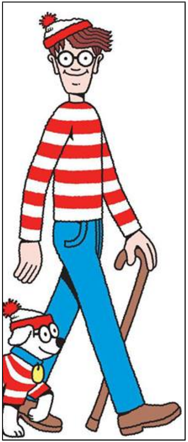
Edge Detection

Finding Waldo

- Let's revisit the problem of finding Waldo
- And let's take a simple example

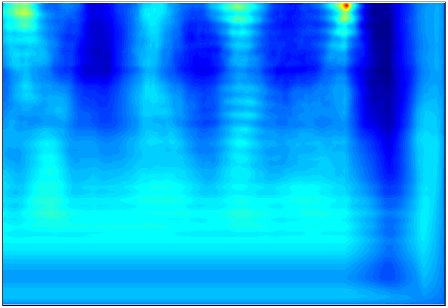
image



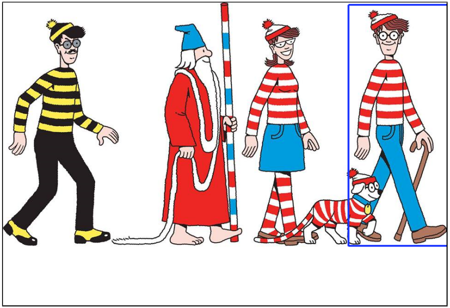
template (filter)

Finding Waldo

- Let's revisit the problem of finding Waldo
- And let's take a simple example



normalized cross-correlation



Waldo detection
(putting box around max response)

Finding Waldo

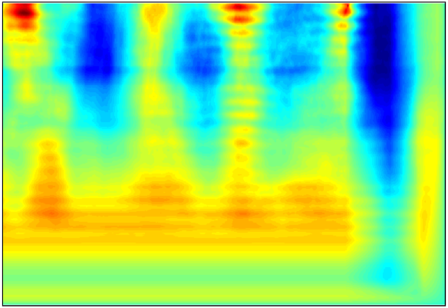
- Now imagine Waldo goes shopping
- ... but our filter **doesn't know that**

image

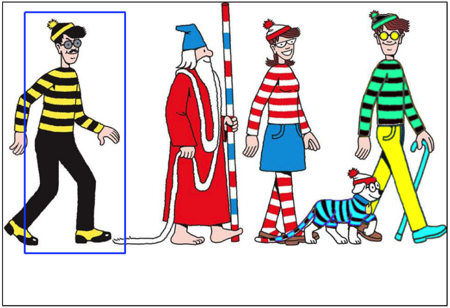
template (filter)

Finding Waldo

- Now imagine Waldo goes shopping (and the dog too)
- ... but our filter **doesn't know that**



normalized cross-correlation



Waldo detection
(putting box around max response)

Finding Waldo (again)

- What can we do to find Waldo again?

Finding Waldo (again)

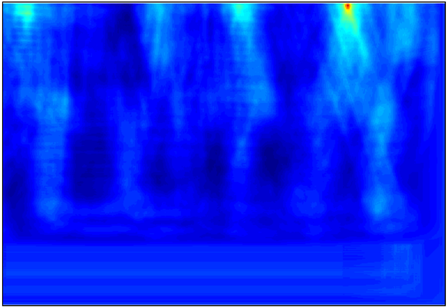
- What can we do to find Waldo again?
- **Edges!!!**

image

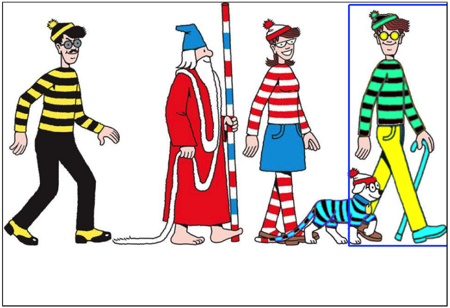
template (filter)

Finding Waldo (again)

- What can we do to find Waldo again?
- **Edges!!!**

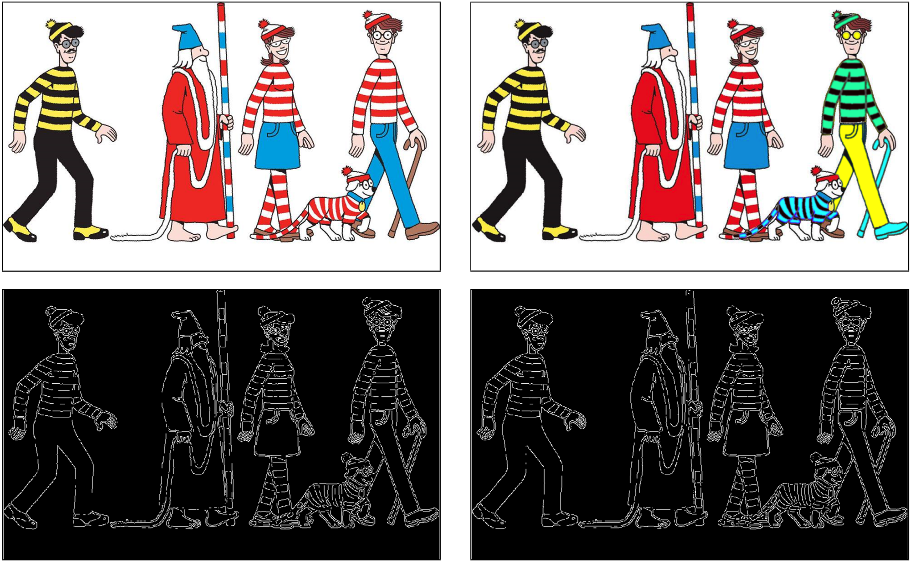


normalized cross-correlation
(using the edge maps)



Waldo detection
(putting box around max response)

Waldo and Edges



Edge detection

- Map image to a set of **curves** or **line segments** or **contours**.
- More compact than pixels.
- Edges are invariant to changes in illumination
- Important for recognition

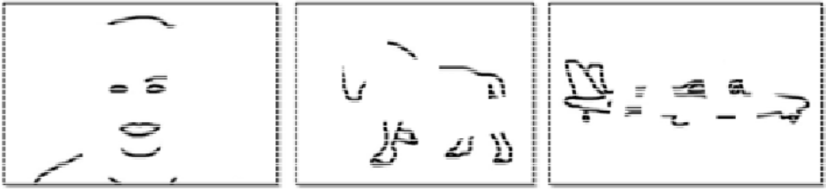


Figure: [Shotton et al. PAMI, 07]

[Source: K. Grauman]

Edge detection

- Map image to a set of **curves** or **line segments** or **contours**.
- More compact than pixels.
- Edges are invariant to changes in illumination
- Important for recognition
- Important for various applications

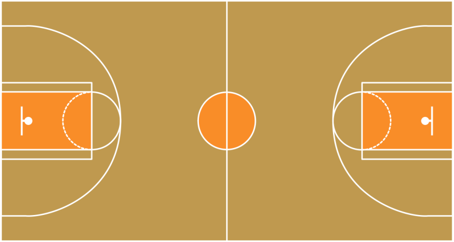


Figure: Parse basketball court (left) to figure out how far the guy is from net

Edge detection

- Map image to a set of **curves** or **line segments** or **contours**.
- More compact than pixels.
- Edges are invariant to changes in illumination
- Important for recognition
- Important for various applications

Figure: How can a robot pick up or grasp objects?

Edge detection

- Map image to a set of **curves** or **line segments** or **contours**.
- More compact than pixels.
- Edges are invariant to changes in illumination
- Important for recognition
- Important for various applications

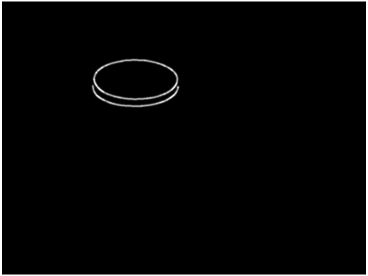
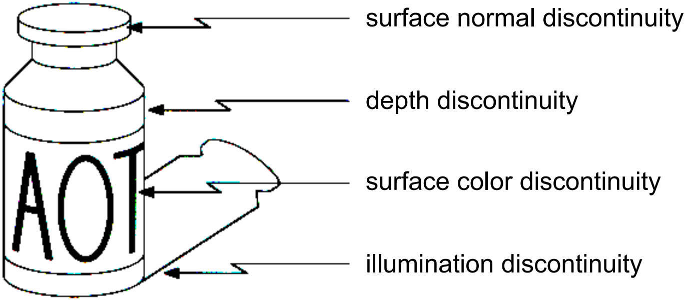



Figure: How can a robot pick up or grasp objects?

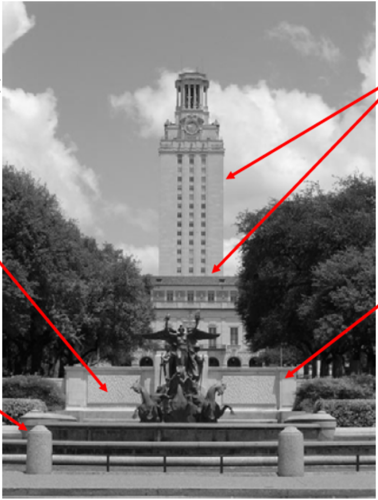
Origin of Edges

- Edges are caused by a variety of factors



[Source: N. Snavely]

What Causes an Edge?



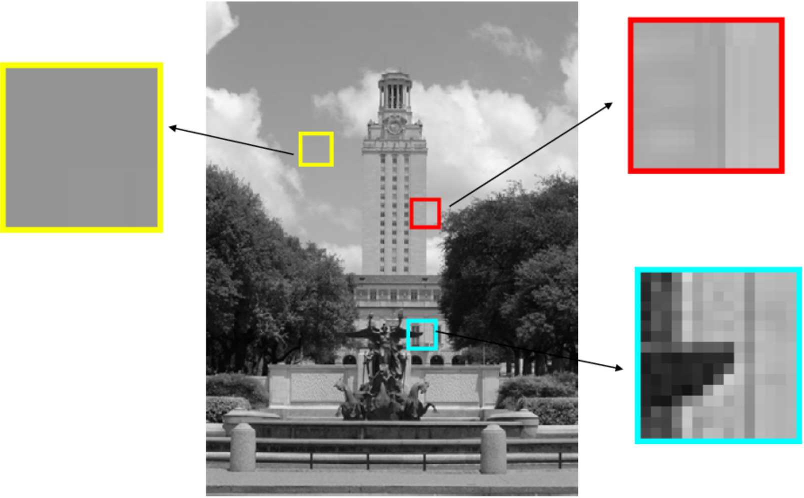
Reflectance change: appearance information, texture

Depth discontinuity: object boundary

Cast shadows

Change in surface orientation: shape

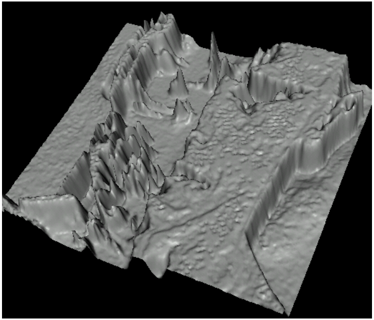
[Source: K. Grauman]



[Source: K. Grauman]

Images as Functions

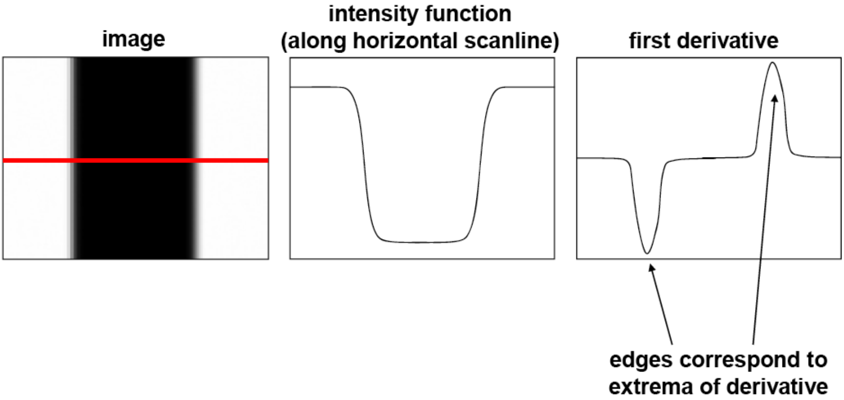
- Edges look like steep cliffs



[Source: N. Snavely]

Characterizing Edges

- An **edge** is a place of rapid change in the image intensity function.



[Source: S. Lazebnik]

How to Implement Derivatives with Convolution

How can we differentiate a digital image $f[x, y]$?

- If image f was continuous, then compute the partial derivative as

$$\frac{\partial f(x,y)}{\partial x} = \lim_{\epsilon \to 0} \frac{f(x+\epsilon, y) - f(x)}{\epsilon}$$

How to Implement Derivatives with Convolution

How can we differentiate a digital image $f[x, y]$?

- If image f was continuous, then compute the partial derivative as

$$\frac{\partial f(x,y)}{\partial x} = \lim_{\epsilon \to 0} \frac{f(x+\epsilon, y) - f(x)}{\epsilon}$$

- Since it's discrete, take discrete derivative (finite difference)

$$\frac{\partial f(x,y)}{\partial x} \approx \frac{f[x+1, y] - f[x]}{1}$$

How to Implement Derivatives with Convolution

How can we differentiate a digital image $f[x, y]$?

- If image f was continuous, then compute the partial derivative as

$$\frac{\partial f(x,y)}{\partial x} = \lim_{\epsilon \to 0} \frac{f(x+\epsilon, y) - f(x)}{\epsilon}$$

- Since it's discrete, take discrete derivative (finite difference)

$$\frac{\partial f(x,y)}{\partial x} \approx \frac{f[x+1, y] - f[x]}{1}$$

- What would be the filter to implement this using correlation/convolution?

How to Implement Derivatives with Convolution

How can we differentiate a digital image $f[x, y]$?

- If image f was continuous, then compute the partial derivative as

$$\frac{\partial f(x,y)}{\partial x} = \lim_{\epsilon \to 0} \frac{f(x+\epsilon, y) - f(x)}{\epsilon}$$

- Since it's discrete, take discrete derivative (finite difference)

$$\frac{\partial f(x,y)}{\partial x} \approx \frac{f[x+1, y] - f[x]}{1}$$

- What would be the filter to implement this using correlation/convolution?

$\frac{\partial f}{\partial x}$:

H_x

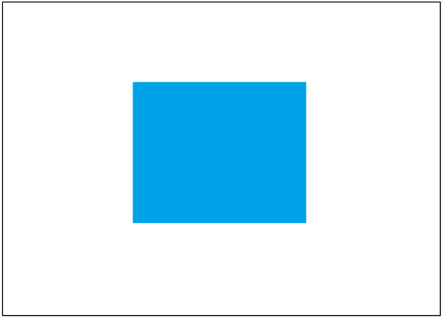
$\frac{\partial f}{\partial y}$:

H_y

[Source: S. Seitz]

Examples: Partial Derivatives of an Image

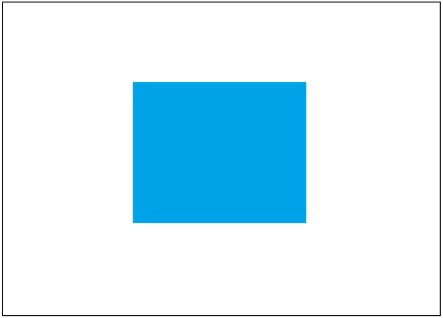
- How does the horizontal derivative using the filter $[-1, 1]$ look like?



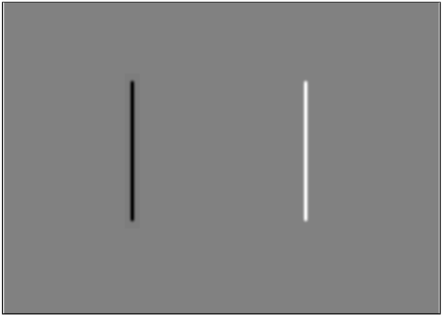
Image

Examples: Partial Derivatives of an Image

- How does the horizontal derivative using the filter $[-1, 1]$ look like?

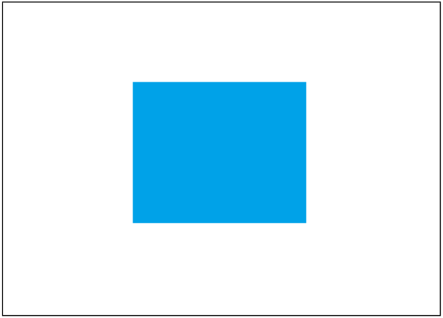


Image



$\frac{\partial f(x,y)}{\partial x}$ with $[-1, 1]$ and correlation

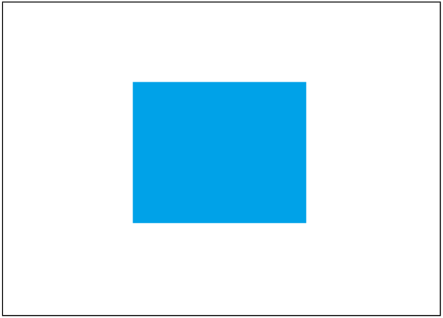
- How about the vertical derivative using filter $[-1, 1]^T$?



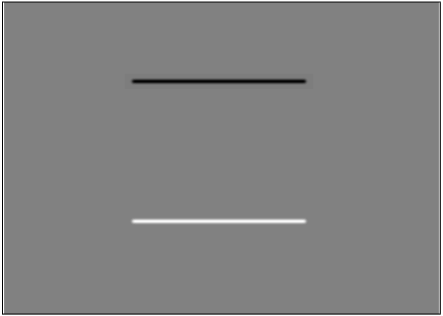
Image

Examples: Partial Derivatives of an Image

- How about the vertical derivative using filter $[-1, 1]^T$?



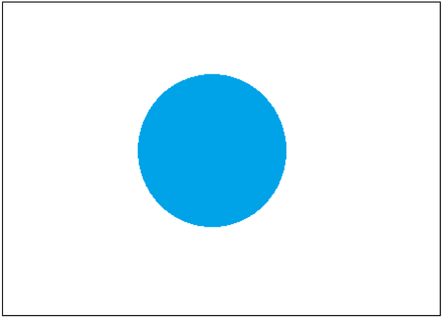
Image



$\frac{\partial f(x,y)}{\partial y}$ with $[-1, 1]^T$ and correlation

Examples: Partial Derivatives of an Image

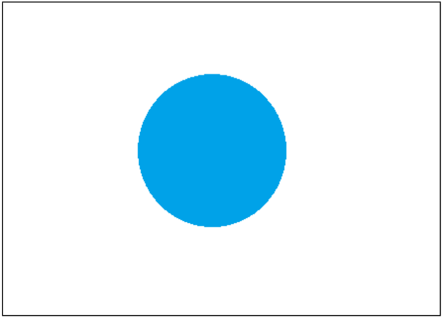
- How does the horizontal derivative using the filter $[-1, 1]$ look like?



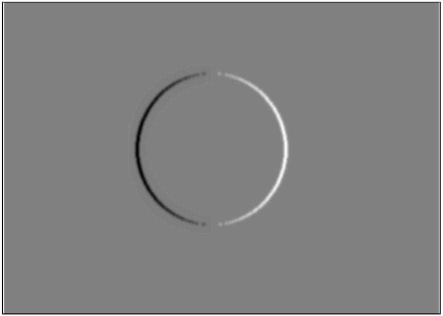
Image

Examples: Partial Derivatives of an Image

- How does the horizontal derivative using the filter $[-1, 1]$ look like?



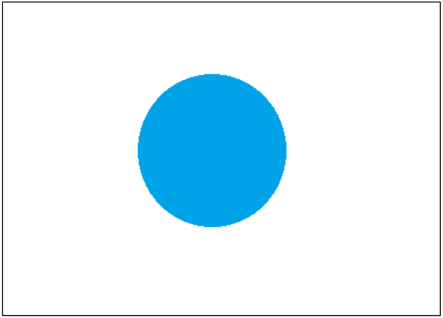
Image



$\frac{\partial f(x,y)}{\partial x}$ with $[-1, 1]$ and correlation

Examples: Partial Derivatives of an Image

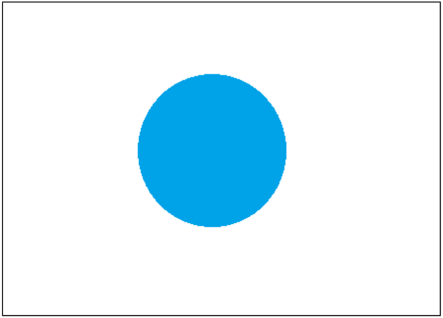
- How about the vertical derivative using filter $[-1, 1]^T$?



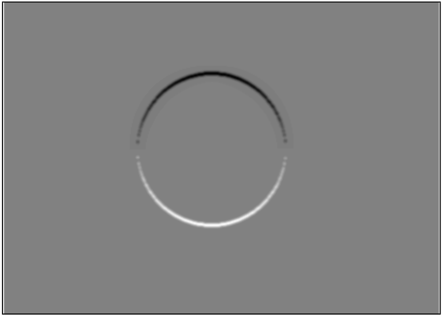
Image

Examples: Partial Derivatives of an Image

- How about the vertical derivative using filter $[-1, 1]^T$?



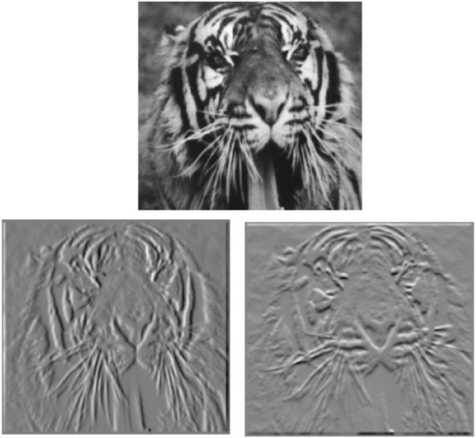
Image



$\frac{\partial f(x,y)}{\partial y}$ with $[-1, 1]^T$ and correlation

$$\frac{\partial f(x,y)}{\partial x}$$

-1	1



$$\frac{\partial f(x,y)}{\partial y}$$

-1
1

? or

1
-1

Figure: Using correlation filters

[Source: K. Grauman]

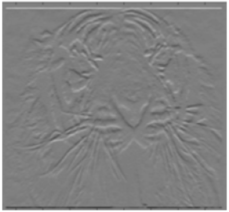
Finite Difference Filters

Prewitt: $M_x = \begin{array}{|c|c|c|}\hline -1 & 0 & 1 \\ \hline -1 & 0 & 1 \\ \hline -1 & 0 & 1 \\ \hline \end{array}$; $M_y = \begin{array}{|c|c|c|}\hline 1 & 1 & 1 \\ \hline 0 & 0 & 0 \\ \hline -1 & -1 & -1 \\ \hline \end{array}$

Sobel: $M_x = \begin{array}{|c|c|c|}\hline -1 & 0 & 1 \\ \hline -2 & 0 & 2 \\ \hline -1 & 0 & 1 \\ \hline \end{array}$; $M_y = \begin{array}{|c|c|c|}\hline 1 & 2 & 1 \\ \hline 0 & 0 & 0 \\ \hline -1 & -2 & -1 \\ \hline \end{array}$

Roberts: $M_x = \begin{array}{|c|c|}\hline 0 & 1 \\ \hline -1 & 0 \\ \hline \end{array}$; $M_y = \begin{array}{|c|c|}\hline 1 & 0 \\ \hline 0 & -1 \\ \hline \end{array}$

```
>> My = fspecial('sobel');
>> outim = imfilter(double(im), My);
>> imagesc(outim);
>> colormap gray;
```



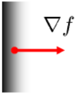
[Source: K. Grauman]

Image Gradient

- The gradient of an image $\nabla f = \left[\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}\right]$

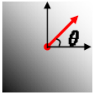
Image Gradient

- The gradient of an image $\nabla f = \left[\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}\right]$
- The gradient points in the direction of most rapid change in intensity



$\nabla f = \left[\frac{\partial f}{\partial x}, 0\right]$

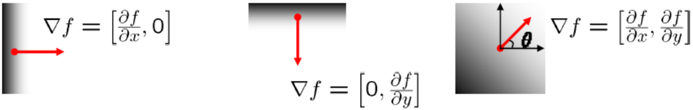
$\nabla f = \left[0, \frac{\partial f}{\partial y}\right]$



$\nabla f = \left[\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}\right]$

Image Gradient

- The gradient of an image $\nabla f = \left[\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}\right]$
- The gradient points in the direction of most rapid change in intensity

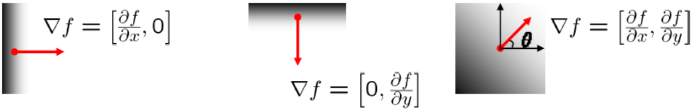


- The **gradient direction** (orientation of edge normal) is given by:

$$\theta = \tan^{-1}\left(\frac{\partial f}{\partial y} \Big/ \frac{\partial f}{\partial x}\right)$$

Image Gradient

- The gradient of an image $\nabla f = \left[\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y} \right]$
- The gradient points in the direction of most rapid change in intensity



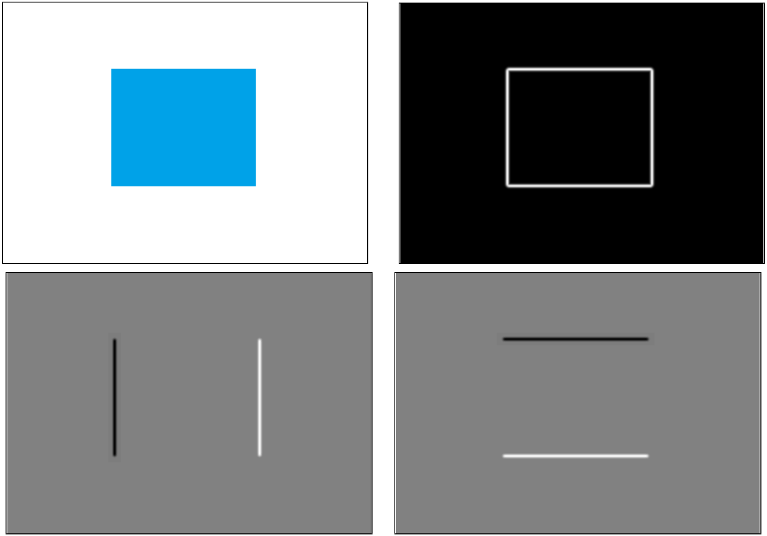
- The **gradient direction** (orientation of edge normal) is given by:

$$\theta = \tan^{-1} \left(\frac{\partial f}{\partial y} / \frac{\partial f}{\partial x} \right)$$

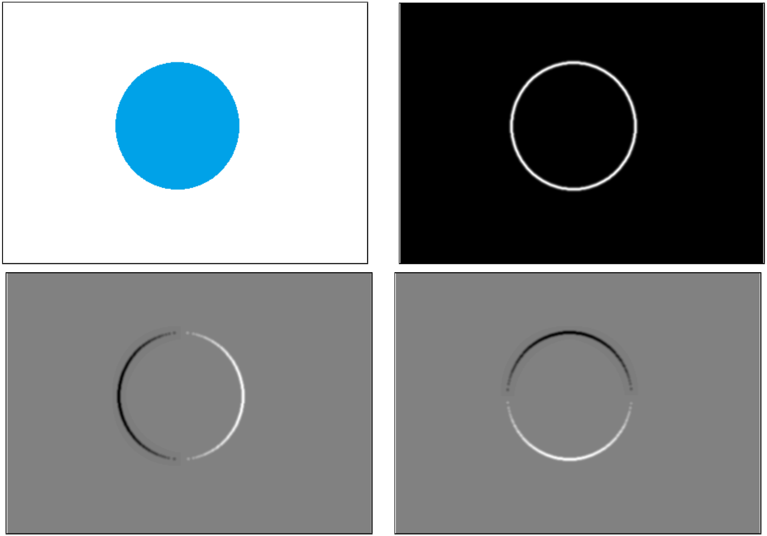
- The **edge strength** is given by the magnitude $||\nabla f|| = \sqrt{(\frac{\partial f}{\partial x})^2 + (\frac{\partial f}{\partial y})^2}$

[Source: S. Seitz]

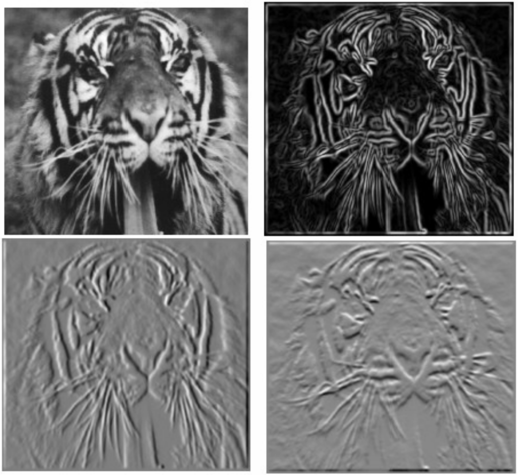
Example: Image Gradient



Example: Image Gradient



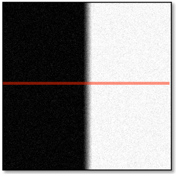
Example: Image Gradient



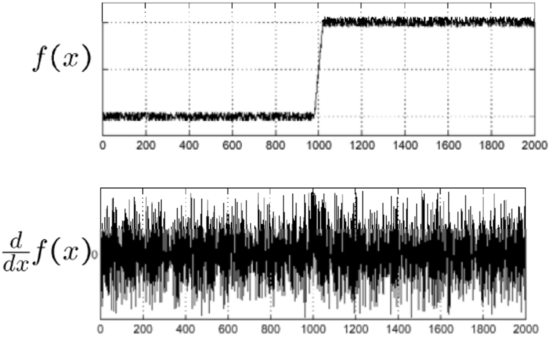
[Source: S. Lazebnik]

Effects of noise

- What if our image is noisy? What can we do?
- Consider a single row or column of the image.
- Plotting intensity as a function of position gives a signal.



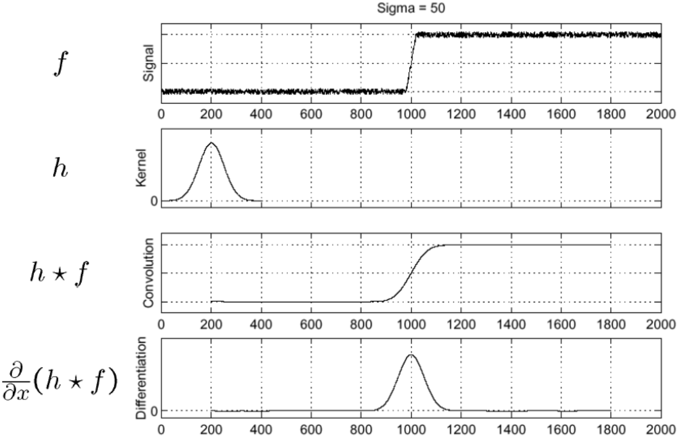
Noisy input image



[Source: S. Seitz]

Effects of noise

- Smooth first with h (e.g. Gaussian), and look for peaks in $\frac{\partial}{\partial x}(h * f)$.



[Source: S. Seitz]

Derivative theorem of convolution

- Differentiation property of convolution

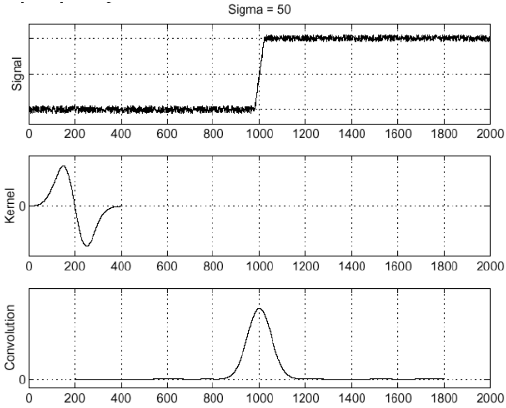
$$\frac{\partial}{\partial x}(h * f) = (\frac{\partial h}{\partial x}) * f = h * (\frac{\partial f}{\partial x})$$

- It saves one operation

f

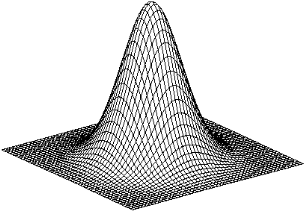
$\frac{\partial}{\partial x}h$

$(\frac{\partial}{\partial x}h) \star f$



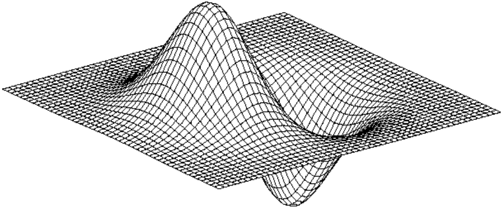
[Source: S. Seitz]

2D Edge Detection Filters



Gaussian

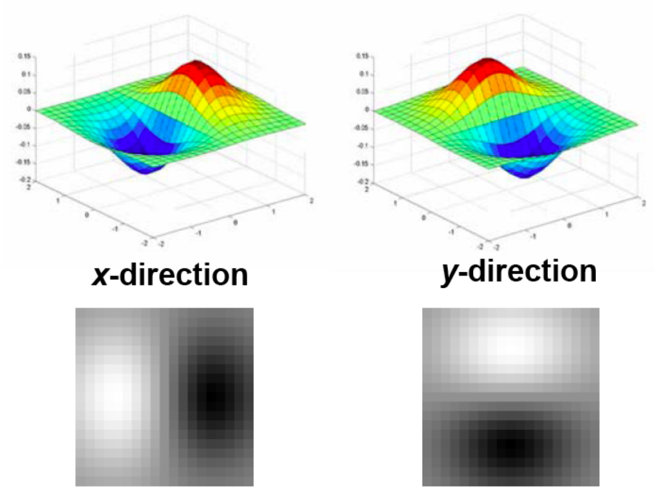
$h_\sigma(x, y) = \frac{1}{2\pi\sigma^2} \exp^{-\frac{u^2+v^2}{2\sigma^2}}$



Derivative of Gaussian (x)

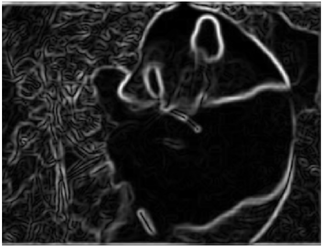
$\frac{\partial}{\partial x} h_\sigma(u, v)$

[Source: N. Snavely]

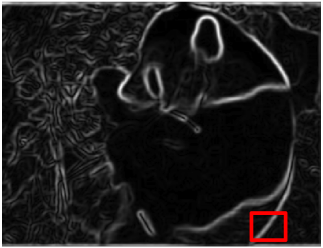


[Source: K. Grauman]

Example



- Applying the Gaussian derivatives to image

- Applying the Gaussian derivatives to image

Properties:

- Zero at a long distance from the edge
- Positive on both sides of the edge
- Highest value at some point in between, on the edge itself

Effect of σ on derivatives

The detected structures differ depending on the **Gaussian's scale parameter**:

- Larger values: detects edges of larger scale
- Smaller values: detects finer structures

σ = 1 pixel σ = 3 pixels

[Source: K. Grauman]

Locating Edges – Canny's Edge Detector

Let's take the most popular picture in computer vision: Lena (appeared in November 1972 issue of Playboy magazine)

[Source: N. Snavely]

Locating Edges – Canny's Edge Detector

Figure: Canny's approach takes gradient magnitude

[Source: N. Snavely]

Locating Edges – Canny's Edge Detector

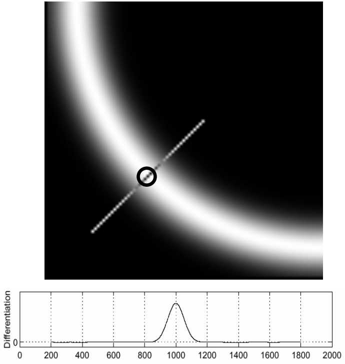
Figure: Thresholding

[Source: N. Snavely]

Locating Edges – Canny's Edge Detector

Figure: Gradient magnitude

[Source: N. Snavely]



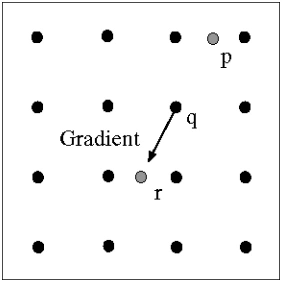


Figure: Gradient magnitude

- Check if pixel is local maximum along gradient direction
- If yes, take it

[Source: N. Snavely]

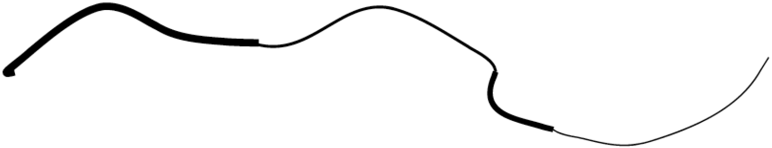
Problem: pixels along this edge didn't survive the thresholding

Figure: Problem with thresholding

[Source: K. Grauman]

Hysteresis thresholding

- Use a high threshold to start edge curves, and a low threshold to continue them



[Source: K. Grauman]

Hysteresis thresholding

original image

high threshold (strong edges)

low threshold (weak edges)

hysteresis threshold

[Source: L. Fei Fei]

Located Edges!

Figure: Thinning: Non-maxima suppression

[Source: N. Snavely]

Canny Edge Detector

Matlab: `edge(image,'canny')`

1. Filter image with derivative of Gaussian (horizontal and vertical directions)
2. Find magnitude and orientation of gradient
3. Non-maximum suppression
4. Linking and thresholding (hysteresis):
   - Define two thresholds: low and high
   - Use the high threshold to start edge curves and the low threshold to continue them

[Source: D. Lowe and L. Fei-Fei]

Canny Edge Detector

- large σ (in step 1) detects "large-scale" edges
- small σ detects fine edges

original — Canny with $\sigma = 1$ — Canny with $\sigma = 2$

[Source: S. Seitz]

Canny edge detector

- Still one of the most widely used edge detectors in computer vision
- J. Canny, A Computational Approach To Edge Detection, IEEE Trans. Pattern Analysis and Machine Intelligence, 8:679-714, 1986.
- Depends on several parameters: σ of the **blur** and the **thresholds**

[Adopted by: R. Urtasun]

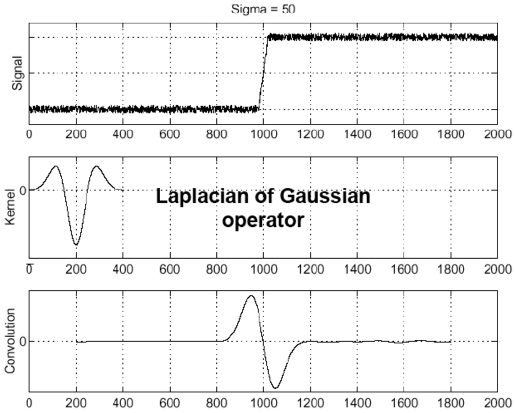
Another Way of Finding Edges: Laplacian of Gaussians

- Edge by detecting **zero-crossings** of bottom graph

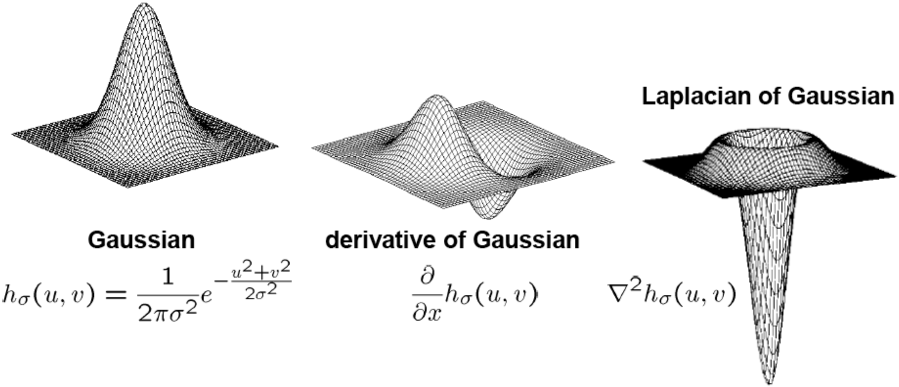
f

$\frac{\partial^2}{\partial x^2} h$

$(\frac{\partial^2}{\partial x^2} h) \star f$



[Source: S. Seitz]



$$h_\sigma(u,v) = \frac{1}{2\pi\sigma^2} e^{-\frac{u^2+v^2}{2\sigma^2}}$$

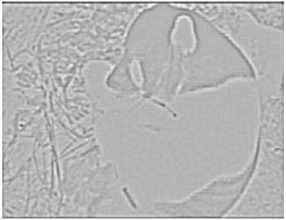
$$\frac{\partial}{\partial x} h_\sigma(u,v)$$

$$\nabla^2 h_\sigma(u,v)$$

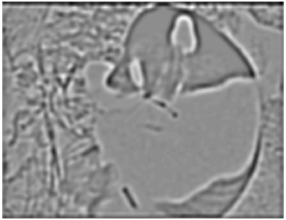
with ∇^2 the Laplacian operator $\nabla^2 f = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2}$

[Source: S. Seitz]

Example



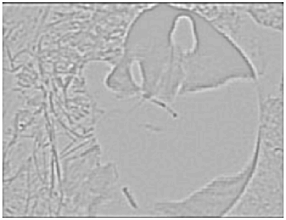
$\sigma = 1$ pixels



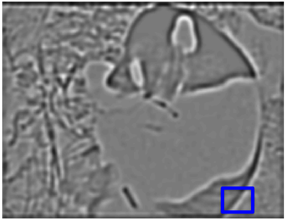
$\sigma = 3$ pixels

- Applying the Laplacian operator to image

Example



$\sigma = 1$ pixels

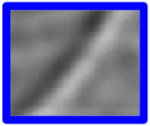


$\sigma = 3$ pixels

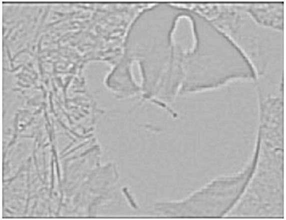
- Applying the Laplacian operator to image

Properties:

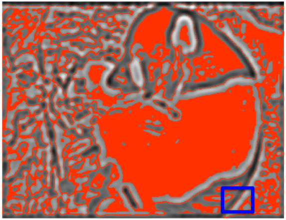
- Zero at a long distance from the edge
- Positive on the darker side of edge
- Negative on the lighter side
- Zero at some point in between, on edge itself



Example



$\sigma = 1$ pixels

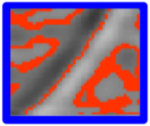


$\sigma = 3$ pixels

- Applying the Laplacian operator to image

Properties:

- Zero at a long distance from the edge
- Positive on the darker side of edge
- Negative on the lighter side
- Zero at some point in between, on edge itself



But Sanja, we are in 2015

This is "old-style" Computer Vision. We are now in the era of successful Machine Learning techniques.

Question: Can we use ML to do a better job at finding edges?

Summary – Stuff You Should Know

Not so good:

- **Horizontal image gradient**: Subtract intensity of left neighbor from pixel's intensity (filtering with $[-1, 1]$)
- **Vertical image gradient**: Subtract intensity of bottom neighbor from pixel's intensity (filtering with $[-1, 1]^T$)

Much better (more robust to noise):

- **Horizontal image gradient**: Apply derivative of Gaussian with respect to x to image (filtering!)
- **Vertical image gradient**: Apply derivative of Gaussian with respect to y to image
- **Magnitude of gradient**: compute the horizontal and vertical image gradients, square them, sum them, and $\sqrt{}$ the sum
- **Edges**: Locations in image where magnitude of gradient is high
- Phenomena that **causes** edges: rapid change in surface's normals, depth discontinuity, rapid changes in color, change in illumination

Summary – Stuff You Should Know

- **Properties of gradient's magnitude**:
  - Zero far away from edge
  - Positive on both sides of the edge
  - Highest value directly on the edge
  - Higher σ emphasizes larger structures
- **Canny's edge detector**:
  - Compute gradient's direction and magnitude
  - Non-maxima suppression
  - Thresholding at two levels and linking

Matlab functions:

- FSPECIAL: gives a few gradients filters (PREWITT, SOBEL, ROBERTS)
- SMOOTHGRADIENT: function to compute gradients with derivatives of Gaussians. Find it in Lecture's 3 code (check class webpage)
- EDGE: use EDGE(I,'CANNY') to detect edges with Canny's method, and EDGE(I,'LOG') for Laplacian method