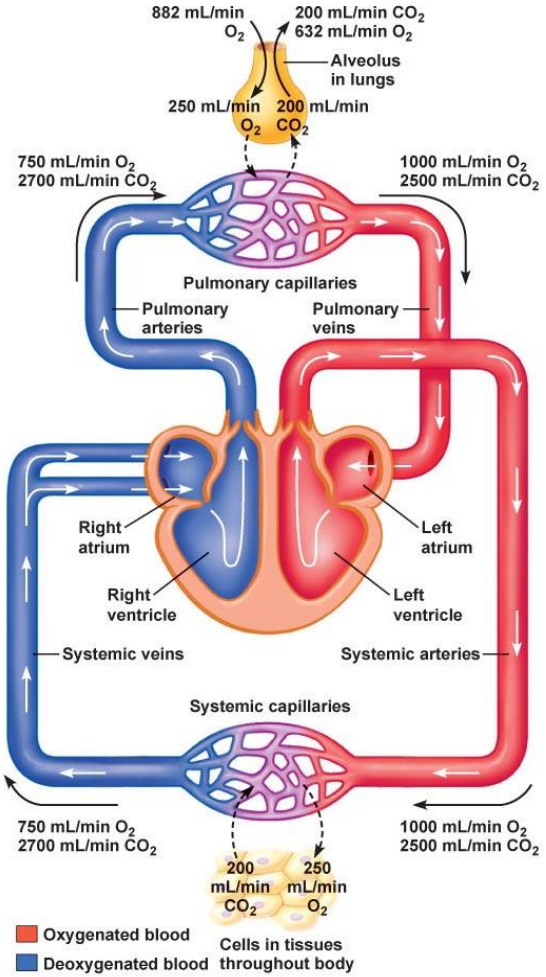
Biomedical Sensors

5.Pulse Oximetry

Reminder: O_2 Transportation

- **Oxygen** in the atmosphere is brought into the lungs by breathing .
- Oxygen generally binds to **hemoglobin (Hb)** in red blood cells when moving through the lungs.
- It is transported throughout the body as arterial blood.
- It carries oxygen from the lung to the tissues where it releases the oxygen to burn nutrients to **provide energy**.



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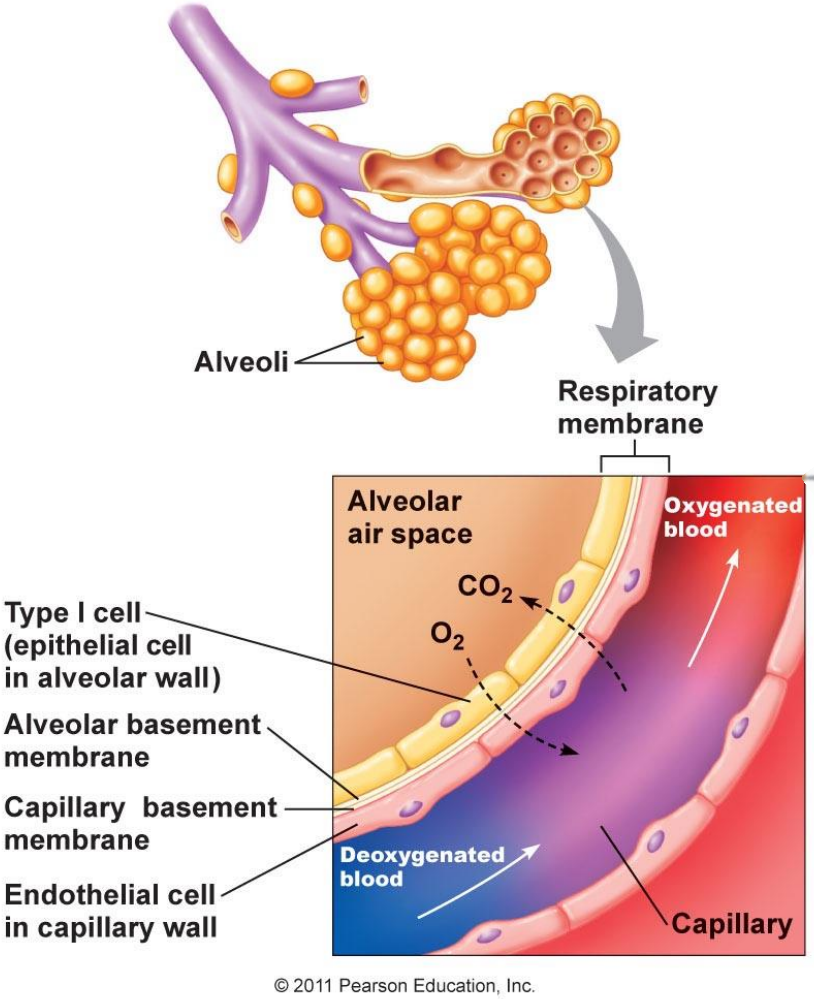
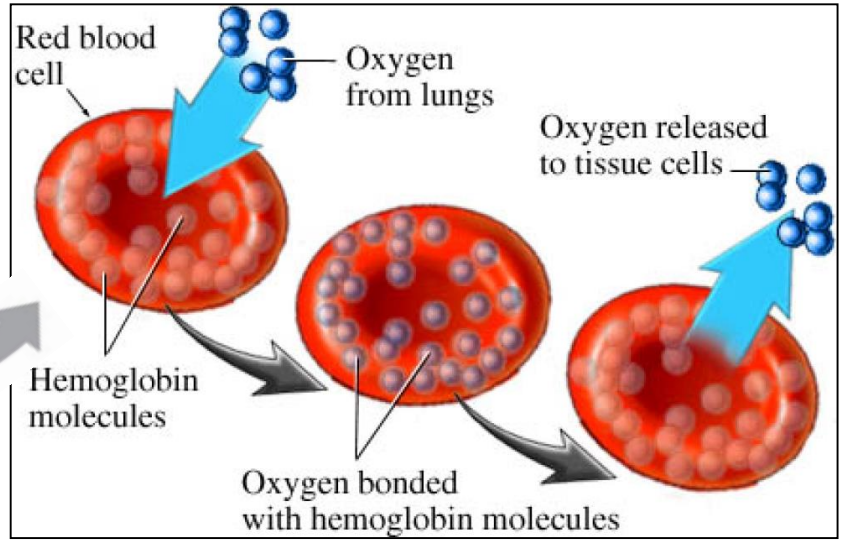
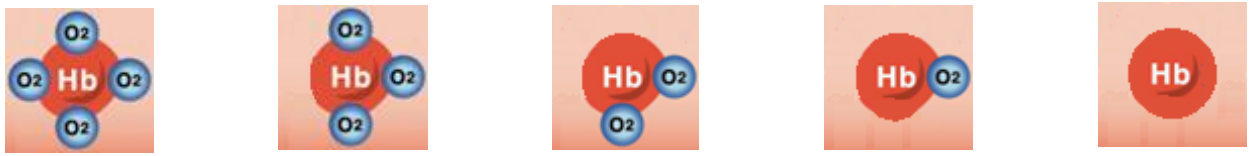
O_2 Transportation

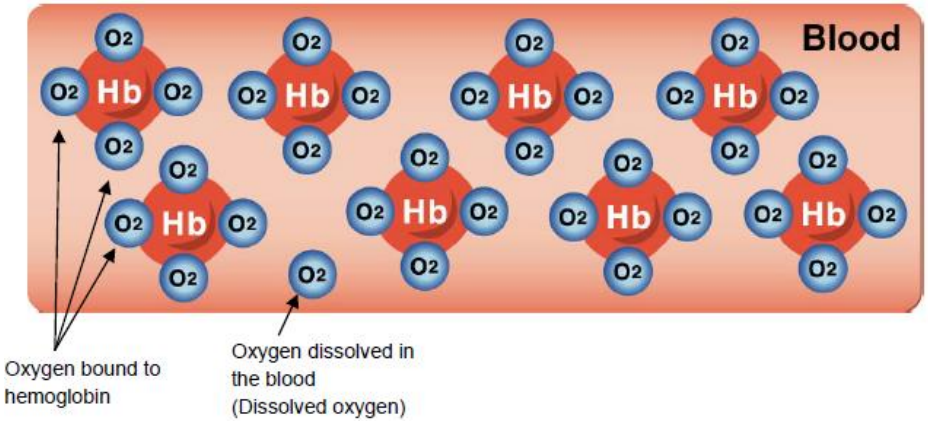




Oxygen contained in 100 ml of blood (20.7 ml)
= Dissolved oxygen (0.3 ml) without Hb
+ Hb-bound oxygen (20.4 ml)

What is an Oximeter?





C_{HbO_2} : concentration of oxyhaemoglobin
C_{Hb} : concentration of deoxyhaemoglobin
without O2

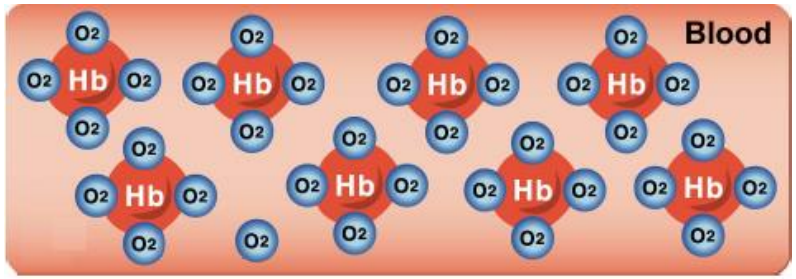
$$SpO_2 = \frac{C_{HbO_2}}{C_{HbO_2} + C_{Hb}}$$

An **oximeter** determines the percentage (%) of hemoglobin in the blood that is saturated with oxygen. The percentage is called blood oxygen saturation, or SpO_2.

Quiz: Blood Oxygen Saturation

What is the SpO_2 in the figures below?

a)

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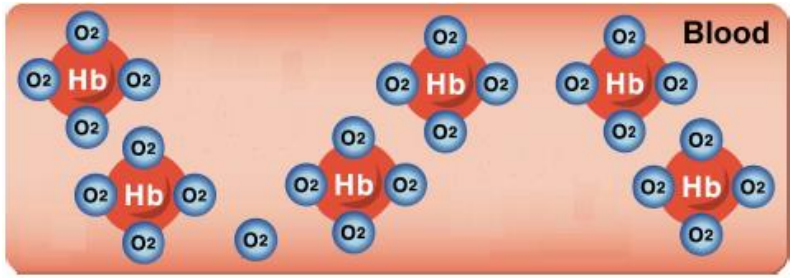
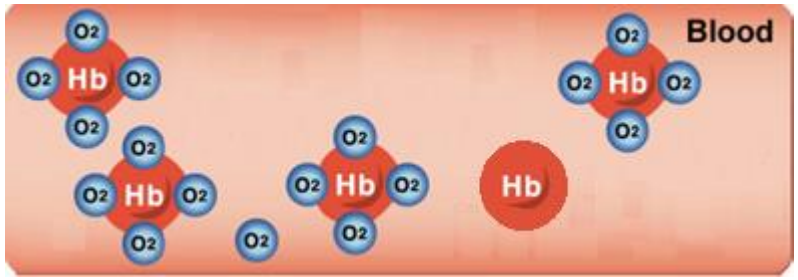
SPO2 = C_hbo2/(C_hbo2+C_hb))
= 1 --> 100%
```

b)




```
100%
```

c)




```
SPO2 = 4/(4+1) =4/5 = 0.8 --> 80%
```

Partial Pressure of Gases

- The partial pressure of a gas is the **proportion of pressure** contributed by an individual gas to the total pressure of a mixture of gases

$$n = mole\,number \cong n_{N_2} + n_{O_2} + n_{CO_2}$$

$$P_{air} = \frac{RT}{V} n \cong \underbrace{\frac{RT}{V} n_{N_2}}_{P_{N_2}} + \underbrace{\frac{RT}{V} n_{O_2}}_{P_{O_2}} + \underbrace{\frac{RT}{V} n_{CO_2}}_{P_{CO_2}}$$

$$P_{N_2} = P_{air} \frac{n_{N_2}}{n};\; P_{O_2} = P_{air} \frac{n_{O_2}}{n};\; P_{CO_2} = P_{air} \frac{n_{CO_2}}{n}$$

$$P_{N_2} = 760\,mmHg \cdot 0.79 \cong 600\,mmHg$$

$$P_{O_2} = 760\,mmHg \cdot 0.21 \cong 160\,mmHg$$

$$P_{CO_2} = 760\,mmHg \cdot 0.0004 \cong 0.3\,mmHg$$

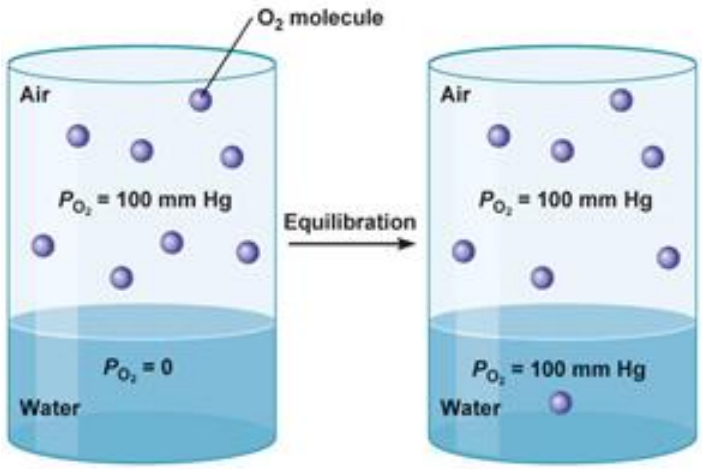
http://droualb.faculty.mjc.edu/Course%20Materials/Physiology%20101/Chapter%20Notes/Fall%202011/chapter_17%20Fall%202011.htm

Partial Pressure of Liquids

- The concentration of a solute gas in a solution is directly proportional to the **partial pressure** of that gas above the solution.

- When a liquid and gas come into contact, the concentration of gas molecules in the liquid is **proportional** to the partial pressure of the gas

- **Henry's law** : $c = k \cdot P$



$c = Molar\ concentration\ of\ gas$

$k = Henry's\ law\ constant\ (gas\ and\ T\ dependant)$

$P = Partial\ pressure\ of\ gas$

Gas Exchange in the Lungs

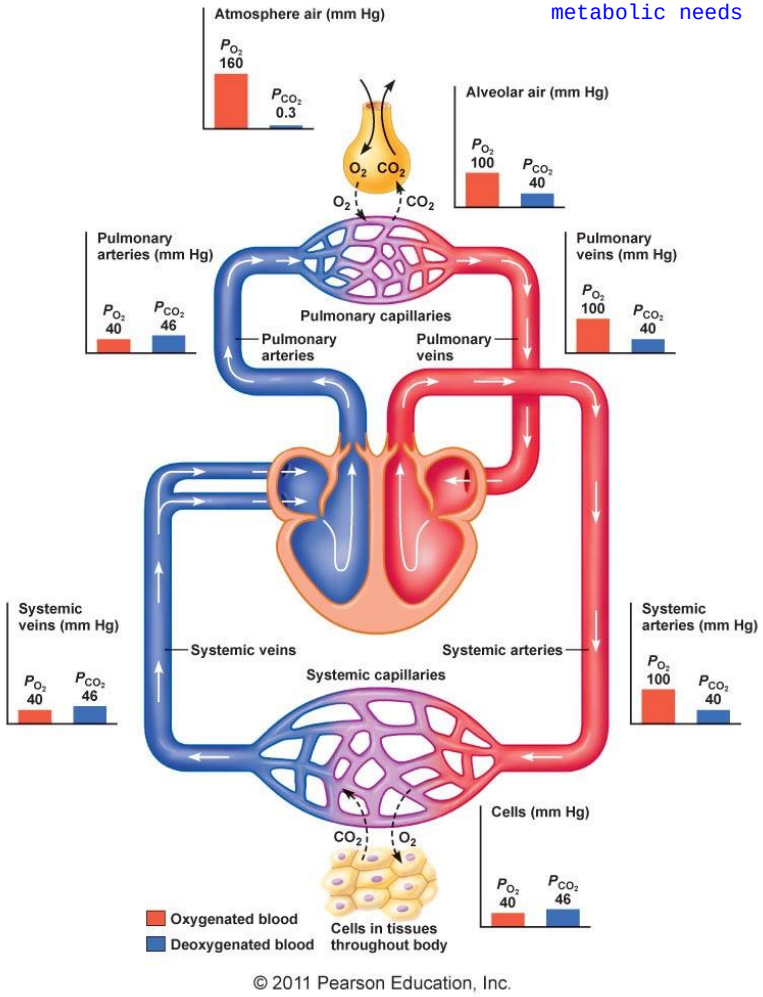
depends also on the metabolic needs

- Gases will diffuse down their **partial pressure gradients**

- Alveolar air is only partially replaced by atmospheric air with each breath:

$$P_{O_2\ alveolar} < P_{O_2\ atmosphere}$$

$$P_{CO_2\ alveolar} > P_{CO_2\ atmosphere}$$

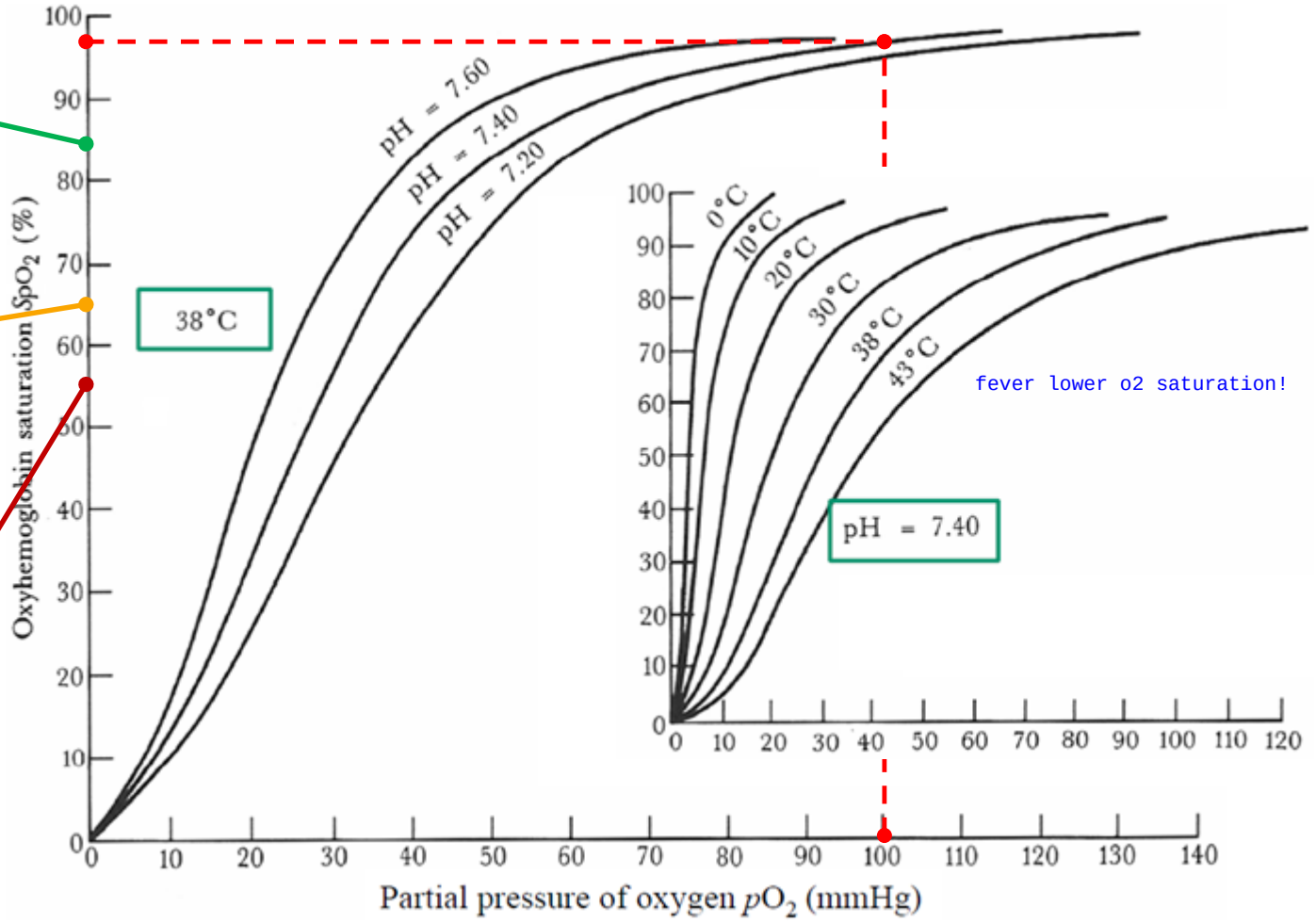


Standard Oxygen Dissociation Curve

>85%
No evidence of impairment

<65%
Impaired mental function on average

<55%
Loss of consciousness on average



Exercise 5.1

1) For an adult with a SpO_2 at 100%, an estimated blood supplies of 5l/min. What is the amount of O_2 supplied to the tissues in ml O_2/min.

2) Knowing that the tissues need an average of 250 ml O_2/min, what is the percentage of O_2 used? What is the vein oxygen saturation? And the corresponding partial pressure? ablesen aus graph

3) What is the effect of altitude on the SpO_2?

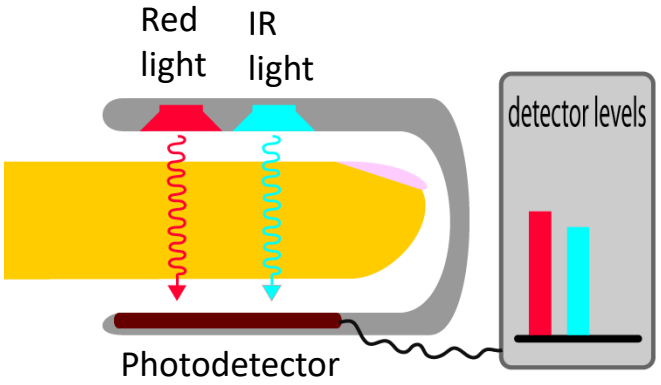
Blood Oximeter Principle

A pulse oximeter relies on the **light absorption** characteristics

Two unknown parameters:

- C_{HbO2} :concentration of oxyhaemoglobin
- C_{Hb} :concentration of deoxyhaemoglobin

$$SpO_2 = \frac{C_{HbO_2}}{C_{HbO_2} + C_{Hb}}$$

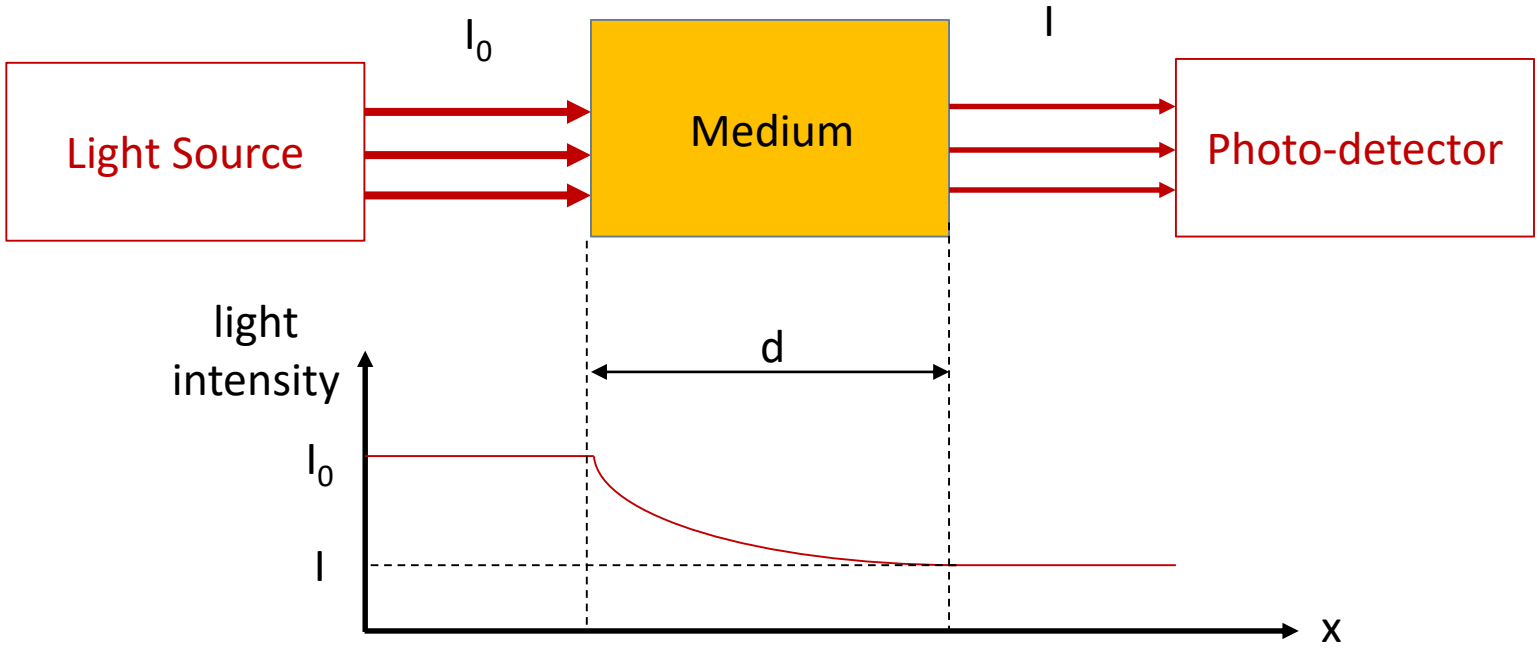


Two equations are required.

- Two wavelengths are used to measure absorption at two wavelength points and calculate outcome as oxygen saturation, i.e. SpO_2.

Reminder: Beer–Lambert Law

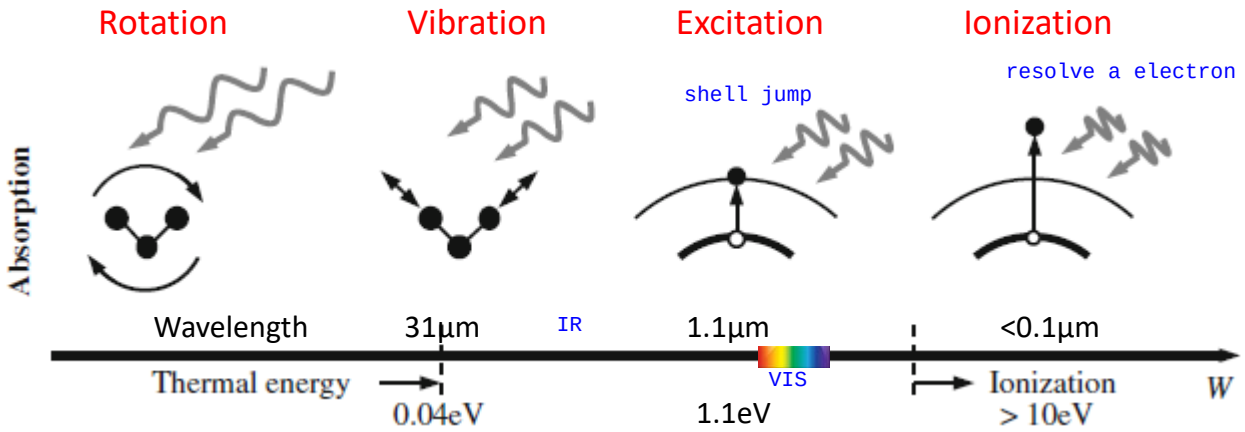
- Beer–Lambert law: the light intensity decreases logarithmically with path length (d) in the medium.



$$I = I_0 \cdot e^{-\varepsilon(\lambda)\cdot C\cdot d}$$

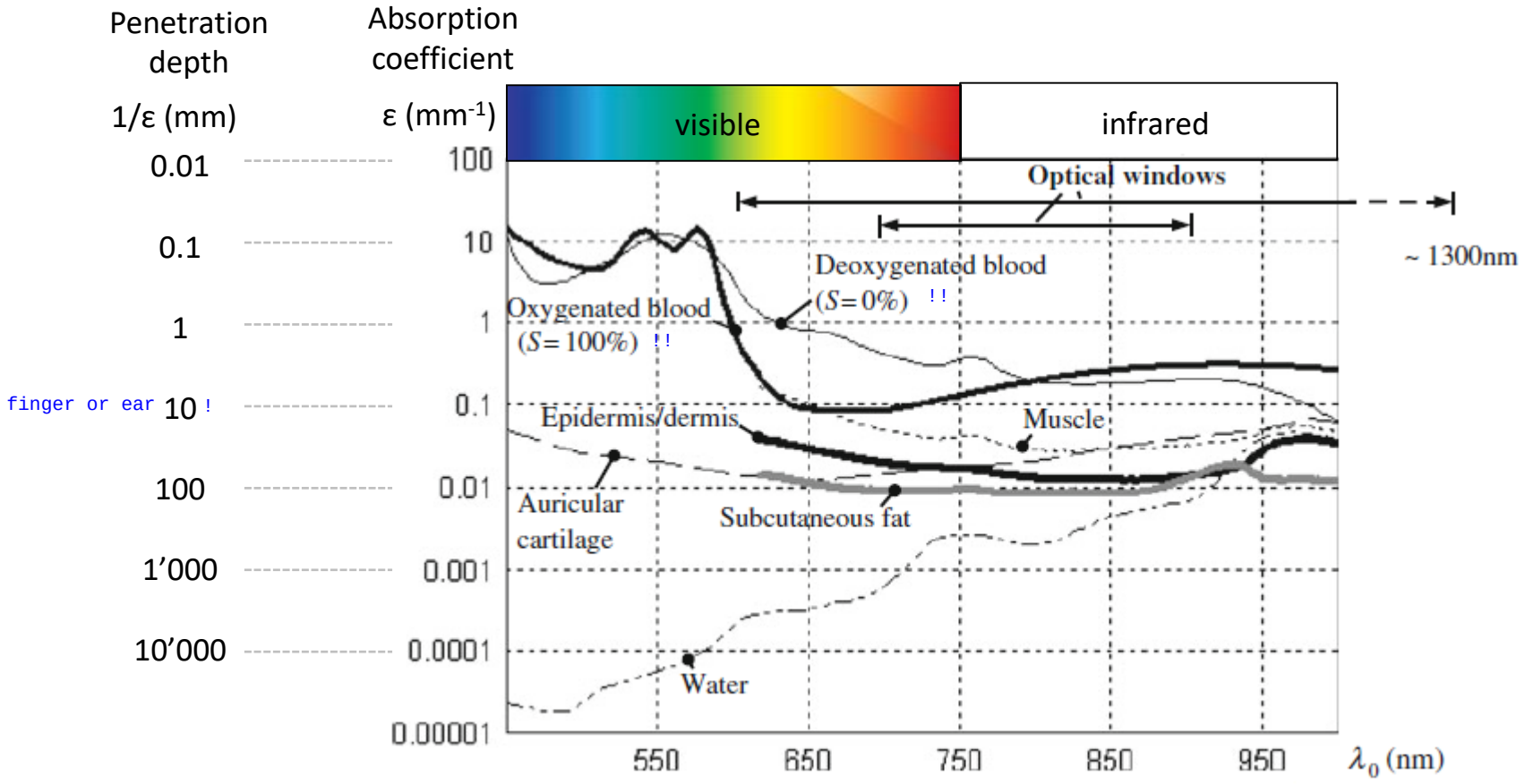
ε: absorption coefficient
λ: wavelength
C: concentration
d: path length

Light Absorption for biological media



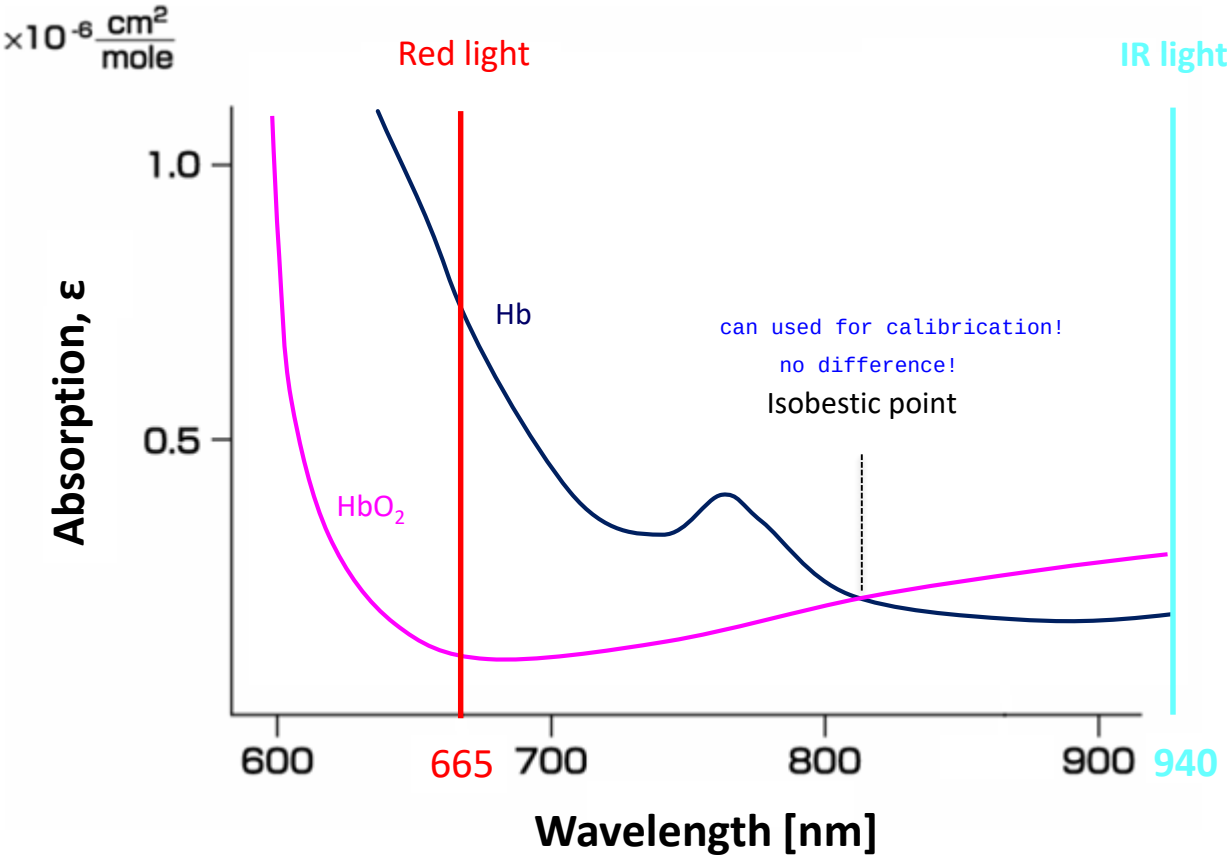
Propagation medium	Index of refraction n for 633 nm	Absorption coefficient ε (mm^{-1}) for 800 nm
Skin (epidermis and dermis)	1.38	1.2×10^{-2}
Skin (subcutaneous fat)	1.45	8.2×10^{-3}
Muscle	1.37	2.8×10^{-2} proportion because also blood in!
Tissue	1.36	10^{-2} proportion because also blood in!
Blood	1.38	0.2 high!!
Bones	1.55	2×10^{-2}
Water (pure)	1.33	2×10^{-3}

Light Absorption for biological media

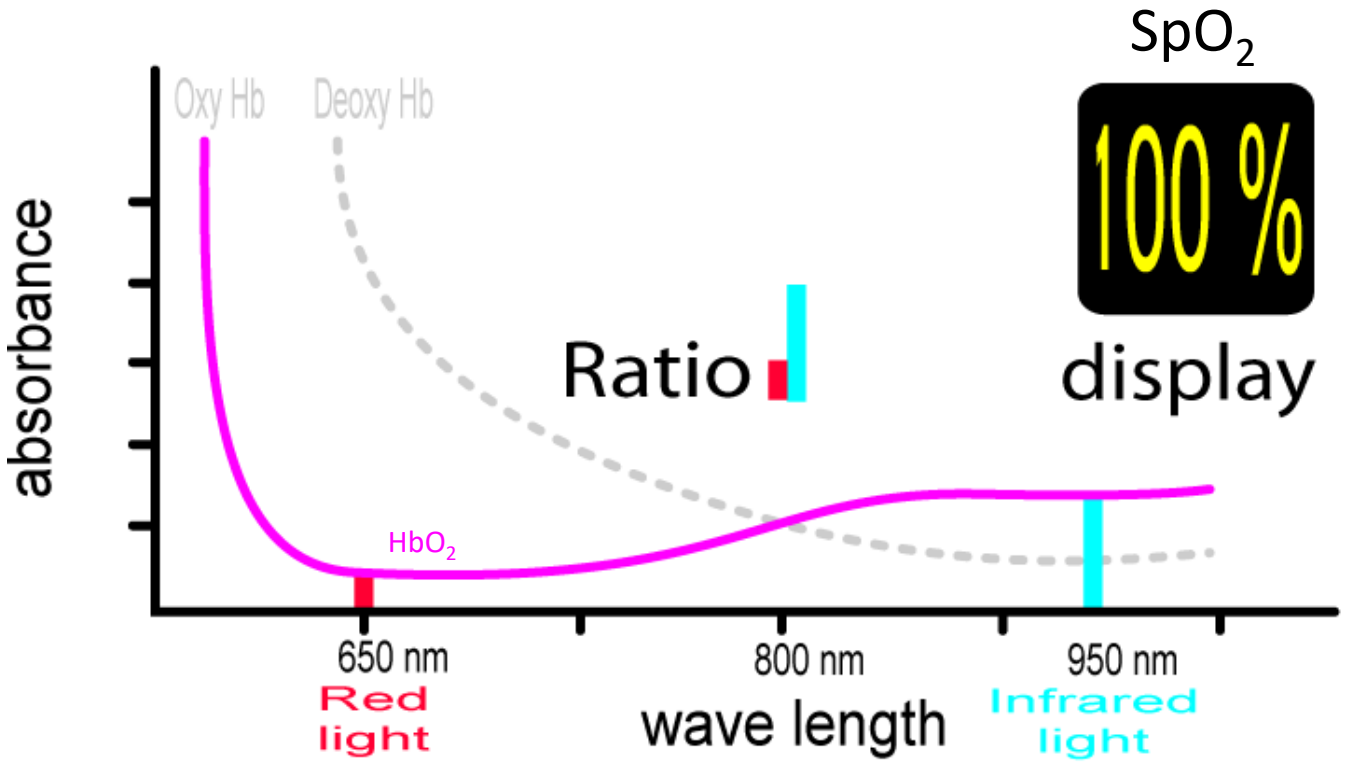


Absorption Spectra of Hb and HbO_2

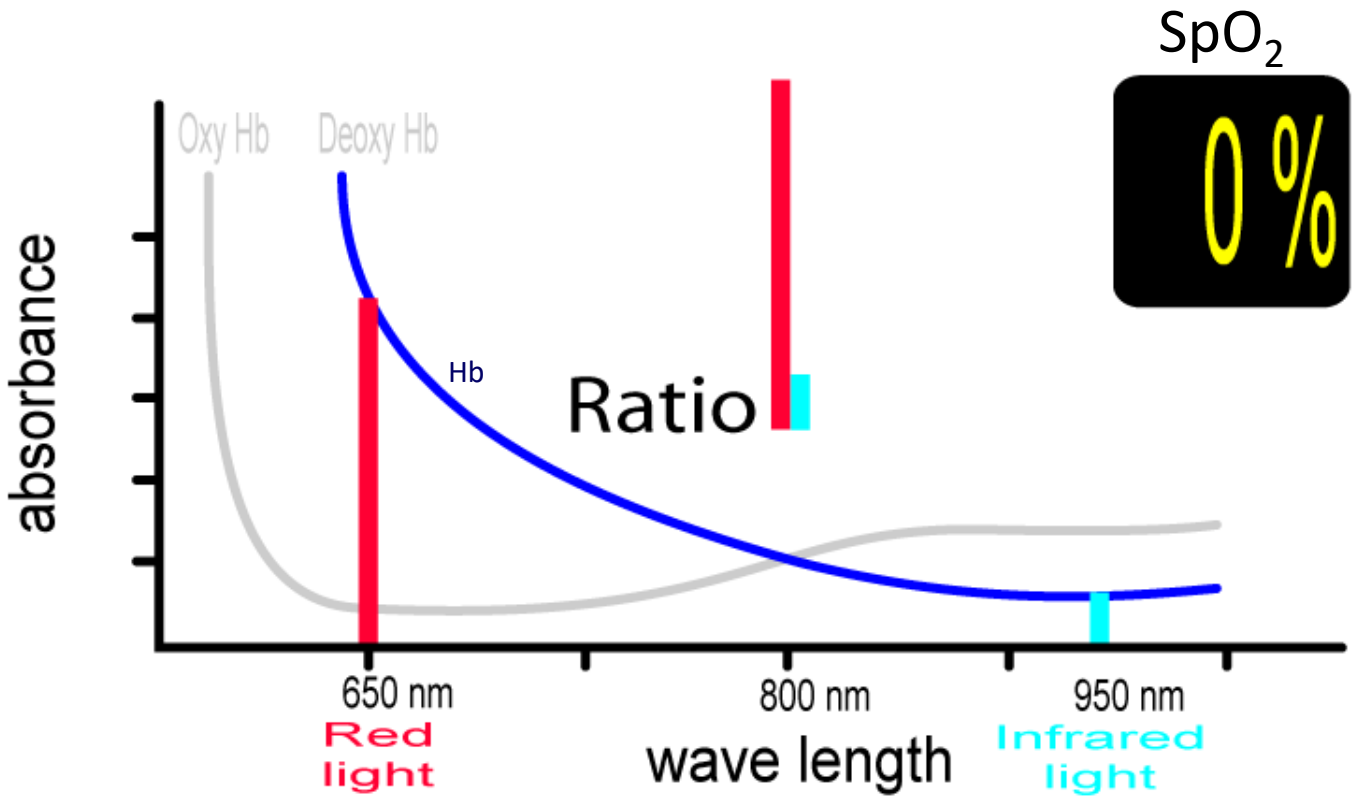
- Haemoglobin (Hb) and oxygenated haemoglobin (HbO_2) differ in their absorption of red and infrared light.



How does the curve for 100% SpO_2 looks like?

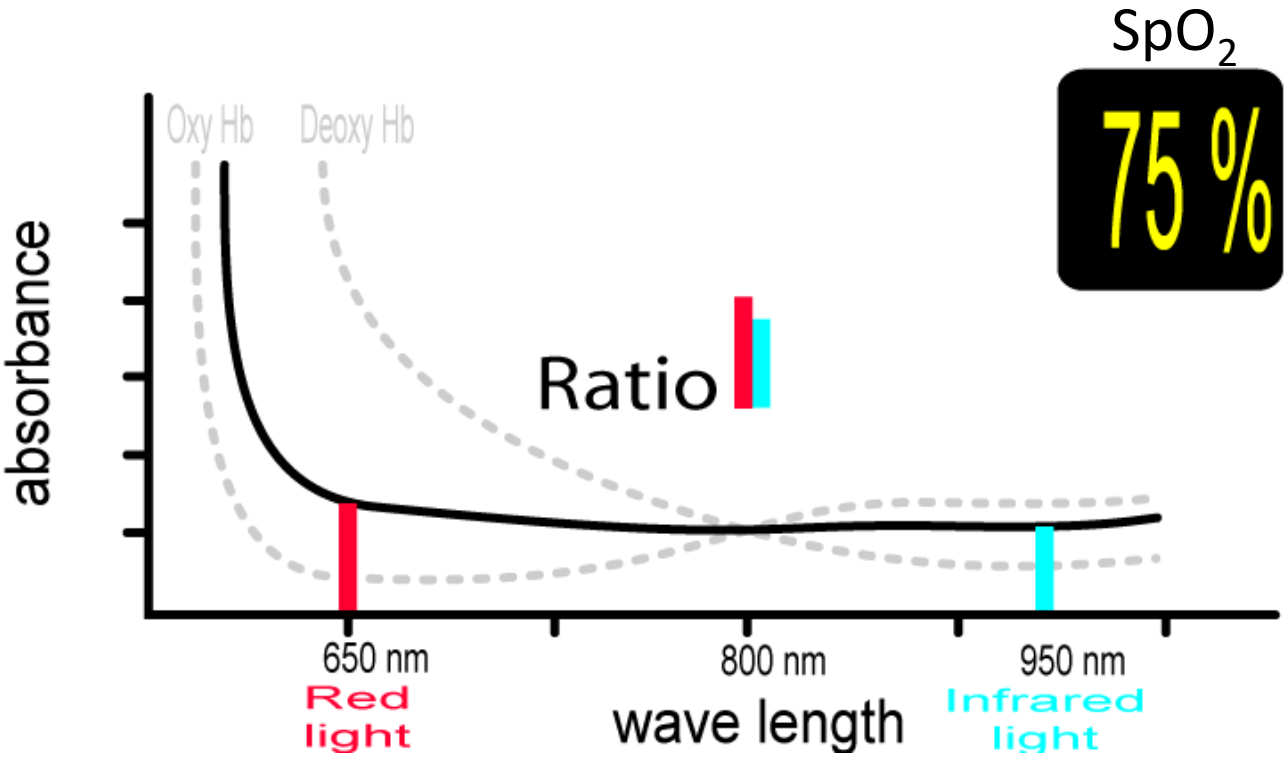


How does the curve for 0% SpO_2 looks like?



…and in-between…

- Blood has both , oxy Hb and deoxy Hb.



- The absorbance pattern is now somewhere in between the oxy Hb curve and deoxy Hb curve

Does it work well?

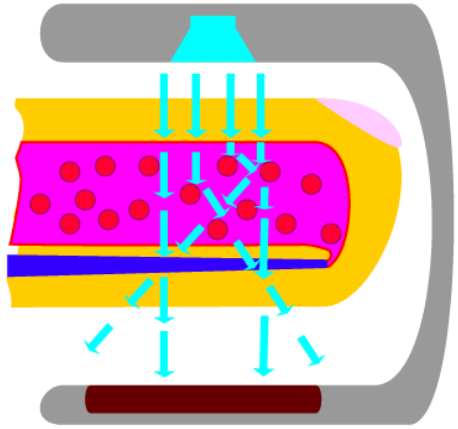
No!

- **Light scattering** is a problem! Therefore Beer and Lamberts Law cannot be applied strictly.

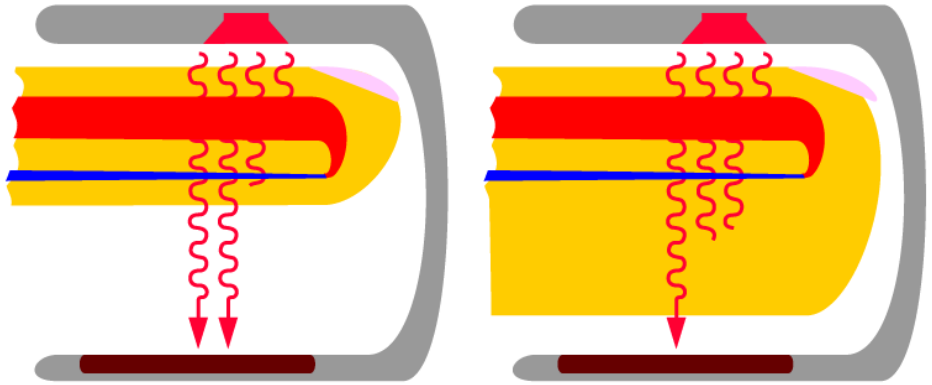
- **Thin finger or fat finger.** The tissues in the thin finger absorbs only a little extra light, while the fatter finger shown on the right absorbs much more light.

Saturation

- Measured SpO_2 is an average value in arteries and in veins circulation.

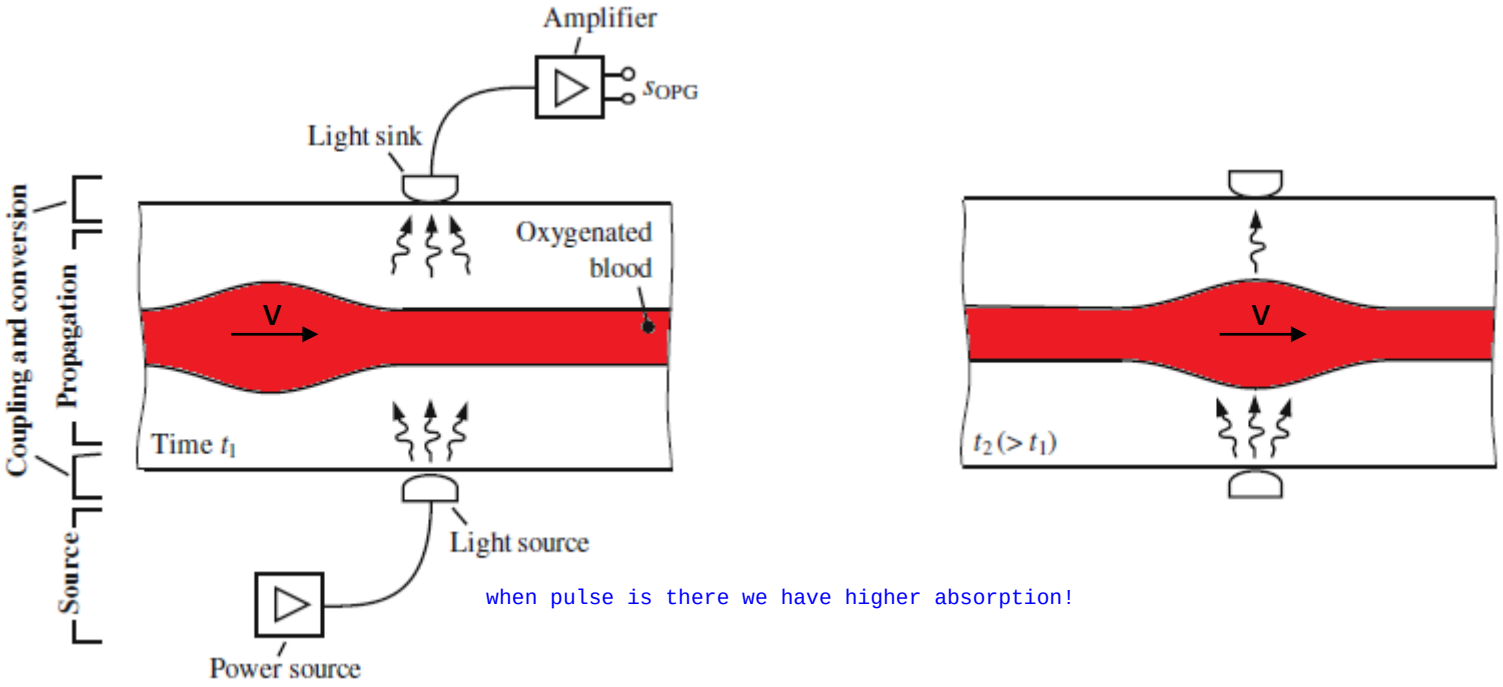


way is lenghten up to 5x!



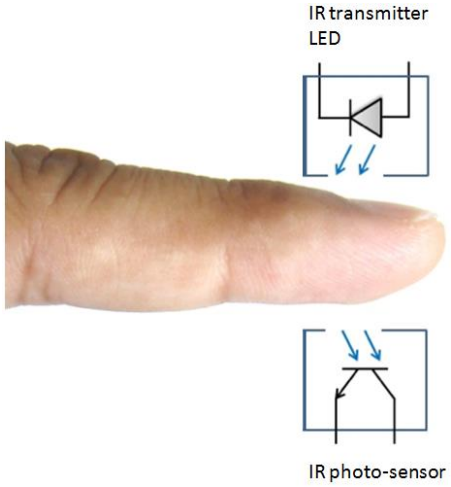
Pulse Propagation in Vessel

- induced optical biosignal:

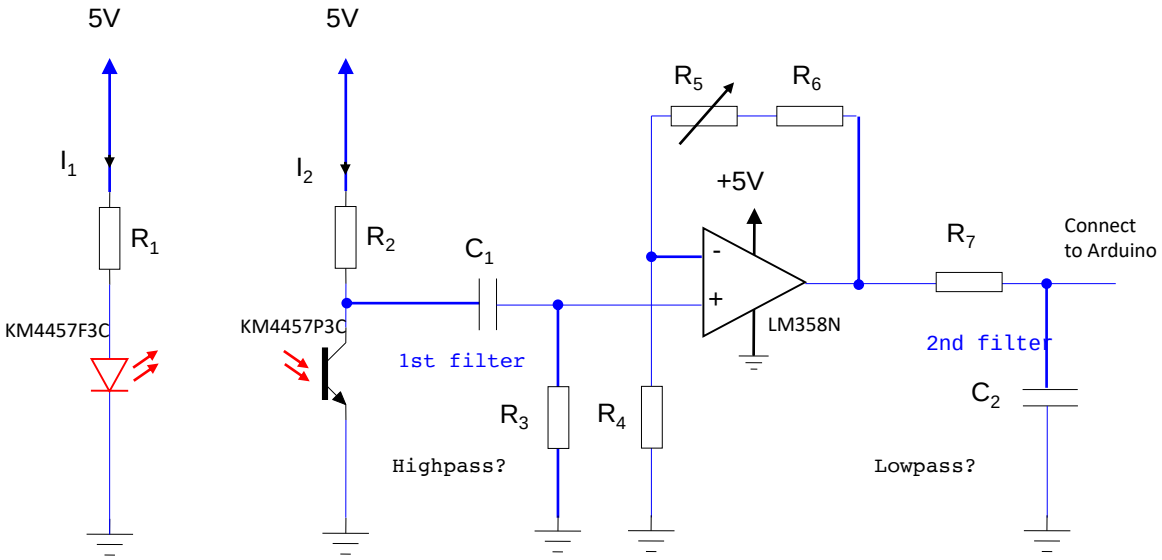


when pulse is there we have higher absorption!

Demo: Photoplethysmogram

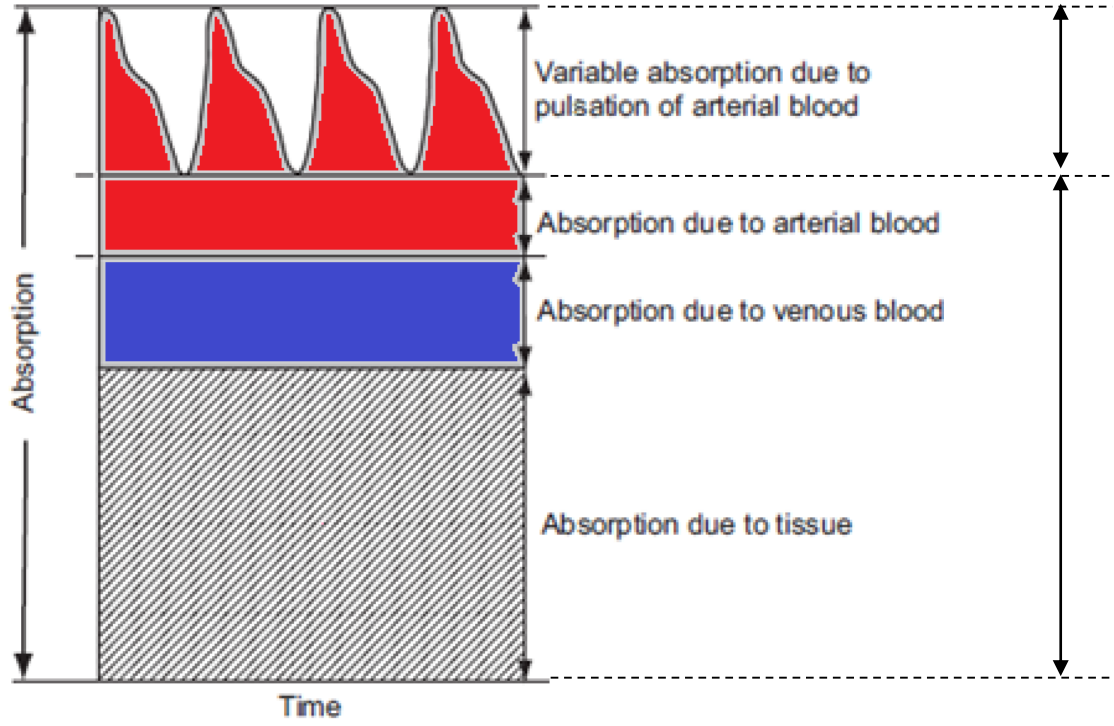


easy circuit



Different Approach: Pulse Oximetry

- Measurement of the change in light transmission through the skin that occurs as a result of arterial pulsation

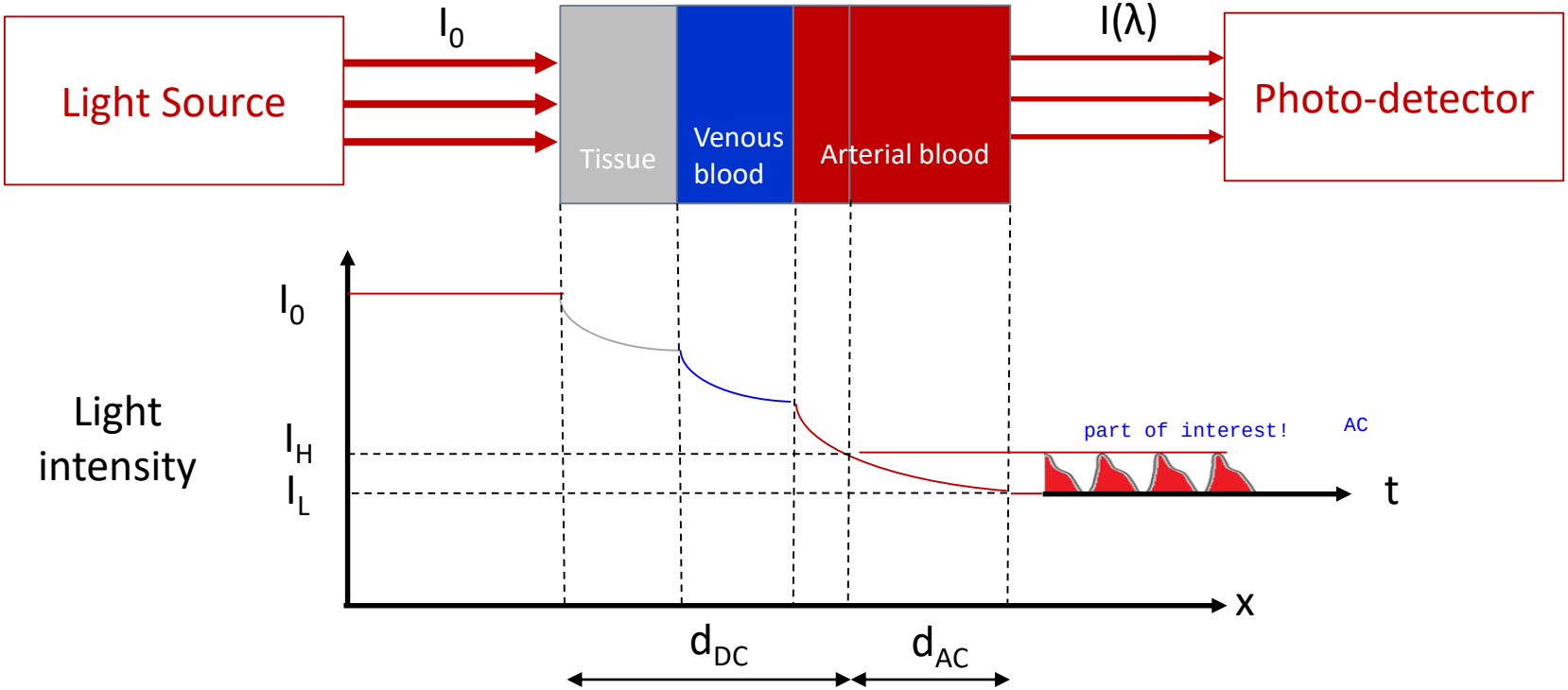


AC (≈1-2%)

we want to filter!

DC (≈98-99%)

Beer–Lambert Law in Blood Vessel



$$I(\lambda) = I_H(\lambda) \cdot e^{-(\varepsilon_{Hb}(\lambda)\cdot C_{Hb} + \varepsilon_{HbO_2}(\lambda)\cdot C_{HbO_2})\cdot d_{AC}}$$

ε_{HbO2}: absorption coefficient of HbO_2
ε_{Hb}: absorption coefficient of Hb
C_{HbO2}: concentration of reduced Haemoglobin (Hb)
C_{Hb}: concentration of reduced Haemoglobin (HbO_2)

I = Intensities!

$$A = \ln\left(\frac{I_L}{I_H}\right) = \left(\varepsilon_{HHb} \cdot c_{HHb} + \varepsilon_{HHbO_2} \cdot c_{HHbO_2}\right) d_{AC}$$

$$SpO_2 = \frac{c_{HHbO_2}}{c_{HHbO_2} + c_{HHb}} \rightarrow \begin{cases} c_{HHbO_2} = SpO_2 \left(c_{HHbO_2} + c_{HHb}\right) \\ c_{HHb} = \left(1 - SpO_2\right)\left(c_{HHbO_2} + c_{HHb}\right) \end{cases}$$

$$A = \ln\left(\frac{I_L}{I_H}\right) = \left(\varepsilon_{HHb}\left(1 - SpO_2\right) + \varepsilon_{HHbO_2} \cdot SpO_2\right)\left(c_{HHbO_2} + c_{HHb}\right) \cdot d_{AC}$$

$$= \left(\varepsilon_{HHb} + \left(\varepsilon_{HHbO_2} - \varepsilon_{HHb}\right) \cdot SpO_2\right)\left(c_{HHbO_2} + c_{HHb}\right) \cdot d_{AC}$$

ratio of absorption

$$R = \frac{A(\lambda_1)}{A(\lambda_2)} = \frac{\varepsilon_{HHb}(\lambda_1) + \left(\varepsilon_{HHbO_2}(\lambda_1) - \varepsilon_{HHb}(\lambda_1)\right) SpO_2}{\varepsilon_{HHb}(\lambda_2) + \left(\varepsilon_{HHbO_2}(\lambda_2) - \varepsilon_{HHb}(\lambda_2)\right) SpO_2}$$

R we measure!

$$SpO_2 = \frac{\varepsilon_{HHb}(\lambda_2) R - \varepsilon_{HHb}(\lambda_1)}{\left(\varepsilon_{HHb}(\lambda_2) - \varepsilon_{HHbO_2}(\lambda_2)\right) R - \left(\varepsilon_{HHb}(\lambda_1) - \varepsilon_{HHbO_2}(\lambda_2)\right)}$$

Beer–Lambert Law in Blood Vessel

The haemoglobin absorbance can be defined as:

Beer–Lambert Law in Blood Vessel

- Measuring at two different wavelengths we can define the ratio R as:

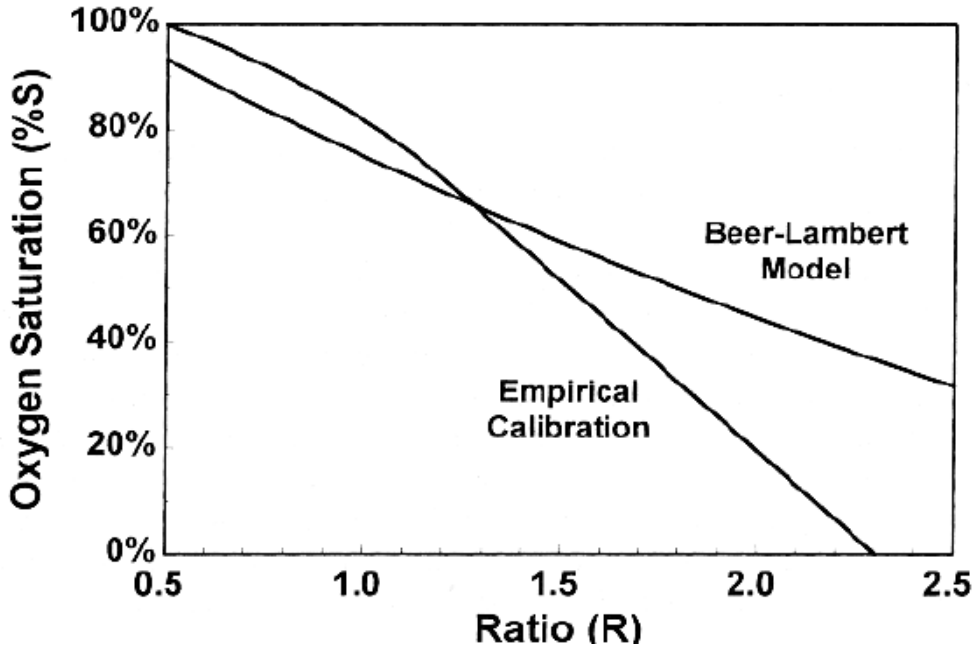
Calibration of Pulse Oximeters

- SpO_2 is usually derived from the empirical equation below. Volunteers are asked to breath lower and lower oxygen concentrations and arterial blood samples are measured

$$SpO_2 = \mathbf{a} - \mathbf{b}R$$

$$\mathbf{a} = \frac{\sum_{i=1}^{n} S_i \sum_{i=1}^{n} R_i^2 - \sum_{i=1}^{n} R_i \sum_{i=1}^{n} R_i S_i}{n\sum_{i=1}^{n} R_i^2 - \left(\sum_{i=1}^{n} R_i\right)^2}$$

$$\mathbf{b} = \frac{n\sum_{i=1}^{n} R_i S_i - \sum_{i=1}^{n} R_i \sum_{i=1}^{n} S_i}{n\sum_{i=1}^{n} R_i^2 - \left(\sum_{i=1}^{n} R_i\right)^2}$$



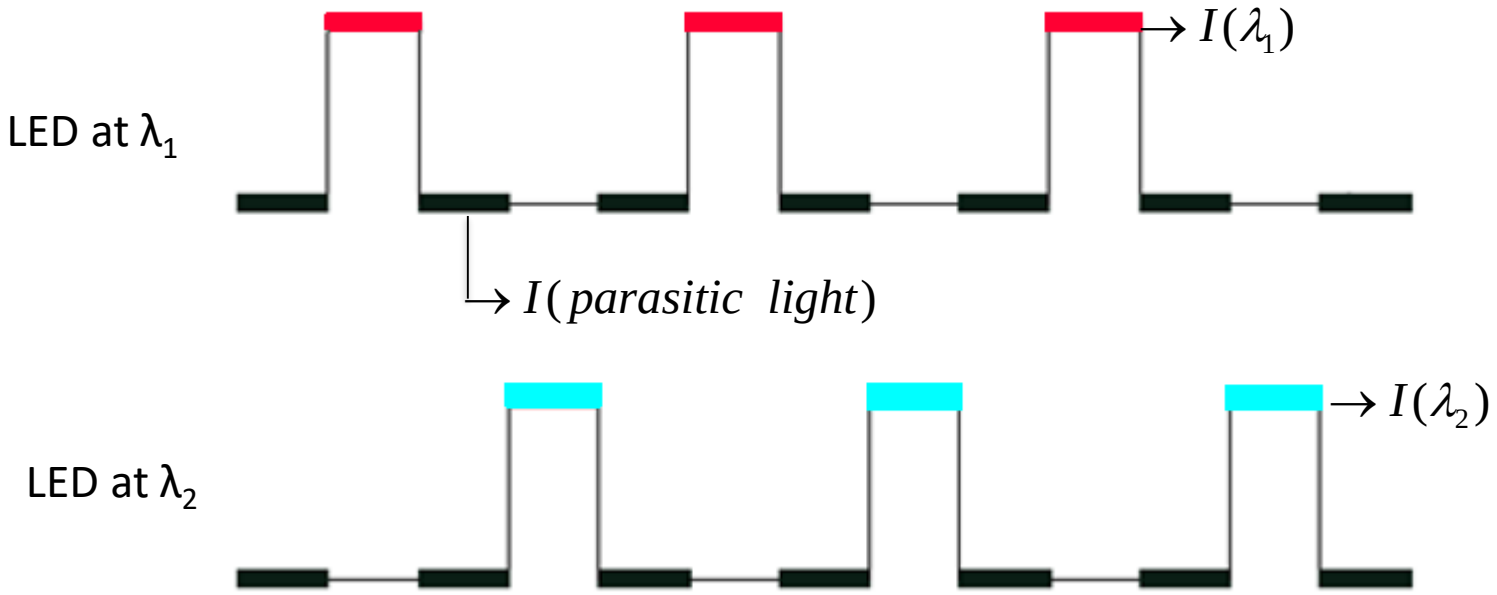
Blood Oximeter Example

- A sensor is placed on a thin part of the patient's body: fingertip or earlobe.

- non-invasive
- continuous measurement

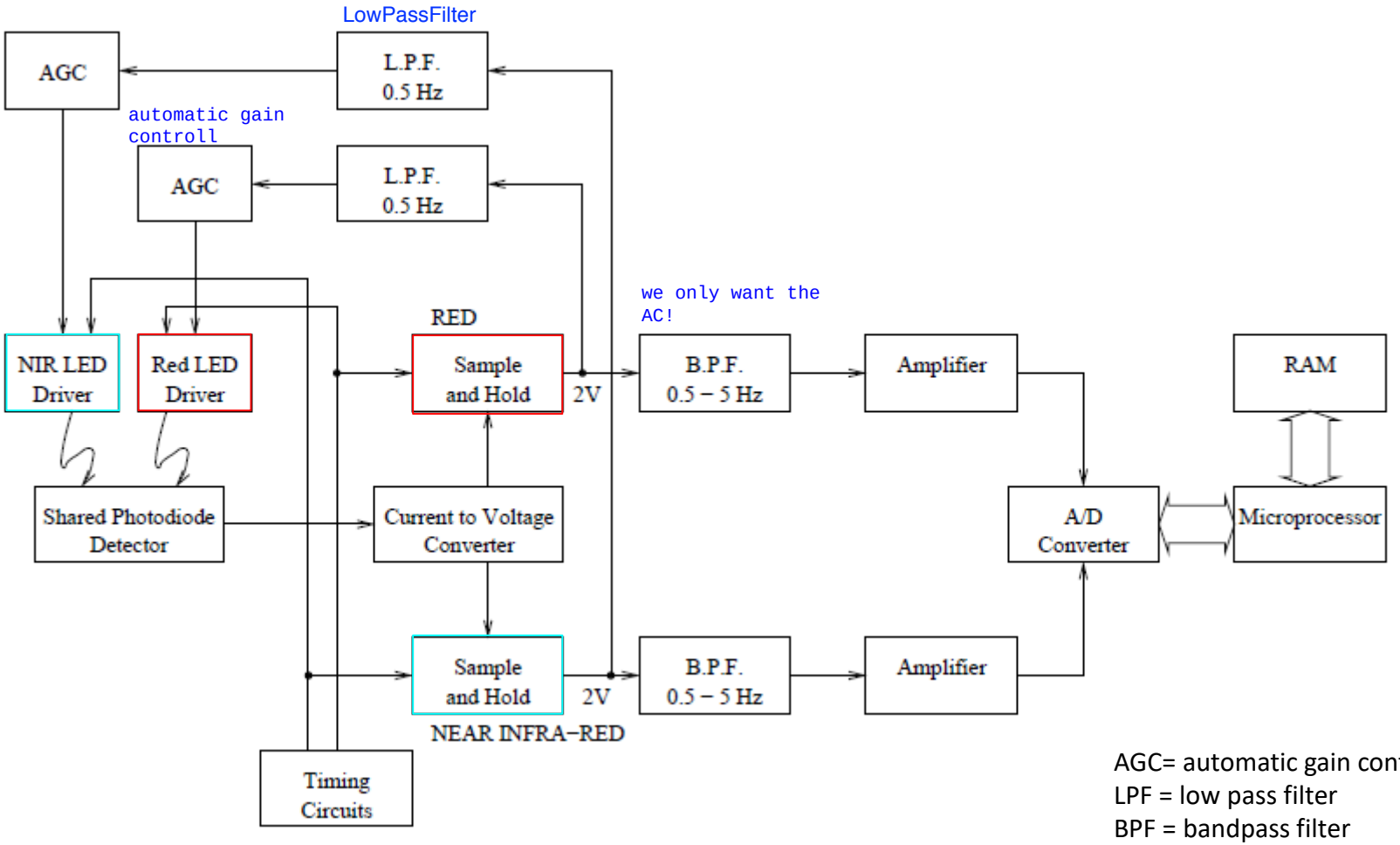
Time Multiplexing

- Both light sources are pulsed to use a single photodetector (photodiode)
- Example of timing signals for the LED drivers:



- LED are turned on and off at a frequency of a few kHz, far more than the cardiac frequency (few Hz)

Block Diagram of a pulse Oximeter



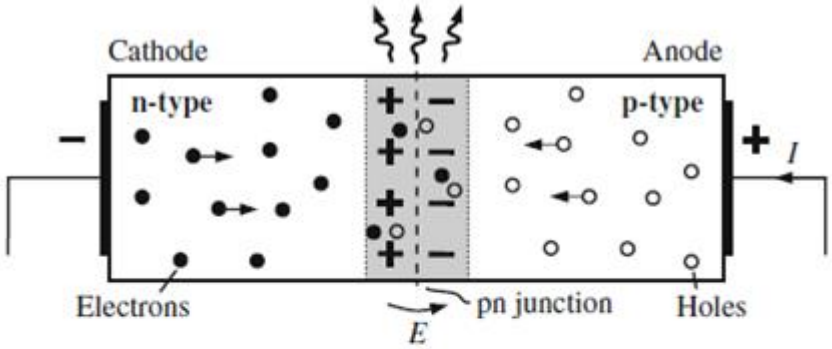
AGC= automatic gain control
LPF = low pass filter
BPF = bandpass filter

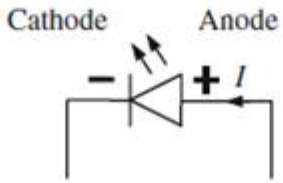
Light Electroluminescent Diode (LED)

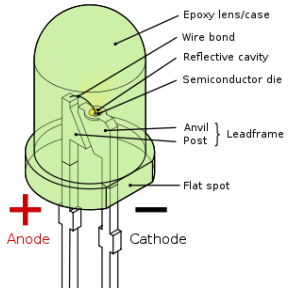
- LEDs are now being manufactured with internal lensing systems to give high intensity outputs.

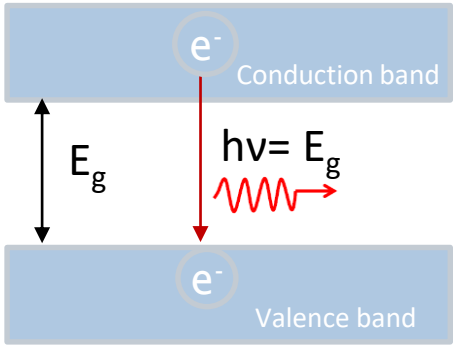
Linsen

but directed!





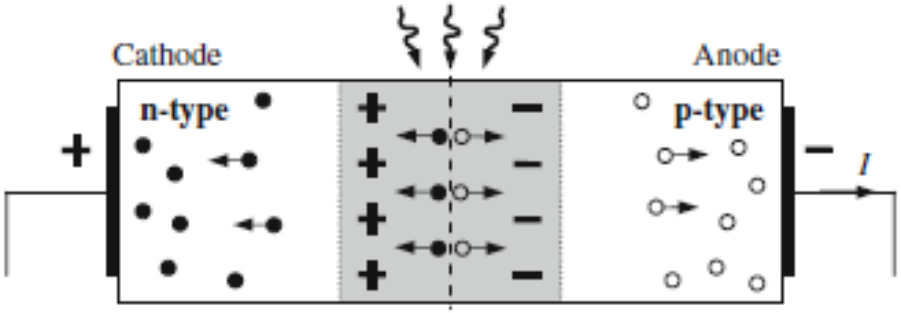


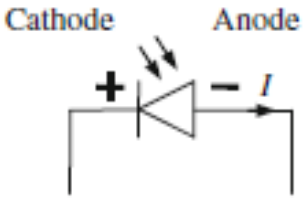


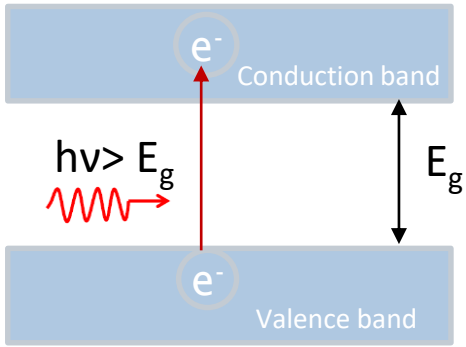
Standardtypen (I_F/I_{LED} = 10 mA)		
Farbe	Halbleiter	U_F/U_{LED}
rot	GaAsP	1,6 V
rot	GaP	2,1 V
orange	GaAsP	1,8 V
grün	GaP	2,1 V
gelb	GaP	2,2 V
blau	GaN	2,9 V

Photodiode

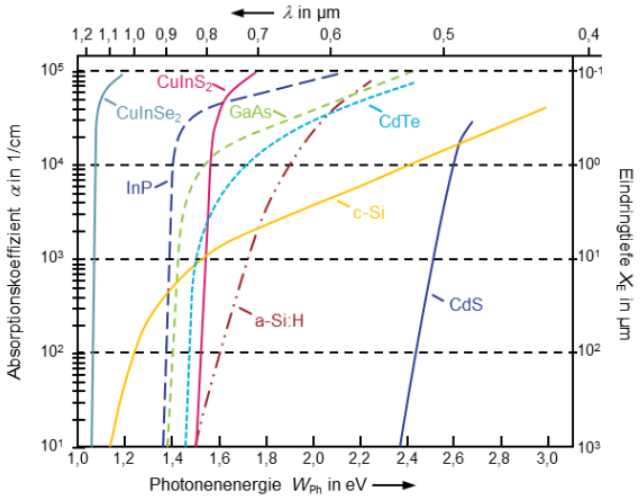
- **p-n junction:** excitations due to photons leads to the formation of electron-hole pairs that get separated at the junction.





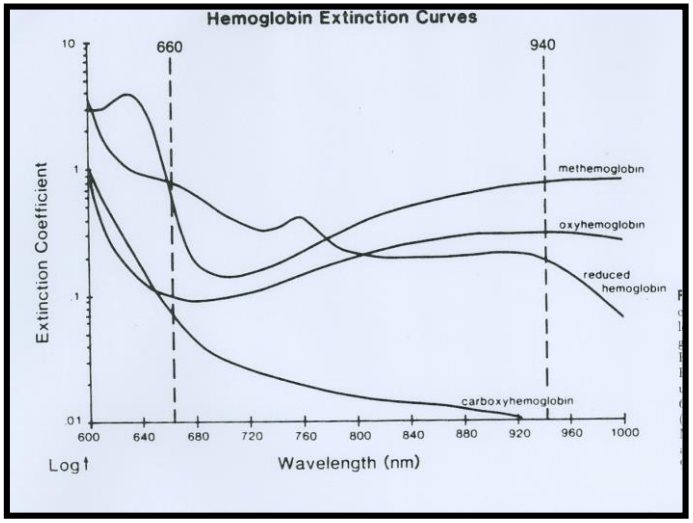


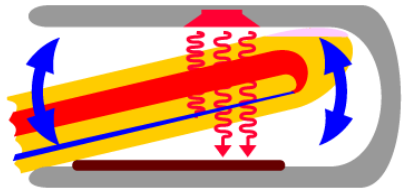
$$\lambda_{limit} = \frac{hc}{E_g}$$

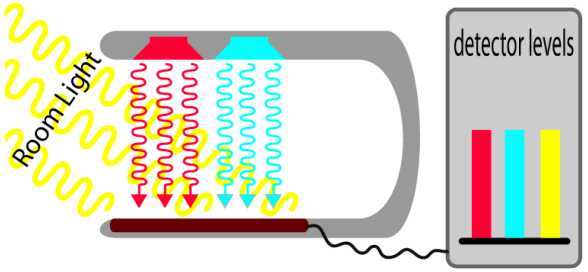


What Factors cause Errors in the pulse Oximeter?

- Abnormal haemoglobin: carboxyhaemoglobin and methaemoglobin
- Medical dyes
- Manicure and pedicure: opaque nail finishes
- Major body motion : Shivering, Parkinsonian tremors
- Blood flow blocked: Caution: blood pressure cuff
- Excessive ambient light
- …







Latest Developments & Summary

Latest Developments:

- Rainbow (several wavelengths) more wavelenght for more information!
- Signal Extraction Technology (SET), contains adaptative noise cancelation technology

Summary:

- Pulse oximetry is **a standard since 1986** in anesthetized patients.
- It measures the arterial saturation of oxygen and ensure that oxygen is adequately transported **to the tissues**.
- Actual devices are mainly based on the measurement of the **pulsatile change** of light absorption

Definitions

Oxygen saturation is an **indicator of** O_2 **transport in the body**, and indicates if sufficient O_2 is being supplied to the body, especially to the lungs.

? heart

Definitions:

- pO_2: partial pressure of dissolved oxygen
- pCO_2: partial pressure of dissolved carbon dioxide

- SaO_2: arterial oxygen saturation
- SpO_2: arterial oxygen saturation (SaO_2) measured by pulsed oximetry

- SvO_2: venous oxygen saturation
- StO_2: tissue oxygen saturation

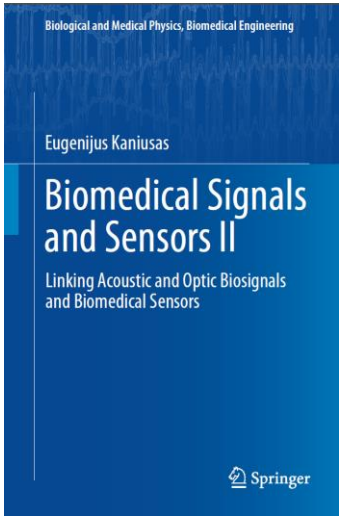
Oximeter Manufacturers

- Masimo
- Covidien (Nellcor)
- Philips (Intellivue)
- GE Healthcare (Ohmeda)
- Smith Medical (Spectro2)
- Konica Minolta (Pulsox)

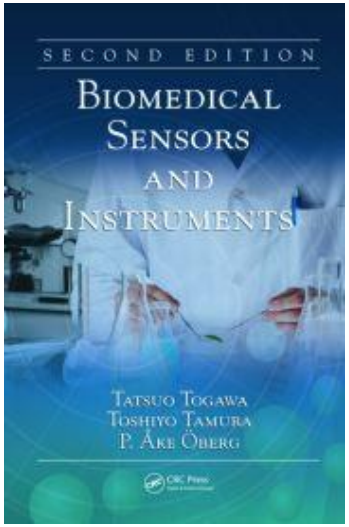
References

Books:

p.237-255



p.91-200



p.378-384

Web:

Basics: http://windward.hawaii.edu/facstaff/miliefsky-m/ZOOL%20142L/aboutPulseOximetry.pdf [accessed April 27, 2017]
Physiology: http://droualb.faculty.mjc.edu/Course%20Materials/Physiology%20101/Chapter%20Notes/Fall%202011/chapter_17%20Fall%202011.htm [accessed April 21, 2017]
Sensor: http://www.howequipmentworks.com/pulse_oximeter/ [accessed April 04, 2015]

Exercise 5.2

- Consider the patent WO 2013/165836 A1 on ilias

1. Does this patent apply to Switzerland, Germany, France, Great Britain, USA, Russia, Japan, China?
2. Describe briefly the main idea of this patent.
3. What is the advantage of this «product»?
4. In Fig 3., what happens at time t_0, t_1 and t_2?
5. On page 6, the text has an error, could you find it?
6. Look at the search report. Is this patent strong or weak?
7. Is this a good patent?