Sensors of velocity, acceleration and vibration

AE3B38SME - Sensors and Measurement

Measurement of velocity

<u>Indirect</u>

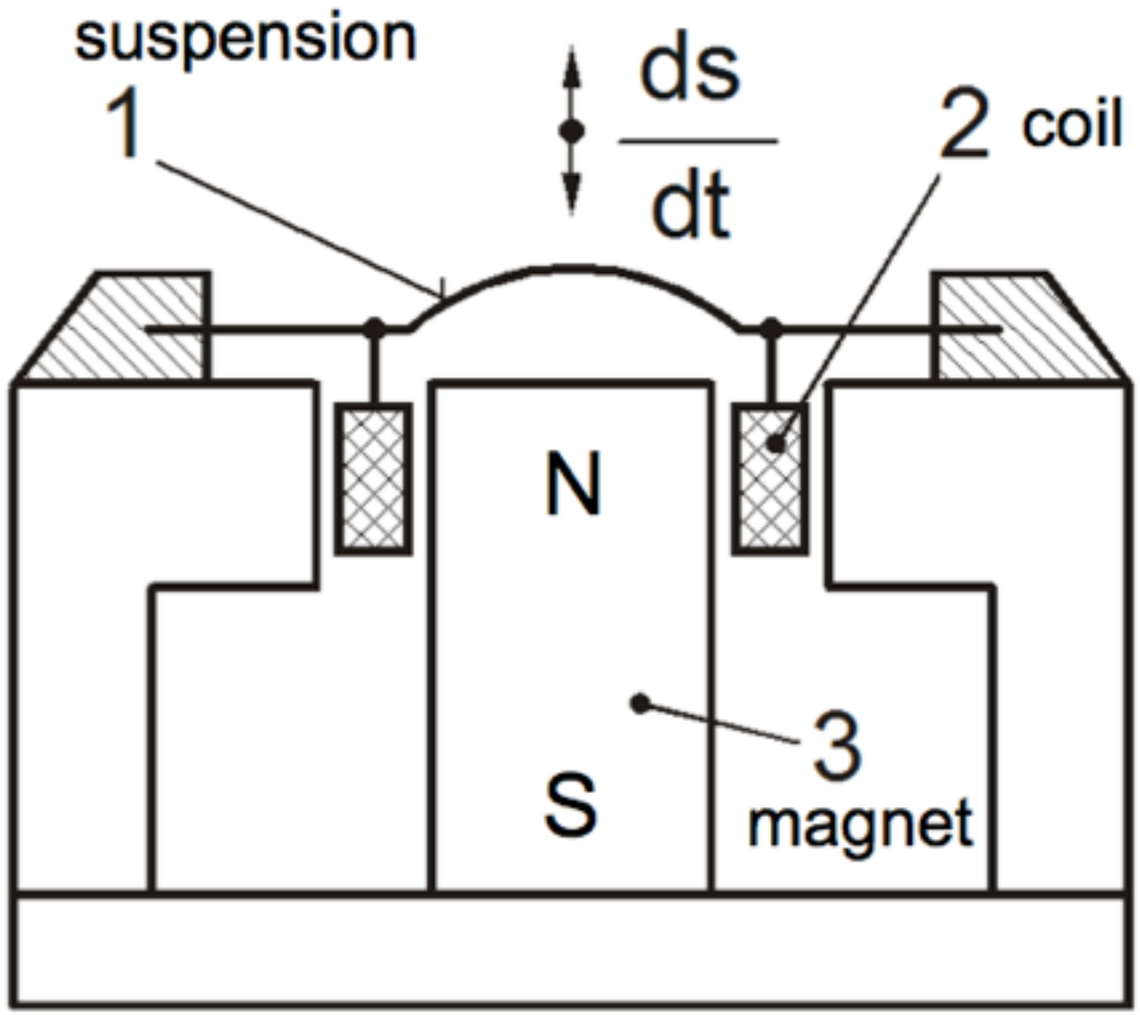
I measure position *s* and I derivate in time

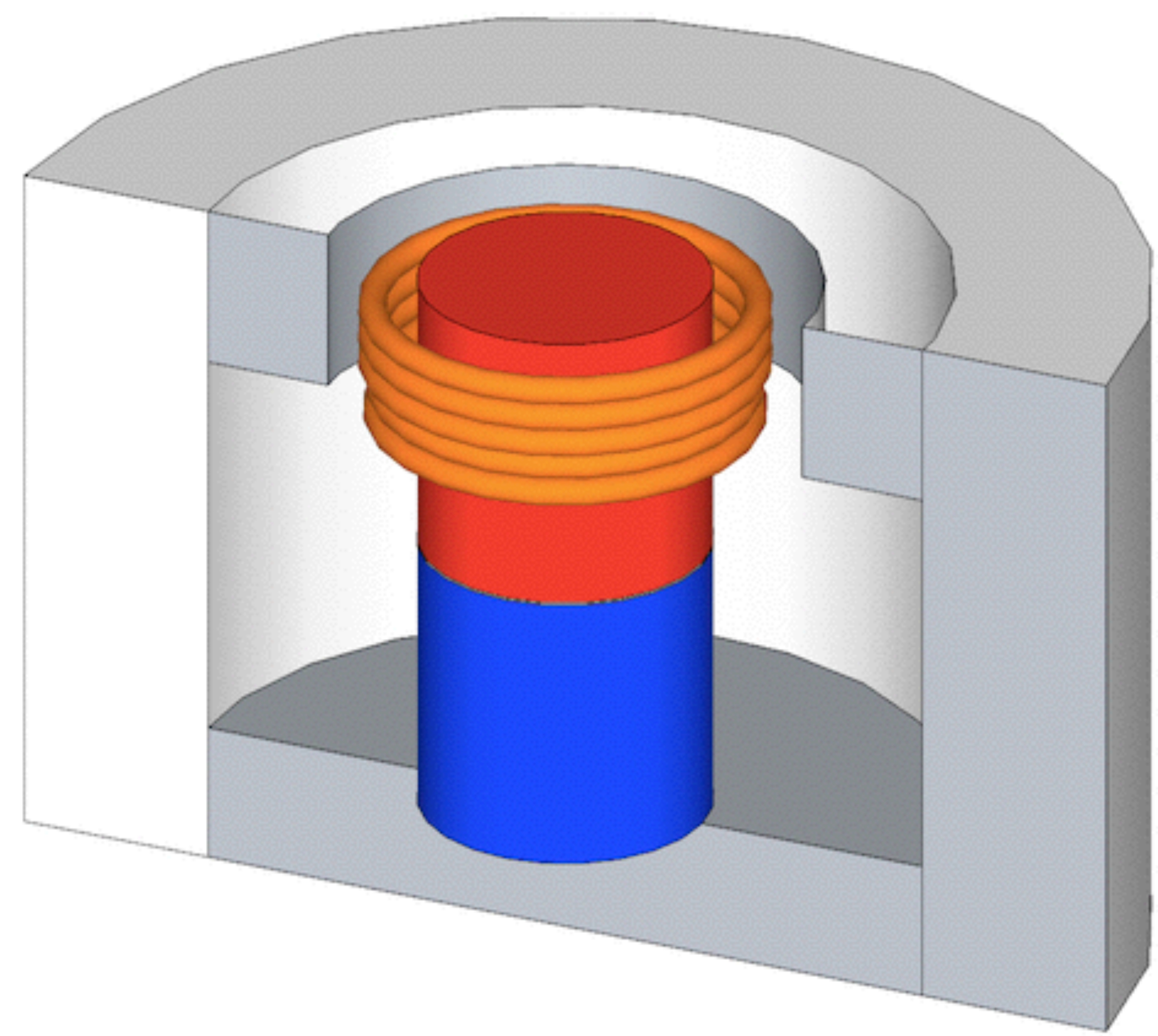
V=ds/dt

<u>Direct</u>

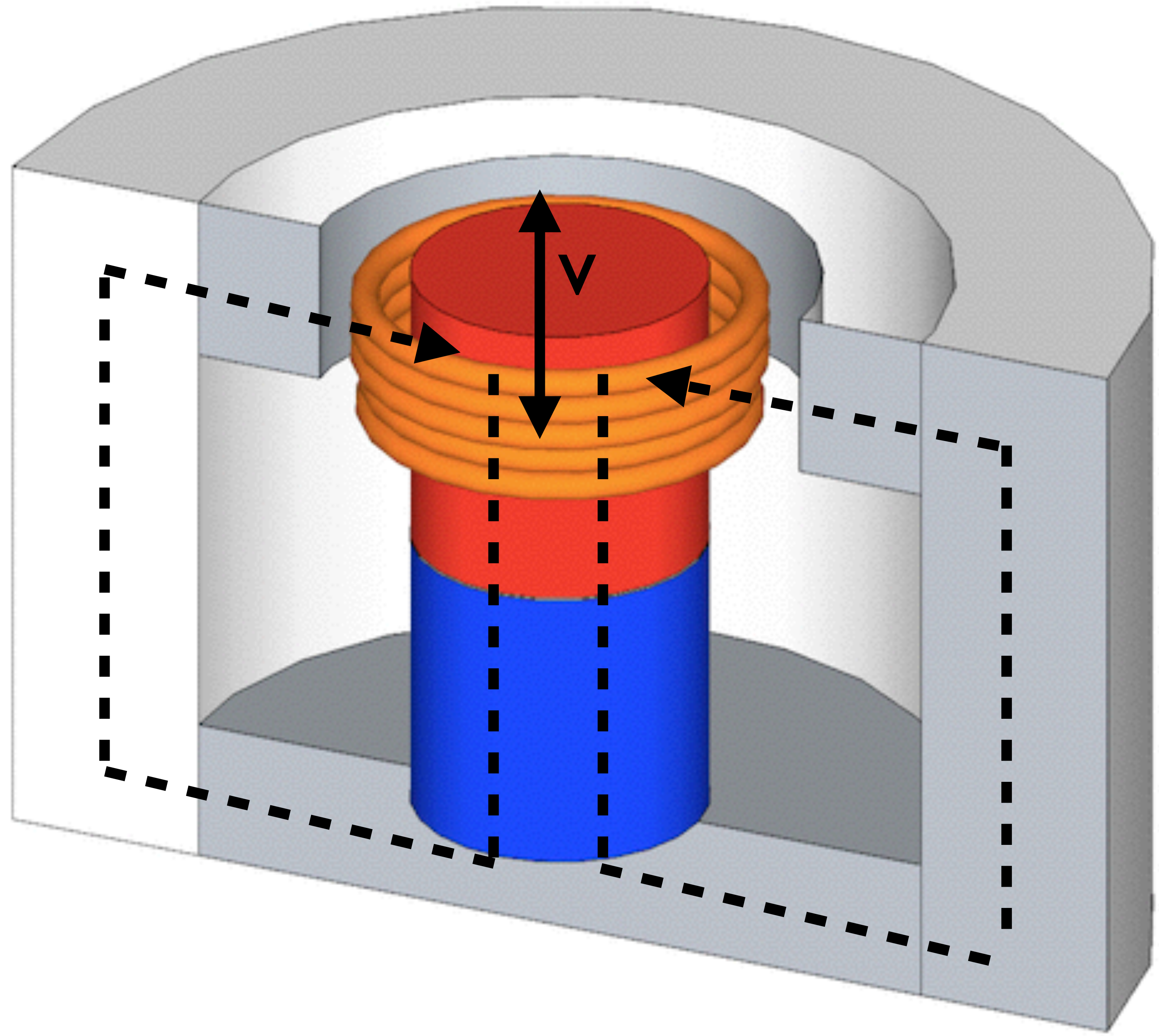
I measure a physical quantity proportional to velocity

Electrodynamic sensor of velocity

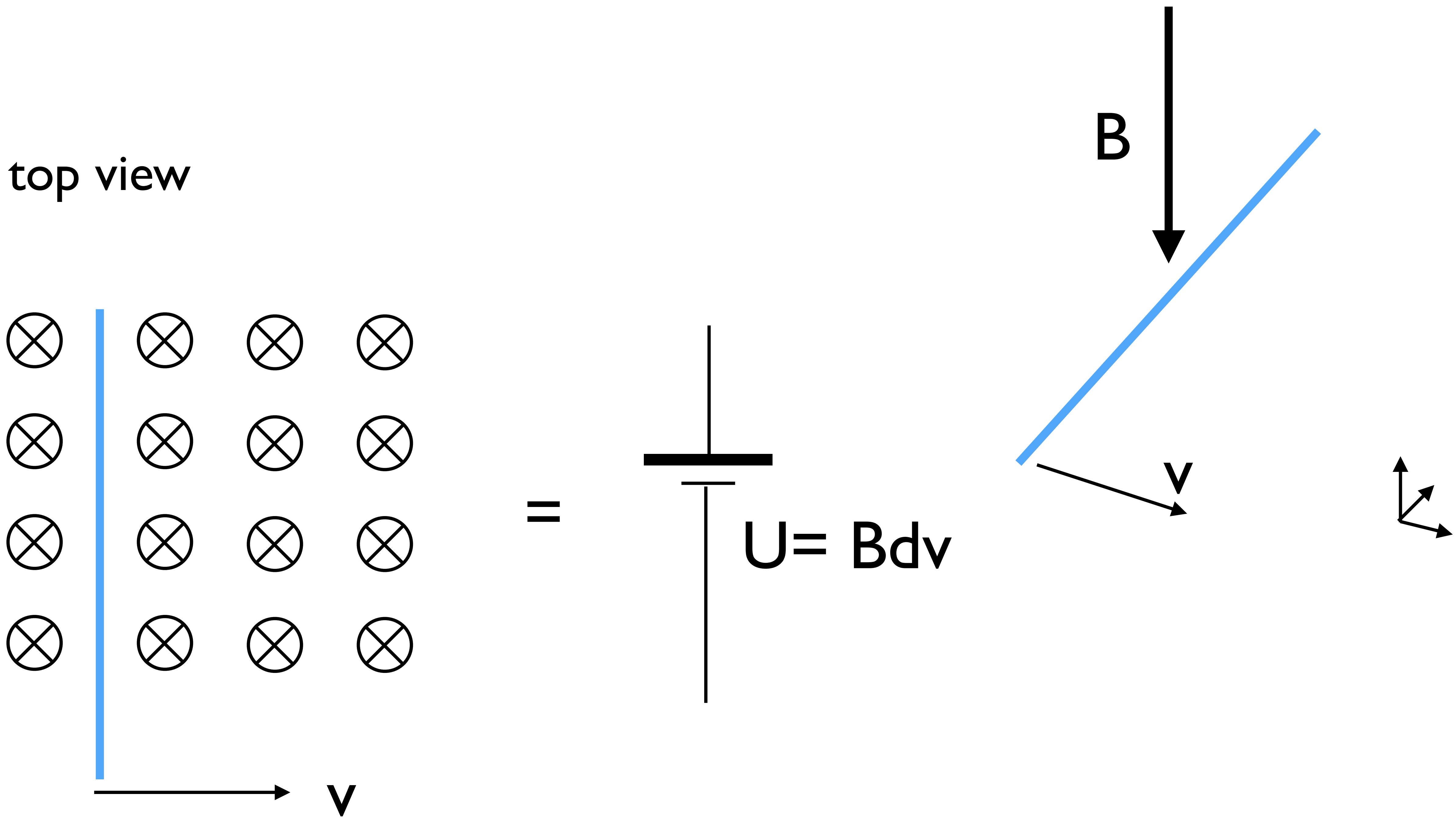




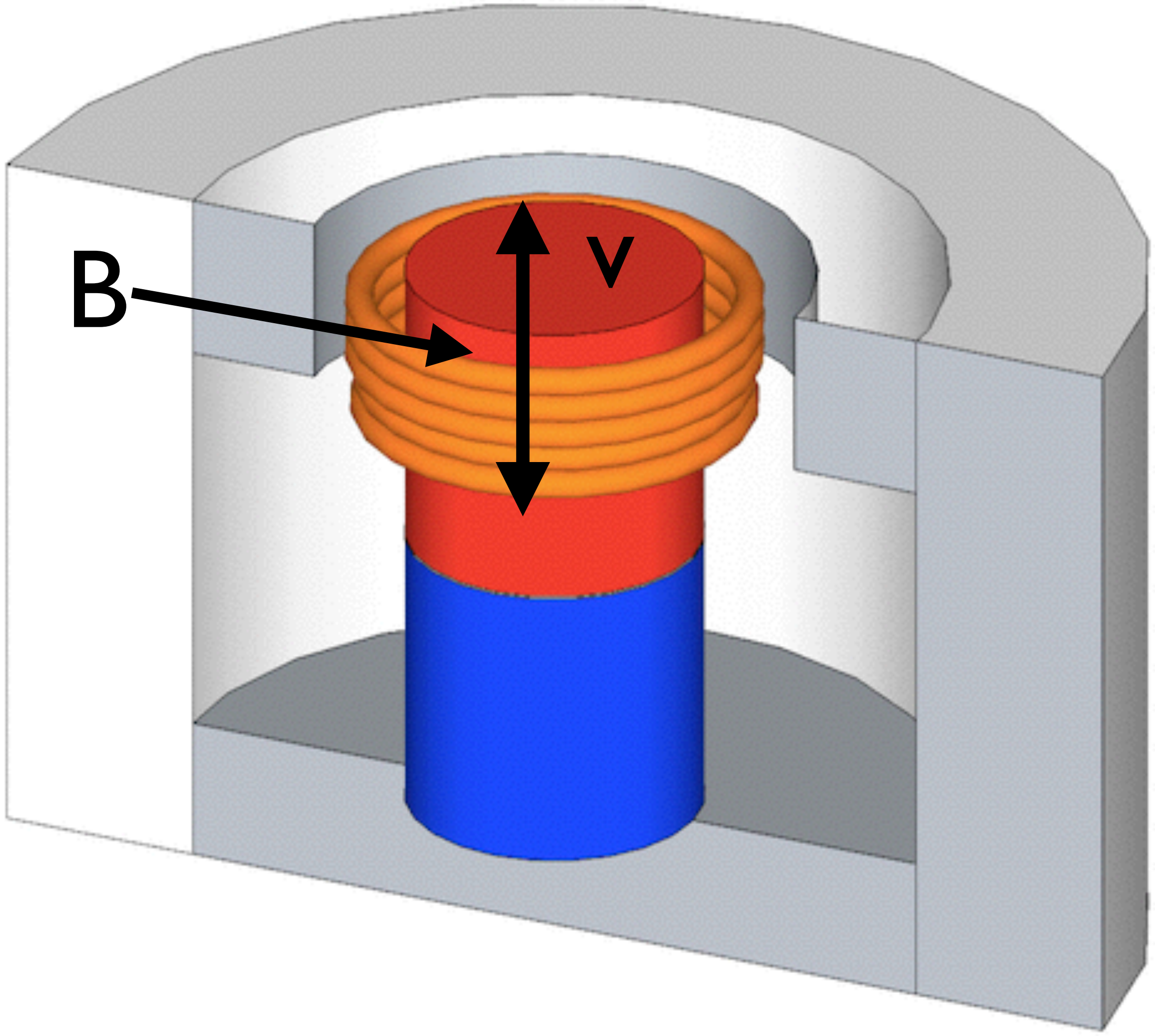
The magnetic field in the yoke

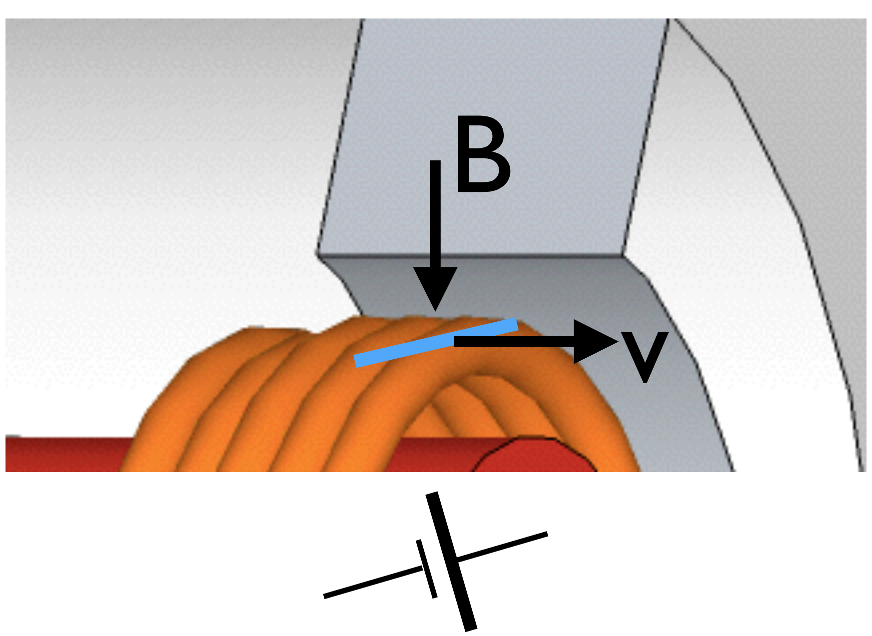


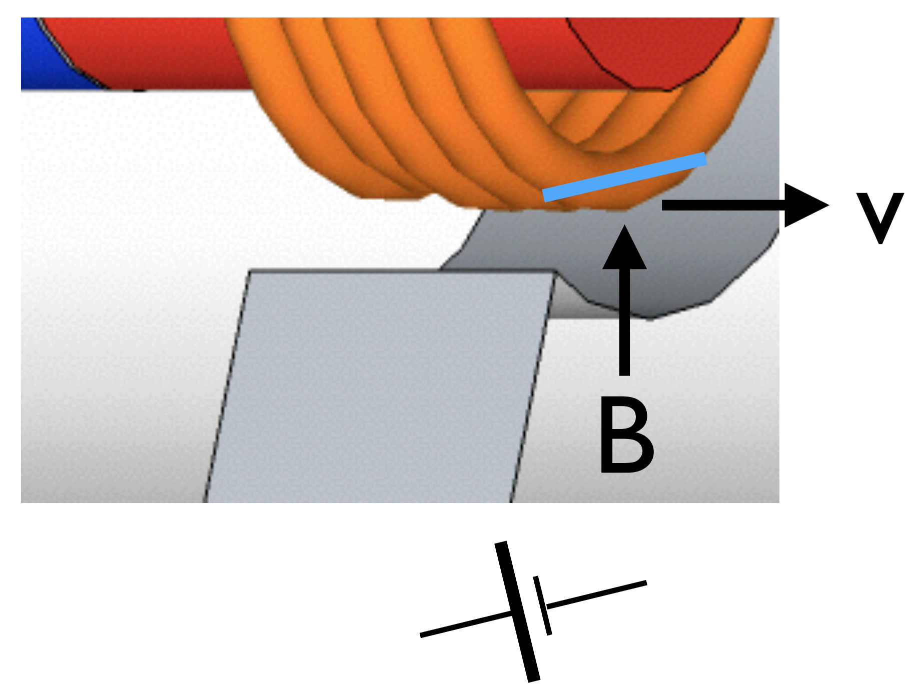
A conductor moving in a magnetic field



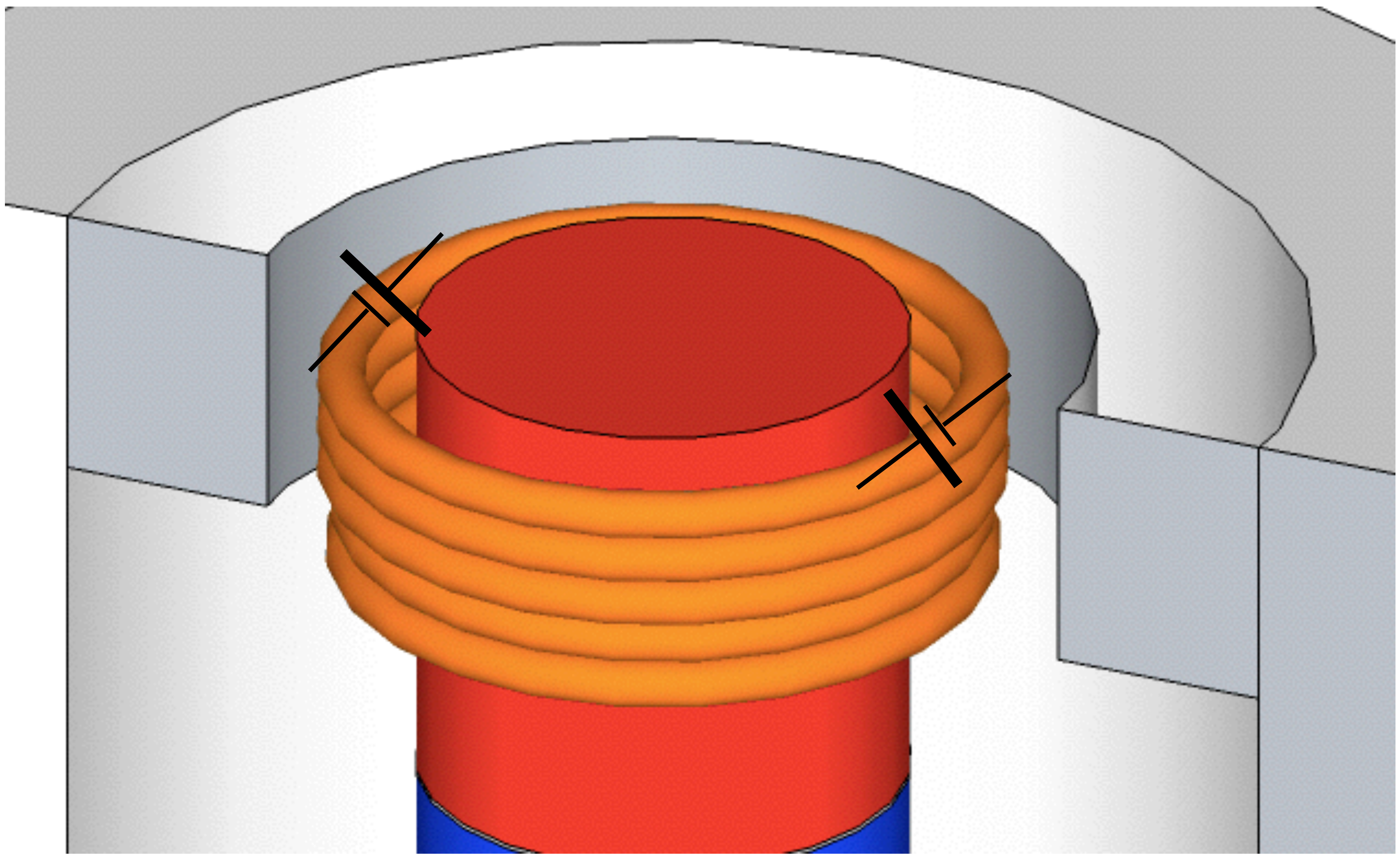
d=length of the wire


B
v

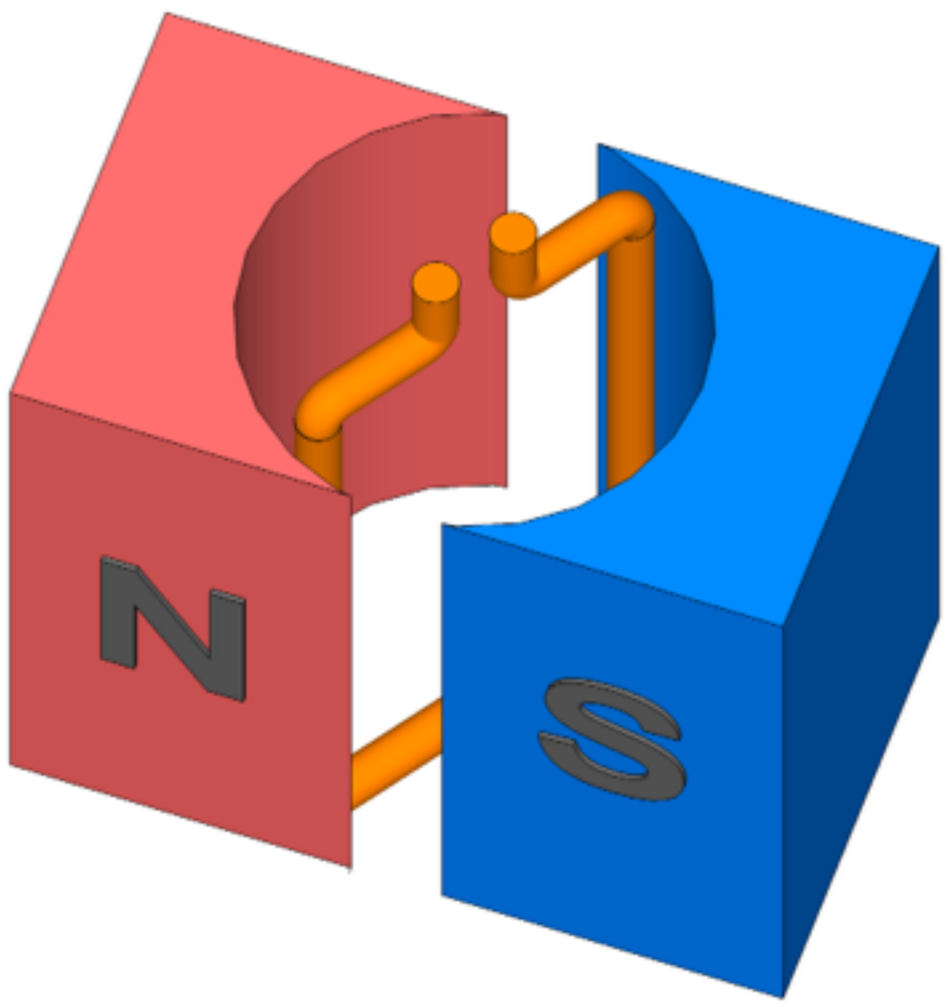

B
v

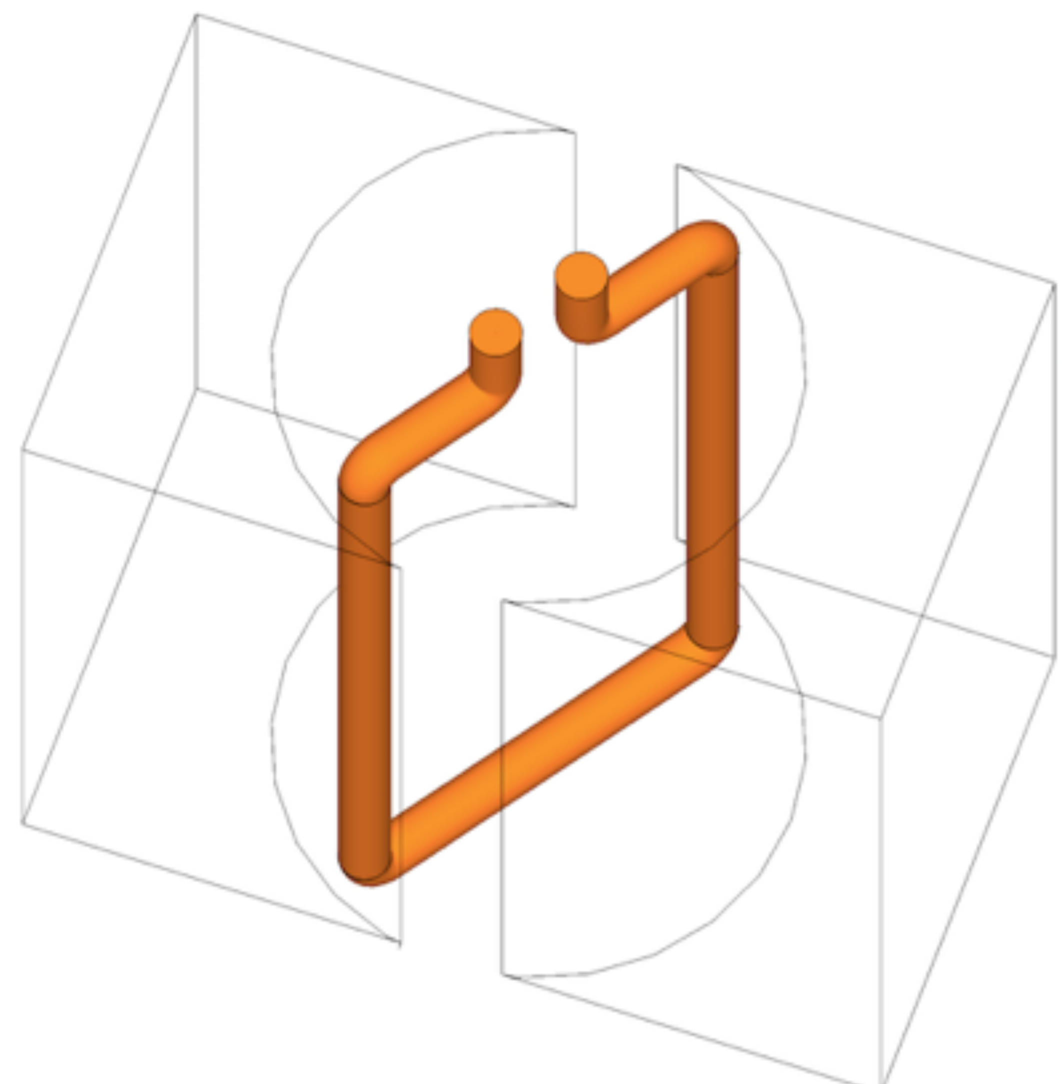

v
B

A voltage is induced in the coil. This voltage is proportional to the velocity.

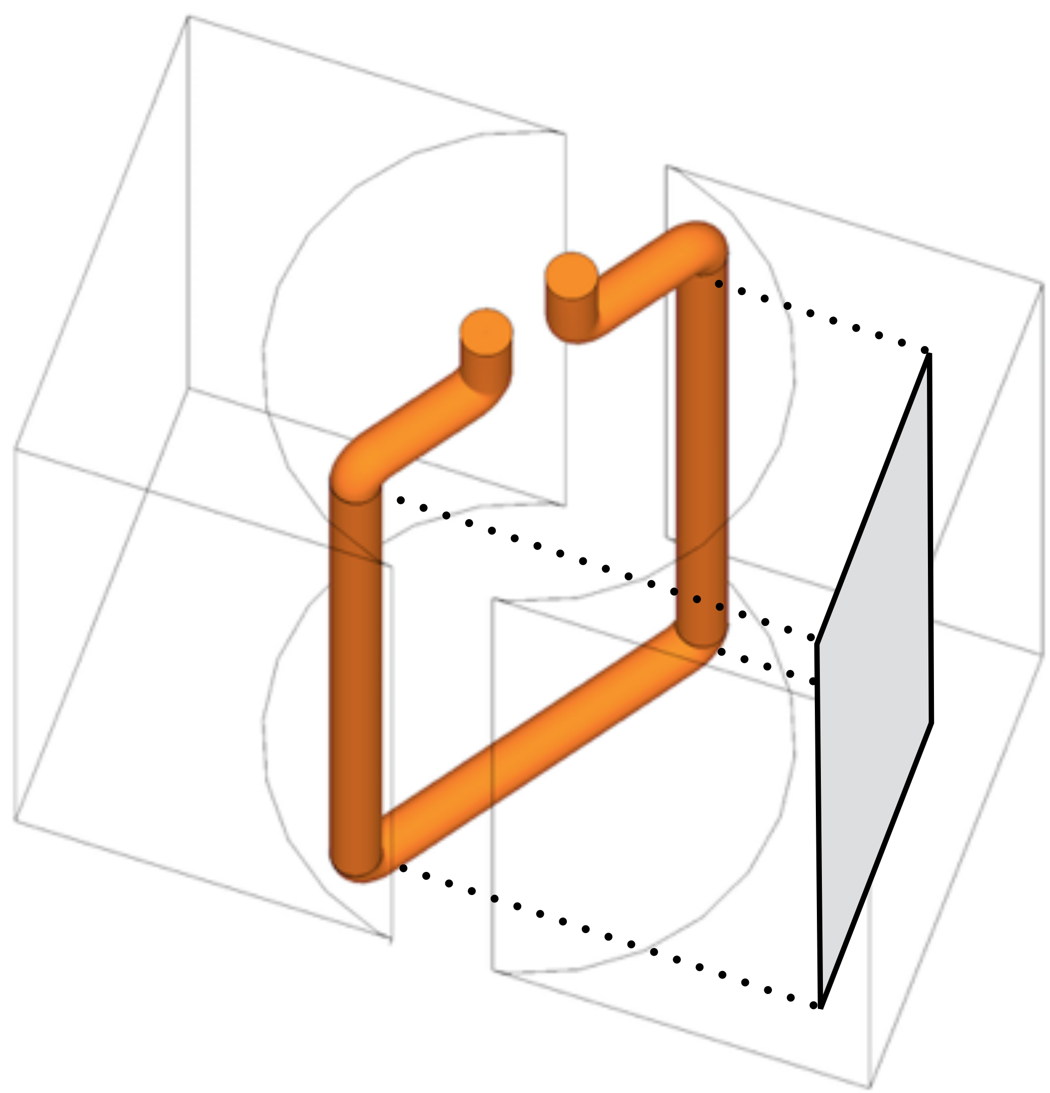


Tachometer based on DC generator



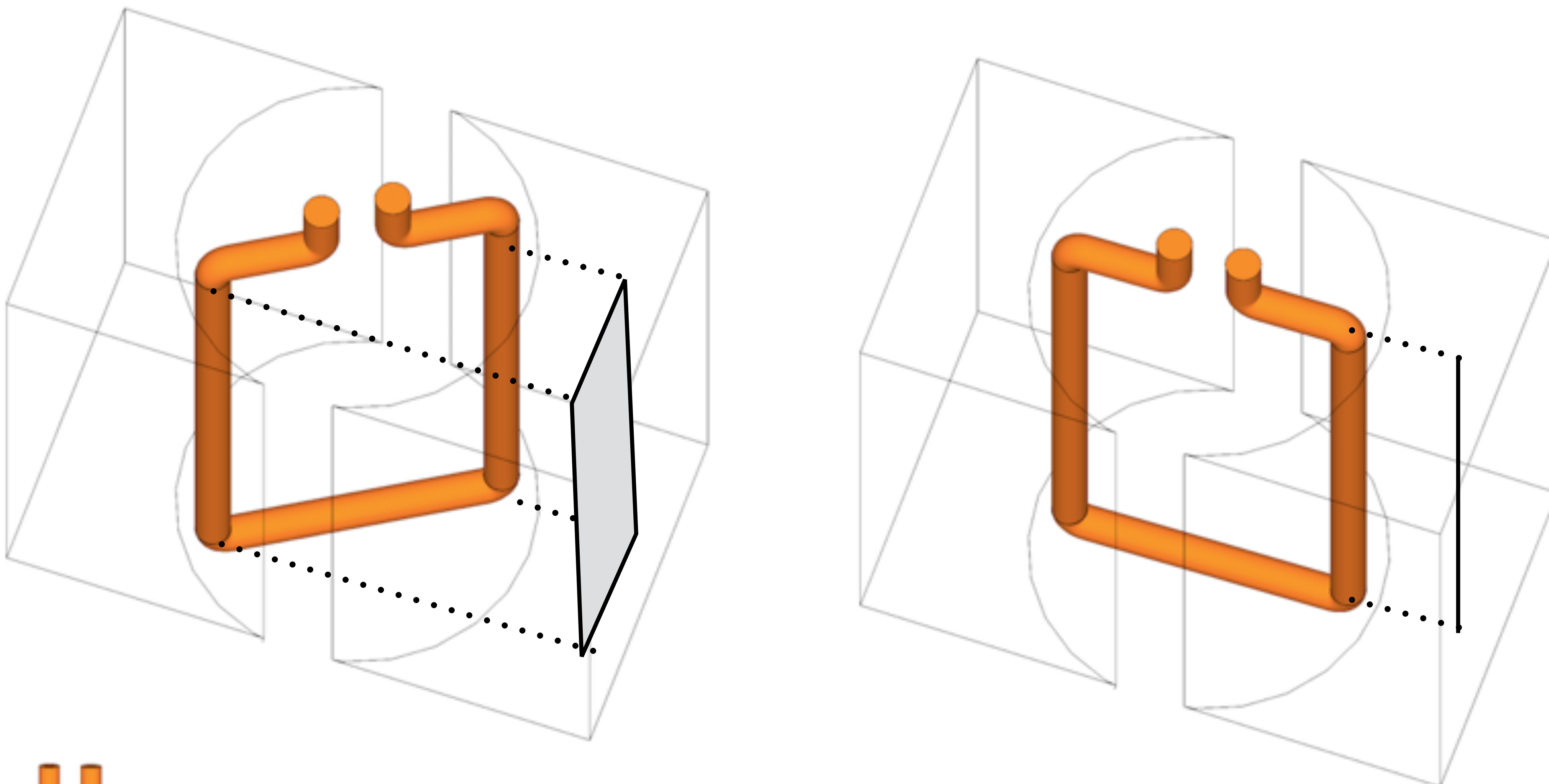


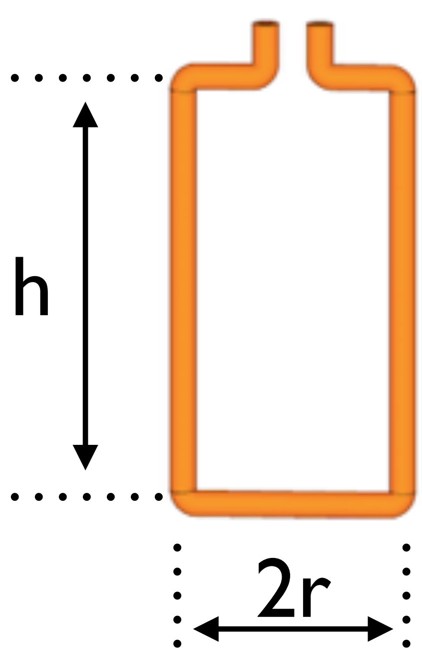
Tachometer based on DC generator



the effective area of the coil depends on the relative angle to the magnetic field

Tachometer based on DC generator





$$V = (2rhN)\omega$$

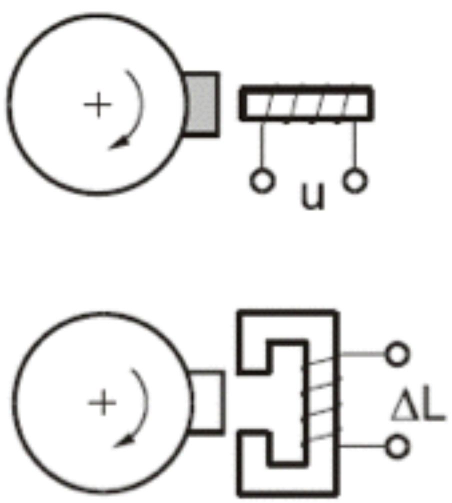
N=number of turns

The induced voltage depends on the rotational speed

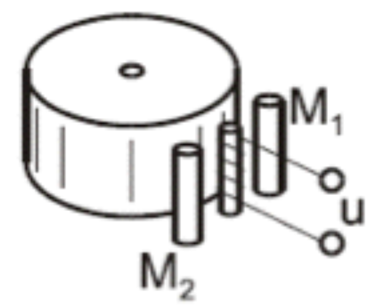
ideally: no load - to avoid effect of inductance at high ω

Sensors of velocity with pulse output

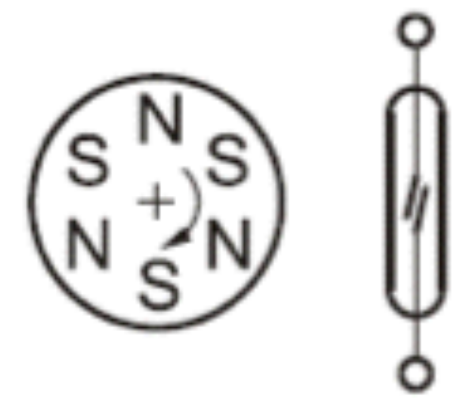
induction



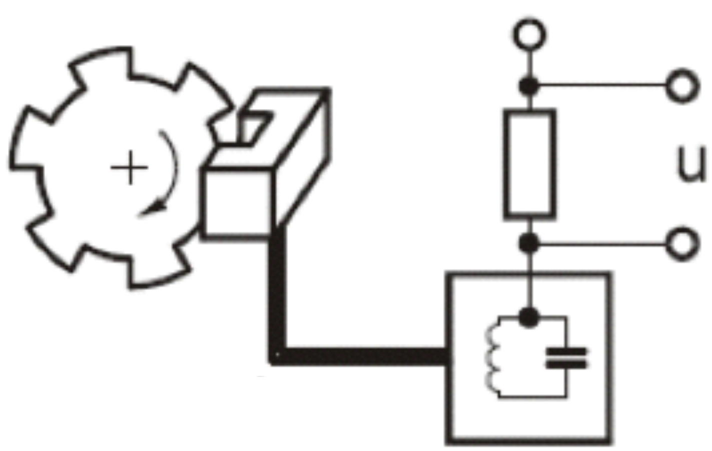
wiegand sensor



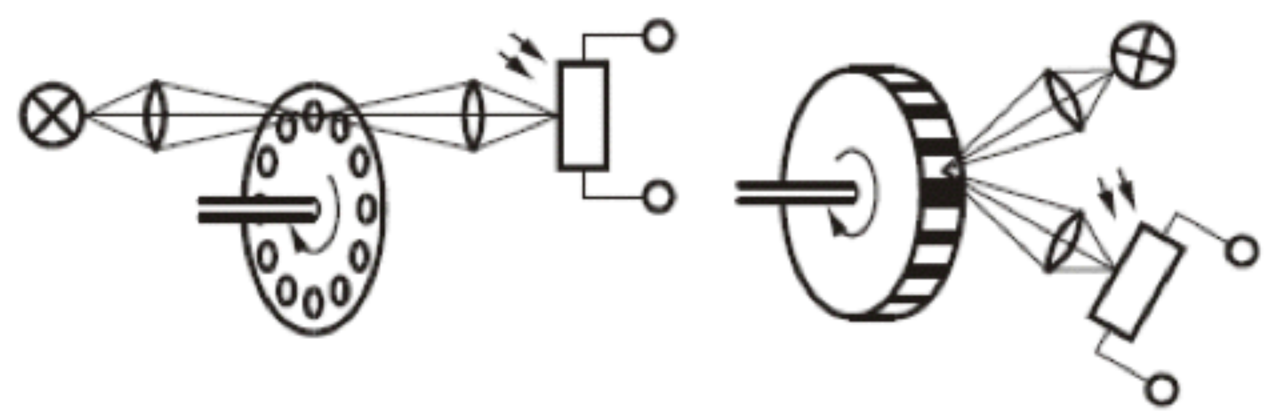
reed sensor



eddy current

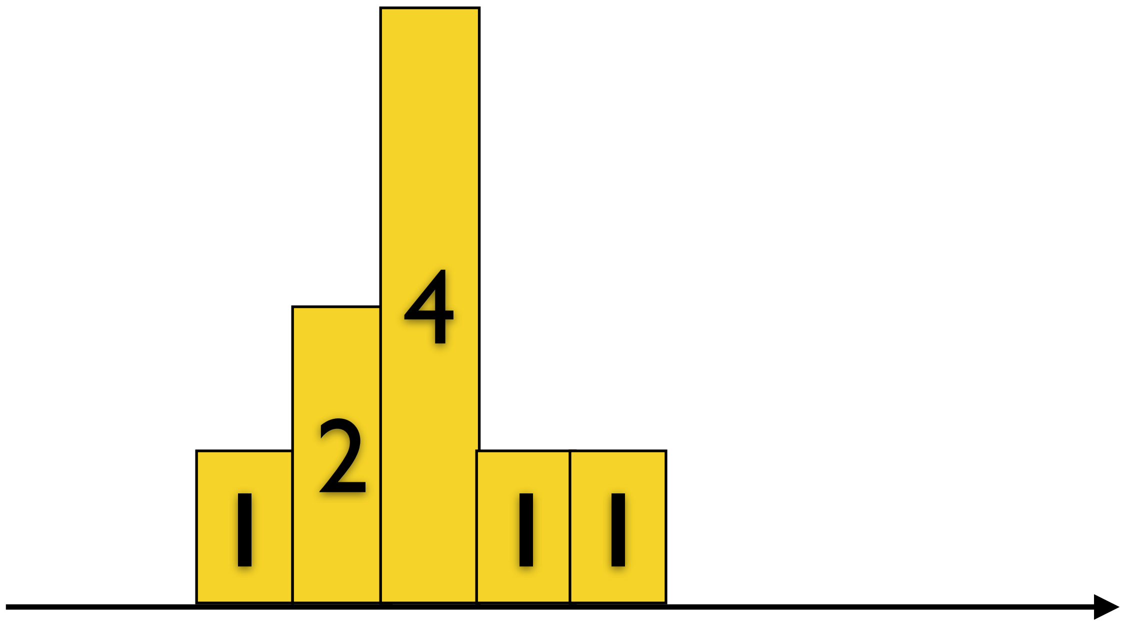


optoelectronics

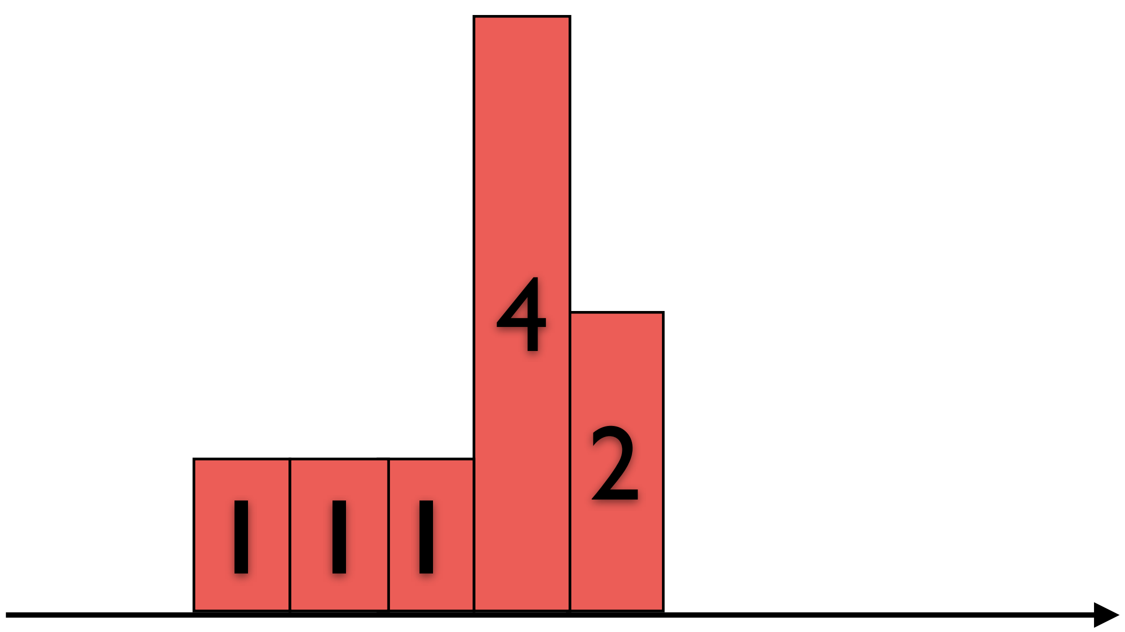


Measurement by means of correlation

what is correlation?

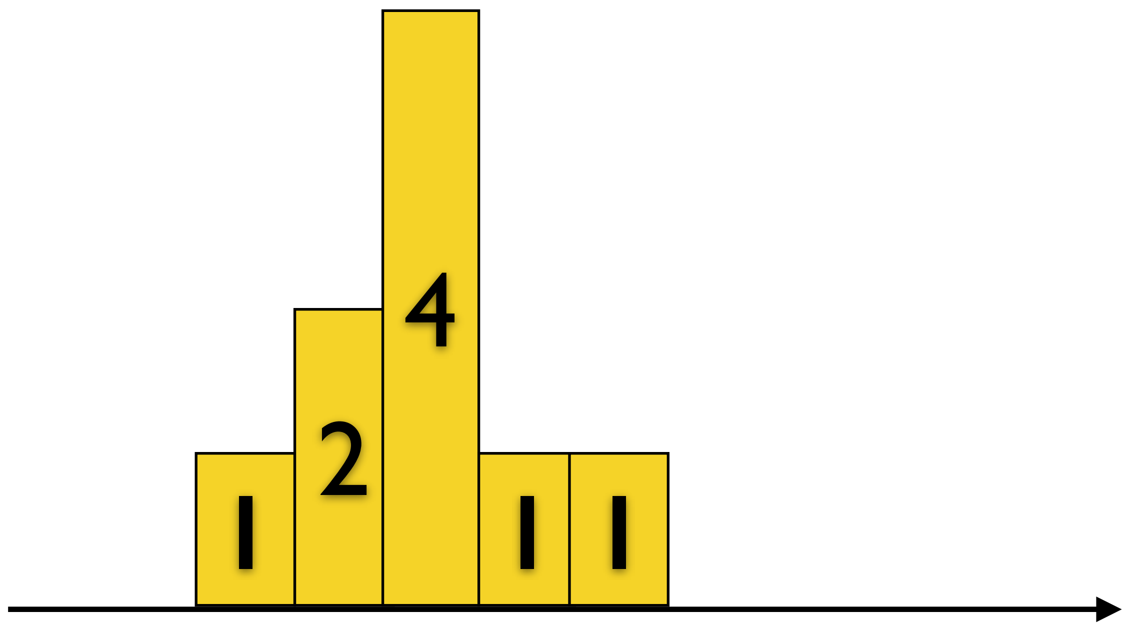


sequence A

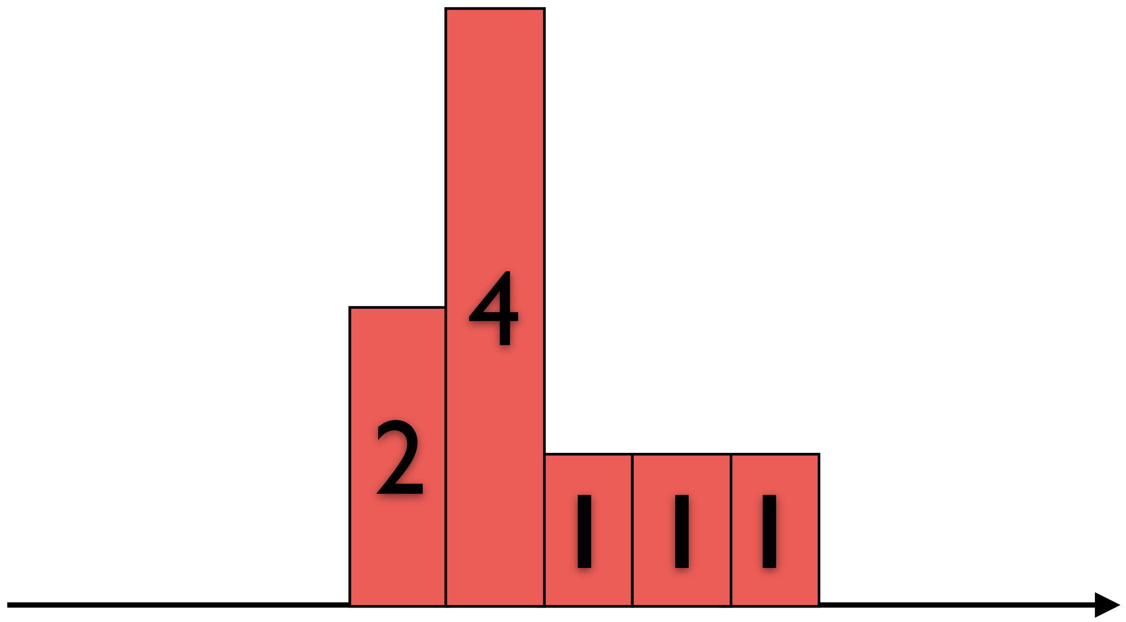


sequence B

A

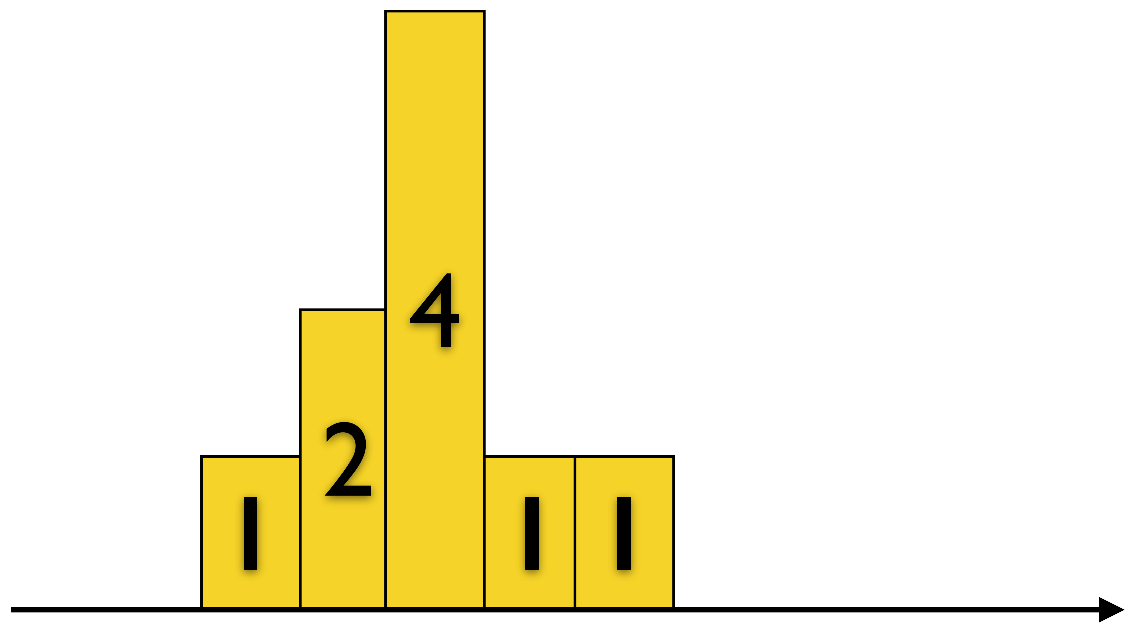


flipped B

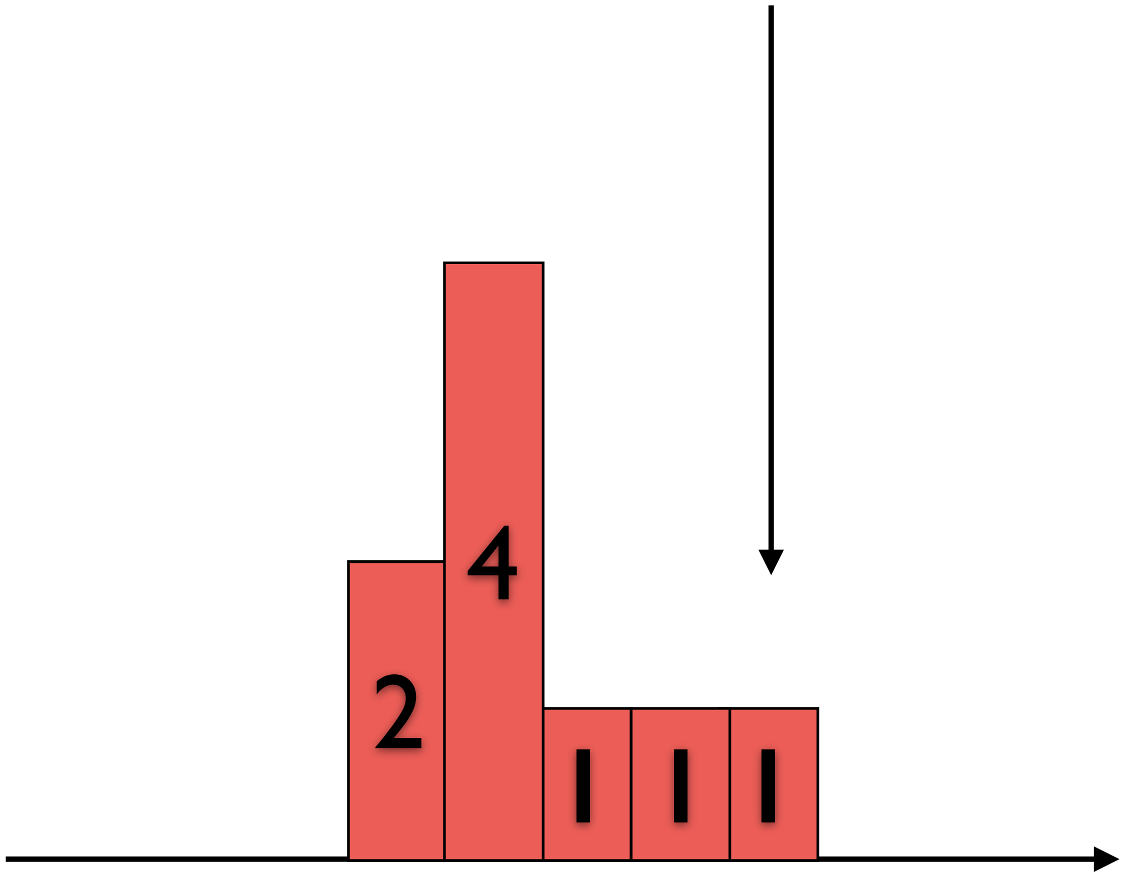


step 1 corr= [1

A



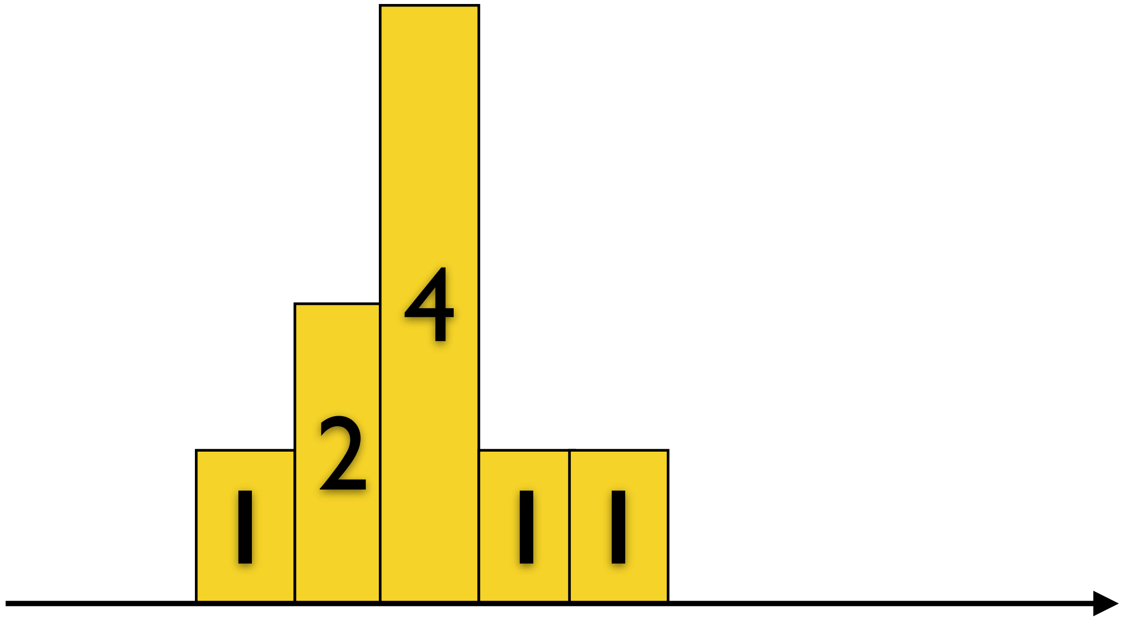
flipped B



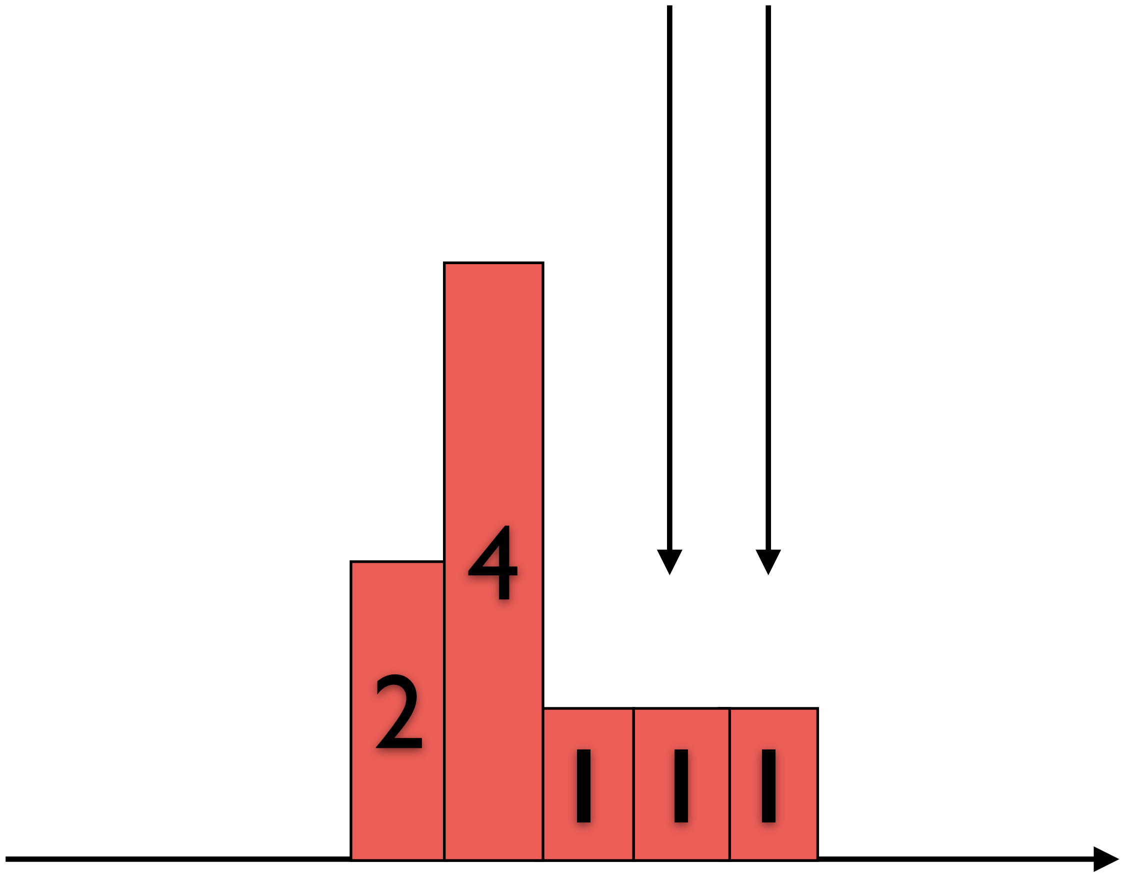
1 x 1 = 1

step 2 corr= [1; 3

A

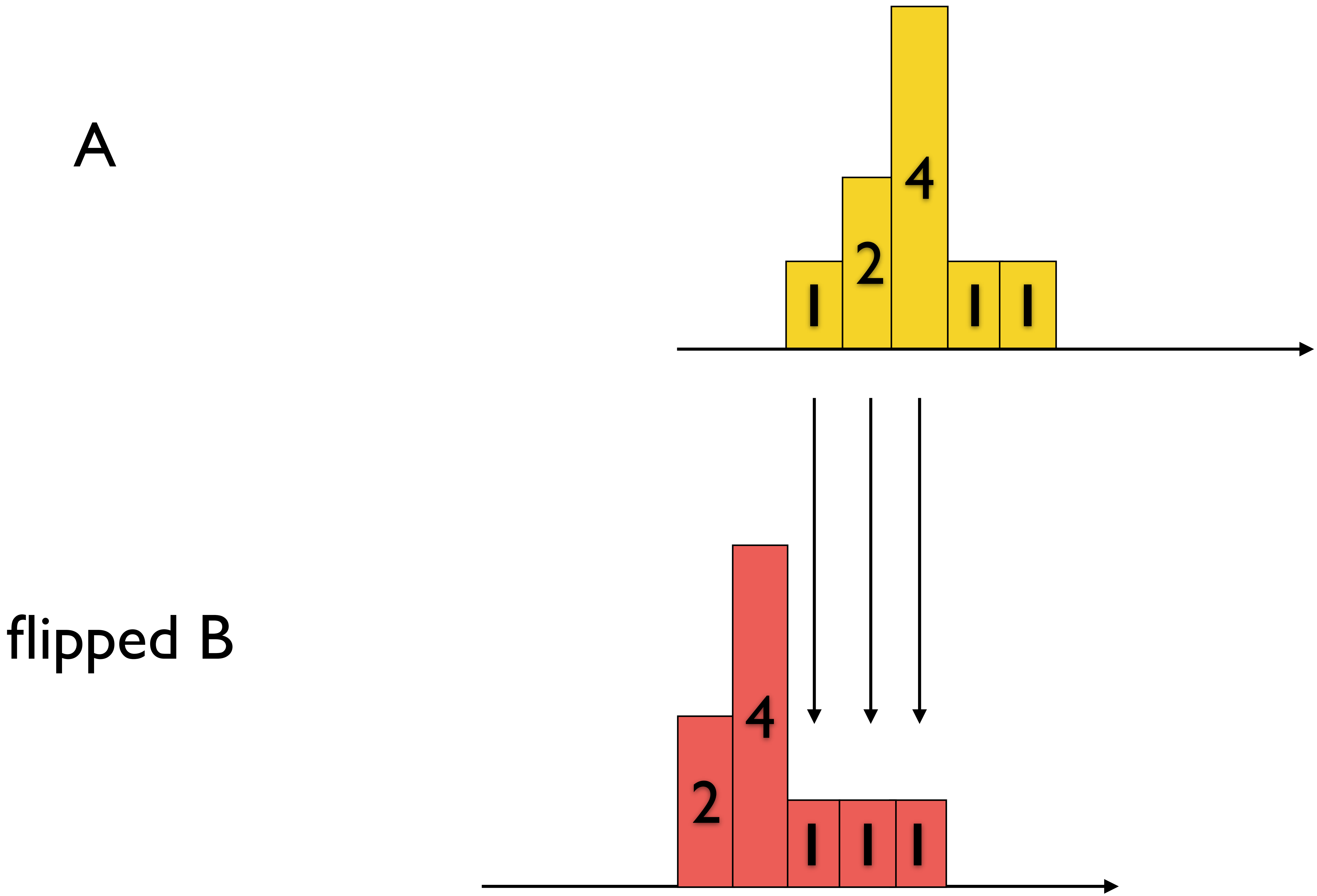


flipped B



1 x 1 + 2 x1 = 3

step 2 corr= [1; 3; 7

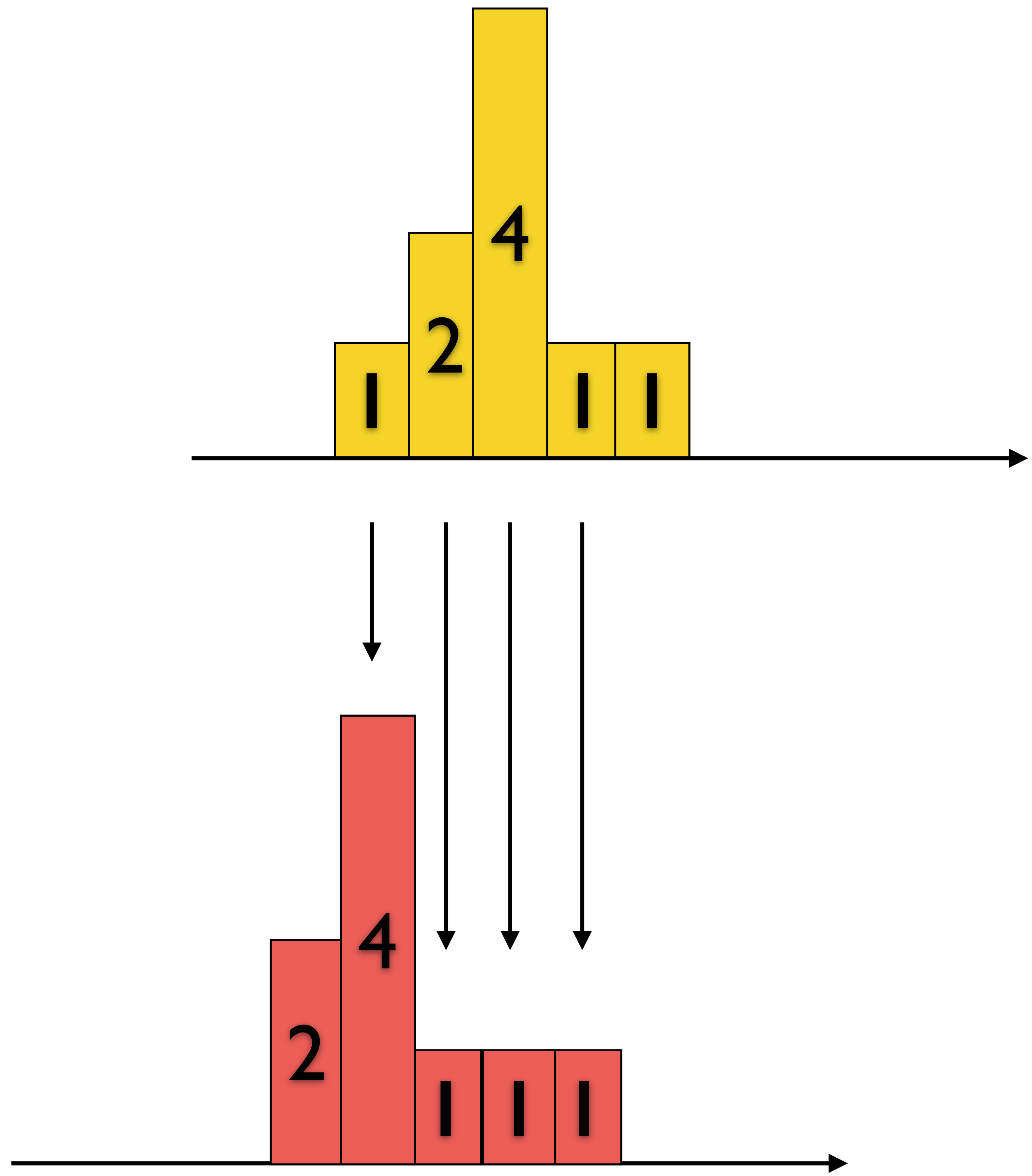


1 x 1 + 2 x1 + 4 x 1 = 7

step 2 corr= [1; 3; 7; 11

A

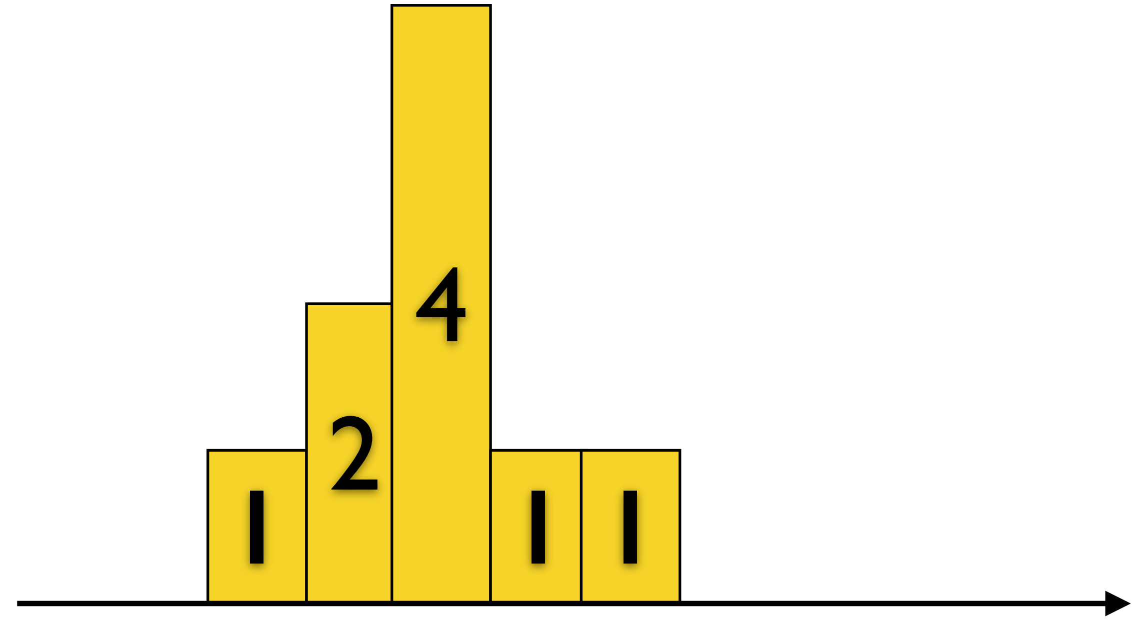
flipped B



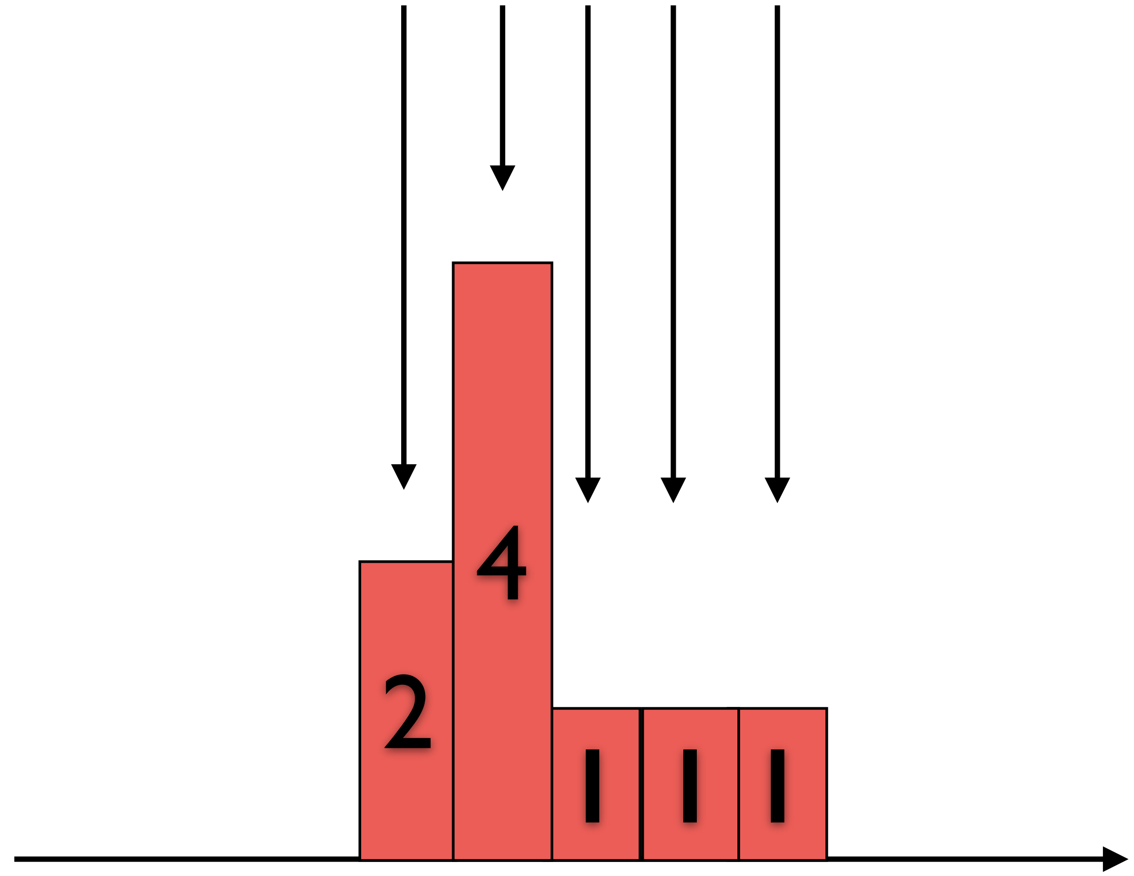
4 x 1 + 2 x1 + 4 x1 + 1 x 1 = 11

step 2 corr= [1; 3; 7; 11; 16

A



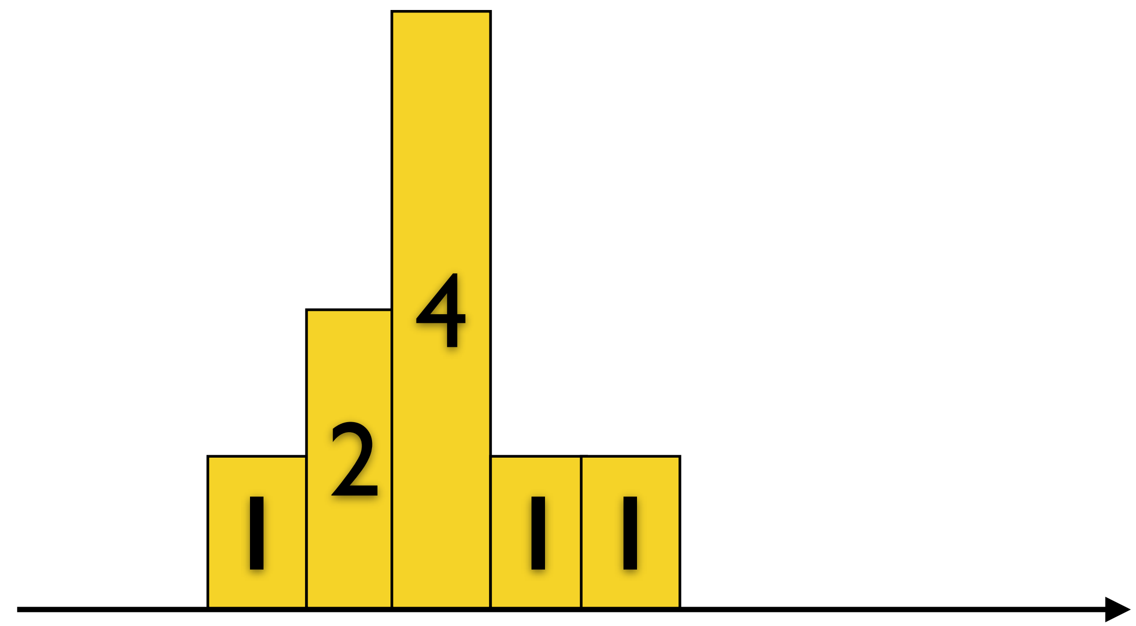
flipped B



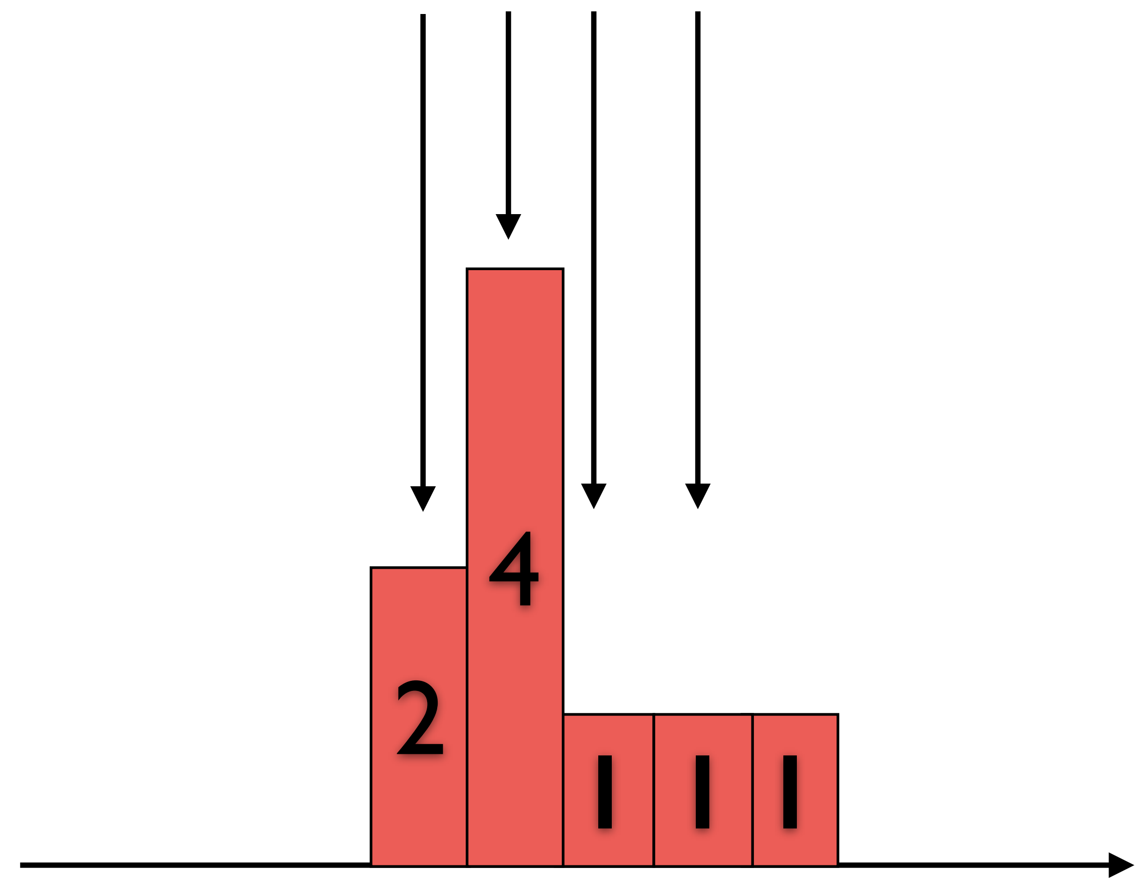
2 x 1 + 2 x 4 + 4 x 1 + 1 x 1 + 1 x 1= 16

step 2 corr= [1; 3; 7; 11; 16; 22

A



flipped B

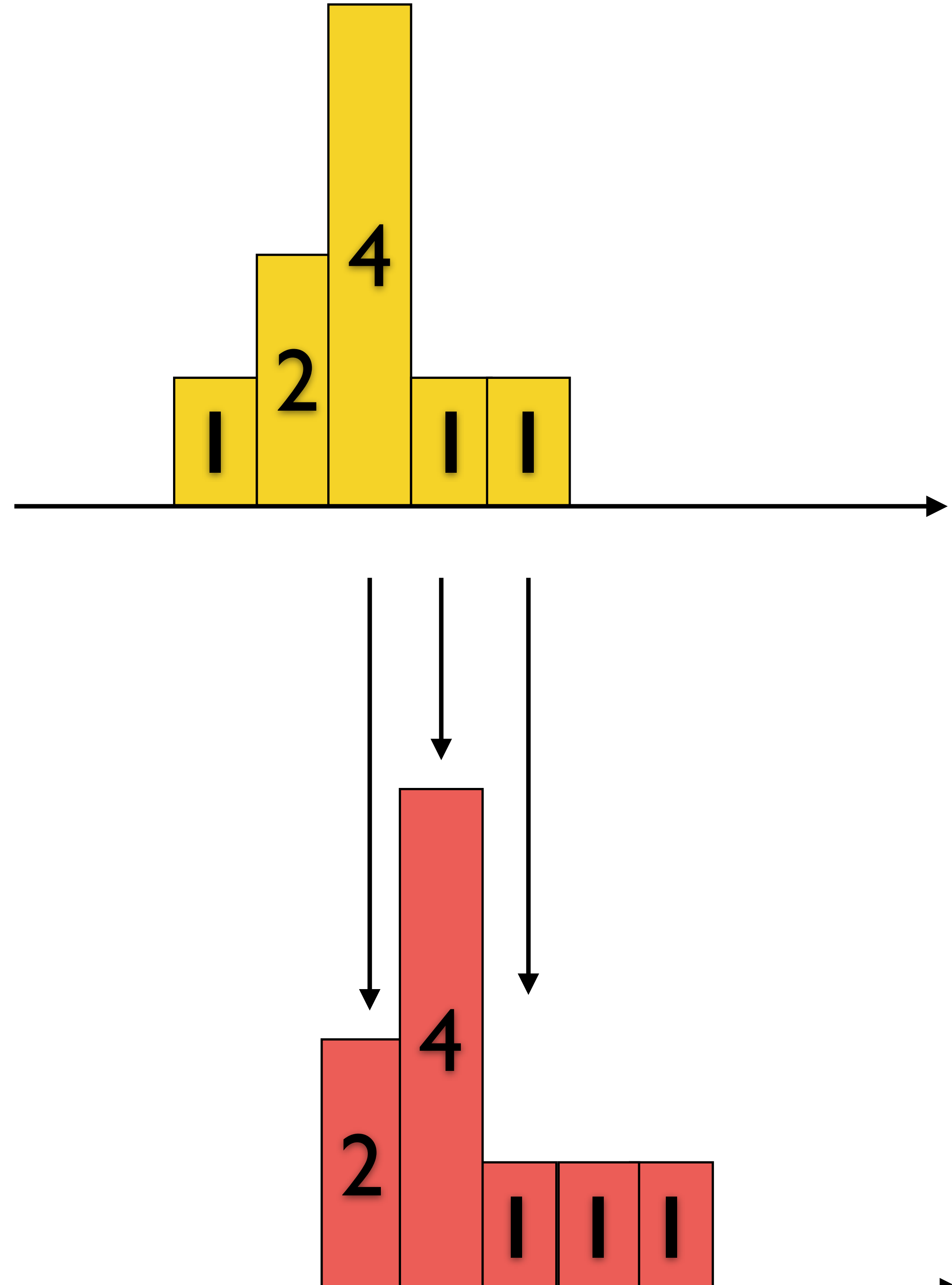


2 x 2 + 4 x 4 + 1 x 1 + 1 x 1= 22

step 2 corr= [1; 3; 7; 11; 16; 22; 13

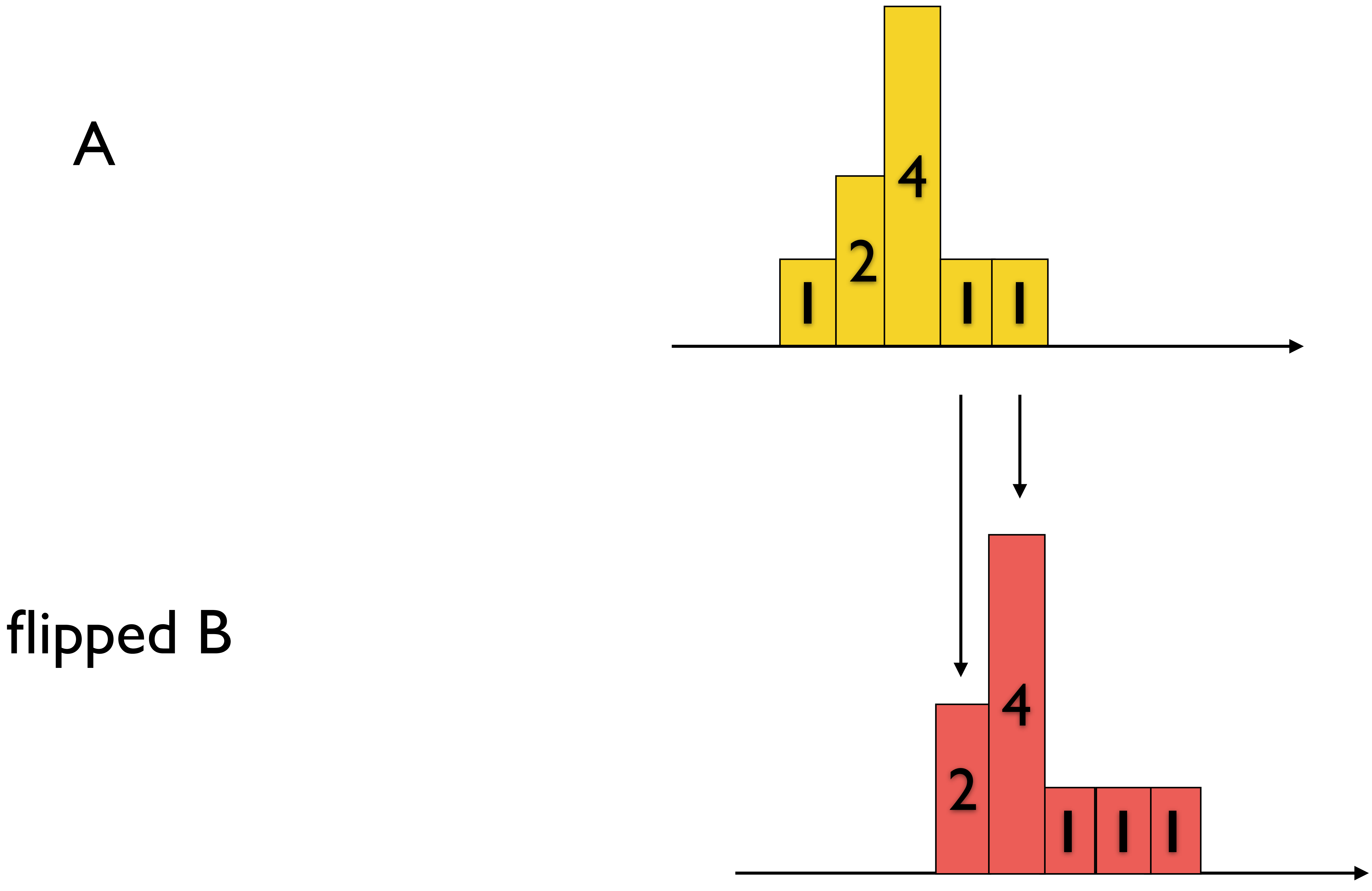
A

flipped B



$4 \times 2 + 4 \times 1 + 1 \times 1 = 13$

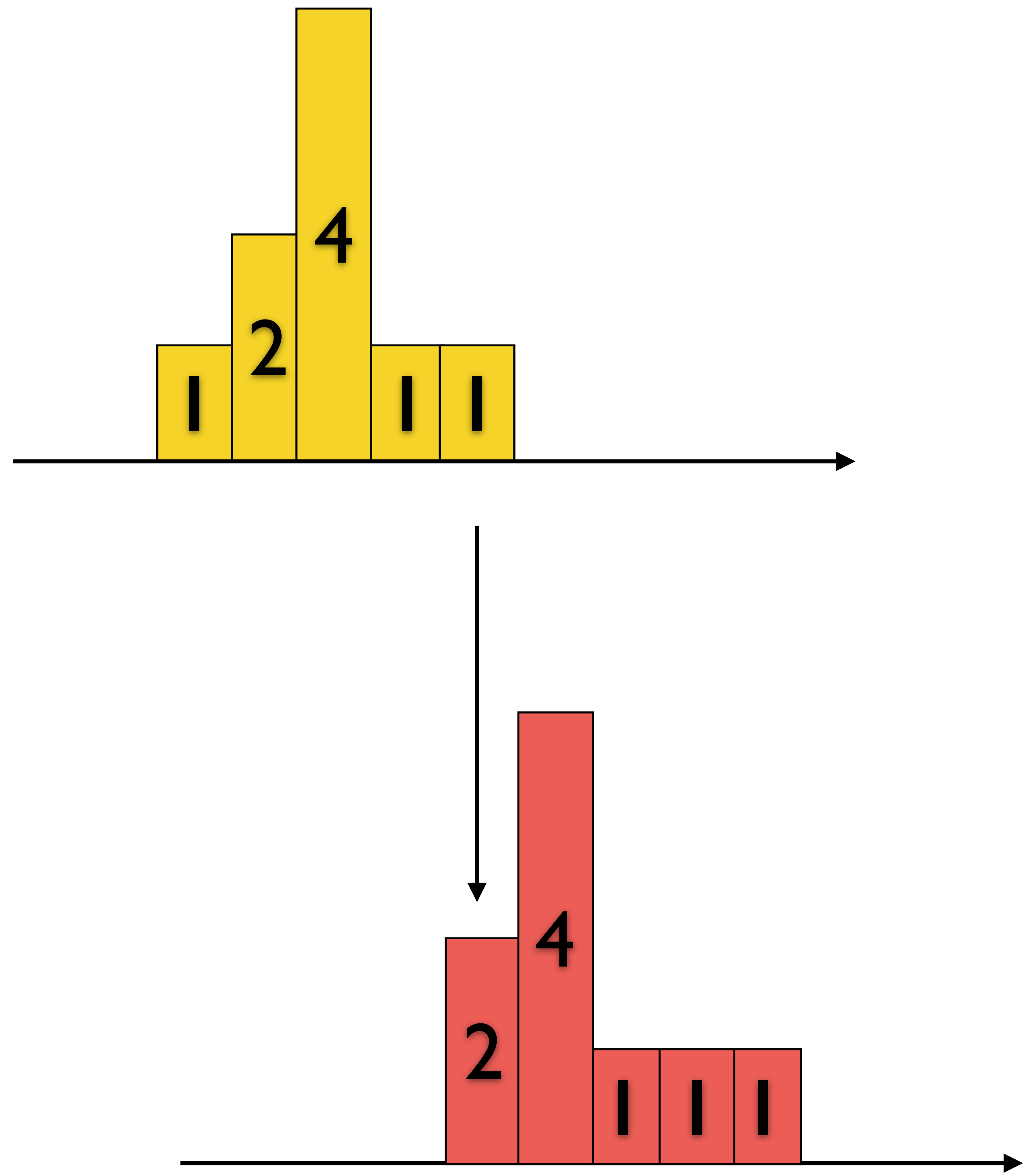
step 2 corr= [1; 3; 7; 11; 16; 22; 13; 6



$2 \times 1 + 4 \times 1 = 6$

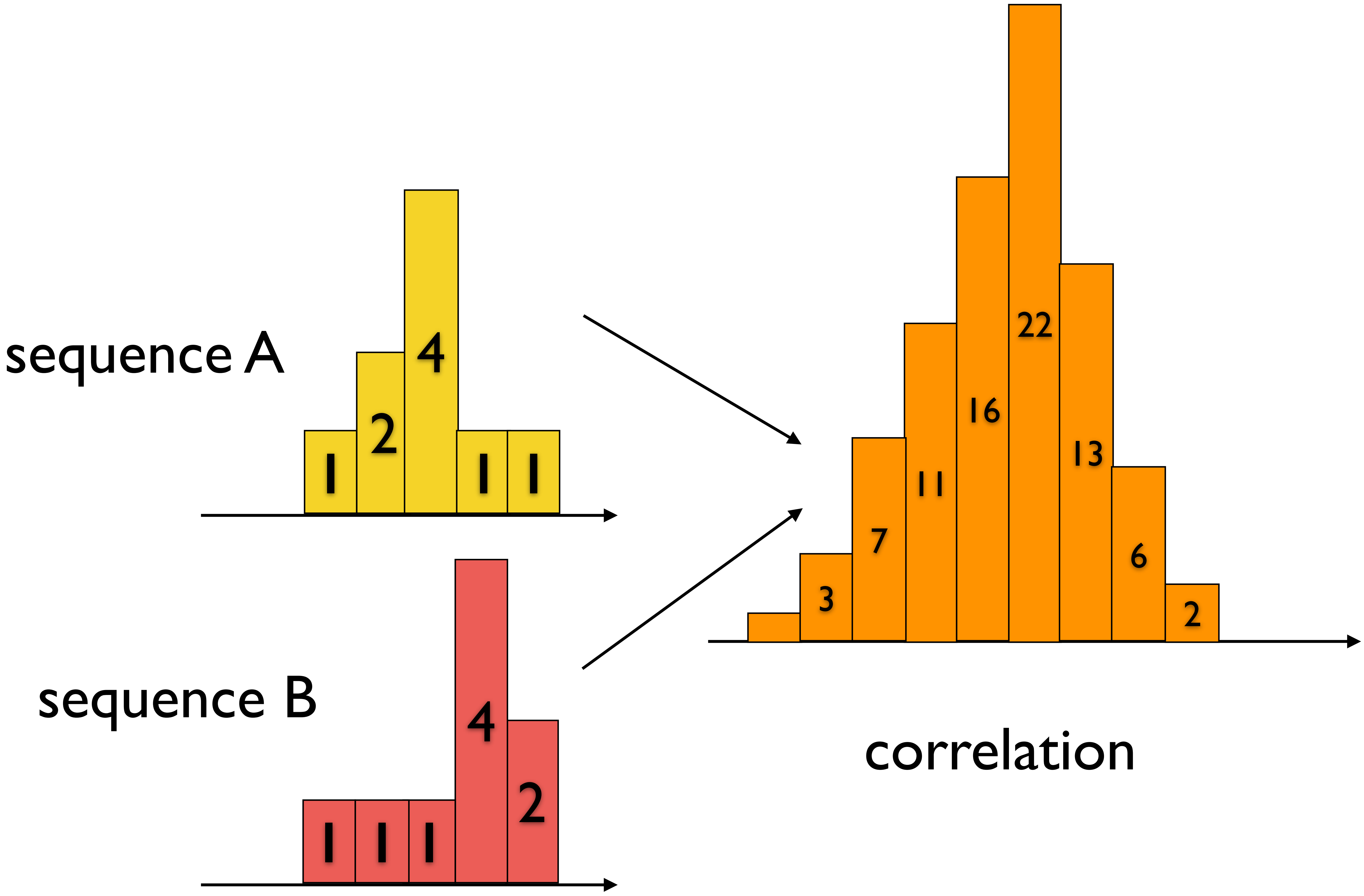
step 2 corr= [1; 3; 7; 11; 16; 22; 13; 6; 2]

A

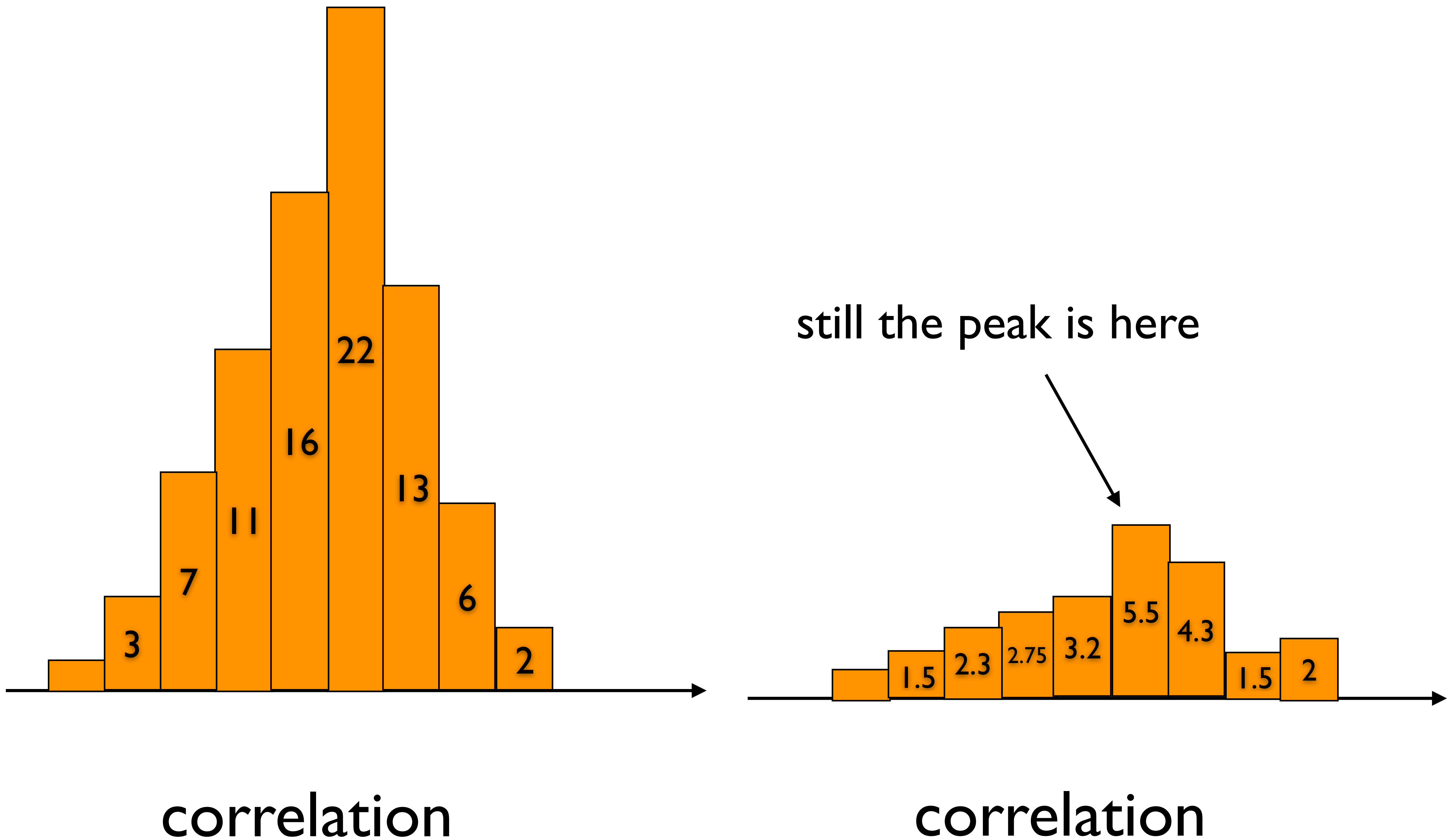


flipped B

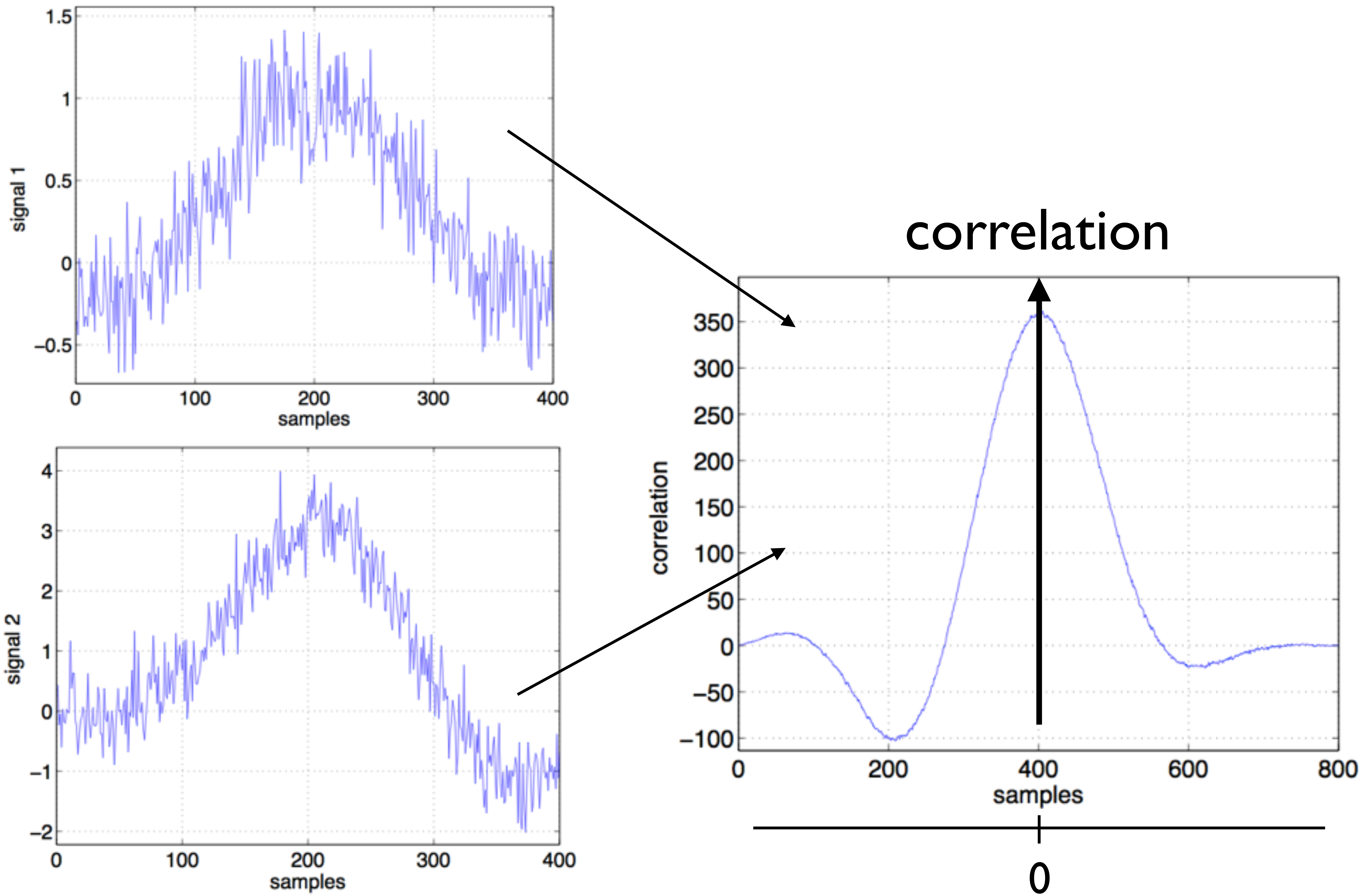
2 x 1 = 2


sequence A
1
2
4
1
1
sequence B
1
1
1
4
2
3
7
11
16
22
13
6
2
correlation

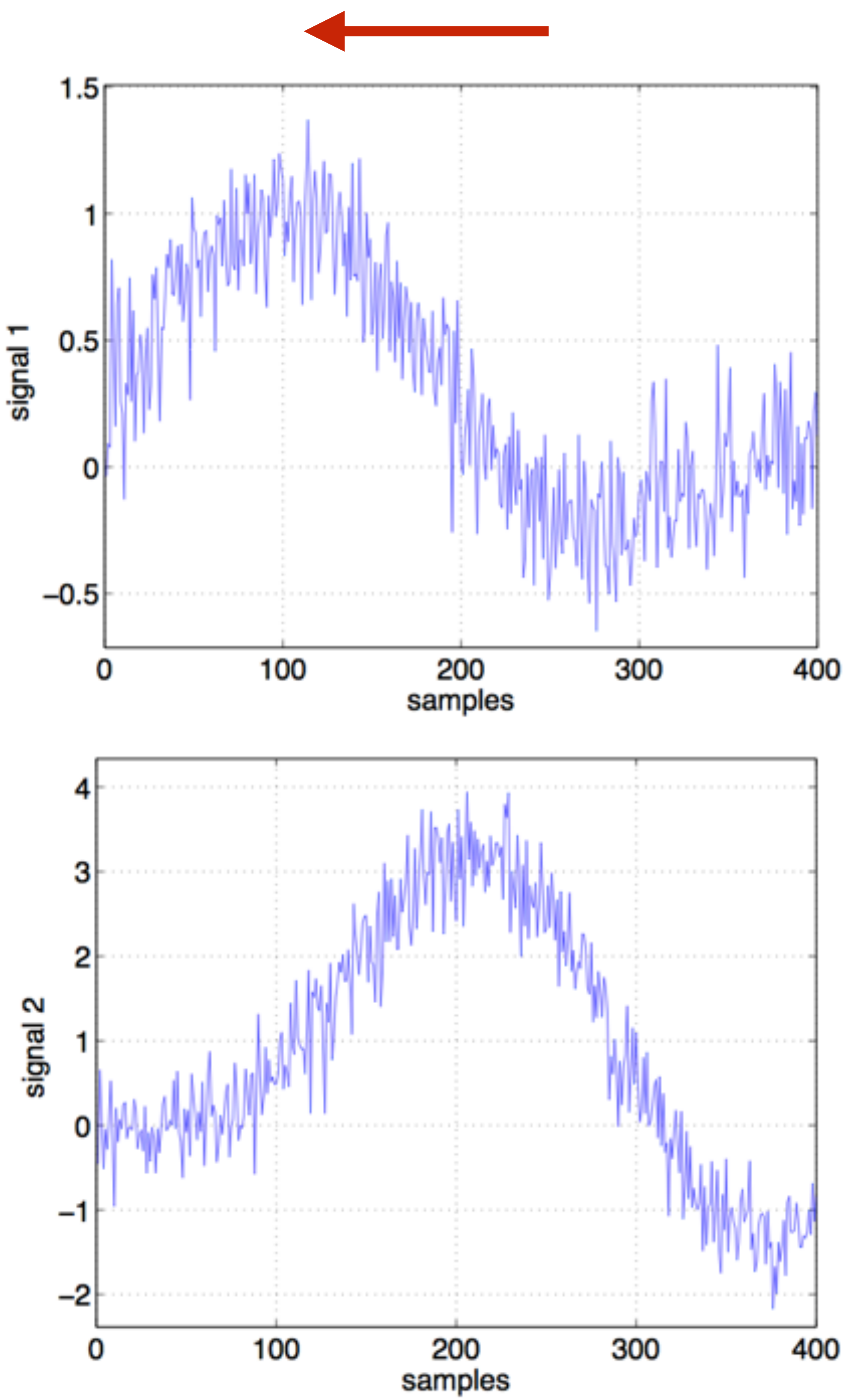
Let us divide by the number of products we summed



The peak in the correlation tells us where the signals are mostly similar

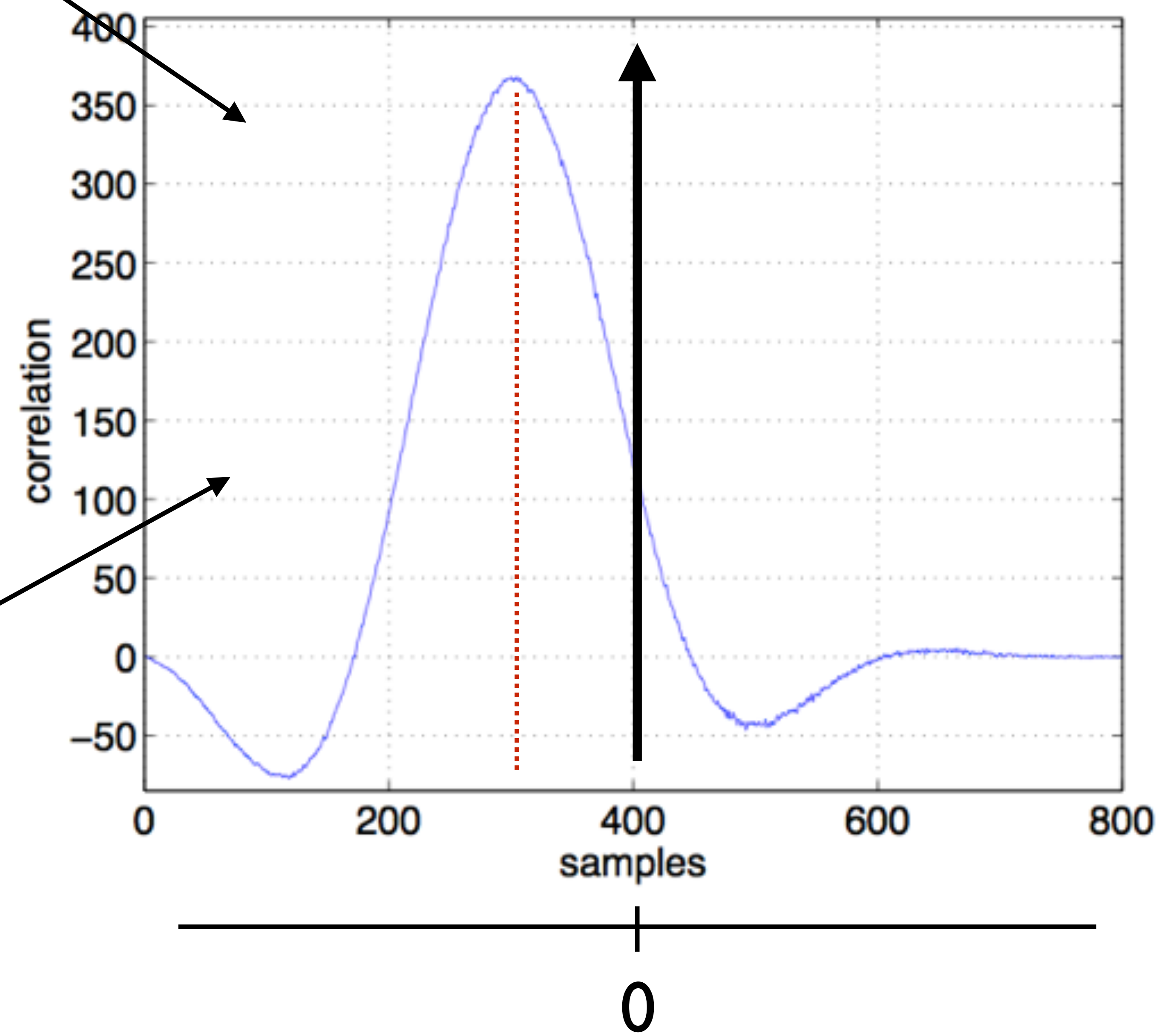


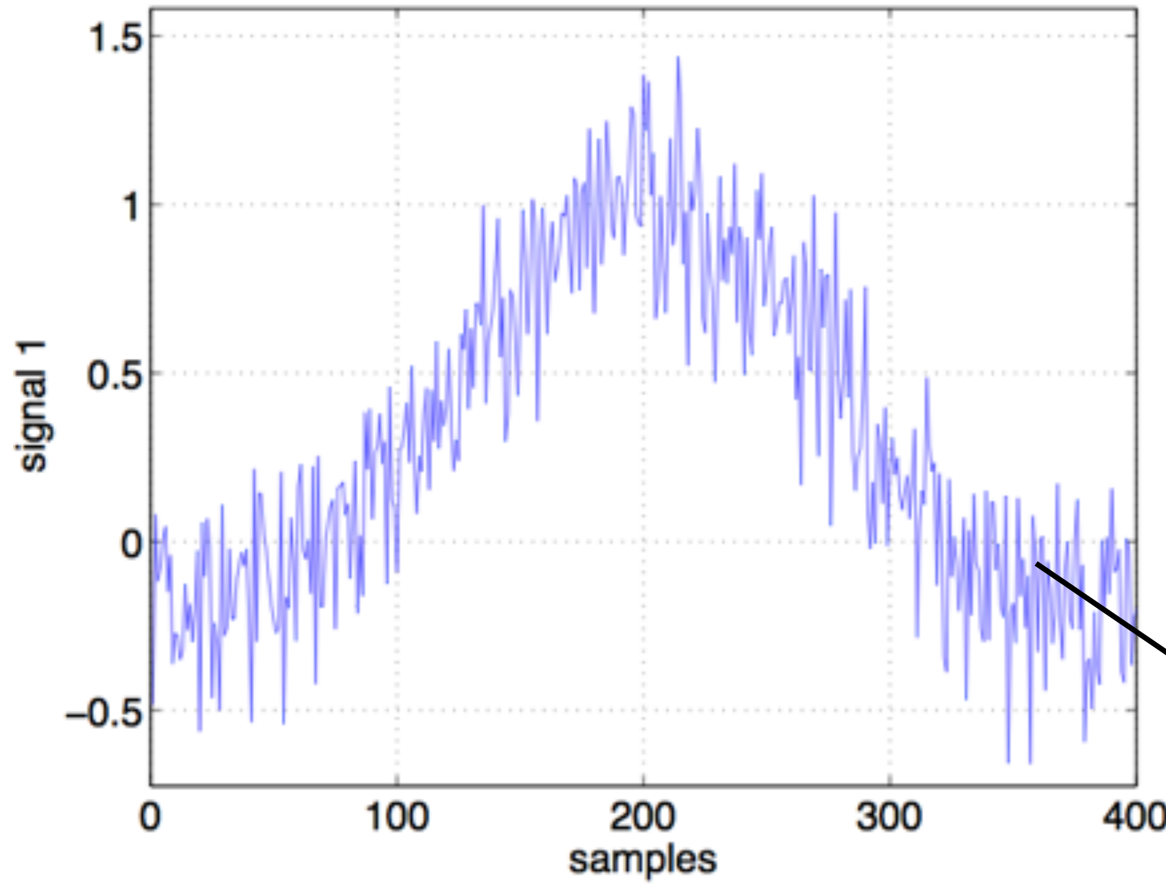
if the first signal moves “to the left”…



…the condition when the signal will be mostly similar will occur earlier

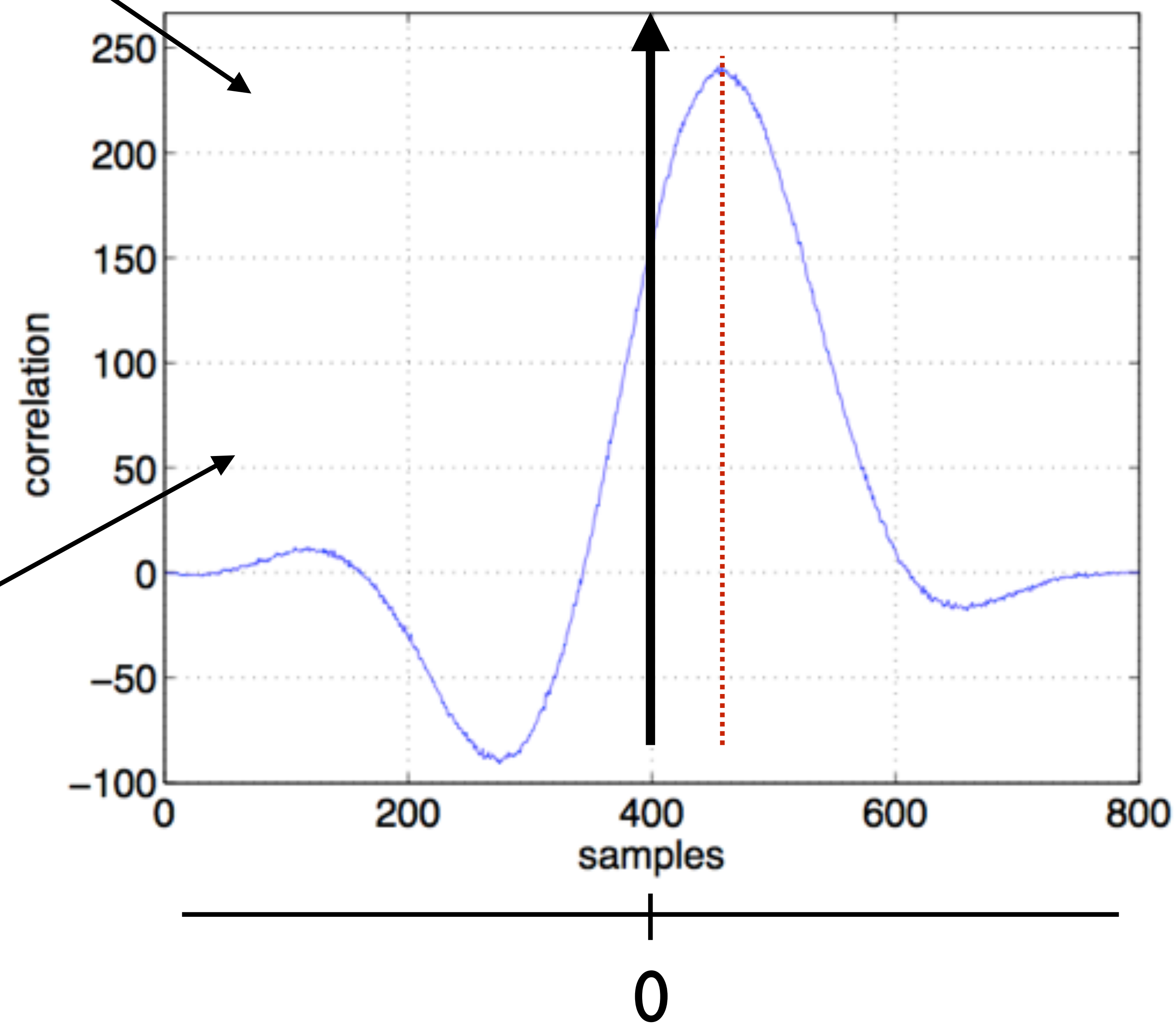
correlation



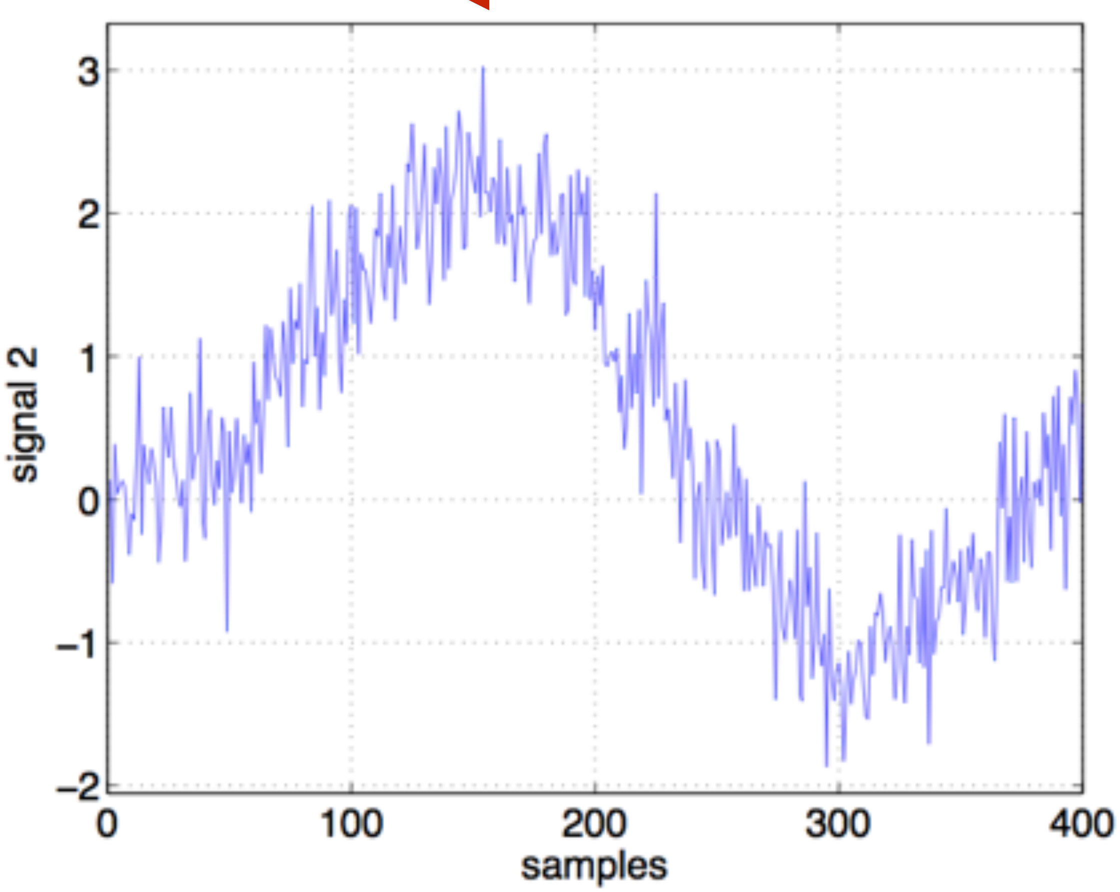


…the condition when the signal will be mostly similar will occur later

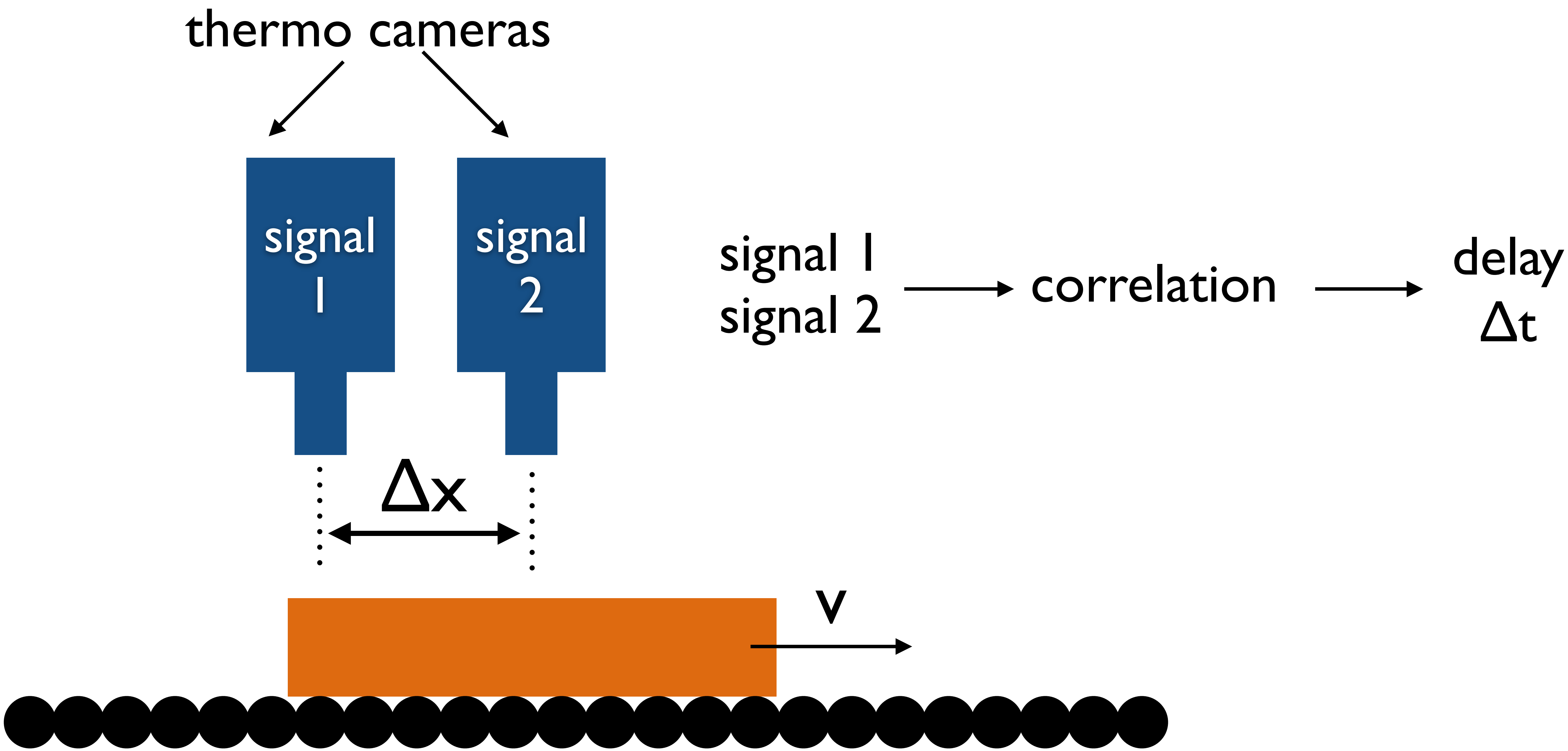
correlation



if the second signal moves "to the left"…

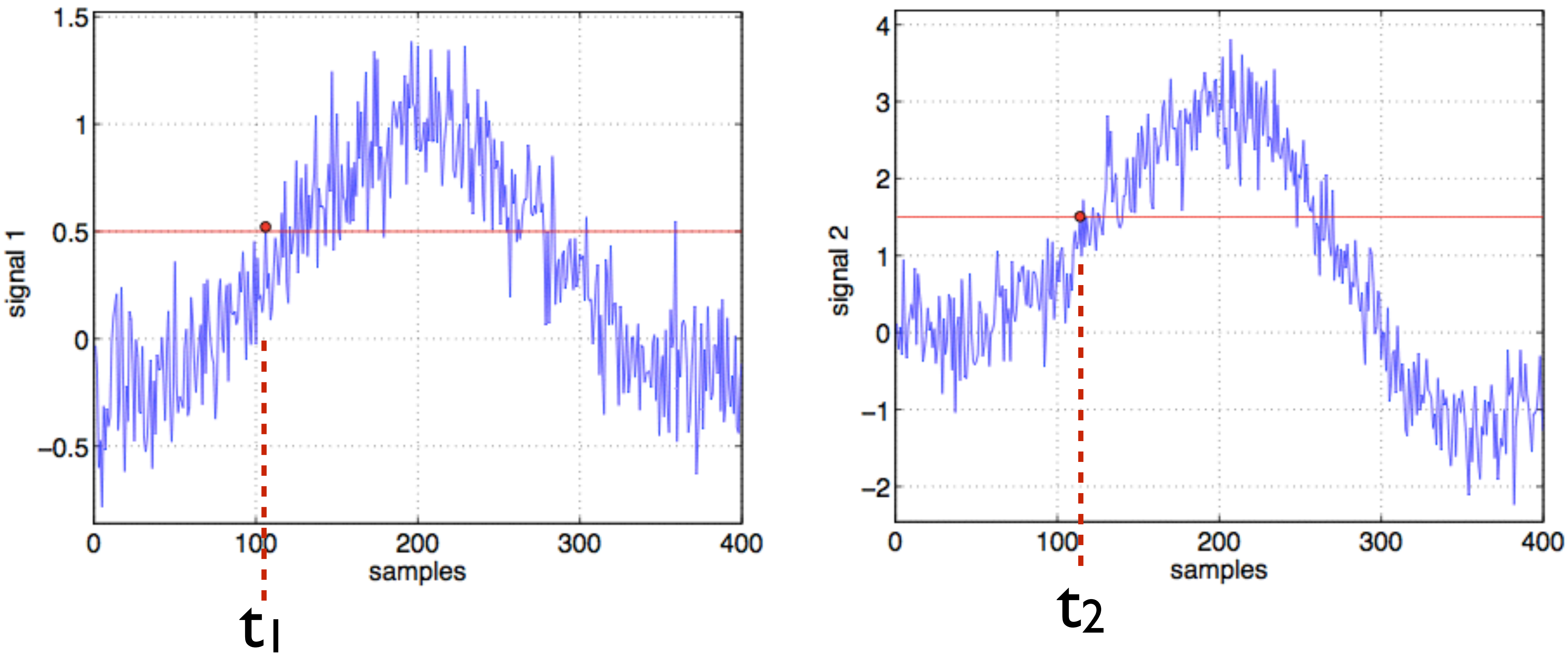


How to use this principle to measure velocity



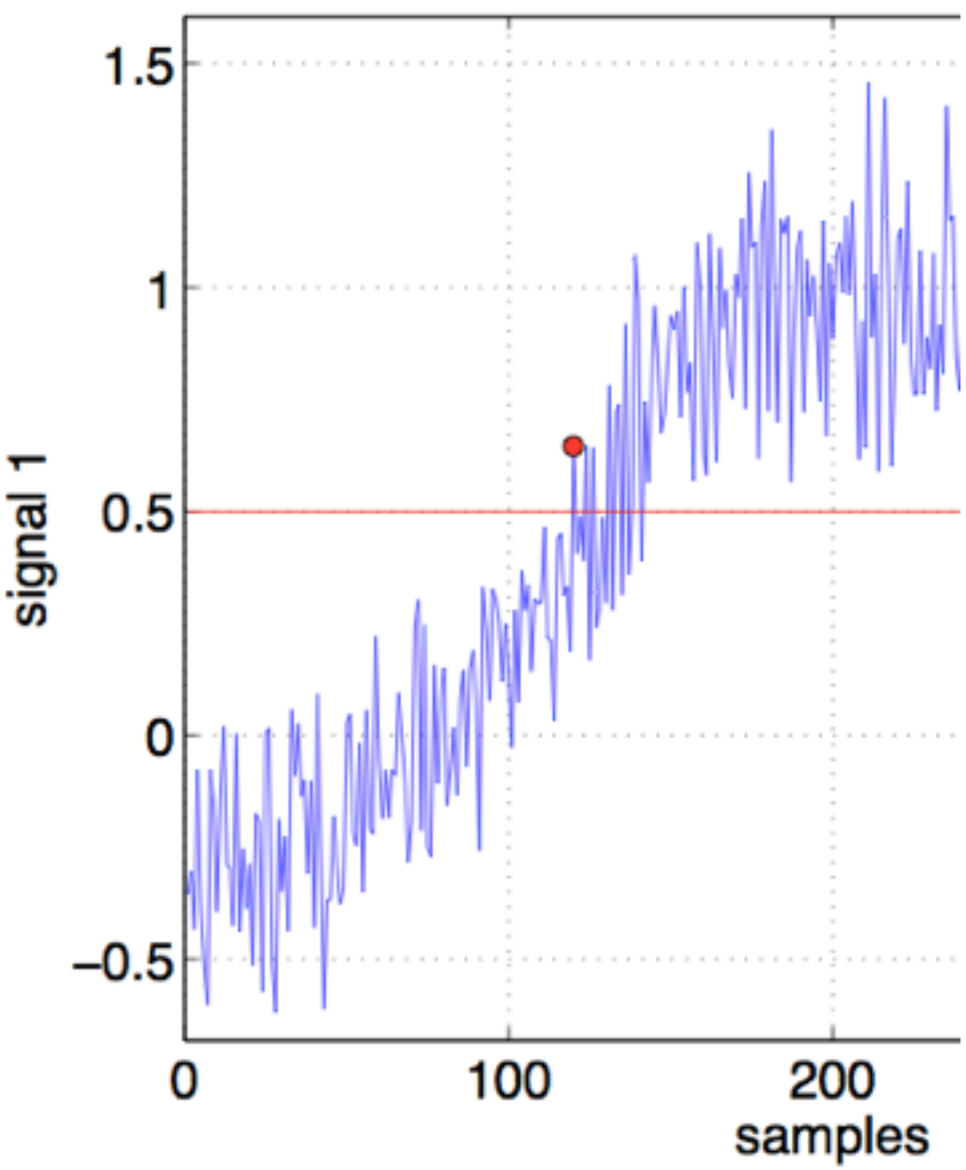
$v = \Delta x / \Delta t$

why not using a threshold?

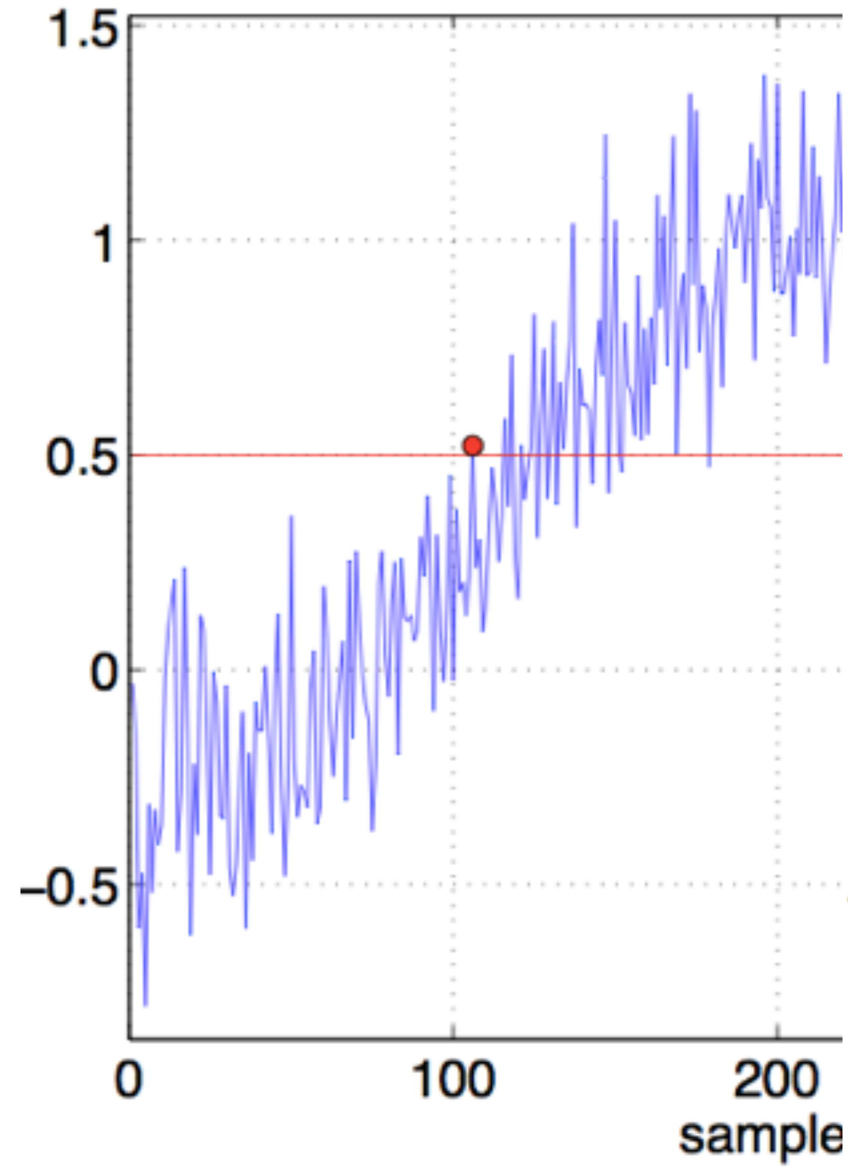


$$\Delta t = t_1 - t_2$$

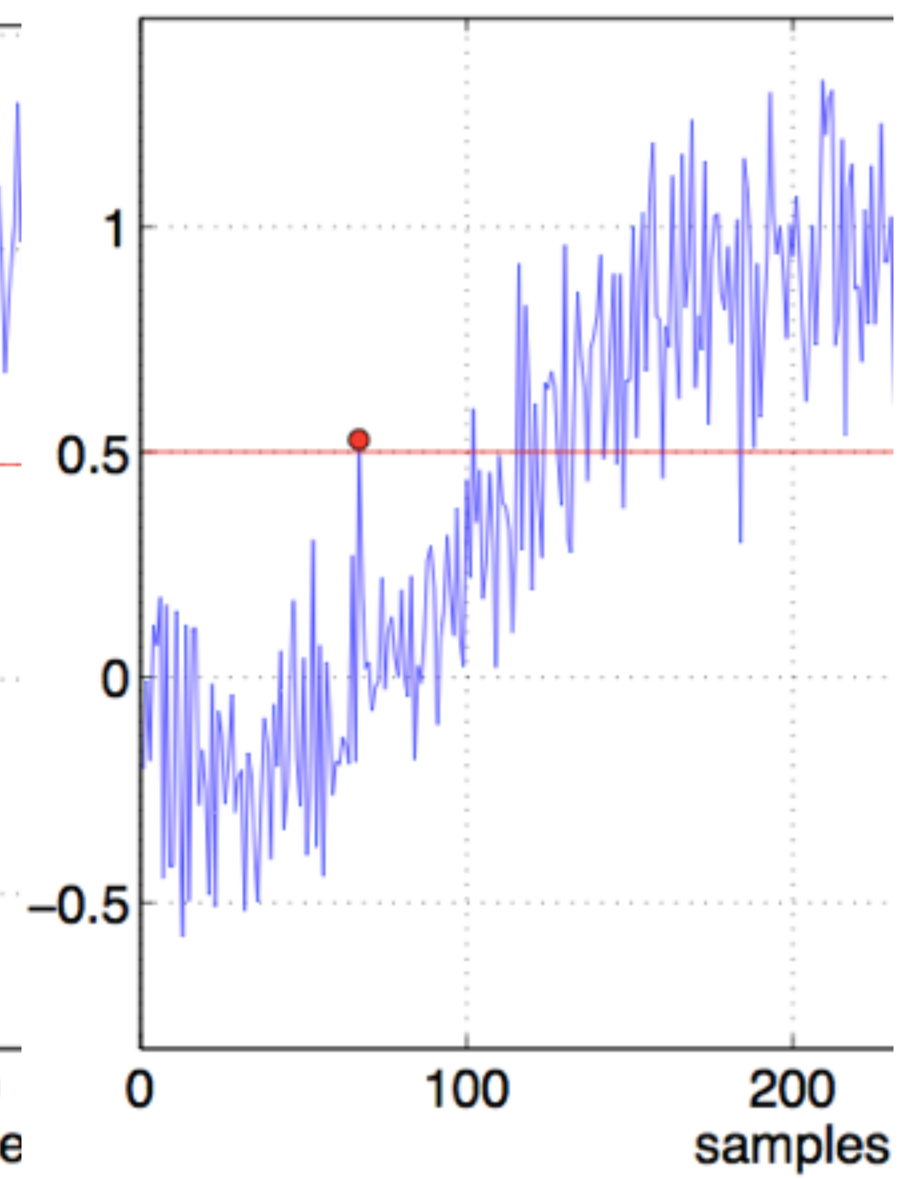
The noise makes this system highly unreliable



120

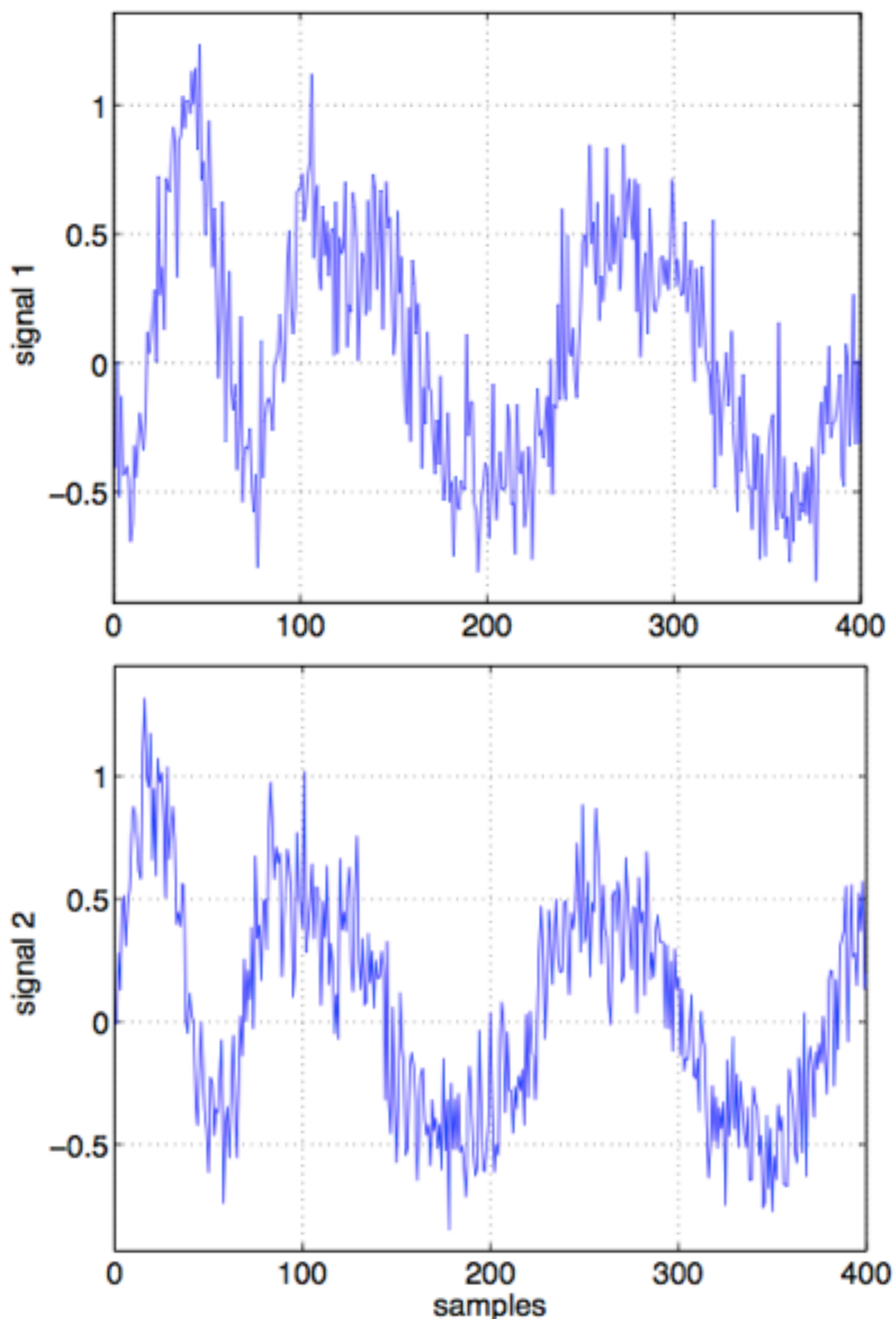


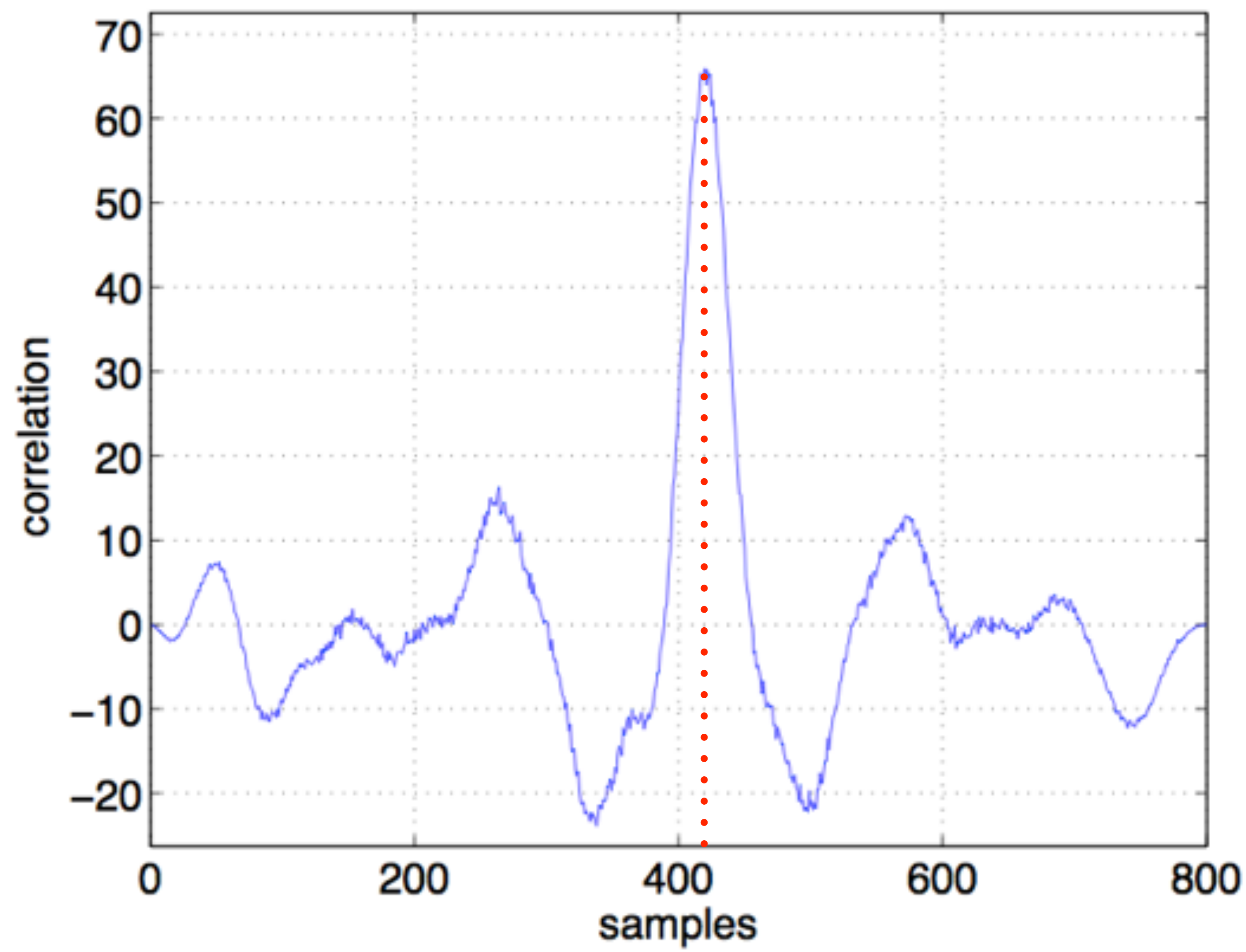
108



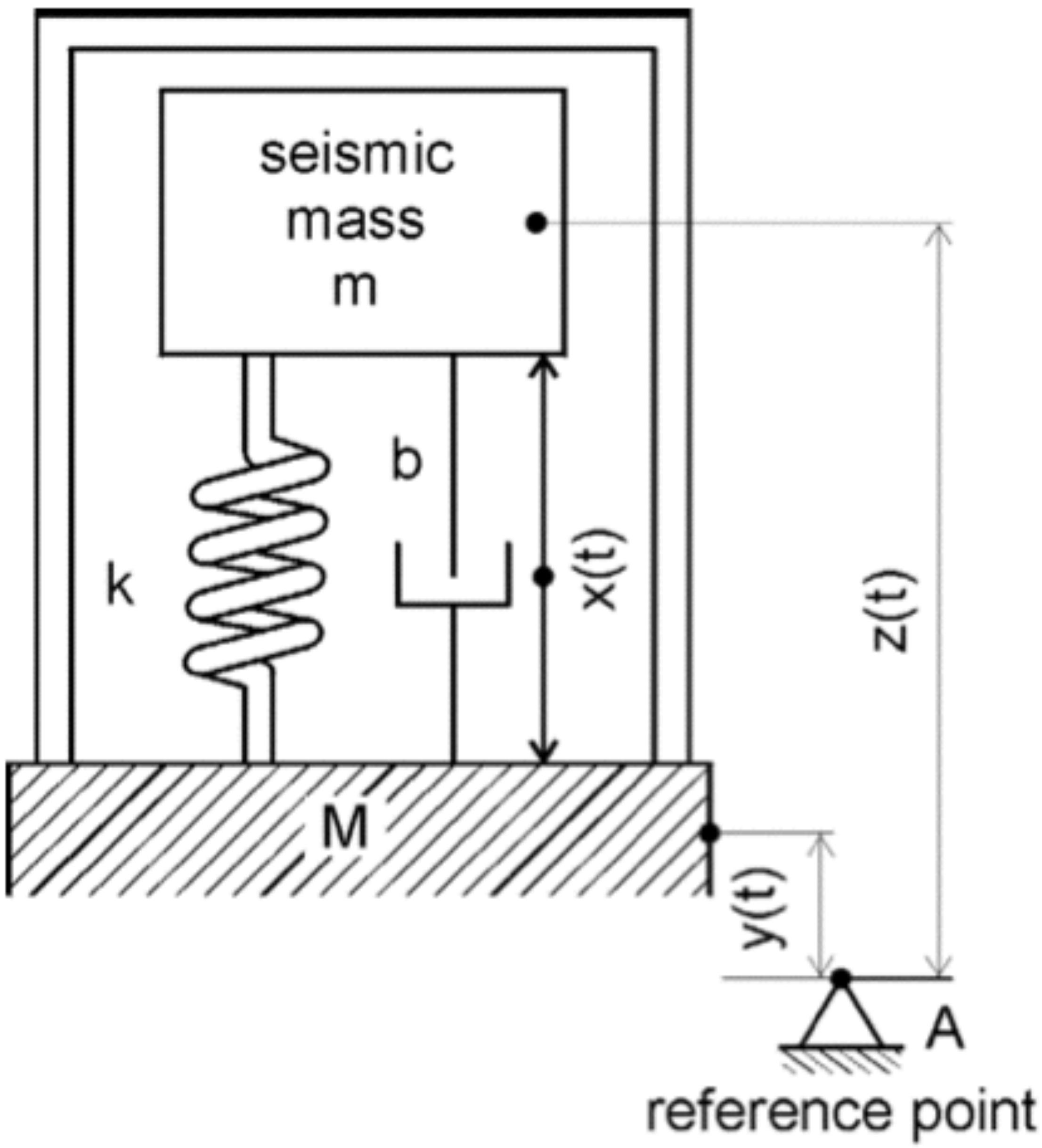
64

Signals do not necessarily need to have a peak. Correlation tells us when they are mostly similar whatever are the signals.





Absolute sensors of vibrations



Equation of motion of mass-spring system

$$m\frac{d^2z}{dt^2} + b\frac{dx}{dt} + kx = 0$$

$$z(t) = x(t) + y(t)$$

$$\boxed{m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = -m\frac{d^2y}{dt^2}}$$

inertial force

spring force

damping

presumption:

$$y(t) = Y(j\omega)e^{j\omega t}$$

Solution:

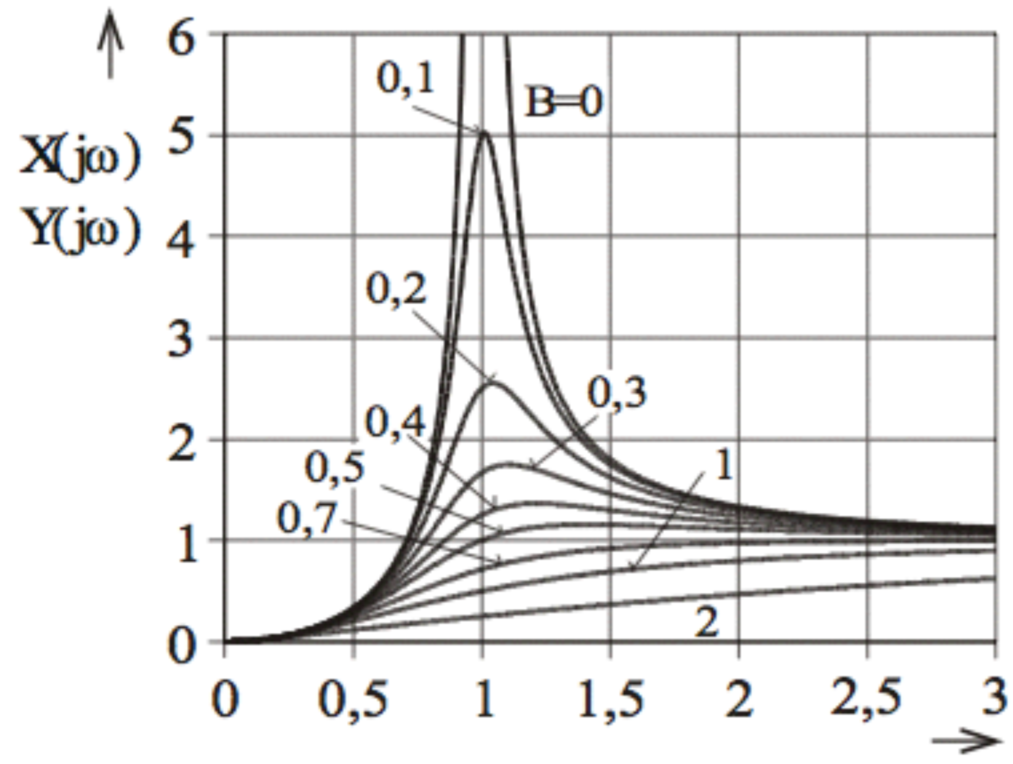
$$\boxed{x(t) = X(j\omega)e^{j(\omega t - \varphi)}}$$

m - mass

k - stiffness (spring constant)

b – viscous friction coefficient

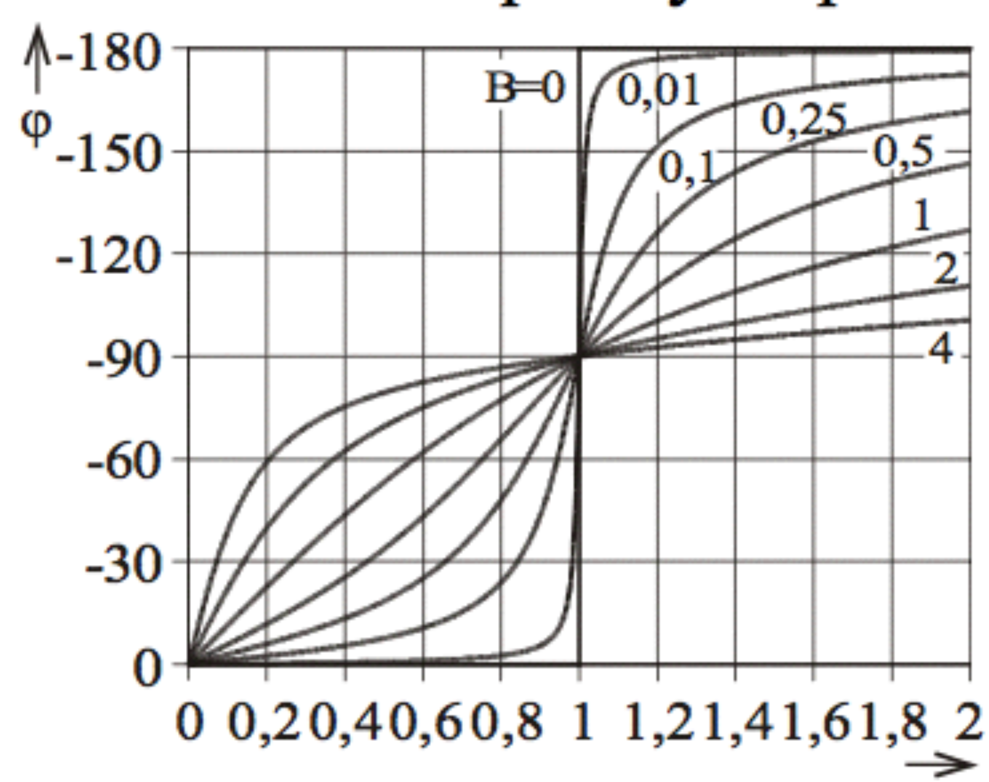
Amplitude frequency response:



a)

$$\left|\frac{X(j\omega)}{Y(j\omega)}\right| = \frac{\Psi^2}{\sqrt{(1-\Psi^2)^2 + (2B\Psi)^2}}$$

Phase frequency response



b)

$$\varphi = \operatorname{arctg}\frac{-2B\Psi}{1-\Psi^2}$$

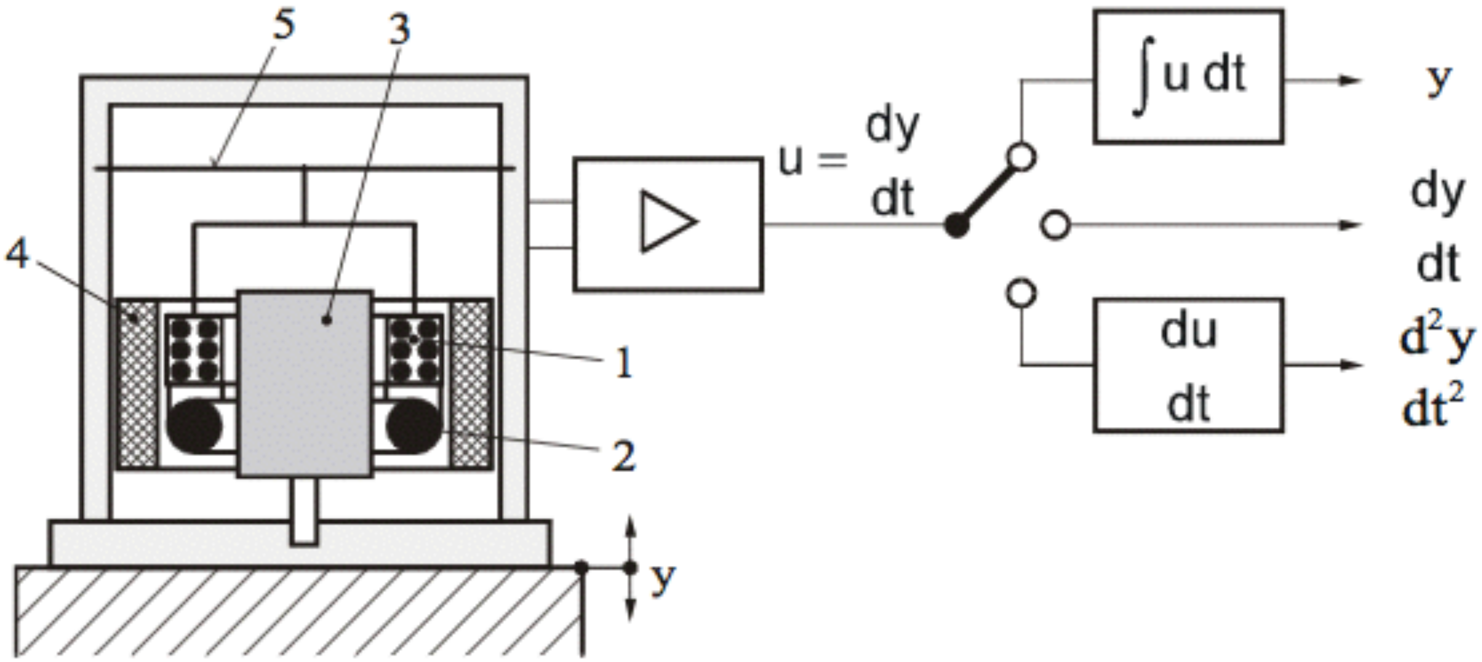
where: $\Psi = \dfrac{\omega}{\omega_0}$ - normalised frequency (referenced to resonance freq.)

$B = \dfrac{b}{b_{kr}}$ - damping ratio

$b_{kr} = 2m\omega_0$ - critical damping ratio

$\omega_0 = \sqrt{\dfrac{k}{m}}$ - resonant frequency

Electrodynamic sensor of vibration



1 - pick-up coil

2 – damping winding

3 – cylindrical part of mg. circuit

4 – permanent magnet

5 - membrane

- seismic mass = mass of coil 1 + mass of winding 2
- viscous damping – due to currents induced in winding 2
- induced voltage $u = \dfrac{d\Phi}{dt}$ proportional to the *velocity* of coil

☺ - universality

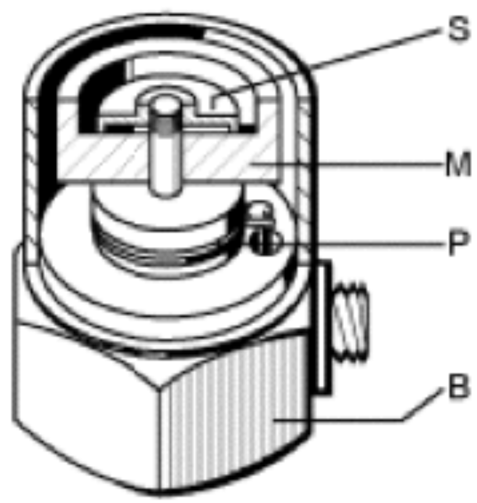
GEOPHONE

- application: vibrations of machines, buildings, occupancy detection

☺ - cheap $f_r = 1 .. 100$ Hz, $m = 20g .. 5$ kg

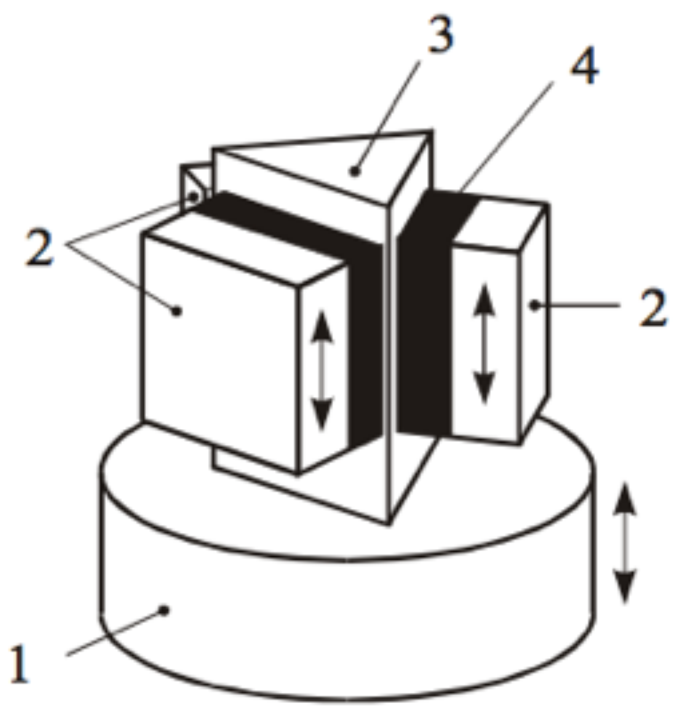
Implementation

Classical (compression, centre mounted)



M = seismic mass
P = piezoelectric element
B = base
S = spring

Shear deformation



Bruel –Kjaer

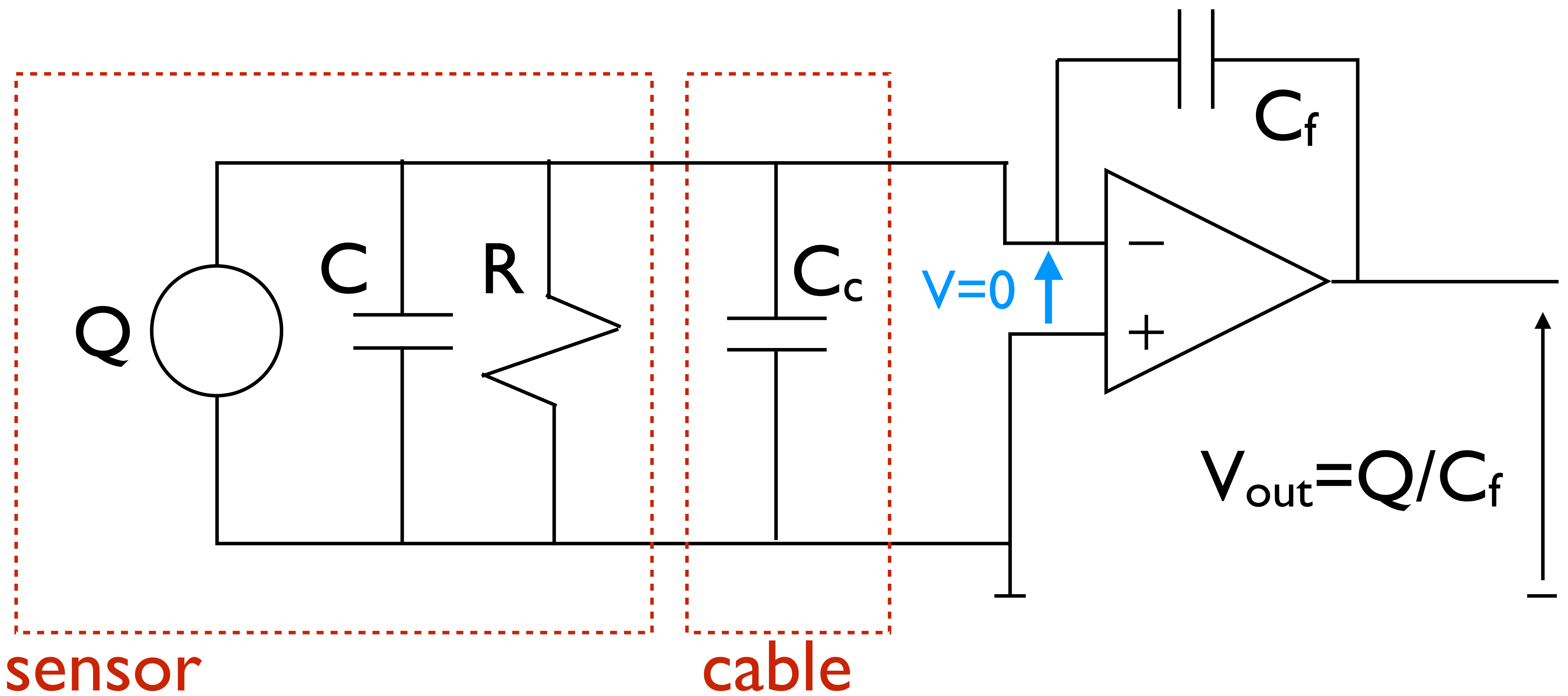
1 = base
2 = mass
3 = central stick
4 = piezoelectric element

less sensitive to deformation of bottom of sensor case, thermal dilatation, acoustic effects

Signal conditioning of piezoelectric sensors

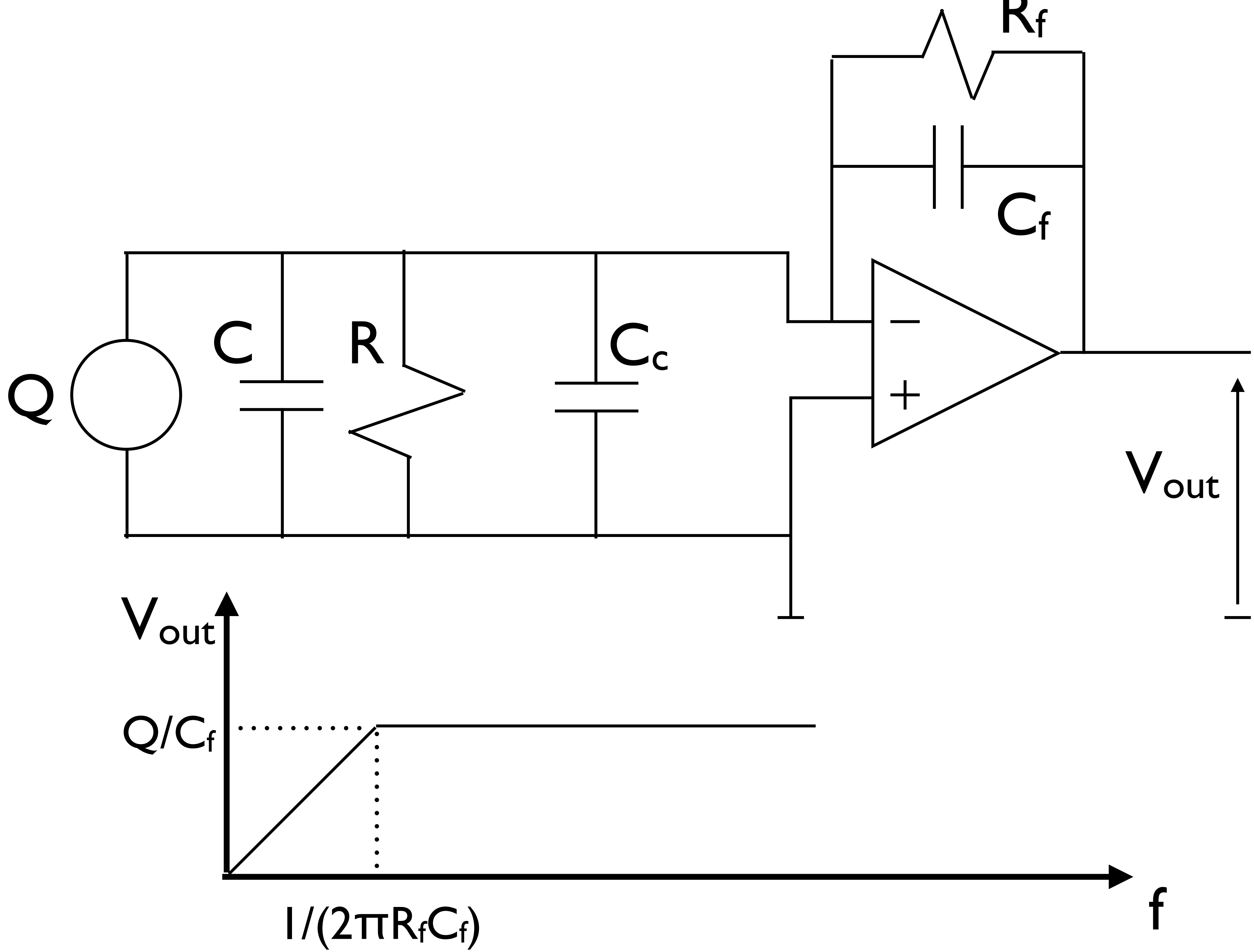
- capacitance of cable affect the voltage if sensor is used in voltage mode amplifier

CHARGE AMPLIFIER

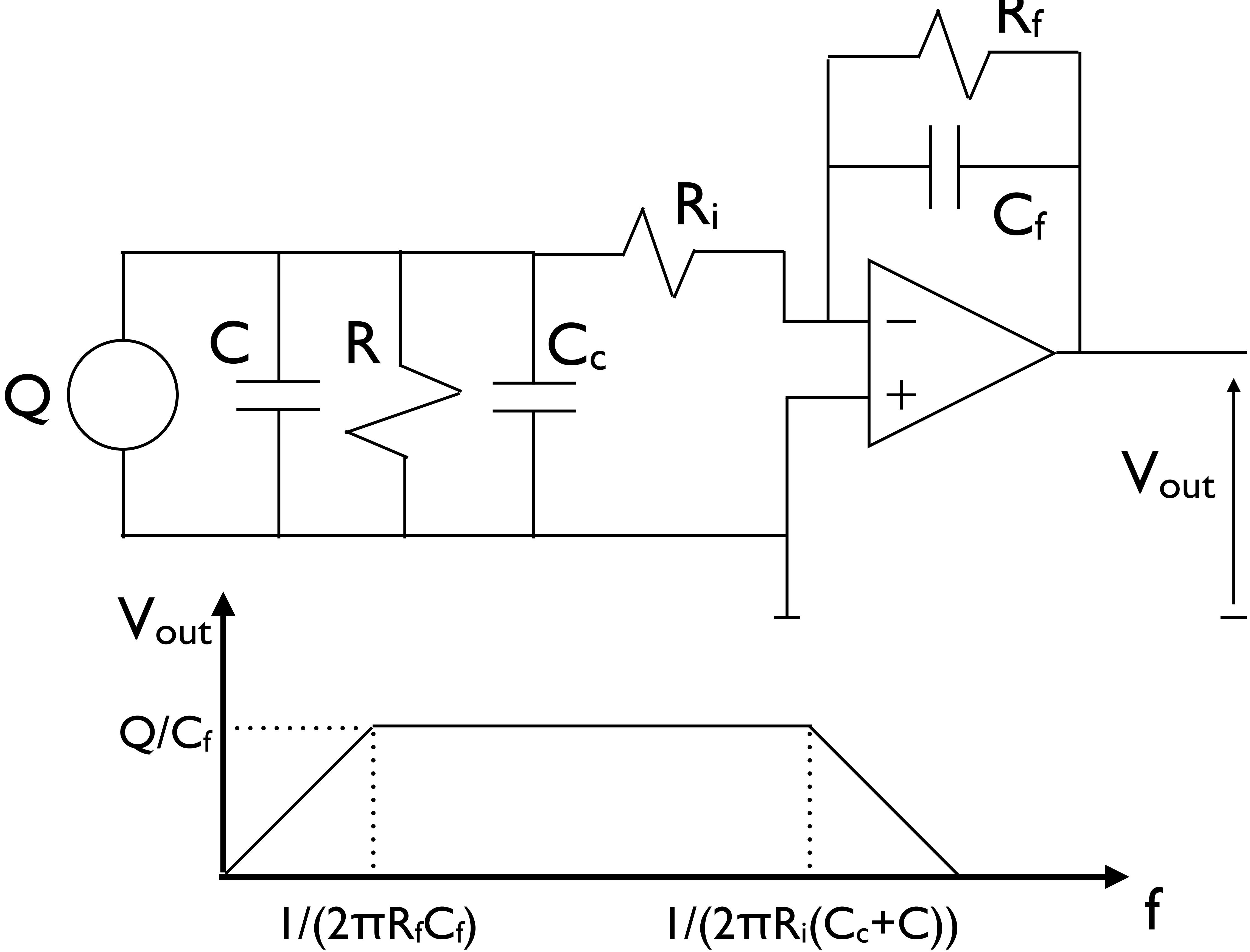


The virtual short circuit grounds the capacities, so that any change in cable's capacity does not affect the output voltage, which depends only on Q and Cf

To avoid saturation of the amplifier R_f is required



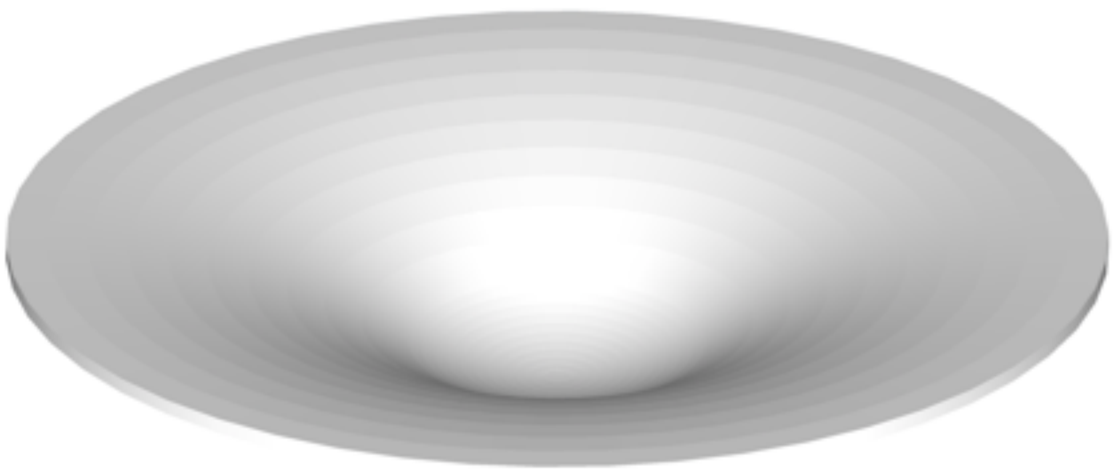
To limit bandwidth (and avoid resonation) R_i is required

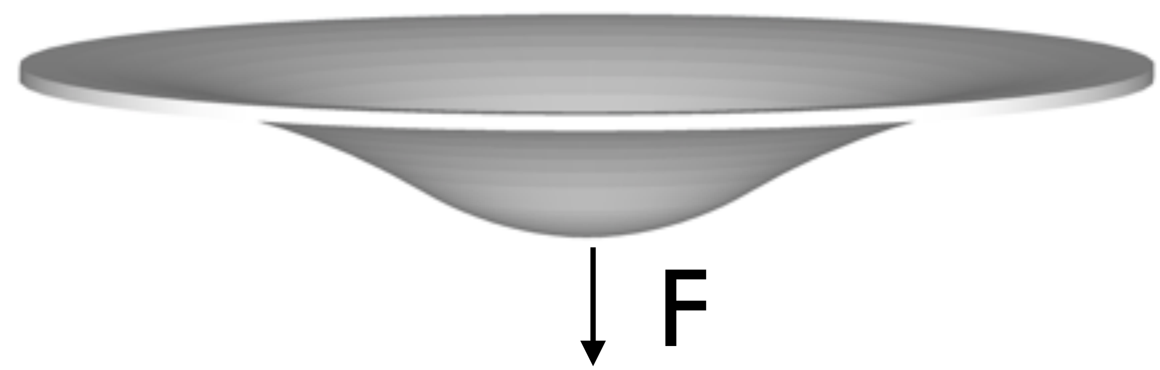


Capacitive accelerometers

Principle: we measure the force produced by acceleration by means of the deformation produced on a capacitor

Basic idea



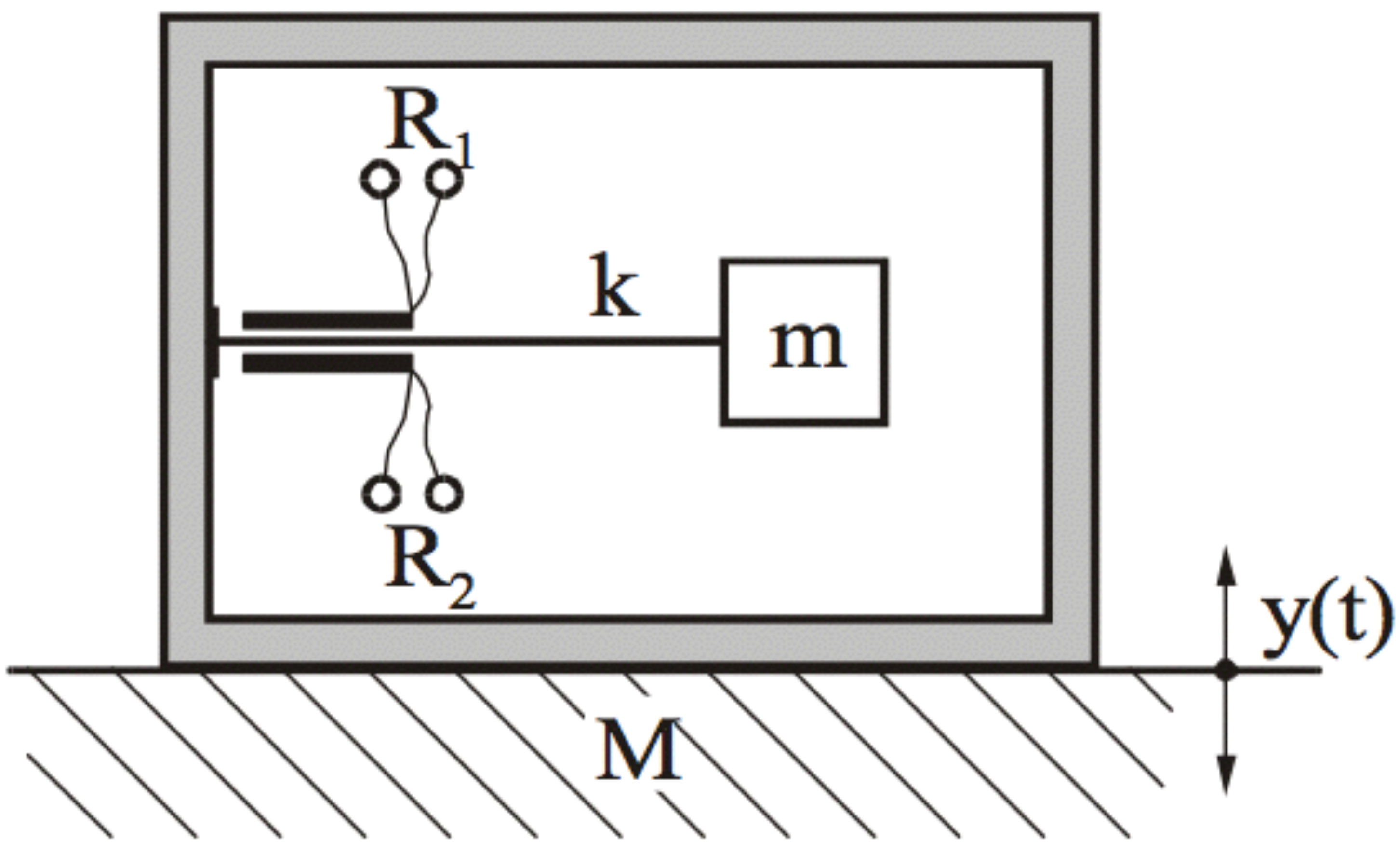


Actual implementation

thin membrane with helical slits and openings

fr= 20 to 15 kHz

Accelerometer with vibrating beam and strain gages

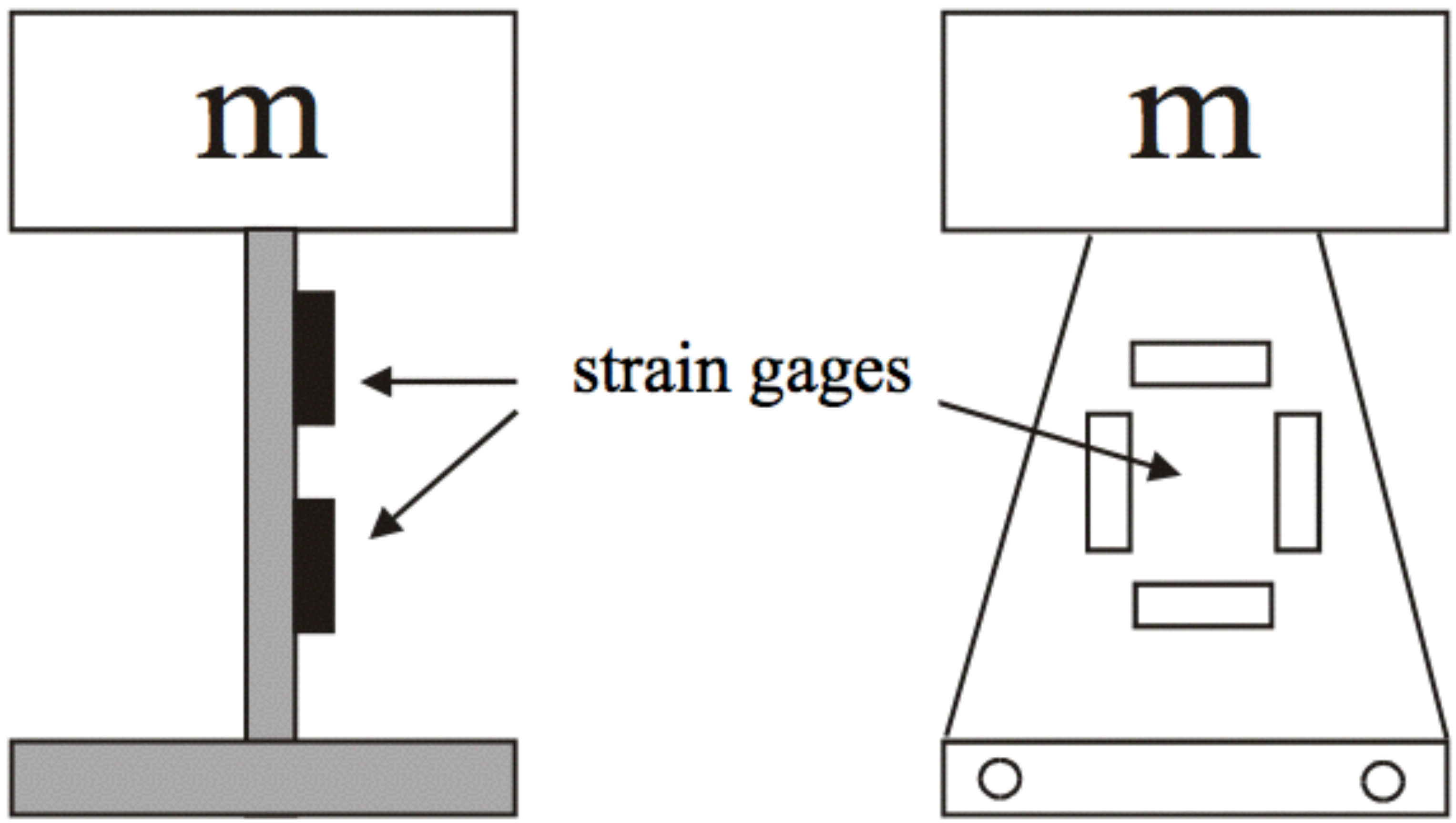


the deformation of the beam is detected by means of strain gages (see more on the lecture about force sensors)

suitable for MEMS

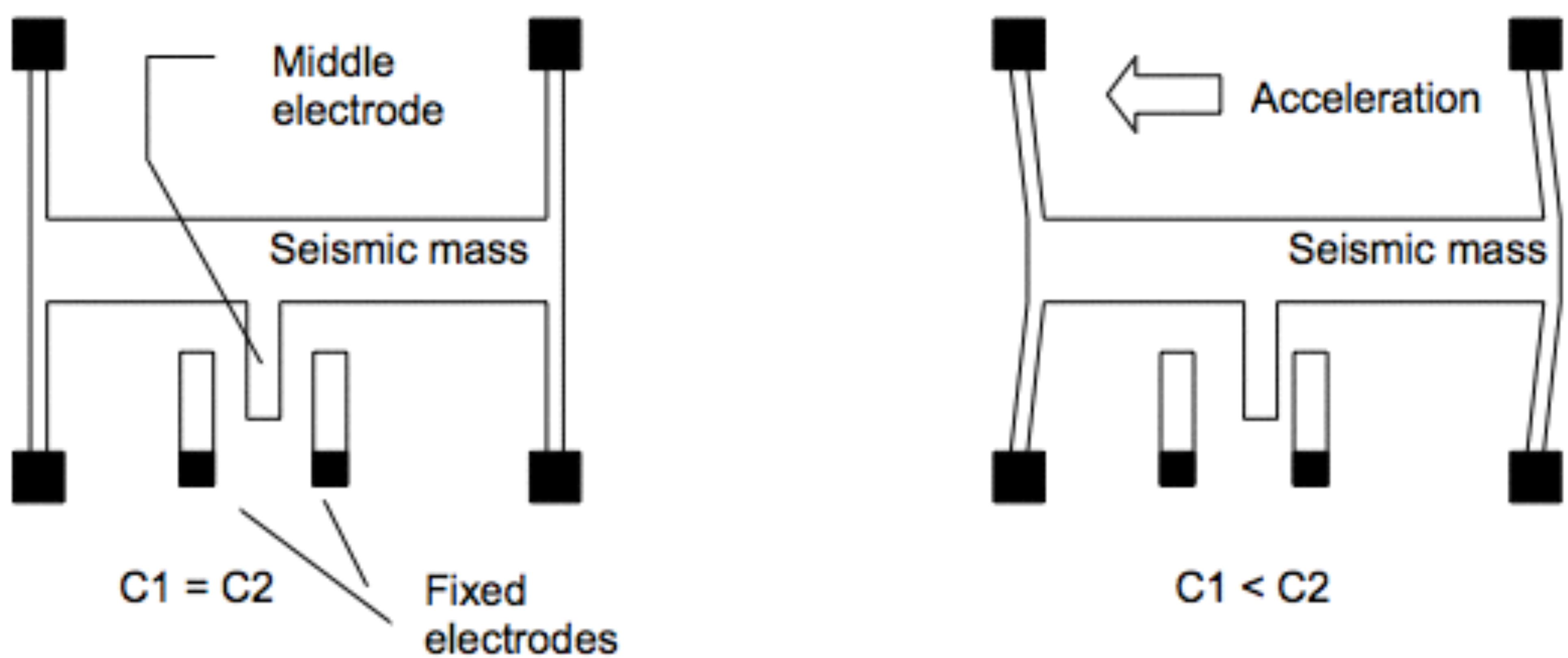
Alternative configuration

e.g. in airbags

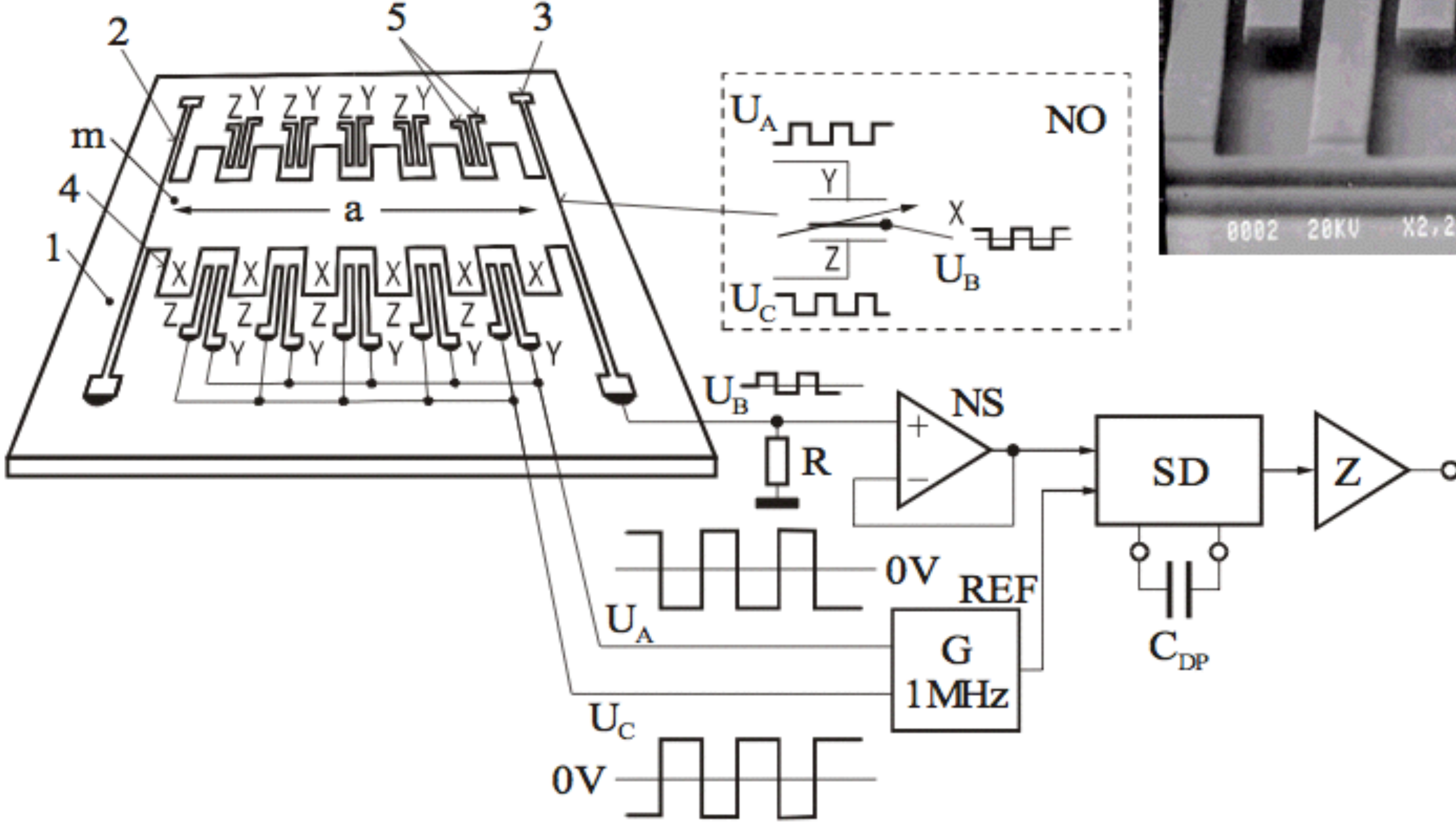


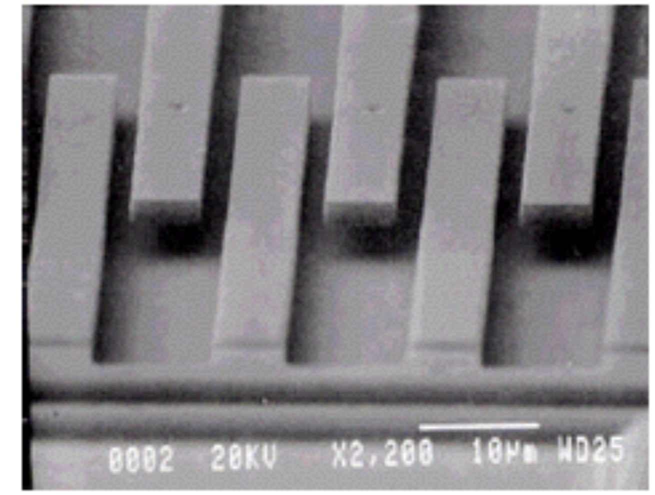
MEMS accelerometers

Basic principle



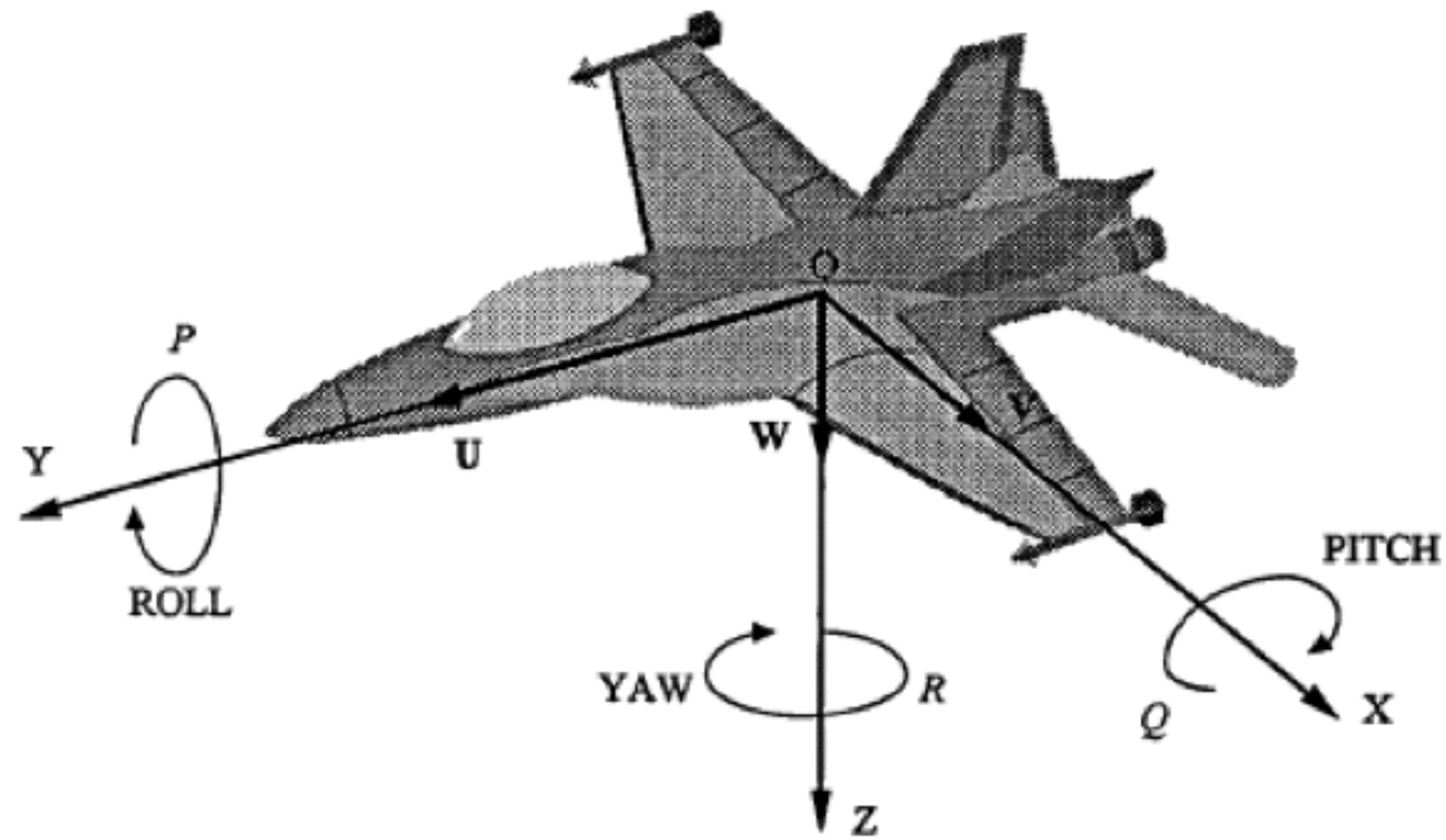
- based on dependence of capacity on distance of electrodes
- differential configuration to improve linearity





1 - platform made from polycrystalline Si
2 - bow strings
3 - anchors on the platform
4 - seismic mass (movable central electrodes)
5 - fixed electrodes

Inertial navigation system



3 sensors of acceleration:

integrating 2 times we obtain position

3 sensor of angular position:

to understand in which direction the plane is moving and then integrate the accelerometers

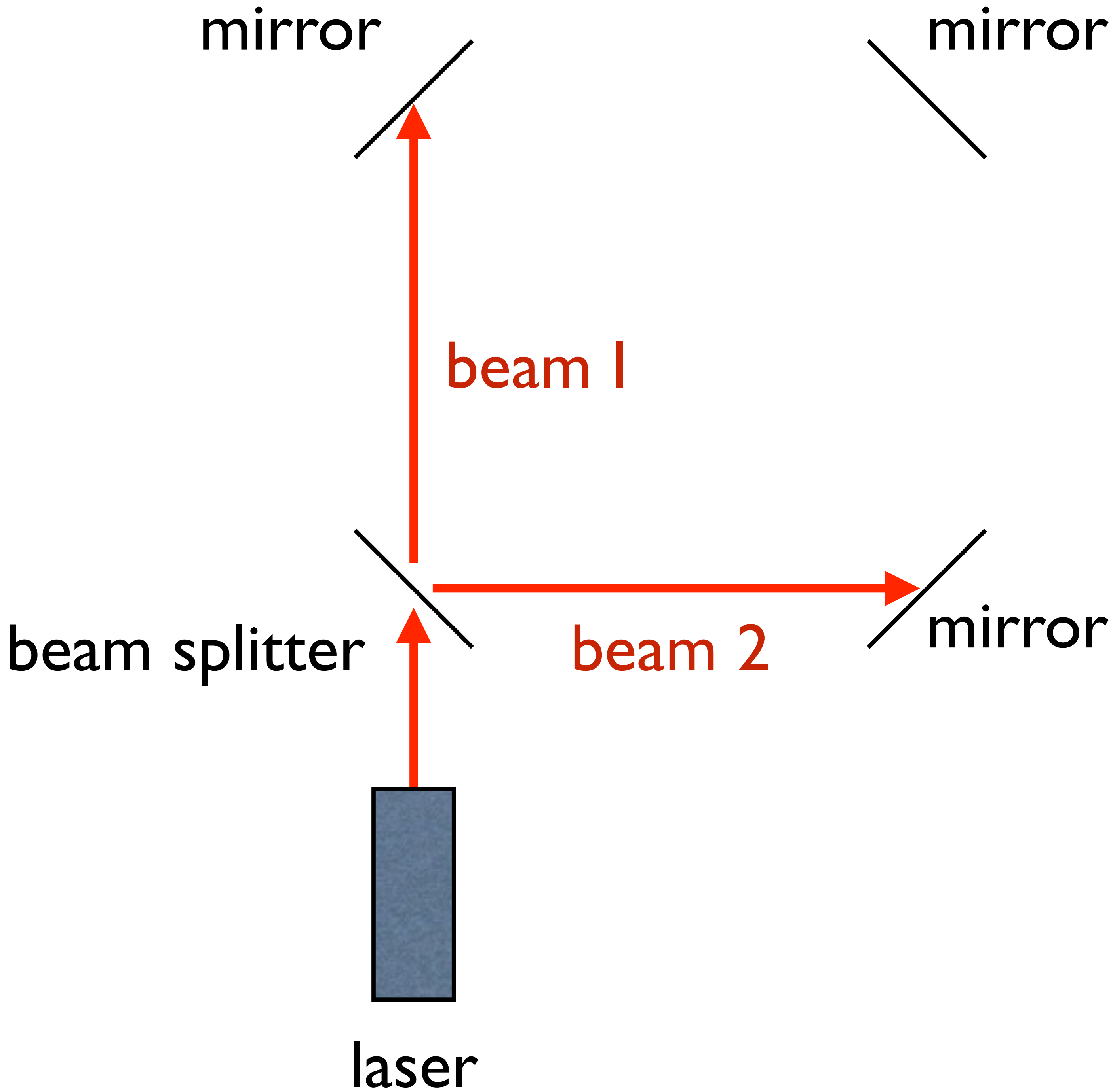
Actual gyroscopes

A mass is free spinning in a gimbal

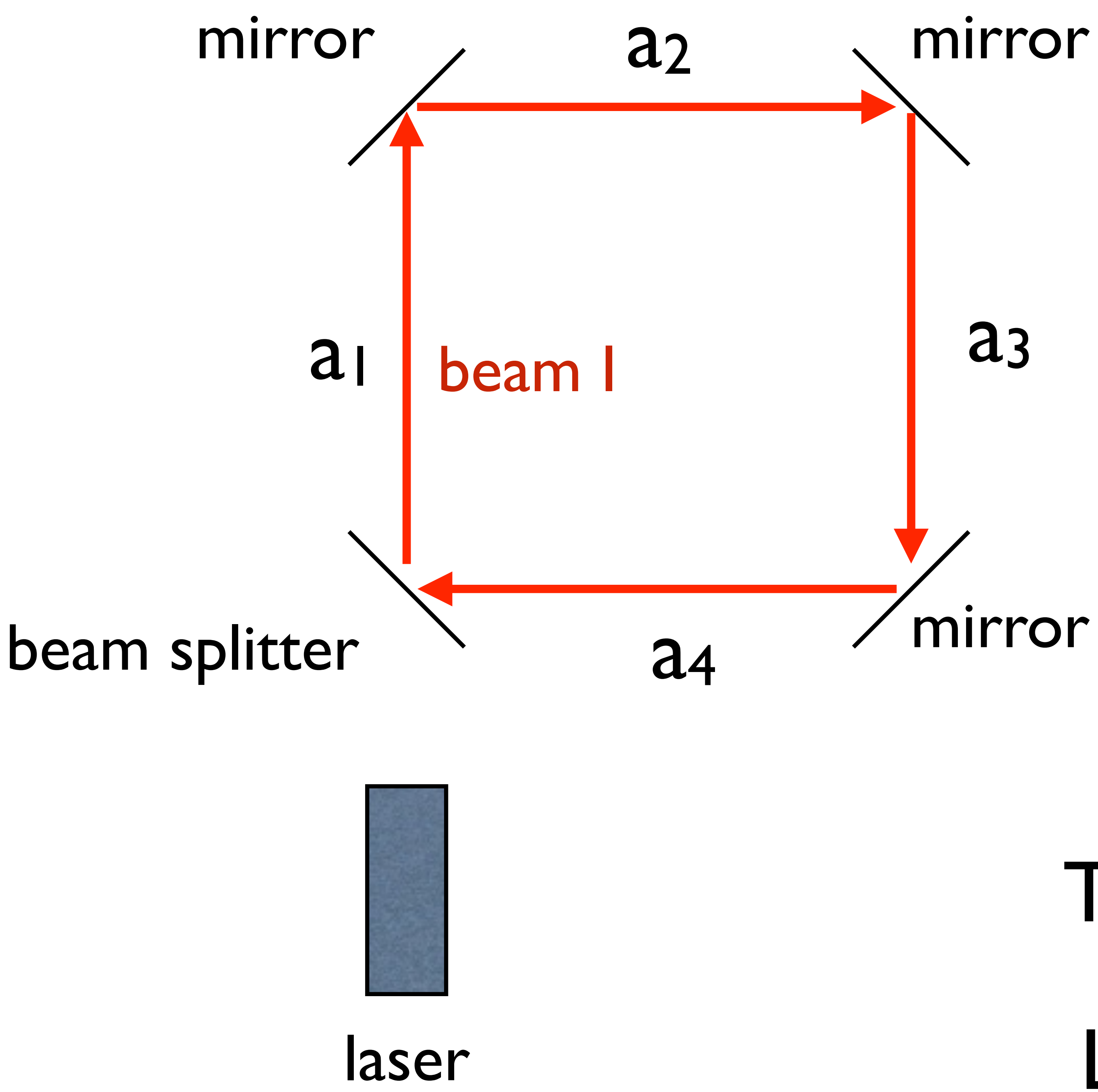
The angular momentum of the spinning mass makes the stay in the same direction

It is used to have a reference of position.

Ring Laser Gyroscopes



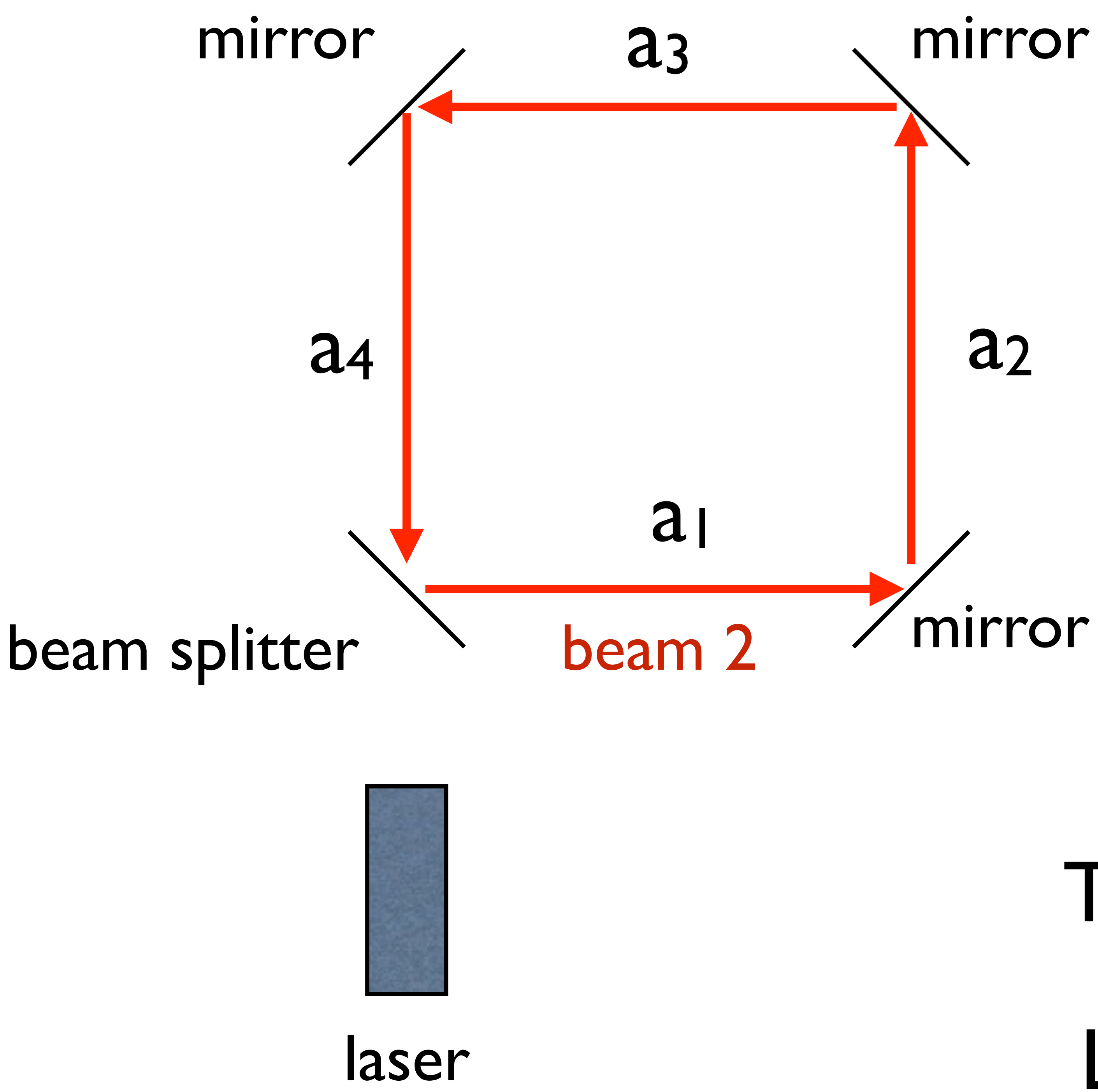
Ring Laser Gyroscopes



Total length of the path

$$L_1 = a_1 + a_2 + a_3 + a_4$$

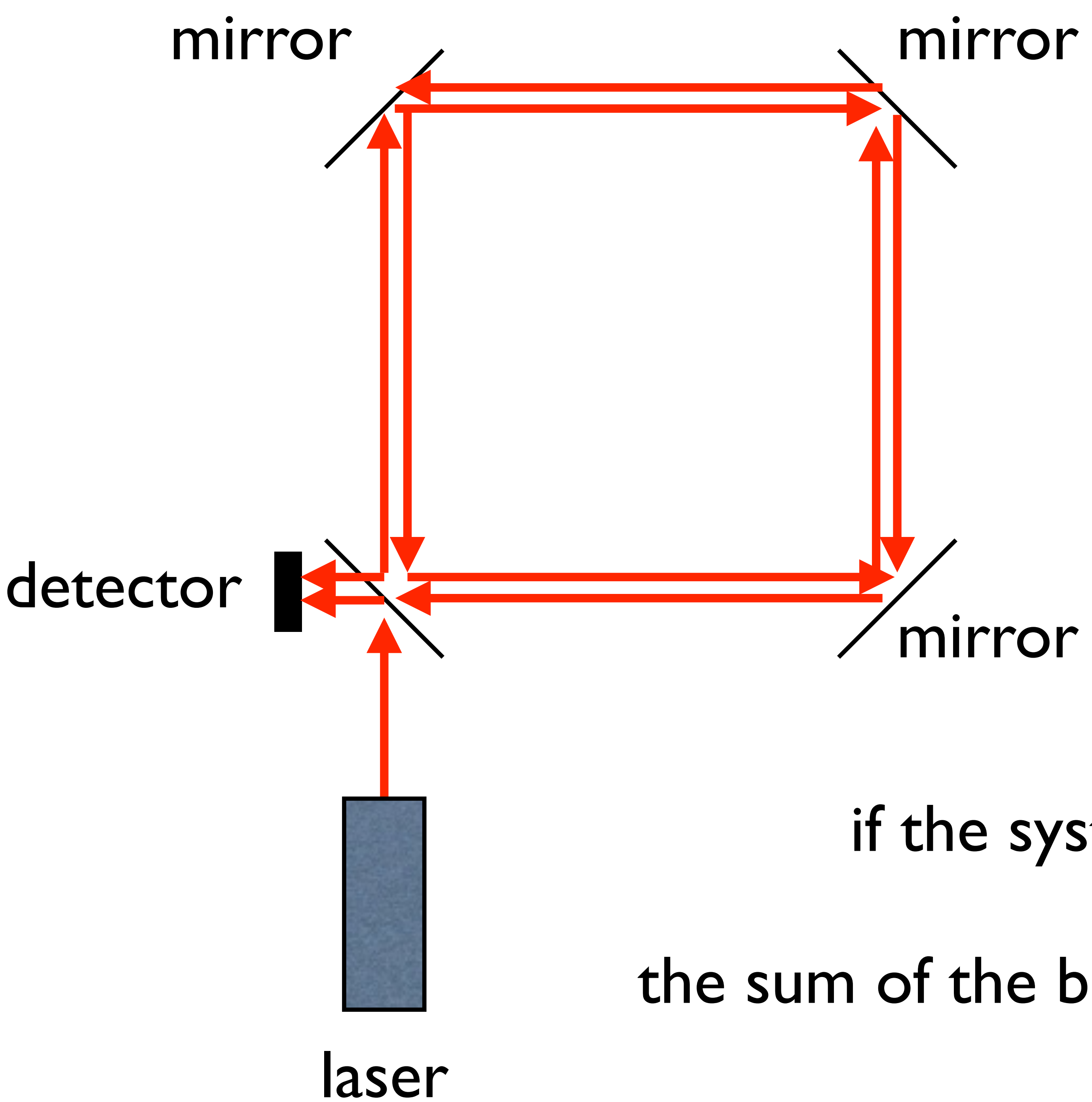
Ring Laser Gyroscopes



Total length of the path

$$L_2=a_1+a_2+a_3+a_4$$

Ring Laser Gyroscopes (RLG)

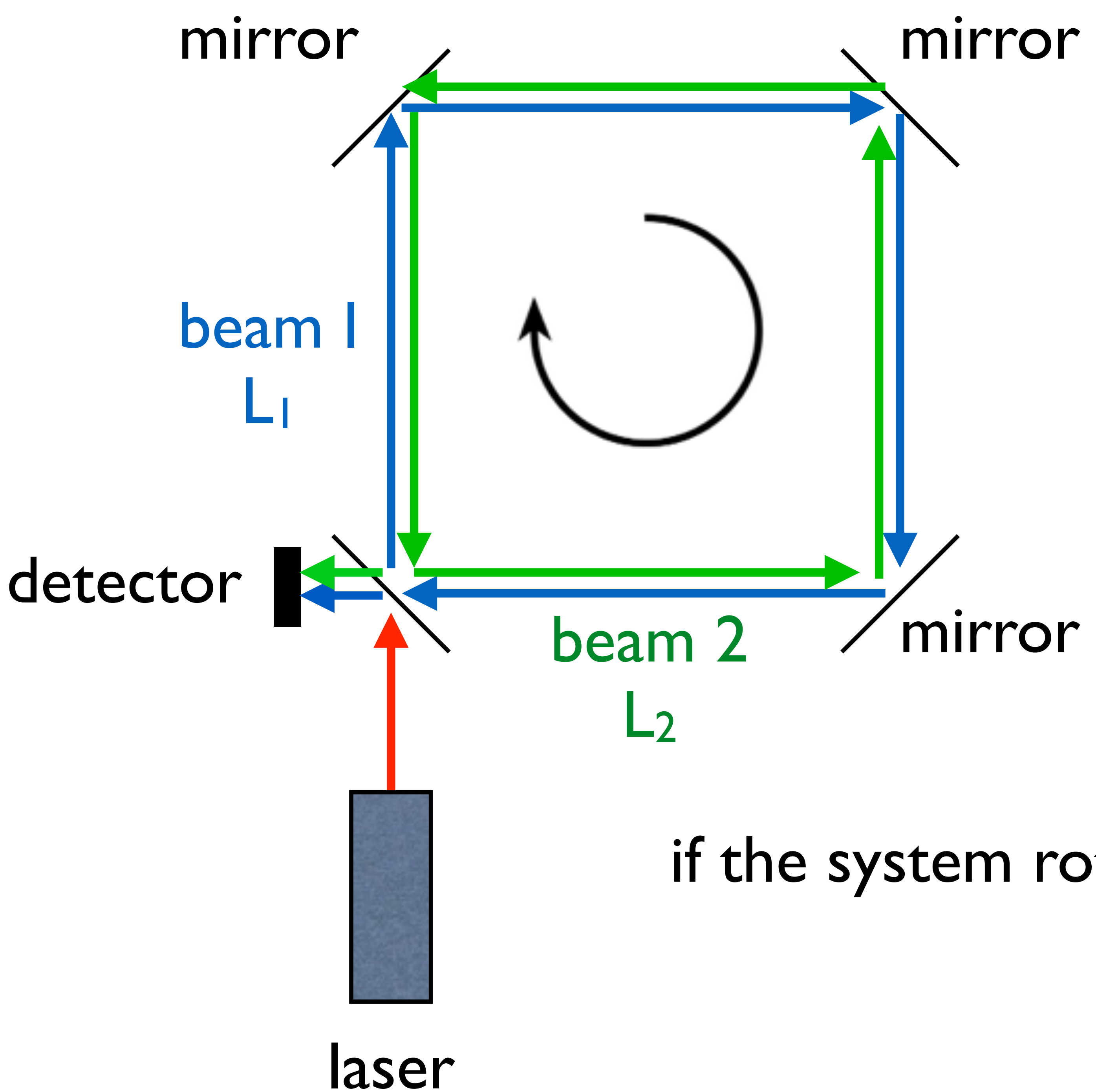


if the system does not move

$L_1=L_2$

the sum of the beams at the detector is null

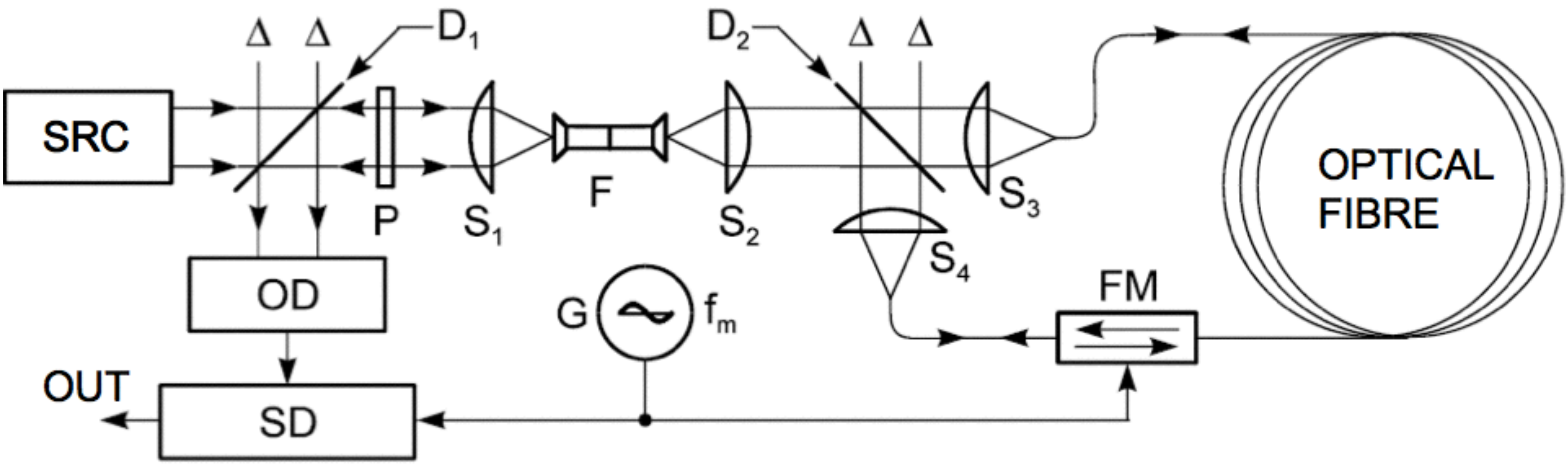
Ring Laser Gyroscopes (RLG)



if the system rotates clockwise apparently

$L_1 < L_2$

Optical fibre gyroscopes



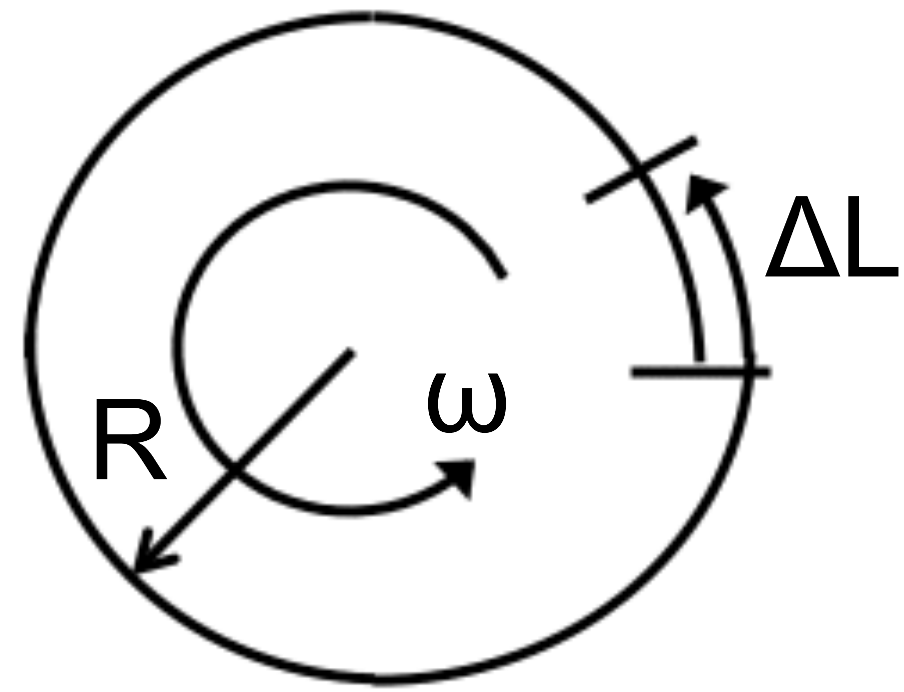
Sagnac interferometer

counterclockwise

$$t_1 = \frac{2\pi R + \Delta L}{c}$$

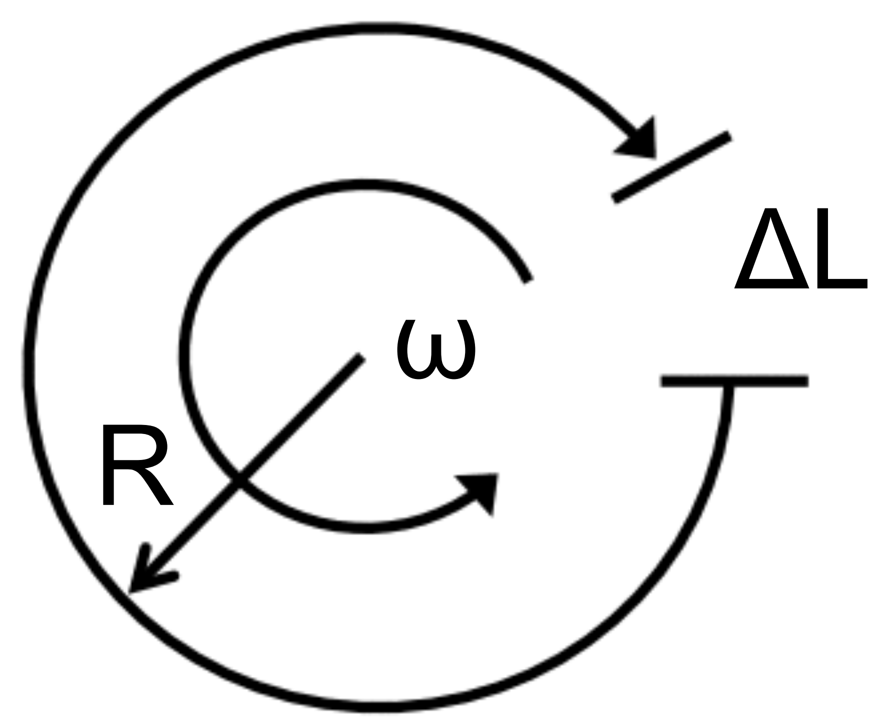
$$\Delta L = R\omega t_1$$

$$t_1 = \frac{2\pi R}{c - R\omega}$$



clockwise

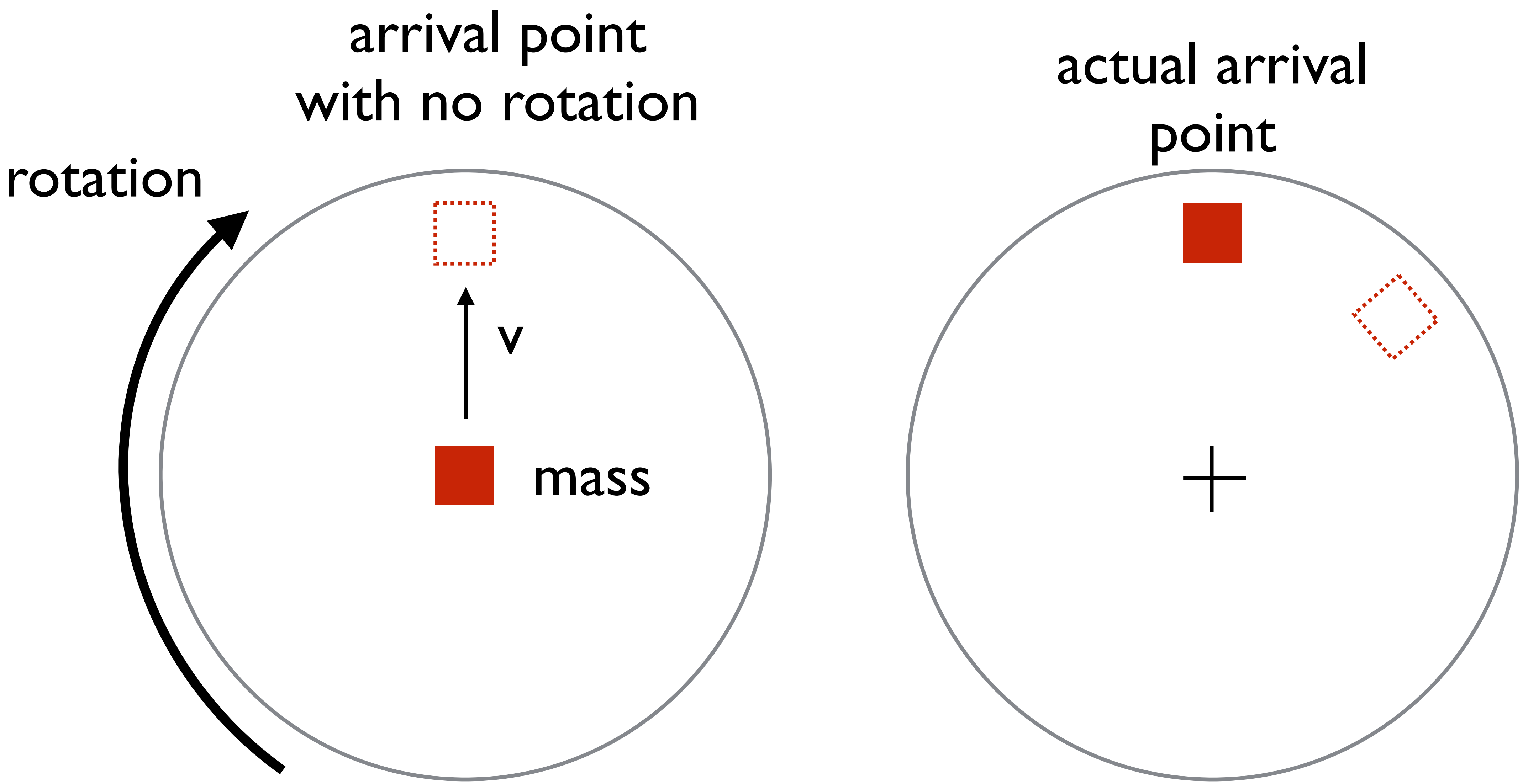
$$t_2 = \frac{2\pi R}{c + R\omega}$$



$$\Delta t = t_1 - t_2 = \frac{4\pi R^2 \omega}{c^2 - R^2\omega^2} \cong \frac{4\pi R^2 \omega}{c^2}$$

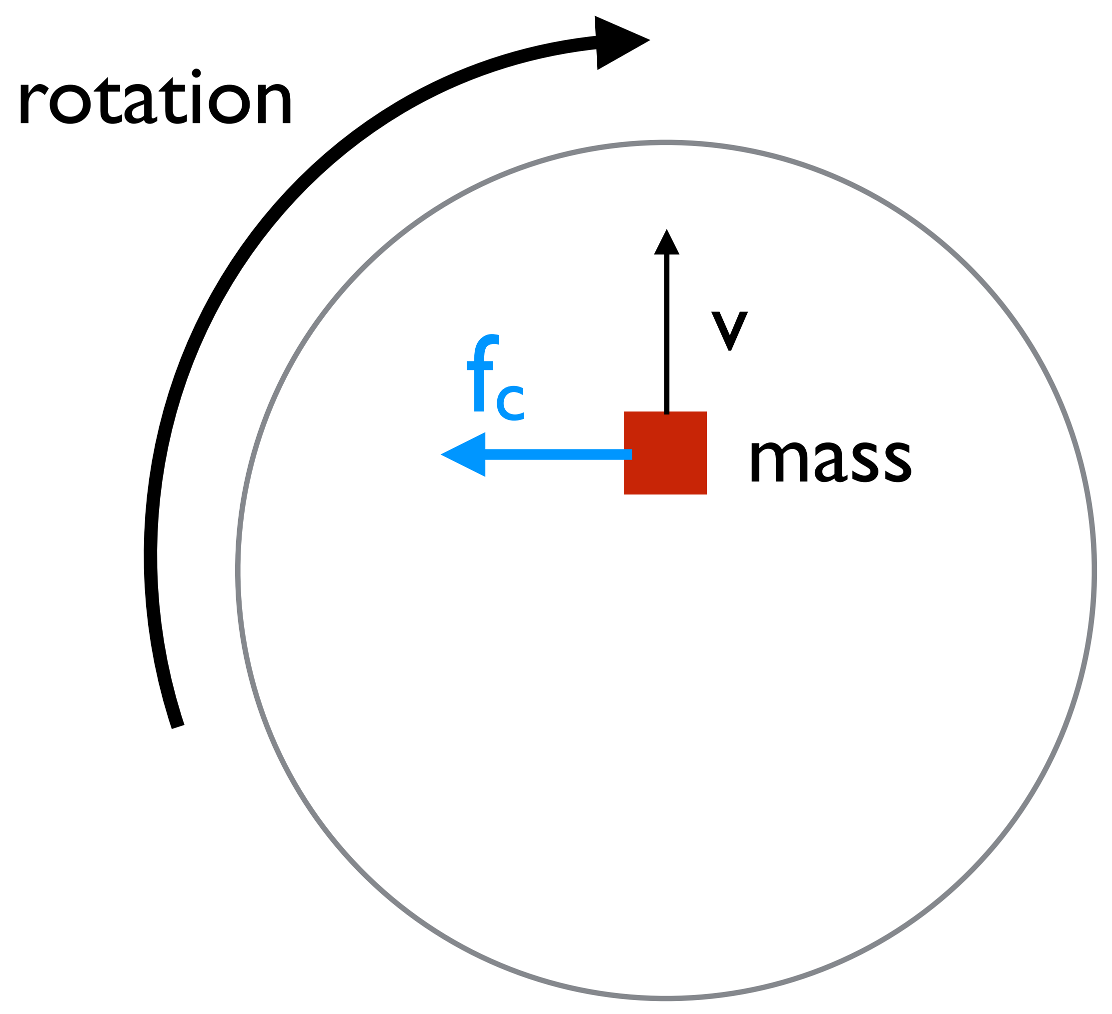
Angular rate sensors based on Coriolis effect

iMEMS® from Analog



Angular rate sensors based on Coriolis effect

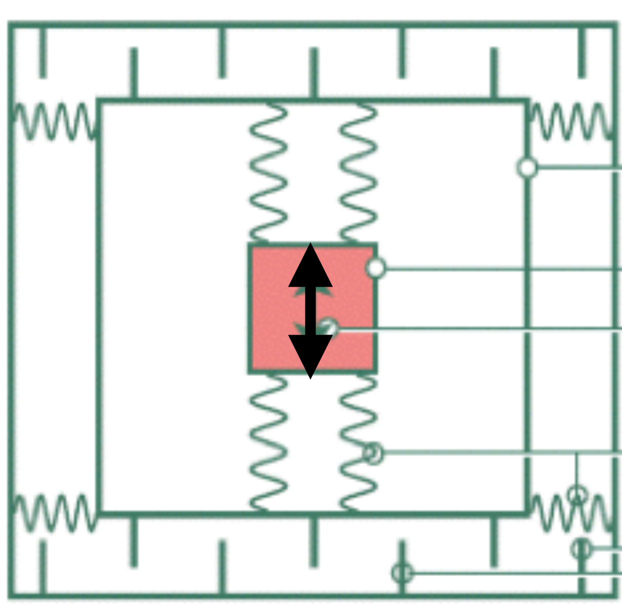
iMEMS® from Analog



Angular rate sensors based on Coriolis effect

iMEMS® from Analog

How to use the Coriolis force to detect rotation?



A mass oscillates vertically.
So, the velocity is periodically

$\uparrow$ v

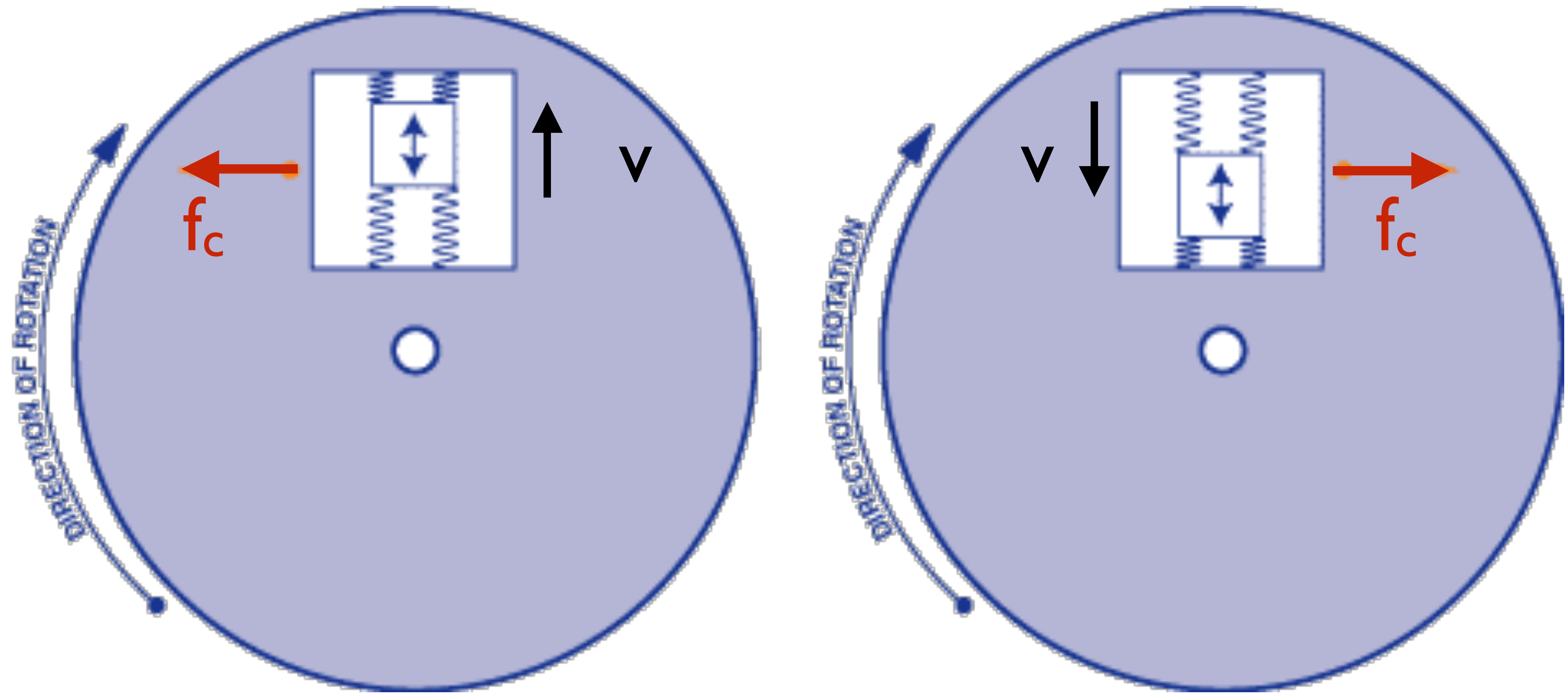
and

$\downarrow$ v

Angular rate sensors based on Coriolis effect

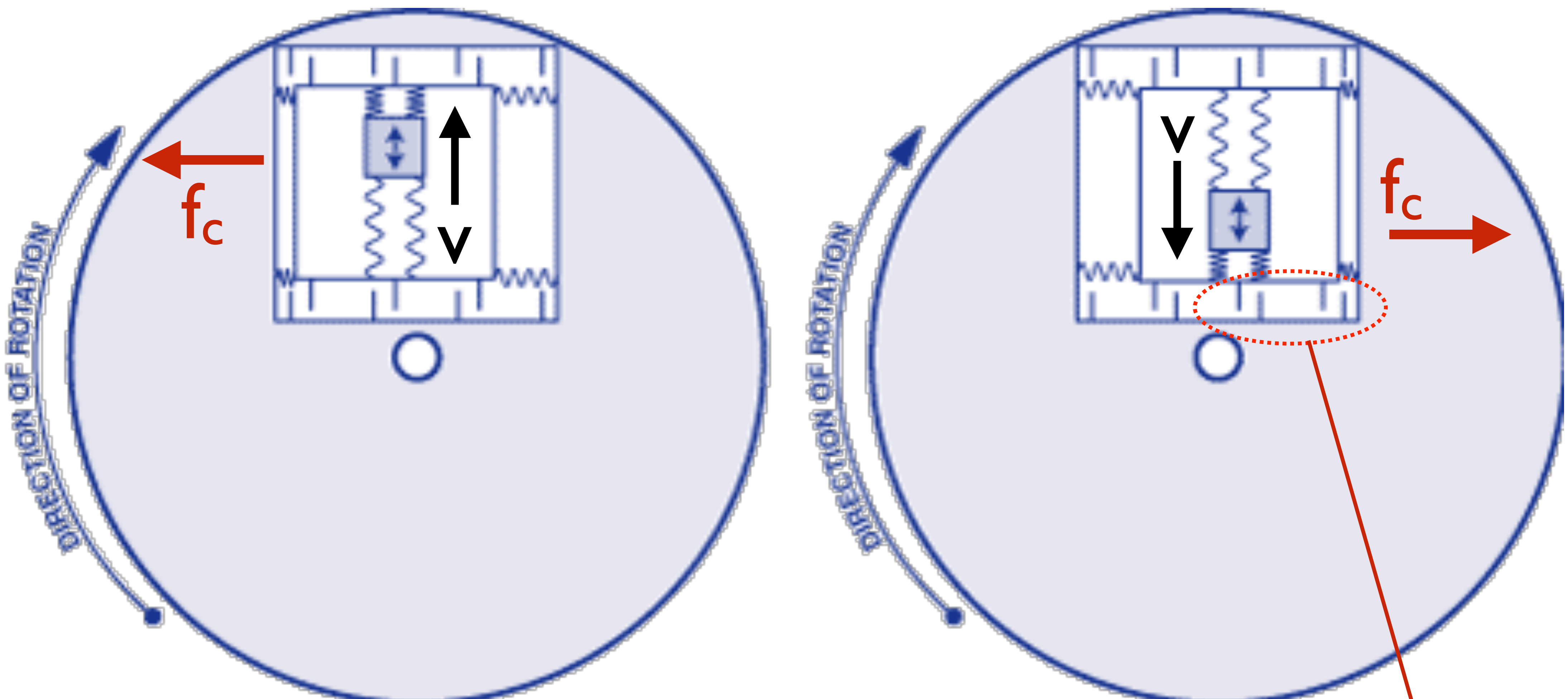
iMEMS® from Analog

According to the direction of v the Coriolis force changes direction



Angular rate sensors based on Coriolis effect

iMEMS® from Analog



horizontal displacement is detected
by capacitive sensor technique