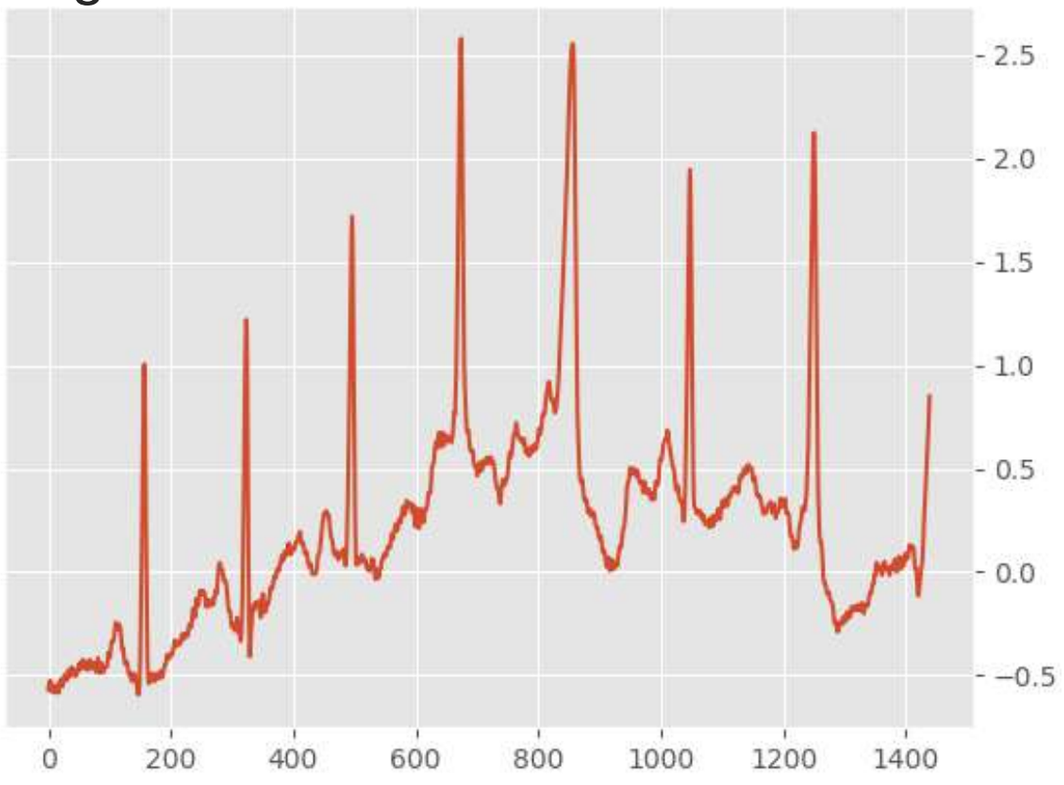
NUS-ISS
Intelligent Sensing and Sense Making

Module 2 - Foundations of sensor signal processing

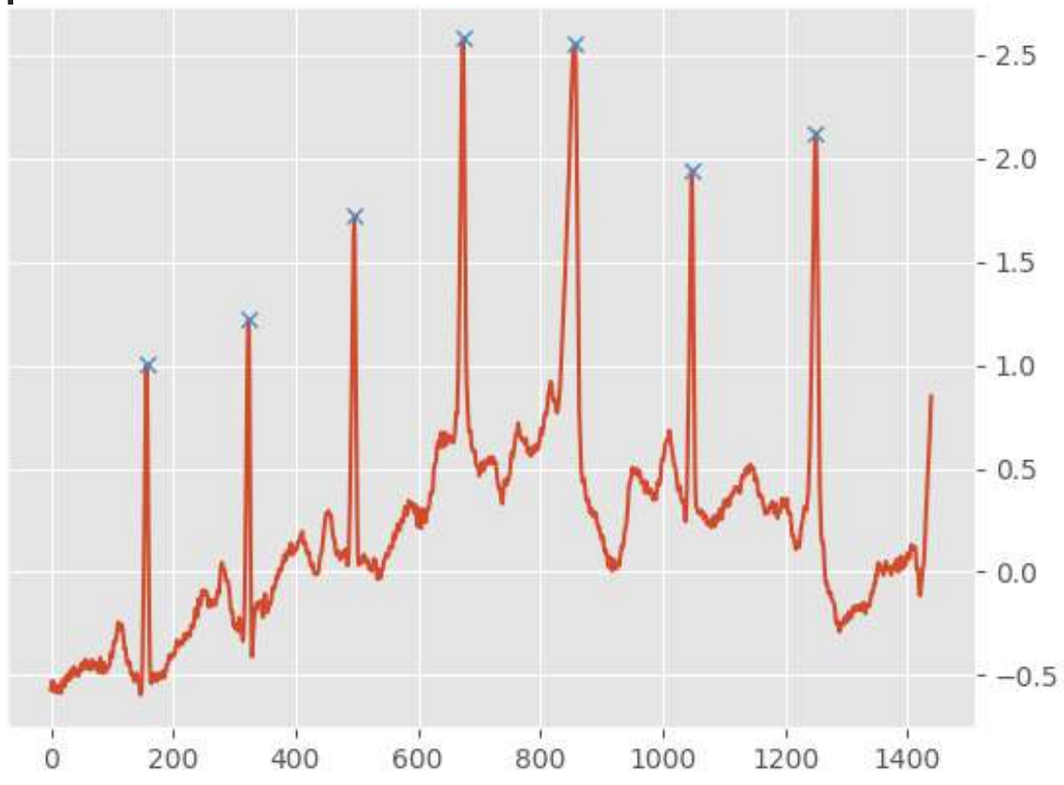
by Nicholas Ho

Problem

original



peaks detected



Peaks

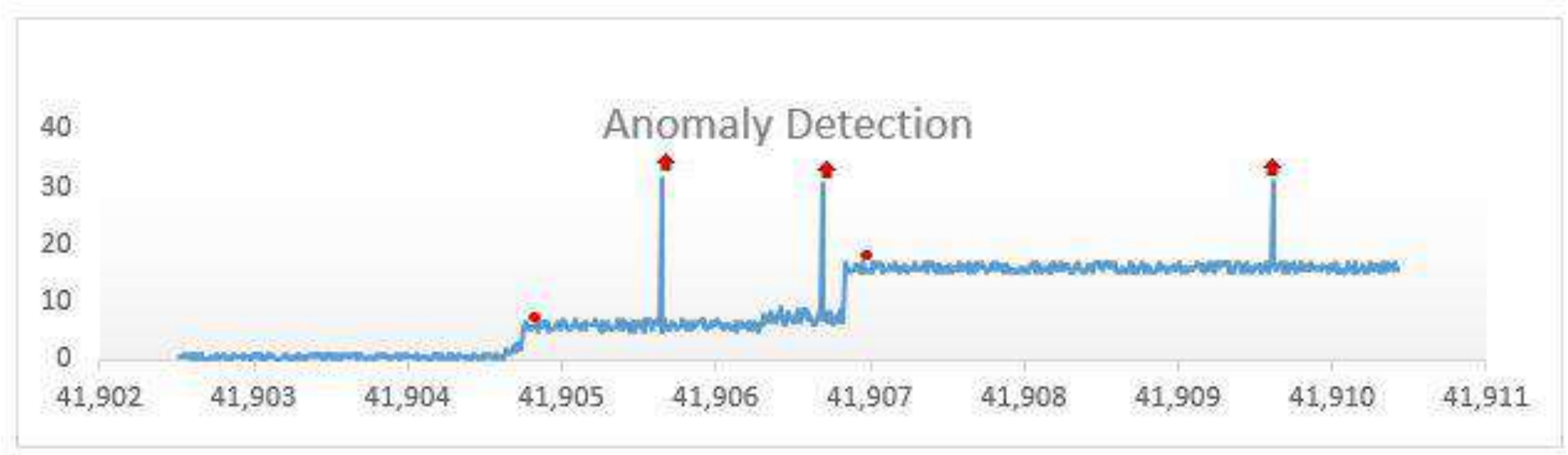
- Peaks: useful topological features of a time-series
- Indicate significant events.
- In network distribution data, indicate sudden high demands
- In server utilization workload, indicate sharp increase in workload

Source: https://pixabay.com/en/alps-mountain-peaks-nature-snow-2194319/

Anomaly detection

For log analytics

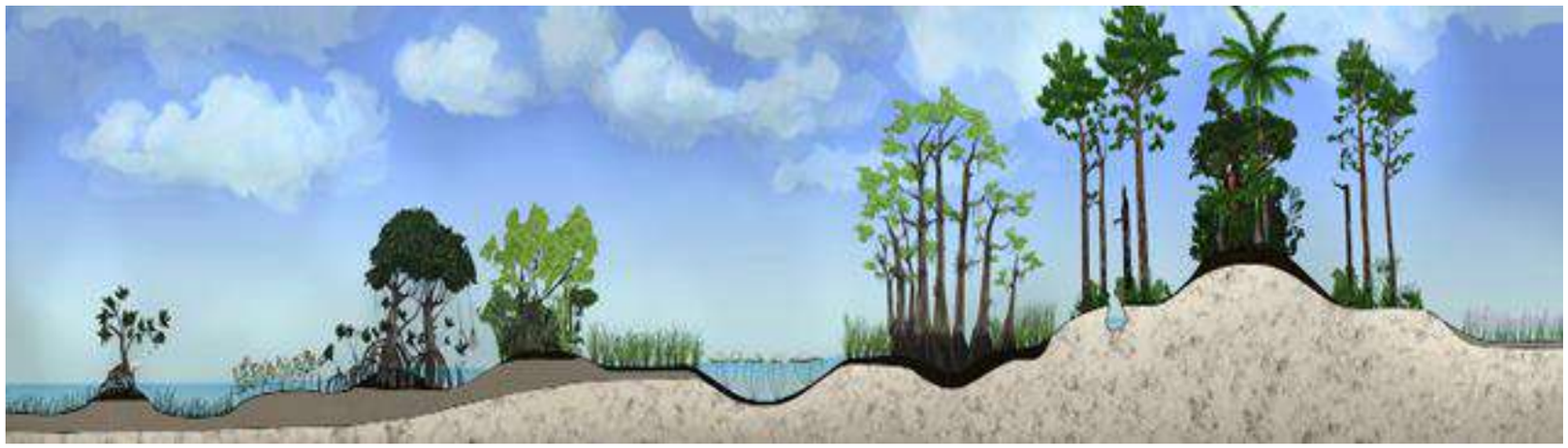
- Time series has 2 distinct level changes and 3 spikes
- Red dots show the time when level change is detected
- Red arrows show detected spikes



Source: https://blogs.technet.microsoft.com/machinelearning/2014/11/05/anomaly-detection-using-machine-learning-to-detect-abnormalities-in-time-series-data/

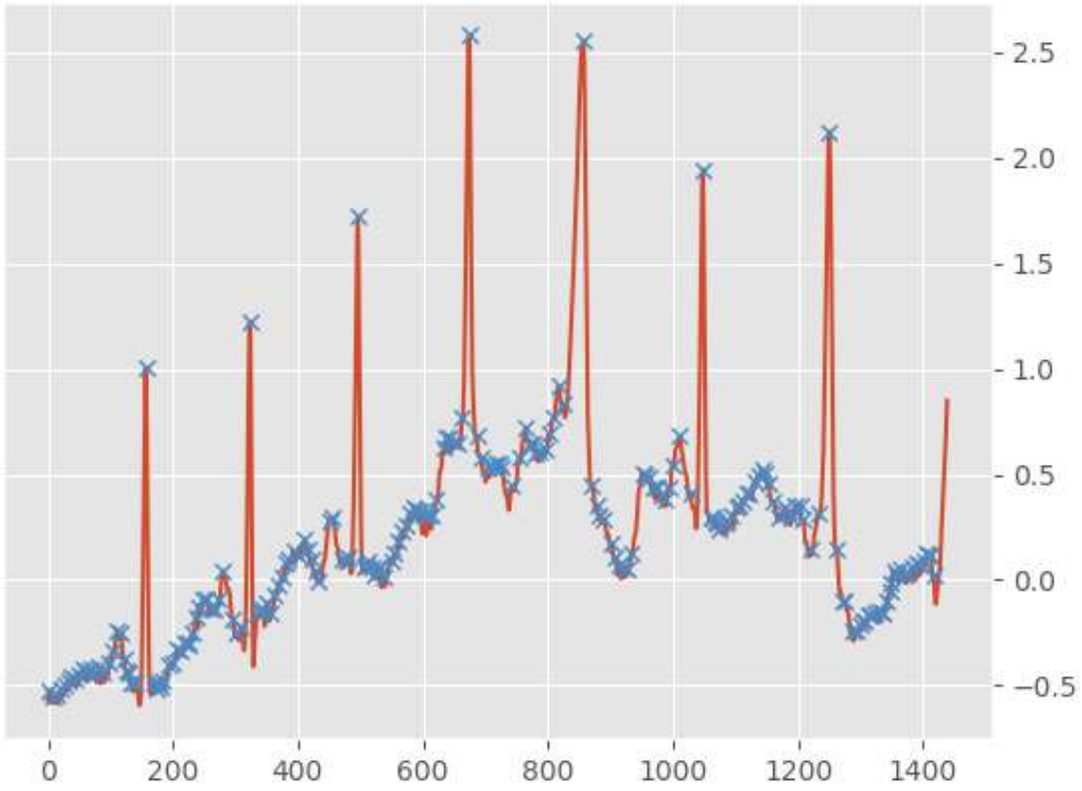
Peaks / Troughs

- Troughs: considered inverted peaks, equally important in many applications
- After peaks detected, analysis of peaks involving
  - identifying periodicity of peaks
  - forecasting the time of occurence and value of next peak
  - identifying dependencies among of peaks of two or more time-series



Source: https://www.nps.gov/ever/learn/education/learning/mntsandvalleys.htm

Peaks / Troughs



- Peaks easily identified visually, but not so straightforward doing through algorithm
- Noise in data creates tremendous amount of false positive
- Some peaks are not result of noise, but still not relevant/desirable in analysis

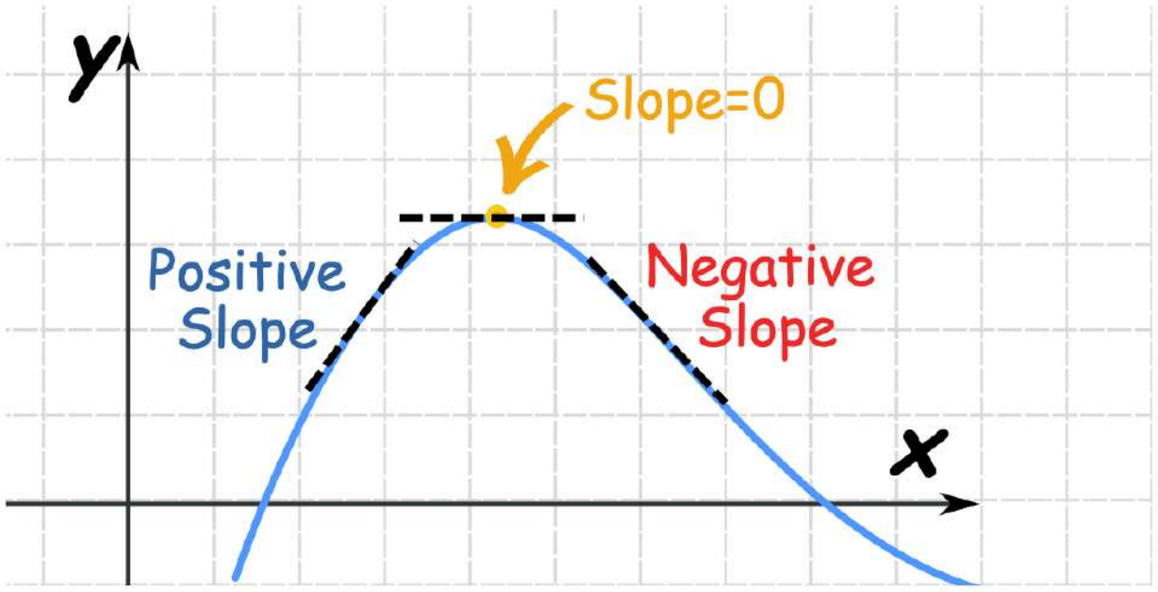
Maxima / Minima

- For a time-continuous signal, peaks / troughs can be determined by searching maxima / minima in the signal

- Assume $y = f(x) \qquad x, y \in R$

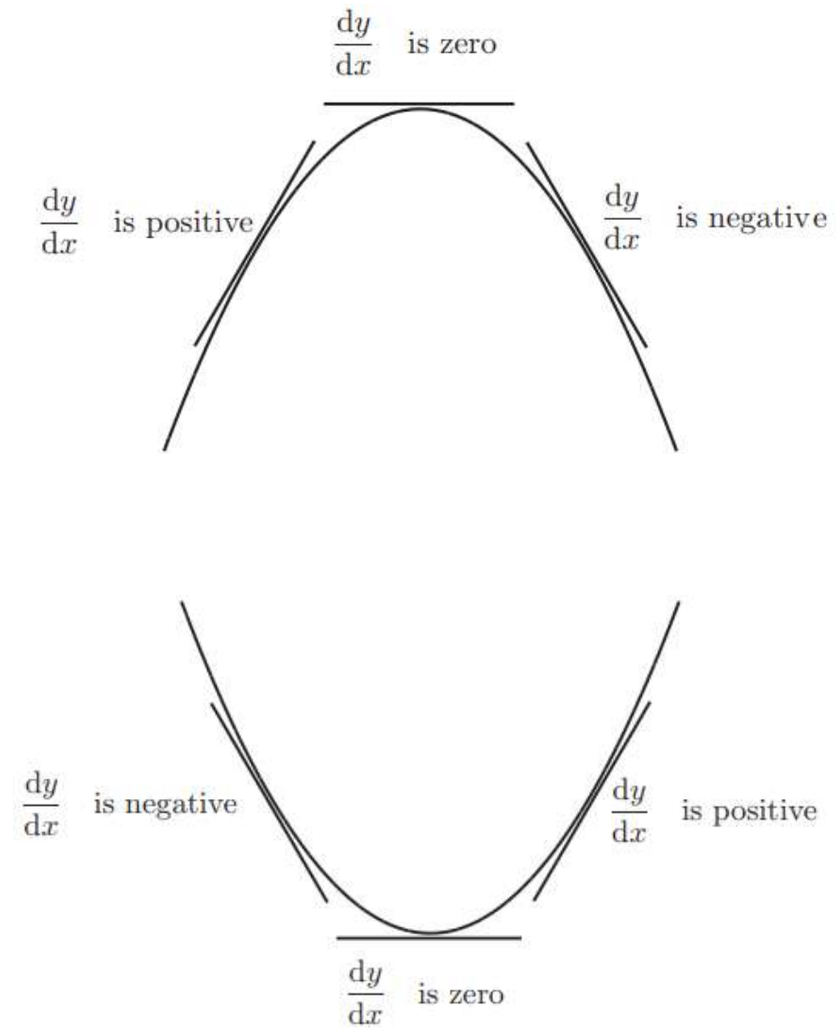
- The maxima and minima are points where

$$\frac{\mathrm{dy}}{\mathrm{d}x} = f'(x) = 0$$



Source: https://www.mathsisfun.com/calculus/maxima-minima.html

Maxima / Minima



Source: https://www.toppr.com/guides/maths/application-of-derivatives/maxima-and-minima/

- At a maxima, f'(x) changes sign from + to -
- At a minima, f'(x) changes sign from - to +
- Question: Is this entire idea applicable to discrete signal?
- Question: Should we search the signal and find the point where f'(x) equals to 0?

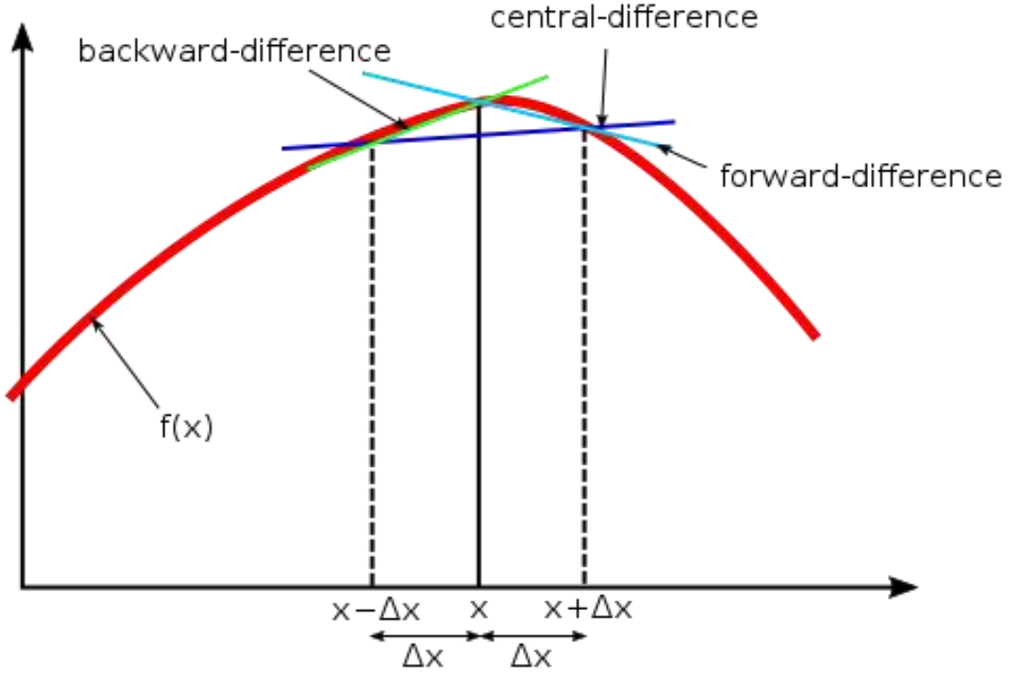
Finite difference

- Forward difference

$$f'(x) = \frac{f(x + \Delta x) - f(x)}{\Delta x}$$

- Backward difference

$$f'(x) = \frac{f(x) - f(x - \Delta x)}{\Delta x}$$

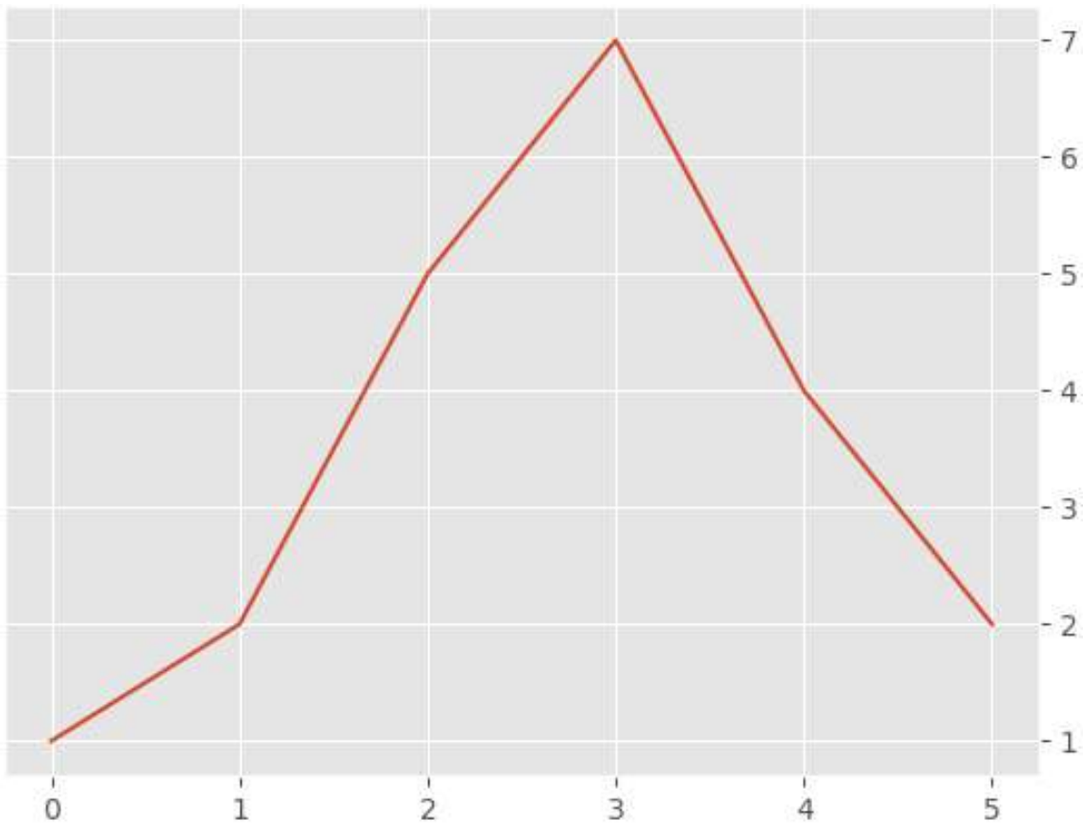


- Central difference

$$f'(x) = \frac{f(x + \Delta x) - f(x - \Delta x)}{2\Delta x}$$

Source: https://www.toppr.com/guides/maths/application-of-derivatives/maxima-and-minima/

Finite difference in numpy



- Import the necessary, create the array

```
> import numpy as np
> sg  = np.array([1,2,5,7,4,2])
```

- Calculate the finite difference (forward difference by default in numpy)

```
> dsg = np.diff(sg)
> dsg
: array([ 1,  3,  2, -3, -2])
```

Plotting ....

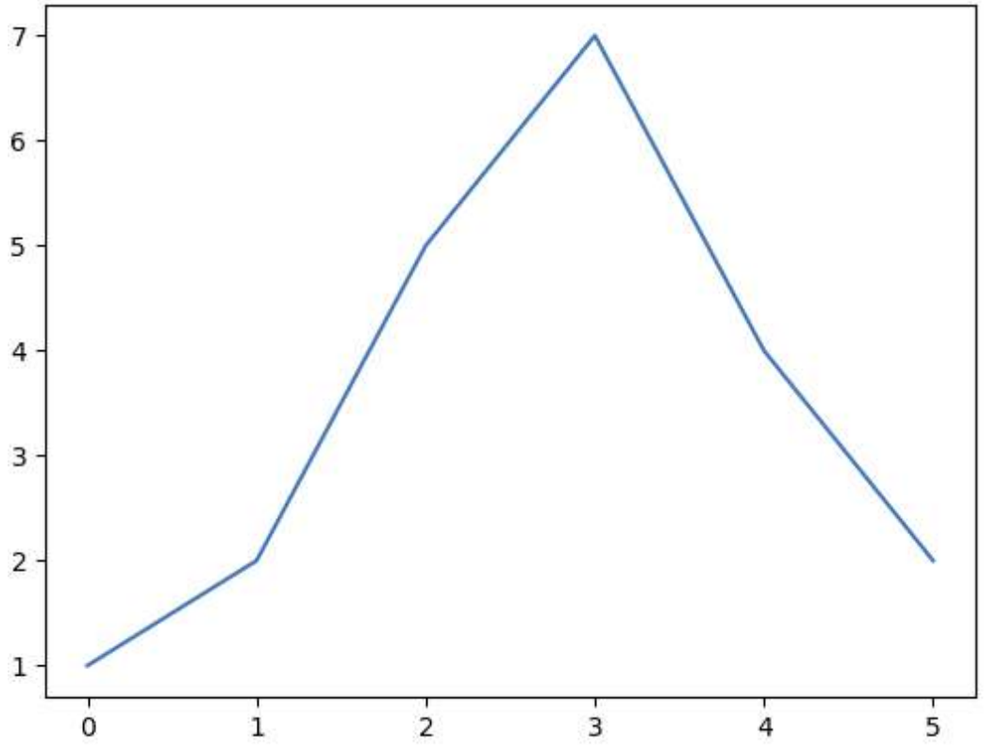
- Use matplotlib to do plotting

```
> import matplotlib.pyplot as plt
```

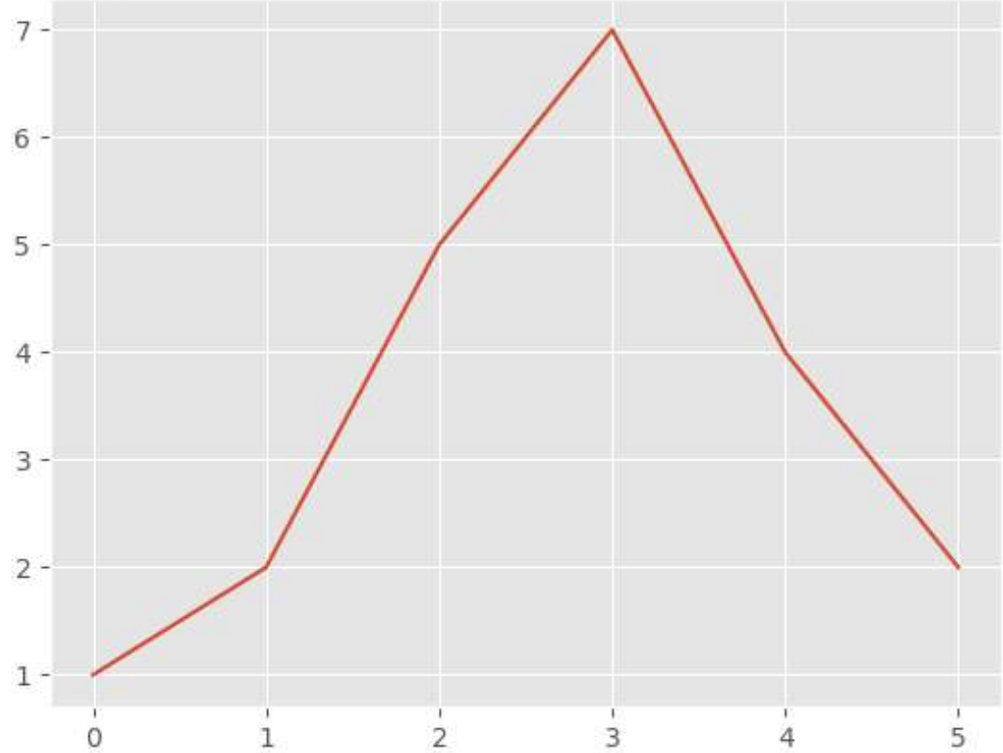
- Change plotting style to 'ggplot', if want to change back to default, set 'classic'

```
> plt.style.use('ggplot')
```

'classic'



'ggplot'



Plotting ....

- Show the y-axis label values at the right side

```
> plt.rcParams['ytick.right']     = True
> plt.rcParams['ytick.labelright']= True
> plt.rcParams['ytick.left']      = False
> plt.rcParams['ytick.labelleft'] = False
```

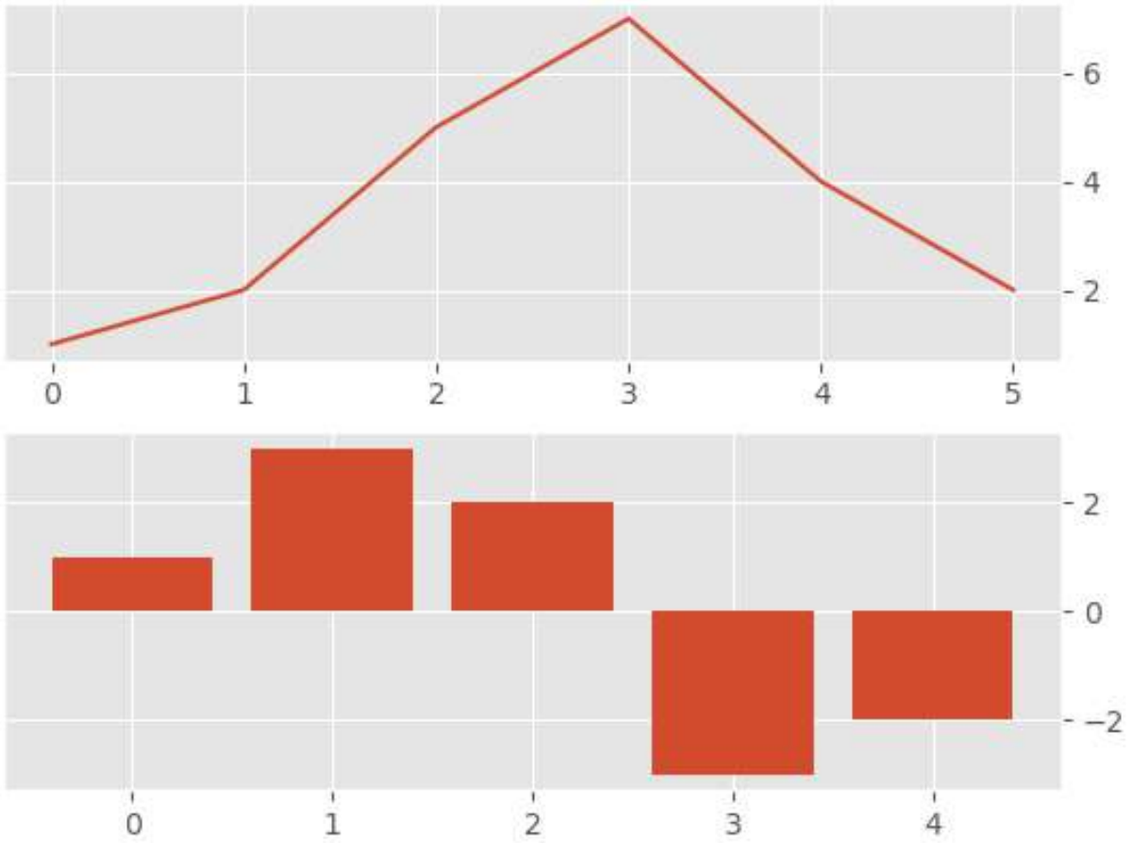
left

right

Finite difference in numpy

- Plot graph and take a look

```
> plt.figure()
> plt.subplot(211)
> plt.plot(sg)
> plt.subplot(212)
> plt.bar(np.arange(dsg.shape[0]),
          dsg,)
```



Looking at this chart, what is the right strategy to search for peaks in discrete signal?

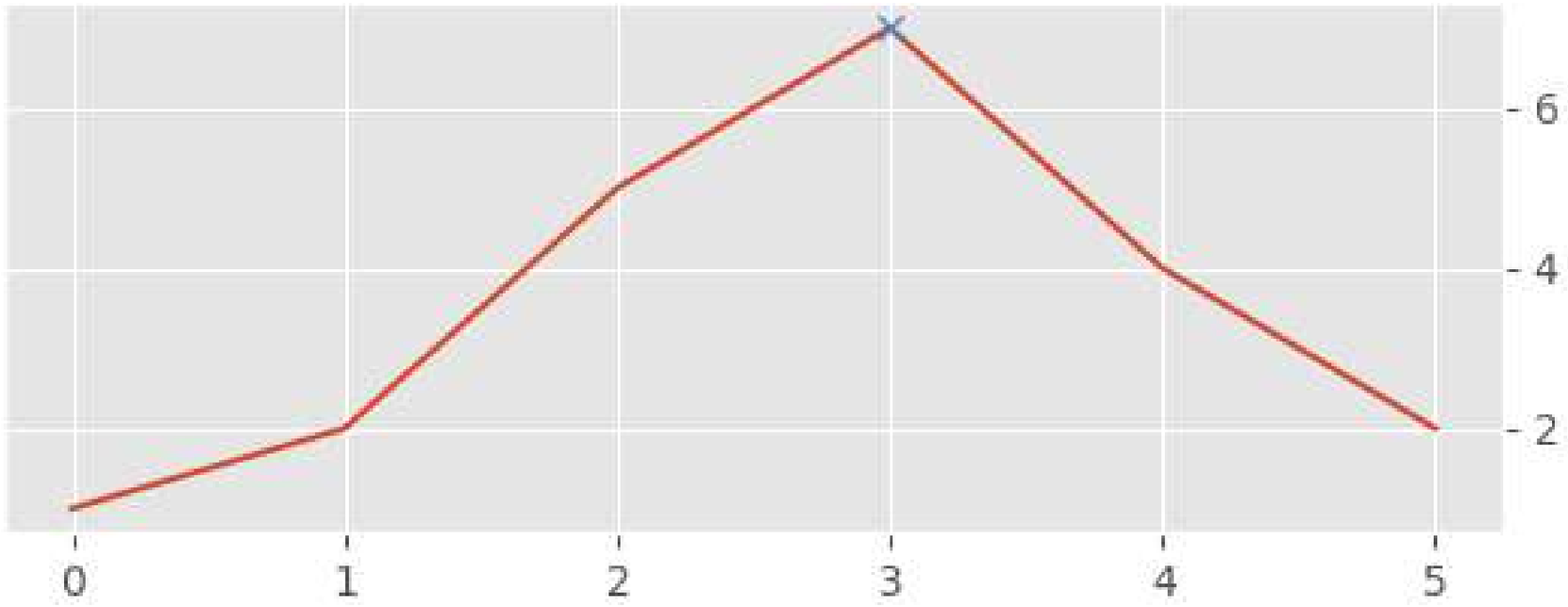
Finding peak

- using `findPeaks` from `scipy`

```
> from scipy.signal import find_peaks as findPeaks
> (Pks,_) = findPeaks(sg)
> Pks
: array([3])
```

- Plot the finding

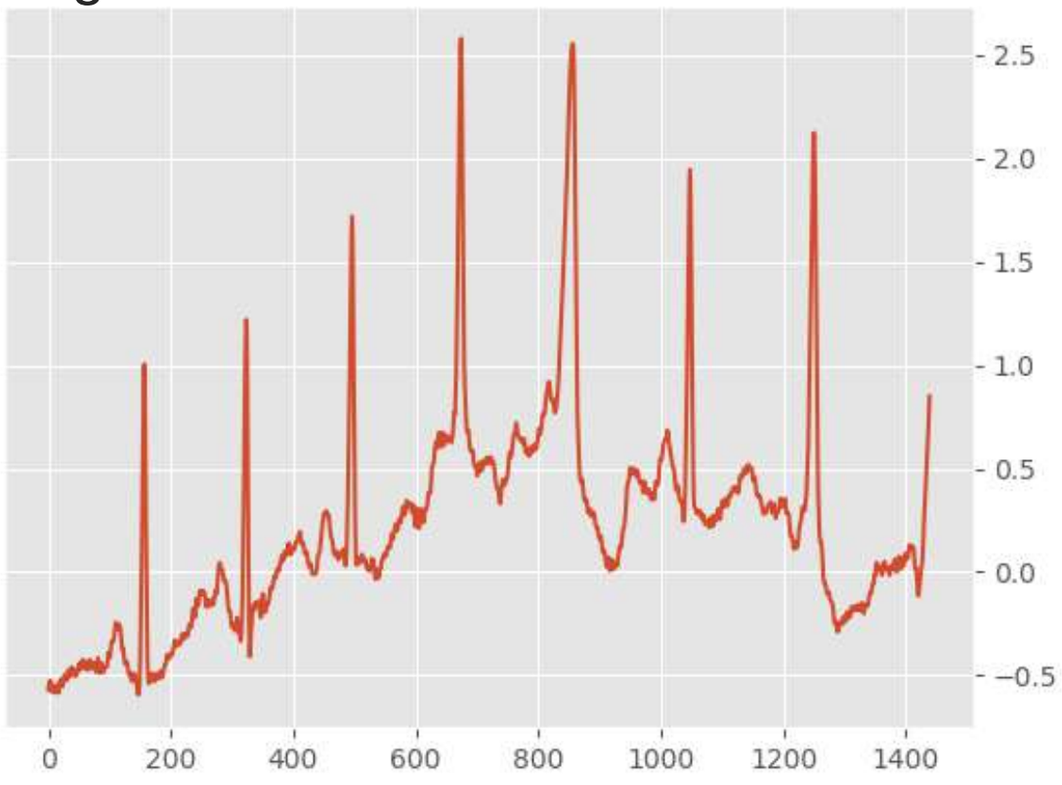
```
> plt.figure()
> plt.plot(sg)
> plt.plot(Pks,sg[Pks],'x')
```



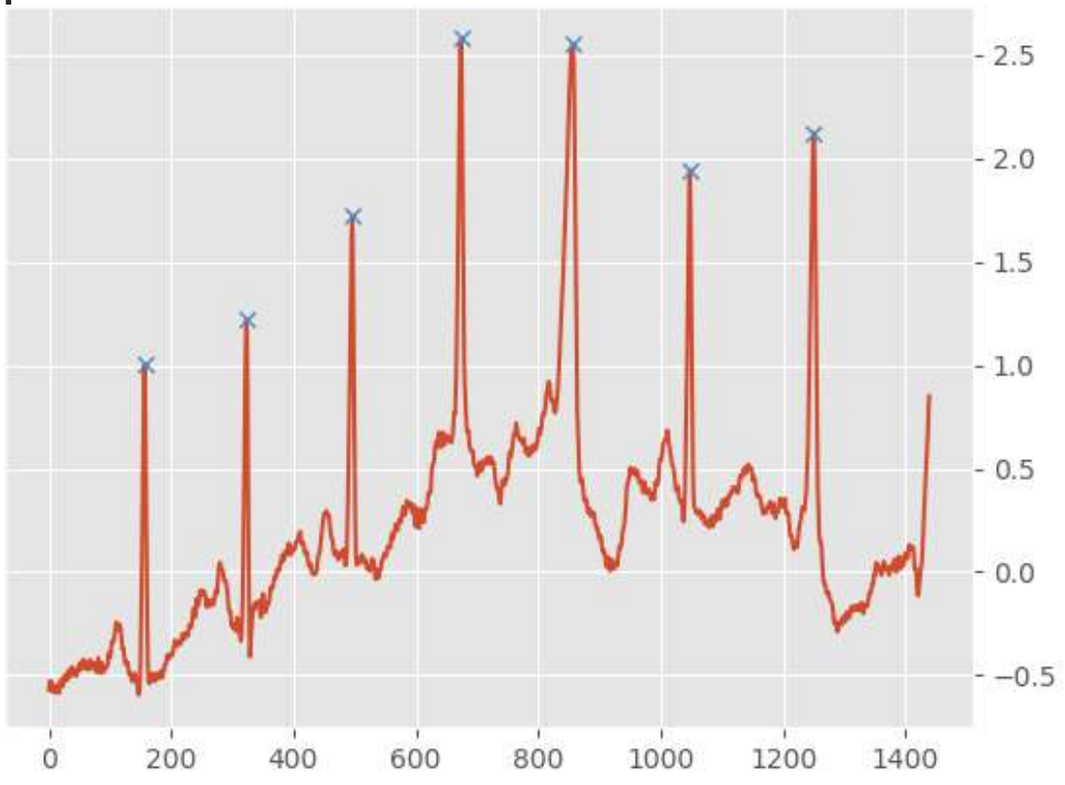
Back to the problem

- Steps to do:
  1. Load data
  2. run `findPeaks`
  3. Fine tune / optimizing
  4. Repeat step 2 and 3 until we get satisfactory detection
  5. Display output

original



peaks detected



Solving the problem

1. Load data

-0.57
-0.545
-0.535
-0.525
-0.545
-0.58
-0.575
-0.565
-0.555
-0.55
-0.57
-0.585
-0.57
-0.56
-0.555
-0.545
-0.565
-0.585
-0.55
-0.535
-0.52
-0.535
-0.55
-0.555
.
.
.

- Many times 1D signal comes in the form of comma-separated values (csv)
  - fields/columns separated by comma
  - record/rows terminated by newline

- Use pandas to read in csv

```
> import pandas as pd
> l1D  = pd.read_csv('ecg1D.csv',
                     header=None)
> ecg1D= l1D[0].values
```

Name ▲	Type	Size	Value
ecg1D	float64	(1440,)	[-0.57 -0.545 -0.535 ... 0.685 0.78 0.85]
l1D	DataFrame	(1440, 1)	Column names: 0

About pandas ...

reading csv...

- Read in a csv with header

```
> pos  = pd.read_csv('pos.csv')
> list(pos)
: ['x', ' y', 'z']
```

- Sometimes it is good to list out the header, because some headers may have an empty space before letters

- To convert a column into a numpy array

```
> y   = pos[' y'].values
```

x, y,z
1.3,0.1,2.2
1.1,0.05,2.6
-0.7,0.3,2.5
-0.5,0.36,2.5

Name ▲	Type	Size	Value
pos	DataFrame	(4, 3)	Column names: x, y, z
y	float64	(4,)	[0.1 0.05 0.3 0.36]

Solving the problem

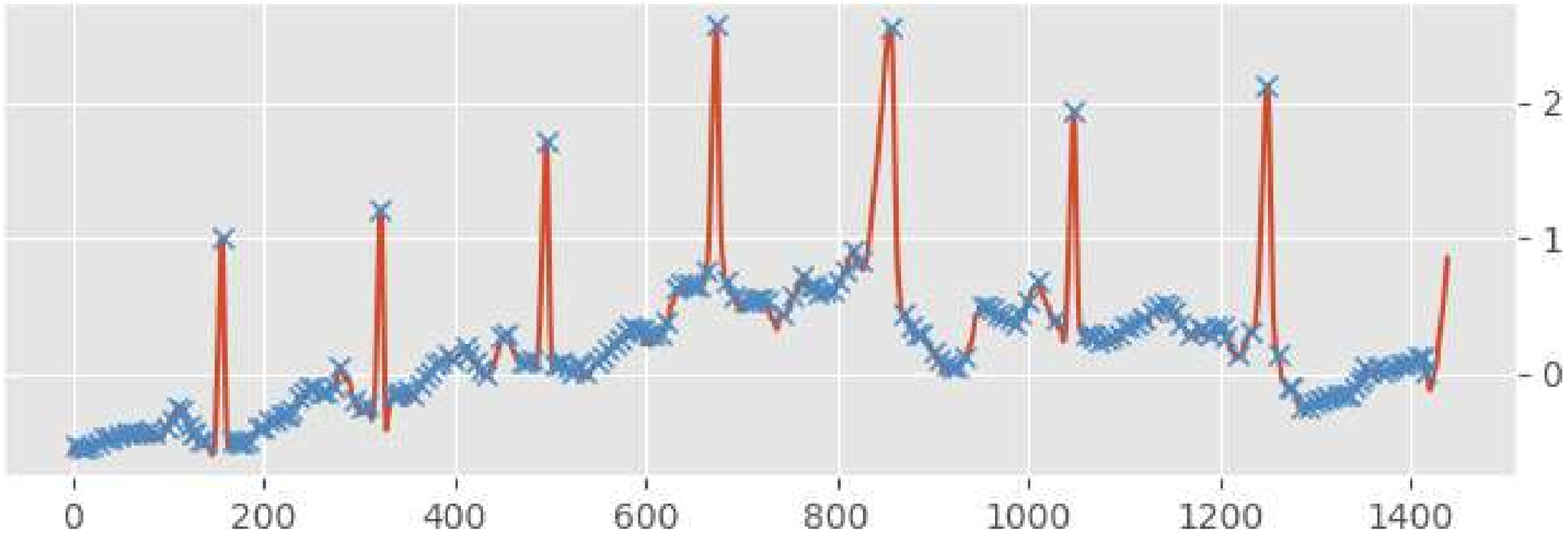
2. run `findPeaks`

- run findPeaks without any adjustment or arguments

```
> from scipy.signal import find_peaks as findPeaks
> (allPks,_) = findPeaks(ecg1D)
```

- Plot the output

```
> plt.figure()
> plt.plot(ecg1D)
> plt.plot(allPks,ecg1D[allPks],'x')
```



Solving the problem

2, 3. fine tune and re-run

`findPeaks`

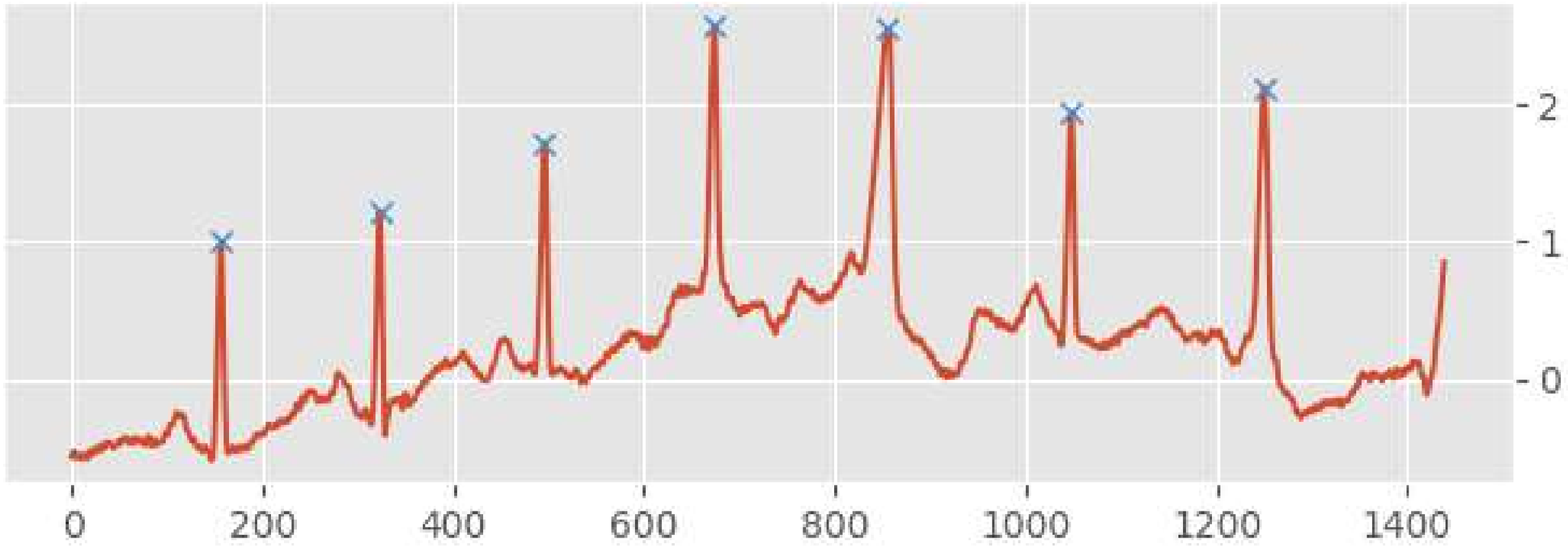
- Add additional arguments to improve outcome

```
> (somePks,_) = findPeaks(ecg1D,height=1)
```

- Get only peaks with height of at least 1

```
> plt.figure()
> plt.plot(ecg1D)
> plt.plot(somePks,ecg1D[somePks],'x')
```

It works, but is this a good strategy?



Solving the problem

2, 3. fine tune and re-run

`findPeaks`

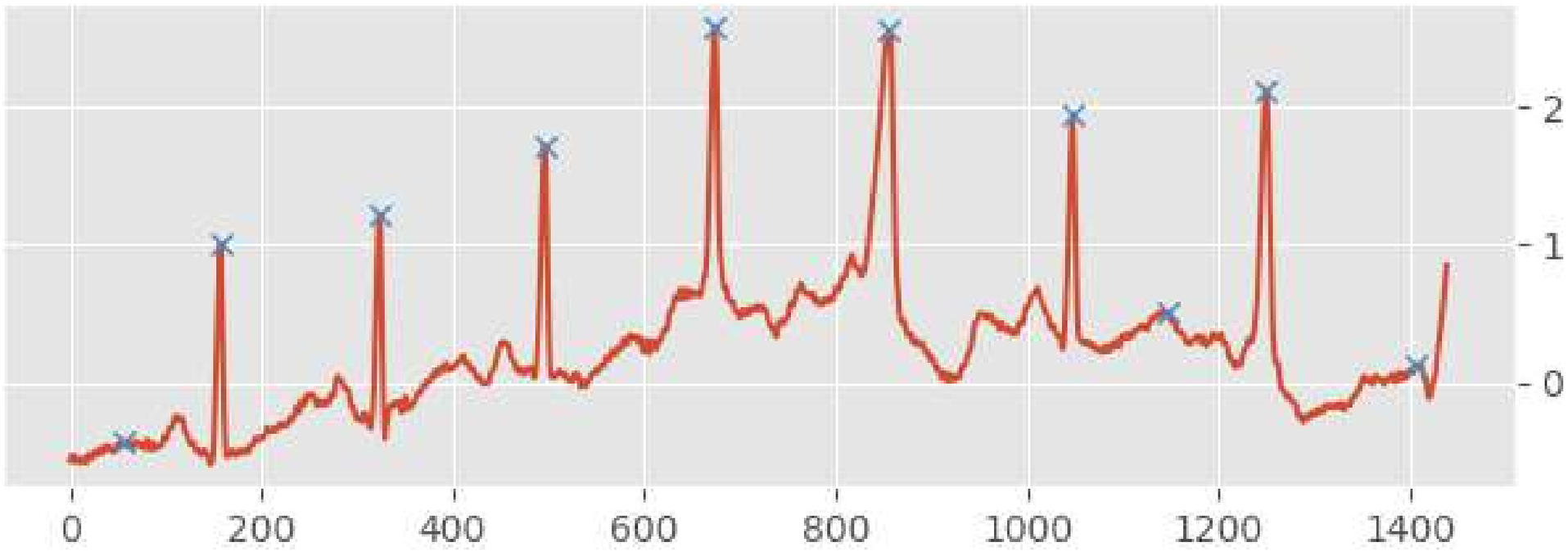
- Try another strategy, use distance

```
> (distPks,_) = findPeaks(ecg1D,distance=100)
```

- Get only peaks with at least 100 points apart

```
> plt.figure()
> plt.plot(ecg1D)
> plt.plot(somePks,ecg1D[somePks],'x')
```

Some points at T wave are picked up, some are not, why?



Solving the problem

2, 3. fine tune and re-run

`findPeaks`

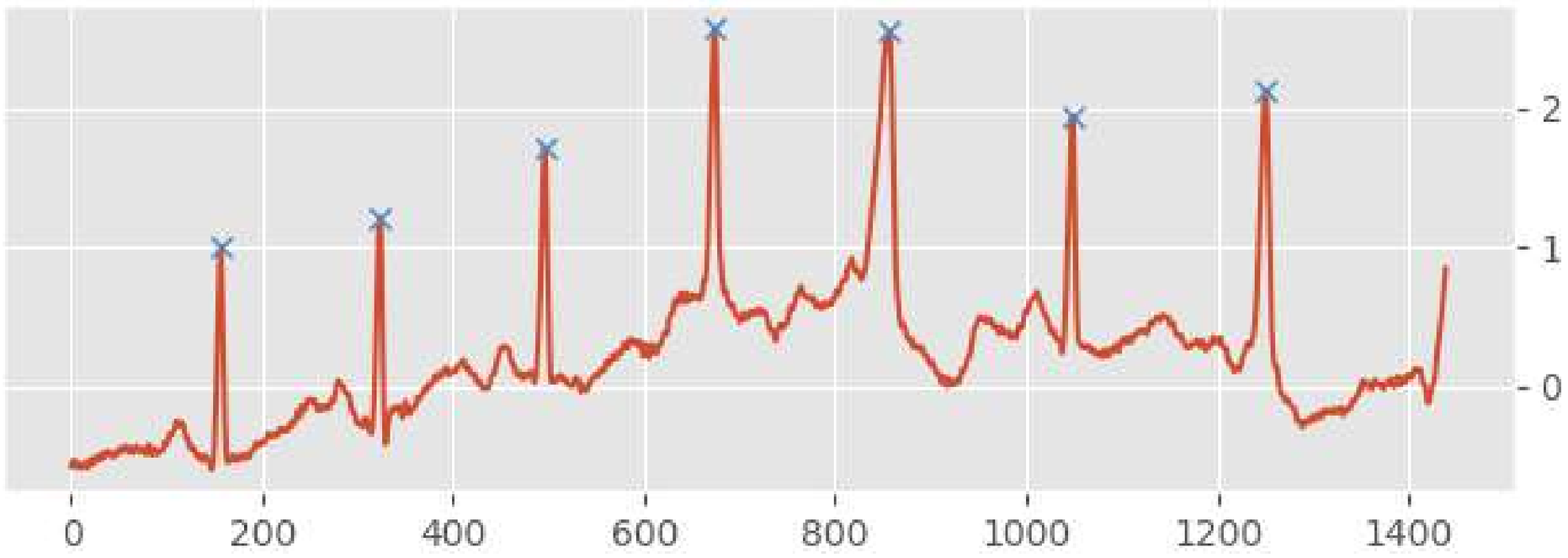
- Use prominence

```
> (prmPks,_) = findPeaks(ecg1D,prominence=0.5)
```

- Get only peaks with prominence of at least 0.5

```
> plt.figure()
> plt.plot(ecg1D)
> plt.plot(prmPks,ecg1D[prmPks],'x')
```

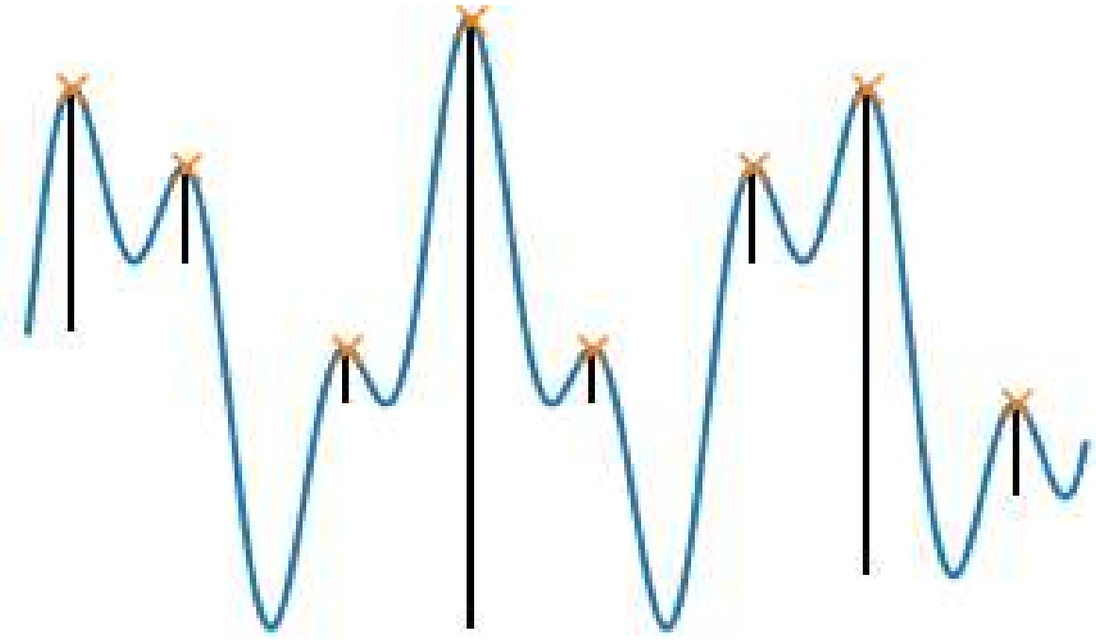
It works, but what is prominence?



Prominence

2, 3. fine tune and re-run

`findPeaks`



- The prominence of a peak measures **how much a peak stands out from the surrounding baseline of the signal**. The strategy:

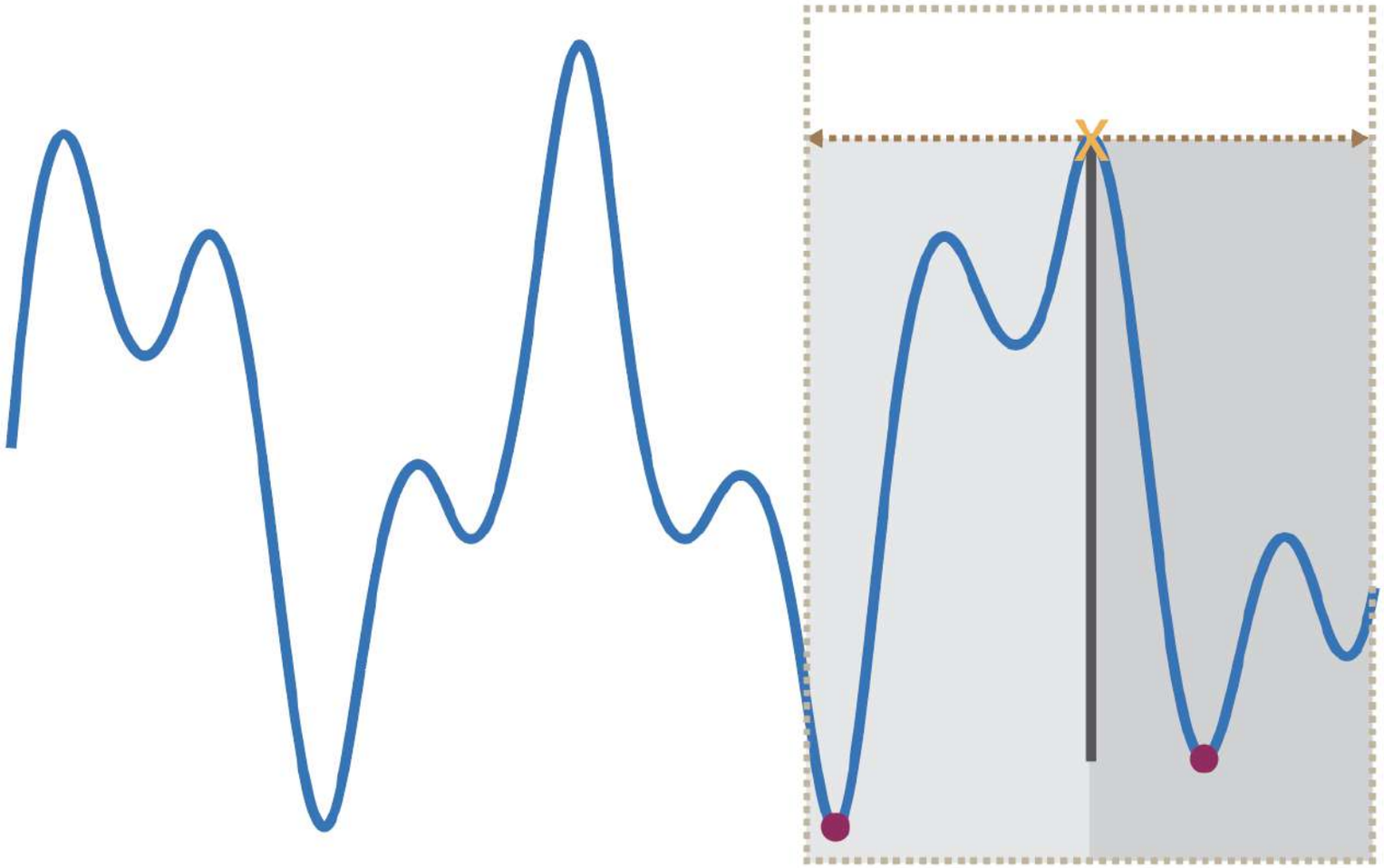
1. Extend a horizontal line from the current peak to the left and right until the line either reaches the window border or intersects the signal again at the slope of a higher peak. An intersection with a peak of the same height is ignored.
2. On each side find the minimal signal value within the interval defined above. These points are the peak's bases.
3. The higher one of the two bases marks the peak's lowest contour line. The prominence can then be calculated as the vertical difference between the peaks height itself and its lowest contour line.

Prominence

2, 3. fine tune and re-run

`findPeaks`

1. Extend a horizontal line from the current peak to the left and right until the line either reaches the window border or intersects the signal again at the slope of a higher peak. An intersection with a peak of the same height is ignored.
2. On each side find the minimal signal value within the interval defined above. These points are the peak's bases.
3. The higher one of the two bases marks the peak's lowest contour line. The prominence can then be calculated as the vertical difference between the peaks height itself and its lowest contour line.

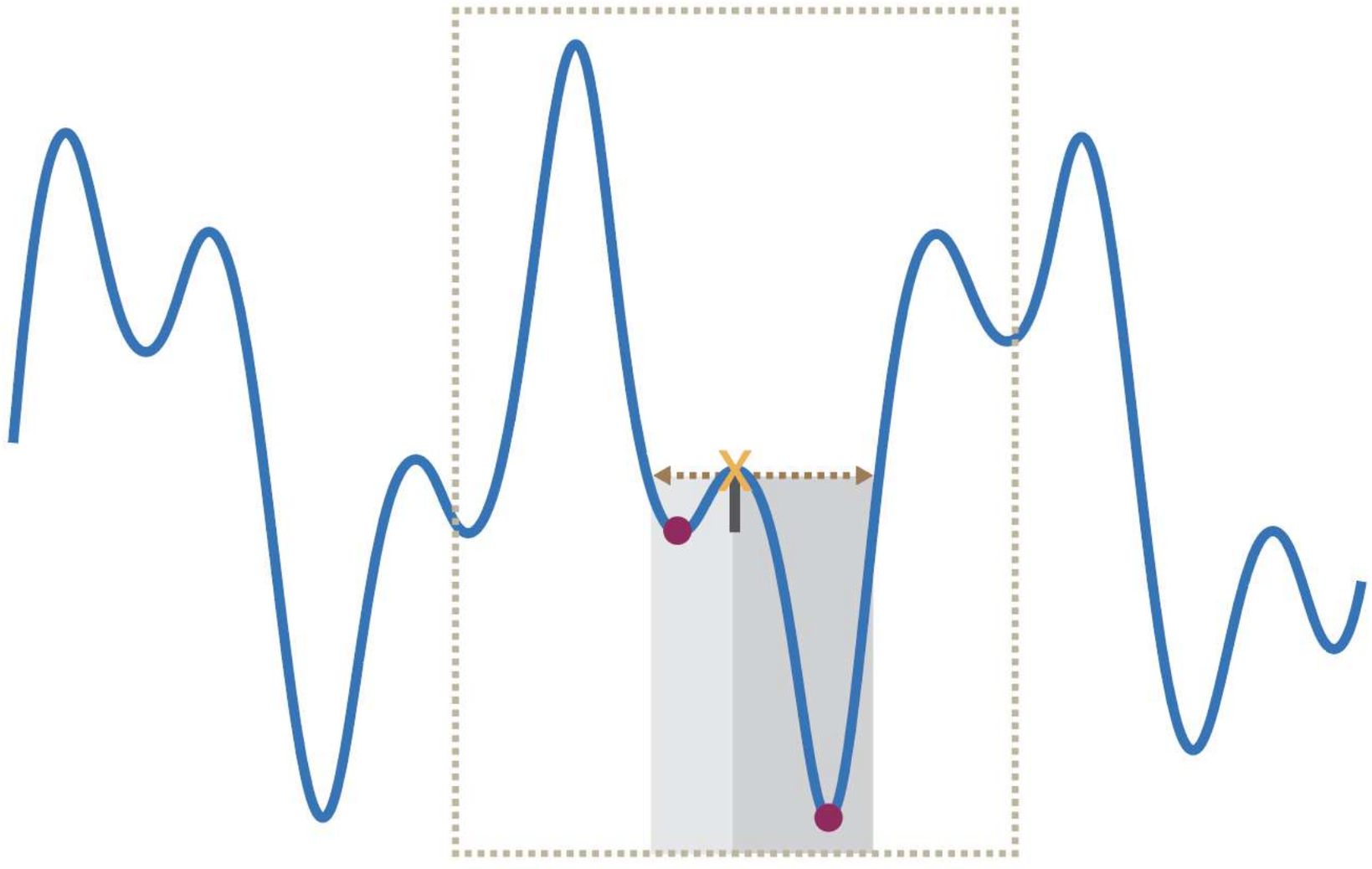


Prominence

2, 3. fine tune and re-run

`findPeaks`

1. Extend a horizontal line from the current peak to the left and right until the line either reaches the window border or intersects the signal again at the slope of a higher peak. An intersection with a peak of the same height is ignored.
2. On each side find the minimal signal value within the interval defined above. These points are the peak's bases.
3. The higher one of the two bases marks the peak's lowest contour line. The prominence can then be calculated as the vertical difference between the peaks height itself and its lowest contour line.

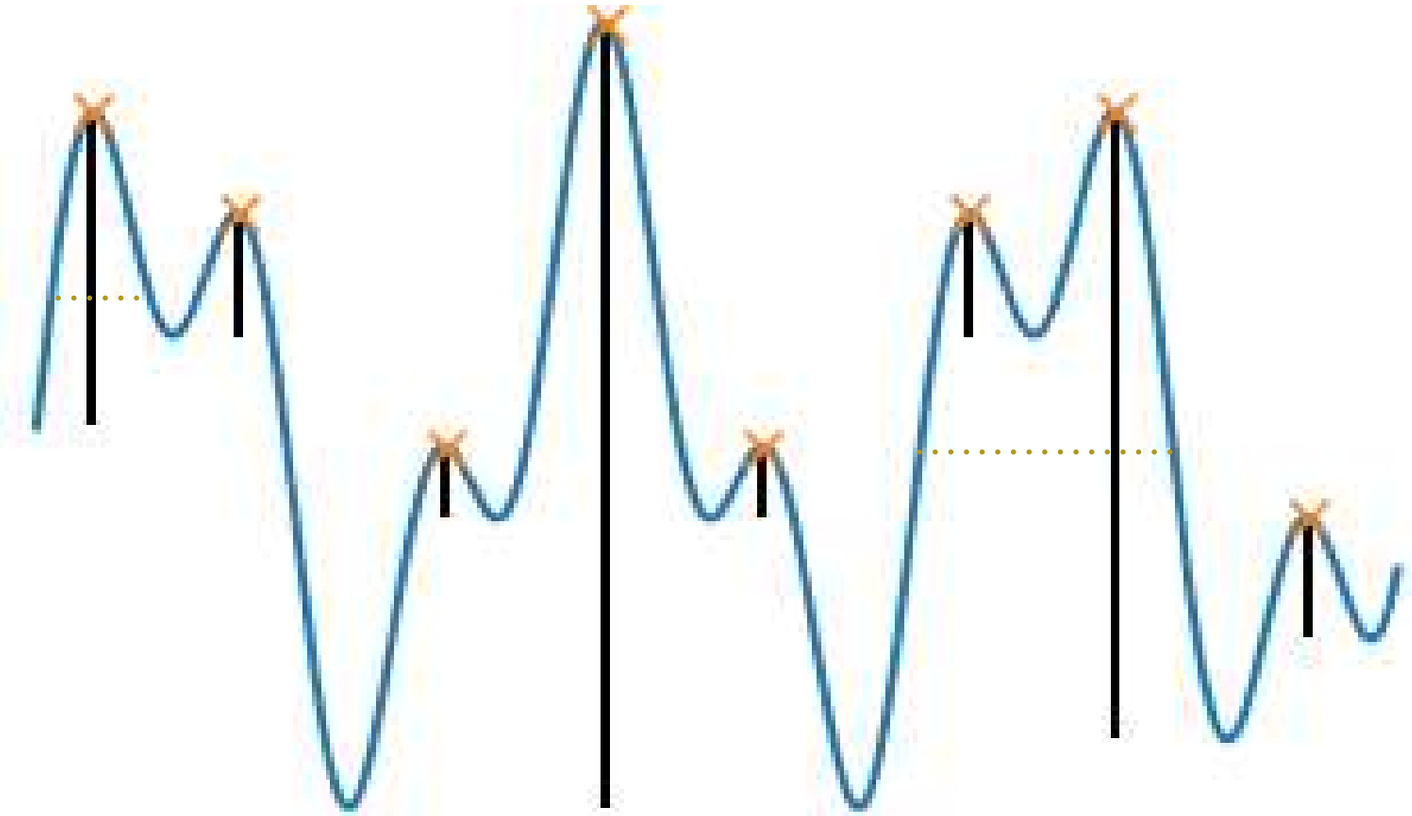


Width

2, 3. fine tune and re-run `findPeaks`

- By default, the width of a peak is defined from the position half of of the prominence
- We can fine-tune the peak searching using multiple parameters

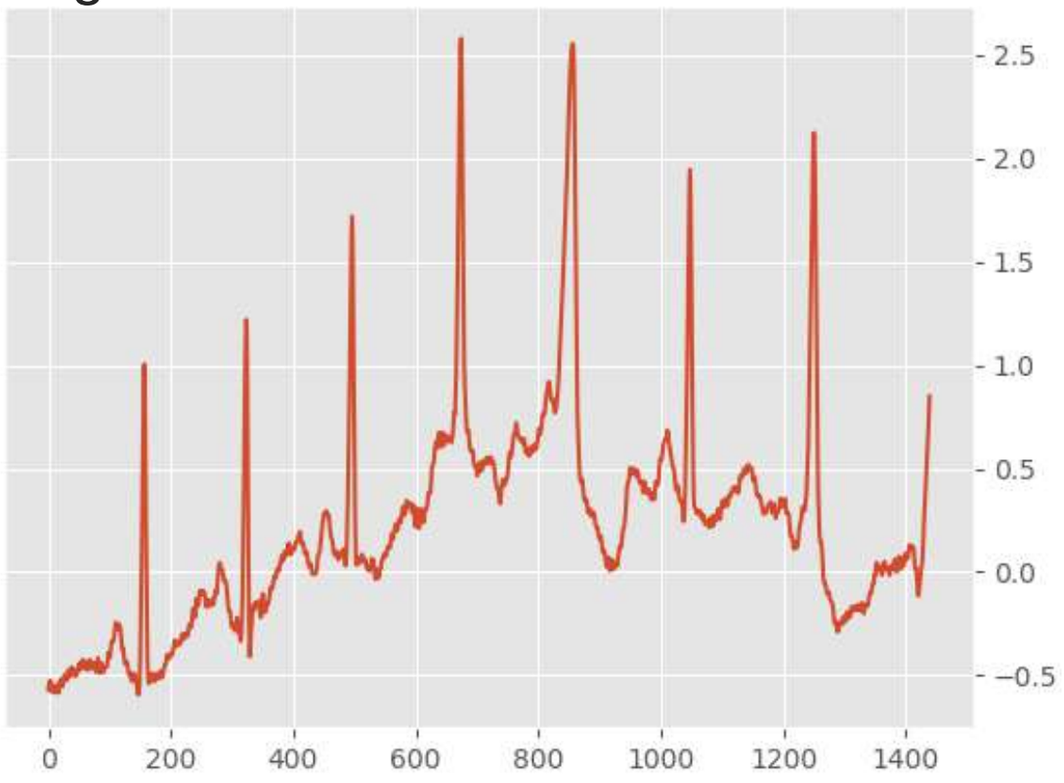
```
findPeaks(x,prominence=0.1,distance=10)
findPeaks(x,distance=5,width=2)
....
```



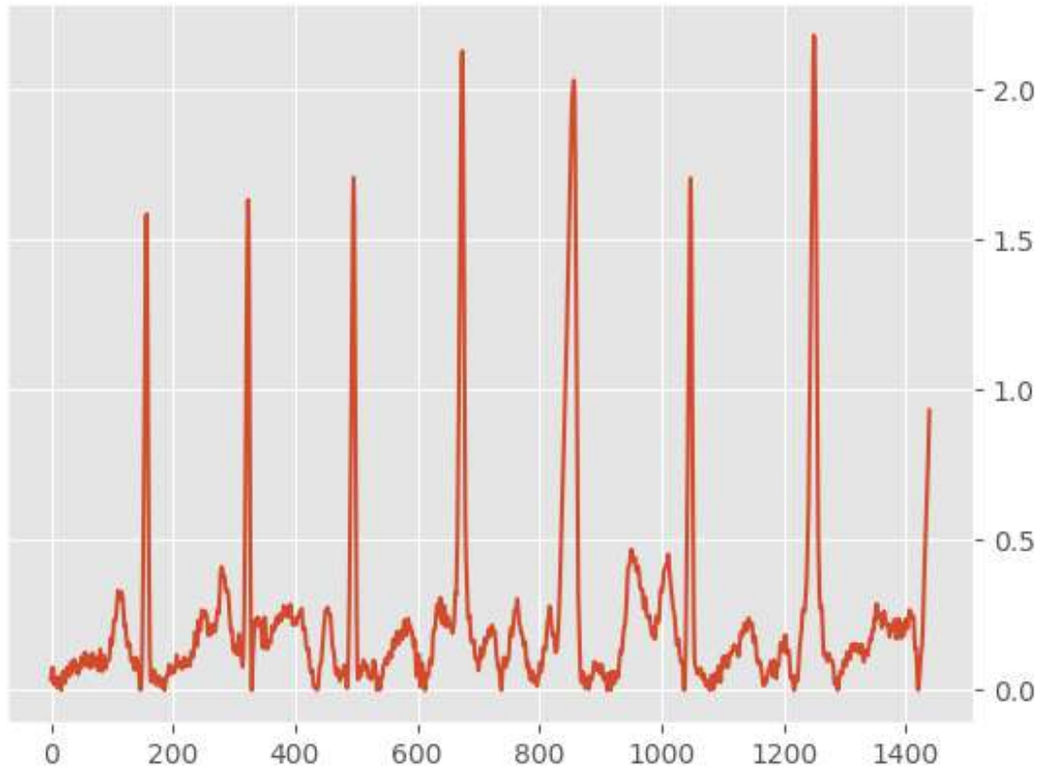
Baseline correction

Problem

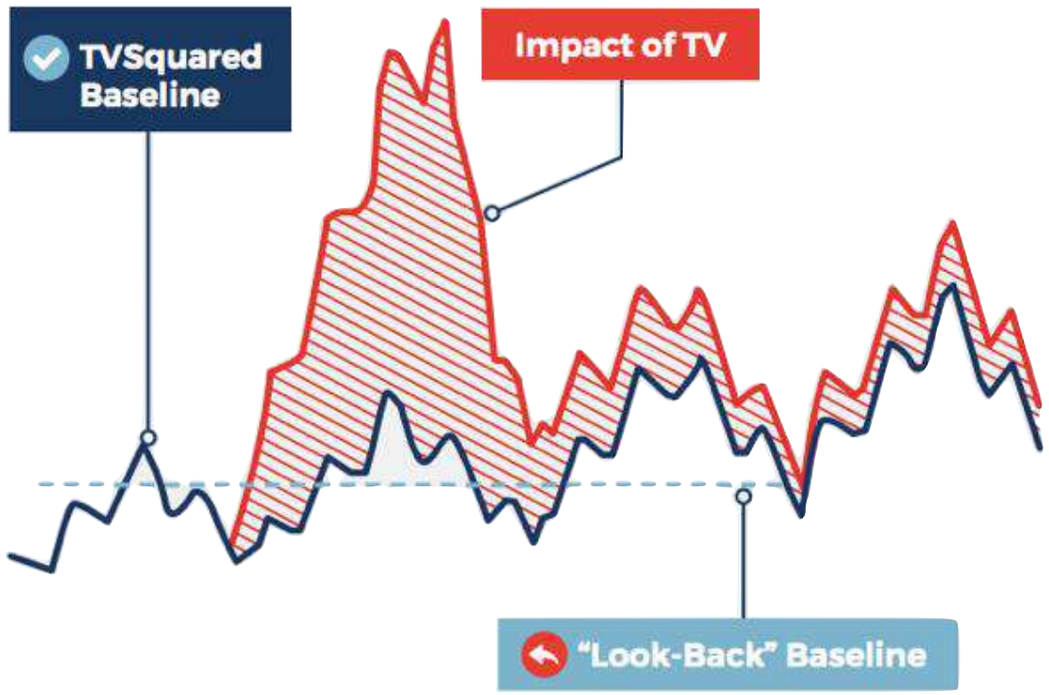
original



baseline corrected



Baseline correction

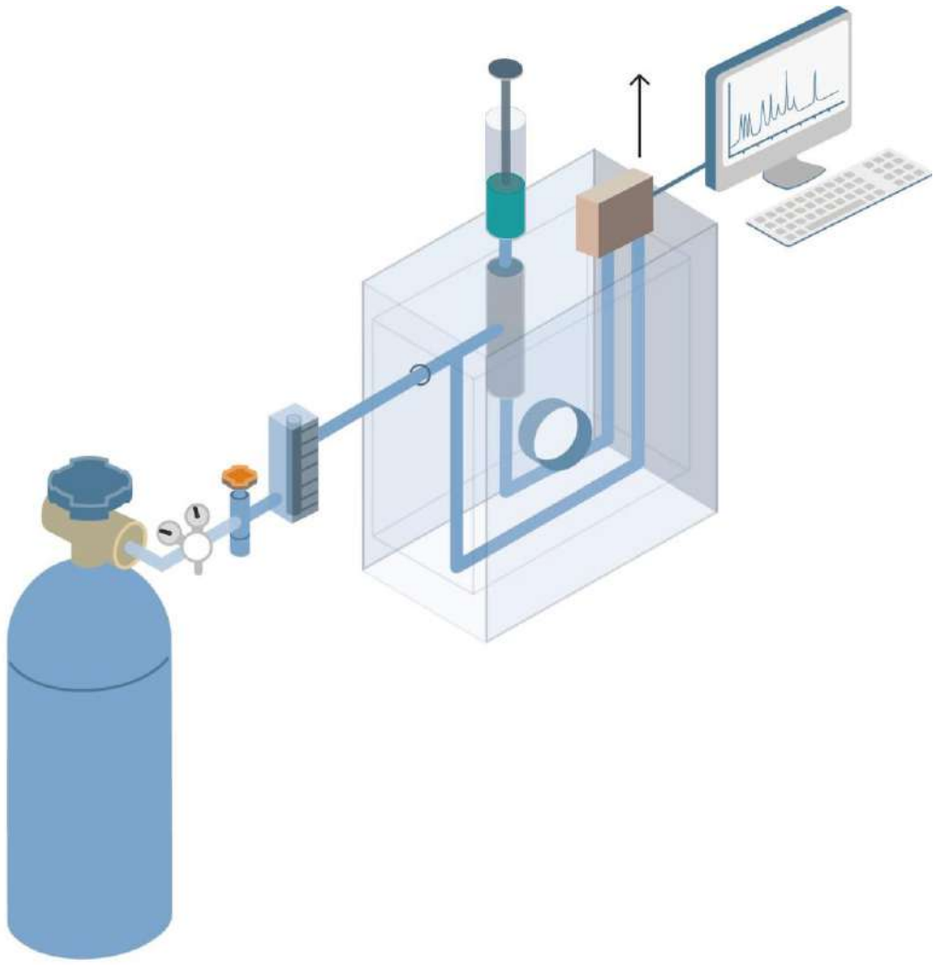


- Unstable baselines occur in many types of instrumental measurements
- Drift in sensor values are common phenomenon, due to changes in environment factors such as temperature and humidity
- They can cause problem, for example, disturb peak detection, pattern comparison
- Correction is routinely needed

Source: https://tvsquared.com/baseline-works-better/

GC chromatogram

Example



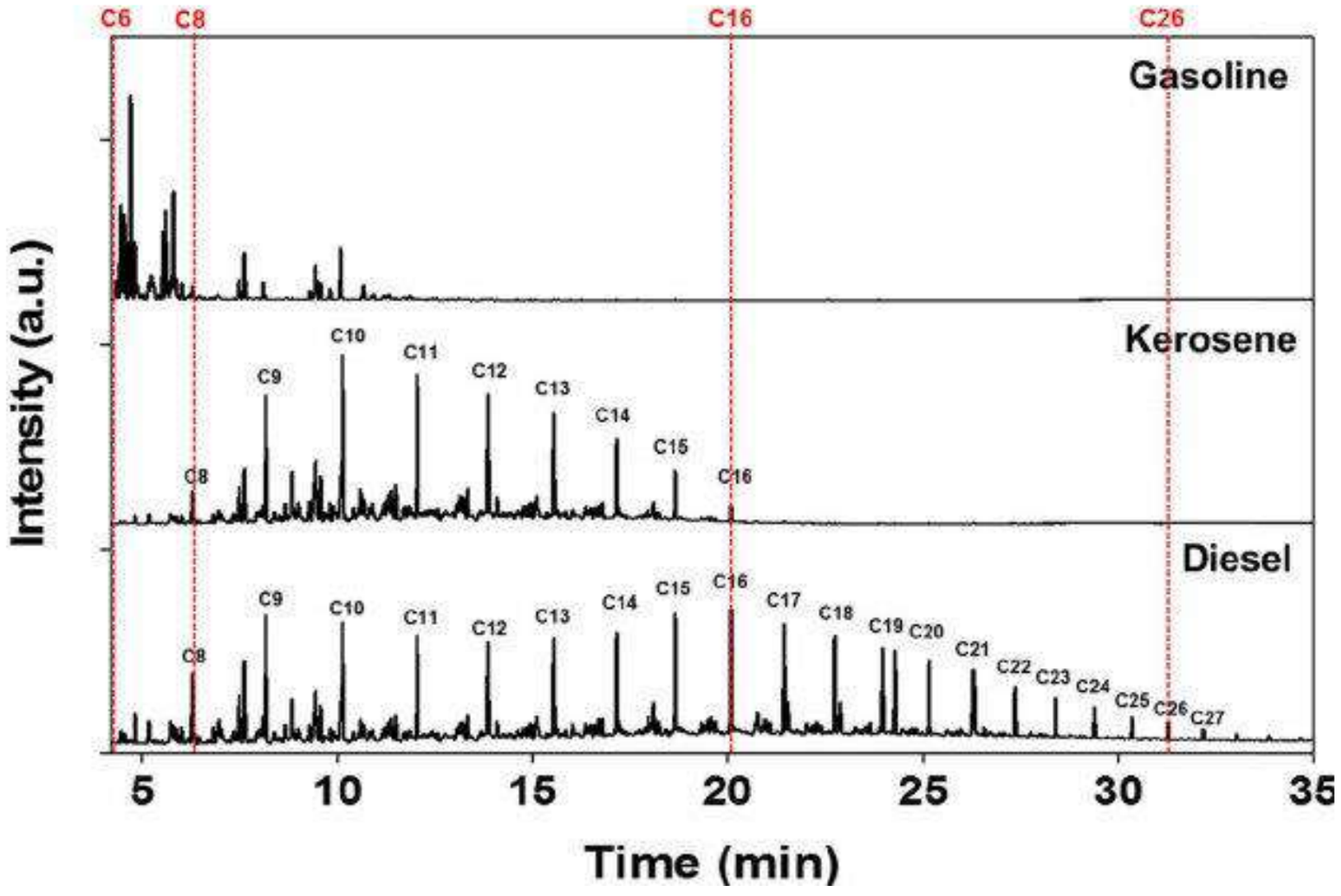
- GC chromatogram: used to analyze content of a chemical product
- Examples: analyzing the contents of a lavender oil; measuring toxic substances in soil, air or water
- Also used extensively in forensic science

Source: http://hiq.linde-gas.com/en/analytical_methods/gas_chromatography/index.html

GC chromatogram

Example

- GC chromatograms of refined petroleum products
- The other name of Gasoline is … petrol



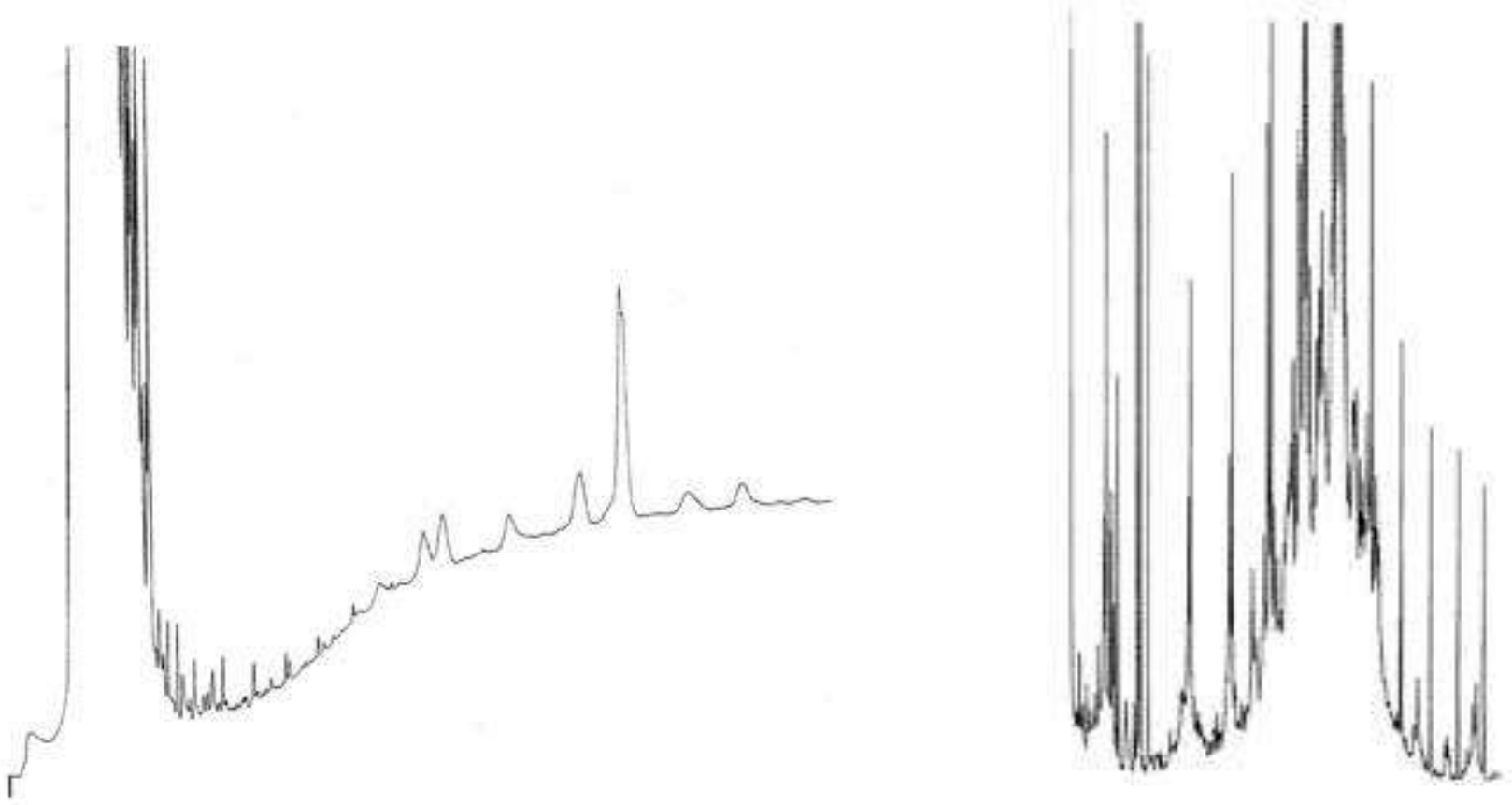
Source: https://www.researchgate.net/publication/275046766_Identification_of_refined_petroleum_products_in_contaminated_soils_using_an_identification_index_for_GC_chromatograms/figures?lo=1

GC chromatogram

Example

- Sometimes the signals acquired are not ideal

- For example ….



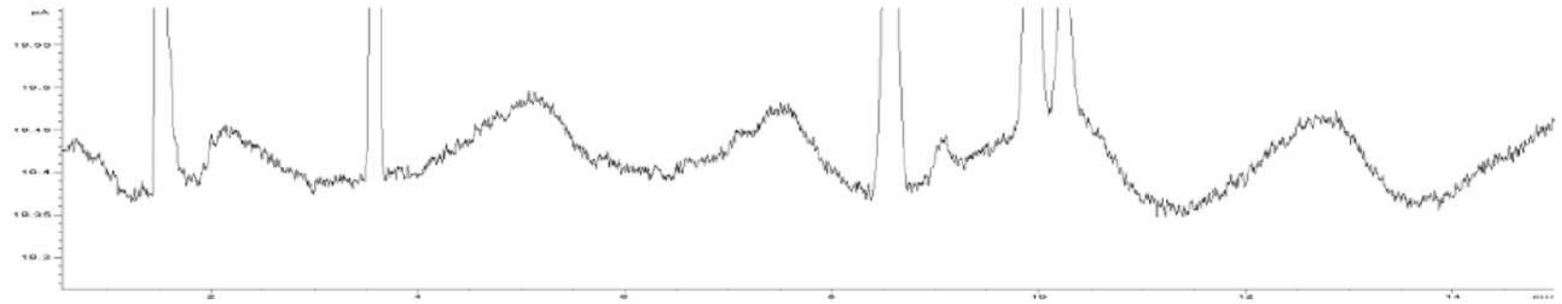
Source: https://chem.libretexts.org/Bookshelves/Analytical_Chemistry/Supplemental_Modules_(Analytical_Chemistry)/Chromedia/01Gas_Chromotography_(GC)/Gas_Chromotography%3A_Basic_Theory/27Some_%27bad%27_GC_chromatograms

GC chromatogram

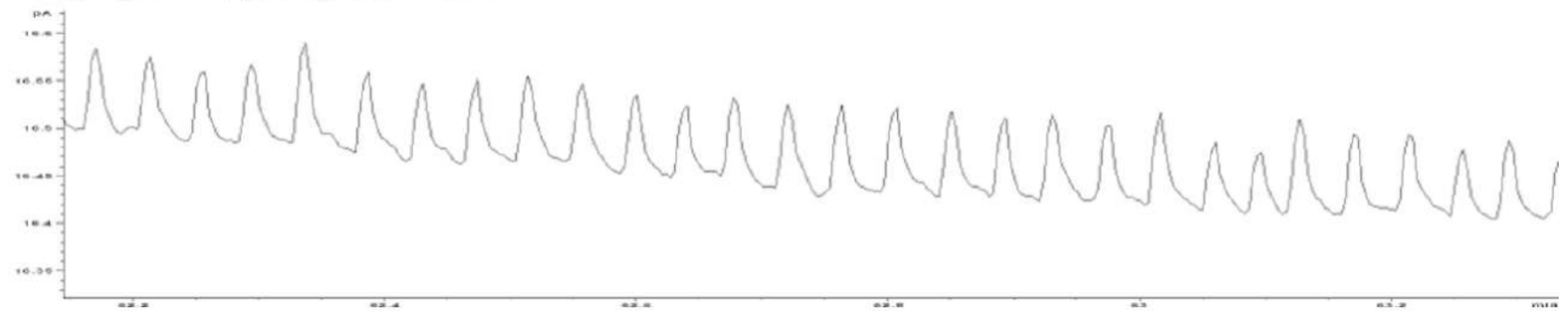
Example

- Sometimes the signals acquired are not ideal

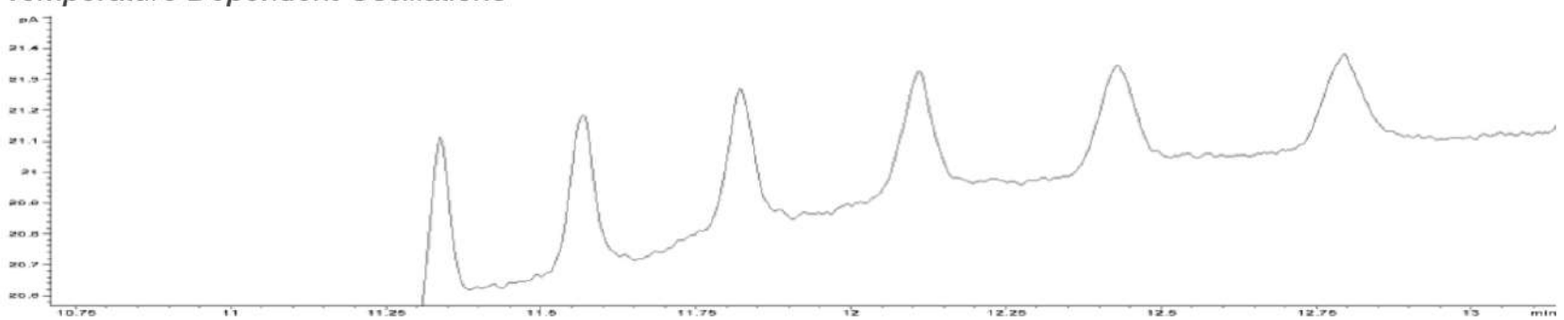
Slow, Low Frequency Oscillations



Fast, Higher Frequency Oscillations



Temperature Dependent Oscillations

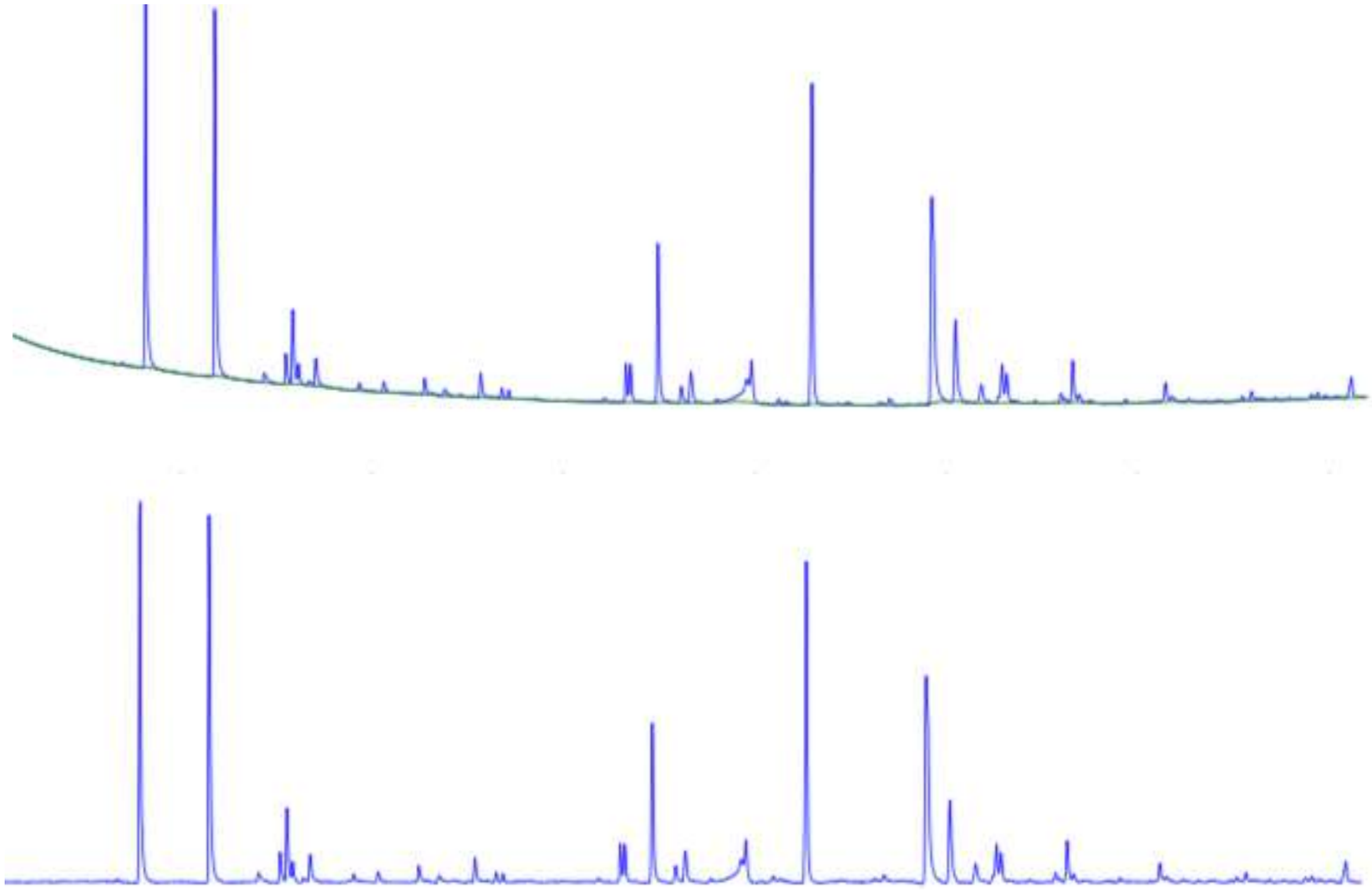


Source: https://www.phenomenex.com/Info/Page/baselineosc

Baseline correction

Example

- Need a solution to correct baseline

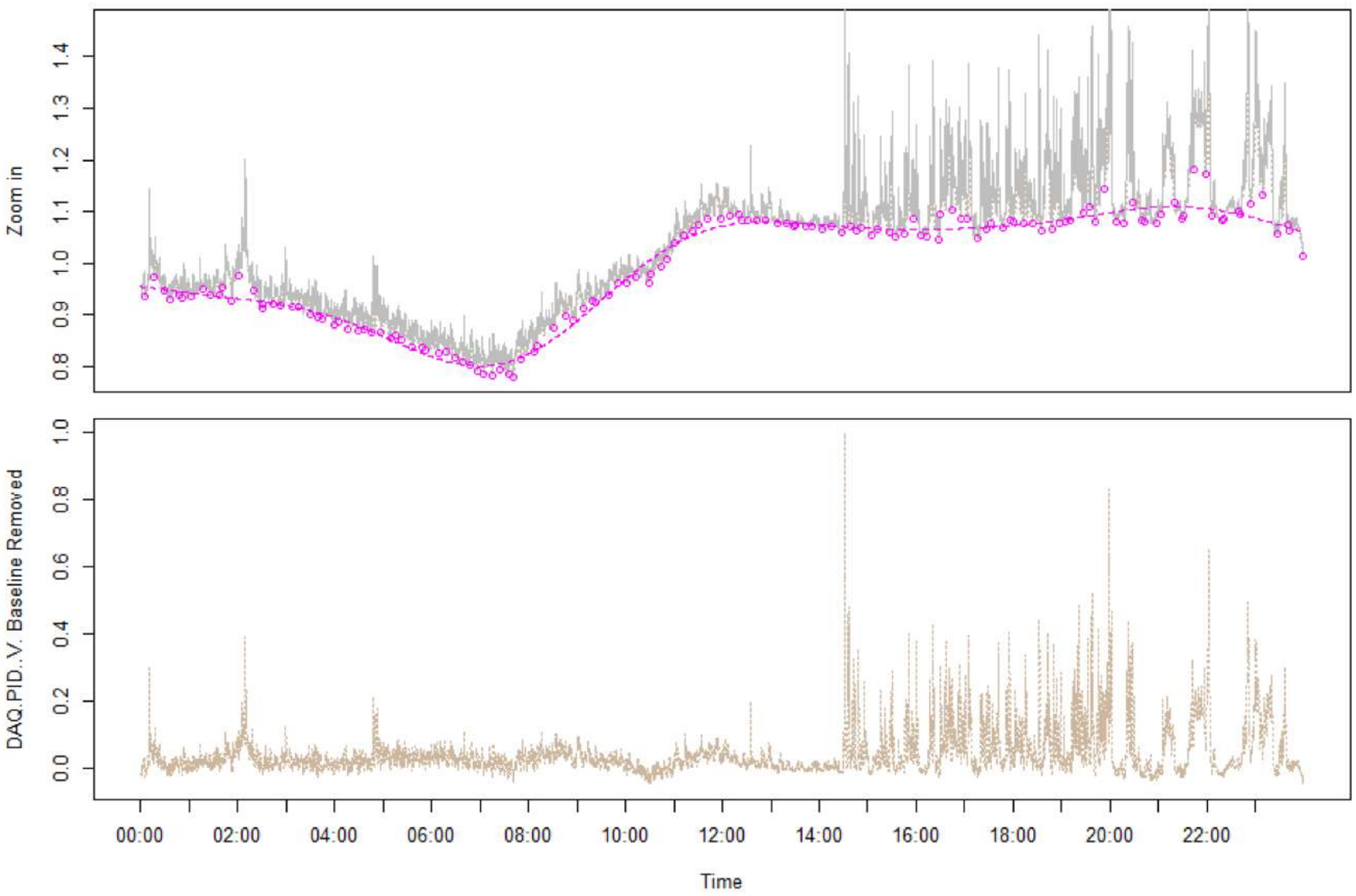


Source: "Baseline correction with asymmetric least square", by Eilers and Boelens

Air quality

Monitoring of particle concentration

- Low cost air sensors have issues of baseline drift, not so useful for particle concentration, but spikes could characterize emissions events



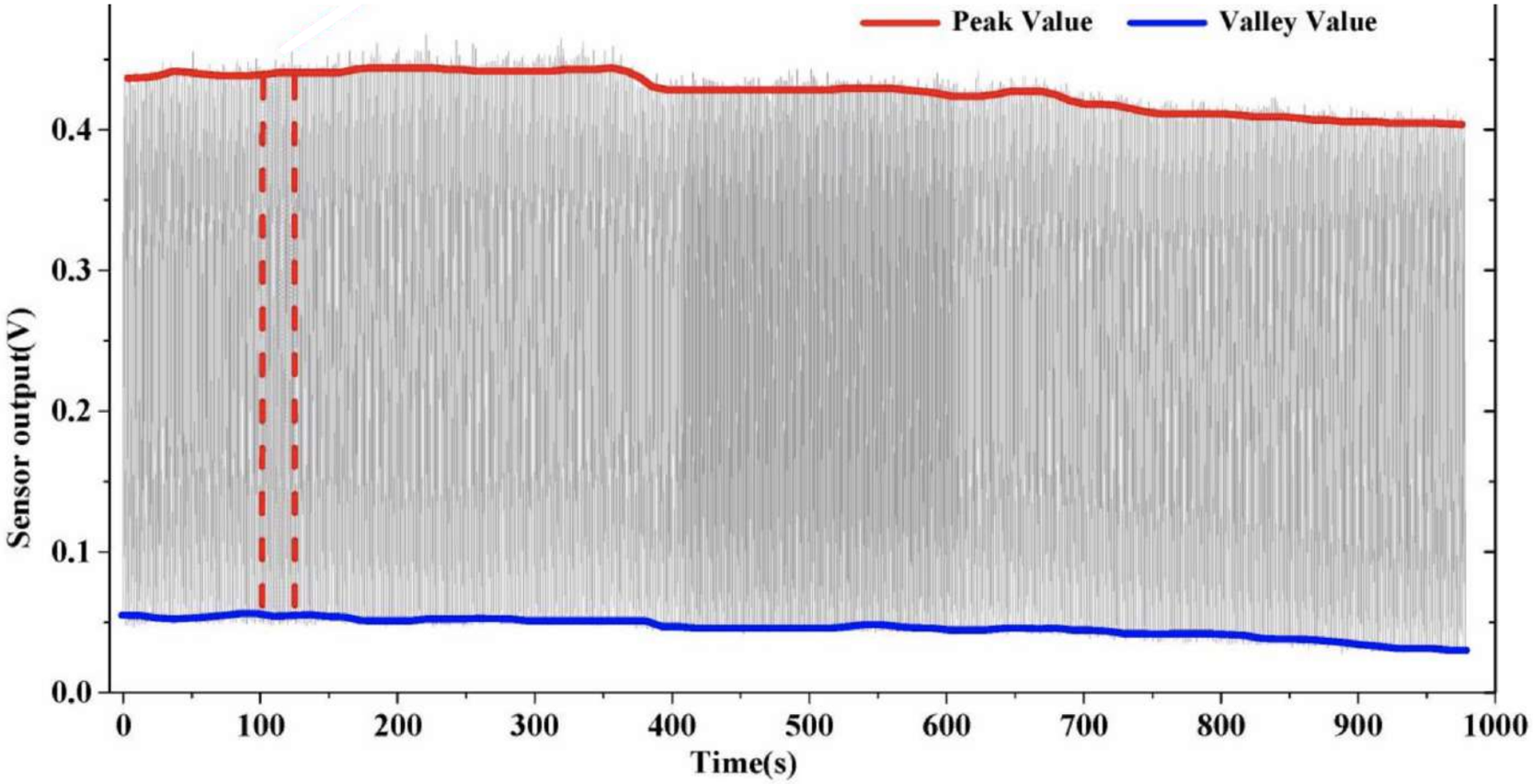
Source: https://cfpub.epa.gov

Respiratory airflow

Monitoring for obstructive sleep apnea-hypopnea syndrome (OSAHS)

- OSAHS: repetitive episodes of airflow reduction, leading to acute gas exchange abnormalities and sleep fragmentation and resulting in neurabehavioral and cardiovascular consequences

- Drift in sensor output becomes a pain point in monitoring



Source: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5134438/

Baseline correction

Basic idea

- Assume **y** is the original signal, **z** as the other signal which has this two properties: smooth, faithful to **y**

$$\mathbf{y} = [y_1, y_2, \ldots, y_i, \ldots y_L]$$
$$\mathbf{z} = [z_1, z_2, \ldots, z_i, \ldots z_L]$$

- The baseline can be estimated by minimizing the penalized least squared function

$$S = \sum_i w_i (y_i - z_i)^2 + \lambda \sum_i (\Delta^2 z_i)^2$$

- where

$$\Delta^2 z_i = (z_i - z_{i-1}) - (z_{i-1} - z_{i-2}) = z_i - 2z_{i-1} + z_{i-2}$$

Source: https://www.mathsisfun.com/calculus/maxima-minima.html

Baseline correction

Basic idea

- The minimization problems leads to the below system of equations

$$(W + \lambda D'D)z = Wy$$

- The baseline corrected signal is then

$$y_c = y - z$$

$$W = \begin{bmatrix} w_1 & 0 & 0 & \cdots & 0 \\ 0 & w_2 & 0 & \cdots & 0 \\ 0 & 0 & w_i & \cdots & 0 \\ \vdots & \vdots & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & w_L \end{bmatrix}$$

$$D = \begin{bmatrix} 1 & & & & \\ -2 & 1 & & & \\ 1 & -2 & \ddots & & \\ & 1 & \ddots & 1 & \\ & & \ddots & -2 & \\ & & & 1 & \end{bmatrix}$$

L-2 columns

L rows

Source: https://www.mathsisfun.com/calculus/maxima-minima.html

Baseline correction

The code

- Define function `alsbase`
- Suggested values:

$$0.001 \leq p \leq 0.1$$

$$10^2 \leq \lambda \leq 10^9$$

- Number of iterations: 5 to 10

```
> from scipy import sparse
> from scipy.sparse.linalg import spsolve
```

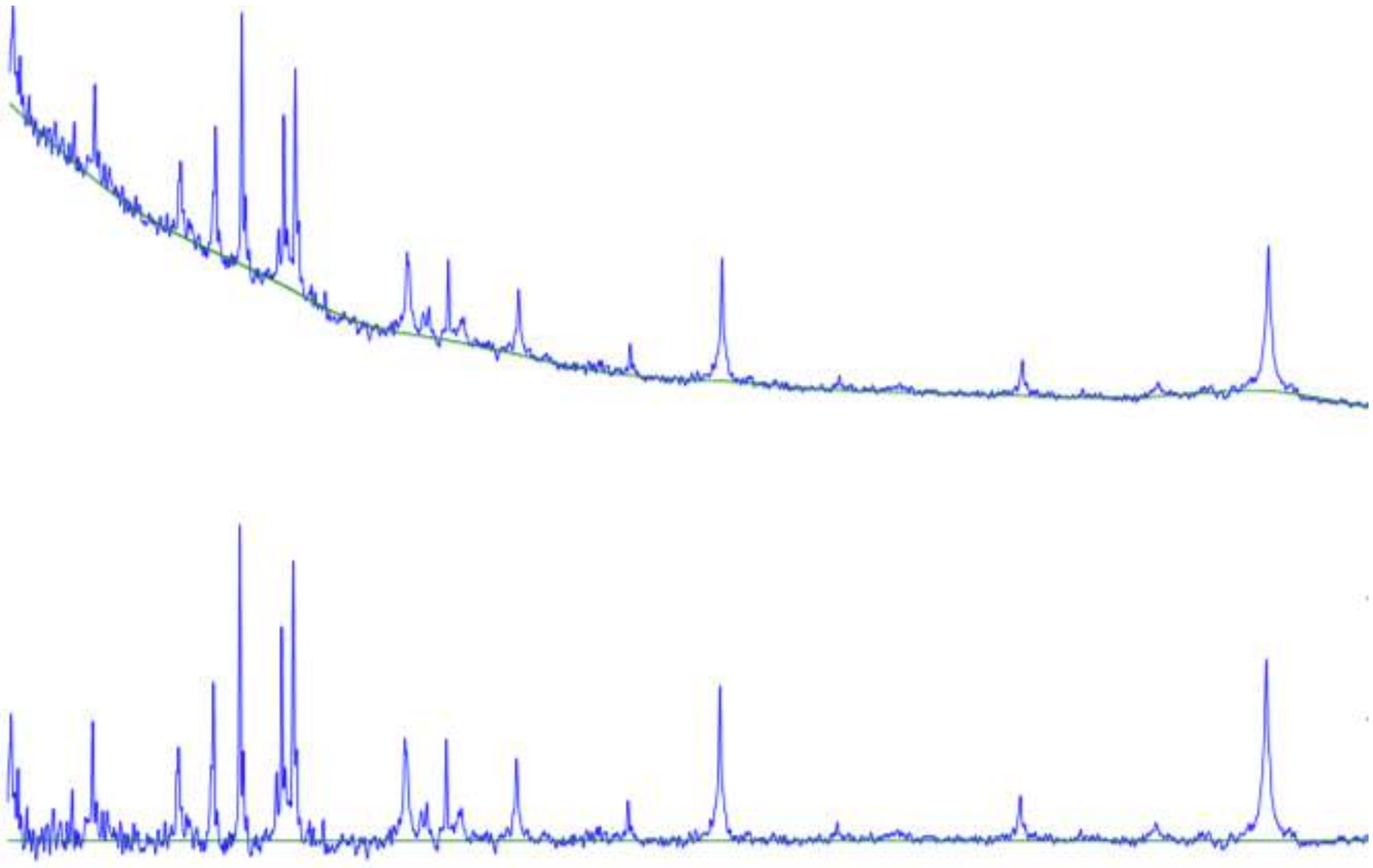
```
> def alsbase(y, lam, p, niter=10):
      L = len(y)
      D = sparse.diags([1,-2,1],[0,-1,-2], shape=(L,L-2))
      w = np.ones(L)

      for i in range(niter):
          W = sparse.spdiags(w, 0, L, L)
          Z = W + lam * D.dot(D.transpose())
          z = spsolve(Z, w*y)
          w = p * (y > z) + (1-p) * (y < z)
      return z
```

Baseline correction

Output example

- Mass spectrum from human blood serum

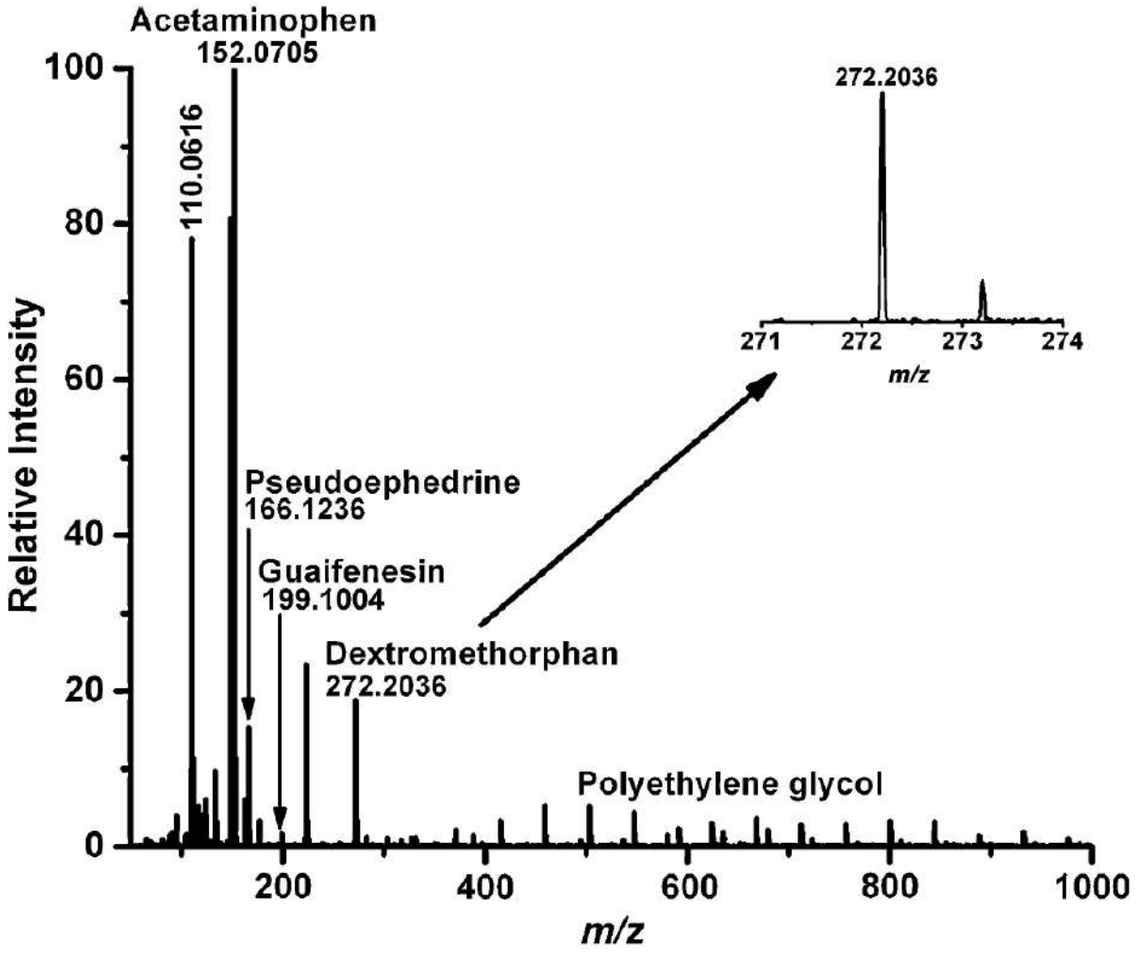


Source: "Baseline correction with asymmetric least square", by Eilers and Boelens

Baseline correction

Example

- What the peaks represent in mass spectrum from human blood serum or urine …



Source: http://www.bindesh.com/publications/rapid-analysis-of-pharmaceuticals-and-excreted-xenobiotic-and-endogenous-metabolites-with-atmospheric-pressure-infrared-maldi-mass-spectrometry/

Baseline correction

Correct the ecg1D

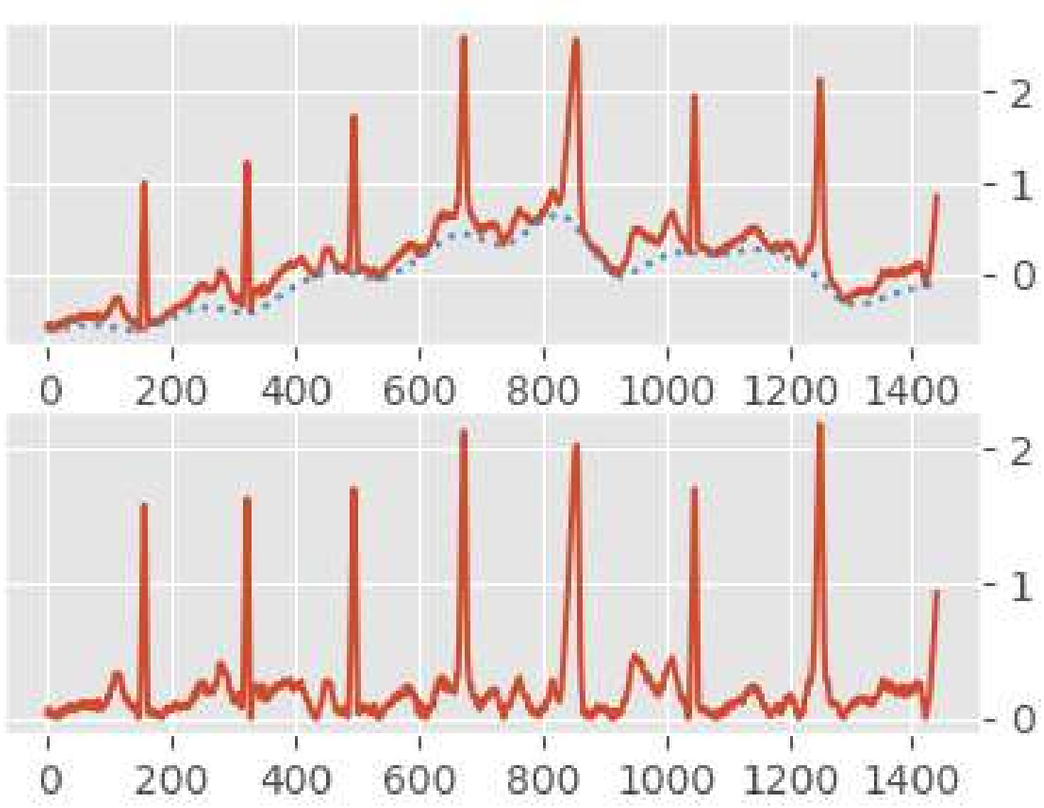
- Put `ecg1D` into `alsbase`

```
> ecgbase     = alsbase(ecg1D, 10^5,0.000005,niter=50)
> ecgcorr     = ecg1D-ecgbase
```

- Plot the output

```
> plt.figure()
> plt.subplot(211)
> plt.plot(ecg1D)

> plt.plot(ecgbase,
           color="C1",
           linestyle='dotted')
> plt.subplot(212)
> plt.plot(ecgcorr)
```



Workshop

Detect all the peaks in all the ECGs and perform baseline correction

- Use pandas to read in csv

```
> import pandas as pd
> l2D  = pd.read_csv('ecg2D.csv',
                     header=None)
```