AQUATIC SENSOR THEORY

Definitions

Item	CO_2 *Engine* ® *K30 3%* Art. No. 030-7-0001
Target gas	Carbon dioxide (CO_2)
Operating Principle	Non-dispersive infrared (NDIR)
Measurement range	0 to $3\%_{vol}$ (extended range up to $10\%_{vol}$)
Accuracy	±300ppm ±3% of reading[1]
Response time ($T_{1/e}$)	20sec diffusion time
Rate of Measurement	0.5Hz
Operating temperature	0 to 50°C
Operating humidity	0 to 95%RH non condensing
Storage temperature	-30 to 70°C
Dimensions	51 x 57 x 14 mm (Length x Width x approximate
Power supply	4.5 to 14.0VDC maximum rating (without reverse protection) stabilised to ±5% over load and line c voltage less than 100mV.[2]
Current Consumption	40mA average <150mA peak current (averaged during IR lamp <300mA peak power (during IR lamp start-up, th
Warm Up time to spec	1 min
Life expectancy	>15 years
Serial communication	UART, Modbus protocol. Direction control pin fo connection to RS485 receiver integrated circuit.
OUT 1	D/A Resolution: 10mV (10 bit) Linear Conversion Range: 1 to 4V = 0 to 2% Electrical Characteristics: R_{OUT} <100 Ω, R_{LOAD} >

Transducer: a device that converts variations in a physical quantity in an electrical signal. Or vice versa.

- pressure, sound, light are sensed with tranducers

Sensor: a device that measures a physical property and records, indicates or otherwise responds to it.

Electrode: a conductor through which electricity enters or leaves a substance.

Electrolyte: a liquid or gel containing ions that allow the passage of a current.

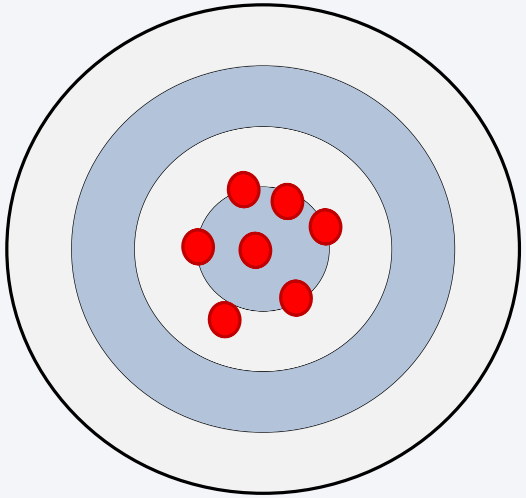
Measurement Range: the minimum and maximum value range in which a sensor works well.

Response Time: How long it takes for the sensor to settle on a new reading after a conditions change.

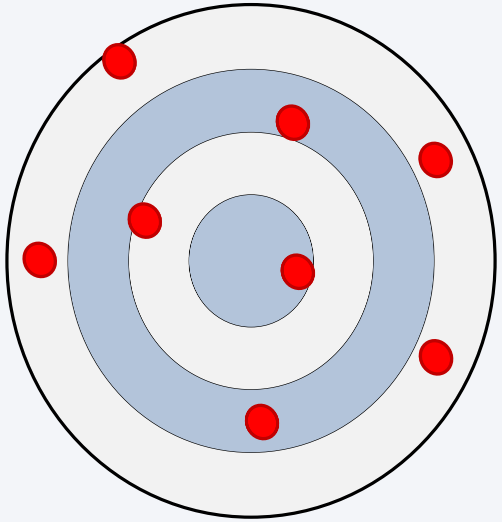
Accuracy: How close the measurement is to the real values. The average of the precision error for a number of instruments.

Precision: How close two or more measurements are to each other. The precision error of a single instrument.

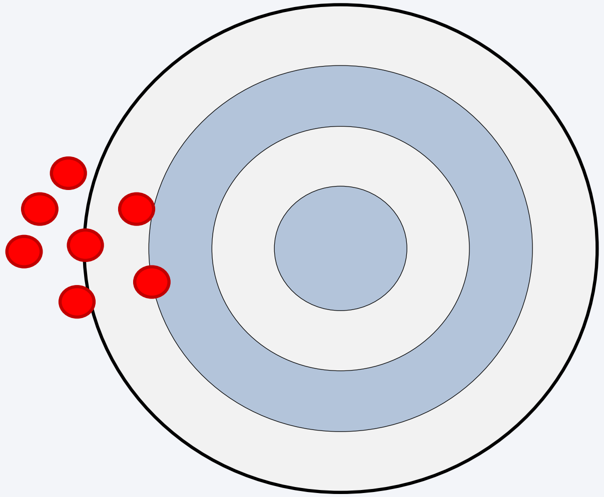
Precision vs. Accuracy



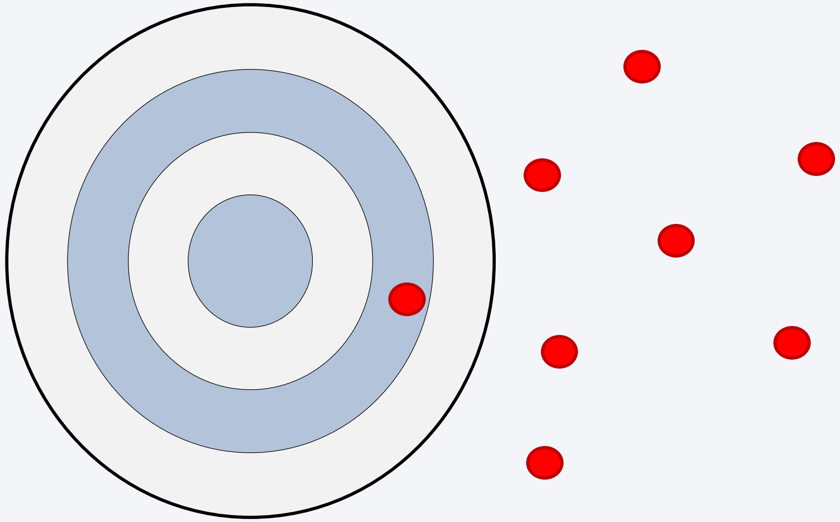
precise & accurate



accurate but imprecise



precise but inaccurate

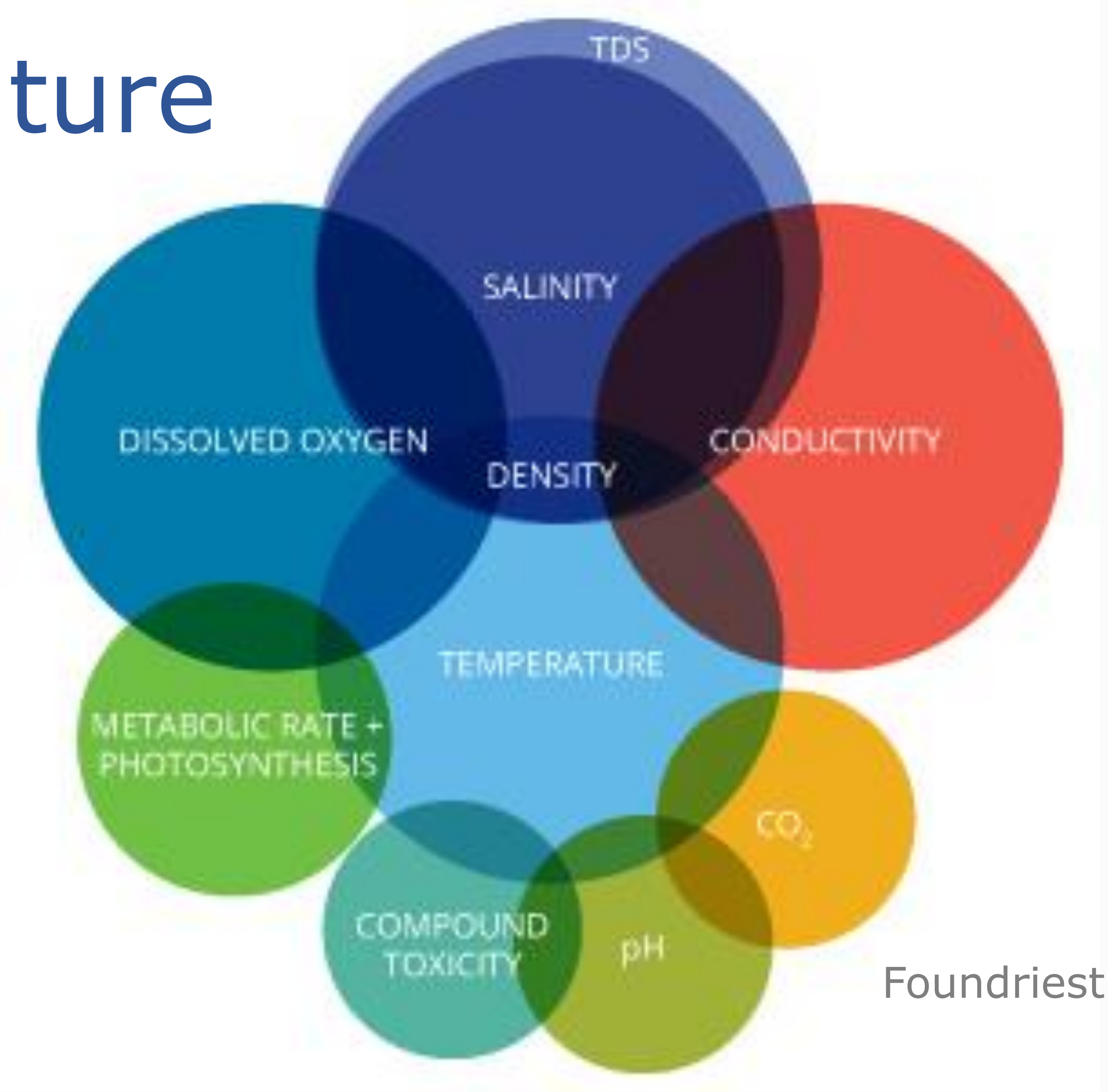


inaccurate & imprecise

Resolution: How finely different physical values of the same variable can be measured. Increasing the bit count in an ADC is useful only if the increase in resolution is greater than noise.

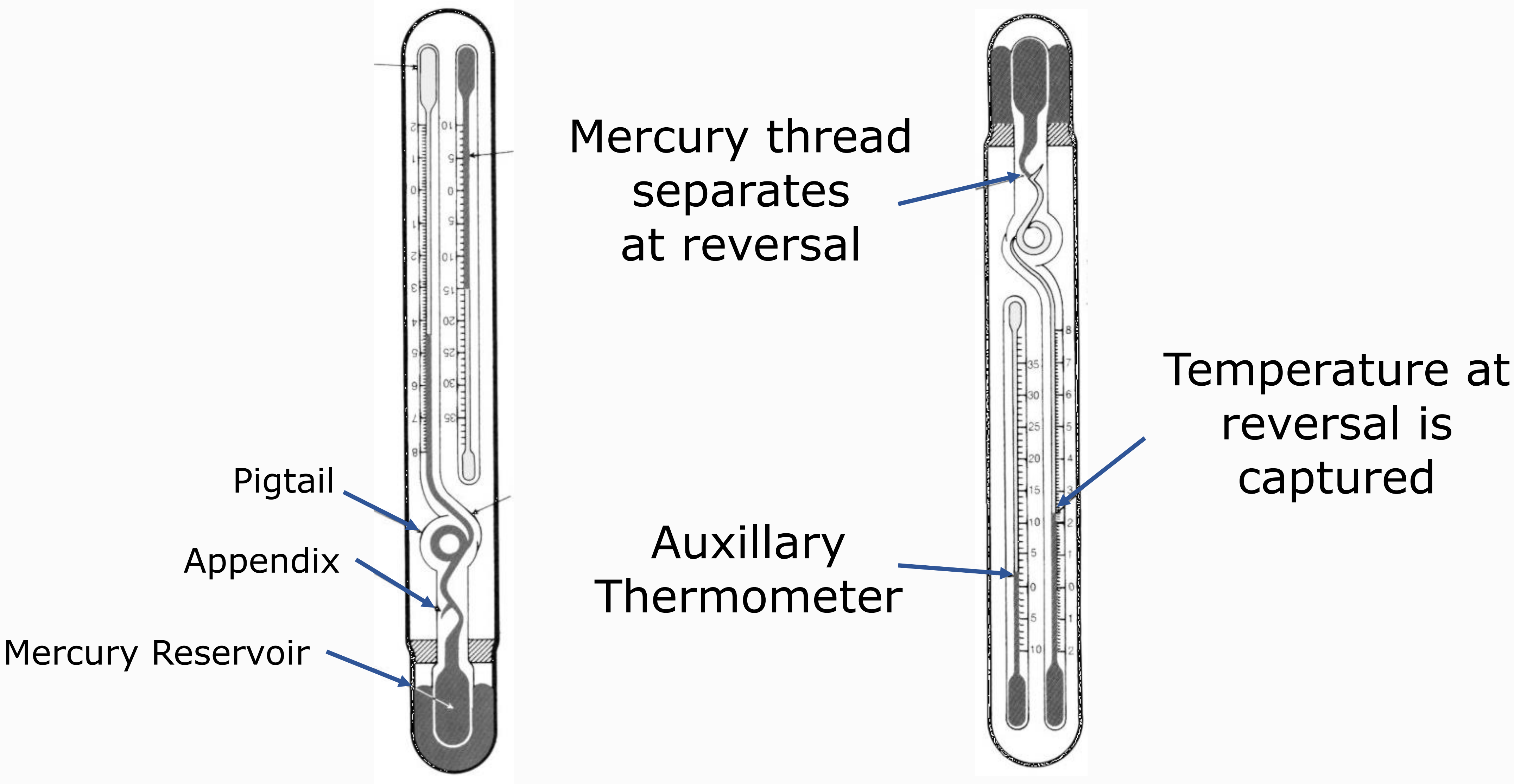
Drift: How the accuracy changes with time.

Temperature



Foundriest

Reversing Thermometer



Reversing Thermometer

- Introduced in London in 1874.
- Primary temperature instrument until ~1970
- Generally considered accurate to 0.02º C

mercury -

- High coefficient of expansion
- Temp range: -37ºC to 365ºC
- Shiny & reflective so it’s easy to see
- Does not stick to glass

alcohol -

- Non-toxic
- Temp range: -115ºC to 78.5ºC
- Sticks to glass & must be dyed in order to see

Reversing Thermometer

Measuring Pressure (Depth):

Using two reversing thermometers – one pressure protected, and one exposed to water pressure, the pressure can be determined by the difference in temperature readings.

$$\text{Depth} = \frac{T_u - T_p}{Q \cdot \rho}$$

Q – pressure constant

ρ – mean density

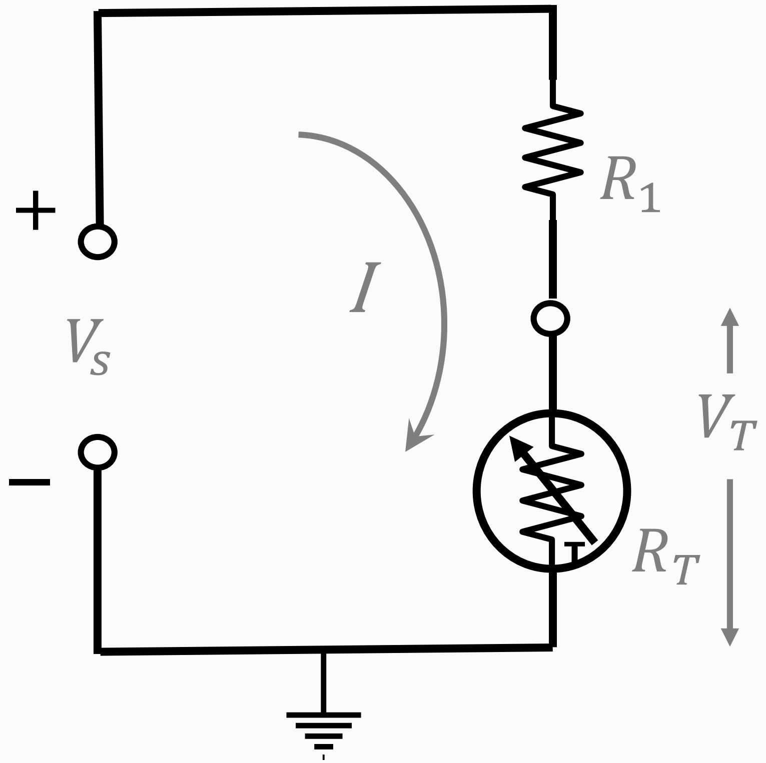
Thermistor (thermal resistor)

- Resistance changes with temperature
- Cheap – the most widely used temp sensor
- Easy to waterproof
- Will work with any voltage
- Potential repeatability of 0.001ºC
- Generally made with metal oxides and coated with epoxy or glass

NTC (neg. temp coefficient) – used for temperature sensing

PTC (pos. temp coefficient) – used for resettable fuses

Thermistor - Converting resistance (R) to temperature



- Thermistor look-up table
- Steinhart-Hart equation:

$$\frac{1}{T_K} = A + B\ln(R) + C\ln(R)^2$$

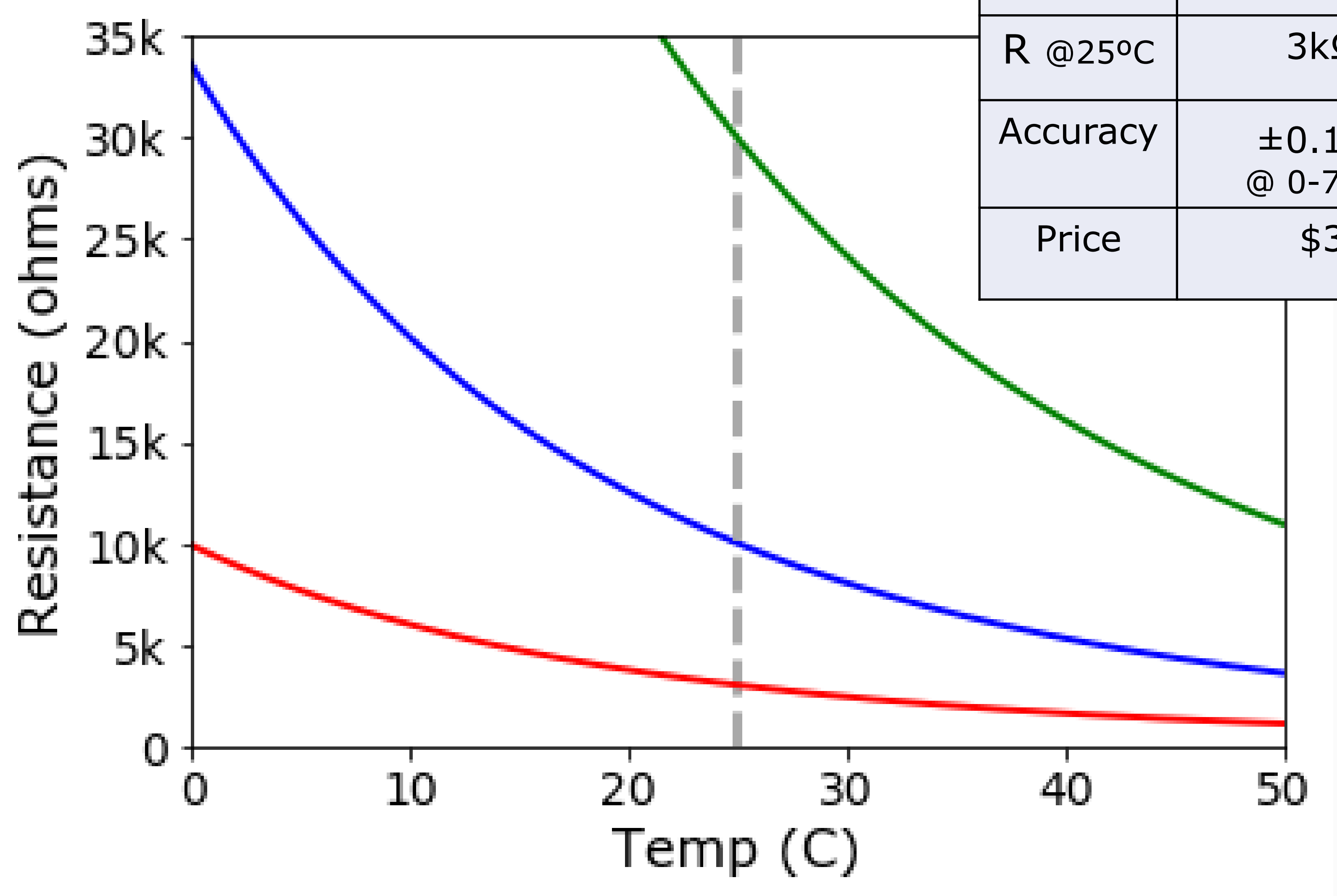
- B parameter equation:

$$\frac{1}{T_K} = \frac{1}{T_0} + \frac{1}{B}\ln\left(\frac{R}{R_0}\right)$$

$$T_K = -273.15°\mathrm{C}$$

Thermistor - comparison

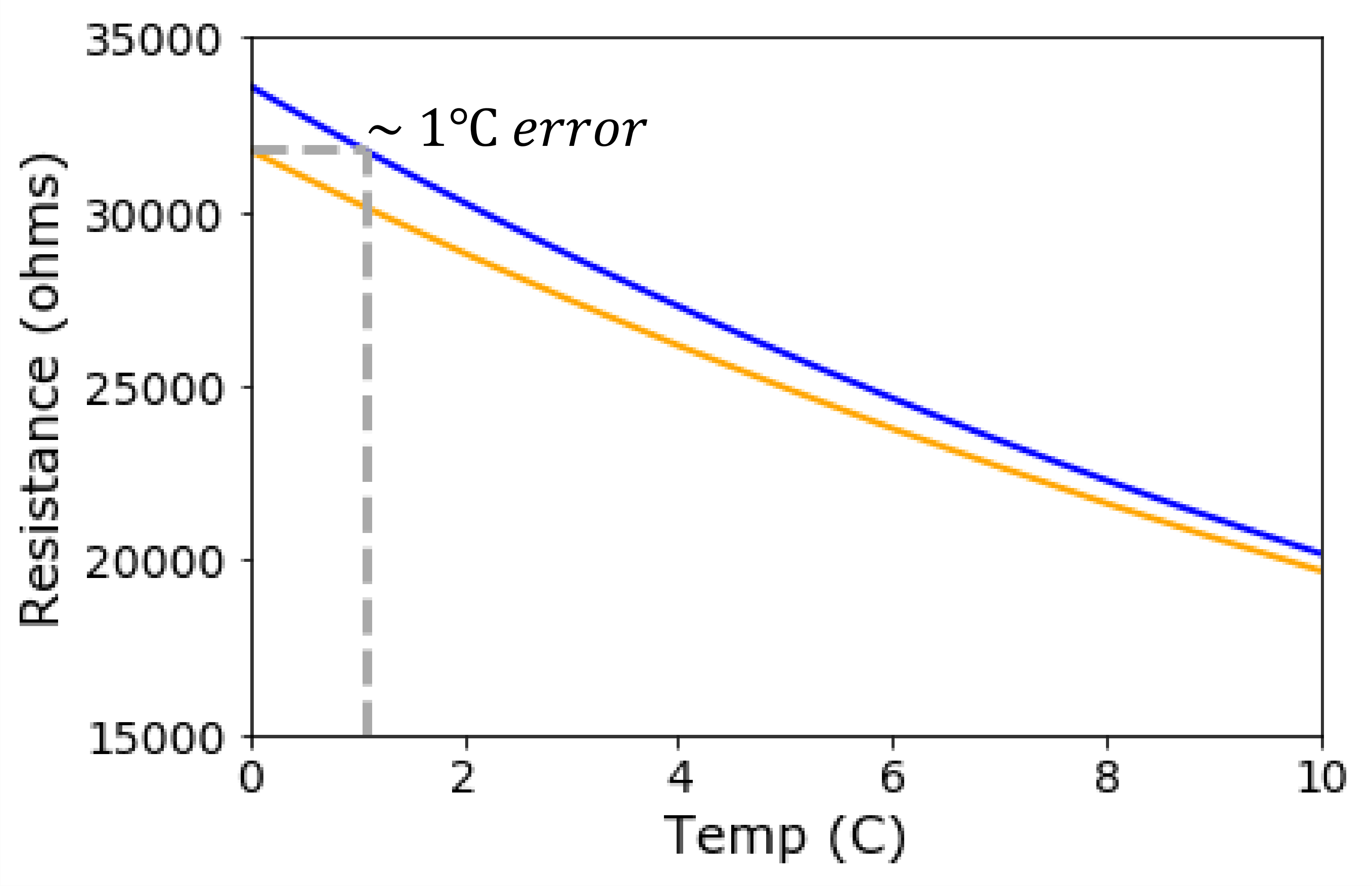
	Littlefuse PS302	Littlefuse PR303	Adafruit 10K
B	3892	3892	3950
R @25ºC	3kΩ	30kΩ	10kΩ
Accuracy	±0.1ºC @ 0-70ºC	±0.05ºC @ 0-50ºC	±0.25ºC @ 25-50ºC
Price	$3	$9	$4 w/leads



- High R: less self-heating
- Small R: more linear

Thermistor – values near freezing

Adafruit 10K



Temp C	R kohms
-2	34.97
-1	33.33
0	31.77
1	30.25
2	28.82
3	27.45
4	26.16
5	24.94
6	23.77
7	22.67
8	21.62
9	20.63
10	19.68

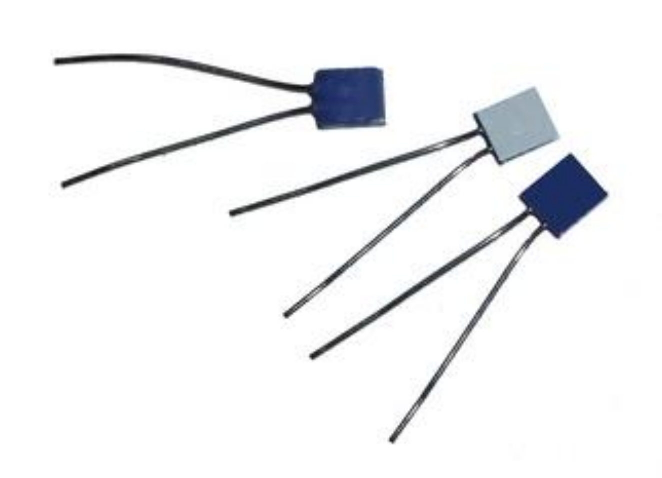
Mfg. look-up table

Thermistor - design considerations

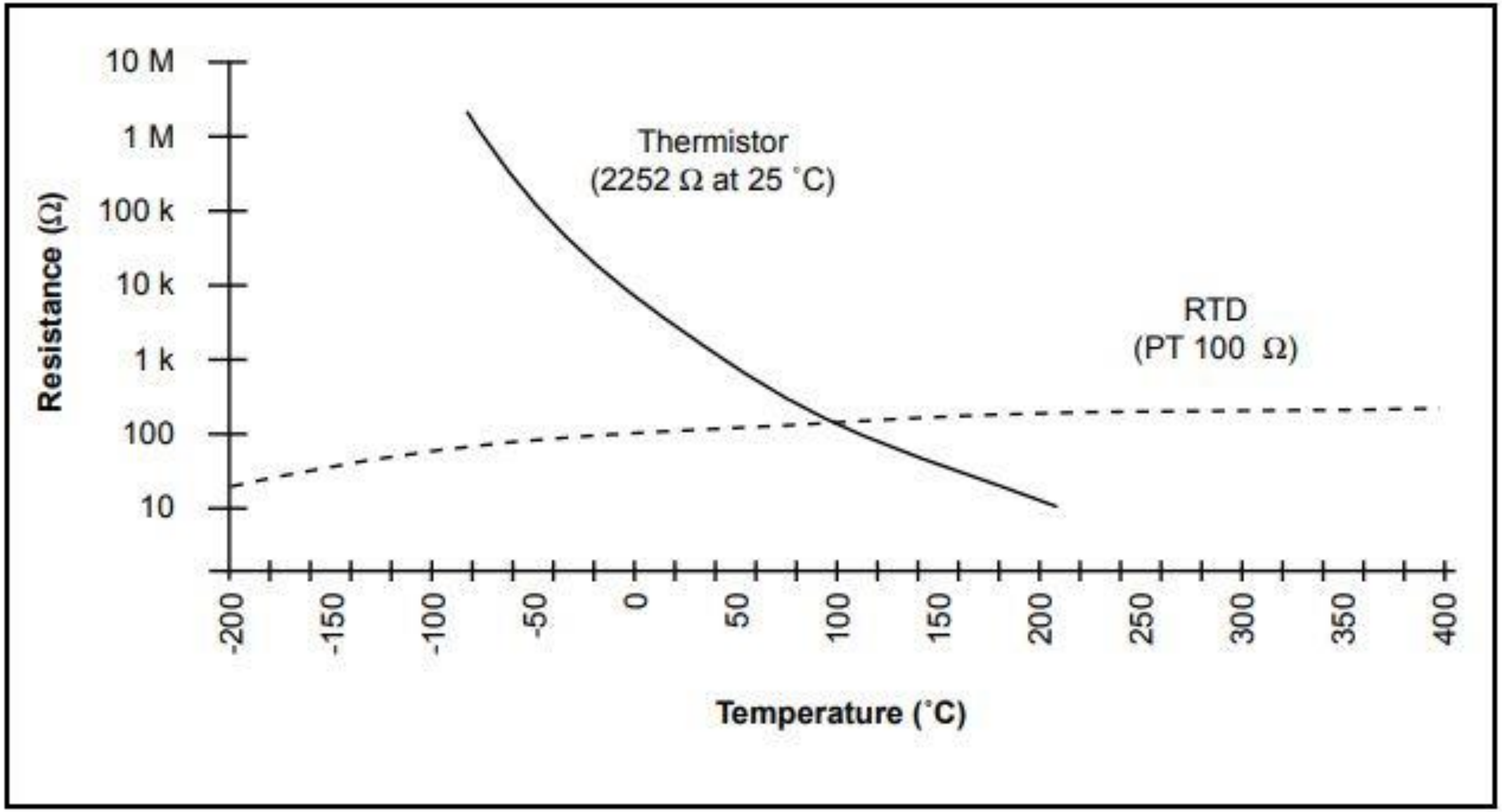
- Resistance at the nominal temperature $(25℃)$
- Avoid self-heating. Keep the current low as possible (*dissipation constant*)
- Sensitivity. Keep the current as high as possible to maximize system sensitivity
- *Time constant* – how fast the resistance changes with temperature.

Resistance-temperature detector (RTD)

- Usually made of highly pure platinum metal (thin film)
- High accuracy and stability as compared to thermocouples or thermistors
- Wide temperature range
- Resistance increases with temperature
  - Adafruit PT100: 100Ω at $0°C$
  - Resistance change with temp: $0.385\Omega/°C$
- Expensive *and* requires an amplifier. $> \$30$



RTD vs thermistor

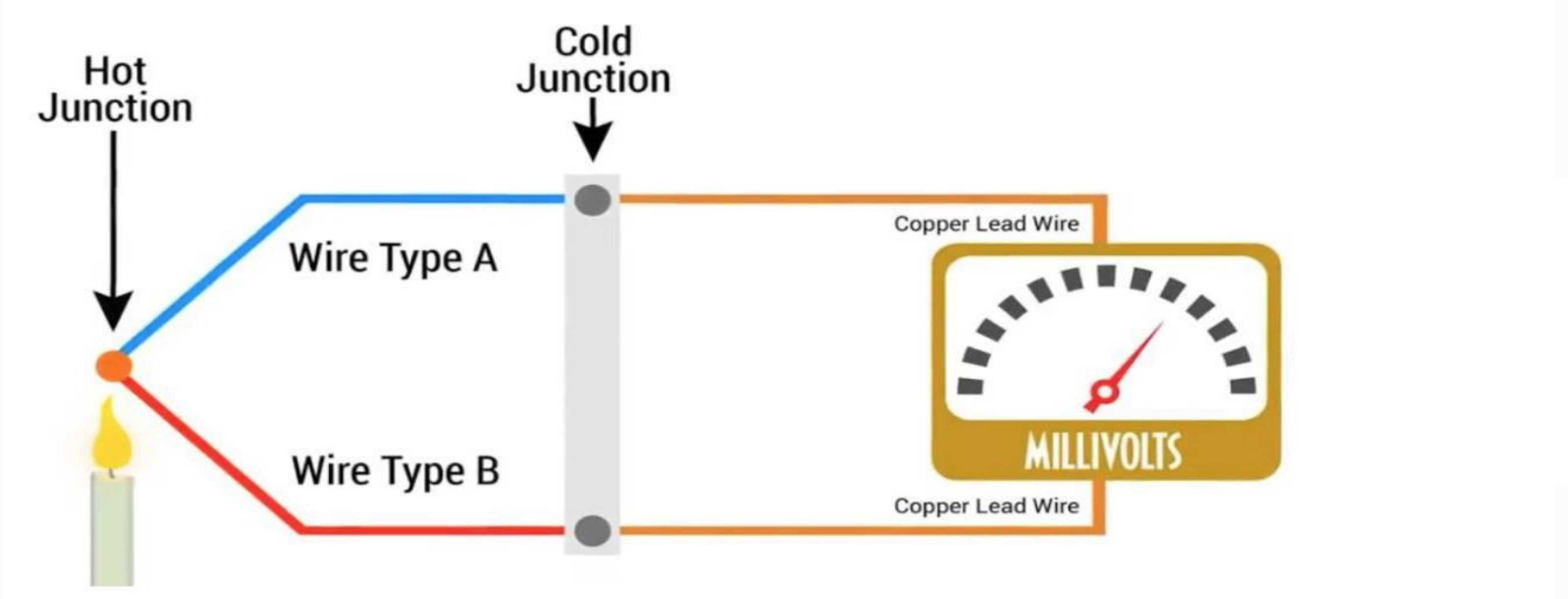


National Instruments

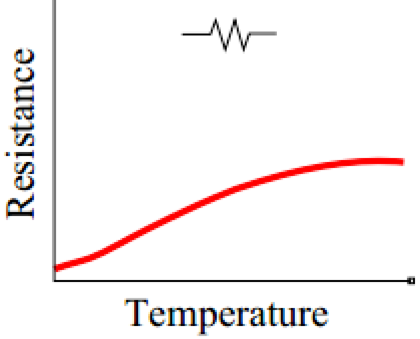
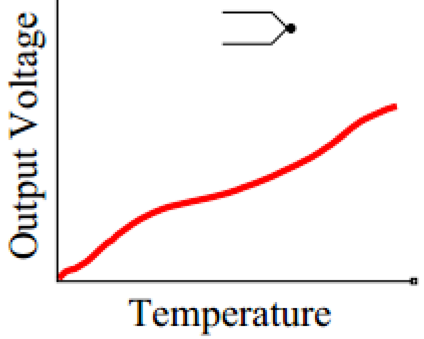
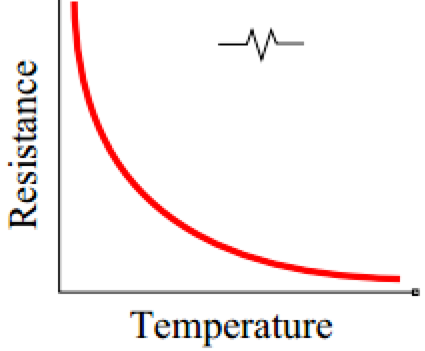
Thermocouple

- Made of two connected but dissimilar metal wires that produce a voltage potential proportional to temperature.

- Most useful in high temperature applications $(> 1350\ ℃)$



$$\frac{\Delta V}{\Delta T} = -\Delta S$$ Seebeck effect

RTD	Thermocouple	Thermistor	
			Output Characteristics
• Most accurate • Best stability • Higher linearity • Best interchangeabilty • Wide temperature range	• Largest variety of styles • Self-powered • Rugged • Largest temperature range • Small size / fast response	• High resistance values • Large resistance change • Two wire ohms measurement • Low sensor cost • Small size / fast response	Advantages
• Current source required • Smaller resistance change • Low absolute resistance • Self heating • Higher sensor cost	• Lowest stability • Low voltage output • Nonlinear • Cold junction reference needed • Lowest sensitivity	• Limited temperature range • Current source required • Nonlinear • Self heating • Fragile	Disadvantages
-260 to 850°C	-200 to 1800°C	-80 to 300°C	Temperature Range

RBR

MEASURE THE BLUE PLANET

RBR*concerto*³ Tx

COORDINATED TEMPERATURE PROFILES, LOGGED OR REALTIME

MEASURE MORE, DEPLOY LONGER, DOWNLOAD FASTER

- 240M readings
- 12 or 24 thermistors
- Long deployments
- Up to 400m in length
- USB-C download

Specifications

Physical

Power:	8 AA cells
Communication:	USB-C or RS-232/485
Storage:	240M readings
Clock drift:	±60 seconds per year
Depth rating:	750m (plastic) 8000m (titanium)
Size:	~355mm x Ø63.3mm/60.3mm (Ti)
Weight:	Configuration dependent
Sampling period:	3s to 24h
Averaging:	3s to 24h

Temperature

Range:	-5°C to 35°C
Initial accuracy:	±0.005°C
Resolution:	<0.00005°C
Time constant:	~30s
Typical stability:	~0.002°C per year

Configuration

Nodes:	12 or 24 node configuration
Length:	400m maximum
Load:	250kg maximum
Clevis pin:	12.7mm
Node diameter:	22mm
Cable diameter:	11.6mm
Node spacing:	150mm C-C minimum

Electric Conductivity

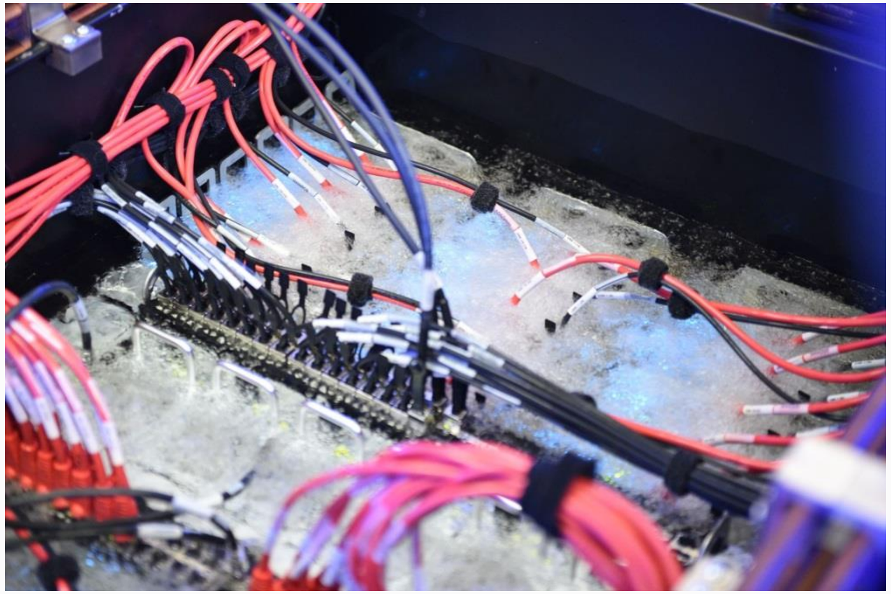
Conductance is the inverse of resistance $\frac{1}{\Omega} = \mho$ (mho)

$$1\,\mho = 1\ \text{seimens (S)}$$

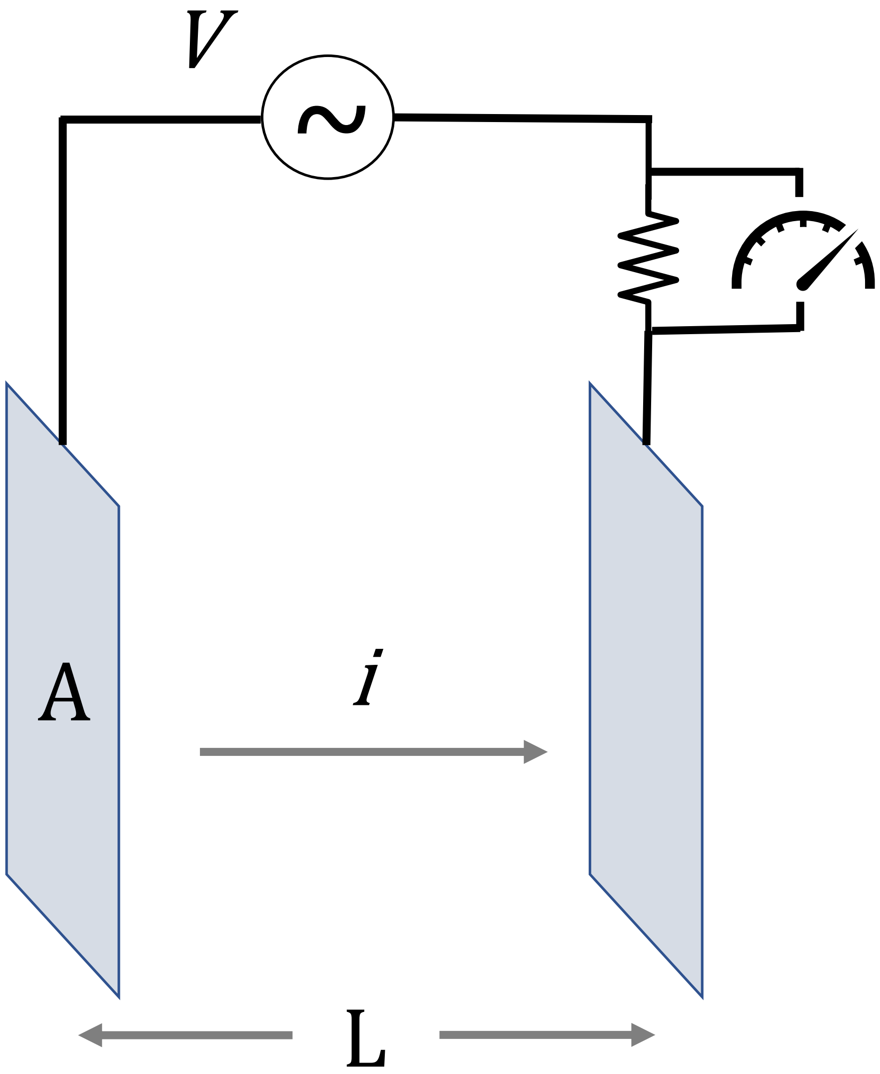
- Conductivity is a measure of water's capacity to pass electrical current.
- Directly related to the concentration of ions in the water.
- Most water bodies have fairly constant conductivity. It's an early indicator of changes in water body

Conductivity of water

Type	Conductivity (μS/cm)
Pure Water	0.05
DI Water	0.1
Distilled Water	0.5 - 3
Rain/Snow	2-100
Tap	50-800
Freshwater Stream	30 - 5000
Industrial Wastewater	10000
Seawater	55000



Conductivity – Two probe

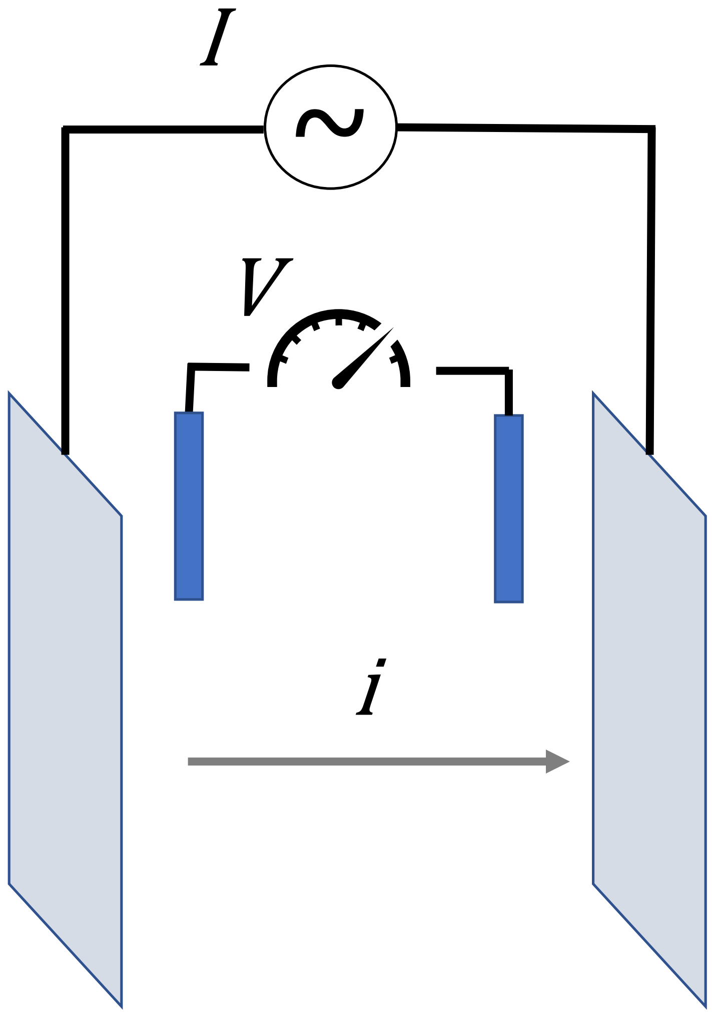


$V =$ Excitation voltage
i = Current induced in the cell
Y = Measured conductance = $f(\frac{i}{V})$ (S)

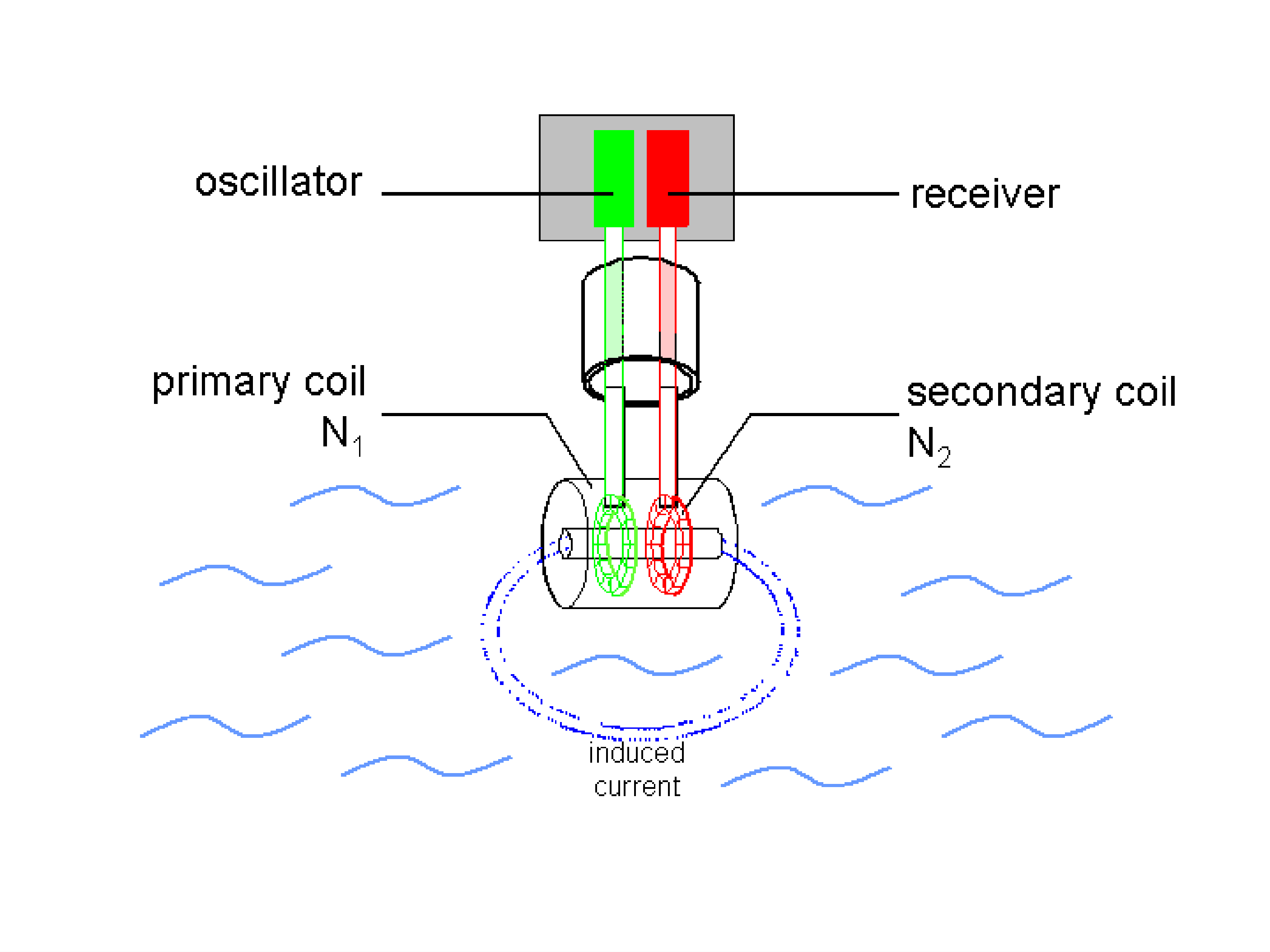
A = Electrode surface area (cm^2)
L = Distance between electrodes (cm)
K = Cell constant L/A (cm^{-1})

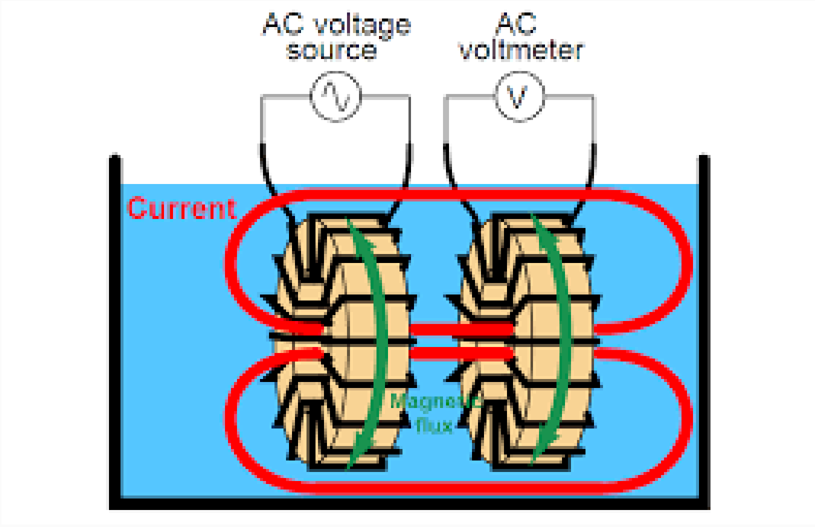
Y_X = Water conductivity = $K \cdot Y$ $(\frac{S}{cm})$

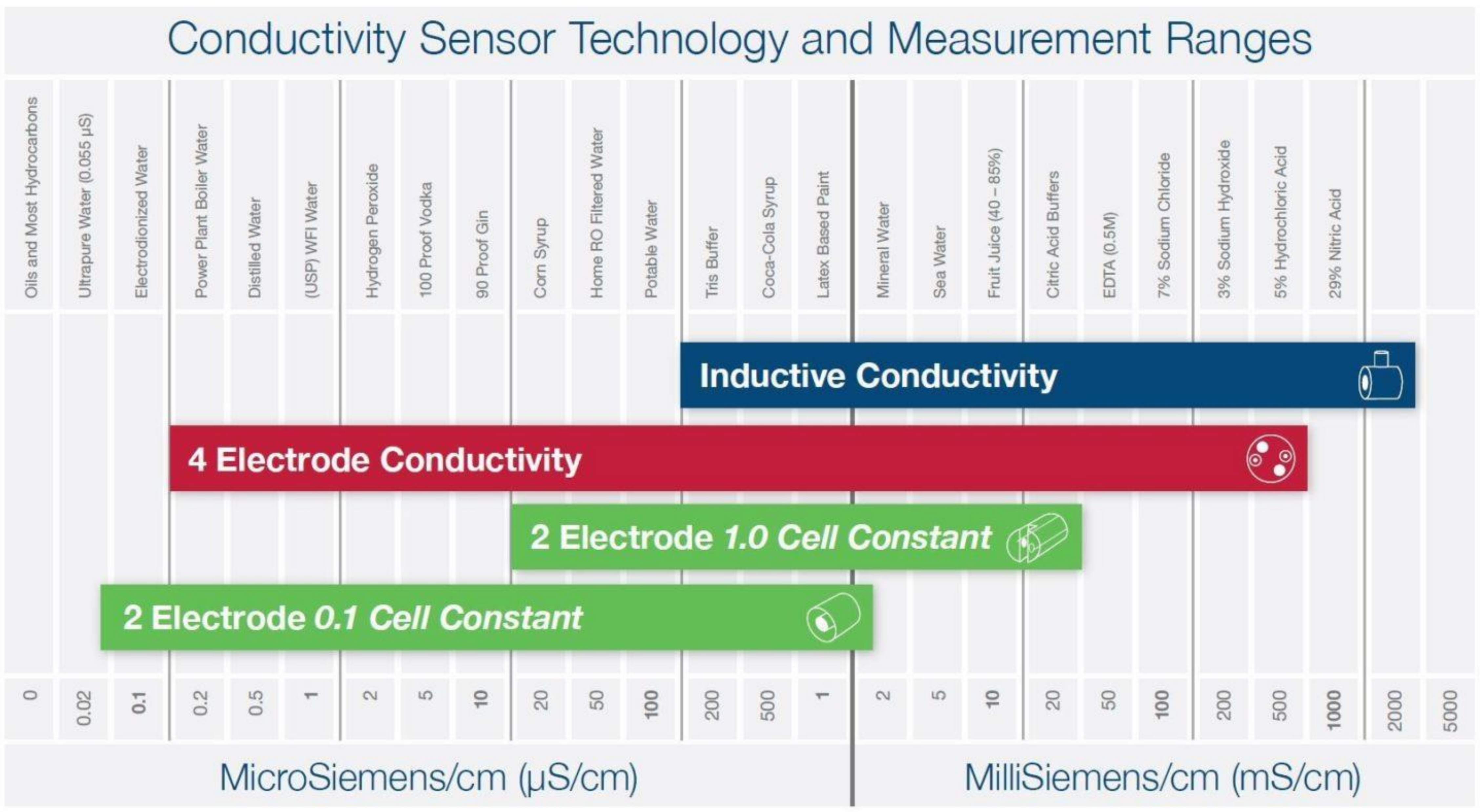
Conductivity – four probe



Inductive conductivity sensor







Conductivity Sensor Technology and Measurement Ranges
Oils and Most Hydrocarbons
Ultrapure Water (0.055 µS)
Electrodionized Water
Power Plant Boiler Water
Distilled Water
(USP) WFI Water
Hydrogen Peroxide
100 Proof Vodka
90 Proof Gin
Corn Syrup
Home RO Filtered Water
Potable Water
Tris Buffer
Coca-Cola Syrup
Latex Based Paint
Mineral Water
Sea Water
Fruit Juice (40 – 85%)
Citric Acid Buffers
EDTA (0.5M)
7% Sodium Chloride
3% Sodium Hydroxide
5% Hydrochloric Acid
29% Nitric Acid
Inductive Conductivity
4 Electrode Conductivity
2 Electrode 1.0 Cell Constant
2 Electrode 0.1 Cell Constant
0
0.02
0.1
0.2
0.5
1
2
5
10
20
50
100
200
500
1
2
5
10
20
50
100
200
500
1000
2000
5000
MicroSiemens/cm (µS/cm)
MilliSiemens/cm (mS/cm)

Hamilton Co.

Specific Conductance is conductance at 25 deg. C

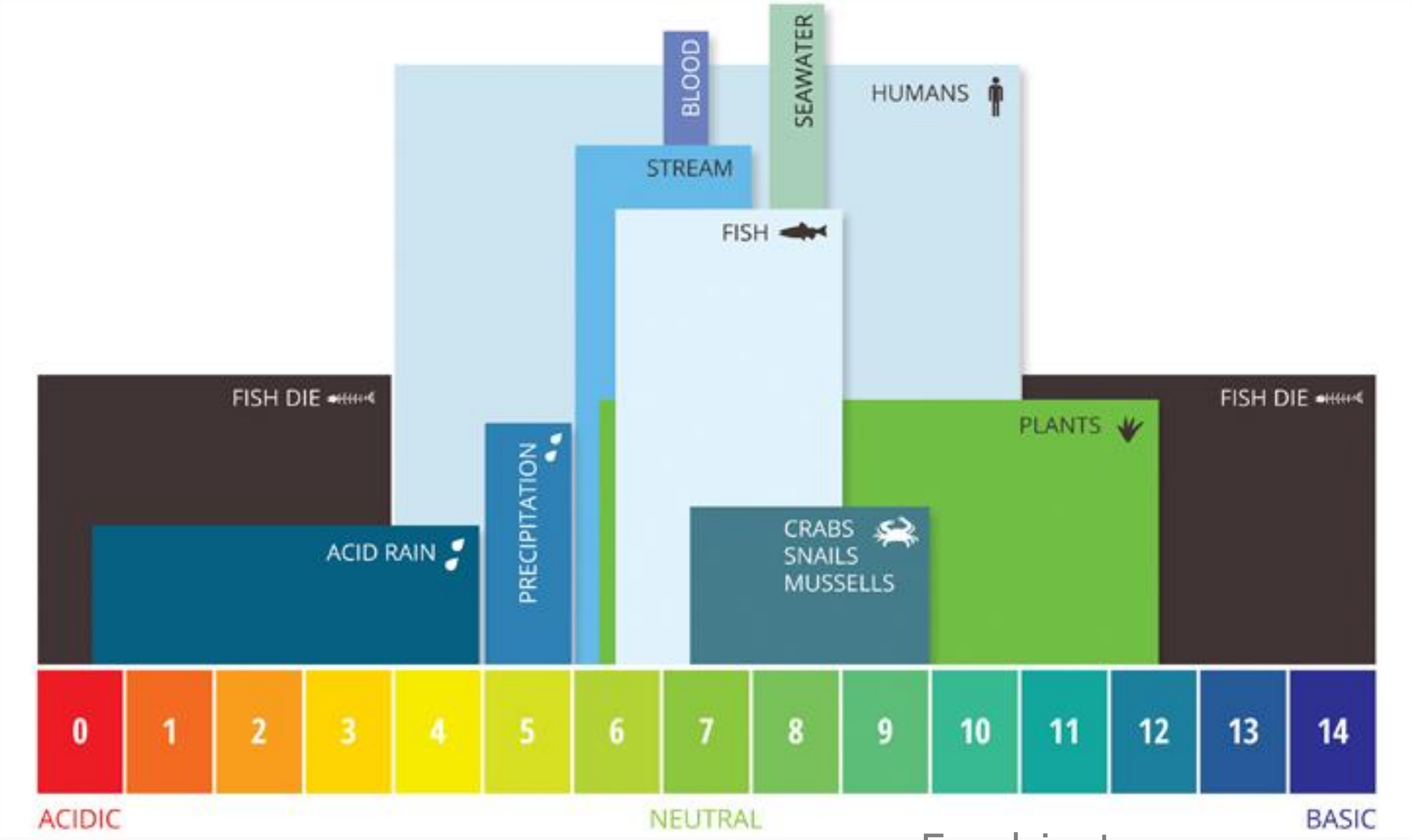
Salinity and TDS can be *estimated* with algorithms using conductance

pH – "potential of hydrogen"

The concentration of hydrogen ions (H^+) in water

https://www.youtube.com/watch?v=PBTn4gTEbkU

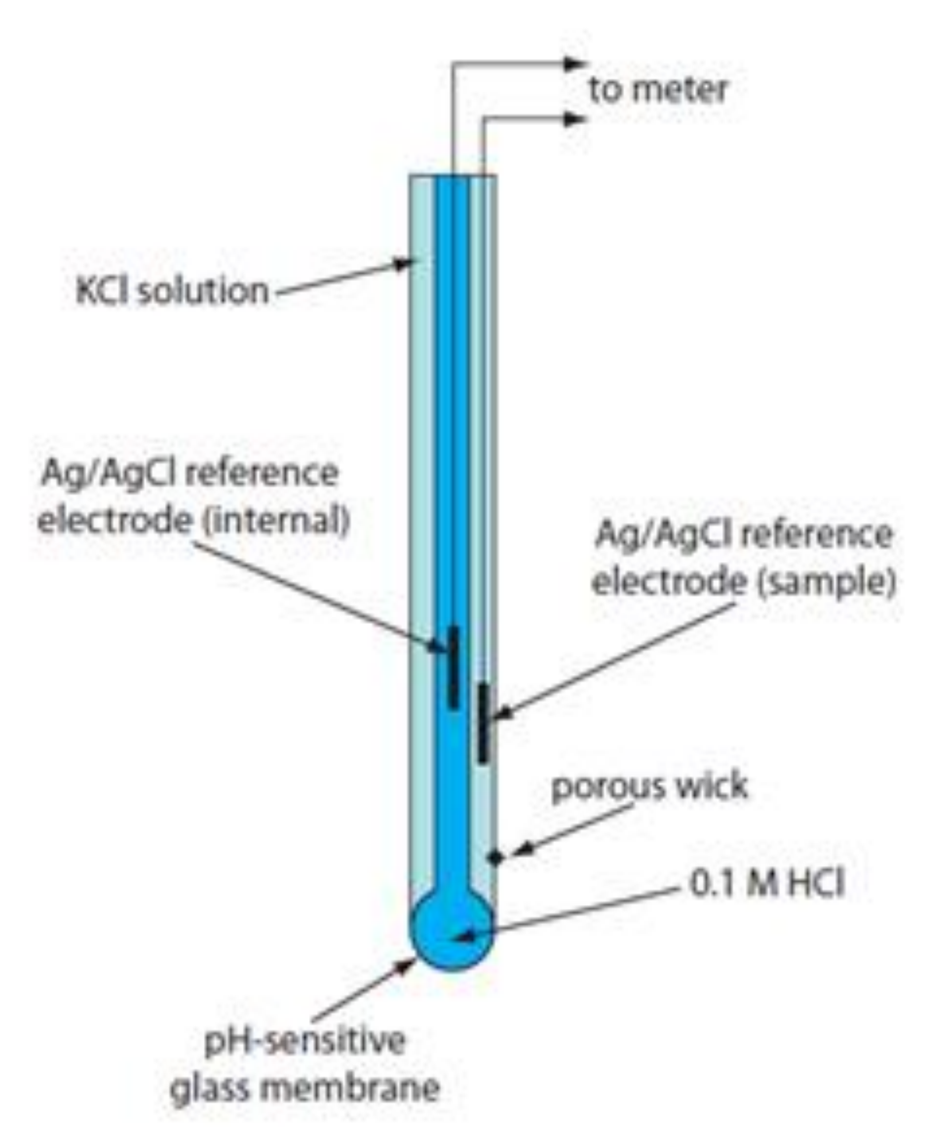
pH



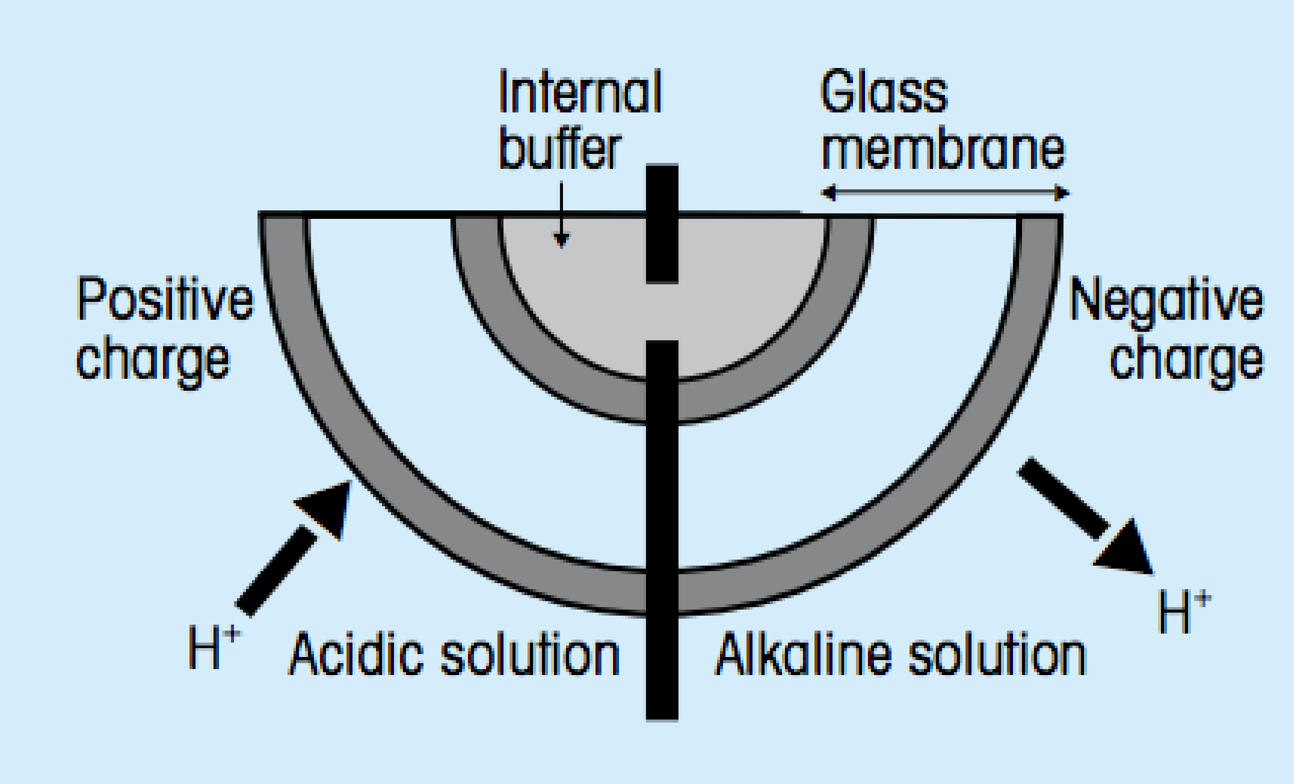
Fondriest.com

pH also affects the solubility and toxicity of chemicals and heavy metals in water.

pH probe



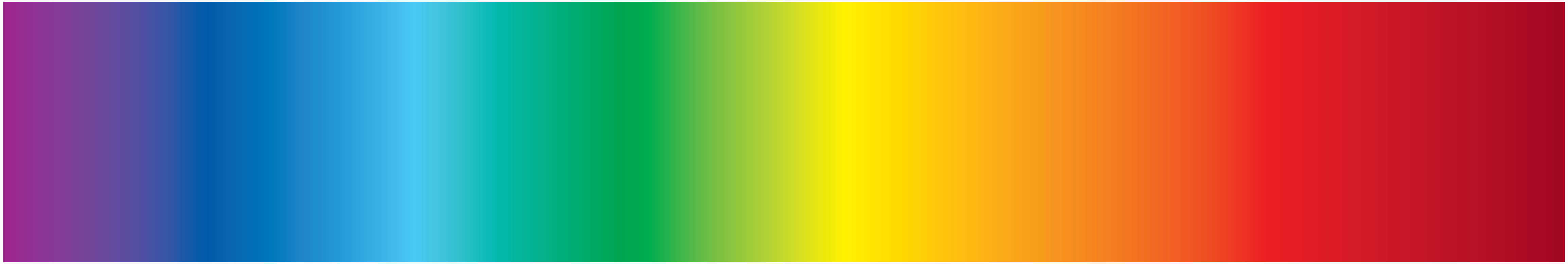
Glass contains either lithium or sodium cations as charge carriers.



Light

Pigments (Chl a, BGA):	Fluorescence
Dissolved gasses (O_2, CO_2):	Spectral Absorption Luminescence
PAR:	Light Intensity
Turbidity:	Light Scattering

Visible Light



Shorter wavelength

Higher frequency

Higher energy

$$\mathrm{E} = h\left(\frac{c}{\lambda}\right) \quad \text{(joules)}$$

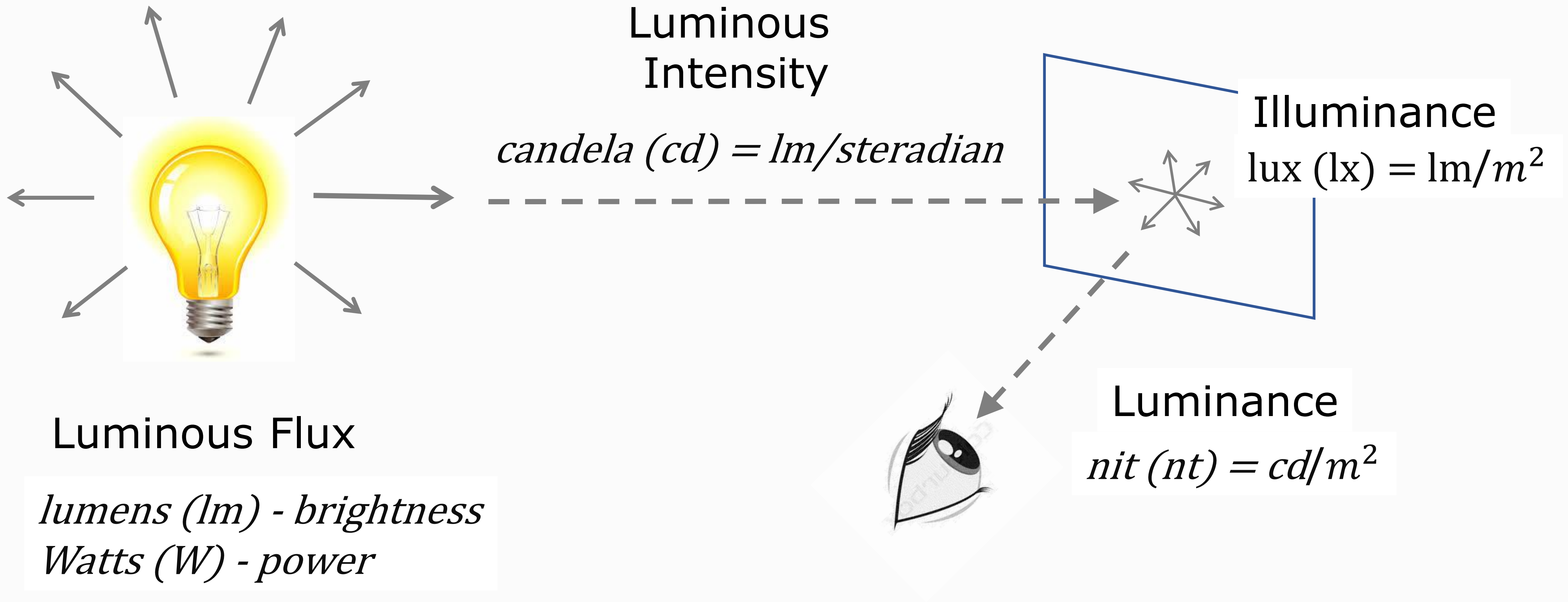
$$c = speed\ of\ light$$
$$h = Planck's\ constant$$

Longer wavelength

Lower frequency

Lower energy

Light - definitions



Light – example lux values

	lux
Moonless clear night	0.02
Full moon on a clear night	0.5-0.3
Civil twilight (dawn, dusk)	3.4
Family living room	50
Office lighting	320-500
Overcast day	1000
Full daylight (indirect sun)	10k-25k
Direct sunlight	32k-100k

Wikipedia

Light – photosynthetic active radiation (PAR)

Plant sciences (incl. phytoplankton) are more interested in photon flux than light energy flux

$$6CO_2 + 12H_2O \rightarrow \underbrace{C_6H_{12}O_6}_{\textit{glucose}} + 6O_2 + 6H_2O$$

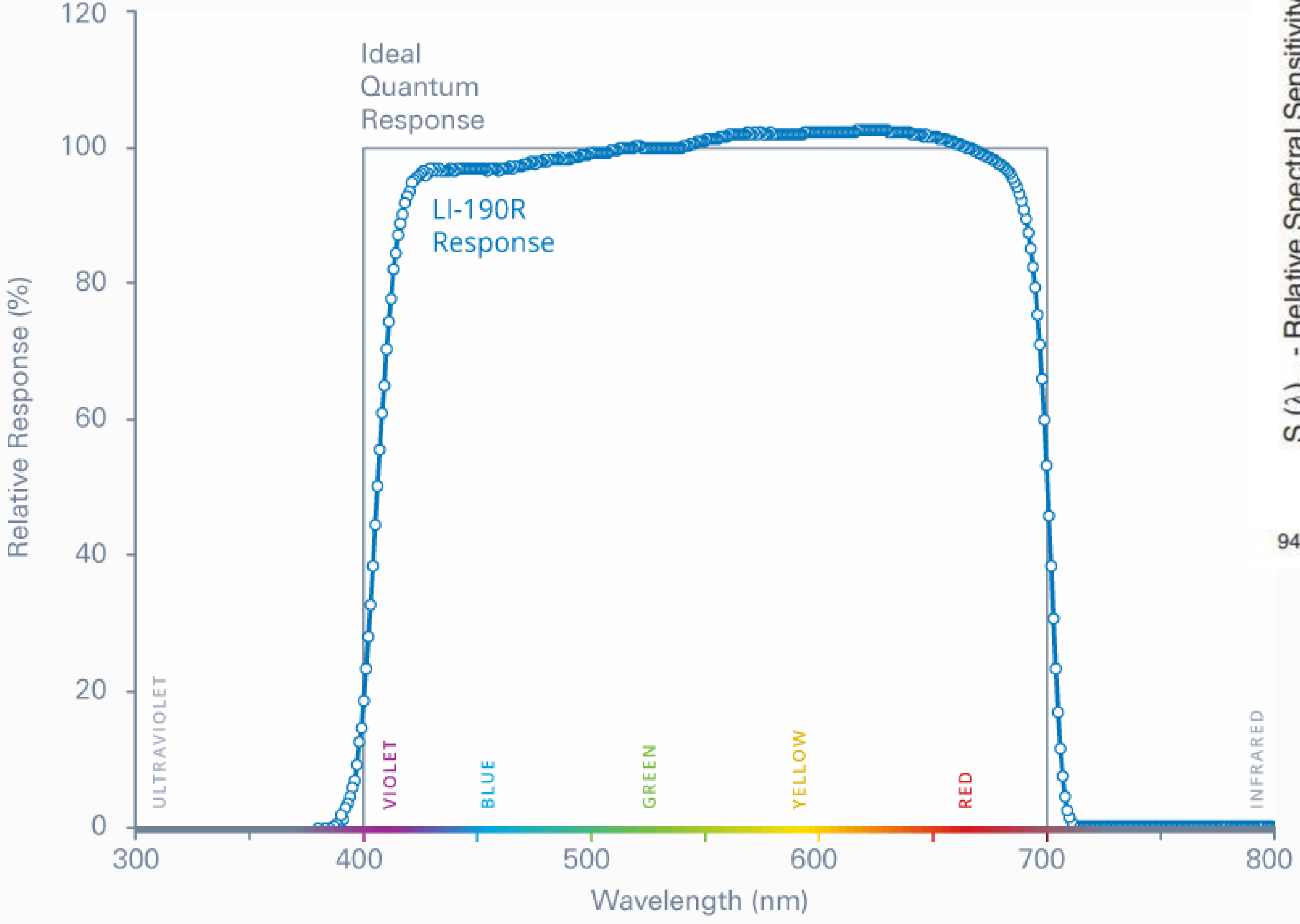
+48 photons

Photosynthetic Photon Flux Density (PPFD) is the photon flux density of PAR

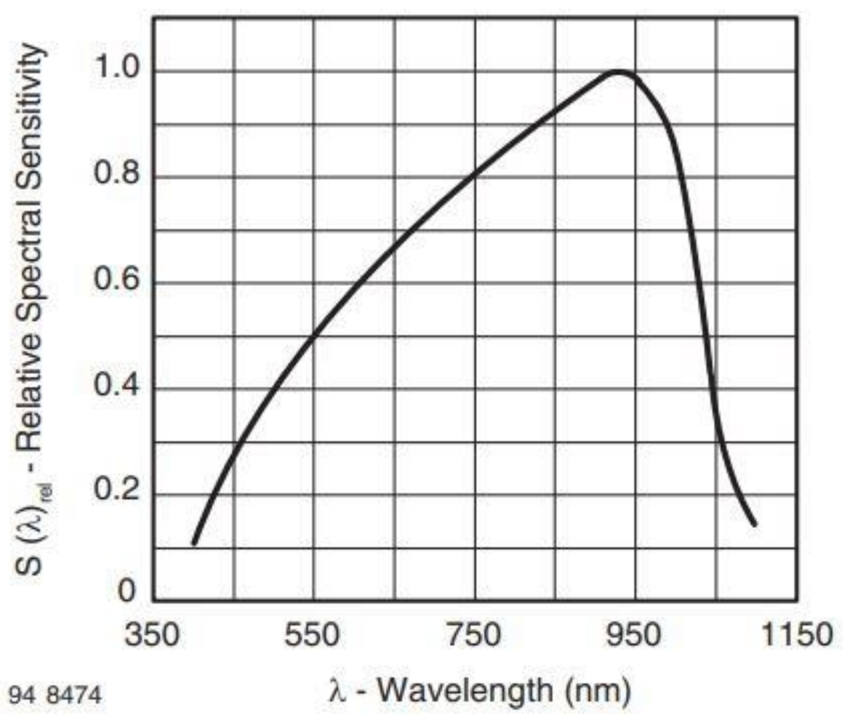
- 400-700nm (visible light)
- count of photons

$$1\, \boldsymbol{\mu mol \cdot m^{-2} \cdot s^{-1}} \equiv 6.022 \times 10^{17} photons \cdot m^{-2} \cdot s^{-1}$$

PAR sensors

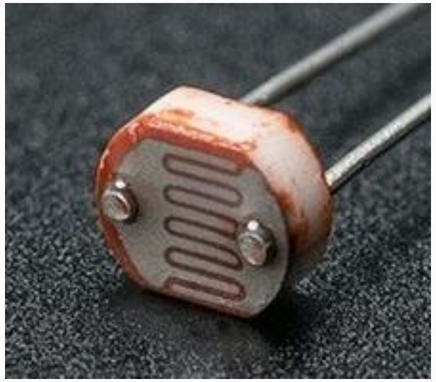


Commercial PAR Sensor



photodiode

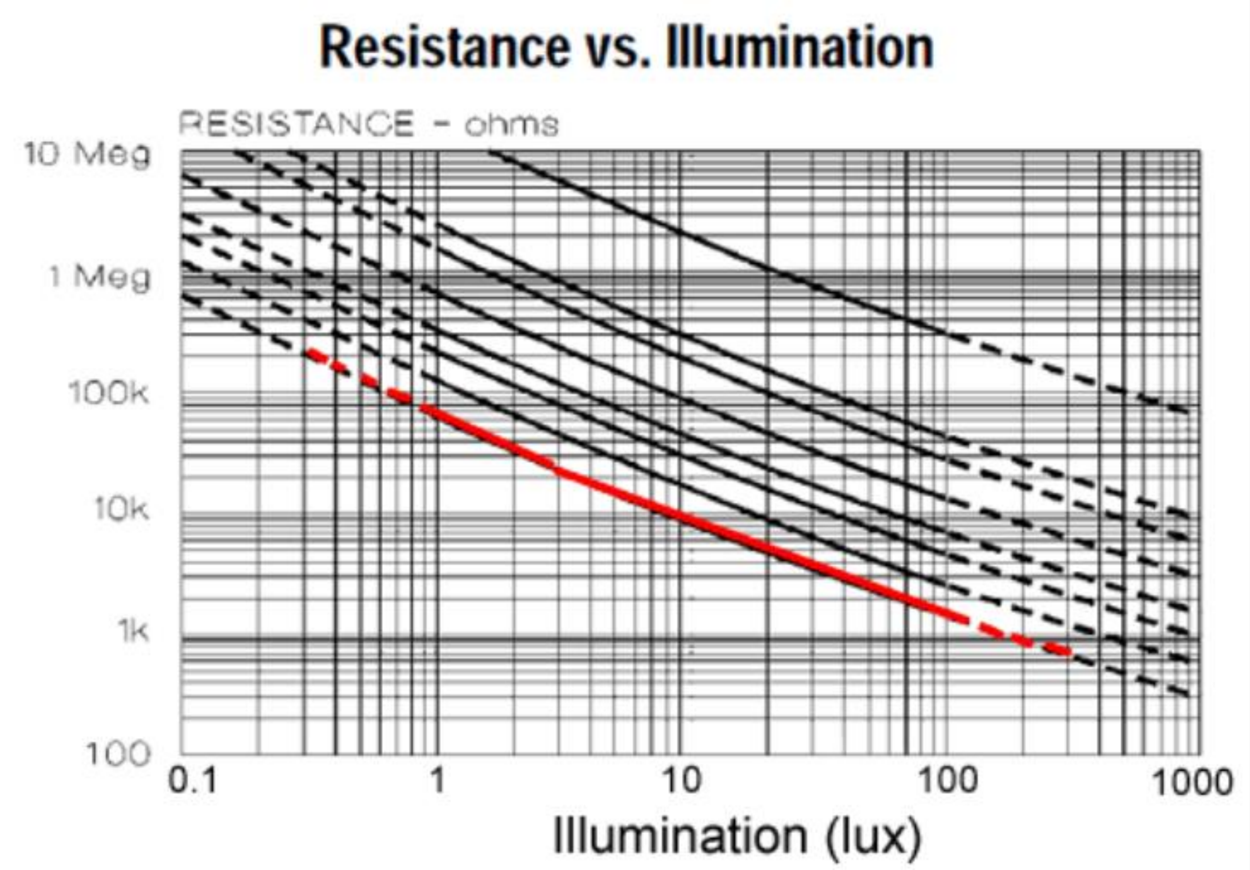
Photo cell (photoresistor)



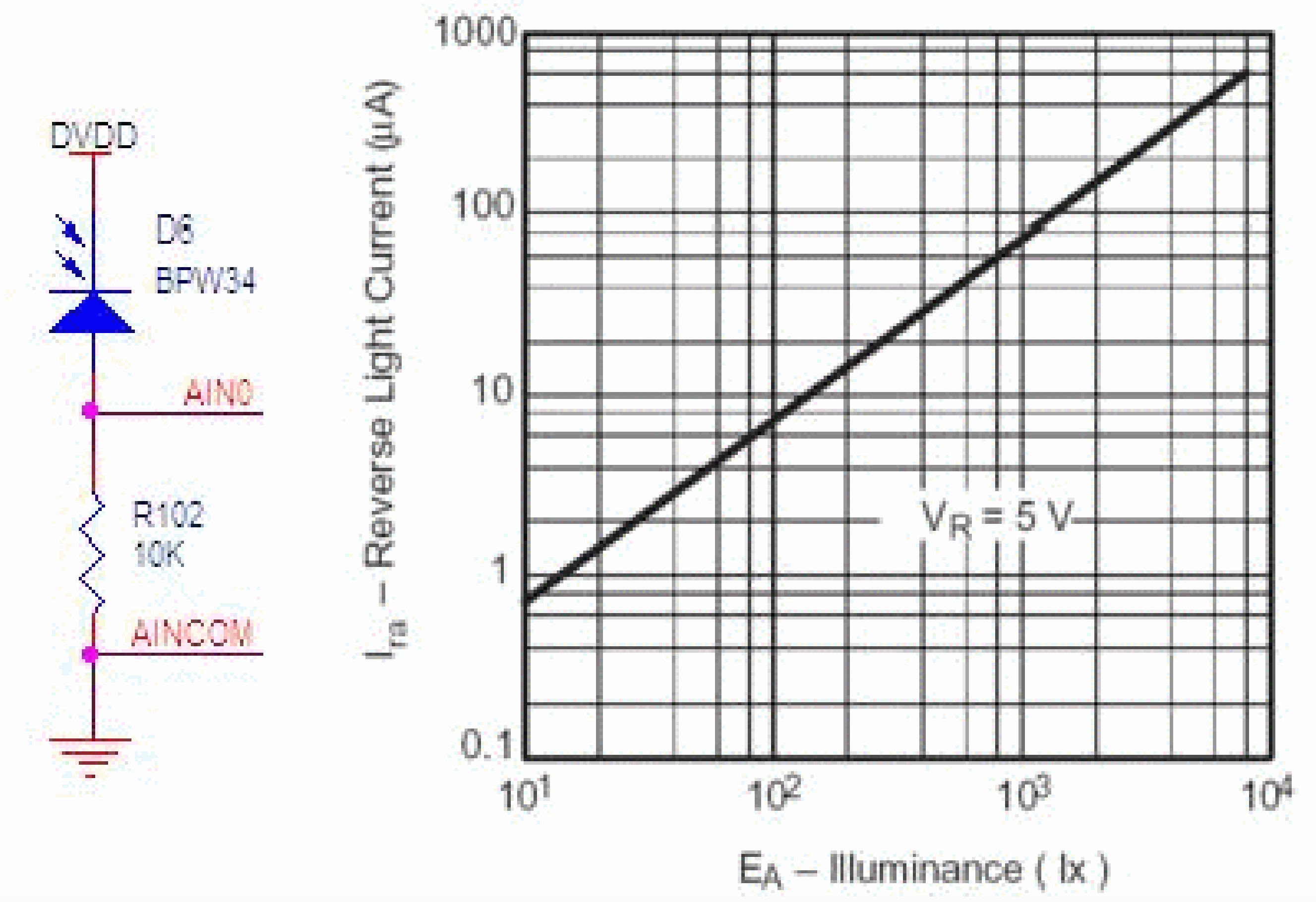
Resistance is a function of light
- 1MΩ (dark)
- 1kΩ @ ~200 lux

Best for course light level estimates (consumer products)

Cheap and simple



Photodiode



- Linear current response with illuminance
- Good sensitivity

Intro to Fluorescense

by ThermoFisher Scientific

Fluorescence

400 500 600 700 nm

← Higher energy

Lower energy →

Excitation:

A molecule absorbs a photon in a specific wavelength band (λ)

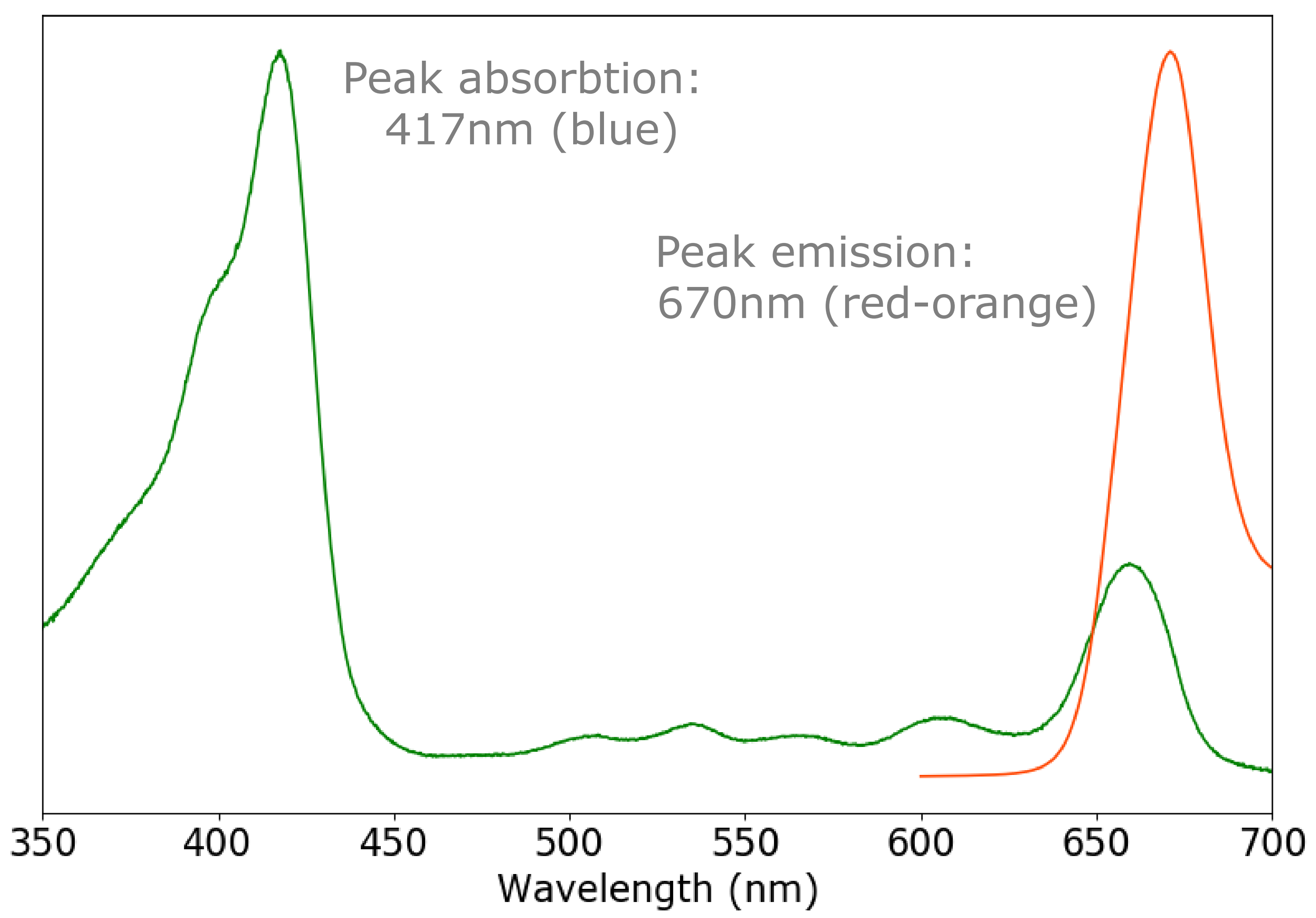
The molecule is "excited" as an electron moves a higher energy state

Emission:

The molecule returns to its original state by emitting a photon

The photon is at a lower energy (longer λ) than the original. Some energy is lost in the process.

Chlorophyll a is a fluorescent pigment



Chlorophyll a – energy use

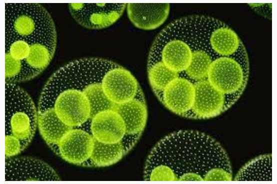
$\rightarrow$ **Chl a** $\rightarrow$

heat

light (orange-red)

photosynthesis

$CO_2 + H_2O + \; \rightarrow O_2 +$ **Sugar** $\rightarrow$



All aquatic algae use *chlorophyll a* for photosynthesis

Fluorescent pigments of algae

Chlorophyll a

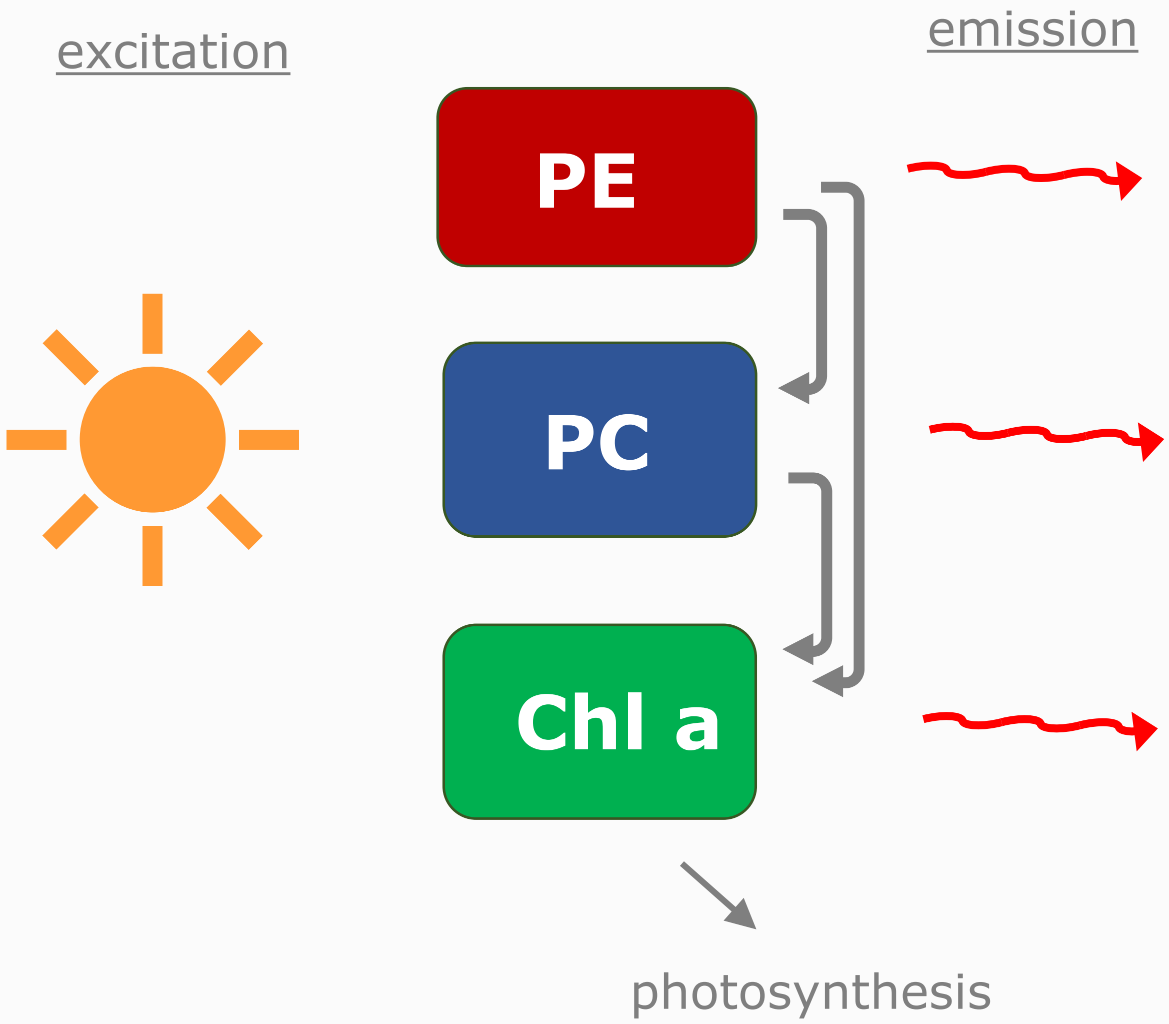
- all algae
- chlorophyll a sensors are relevant for all micro-algae

Phycocyanin (PC)

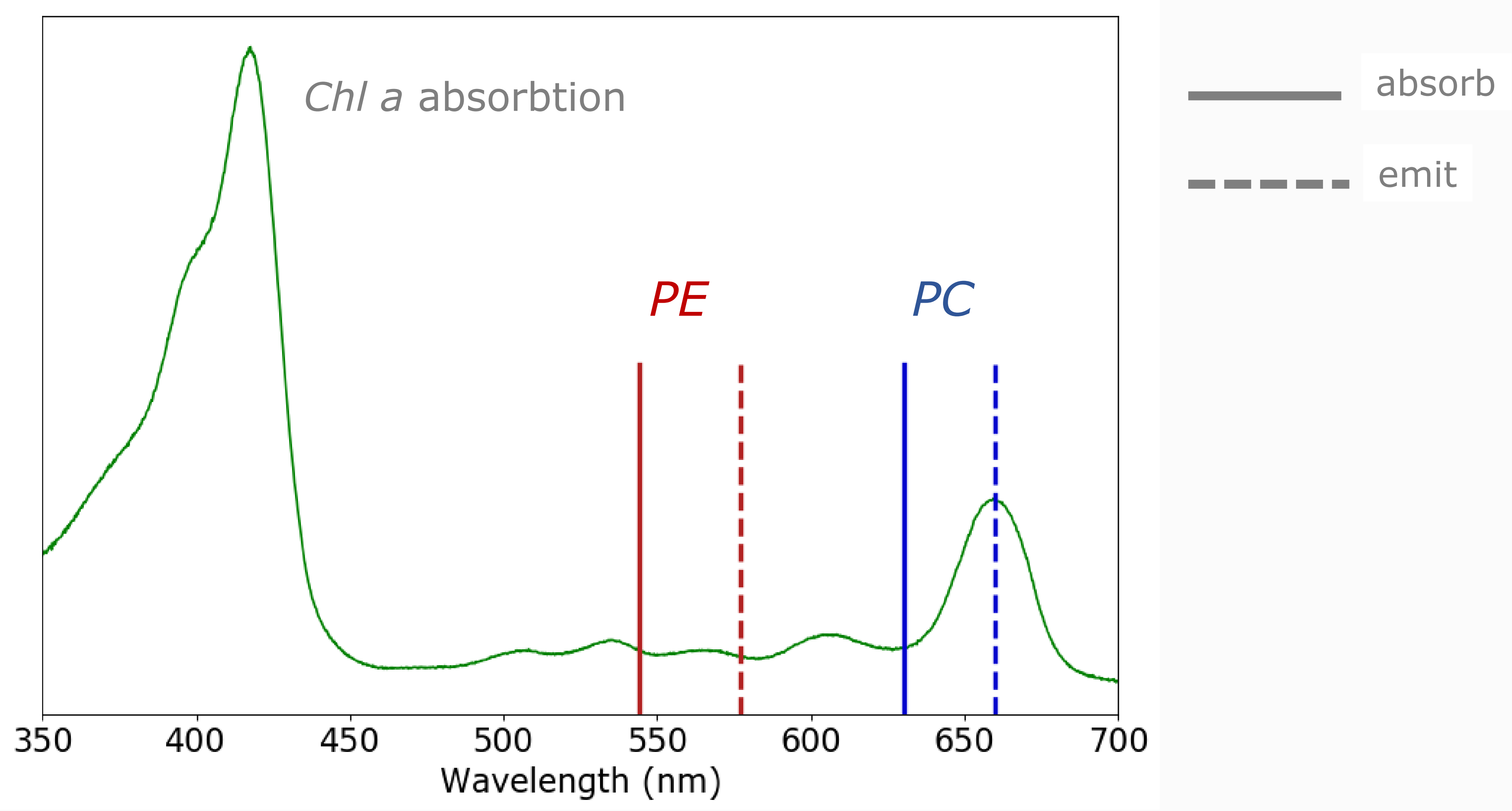
- cyanobacteria (blue-green algae)

Phycoerythrin (PE)

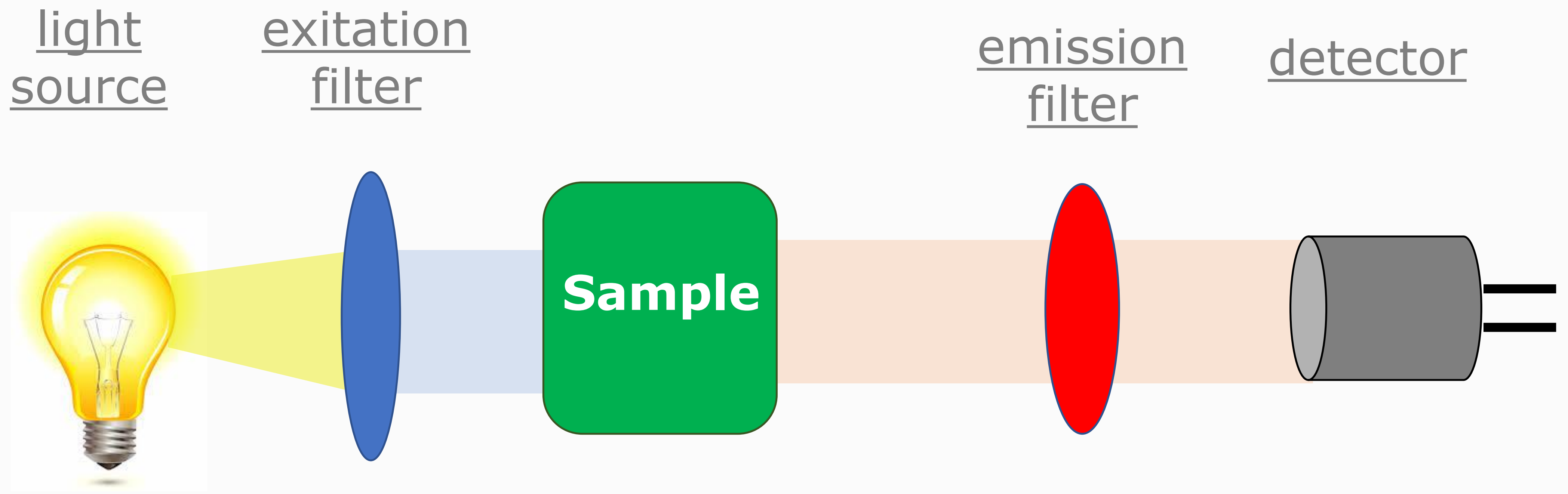
- blue-green algae in marine waters



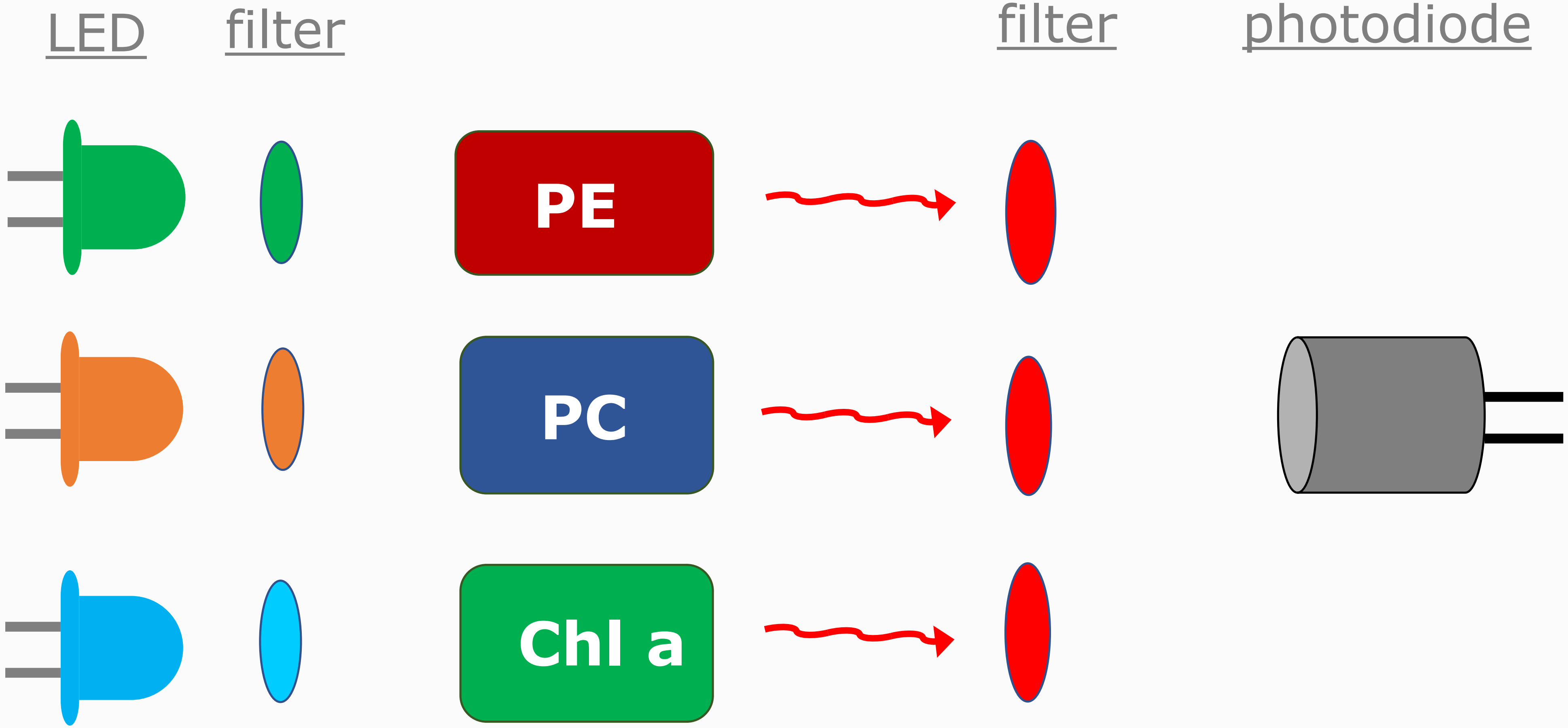
Pigment fluorescence spectrum

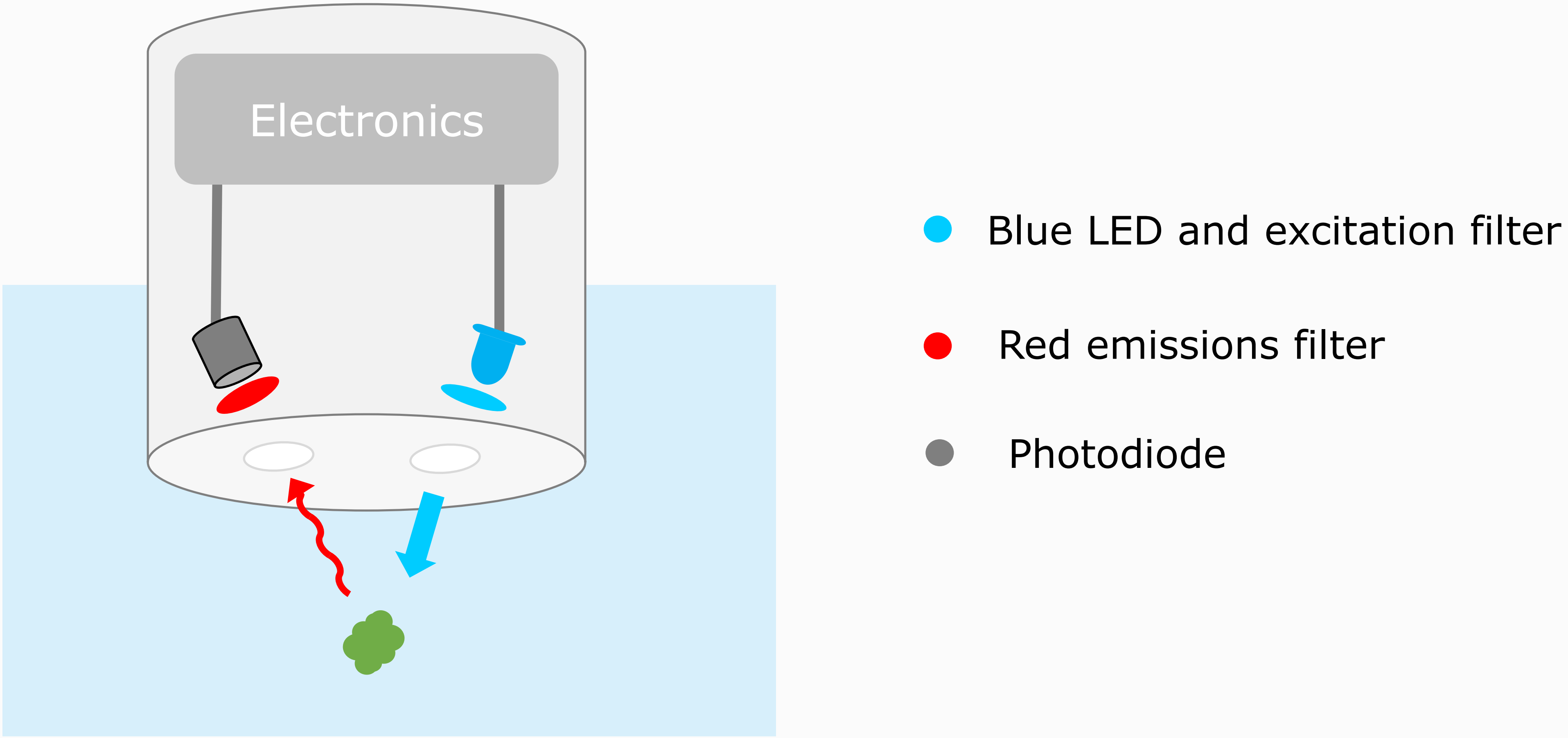


Fluorometers



Fluorometers





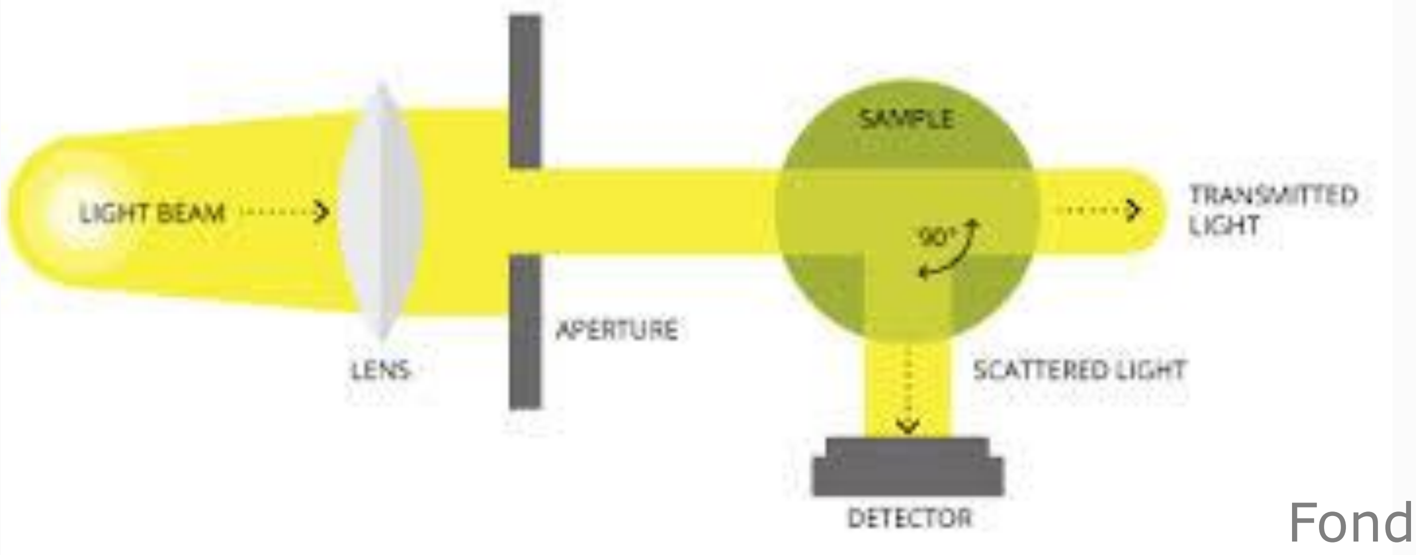
Two-point calibration:

1. deionized water
2. a local sample of water that can be lab-analyzed

Turbidity

Turbidity meters use a light source and detector to measure the light scatter by particles in the water.

Nephelometry - light source and photodetector are set a 90-degree angle to each other. Light scatter and turbidity have a linear relationship at low levels.



Fondriest

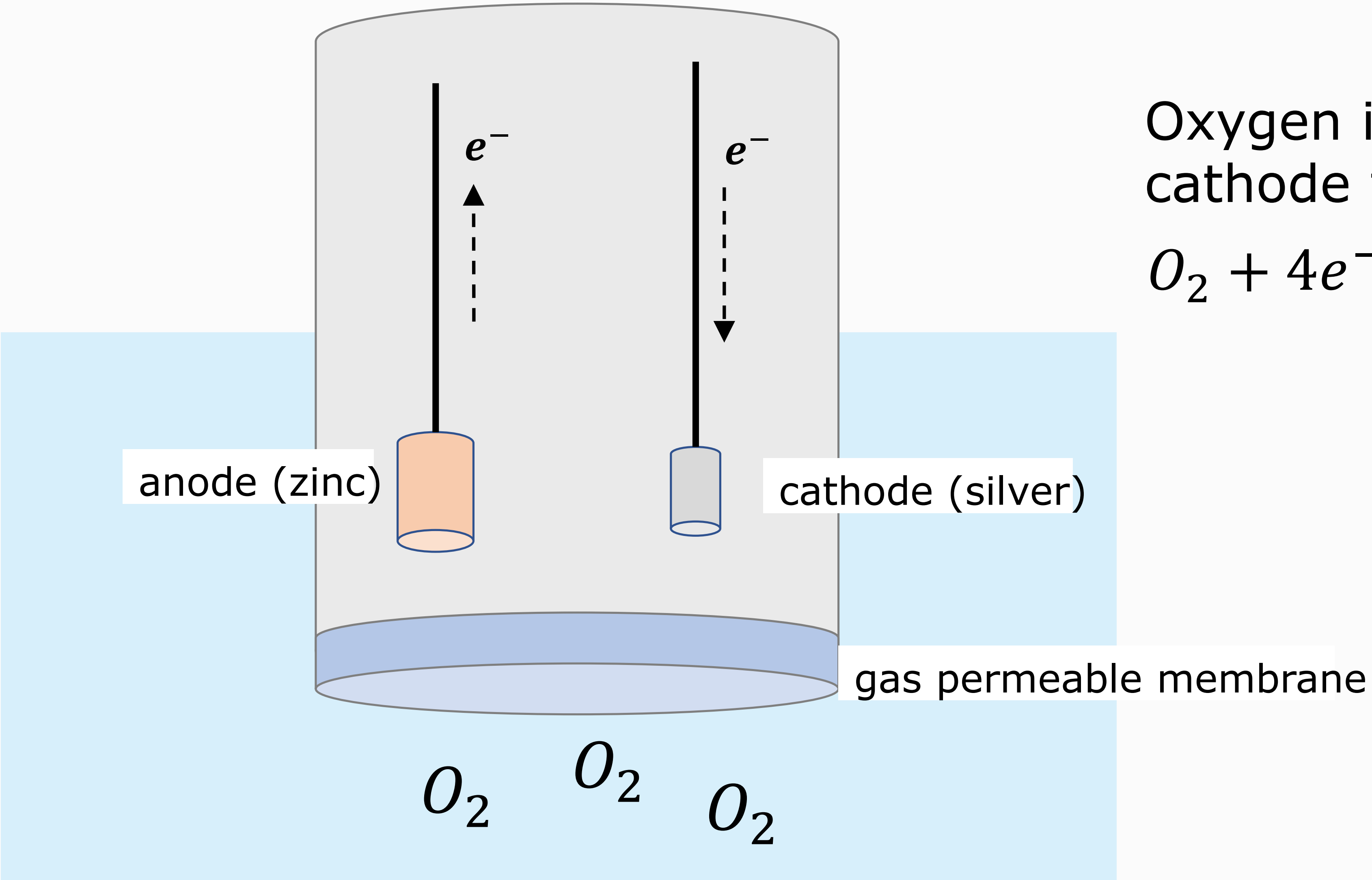
Measurement units have no intrinsic physical, chemical, and biological significance.

NTU – Nephelometric Turbidity Units
FNU – Formazin Nephelometric Units

Results between different instruments and different sources of turbidity are not really comparable.

Total suspended solid (TSS) are the main cause of turbidity, and the most accurate method of measurement is to filter, dry and weigh a sample.

Dissolved Oxygen - galvanic



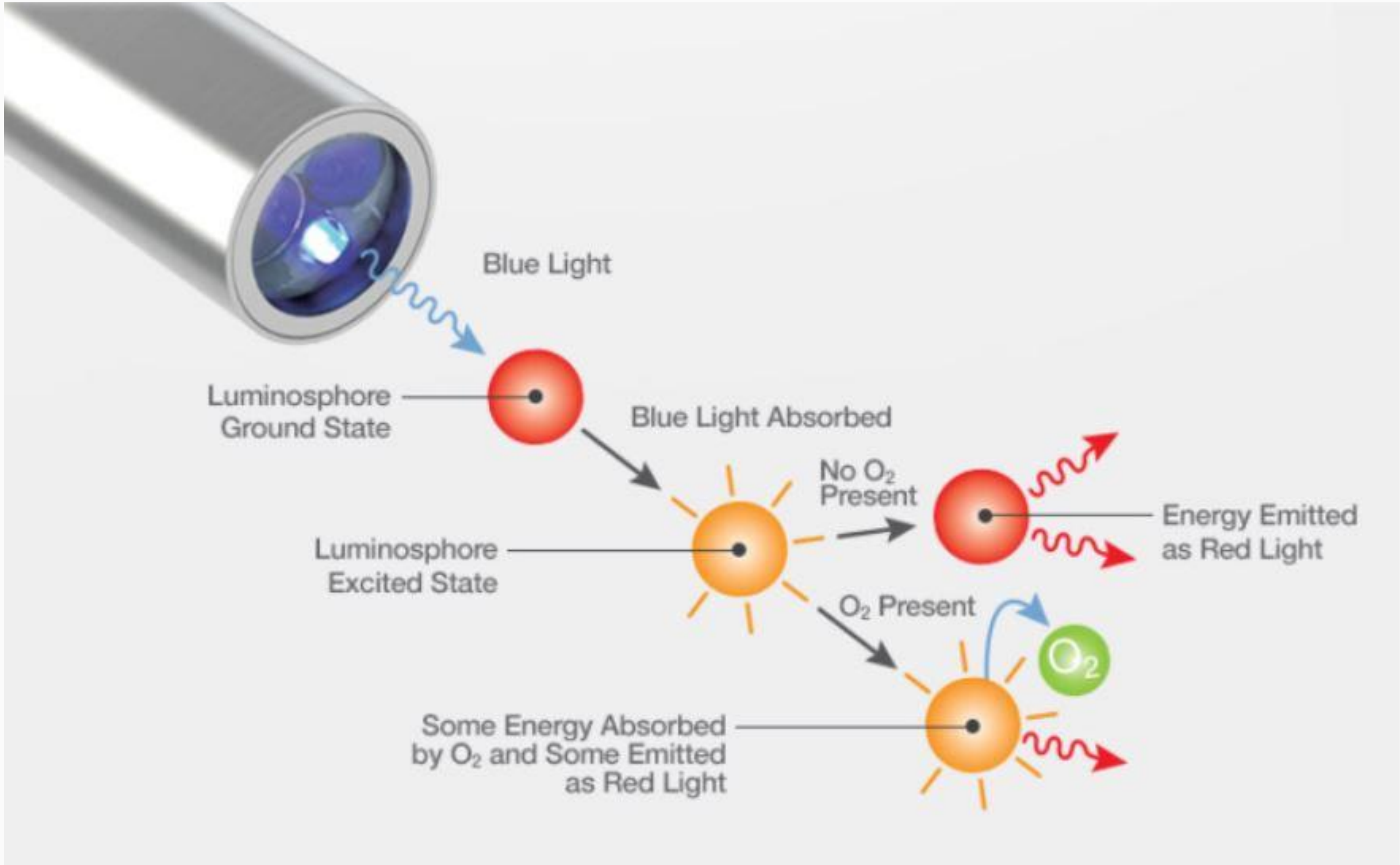
Zinc is oxidized at the anode

$$2Zn \rightarrow 2Zn^{2+} \rightarrow 4e^-$$

Oxygen is reduced at the cathode forming hydroxide

$$O_2 + 4e^- + 2H_2O \rightarrow 4OH^-$$

DO - optical



Hamilton Company

DO

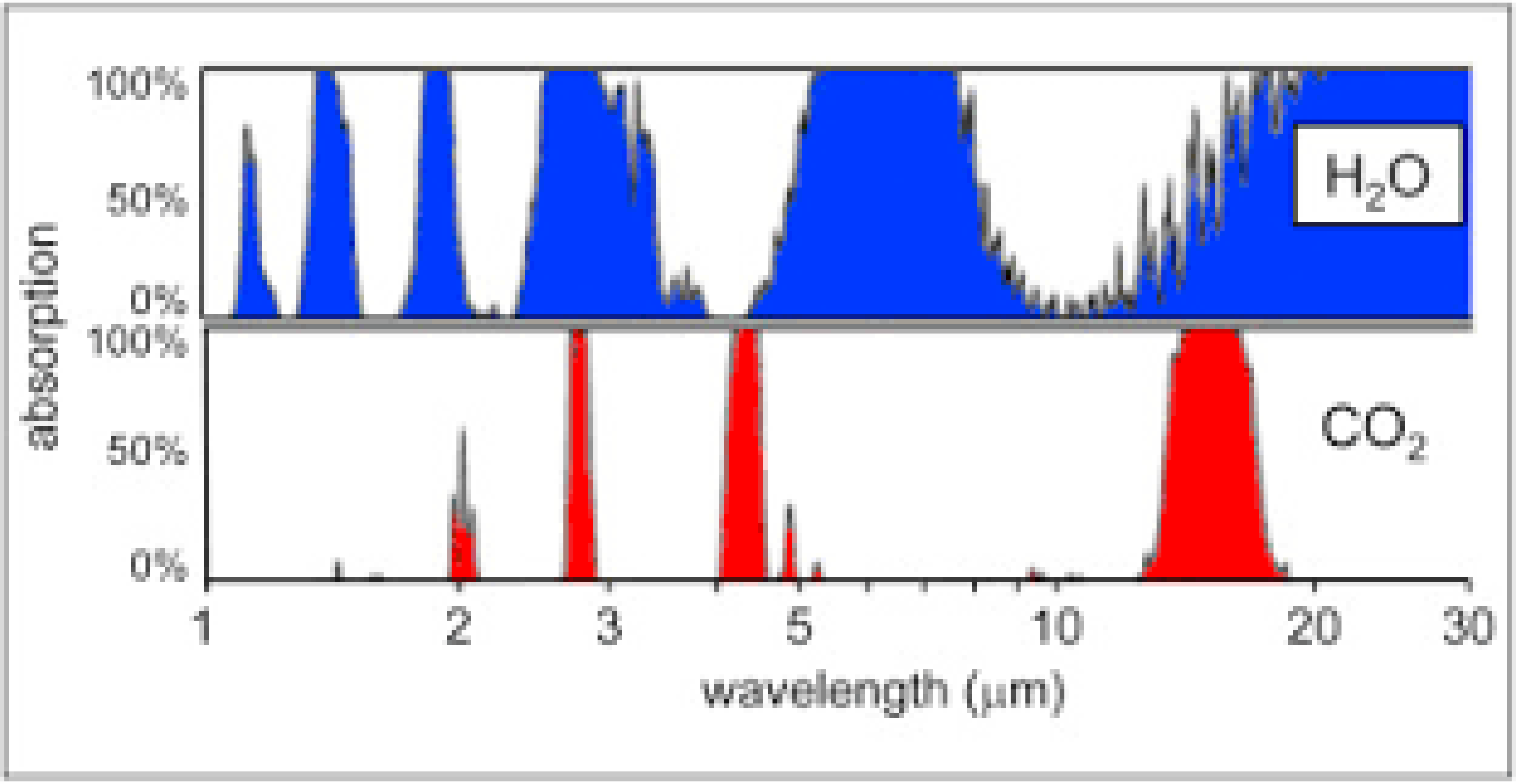
Galvanic

- two-point cal: 0% and 100% saturation
- requires water flow
- uses up the electrolyte and oxidized the anode

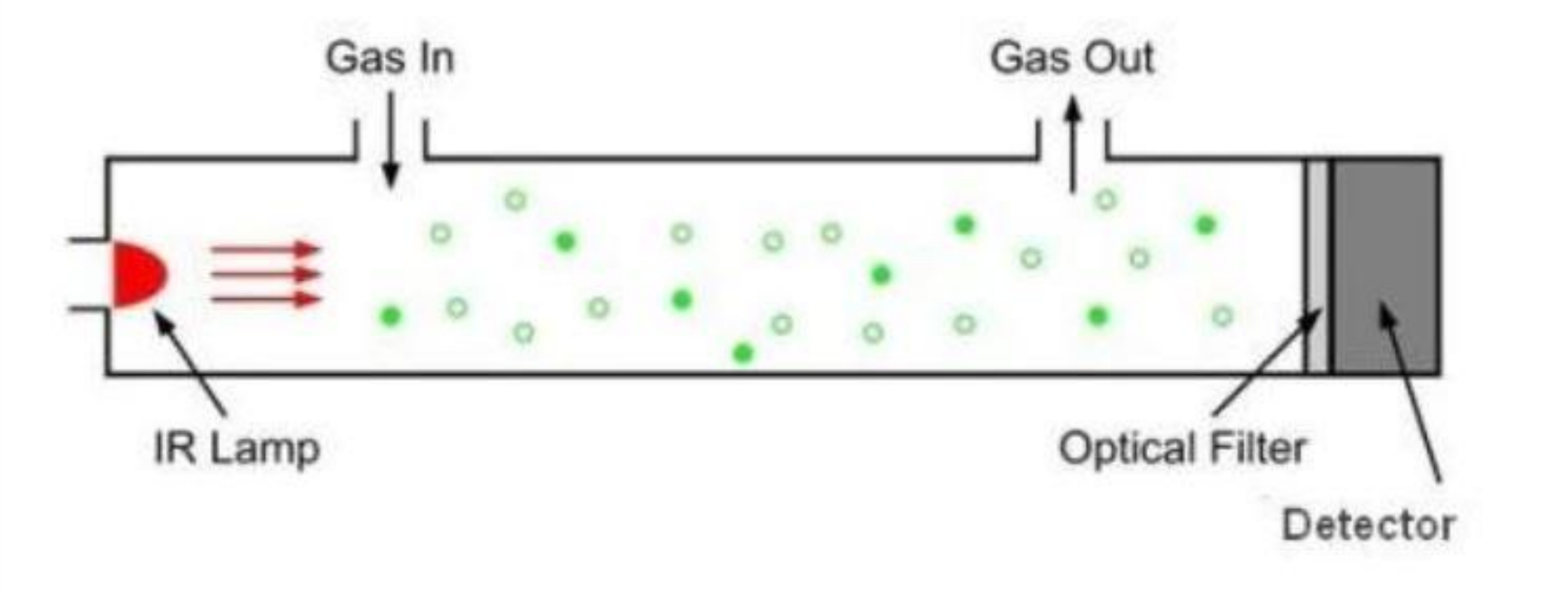
Optical

- one-point cal at 100% saturation
- less maintenance

Carbon Dioxide



Spectral absorbion peak at 4.26um



- The voltage at the light detector is inversely proportional to gas concentration
- Utilize dual paths for prevention sensor drift
- Two-point calibration

Interesting area for DIY

- Many low-cost CO2 sensors on the market
- They can measure dissolved CO2 in water that has diffused through a hydrophobic membrane into a “headspace”.
- Low accuracy – it’s a function of pathlength and emitter/detector bandwidth. But improving.
- Issues with water vapor in the headspace.