Plan for this lecture

• Filters: math and properties
• Types of filters
  – Linear
    • Smoothing
    • Other
  – Non-linear
    • Median
• Texture representation with filters
• Anti-aliasing for image subsampling
How are images represented?

- Color images represented as a matrix with multiple channels (=1 if grayscale)
- Suppose we have a NxM RGB image called “im”
  - \(im[1,1,1]\) = top-left pixel value in R-channel
  - \(im[y, x, b]\) = \(y\) pixels down, \(x\) pixels to right in the \(b\)th channel
  - \(im[N, M, 3]\) = bottom-right pixel in B-channel
- `imread(filename)` returns a uint8 image (values 0 to 255)

Adapted from Derek Hoiem
The same object will look very different across images
Multiple images of the same static scene won’t be identical
How could we reduce the noise, i.e., give an estimate of the true intensities?
What if there’s only one image?
Common types of noise

- **Salt and pepper noise**: random occurrences of black and white pixels

- **Impulse noise**: random occurrences of white pixels

- **Gaussian noise**: variations in intensity drawn from a Gaussian normal distribution

Source: S. Seitz
Gaussian noise

$$f(x, y) = \hat{f}(x, y) + \eta(x, y)$$

Gaussian i.i.d. ("white") noise:
$$\eta(x, y) \sim \mathcal{N}(\mu, \sigma)$$

```matlab
>> noise = randn(size(im)).* sigma;
>> output = im + noise;
```

What is impact of the sigma?
First attempt at a solution

- Let’s replace each pixel with an average of all the values in its neighborhood
- Assumptions:
  - Expect pixels to be like their neighbors
  - Expect noise processes to be independent from pixel to pixel
First attempt at a solution

• Let’s replace each pixel with an average of all the values in its neighborhood

• Moving average in 1D:

Source: S. Marschner
Weighted Moving Average

- Can add weights to our moving average
- *Weights* $[1, 1, 1, 1, 1] / 5$

Source: S. Marschner
Weighted Moving Average

• Non-uniform weights $[1, 4, 6, 4, 1] / 16$

Central pixel =
$(10 \times 1 + 14 \times 4 + 12 \times 6 + 13 \times 4 + 20 \times 1) / 16$

Adapted from S. Marschner
Moving Average In 2D

\[ F[x, y] \quad G[x, y] \]

Source: S. Seitz
Moving Average In 2D

\[ F[x, y] \quad \text{and} \quad G[x, y] \]
Moving Average In 2D

\[ F[x, y] \]

\[ G[x, y] \]
Moving Average In 2D

\[ F[x, y] \]

\[ G[x, y] \]
Moving Average In 2D

\[ F[x, y] \]

\[ G[x, y] \]

Source: S. Seitz
### Moving Average In 2D

**$F[x, y]$**

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**$G[x, y]$**

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Source: S. Seitz
Image filtering

• Compute a function of the local neighborhood at each pixel in the image
  – Function specified by a “filter” or mask saying how to combine values from neighbors.
  – Element-wise multiplication

• Uses of filtering:
  – Enhance an image (denoise, resize, etc)
  – Extract information (texture, edges, etc)
  – Detect patterns (template matching)
Correlation filtering

Say the averaging window size is $2k+1 \times 2k+1$:

\[
G[i, j] = \frac{1}{(2k + 1)^2} \sum_{u=-k}^{k} \sum_{v=-k}^{k} F[i + u, j + v]
\]

Attribute uniform weight to each pixel
Loop over all pixels in neighborhood around image pixel $F[i,j]$.

Now generalize to allow different weights depending on neighboring pixel’s relative position:

\[
G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i + u, j + v]
\]

Non-uniform weights

Kristen Grauman
Correlation filtering

\[ G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i + u, j + v] \]

This is called **cross-correlation**, denoted \( G = H \otimes F \)

Filtering an image: replace each pixel with a linear combination of its neighbors.

The filter a.k.a. kernel a.k.a. mask \( H[u, v] \) is the prescription for the weights in the linear combination.

Adapted from Kristen Grauman
Averaging filter

- What values belong in the kernel $H$ for the moving average example?

$$G = H \otimes F$$
Smoothing by averaging

What if the filter size was 5 x 5 instead of 3 x 3?
Gaussian filter

- What if we want nearest neighboring pixels to have the most influence on the output?

This kernel is an approximation of a 2d Gaussian function:

\[ h(u, v) = \frac{1}{2\pi\sigma^2} e^{-\frac{u^2+v^2}{\sigma^2}} \]

\[ F[x, y] \]

\[ H[u, v] \]

Source: S. Seitz
Smoothing with a Gaussian

Vs box filter
Gaussian filters

• What parameters matter here?

• **Size** of kernel or mask
  
  – Note, Gaussian function has infinite support, but discrete filters use finite kernels

\[
\begin{align*}
\sigma &= 5 \text{ with } 10 \times 10 \text{ kernel} \\
\sigma &= 5 \text{ with } 30 \times 30 \text{ kernel}
\end{align*}
\]
Gaussian filters

• What parameters matter here?
• **Variance** of Gaussian: determines extent of smoothing

\[
\sigma = 2 \text{ with } 30 \times 30 \text{ kernel}
\]

\[
\sigma = 5 \text{ with } 30 \times 30 \text{ kernel}
\]
Gaussian filters

How big should the filter be?

- Values at edges should be near zero ← important!
- Rule of thumb for Gaussian: set filter half-width to about $3 \sigma$

Source: Derek Hoiem
Smoothing with a Gaussian

Parameter $\sigma$ is the “scale” / “width” / “spread” of the Gaussian kernel, and controls the amount of smoothing.

```matlab
for sigma=1:3:10
    h = fspecial('gaussian', fsize, sigma);
    out = imfilter(im, h);
    imshow(out);
    pause;
end
```

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Convolution

- Convolution:
  - Flip the filter in both dimensions (bottom to top, right to left)
  - Then apply cross-correlation

\[
G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i - u, j - v]
\]

\[
G = H \ast F
\]

Notation for convolution operator
Convolution vs. correlation

Convolution

\[ G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i - u, j - v] \]

\[ G = H \ast F \]

Cross-correlation

\[ G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i + u, j + v] \]

\[ G = H \otimes F \]

For a Gaussian or box filter, how will the outputs differ?
Convolution vs. correlation

Cross-correlation

\[ G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i + u, j + v] \]

\[ G = H \otimes F \]

Convolution

\[ G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i - u, j - v] \]

\[ G = H \ast F \]
**Convolution vs. correlation**

**Cross-correlation**

\[
G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i + u, j + v]
\]

\[
G = H \otimes F
\]

**Convolution**

\[
G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i - u, j - v]
\]

\[
G = H \star F
\]
Convolution vs. correlation

Cross-correlation

\[ G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i + u, j + v] \]

\[ G = H \otimes F \]

Convolution

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\[ G = H \ast F \]
Convolution vs. correlation

Cross-correlation

\[
G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v]F[i + u, j + v]
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\[G = H \otimes F\]

Convolution

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G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v]F[i - u, j - v]
\]

\[G = H \ast F\]
Convolution vs. correlation

**Cross-correlation**

\[
G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i + u, j + v]
\]

\[
G = H \otimes F
\]

For \( u = -1, v = -1 \):

\[
F = \begin{bmatrix}
5 & 2 & 5 & 4 & 4 \\
5 & 200 & 3 & 200 & 4 \\
1 & 5 & 5 & 4 & 4 \\
5 & 5 & 1 & 1 & 2 \\
200 & 1 & 3 & 5 & 200 \\
1 & 200 & 200 & 200 & 1
\end{bmatrix}
\]

**Convolution**

\[
G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i - u, j - v]
\]

\[
G = H \ast F
\]
Convolution vs. correlation

Cross-correlation

\[ G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i + u, j + v] \]

\[ G = H \otimes F \]

\[ u = -1, v = -1 \]
\[ v = 0 \]

Convolution

\[ G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i - u, j - v] \]

\[ G = H \ast F \]
Convolution vs. correlation

**Cross-correlation**

\[
G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i + u, j + v]
\]

\[
G = H \otimes F
\]

- \(u = -1, \ v = -1\)
- \(v = 0\)
- \(v = +1\)

**Convolution**

\[
G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i - u, j - v]
\]

\[
G = H \ast F
\]
Convolution vs. correlation

Cross-correlation

\[ G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i + u, j + v] \]

\[ G = H \otimes F \]

u = -1, v = -1
v = 0
v = +1
u = 0, v = -1

Convolution

\[ G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i - u, j - v] \]

\[ G = H \ast F \]
Properties of smoothing filters

• **Smoothing**
  – Values positive
  – Sum to 1 → overall intensity same as input
  – Amount of smoothing proportional to mask size
  – Remove “high-frequency” components; “low-pass” filter
Predict the outputs using correlation filtering

- $(0 \ 0 \ 0) \ast (0 \ 1 \ 0) \ 0 \ 0 \ 0 = ?$
- $(0 \ 0 \ 0) \ast (0 \ 0 \ 1) \ 0 \ 0 \ 0 = ?$
- $(0 \ 0 \ 0) \ast (0 \ 2 \ 0) \ - \frac{1}{9} (1 \ 1 \ 1) \ 1 \ 1 \ 1 = ?$

Kristen Grauman
Practice with linear filters

Original

Source: D. Lowe
Practice with linear filters

Original

Filtered
(no change)

Source: D. Lowe
Practice with linear filters

Original

\[
\begin{array}{ccc}
0 & 0 & 0 \\
0 & 0 & 1 \\
0 & 0 & 0 \\
\end{array}
\]

Source: D. Lowe
Practice with linear filters
Practice with linear filters

Original

\[
\begin{array}{ccc}
1 & 1 & 1 \\
1 & 1 & 1 \\
1 & 1 & 1 \\
\end{array}
\]

\[\frac{1}{9}\]

Source: D. Lowe
Practice with linear filters

Original

Blur (with a box filter)

Source: D. Lowe
Practice with linear filters

Original

\[
\begin{array}{ccc}
0 & 0 & 0 \\
0 & 2 & 0 \\
0 & 0 & 0 \\
\end{array}
\]

\[ - \frac{1}{9} \]

\[
\begin{array}{ccc}
1 & 1 & 1 \\
1 & 1 & 1 \\
1 & 1 & 1 \\
\end{array}
\]

?
Practice with linear filters

Original

Sharpening filter: accentuates differences with local average

Source: D. Lowe
Original image

Image minus blur = details

\[ \begin{bmatrix} 0 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 0 \end{bmatrix} - \frac{1}{9} \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} = \]

\[ \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \left( \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} - \frac{1}{9} \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \right) \]
Sharpening

before  

after
Filters for computing gradients

\[
\begin{bmatrix}
1 & 0 & -1 \\
2 & 0 & -2 \\
1 & 0 & -1 \\
\end{bmatrix}
\]

intensity image

* =

Slide credit: Derek Hoiem
Filters for computing \textit{gradients}

\[ +1*a + 0*b + (-1)*c = a - c \]

Input image
White = 1, black = 0

Filter: \([+1 \ 0 \ -1]\)

Output image
Median filter

- No new pixel values introduced
- Removes spikes: good for impulse, salt & pepper noise
- Non-linear filter
Median filter

- Median filter is edge preserving
Boundary issues

- What is the size of the output?
  - ‘full’: output size is larger than the size of $f$
  - ‘same’: output size is same as $f$

$f = \text{image}$
$h = \text{filter}$

Adapted from S. Lazebnik
Boundary issues

• What about near the edge?
  – the filter window might fall off the edge of the image (in ‘same’ or ‘full’)
  – need to extrapolate
  – methods:
    - clip filter (black)
    - wrap around
    - copy edge
    - reflect across edge

Source: S. Marschner
Properties of convolution

- Commutative:
  \[ f * g = g * f \]

- Associative
  \[ (f * g) * h = f * (g * h) \]

- Distributes over addition
  \[ f * (g + h) = (f * g) + (f * h) \]

- Scalars factor out
  \[ kf * g = f * kg = k(f * g) \]

- Identity:
  \[ \text{unit impulse } e = [\ldots, 0, 0, 1, 0, 0, \ldots]. \quad f * e = f \]
Separability of filters

• Some filters are separable
• For such filters, filtering can be factored into two steps:
  – Convolve all rows
  – Convolve all columns
Separability example

2D filtering (center location only)

The filter factors into an outer product of 1D filters:

Perform filtering along rows:

Followed by filtering along the remaining column:
Application: Hybrid Images

What you see...

I see an angry guy

From Far Away

It's a woman!

Up Close
Application: Hybrid Images


Gaussian Filter

Laplacian Filter (sharpening)

unit impulse

Gaussian

Laplacian of Gaussian

Kristen Grauman
Application: Hybrid Images
Application: Hybrid Images

Changing expression

Sad  Surprised
Plan for this lecture

• Filters: math and properties
• Types of filters
  – Linear
    • Smoothing
    • Other
  – Non-linear
    • Median
• Texture representation with filters
• Anti-aliasing for image subsampling
Texture

Due to:
Patterns, marks, etches, blobs, holes, relief, etc.

Kristen Grauman
Includes: more regular patterns
Includes: more random patterns
Why analyze texture?

• Important for how we perceive objects
• Can be an important appearance cue that allows us to distinguish objects, especially if shape is similar across objects

Adapted from Kristen Grauman
Texture representation

• Textures are made up of repeated local patterns, so:
  – Find the patterns
    • Use filters that look like patterns (spots, bars, raw patches...)
    • Consider magnitude of response
  – Describe their statistics within each local window
    • E.g. mean, standard deviation
Derivative of Gaussian filter

Figures from Noah Snavely
Texture representation: example

- Original image
- Derivative filter responses, squared
- Statistics to summarize patterns in small windows

<table>
<thead>
<tr>
<th>Win. #1</th>
<th>mean $d/dx$ value</th>
<th>mean $d/dy$ value</th>
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<tbody>
<tr>
<td>Win. #1</td>
<td>4</td>
<td>10</td>
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</table>
Texture representation: example

- Original image
- Derivative filter responses, squared
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<td>7</td>
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|          |                                   |                                  |...
Texture representation: example

Original image

Derivative filter responses, squared

Statistics to summarize patterns in small windows

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<tr>
<td>Win. #9</td>
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Kristen Grauman
Texture representation: example

- Dimension 1 (mean d/dx value)
- Dimension 2 (mean d/dy value)

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Statistics to summarize patterns in small windows
Texture representation: example

Windows with primarily horizontal edges

Windows with small gradient in both directions

Windows with primarily vertical edges

Both

Dimension 1 (mean \( \frac{d}{dx} \) value)

Dimension 2 (mean \( \frac{d}{dy} \) value)

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Statistics to summarize patterns in small windows

Kristen Grauman
Texture representation: example

original image

derivative filter responses, squared

visualization of the assignment to texture “types”
Texture representation: example

Statistics to summarize patterns in small windows

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<td>10</td>
</tr>
<tr>
<td>Win. #2</td>
<td>18</td>
<td>7</td>
</tr>
<tr>
<td>Win. #9</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

Far: dissimilar textures

Close: similar textures

Kristen Grauman
Computing distances using texture

\[
D(a, b) = \sqrt{(a_1 - b_1)^2 + (a_2 - b_2)^2} = \sqrt{\sum_{i=1}^{d} (a_i - b_i)^2}
\]

Euclidean distance (L_2)
Texture representation: example

Distance reveals how dissimilar texture from window a is from texture in window b.

Kristen Grauman
Filter banks

• Our previous example used two filters, and resulted in a 2-dimensional feature vector to describe texture in a window.
  – x and y derivatives revealed something about local structure.

• We can generalize to apply a collection of multiple (d) filters: a “filter bank”

• Then our feature vectors will be d-dimensional.
Filter banks

• What filters to put in the bank?
  – Typically we want a combination of scales and orientations, different types of patterns.

Matlab code available for these examples:
http://www.robots.ox.ac.uk/~vgg/research/texclass/filters.html
Filter bank
Showing magnitude of responses

Kristen Grauman
Vectors of texture responses

To represent pixel, form a "feature vector" from the responses at that pixel.

1x38 vector representation feature

[r1, r2, ..., r38]

Adapted from Kristen Grauman
Vectors of texture responses

To represent pixel, form a “feature vector” from the responses at that pixel.

To represent *image*, compute statistics over all pixel feature vectors, e.g. their mean.

\[
\begin{bmatrix}
  r_{(1,1)}^1, & r_{(1,1)}^2, & \ldots, & r_{(1,1)}^{38} \\
  r_{(1,2)}^1, & r_{(1,2)}^2, & \ldots, & r_{(1,2)}^{38} \\
  \vdots \\
  r_{(W,H)}^1, & r_{(W,H)}^2, & \ldots, & r_{(W,H)}^{38}
\end{bmatrix}
\]

\[
[\text{mean}(r_{(:)}^1), \ \text{mean}(r_{(:)}^2), \ \ldots, \ \text{mean}(r_{(:)}^{38})]
\]
You try: Can you match the texture to the response?

Filters

1

2

3

Mean abs responses

A

B

C

Derek Hoiem
Representing texture by mean abs response
Classifying materials, “stuff”

Figure by Varma & Zisserman
Plan for next two lectures

• Filters: math and properties
• Types of filters
  – Linear
    • Smoothing
    • Other
  – Non-linear
    • Median
• Texture representation with filters
• Anti-aliasing for image subsampling
Why does a lower resolution image still make sense to us? What do we lose?
Subsampling by a factor of 2

Throw away every other row and column to create a 1/2 size image
Aliasing problem

• 1D example (sinewave):

Source: S. Marschner
Aliasing problem

• 1D example (sinewave):
Aliasing problem

- Sub-sampling may be dangerous....
- Characteristic errors may appear:
  - “Wagon wheels rolling the wrong way in movies”
  - “Striped shirts look funny on color television”

Adapted from D. Forsyth, image from https://en.wikipedia.org/wiki/Aliasing
Sampling and aliasing
Nyquist-Shannon Sampling Theorem

- When sampling a signal at discrete intervals, the sampling frequency must be $\geq 2 \times f_{\text{max}}$
- $f_{\text{max}} = \text{max frequency of the input signal}$
- This will allows to reconstruct the original perfectly from the sampled version
Anti-aliasing

Solutions:

• Sample more often

• Get rid of high frequencies
  – What are these in the case of images?
  – Will lose information, but it’s better than aliasing
  – Apply a smoothing filter
Algorithm for downsampling by factor of 2

1. Start with image\((h, w)\)
2. Apply low-pass filter
   \[
   \text{im\_blur} = \text{imfilter}(\text{image}, \text{fspecial}('\text{gaussian}', 7, 1))
   \]
3. Sample every other pixel
   \[
   \text{im\_small} = \text{im\_blur}(1:2:end, 1:2:end);
   \]
Anti-aliasing

Forsyth and Ponce 2002
Subsampling without pre-filtering

1/2

1/4 (2x zoom)

1/8 (4x zoom)

Slide by Steve Seitz
Subsampling with Gaussian pre-filtering

Gaussian 1/2  G 1/4  G 1/8
Summary

• Filters useful for
  – Enhancing images (smoothing, removing noise), e.g.
    • Box filter (linear)
    • Gaussian filter (linear)
    • Median filter
  – Detecting patterns (e.g. gradients)

• Texture is a useful property that is often indicative of materials, appearance cues
  – Texture representations summarize repeating patterns of local structure

• Can use filtering to reduce the effects of subsampling