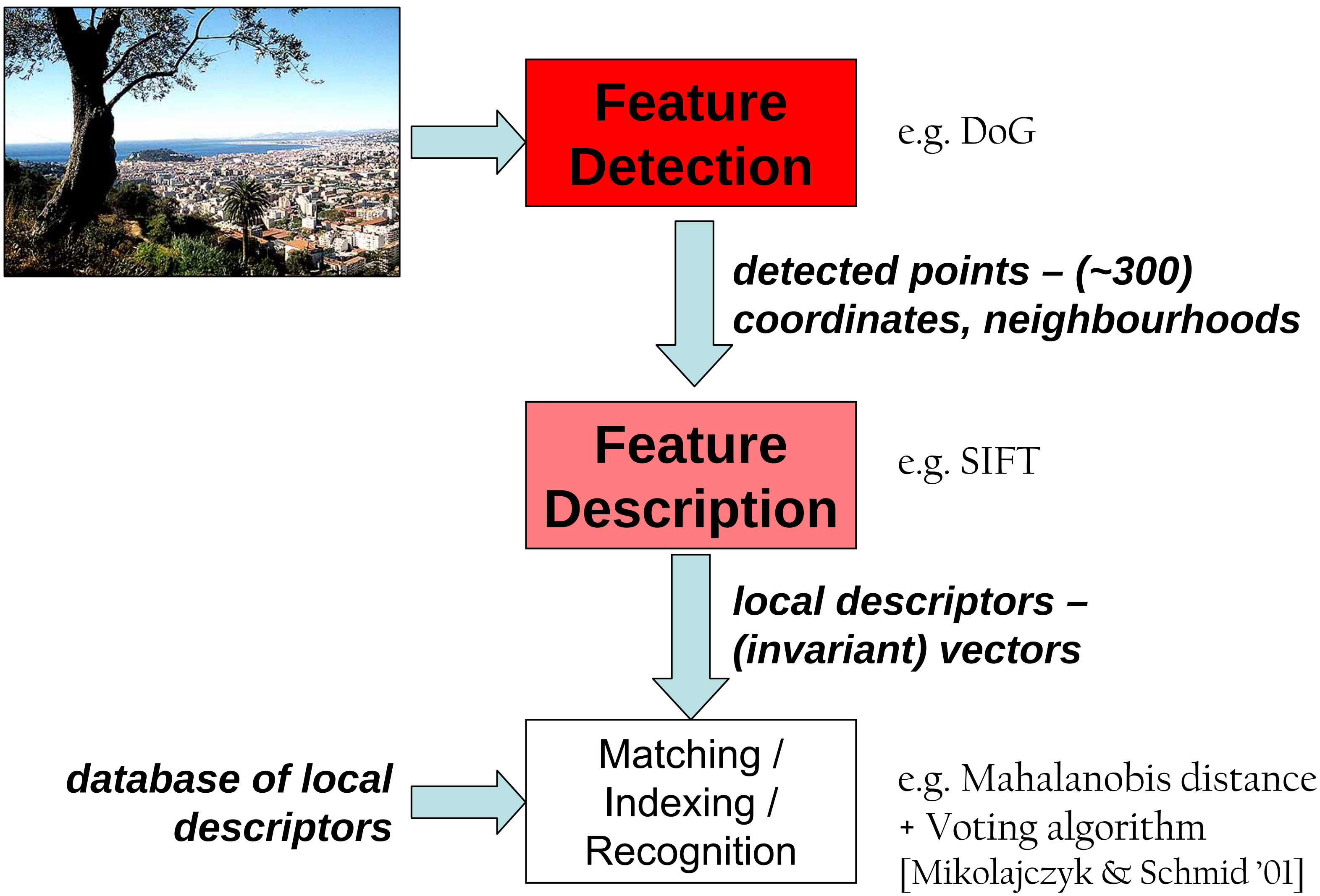
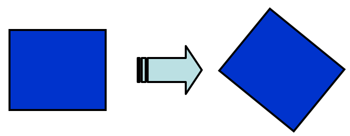
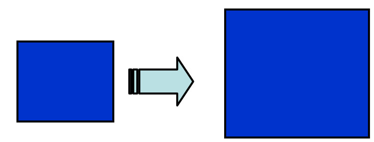
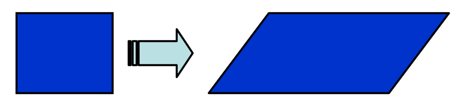
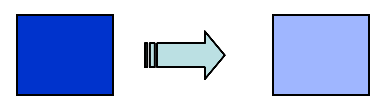
Feature detectors and descriptors

Fei-Fei Li


Feature Detection
e.g. DoG
detected points – (~300)
coordinates, neighbourhoods
Feature Description
e.g. SIFT
local descriptors –
(invariant) vectors
database of local descriptors
Matching / Indexing / Recognition
e.g. Mahalanobis distance
+ Voting algorithm
[Mikolajczyk & Schmid '01]

Some of the challenges…

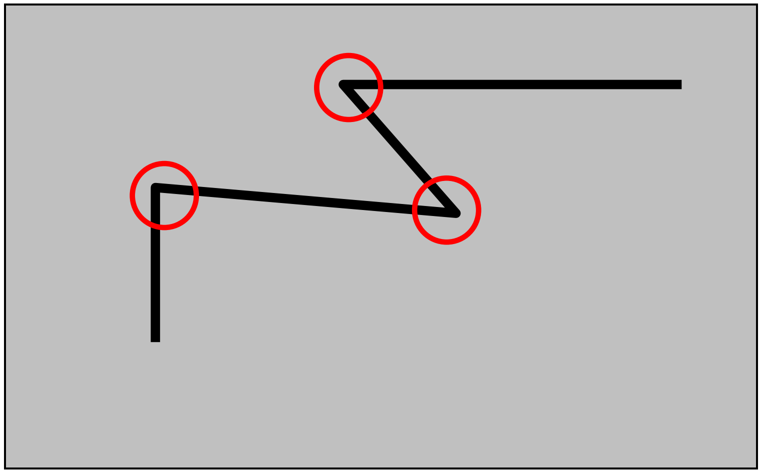
- Geometry
  – Rotation 
  – Similarity (rotation + uniform scale) 
  – Affine (scale dependent on direction) valid for: orthographic camera, locally planar object 
- Photometry
  – Affine intensity change ($I \rightarrow a\,I + b$) 

Detector	Descrip-tor	Intensity	Rotation	Scale	Affine
Harris corner	2nd moment(s)				
Mikolajczyk & Schmid '01, '02	2nd moment(s)				
Tuytelaars, '00	2nd moment(s)				
Lowe '99 (DoG)	SIFT, PCA-SIFT				
Kadir & Brady, 01					
Matas, '02					
others	others				

Detector	Descriptor	Intensity	Rotation	Scale	Affine
Harris corner	2^{nd} moment(s)				
Mikolajczyk & Schmid ’01, ‘02	2^{nd} moment(s)				
Tuytelaars, ‘00	2^{nd} moment(s)				
Lowe ’99 (DoG)	SIFT, PCA-SIFT				
Kadir & Brady, 01					
Matas, ‘02					
others	others				

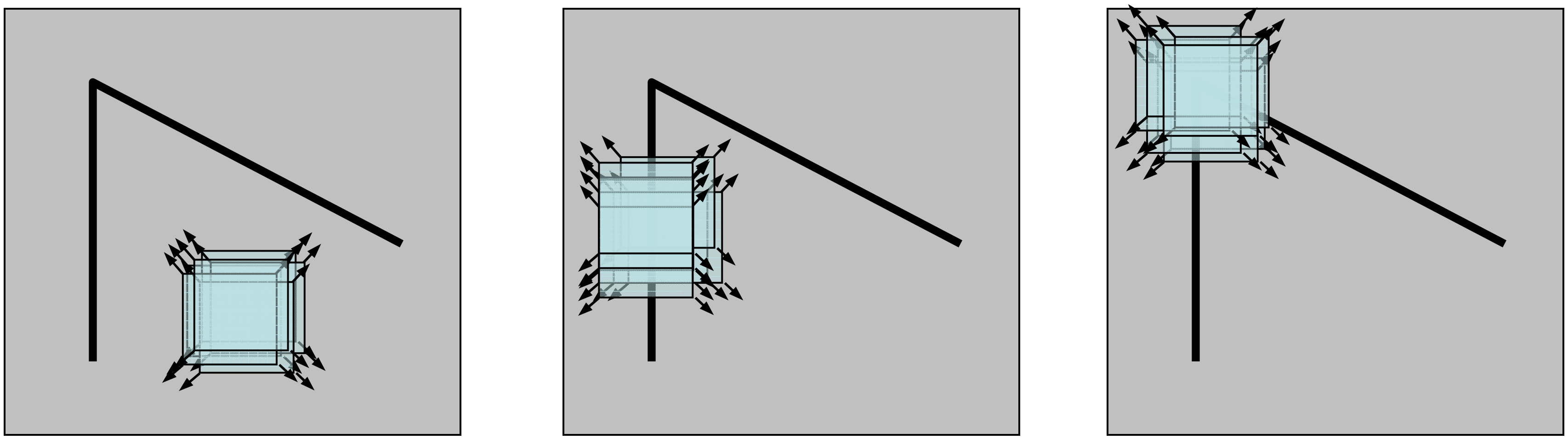
An introductory example:

Harris corner detector



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

Harris Detector: Basic Idea



"flat" region:
no change in
all directions

"edge":
no change along
the edge direction

"corner":
significant change
in all directions

Harris Detector: Mathematics

Change of intensity for the shift [*u*,*v*]:

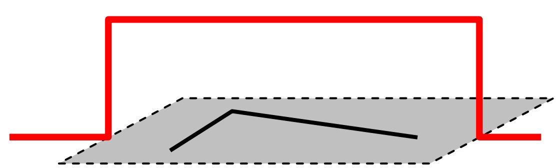
$$E(u,v) = \sum_{x,y} w(x,y)\left[I(x+u,y+v) - I(x,y)\right]^2$$

Window function

Shifted intensity

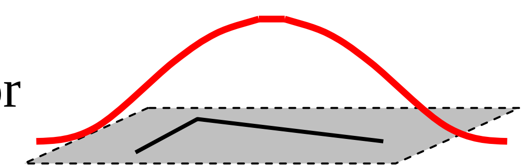
Intensity

Window function $w(x,y)$ =



1 in window, 0 outside

or



Gaussian

Harris Detector: Mathematics

For small shifts $[u,v]$ we have a *bilinear* approximation:

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

where M is a 2×2 matrix computed from image derivatives:

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

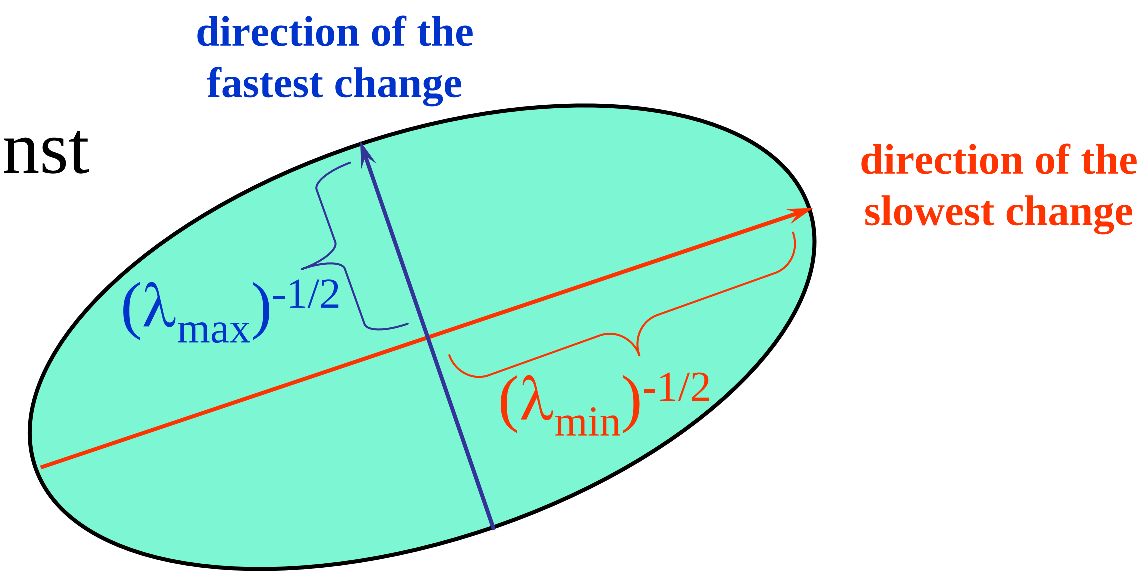
Harris Detector: Mathematics

Intensity change in shifting window: eigenvalue analysis

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

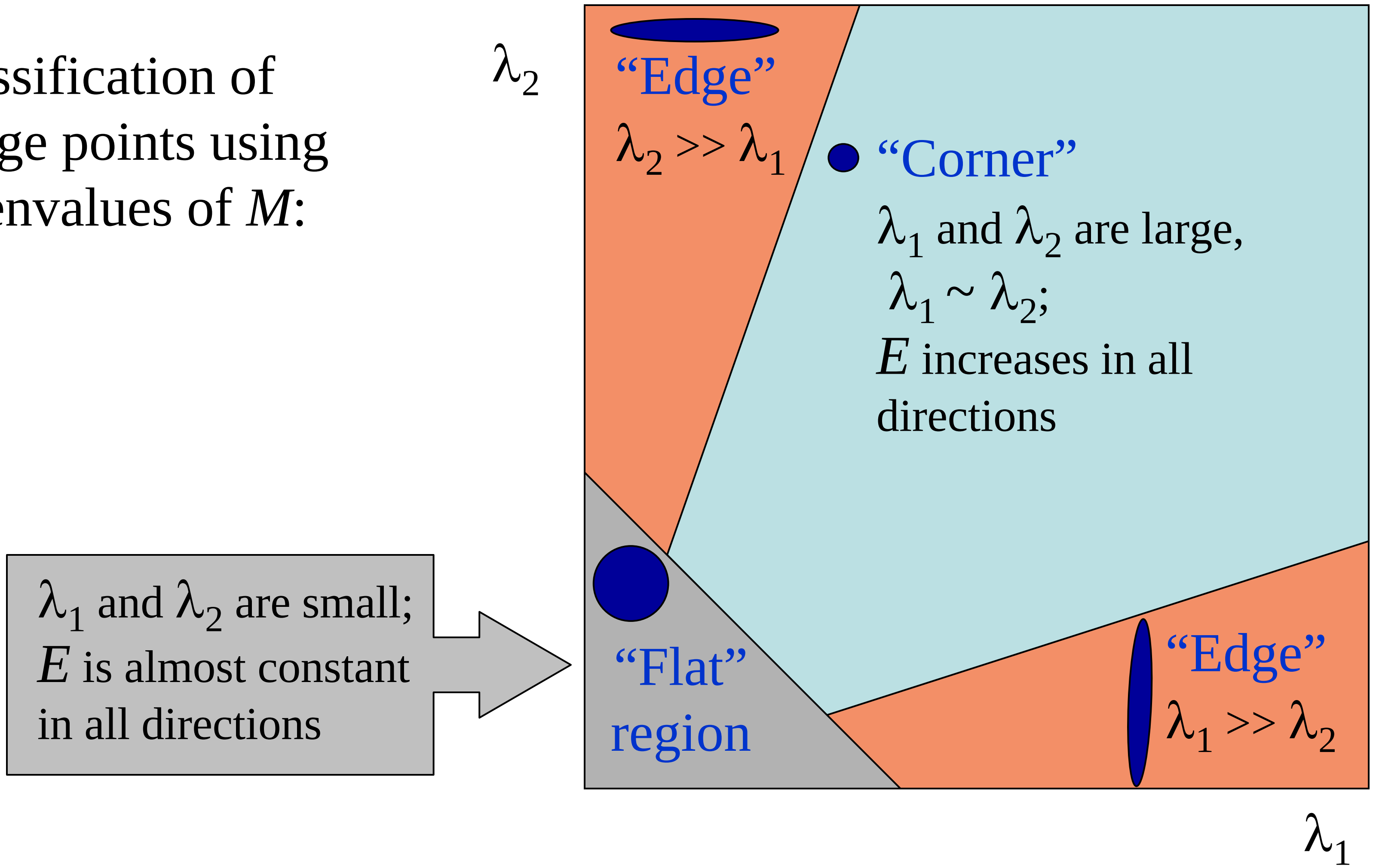
λ_1, λ_2 – eigenvalues of M

Ellipse $E(u,v)$ = const



Harris Detector: Mathematics

Classification of image points using eigenvalues of M:



Harris Detector: Mathematics

Measure of corner response:

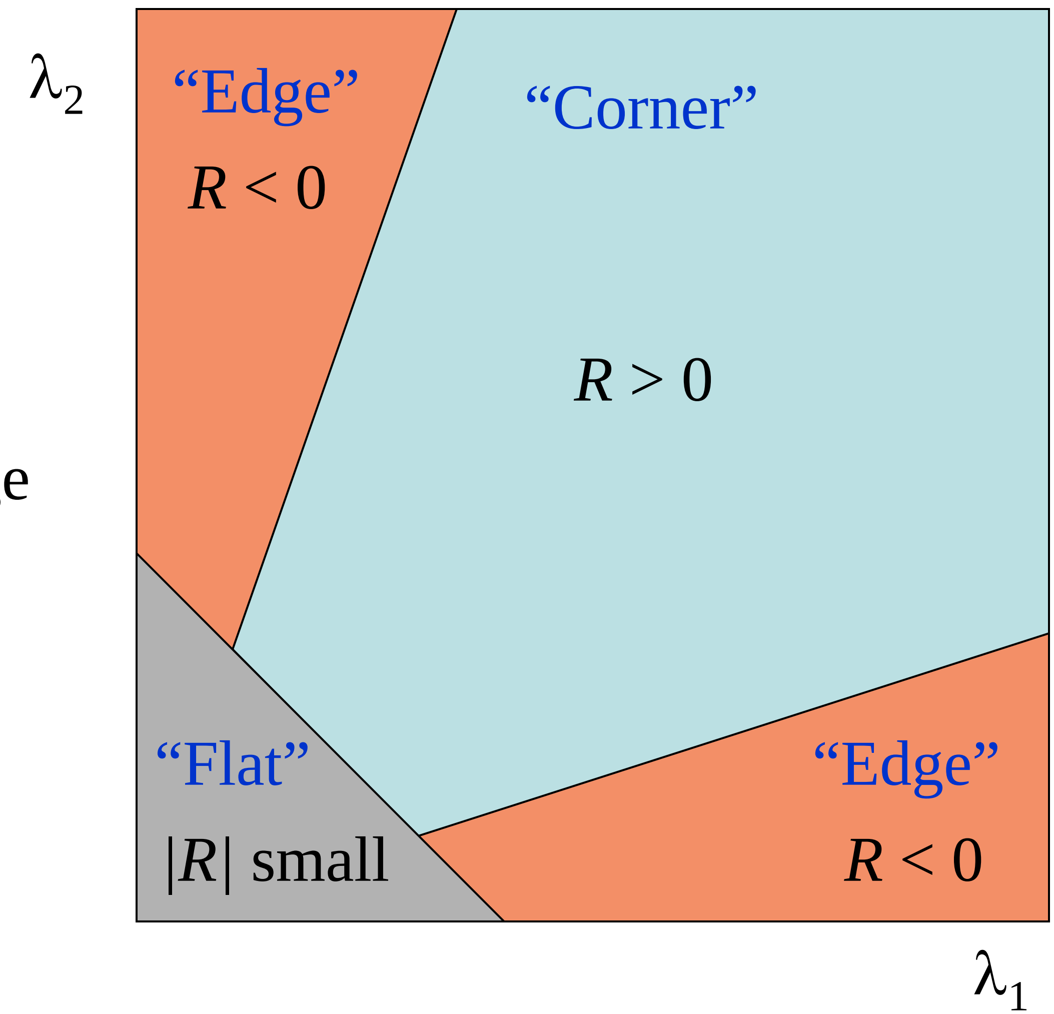
$$R = \det M - k\left(\operatorname{trace} M\right)^2$$

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

(*k* – empirical constant, *k* = 0.04-0.06)

Harris Detector: Mathematics

- R depends only on eigenvalues of M
- R is large for a corner
- R is negative with large magnitude for an edge
- $|R|$ is small for a flat region



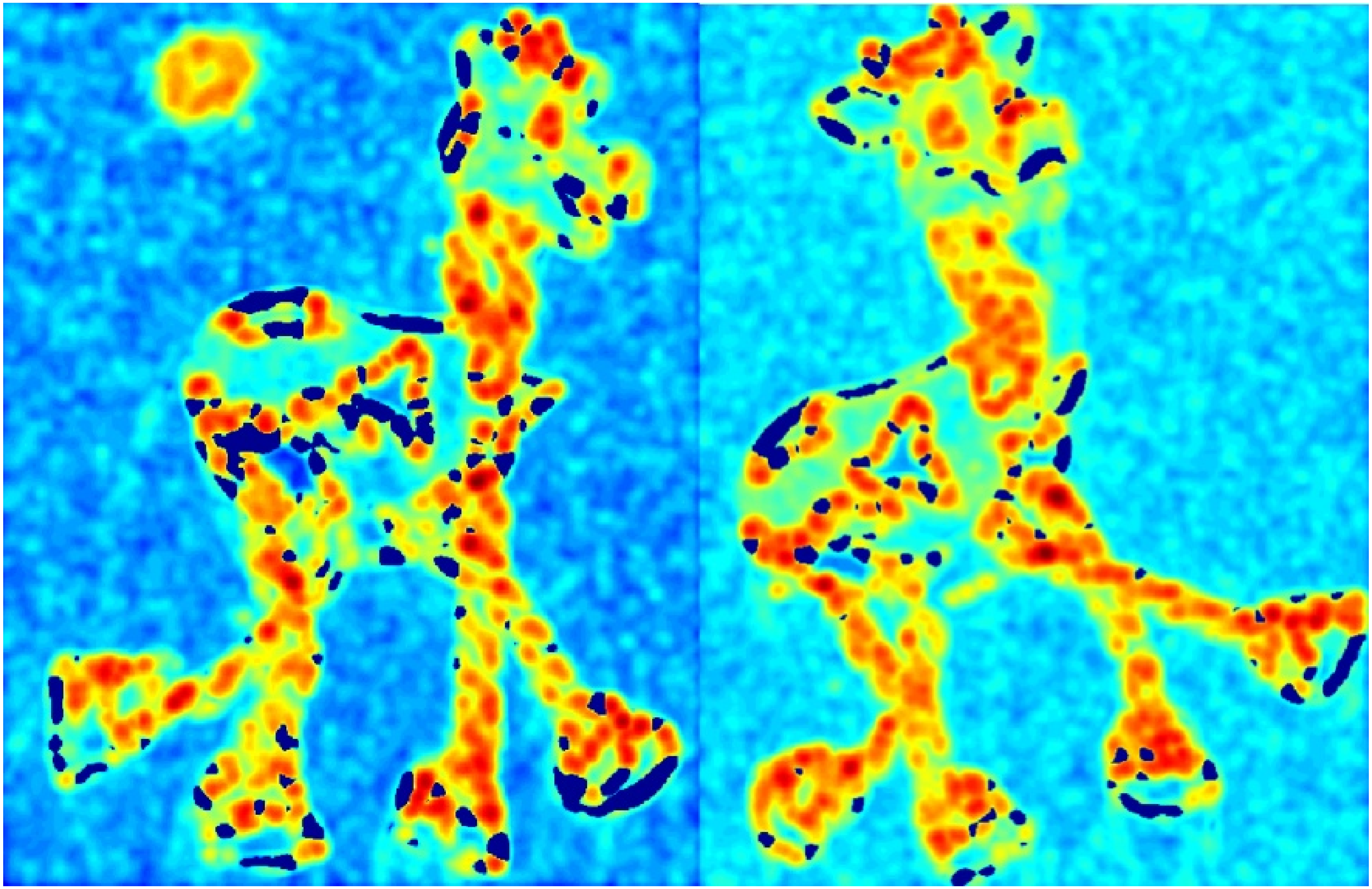
Harris Detector

- The Algorithm:
  - Find points with large corner response function R (R > threshold)
  - Take the points of local maxima of R

Harris Detector: Workflow

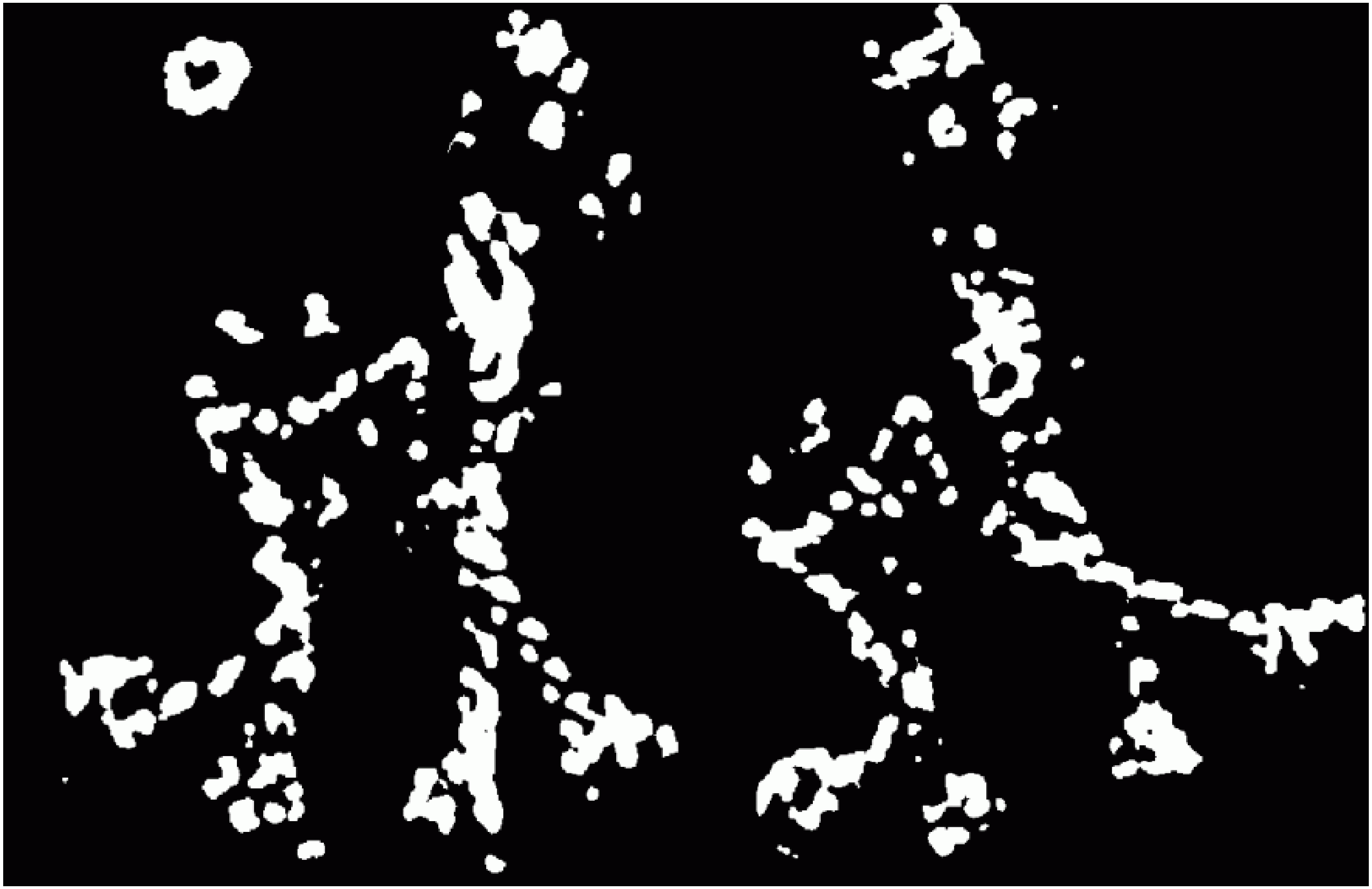
Harris Detector: Workflow

Compute corner response R



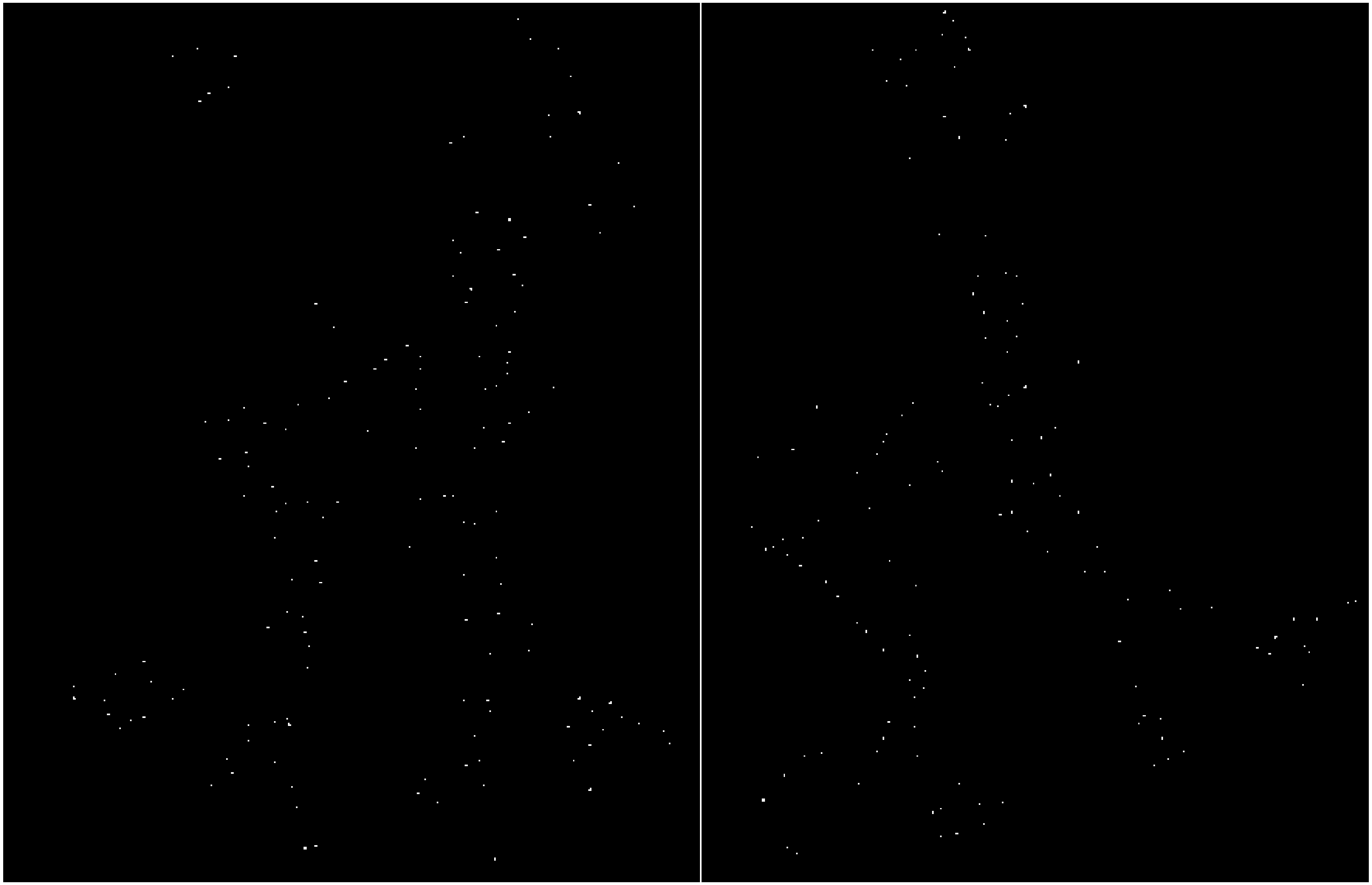
Harris Detector: Workflow

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: Summary

- Average intensity change in direction $[u,v]$ can be expressed as a bilinear form:

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

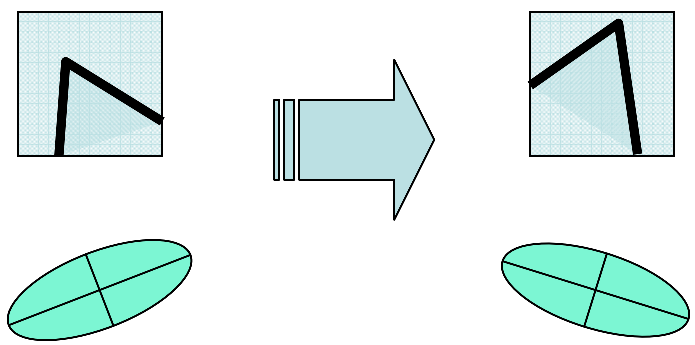
- Describe a point in terms of eigenvalues of M: *measure of corner response*

$$R = \lambda_1 \lambda_2 - k(\lambda_1 + \lambda_2)^2$$

- A good (corner) point should have a *large intensity change* in *all directions*, i.e. R should be large positive

Harris Detector: Some Properties

- Rotation invariance



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

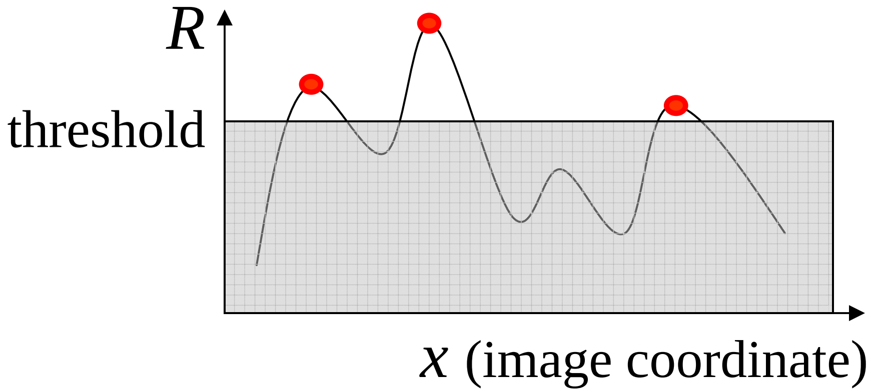
Corner response R is invariant to image rotation

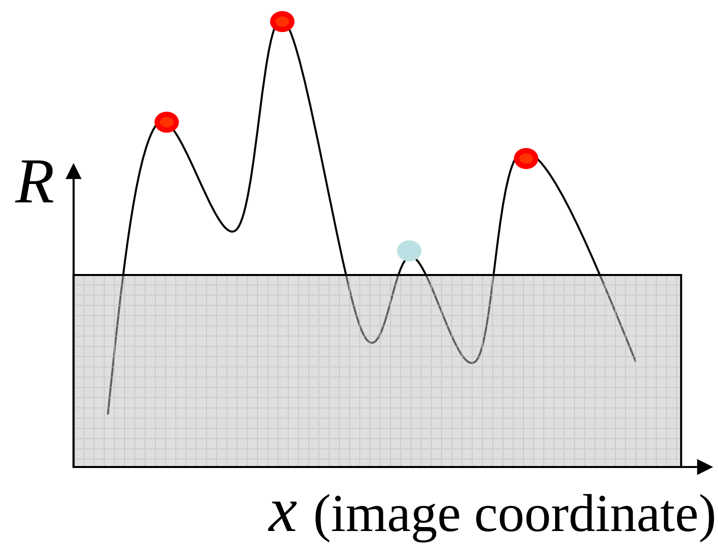
Harris Detector: Some Properties

- Partial invariance to *affine intensity* change

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

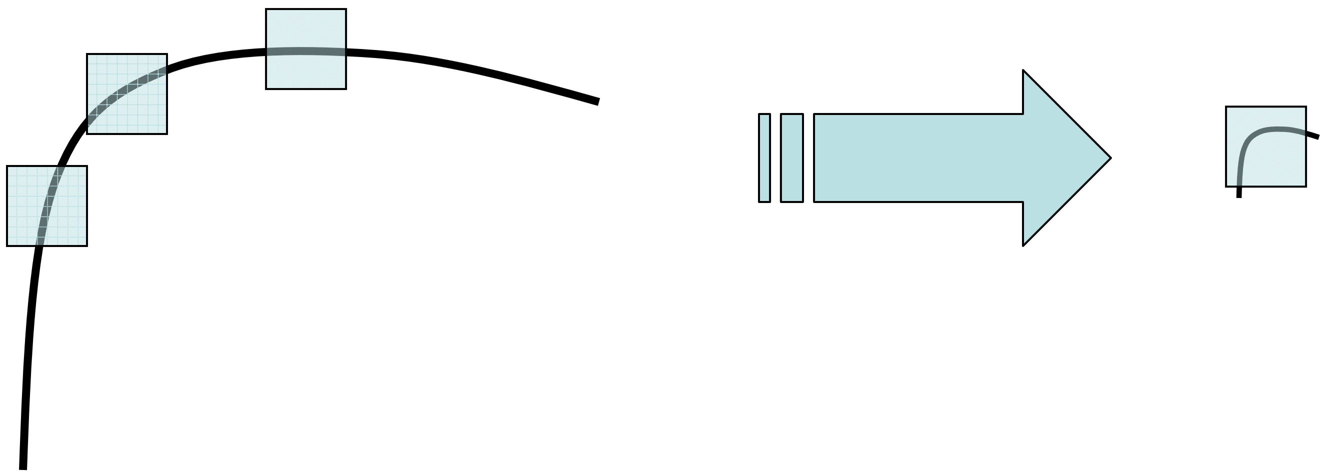
  ✓ Intensity scale: $I \rightarrow a\, I$





Harris Detector: Some Properties

- But: non-invariant to *image scale*!



All points will be classified as edges

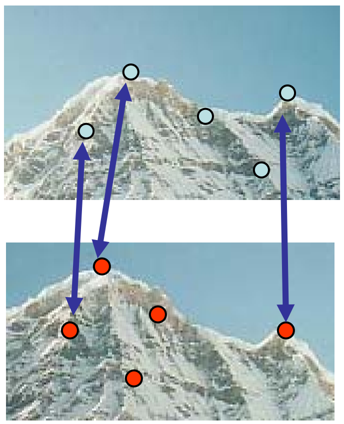
Corner !

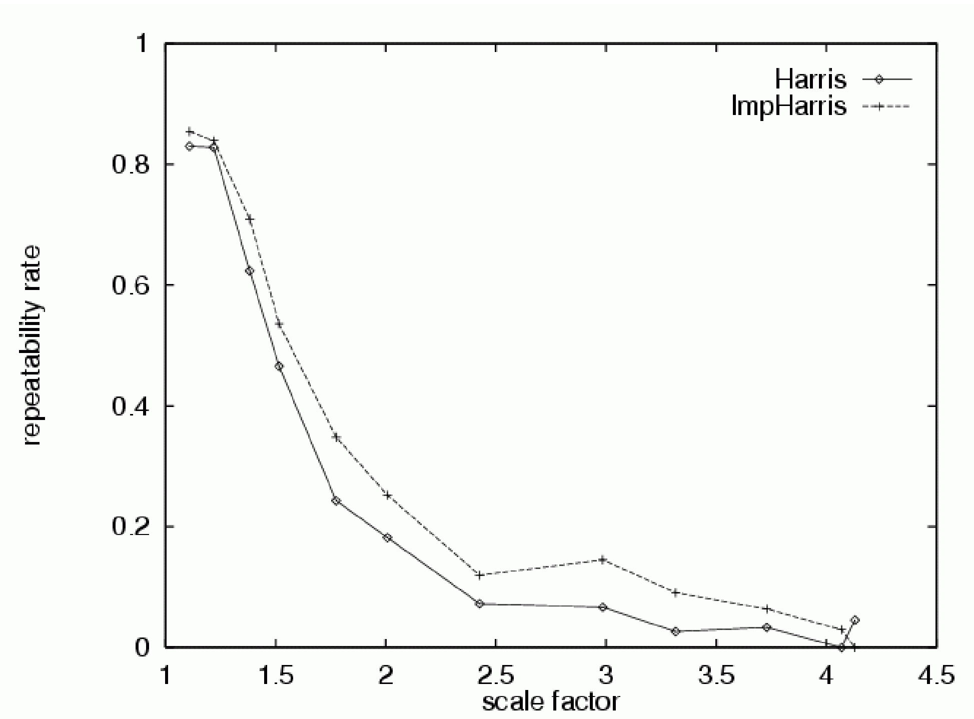
Harris Detector: Some Properties

- Quality of Harris detector for different scale changes

Repeatability rate:

$$\frac{\text{\# correspondences}}{\text{\# possible correspondences}}$$





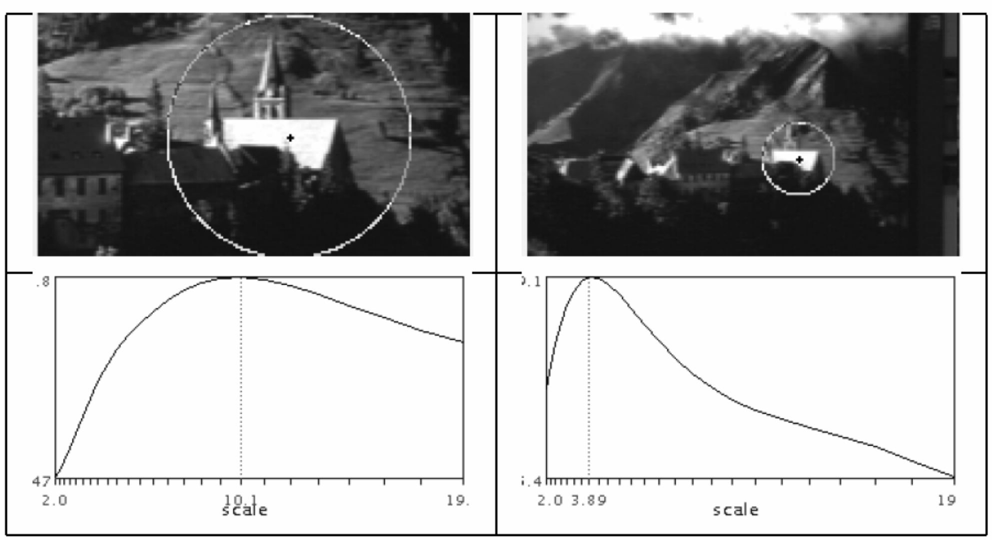
C.Schmid et.al. "Evaluation of Interest Point Detectors". IJCV 2000

Detector	Descriptor	Intensity	Rotation	Scale	Affine
Harris corner	2nd moment(s)	Yes	Yes	No	No
Mikolajczyk & Schmid '01, '02	2nd moment(s)				
Tuytelaars, '00	2nd moment(s)				
Lowe '99 (DoG)	SIFT, PCA-SIFT				
Kadir & Brady, 01					
Matas, '02					
others	others				

Detector	Descriptor	Intensity	Rotation	Scale	Affine
Harris corner	2nd moment(s)	Yes	Yes	No	No
Mikolajczyk & Schmid '01, '02	2nd moment(s)				
Tuytelaars, '00	2nd moment(s)				
Lowe '99 (DoG)	SIFT, PCA-SIFT				
Kadir & Brady, 01					
Matas, '02					
others	others				

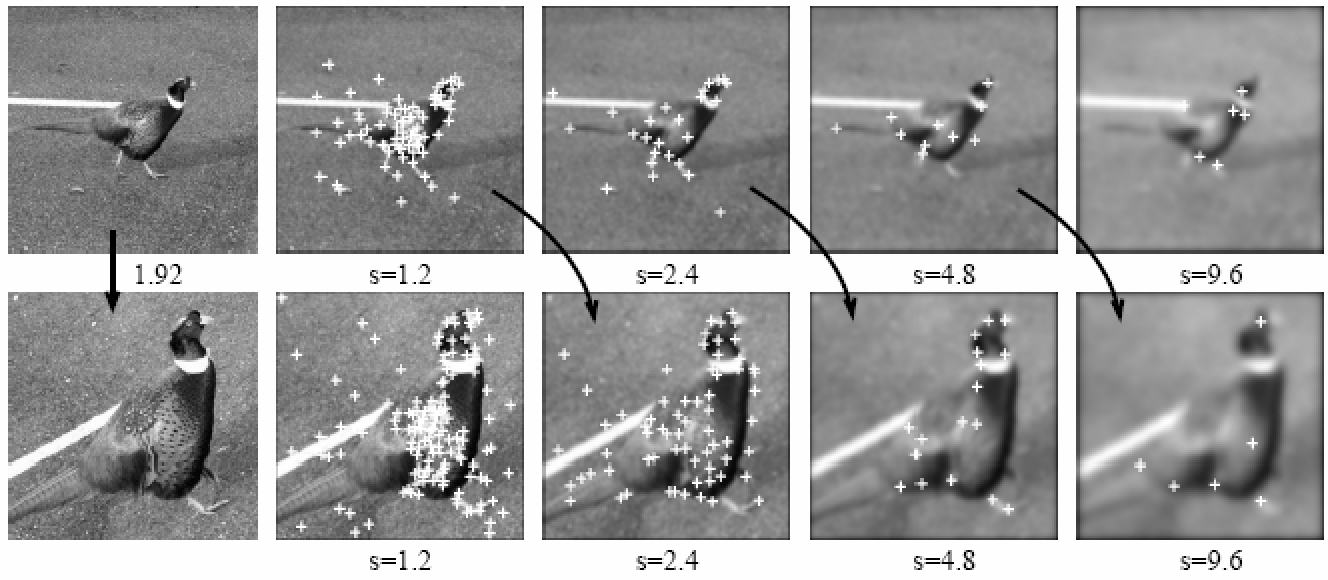
Interest point detectors
Harris-Laplace [***Mikolajczyk & Schmid*** **'01]**

- Adds scale invariance to Harris points
  - Set $s_i = \lambda s_d$
  - Detect at several scales by varying s_d
  - Only take local maxima (8-neighbourhood) of scale adapted Harris points
  - Further restrict to scales at which Laplacian is local maximum



Interest point detectors

Harris-Laplace [***Mikolajczyk & Schmid*** **'01**]



- Selected scale determines size of support region
- Laplacian justified experimentally
  - compared to gradient squared & DoG
  - [*Lindeberg* '98] gives thorough analysis of scale-space

Interest point detectors

Harris-Affine [***Mikolajczyk & Schmid* '02**]

- Adds invariance to affine image transformations
- Initial locations and isotropic scale found by Harris-Laplace
- Affine invariant neighbourhood evolved iteratively using the 2nd moment matrix μ:

$$g(\Sigma) = \frac{1}{2\pi\sqrt{|\Sigma|}} \exp\left(-\frac{\mathbf{x}^T \Sigma^{-1} \mathbf{x}}{2}\right)$$

$$L(\mathbf{x}, \Sigma) = g(\Sigma) \otimes I(\mathbf{x})$$

$$\mu(\mathbf{x}, \Sigma_I, \Sigma_D) = g(\Sigma_I) \otimes ((\nabla L(\mathbf{x}, \Sigma_D))(\nabla L(\mathbf{x}, \Sigma_D))^T)$$

Interest point detectors

Harris-Affine [***Mikolajczyk & Schmid*** **'02]**

For affinely related points:

$$\mathbf{x}_L = A\mathbf{x}_R$$

If $\mu(\mathbf{x}_L, \Sigma_{I,L}, \Sigma_{D,L}) = M_L \quad \Sigma_{I,L} = tM_L^{-1} \quad \Sigma_{D,L} = dM_L^{-1}$

and $\mu(\mathbf{x}_R, \Sigma_{I,R}, \Sigma_{D,R}) = M_R \quad \Sigma_{I,R} = tM_R^{-1} \quad \Sigma_{D,R} = dM_R^{-1}$

Then by normalising:

$\mathbf{x}'_L \rightarrow M_L^{-1/2}\mathbf{x}_L$ and $\mathbf{x}'_R \rightarrow M_R^{-1/2}\mathbf{x}_R$

We get:

$$\mathbf{x}'_L \rightarrow R\mathbf{x}'_R$$

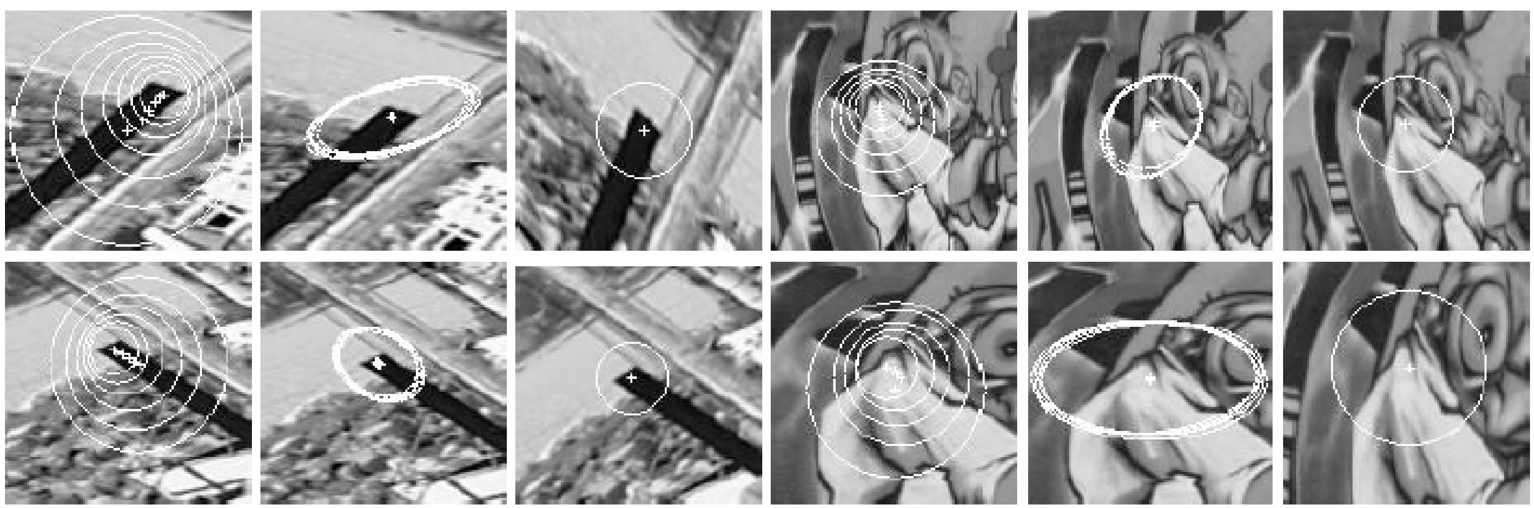
so the normalised regions are related by a pure rotation

See also [*Lindeberg & Garding* '97] and [*Baumberg* '00]

Interest point detectors

Harris-Affine [***Mikolajczyk & Schmid* ’02**]

- Algorithm iteratively adapts
  - shape of support region
  - spatial location $x^{(k)}$
  - integration scale σ_I (based on Laplacian)
  - derivation scale $\sigma_D = s\sigma_I$



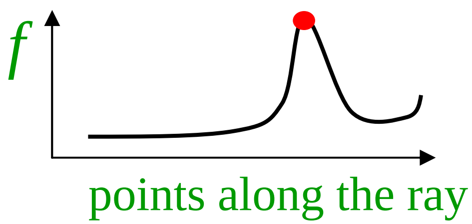
(a) (b) (c) (a) (b) (c)

Detector	Descriptor	Intensity	Rotation	Scale	Affine
Harris corner	2nd moment(s)	Yes	Yes	No	No
Mikolajczyk & Schmid '01, '02	2nd moment(s)	Yes	Yes	Yes	Yes
Tuytelaars, '00	2nd moment(s)				
Lowe '99 (DoG)	SIFT, PCA-SIFT				
Kadir & Brady, 01					
Matas, '02					
others	others				

Detector	Descriptor	Intensity	Rotation	Scale	Affine
Harris corner	2^{nd} moment(s)	Yes	Yes	No	No
Mikolajczyk & Schmid ’01, ‘02	2^{nd} moment(s)	Yes	Yes	Yes	Yes
Tuytelaars, ‘00	2^{nd} moment(s)				
Lowe ’99 (DoG)	SIFT, PCA-SIFT				
Kadir & Brady, 01					
Matas, ‘02					
others	others				

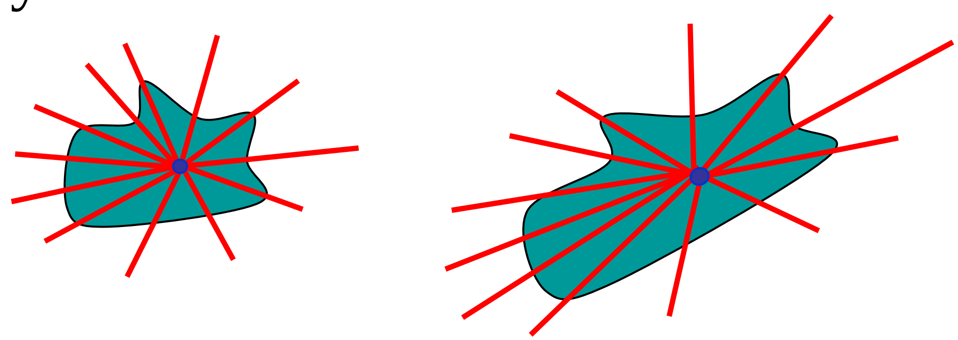
Affine Invariant Detection

- Take a local intensity extremum as initial point
- Go along every ray starting from this point and stop when extremum of function f is reached



$$f(t) = \frac{\left| I(t) - I_0 \right|}{\frac{1}{t} \int_o^t \left| I(t) - I_0 \right| dt}$$

- We will obtain approximately corresponding regions



T.Tuytelaars, L.V.Gool. "Wide Baseline Stereo Matching Based on Local, Affinely Invariant Regions". BMVC 2000.

Affine Invariant Detection

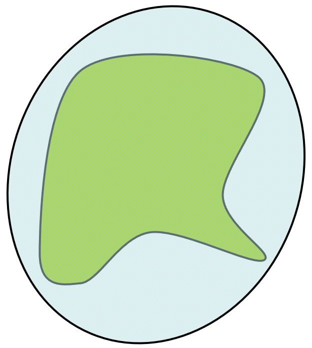
- The regions found may not exactly correspond, so we approximate them with ellipses

- Geometric Moments:

$$m_{pq} = \int_{\mathbb{R}^2} x^p y^q f(x, y)\, dxdy$$

Fact: moments m_{pq} uniquely determine the function f

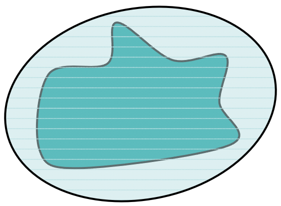
Taking f to be the characteristic function of a region (1 inside, 0 outside), moments of orders up to 2 allow to approximate the region by an ellipse



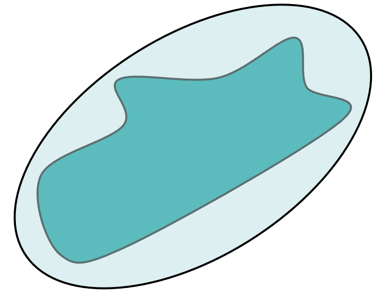
This ellipse will have the same moments of orders up to 2 as the original region

Affine Invariant Detection

- Covariance matrix of region points defines an ellipse:



$$q = Ap$$



$$p^T \Sigma_1^{-1} p = 1 \qquad q^T \Sigma_2^{-1} q = 1$$

$$\Sigma_1 = \langle pp^T \rangle_{\text{region 1}} \qquad \Sigma_2 = \langle qq^T \rangle_{\text{region 2}}$$

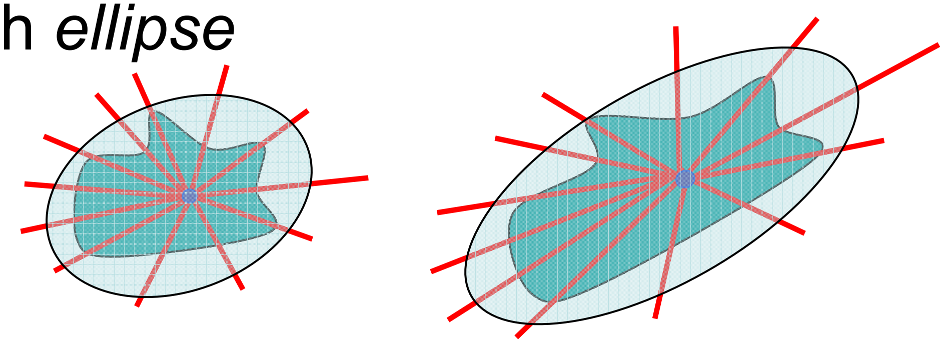
($p = [x, y]^T$ is relative to the center of mass)

$$\Sigma_2 = A \Sigma_1 A^T$$

Ellipses, computed for corresponding regions, also correspond!

Affine Invariant Detection

- Algorithm summary (detection of affine invariant region):
  - Start from a *local intensity extremum* point
  - Go in *every direction* until the point of extremum of some function *f*
  - Curve connecting the points is the region boundary
  - Compute *geometric moments* of orders up to 2 for this region
  - Replace the region with *ellipse*



T.Tuytelaars, L.V.Gool. "Wide Baseline Stereo Matching Based on Local, Affinely Invariant Regions". BMVC 2000.

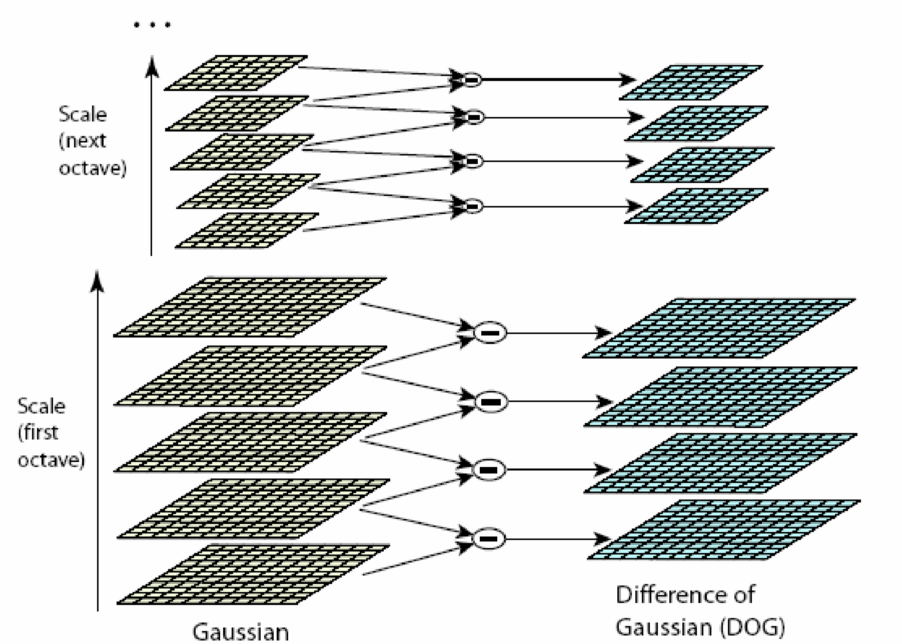
Detector	Descriptor	Intensity	Rotation	Scale	Affine
Harris corner	2^{nd} moment(s)	Yes	Yes	No	No
Mikolajczyk & Schmid ’01, ‘02	2^{nd} moment(s)	Yes	Yes	Yes	Yes
Tuytelaars, ‘00	2^{nd} moment(s)	Yes	Yes	No (Yes ’04 ?)	Yes
Lowe ’99 (DoG)	SIFT, PCA-SIFT				
Kadir & Brady, 01					
Matas, ‘02					
others	others				

Detector	Descriptor	Intensity	Rotation	Scale	Affine
Harris corner	2^{nd} moment(s)	Yes	Yes	No	No
Mikolajczyk & Schmid ’01, ‘02	2^{nd} moment(s)	Yes	Yes	Yes	Yes
Tuytelaars, ‘00	2^{nd} moment(s)	Yes	Yes	No (Yes ’04 ?)	Yes
Lowe ’99 (DoG)	SIFT, PCA-SIFT				
Kadir & Brady, 01					
Matas, ‘02					
others	others				

Interest point detectors

Difference of Gaussians **[*Lowe* '99]**

- Difference of Gaussians in scale-space
  - detects 'blob'-like features
- Can be computed efficiently with image pyramid
- Approximates Laplacian for correct scale factor
- Invariant to rotation and scale changes



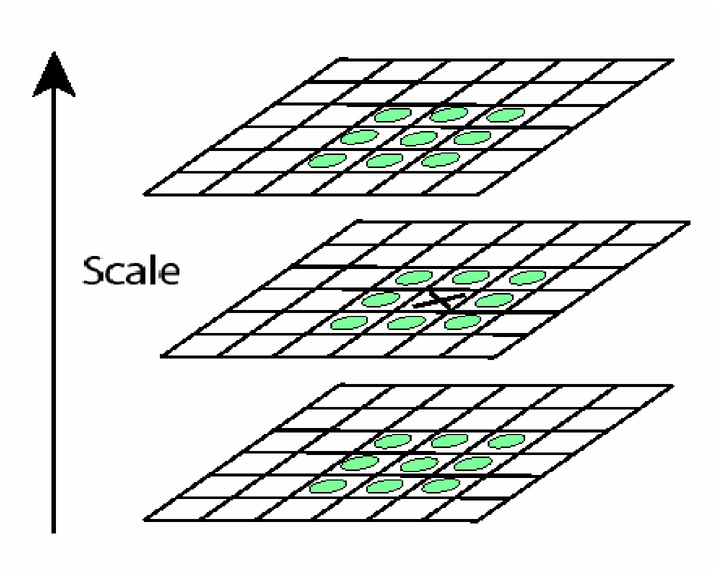
Key point localization

- Detect maxima and minima of difference-of-Gaussian in scale space (Lowe, 1999)
- Fit a quadratic to surrounding values for sub-pixel and sub-scale interpolation (Brown & Lowe, 2002)
- Taylor expansion around point:

$$D(\mathbf{x}) = D + \frac{\partial D^T}{\partial \mathbf{x}}\mathbf{x} + \frac{1}{2}\mathbf{x}^T \frac{\partial^2 D}{\partial \mathbf{x}^2}\mathbf{x}$$

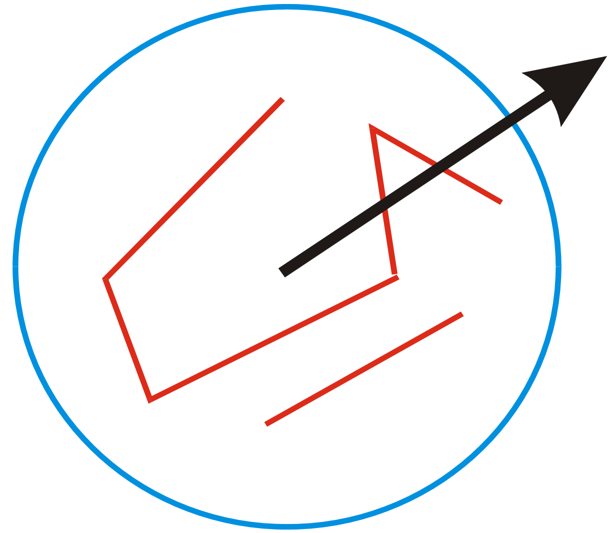
- Offset of extremum (use finite differences for derivatives):

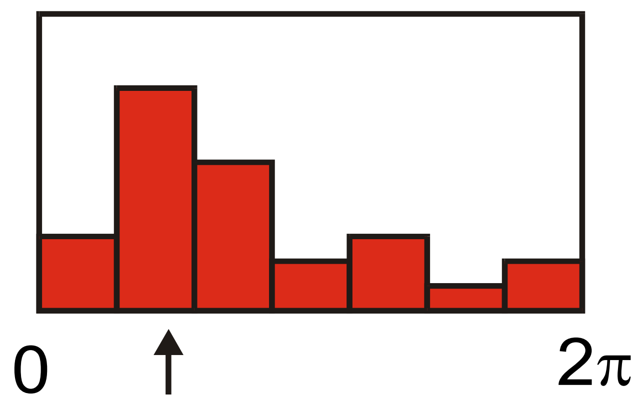
$$\hat{\mathbf{x}} = -\frac{\partial^2 D}{\partial \mathbf{x}^2}^{-1} \frac{\partial D}{\partial \mathbf{x}}$$



Select canonical orientation

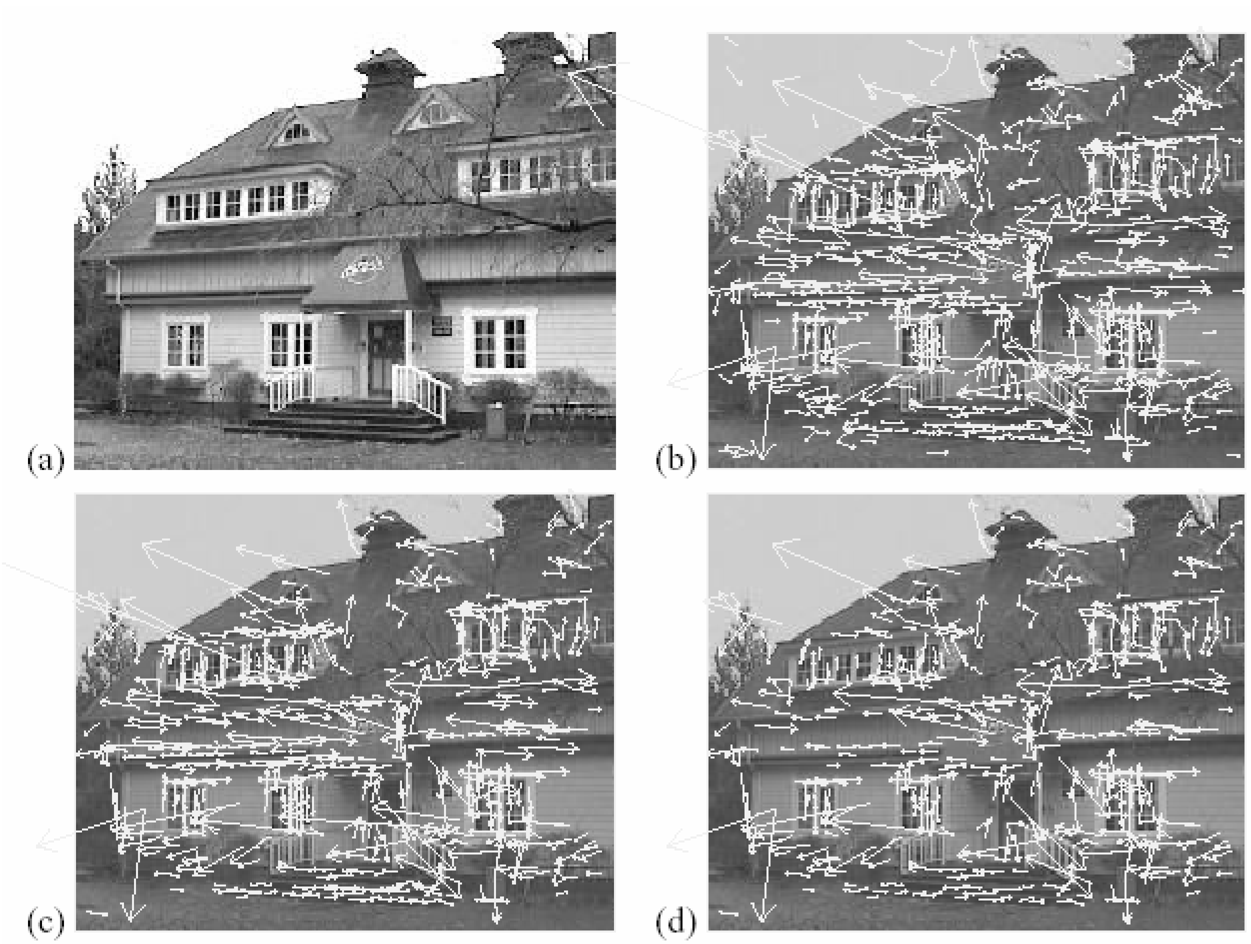
- Create histogram of local gradient directions computed at selected scale
- Assign canonical orientation at peak of smoothed histogram
- Each key specifies stable 2D coordinates (x, y, scale, orientation)





Example of keypoint detection

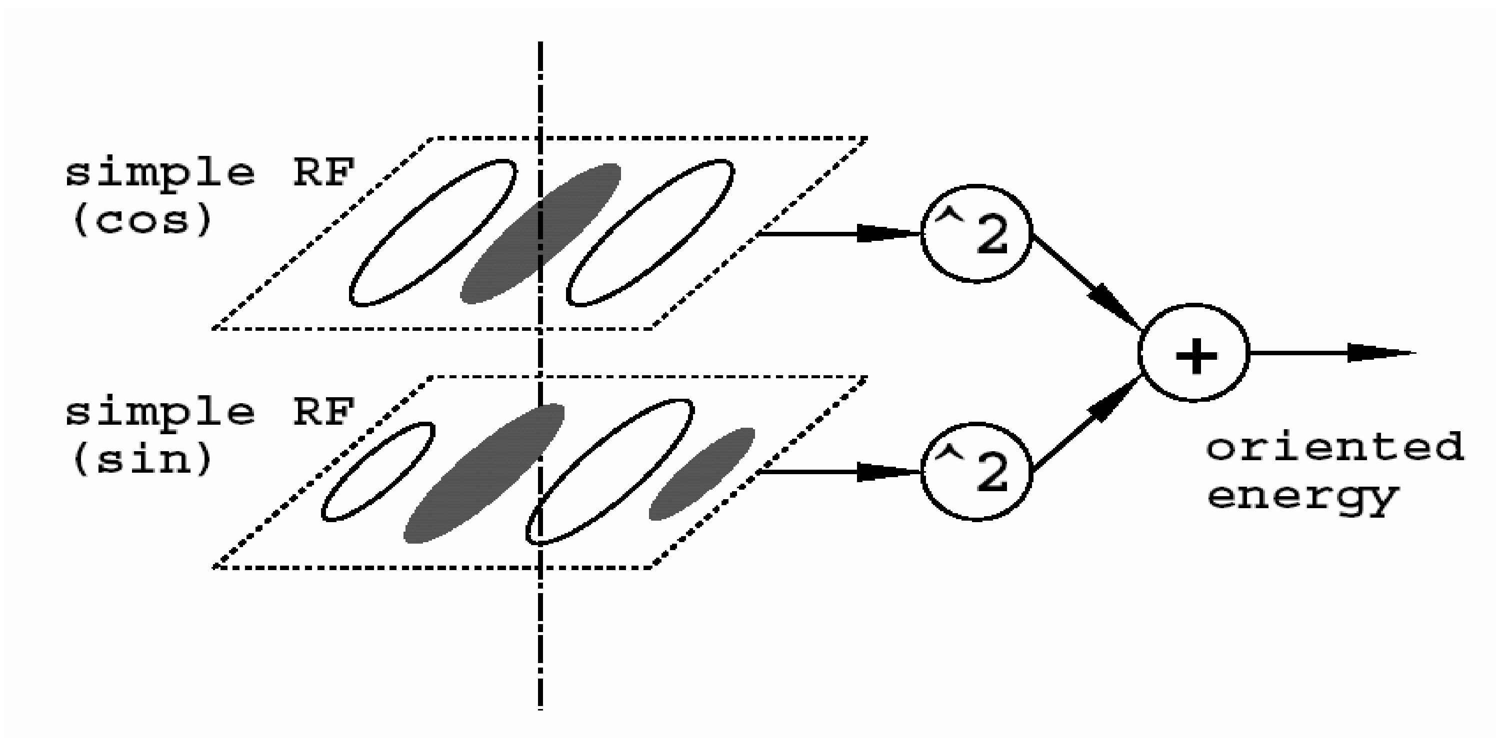
Threshold on value at DOG peak and on ratio of principle curvatures (Harris approach)



(a) 233x189 image
(b) 832 DOG extrema
(c) 729 left after peak value threshold
(d) 536 left after testing ratio of principle curvatures

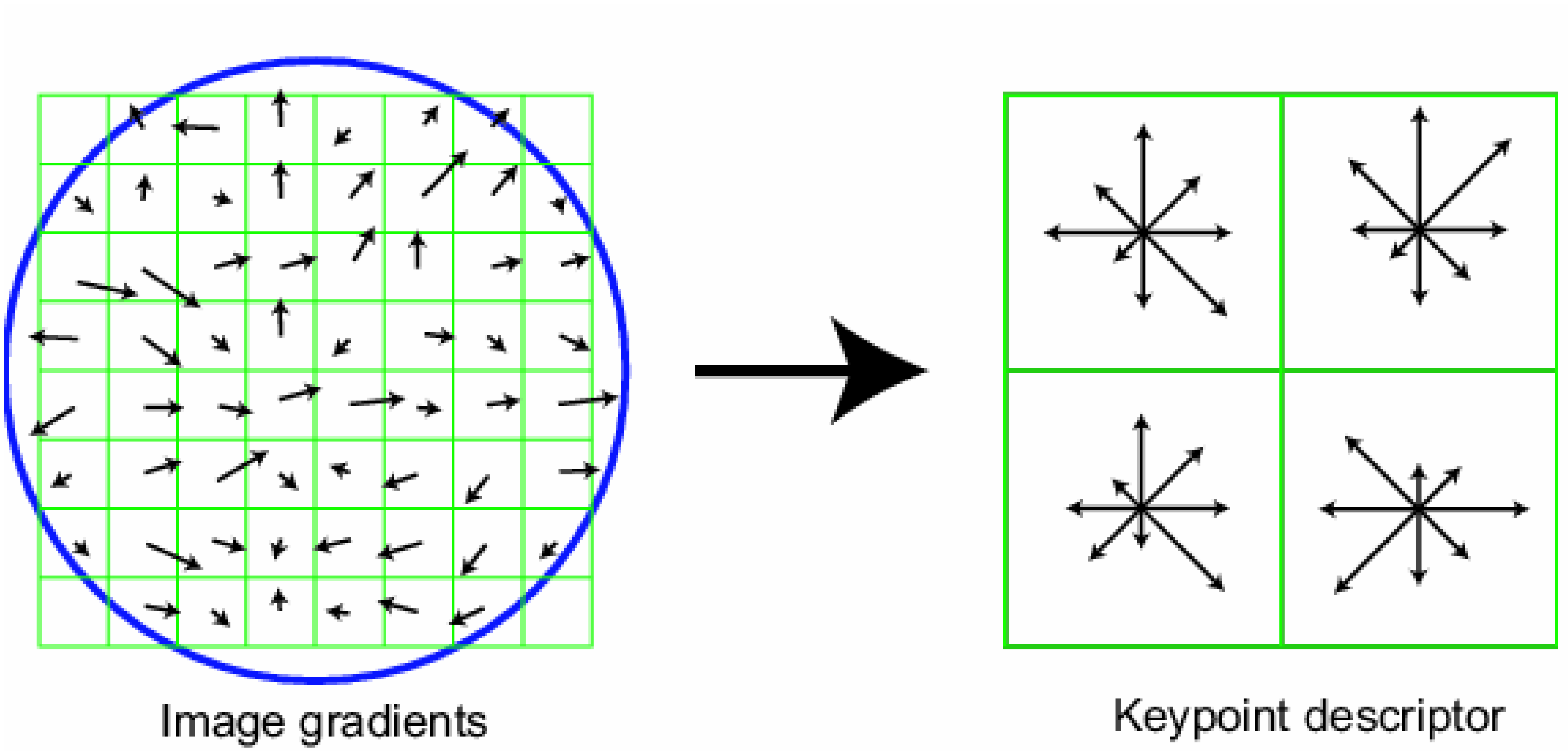
Creating features stable to viewpoint change

- Edelman, Intrator & Poggio (97) showed that complex cell outputs are better for 3D recognition than simple correlation



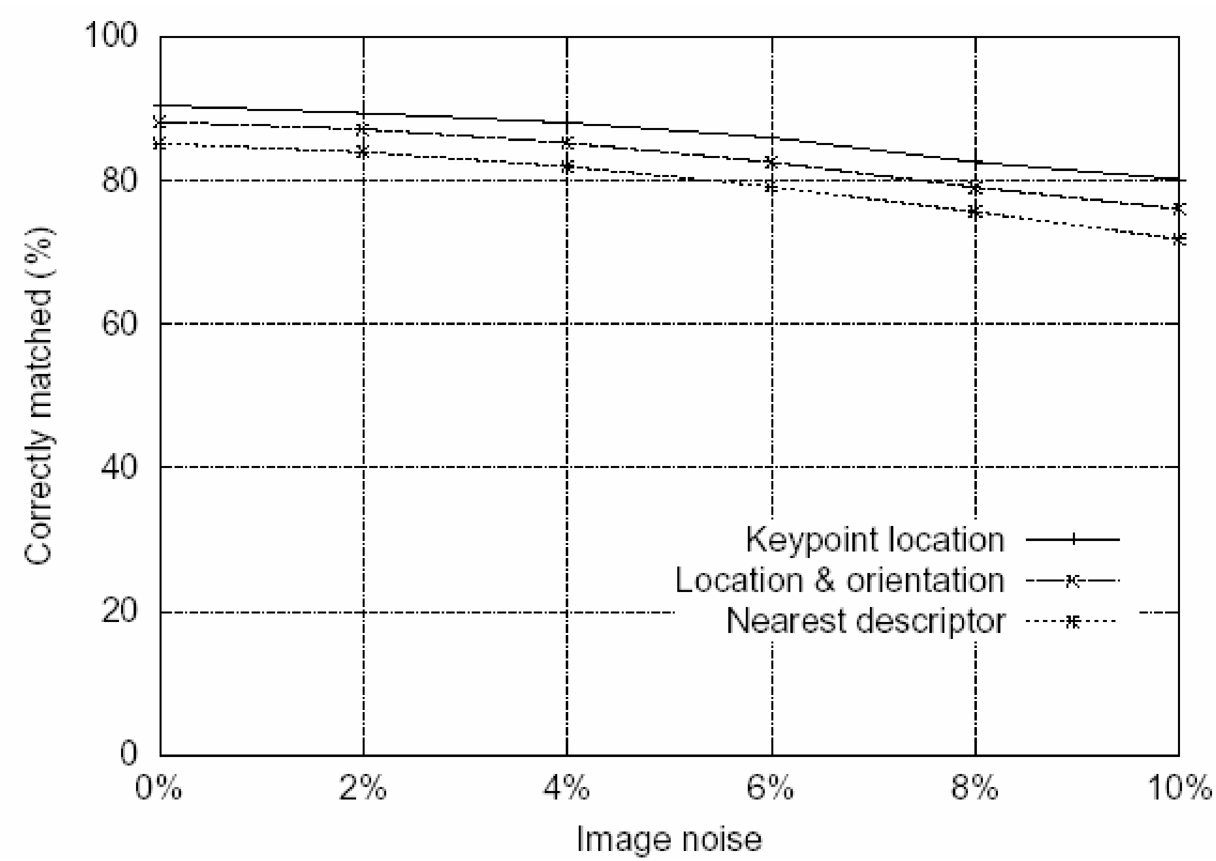
SIFT vector formation

- Thresholded image gradients are sampled over 16x16 array of locations in scale space
- Create array of orientation histograms
- 8 orientations x 4x4 histogram array = 128 dimensions



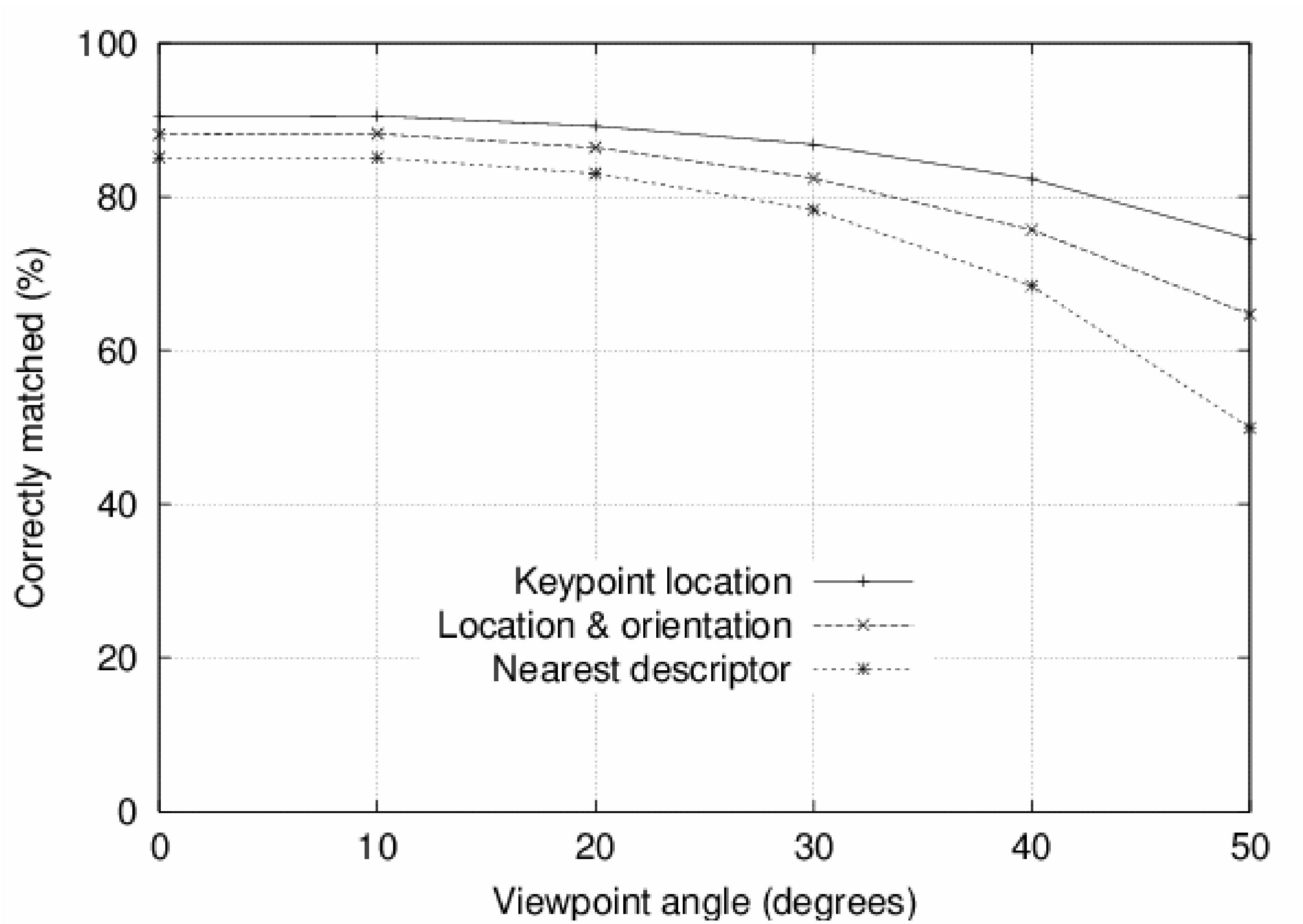
Feature stability to noise

- Match features after random change in image scale & orientation, with differing levels of image noise
- Find nearest neighbor in database of 30,000 features



Feature stability to affine change

- Match features after random change in image scale & orientation, with 2% image noise, and affine distortion
- Find nearest neighbor in database of 30,000 features

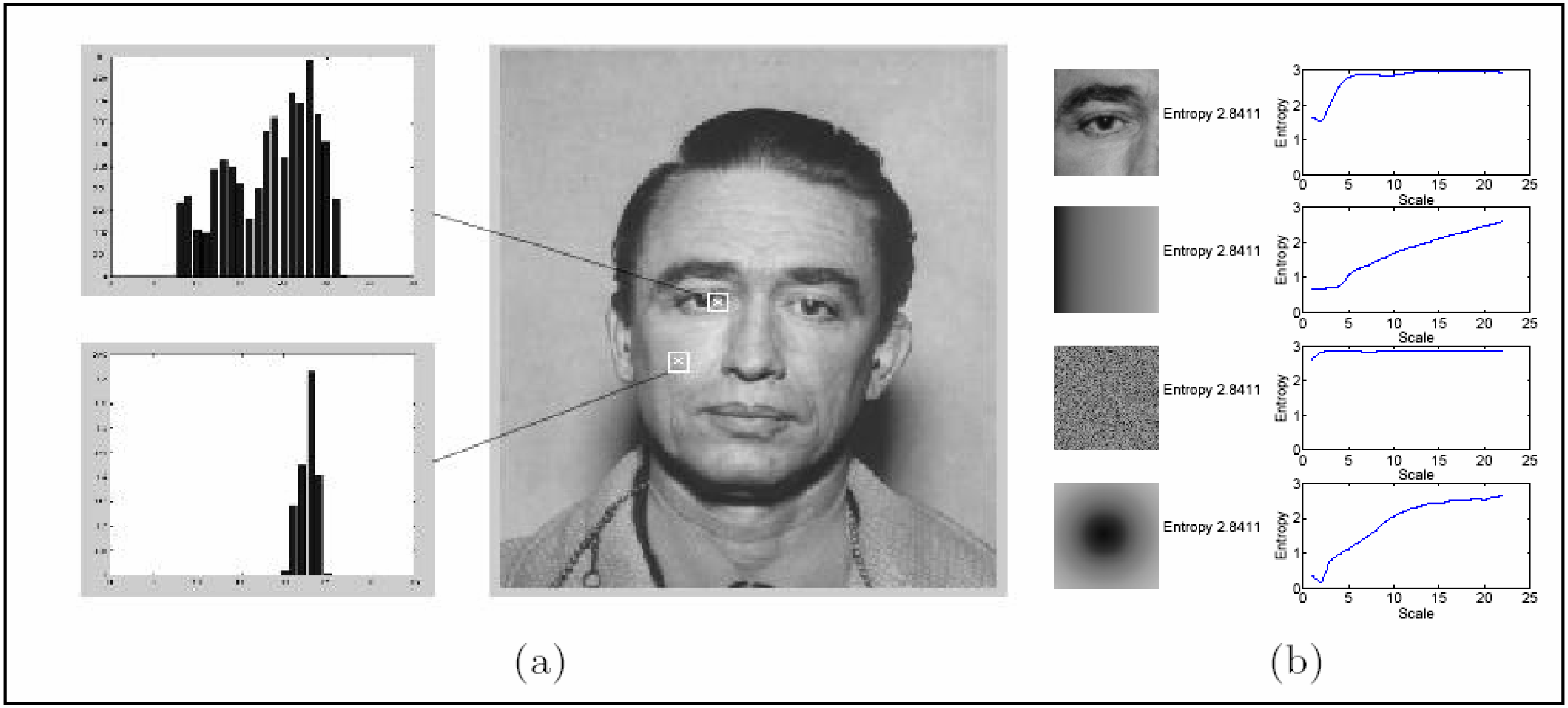


Detector	Descriptor	Intensity	Rotation	Scale	Affine
Harris corner	2^{nd} moment(s)	Yes	Yes	No	No
Mikolajczyk & Schmid ’01, ‘02	2^{nd} moment(s)	Yes	Yes	Yes	Yes
Tuytelaars, ‘00	2^{nd} moment(s)	Yes	Yes	No (Yes ’04 ?)	Yes
Lowe ’99 (DoG)	SIFT, PCA-SIFT	Yes	Yes	Yes	Yes
Kadir & Brady, 01					
Matas, ‘02					
others	others				

Detector	Descriptor	Intensity	Rotation	Scale	Affine
Harris corner	2nd moment(s)	Yes	Yes	No	No
Mikolajczyk & Schmid '01, '02	2nd moment(s)	Yes	Yes	Yes	Yes
Tuytelaars, '00	2nd moment(s)	Yes	Yes	No (Yes '04 ?)	Yes
Lowe '99 (DoG)	SIFT, PCA-SIFT	Yes	Yes	Yes	Yes
Kadir & Brady, 01					
Matas, '02					
others	others				

Other interest point detectors

Scale Saliency **[*Kadir & Brady* '01, '03]**



Other interest point detectors
Scale Saliency [***Kadir & Brady*** **'01, '03]**

- Uses entropy measure of local pdf of intensities:

$$H_D(s,\mathbf{x}) = -\int_{d\in D} p(d,s,\mathbf{x}) \log_2 p(d,s,\mathbf{x}).\mathrm{d}d$$

- Takes local maxima in scale
- Weights with 'change' of distribution with scale:

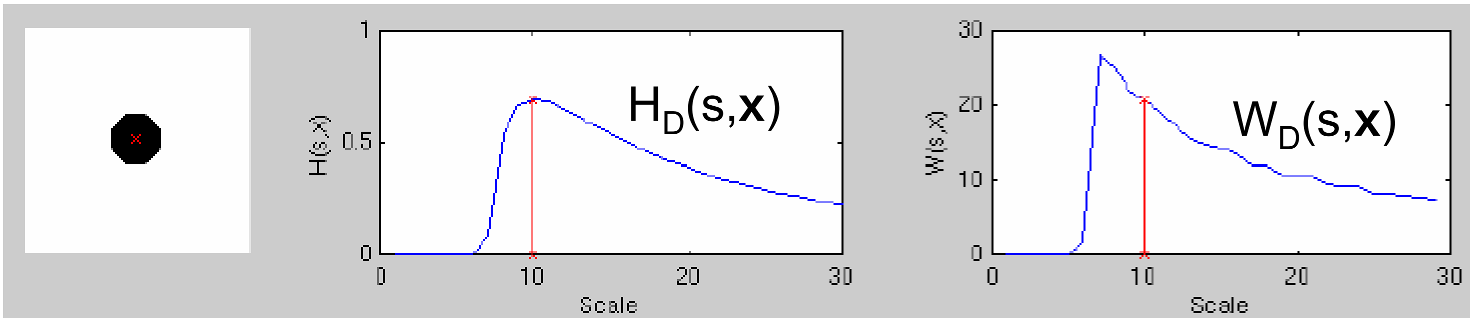
$$W_D(s,\mathbf{x}) = s\int_{d\in D} \left| \frac{\partial}{\partial s} p(d,s,\mathbf{x}) \right| .\mathrm{d}d$$

- To get saliency measure:

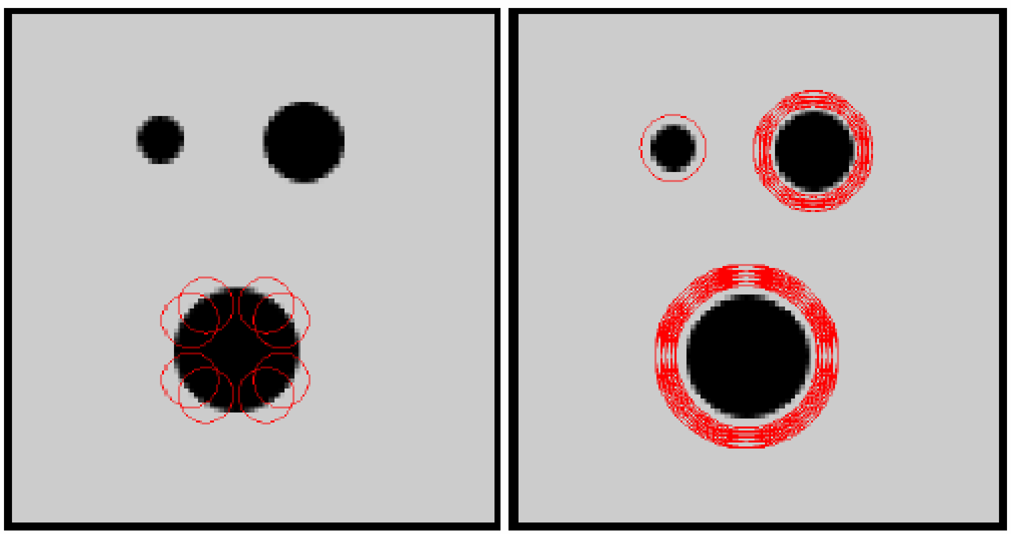
$$Y_D(s,\mathbf{x}) = H_D(s,\mathbf{x}) \times W_D(s,\mathbf{x})$$

Other interest point detectors

Scale Saliency [***Kadir & Brady*** **’01, ’03]**



Just using $H_D(s,\mathbf{x})$



Using $Y_D(s,\mathbf{x}) = H_D W_D$

Most salient parts detected

Other interest point detectors
maximum stable extremal regions [matas et al. 02]

- Sweep threshold of intensity from black to white
- Locate regions based on stability of region with respect to change of threshold

Detector	Descriptor	Intensity	Rotation	Scale	Affine
Harris corner	2^{nd} moment(s)	Yes	Yes	No	No
Mikolajczyk & Schmid ’01, ‘02	2^{nd} moment(s)	Yes	Yes	Yes	Yes
Tuytelaars, ‘00	2^{nd} moment(s)	Yes	Yes	No (Yes ’04 ?)	Yes
Lowe ’99 (DoG)	SIFT, PCA-SIFT	Yes	Yes	Yes	Yes
Kadir & Brady, 01		Yes	Yes	Yes	?
Matas, ’02		Yes	Yes	Yes	?
others	others				

Detector	Descriptor	Intensity	Rotation	Scale	Affine
Harris corner	2nd moment(s)	Yes	Yes	No	No
Mikolajczyk & Schmid ’01, ‘02	2nd moment(s)	Yes	Yes	Yes	Yes
Tuytelaars, ‘00	2nd moment(s)	Yes	Yes	No (Yes ’04 ?)	Yes
Lowe ’99 (DoG)	SIFT, PCA-SIFT	Yes	Yes	Yes	Yes
Kadir & Brady, 01		Yes	Yes	Yes	?
Matas, ’02		Yes	Yes	Yes	?
others	others				

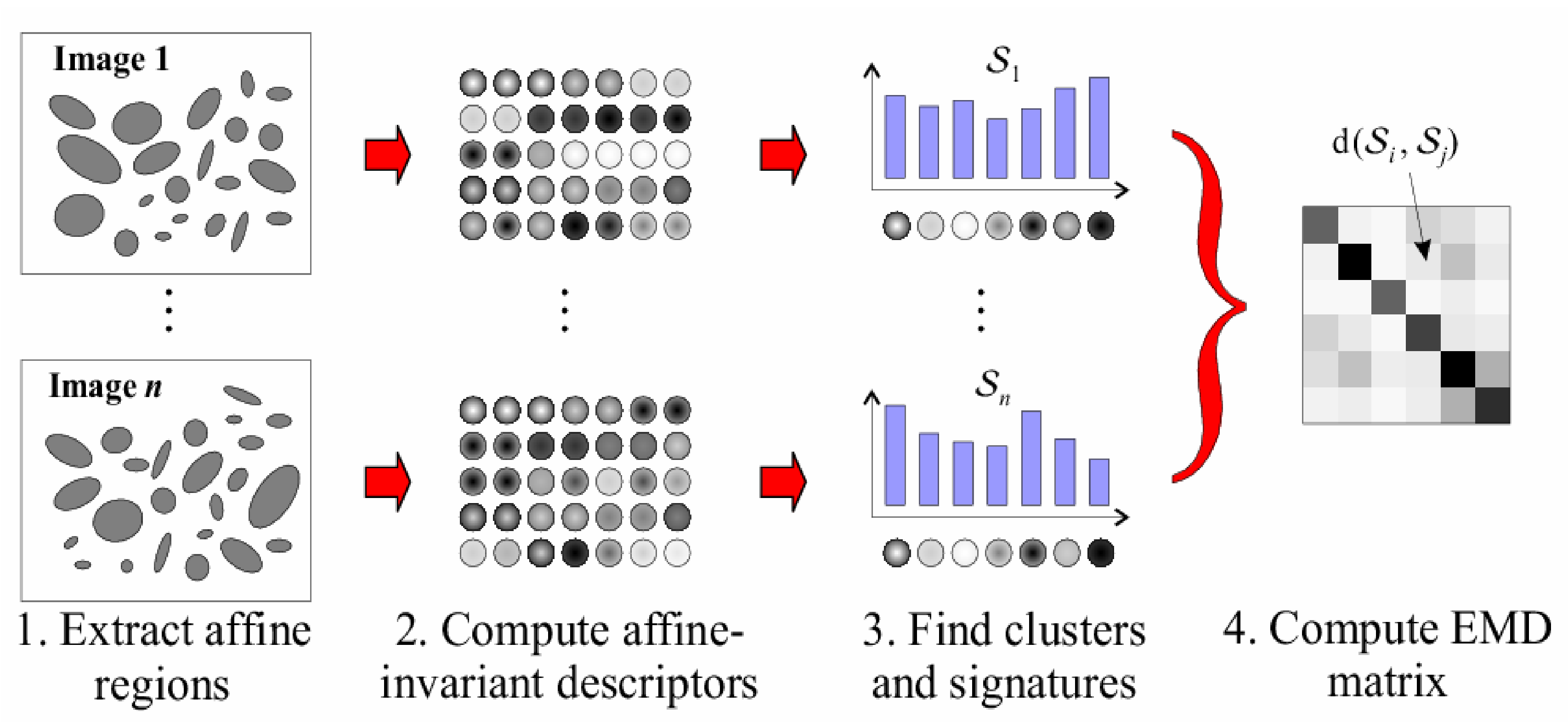
Affine-invariant texture recognition

- Texture recognition under viewpoint changes and non-rigid transformations

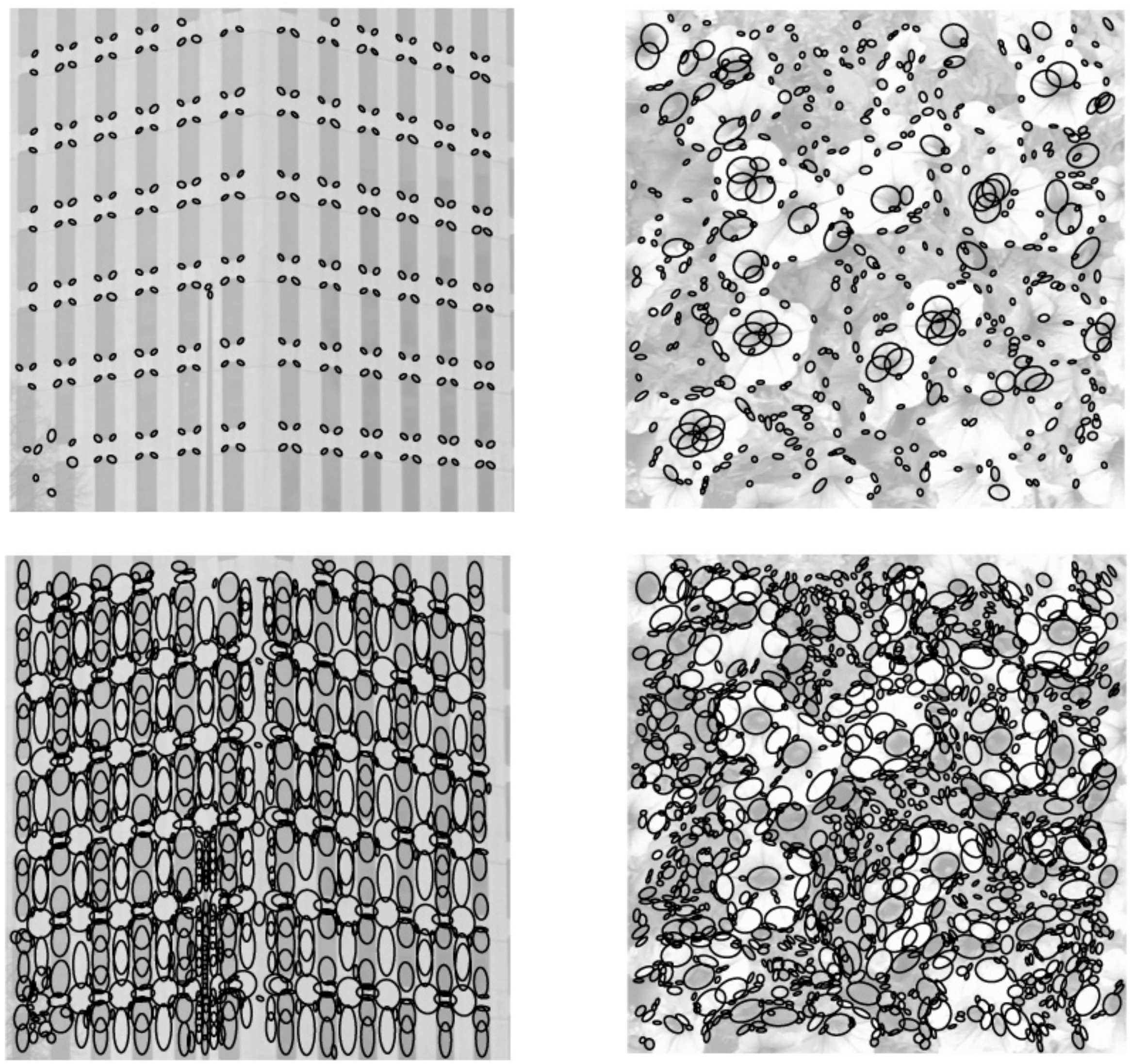
- Use of affine-invariant regions
  - invariance to viewpoint changes
  - spatial selection => more compact representation, reduction of redundancy in texton dictionary

[A sparse texture representation using affine-invariant regions, S. Lazebnik, C. Schmid and J. Ponce, CVPR 2003]

Overview of the approach



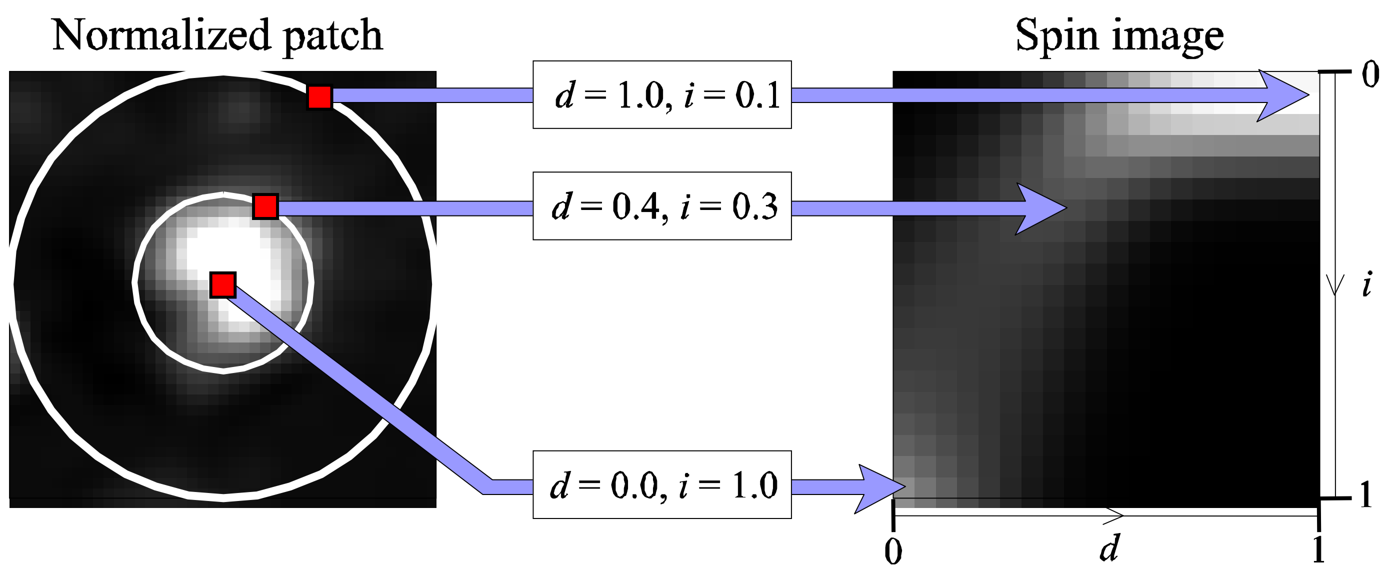
Region extraction



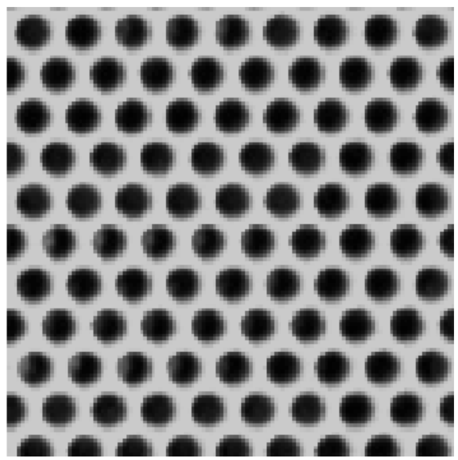
Harris detector

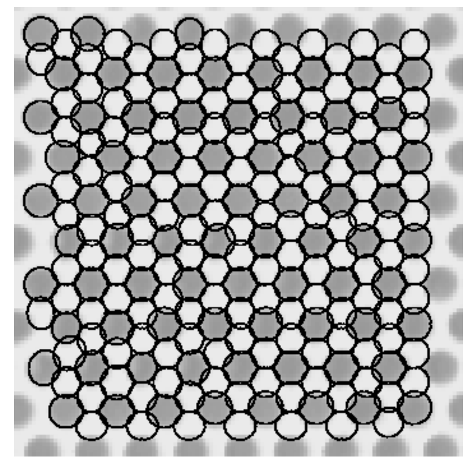
Laplace detector

Descriptors – Spin images



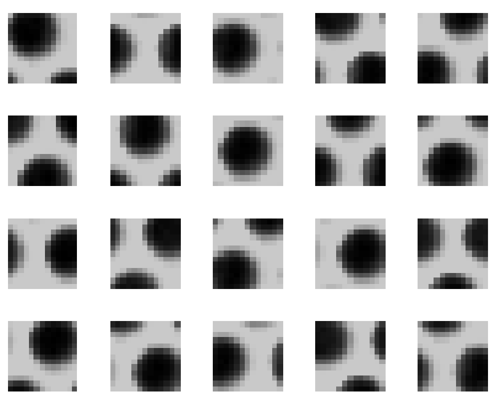
Spatial selection

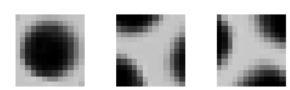




clustering each pixel

clustering selected pixels





Signature and EMD

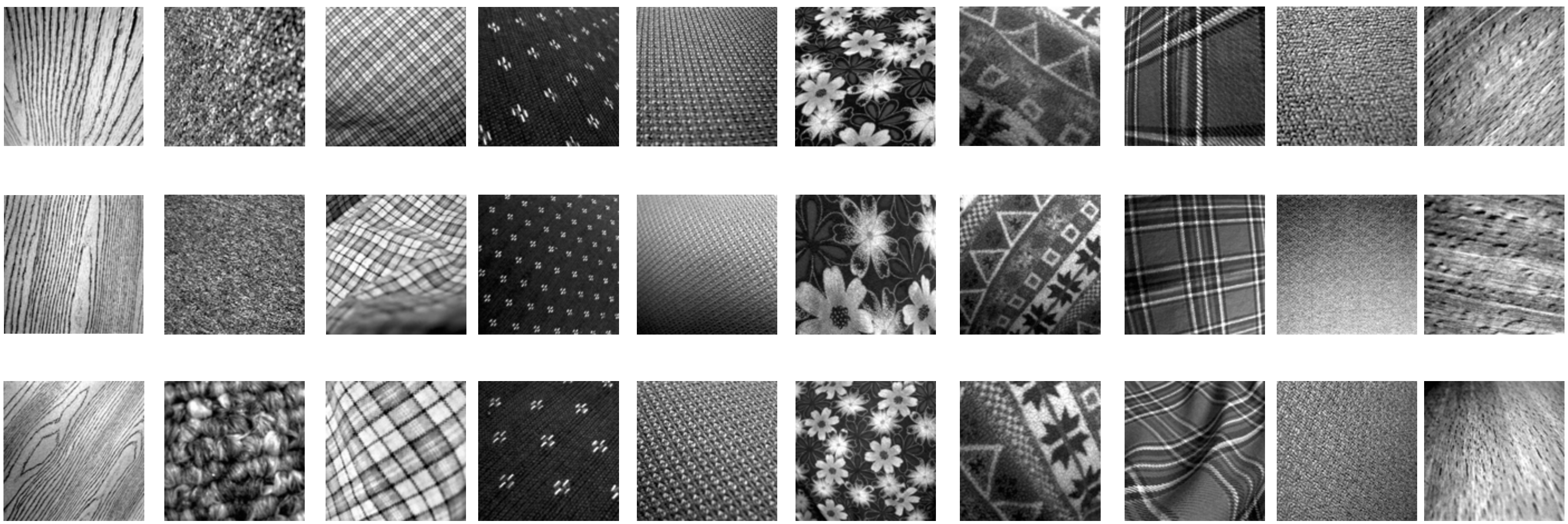
- Hierarchical clustering
  => Signature : $S = \{ (\boldsymbol{m}_1, w_1), \ldots, (\boldsymbol{m}_k, w_k) \}$

- Earth movers distance

  $\boldsymbol{D}(S, S') = [\sum_{i,j} f_{ij}\, d(\boldsymbol{m}_i, \boldsymbol{m'}_j)] / [\sum_{i,j} f_{ij}]$

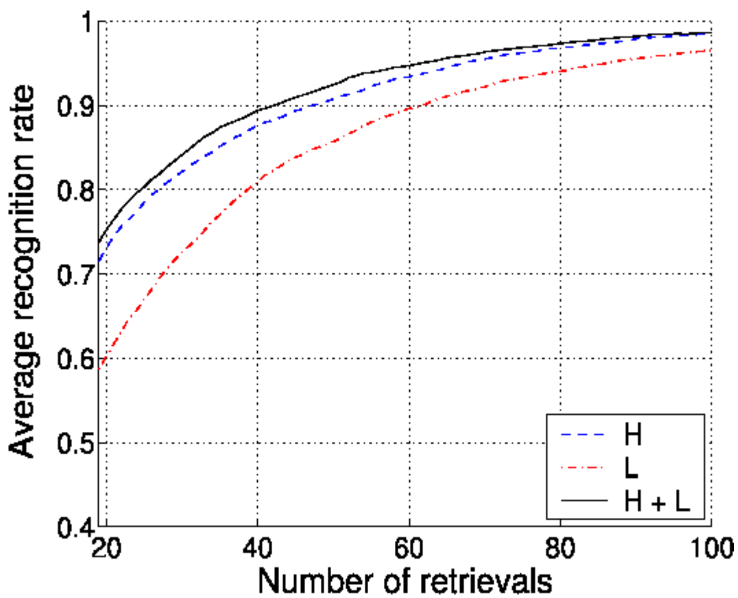
  – robust distance, optimizes the flow between distributions
  – can match signatures of different size
  – not sensitive to the number of clusters

Database with viewpoint changes

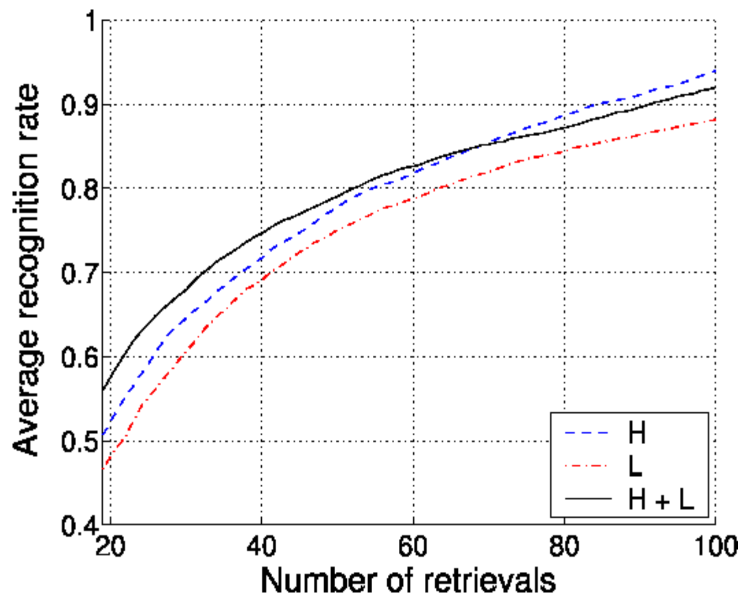


20 samples of 10 different textures

Results



Spin images



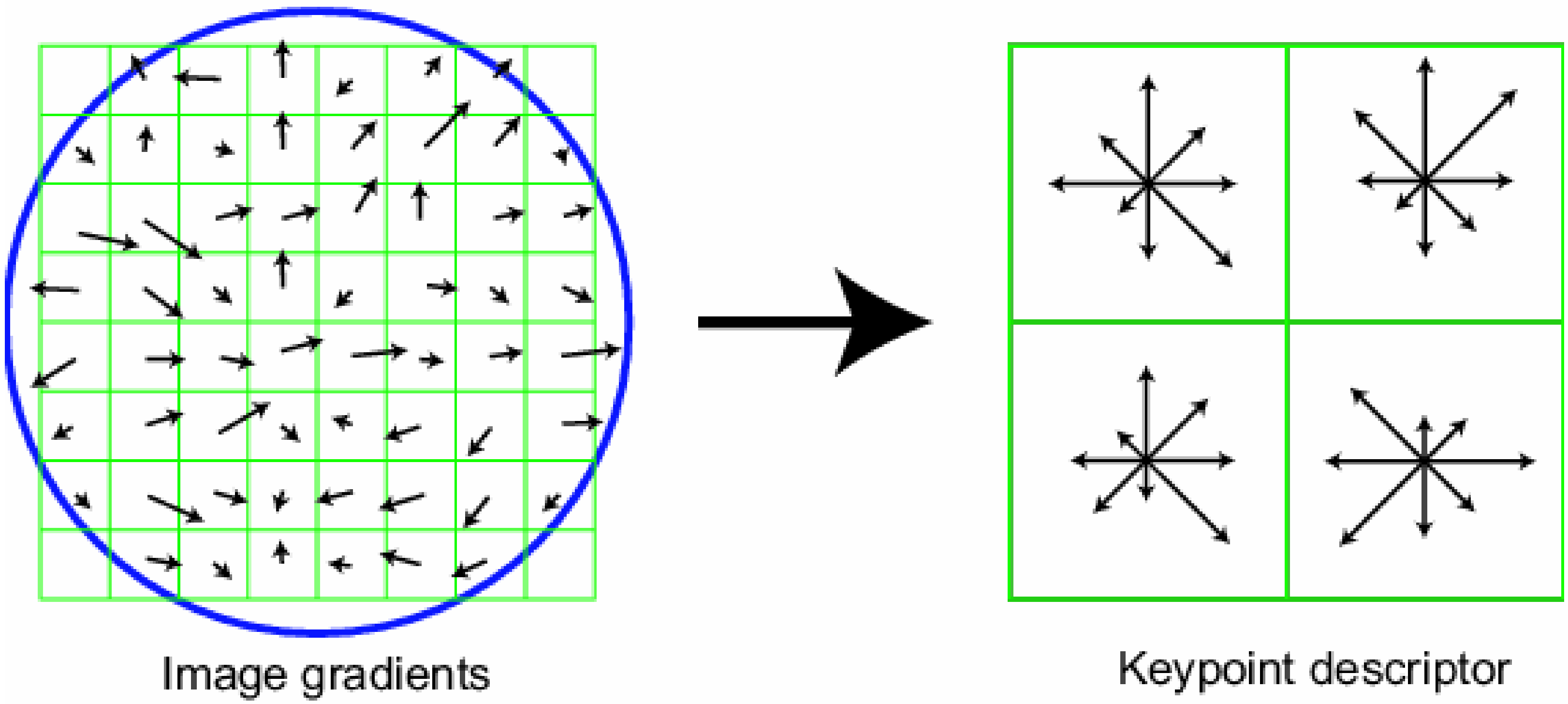
Gabor-like filters

Feature detectors and descriptors

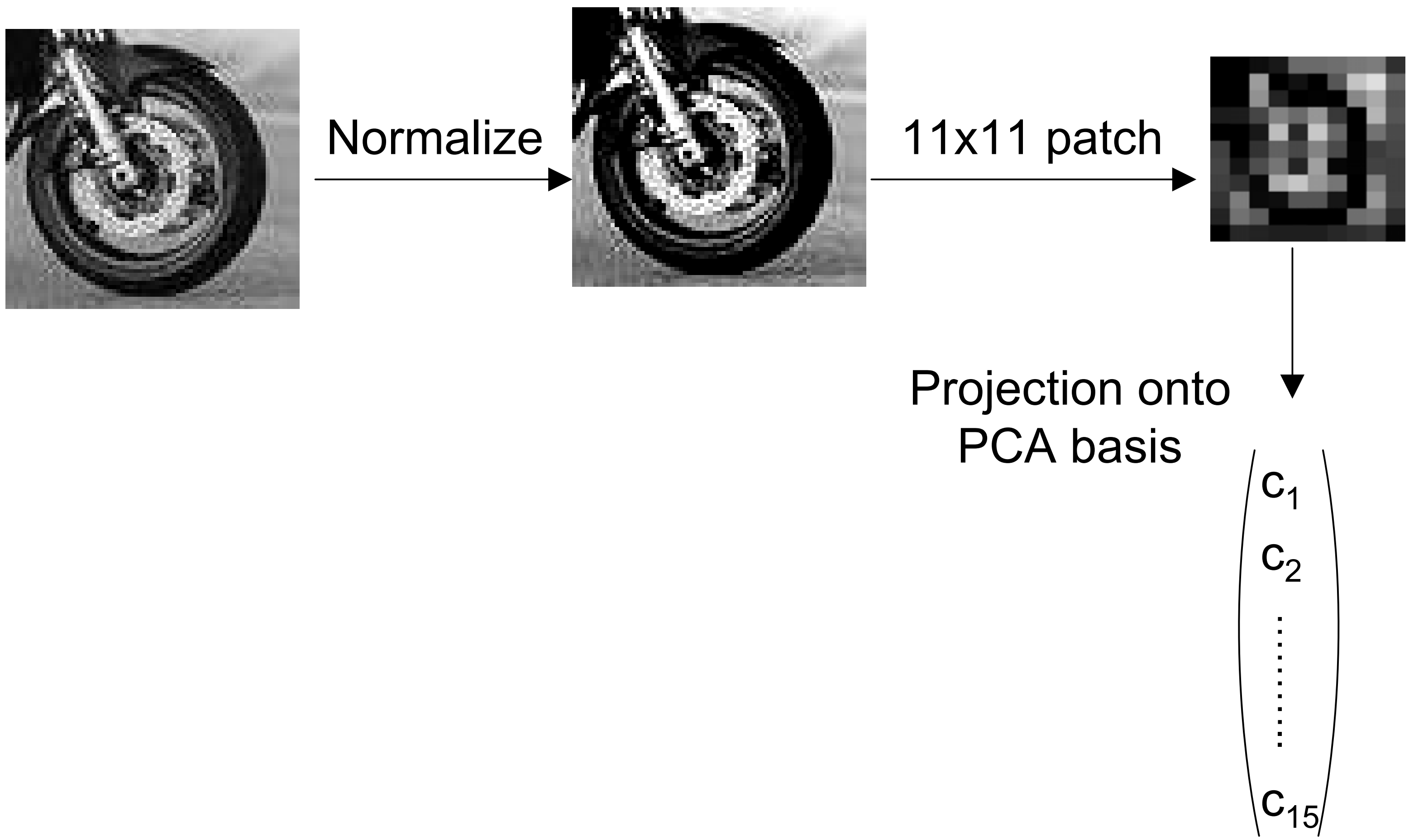
Widely used descriptors

- SIFT
- Gray-scale intensity values
- Steerable filters
- GLOH
- Shape context & geometric blur

SIFT

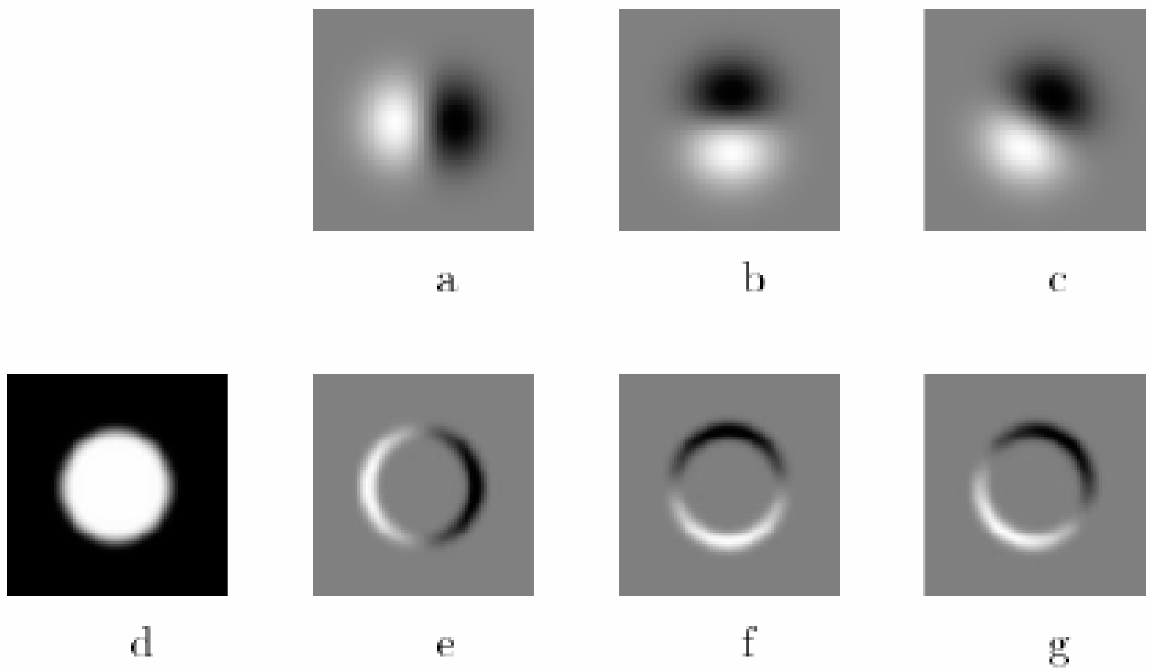


Gray-scale intensity



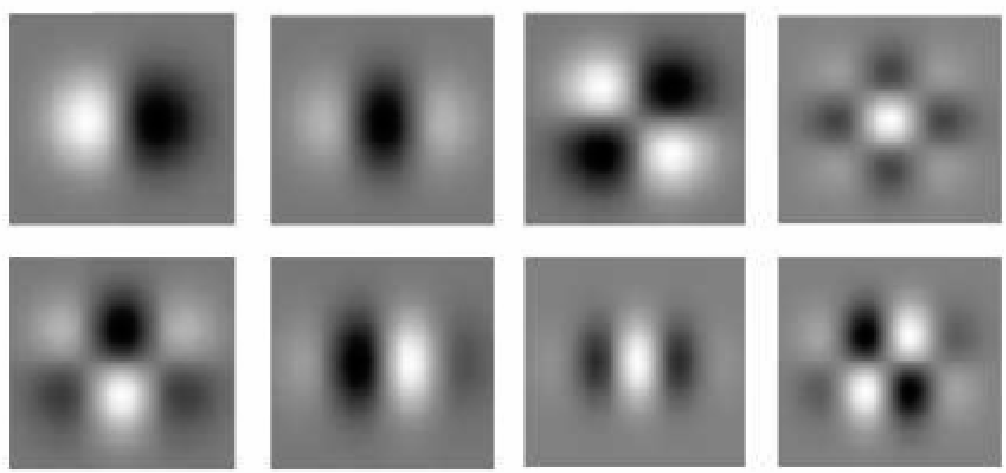
Steerable filters

$$
\begin{aligned}
R_1^{0^\circ} &= G_1^0 * I \\
R_1^{90^\circ} &= G_1^{90} * I \\
\text{then} & \\
R_1^{\theta} &= \cos(\theta) R_1^{0^\circ} + \sin(\theta) R_1^{90^\circ}
\end{aligned}
$$



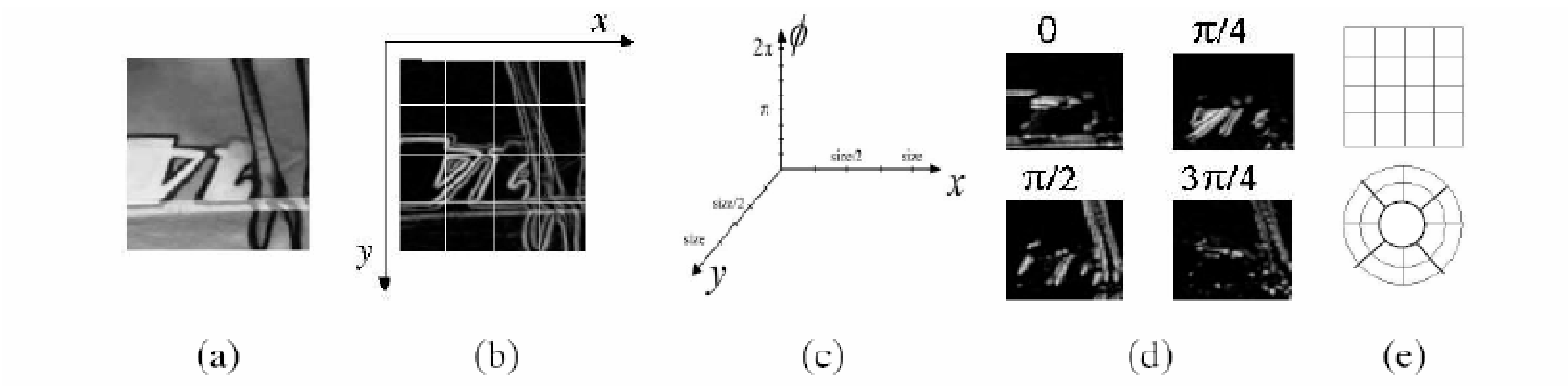
Steerable filters

Gaussian derivatives up to 4^{th} order. The remaining derivatives can be computed by rotation of 90 degrees.

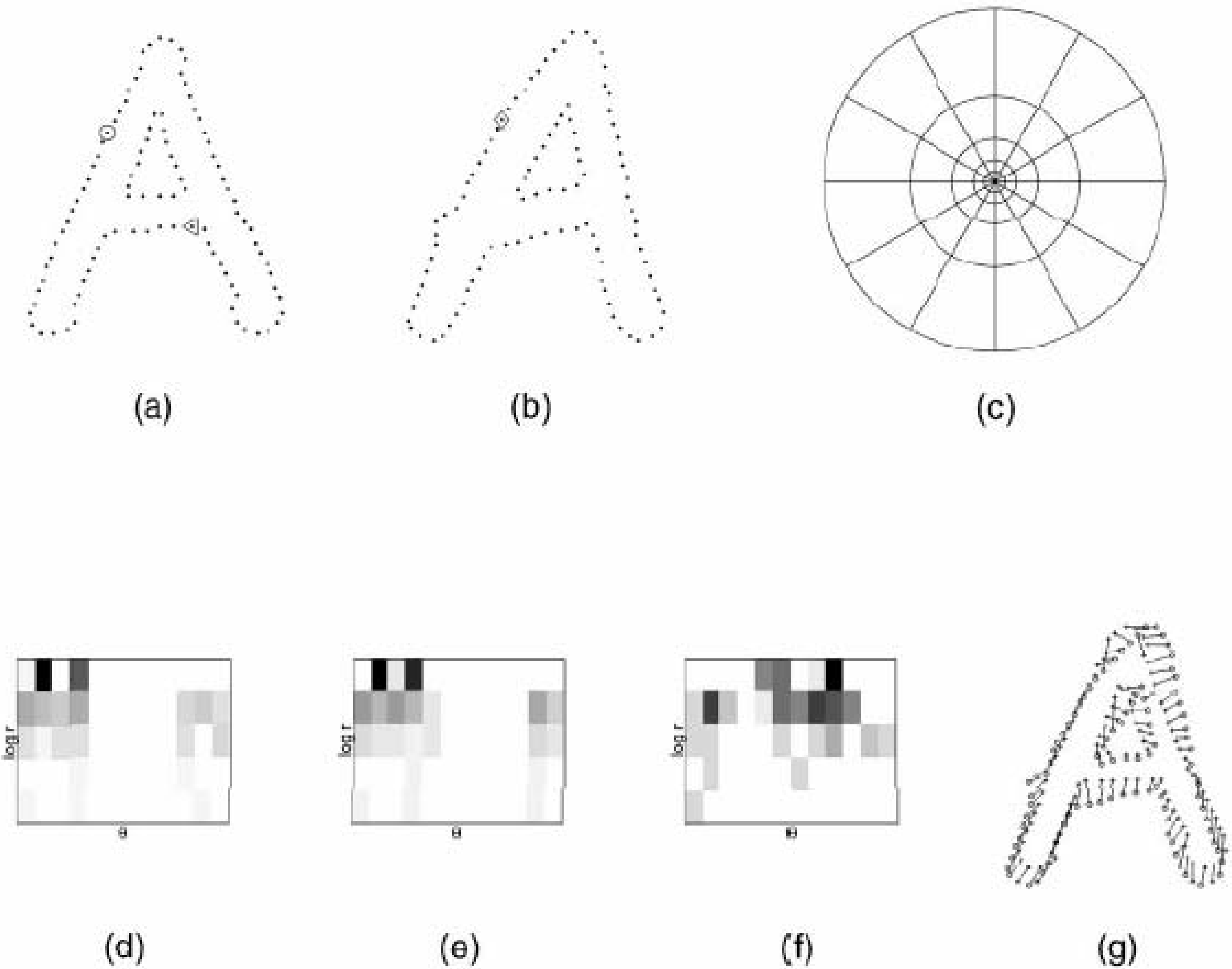


GLOH

- GLOH: Gradient Location and Orientation Histogram(Miko04)
  - Very similar to SIFT.
  - Log-polar location grid:
    - 3 bins in radial direction;
    - 8 bins in angular direction
    - Gradient orientation quantized in 16 bins.
  - Total: (2x8+1)*16=272 bins→PCA dimension reduction.

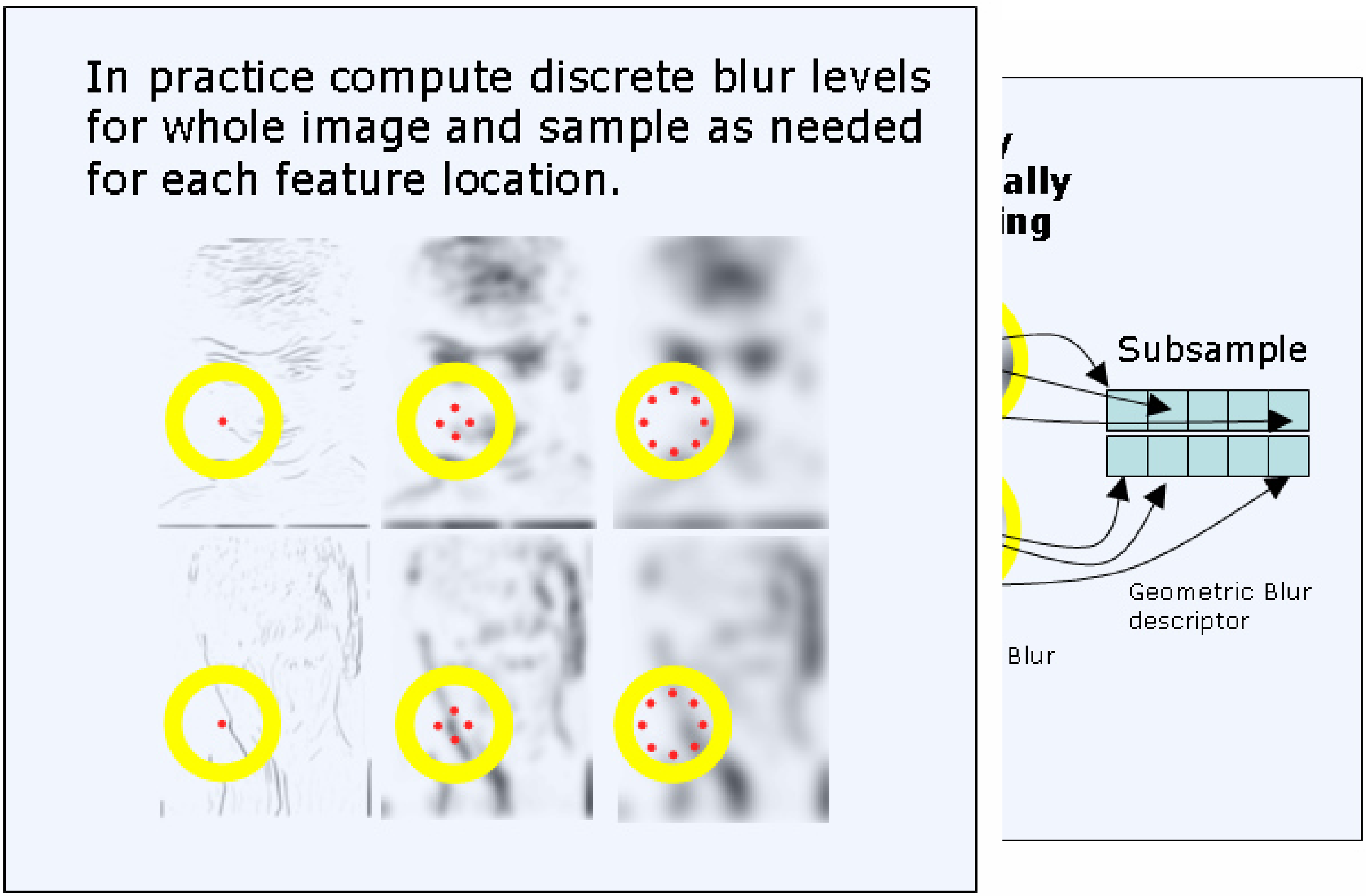


Shape context



Belongie et al. 2002

Geometric blur



Berg et al. 2001

Geometric blur