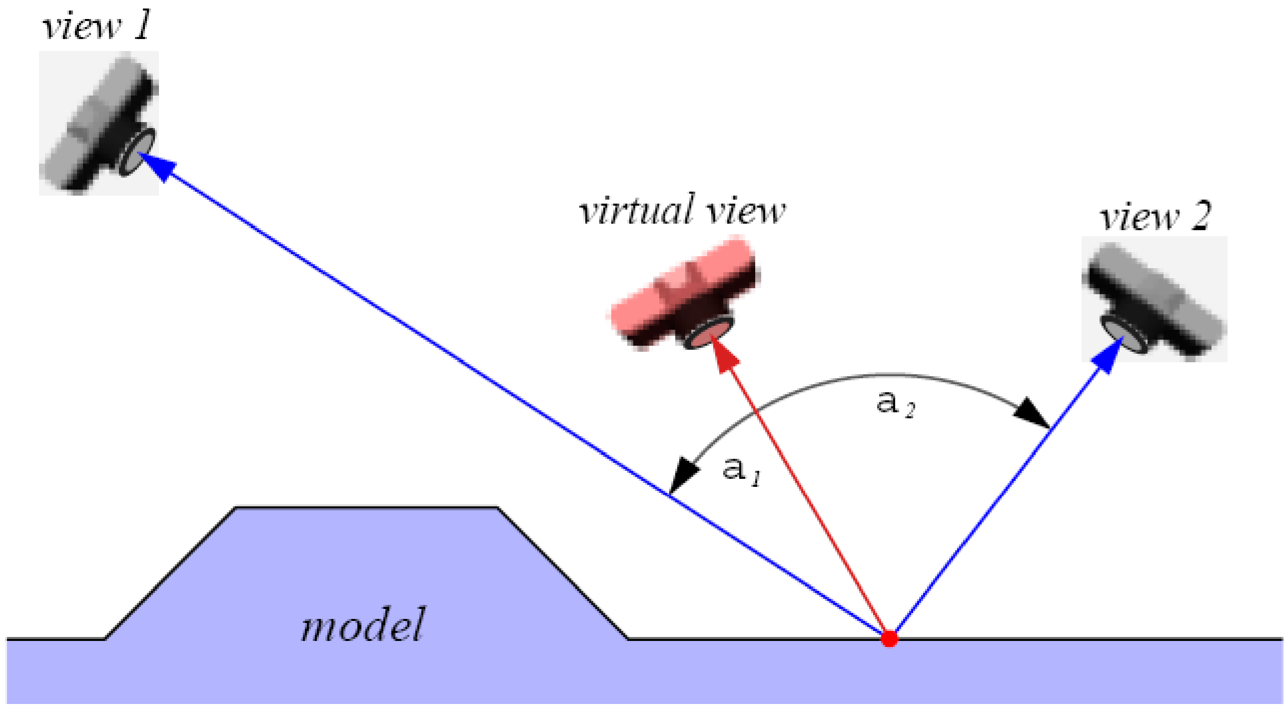
Texture mapping



Texture mapping



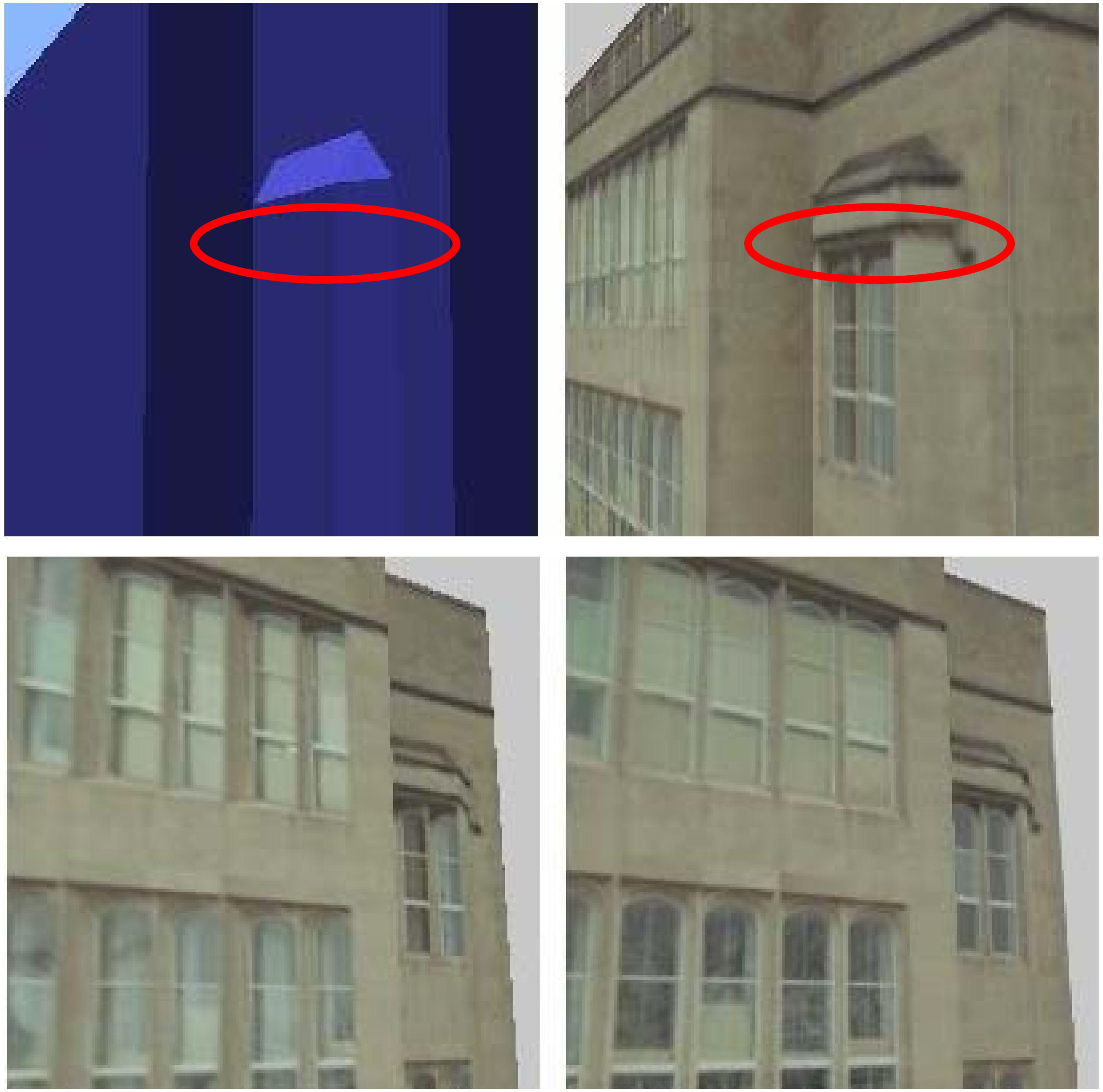
View-dependent texture mapping



View-dependent texture mapping

DigiVFX

model



VDTM

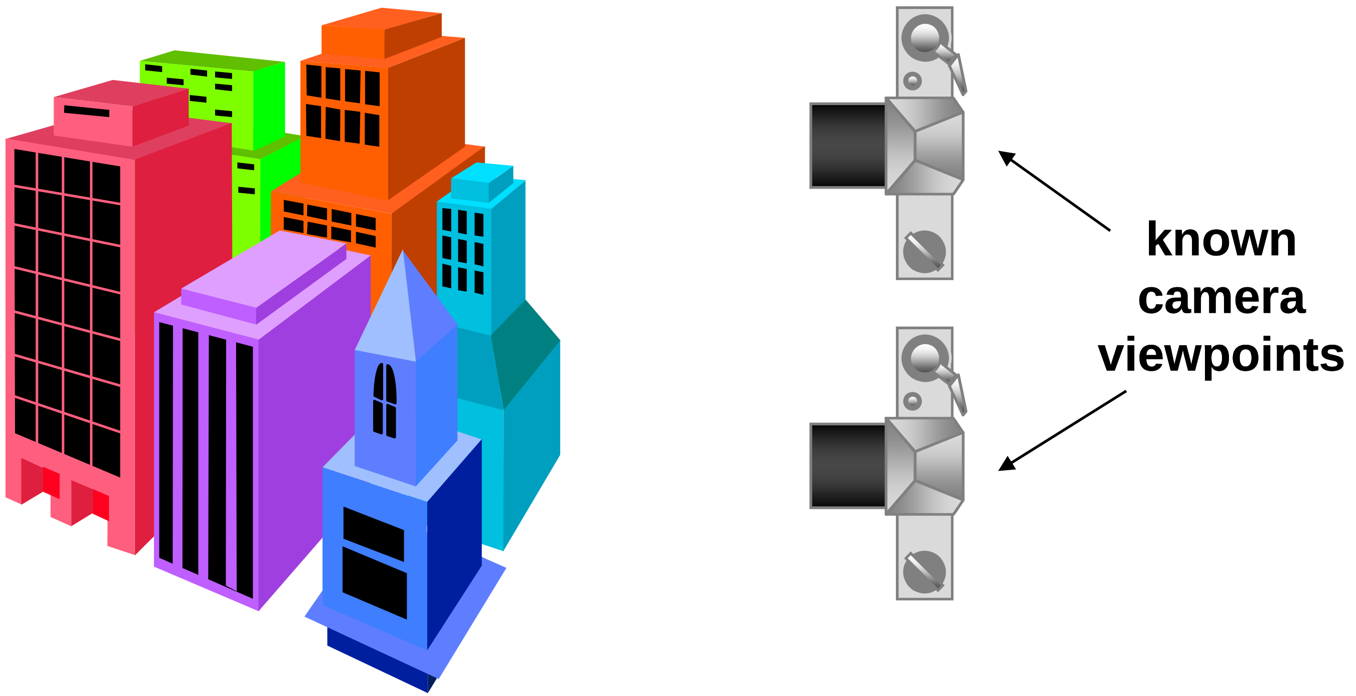
single texture map

VDTM

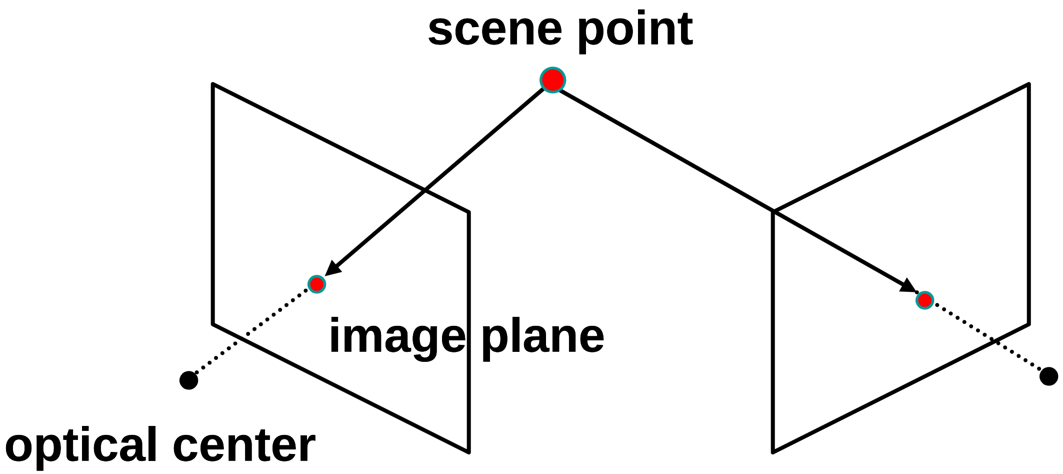
View-dependent texture mapping

Model-based stereo

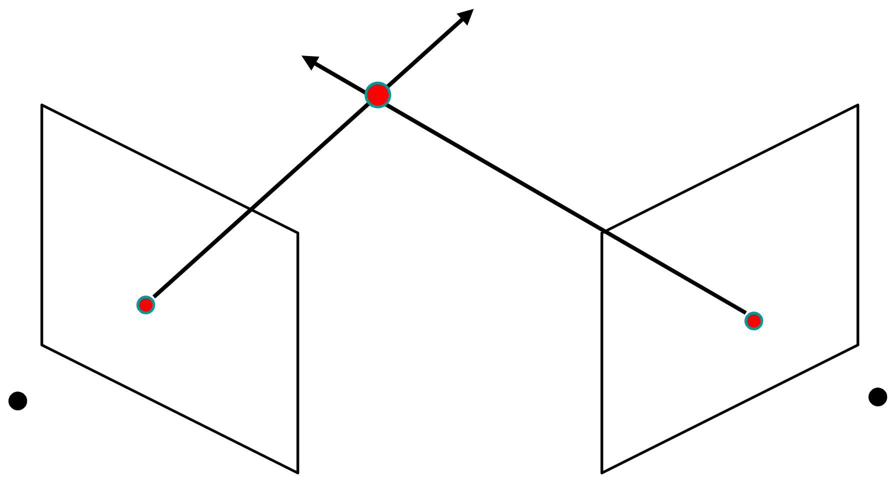
- Use stereo to refine the geometry



Stereo



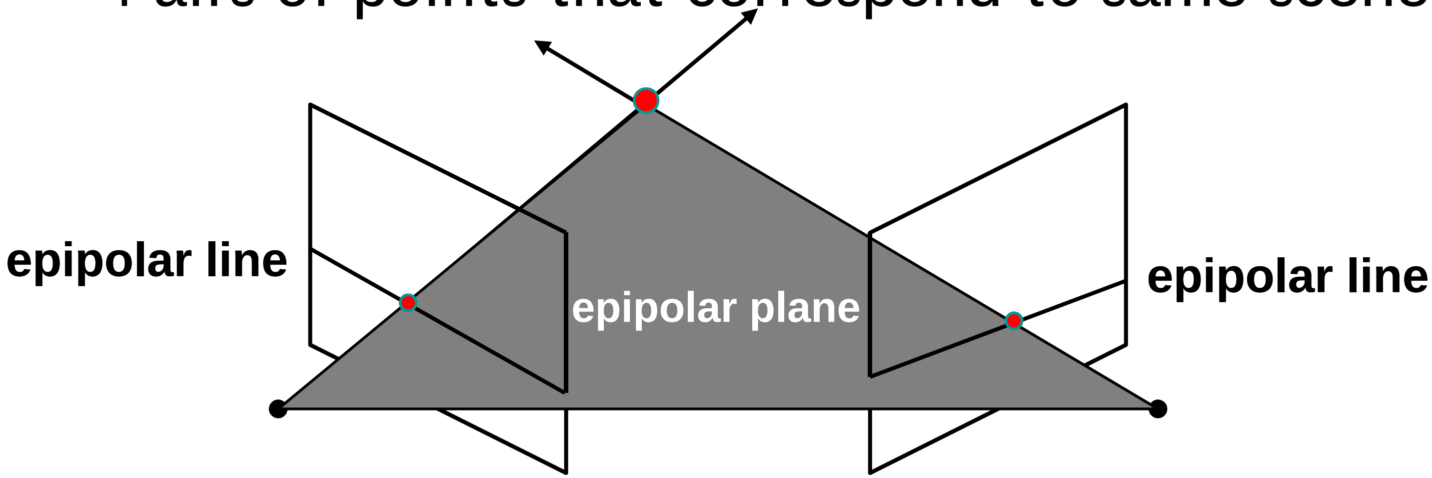
Stereo



- Basic Principle: Triangulation
  - Gives reconstruction as intersection of two rays
  - Requires
    - calibration
    - *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*

Finding correspondences

- apply feature matching criterion (e.g., correlation or Lucas-Kanade) at *all* pixels simultaneously
- search only over epipolar lines (much fewer candidate positions)

Image registration (revisited)

- How do we determine correspondences?
  - *block matching* or *SSD* (sum squared differences)

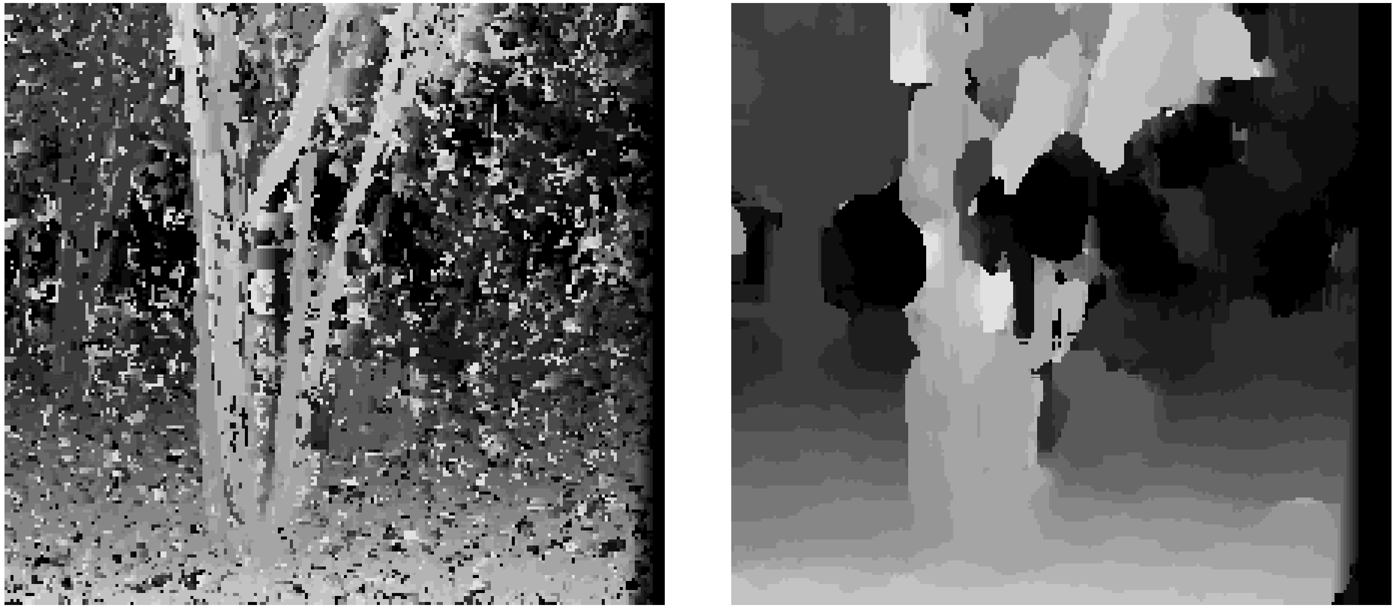
$$E(x,y;d) = \sum_{(x',y') \in N(x,y)} [I_L(x'+d,y') - I_R(x',y')]^2$$

d is the *disparity* (horizontal motion)

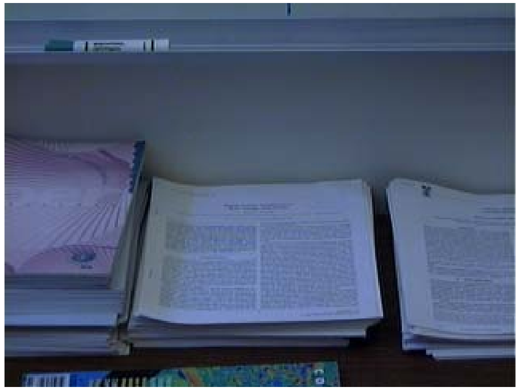
- How big should the neighborhood be?

Neighborhood size

- Smaller neighborhood: more details
- Larger neighborhood: fewer isolated mistakes

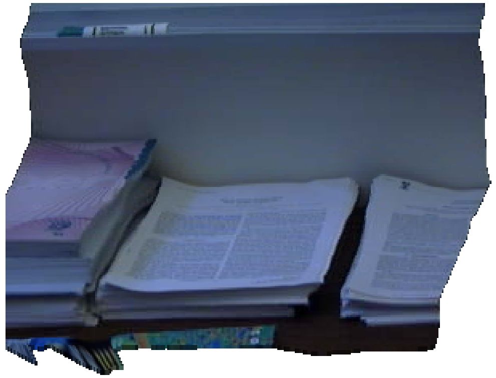


Depth from disparity

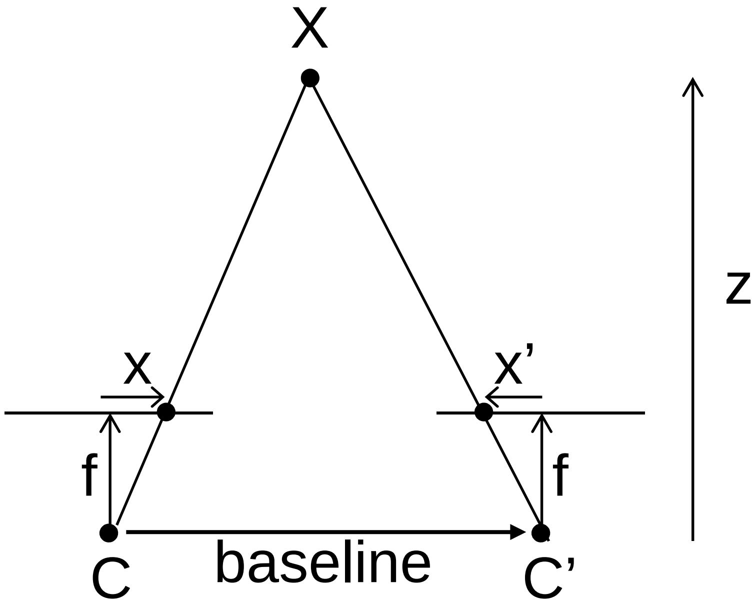


input image (1 of 2)

depth map
[Szeliski & Kang '95]



3D rendering



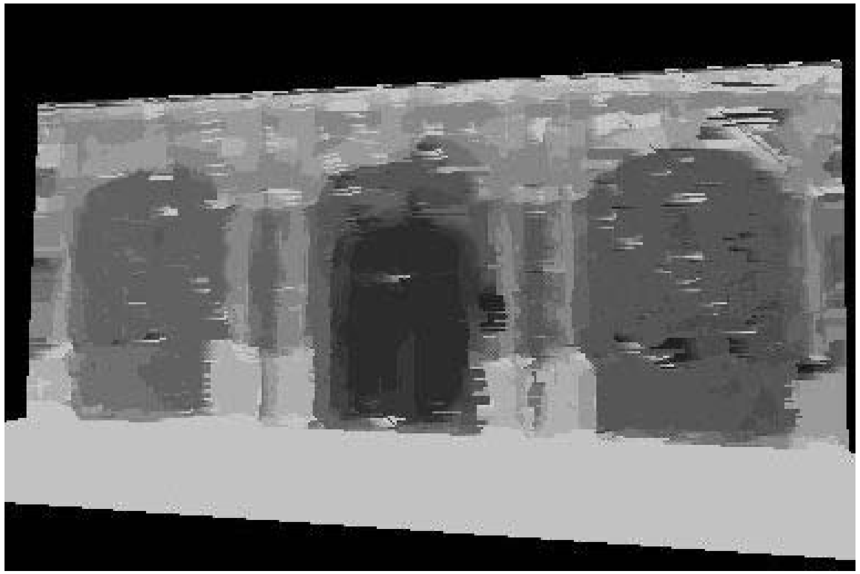
$$disparity = x - x' = \frac{baseline * f}{z}$$

Stereo reconstruction pipeline

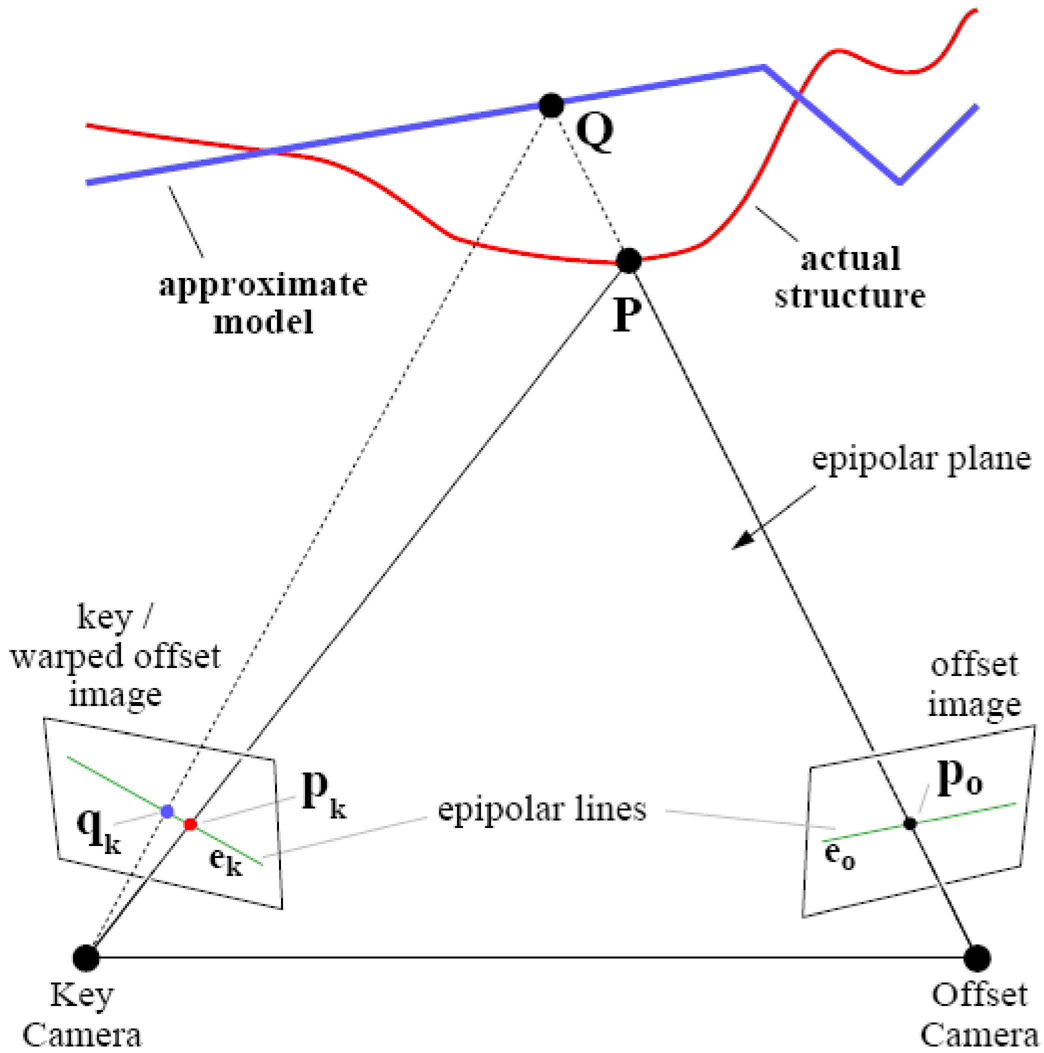
DigiVFX

- Steps
  - Calibrate cameras
  - Rectify images
  - Compute disparity
  - Estimate depth
- What will cause errors?
  - Camera calibration errors
  - Poor image resolution
  - Occlusions
  - Violations of brightness constancy (specular reflections)
  - Large motions
  - Low-contrast image regions

Model-based stereo



Epipolar geometry

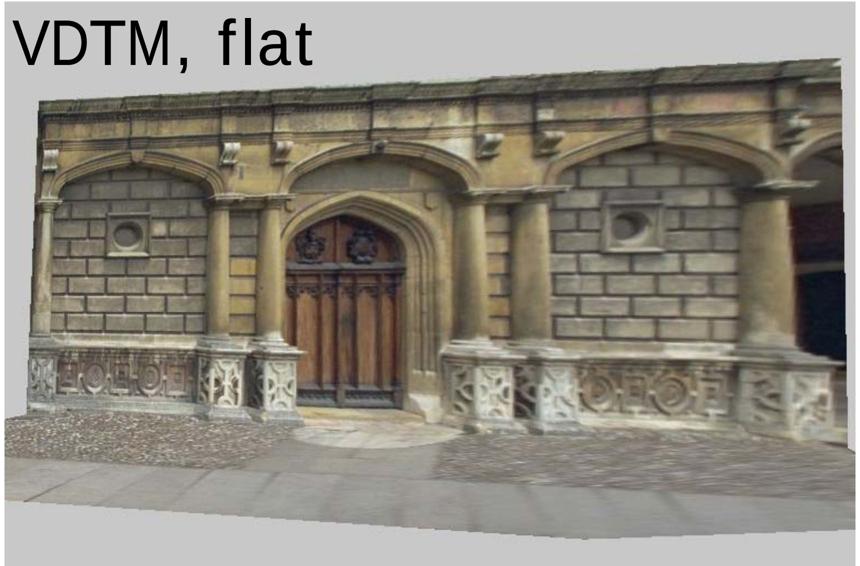


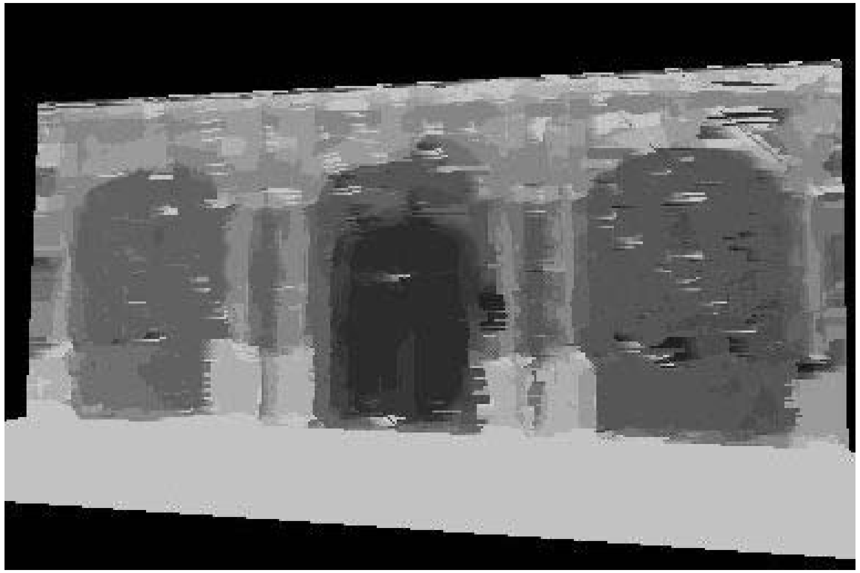
Results

Comparisons

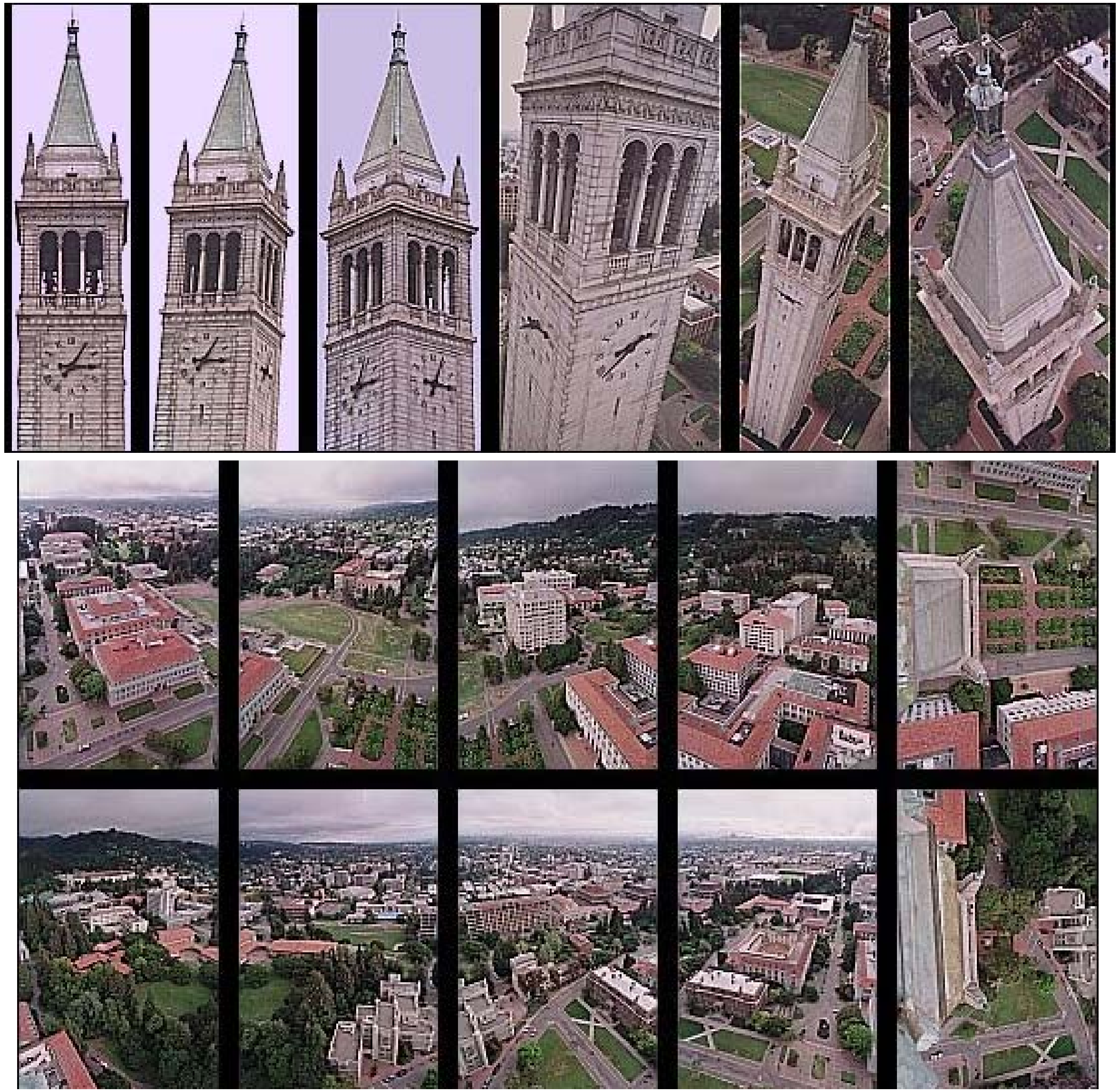
DigiVFX


single texture, flat


VDTM, flat

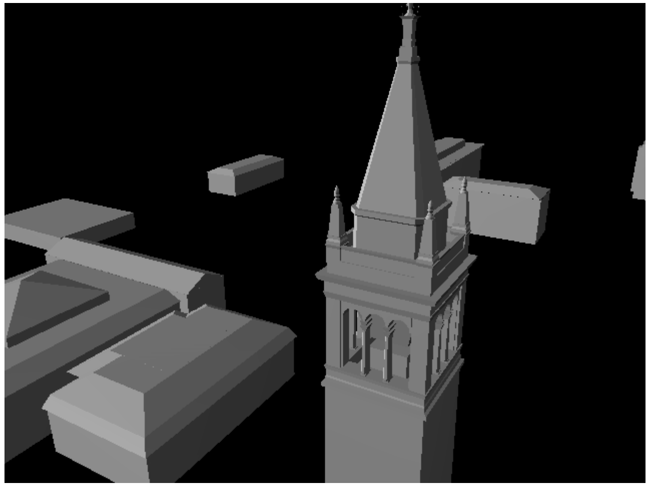

VDTM, model-based stereo

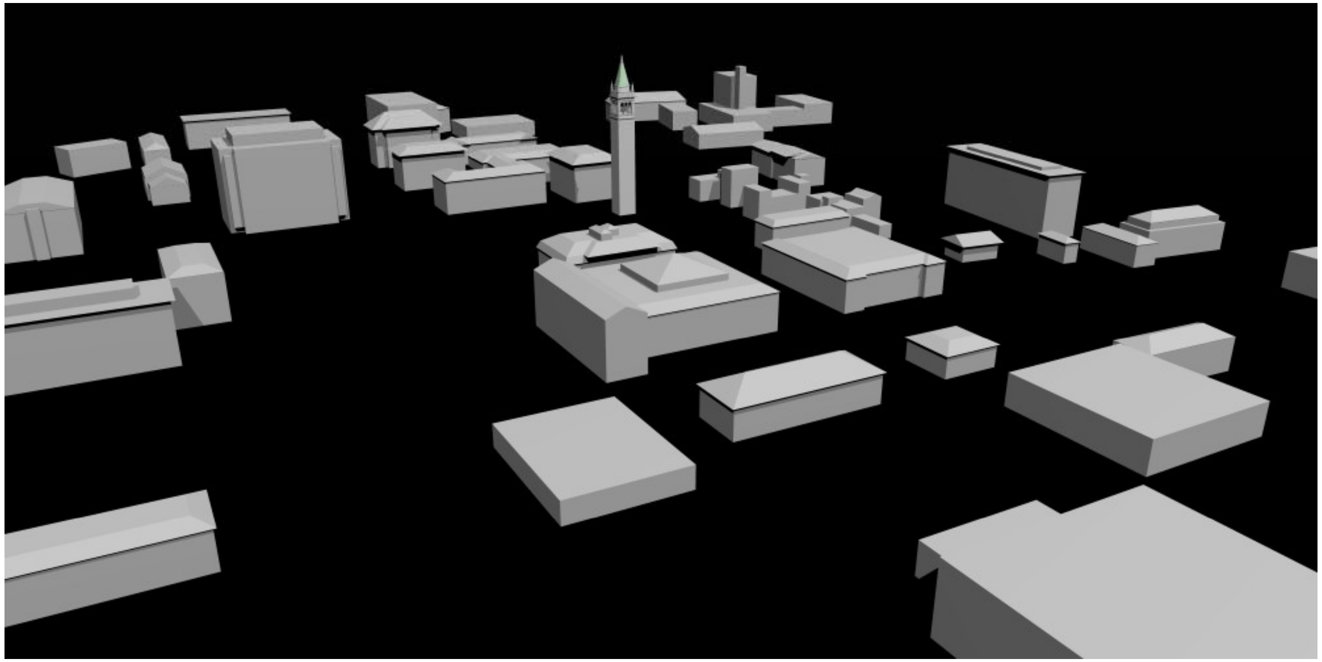
Final results

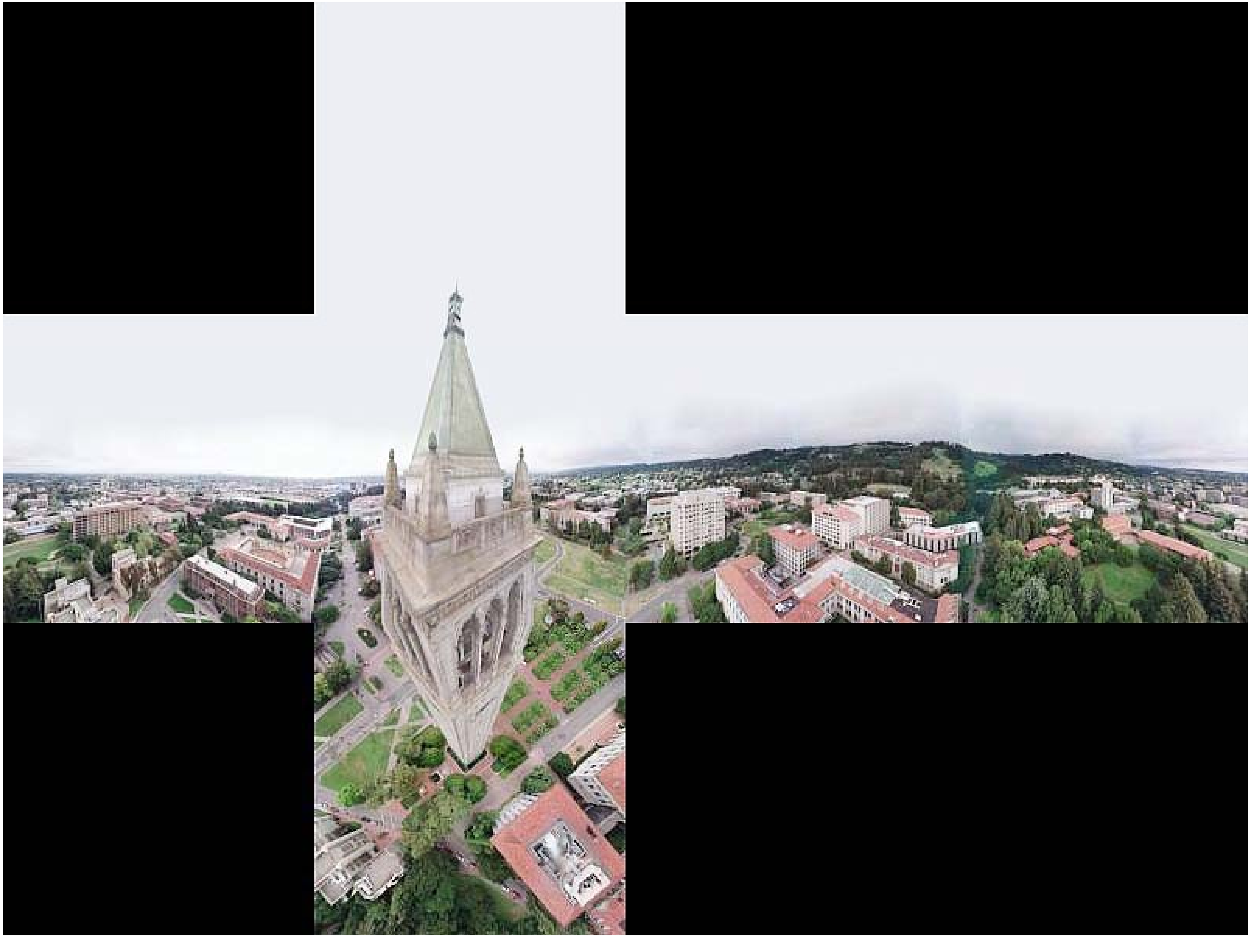


Kite photography

Final results

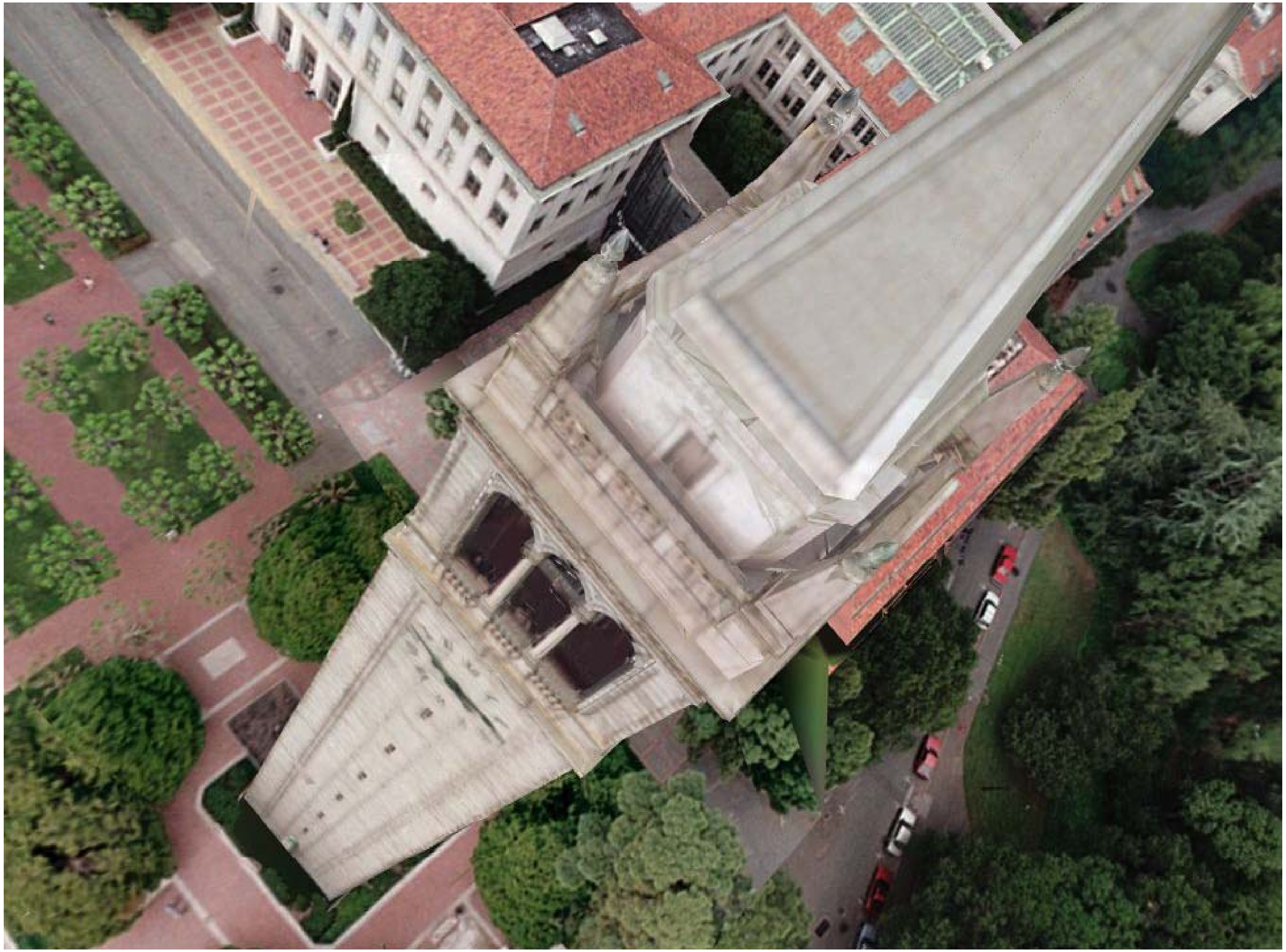






Results

Results



Commercial packages

- REALVIZ ImageModeler

The Matrix

Cinefex #79, October 1999.

Since the bullet-time rig would be visible in shots featuring a 360-degree sweep of the characters, it was employed only for the shooting of the foreground subject – namely, the actors or their stunt doubles – necessitating a different approach for the backgrounds. Shot separately, the backgrounds used a virtual cinematography process that allowed a 360-degree environment to be constructed in the computer from stills taken on set. This approach for generating the backgrounds was based on the Berkeley Tower flyover, a novel image-based rendering technique presented at Siggraph '97 by George Borshukov and Paul Debevec, a researcher at UC Berkeley. The technique employed twenty stills of that town's college campus to create a virtual environment through which the camera could travel. "Instead of reinventing the background in traditional CG fashion – painting textures, shooting orthographic views of the set, and then proceeding to texture replication – we generated a completely free, high-resolution camera move that would have been impossible to achieve using traditional CG," Borshukov said, "and we did it working from just a handful of stills."

The Matrix

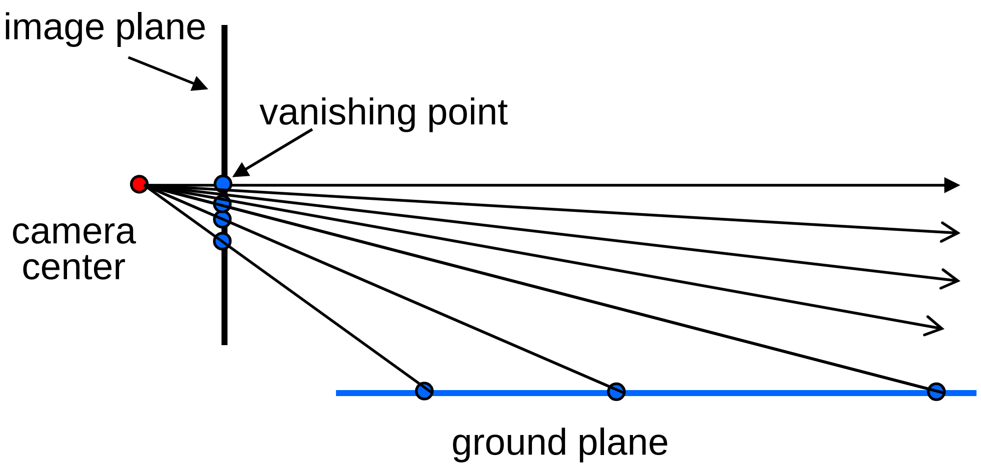
- *Academy Awards for Scientific and Technical achievement for 2000*

  To George Borshukov, Kim Libreri and Dan Piponi for the development of a system for image-based rendering allowing choreographed camera movements through computer graphic reconstructed sets.

This was used in The Matrix and Mission Impossible II; See The Matrix Disc #2 for more details

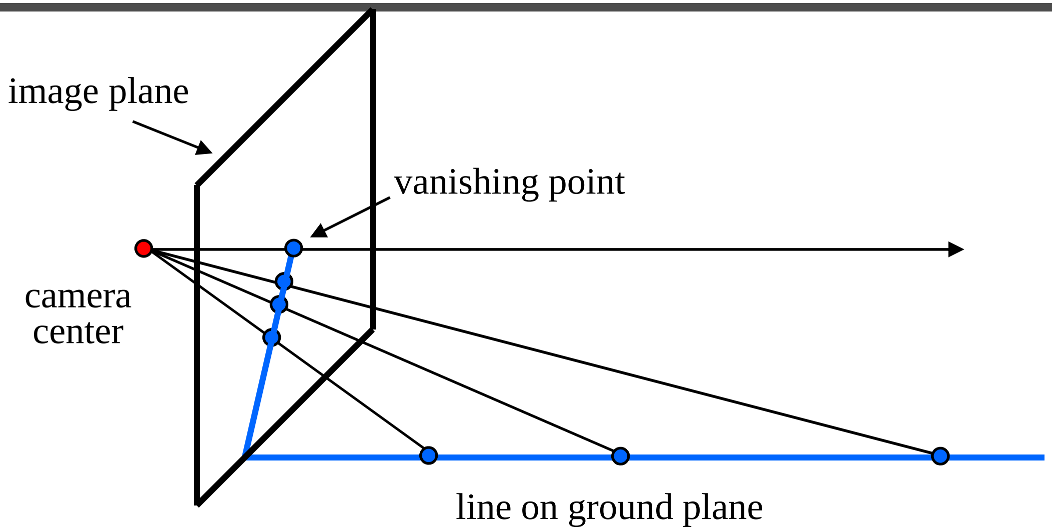
Models from single images

Vanishing points

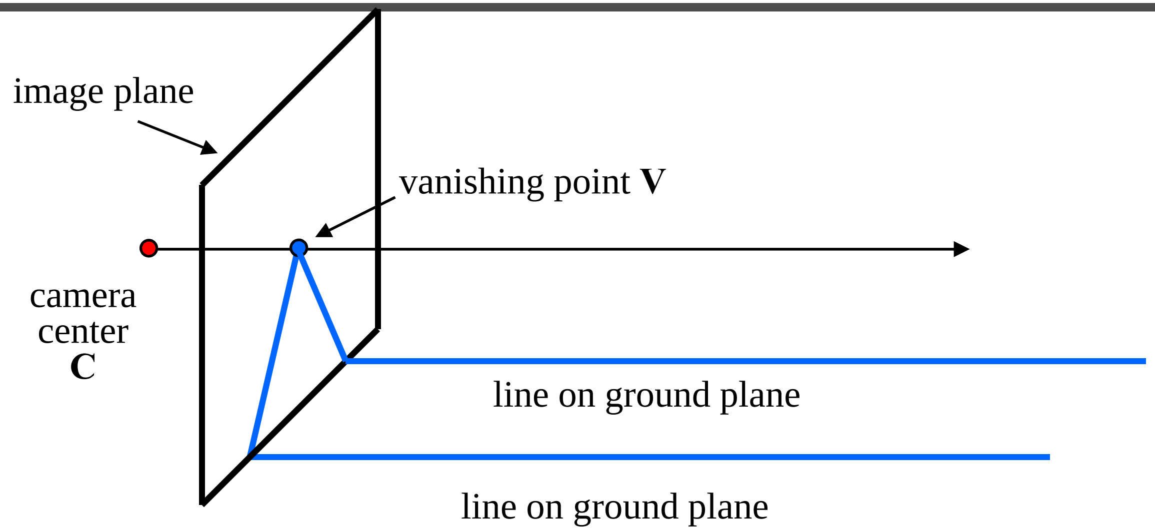


- Vanishing point
  - projection of a point at infinity

Vanishing points (2D)

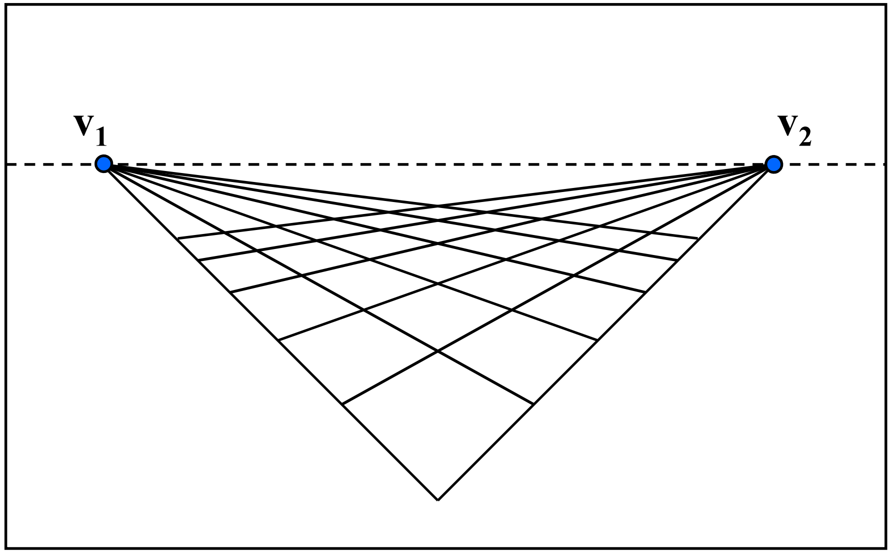


Vanishing points



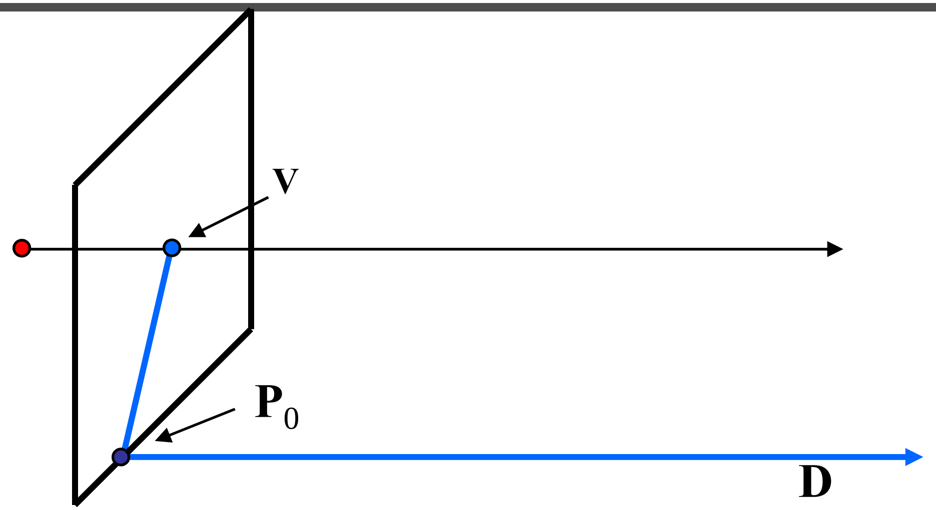
- Properties
  - Any two parallel lines have the same vanishing point **v**
  - The ray from **C** through **v** is parallel to the lines
  - An image may have more than one vanishing point

Vanishing lines



- Multiple Vanishing Points
  - Any set of parallel lines on the plane define a vanishing point
  - The union of all of these vanishing points is the *horizon line*
    - also called *vanishing line*
  - Note that different planes define different vanishing lines

Computing vanishing points



$$\mathbf{P} = \mathbf{P}_0 + t\mathbf{D}$$

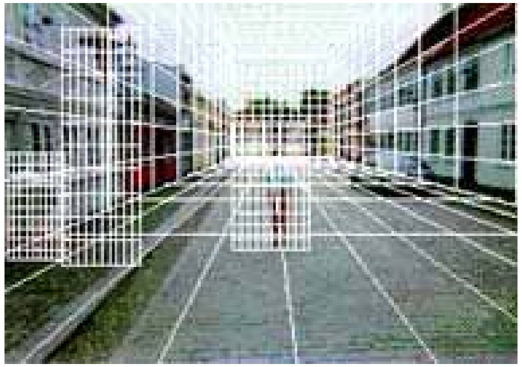
$$\mathbf{P}_t = \begin{bmatrix} P_X + tD_X \\ P_Y + tD_Y \\ P_Z + tD_Z \\ 1 \end{bmatrix} \cong \begin{bmatrix} P_X / t + D_X \\ P_Y / t + D_Y \\ P_Z / t + D_Z \\ 1/t \end{bmatrix} \qquad t \to \infty \qquad \mathbf{P}_\infty \cong \begin{bmatrix} D_X \\ D_Y \\ D_Z \\ 0 \end{bmatrix}$$

- Properties $\mathbf{v} = \mathbf{\Pi} \mathbf{P}_\infty$
  - $\mathbf{P}_\infty$ is a point at *infinity*, **v** is its projection
  - They depend only on line *direction*
  - Parallel lines $\mathbf{P}_0$ + t**D**, $\mathbf{P}_1$ + t**D** intersect at $\mathbf{P}_\infty$

Tour into pictures

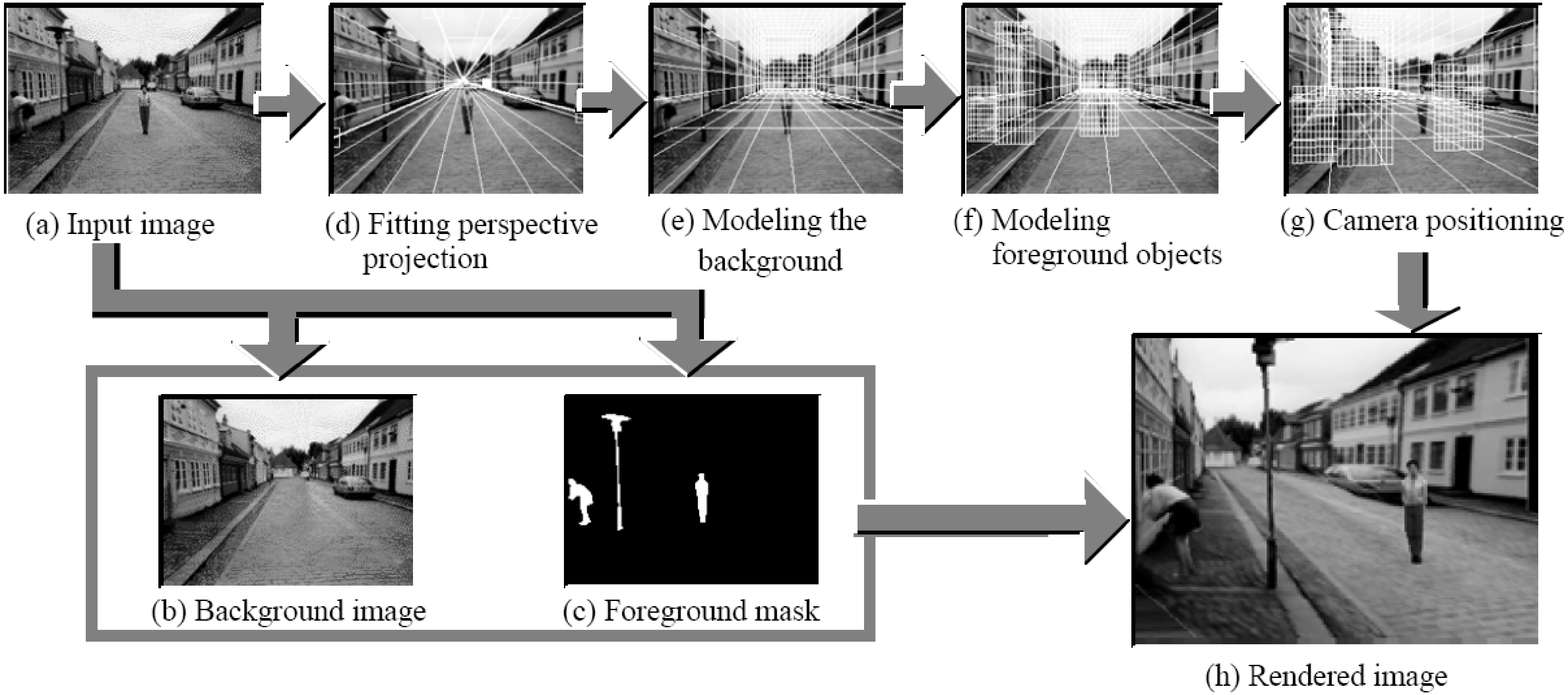
- Create a 3D “theatre stage” of five billboards

- Specify foreground objects through bounding polygons



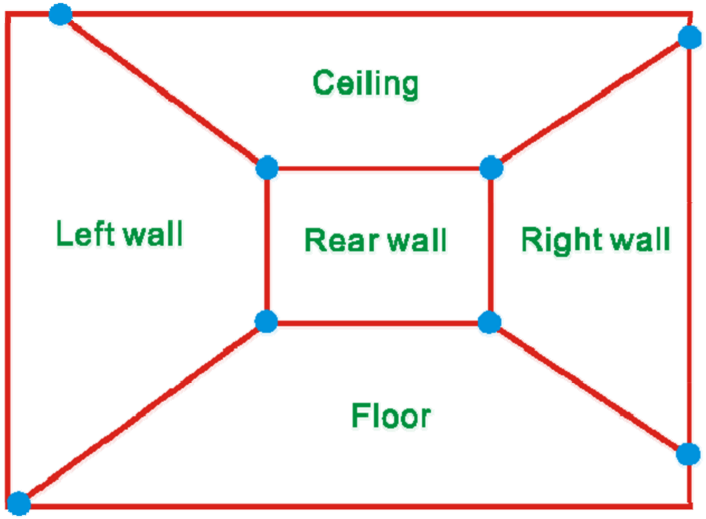
- Use camera transformations to navigate through the scene

Tour into pictures

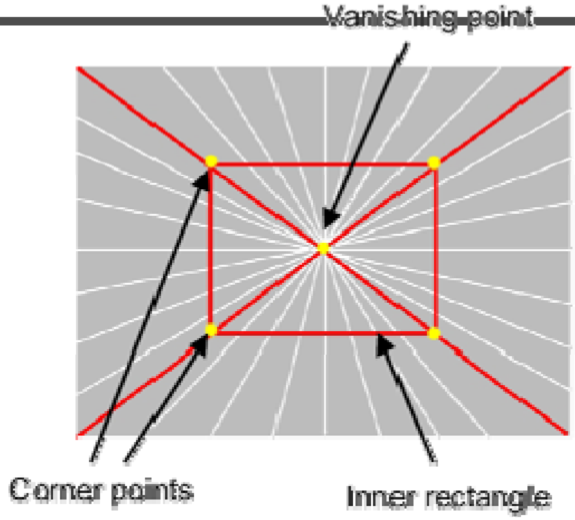


The idea

- Many scenes (especially paintings), can be represented as an axis-aligned box volume (i.e. a stage)
- Key assumptions:
  - All walls of volume are orthogonal
  - Camera view plane is parallel to back of volume
  - Camera up is normal to volume bottom
  - Volume bottom is y=0
- Can use the vanishing point to fit the box to the particular Scene!



Fitting the box volume

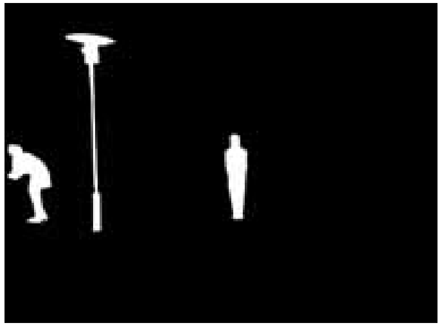


- User controls the inner box and the vanishing point placement (6 DOF)

Foreground Objects

- Use separate billboard for each

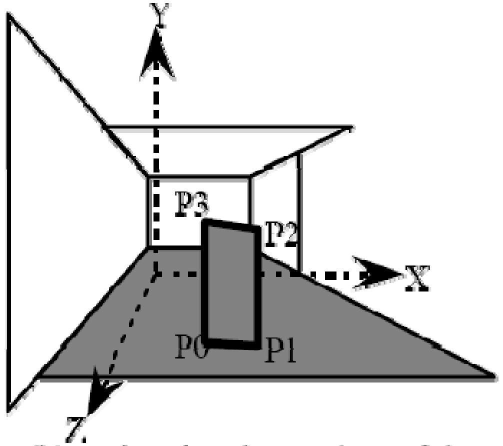
- For this to work, three separate images used:
  - Original image.
  - Mask to isolate desired foreground images.
  - Background with objects removed



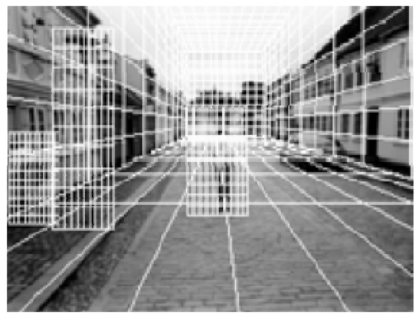
Foreground Objects

- Add vertical rectangles for each foreground object
- Can compute 3D coordinates P0, P1 since they are on known plane.
- P2, P3 can be computed as before (similar triangles)

(a) Specifying of a foreground object



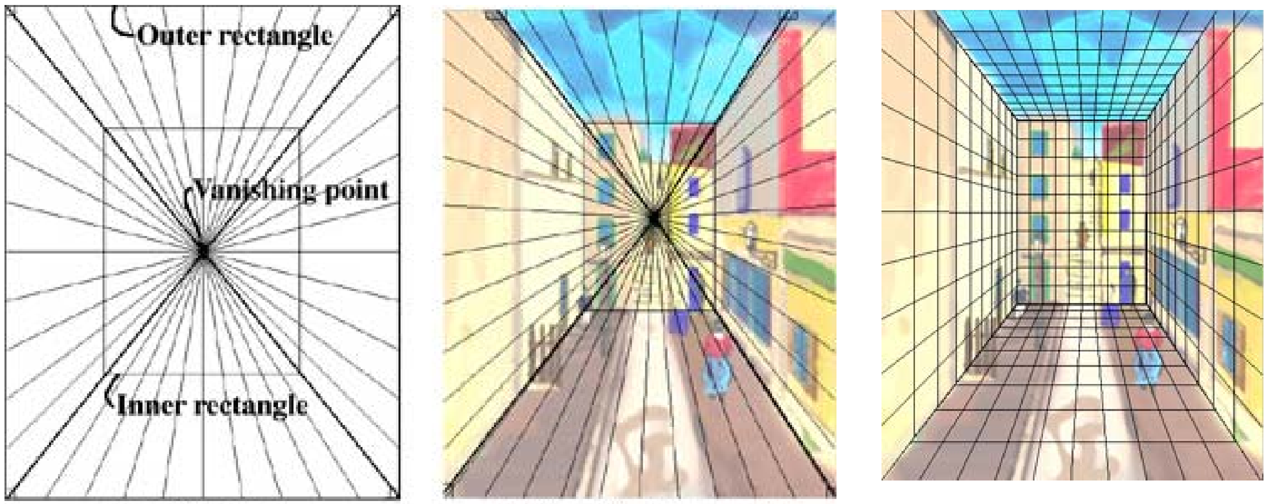
(b) Estimating the vertices of the foreground object model



(c) Three foreground object models

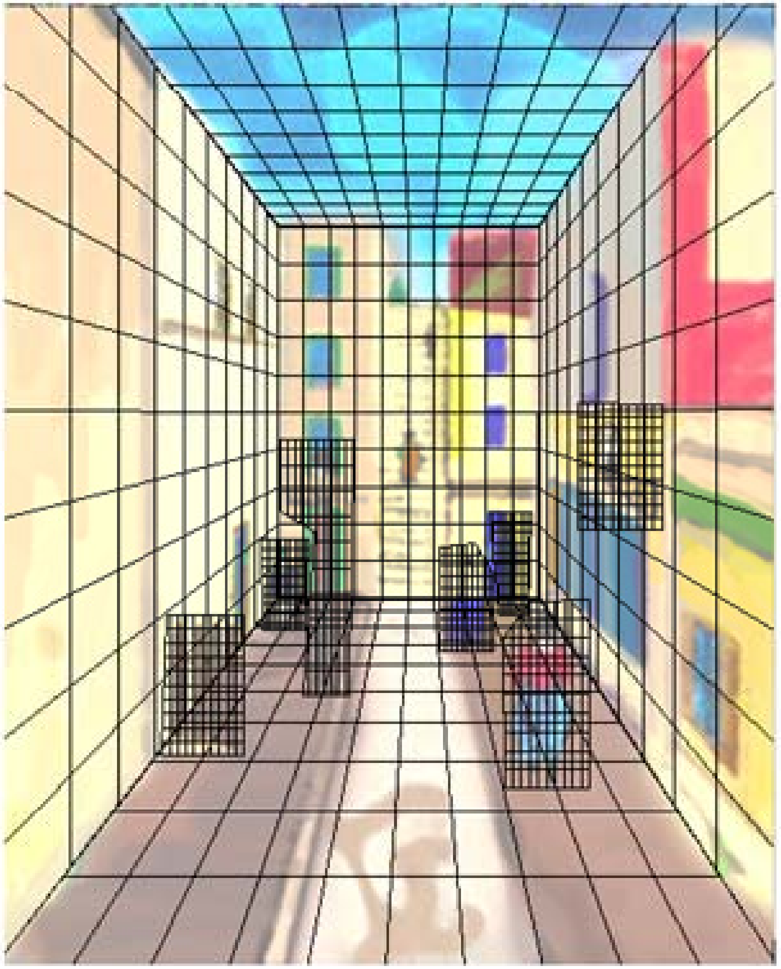
Example

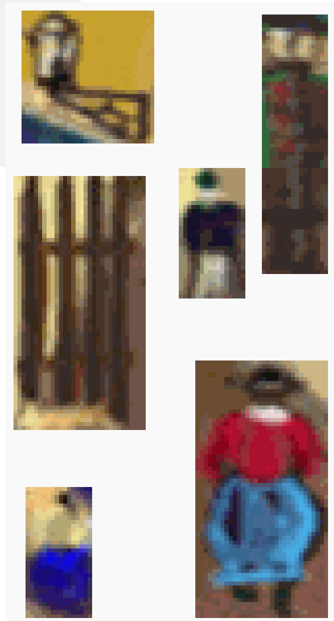
(a) Input image (b) Background (c) Foreground mask



(a) Initial state (b) Specification result

Example

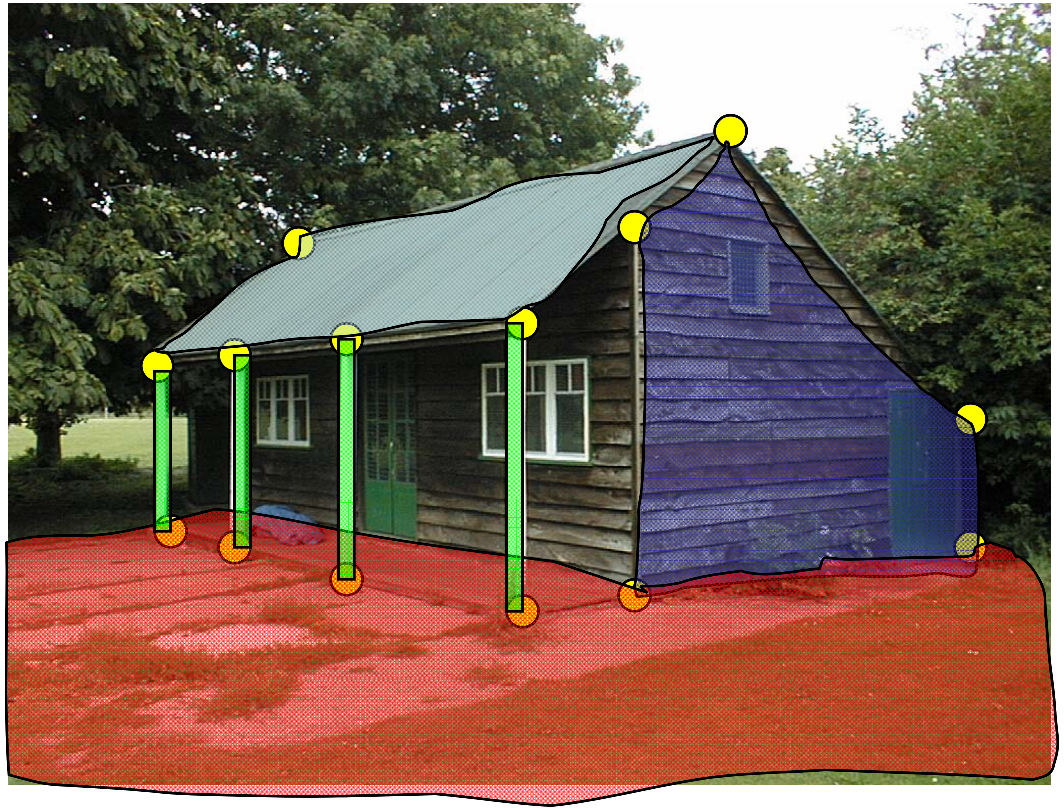




glTip

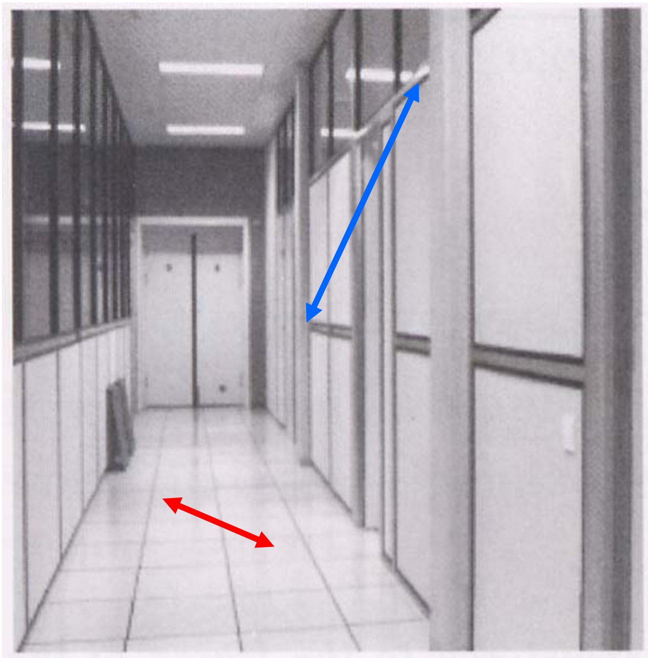
- http://www.cs.ust.hk/~cpegnel/glTIP/

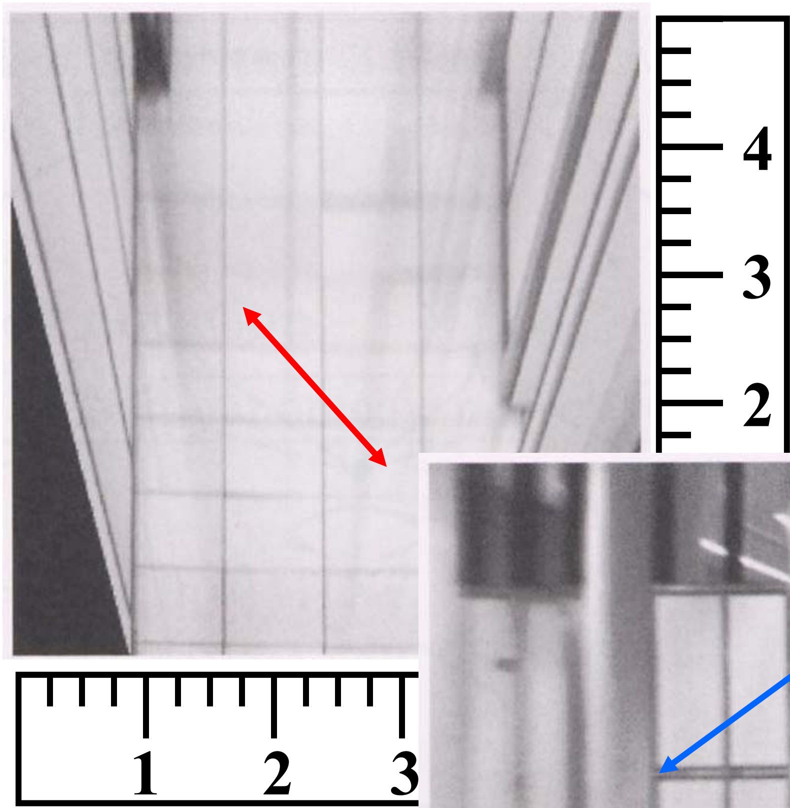
Criminisi *et al.* ICCV 1999

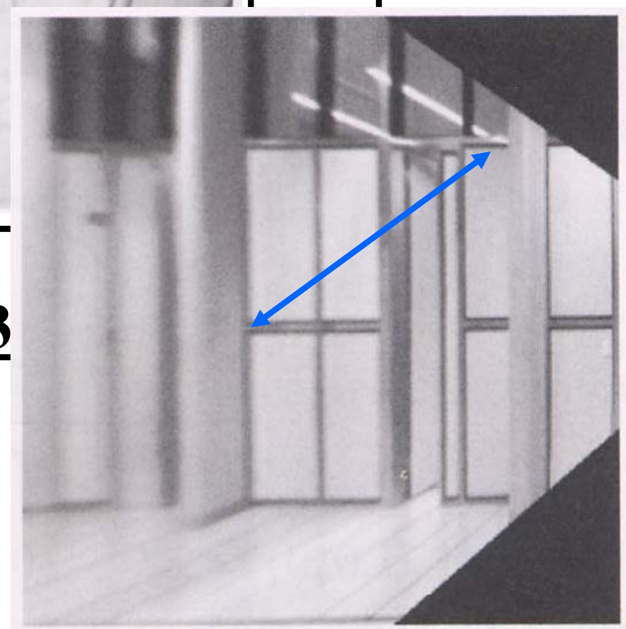


1. Find world coordinates (X,Y,Z) for a few points
2. Connect the points with planes to model geometry
   - Texture map the planes

Measurements on planes



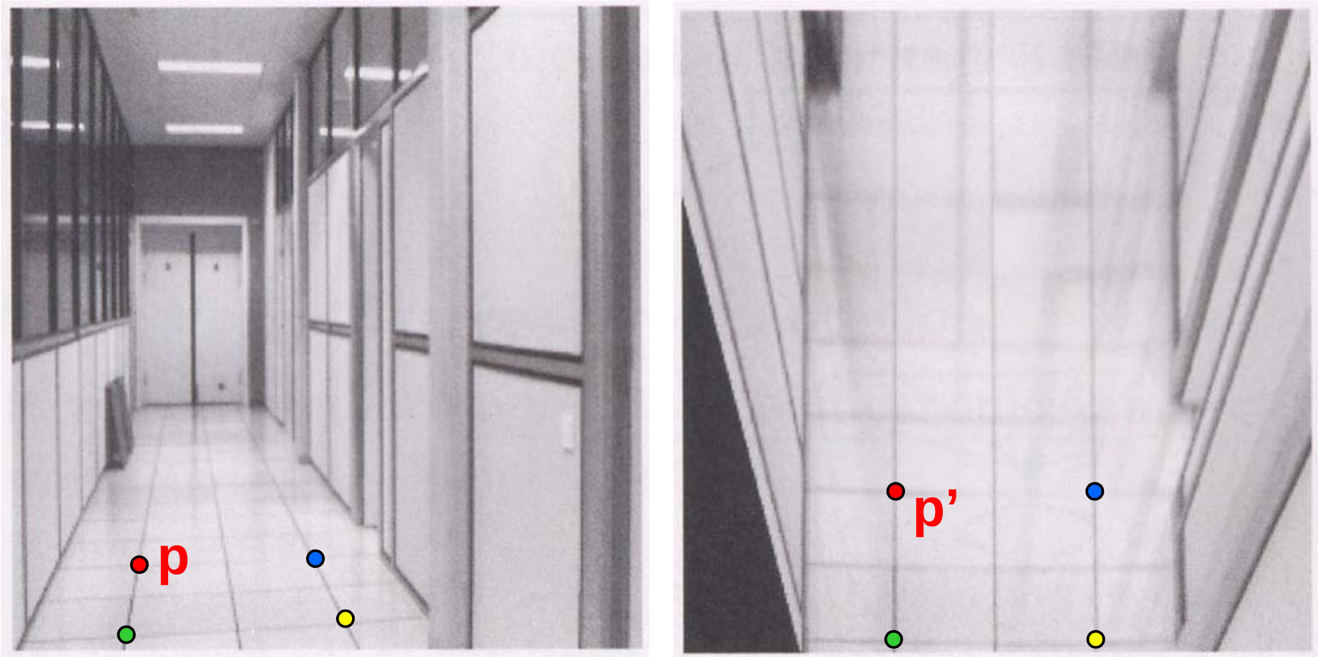




Approach: unwarp then measure

What kind of warp is this?

Image rectification



To unwarp (rectify) an image

- solve for homography **H** given **p** and **p’**
- solve equations of the form: w**p’** = **Hp**
  - linear in unknowns: w and coefficients of **H**
  - H is defined up to an arbitrary scale factor
  - how many points are necessary to solve for **H**?

Solving for homographies

$$\begin{bmatrix} x_i' \\ y_i' \\ 1 \end{bmatrix} \cong \begin{bmatrix} h_{00} & h_{01} & h_{02} \\ h_{10} & h_{11} & h_{12} \\ h_{20} & h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix}$$

$$\begin{aligned} x_i' &= \frac{h_{00}x_i + h_{01}y_i + h_{02}}{h_{20}x_i + h_{21}y_i + h_{22}} \\ y_i' &= \frac{h_{10}x_i + h_{11}y_i + h_{12}}{h_{20}x_i + h_{21}y_i + h_{22}} \end{aligned}$$

$$\begin{aligned} x_i'(h_{20}x_i + h_{21}y_i + h_{22}) &= h_{00}x_i + h_{01}y_i + h_{02} \\ y_i'(h_{20}x_i + h_{21}y_i + h_{22}) &= h_{10}x_i + h_{11}y_i + h_{12} \end{aligned}$$

$$\begin{bmatrix} x_i & y_i & 1 & 0 & 0 & 0 & -x_i'x_i & -x_i'y_i & -x_i' \\ 0 & 0 & 0 & x_i & y_i & 1 & -y_i'x_i & -y_i'y_i & -y_i' \end{bmatrix} \begin{bmatrix} h_{00} \\ h_{01} \\ h_{02} \\ h_{10} \\ h_{11} \\ h_{12} \\ h_{20} \\ h_{21} \\ h_{22} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Solving for homographies

$$\begin{bmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 & -x'_1 x_1 & -x'_1 y_1 & -x'_1 \\ 0 & 0 & 0 & x_1 & y_1 & 1 & -y'_1 x_1 & -y'_1 y_1 & -y'_1 \\ & & & & \vdots & & & & \\ x_n & y_n & 1 & 0 & 0 & 0 & -x'_n x_n & -x'_n y_n & -x'_n \\ 0 & 0 & 0 & x_n & y_n & 1 & -y'_n x_n & -y'_n y_n & -y'_n \end{bmatrix} \begin{bmatrix} h_{00} \\ h_{01} \\ h_{02} \\ h_{10} \\ h_{11} \\ h_{12} \\ h_{20} \\ h_{21} \\ h_{22} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix}$$

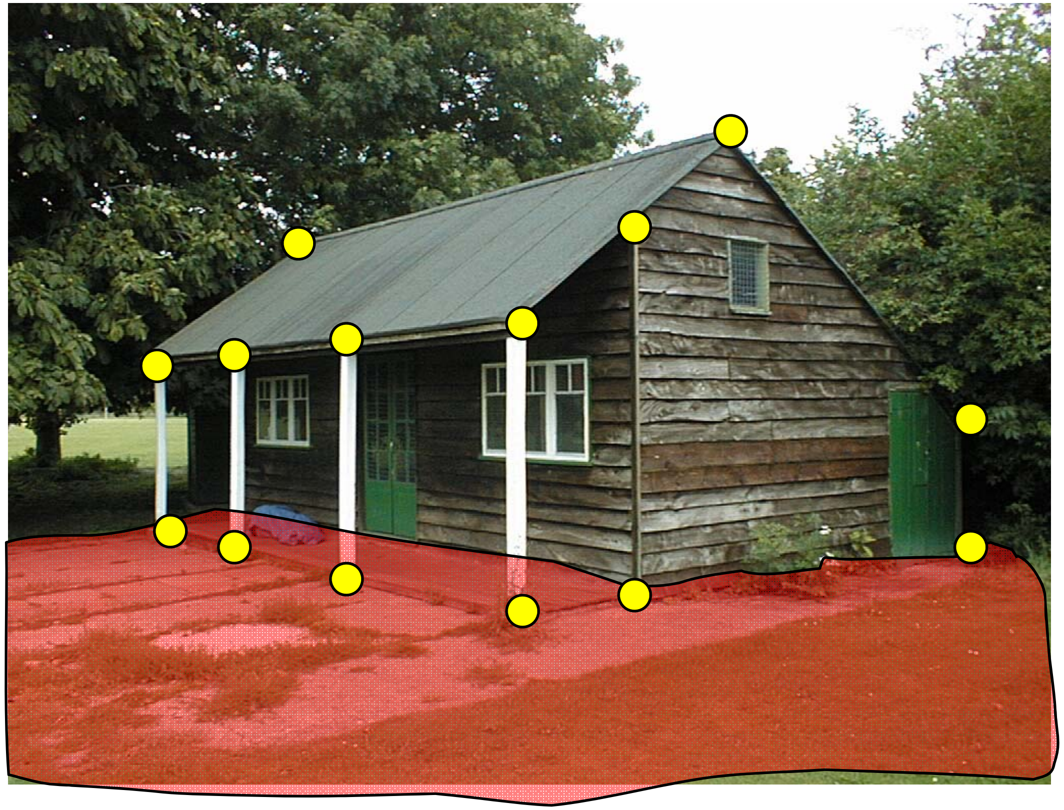
$\mathbf{A}$ ($2n \times 9$) $\quad \mathbf{h}$ (9) $\quad \mathbf{0}$ ($2n$)

- Defines a least squares problem:

$$\text{minimize } \|\mathbf{Ah} - \mathbf{0}\|^2$$

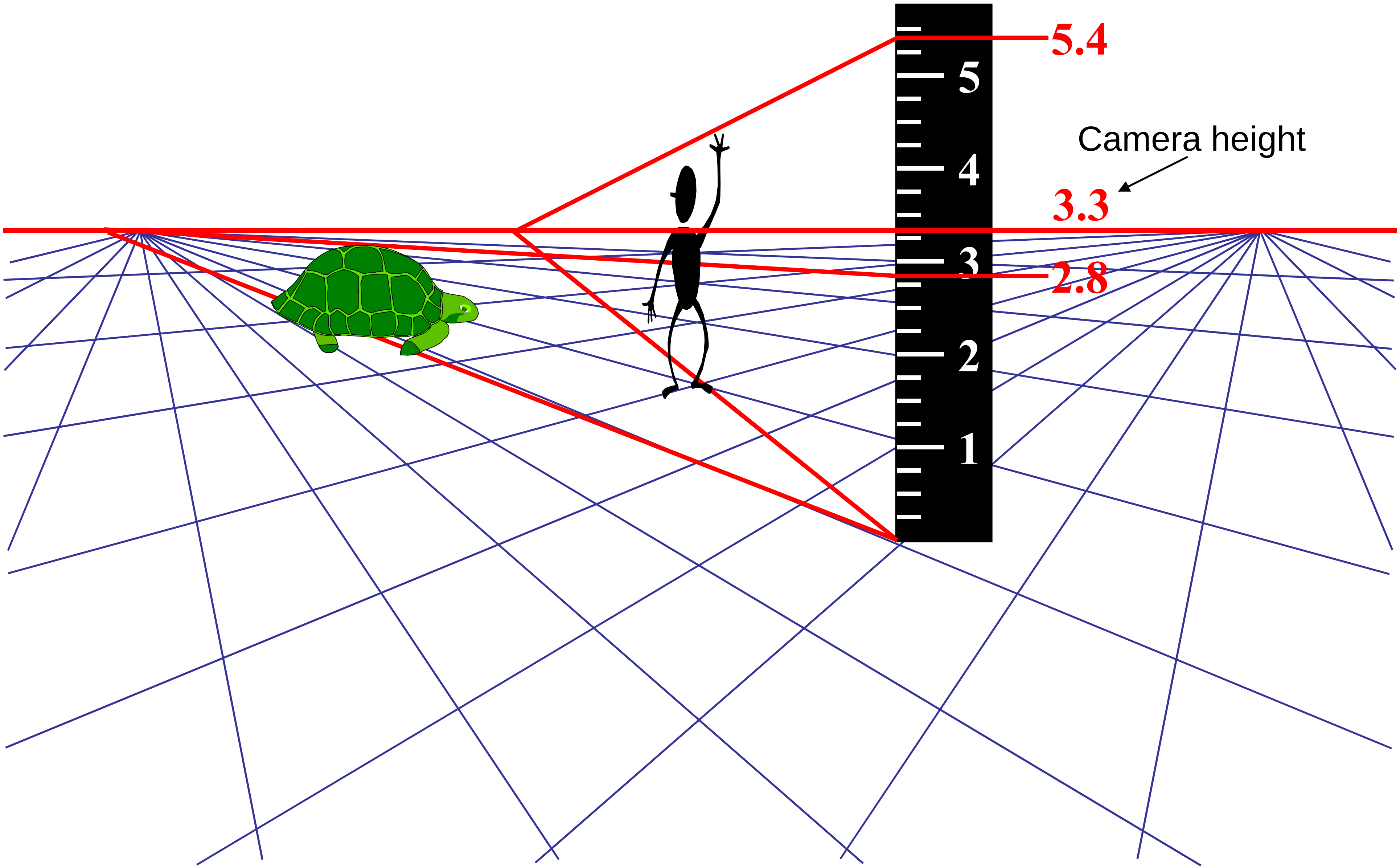
  - Since **h** is only defined up to scale, solve for unit vector $\hat{\mathbf{h}}$
  - Works with 4 or more points

Finding world coordinates (X,Y,Z)

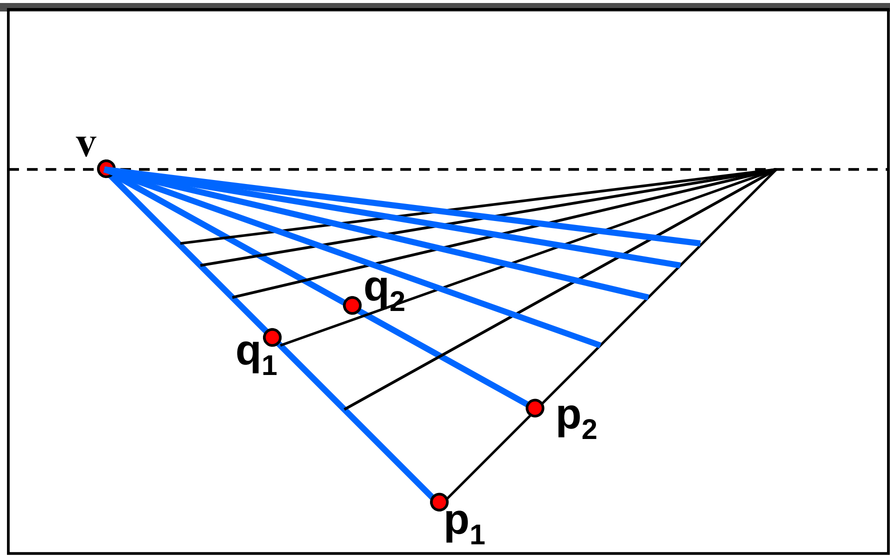


1. Define the ground plane (Z=0)
2. Compute points (X,Y,0) on that plane
3. Compute the *heights* Z of all other points

Measuring height



Computing vanishing points



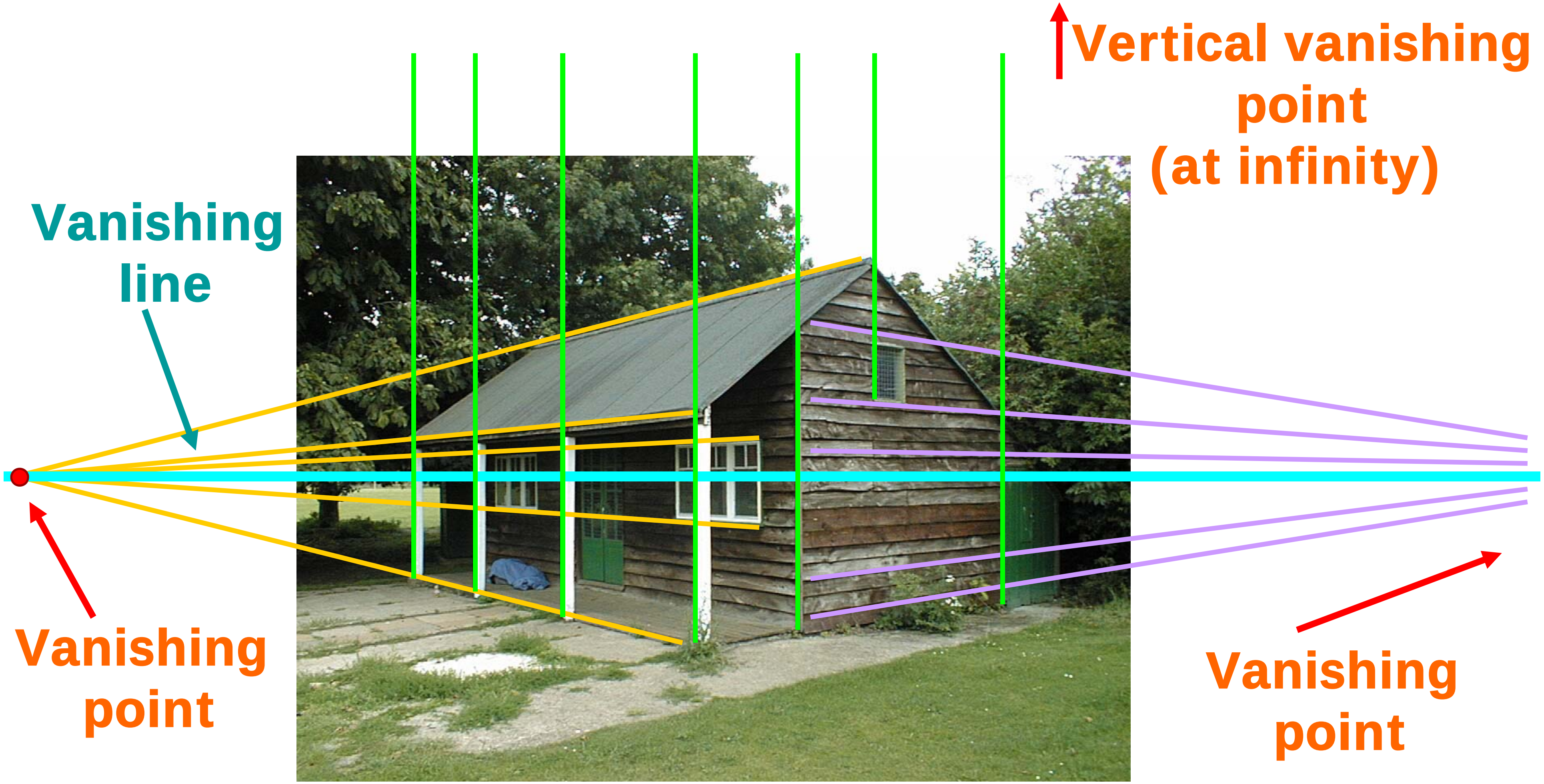
- Intersect p_1q_1 with p_2q_2

- Least squares version
  - Better to use more than two lines and compute the "closest" point of intersection
  - See notes by Bob Collins for one good way of doing this:
    - http://www-2.cs.cmu.edu/~ph/869/www/notes/vanishing.txt

Criminisi et al., ICCV 99

- Load in an image
- Click on lines parallel to X axis
  - repeat for Y, Z axes
- Compute vanishing points

Criminisi et al., ICCV 99

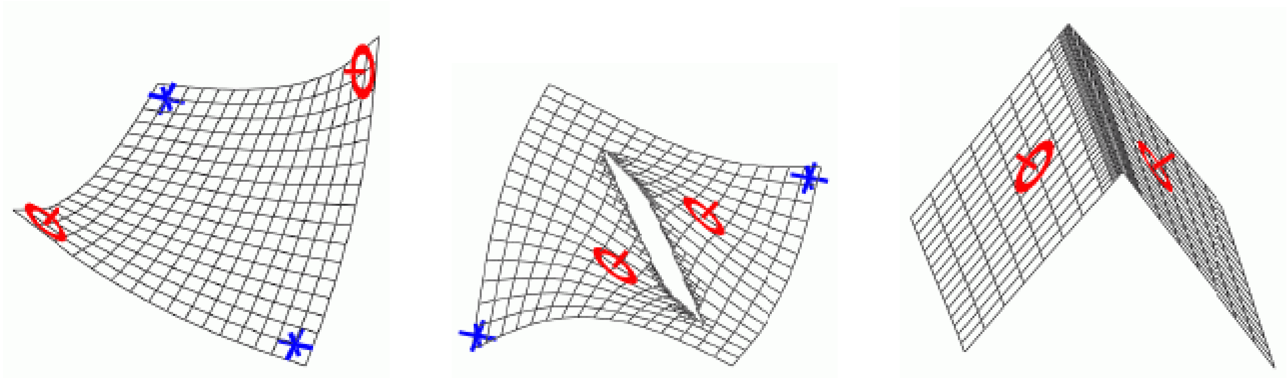


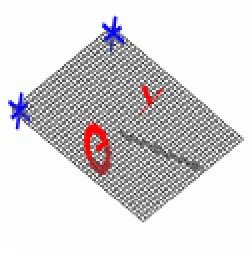
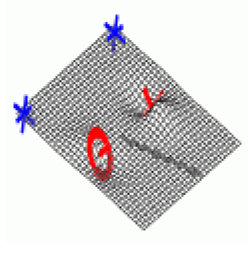
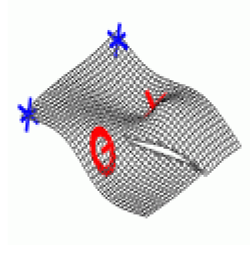
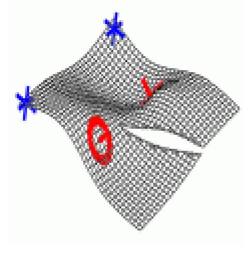
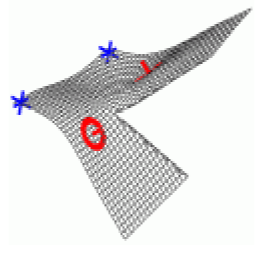
Criminisi et al., ICCV 99

- Load in an image
- Click on lines parallel to X axis
  - repeat for Y, Z axes
- Compute vanishing points
- Specify 3D and 2D positions of 4 points on reference plane
- Compute homography H
- Specify a reference height
- Compute 3D positions of several points
- Create a 3D model from these points
- Extract texture maps
- Output a VRML model

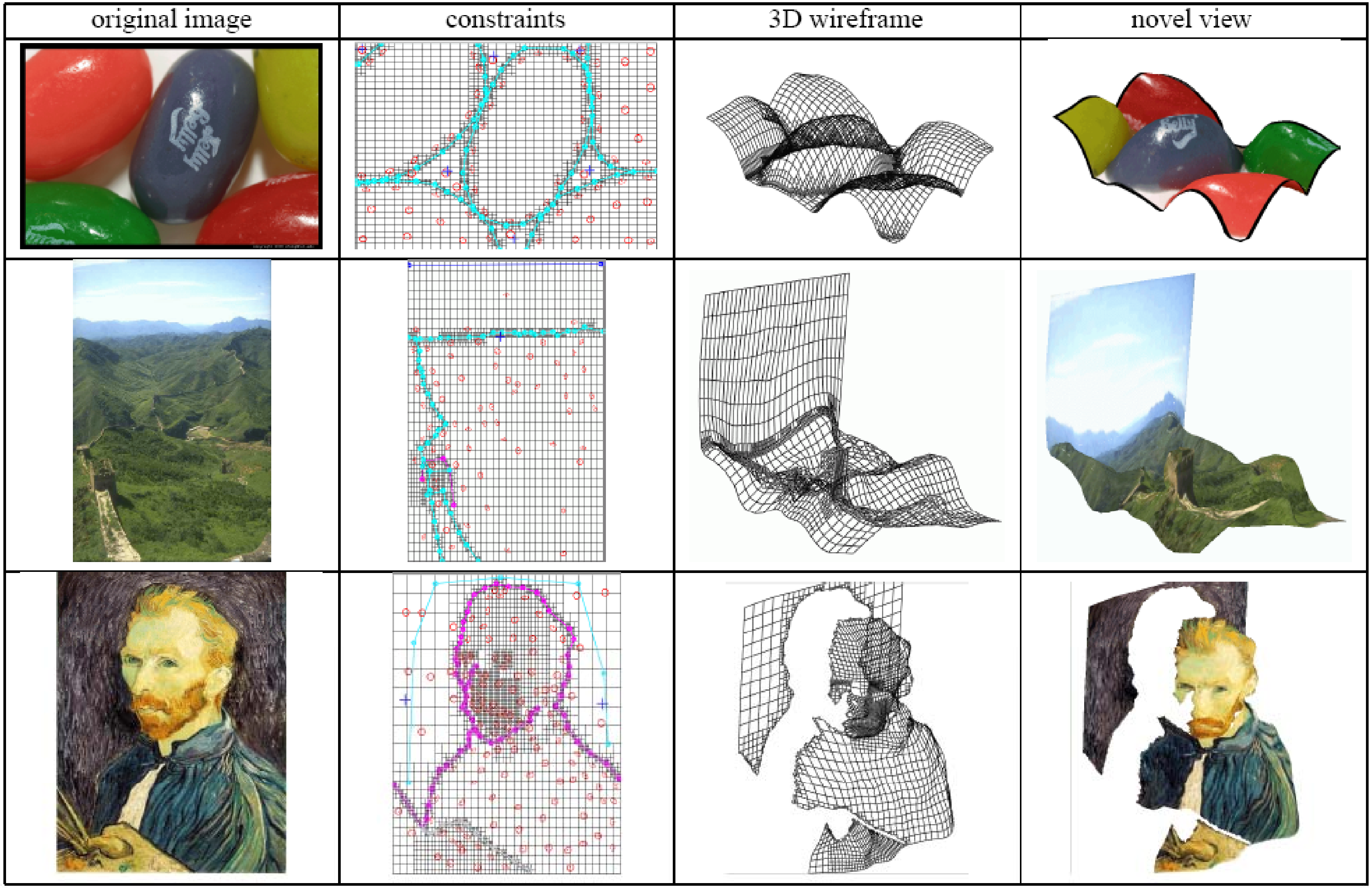
Results

Zhang *et. al.* CVPR 2001

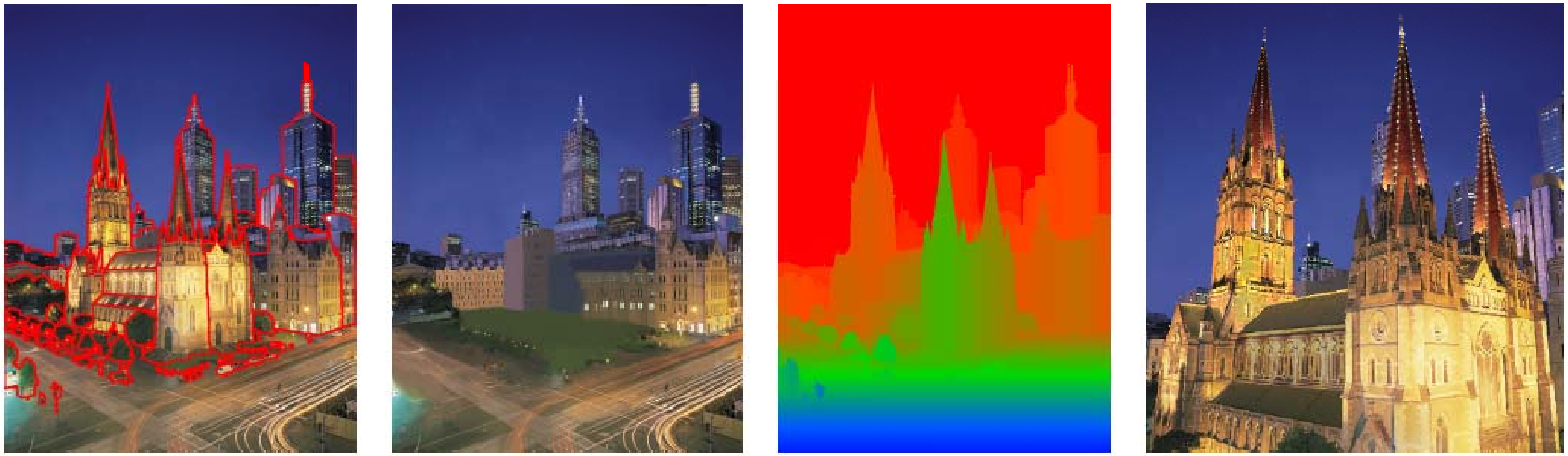


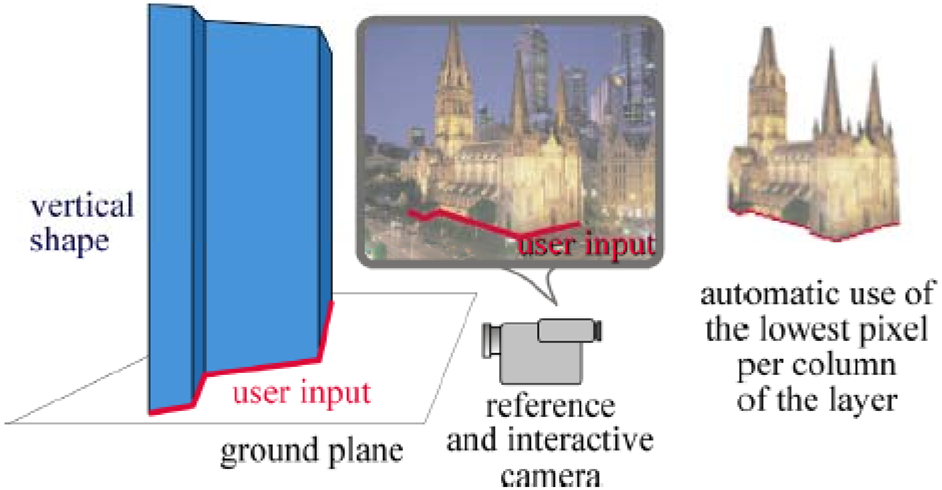
Methods	Iteration 0	Iteration 200	Iteration 1200	Iteration 2500	Iteration 9500
No hierarchical transformation					

Zhang *et. al.* CVPR 2001

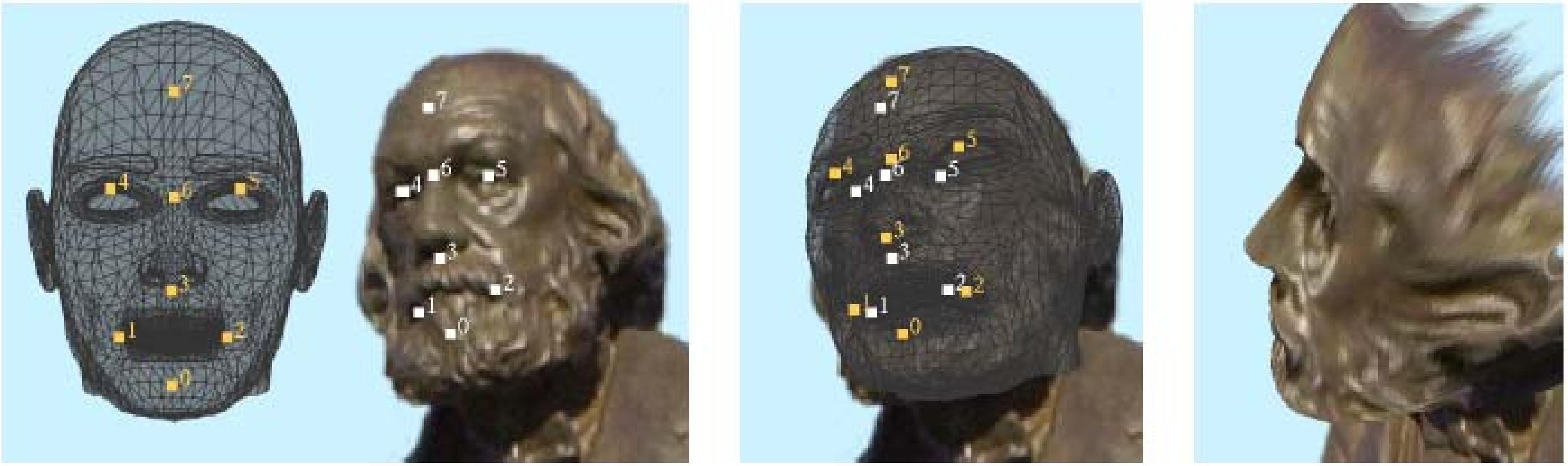


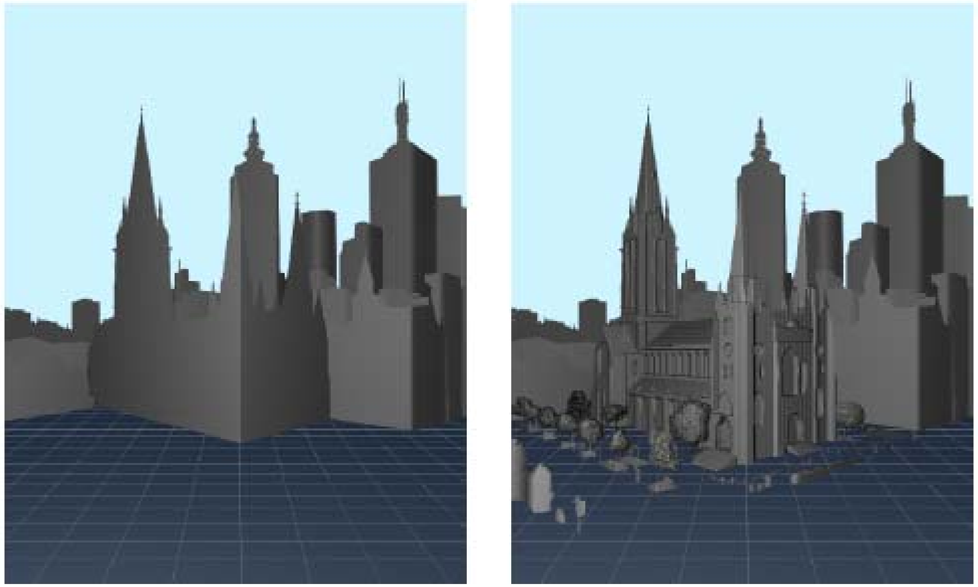
Oh *et. al.* SIGGRAPH 2001





Oh *et. al.* SIGGRAPH 2001

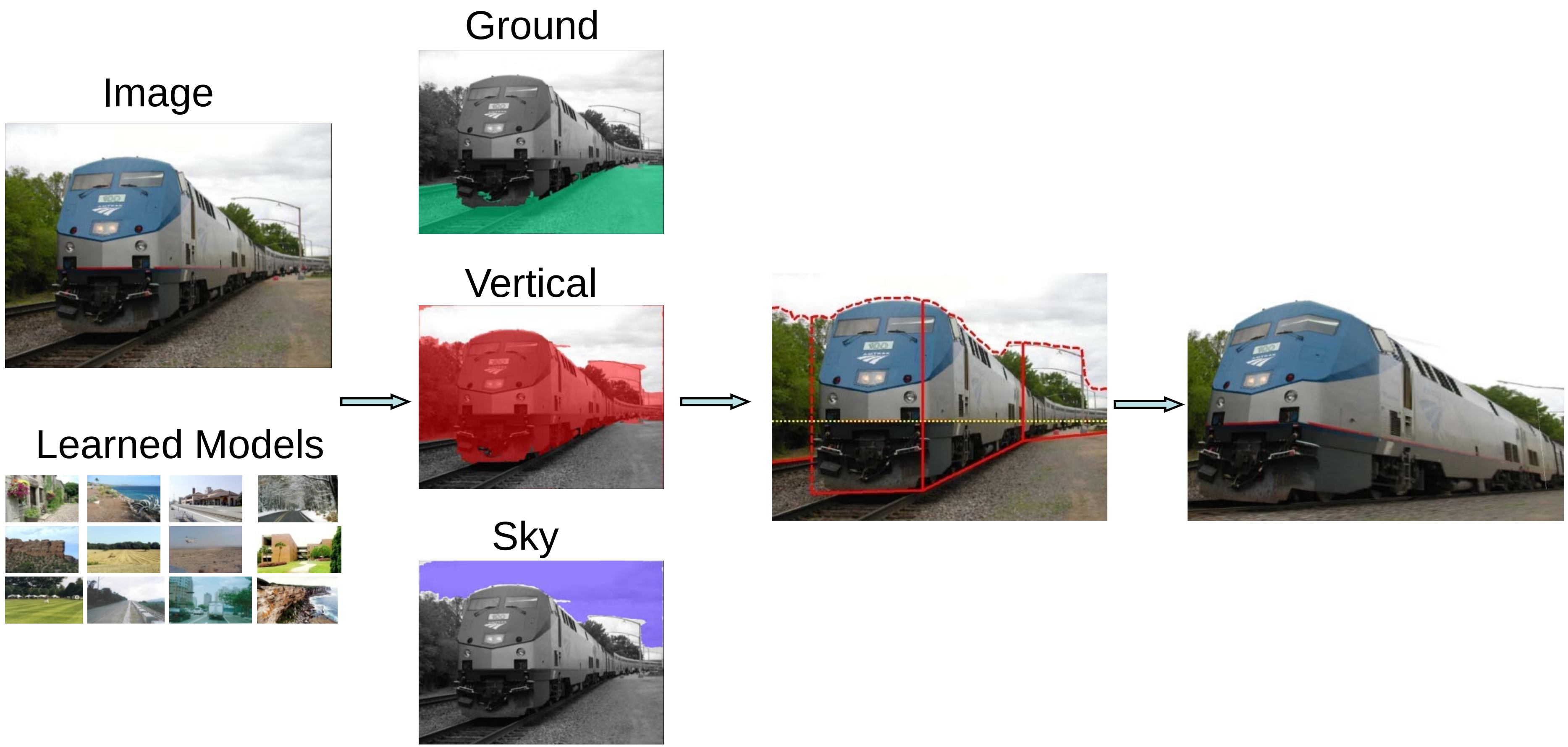




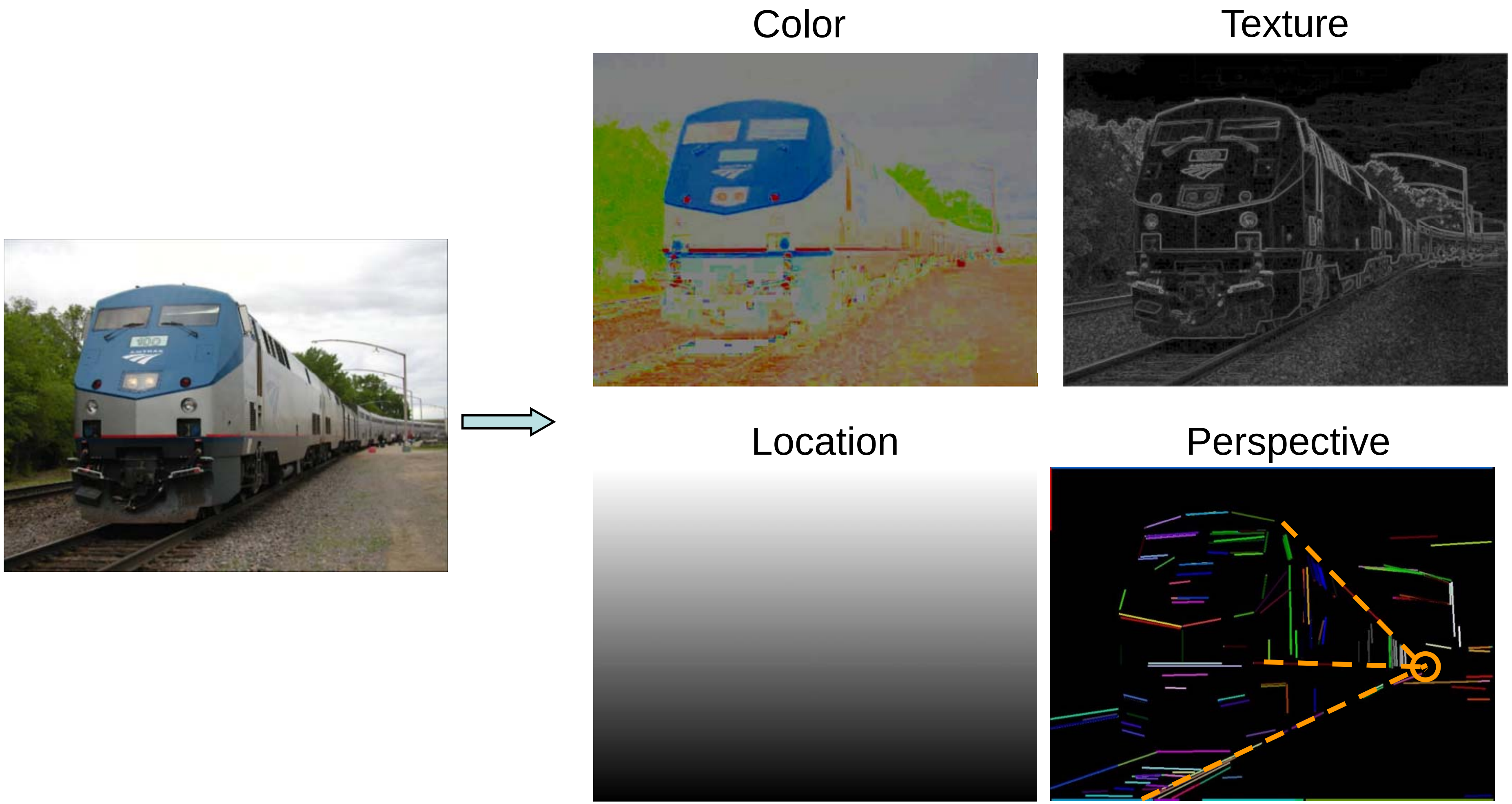
video

Automatic popup

Input | Geometric Labels | Cut'n'Fold | 3D Model



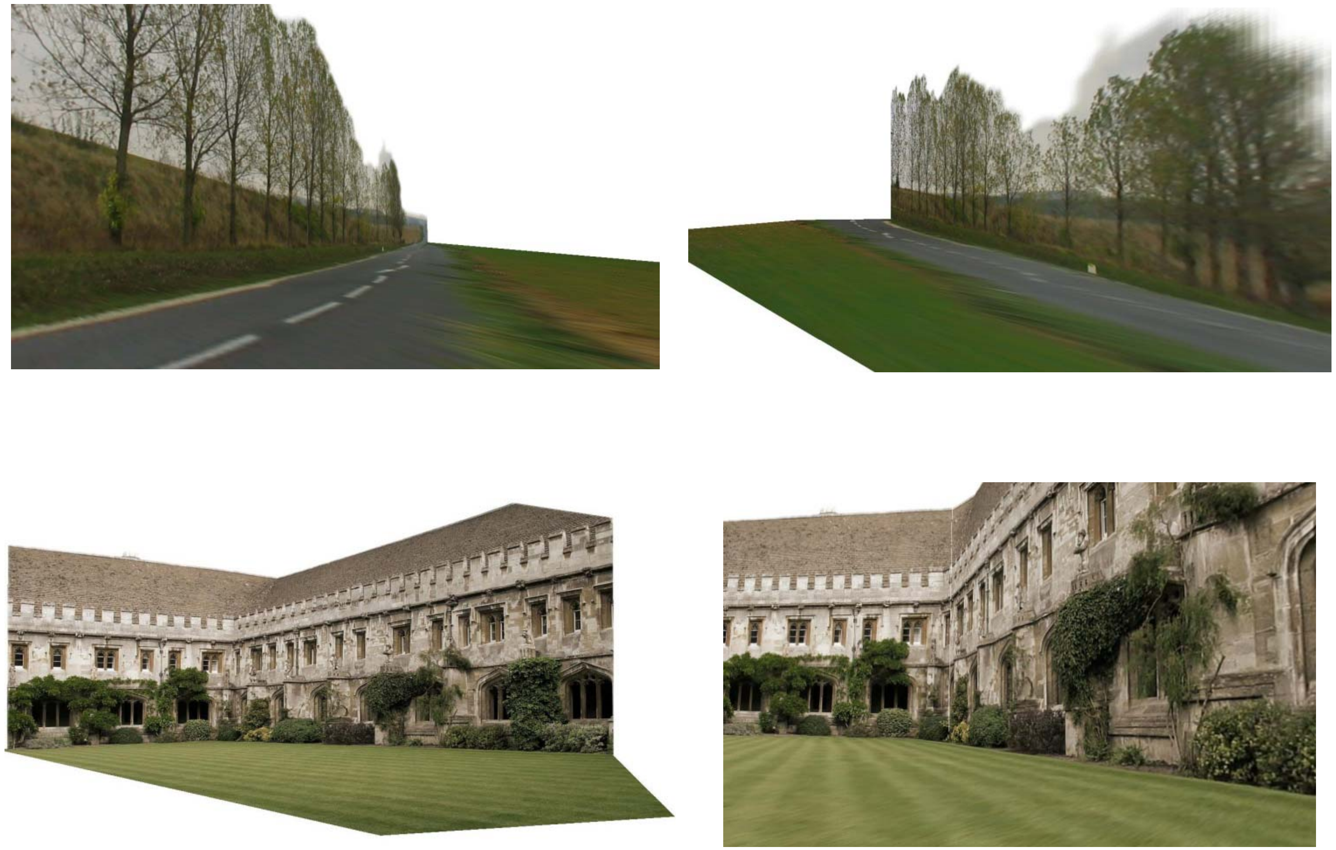
Geometric cues



Automatic popup

Feature Descriptions	Num	Used
Color	**15**	**15**
C1. RGB values: mean	3	3
C2. HSV values: conversion from mean RGB values	3	3
C3. Hue: histogram (5 bins) and entropy	6	6
C4. Saturation: histogram (3 bins) and entropy	3	3
Texture	**29**	**13**
T1. DOOG Filters: mean abs response	12	3
T2. DOOG Filters: mean of variables in T1	1	0
T3. DOOG Filters: id of max of variables in T1	1	1
T4. DOOG Filters: (max - median) of variables in T1	1	1
T5. Textons: mean abs response	12	7
T6. Textons: max of variables in T5	1	0
T7. Textons: (max - median) of variables in T5	1	1
Location and Shape	**12**	**10**
L1. Location: normalized x and y, mean	2	2
L2. Location: norm. x and y, 10^{th} and 90^{th} percentile	4	4
L3. Location: norm. y wrt horizon, 10^{th} and 90^{th} pctl	2	2
L4. Shape: number of superpixels in constellation	1	1
L5. Shape: number of sides of convex hull	1	0
L6. Shape: $num\ pixels/area(convex\ hull)$	1	1
L7. Shape: whether the constellation region is contiguous	1	0
3D Geometry	**35**	**28**
G1. Long Lines: total number in constellation region	1	1
G2. Long Lines: % of nearly parallel pairs of lines	1	1
G3. Line Intersection: hist. over 12 orientations, entropy	13	11
G4. Line Intersection: % right of center	1	1
G5. Line Intersection: % above center	1	1
G6. Line Intersection: % far from center at 8 orientations	8	4
G7. Line Intersection: % very far from center at 8 orientations	8	5
G8. Texture gradient: x and y "edginess" (T2) center	2	2

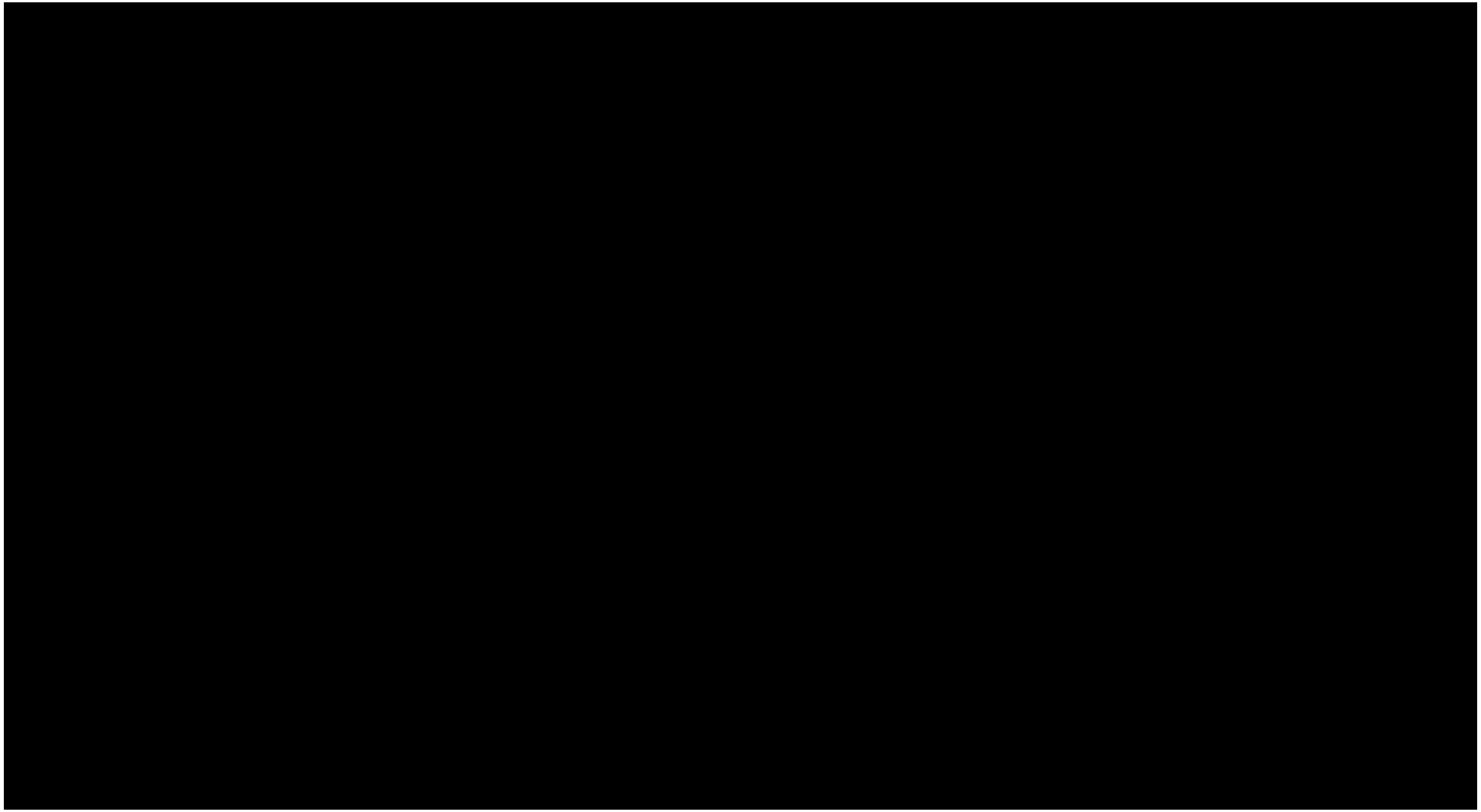
Results



Input Images

Automatic Photo Pop-up

Results



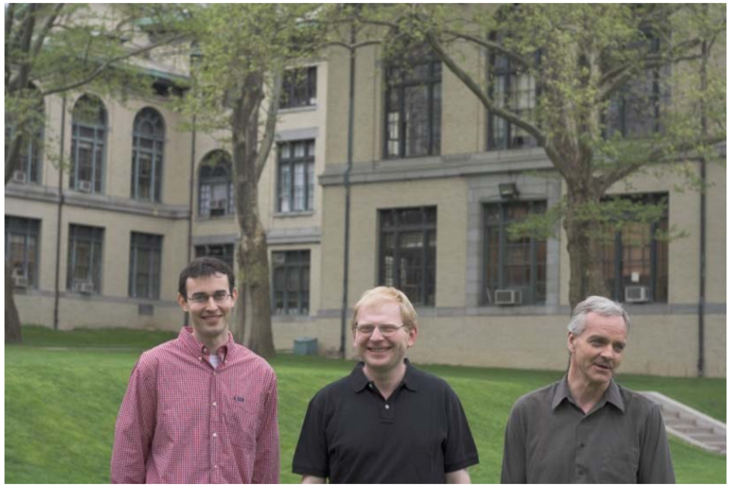
This approach works roughly for 35% of images.

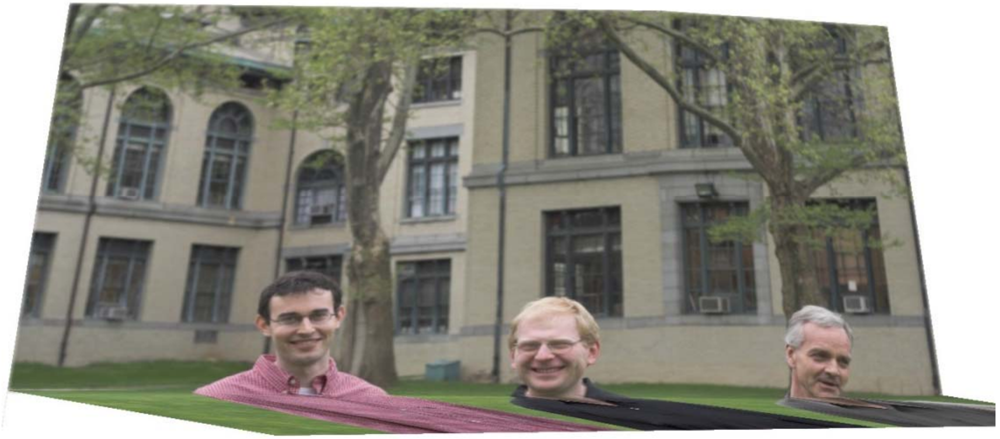
Failures

Labeling Errors

Failures

Foreground Objects





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