Single-view 3D Reconstruction

Computational Photography

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Some slides from Alyosha Efros, Steve Seitz

Office hours

- Amin: today (5pm)
- Derek: tomorrow (11am), Monday (2pm)

Message from Google

- Looking for people who can develop computational photography algorithms for cameras
  - E.g., take multiple pictures and do HDR or improve resolution or contrast
- Skills include knowledge of algorithms and ability to prototype and implement on camera platform

Project 3

- Do in teams of two
- Pick your partner now, will hand out mirrored spheres for light probes on Tues

Take-home question

Suppose you have estimated finite three vanishing points corresponding to orthogonal directions:

1) How to solve for intrinsic matrix? (assume K has three parameters)
   - The transpose of the rotation matrix is its inverse
   - Use the fact that the 3D directions are orthogonal
2) How to recover the rotation matrix that is aligned with the 3D axes defined by these points?
   - In homogeneous coordinates, 3d point at infinity is (X, Y, Z, 0)

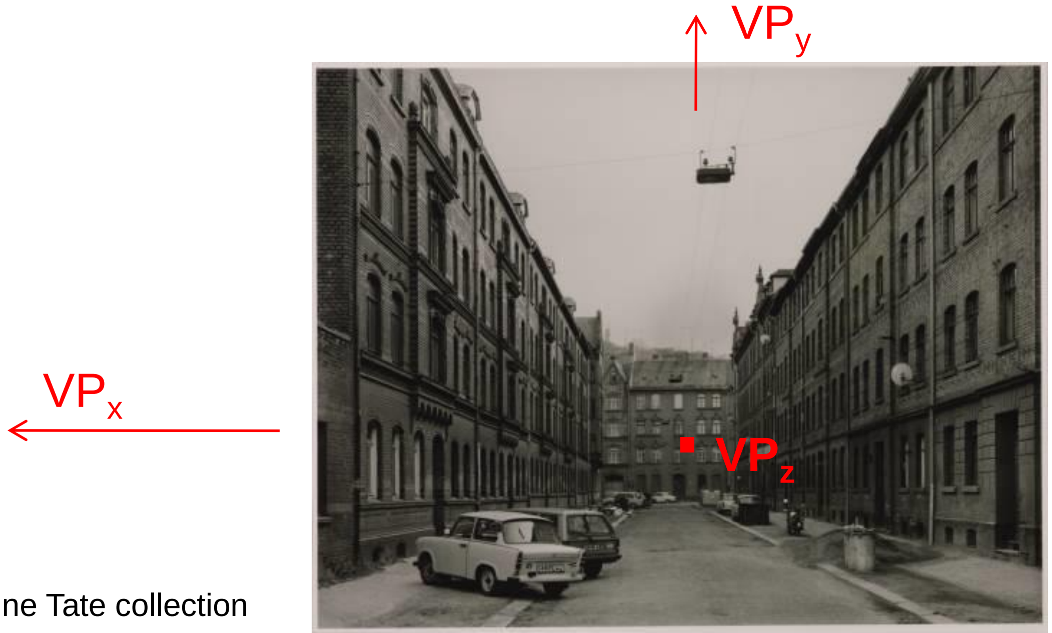


Photo from online Tate collection

Take-home question

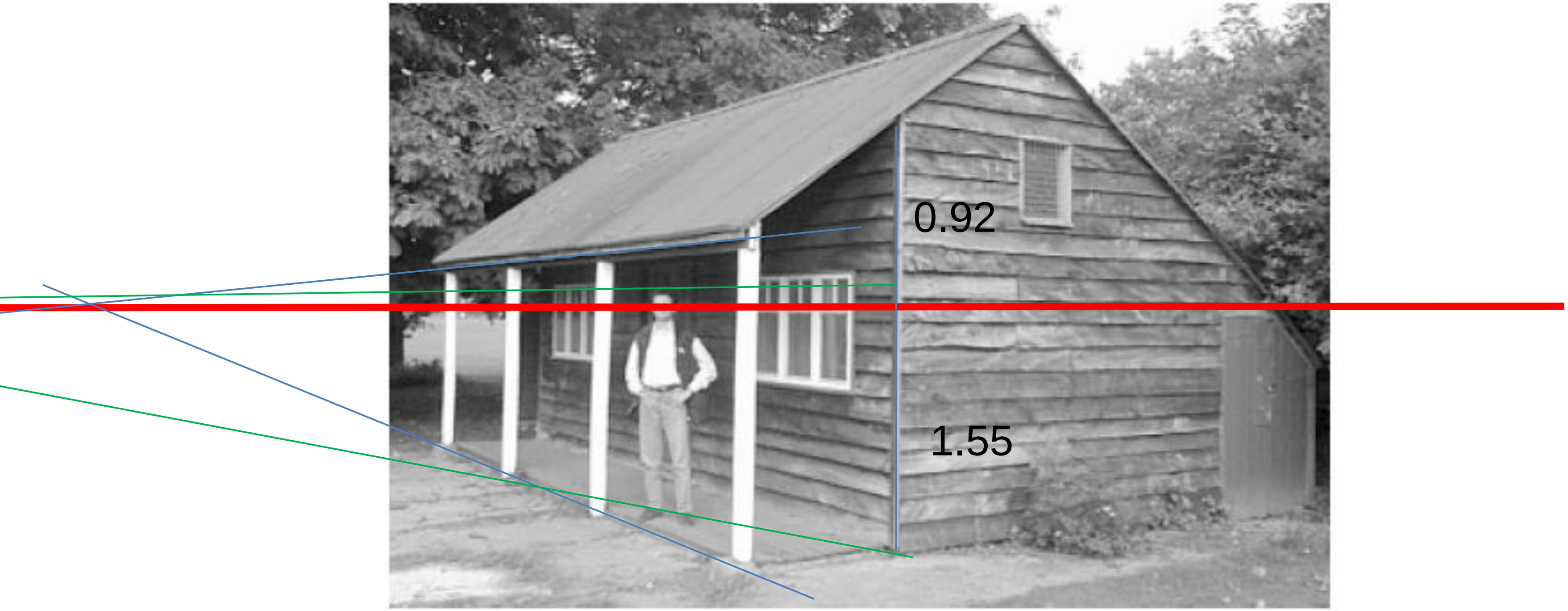
Assume that the man is 6 ft tall.

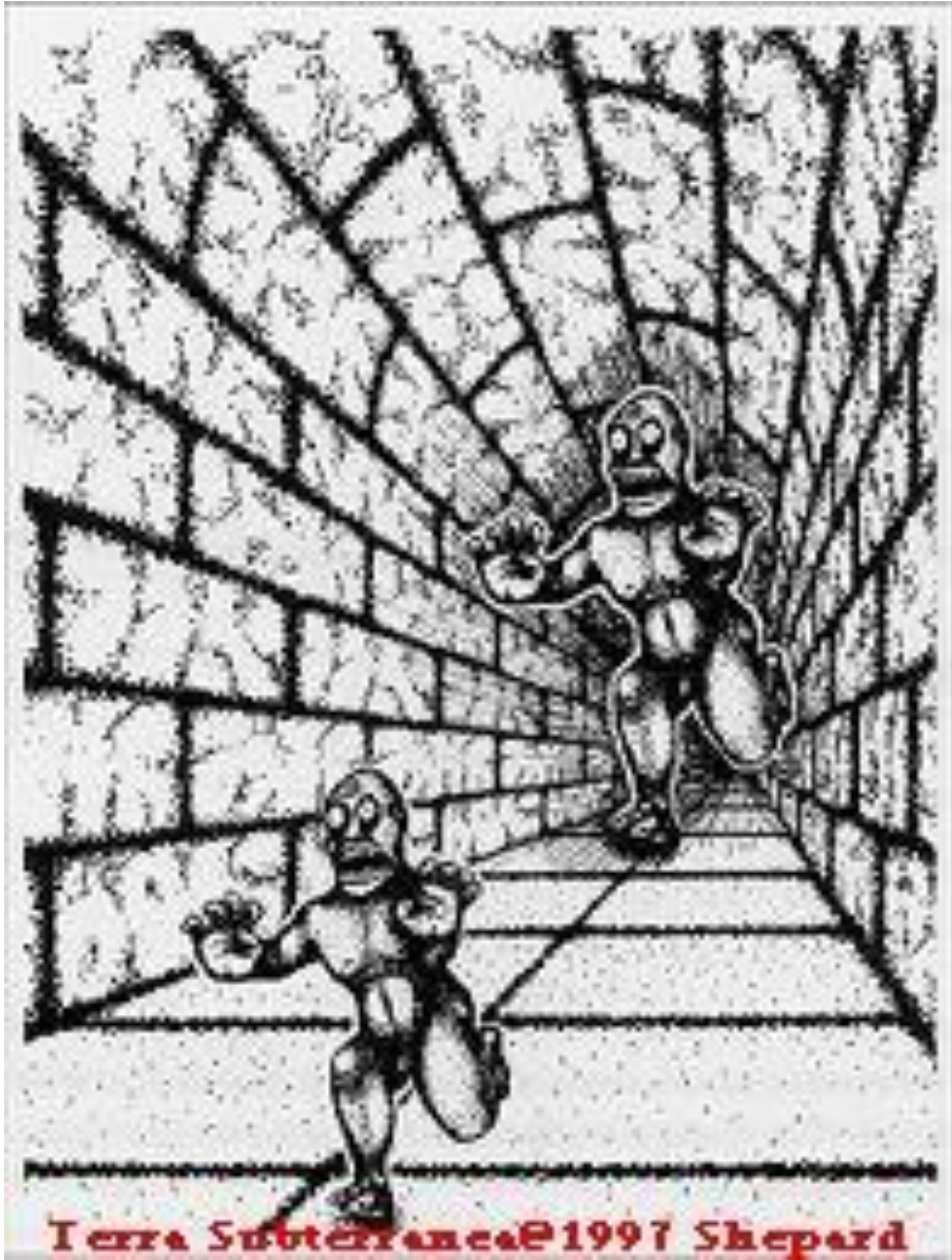
- What is the height of the front of the building?
- What is the height of the camera?

Take-home question

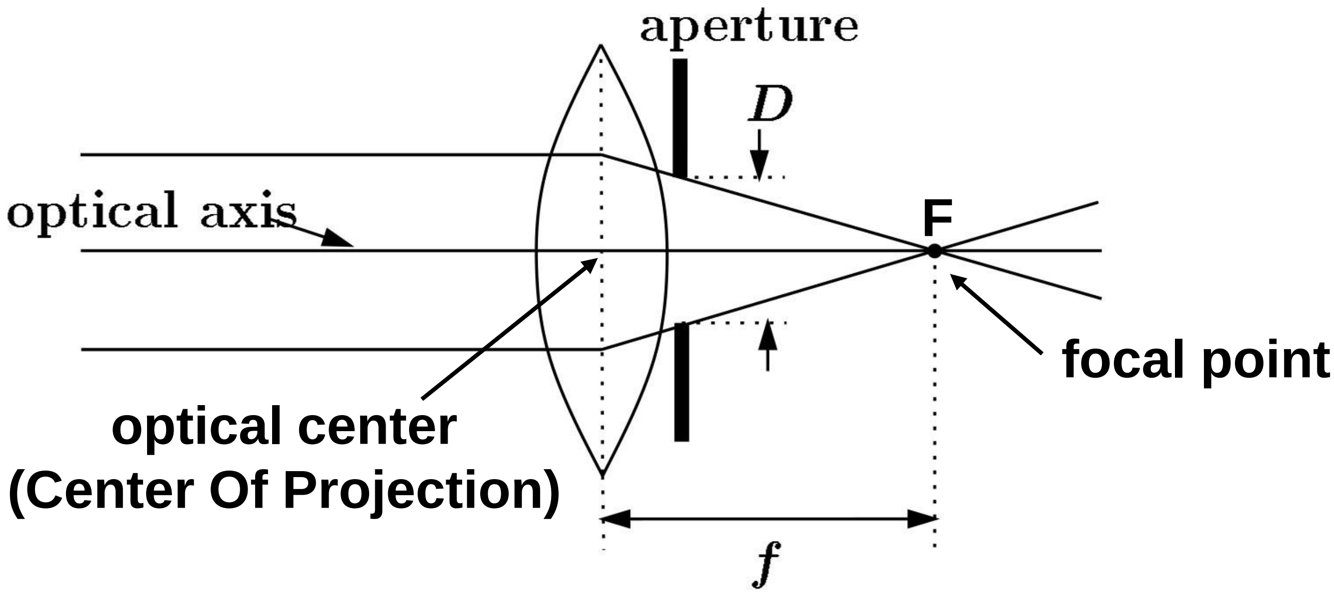
Assume that the man is 6 ft tall. (0.92+1.55)/1.55*6=9.56

- What is the height of the front of the building?
- What is the height of the camera? ~5'7




Terra Subterranea©1997 Shepard

Focal length, aperture, depth of field



- Increase in focal length “zooms in”, decreasing field of view (and light per pixel), increasing depth of field (less blur)

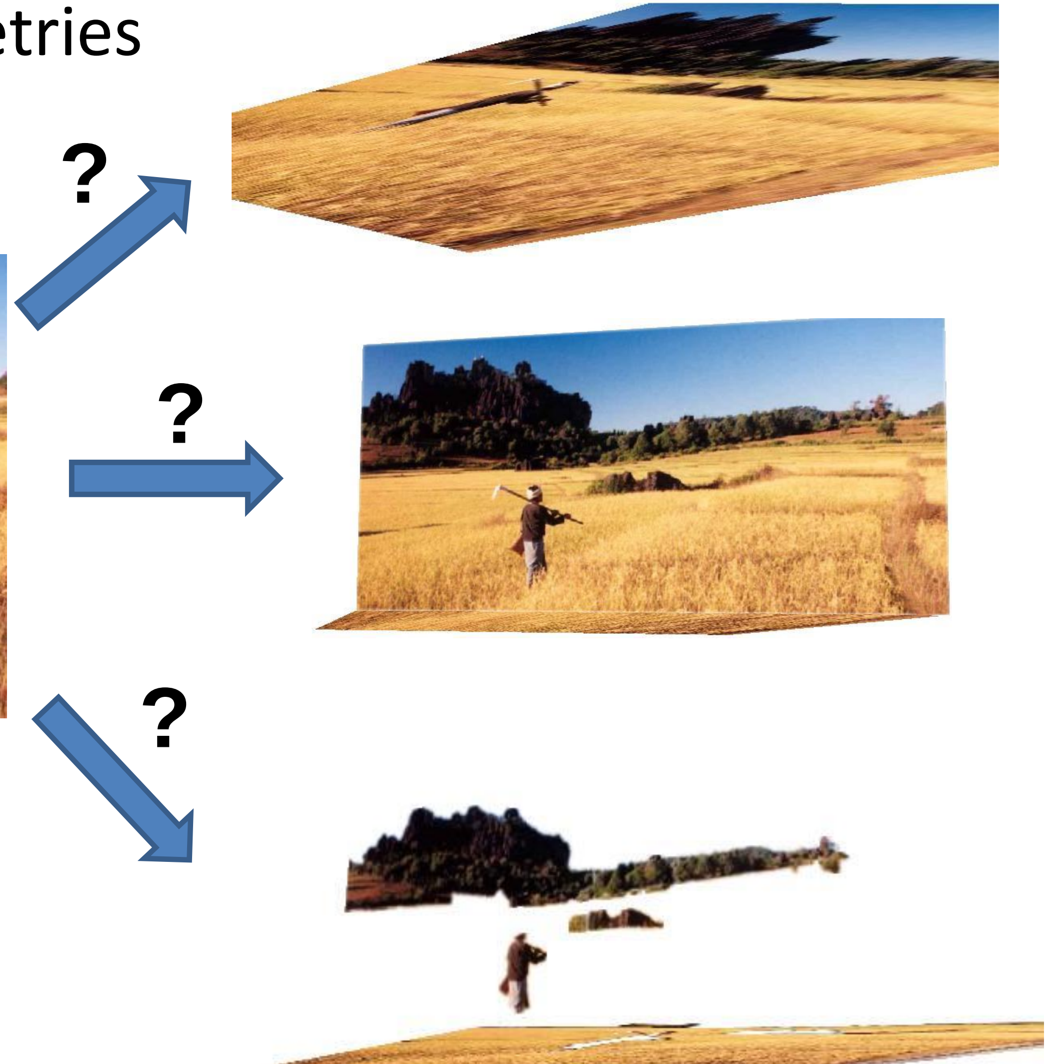
- Increase in aperture lets more light in but decreases depth of field

Slide source: Seitz

Today’s class: 3D Reconstruction

The challenge

One 2D image could be generated by an infinite number of 3D geometries



The solution

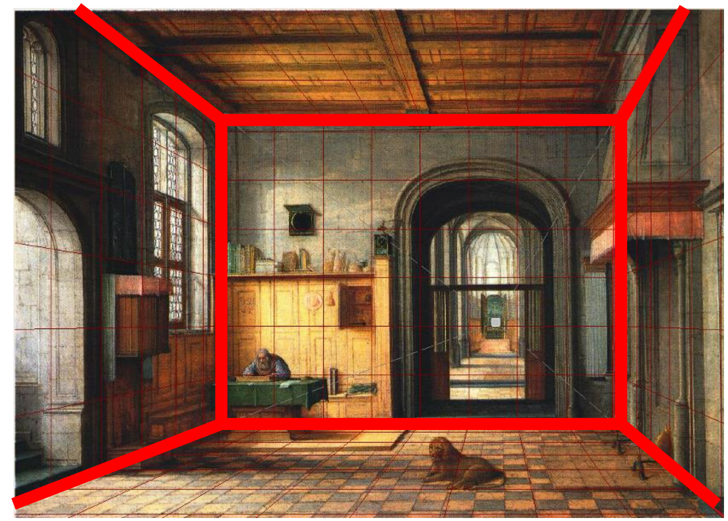
Make simplifying assumptions about 3D geometry

Unlikely

Likely

Today's class: Two Models

- Box + frontal billboards



- Ground plane + non-frontal billboards

“Tour into the Picture” (Horry et al. SIGGRAPH ’97)

Create a 3D “theatre stage” of five billboards

Specify foreground objects through bounding polygons

Use camera transformations to navigate through the scene

The idea

Many scenes can be represented as an axis-aligned box volume (i.e. a stage)

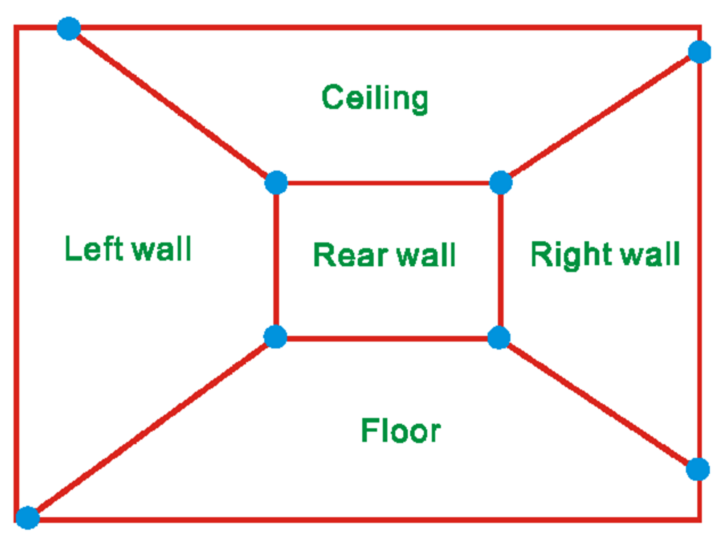
Key assumptions

- All walls are orthogonal
- Camera view plane is parallel to back of volume

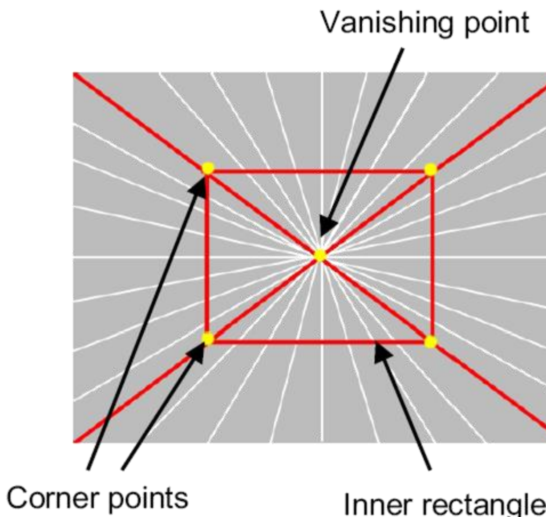
How many vanishing points does the box have?

- Three, but two at infinity
- Single-point perspective

Can use the vanishing point to fit the box to the particular scene



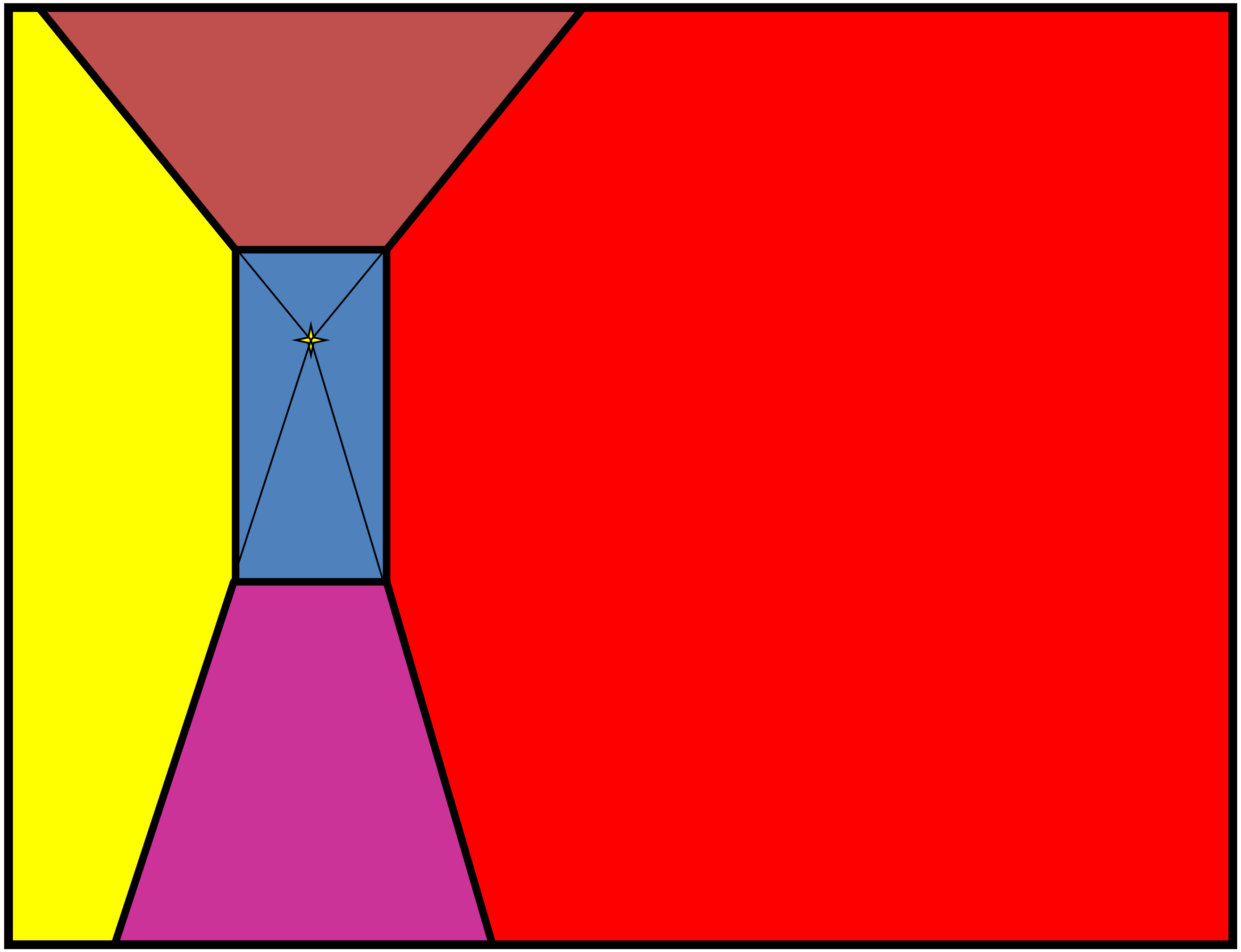
Step 1: specify scene geometry



- User controls the inner box and the vanishing point placement (# of DOF?)

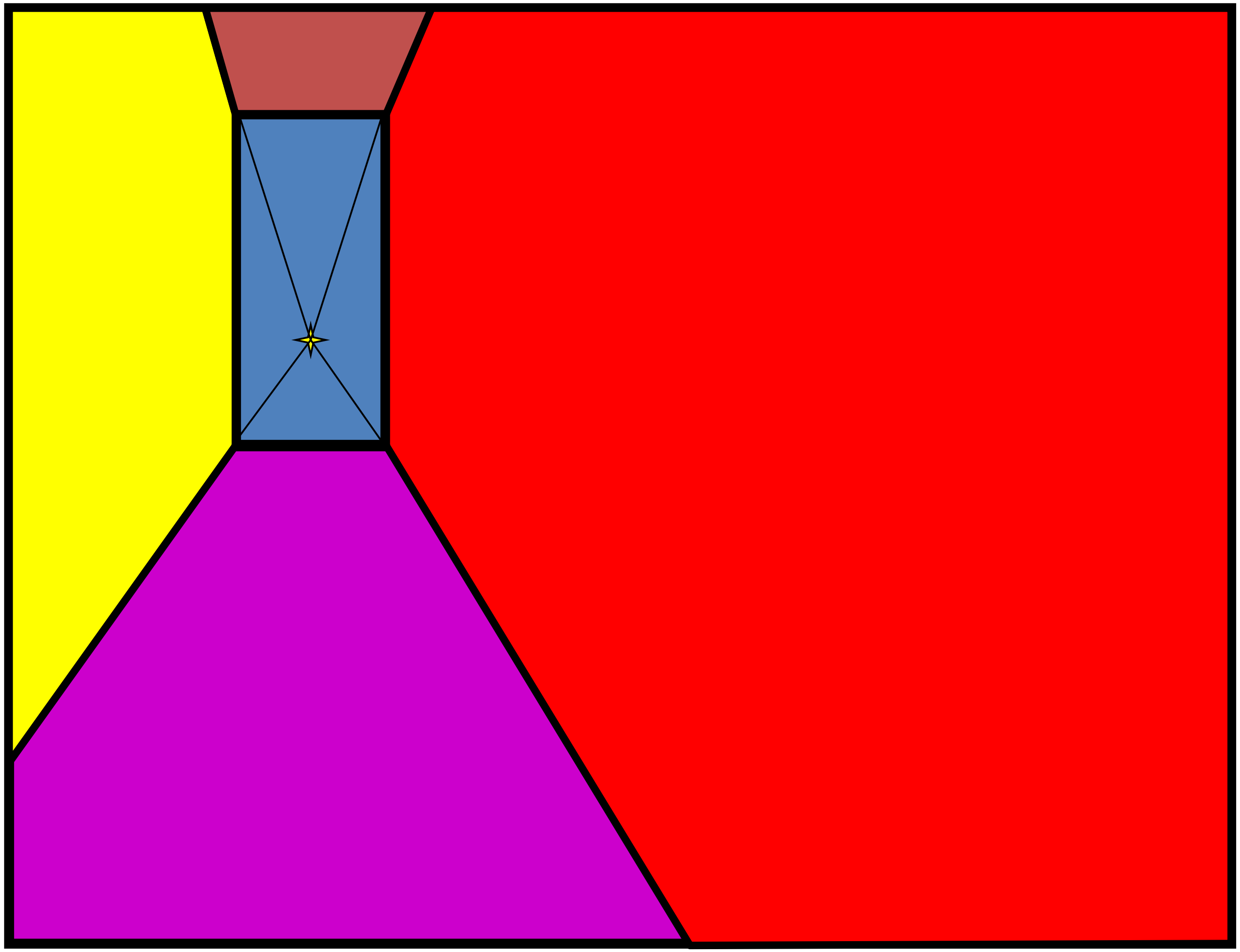
- Q: What's the significance of the vanishing point location?
- A: It's at eye (camera) level: ray from center of projection to VP is perpendicular to image plane
  - Under single-point perspective assumptions, the VP should be the principal point of the image

Example of user input: vanishing point and back face of view volume are defined



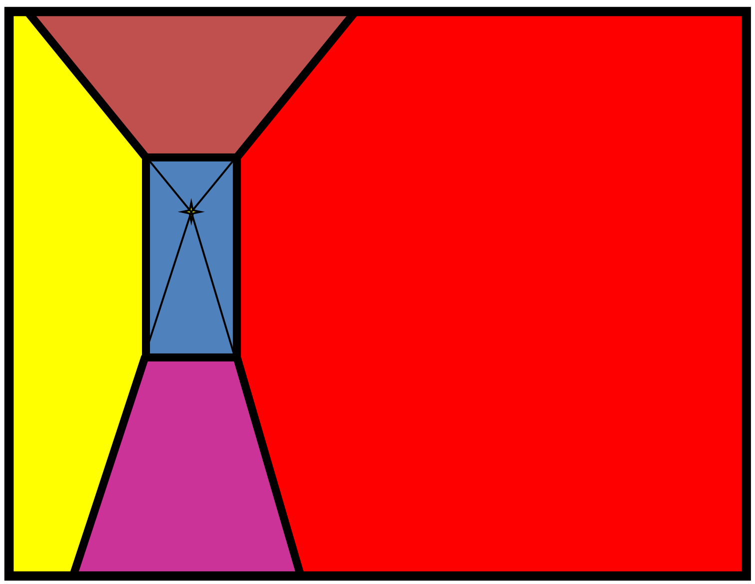
High Camera

Example of user input: vanishing point and back face of view volume are defined

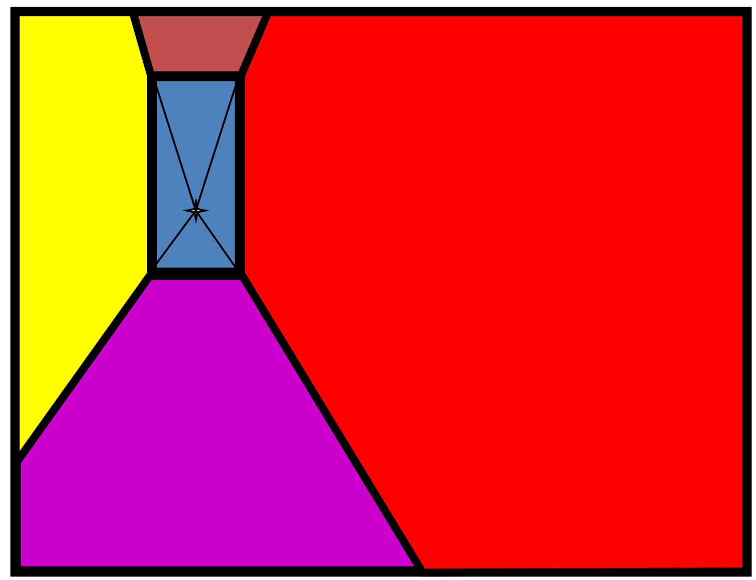


Low Camera

Comparison of how image is subdivided based on two different camera positions. You should see how moving the box corresponds to moving the eyepoint in the 3D world.

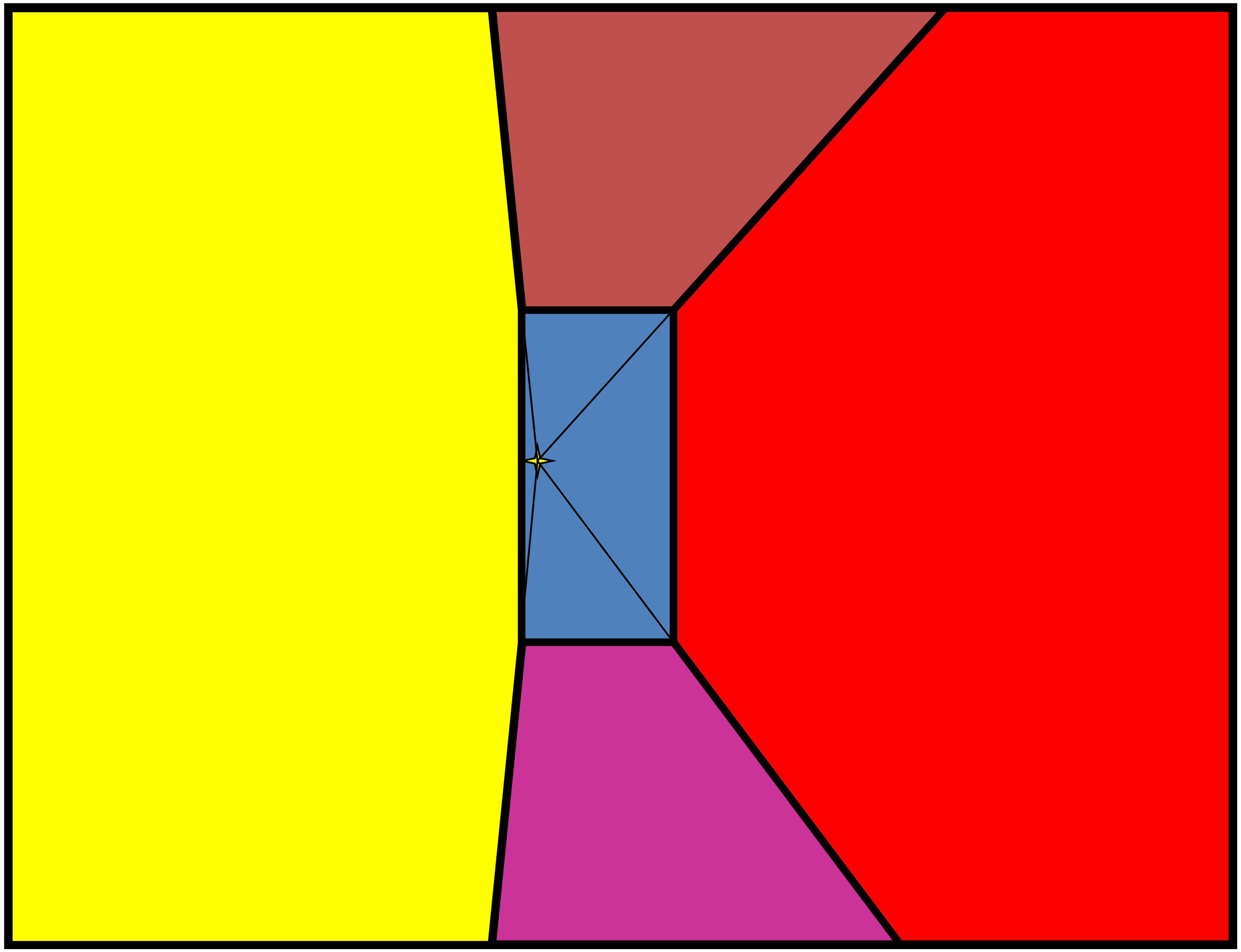


High Camera



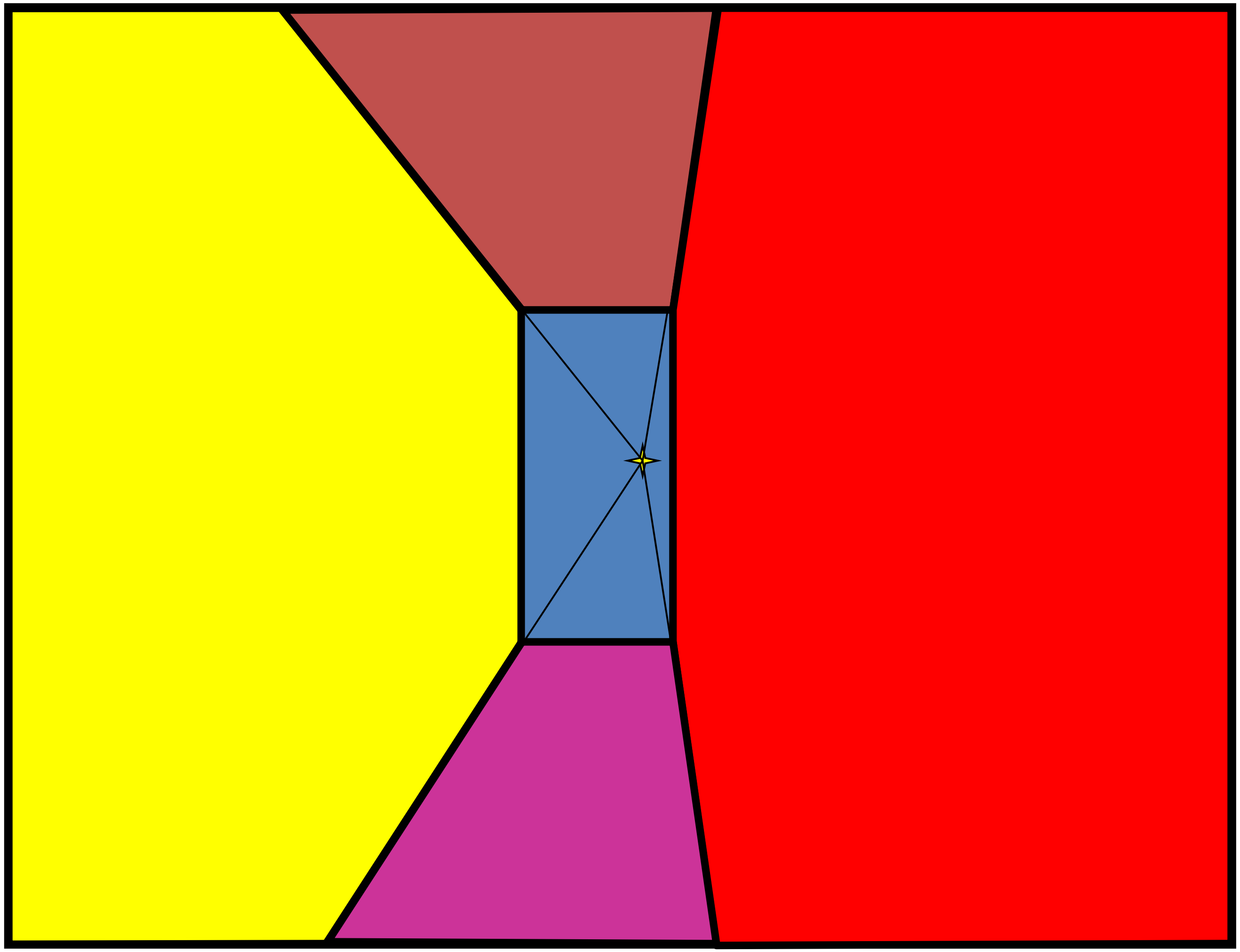
Low Camera

Another example of user input: vanishing point and back face of view volume are defined



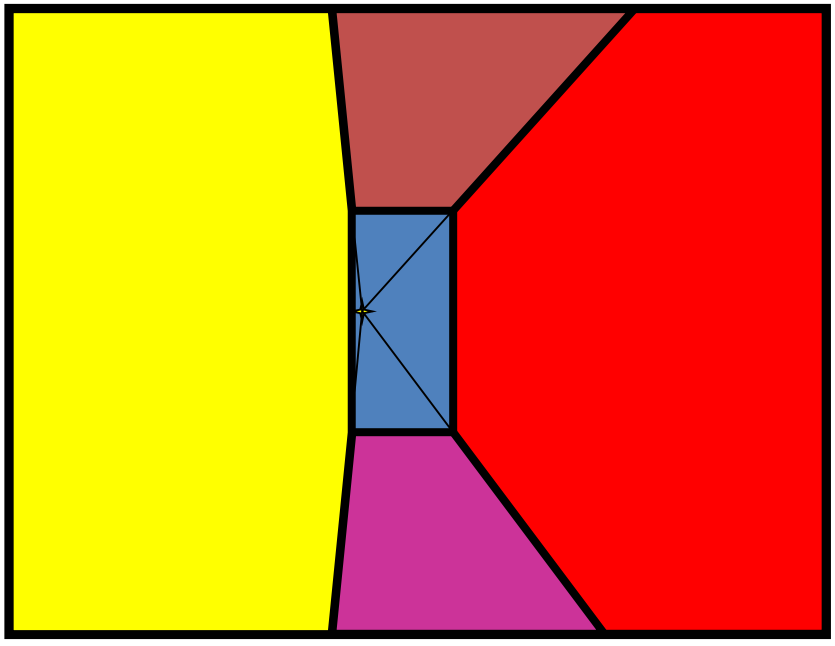
Left Camera

Another example of user input: vanishing point and back face of view volume are defined

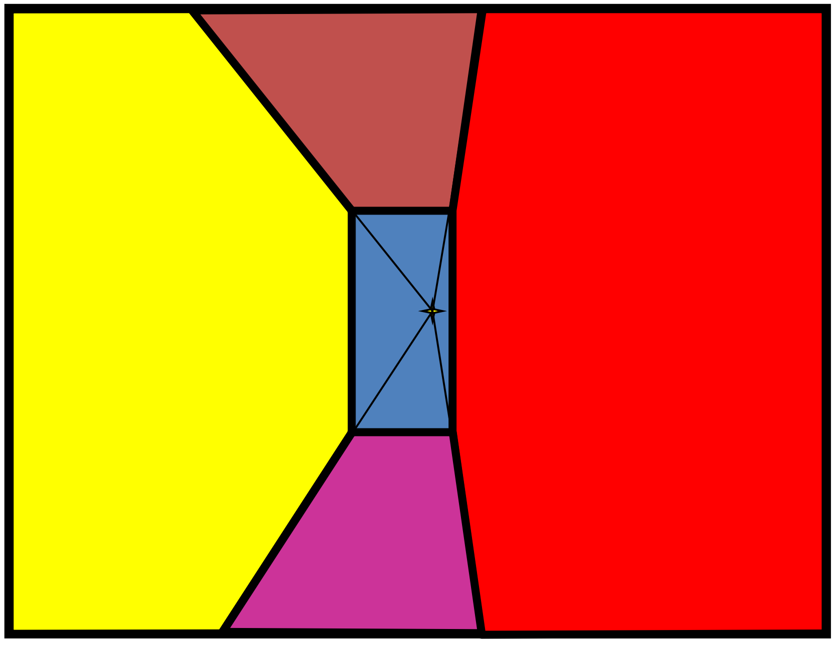


Right Camera

Comparison of two camera placements – left and right. Corresponding subdivisions match view you would see if you looked down a hallway.



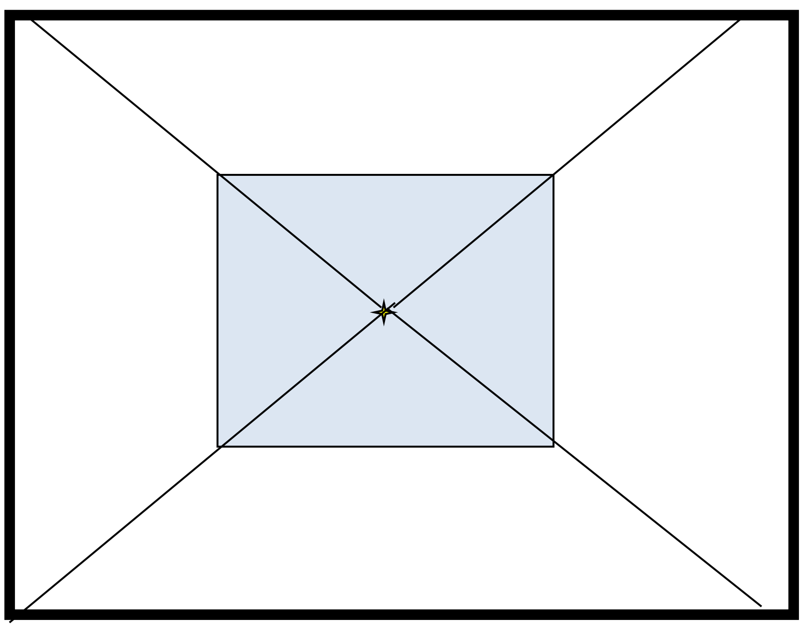
Left Camera



Right Camera

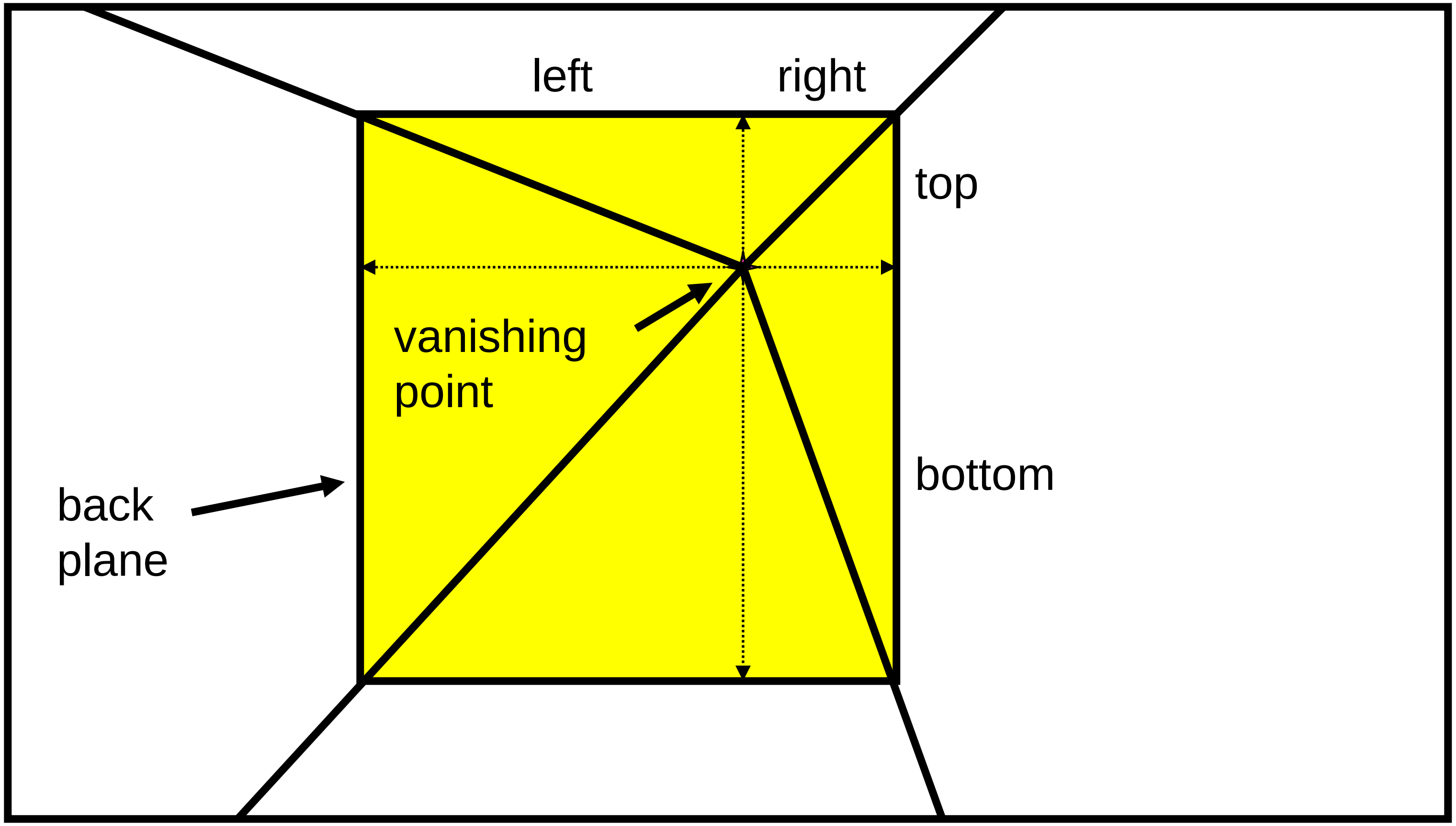
Question

- Think about the camera center and image plane…
  - What happens when we move the box?
  - What happens when we move the vanishing point?



2D to 3D conversion

- First, we can get ratios

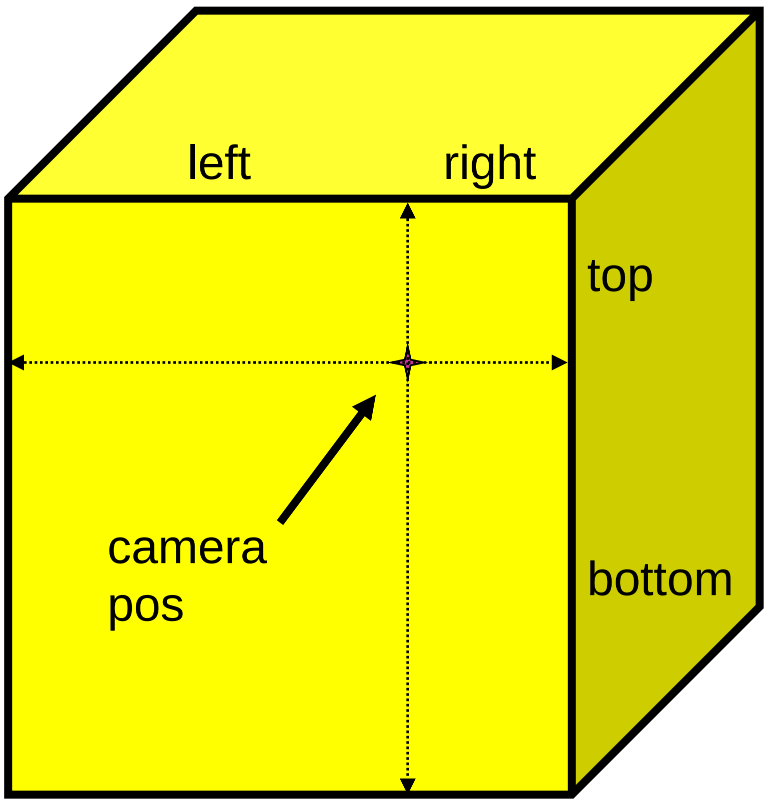


2D to 3D conversion

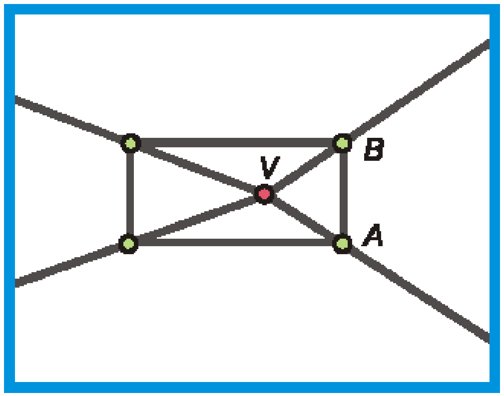
Size of user-defined back plane determines width/height throughout box (orthogonal sides)

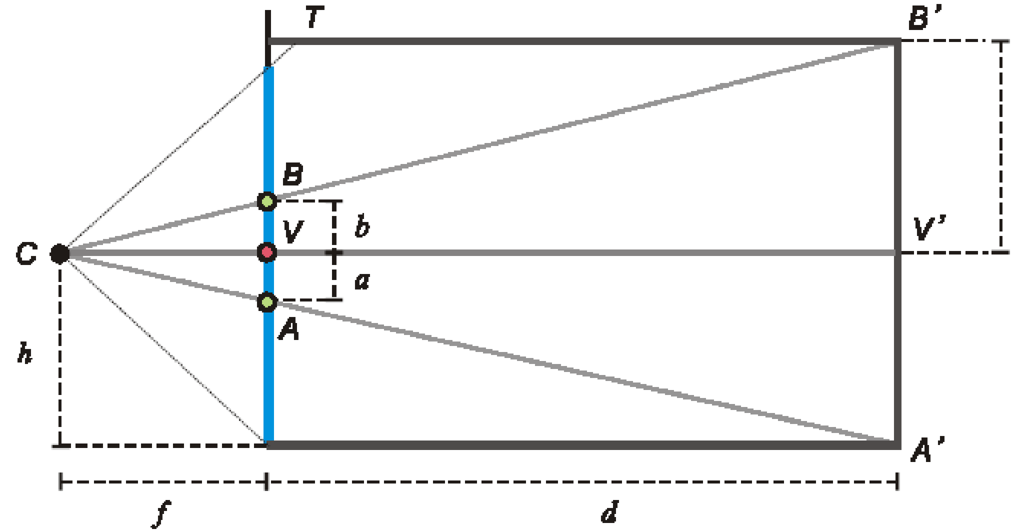
Use top versus side ratio to determine relative height and width dimensions of box

Left/right and top/bot ratios determine part of 3D camera placement



Depth of the box





- Can compute by similar triangles (CVA vs. CV'A')
- Need to know focal length f (or FOV)

- Note: can compute position on any object on the ground
  - Simple unprojection
  - What about things off the ground?

Step 2: map image textures into frontal view

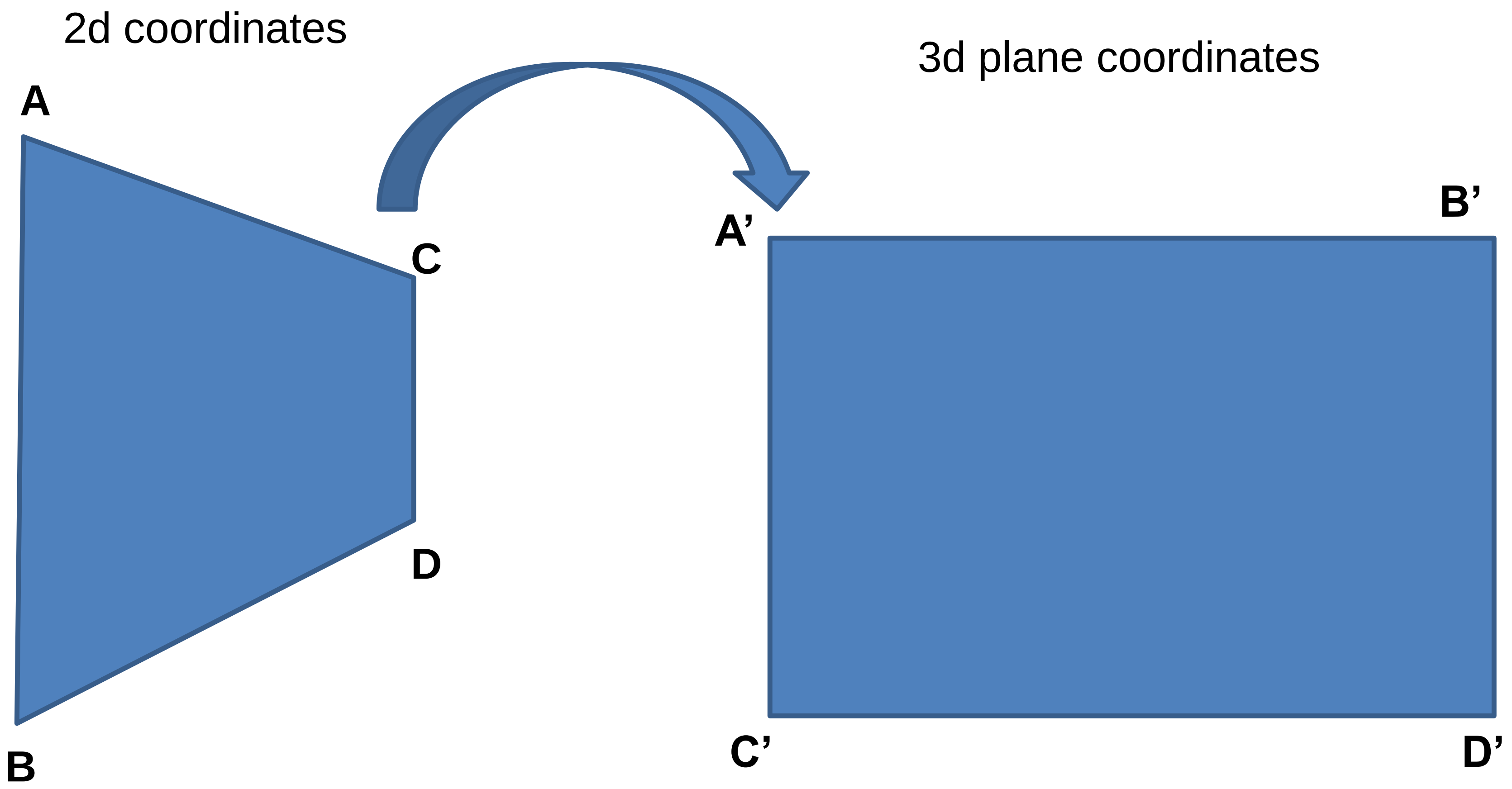
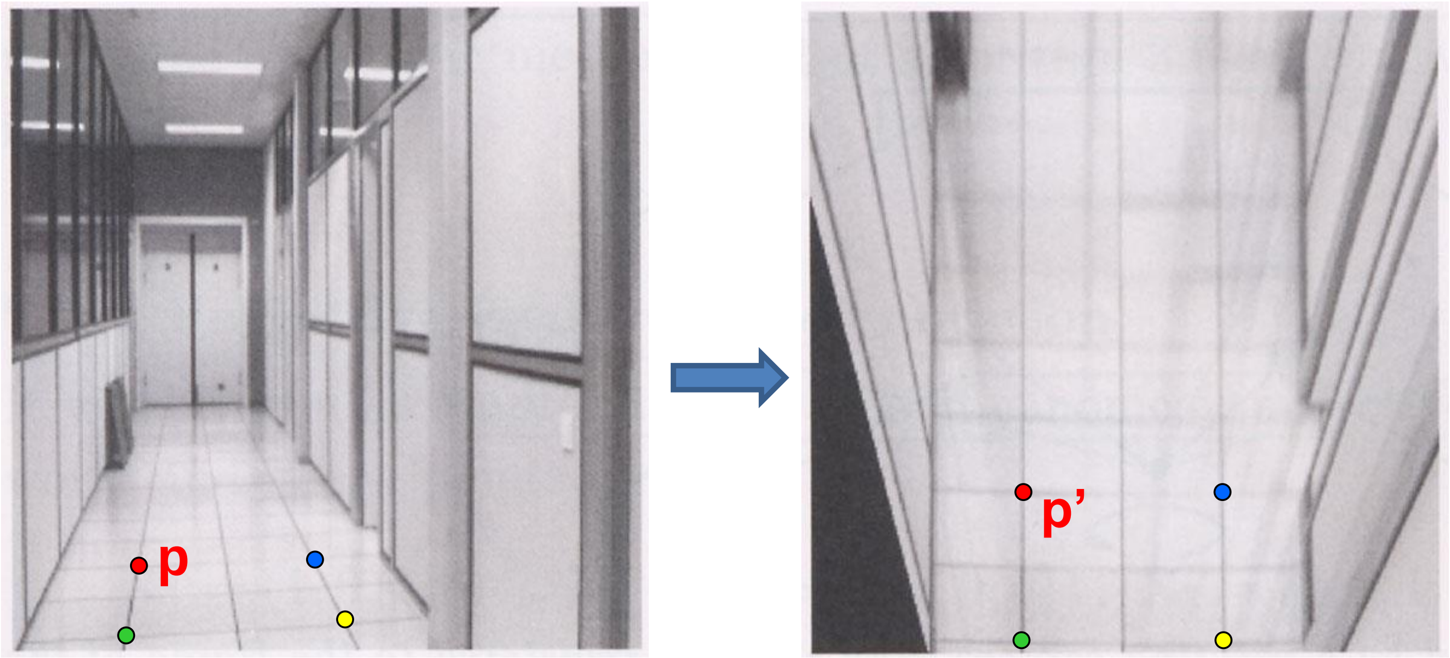


Image rectification



To unwarp (rectify) an image solve for homography **H** given **p** and **p'**: w**p'=Hp**

Computing homography

Assume we have four matched points: How do we compute homography **H**?

Direct Linear Transformation (DLT)

$$\mathbf{p}' = \mathbf{H}\mathbf{p} \qquad \mathbf{p}' = \begin{bmatrix} w'u' \\ w'v' \\ w' \end{bmatrix} \qquad \mathbf{H} = \begin{bmatrix} h_1 & h_2 & h_3 \\ h_4 & h_5 & h_6 \\ h_7 & h_8 & h_9 \end{bmatrix}$$

$$\begin{bmatrix} -u & -v & -1 & 0 & 0 & 0 & uu' & vu' & u' \\ 0 & 0 & 0 & -u & -v & -1 & uv' & vv' & v' \end{bmatrix} \mathbf{h} = \mathbf{0} \qquad \mathbf{h} = \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ h_5 \\ h_6 \\ h_7 \\ h_8 \\ h_9 \end{bmatrix}$$

Computing homography

Direct Linear Transform

$$\begin{bmatrix} -u_1 & -v_1 & -1 & 0 & 0 & 0 & u_1u_1' & v_1u_1' & u_1' \\ 0 & 0 & 0 & -u_1 & -v_1 & -1 & u_1v_1' & v_1v_1' & v_1' \\ & & & & \vdots & & & & \\ 0 & 0 & 0 & -u_n & -v_n & -1 & u_nv_n' & v_nv_n' & v_n' \end{bmatrix} \mathbf{h} = \mathbf{0} \Rightarrow \mathbf{Ah} = \mathbf{0}$$

- Apply SVD: $\boldsymbol{USV}^T = \boldsymbol{A}$
- $\boldsymbol{h} = \boldsymbol{V}_{\text{smallest}}$ (column of $\boldsymbol{V}^T$ corr. to smallest singular value)

$$\mathbf{h} = \begin{bmatrix} h_1 \\ h_2 \\ \vdots \\ h_9 \end{bmatrix} \quad \mathbf{H} = \begin{bmatrix} h_1 & h_2 & h_3 \\ h_4 & h_5 & h_6 \\ h_7 & h_8 & h_9 \end{bmatrix}$$

Matlab

```
[U, S, V] = svd(A);
h = V(:, end);
```

Explanation of SVD, solving systems of linear equations, derivation of solution here

Solving for homographies (more detail)

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

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

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

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

Solving for homographies (more detail)

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

A **h** **0**

2n × 9 **9** **2n**

Defines a least squares problem: $\text{minimize } \|\mathbf{A}\mathbf{h} - \mathbf{0}\|^2$

- Since **h** is only defined up to scale, solve for unit vector $\hat{\mathbf{h}}$
- Solution: $\hat{\mathbf{h}}$ = eigenvector of $\mathbf{A}^T\mathbf{A}$ with smallest eigenvalue
- Works with 4 or more points

Tour into the picture algorithm

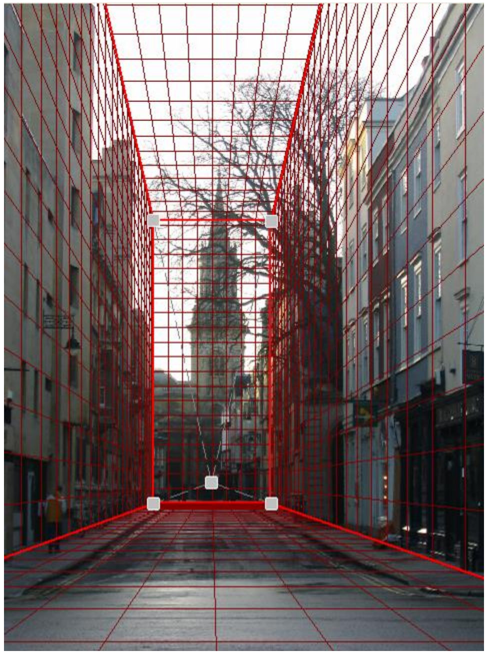
1. Set the box corners

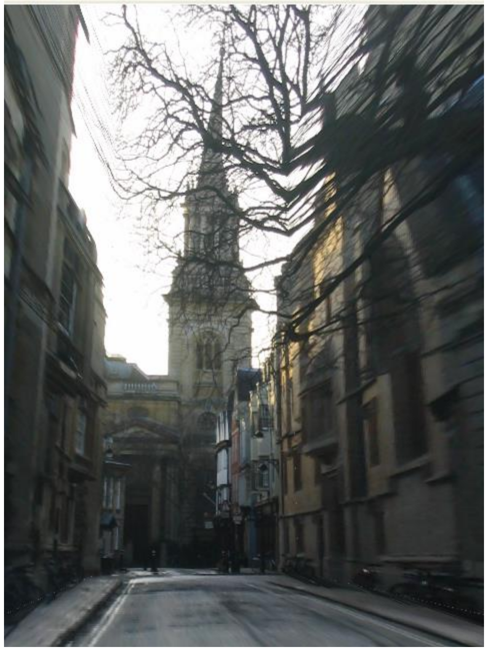
Tour into the picture algorithm

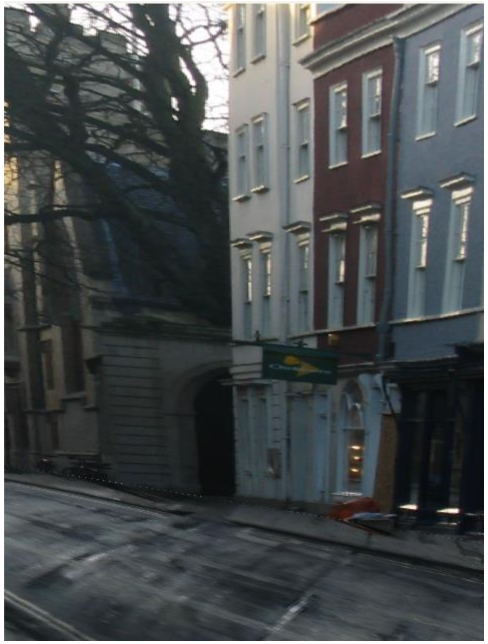
1. Set the box corners
2. Set the VP
3. Get 3D coordinates
   - Compute height, width, and depth of box
4. Get texture maps
   - homographies for each face
5. Create file to store plane coordinates and texture maps

Result

Render from new views







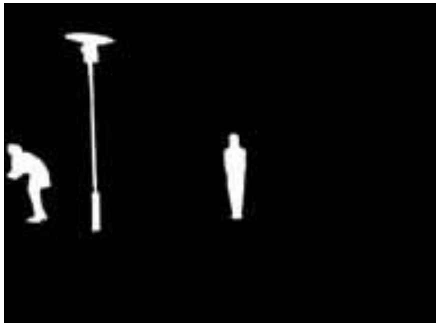
http://www.cs.cmu.edu/afs/cs.cmu.edu/academic/class/15463-f08/www/proj5/www/dmillett/

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

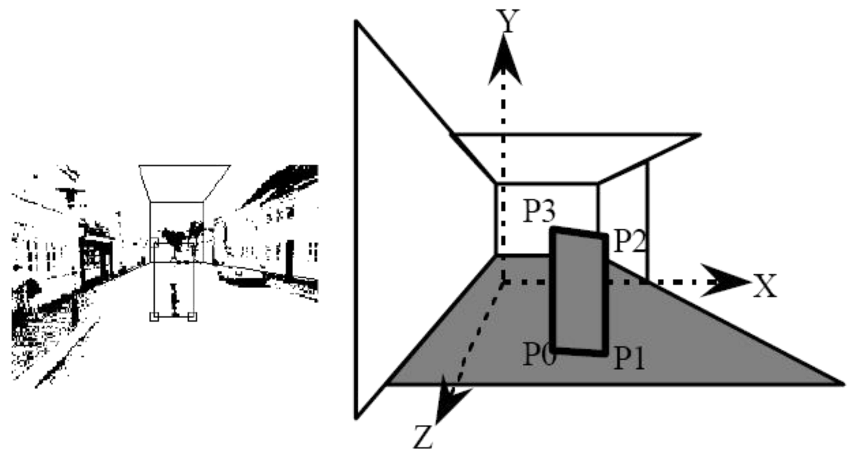


Foreground Objects

Add vertical rectangles for each foreground object

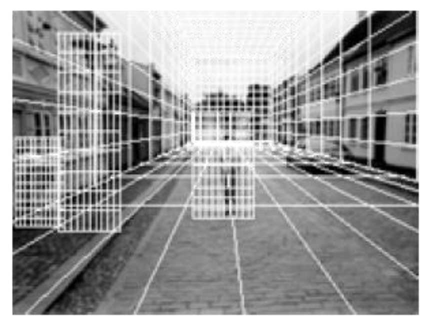
Can compute 3D coordinates P0, P1 since they are on known plane.

P2, P3 can be computed as before (similar triangles)



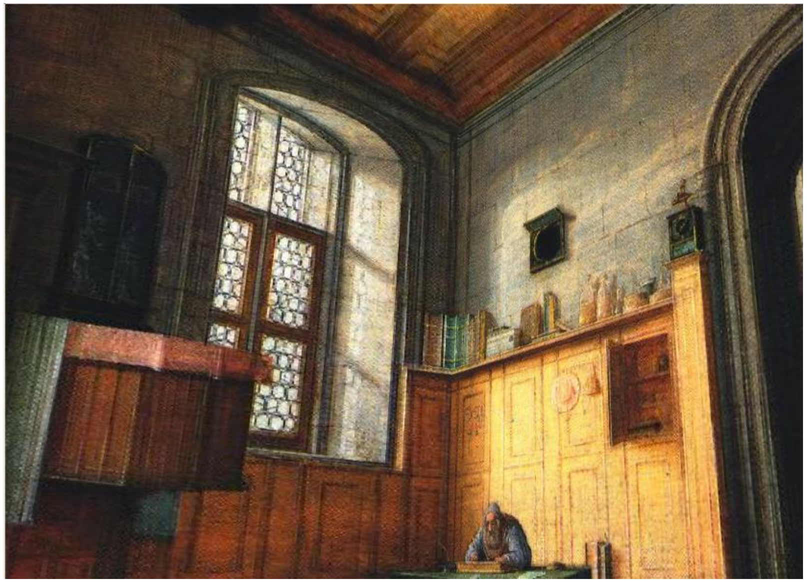
(a) Specifying of a foreground object

(b) Estimating the vertices of the foreground object model



(c) Three foreground object models

Foreground Result



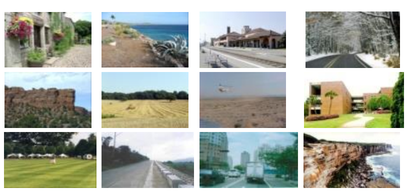
Video from CMU class:
http://www.youtube.com/watch?v=dUAtdmGwcuM

Automatic Photo Pop-up

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

Image

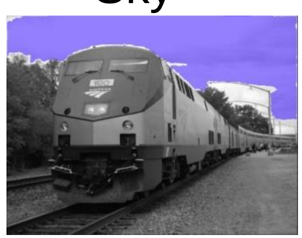
Learned Models

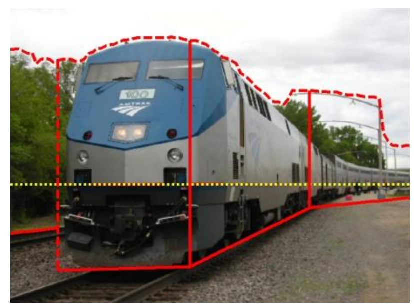


Ground

Vertical

Sky



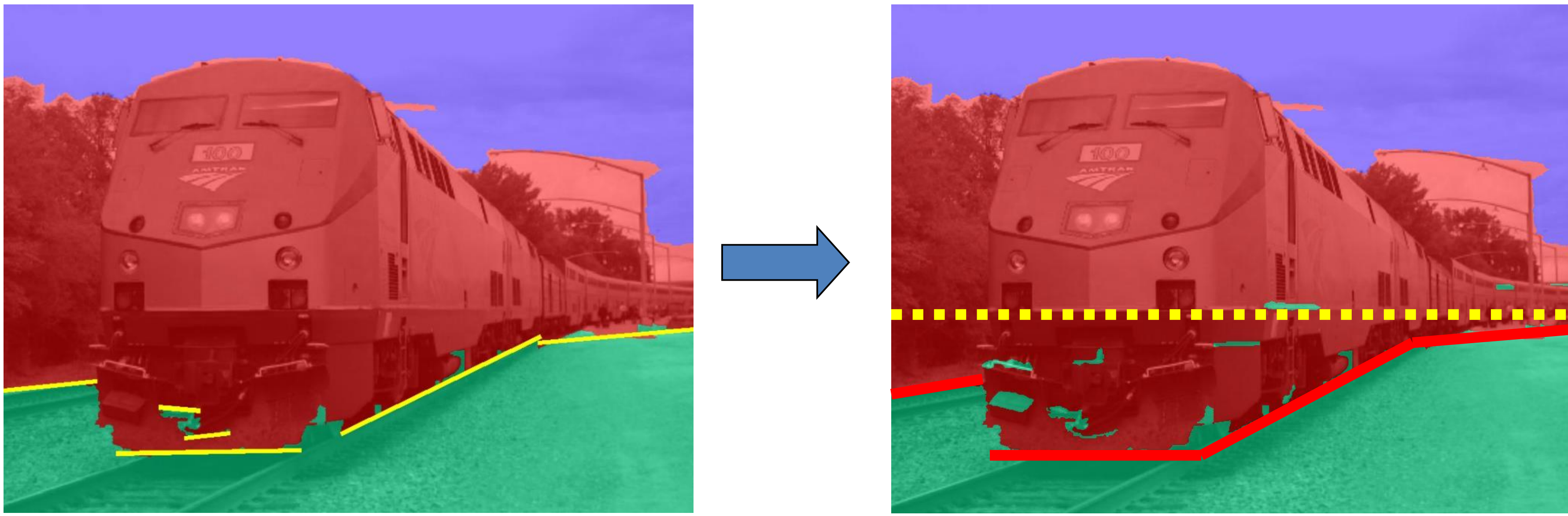


Hoiem et al. 2005

Cutting and Folding

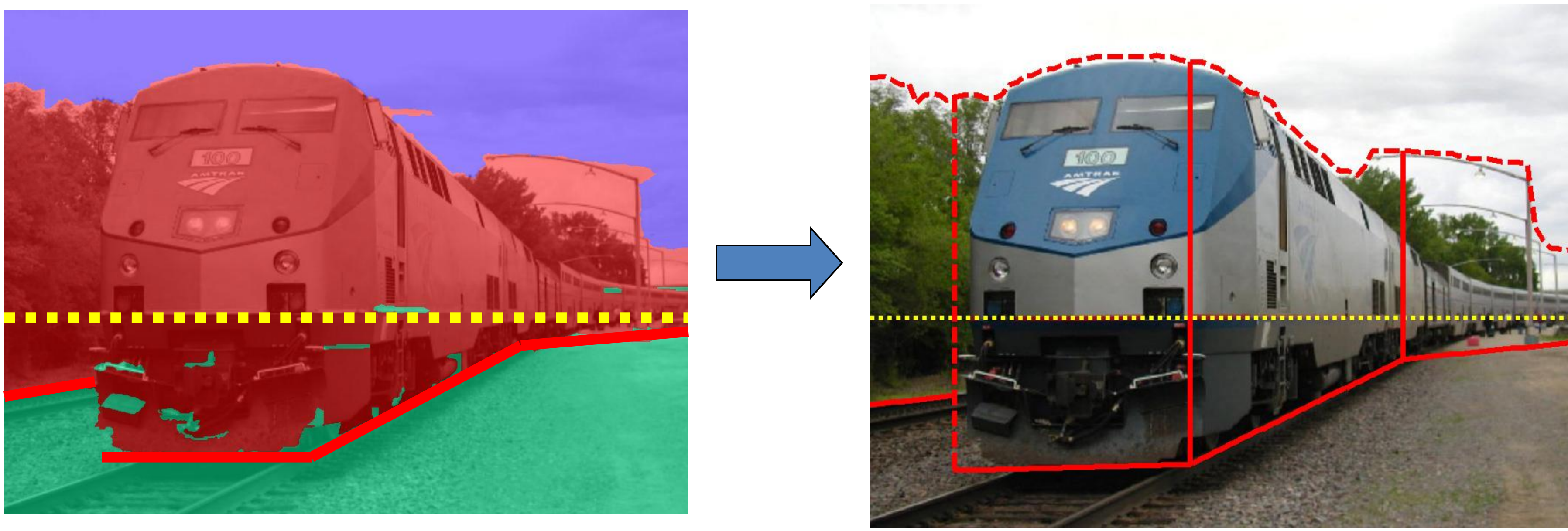
- Fit ground-vertical boundary
  - Iterative Hough transform

Cutting and Folding



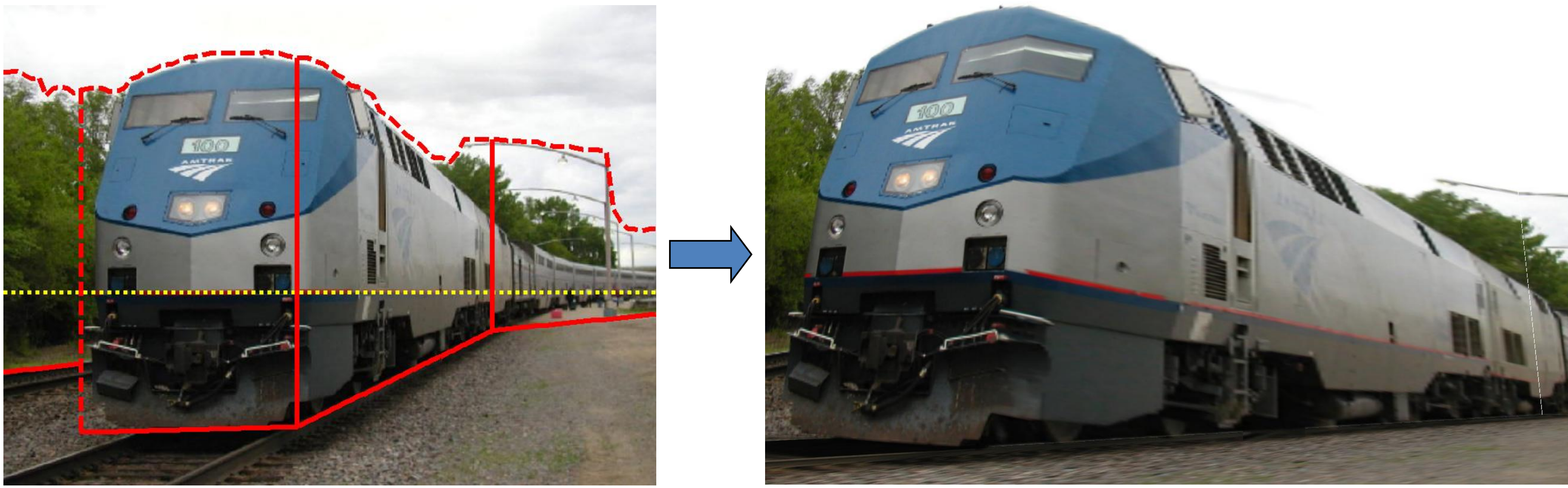
- Form polylines from boundary segments
  - Join segments that intersect at slight angles
  - Remove small overlapping polylines
- Estimate horizon position from perspective cues

Cutting and Folding



- ``Fold’’ along polylines and at corners
- ``Cut’’ at ends of polylines and along vertical-sky boundary

Cutting and Folding

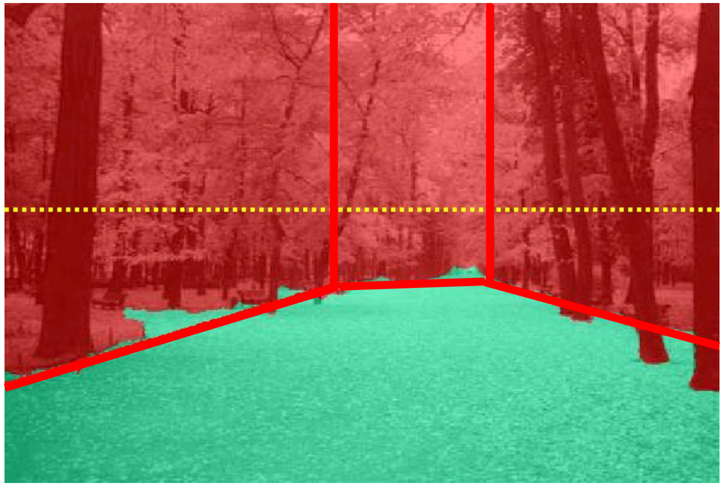


- Construct 3D model
- Texture map

Results

http://www.cs.illinois.edu/homes/dhoiem/projects/popup/

Input Image



Cut and Fold

Automatic Photo Pop-up

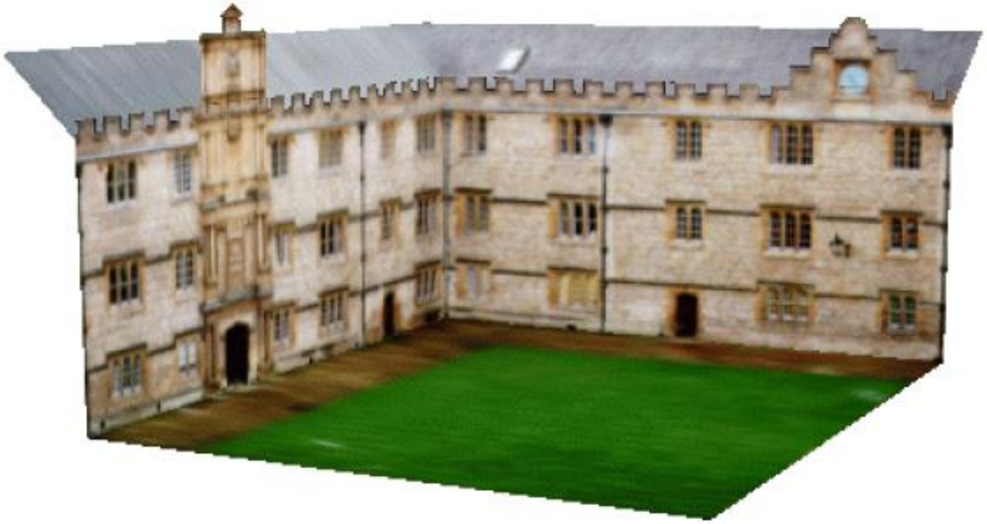
Results

Input Image

Automatic Photo Pop-up

Comparison with Manual Method

Input Image



[Liebowitz et al. 1999]

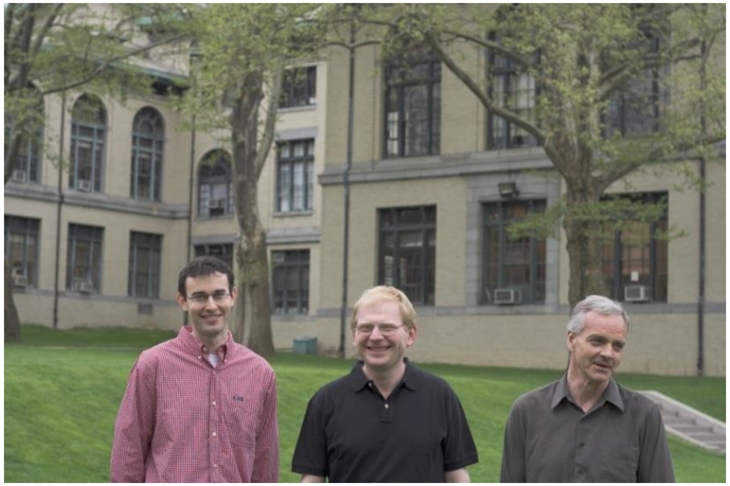
Automatic Photo Pop-up (15 sec)!

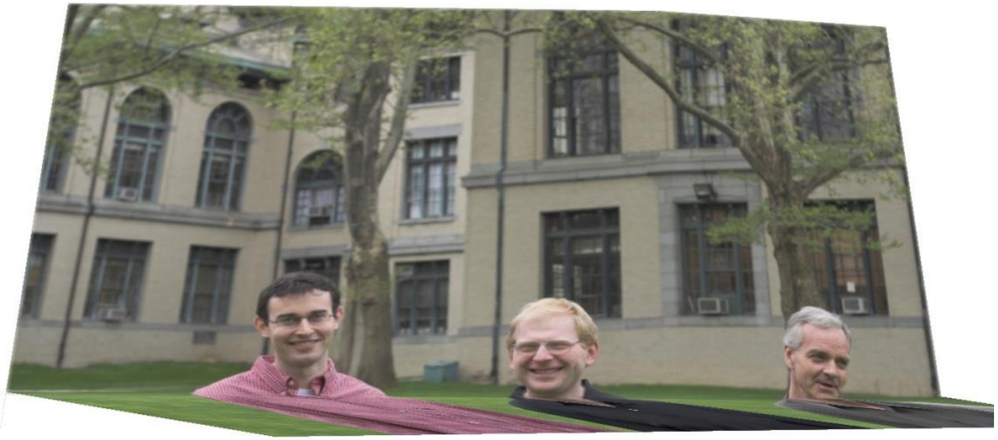
Failures

Labeling Errors

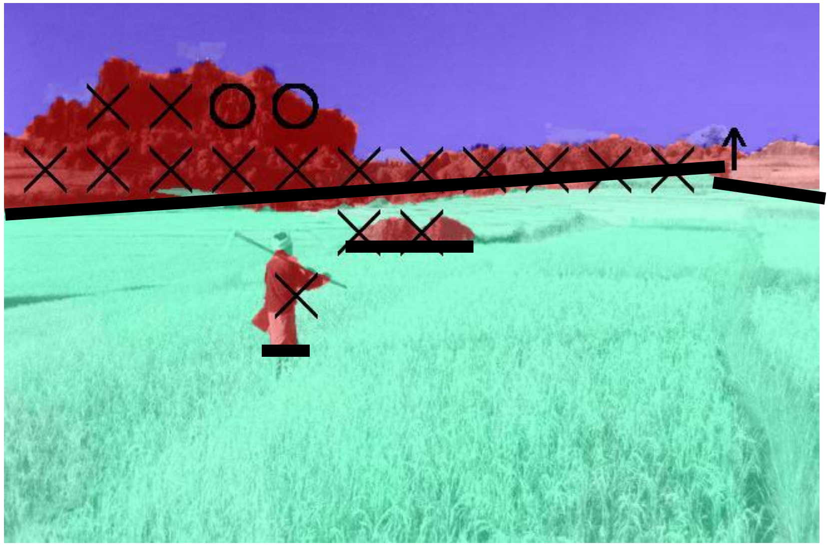
Failures

Foreground Objects

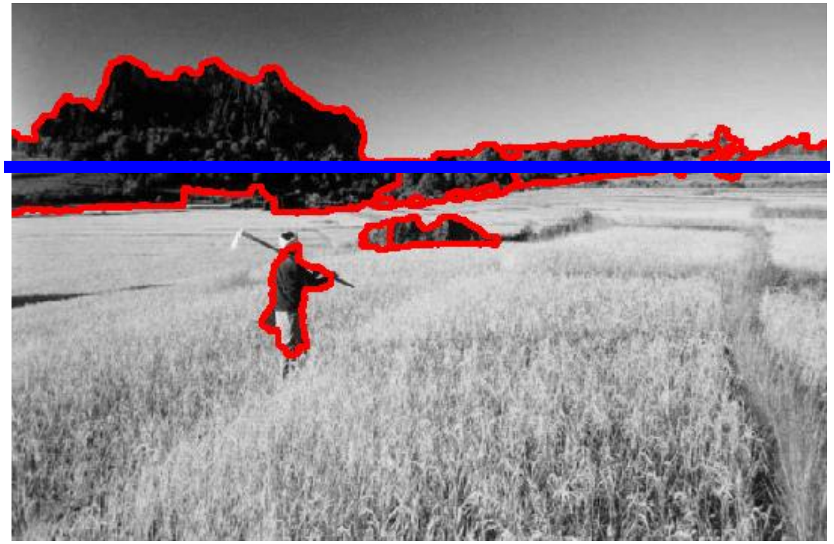




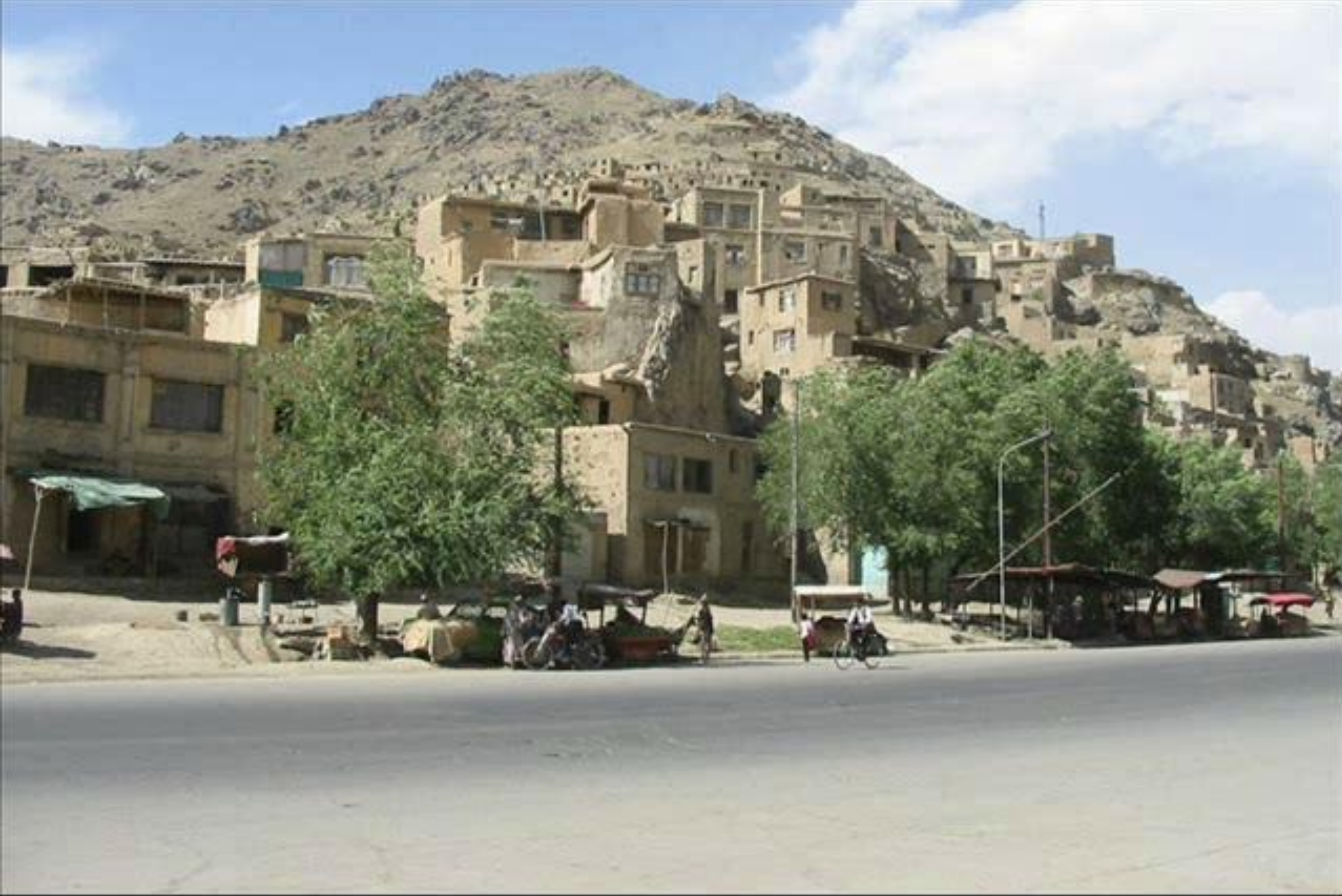
Adding Foreground Labels



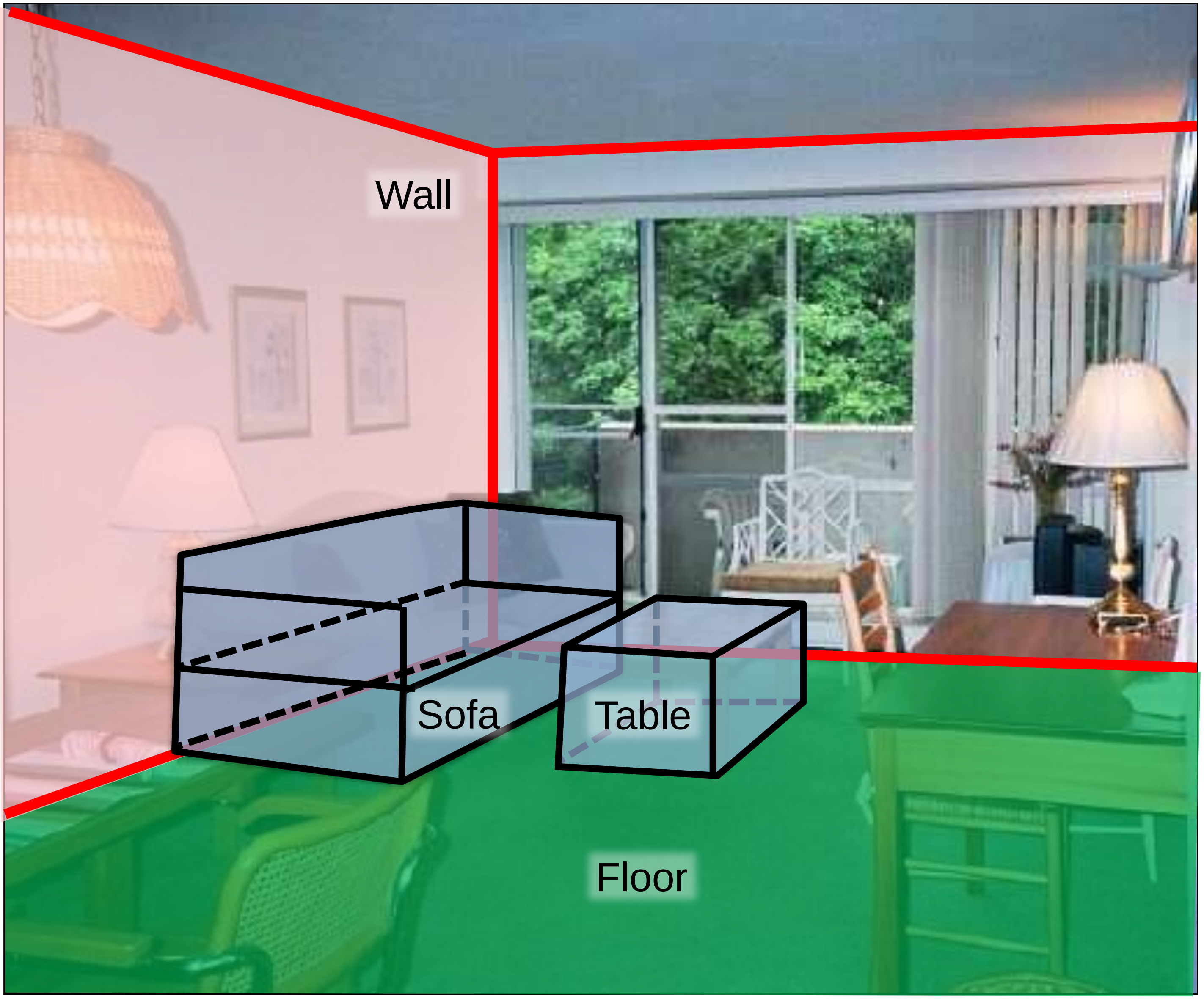
Recovered Surface Labels +
Ground-Vertical Boundary Fit



Object Boundaries + Horizon

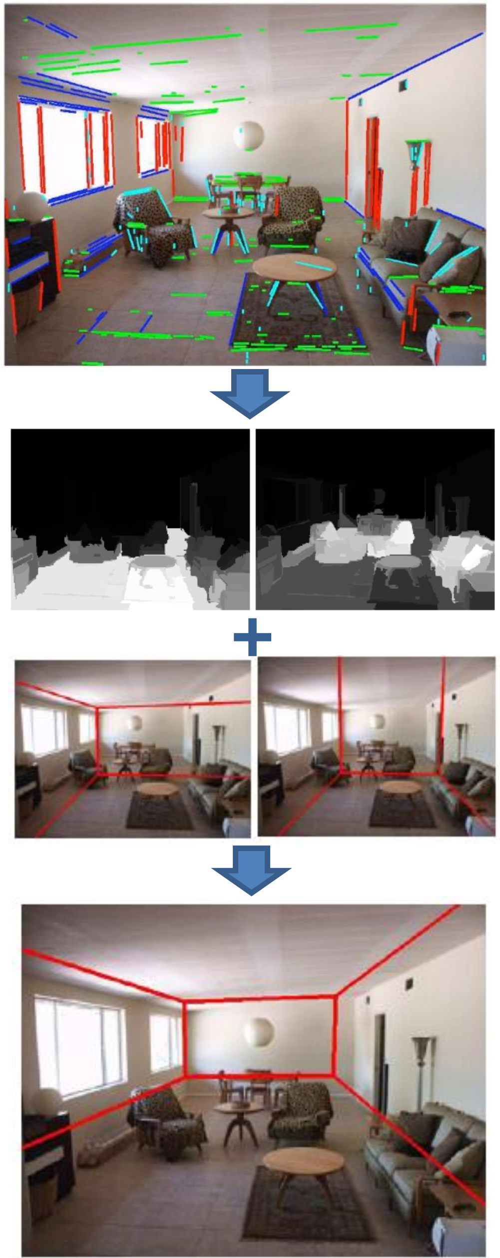


Fitting boxes to indoor scenes



Box Layout Algorithm

Hedau et al. 2010



1. Detect edges
2. Estimate 3 orthogonal vanishing points
3. Apply region classifier to label pixels with visible surfaces
   - Boosted decision trees on region based on color, texture, edges, position
4. Generate box candidates by sampling pairs of rays from VPs
5. Score each box based on edges and pixel labels
   - Learn score via structured learning
6. Jointly refine box layout and pixel labels to get final estimate

Experimental results

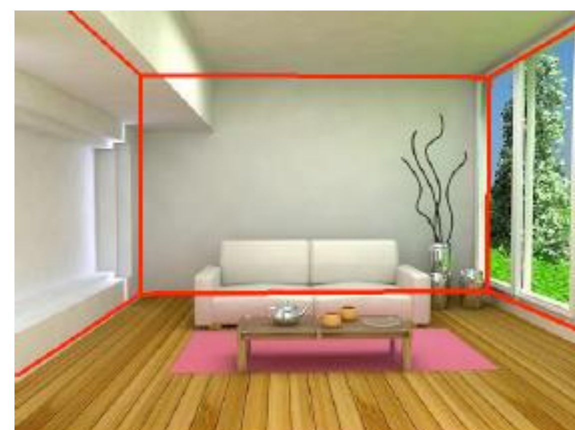

Detected Edges


Surface Labels


Box Layout


Detected Edges


Surface Labels

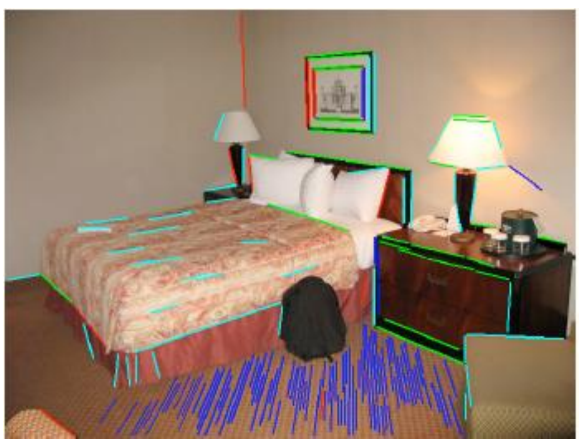

Box Layout

Experimental results


Detected Edges


Surface Labels

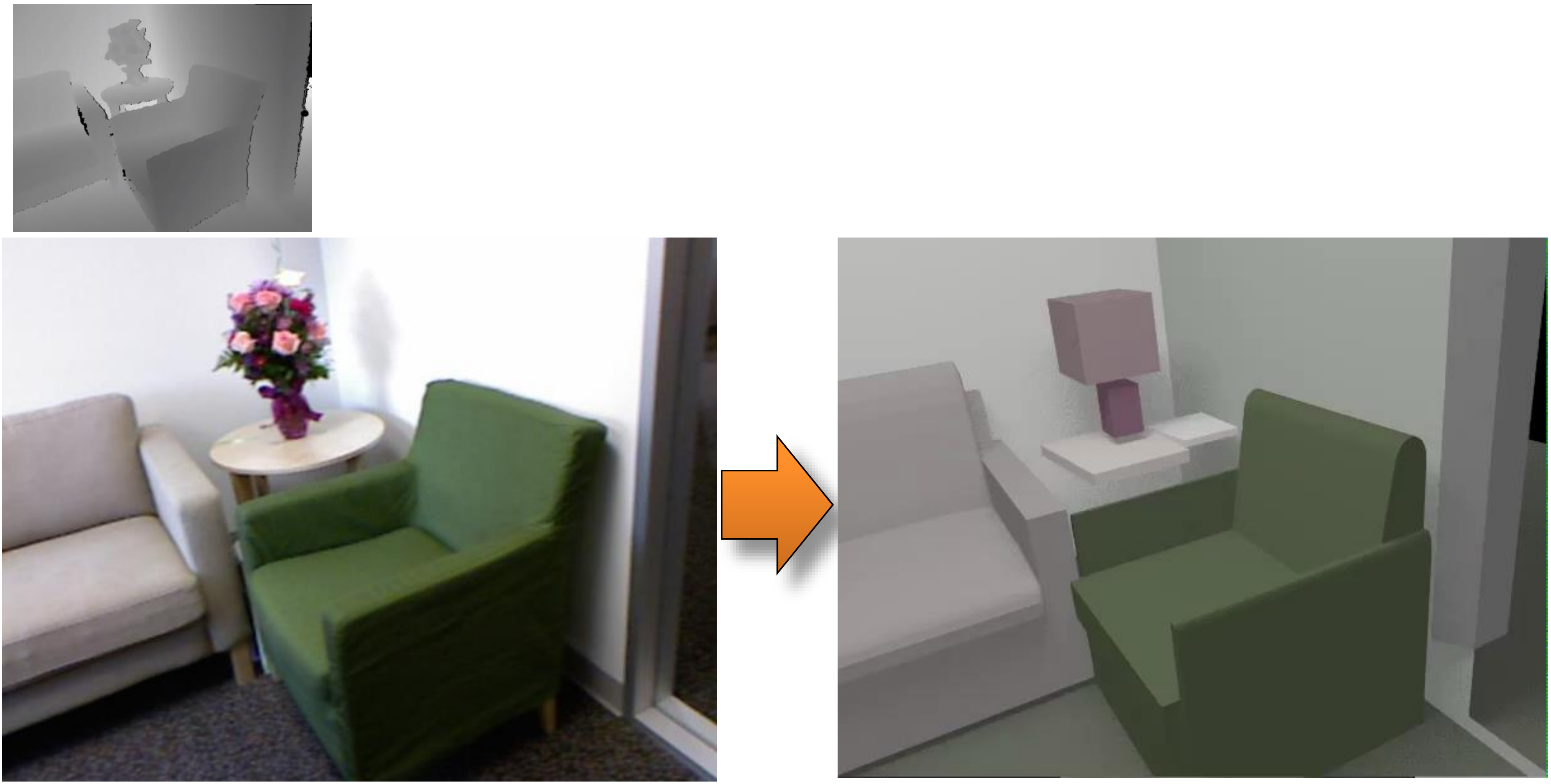

Box Layout


Detected Edges


Surface Labels

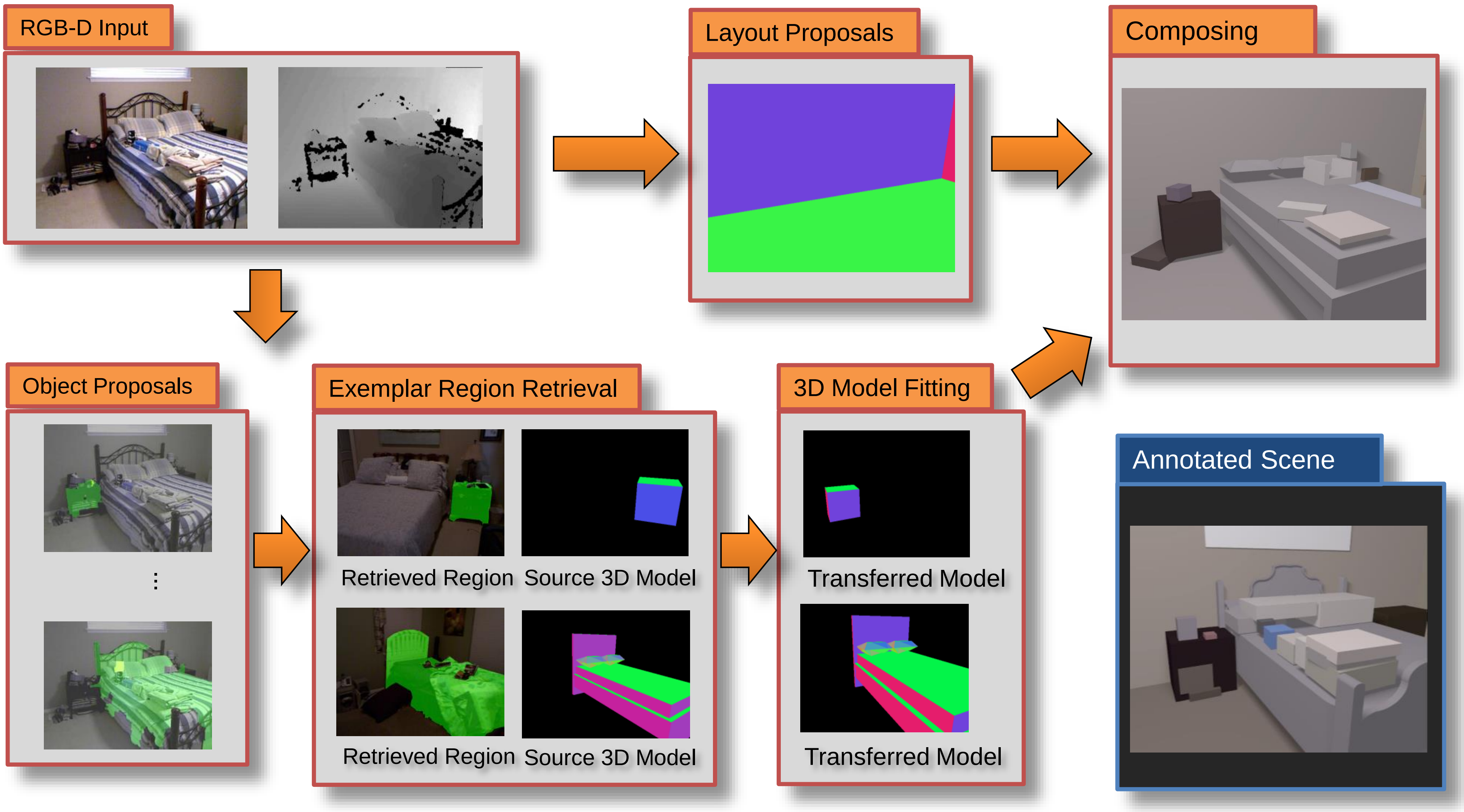

Box Layout

Complete 3D from RGBD

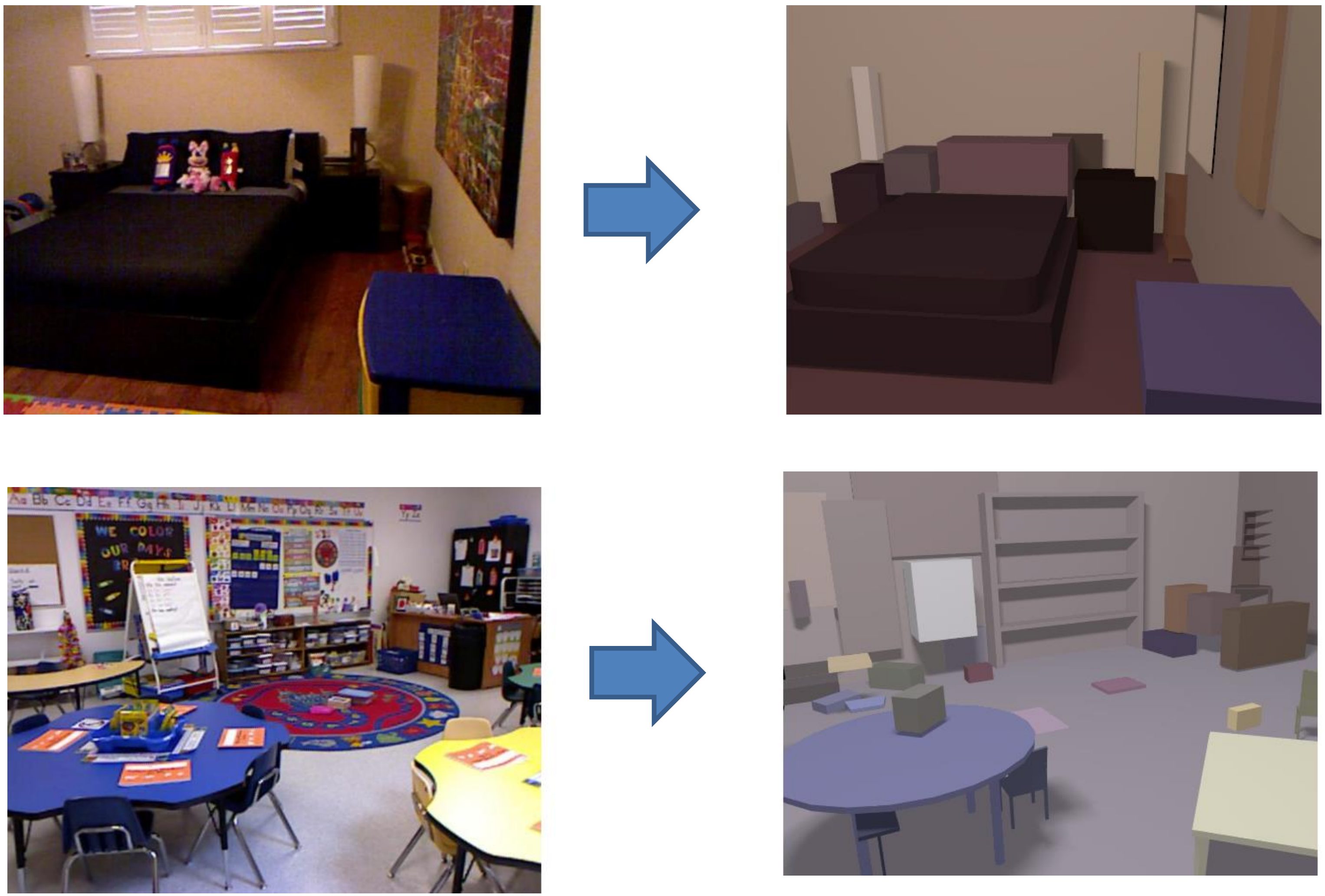


Guo Hoiem, to be submitted

Complete 3D from RGBD



Complete 3D from RGBD



Final project ideas

- If a one-person project:
  - Interactive program to make 3D model from an image (e.g., output in VRML, or draw path for animation)

- If a two-person team, 2^{nd} person:
  - Add tools for cutting out foreground objects and automatic hole-filling

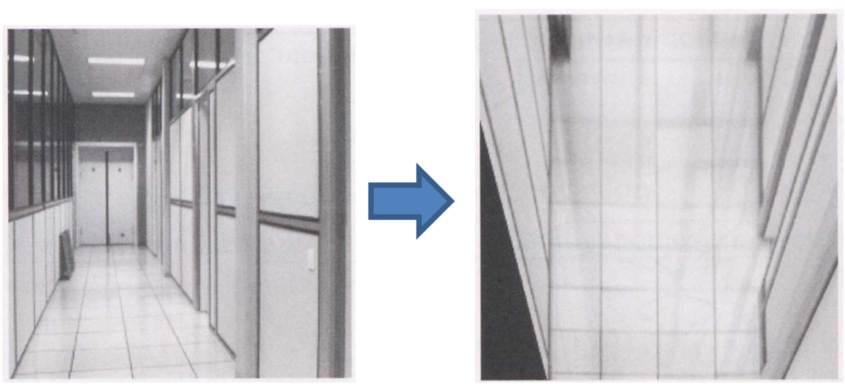
Summary

- 2D→3D is mathematically impossible

  (but we do it without even thinking)

- Need right assumptions about the world geometry

- Important tools
  - Vanishing points
  - Camera matrix
  - Homography



Next Week

- Project 3 is due Monday
- Next three classes: image-based lighting
  - How to model light
  - Recover HDR image from multiple LDR images
  - Recover lighting model from an image
  - Render object into a scene with correct lighting and geometry