Computer Vision - Lecture 11

Local Features

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Bastian Leibe
RWTH Aachen
http://www.vision.rwth-aachen.de

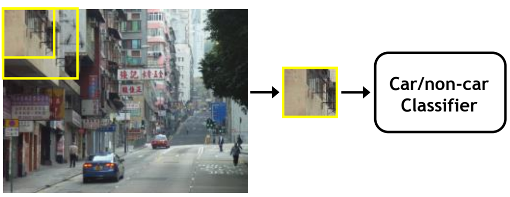
leibe@vision.rwth-aachen.de

Course Outline

- Image Processing Basics
- Segmentation & Grouping
- Object Recognition & Categorization I
  - Global Representations
  - Sliding Window based Object Detection
- Local Features & Matching
  - Local Features - Detection and Description
  - Recognition with Local Features
- Object Categorization II
  - Part based Approaches
  - Deep Learning Approaches
- 3D Reconstruction
- Motion and Tracking

Recap: Sliding-Window Object Detection

- If object may be in a cluttered scene, slide a window around looking for it.



- Essentially, this is a brute-force approach with many local decisions.

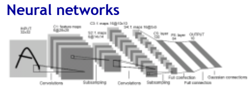
Slide credit: Kristen Grauman

Classifier Construction: Many Choices...

Nearest Neighbor

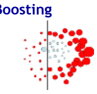
Shakhnarovich, Viola, Darrell 2003
Berg, Berg, Malik 2005,
Boiman, Shechtman, Irani 2008, ...

Neural networks



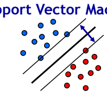
LeCun, Bottou, Bengio, Haffner 1998
Rowley, Baluja, Kanade 1998
...

Boosting



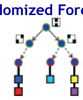
Viola, Jones 2001,
Torralba et al. 2004,
Opelt et al. 2006,
Benenson 2012, ...

Support Vector Machines



Vapnik, Schölkopf 1995,
Papageorgiou, Poggio '01,
Dalal, Triggs 2005,
Vedaldi, Zisserman 2012

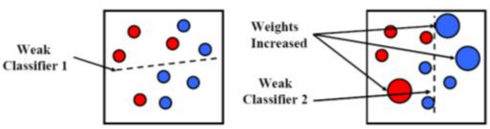
Randomized Forests

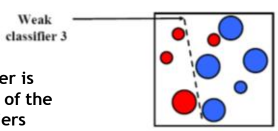


Amit, Geman 1997,
Breiman 2001,
Lepetit, Fua 2006,
Gall, Lempitsky 2009,...

Slide adapted from Kristen Grauman

Recap: AdaBoost



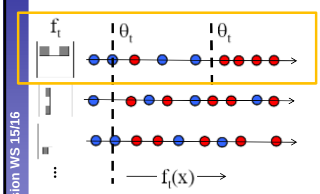


Final classifier is combination of the weak classifiers

Slide credit: Kristen Grauman

Recap: AdaBoost Feature+Classifier Selection

- Want to select the single rectangle feature and threshold that best separates positive (faces) and negative (non-faces) training examples, in terms of *weighted* error.



Outputs of a possible rectangle feature on faces and non-faces.

Resulting weak classifier:

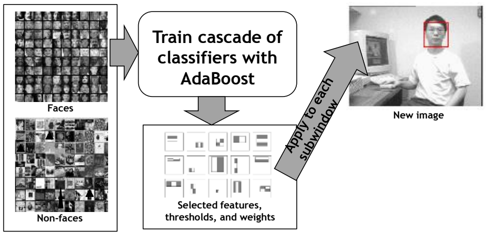
$$h_t(x) = \begin{cases} +1 & \text{if } f_t(x) > \theta_t \\ -1 & \text{otherwise} \end{cases}$$

For next round, reweight the examples according to errors, choose another filter/threshold combo.

Slide credit: Kristen Grauman

[Viola & Jones, CVPR 2001]

Recap: Viola-Jones Face Detector



- Train with 5K positives, 350M negatives
- Real-time detector using 38 layer cascade
- 6061 features in final layer
- [Implementation available in OpenCV: http://sourceforge.net/projects/opencvlibrary/]

Slide credit: Kristen Grauman

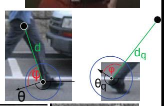
Topics of This Lecture

- Local Invariant Features
  - Motivation
  - Requirements, Invariances
- Keypoint Localization
  - Harris detector
  - Hessian detector
- Scale Invariant Region Selection
  - Automatic scale selection
  - Laplacian-of-Gaussian detector
  - Difference-of-Gaussian detector
  - Combinations
- Local Descriptors
  - Orientation normalization
  - SIFT

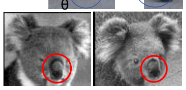
Motivation

- Global representations have major limitations
- Instead, describe and match only local regions
- Increased robustness to
  - Occlusions

  - Articulation

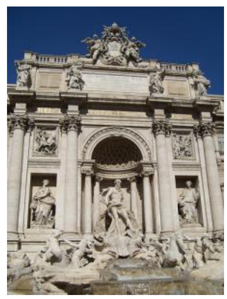


  - Intra-category variations



Application: Image Matching

by Diva Sian



by swashford

Slide credit: Steve Seitz

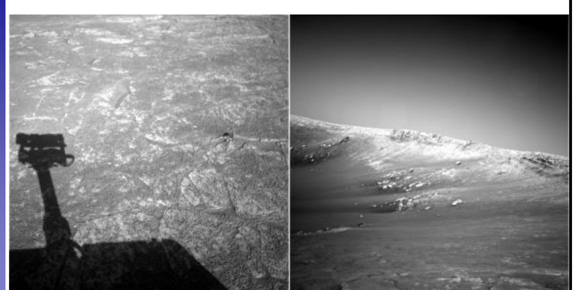
Harder Case

by Diva Sian

by scgbt

Slide credit: Steve Seitz

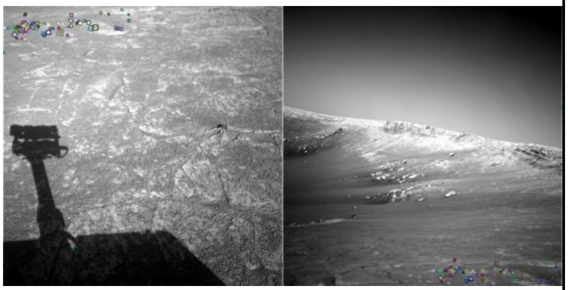
Harder Still?



NASA Mars Rover images

Slide credit: Steve Seitz

Answer Below (Look for tiny colored squares)



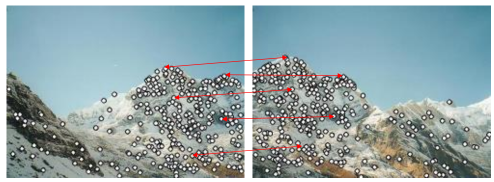
NASA Mars Rover images
with SIFT feature matches
(Figure by Noah Snavely)

Application: Image Stitching

Application: Image Stitching

- **Procedure:**
  - Detect feature points in both images

Application: Image Stitching

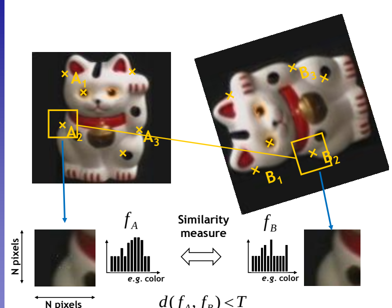


- **Procedure:**
  - Detect feature points in both images
  - Find corresponding pairs

Application: Image Stitching

- **Procedure:**
  - Detect feature points in both images
  - Find corresponding pairs
  - Use these pairs to align the images

General Approach



1. Find a set of distinctive key-points
2. Define a region around each keypoint
3. Extract and normalize the region content
4. Compute a local descriptor from the normalized region
5. Match local descriptors

Common Requirements

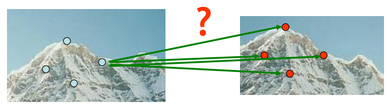
- **Problem 1:**
  - Detect the same point *independently* in both images

No chance to match!

We need a repeatable detector!

Common Requirements

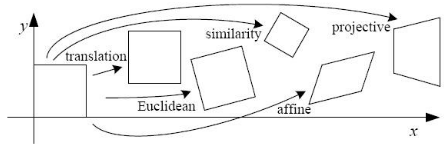
- **Problem 1:**
  - Detect the same point *independently* in both images
- **Problem 2:**
  - For each point correctly recognize the corresponding one



We need a reliable and distinctive descriptor!

Invariance: Geometric Transformations

Levels of Geometric Invariance



Requirements

- Region extraction needs to be repeatable and accurate
  - Invariant to translation, rotation, scale changes
  - Robust or covariant to out-of-plane (≈affine) transformations
  - Robust to lighting variations, noise, blur, quantization
- Locality: Features are local, therefore robust to occlusion and clutter.
- Quantity: We need a sufficient number of regions to cover the object.
- Distinctiveness: The regions should contain “interesting” structure.
- Efficiency: Close to real-time performance.

Many Existing Detectors Available

- Hessian & Harris — [Beaudet ‘78], [Harris ‘88]
- Laplacian, DoG — [Lindeberg ‘98], [Lowe ‘99]
- Harris-/Hessian-Laplace — [Mikolajczyk & Schmid ‘01]
- Harris-/Hessian-Affine — [Mikolajczyk & Schmid ‘04]
- EBR and IBR — [Tuytelaars & Van Gool ‘04]
- MSER — [Matas ‘02]
- Salient Regions — [Kadir & Brady ‘01]
- Others…

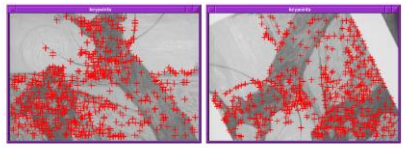
- *Those detectors have become a basic building block for many recent applications in Computer Vision.*

Keypoint Localization

- Goals:
  - Repeatable detection
  - Precise localization
  - Interesting content

$\Rightarrow$ *Look for two-dimensional signal changes*

Finding Corners



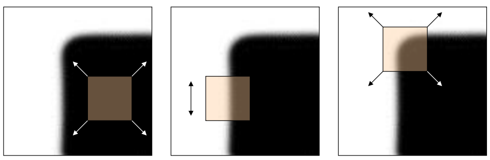
- Key property:
  - In the region around a corner, image gradient has two or more dominant directions
- Corners are *repeatable* and *distinctive*

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

Slide credit: Svetlana Lazebnik

Corners as Distinctive Interest Points

- Design criteria
  - We should easily recognize the point by looking through a small window (*locality*)
  - Shifting the window in *any direction* should give *a large change* in intensity (*good localization*)



"flat" region: no change in all directions

"edge": no change along the edge direction

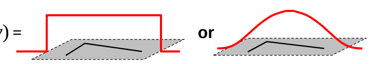
"corner": significant change in all directions

Slide credit: Alexei Efros

Harris Detector Formulation

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

$$E(u,v) = \sum_{x,y} \underbrace{w(x,y)}_{\text{Window function}} \big[\underbrace{I(x+u,y+v)}_{\text{Shifted intensity}} - \underbrace{I(x,y)}_{\text{Intensity}}\big]^2$$

Window function $w(x,y) =$ 

1 in window, 0 outside — or — Gaussian

Slide credit: Rick Szeliski

Harris Detector Formulation

- This measure of change can be approximated by:

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

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

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

Gradient with respect to x, times gradient with respect to y

Sum over image region - the area we are checking for corner

$$M = \begin{bmatrix} \sum I_x I_x & \sum I_x I_y \\ \sum I_x I_y & \sum I_y I_y \end{bmatrix} = \sum \begin{bmatrix} I_x \\ I_y \end{bmatrix} [I_x \; I_y]$$

Slide credit: Rick Szeliski

Harris Detector Formulation

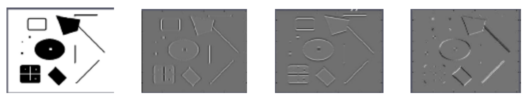


Image I — I_x — I_y — $I_x I_y$

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

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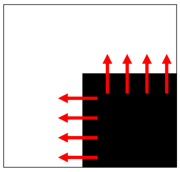
Slide credit: Rick Szeliski

What Does This Matrix Reveal?

- First, let's consider an axis-aligned corner:



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What Does This Matrix Reveal?

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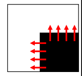

$$M = \begin{bmatrix} \sum I_x^2 & \sum I_x I_y \\ \sum I_x I_y & \sum I_y^2 \end{bmatrix} = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix}$$

- This means:
  - Dominant gradient directions align with x or y axis
  - If either λ is close to 0, then this is not a corner, so look for locations where both are large.
- What if we have a corner that is not aligned with the image axes?

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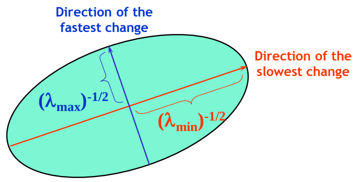
General Case

- Since M is symmetric, we have $M = R^{-1}\begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} R$

  (Eigenvalue decomposition)

- We can visualize M as an ellipse with axis lengths determined by the eigenvalues and orientation determined by R



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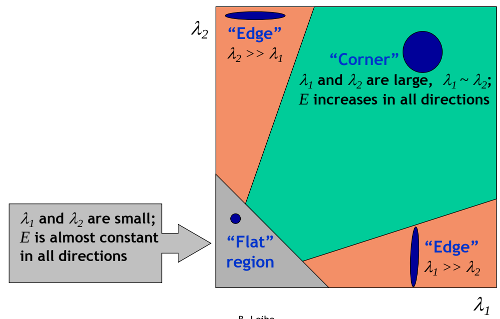
adapted from Darya Frolova, Denis Simakov

Interpreting the Eigenvalues

- Classification of image points using eigenvalues of M:



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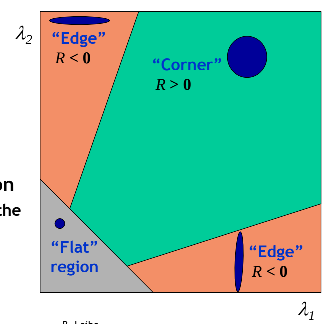
Corner Response Function

$$R = \det(M) - \alpha \operatorname{trace}(M)^2 = \lambda_1\lambda_2 - \alpha(\lambda_1 + \lambda_2)^2$$



- Fast approximation
  - Avoid computing the eigenvalues
  - α: constant (0.04 to 0.06)

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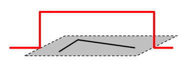
Window Function $w(x,y)$

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

- Option 1: uniform window
  - Sum over square window

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

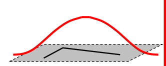


1 in window, 0 outside

  - Problem: not rotation invariant

- Option 2: Smooth with Gaussian
  - Gaussian already performs weighted sum

$$M = g(\sigma) * \begin{bmatrix} I_x^2 & I_x I_y \\ I_x I_y & I_y^2 \end{bmatrix}$$



Gaussian

  - Result is rotation invariant

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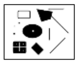
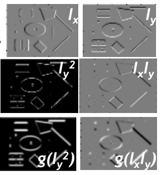
Summary: Harris Detector [Harris88]

- Compute second moment matrix (autocorrelation matrix)



$$M(\sigma_I,\sigma_D) = g(\sigma_I) * \begin{bmatrix} I_x^2(\sigma_D) & I_x I_y(\sigma_D) \\ I_x I_y(\sigma_D) & I_y^2(\sigma_D) \end{bmatrix}$$

1. Image derivatives
2. Square of derivatives
3. Gaussian filter $g(\sigma_I)$



4. Cornerness function – two strong eigenvalues

$$R = \det[M(\sigma_I,\sigma_D)] - \alpha[\mathrm{trace}(M(\sigma_I,\sigma_D))]^2$$
$$= g(I_x^2)g(I_y^2) - [g(I_xI_y)]^2 - \alpha[g(I_x^2) + g(I_y^2)]^2$$

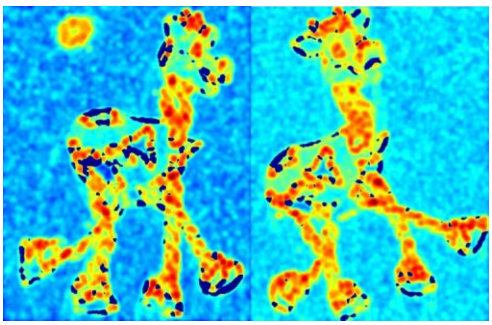
5. Perform non-maximum suppression

Slide credit: Krystian Mikolajczyk

Harris Detector: Workflow

Slide adapted from Darya Frolova, Denis Simakov

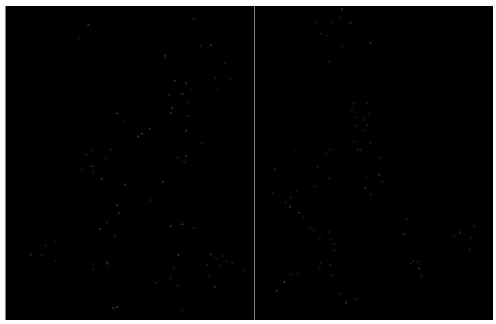
Harris Detector: Workflow



- Compute corner responses R

Slide adapted from Darya Frolova, Denis Simakov

Harris Detector: Workflow



- Take only the local maxima of R, where R > threshold.

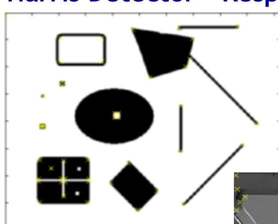
Slide adapted from Darya Frolova, Denis Simakov

Harris Detector: Workflow

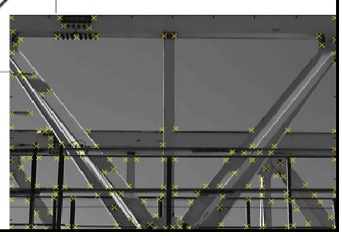
- Resulting Harris points

Slide adapted from Darya Frolova, Denis Simakov

Harris Detector – Responses [Harris88]



Effect: A very precise corner detector.



Slide credit: Krystian Mikolajczyk

Harris Detector - Responses [Harris88]

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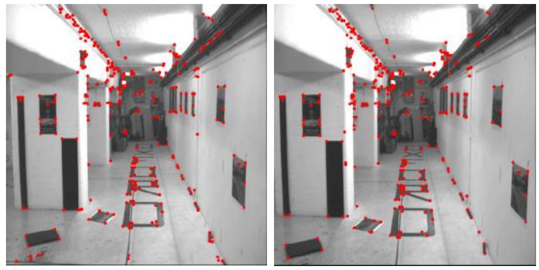
Harris Detector - Responses [Harris88]

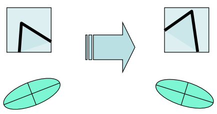


- Results are well suited for finding stereo correspondences

Slide credit: Kristen Grauman

Harris Detector: Properties

- Rotation invariance?



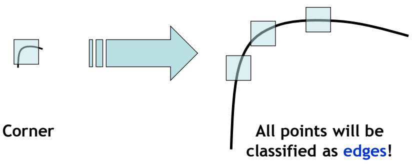
Ellipse rotates but its shape (i.e. eigenvalues) remains the same

Corner response R is invariant to image rotation

Slide credit: Kristen Grauman

Harris Detector: Properties

- Rotation invariance
- Scale invariance?



Corner

All points will be classified as edges!

Not invariant to image scale!

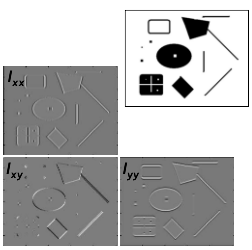
Slide credit: Kristen Grauman

Hessian Detector [Beaudet78]

- Hessian determinant

$$Hessian(I) = \begin{bmatrix} I_{xx} & I_{xy} \\ I_{xy} & I_{yy} \end{bmatrix}$$

Note: these are 2nd derivatives!



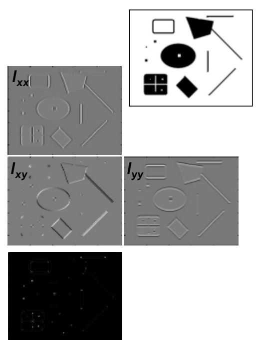
Intuition: Search for strong derivatives in two orthogonal directions

Slide credit: Krystian Mikolajczyk

Hessian Detector [Beaudet78]

- Hessian determinant

$$Hessian(I) = \begin{bmatrix} I_{xx} & I_{xy} \\ I_{xy} & I_{yy} \end{bmatrix}$$



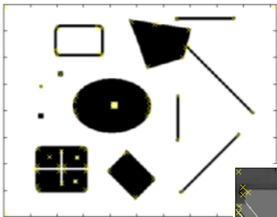
$$\det(Hessian(I)) = I_{xx} I_{yy} - I_{xy}^2$$

In Matlab:

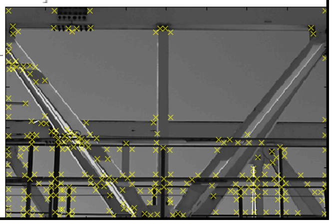
$$I_{xx} .* I_{yy} - (I_{xy})\wedge 2$$

Slide credit: Krystian Mikolajczyk

Hessian Detector – Responses [Beaudet78]



Effect: Responses mainly on corners and strongly textured areas.



Hessian Detector – Responses [Beaudet78]

Topics of This Lecture

- Local Invariant Features
  - Motivation
  - Requirements, Invariances
- Keypoint Localization
  - Harris detector
  - Hessian detector
- **Scale Invariant Region Selection**
  - Automatic scale selection
  - Laplacian-of-Gaussian detector
  - Difference-of-Gaussian detector
  - Combinations
- Local Descriptors
  - Orientation normalization
  - SIFT

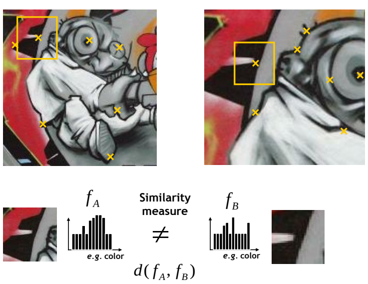
From Points to Regions…

- The Harris and Hessian operators define interest points.
  - Precise localization
  - High repeatability

- In order to compare those points, we need to compute a descriptor over a region.
  - How can we define such a region in a scale invariant manner?
- *I.e. how can we detect scale invariant interest regions?*

Naïve Approach: Exhaustive Search

- Multi-scale procedure
  - Compare descriptors while varying the patch size



Naïve Approach: Exhaustive Search

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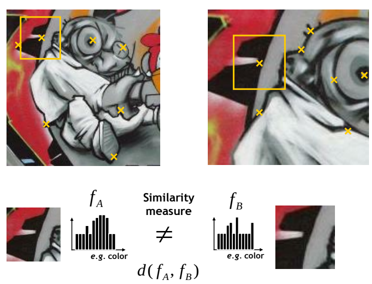

Naïve Approach: Exhaustive Search

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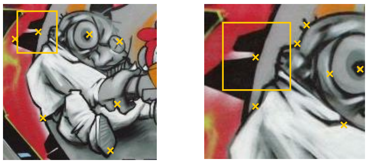

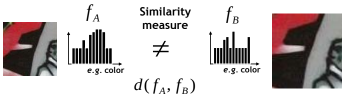

Naïve Approach: Exhaustive Search

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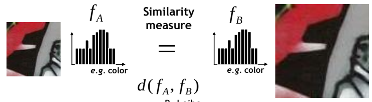
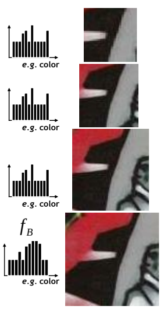
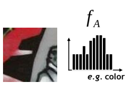


Naïve Approach: Exhaustive Search

- Comparing descriptors while varying the patch size
  - Computationally inefficient
  - Inefficient but possible for matching
  - Prohibitive for retrieval in large databases
  - Prohibitive for recognition





Similarity measure

$=$

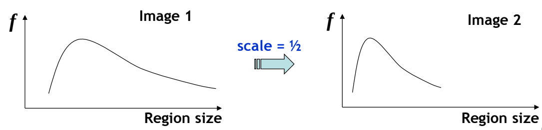
$d(f_A, f_B)$

Automatic Scale Selection

- Solution:
  - Design a function on the region, which is “scale invariant” (*the same for corresponding regions, even if they are at different scales*)

    Example: average intensity. For corresponding regions (even of different sizes) it will be the same.

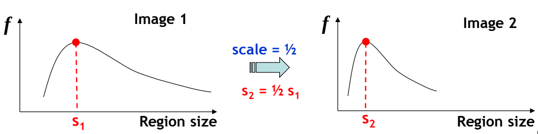
  - For a point in one image, we can consider it as a function of region size (patch width)



Automatic Scale Selection

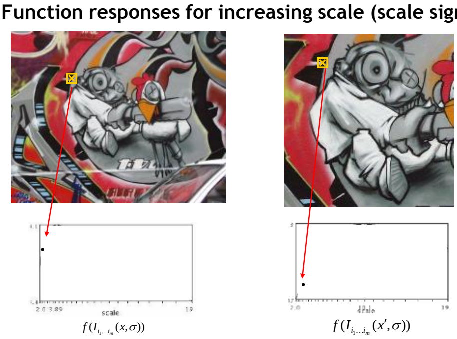
- Common approach:
  - Take a local maximum of this function.
  - Observation: region size for which the maximum is achieved should be *invariant* to image scale.

Important: this scale invariant region size is found in each image independently!



Automatic Scale Selection

- Function responses for increasing scale (scale signature)



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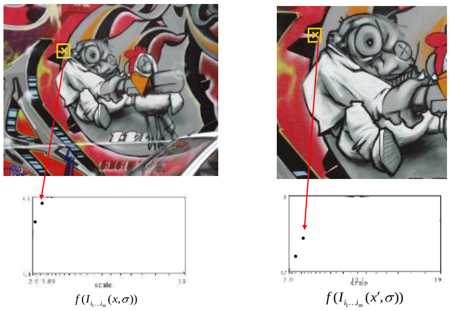
Automatic Scale Selection

- Function responses for increasing scale (scale signature)



Slide credit: Krystian Mikolajczyk

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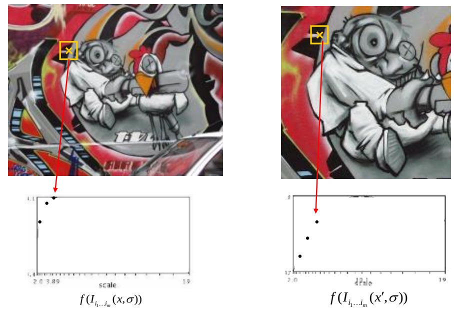
Automatic Scale Selection

- Function responses for increasing scale (scale signature)



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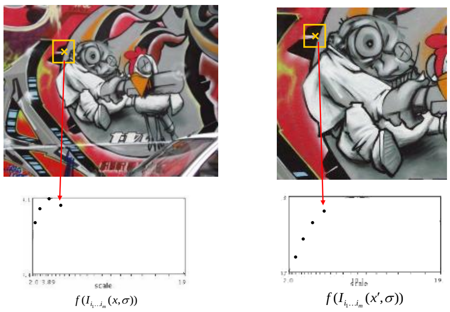
Automatic Scale Selection

- Function responses for increasing scale (scale signature)



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Automatic Scale Selection

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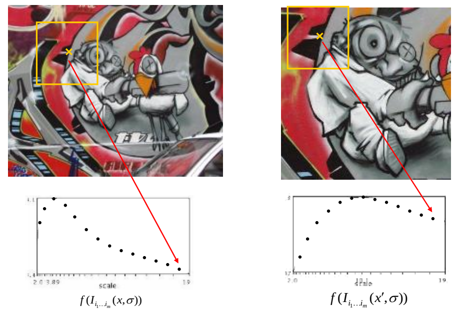

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Automatic Scale Selection

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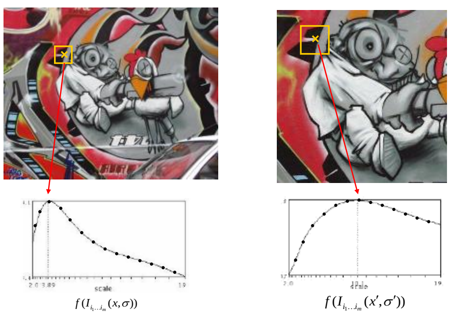

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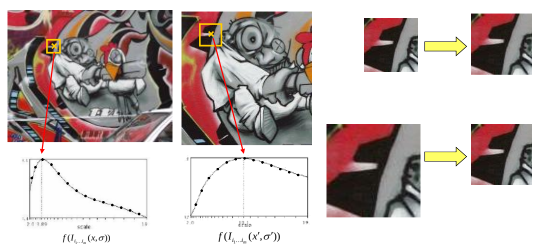
Automatic Scale Selection

- Normalize: Rescale to fixed size



Slide credit: Tinne Tuytelaars

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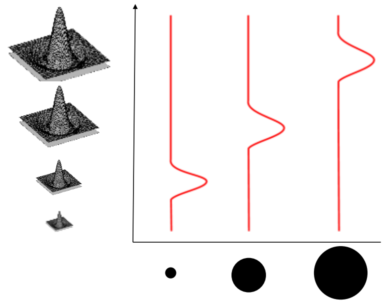
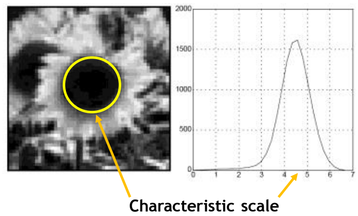
What Is A Useful Signature Function?

- Laplacian-of-Gaussian = "blob" detector



Characteristic Scale

- We define the *characteristic scale* as the scale that produces peak of Laplacian response

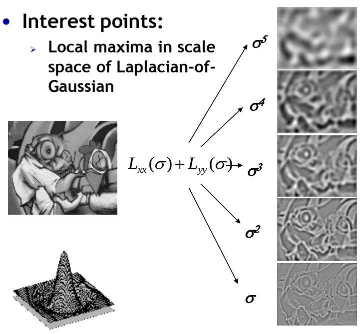


T. Lindeberg (1998). "Feature detection with automatic scale selection." *International Journal of Computer Vision* 30 (2): pp 77--116.

Slide credit: Svetlana Lazebnik

Laplacian-of-Gaussian (LoG)

- Interest points:
  - Local maxima in scale space of Laplacian-of-Gaussian



Slide adapted from Krystian Mikolajczyk

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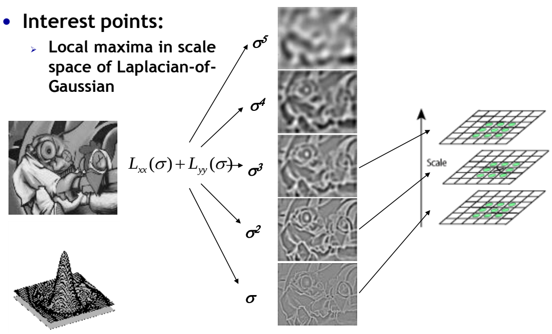

Slide adapted from Krystian Mikolajczyk

Laplacian-of-Gaussian (LoG)

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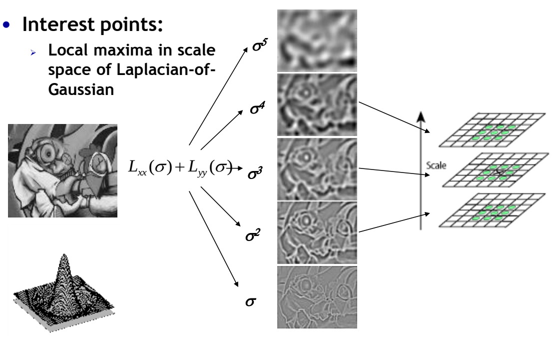
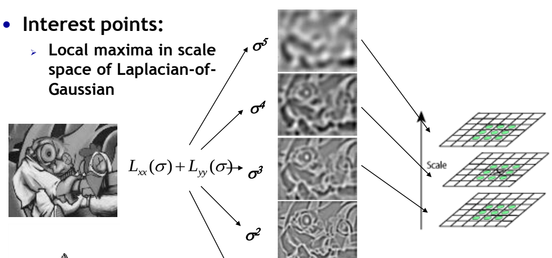


Slide adapted from Krystian Mikolajczyk

Laplacian-of-Gaussian (LoG)

- Interest points:
  - Local maxima in scale space of Laplacian-of-Gaussian



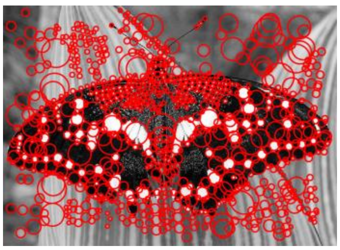
⇒ List of *(x, y, σ)*

Slide adapted from Krystian Mikolajczyk

LoG Detector: Workflow

LoG Detector: Workflow

LoG Detector: Workflow



Technical Detail

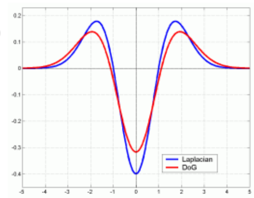
- We can efficiently approximate the Laplacian with a difference of Gaussians:

$$L = \sigma^2 \left(G_{xx}(x,y,\sigma) + G_{yy}(x,y,\sigma) \right)$$

(Laplacian)

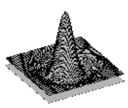
$$DoG = G(x,y,k\sigma) - G(x,y,\sigma)$$

(Difference of Gaussians)



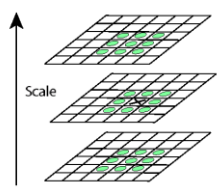
Difference-of-Gaussian (DoG)

- Difference of Gaussians as approximation of the LoG
  - This is used e.g. in Lowe's SIFT pipeline for feature detection.
- Advantages
  - No need to compute 2nd derivatives
  - Gaussians are computed anyway, e.g. in a Gaussian pyramid.



Key point localization with DoG

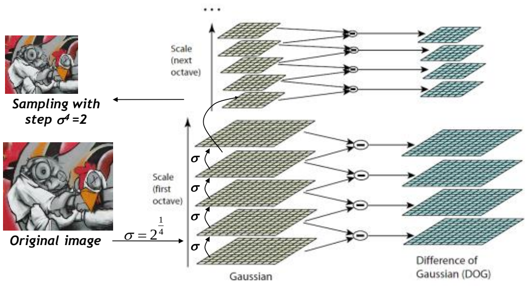
- Detect maxima of difference-of-Gaussian (DoG) in scale space
- Then reject points with low contrast (threshold)
- Eliminate edge responses



Candidate keypoints: list of (x,y,σ)

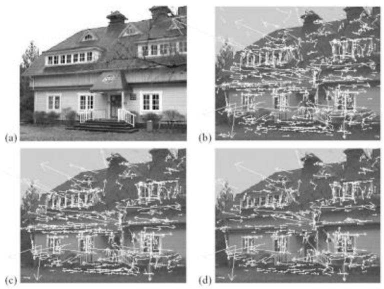
DoG - Efficient Computation

- Computation in Gaussian scale pyramid



Results: Lowe's DoG

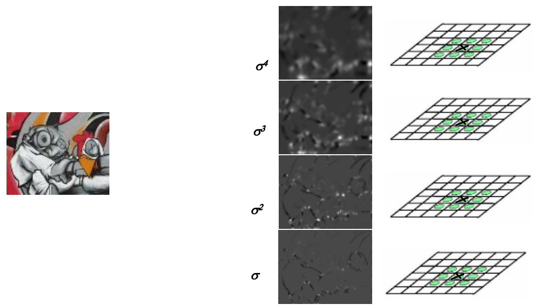
Example of Keypoint Detection



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

Harris-Laplace [Mikolajczyk '01]

1. Initialization: Multiscale Harris corner detection

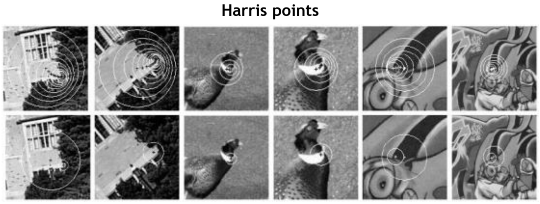


Computing Harris function Detecting local maxima

Harris-Laplace [Mikolajczyk '01]

1. Initialization: Multiscale Harris corner detection
2. Scale selection based on Laplacian (same procedure with Hessian ⇒ Hessian-Laplace)

Harris points



Harris-Laplace points

Summary: Scale Invariant Detection

- **Given:** Two images of the same scene with a large *scale difference* between them.
- **Goal:** Find *the same* interest points *independently* in each image.
- **Solution:** Search for *maxima* of suitable functions in *scale* and in *space* (over the image).
- Two strategies
  - Laplacian-of-Gaussian (LoG)
  - Difference-of-Gaussian (DoG) as a fast approximation
  - *These can be used either on their own, or in combinations with single-scale keypoint detectors (Harris, Hessian).*

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You Can Try It At Home…

- For most local feature detectors, executables are available online:
- http://robots.ox.ac.uk/~vgg/research/affine
- http://www.cs.ubc.ca/~lowe/keypoints/
- http://www.vision.ee.ethz.ch/~surf
- http://homes.esat.kuleuven.be/~ncorneli/gpusurf/

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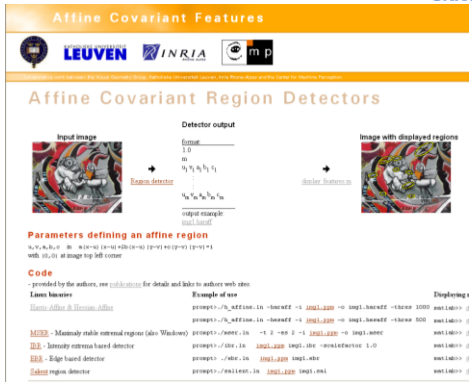

http://www.robots.ox.ac.uk/~vgg/research/affine/detectors.html#binaries

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References and Further Reading

- Read David Lowe's SIFT paper
  - D. Lowe, Distinctive image features from scale-invariant keypoints, *IJCV* 60(2), pp. 91-110, 2004
- Good survey paper on Int. Pt. detectors and descriptors
  - T. Tuytelaars, K. Mikolajczyk, *Local Invariant Feature Detectors: A Survey*, Foundations and Trends in Computer Graphics and Vision, Vol. 3, No. 3, pp 177-280, 2008.
- Try the example code, binaries, and Matlab wrappers
  - Good starting point: Oxford interest point page http://www.robots.ox.ac.uk/~vgg/research/affine/detectors.html#binaries