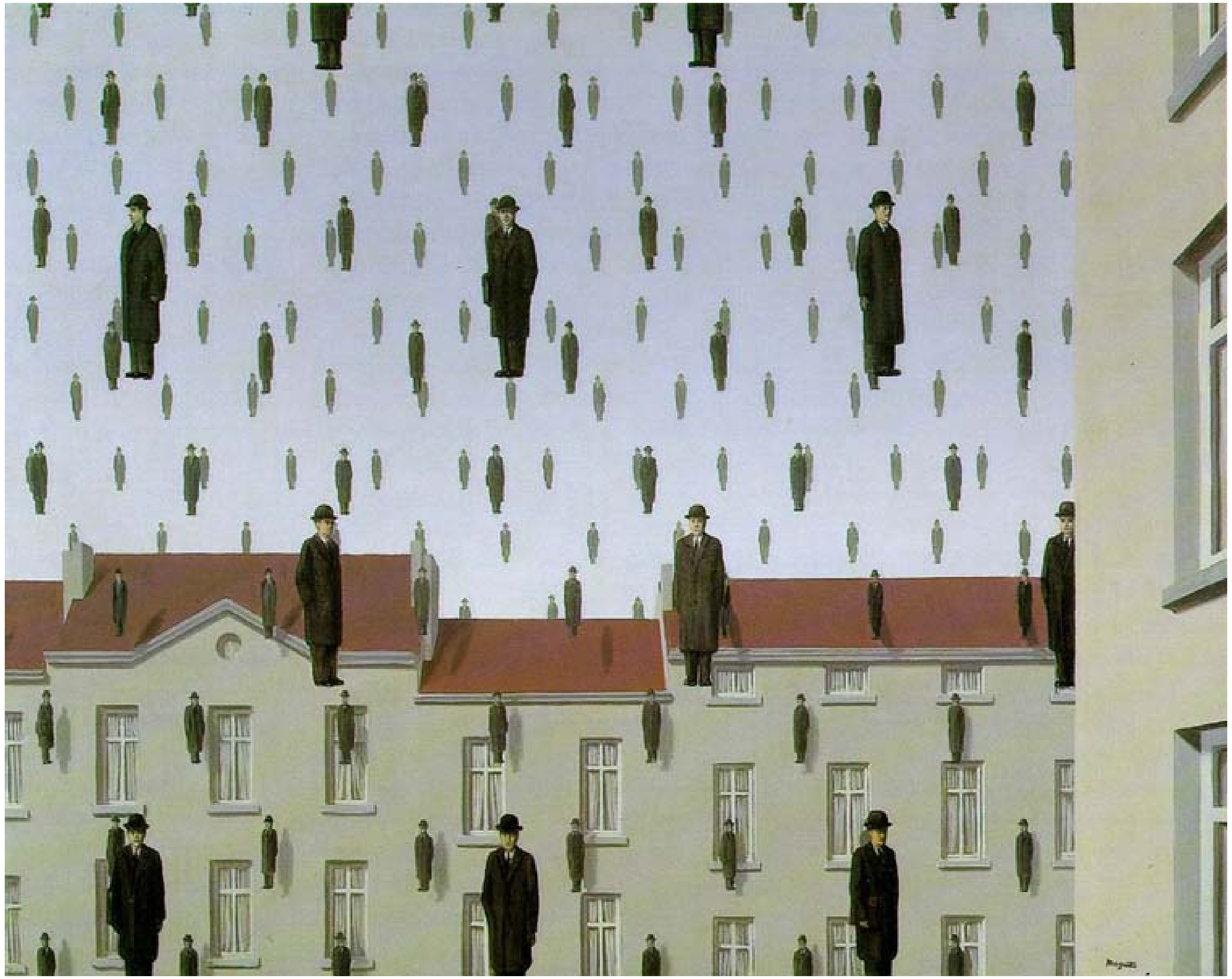
Templates and Image Pyramids



Computational Photography

Derek Hoiem, University of Illinois

Why does a lower resolution image still make sense to us? What do we lose?

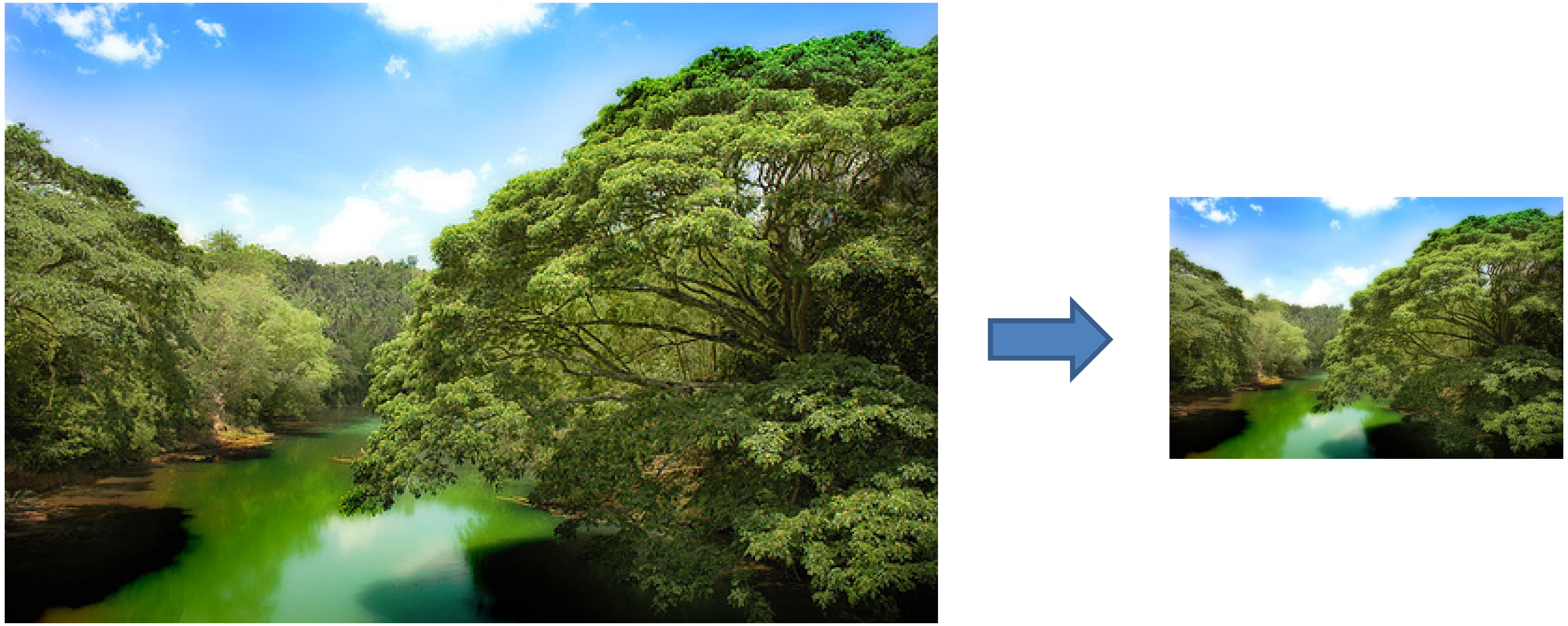
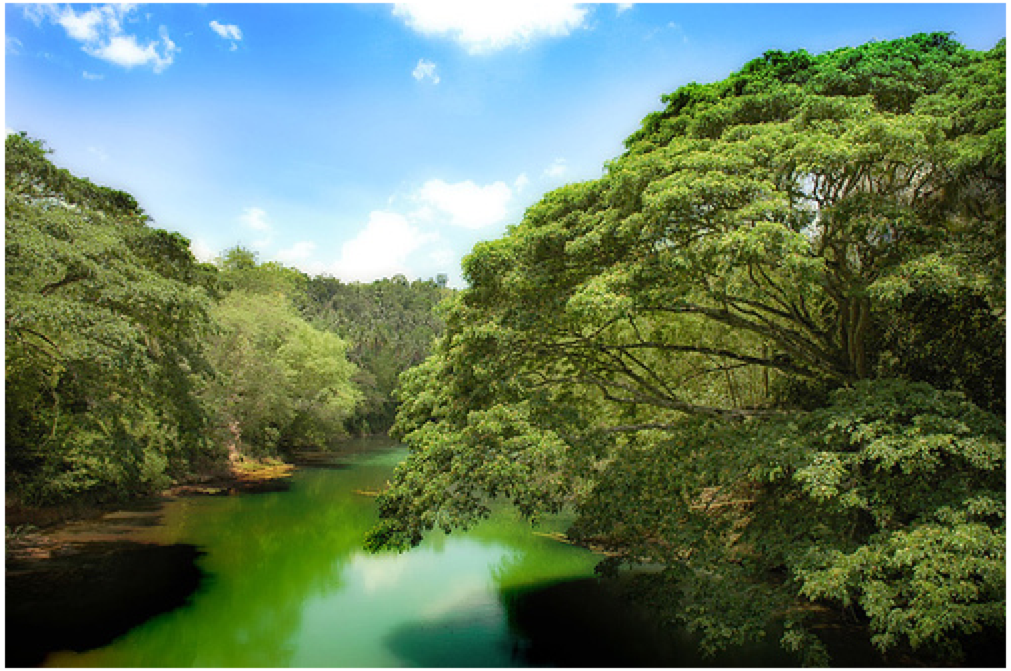


Image: http://www.flickr.com/photos/igorms/136916757/

Why does a lower resolution image still make sense to us? What do we lose?



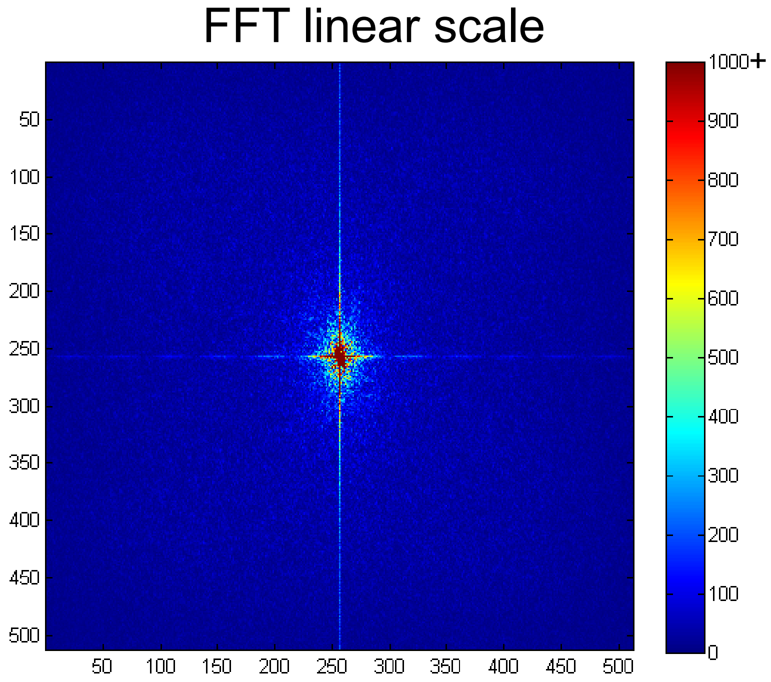
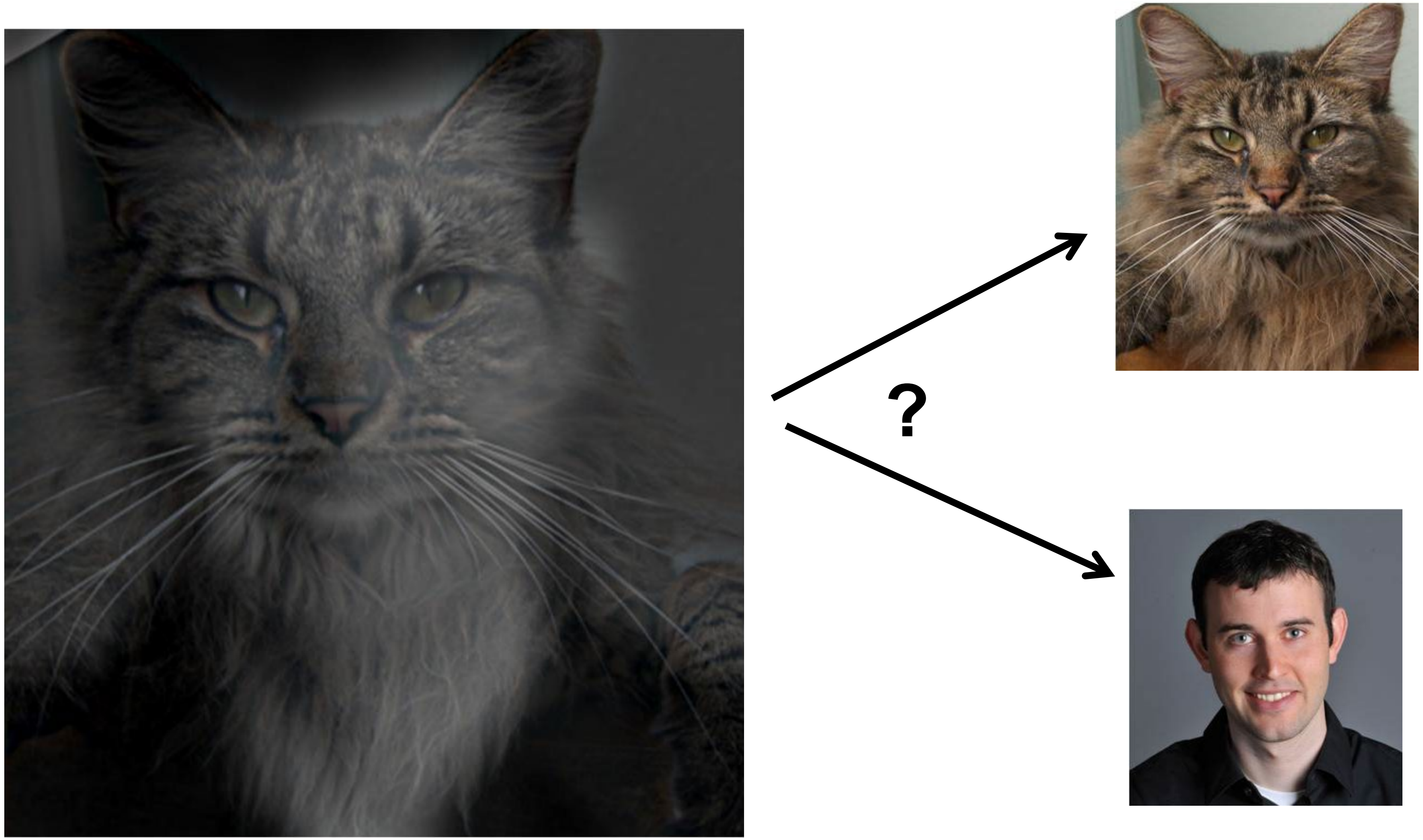


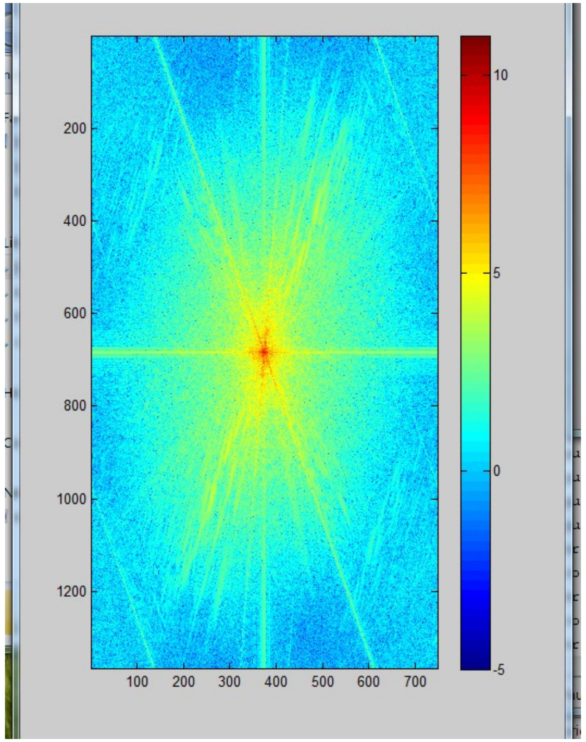
Image: http://www.flickr.com/photos/igorms/136916757/

Why do we get different, distance-dependent interpretations of hybrid images?



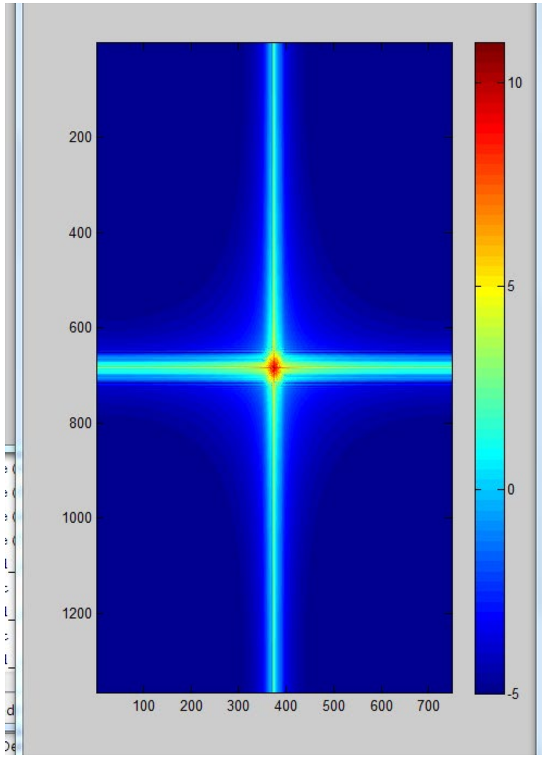
Hybrid Image in FFT

Hybrid Image



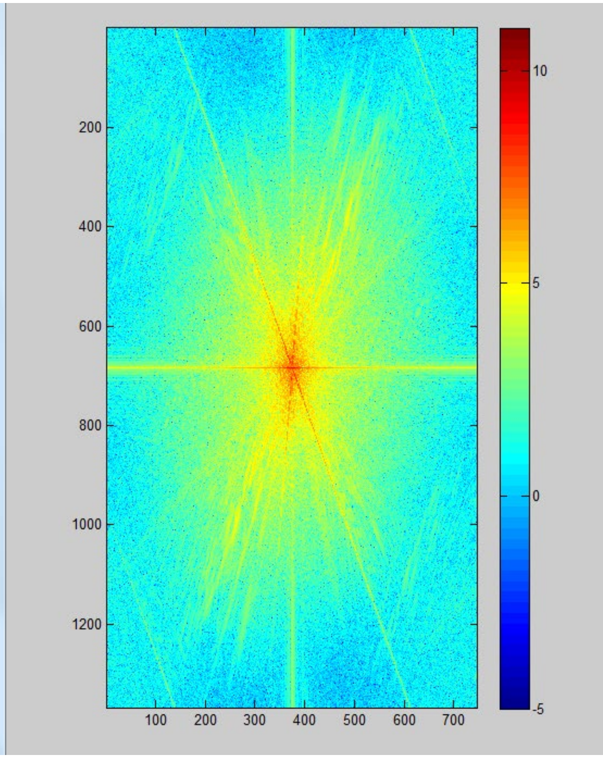
=

Low-passed Image



+

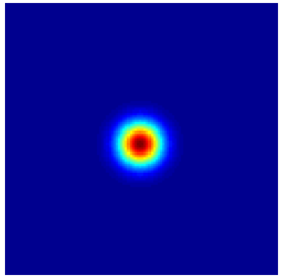
High-passed Image



Review

1. Match the spatial domain image to the Fourier magnitude image

1



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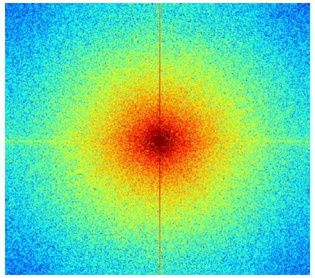
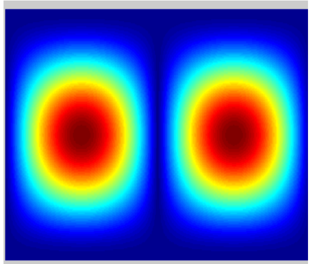
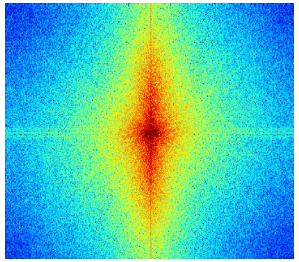


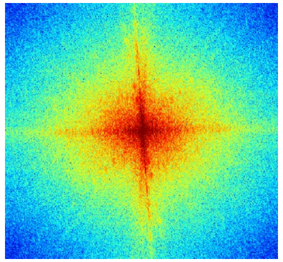
3



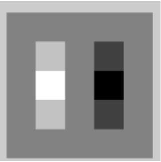
4



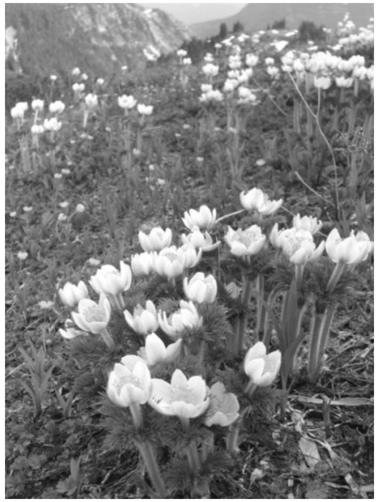
5



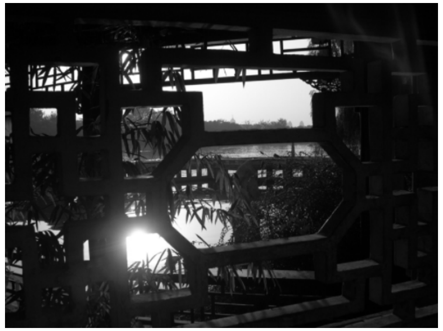
A



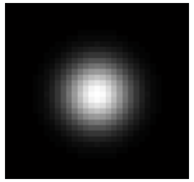
B



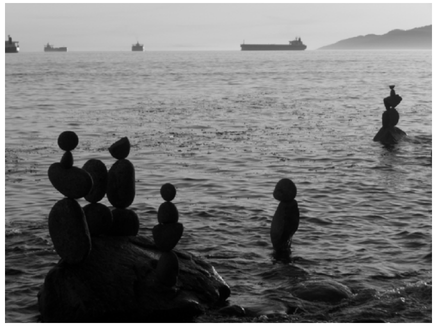
C



D



E



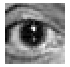
Today’s class: applications of filtering

- Template matching

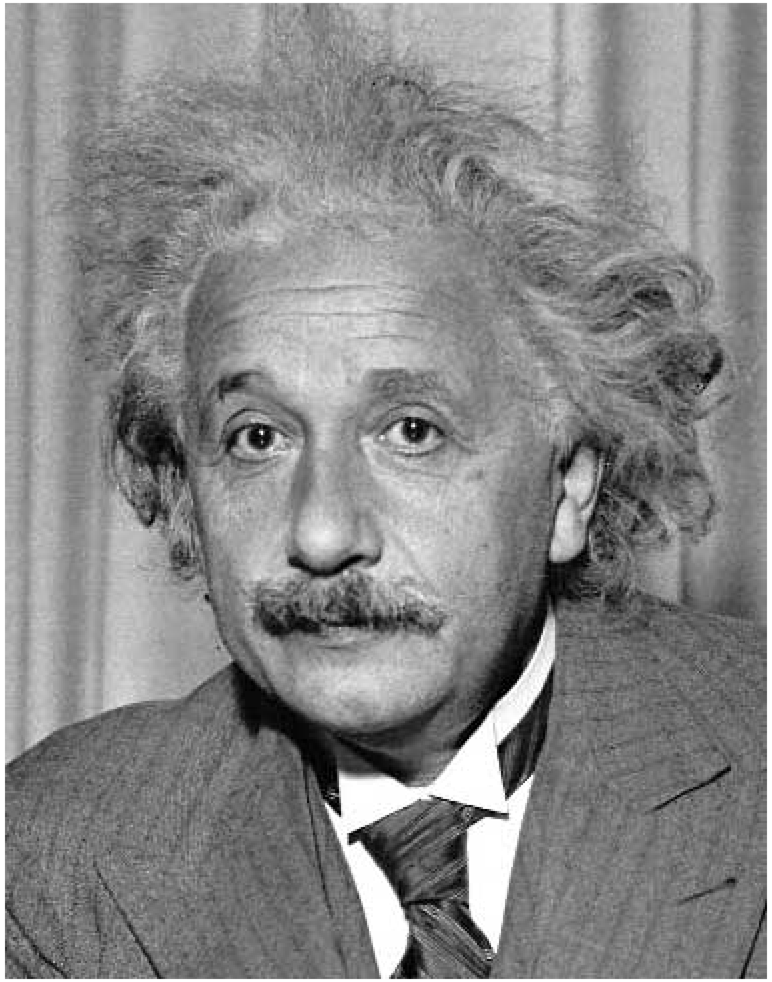
- Coarse-to-fine alignment

- Denoising, Compression

Template matching

- Goal: find  in image

- Main challenge: What is a good similarity or distance measure between two patches?
  - Correlation
  - Zero-mean correlation
  - Sum Square Difference
  - Normalized Cross Correlation

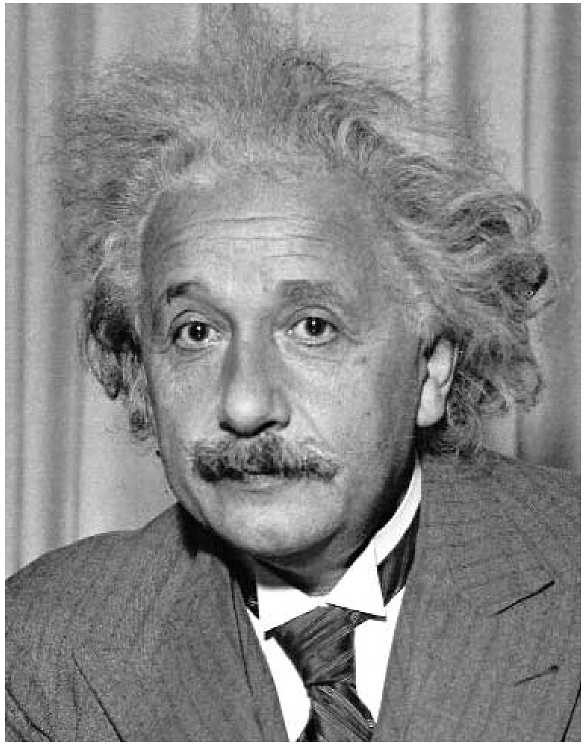


Matching with filters

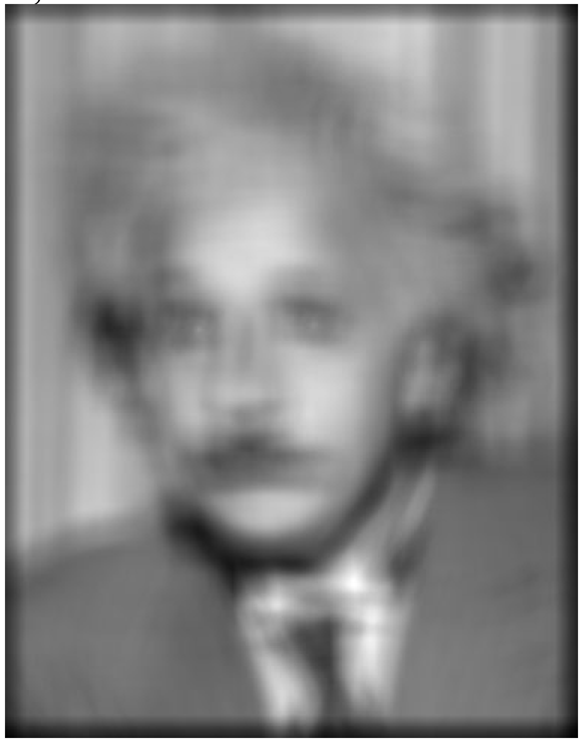
- Goal: find in image
- Method 0: filter the image with eye patch

$$h[m,n]=\sum_{k,l} g[k,l]\, f[m+k,n+l]$$

f = image
g = filter



Input



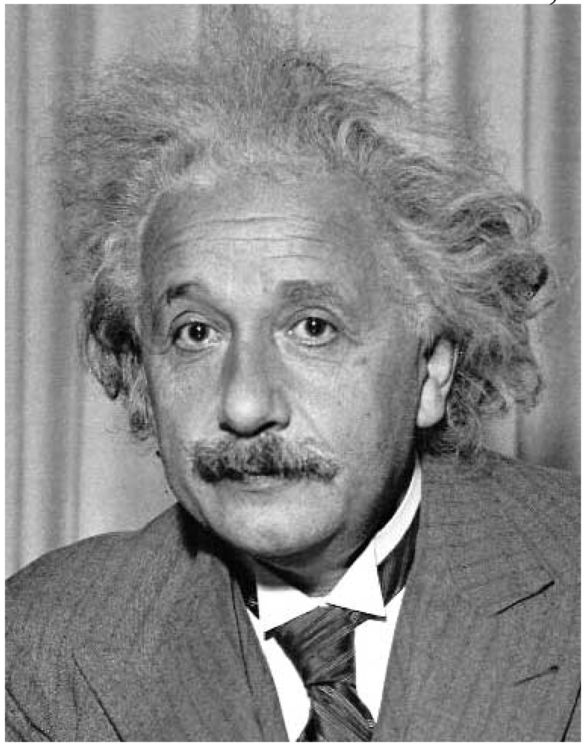
Filtered Image

What went wrong?

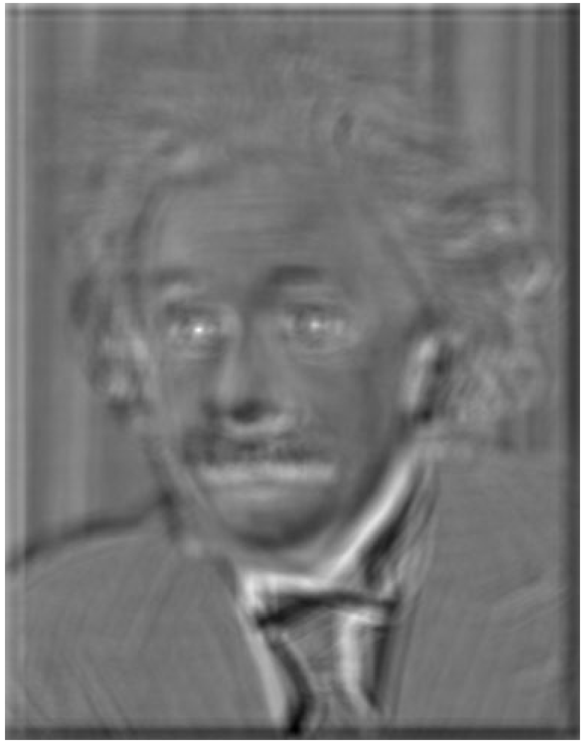
Matching with filters

- Goal: find in image
- Method 1: filter the image with zero-mean eye

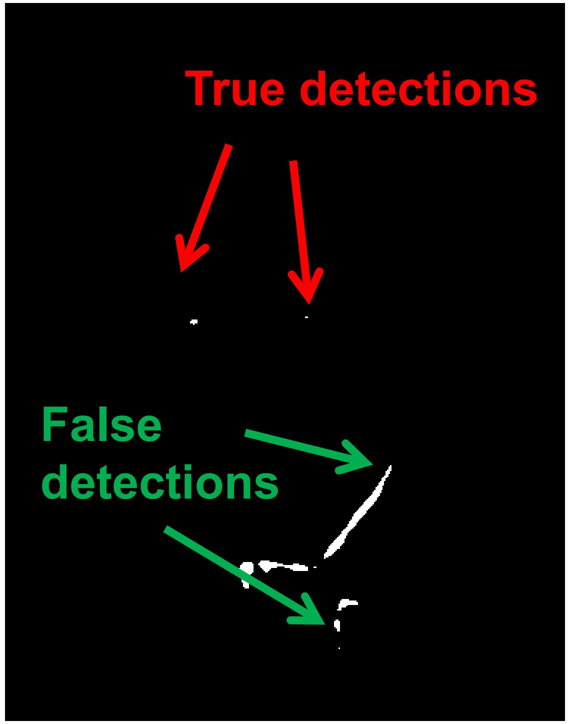
$$h[m,n] = \sum_{k,l} (f[k,l] - \underbrace{\bar{f}}_{\text{mean of f}})(g[m+k,n+l])$$



Input



Filtered Image (scaled)

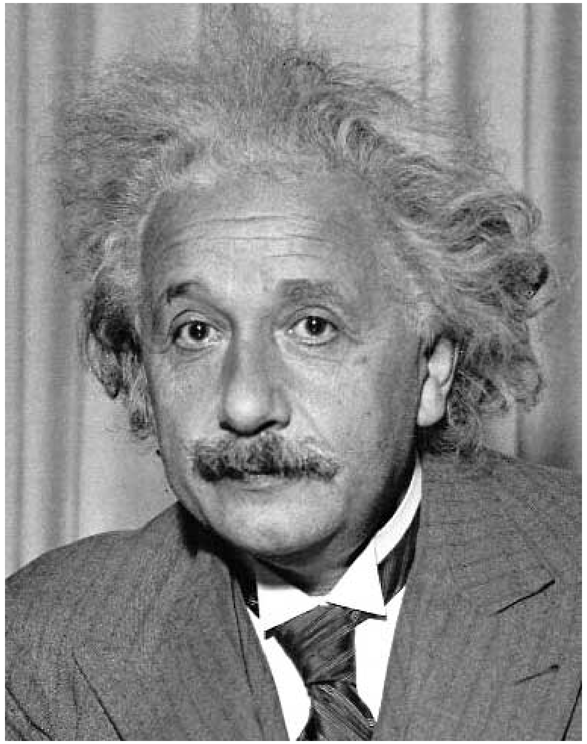


Thresholded Image

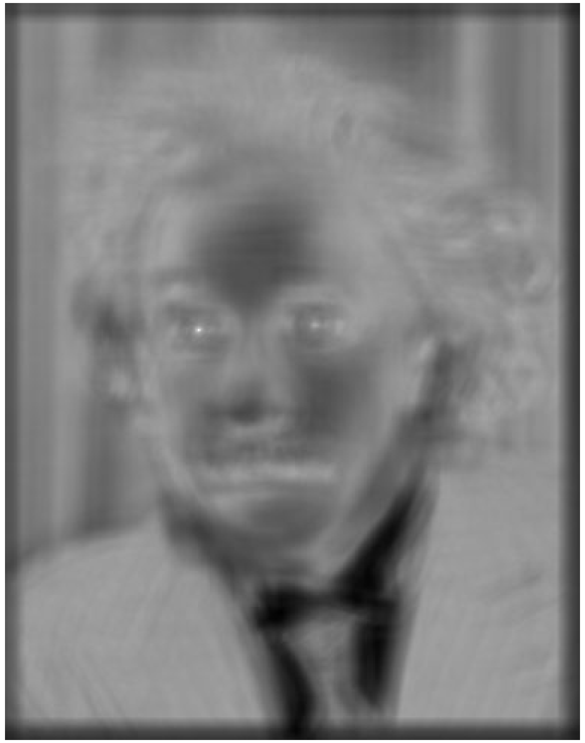
Matching with filters

- Goal: find in image
- Method 2: SSD

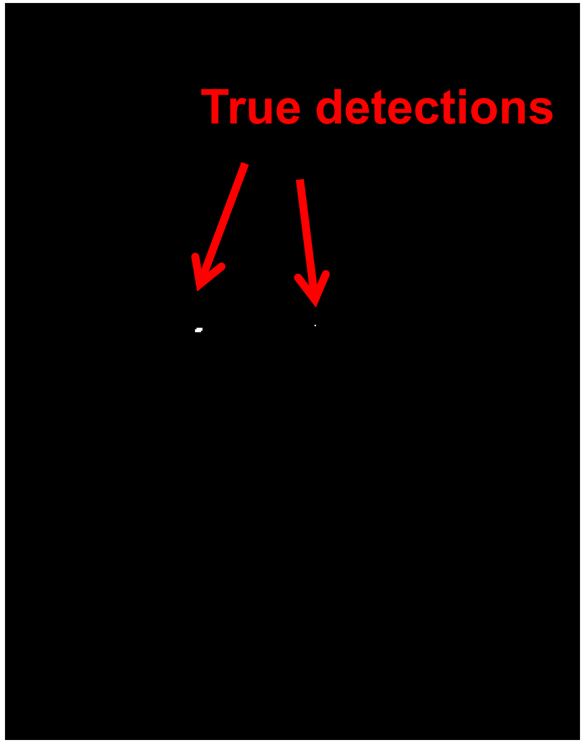
$$h[m,n]=\sum_{k,l}(g[k,l]-f[m+k,n+l])^2$$



Input



1- sqrt(SSD)



Thresholded Image

Matching with filters

Can SSD be implemented with linear filters?

$$h[m,n] = \sum_{k,l} (g[k,l] - f[m+k,n+l])^2$$

$$h[m,n] = \sum_{k,l} (g[k,l]^2 - 2f[m+k,n+l] \cdot g[k,l] + f[m+k,n+l]^2)$$

$$h[m,n] = \sum_{k,l} g[k,l]^2 - 2\sum_{k,l} f[m+k,n+l] \cdot g[k,l] + \sum_{k,l} f[m+k,n+l]^2$$

$$h = \sum_{k,l} \underset{\uparrow}{g[k,l]^2} - 2\,\underset{\uparrow}{\mathrm{filter}(f,g)} + \mathrm{filter}(\underset{\uparrow}{f.\hat{}2}, \mathrm{ones}(g.\mathrm{shape}))$$

constant

linear filter

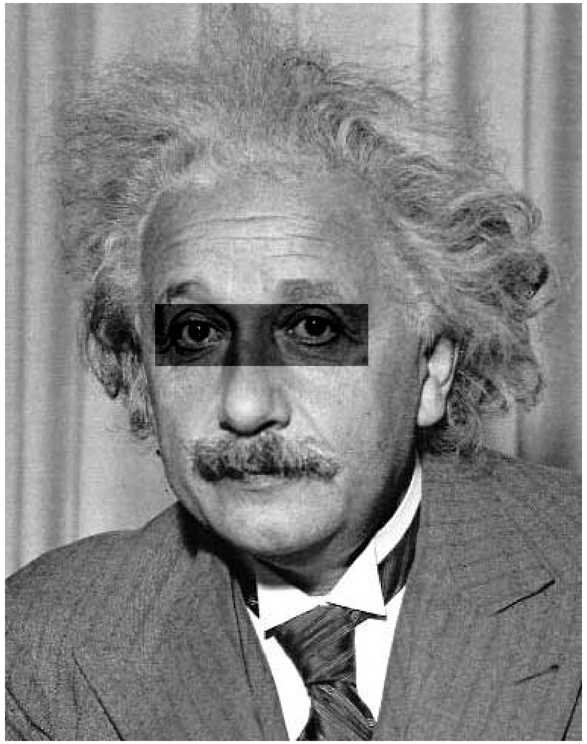
Element-wise square f, then
sum with ones kernel of size g

Matching with filters

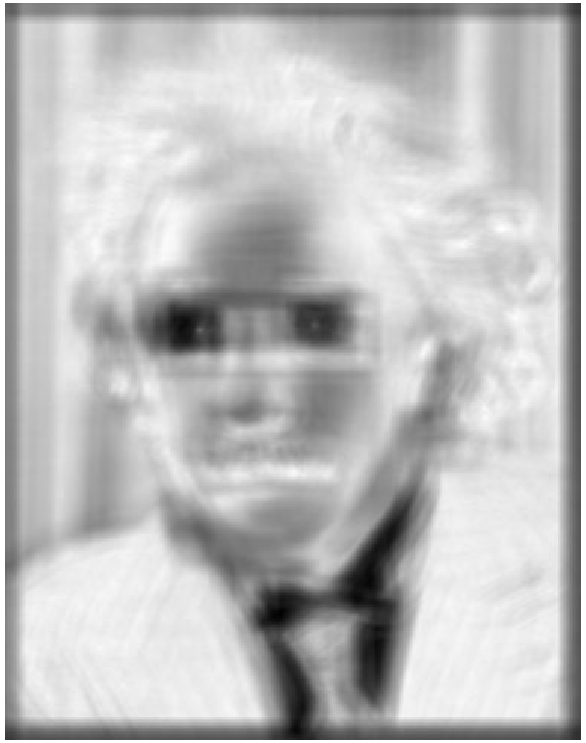
- Goal: find in image
- Method 2: SSD

$$h[m,n]=\sum_{k,l}(g[k,l]-f[m+k,n+l])^2$$

What's the potential downside of SSD?



Input



1- sqrt(SSD)

Matching with filters

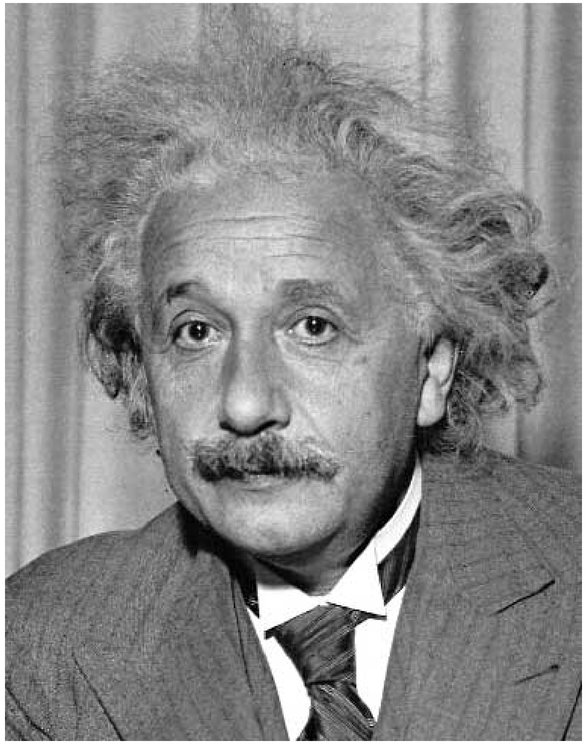
- Goal: find in image
- Method 3: Normalized cross-correlation

$$h[m,n]=\frac{\sum_{k,l}(g[k,l]-\overset{\substack{\text{mean template}\\\downarrow}}{\bar{g}})(f[m+k,n+l]-\overset{\substack{\text{mean image patch}\\\downarrow}}{\bar{f}_{m,n}})}{\left(\sum_{k,l}(g[k,l]-\bar{g})^2\sum_{k,l}(f[m+k,n+l]-\bar{f}_{m,n})^2\right)^{0.5}}$$

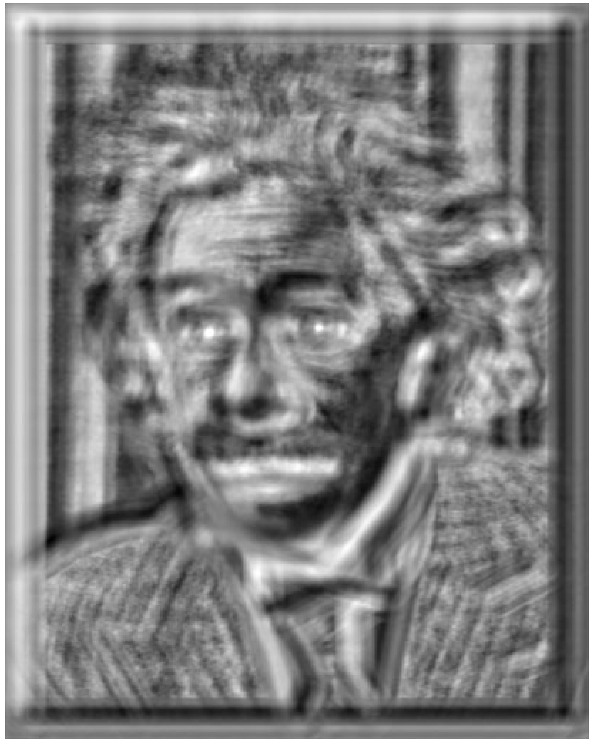
Python: `cv2.matchTemplate(im,template,cv2.TM_CCOEFF_NORMED)`

Matching with filters

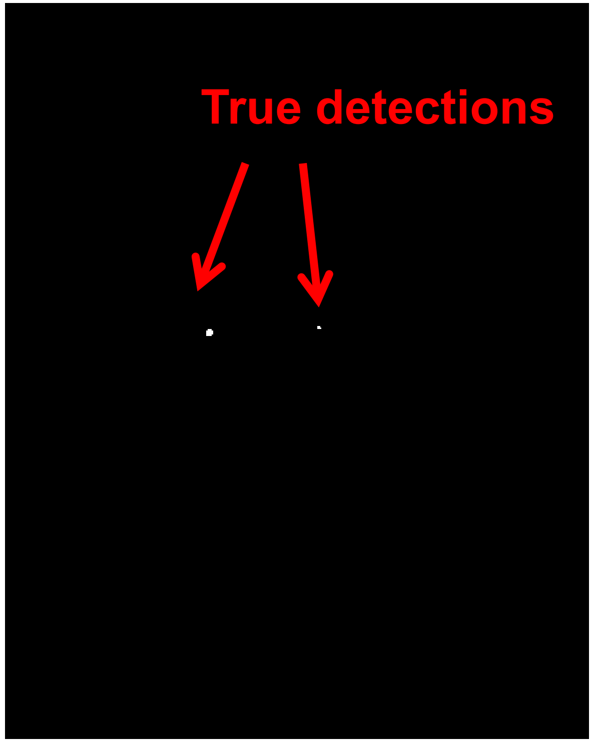
- Goal: find in image
- Method 3: Normalized cross-correlation



Input



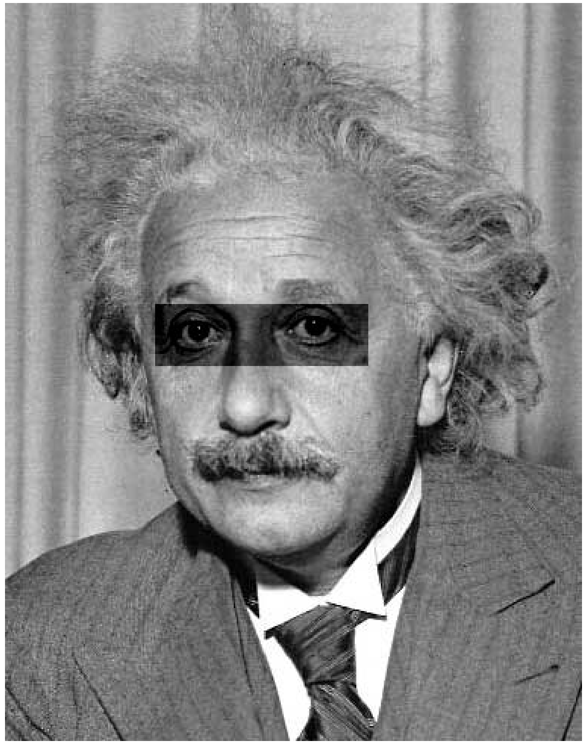
Normalized X-Correlation



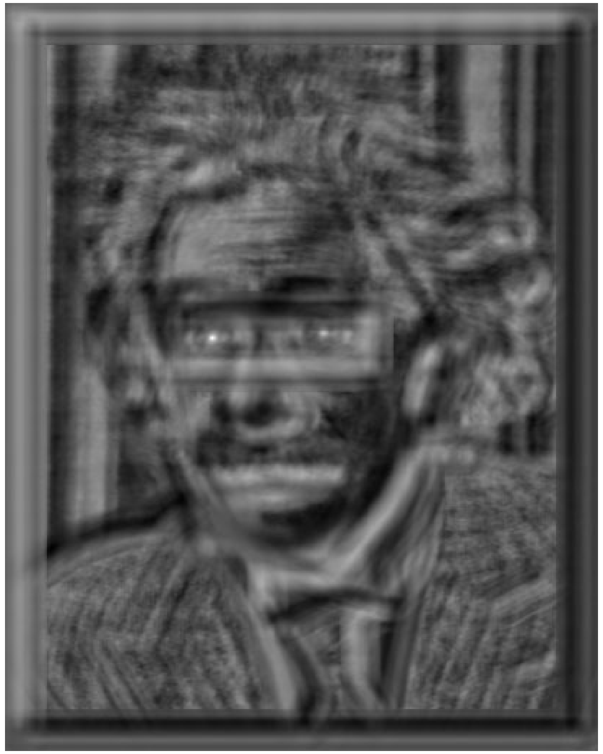
Thresholded Image

Matching with filters

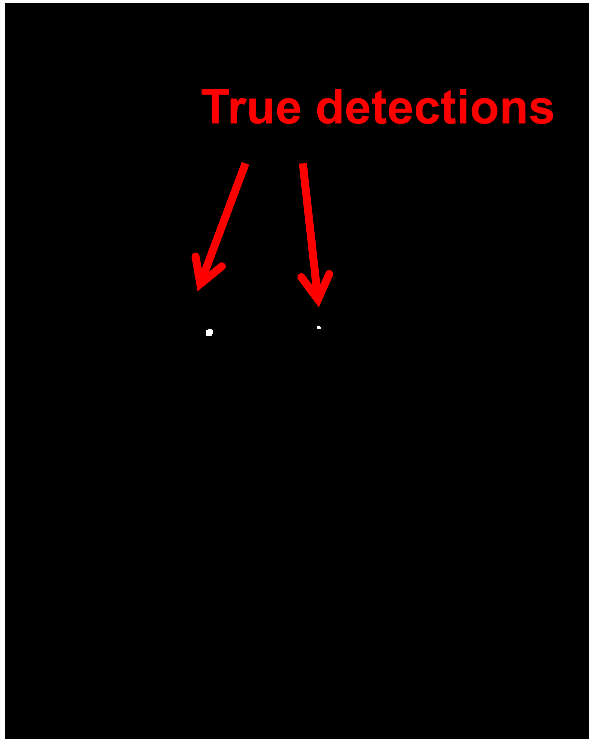
- Goal: find in image
- Method 3: Normalized cross-correlation



Input



Normalized X-Correlation



Thresholded Image

Q: What is the best method to use?

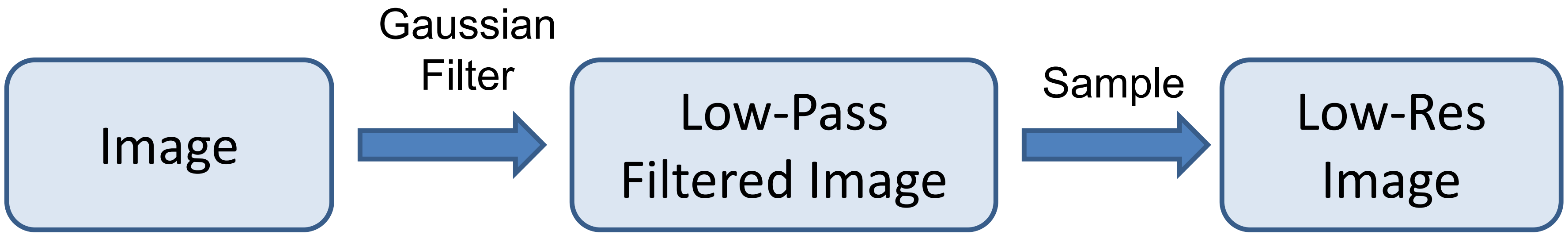
A: Depends

- Zero-mean filter: fastest but not a great matcher
- SSD: next fastest, sensitive to overall intensity
- Normalized cross-correlation: slowest, invariant to local average intensity and contrast

Q: What if we want to find larger or smaller eyes?

A: Image Pyramid

Review of Sampling



Image

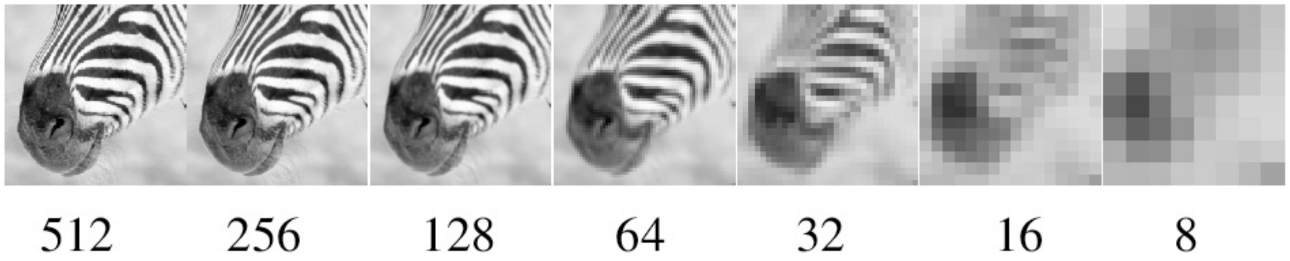
Gaussian Filter

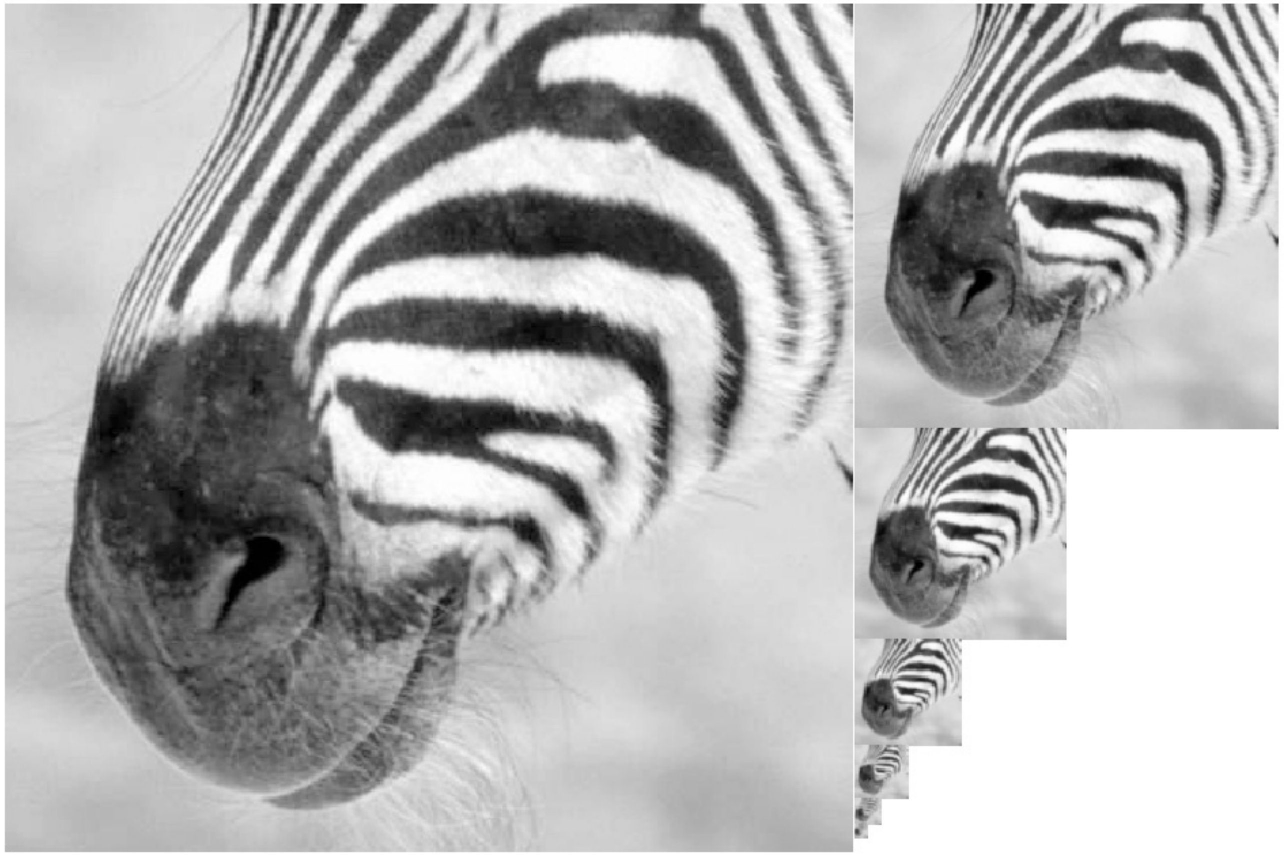
Low-Pass Filtered Image

Sample

Low-Res Image

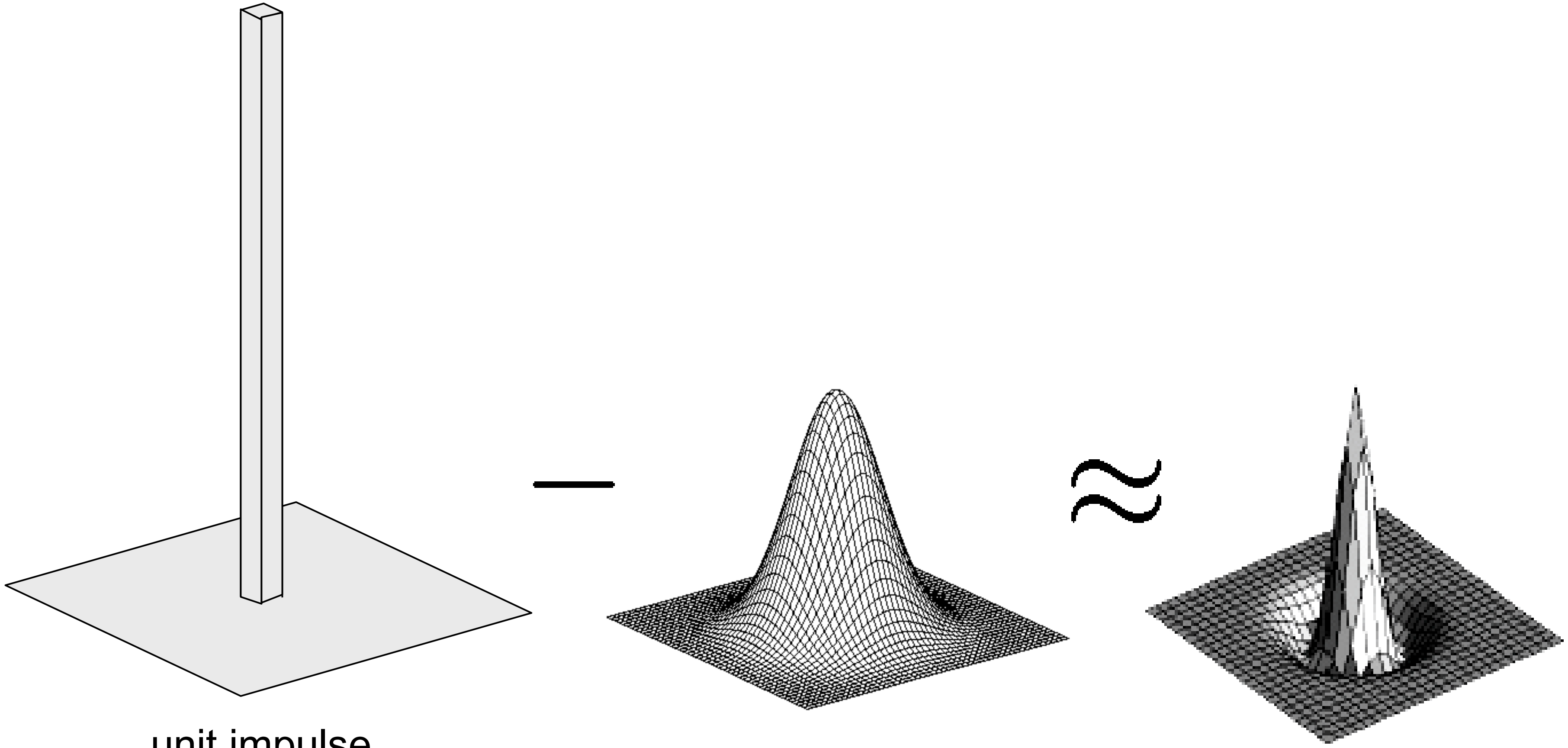
Gaussian pyramid





Source: Forsyth

Laplacian filter



unit impulse

−

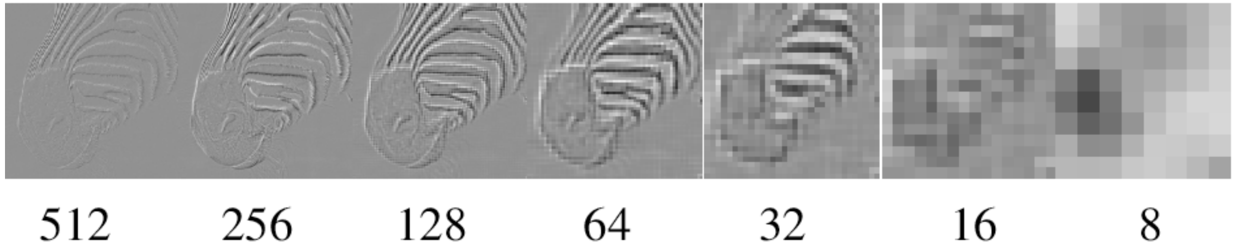
Gaussian

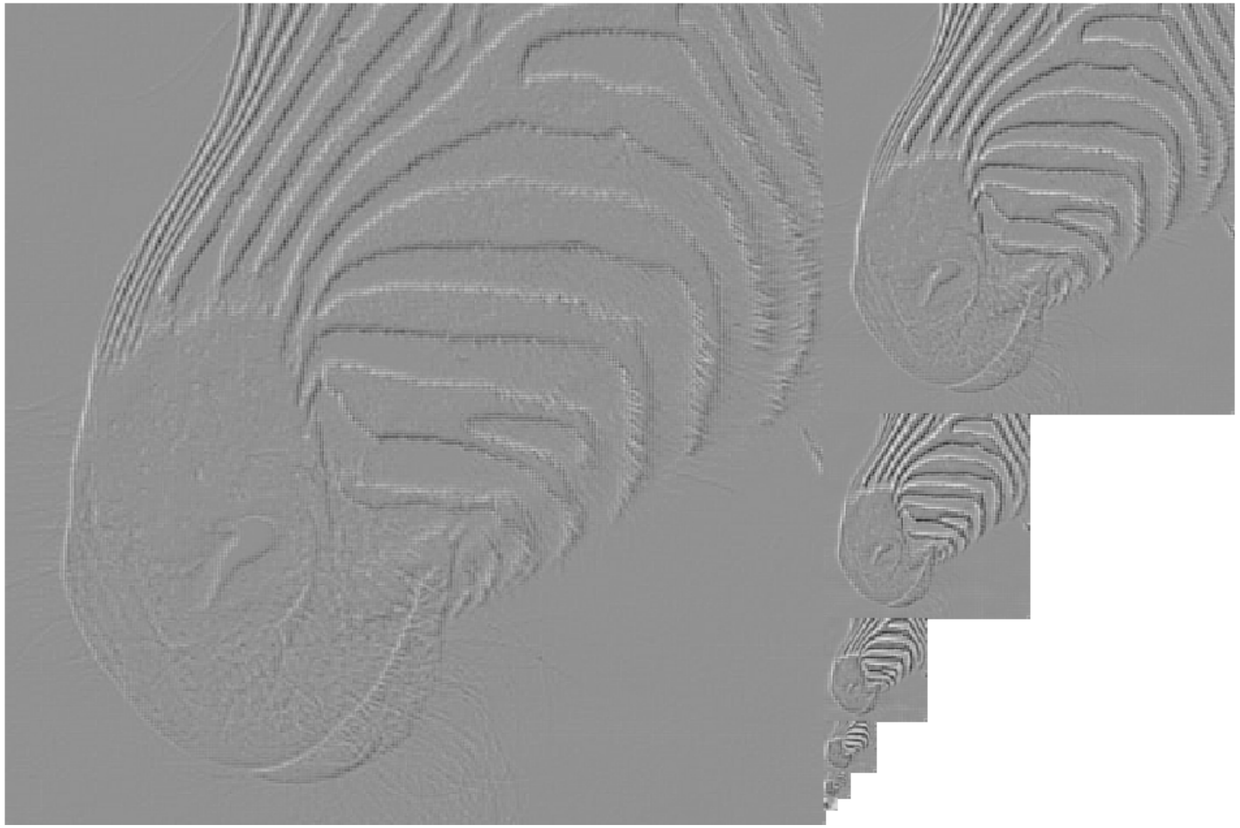
≈

Laplacian of Gaussian

Source: Lazebnik

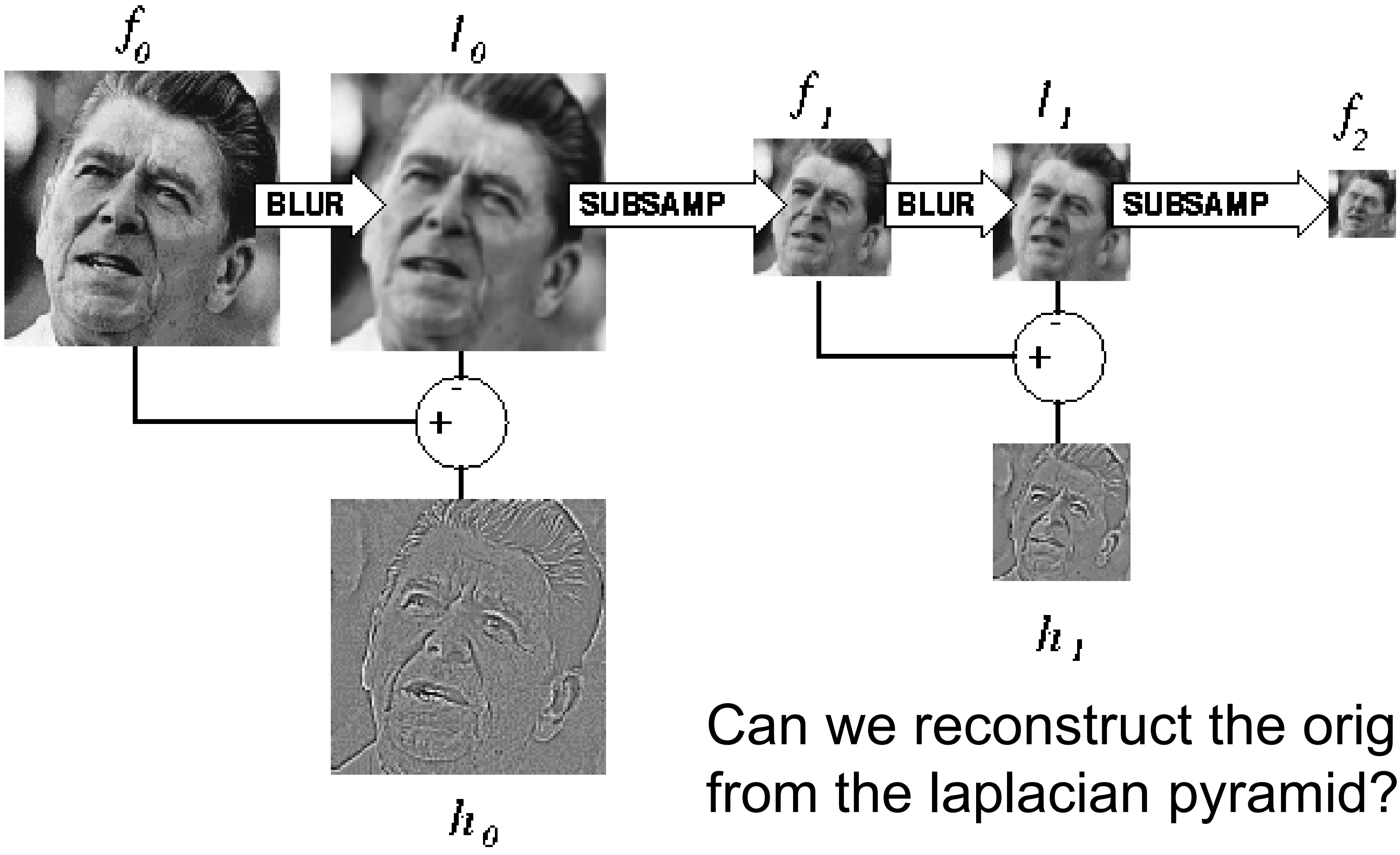
Laplacian pyramid





Source: Forsyth

Computing Gaussian/Laplacian Pyramid



Can we reconstruct the original from the laplacian pyramid?

Creating a 2-level Laplacian pyramid

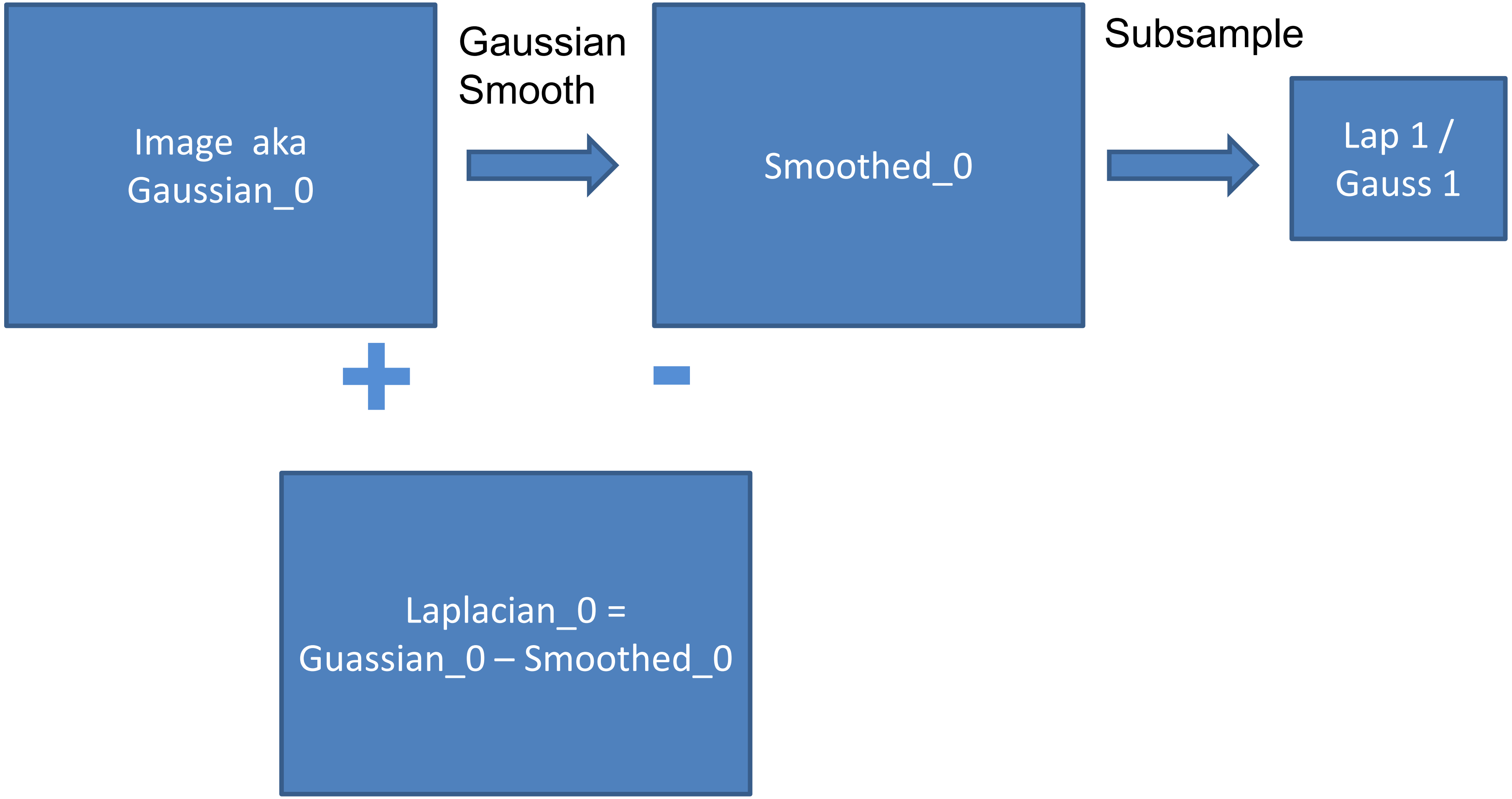


Image aka Gaussian_0

Gaussian Smooth

Smoothed_0

Subsample

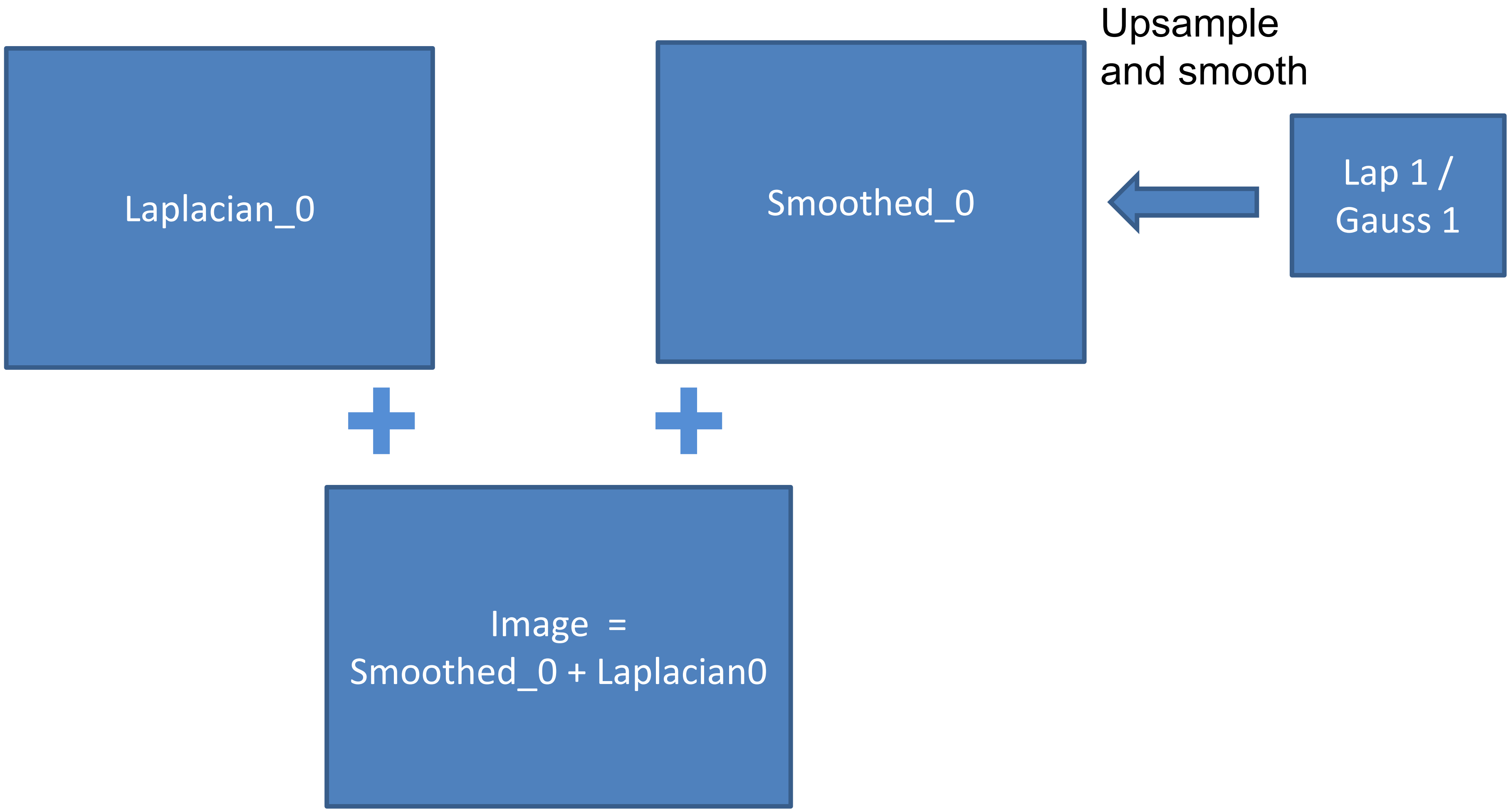
Lap 1 / Gauss 1

+

-

Laplacian_0 = Guassian_0 – Smoothed_0

Reconstructing the image from Laplacian pyramid



Upsample and smooth

Laplacian_0

Smoothed_0

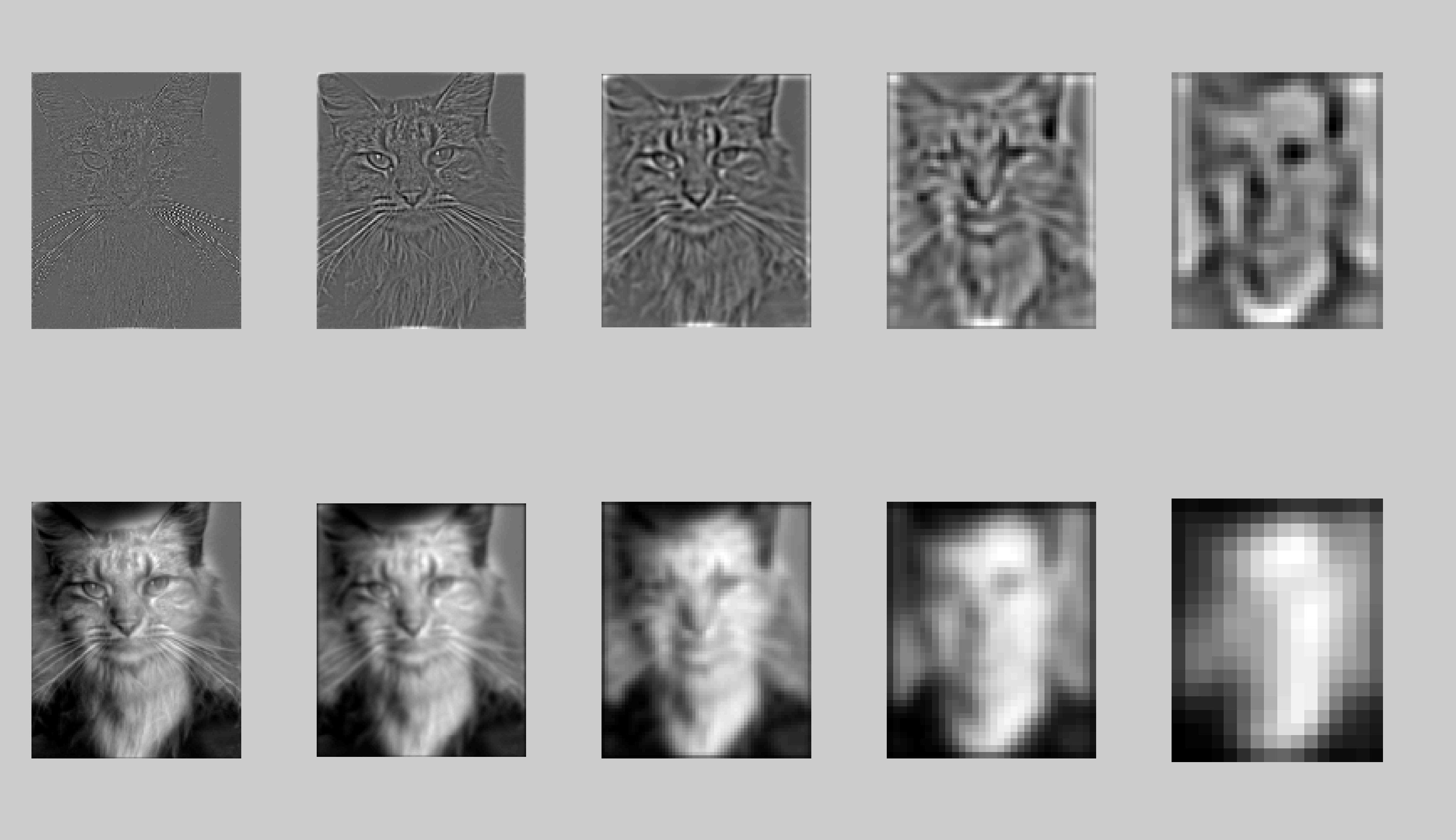
Lap 1 / Gauss 1

Image = Smoothed_0 + Laplacian0

Hybrid Image in Laplacian Pyramid

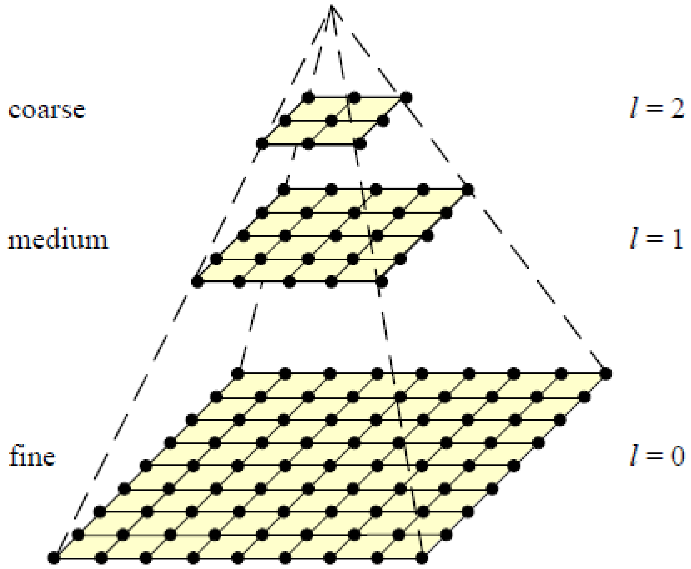
Extra points for project 1

High frequency → Low frequency

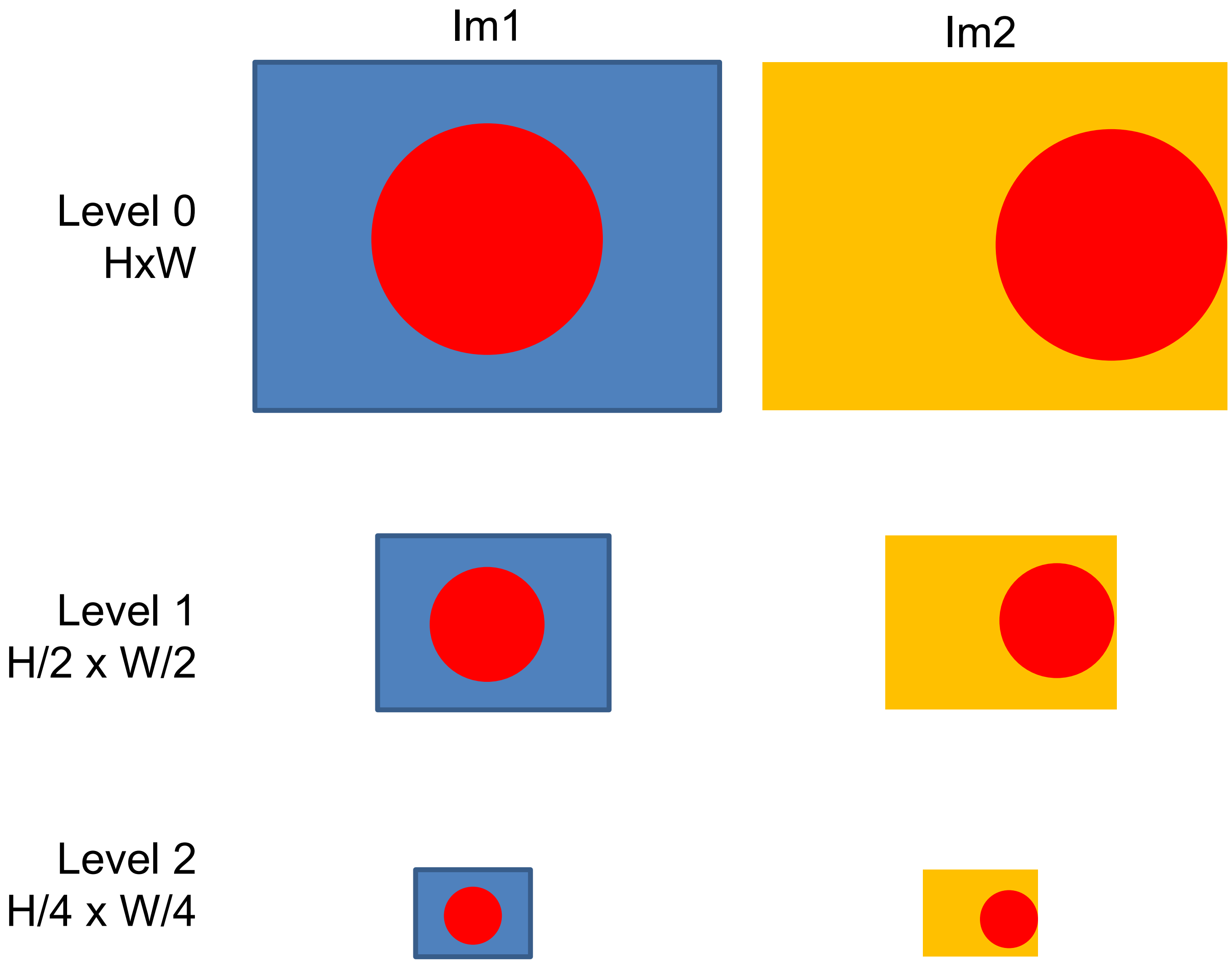


Coarse-to-fine Image Registration

1. Compute Gaussian pyramid
2. Align with coarse pyramid
   - Find minimum SSD position
3. Successively align with finer pyramids
   - Search small range (e.g., 5x5) centered around position determined at coarser scale



Coarse-to-fine Image Registration



Im1

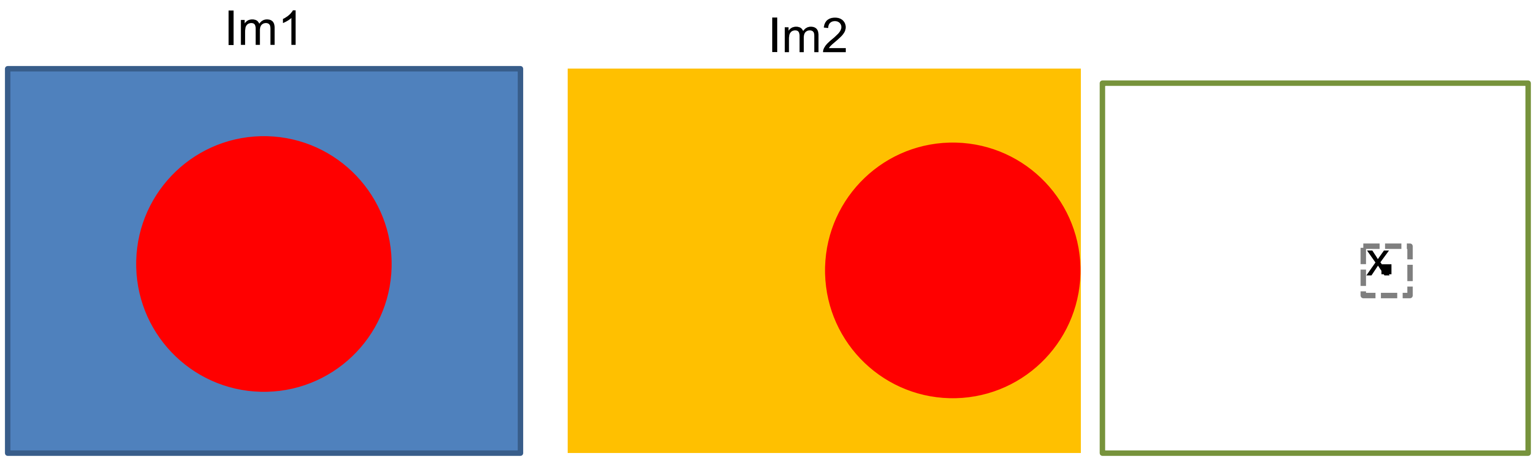
Im2

Level 0
HxW

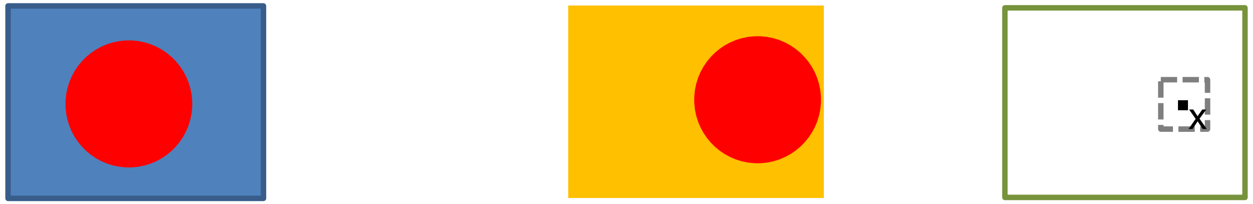
Level 1
H/2 x W/2

Level 2
H/4 x W/4

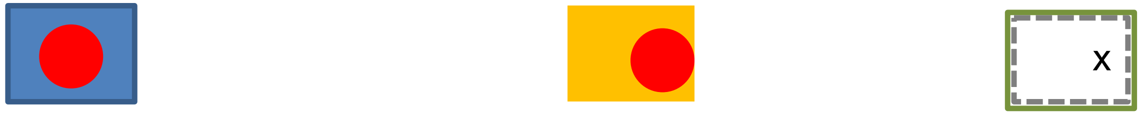
Coarse-to-fine Image Registration



$$tx_0, ty_0 = \underset{tx\in 2\cdot tx_1+\{-s..s\}, ty=2\cdot ty_1+\{-s..s\}}{\operatorname{argmin}} \mathrm{SSD}(im1_1, \mathrm{translate}(im2_1, tx, ty))$$



$$tx_1, ty_1 = \underset{tx\in 2\cdot tx_2+\{-s..s\}, ty=2\cdot ty_2+\{-s..s\}}{\operatorname{argmin}} \mathrm{SSD}(im1_1, \mathrm{translate}(im2_1, tx, ty))$$



$$tx_2, ty_2 = \underset{tx\in\left\{-\frac{W}{8}..\frac{W}{8}\right\}, ty\in\{-\frac{H}{8}..\frac{H}{8}\}}{\operatorname{argmin}} \mathrm{SSD}(im1_2, \mathrm{translate}(im2_2, tx, ty))$$

Coarse-to-fine Image Registration

1. Compute Gaussian pyramid
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   - Find minimum SSD position
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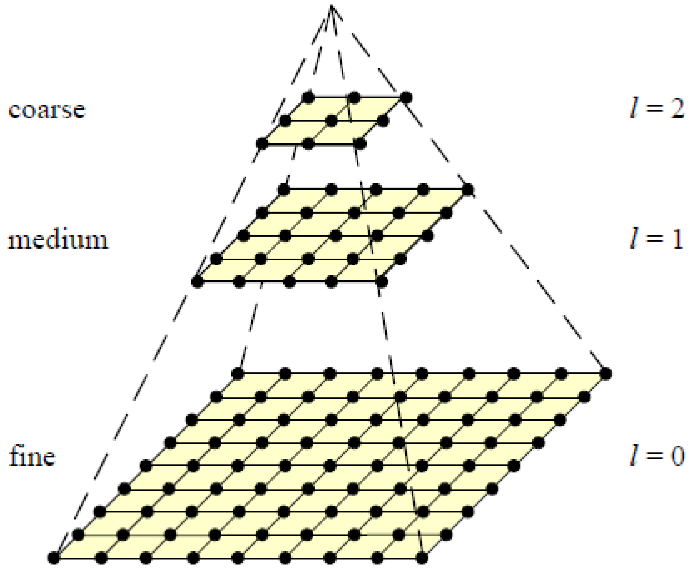


Why is this faster?

Are we guaranteed to get the same result?

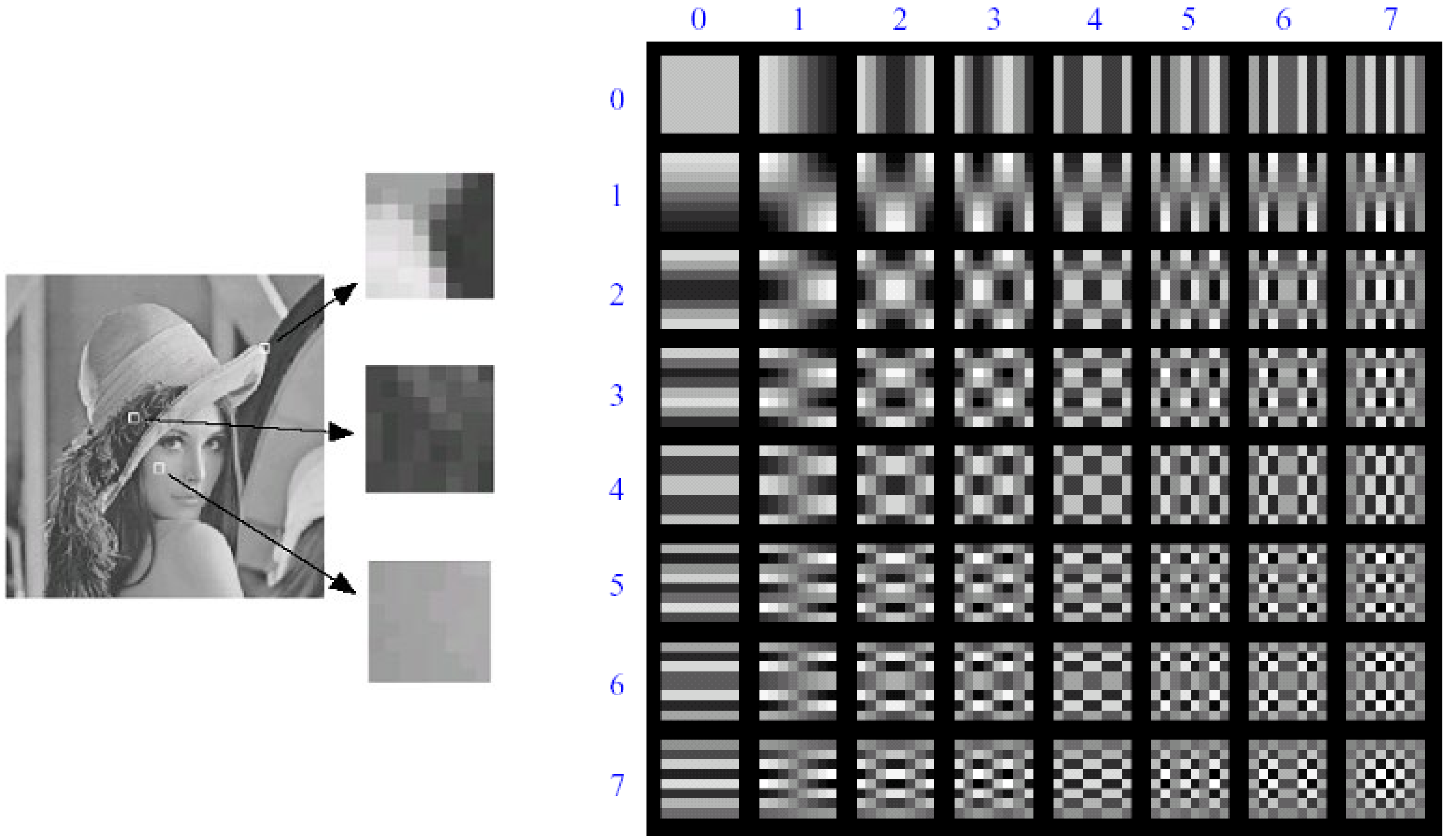
Question

Can you align the images using the FFT?

Compression

How is it that a 4MP image can be compressed to a few hundred KB without a noticeable change?

Lossy Image Compression (JPEG)

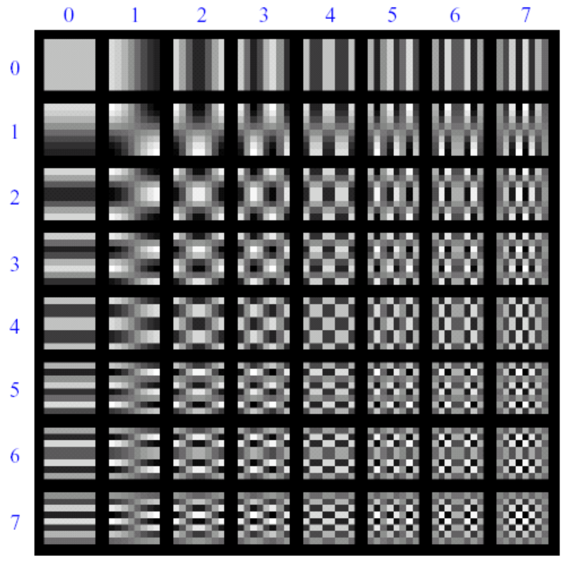


Block-based Discrete Cosine Transform (DCT)

Slides: Efros

Using DCT in JPEG

- The first coefficient $\mathrm{B}(0,0)$ is the DC component, the average intensity
- The top-left coeffs represent low frequencies, the bottom right – high frequencies



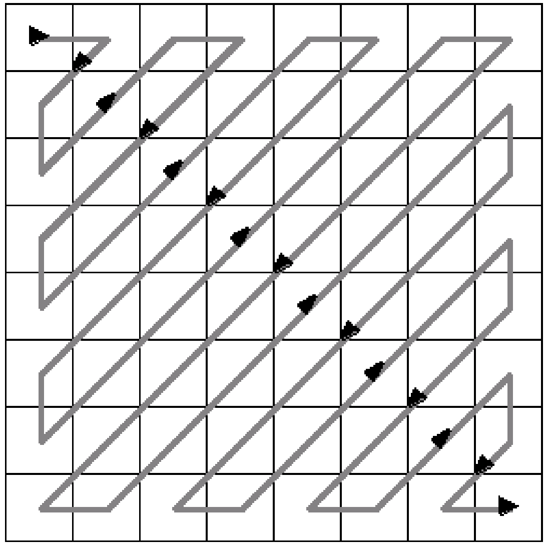


Image compression using DCT

- Quantize
  - More coarsely for high frequencies (which also tend to have smaller values)
  - Many quantized high frequency values will be zero
- Encode
  - Can decode with inverse dct

Filter responses

$$G = \begin{array}{cc}
\begin{array}{cccccccc} & & & \overset{u}{\longrightarrow} & & & & \end{array} & \\
\begin{bmatrix}
-415.38 & -30.19 & -61.20 & 27.24 & 56.13 & -20.10 & -2.39 & 0.46 \\
4.47 & -21.86 & -60.76 & 10.25 & 13.15 & -7.09 & -8.54 & 4.88 \\
-46.83 & 7.37 & 77.13 & -24.56 & -28.91 & 9.93 & 5.42 & -5.65 \\
-48.53 & 12.07 & 34.10 & -14.76 & -10.24 & 6.30 & 1.83 & 1.95 \\
12.12 & -6.55 & -13.20 & -3.95 & -1.88 & 1.75 & -2.79 & 3.14 \\
-7.73 & 2.91 & 2.38 & -5.94 & -2.38 & 0.94 & 4.30 & 1.85 \\
-1.03 & 0.18 & 0.42 & -2.42 & -0.88 & -3.02 & 4.12 & -0.66 \\
-0.17 & 0.14 & -1.07 & -4.19 & -1.17 & -0.10 & 0.50 & 1.68
\end{bmatrix} & \Big\downarrow v
\end{array}$$

Quantized values

$$B = \begin{bmatrix}
-26 & -3 & -6 & 2 & 2 & -1 & 0 & 0 \\
0 & -2 & -4 & 1 & 1 & 0 & 0 & 0 \\
-3 & 1 & 5 & -1 & -1 & 0 & 0 & 0 \\
-3 & 1 & 2 & -1 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}$$

Quantization table

$$Q = \begin{bmatrix}
16 & 11 & 10 & 16 & 24 & 40 & 51 & 61 \\
12 & 12 & 14 & 19 & 26 & 58 & 60 & 55 \\
14 & 13 & 16 & 24 & 40 & 57 & 69 & 56 \\
14 & 17 & 22 & 29 & 51 & 87 & 80 & 62 \\
18 & 22 & 37 & 56 & 68 & 109 & 103 & 77 \\
24 & 35 & 55 & 64 & 81 & 104 & 113 & 92 \\
49 & 64 & 78 & 87 & 103 & 121 & 120 & 101 \\
72 & 92 & 95 & 98 & 112 & 100 & 103 & 99
\end{bmatrix}$$

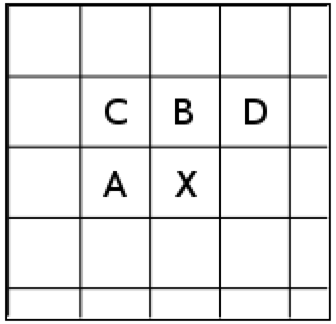
JPEG Compression Summary

1. Convert image to YCrCb
2. Subsample color by factor of 2
   - People have bad resolution for color
3. Split into blocks (8x8, typically), subtract 128
4. For each block
   a. Compute DCT coefficients
   b. Coarsely quantize
      - Many high frequency components will become zero
   c. Encode (e.g., with Huffman coding)

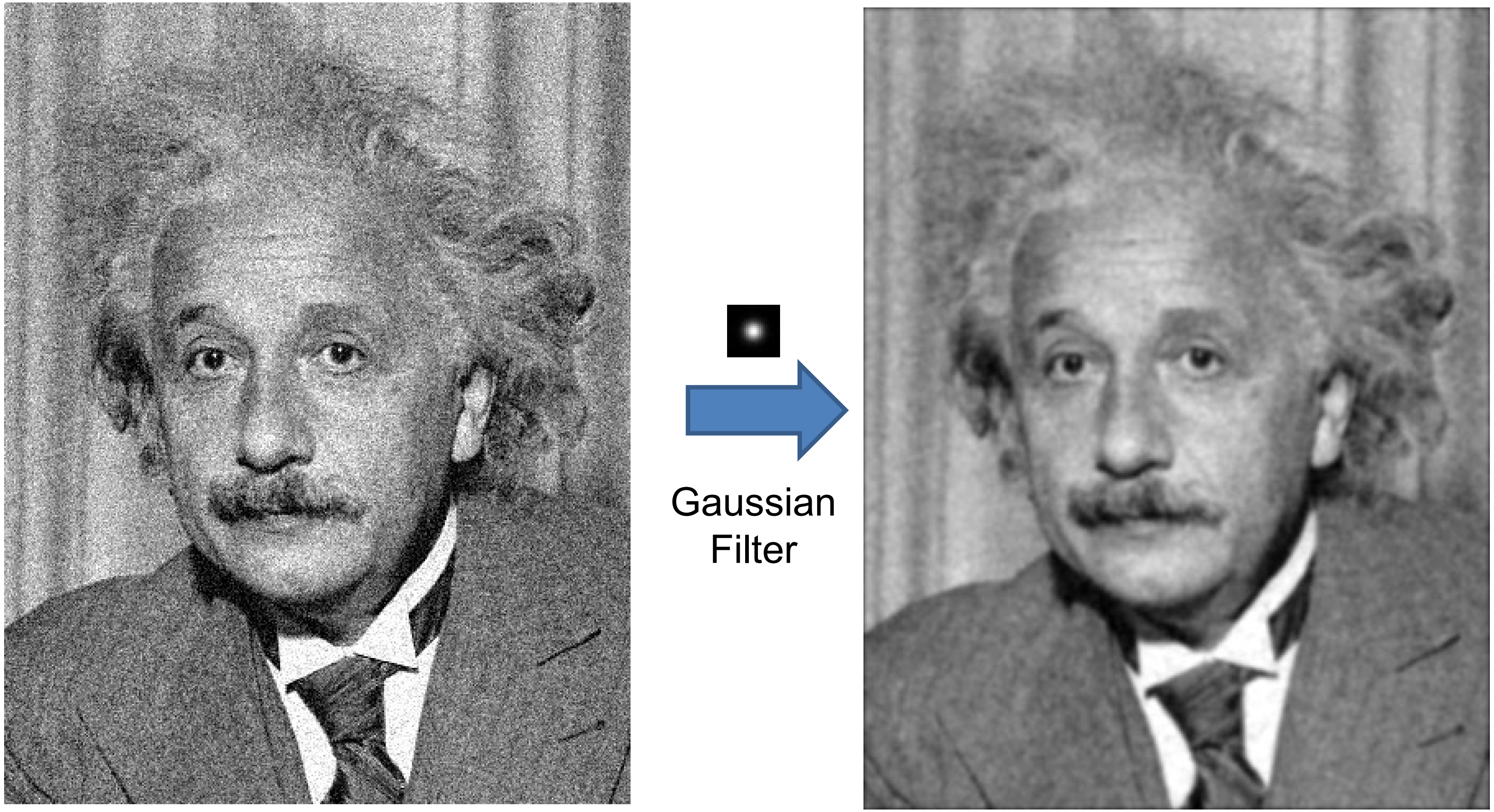
http://en.wikipedia.org/wiki/YCbCr
http://en.wikipedia.org/wiki/JPEG

Lossless compression (PNG)

1. Predict that a pixel's value based on its upper-left neighborhood
2. Store difference of predicted and actual value
3. Pkzip it (DEFLATE algorithm)



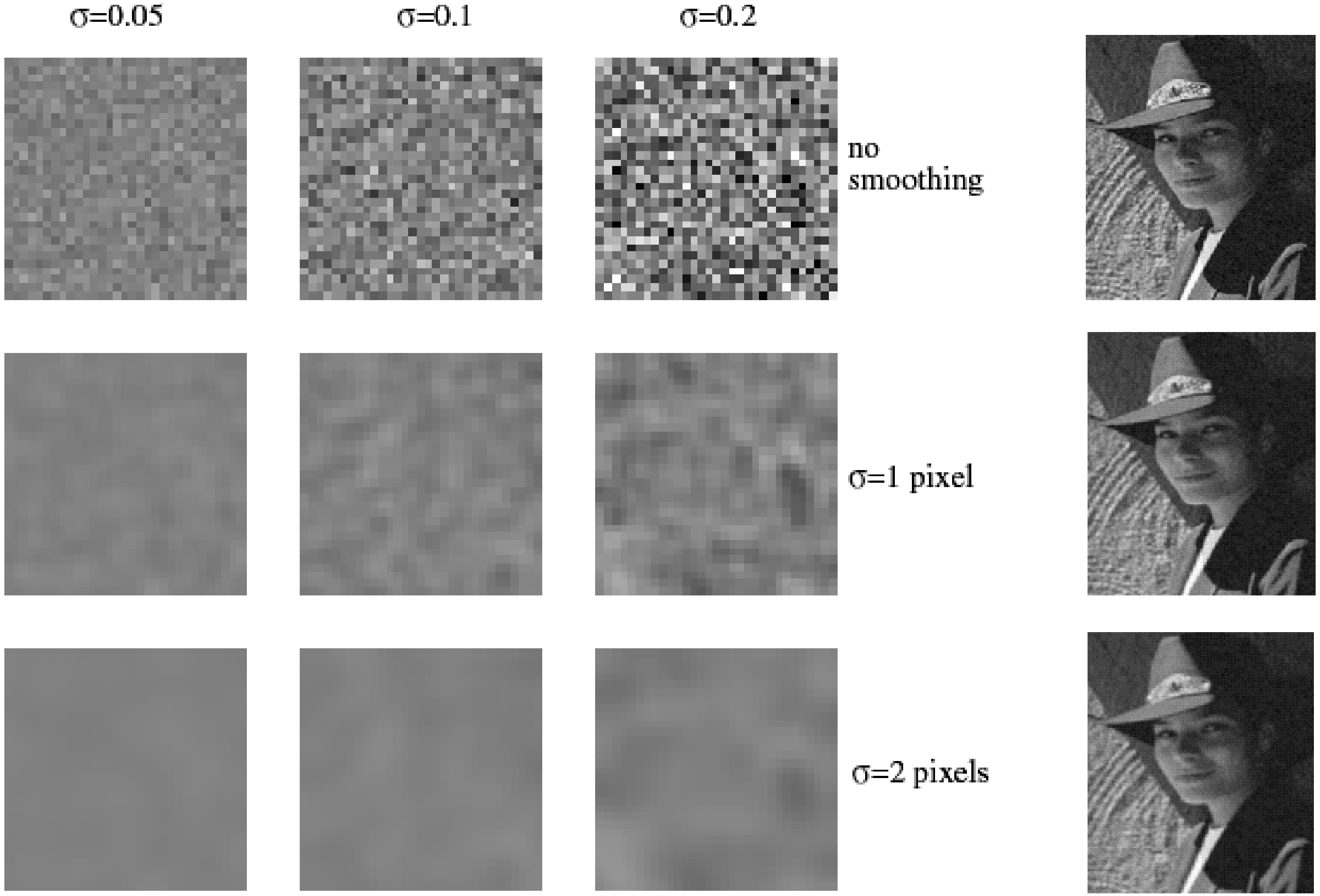
Denoising



Gaussian Filter

Additive Gaussian Noise

Reducing Gaussian noise

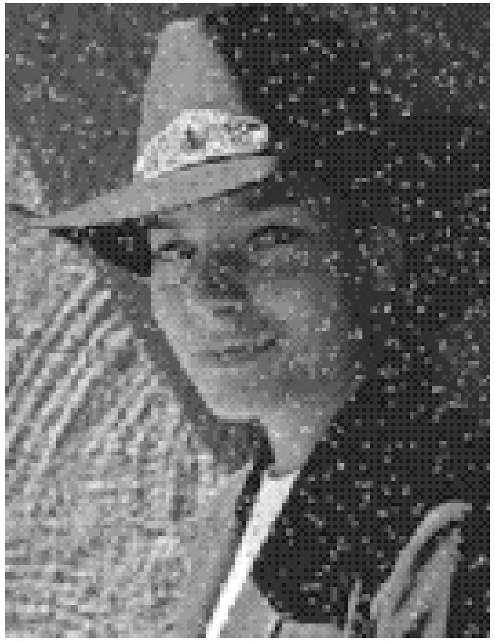


Smoothing with larger standard deviations suppresses noise, but also blurs the image

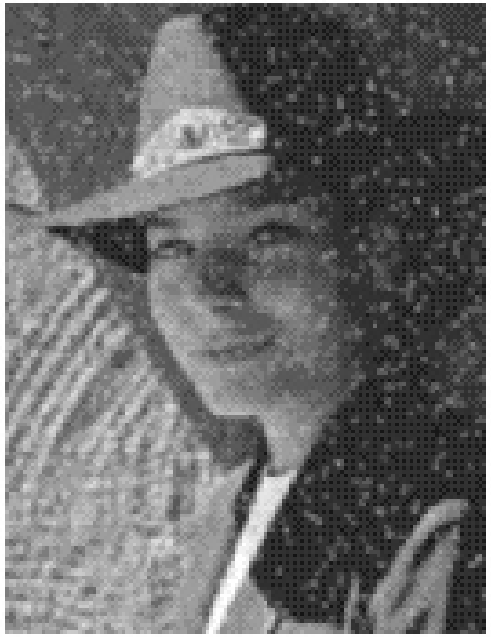
Source: S. Lazebnik

Reducing salt-and-pepper noise by Gaussian smoothing

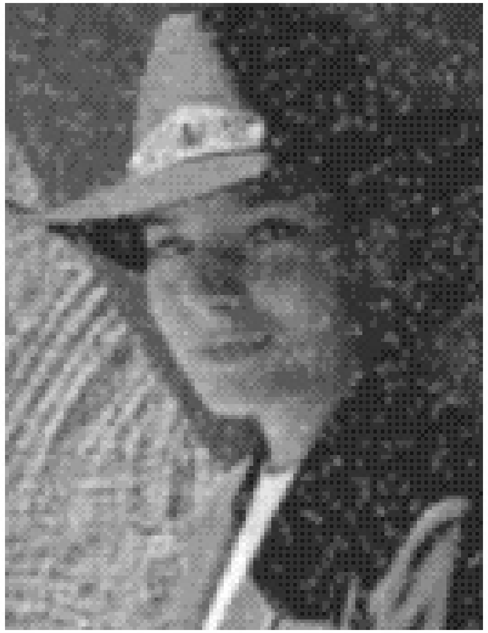
3x3



5x5

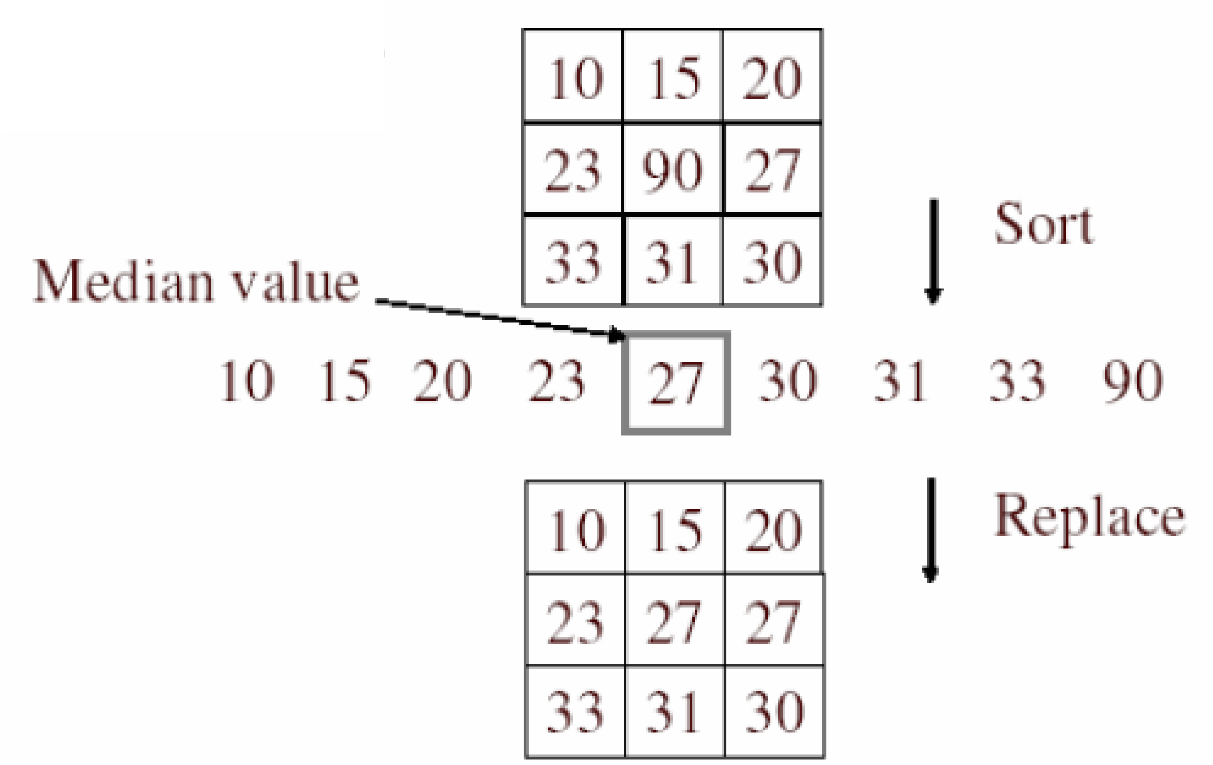


7x7



Alternative idea: Median filtering

- A **median filter** operates over a window by selecting the median intensity in the window



10	15	20
23	90	27
33	31	30

Sort

Median value

10 15 20 23 $\boxed{27}$ 30 31 33 90

Replace

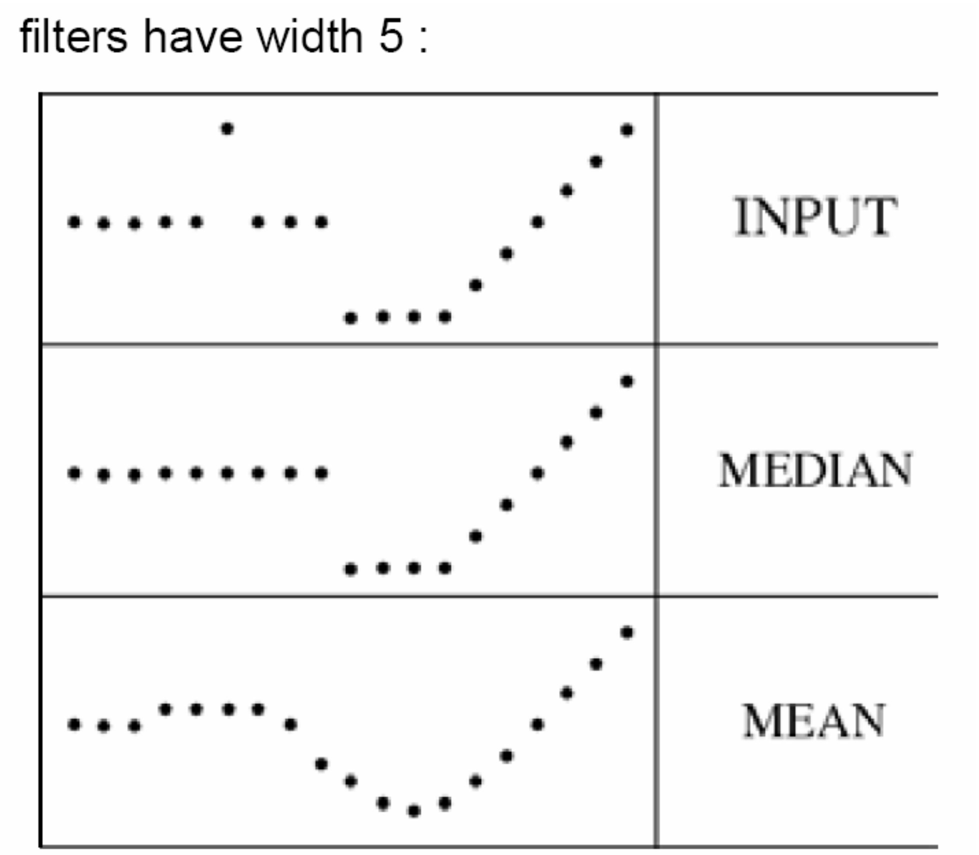
10	15	20
23	27	27
33	31	30

- Is median filtering linear?

Source: K. Grauman

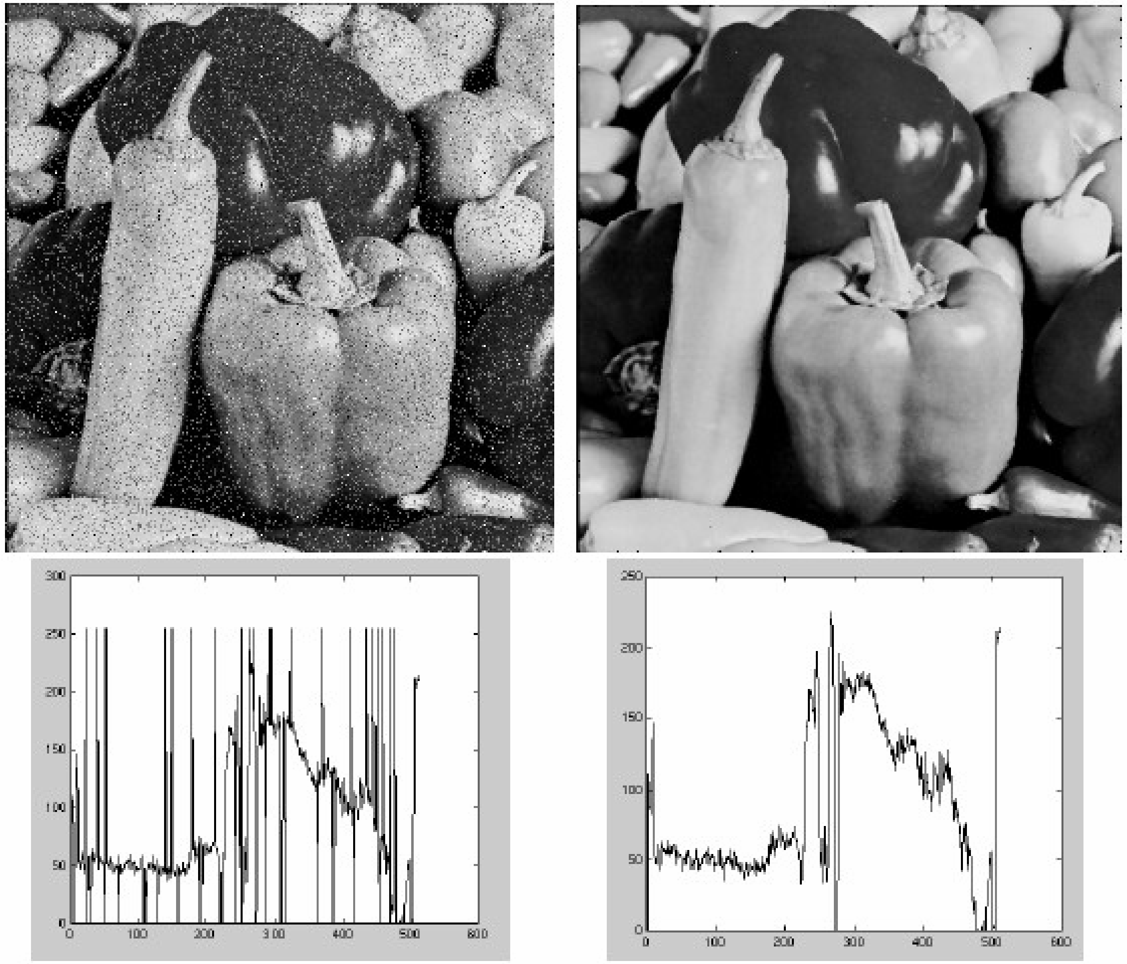
Median filter

- What advantage does median filtering have over Gaussian filtering?
  - Robustness to outliers



Source: K. Grauman

Median filter



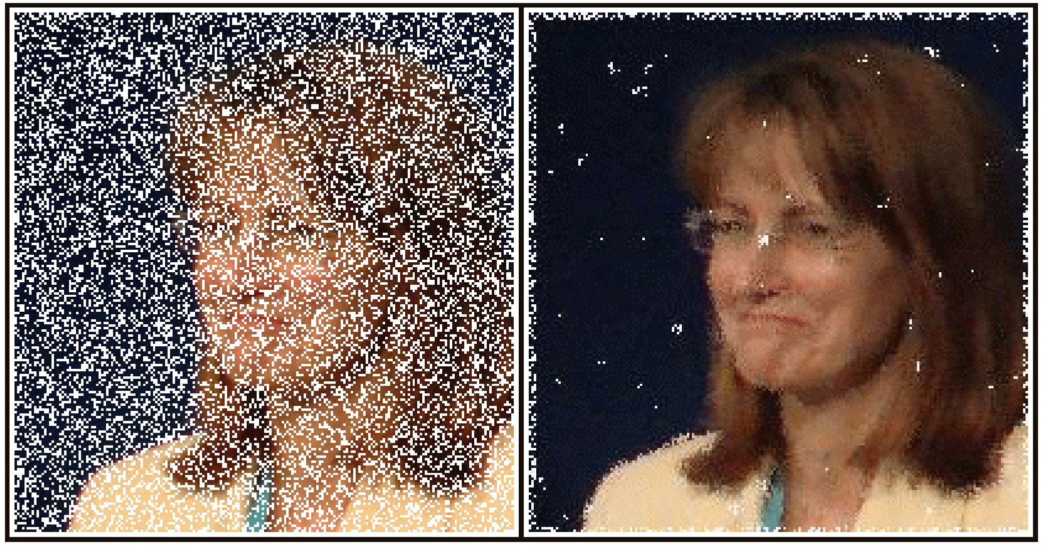
Salt-and-pepper noise

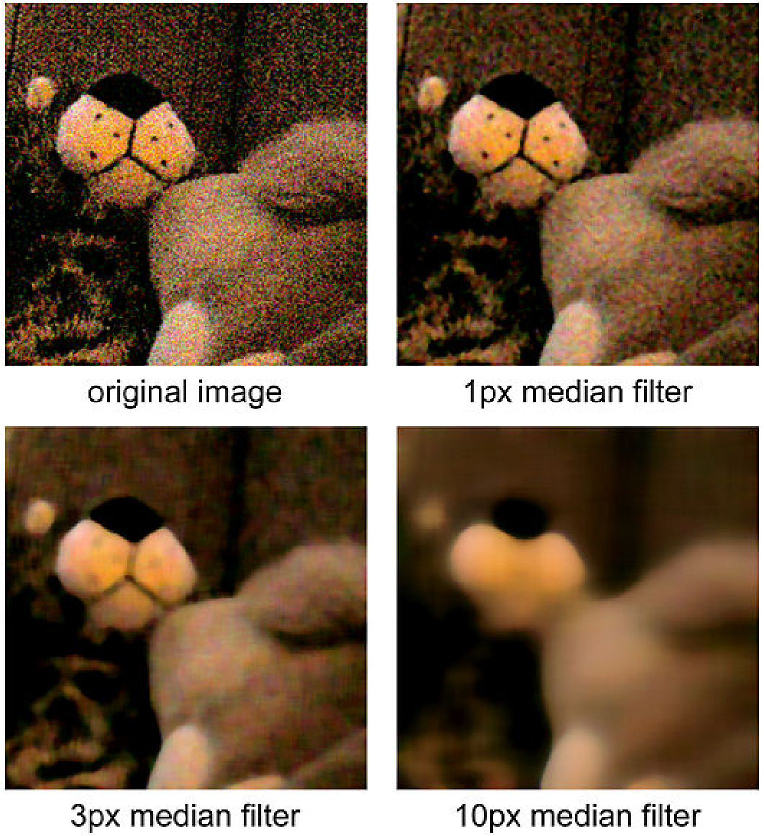
Median filtered

Python: scipy.ndimage.median_filter (image, size)

Source: M. Hebert

Median Filtered Examples





original image

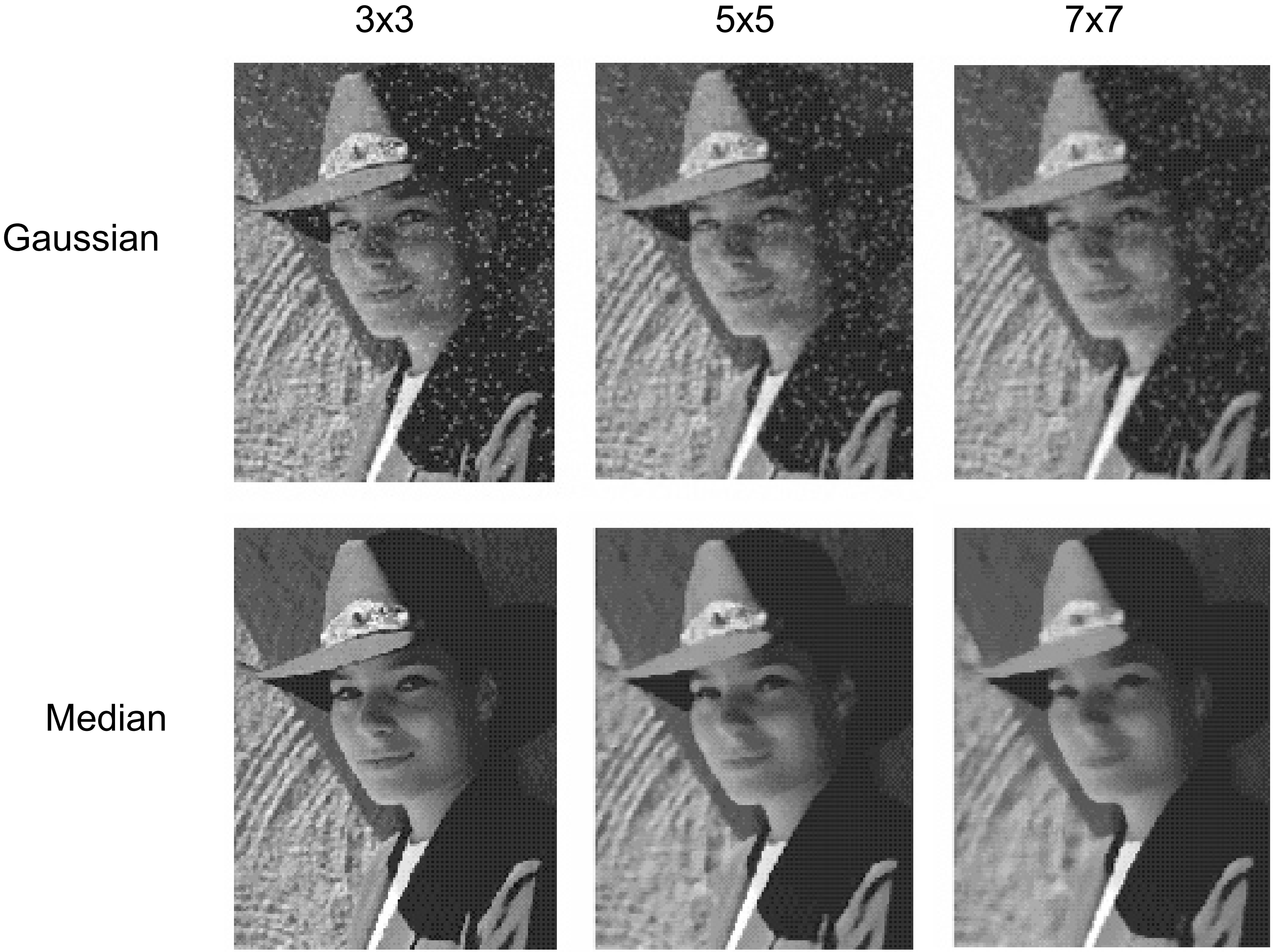
1px median filter

3px median filter

10px median filter

http://en.wikipedia.org/wiki/File:Medianfilterp.png
http://en.wikipedia.org/wiki/File:Median_filter_example.jpg

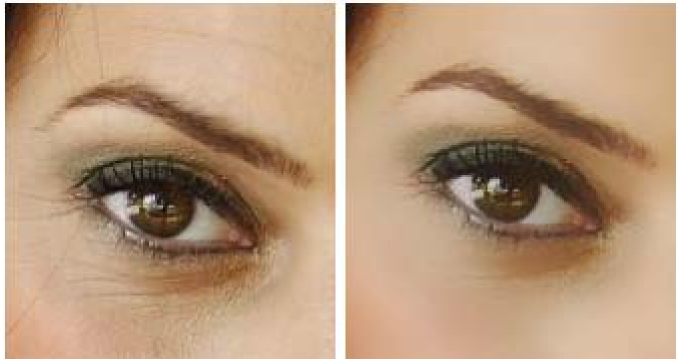
Median vs. Gaussian filtering



Other filter choices

- Weighted median (pixels further from center count less)
- Clipped mean (average, ignoring few brightest and darkest pixels)
- Bilateral filtering (weight by spatial distance *and* intensity difference)

```
cv2.bilateralFilter(size, sigma_color, signal_spatial)
```



Bilateral filtering

Image: http://vision.ai.uiuc.edu/?p=1455

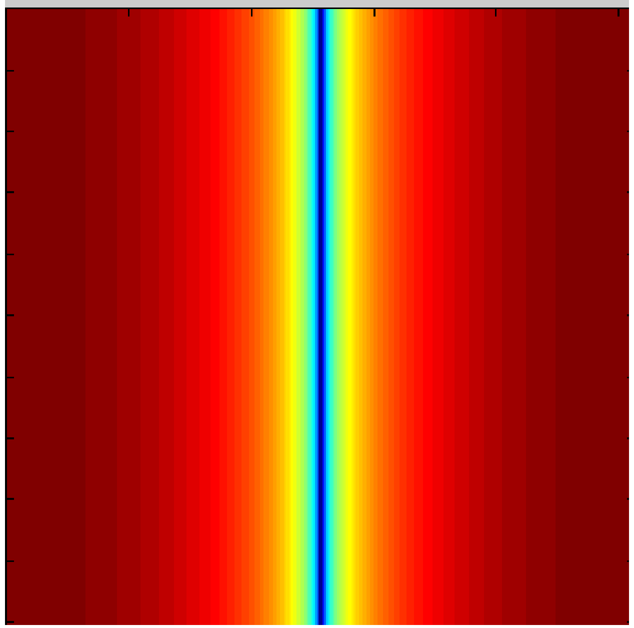
Review of Last 3 Days

- Filtering in spatial domain
  - Slide filter over image and take dot product at each position
  - Remember linearity (for linear filters)

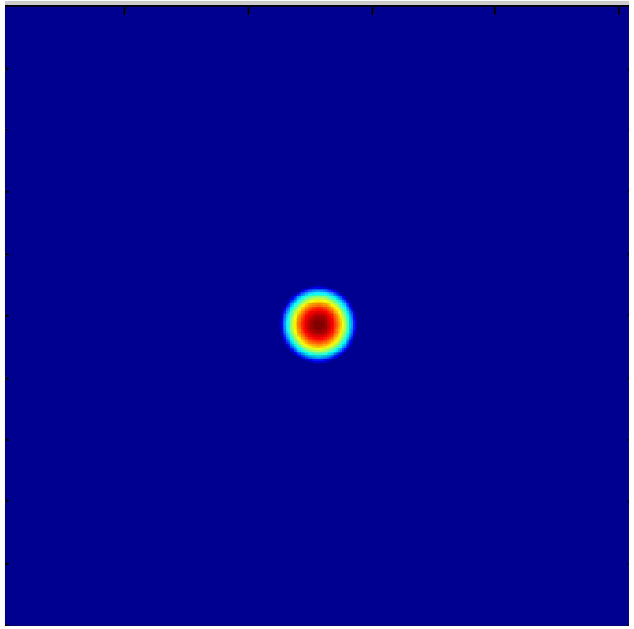
Review of Last 3 Days

- Linear filters for basic processing
  - Edge filter (high-pass)
  - Gaussian filter (low-pass)

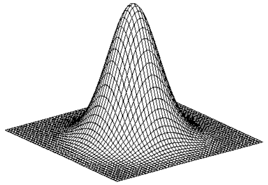
[-1 1]



FFT of Gradient Filter



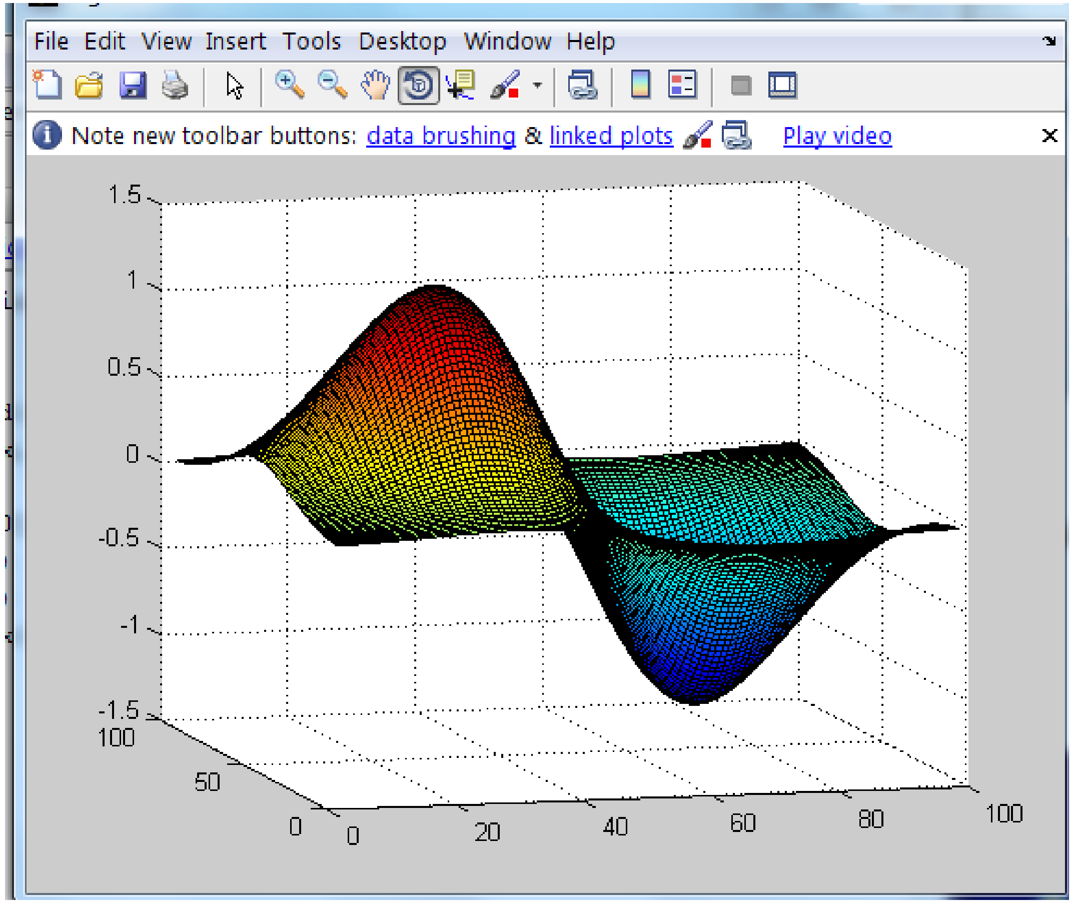
FFT of Gaussian



Gaussian

Review of Last 3 Days

- Derivative of Gaussian



File Edit View Insert Tools Desktop Window Help
Note new toolbar buttons: data brushing & linked plots
Play video
1.5
1
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-0.5
-1
-1.5
100
50
0
0
20
40
60
80
100

Review of Last 3 Days

- Filtering in frequency domain
  - Can be faster than filtering in spatial domain (for large filters)
  - Can help understand effect of filter
  - Algorithm:
    1. Convert image and filter to FFT
    2. Pointwise-multiply FFTs
    3. Convert result to spatial domain with inverse FFT

Review of Last 3 Days

- Applications of filters
  - Template matching (SSD or normalized x-corr)
    - SSD can be done with linear filters, is sensitive to overall intensity
  - Gaussian pyramid
    - Coarse-to-fine search, multi-scale detection
  - Laplacian pyramid
    - Can be used for blending (later)
    - More compact image representation

Review of Last 3 Days

- Applications of filters
  - Downsampling
    - Need to sufficiently low-pass before downsampling
  - Compression
    - In JPEG, coarsely quantize high frequencies
  - Reducing noise (important for aesthetics and for later processing such as edge detection)
    - Gaussian filter, median filter, bilateral filter

Next lecture

- Light and color