Automatic Image Alignment

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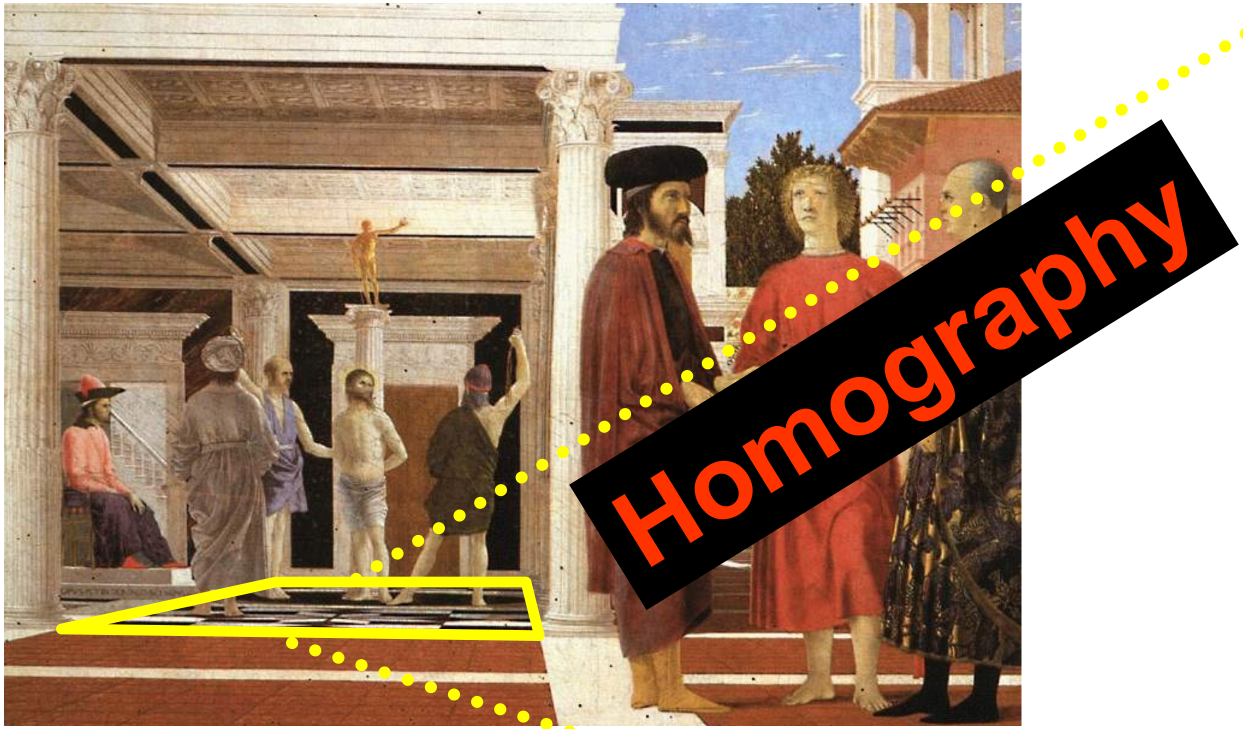
CS180: Intro to Comp. Vision and Comp. Photo
Alexei Efros, UC Berkeley, Fall 2024

with a lot of slides stolen from
Steve Seitz and Rick Szeliski

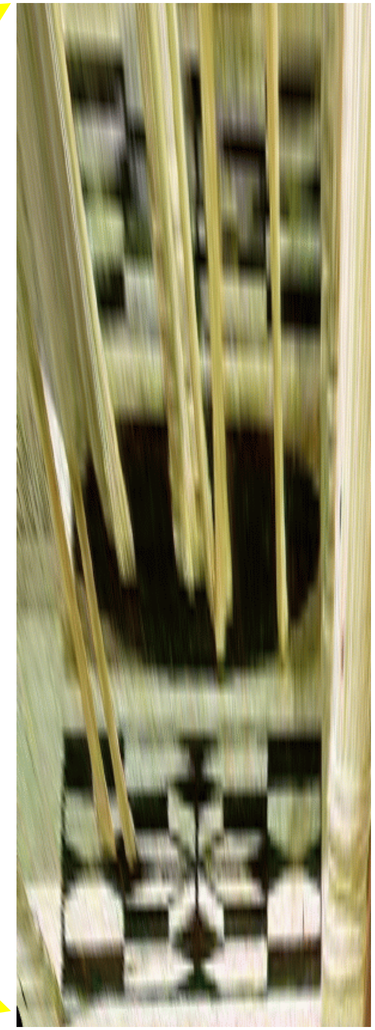
From last lecture…

Analysing patterns and shapes

What is the shape of the b/w floor pattern?



The floor (enlarged)

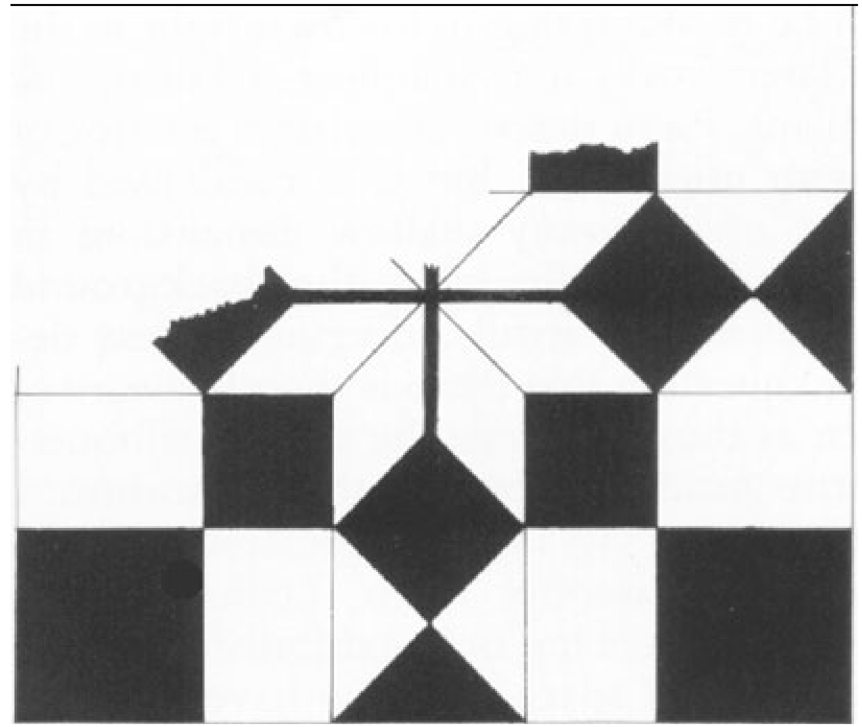


Automatically rectified floor

Slide from Criminisi

Analysing patterns and shapes

Automatic rectification



From Martin Kemp *The Science of Art* *(manual reconstruction)*

2 patterns have been discovered !

Slide from Criminisi

Julian Beever: Manual Homographies

http://users.skynet.be/J.Beever/pave.htm

Holbein, *The Ambassadors*

Mosaics: stitching images together

virtual wide-angle camera

Why Mosaic?

Are you getting the whole picture?

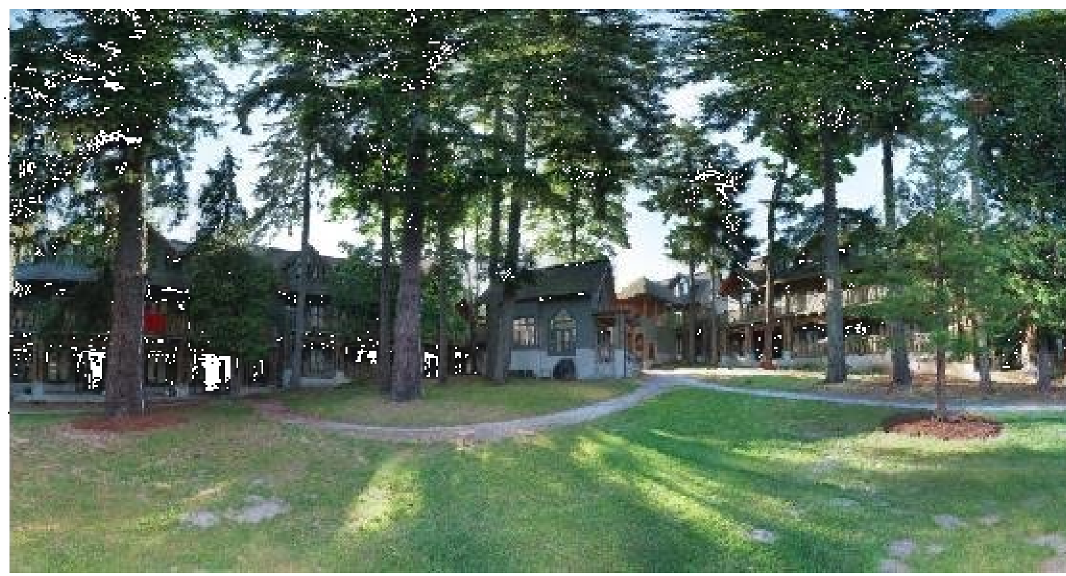
- Compact Camera FOV = 50 x 35°

Slide from Brown & Lowe

Why Mosaic?

Are you getting the whole picture?

- Compact Camera FOV = 50 x 35°
- Human FOV = 200 x 135°

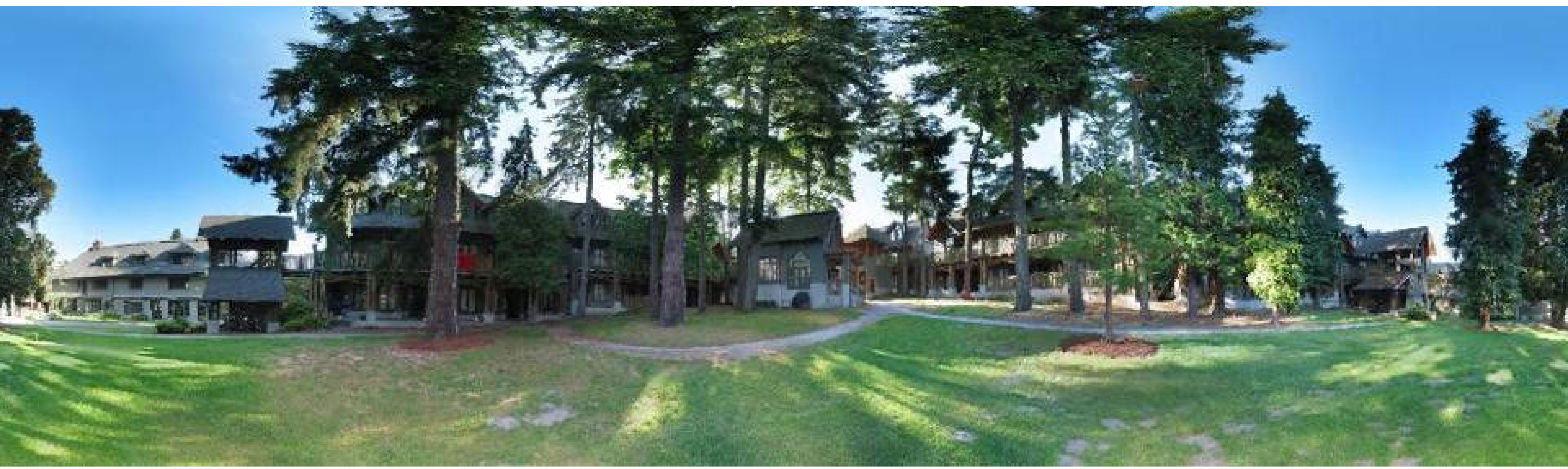


Slide from Brown & Lowe

Why Mosaic?

Are you getting the whole picture?

- Compact Camera FOV = 50 x 35°
- Human FOV = 200 x 135°
- Panoramic Mosaic = 360 x 180°



Slide from Brown & Lowe

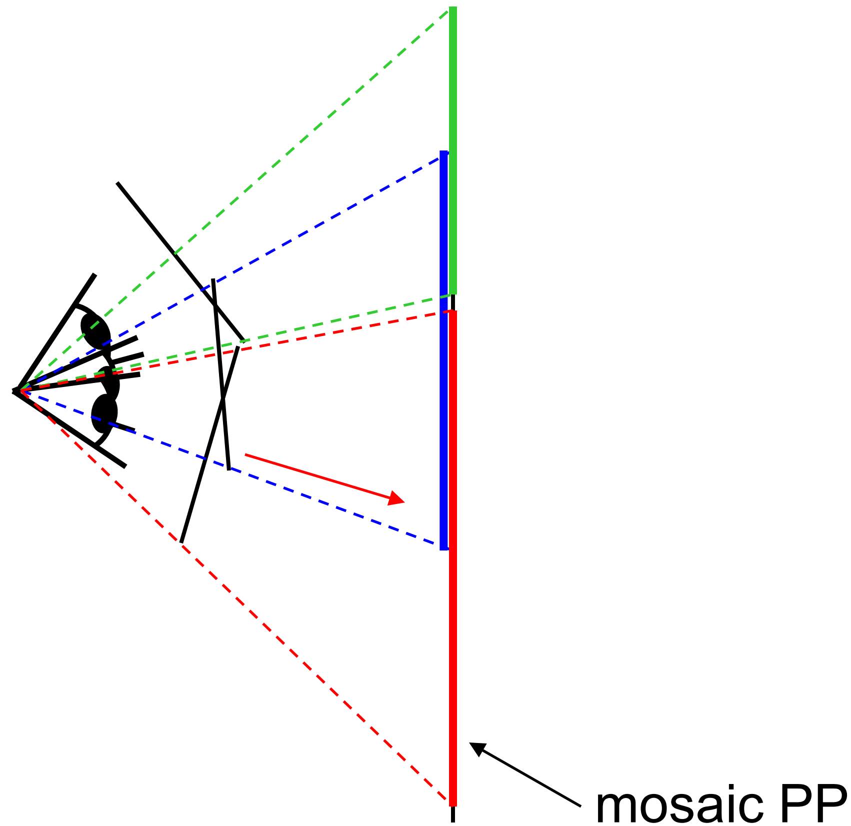
Naïve Stitching

left on top

right on top

Translations are not enough to align the images

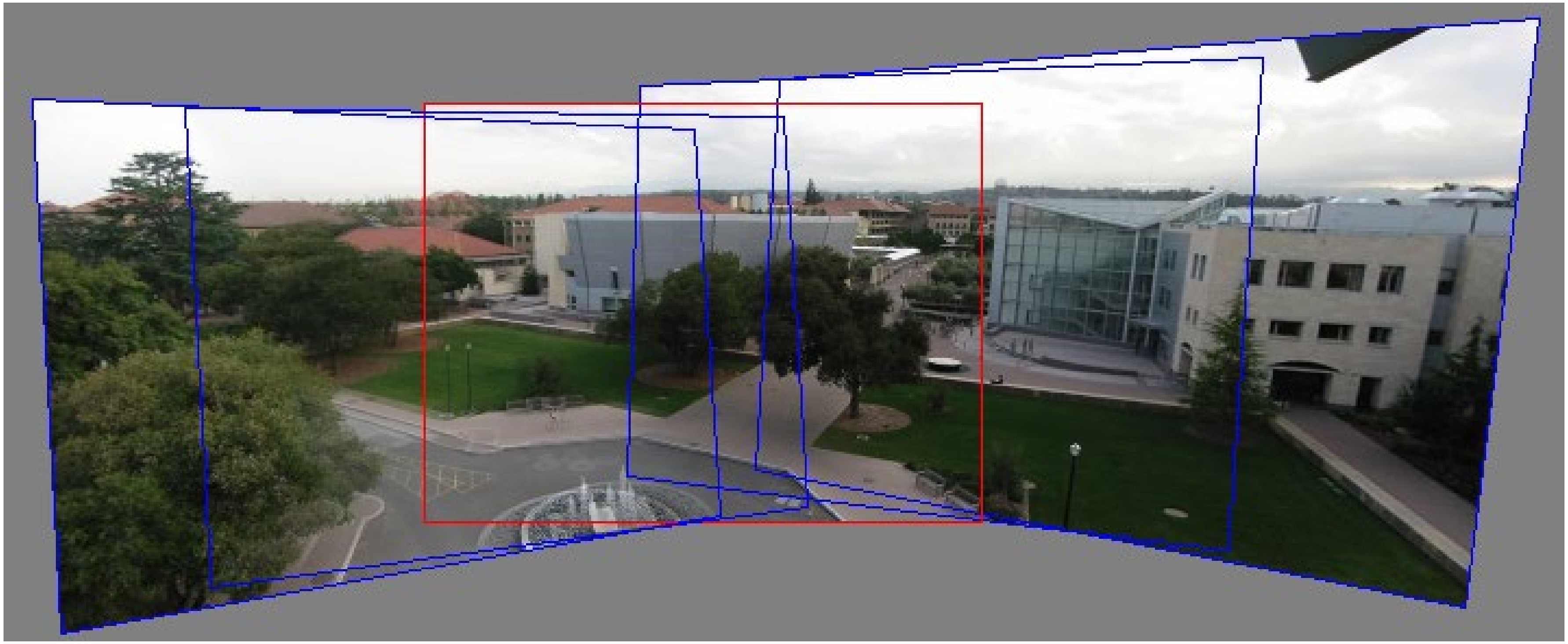
Image reprojection



The mosaic has a natural interpretation in 3D

- The images are reprojected onto a common plane
- The mosaic is formed on this plane
- Mosaic is a *synthetic wide-angle camera*

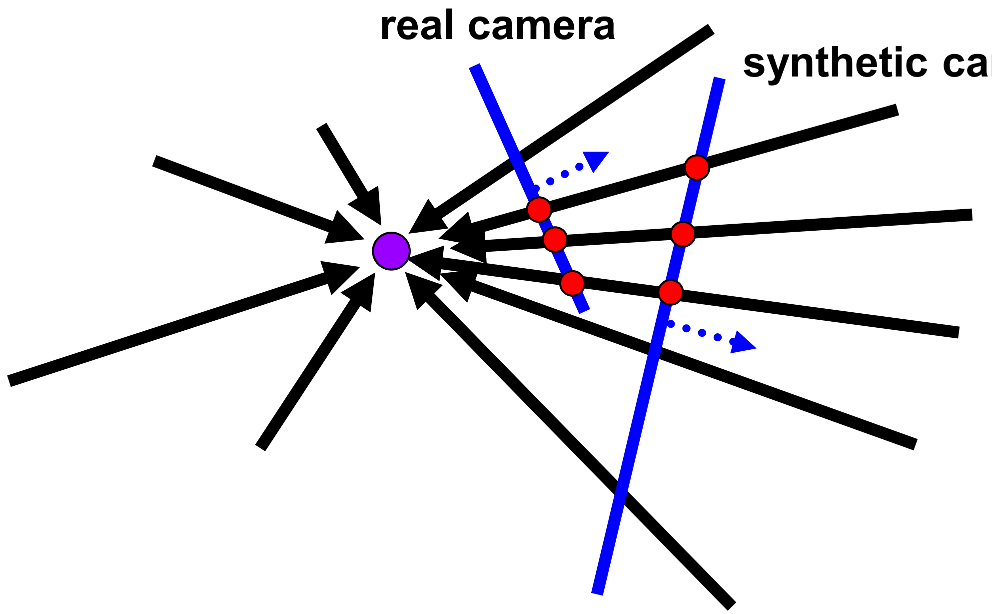
Panoramas



1. Pick one image (red)
2. Warp the other images towards it (usually, one by one)
3. blend

Tricky question…

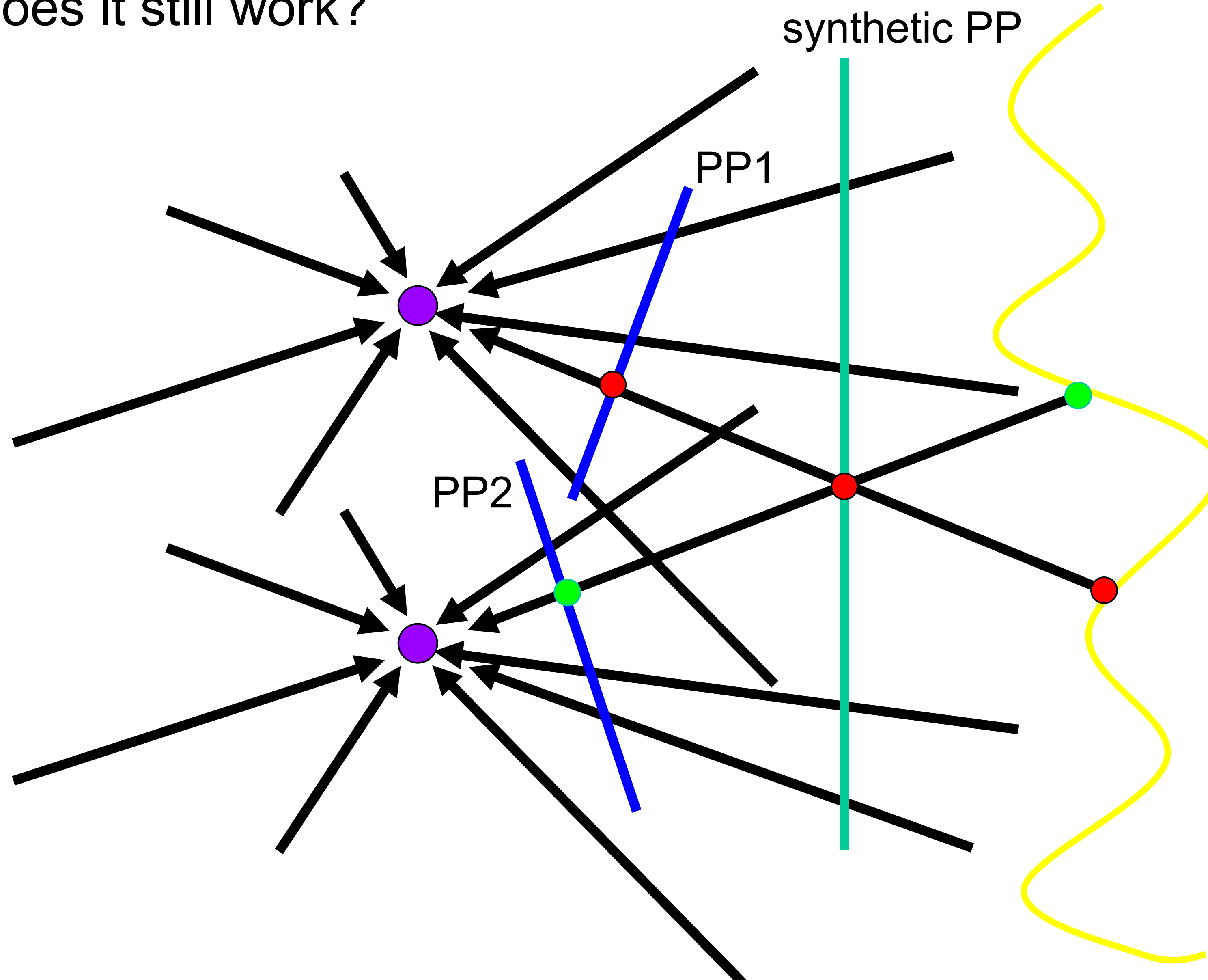
We can generate any synthetic camera view as long as it has the same center of projection!



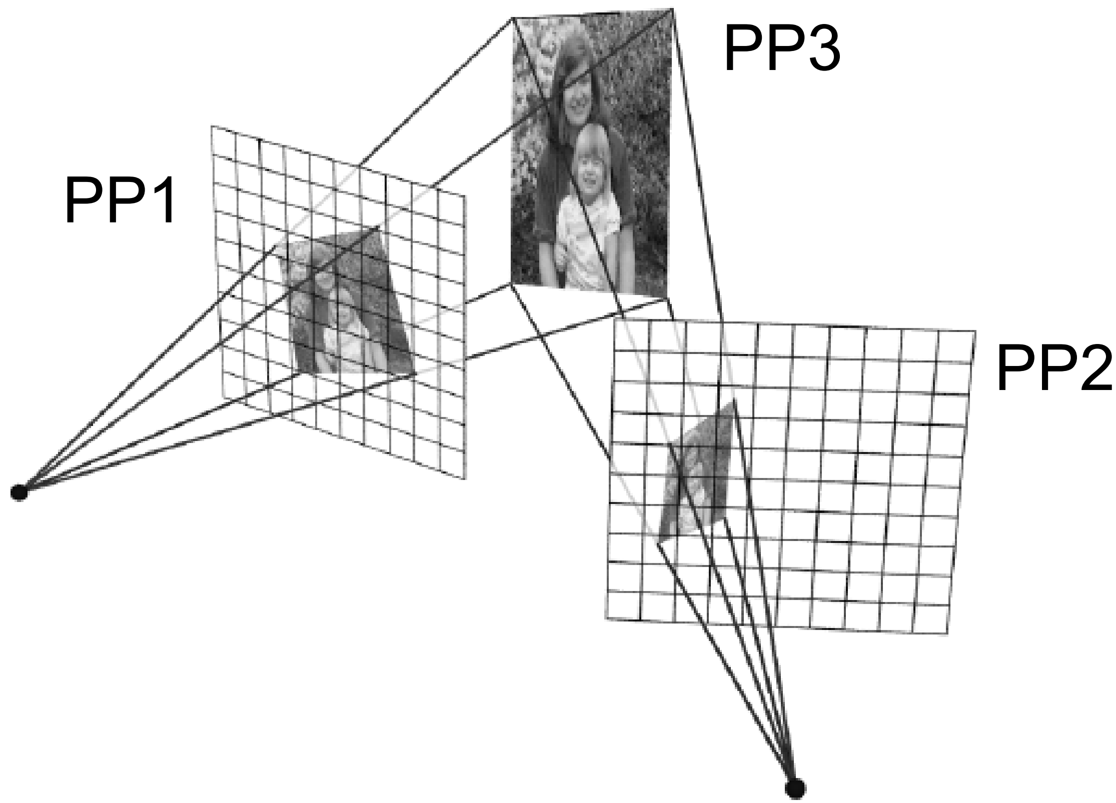
What happens if we move the center of projection?

changing camera center

Does it still work?



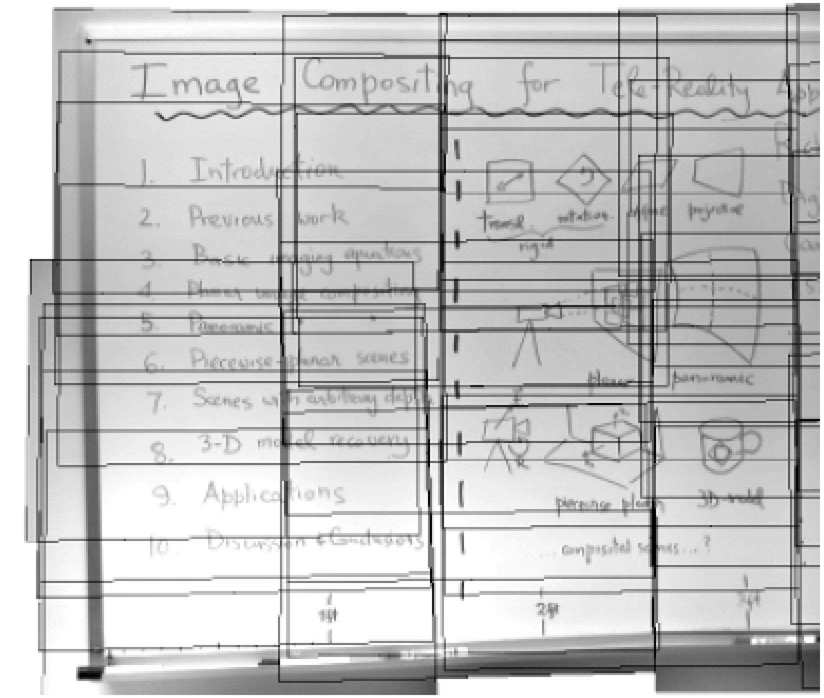
Planar scene (or far away)

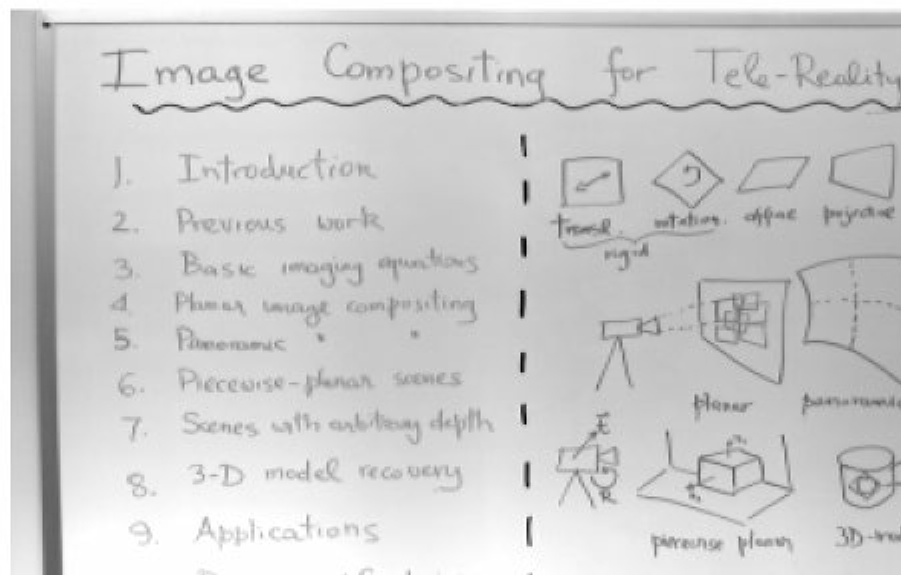


PP3 is a projection plane of both centers of projection, so we are OK!

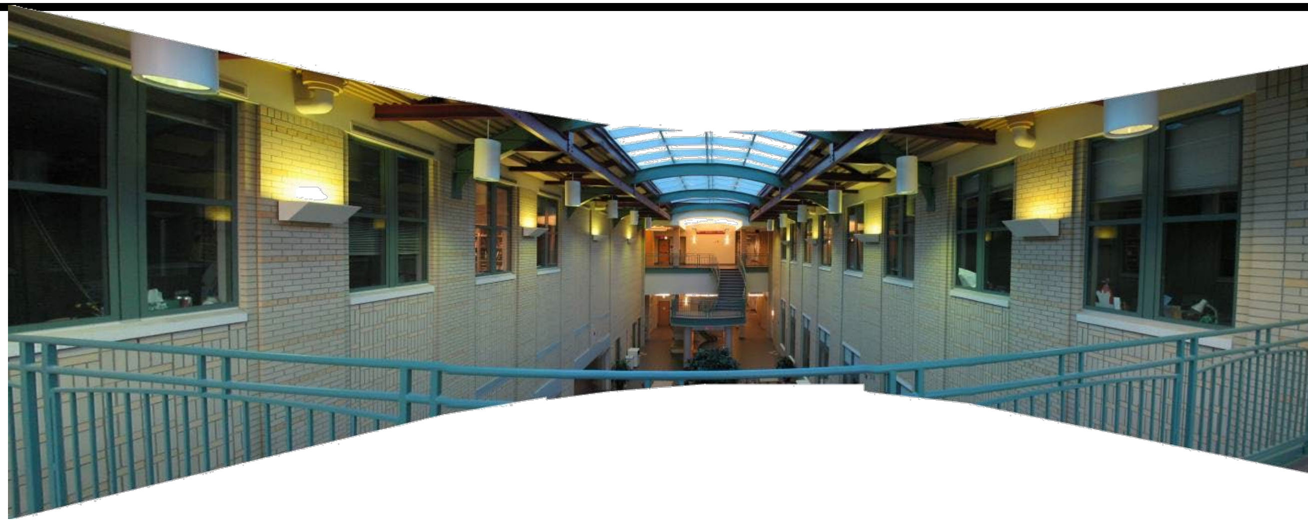
This is how big aerial photographs are made

Planar mosaic





Programming Project #4 (part 1)



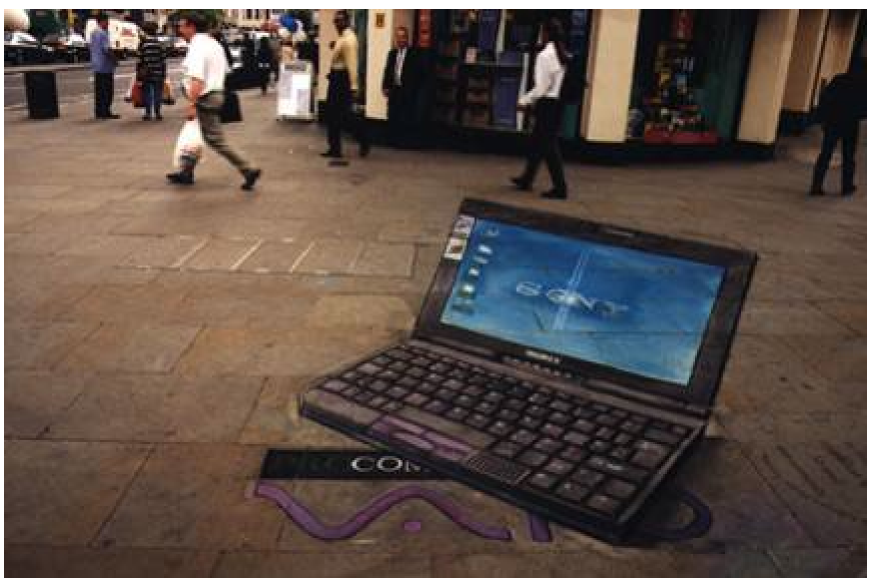
Homographies and Panoramic Mosaics

- Capture photographs
  - Might want to use tripod
- Compute homographies (define correspondences)
  - will need to figure out how to setup system of eqs.
- (un)warp an image (undo perspective distortion)
- Produce panoramic mosaics (with blending)

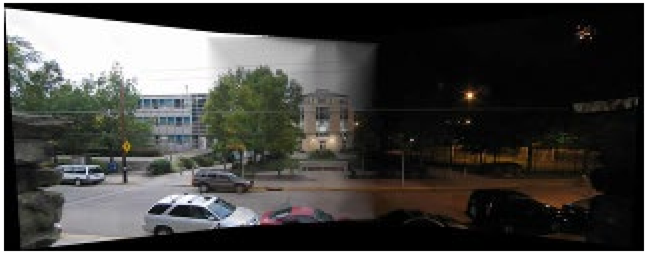
Bells and Whistles

Blending and Compositing

- use homographies to combine images or video and images together in an interesting (fun) way. E.g.
  - put fake graffiti on buildings or chalk drawings on the ground
  - replace a road sign with your own poster
  - project a movie onto a building wall
  - etc.



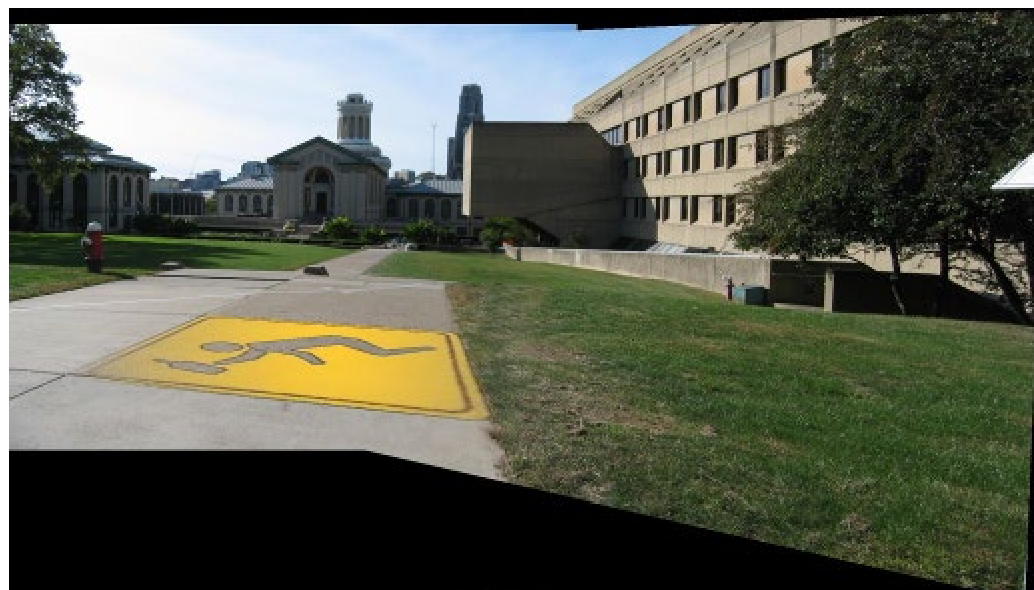
From previous year's classes



Ben Hollis, 2004

Ben Hollis, 2004

Matt Pucevich , 2004



Eunjeong Ryu (E.J), 2004

Bells and Whistles

Capture creative/cool/bizzare panoramas

- Example from UW (by Brett Allen):

- Ever wondered what is happening inside your fridge while you are not looking?

Capture a 360 panorama (quite tricky…)

Example homography final project

Simplification: Two-band Blending

Brown & Lowe, 2003

- Only use two bands: high freq. and low freq.
- Blends low freq. smoothly
- Blend high freq. with no smoothing: use binary alpha

2-band "Laplacian Stack" Blending

Low frequency (λ > 2 pixels)

High frequency (λ < 2 pixels)

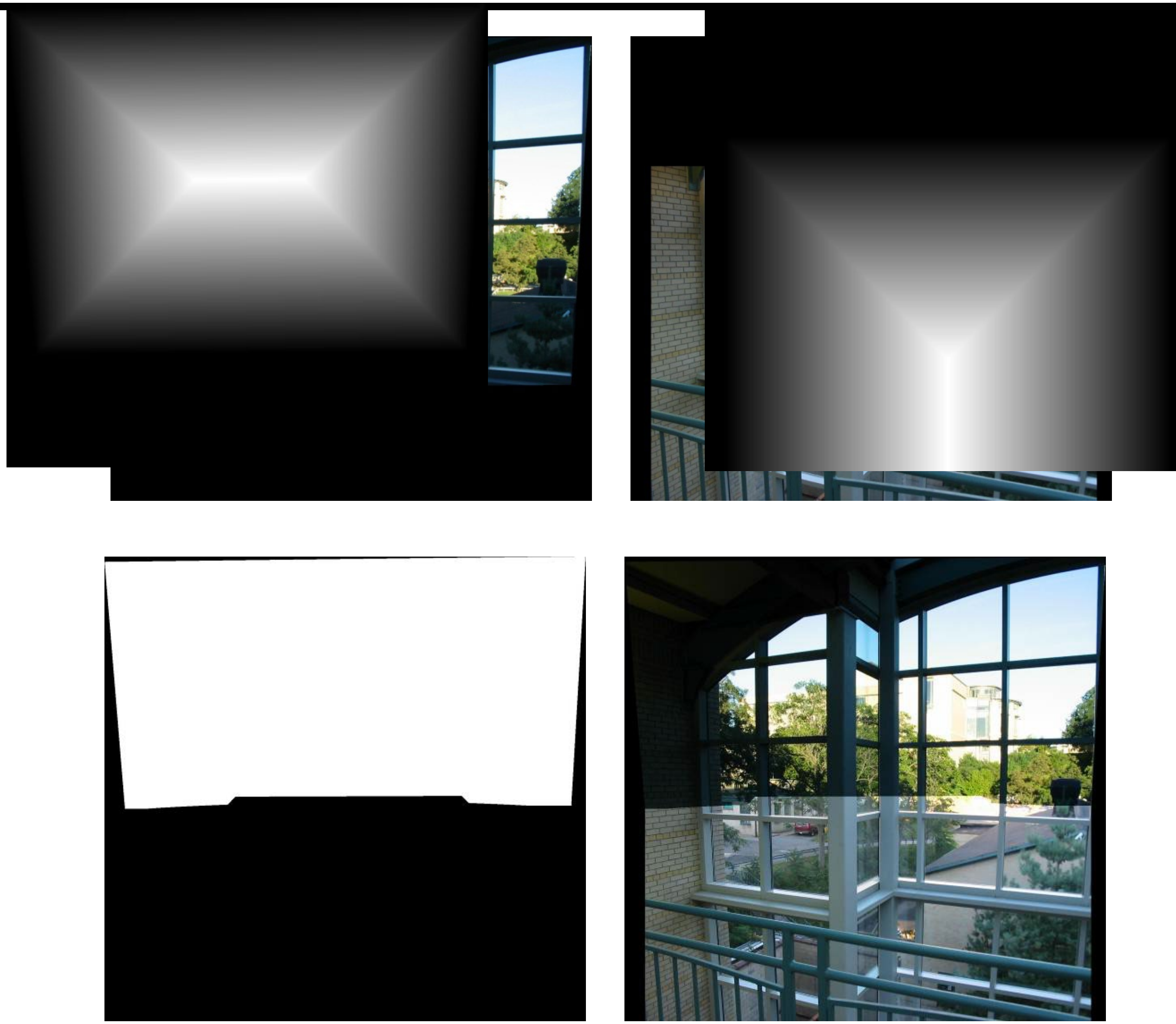
Linear Blending

2-band Blending

Setting alpha: simple averaging

Alpha = .5 in overlap region

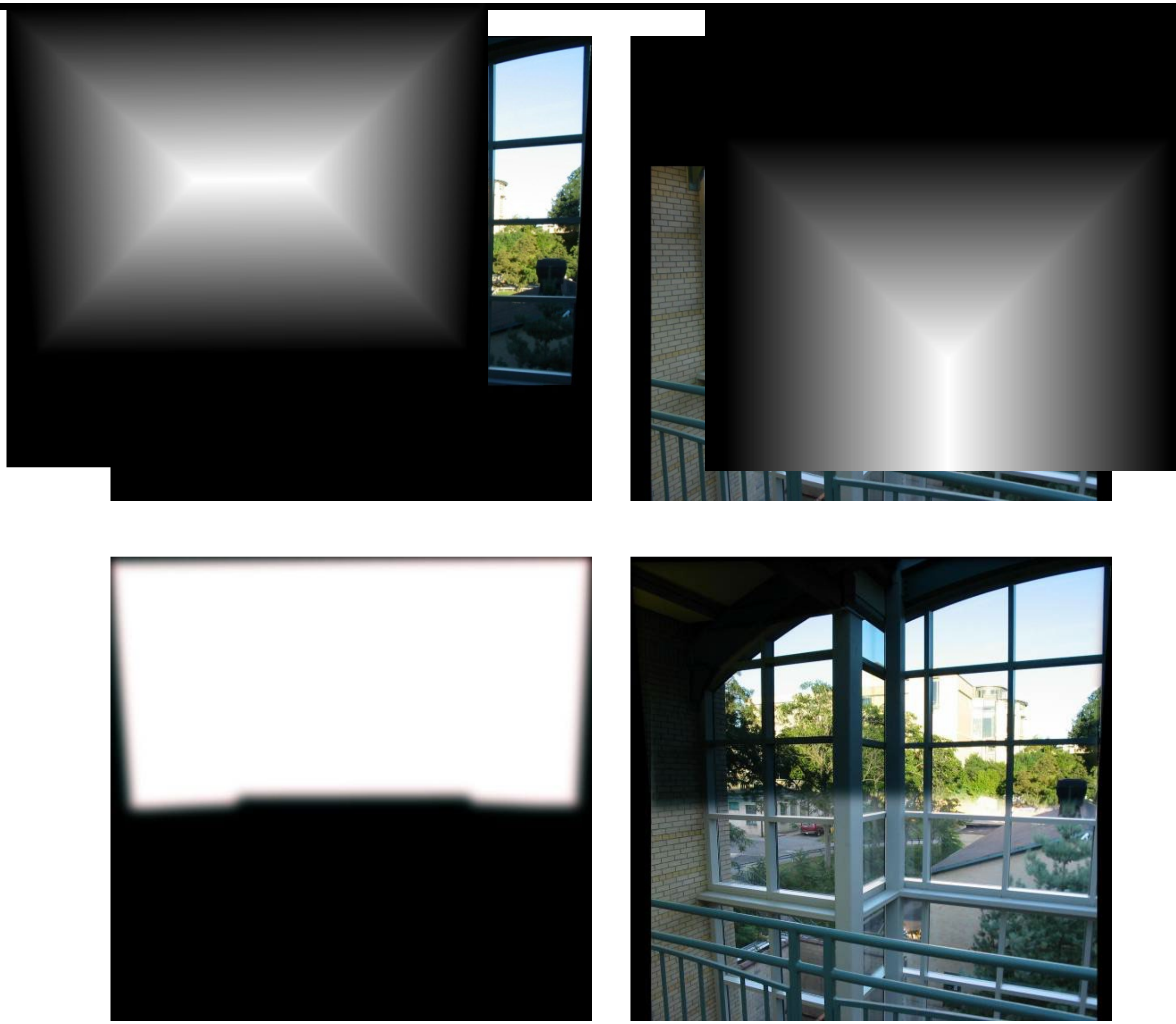
Setting alpha: center seam



Distance Transform
`bwdist`

Alpha = logical(dtrans1>dtrans2)

Setting alpha: blurred seam

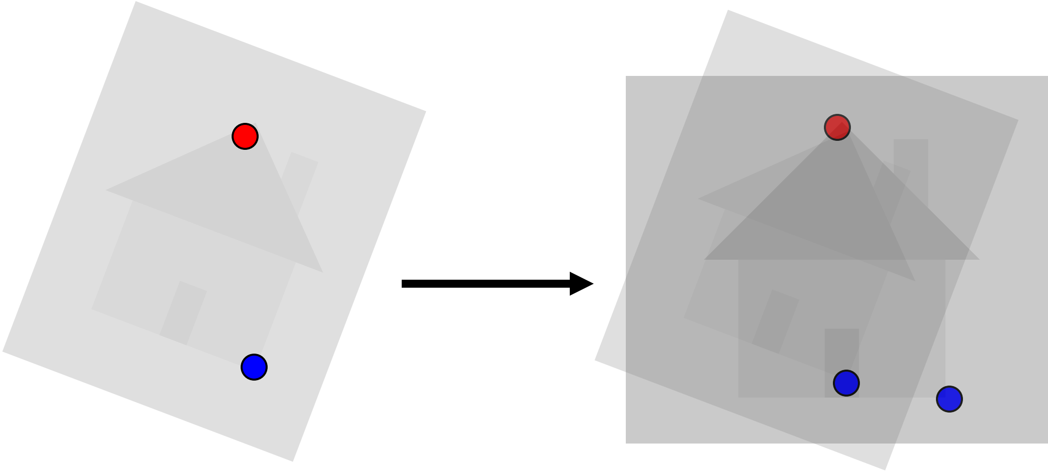


Distance transform

Alpha = blurred

Live Homography…

Image Alignment



How do we align two images automatically?

Two broad approaches:

- Feature-based alignment
  - Find a few matching features in both images
  - compute alignment
- Direct (pixel-based) alignment
  - Search for alignment where most pixels agree

Direct Alignment

The simplest approach is a brute force search (hw1)

- Need to define image matching function
  - L2, Normalized Correlation, edge matching, etc.
- Search over all parameters within a reasonable range:

e.g. for translation:

```
for tx=x0:step:x1,
  for ty=y0:step:y1,
     compare image1(x,y) to image2(x+tx,y+ty)
  end;
end;
```

Need to pick correct `x0,x1` and `step`

- What happens if `step` is too large?

Direct Alignment (brute force)

What if we want to search for more complicated transformation, e.g. homography?

$$\begin{bmatrix} wx' \\ wy' \\ w \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

```
for a=a0:astep:a1,
  for b=b0:bstep:b1,
    for c=c0:cstep:c1,
      for d=d0:dstep:d1,
        for e=e0:estep:e1,
          for f=f0:fstep:f1,
             for g=g0:gstep:g1,
                for h=h0:hstep:h1,
     compare image1 to H(image2)
end; end; end; end; end; end; end; end;
```

Problems with brute force

Not realistic

- Search in $O(N^8)$ is problematic
- Not clear how to set starting/stopping value and step

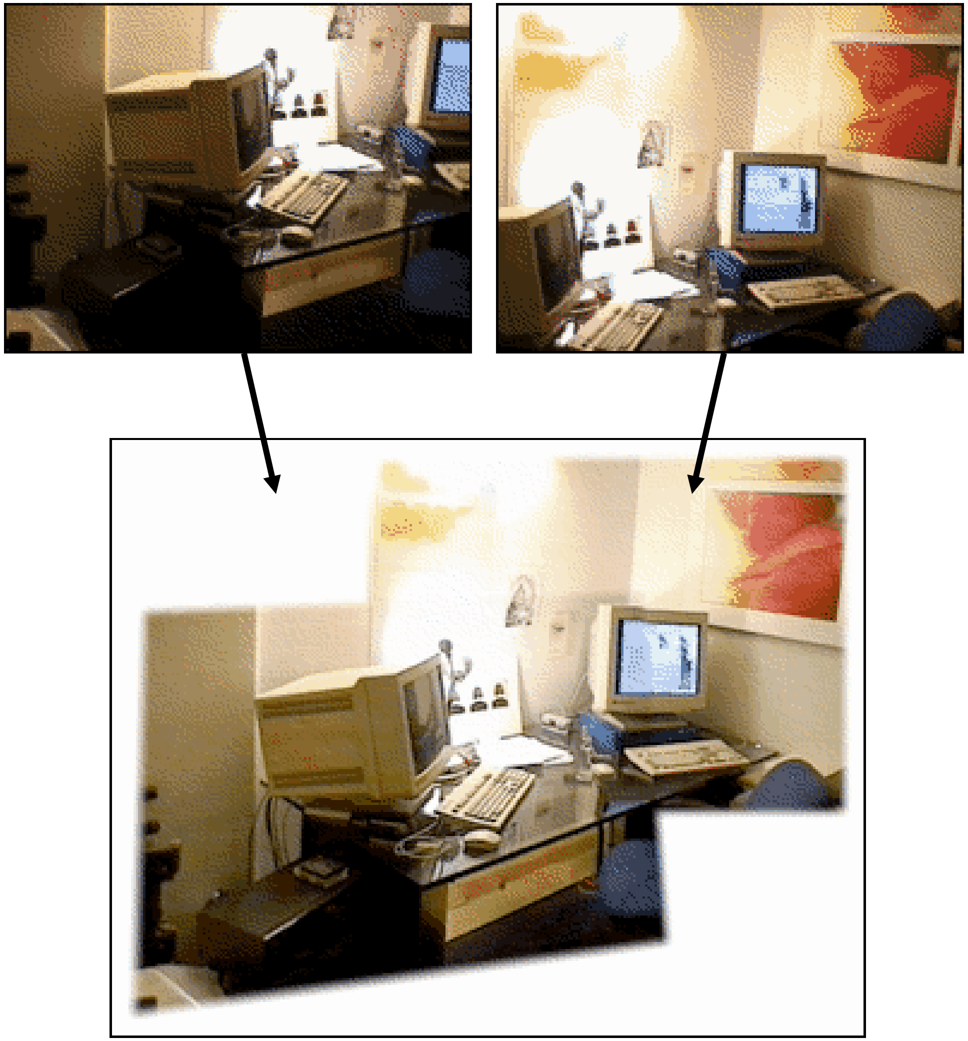
What can we do?

- Use pyramid search to limit starting/stopping/step values

Alternative: gradient decent on the error function

- i.e. how do I tweak my current estimate to make the SSD error go down?
- Can do sub-pixel accuracy
- BIG assumption?
  - Images are already almost aligned (<2 pixels difference!)
  - Can improve with pyramid
- Same tool as in **motion estimation**

Image alignment



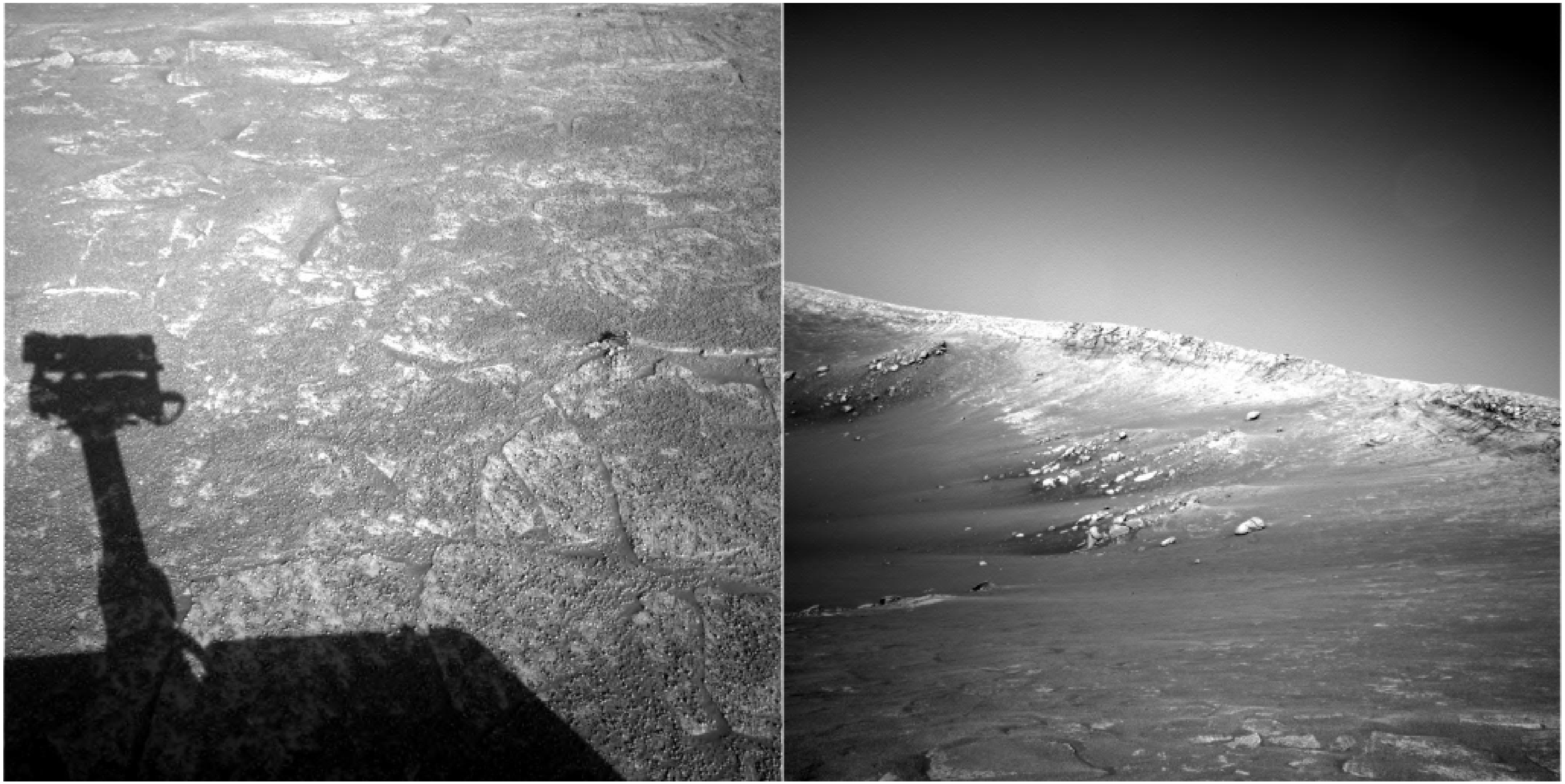
Feature-based alignment

1. **Feature Detection**: find a few important features (aka Interest Points) in each image separately
2. **Feature Matching**: match them across two images
3. **Compute image transformation**: as per Project 4, Part I

How do we choose good features automatically?

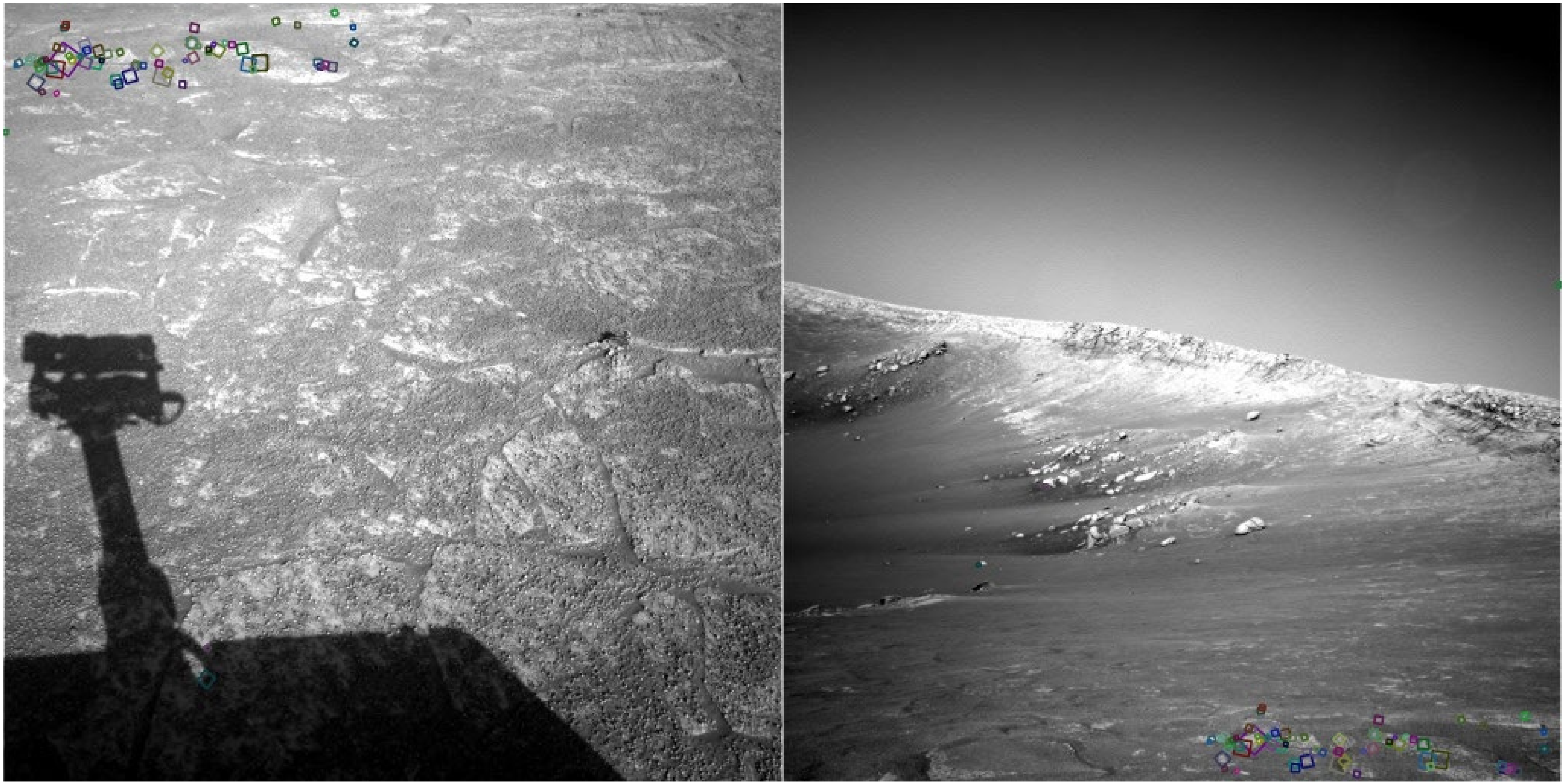
- They must be prominent in both images
- Easy to localize
- Think how you did that by hand in Project #4 Part I
- Corners!

A hard feature matching problem



NASA Mars Rover images

Answer below (look for tiny colored squares…)



NASA Mars Rover images
with SIFT feature matches
Figure by Noah Snavely

Feature Detection

Feature Matching

How do we match the features between the images?

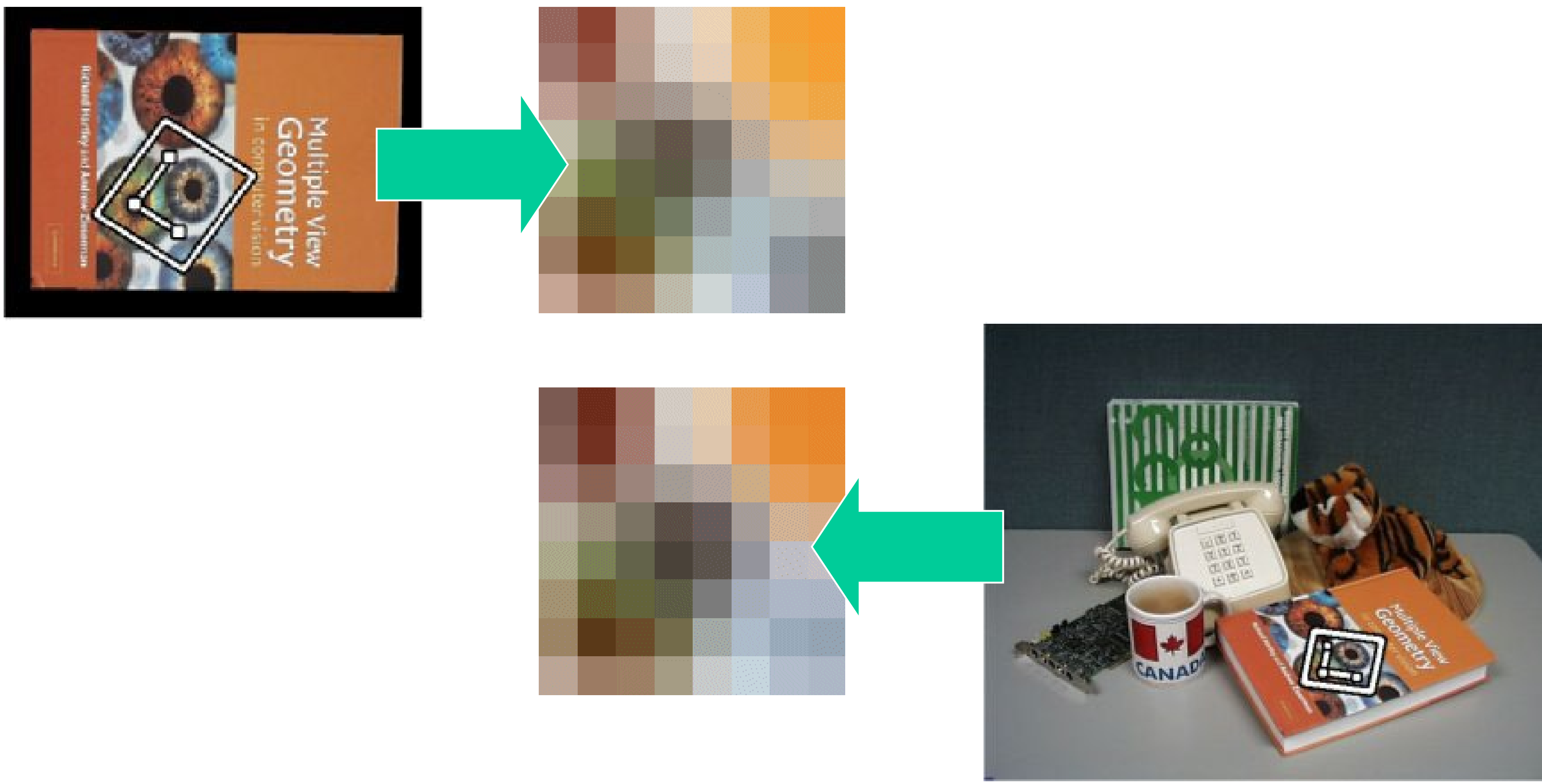
- Need a way to <u>describe</u> a region around each feature
  - e.g. image patch around each feature
- Use successful matches to estimate homography
  - Need to do something to get rid of outliers

Issues:

- What if the image patches for several interest points look similar?
  - Make patch size bigger
- What if the image patches for the same feature look different due to scale, rotation, etc.
  - Need an invariant descriptor

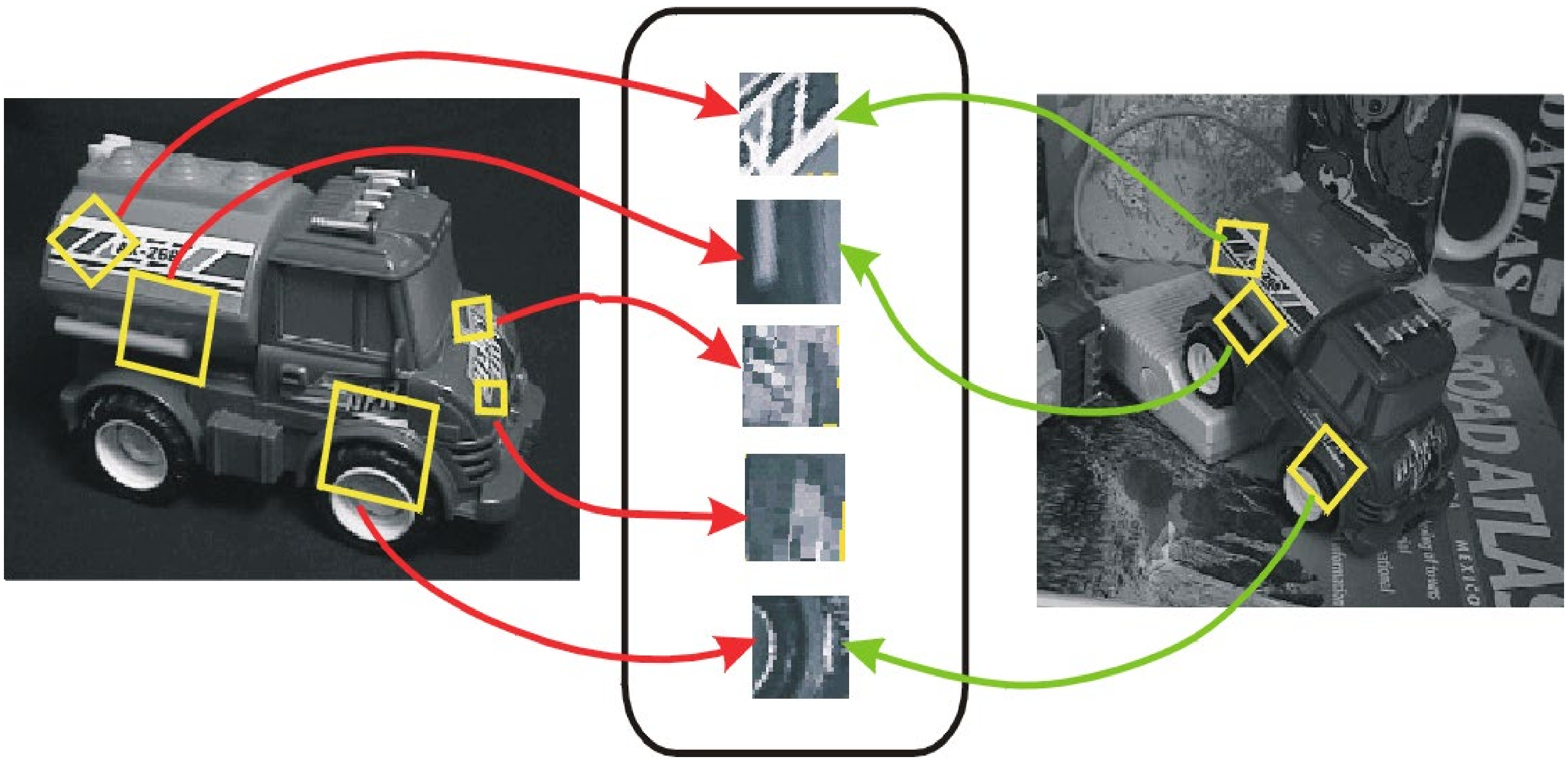
Invariant Feature Descriptors

Schmid & Mohr 1997, Lowe 1999, Baumberg 2000, Tuytelaars & Van Gool 2000, Mikolajczyk & Schmid 2001, Brown & Lowe 2002, Matas et. al. 2002, Schaffalitzky & Zisserman 2002



Invariant Local Features

Image content is transformed into local feature coordinates that are invariant to translation, rotation, scale, and other imaging parameters



Features Descriptors

Applications

Feature points are used for:

- Image alignment (homography, fundamental matrix)
- 3D reconstruction
- Motion tracking
- Object recognition
- Indexing and database retrieval
- Robot navigation
- … other

Today's lecture

- 1 Feature detector
  - scale invariant Harris corners
- 1 Feature descriptor
  - patches, oriented patches

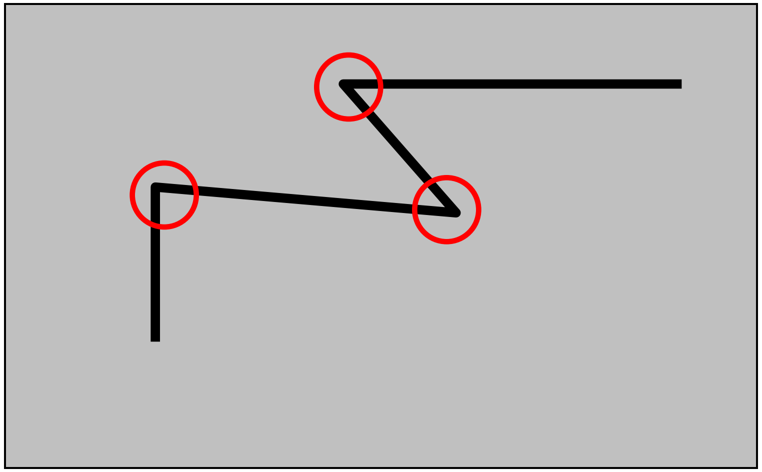
Reading:

Multi-image Matching using Multi-scale image patches, CVPR 2005

Feature Detector – Harris Corner

Harris corner detector

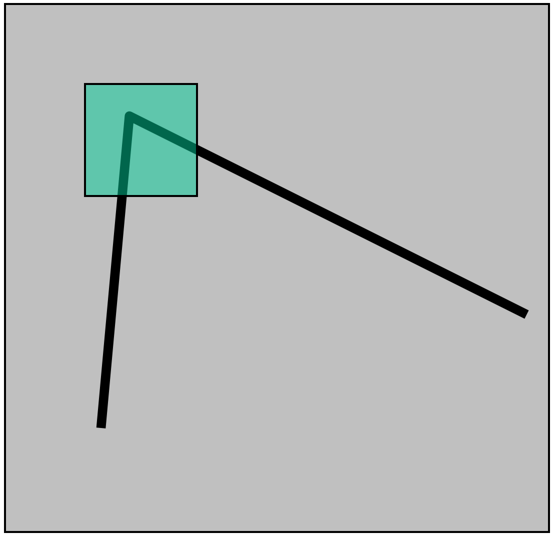
C.Harris, M.Stephens. “A Combined Corner and Edge Detector”. 1988



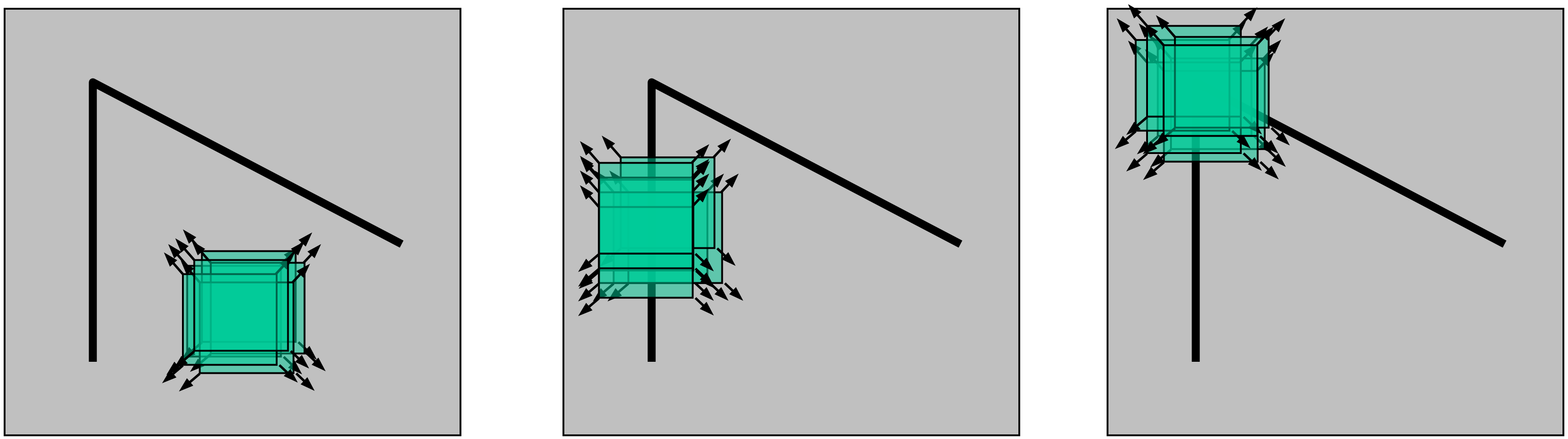
The Basic Idea

We should easily recognize the point by looking through a small window

Shifting a window in *any direction* should give *a large change* in intensity



Harris Detector: Basic Idea



"flat" region:
no change in
all directions

"edge":
no change along
the edge direction

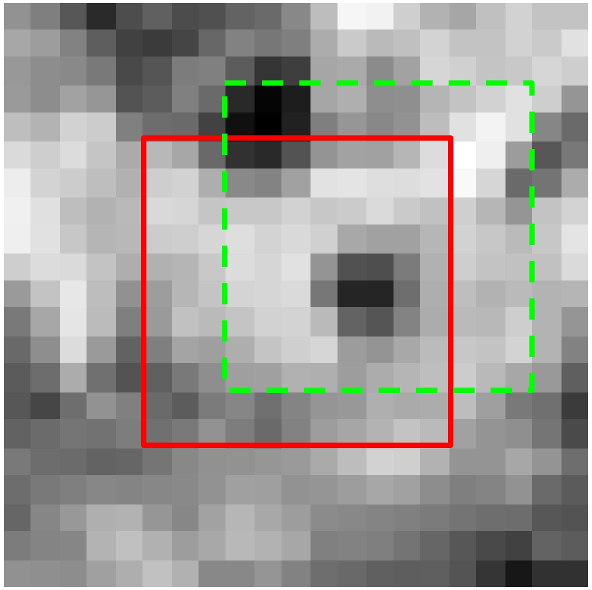
"corner":
significant change
in all directions

Corner Detection: Mathematics

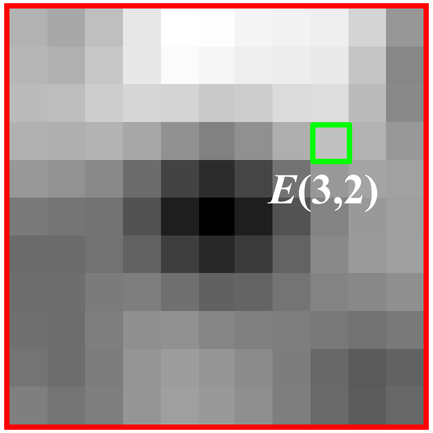
Change in appearance of window *W* for the shift [*u,v*]:

$$E(u,v) = \sum_{(x,y)\in W} [I(x+u, y+v) - I(x,y)]^2$$

$I(x, y)$



$E(u, v)$



Corner Detection: Mathematics

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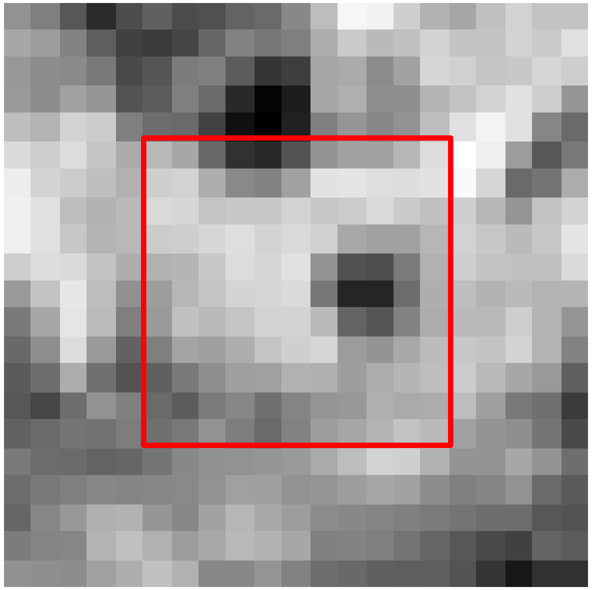
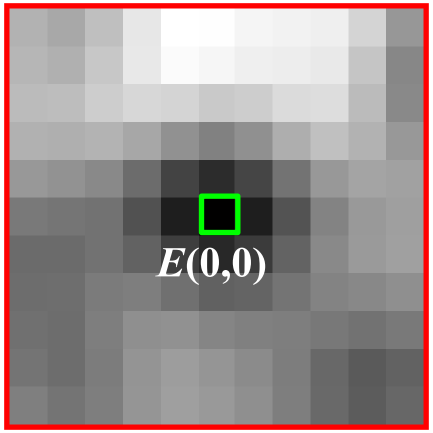


$E(u, v)$



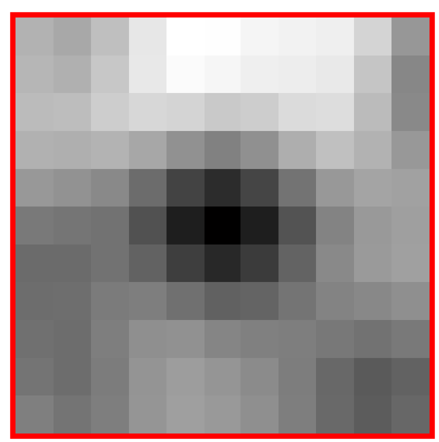
Corner Detection: Mathematics

Change in appearance of window *W* for the shift [*u,v*]:

$$E(u,v) = \sum_{(x,y)\in W} [I(x+u, y+v) - I(x,y)]^2$$

We want to find out how this function behaves for small shifts

$E(u, v)$



Corner Detection: Mathematics

- First-order Taylor approximation for small motions [*u*, *v*]:

$$
\begin{aligned}
I(x+u, y+v) &= I(x,y) + I_x u + I_y v + \text{higher order terms} \\
&\approx I(x,y) + I_x u + I_y v \\
&= I(x,y) + \begin{bmatrix} I_x & I_y \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix}
\end{aligned}
$$

- Let's plug this into

$$E(u,v) = \sum_{(x,y)\in W} [I(x+u, y+v) - I(x,y)]^2$$

Corner Detection: Mathematics

$$E(u,v) = \sum_{(x,y)\in W} [I(x+u, y+v) - I(x,y)]^2$$

$$\approx \sum_{(x,y)\in W} [I(x,y) + \begin{bmatrix} I_x & I_y \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix} - I(x,y)]^2$$

$$= \sum_{(x,y)\in W} \left(\begin{bmatrix} I_x & I_y \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix} \right)^2$$

$$= \sum_{(x,y)\in W} \begin{bmatrix} u & v \end{bmatrix} \begin{bmatrix} I_x^2 & I_x I_y \\ I_x I_y & I_y^2 \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix}$$

Corner Detection: Mathematics

The quadratic approximation simplifies to

$$E(u,v) \approx \begin{bmatrix} u & v \end{bmatrix} M \begin{bmatrix} u \\ v \end{bmatrix}$$

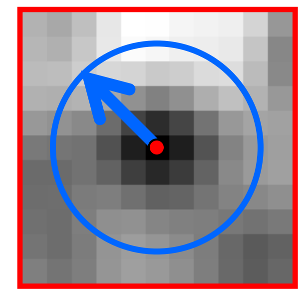
where *M* is a *second moment matrix* computed from image derivatives:

$$M = \sum_{(x,y)\in W} \begin{bmatrix} I_x^2 & I_x I_y \\ I_x I_y & I_y^2 \end{bmatrix}$$

Interpreting the second moment matrix

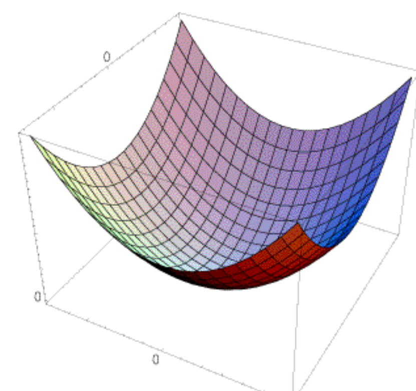
- The surface $E(u,v)$ is locally approximated by a quadratic form. Let's try to understand its shape.
  - Specifically, in which directions does it have the smallest/greatest change?

$E(u,v)$



$$E(u,v) \approx [u \ \ v] \ M \begin{bmatrix} u \\ v \end{bmatrix}$$

$$M = \sum_{(x,y)\in W} \begin{bmatrix} I_x^2 & I_x I_y \\ I_x I_y & I_y^2 \end{bmatrix}$$



Interpreting the second moment matrix

First, consider the axis-aligned case (gradients are either horizontal or vertical)

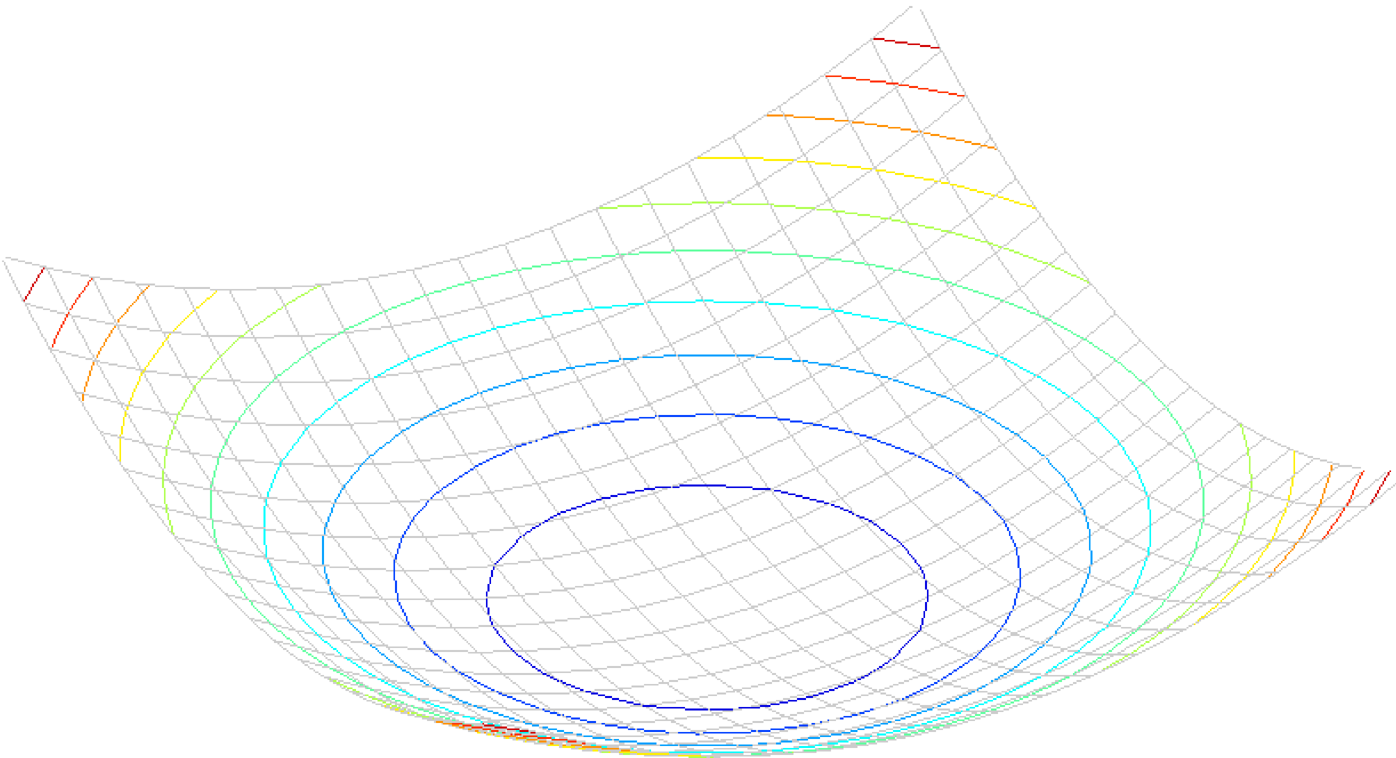
$$M = \sum_{(x,y)\in W} \begin{bmatrix} I_x^2 & I_x I_y \\ I_x I_y & I_y^2 \end{bmatrix} = \begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix}$$

If either *a* or *b* is close to 0, then this is **not** a corner, so look for locations where both are large.

Interpreting the second moment matrix

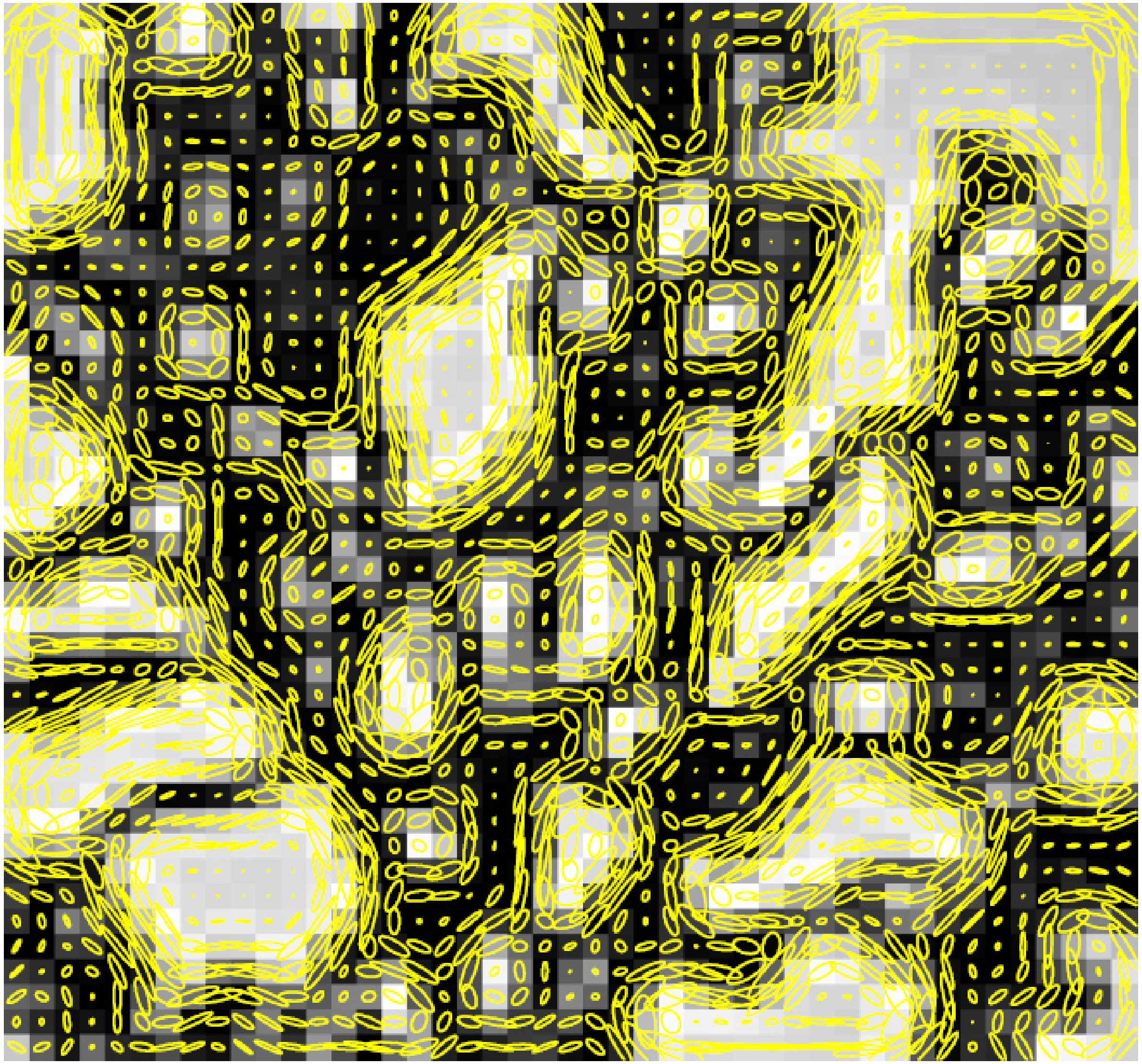
Consider a horizontal "slice" of $E(u, v)$: $$[u\ \ v]\ M \begin{bmatrix} u \\ v \end{bmatrix} = \text{const}$$

This is the equation of an ellipse.



Visualization of second moment matrices

Visualization of second moment matrices



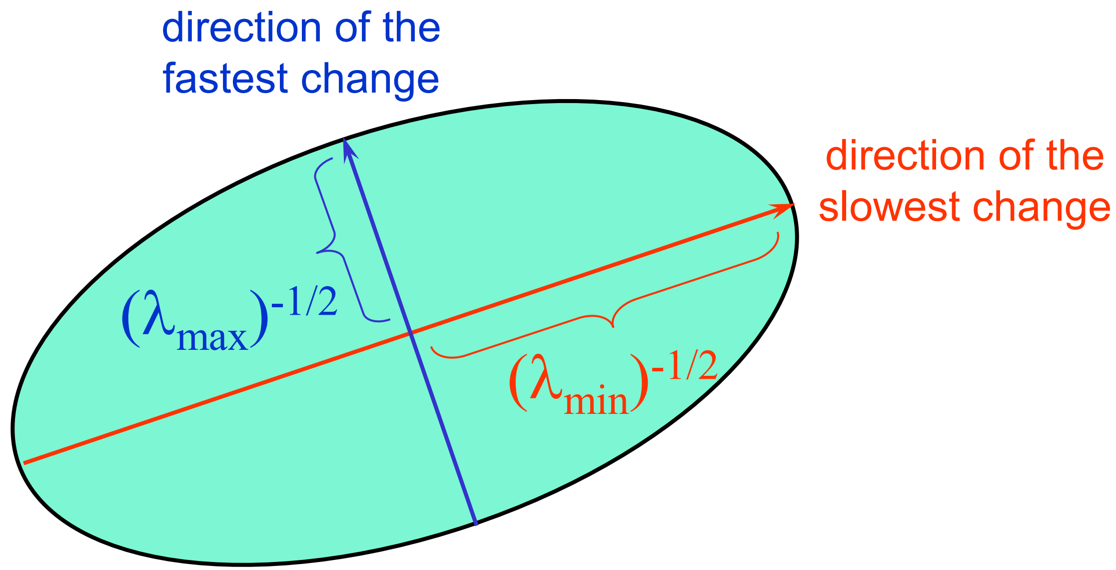
Interpreting the second moment matrix

Consider a horizontal "slice" of $E(u, v)$: $$[u \;\; v] \; M \begin{bmatrix} u \\ v \end{bmatrix} = \text{const}$$

This is the equation of an ellipse.

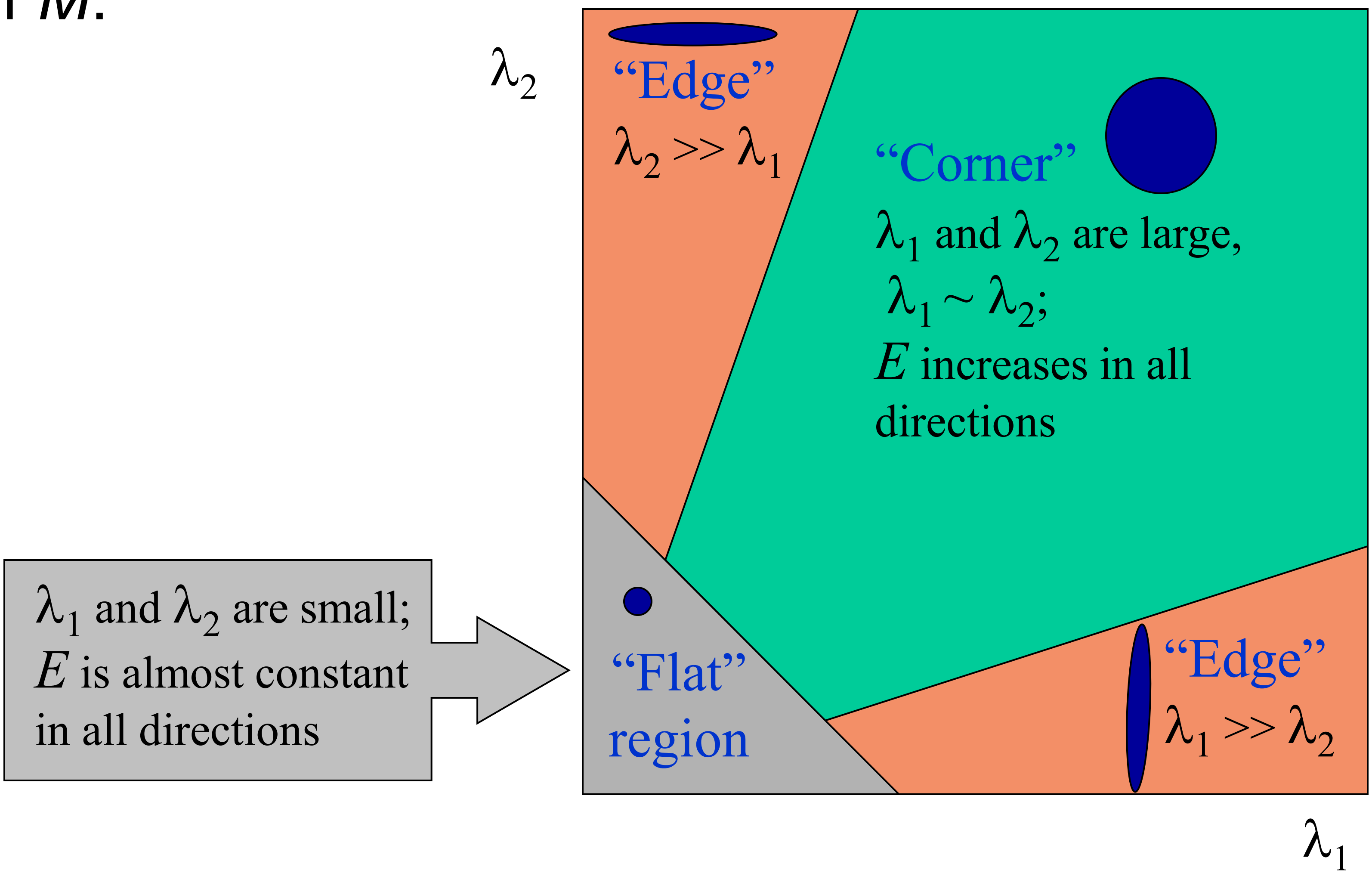
Diagonalization of M: $$M = R^{-1} \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} R$$

The axis lengths of the ellipse are determined by the eigenvalues and the orientation is determined by *R*



Interpreting the eigenvalues

Classification of image points using eigenvalues of *M*:



Harris Detector: Mathematics

Measure of corner response:

$$R = \frac{\det M}{\operatorname{Trace} M}$$

$$\det M = \lambda_1 \lambda_2$$
$$\operatorname{trace} M = \lambda_1 + \lambda_2$$

Harris detector: Steps

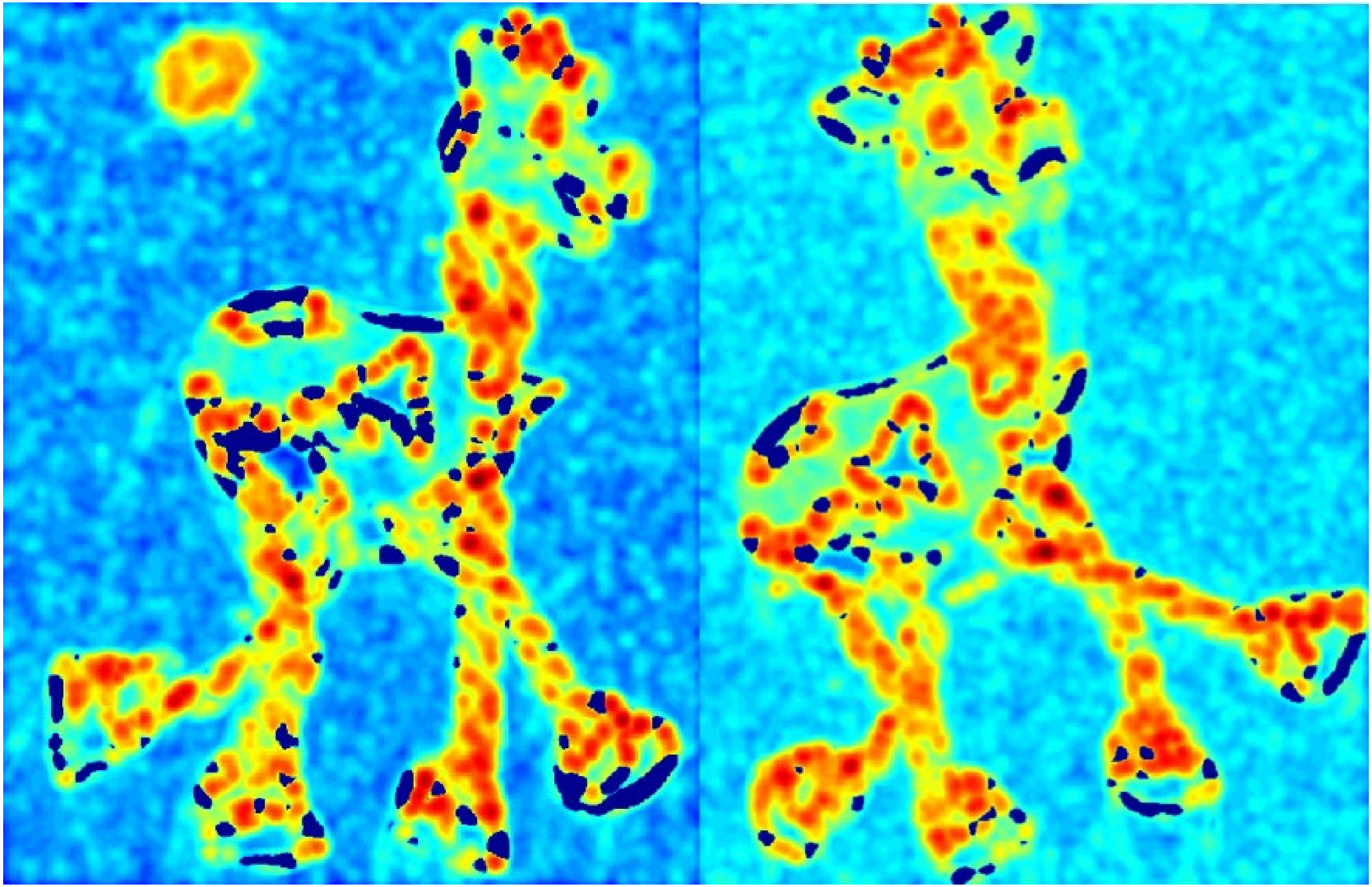
1. Compute Gaussian derivatives at each pixel
2. Compute second moment matrix *M* in a Gaussian window around each pixel
3. Compute corner response function *R*
4. Threshold *R*
5. Find local maxima of response function (nonmaximum suppression)

C.Harris and M.Stephens. "A Combined Corner and Edge Detector." ***Proceedings of the 4th Alvey Vision Conference*: pages 147—151, 1988.**

Harris Detector: Workflow

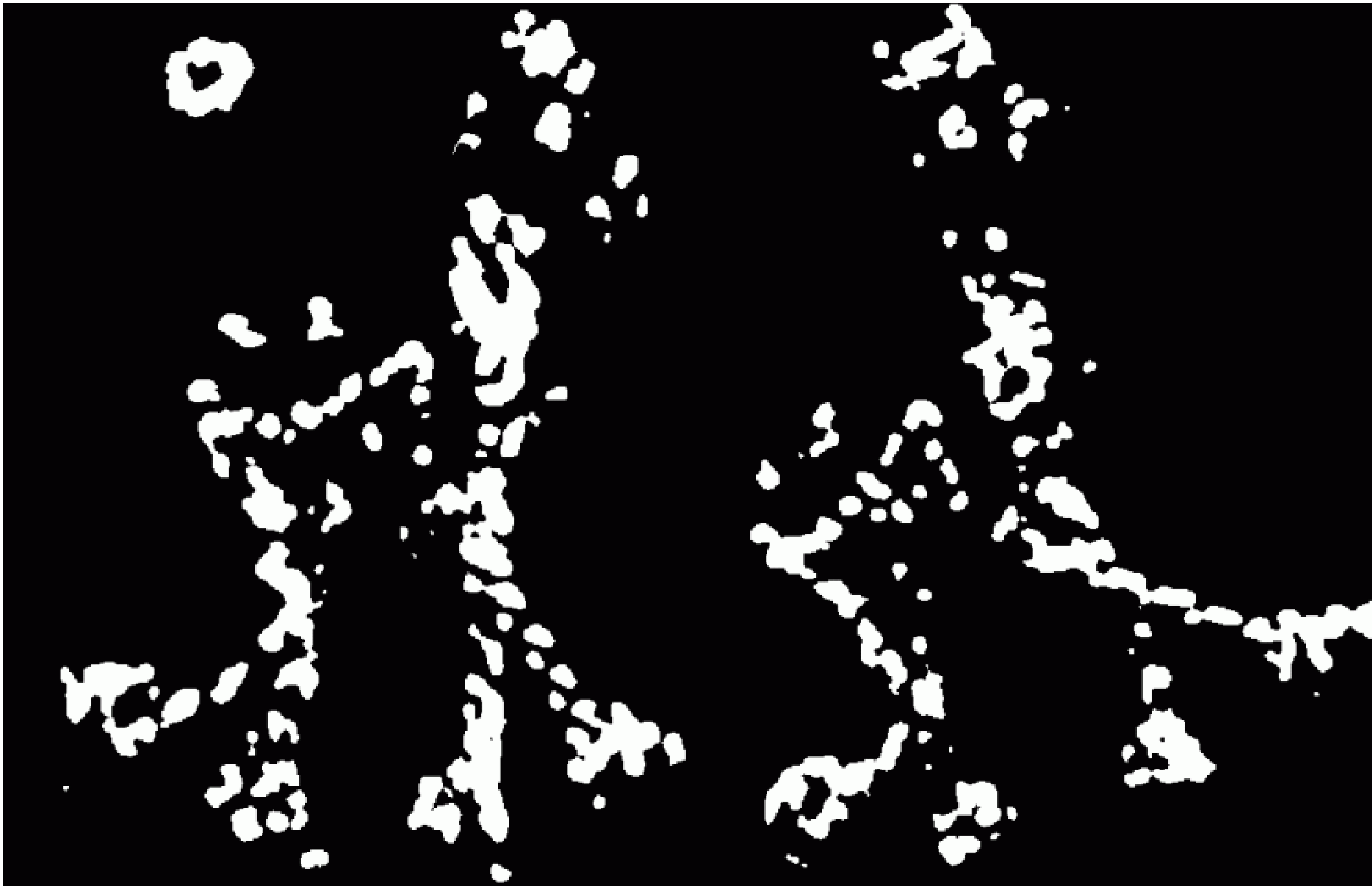
Harris Detector: Workflow

Compute corner response R



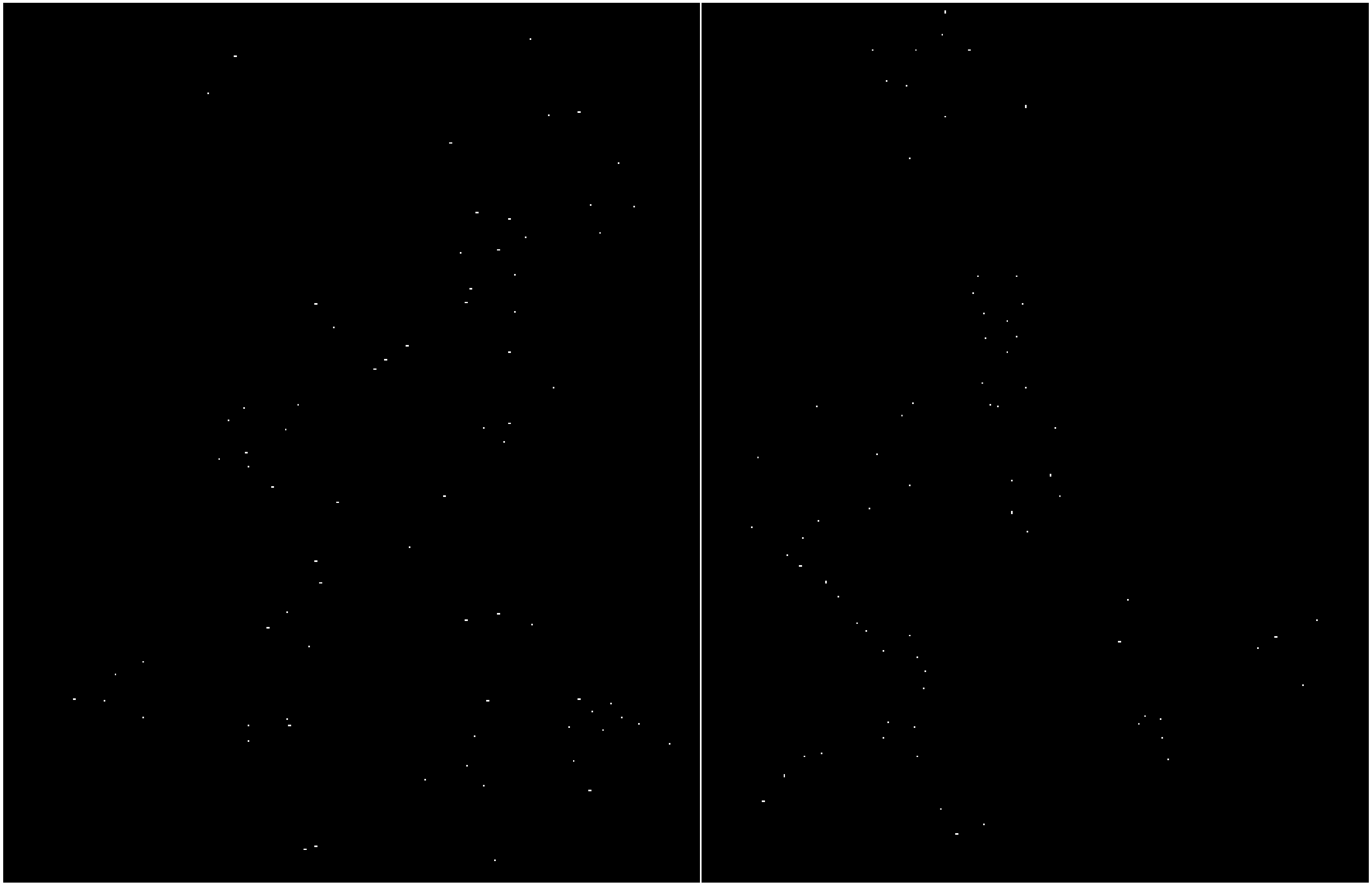
Harris Detector: Workflow

Find points with large corner response: R>threshold



Harris Detector: Workflow

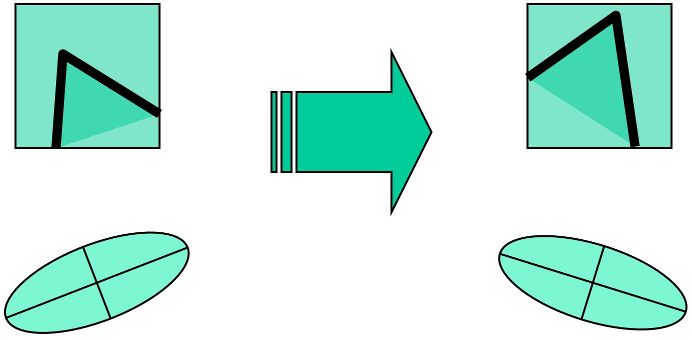
Take only the points of local maxima of R



Harris Detector: Workflow

Harris Detector: Some Properties

Rotation invariance



Ellipse rotates but its shape (i.e. eigenvalues) remains the same

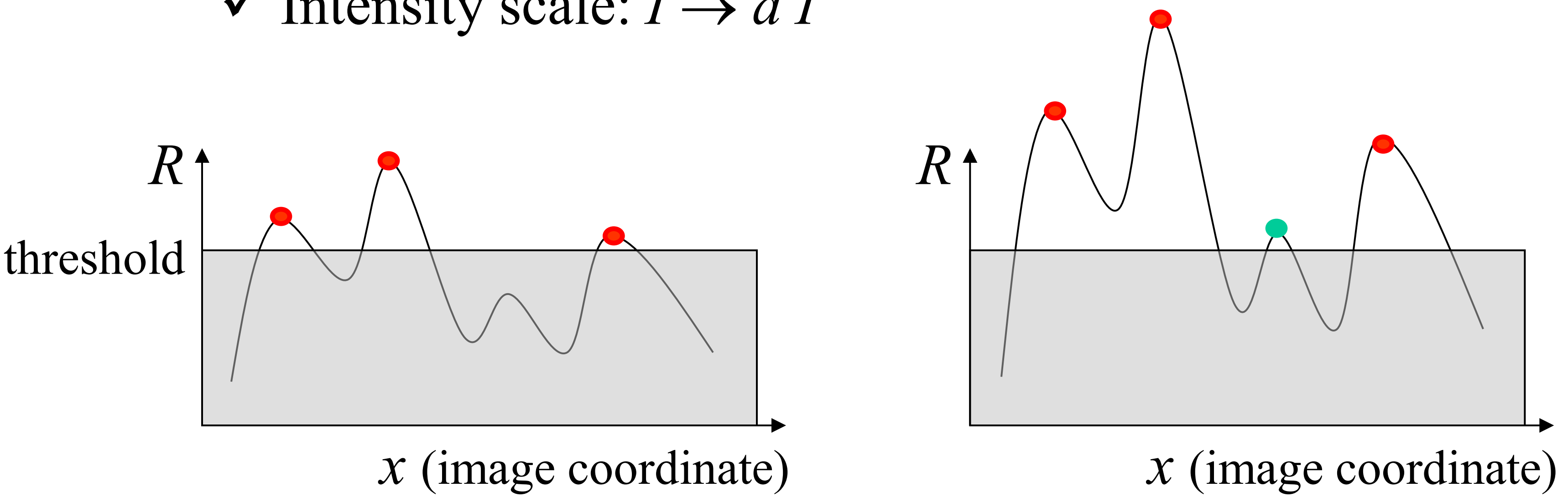
Corner response R is invariant to image rotation

Harris Detector: Some Properties

Partial invariance to *affine intensity* change

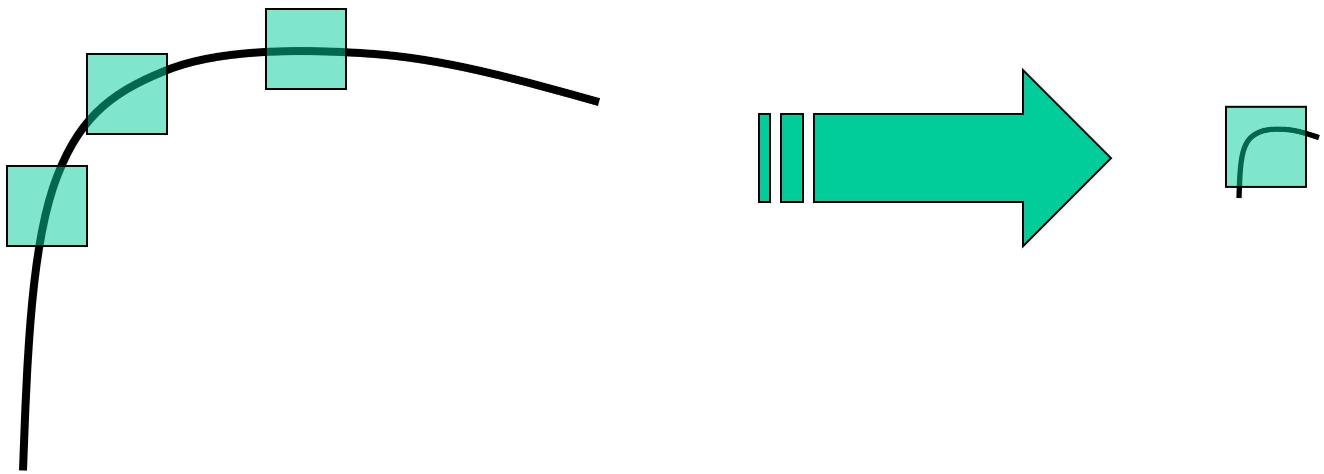
✓ Only derivatives are used => invariance to intensity shift $I \rightarrow I + b$

✓ Intensity scale: $I \rightarrow a\, I$



Harris Detector: Some Properties

But: non-invariant to *image scale*!



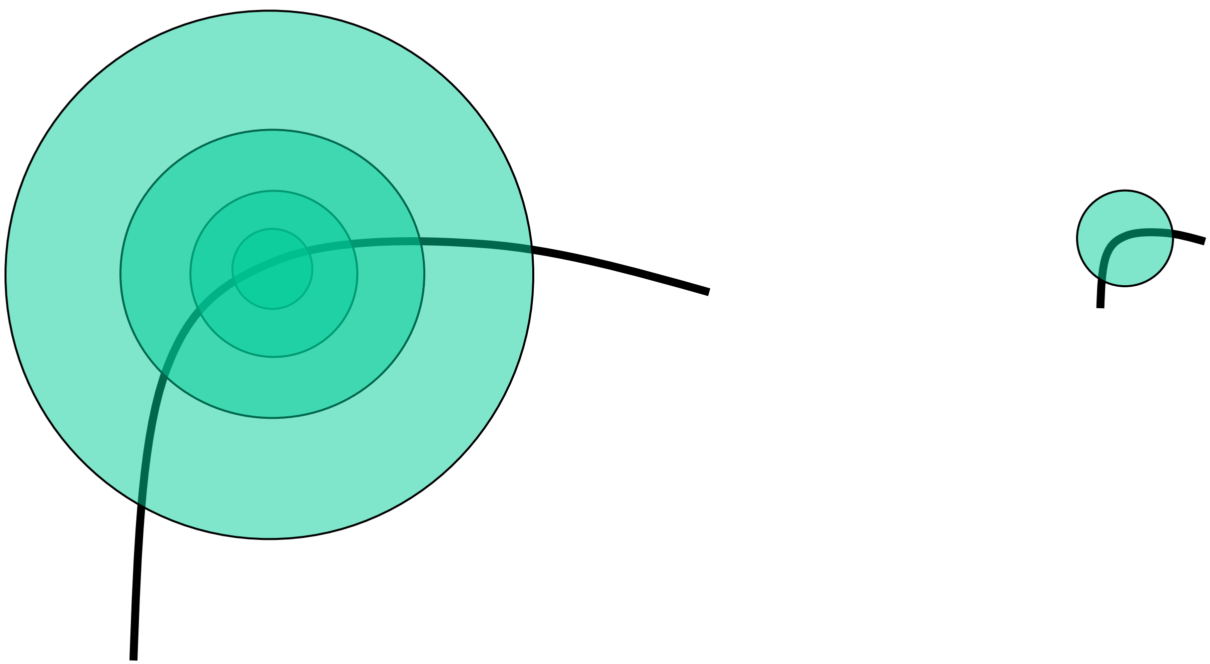
All points will be classified as edges

Corner !

Scale Invariant Detection

Consider regions (e.g. circles) of different sizes around a point

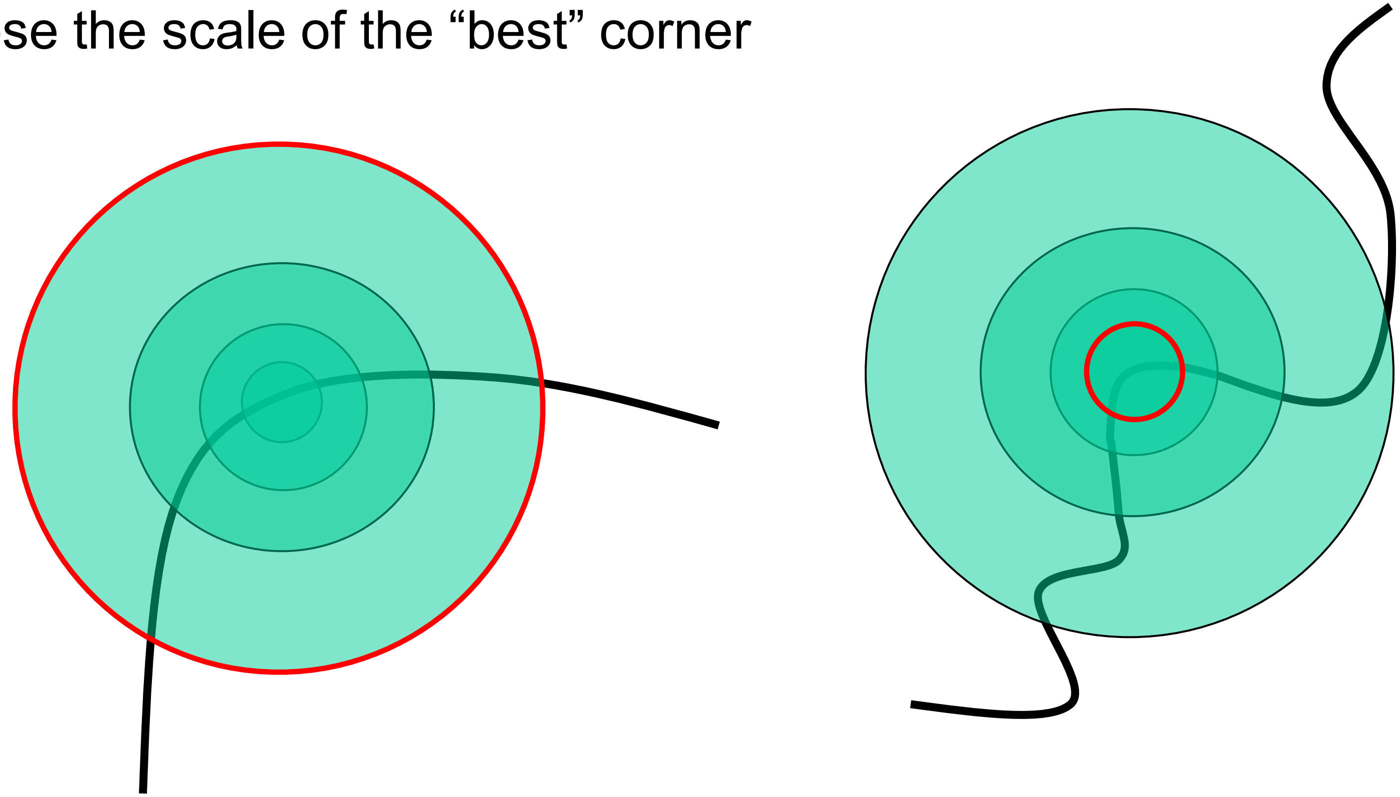
Regions of corresponding sizes will look the same in both images



Scale Invariant Detection

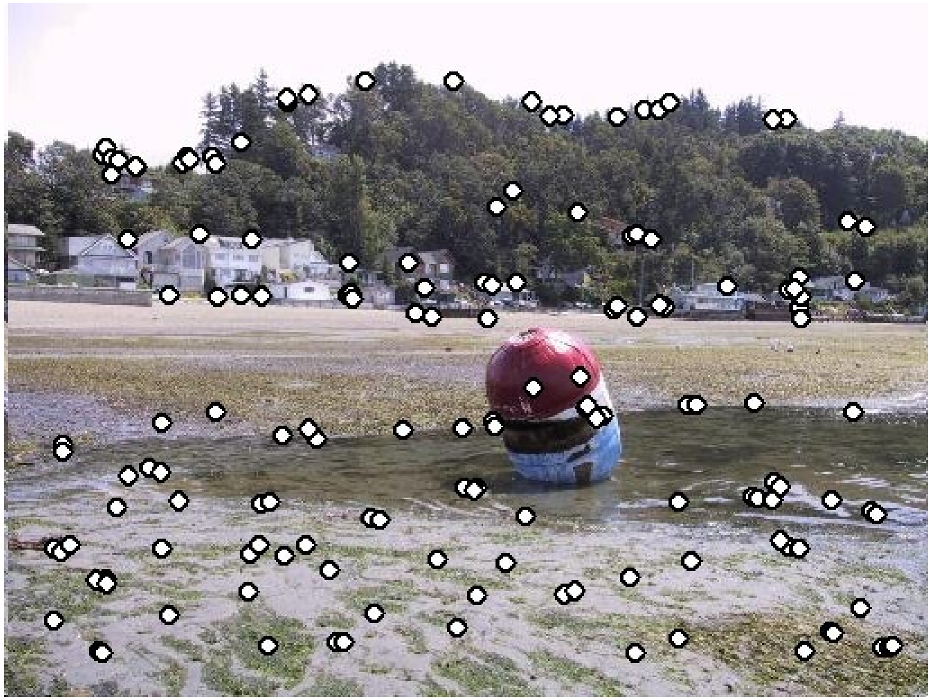
The problem: how do we choose corresponding circles *independently* in each image?

Choose the scale of the “best” corner



Feature selection

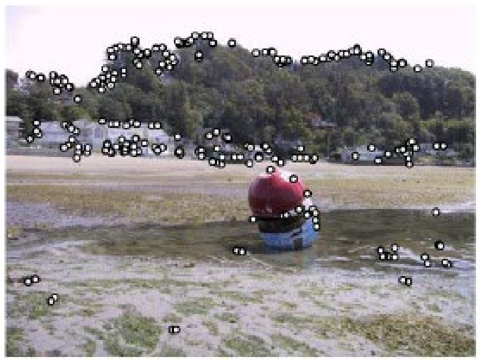
Distribute points evenly over the image



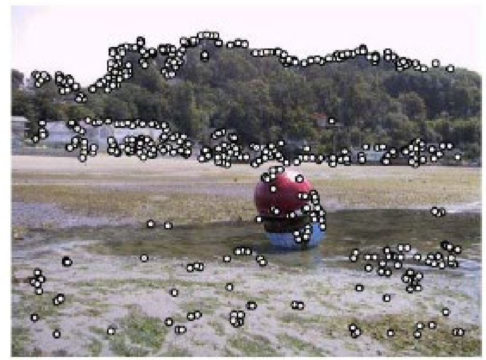
Adaptive Non-maximal Suppression

Desired: Fixed # of features per image

- Want evenly distributed spatially…
- Sort points by non-maximal suppression radius [Brown, Szeliski, Winder, CVPR'05]



(a) Strongest 250



(b) Strongest 500

(c) ANMS 250, $r = 24$

(d) ANMS 500, $r = 16$