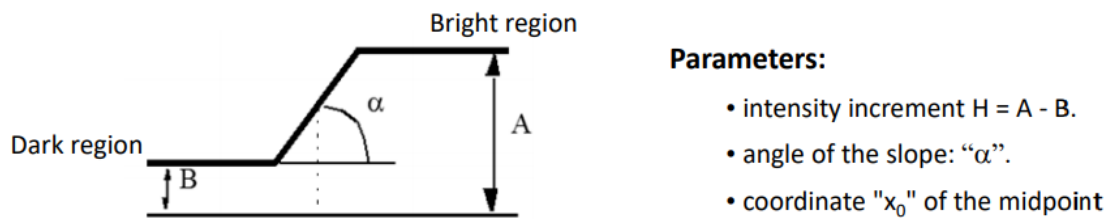# 3.1 Operators based on first derivative

Let's suppose an image processing technique that pursues the finding of those pixels in images that exhibit brightness variations, that is, their intensity differ from that of their neighbor pixels. Such pixels are often called **edges**, so this technique receives the name of **edge detection**. Edge detection has many applications in computer vision tasks like image segmentation or data extraction. We will explore some of them later in this book.

As commented, edges can be defined as transitions between image regions that have different gray levels (intensities). In this way, the unidimensional, continuous model of an ideal edge is:

Parameters:
- intensity increment H = A - B.
- angle of the slope: "α".
- coordinate "x_0" of the midpoint

That is, and edge is defined by three parameters: its change in intensity, the angle of its slope, and its midpoint. However, in real images that model is not exactly followed by edges since images are discrete, and they are corrupted by noise.

Moreover, **the nature of edges may be diverse**:

- occlusion borders,
- different orientation of surfaces,
- different reflectance properties,
- different textures,
- illumination effects: shadows, reflections, etc.

Error types related to edge detection

Finding edges properly is not a straightforward task, as there exist different errors that can appear when applying edge detection techniques:

- **Detection error.** A good detector exhibits a low ratio of false negative and false positive, that is:
  - False negatives: Existing edges that are not detected.
  - False positives: Detected objects that are not real.
- **Localization error.** Edges are detected, but they are not at the real, exact position.
- **Multiple response.** Multiple detections are raised for the same edge (the edge is thick).

The following figure illustrates such errors.

Thereby, when designing a good edge detector, the goal is to achieve low detection and localization errors, as well as to avoid multiple responses.

Operators based on first derivative (gradient)

In the upcoming chapters, we are going to investigate and implement different edge detection methods. All of them are based on our dear convolution operation, having their own pros and cons.

Concretely, in this notebook we will cover **first-derivative** based operators, which try to detect borders by looking at abrupt intensity differences in neighbor pixels. In the image below we can see two functions $f(x)$ (first row) and how their derivatives (second row) reach their maximum values at the points where the functions' values change more abruptly (around x_o).
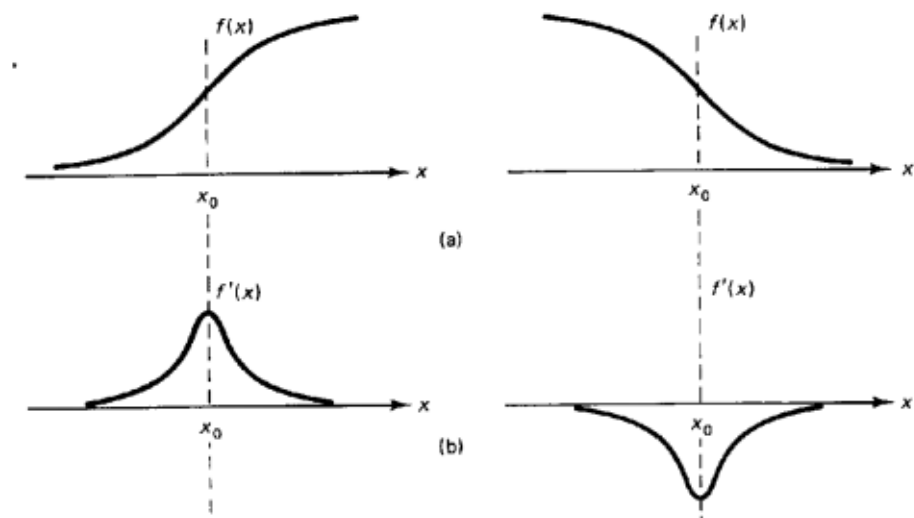
If we are dealing with a **two-dimensional** continuous function $f(x, y)$, its derivative is a *vector* (**gradient**) defined as:

$$\nabla f(x, y) = \begin{bmatrix} \frac{\partial}{\partial x} f(x, y) \\ \frac{\partial}{\partial y} f(x, y) \end{bmatrix} = \begin{bmatrix} f_x(x, y) \\ f_y(x, y) \end{bmatrix}$$
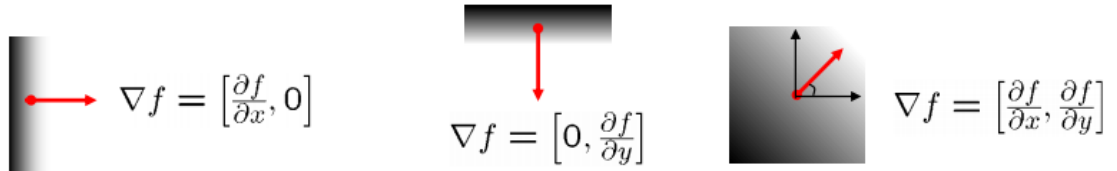
which points at the *direction* of maximum (positive) variation of $f(x, y)$:

$$\alpha(x, y) = \arctan\left(\frac{f_y(x, y)}{f_x(x, y)}\right)$$

and has a *module* proportional to the strength of this variation:

$$|\nabla f(x, y)| = \sqrt{(f_x(x, y))^2 + (f_y(x, y))^2} \approx |f_x(x, y)| + |f_y(x, y)|$$

The image below shows examples of gradient vectors:

Concretely, the techniques based on the first derivative explored here are:

- Discrete approximations of a **gradient operator** (Sobel, Prewitt, Roberts, etc., Section 3.1.1).

Problem context - Edge detection for medical images

Edge detection in medical images is of capital importance for the diagnosis of different diseases (e.g., the detection of tumor cells) in human organs such as lungs and prostates, becoming an essential pre-processing step in medical image segmentation.

In this context, *Hospital Clínico*, a very busy hospital in Málaga, is asking local engineering students to join their research team. They are looking for a person with knowledge in image processing and, in order to ensure it, they have published 3 medical images: `medical_1.jpg`, `medical_2.jpg` and `medical_3.jpg`. They have asked us to perform accurate edge detection in the three images, as well as to provide an explanation of how it has been made.

```
In [28]: import numpy as np
         from scipy import signal
         import cv2
         import matplotlib.pyplot as plt
         import matplotlib
         from ipywidgets import interactive, fixed, widgets
         matplotlib.rcParams['figure.figsize'] = (15.0, 15.0)

         images_path = './images/'

         def sobel_h_55():
             return np.array([
                 [1,2,0,-2,-1],
                 [2,3,0,-3,-2],
                 [3,5,0,-5,-3],
                 [2,3,0,-3,-2],
                 [1,2,0,-2,-1],
             ])*1/9

         def sobel_v_55():
             return np.transpose(sobel_h_55())*-1

         def general_h_kernel(k):
             return np.array([
                 [1,0,-1],
                 [k,0,-k],
                 [1,0,-1]
             ])*1/(2+k)

         def general_v_kernel(k):
             return np.transpose(general_h_kernel(k))*-1
```

To face this challenge, we are going to use plenty edge detection methods, which will be tested and compared in order to determine the best option.

ASSIGNMENT 1: Taking a look at images

First, **display the provided images** to get an idea about what we are dealing with.

Note: As most medical images does not provide color information, we are going to use border detection in grayscale images.

Tip: Different approaches can be followed for edge detection in color images, like converting to YCrCb color space (appendix 2), or detecting edges on each RGB channel.

```
In [29]: # ASSIGNMENT 1
         # Display the provided images in a 1x3 plot to see what are we deal.
         # Write your code here!

         # Read the images
         medical_1 = cv2.imread(images_path + 'medical_1.jpg', 0)
         medical_2 = cv2.imread(images_path + 'medical_2.jpg', 0)
         medical_3 = cv2.imread(images_path + 'medical_3.jpg', 0)

         # And show them
         plt.subplot(131)
```
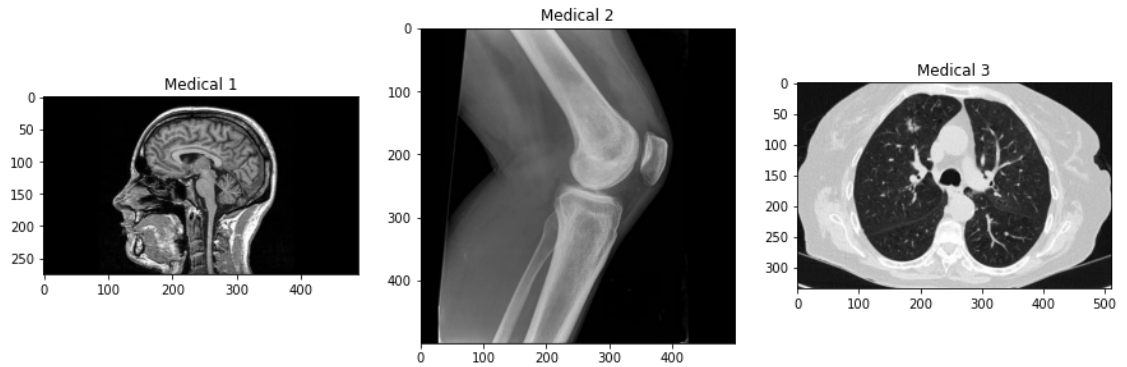
```
plt.imshow(medical_1, cmap='gray')
plt.title('Medical 1')

plt.subplot(132)
plt.imshow(medical_2, cmap='gray')
plt.title('Medical 2')

plt.subplot(133)
plt.imshow(medical_3, cmap='gray')
plt.title('Medical 3')
plt.show()
```


3.1.1 Discrete approximations of a gradient operator

The first bunch of methods that we are going to explore carry out a **discrete approximation of a gradient operator** based on the differences between gray (intensity) levels. For example, in order to obtain the derivative in the rows' direction, we could apply:

- Backward difference of pixels along a row:

$$f_x(x, y) \approx G_R(i, j) = [F(i, j) - F(i - 1, j)]/T$$

0	0	0
0	1	-1
0	0	0

- Symmetric difference of pixels along a row:

$$f_x(x, y) \approx G_R(i, j) = [F(i + 1, j) - F(i - 1, j)]/2T$$

0	0	0
1	0	-1
0	0	0

These approximations are typically implemented through the convolution of the image with a pair of templates H_C (for columns, detecting vertical edges) and H_R (for rows, detecting horizontal ones), that is:

$$G_R(i, j) = F(i, j) \otimes H_R(i, j)$$
$$G_C(i, j) = F(i, j) \otimes H_C(i, j)$$

Perhaps the most popular operator doing this is such of **Sobel**, although there are many of them that provide acceptable results. These operators use the aforementioned two kernels (typically of size 3×3 or 5×5) which are convolved with the original image to calculate approximations of the derivatives.

These are some examples (first column: operator name; second one: H_R; third column:

H_C):

Roberts		0	0	0		-1	0	0
		0	0	1		0	1	0
		0	-1	0		0	0	0

Prewitt	$\frac{1}{3}$	1	0	-1	$\frac{1}{3}$	-1	-1	-1
		1	0	-1		0	0	0
		1	0	-1		1	1	1

Sobel	$\frac{1}{4}$	1	0	-1	$\frac{1}{4}$	-1	-2	-1
		2	0	-2		0	0	0
		1	0	-1		1	2	1

Frei-Chen	$\frac{1}{2+\sqrt{2}}$	1	0	-1	$\frac{1}{2+\sqrt{2}}$	-1	$-\sqrt{2}$	-1
		$\sqrt{2}$	0	$-\sqrt{2}$		0	0	0
		1	0	-1		1	$\sqrt{2}$	1

|								
In general	$\frac{1}{2+K}$	1	0	-1	$\frac{1}{2+K}$	-1	$-K$	-1
		K	0	$-K$		0	0	0
		1	0	-1		1	K	1

At this point we know how to perform a discrete approximation of a gradient operator through the application of a convolution operation with two different kernels, that is:

$$\nabla F(x, y) = \begin{bmatrix} F \otimes H_C \\ F \otimes H_R \end{bmatrix}$$

But, how could we use the output of those computations to detect edges? The following figure clarifies that!

Gradient image|G(i,j)|

$> \text{Threshold at } (i_0, j_0)$ — no

yes

(i_0, j_0) is an edge point
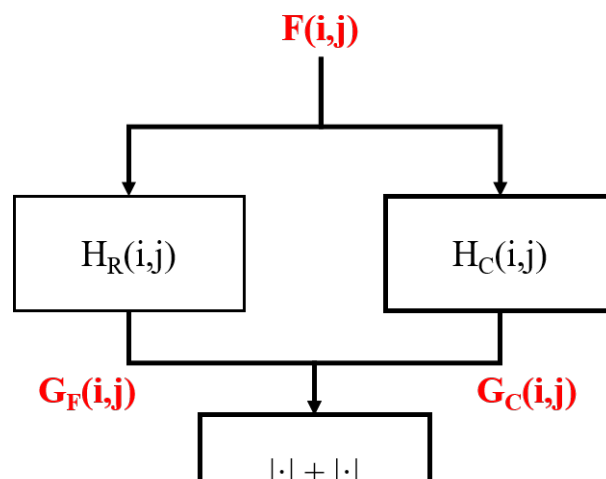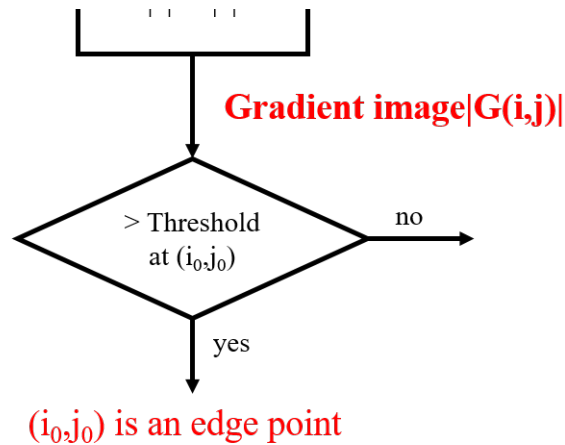
Kernel sizes

As discussed, kernels can be of different size, and that size directly affects the quality of the detection and the localization (e.g. Sobel 3×3 or 5×5):

- Small template:
  - more precise localization (good localization).
  - more affected by noise (likely produces false positives).
- Large template:
  - less precise localization.
  - more robust to noise (good detector).
  - higher computational cost ($O(N \times N)$).

ASSIGNMENT 2: Playing with Sobel derivatives

Now that we have acquired a basic understanding of these methods, let's complete the following code cell to employ the Sobel kernels (S_x, S_y) to compute both derivatives and display them along with the original image (medical_3.jpg).

*Notice that the derivative image values can be positive **and negative**, caused by the negative values in the kernel. This implies that the desired depth of the destination image (ddepth) has to be at least a signed data type when calling to the filter2D() method.*

In [30]:
```python
# ASSIGNMENT 2
# Read one of the images, compute both kernel derivatives, apply the
# Write your code here!

# Read the image
image = cv2.imread(images_path + 'medical_3.jpg', 0)

# Define horizontal and vertical kernels
kernel_h = general_h_kernel(2)
kernel_v = general_v_kernel(2)

# Apply convolution
d_horizontal = cv2.filter2D(image,cv2.CV_16S,kernel_h) # Using ddep
d_vertical = cv2.filter2D(image,cv2.CV_16S,kernel_v)

# And show them!
plt.subplot(131)
```
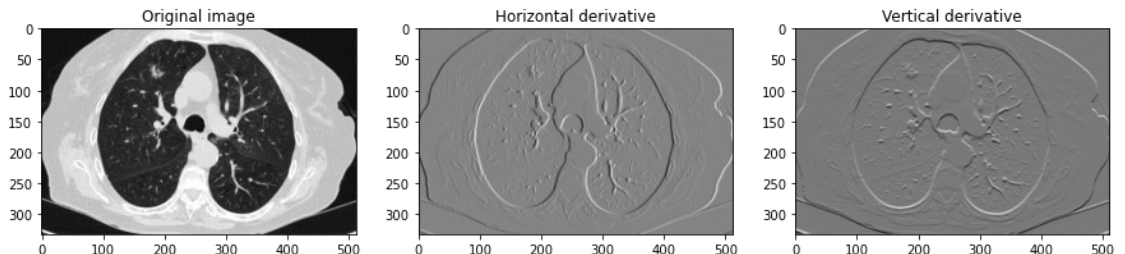
```
plt.imshow(image, cmap='gray')
plt.title('Original image')

plt.subplot(132)
plt.imshow(d_horizontal, cmap='gray')
plt.title('Horizontal derivative')

plt.subplot(133)
plt.imshow(d_vertical, cmap='gray')
plt.title('Vertical derivative');
```


Once we have computed both derivative images G_C and G_R, we can determine the *complete* edge image by computing the image gradient magnitude and then binarizing the result. Recall that the image codifying the gradient magnitude can be computed as:

$$|\nabla F(x, y)| = \sqrt{(F \otimes G_C)^2 + (F \otimes G_R)^2} \approx |F \otimes G_C| + |F \otimes G_R|$$

ASSIGNMENT 3a: Time to detect edges

Complete `edge_detection_chart()` that computes the gradient image of an input one using `kernel_h` and `kernel_v` (kernels for horizontal and vertical derivatives respectively) and **binarize the resultant image** (final edges image) using `threshold`. Then display in a 1x3 plot `image`, the gradient image, and finally, an image with the detected edges! (Only if `verbose` is True).

Tip: you should normalize (https://docs.opencv.org/2.4/modules/core/doc /operations_on_arrays.html#normalize) gradient image before thresholding.

Interesting functions: np.absolute() (https://numpy.org/doc/stable/reference /generated/numpy.absolute.html), np.add() (https://numpy.org/doc/stable/reference /generated/numpy.add.html), cv2.threshold() (https://docs.opencv.org/master /d7/d1b/group__imgproc__misc.html#gae8a4a146d1ca78c626a53577199e9c57)

```
In [31]: # ASSIGNMENT 3a
         # Implement a function that that computes the gradient of an image,
         # It must also binarize the resulting image using a threshold
         # Show the input image, the gradient image (normalized) and the bina
         def edge_detection_chart(image, kernel_h, kernel_v, threshold, verbo
             """ Computed the gradient of the image, binarizes and display i

                 Args:
                     image: Input image
                     kernel_h: kernel for horizontal derivative
                     kernel_v: kernel for vertical derivative
                     threshold: threshold value for binarization
                     verbose: Only show images if this is True
```

```
        Returns:
            edges: edges binary image
    """
    # Write your code here!

    # Compute derivatives
    d_h = cv2.filter2D(image, cv2.CV_16S, kernel_h) # horizontal
    d_v = cv2.filter2D(image, cv2.CV_16S, kernel_v) # vertical

    # Compute gradient
    gradient_image = np.absolute(np.add(d_h, d_v)) # Hint: You have

    #Normalize gradient
    norm_gradient = np.copy(image)
    norm_gradient = cv2.normalize(gradient_image, norm_gradient, 0,

    # Threshold to get edges
    ret, edges = cv2.threshold(norm_gradient, threshold, 255, cv2.Th

    if verbose:
        # Show the initial image
        plt.subplot(131)
        plt.imshow(image, cmap='gray')
        plt.title('Original image')

        # Show the gradient image
        plt.subplot(132)
        plt.imshow(gradient_image, cmap='gray')
        plt.title('Gradient image')

        # Show edges image
        plt.subplot(133)
        plt.imshow(edges, cmap='gray')
        plt.title('Edges detected')

    return edges
```

You can use next code to **test if your results are correct**:

```
In [32]: image = np.array([[10,60,20],[60,22,74],[72,132,2]], dtype=np.uint8

# Sobel derivatives
kernel_h = np.array([[1,0,-1],[2,0,-2],[1,0,-1]])*1/4
kernel_v = np.array([[-1,-2,-1],[0,0,0],[1,2,1]])*1/4

print(edge_detection_chart(image, kernel_h, kernel_v, 100))
```

```
[[  0   0   0]
 [255 255 255]
 [  0 255   0]]
```

Expected output:

```
[[  0   0   0]
 [255 255 255]
 [  0 255   0]]
```

ASSIGNMENT 3b: Testing our detector

Now **try the implemented method** with different size Sobel kernels (3×3, 5×5, ...) and with other operators (Roberts, Prewitt, ...).

```
In [33]:  # ASSIGNMENT 3b
          # Read the image, set you kernels (Sobel, Roberts, Prewitt, etc.) a
          # Write your code here!

          # Read image
          image = cv2.imread(images_path + 'medical_3.jpg', cv2.IMREAD_GRAYSC

          # Define kernel (Sobel, Roberts, Prewitt, ...)
          # # Roberts
          kernel_h = np.array([
              [0,0,0],
              [0,0,1],
              [0,-1,0]
          ])
          kernel_v = np.array([
              [-1,0,0],
              [0,1,0],
              [0,0,0]
          ])

          # Prewitt
          # kernel_h = general_h_kernel(1)
          # kernel_v = general_v_kernel(1)

          # # Sobel 3x3
          # kernel_h = general_h_kernel(2)
          # kernel_v = general_v_kernel(2)

          # Sobel 5x5
          kernel_h = sobel_h_55()
          kernel_v = sobel_v_55()

          # # Frei-Chen
          # kernel_h = general_h_kernel(np.sqrt(2))
          # kernel_v = general_v_kernel(np.sqrt(2))

          #Interact with your code!
          interactive( edge_detection_chart, image=fixed(image), kernel_h=fix
```

```
interactive(children=(IntSlider(value=120, description='threshold
', max=255, step=10), Output()), _dom_classes…
```

Thinking about it (1)

Now, **answer following questions**:

- What happens if we use a bigger kernel?

  Si usamos un kernel mas grande este puede dar errores de multiple respuesta ya que segun la imagenes donde se detectan los bordes, estos se ven más gruesos que un pixel, haciendo que no tenga tanta precision como un kernel pequeño

- There are differences between Sobel and other operators?

  Las principales diferencias que dependen de la K en los kernels genericos como frei-chen, sobel y prewit la cual varian su deteccion del borde siendo más gruesos o finos
- What errors appear using those operators?

  Con cualquiera de los operadores vamos a obtener errores de multiple respuesta y falsos negativos y positivos pero estos ultimos en menor medida si son kernels pequeños
- Why kernels usually are divided by a number? (e.g. 3×3 Sobel is divided by 4)

  Para normalizar el kernel y que la operacion de convulucion los valores queden entre 0-255

3.1.2 DroG operator

Despite the simplicity of the previous techniques, they have a remarkable drawback: their performance is highly influenced by image noise. Taking a look at the following figure we can see how, having an apparently not so noisy function (first row), where it is easy to visually detect a step (an abrupt change in its values) around 1000, the response of the derivative with that level of noise is as bigger as the step itself!
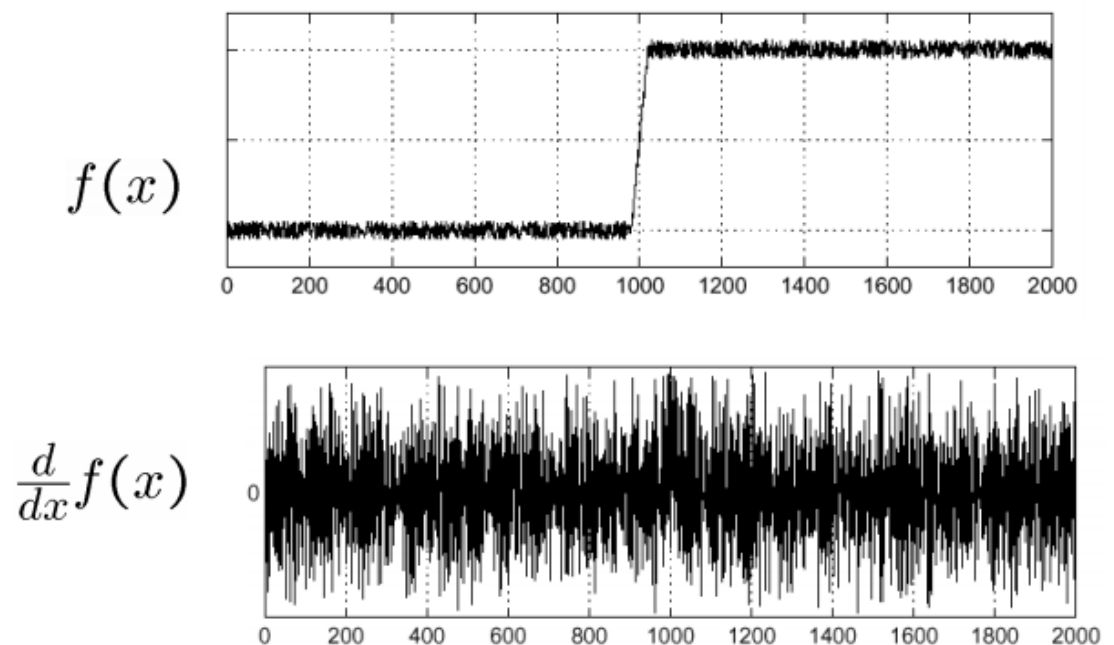
Source: S. Seitz

But not everything is lost! An already studied image processing technique can be used to mitigate such noise: **image smoothing**, and more concretely, **Gaussian filtering!** The basic idea is to smooth the image and then apply a gradient operator, that is to compute $\frac{\partial}{\partial x}(f \otimes g)$. Not only that, this can be done even more efficiently thanks to the convolution derivative property:

$$\frac{\partial}{\partial x}(f \otimes g) = f \otimes \frac{\partial}{\partial x}g$$

That is, precomputing the resultant kernels from the convolution of the Gaussisan filtering and the Sobel ones, and then convolving them with the image to be processed. With that we save one operation!

This combination of smoothing and gradient is usually called **Derivative of Gaussian operator (DroG)**. Formally:

$$\nabla[f(x, y) \otimes g_\sigma(x, y)] = f(x, y) \otimes \nabla[g_\sigma(x, y)] = f(x, y) \otimes \text{DroG}(x, y)$$

$$DroG(x, y) = \nabla[g_\sigma(x, y)] = \underbrace{\begin{bmatrix} \frac{\partial}{\partial x}[g_\sigma(x)g_\sigma(y)] \\ \frac{\partial}{\partial y}[g_\sigma(x)g_\sigma(y)] \end{bmatrix}}_{\text{separability}} = \underbrace{\begin{bmatrix} \frac{-xg_\sigma(x,y)}{\sigma^2} \\ \frac{-yg_\sigma(x,y)}{\sigma^2} \end{bmatrix}}_{g(x)'=-xg(x)/\sigma^2}$$

Remember from the previous notebooks the expression of the Gaussian distribution with 2 variables centered at the origin of coordinates, where the standard deviation σ controls the degree of smoothness:

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

Take into account that the DroG template or kernel is **created just once**! Then it can applied to as many images as you want.

ASSIGNMENT 4: Applying DroG

We would like to try this robust edge detection technique, so complete the `gaussian_kernel()` method that:

1. constructs a 2D gaussian filter (that is, $g_\sigma(x, y)$ in the previous DroG definition) from a 1D one, and
2. derives it, getting the DroG template (in other words, compute $-xg_\sigma(x, y)/\sigma^2$ and $-yg_\sigma(x, y)/\sigma^2$).
3. Finally, it calls our function `edge_detection_chart()`, but using the DroG template instead of the Sobel one.

Its inputs are:

- an image to be processed,
- the kernel aperture size,
- the standard deviation, and
- the gradient image binaritazion threshold.

In [23]:
```
# ASSIGNMENT 4
# Implement a function that builds the horizontal and vertical DroG
```

```python
# Inputs: an image, the kernel aperture size, the Gaussian standard
# It returns the horizontal and vertical kernels
def gaussian_kernel(image, w_kernel, sigma, threshold, verbose=False
    """ Construct the DroG operator and call edge_detection_chart.

        Args:
            image: Input image
            w_kernel: Kernel aperture size
            sigma: Standard deviation of the Gaussian distribution
            threshold: Threshold value for binarization
            verbose: Only show images if this is True

        Returns:
            DroG_h, DroG_v: DroG kernerl for computing horizontal a
    """
    # Write your code here!

    # Create the 1D gaussian filter
    s = sigma
    w = w_kernel
    gaussian_kernel_1D = np.array([(np.exp(-(z**2)/(2*(s**2)))))/(s

    # Get the 2D gaussian filter from the 1D one.
    vertical_kernel = gaussian_kernel_1D.reshape(2*w+1,1)
    horizontal_kernel = gaussian_kernel_1D.reshape(1,2*w+1)
    gaussian_kernel_2D = signal.convolve2d(vertical_kernel, horizon

    # Construct DroG

    # Define x and y axis
    x = np.arange(-w,w+1)
    y = np.vstack(x)

    # Get the kernels for detecting horizontal and vertical edges
    DroG_h = x*(-gaussian_kernel_2D)/s**2 # Horizontal derivative
    DroG_v = y*(-gaussian_kernel_2D)/s**2 # Vertical derivative

    # Call edge detection chart using DroG
    edge_detection_chart(image, DroG_h, DroG_v, threshold, verbose)

    return DroG_h, DroG_v
```

You can use next code to **test if results are correct**:

```python
In [24]: # Create an input image
         image = np.array([[10,60,20],[60,22,74],[72,132,2]], dtype=np.uint8

         # Apply the Gaussian kernel
         gaussian_kernel(image, w_kernel=1, sigma=1.2, threshold=100)
```

```
Out[24]: (array([[ 0.03832673, -0.        , -0.03832673],
                 [ 0.05423735, -0.        , -0.05423735],
                 [ 0.03832673, -0.        , -0.03832673]]),
          array([[ 0.03832673,  0.05423735,  0.03832673],
                 [-0.        , -0.        , -0.        ],
                 [-0.03832673, -0.05423735, -0.03832673]]))
```

Expected output:

```
(array([[ 0.03832673, -0.        , -0.03832673],
        [ 0.05423735, -0.        , -0.05423735],
        [ 0.03832673, -0.        , -0.03832673]]),
 array([[ 0.03832673,  0.05423735,  0.03832673],
        [-0.        , -0.        , -0.        ],
        [-0.03832673, -0.05423735, -0.03832673]]))
```

Thinking about it (2)

Now **try this method** and play with its interactive parameters in the next code cell. Then **answer the following questions**:

- What happens if a bigger kernel is used?

  Pues que pierde detalle al suavizar, y por tanto no se detectan bordes donde deberian de estar
- What kind of errors appear and disappear whenever sigma is modified?

  Cuando el sigma es muy pequeño el error predominante es el de fallo de detección (falsos positivos y falsos negativos) Y cuando es grande el error mas comun es de multiple respuesta ya que los bordes comienzan a ser mas gruesos
- Why the gradient image have lower values than the one from the original image? *Tip: image normalization (https://stackoverflow.com/questions/40645985/opencv-python-normalize-image/42164670)*

  Por el normalizado que aplica OpenCV a la imagen
- Now that you have tried different techniques, in your opinion, which is the best one for this type of images?

  Yo creo que la mejor tecnica seria la de DroG ya que con los parametros correctos podriamos eliminar la mayoria de errores con bastante eficacia

In [25]:
```python
# Read the image
image = cv2.imread(images_path + 'medical_3.jpg', 0)

# Interact with the three input parameters
interactive(gaussian_kernel, image=fixed(image), w_kernel=(1,5,1),
```

```
interactive(children=(IntSlider(value=3, description='w_kernel', m
ax=5, min=1), FloatSlider(value=2.4, descrip…
```

ASSIGNMENT 5: Measuring efficiency

Finally, **you are asked to** compare the execution time of creating a DroG template using your previous code (combining two 1-D gaussian filters), with creating a DroG template by directly building the 2-D gaussian filter. Play with different (big) aperture sizes (up to 500).

Interesting resource: how to measure execution time in Python (https://stackoverflow.com/questions/14452145/how-to-measure-time-taken-between-lines-of-code-in-python)

In [26]:
```python
# ASSIGNMENT 5
# Write your code here!

import time

print("Measuring the execution time needed for ...")

s = 1
w = 500

start = time.process_time() # Start timer

# FIRST WAY: Building the 2D gaussian filter from the 1D one

# Create 1D Gaussian filter
gaussian_kernel_1D = np.array([(np.exp(-(z**2)/(2*(s**2)))))/(s * np

# Get the 2D gaussian filter from the 1D one.
vertical_kernel = gaussian_kernel_1D.reshape(2*w+1,1)
horizontal_kernel = gaussian_kernel_1D.reshape(1,2*w+1)
gaussian_kernel_2D = signal.convolve2d(vertical_kernel, horizontal_

# Construct DroG

# Define x and y axis
x = np.arange(-w,w+1)
y = np.vstack(x)

# Get the kernels for detecting horizontal and vertical edges
DroG_h = gaussian_kernel_2D*(-x)/s**2 # Horizontal derivative
DroG_v = gaussian_kernel_2D*(-y)/s**2 # Vertical derivative
print("DroG building time using 1D Gaussian:", round(time.process_t

start = time.process_time() # Start timer

# SECOND WAY: Directly building the 2D gaussian filter

# Create 2D Gaussian filter
gaussian_kernel_2D = np.array([[(np.exp(-((z**2)+(k**2))/(2*(s**2))

# Define x and y axis
x = np.arange(-w,w+1)
y = np.vstack(x)

# Construct DroG
DroG_h = gaussian_kernel_2D*(-x)/s**2 # Horizontal derivative
DroG_v = gaussian_kernel_2D*(-y)/s**2 # Vertical derivative

print("DroG building time using 2D Gaussian:", round(time.process_t
```

```
Measuring the execution time needed for ...
DroG building time using 1D Gaussian: 3.1673 seconds
DroG building time using 2D Gaussian: 3.78574 seconds
```

Conclusion

Awesome! Now you have expertise in more applications of the convolution operator. In
this notebook you:

- Learned basic operators for edge detection that perform a **discrete approximation of a gradient operator**.
- Learned **how to construct a DroG kernel** in an efficient way.
- Played a bit with them in the context of medical images, discovering some real and meaningful utilities.