Lecture 1

What, When, Why measure

o) When

- → During design phase
- → During prototyping phase
- → During production Engineering
- → While bringing new equipment/system into service
- → Operating installations
- → Maintaining installations

o) What

→ We measure all and only the parameters that are indispensable to reach the goal

Remember: it costs

o) In Telecommunications

→ Large number of technologies
SW/HW
Electrical, optical, mechanical, thermal quantities

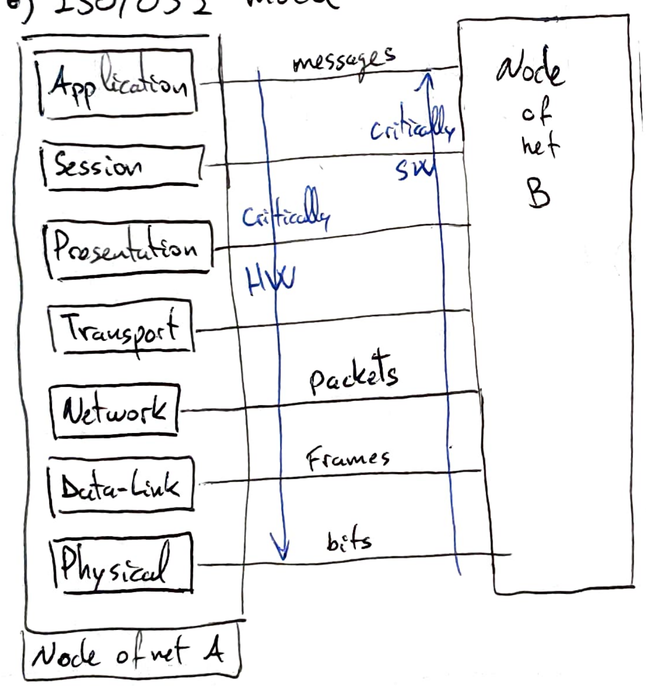
→ Complex systems
reliability important
self diagnosis of faults necessary

→ Instalations extend thosands of kilometers

→ Very high speed signals

→ Analog and digital signals

o) ISO/OSI model



o) Layers

→ Physical (Layer 1)
- * cabling technology (copper fiber)
- * wireless tech
- * network topology (bus, ring)
- * standards

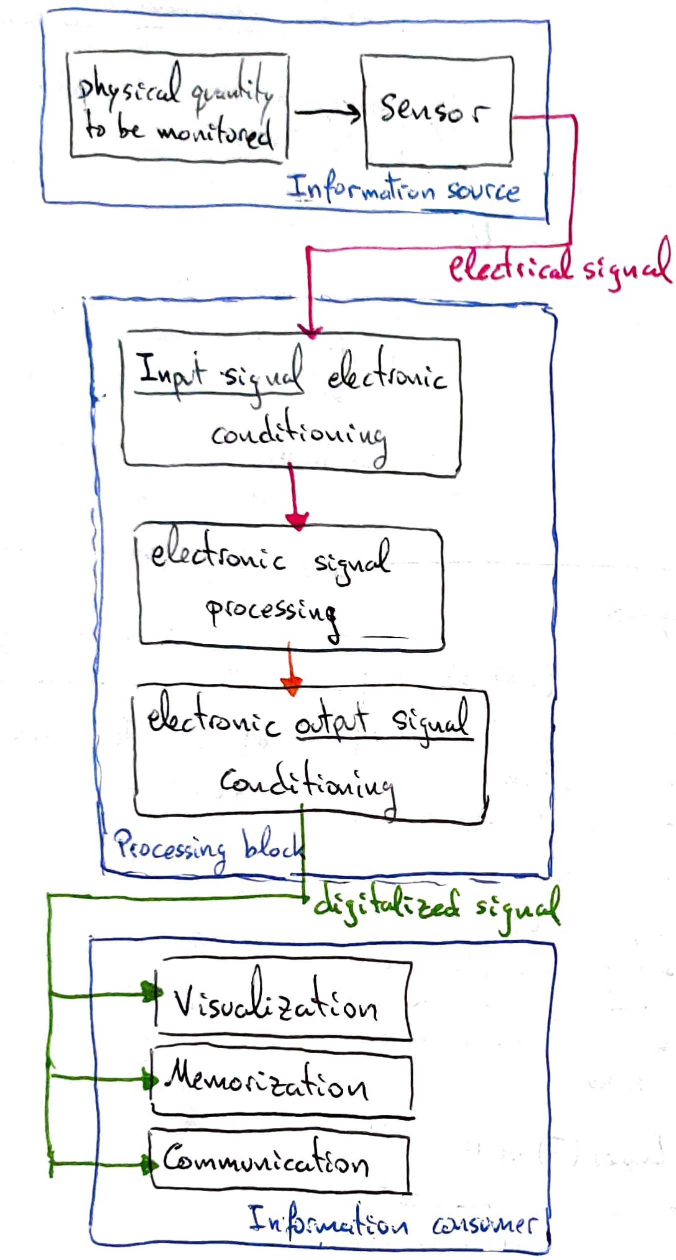
→ Layers (2-6)
- * Test procedures to prove efficacy of network
- * Mainly (not exclusively) SW tech

→ Application (Layer 7)
- * Application oriented test like specifications checking

o) Quality of service

* User POV
  response time, quality of image
* Operator POV
  - finding measurable quantities correlated to the quality of
  - monitoring quantities

Measuring Chain



- To measure a physical quantity we need a sensor that converts this phy. qu. to an electric signal (voltage or current)

- Then we want to process this signal. The output of the sensor will be the input of the processing chain
  For instance, the signal could be low, so we prepare the signal to make it visible for the user.

- Finally make this signal available for the user

- Signal Processing

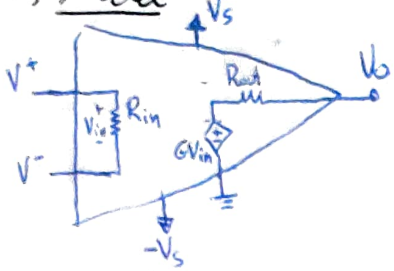
→ Analog Processing
- linear amplif., addition, difference
- integration, derivation, linear filtering
- non-linear amplif., multiplication, division
- scansion

→ Analog to dig. conversion
- sampling
- conversion

→ Digital processing
- Hardware
- Software

OPAMP

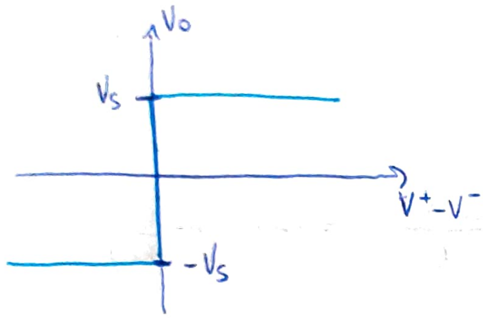
Model



$$\boxed{V_o = G\left(V^+ - V^-\right)}$$

* Open loop: Gain is very large it reaches saturation
  It acts as a comparator
* Active device (needs voltage supply)
* Non-linear

Ideal opamp



Input-output characteristics

$G = \infty$

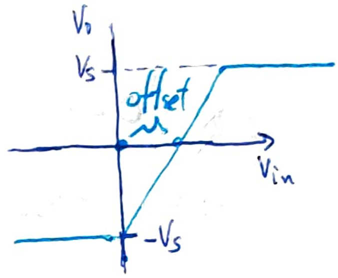
$R_{in} = \infty \Rightarrow i_{in} = 0$

$R_{out} = 0$

$BW = \infty$

Real Opamp

Input-output characteristics



depends on freq
G = very high

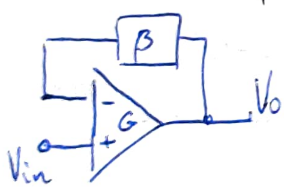
R_{in} = very high

R_{out} = very small

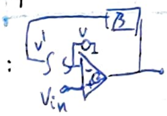
→ Response time different from zero

→ There is an offset

Closed loop



* Put a portion of the output in the inverted input
* Transfer function: Relation between input and output $T_{(s)} = \dfrac{V_o(s)}{V_{in}(s)}$
* Open loop:

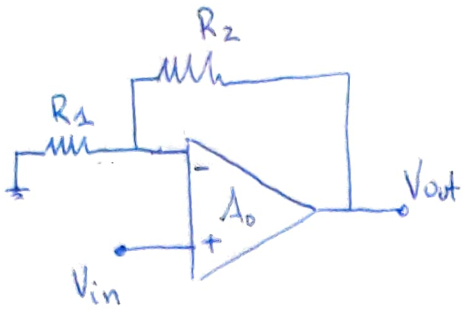


$G_{loop} = -G \cdot \beta$

* Closed loop Transfer function $T(s) = \dfrac{G(s)}{1 - G_{loop}} = \dfrac{G(s)}{1 + G(s)\beta(s)}$

* Ideal opamp ⇒ Independent from freq.
* $G \to \infty$ ⇒ $T(s) \simeq \dfrac{1}{\beta}$ → $V_o = \dfrac{1}{\beta} V_{in}$ $\beta \neq 0$ otherwise saturation at output
  ⇒ $V^+ - V^- \simeq 0$ → when there is feedback opamp the voltage difference at input is zero ⇒ Voltage follower (buffer)
  $\beta = 1$

Non-Inverting Amplifier



$$\boxed{V_{out} = \left(1 + \frac{R_2}{R_1}\right) V_{in}}$$

* A_0 small
* gain $< 10^2 - 10^3$
* $R_2 \in [2, 100]\ k\Omega$
* Z_{in} very high

* Solving

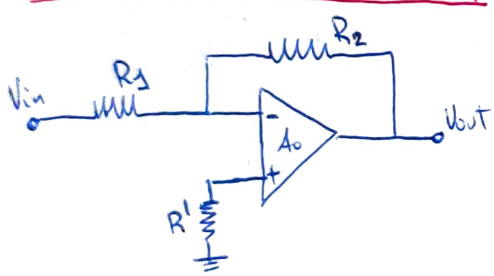
$V^+ = V^- = V_{in}$

$$\left.\begin{aligned} V_1 &= 0 - V_{in} \\ V_2 &= V_{in} - V_{out} \\ i &= \frac{V_1}{R_1} = \frac{V_2}{R_2} \end{aligned}\right\}$$

$$\frac{0 - V_{in}}{R_1} = \frac{V_{in} - V_{out}}{R_2} \Rightarrow -V_{in}\left(1 + \frac{R_2}{R_1}\right) = -V_{out}$$

$$V_{out} = \left(1 + \frac{R_2}{R_1}\right) V_{in}$$

Inverting Amplifier



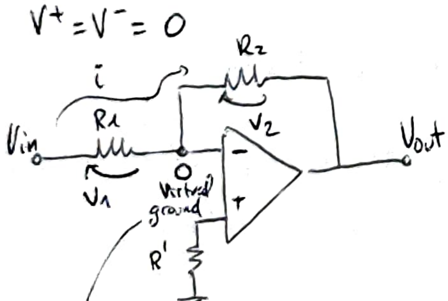
$$\boxed{V_{out} = -\frac{R_2}{R_1} V_{in}}$$

$$R' = \frac{R_1 R_2}{R_1 + R_2}$$

* A_0 small
* gain $\in [0{,}1 - 10^3]$
* Z_{in} relatively low

* Solving

$V^+ = V^- = 0$



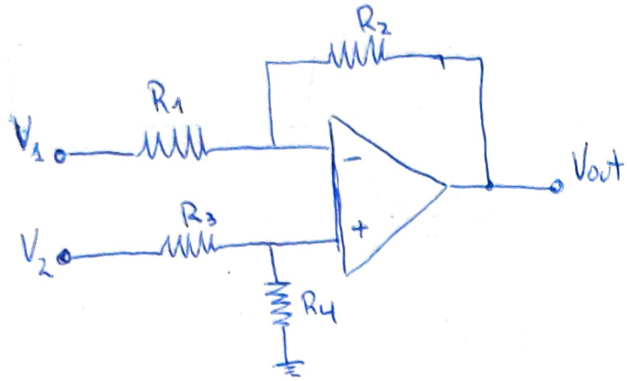
we cannot put a ground!
it is the feedback loop
that maintains this voltage = 0 V

$$\left.\begin{aligned} V_1 &= \frac{V_{in} - 0}{R_1} \\ V_2 &= \frac{0 - V_{out}}{R_2} \\ i &= \frac{V_1}{R_1} = \frac{V_2}{R_2} \end{aligned}\right\}$$

$$\frac{V_{in} - 0}{R_1} = \frac{0 - V_{out}}{R_2} \Rightarrow$$

$$V_{out} = -\frac{R_2}{R_1} V_{in}$$

Difference Amplifier

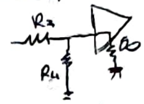


$$\boxed{R_1 = R_3 \ \& \ R_2 = R_4 \qquad V_{out} = \frac{R_2}{R_1}(V_2 - V_1)}$$

* Zin from V_1

$Z_{in} = R_1$

* Zin from V_2



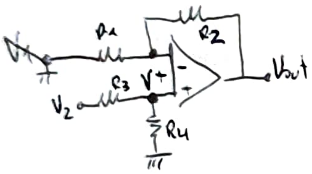
$Z_{in} = R_3 + R_4$

* Unbalanced difference amplified at inputs

* Solving

•) If I switch off V_2: $\Rightarrow$ I have the inverting amplifier: $V_{o1} = -\frac{R_2}{R_1} V_1$

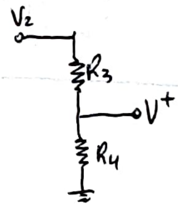
•) If I switch off V_1: $\Rightarrow$



For V^+ I have non-inverted Amplifier $\Rightarrow$ { I set V^+ as a voltage divider

$\Downarrow$

$$V_{o2} = \frac{R_4}{R_3 + R_4} \cdot V_2 \cdot \left(1 + \frac{R_2}{R_1}\right)$$



$V_2 = I\,(R_3 + R_4)$

$I = \frac{V^+ - 0}{R_4}$

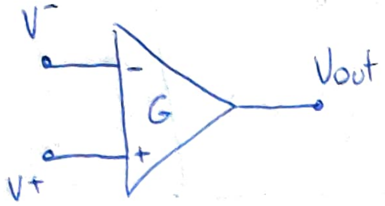
$V^+ = \frac{R_4}{R_3 + R_4} V_2$

•) Add the solutions

$$V_{out} = V_{o1} + V_{o2} = -\frac{R_2}{R_1} V_1 + \frac{R_4}{R_3 + R_4}\left(1 + \frac{R_2}{R_1}\right) V_2 \underset{R_2 = R_4}{\overset{R_1 = R_3}{=}} -\frac{R_2}{R_1} V_1 + \frac{R_2}{R_1 + R_4}\left(\frac{R_1 + R_2}{R_1}\right) V_2$$

$$V_{out} = \frac{R_2}{R_1}(V_2 - V_1)$$

Common Mode Rejection Ratio (CMRR)



The gain could be not equal for V^+ and V^- $\Rightarrow$ $\boxed{V_{out} = G^+V^+ - G^-V^-}$

Differential gain $\Rightarrow$ $G_D = \dfrac{G^+ + G^-}{2}$

Common mode gain $\Rightarrow$ $G_c = G^+ - G^-$

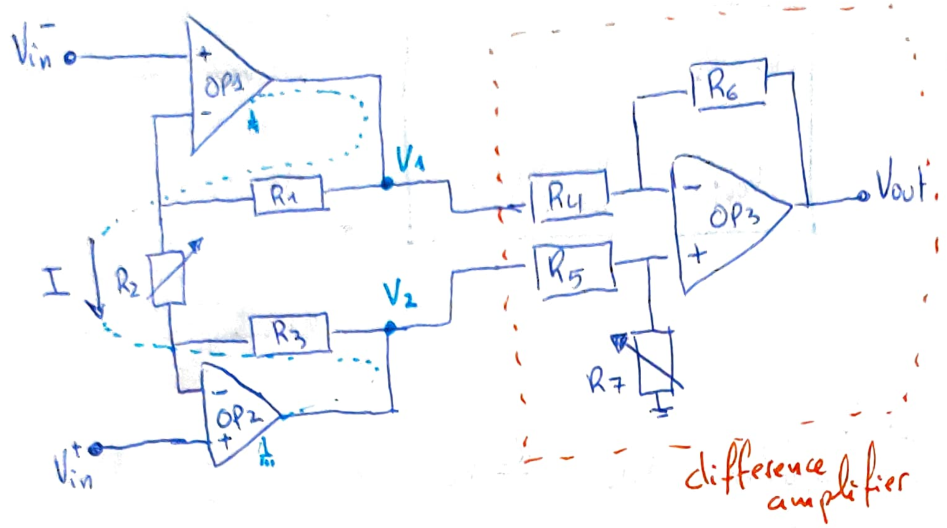
$$\left.\begin{matrix} G^+ = G_D + \dfrac{G_c}{2} \\ G^- = G_D - \dfrac{G_c}{2} \end{matrix}\right.$$

- Common mode Rejection Ratio : $\boxed{CMRR = \dfrac{G_D}{G_c}}$

  * Ideal opamp : $CMRR \to \infty$
  * In log: $CMRR = 20\log\left(\dfrac{G_D}{G_c}\right)$

- Output: $\boxed{V_{out} = G_D\,(V^+ - V^-) + G_c\,\underbrace{\left(\dfrac{V^+ + V^-}{2}\right)}_{\text{common mode voltage}}}$

Instrumentation Amplifier



$$R_1 = R_3,\ R_5 = R_4,\ R_6 = R_7$$

$$V_{out} = \frac{R_6}{R_4}\left(1 + \frac{2R_1}{R_2}\right)\left(V_{in}^+ - V_{in}^-\right)$$

* Solving

$$I = \frac{V_{in}^- - V_{in}^+}{R_2}$$

o) Drop voltages

$$V_1 = V_{in}^- + V_a = V_{in}^- + R_1 \cdot I$$

$$V_2 = V_{in}^+ - V_b = V_{in}^+ - R_3 I$$

o) Using difference ampli results

$$V_{out} = V_2 \underbrace{\frac{R_7}{R_5 + R_7}\left(1 + \frac{R_6}{R_4}\right)}_{G^+} - V_1 \underbrace{\frac{R_6}{R_4}}_{G^-}$$

If we put all together (current, drop voltages) we get Vout

To get the best CMRR we just need to tune one of the resistance: R_4, R_5, R_6, R_7

To adjust the total gain we just need to tune one resistance: R_2

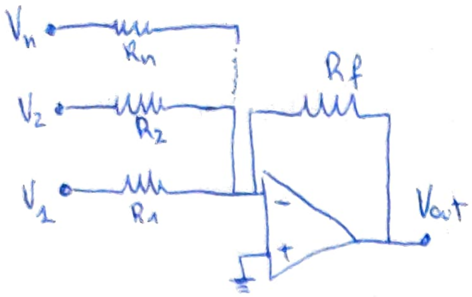
↳ Independently

* Equivalent impedance from $V_{in}^+ \rightarrow Z_{in} = \infty$

$V_{in}^- \rightarrow Z_{in} = \infty$

* Usually the information is in voltage difference

Summing Amplifier



$$R_1 = R_2 = \cdots = R_n = R$$

$$V_{out} = -\frac{R_f}{R_1}\sum_{i=1}^{n} V_i$$

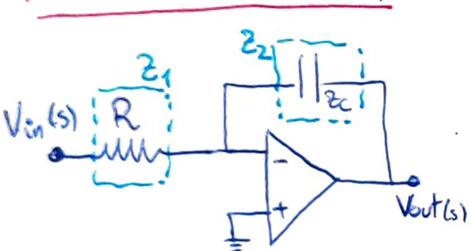
* To get very accurate summer, means same voltage in, we have to tune resistance
* To avoid the minus we add another block

Inversor

* Solving

We switch off all voltages except one. We do that with all of voltages $\Rightarrow$ We get the inverting amplifier $V_1 \neq 0 \quad V_2 = \cdots = V_n = 0$ $\quad V_{out_1} = -\frac{R_f}{R_1} V_1 \Rightarrow V_{out} = -\frac{R_f}{R_1}V_1 - \frac{R_f}{R_2}V_2 \ldots$

Integrator

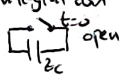


$$V_{out}(s) = -\frac{1}{sC}\cdot\frac{1}{R}V_{in}(s)$$

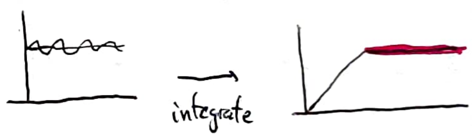
$\frac{1}{s} \rightarrow$ integration operator $\downarrow$ in time dom.

$$V_{out}(t) = -\frac{1}{RC}\int_0^t V_{in}(t)\,dt + V_0$$

V_0: zero if we use switch to start the integration at $t=0$



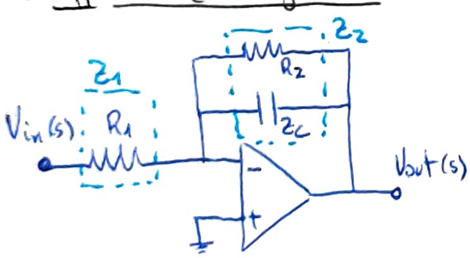
* We use laplace domain
* Problem: If there is DC component the output will saturate



* Solving: Inverting amplif.

$$V_{out} = -\frac{Z_2}{Z_1}V_{in}, \quad Z_C = \frac{1}{sC}$$

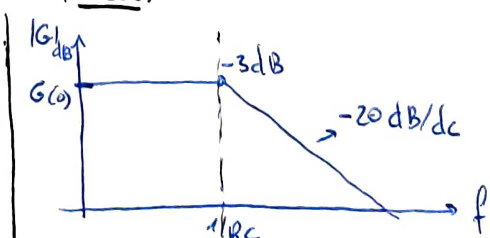
$\Rightarrow$ Approximate integrator



$$V_{out}(s) = -\frac{R_2}{R_1}\left(\frac{1}{1+sCR_2}\right)V_{in}(s)$$

* Now it will behave like amplifier for $s=0$ ($s=0 \Rightarrow Z_C = \infty \Rightarrow R_2 \parallel Z_C = R_2$) ($s=0$ is DC component)

* Bode:



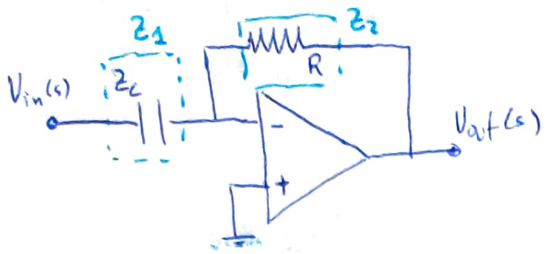
Very low freqs is an amplifier | For high freqs it is work as an integrator

* Solving

$$Z_2 = R_2 \parallel Z_C = \frac{R_2\cdot\frac{1}{sC}}{R_2+\frac{1}{sC}} = \frac{\frac{R_2}{sC}}{\frac{sCR_2+1}{sC}} = \frac{R_2}{sCR_2+1}$$

$$V_{out} = -\frac{Z_2}{Z_1}V_{in} = -\frac{R_2}{R_1}\cdot\frac{1}{(1+sCR_2)}V_{in}$$

Differentiator



$V_{out}(s) = -sCR\, V_{in}(s)$

s → derivation operator | in time dom.

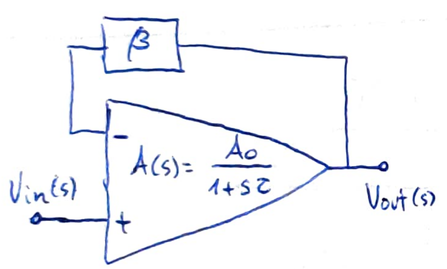
$V_{out}(t) = -RC \dfrac{dV_{in}(t)}{dt}$

⊛ The good performance of the circuit depends on the BW
Some freqs. could lead to instability (oscillation)

⊛ Solving the problem
- Add small resistor in series with the capacitor

Opamp: Small signals behaviour

A better model for real Opamp



Same transfer function: $T(s) = \dfrac{V_{out}(s)}{V_{in}(s)} = \dfrac{A(s)}{1+\beta A(s)}$

Solving:

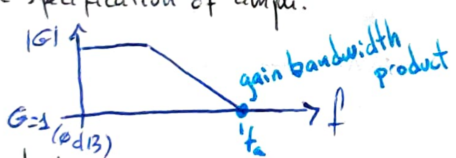
$$T(s) = \frac{A_0}{1+s\tau} \cdot \frac{1}{1+\frac{\beta_0 A_0}{1+s\tau}} = \frac{A_0}{1+s\tau+\beta_0 A_0} = \underbrace{\frac{A_0}{1+\beta_0 A_0}}_{A_0'} \cdot \frac{1}{1+s\underbrace{\left(\frac{\tau}{1+\beta_0 A_0}\right)}_{\tau'}}$$

* The gain is reduced
* The pole is shifted

$$\boxed{A_0' \cdot \frac{1}{\tau'} = A_0 \cdot \frac{1}{\tau} = \text{constant}}$$

* This product: Gain × BW = constant is independent of the configuration of amplifier (β affects the amplification and band pass the same way)

* Bandwidth gain product is a specification of ampli.



* Prob 1

We want G=10
We have gain BW prod = 1 MHz
BW ? ⇒ $G \times BW = C$ ⇒ $BW = \dfrac{C}{G} = \dfrac{1\,MHz}{10}$
⇒ BW = 100 kHz

* Prob 2

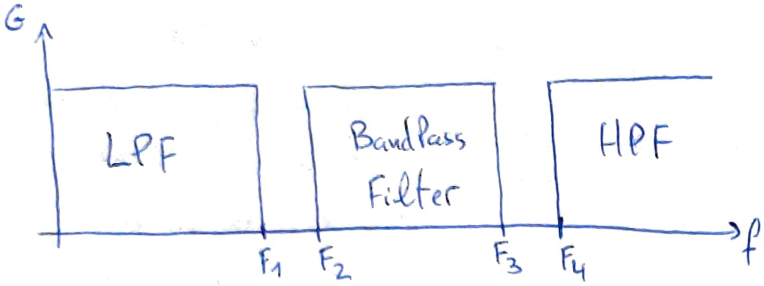
We want BW = 200 kHz
We want G = 10
G-BW prd = 1 MHz

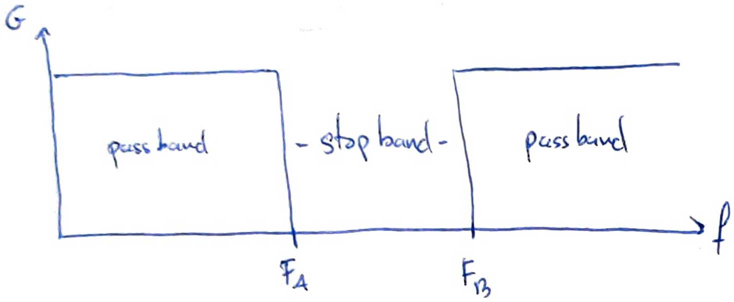
} We need at least two stages

stage 1: $G_1 = \sqrt{10}$
Stage 2: $G_2 = \sqrt{10}$
> $G_{tot} = G_1 \cdot G_2 = 10$

stage 1
$G \cdot BW = \sqrt{10} \cdot 200\,kHz < 1\,MHz$ ✓

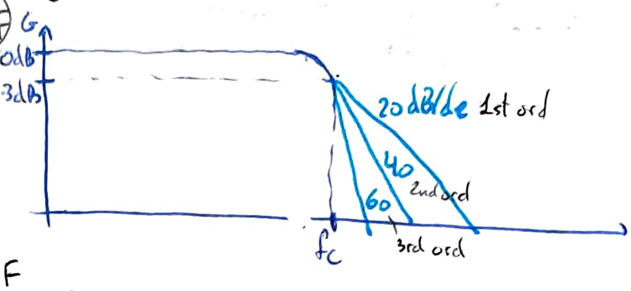
Filters



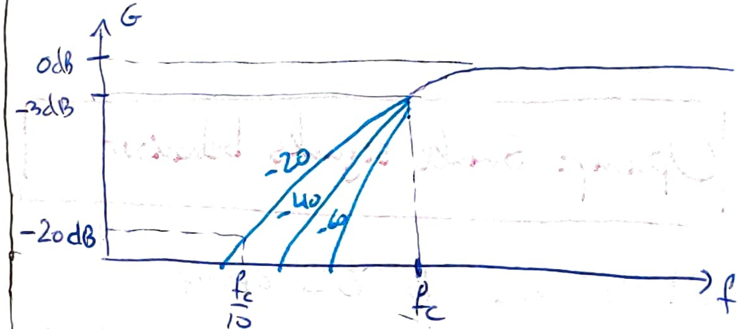


HPF
* We characterise the LPF by the slope of transfer functions in the cut-off region

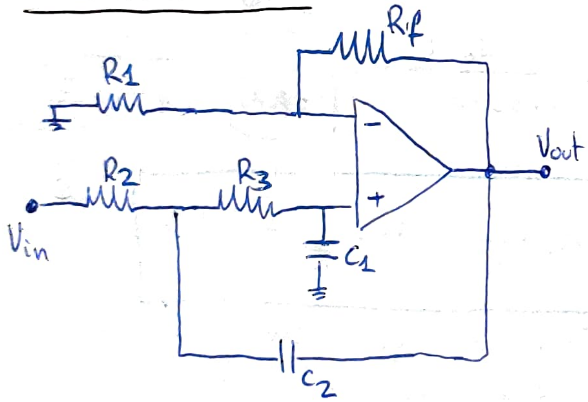
LPF



HPF



2nd order LPF



2nd order HPF