Image processing

Daniel Leventhal
Adapted from Brian Curless
CSE 457
Autumn 2011

Reading

Jain, Kasturi, Schunck, *Machine Vision*. McGraw-Hill, 1995. Sections 4.2-4.4, 4.5(intro), 4.5.5, 4.5.6, 5.1-5.4. [online handut]

What is an image?

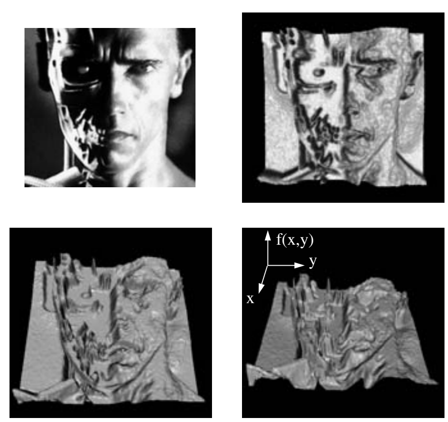
We can think of an **image** as a function, *f*, from $\mathbb{R}^2$ to $\mathbb{R}$:

- *f* (x, y) gives the intensity of a channel at position (x, y)
- Realistically, we expect the image only to be defined over a rectangle, with a finite range:
  - $f : [a, b] \times [c, d] \rightarrow [0,1]$

A color image is just three functions pasted together. We can write this as a "vector-valued" function:

$$f(x,y) = \begin{bmatrix} r(x,y) \\ g(x,y) \\ b(x,y) \end{bmatrix}$$

Images as functions



What is a digital image?

In computer graphics, we usually operate on **digital** (**discrete**) images:

- **Sample** the space on a regular grid
- **Quantize** each sample (round to nearest integer)

If our samples are Δ apart, we can write this as:

$f[i, j] = \text{Quantize}\{\, f(i\,\Delta, j\,\Delta) \,\}$

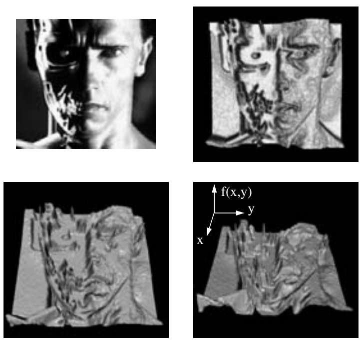


Image processing

An **image processing** operation typically defines a new image *g* in terms of an existing image *f*.

The simplest operations are those that transform each pixel in isolation. These pixel-to-pixel operations can be written:

$$g(x, y) = t(f(x, y))$$

Examples: threshold, RGB → grayscale

Note: a typical choice for mapping to grayscale is to apply the YIQ television matrix and keep the Y.

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.523 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Noise

Image processing is also useful for noise reduction and edge enhancement. We will focus on these applications for the remainder of the lecture…

Common types of noise:

- **Salt and pepper noise**: contains random occurrences of black and white pixels
- **Impulse noise:** contains random occurrences of white pixels
- **Gaussian noise**: variations in intensity drawn from a Gaussian normal distribution

Ideal noise reduction

Ideal noise reduction

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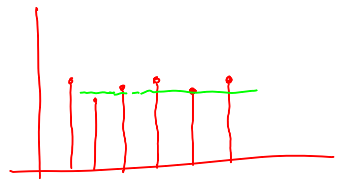
Practical noise reduction

How can we "smooth" away noise in a single image?



Is there a more abstract way to represent this sort of operation? *Of course there is!*

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Discrete convolution

One of the most common methods for filtering an image is called **discrete convolution**. (We will just call this "convolution" from here on.)

In 1D, convolution is defined as:

$$\begin{aligned} g[n] &= f[n] * h[n] \\ &= \sum_{n'} f[n']h[n-n'] \\ &= \sum_{n'} f[n']\tilde{h}[n'-n] \end{aligned}$$

where $\tilde{h}[n] = h[-n]$.

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Discrete convolution

One can show that convolution has some convenient properties. Given functions *a, b, c*:

$$\begin{aligned} a*b &= b*a \\ (a*b)*c &= a*(b*c) \\ a*(b+c) &= a*b+a*c \end{aligned}$$

We'll make use of these properties later…

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Convolution in 2D

In two dimensions, convolution becomes:

$$
\begin{aligned}
g[n,m] &= f[n,m] * h[n,m] \\
&= \sum_{m'} \sum_{n'} f[n',m'] h[n-n', m-m'] \\
&= \sum_{m'} \sum_{n'} f[n',m'] \tilde{h}[n'-n, m'-m]
\end{aligned}
$$

where $\tilde{h}[n,m] = h[-n,-m]$.

Convolution representation

Since f and h are defined over finite regions, we can write them out in two-dimensional arrays:

128	54	9	78	100
145	98	240	233	86
89	177	246	228	127
67	90	255	237	95
106	111	128	167	20
221	154	97	123	0

size/extent
support
footprint

X 0.1	X 0.1	X 0.1
X 0.1	X 0.2	X 0.1
X 0.1	X 0.1	X 0.1

zero outside boundary

Note: *This is not matrix multiplication*!

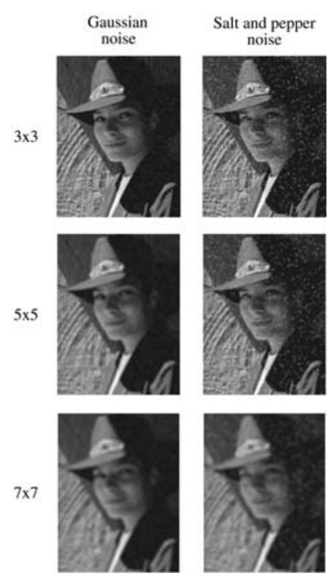
Q: What happens at the boundary of the image?

Mean filters

How can we represent our noise-reducing averaging as a convolution filter (know as a **mean filter**)?

$$\frac{1}{N^2}\left[\begin{matrix} 1 & \cdots & 1 \\ \vdots & & \\ \vdots & & \end{matrix}\right]\Bigg\} N$$

Effect of mean filters



Gaussian filters

Gaussian filters weigh pixels based on their distance from the center of the convolution filter. In particular:

$$h[n,m] = \frac{e^{-(n^2+m^2)/(2\sigma^2)}}{C}$$

This does a decent job of blurring noise while preserving features of the image.

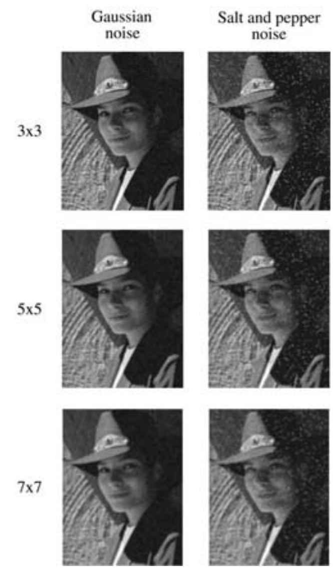
What parameter controls the width of the Gaussian? σ

What happens to the image as the Gaussian filter kernel gets wider?

What is the constant C? What should we set it to?

$$\sum_n \sum_m e^{-(n^2+m^2)/(2\sigma^2)}$$

Effect of Gaussian filters



Median filters

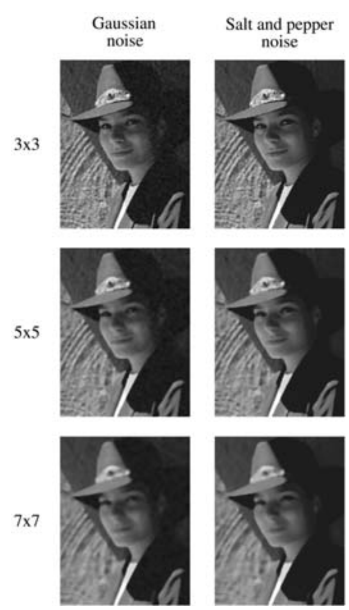
A **median filter** operates over an *m*x*m* region by selecting the median intensity in the region.

What advantage does a median filter have over a mean filter? Removes outliers?

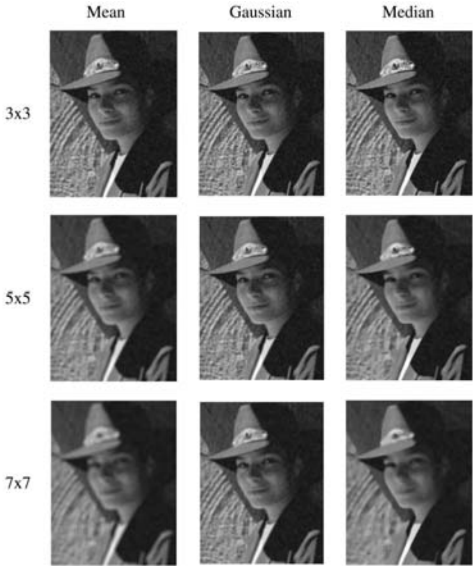
Is a median filter a kind of convolution?

No   Need to Sort

Effect of median filters



Comparison: Gaussian noise



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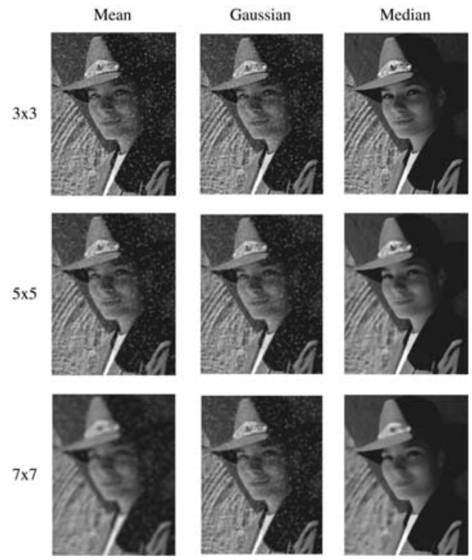
Comparison: salt and pepper noise



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Edge detection

One of the most important uses of image processing is **edge detection:**

- Really easy for humans
- Really difficult for computers

- Fundamental in computer vision
- Important in many graphics applications

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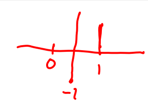
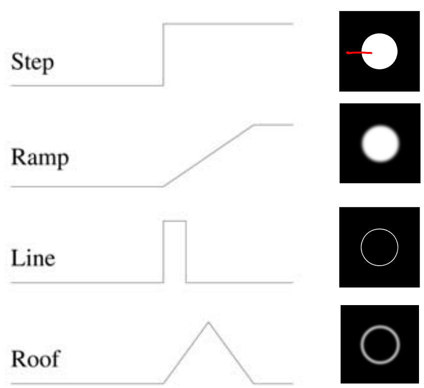
What is an edge?

$\tilde{h}$





Q: How might you detect an edge in 1D?

$\frac{\partial f}{\partial x} \approx f[n+1] - f[n]$

$\left|\frac{\partial f}{\partial x}\right| >$ threshold

$\tilde{h} = [0\ -1\ 1]$ $h = [1\ -1\ 0]$

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Gradients

The **gradient** is the 2D equivalent of the derivative:

$$\nabla f(x,y) = \left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y} \right)$$

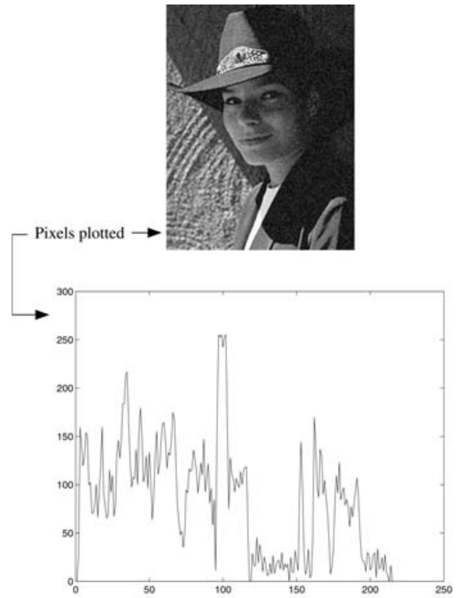
Properties of the gradient $\tan\theta = \frac{\partial f / \partial y}{\partial f / \partial x}$

- It's a vector
- Points in the direction of maximum increase of f
- Magnitude is rate of increase $|\nabla f| = \sqrt{\frac{\partial f}{\partial x}^2 + \frac{\partial f}{\partial y}^2}$

How can we approximate the gradient in a discrete image?

$$f_x[n,m] = f[n+1,m] - f[n,m]$$
$$f_y[n,m] = f[n,m+1] - f[n,m]$$
$$\tilde{h}_x = [0\ -1\ 1] \qquad \tilde{h}_y = \begin{bmatrix} 0 \\ -1 \\ 1 \end{bmatrix}$$

Less than ideal edges



Steps in edge detection

Edge detection algorithms typically proceed in three or four steps:

- **Filtering**: cut down on noise
- **Enhancement**: amplify the difference between edges and non-edges
- **Detection**: use a threshold operation
- **Localization** (optional): estimate geometry of edges as 1D contours that can pass between pixels

Edge enhancement

A popular gradient filter is the **Sobel operator**:

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

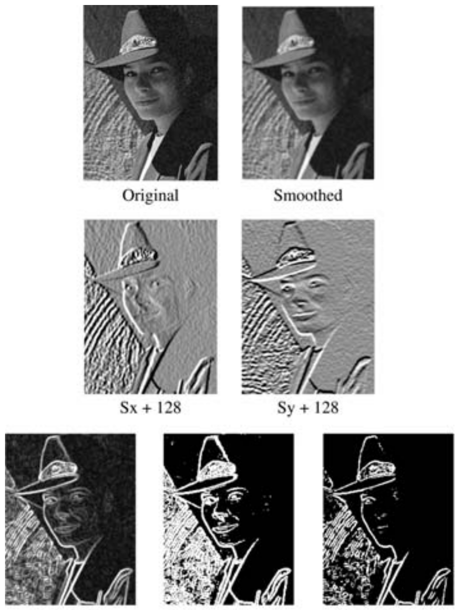
$$\tilde{s}_x = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}$$

$$\tilde{s}_y = \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix}$$

We can then compute the magnitude of the vector $(\tilde{s}_x, \tilde{s}_y)$.

Note that these operators are conveniently "pre-flipped" for convolution, so you can directly slide these across an image without flipping first.

Results of Sobel edge detection



Original | Smoothed

Sx + 128 | Sy + 128

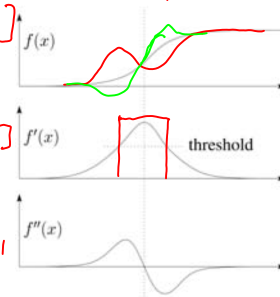
Magnitude | Threshold = 64 | Threshold = 128

Second derivative operators

$f(x)+f''(x)$ $f(x)-f''(x)$

$h_x=[1\ -1\ 0]$

$\tilde{h}_x=[0\ -1\ 1]$



$h_{xx}=[1\ -2\ 1]$ $h_{yy}=\begin{bmatrix}1\\-2\\1\end{bmatrix}$

The Sobel operator can produce thick edges. Ideally we're looking for infinitely thin boundaries.

An alternative approach is to look for local extrema in the first derivative: places where the change in the gradient is highest.

Q: A peak in the first derivative corresponds to what in the second derivative? 0

Q: How might we write this as a convolution filter?

Localization with the Laplacian

An equivalent measure of the second derivative in 2D is the **Laplacian**:

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

$\frac{\partial^2 f}{\partial x^2}=[1\ -2\ 1]$ $\begin{bmatrix}0&0&0\\1&-2&1\\0&0&0\end{bmatrix}=\frac{\partial^2}{\partial x^2}$

$\frac{\partial^2 f}{\partial y^2}=\begin{bmatrix}1\\-2\\1\end{bmatrix}$ $\begin{bmatrix}0&1&0\\0&-2&0\\0&1&0\end{bmatrix}=\frac{\partial^2}{\partial y^2}$

Using the same arguments we used to compute the gradient filters, we can derive a Laplacian filter to be:

$$\Delta = \begin{bmatrix}0 & 1 & 0\\ 1 & -4 & 1\\ 0 & 1 & 0\end{bmatrix}$$

(The symbol Δ is often used to refer to the *discrete* Laplacian filter.)

Zero crossings in a Laplacian filtered image can be used to localize edges.

Localization with the Laplacian

Original | Smoothed

Laplacian (+128)

-10 +20

+5 +7

Sharpening with the Laplacian


Original


Laplacian (+128)


Original + Laplacian


Original - Laplacian

Why does the sign make a difference?

How can you write the filter that makes the sharpened image?

Sharpening as a filter

$$S = f - \Delta * f$$
$$= 1 * f - \Delta * f$$
$$= (1 - \Delta) * f$$
$$= \left(\begin{bmatrix} 1 \end{bmatrix} - \begin{bmatrix} 0 & 1 & 0 \\ 1 & 4 & 1 \\ 0 & 1 & 0 \end{bmatrix} \right) * f$$
$$= \left(\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} - \begin{bmatrix} 0 & 1 & 0 \\ 1 & 4 & 1 \\ 0 & 1 & 0 \end{bmatrix} \right) * f$$
$$= \begin{bmatrix} 0 & -1 & 0 \\ -1 & 5 & -1 \\ 0 & -1 & 0 \end{bmatrix} * f$$
$$S = f - \lambda \Delta * f = \begin{bmatrix} 0 & -\lambda & 0 \\ -\lambda & 1+4\lambda & -\lambda \\ 0 & -\lambda & 0 \end{bmatrix} * f$$
$$0 \leq \lambda \leq 1$$

Summary

What you should take away from this lecture:

- The meanings of all the boldfaced terms.
- How noise reduction is done
- How discrete convolution filtering works
- The effect of mean, Gaussian, and median filters
- What an image gradient is and how it can be computed
- How edge detection is done
- What the Laplacian image is and how it is used in either edge detection or image sharpening