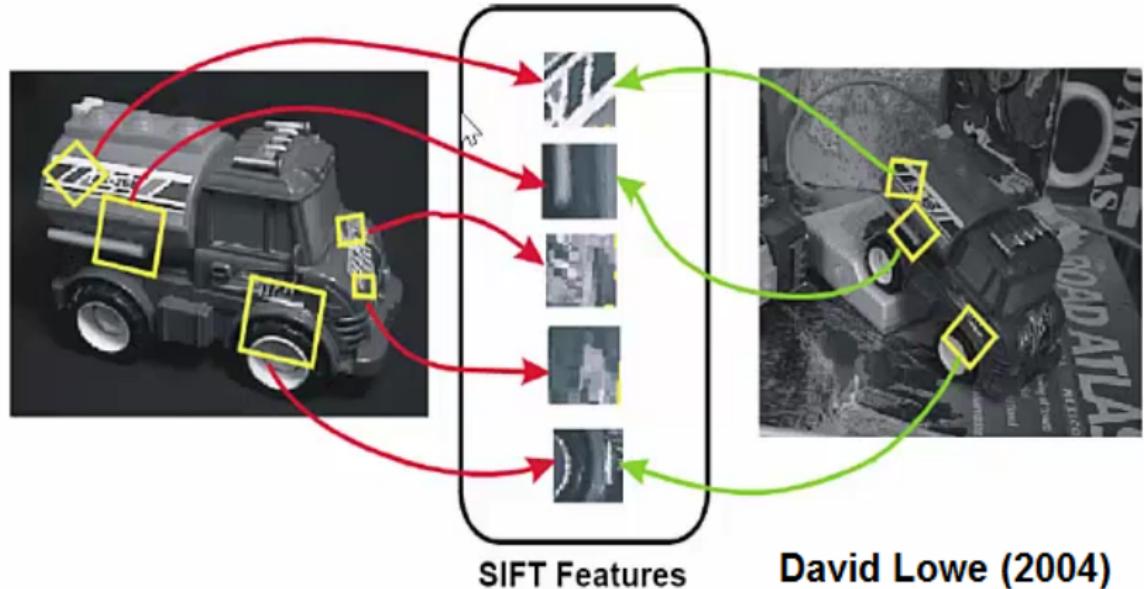


Image Features:

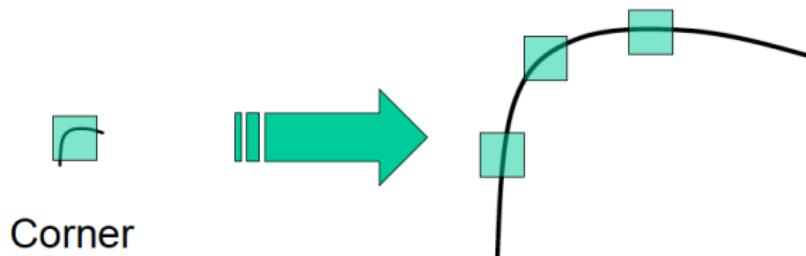
Scale Invariant Interest Point Detection

Scale Invariant Feature Transform



Remember from Harris Corner Detector

- Scale?



All points will
be classified
as edges

- Corner location is **not scale invariant!**

[Source: J. Hays]

Our Goal: Matching Objects / Images

- Our goal is to be able to match an object in different images where the object appears in different scale, rotation, viewpoints, etc. **How?**

image 1



image 2



Figure: We want to be able to match these two objects / images

Our Goal: Matching Objects / Images

- Our goal is to be able to match an object in different images where the object appears in different scale, rotation, viewpoints, etc. **How?**

image 1



image 2



Figure: But these shouldn't be matched!

Our Goal: Matching Objects / Images

- Our goal is to be able to match an object in different images where the object appears in different scale, rotation, viewpoints, etc. **How?**
 - Find interest points on each image

image 1



Figure: Find some interest points in an image

Our Goal: Matching Objects / Images

- Our goal is to be able to match an object in different images where the object appears in different scale, rotation, viewpoints, etc. **How?**
 - Find interest points on each image

image 2



Figure: And **independently** in other images

Our Goal: Matching Objects / Images

- Our goal is to be able to match an object in different images where the object appears in different scale, rotation, viewpoints, etc. **How?**
 - Find interest points on each image

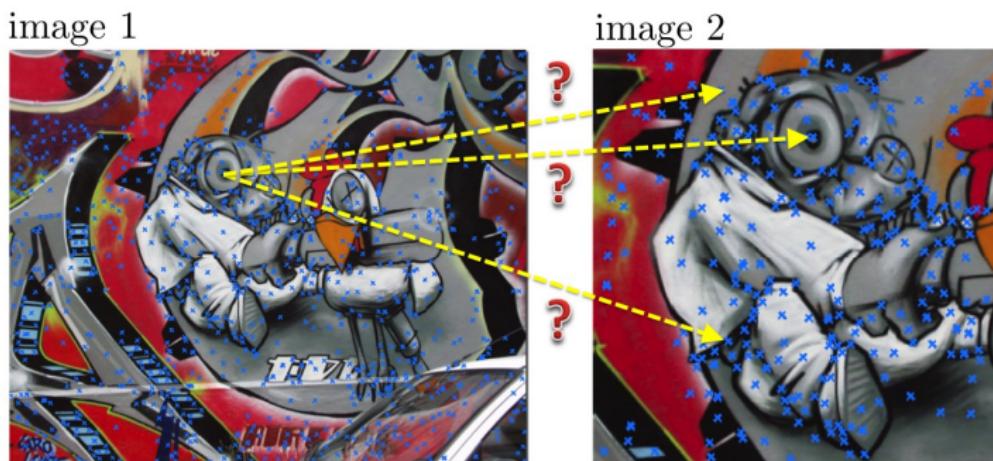


Figure: How can we match points??

Our Goal: Matching Objects / Images

- Our goal is to be able to match an object in different images where the object appears in different scale, rotation, viewpoints, etc. **How?**
 - Find interest points on each image
 - Form a vector description of each point. How? **What size? Length?**

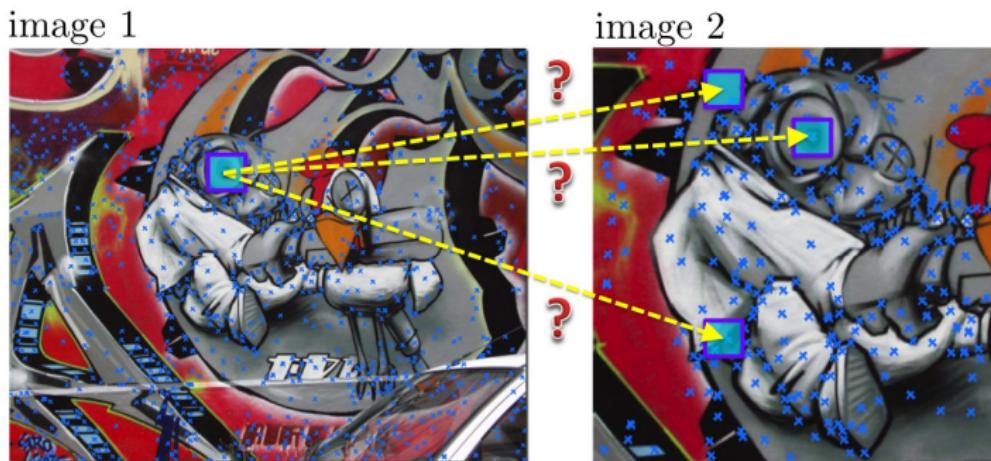


Figure: We could match if we took a patch around each point, and describe it with a feature vector (we know how to compare vectors)

Our Goal: Matching Objects / Images

- Our goal is to be able to match an object in different images where the object appears in different scale, rotation, viewpoints, etc. **How?**
 - Find **scale invariant** interest points on each image
 - Form a vector description of each point. **How?** **What size? Length?**

image 1

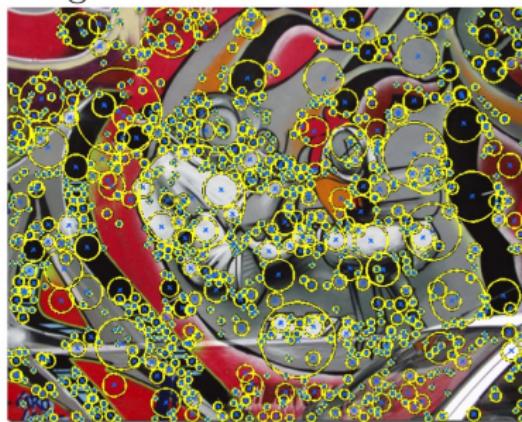


Figure: What if my interest point detector tells me the size (scale) of the patch?
We are hoping that this “canonical” size somehow reflects size of the object.

Our Goal: Matching Objects / Images

- Our goal is to be able to match an object in different images where the object appears in different scale, rotation, viewpoints, etc. **How?**
 - Find **scale invariant** interest points on each image
 - Form a vector description of each point. **How?** **What size?** **Length?**

image 1



Figure: And then we can form our feature vectors with respect to this size (how?)

Our Goal: Matching Objects / Images

- Our goal is to be able to match an object in different images where the object appears in different scale, rotation, viewpoints, etc. **How?**
 - Find **scale invariant** interest points on each image
 - Form a vector description of each point. How? **What size? Length?**
 - Matching

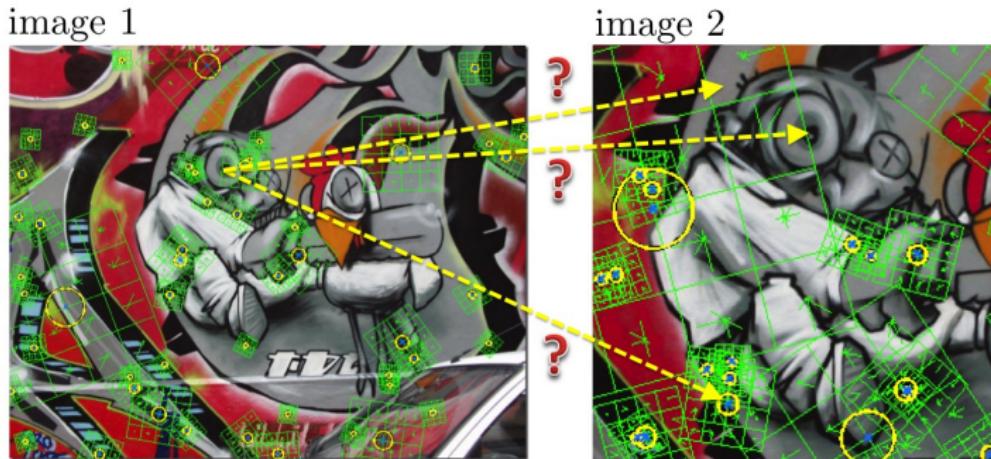


Figure: Then life is easy: we find the best matches and compute a transformation (scale, rotation, etc) of the object – in a later lecture

Our Goal: Matching Objects / Images

- Our goal is to be able to match an object in different images where the object appears in different scale, rotation, viewpoints, etc. **How?**
 - Find **scale invariant** interest points on each image
 - Form a vector description of each point. How? **What size? Length?**
 - Matching

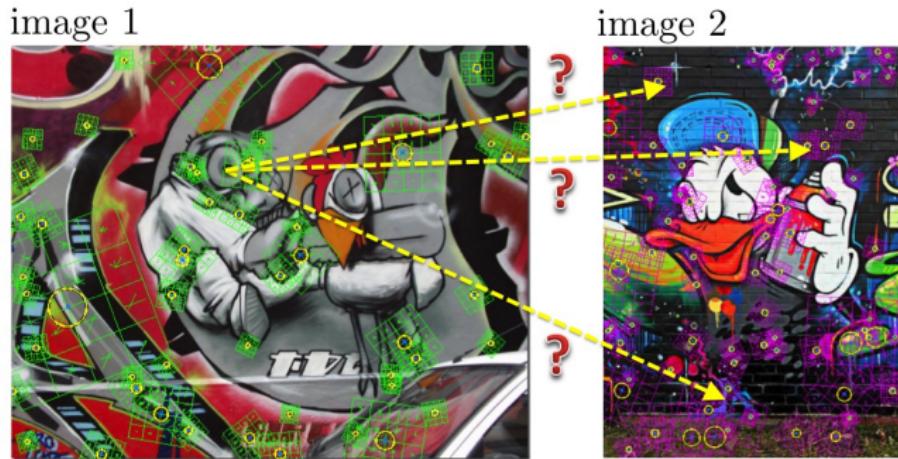


Figure: And we are hoping that our feature vectors and our matching algorithm will be able to say that this image does not contain our object!

Our Goal: Matching Objects / Images

- Our goal is to be able to match an object in different images where the object appears in different scale, rotation, viewpoints, etc. **How?**
 - Find **scale invariant** interest points on each image **Let's do this first!**
 - Form a vector description of each point. How? **What size? Length?**
 - Matching

Scale Invariant Interest Points

How can we **independently** select interest points in each image, such that the detections are repeatable across different scales?

image 1



image 2



[Source: K. Grauman]

Scale Invariant Interest Points

How can we **independently** select interest points in each image, such that the detections are repeatable across different scales?

image 1



If I detect an interest point here

image 2



Then I also want to detect one here

[Source: K. Grauman]

Scale Invariant Interest Points

How can we **independently** select interest points in each image, such that the detections are repeatable across different scales?

- Extract features at a variety of scales, e.g., by using multiple resolutions in a pyramid, and then matching features at the “*corresponding*” level.
- When does this work?

image 1



If I detect an interest point here

image 2

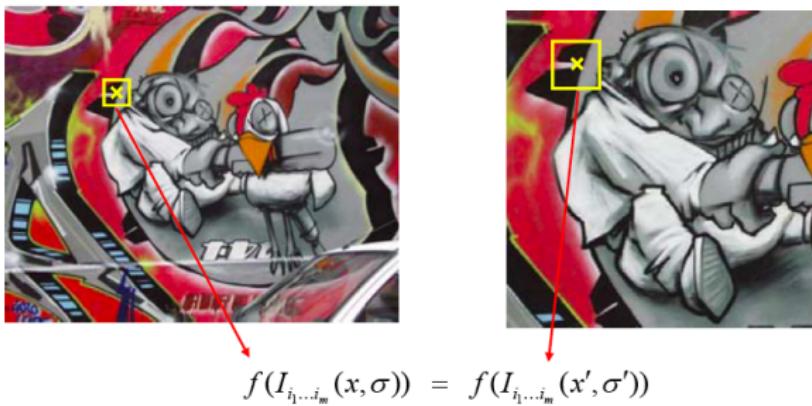


Then I also want to detect one here

Scale Invariant Interest Points

How can we **independently** select interest points in each image, such that the detections are repeatable across different scales?

- More efficient to extract features that are stable in both location and scale.

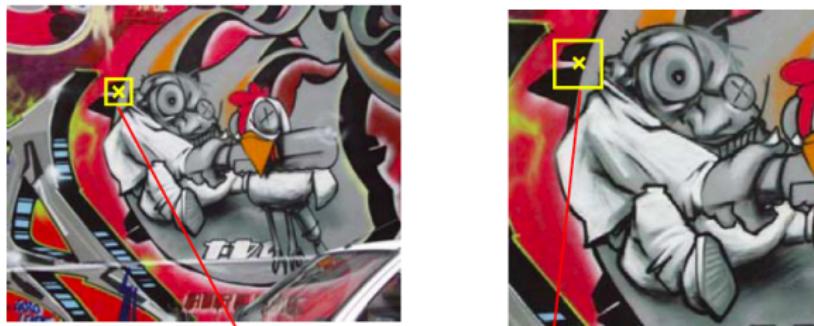


[Source: K. Grauman]

Scale Invariant Interest Points

How can we **independently** select interest points in each image, such that the detections are repeatable across different scales?

- With the Harris corner detector we found a maxima in a spatial search window
- Find scale that gives local maxima of a function f in both position and scale.

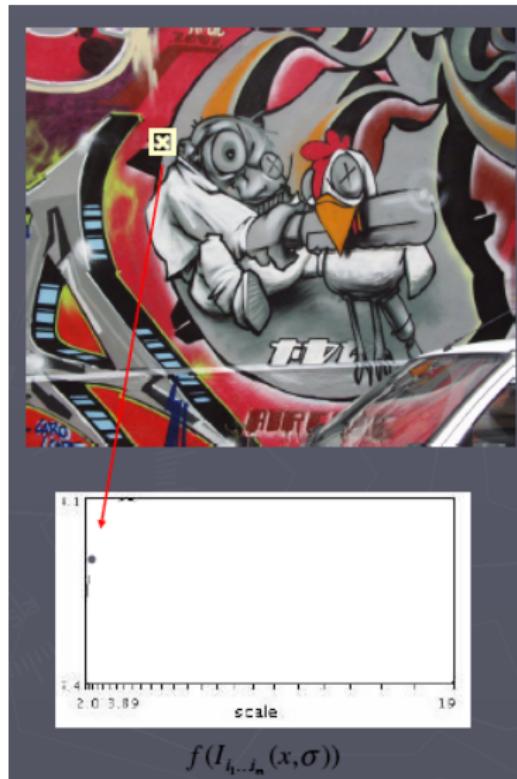


$$f(I_{h \dots i_m}(x, \sigma)) = f(I_{h \dots i_m}(x', \sigma'))$$

[Source: K. Grauman]

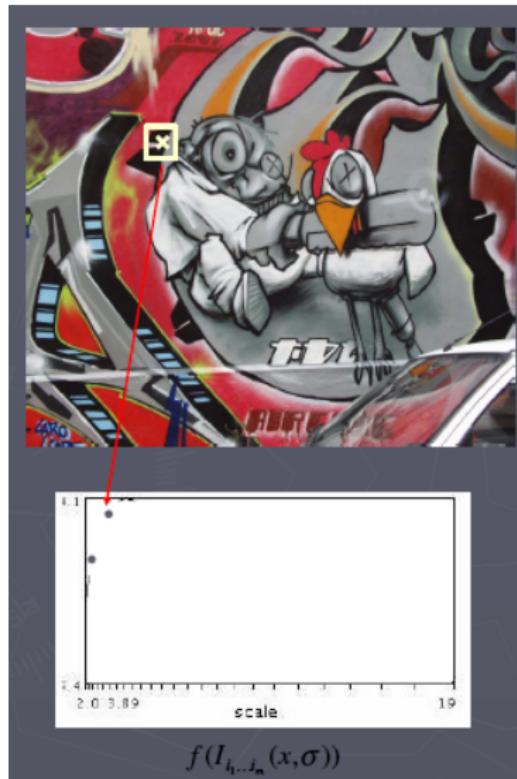
Automatic Scale Selection

Function responses for increasing scale (scale signature).



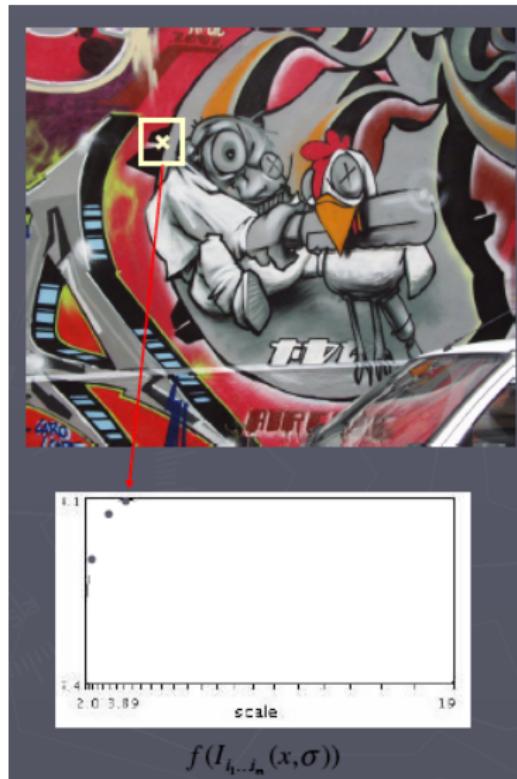
Automatic Scale Selection

Function responses for increasing scale (scale signature).



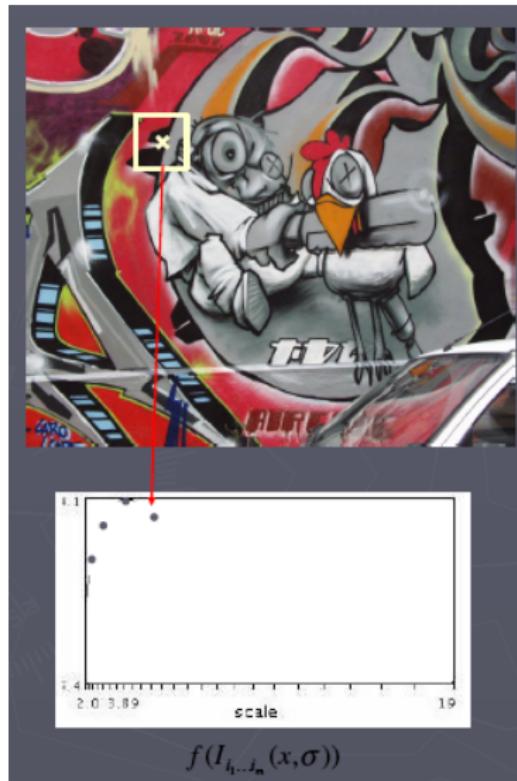
Automatic Scale Selection

Function responses for increasing scale (scale signature).



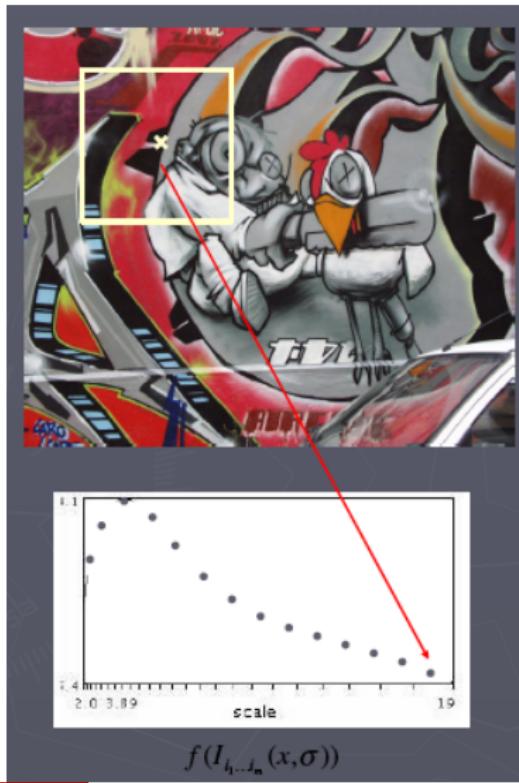
Automatic Scale Selection

Function responses for increasing scale (scale signature).



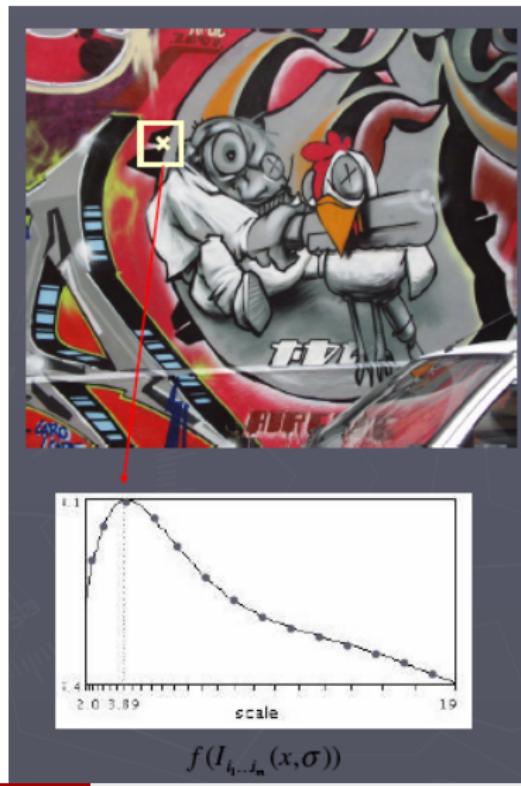
Automatic Scale Selection

Function responses for increasing scale (scale signature).



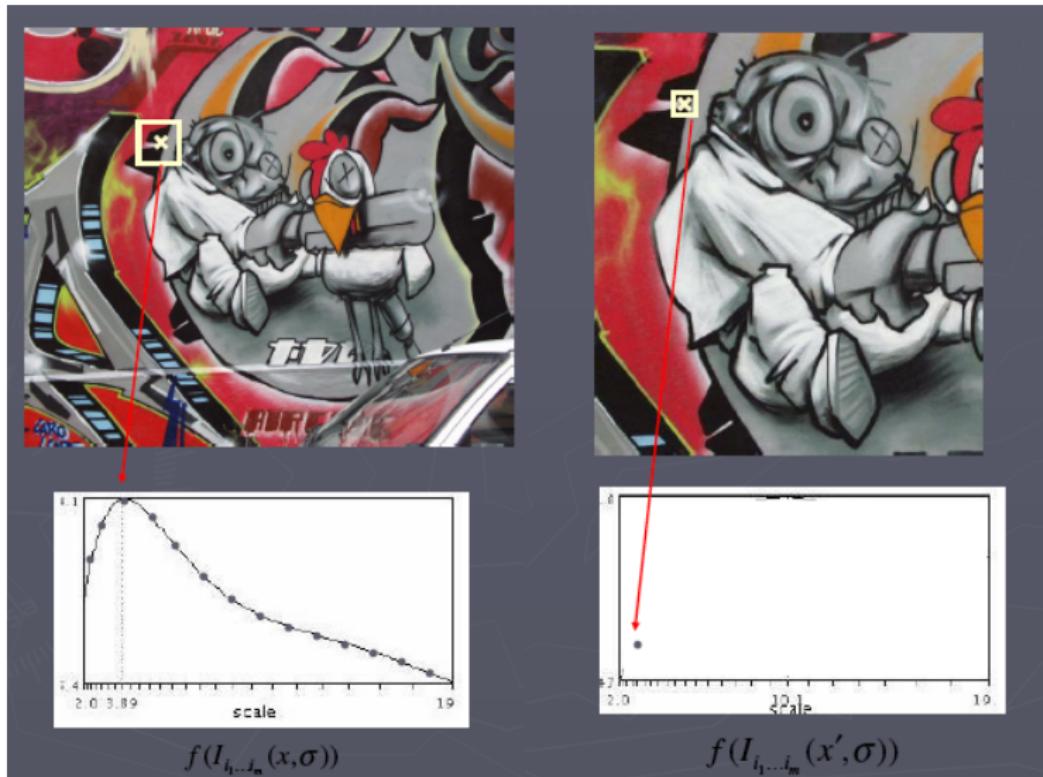
Automatic Scale Selection

Function responses for increasing scale (scale signature).



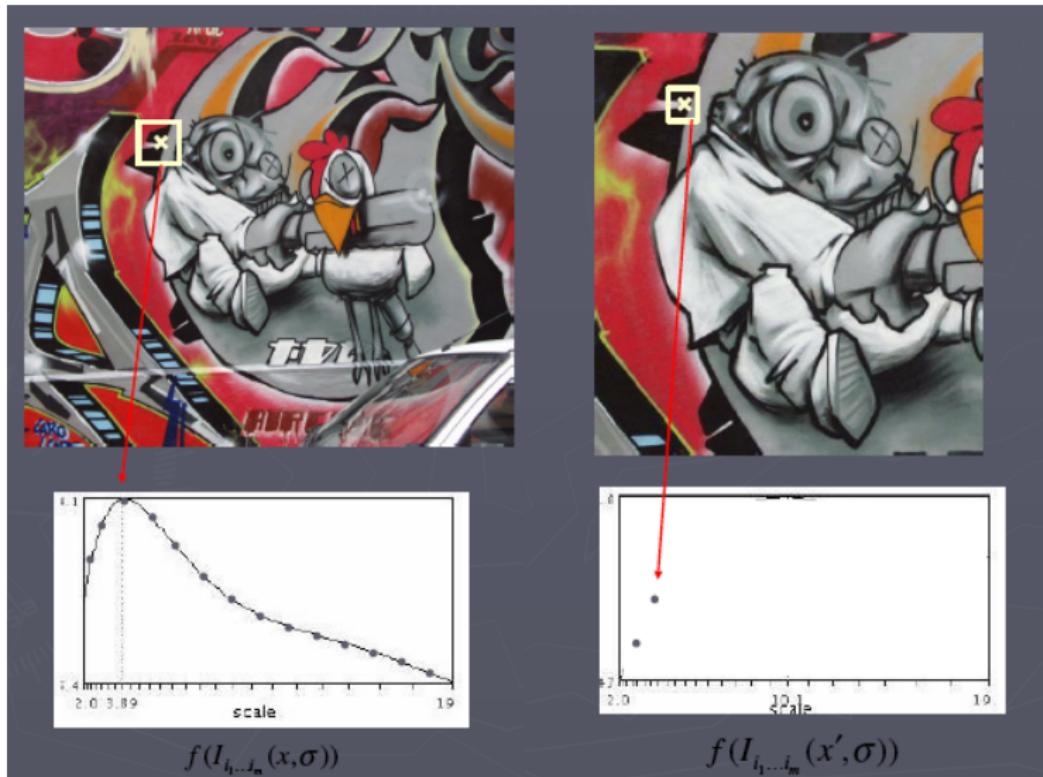
Automatic Scale Selection

Function responses for increasing scale (scale signature).



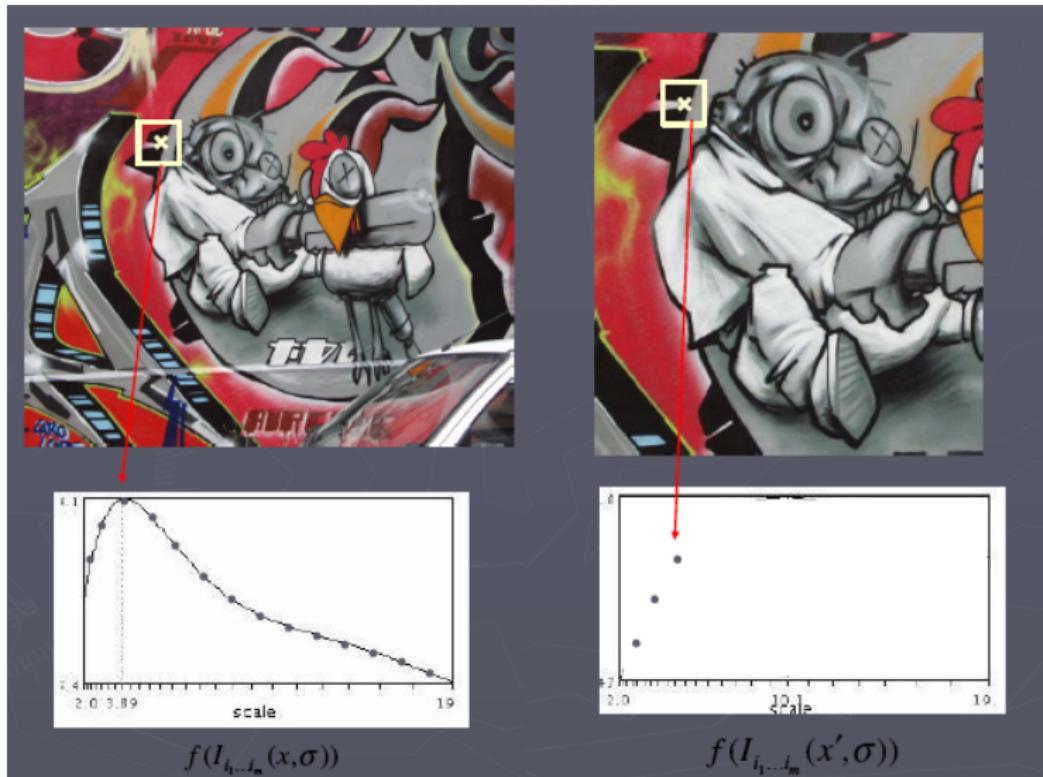
Automatic Scale Selection

Function responses for increasing scale (scale signature).



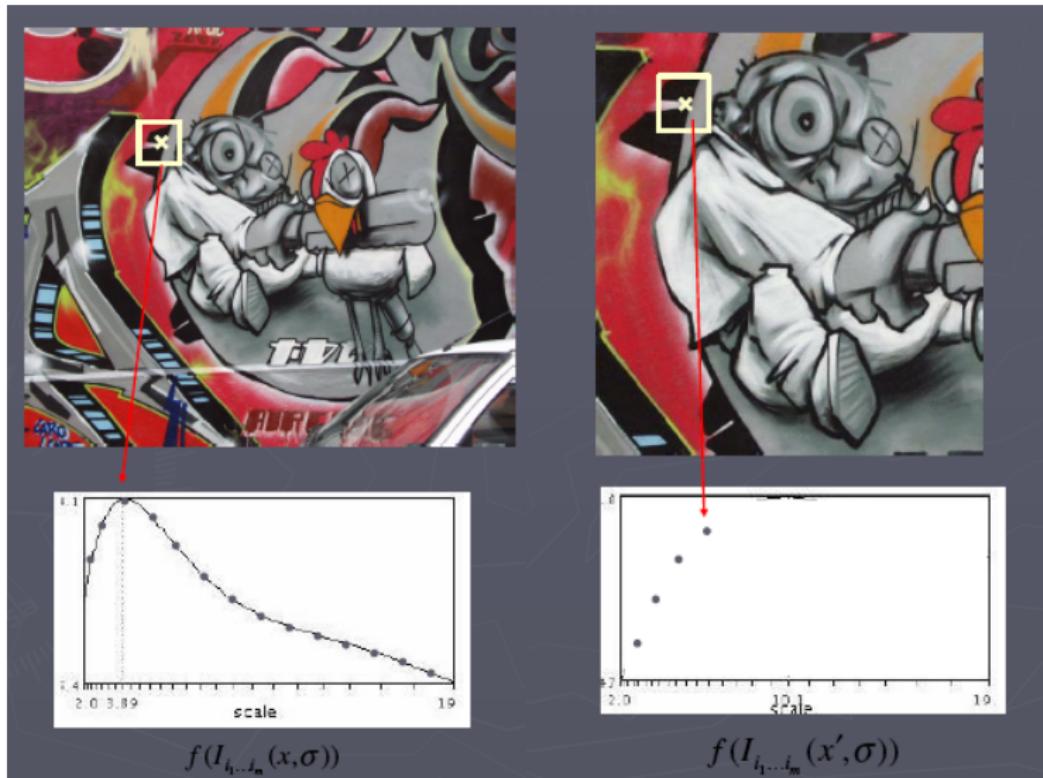
Automatic Scale Selection

Function responses for increasing scale (scale signature).



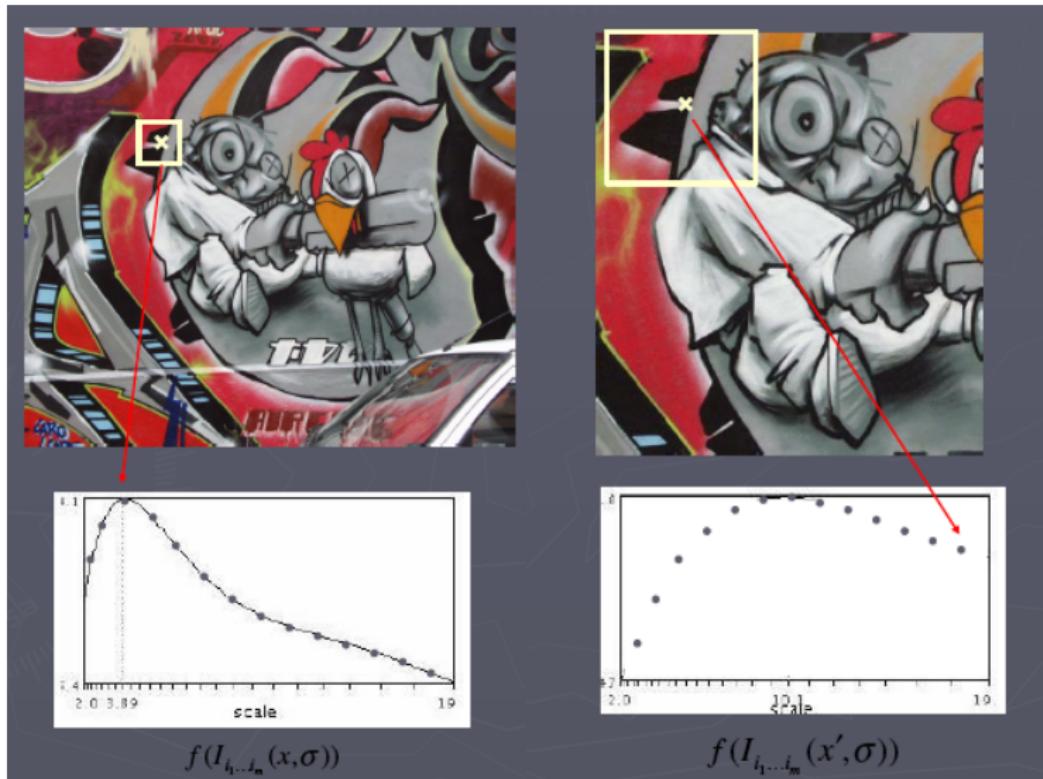
Automatic Scale Selection

Function responses for increasing scale (scale signature).



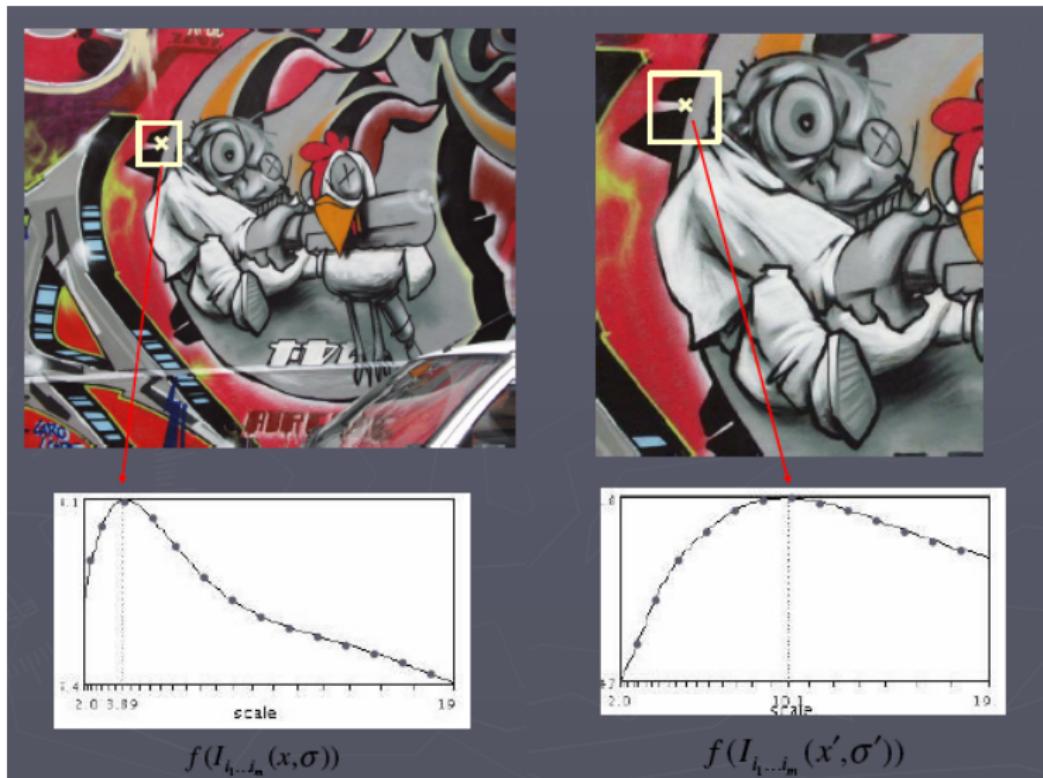
Automatic Scale Selection

Function responses for increasing scale (scale signature).



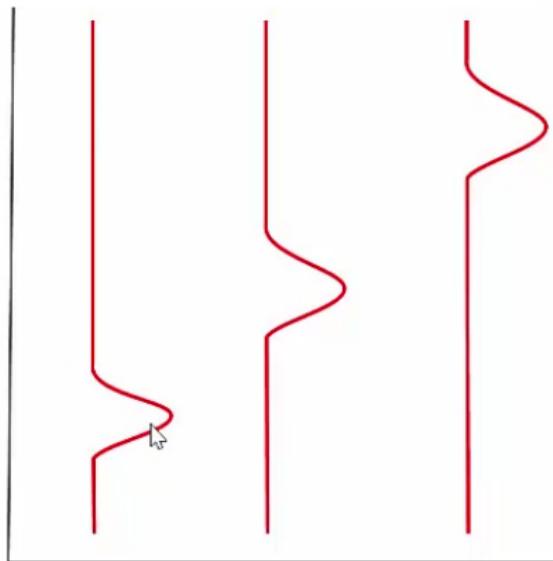
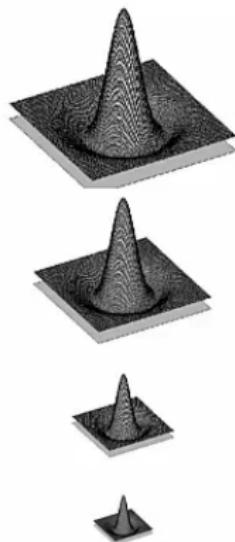
Automatic Scale Selection

Function responses for increasing scale (scale signature).



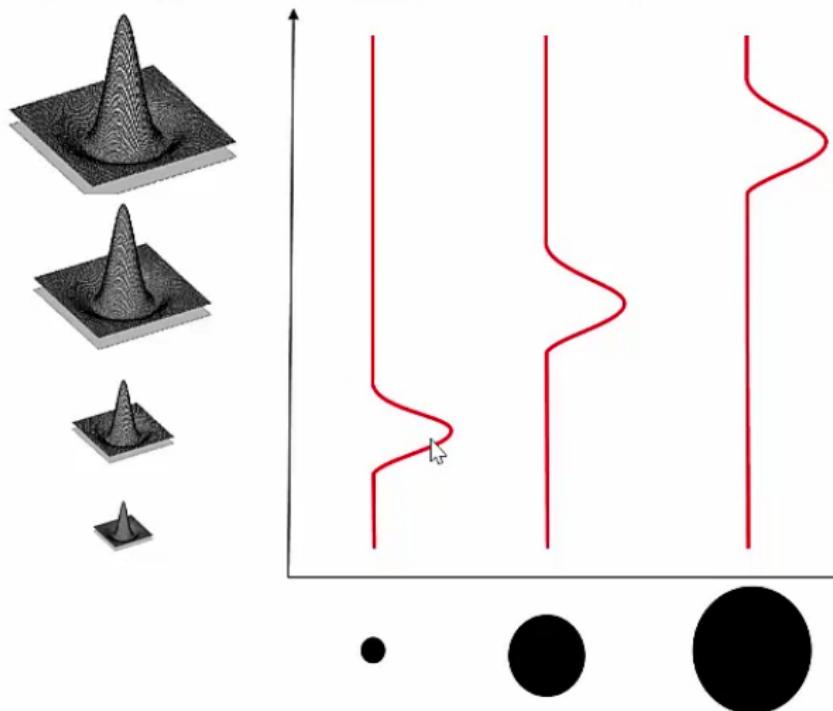
What Can the Signature Function Be?

Mexican Hat = “blob” detector



What Can the Signature Function Be?

- Laplacian-of-Gaussian = “blob” detector

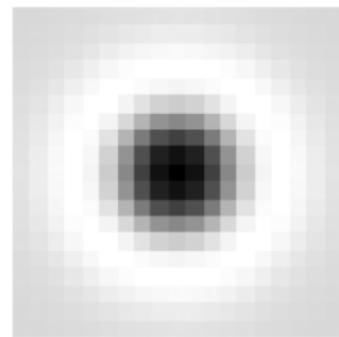
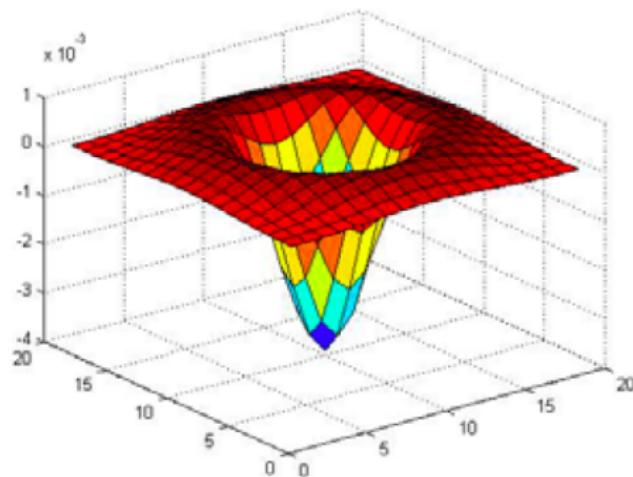


Blob Detection – Laplacian of Gaussian

- Laplacian of Gaussian: We mentioned it for edge detection

$$\nabla^2 g(x, y, \sigma) = \frac{\partial^2 g(x, y, \sigma)}{\partial x^2} + \frac{\partial^2 g(x, y, \sigma)}{\partial y^2}, \quad \text{where } g \text{ is a Gaussian}$$

- It is a circularly symmetric operator (finds difference in all directions)
- It can be used for 2D blob detection! How?

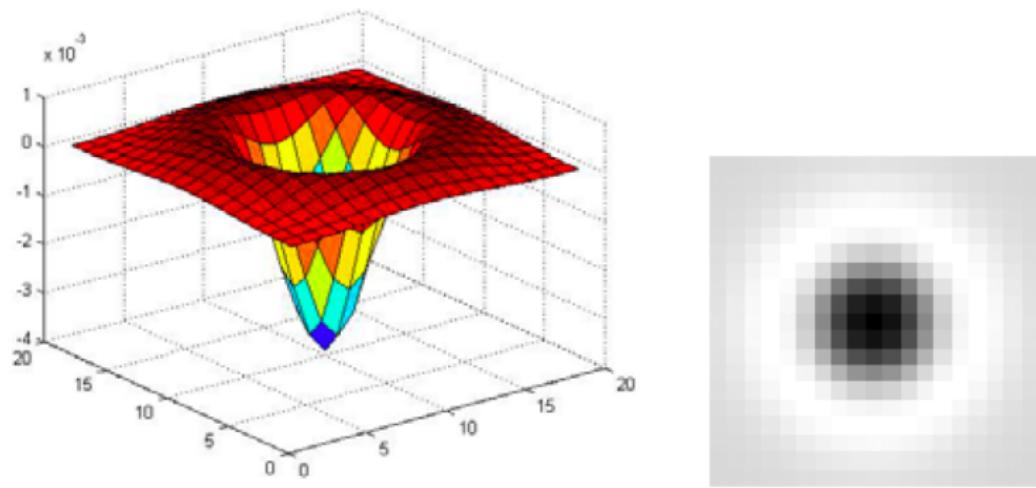


Blob Detection – Laplacian of Gaussian

- Laplacian of Gaussian: We mentioned it for edge detection

$$\nabla^2 g(x, y, \sigma) = -\frac{1}{\pi\sigma^4} \left(1 - \frac{x^2 + y^2}{2\sigma^2}\right) \exp^{-\frac{x^2+y^2}{2\sigma^2}}$$

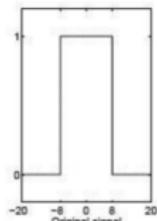
- It is a circularly symmetric operator (finds difference in all directions)
- It can be used for 2D blob detection! How?



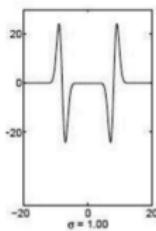
Blob Detection – Laplacian of Gaussian

- It can be used for 2D blob detection! How?

Original signal



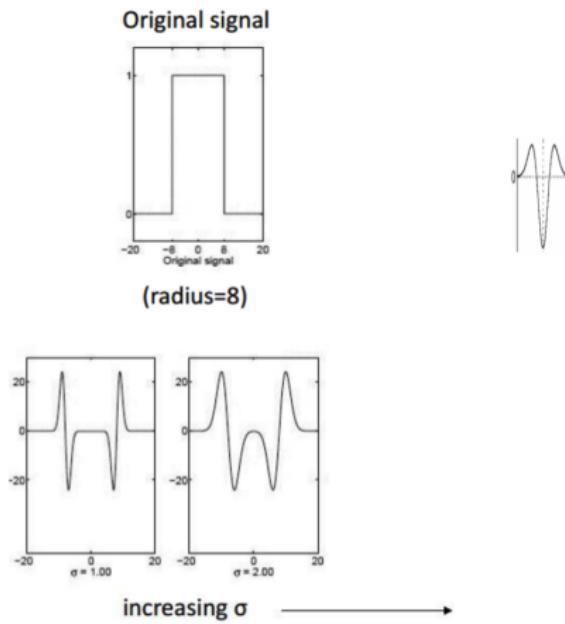
(radius=8)



[Source: F. Flores-Mangas]

Blob Detection – Laplacian of Gaussian

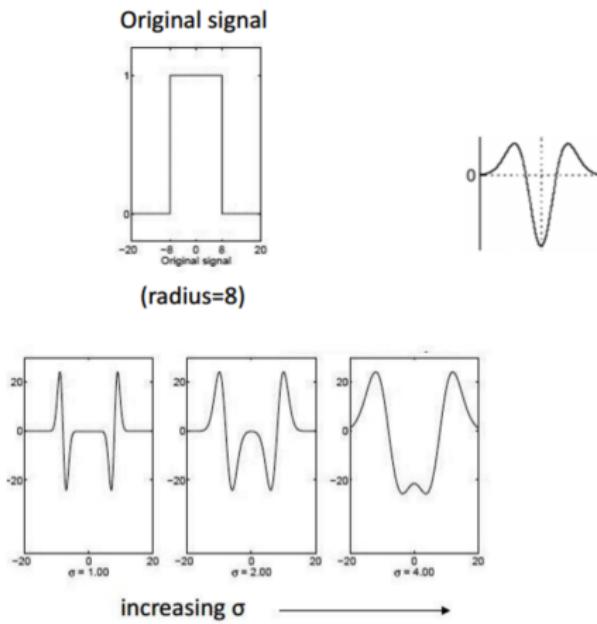
- It can be used for 2D blob detection! How?



[Source: F. Flores-Mangas]

Blob Detection – Laplacian of Gaussian

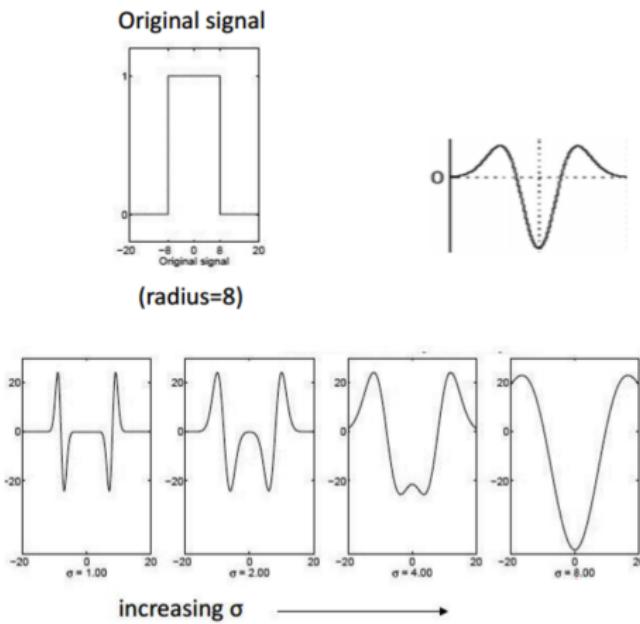
- It can be used for 2D blob detection! How?



[Source: F. Flores-Mangas]

Blob Detection – Laplacian of Gaussian

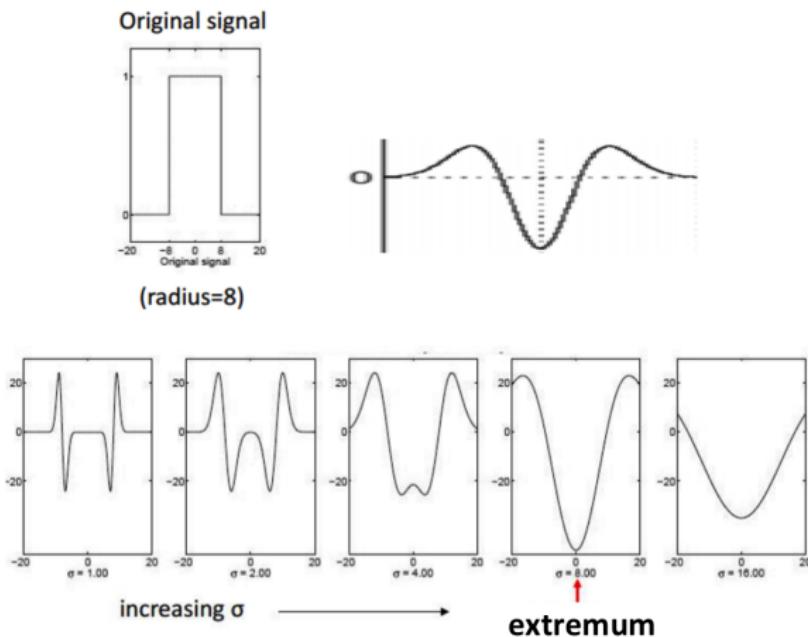
- It can be used for 2D blob detection! How?



[Source: F. Flores-Mangas]

Blob Detection – Laplacian of Gaussian

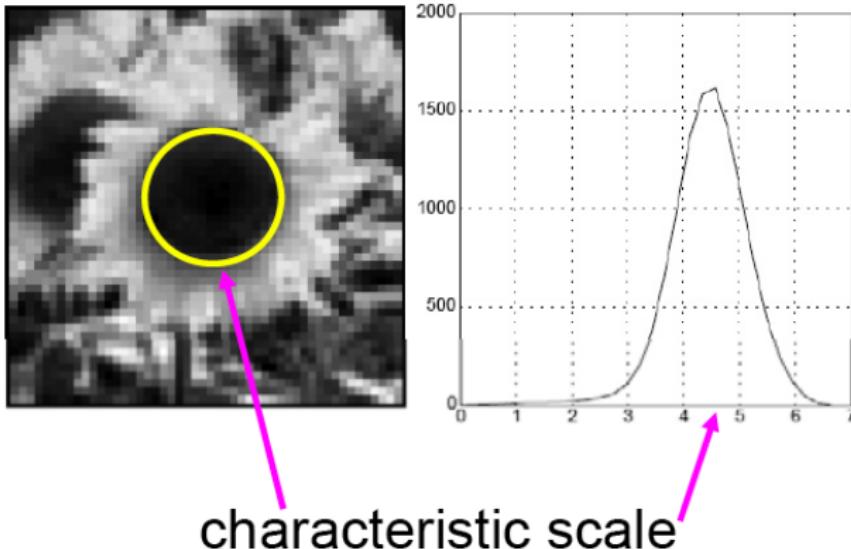
- It can be used for 2D blob detection! How?



[Source: F. Flores-Mangas]

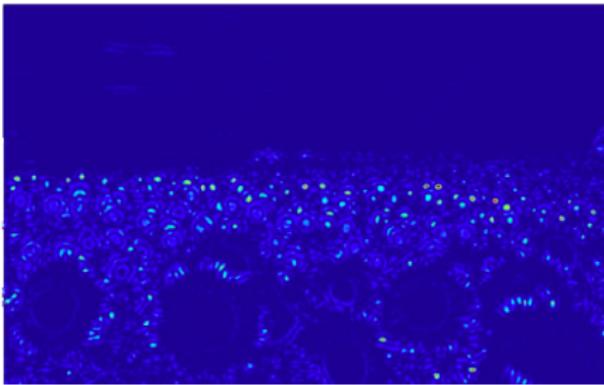
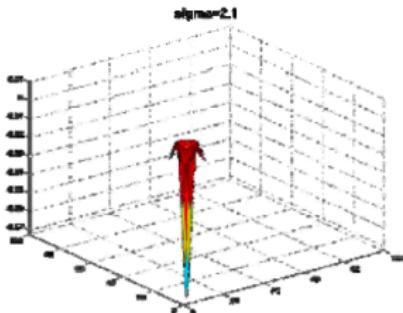
Characteristic Scale

- We define the **characteristic scale** as the scale that produces peak (minimum or maximum) of the Laplacian response



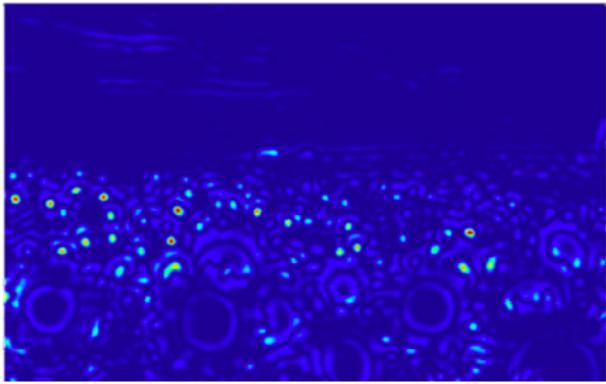
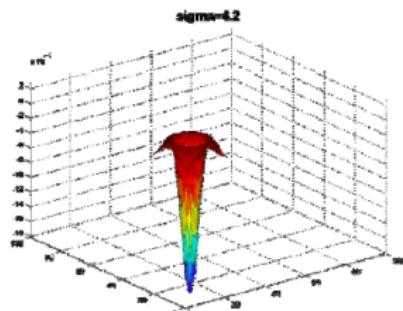
[Source: S. Lazebnik]

Example



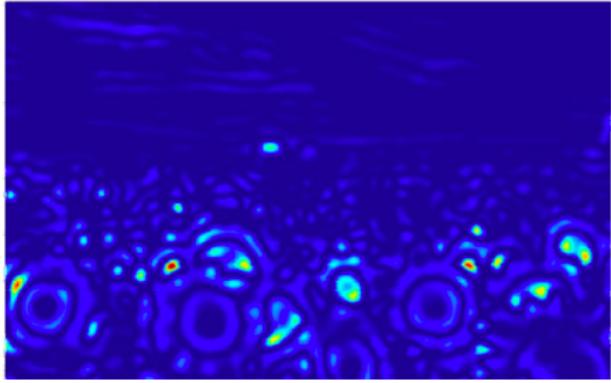
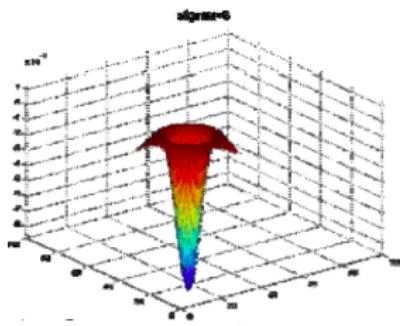
[Source: K. Grauman]

Example



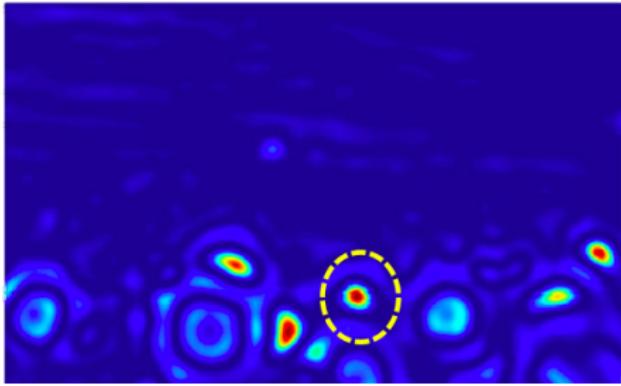
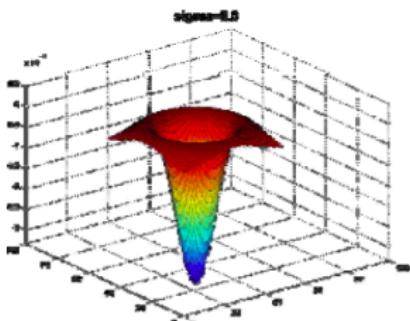
[Source: K. Grauman]

Example



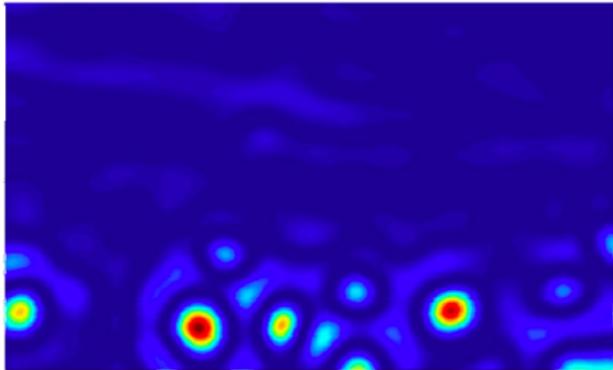
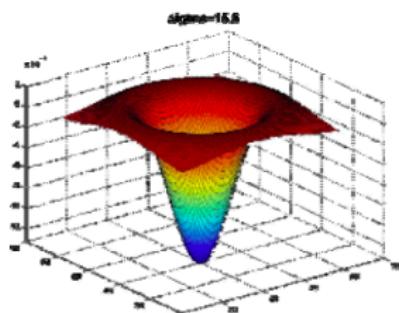
[Source: K. Grauman]

Example



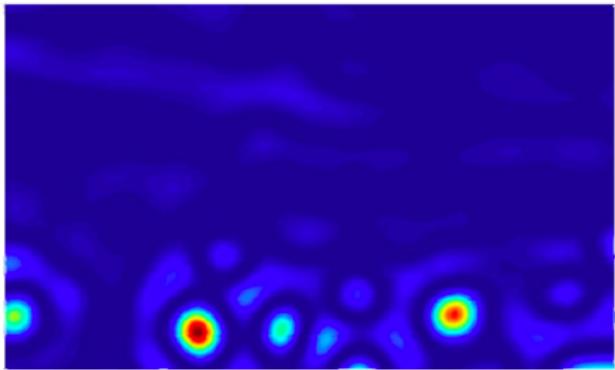
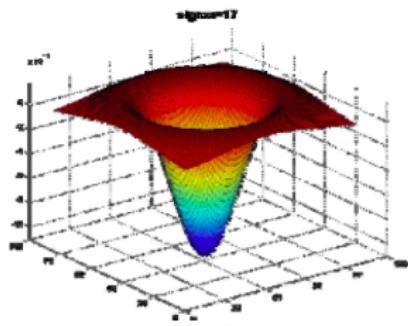
[Source: K. Grauman]

Example



[Source: K. Grauman]

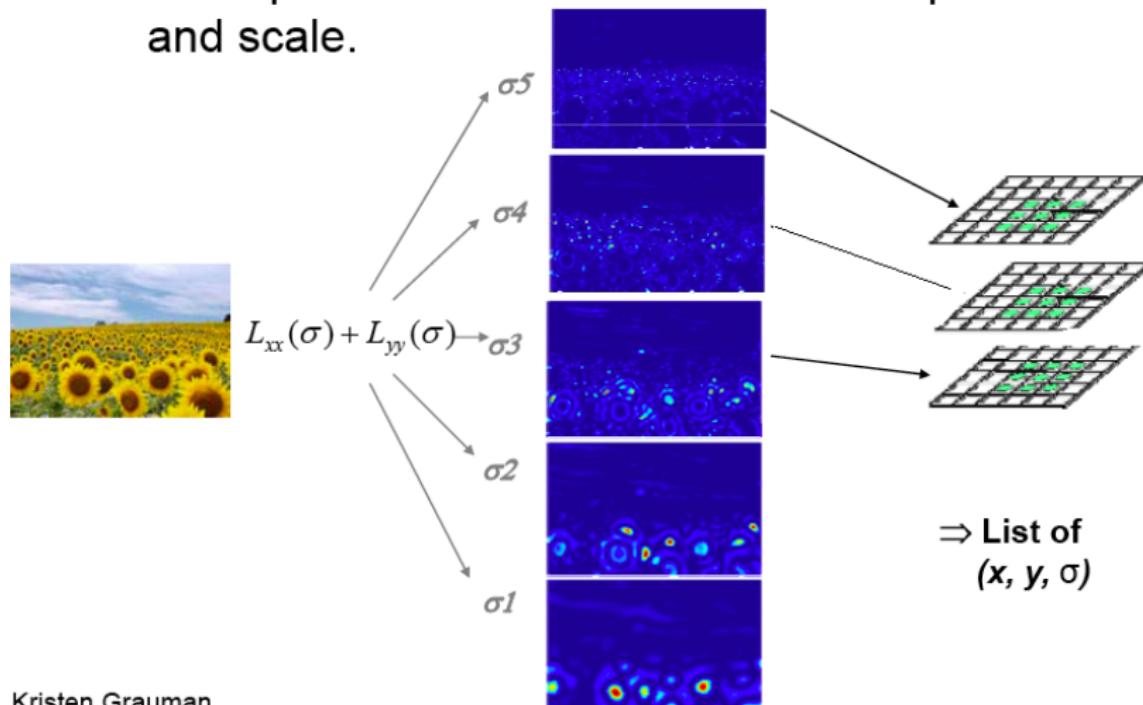
Example



[Source: K. Grauman]

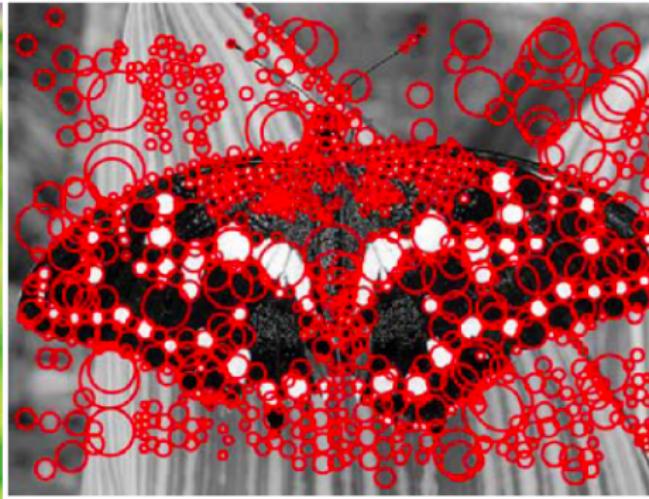
Scale Invariant Interest Points

Interest points are local maxima in both position and scale.



Kristen Grauman

Example



[Source: S. Lazebnik]

Blob Detection – Laplacian of Gaussian

- That's nice. But can we do faster?
- Remember again the Laplacian of Gaussian:

$$\nabla^2 g(x, y, \sigma) = \frac{\partial^2 g(x, y, \sigma)}{\partial x^2} + \frac{\partial^2 g(x, y, \sigma)}{\partial y^2},$$

where g is a Gaussian

Blob Detection – Laplacian of Gaussian

- That's nice. But can we do faster?
- Remember again the Laplacian of Gaussian:

$$\nabla^2 g(x, y, \sigma) = \frac{\partial^2 g(x, y, \sigma)}{\partial x^2} + \frac{\partial^2 g(x, y, \sigma)}{\partial y^2}, \quad \text{where } g \text{ is a Gaussian}$$

$$\nabla^2 g(x, y, \sigma) = -\frac{1}{\pi \sigma^4} \left(1 - \frac{x^2 + y^2}{2\sigma^2}\right) \exp^{-\frac{x^2+y^2}{2\sigma^2}}$$

- Is this separable?
- Larger scale (σ), larger the filters (more work for convolution)
- Can we do it faster?

Approximate the Laplacian of Gaussian

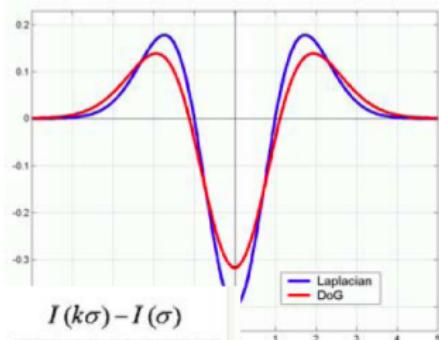
- We can approximate the Laplacian with a difference of Gaussians; and use separable convolution.

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

(Laplacian)

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

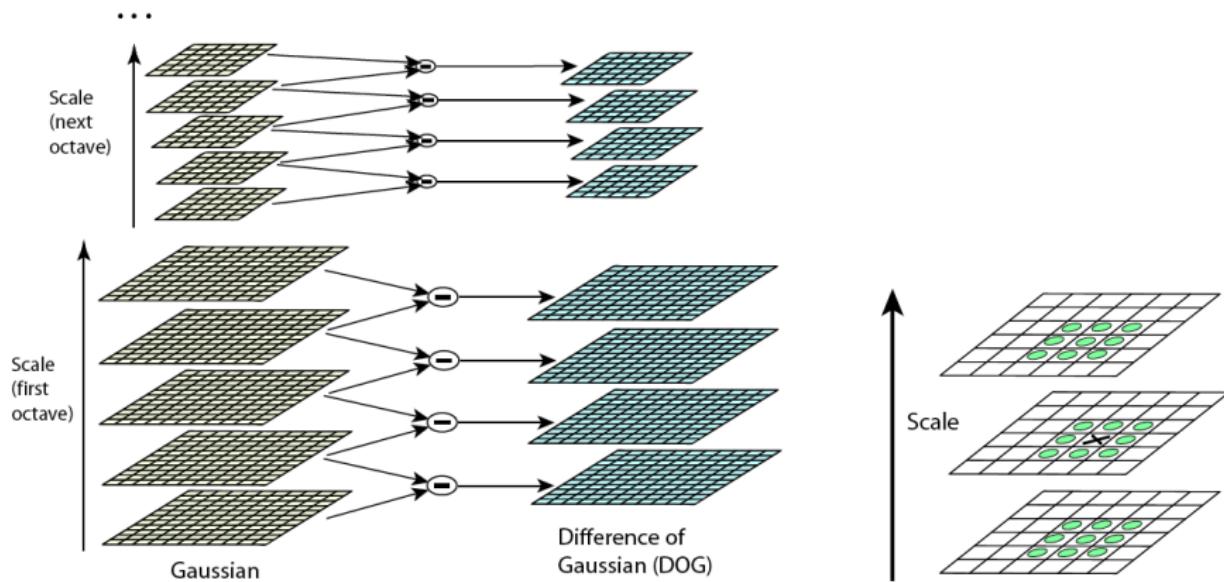
(Difference of Gaussians)



[Source: K. Grauman]

Lowe's DoG

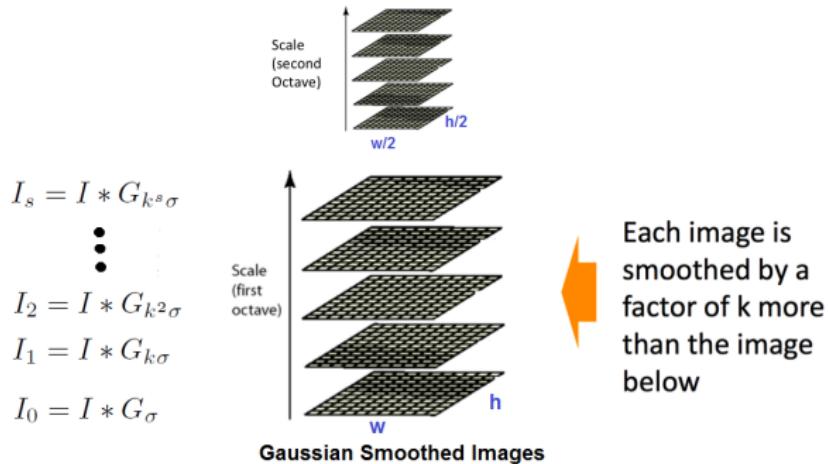
- Lowe (2004) proposed computing a set of sub-octave Difference of Gaussian filters looking for 3D (space+scale) maxima in the resulting structure



[Source: R. Szeliski]

Lowe's DoG

- First compute a Gaussian image pyramid



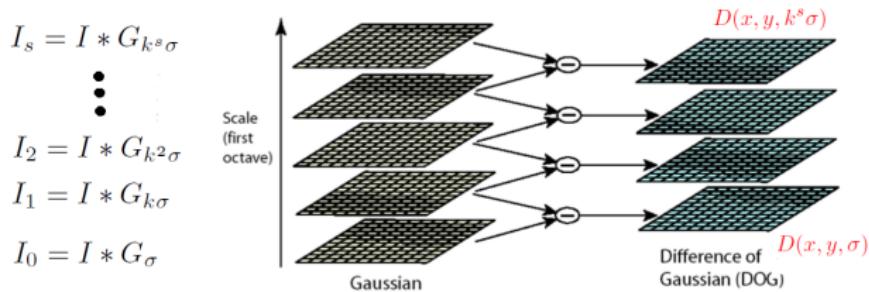
[Source: F. Flores-Mangas]

Lowe's DoG

- First compute a Gaussian image pyramid
- Compute Difference of Gaussians

$$D(x, y, \rho) = I(x, y) * (G(x, y, k\rho) - G(x, y, \rho))$$

for $\rho = \{\sigma, k\sigma, k^2\sigma, \dots, k^{s-1}\sigma\}, \quad k = 2^{1/s}$



[Source: F. Flores-Mangas]

Lowe's DoG

- First compute a Gaussian image pyramid
- Compute Difference of Gaussians
- At every scale

[Source: F. Flores-Mangas]

Lowe's DoG

- First compute a Gaussian image pyramid
- Compute Difference of Gaussians
- At every scale
- Find local maxima in scale
- A bit of pruning of bad maxima and we're done!

[Source: F. Flores-Mangas]

Examples



Figure: Let's first try out some synthetic images

Examples

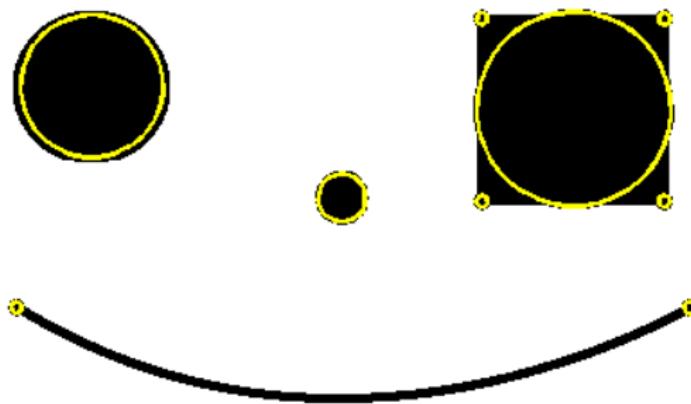


Figure: Detected interest points (kind of make sense)

Examples



Figure: Other roundy objects

Examples

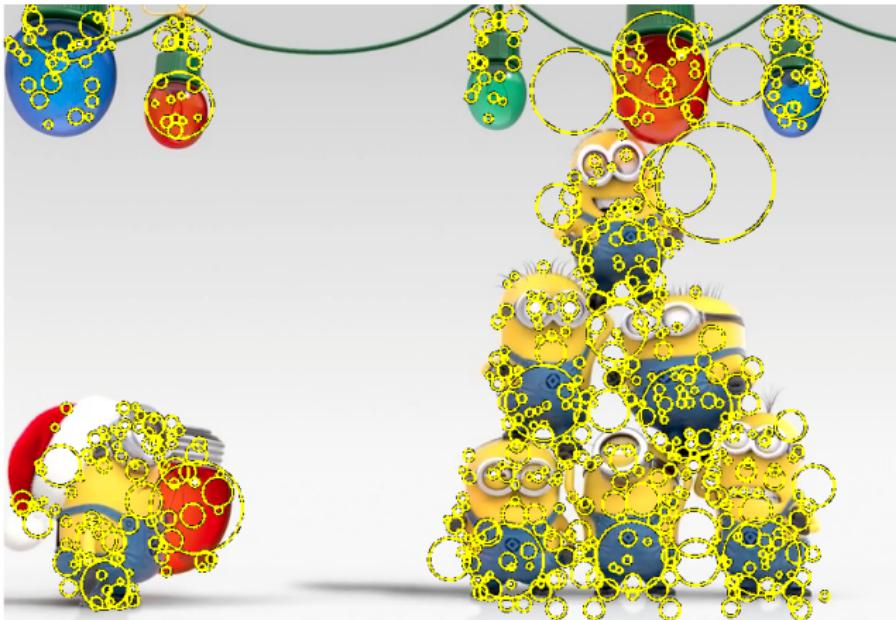


Figure: Detected interest points

Examples



Figure: Real images

Examples

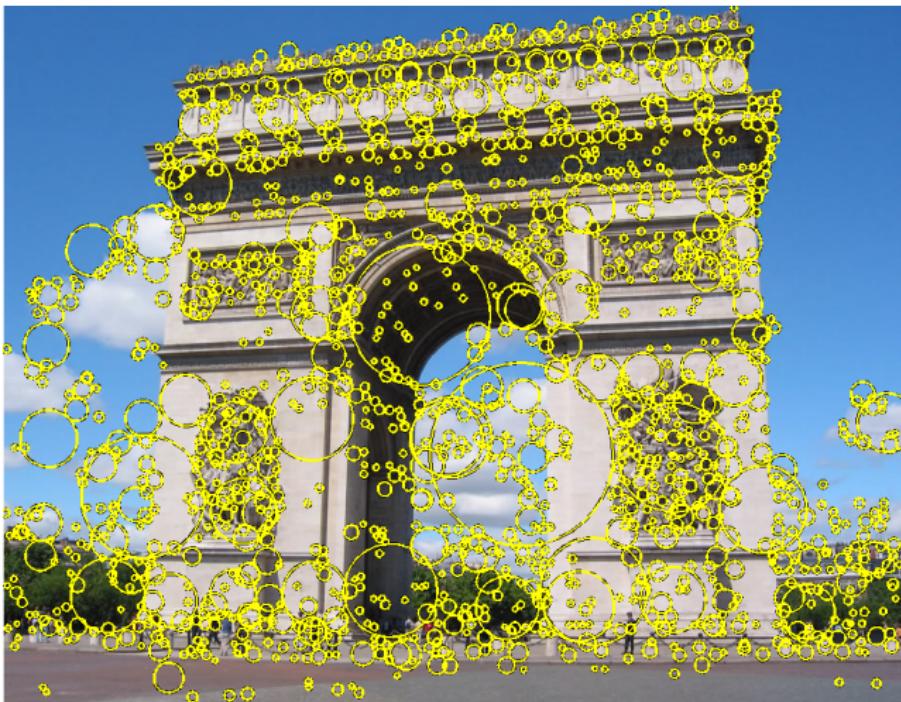


Figure: Detected interest points

Examples



Other Interest Point Detectors (Many Good Options!)

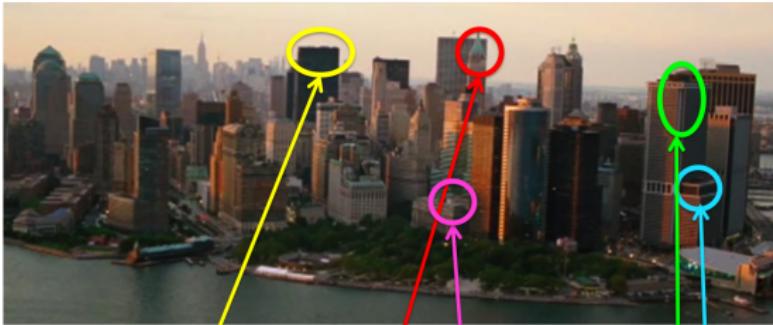
- Lindeberg: Laplacian of Gaussian
- Lowe: DoG (typically called the SIFT interest point detector)
- Mikolajczyk & Schmid: Hessian/Harris-Laplacian/Affine
- Tuyttelaars & Van Gool: EBR and IBR
- Matas: MSER
- Kadir & Brady: Salient Regions

Summary – Stuff You Should Know

- To match the same scene or object under different viewpoint, it's useful to first detect **interest points** (keypoints)
- We looked at these interest point detectors:
 - Harris corner detector: translation and rotation but not scale invariant
 - Scale invariant interest points: Laplacian of Gaussians and Lowe's DoG
- Harris' approach computes I_x^2 , I_y^2 and $I_x I_y$, and blurs each one with a Gaussian. Denote with: $A = g * I_x^2$, $B = g * (I_x I_y)$ and $C = g * I_y^2$. Then $M_{xy} = \begin{pmatrix} A(x,y) & B(x,y) \\ B(x,y) & C(x,y) \end{pmatrix}$ characterizes the shape of E_{WSSD} for a window around (x,y) . Compute "cornerness" score for each (x,y) as $R(x,y) = \det(M_{xy}) - \alpha \text{trace}(M_{xy})^2$. Find $R(x,y) > \text{threshold}$ and do non-maxima suppression to find corners.
- Lowe's approach creates a Gaussian pyramid with s blurring levels per octave, computes difference between consecutive levels, and finds local extrema in space and scale

Let's Remember How Interest Point Stuff Started

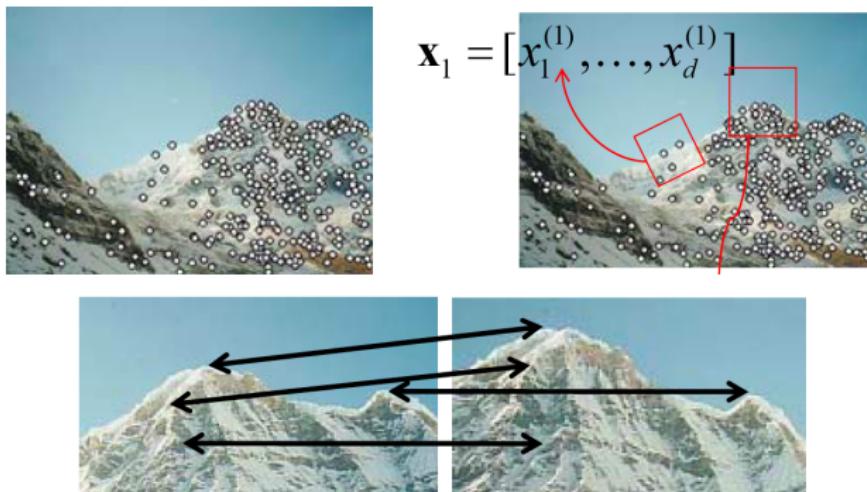
- Which city is in the photo above?



New York City

Local Features

- **Detection:** Identify the interest points.
- **Description:** Extract **feature vector** descriptor around each interest point.
- **Matching:** Determine correspondence between descriptors in two views.



[Source: K. Grauman]

SIFT Interest Points

- Works pretty well in variety of settings

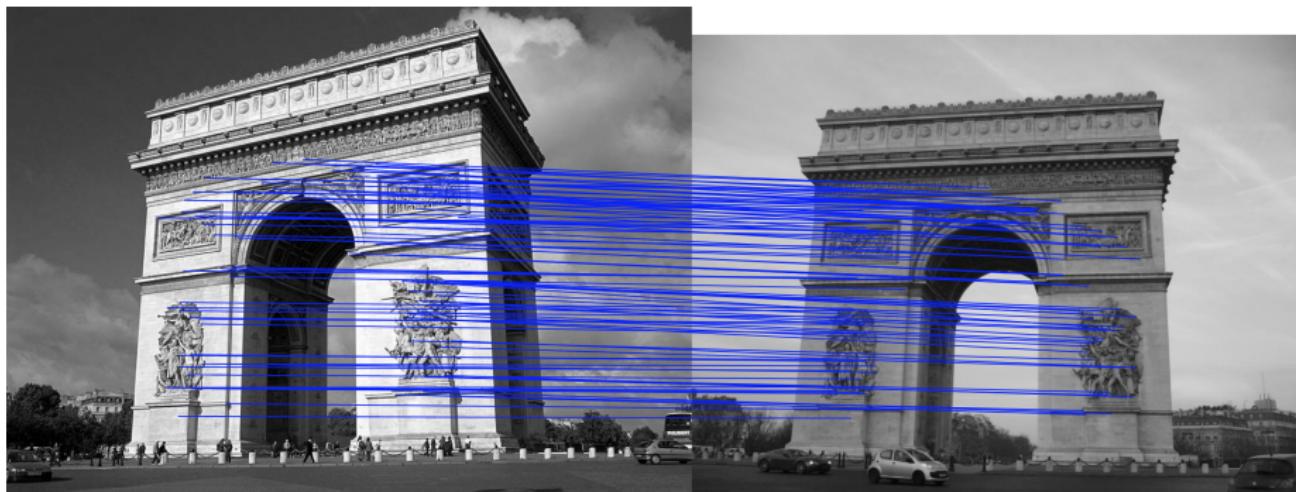


Figure: Lowe's interest point detector finds scale-invariant points that can be reliably matched across different images. (We will talk about how to do matching soon)

SIFT Interest Points

- Works pretty well in variety of settings



Figure: Lowe's interest point detector finds scale-invariant points that can be reliably matched across different images. (We will talk about how to do matching soon)

SIFT Interest Points

- Works pretty well in variety of settings

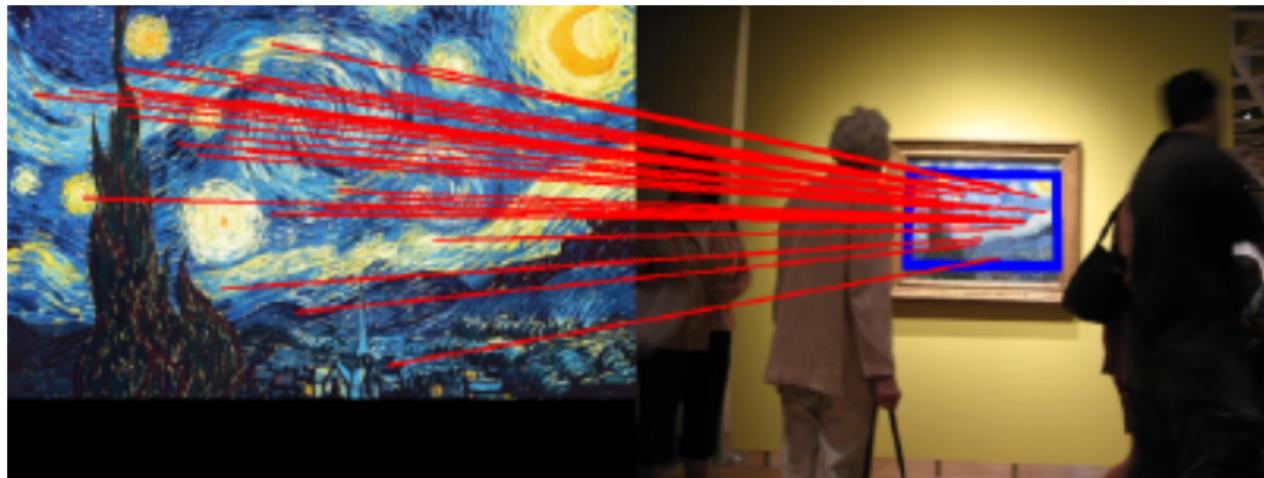


Figure: Lowe's interest point detector finds scale-invariant points that can be reliably matched across different images. (We will talk about how to do matching soon)

SIFT Interest Points

- What about in different lighting/weather conditions?



SIFT Interest Points

[Pic from: Y. Verdie, K. M. Yi, P. Fua and V. Lepetit. TILDE: A Temporally Invariant Learned DEtector. CVPR'15]

- Fails in very different lighting conditions

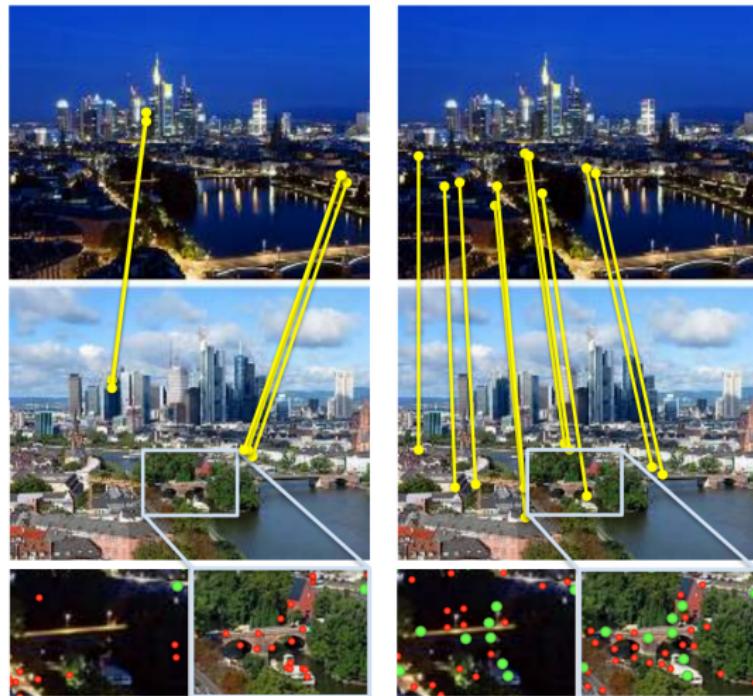


Figure: Green point(s) are repeatable interest points, red are non-repeatable

SIFT Interest Points

[Pic from: Y. Verdie, K. M. Yi, P. Fua and V. Lepetit. TILDE: A Temporally Invariant Learned DEtector. CVPR'15]

- Can we use Machine Learning to detect interest points more reliably?



SIFT

Learned Interest Point Detector?

Training Data

- What can we use?

Training Data

- What can we use? Data from webcams!



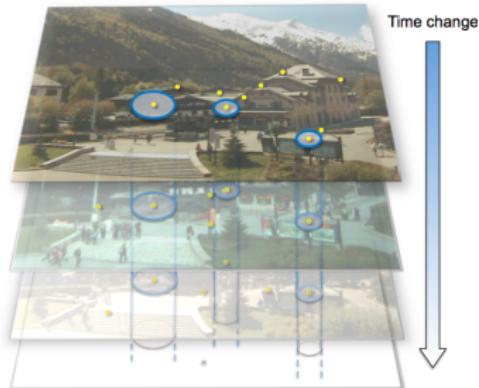
Training Data

- Now that we have training images, how shall we train the detector?



Training the Detector

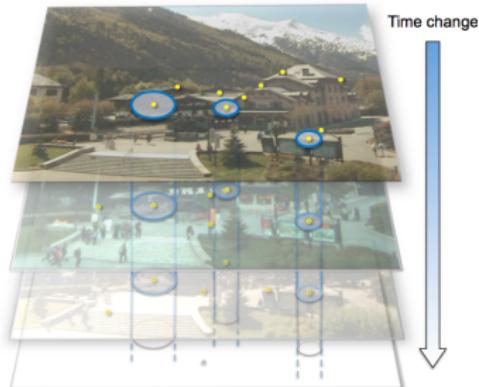
- Detect e.g. SIFT Interest Points in images across time
- Keep only those that are repeatable across time.
- These are our (super reliable) positive training examples. What about negative examples?



(a) Stack of training images

Training the Detector

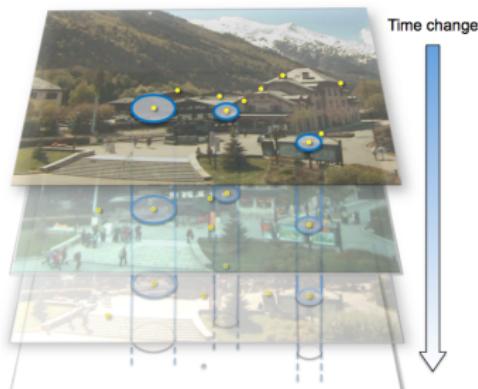
- Detect e.g. SIFT Interest Points in images across time
- Keep only those that are repeatable across time.
- These are our (super reliable) positive training examples. What about negative examples? All other points with some distance wrt positive points



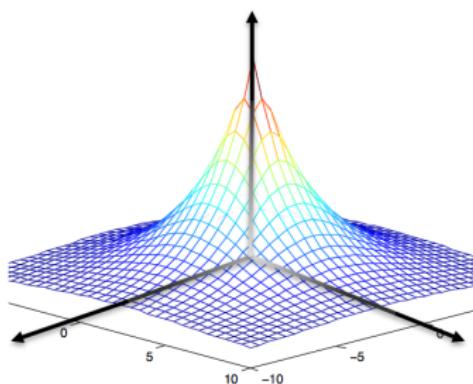
(a) Stack of training images

Training the Detector

- Detect e.g. SIFT Interest Points in images across time
- Keep only those that are repeatable across time.
- These are our (super reliable) positive training examples. What about negative examples? All other points with some distance wrt positive points
- Take a patch around each point, extract some features on it.
- Train a classifier or a regressor



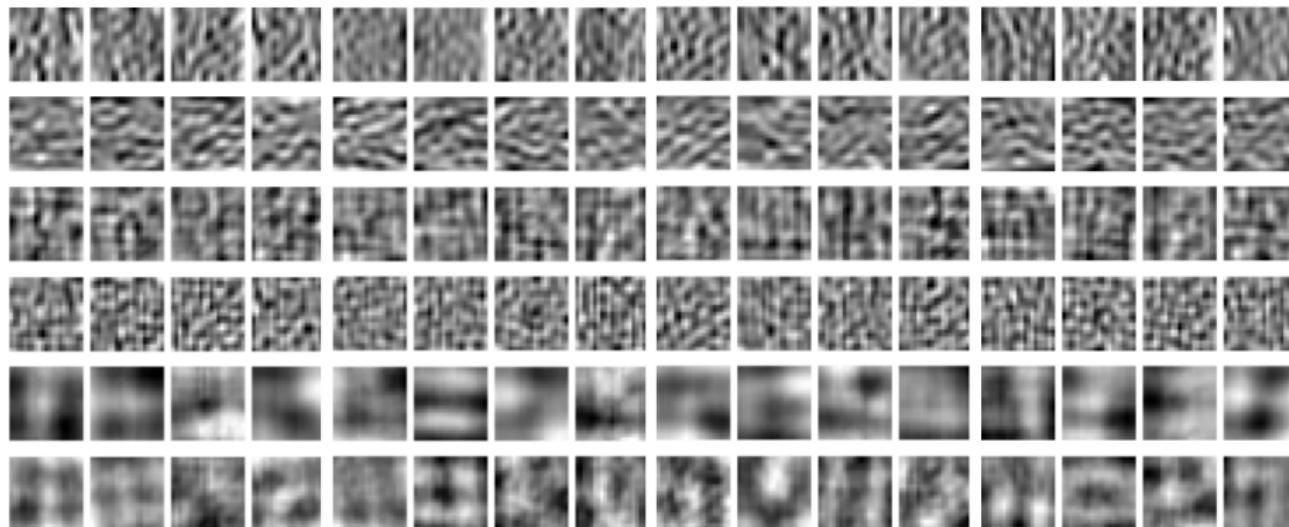
(a) Stack of training images



(b) Desired response on positive samples

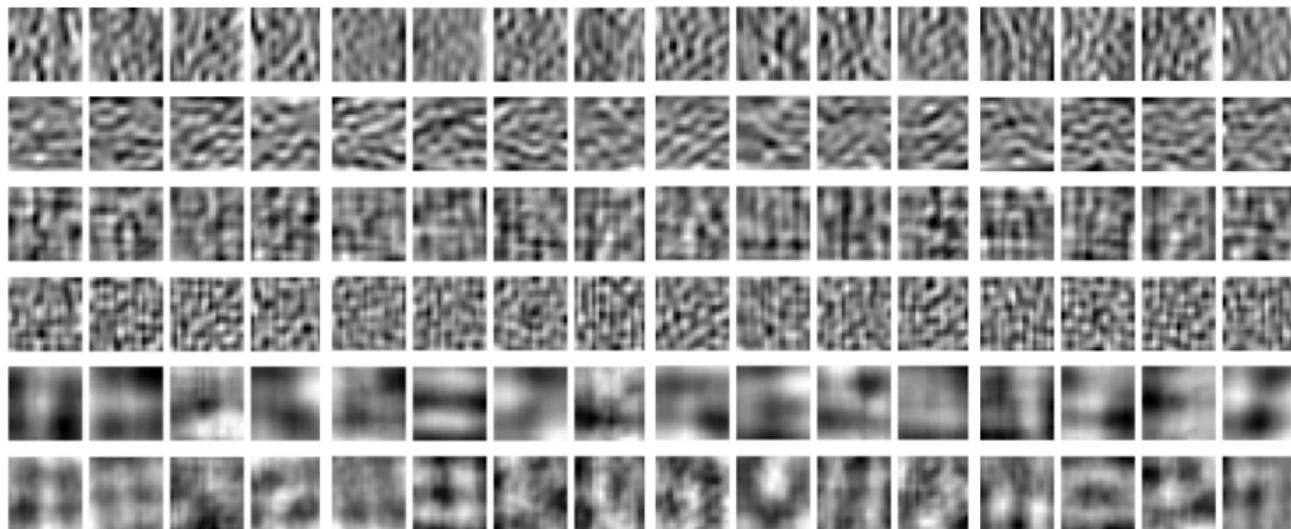
Trained Filters

- Remember from the lecture where we trained a classifier to detect edges:
If we train a linear classifier on a patch, it can be seen as a filter



Trained Filters

- Remember from the lecture where we trained a classifier to detect edges:
If we train a linear classifier on a patch, it can be seen as a filter



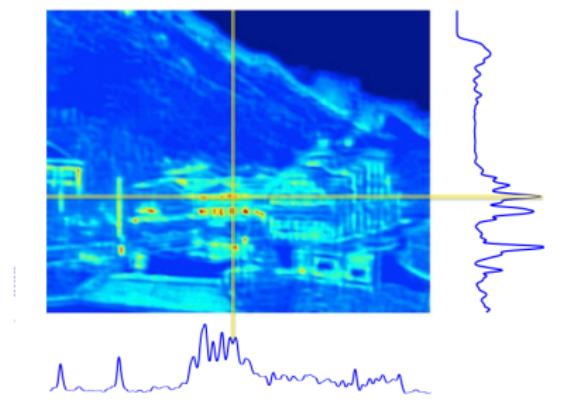
Tiny lesson learned: Sometime our intermediate results (filters in this case) don't look interpretable at all, but they still do the job

Using the Learned Interest Point Detector

- Now that we trained our detector, how can we use it on new images?

Using the Learned Interest Point Detector

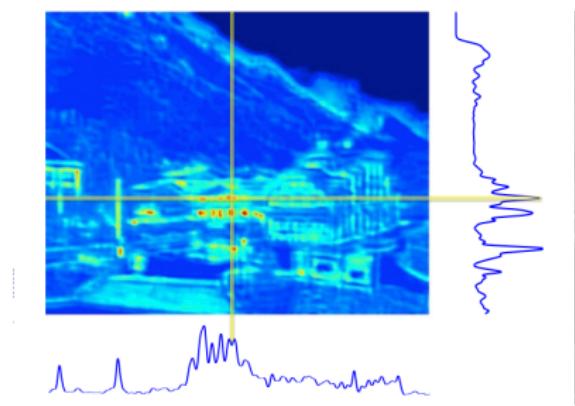
- Apply our filter on each image patch (convolution, if it's a linear classifier)



(c) Regressor response for a new image

Using the Learned Interest Point Detector

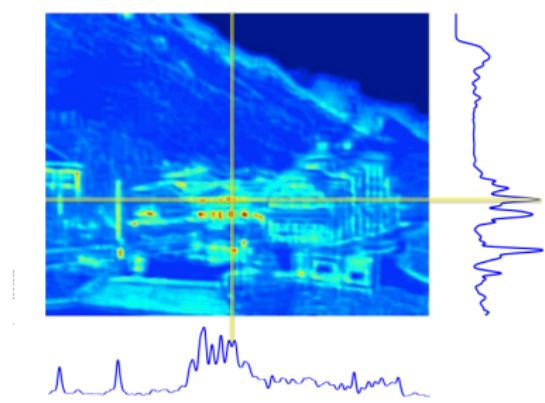
- Apply our filter on each image patch (convolution, if it's a linear classifier)
- This has response everywhere. How can we find the actual interest **points**?



(c) Regressor response for a new image

Using the Learned Interest Point Detector

- Apply our filter on each image patch (convolution, if it's a linear classifier)
- This has response everywhere. How can we find the actual interest **points**?
- Non-maxima suppression (keep only points that are local maxima)



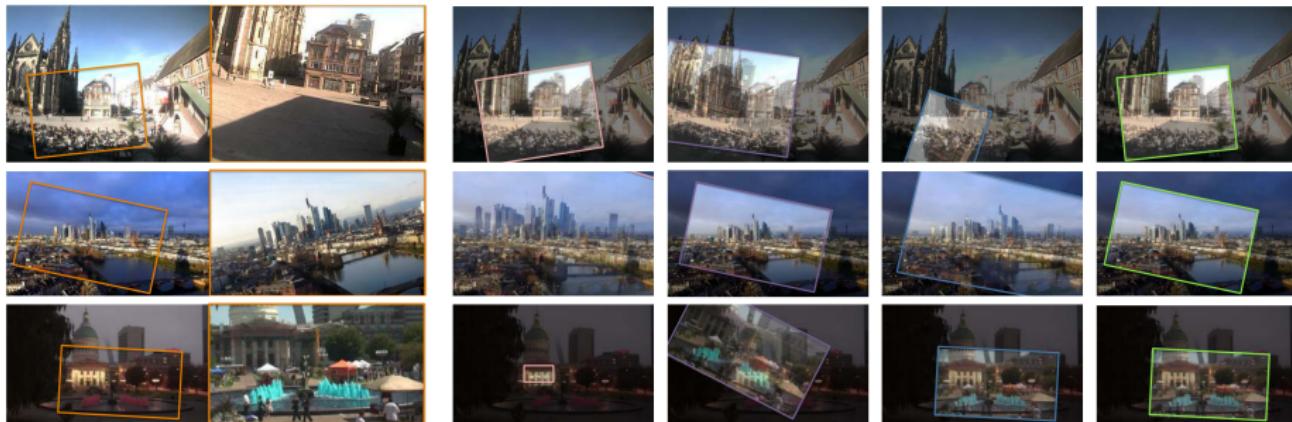
(c) Regressor response for a new image



(d) Keypoints detected in the new image

Results

- Visually check how well we can now match with new interest points



(a) Original images

(b) SIFT

(c) SURF

(d) FAST-9

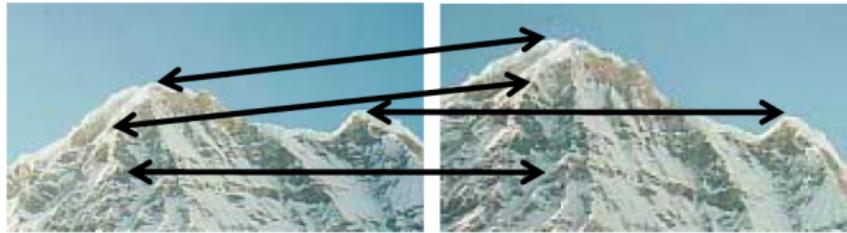
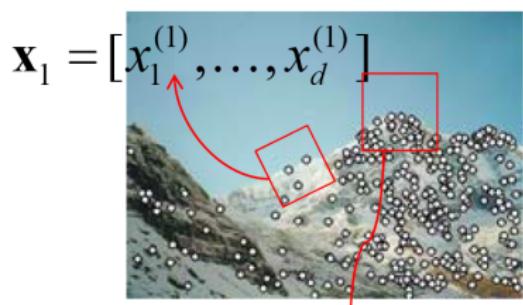
(e) Our keypoints

- SIFT, SURF are hand-designed interest point detectors
- FAST is trained to detect corners fast: First employs a slow method to detect corners, then trains decision trees to detect them really fast

[E. Rosten and T. Drummond. Machine Learning for HighSpeed Corner Detection. ECCV 2006
Paper: http://www.edwardrosten.com/work/rosten_2006_machine.pdf]

Local Descriptors – Next Time

- **Detection:** Identify the interest points.
- **Description:** Extract a feature descriptor around each interest point.
- **Matching:** Determine correspondence between descriptors in two views.



[Source: K. Grauman]