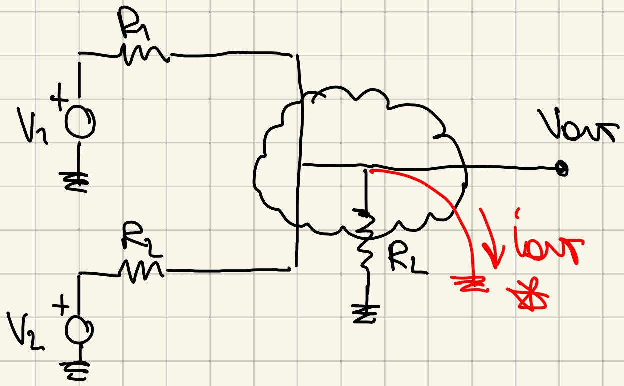
ES03 - OPAMP STAGES

VOLTAGE (AND CURRENT) ADDER



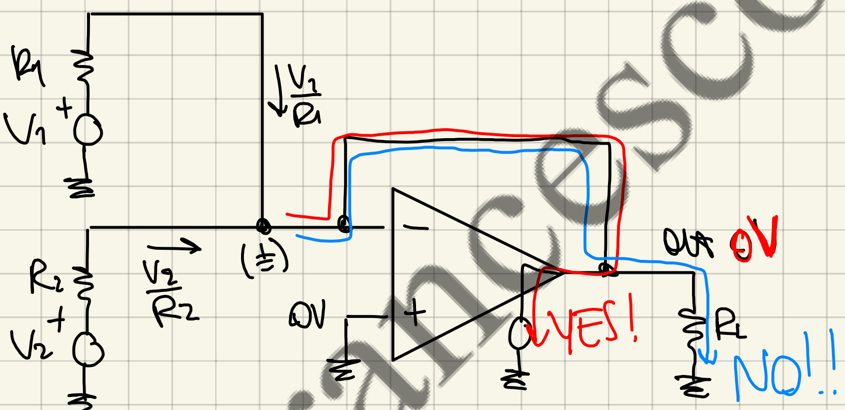
$$V_{OUT} = V_{OUT}(V_1) + V_{OUT}(V_2) = V_1 \frac{R_L \| R_2}{R_1 + R_L \| R_2} + V_2 \frac{R_L \| R_1}{R_2 + R_L \| R_1}$$

We don't like this adding node bcz if V_1 stays the same but V_2 changes also V_{OUT} changes. Furthermore, there is the cross-talk issue

Another solution could be: *

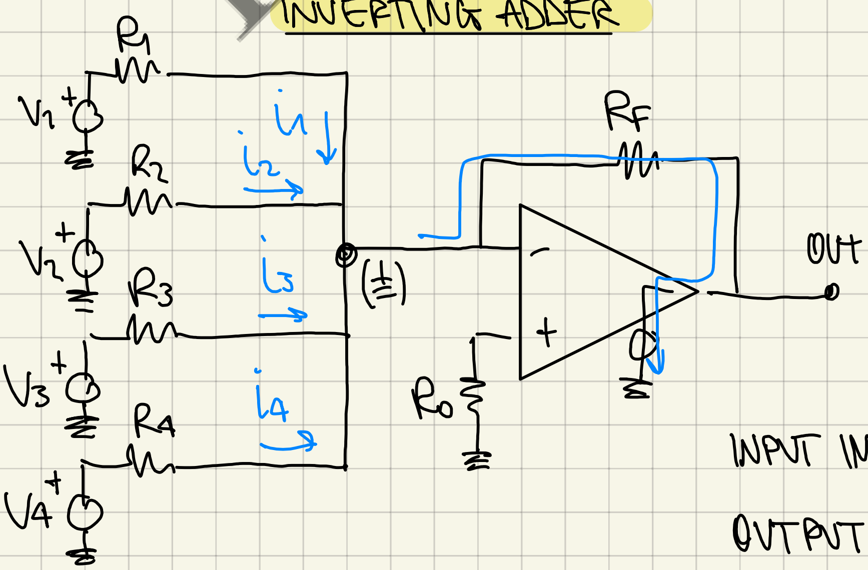
↳ This time $i_{OUT} = \frac{V_1}{R_1} + \frac{V_2}{R_2}$ → There is no coupling (no cross-talk) but this is not the amplification I'm glad to have

→ I want a ground, but it has to be virtual



Now if I want the output not to be 0V:

INVERTING ADDER

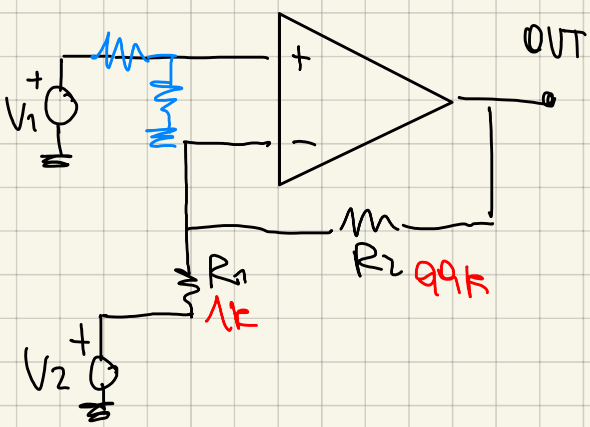


$$V_{OUT} = -\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \frac{V_4}{R_4}\right) \cdot R_F$$

INPUT IMPEDANCE $Z_{IN} = R_1$

OUTPUT IMPEDANCE $Z_{OUT} = 0$

VOLTAGE SUBTRACTOR



$$V_{out} = V_1\left(1+\frac{R_2}{R_1}\right) + V_2\left(-\frac{R_2}{R_1}\right) = V_1\underbrace{\left(1+\frac{R_2}{R_1}\right)}_{100} - V_2\underbrace{\left(\frac{R_2}{R_1}\right)}_{99}$$

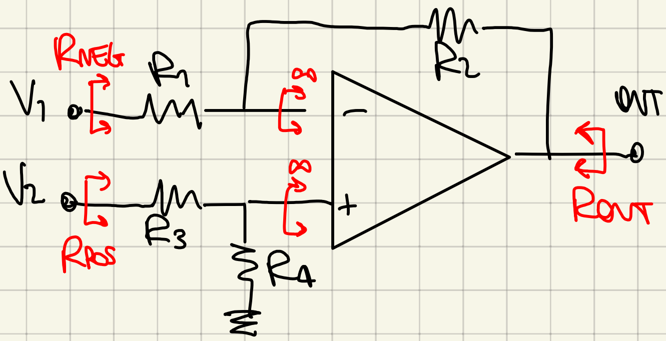
There is always a mismatch: the ⊕ input gets amplified more than the ⊖ input

How can we modify the circuit in order to have the same amplification?

Since V_1 gets amplified more than V_2, we should attenuate it

↓

Let's introduce an attenuator

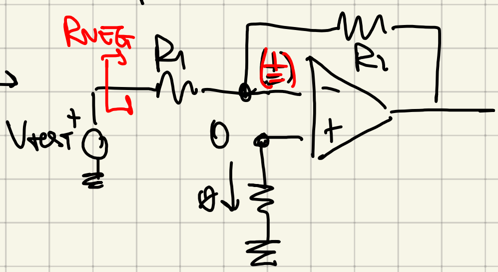


$$V_{out} = V_2\frac{R_4}{R_3+R_4}\left(1+\frac{R_2}{R_1}\right) - V_1\frac{R_2}{R_1} = V_2\frac{1}{1+R_3/R_4}\left(1+\frac{R_2}{R_1}\right) - V_1\frac{R_2}{R_1}$$

$$= V_2\frac{R_4/R_3}{1+R_4/R_3}\left(1+\frac{R_2}{R_1}\right) - V_1\frac{R_2}{R_1}$$

when $\frac{R_2}{R_1} = \frac{R_4}{R_3} \rightarrow V_{out} = V_2\frac{R_4}{R_3} - V_1\frac{R_2}{R_1} = \frac{R_2}{R_1}V_{diff}$ where $V_{diff} = V_2 - V_1$

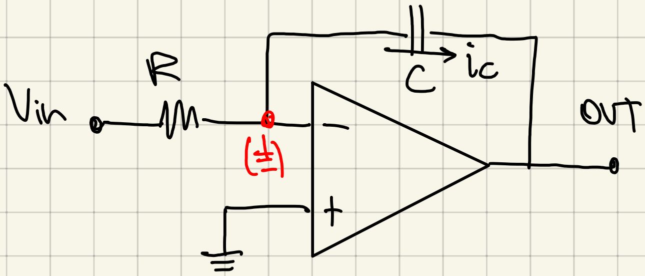
INPUT IMPEDANCE $\begin{cases} R_{POS} = R_3 + R_4 \\ R_{NEG} = R_1 \end{cases}$ →



OUTPUT IMPEDANCE $R_{OUT} \approx 0$

$R_{NEG} \neq R_{POS} \Rightarrow$ ISSUE !!!

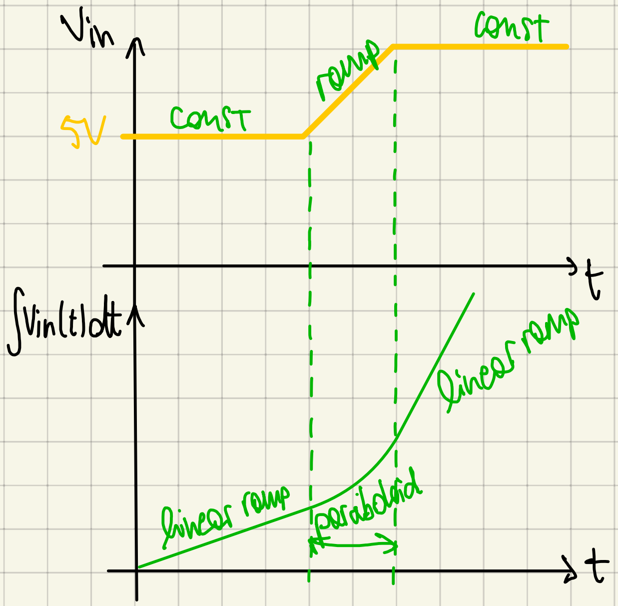
IDEAL VOLTAGE INTEGRATOR



$$i_{IN} = \frac{V_{in}}{R}$$

$$\begin{cases} V_{OUT} = V_C = -\frac{1}{C}\int i_C(t)\,dt \\ i_C = i_{IN} \end{cases}$$

$$\rightarrow \boxed{V_{OUT} = -\frac{1}{RC}\int V_{in}(t)\,dt}$$



$R = V/I = [V/A]$ $\quad I = \frac{dQ}{dt} = \left[\frac{C}{s}\right]$

$C = Q/V = [C/V]$

$$RC = [\Omega][F] = \left[\frac{V}{A}\right]\cdot\left[\frac{C}{V}\right] = \left[\frac{\cancel{V}}{\cancel{C}/s}\right]\left[\frac{\cancel{C}}{\cancel{V}}\right] = [s]$$

$$A_v(s) = \underbrace{\frac{V_{OUT}(s)}{V_{in}(s)}}_{\text{inverting stage}} = -\frac{Z_2(s)}{Z_1(s)} = -\frac{1/sC}{R} = -\frac{1}{sRC} = -\frac{1}{s\tau}$$

$s = \alpha + j2\pi f$ $\qquad \frac{1}{s}$ = integration operator

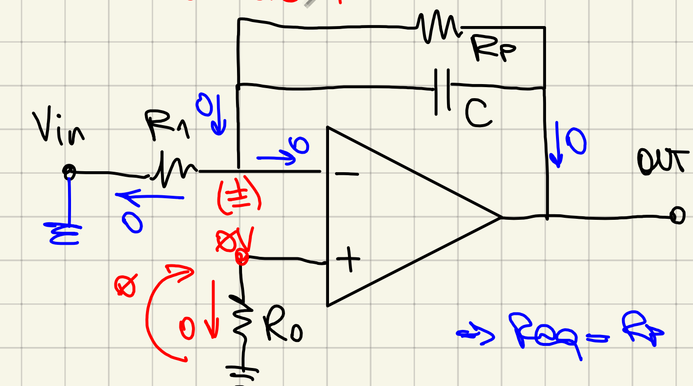
@DC → C open $\quad A_v(0) = -\frac{1}{sRC}\Big|_{s\to 0} \longrightarrow \infty$ ⇒ hence eventually the OpAmp always saturates

↳ @DC, since the capacitor is open and the input and output are not touching each other, the OpAmp cannot control its input so the v.g. can no longer exist for long period of time

How can we solve the issue that $A_v(0) \rightarrow \infty$?

REAL VOLTAGE INTEGRATOR

→ we add R_P in ∥ to C in order to guarantee even @ DC a feedback path!! R_P causes a modification in the Bode diagram

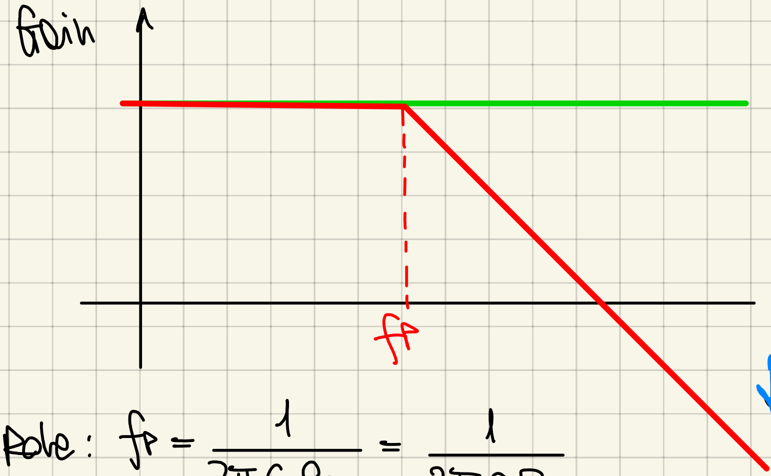


pole calculation

Asymptotic analysis:

@DC → C open → $A_v(0) = -R_P/R_1$

@HF → C short → $A_v(\infty) = 0$



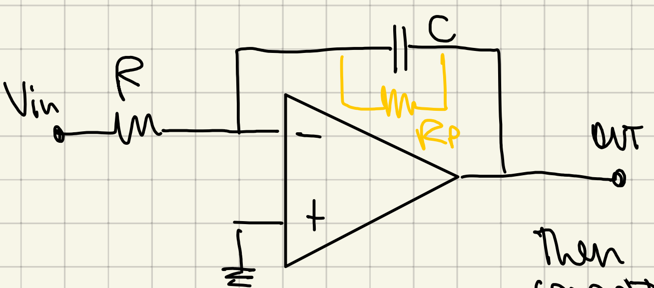
$|-R_f/R_1| = |A_v(0)|$

LPF behavior

$\downarrow A_v(\infty) = 0$

Pole: $f_p = \dfrac{1}{2\pi C R_{eq}} = \dfrac{1}{2\pi C R_f}$

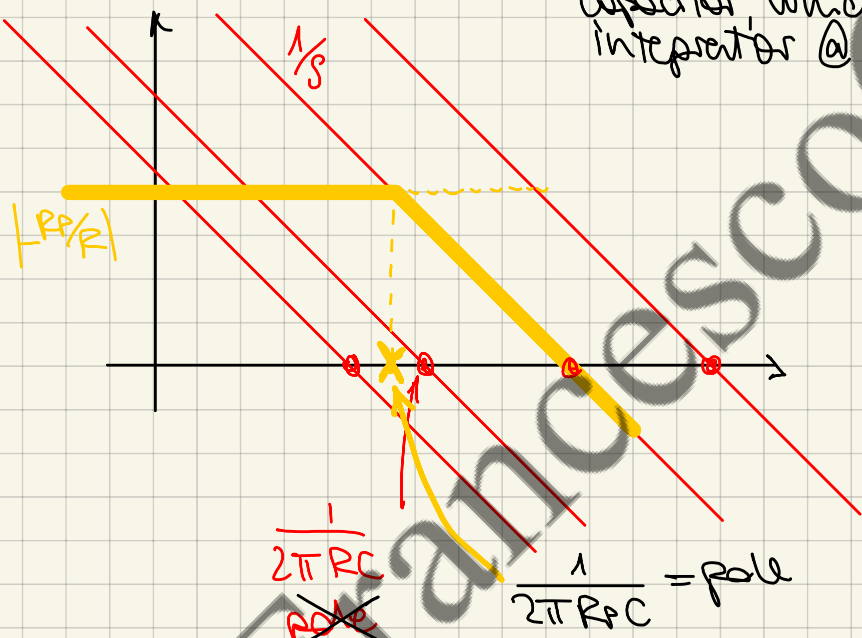
There is also another way to study the circuit:



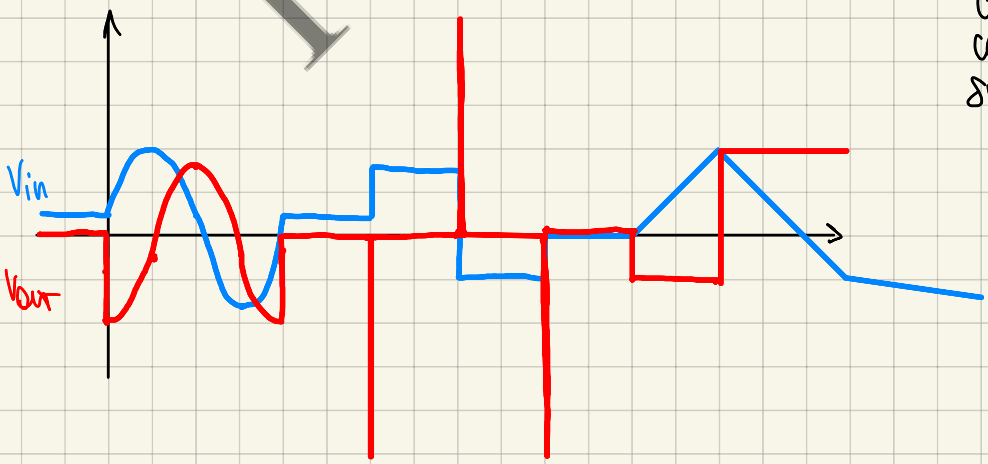
We know that it is an integrator, so its gain is:

$$G(s) = -\frac{1}{RC}\,\frac{1}{s}$$

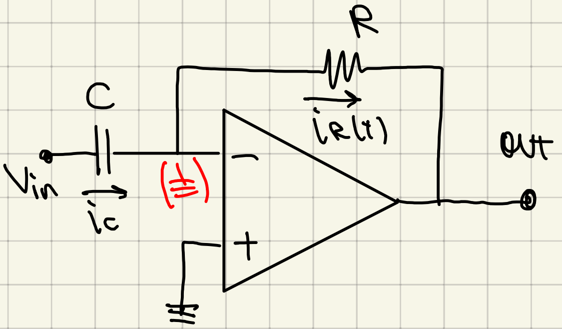
Then we add a resistor in parallel to the capacitor, which causes the saturation of the integrator @ low freq.s.



INPUT	OUTPUT
sinusoid	cosinusoid
constant value	zero out
constant slope	constant out
sudden step	Dirac Delta



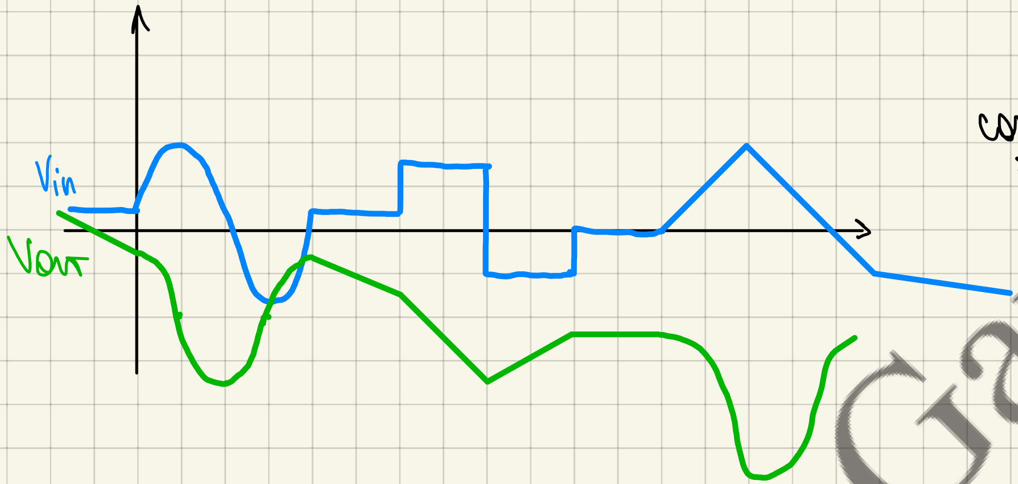
IDEAL VOLTAGE DERIVATOR



time domain analysis:

$$V_{out} = -i_R(t)\cdot R = -i_C(t)\cdot R = -C\frac{dV_C(t)}{dt}R = -RC\frac{dV_{in}(t)}{dt}$$

$$\rightarrow \boxed{V_{out}(t) = -RC\frac{dV_{in}(t)}{dt}}$$

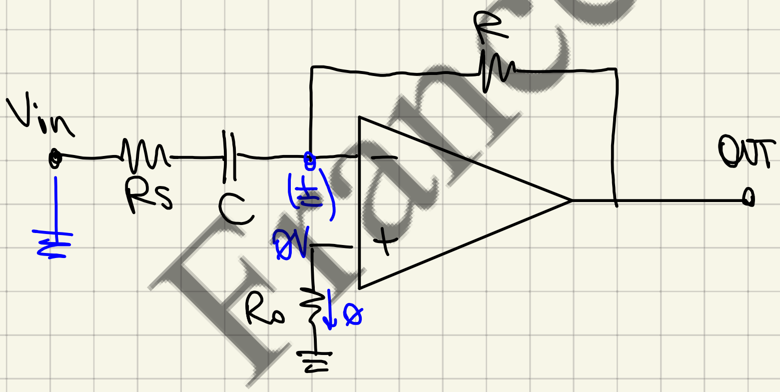


INPUT	OUTPUT
constant value	ramp
zero value	zero value
ramp	paraboloid
sine	cosine

@DC → C is open → $A_v(0) = 0$

@HF → C is short → $A_v(\infty) = \infty$ ISSUE !!

REAL VOLTAGE DERIVATOR



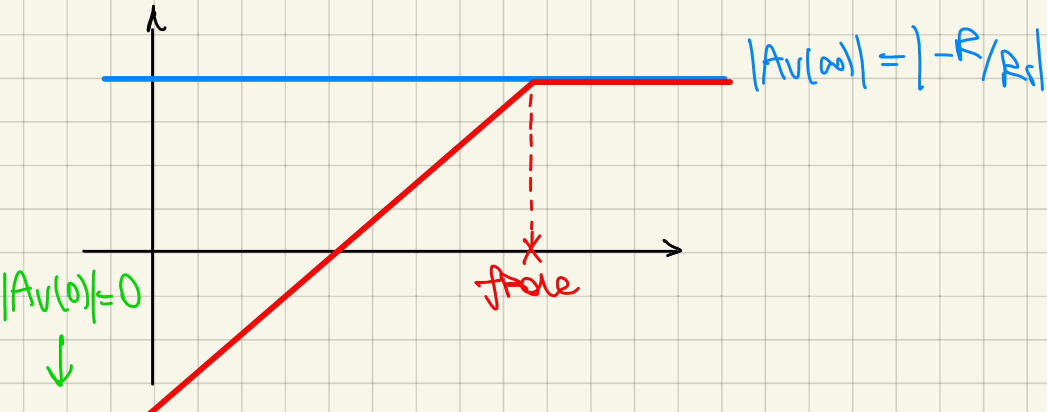
@DC → $A_v(0) = 0$

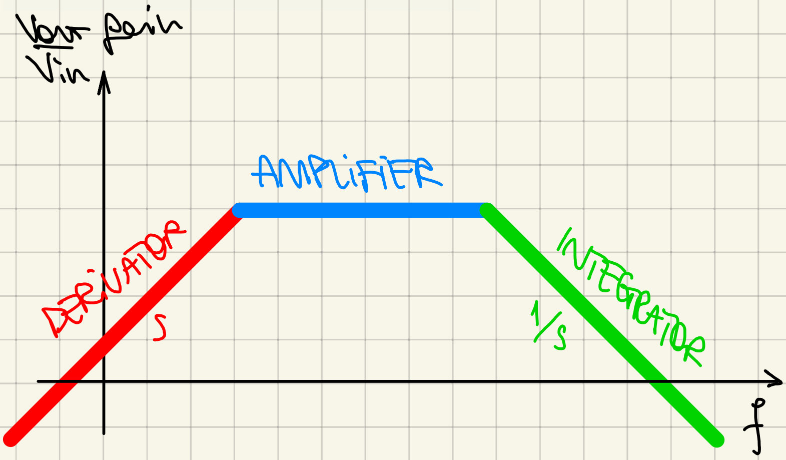
@HF → $A_v(\infty) = -R/R_s$

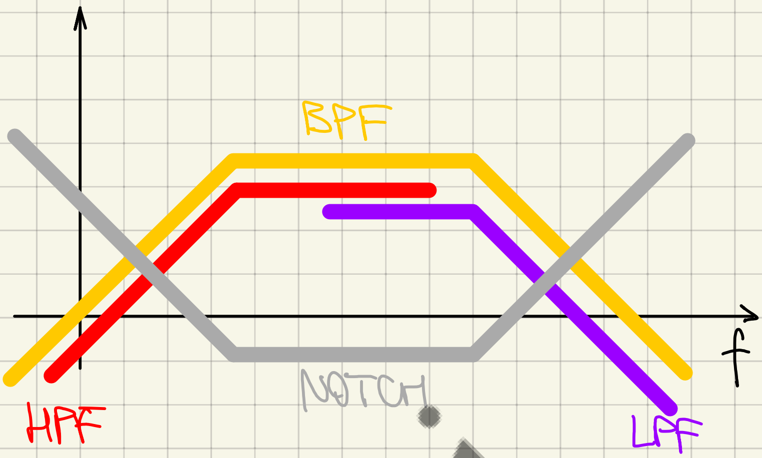
pole = ? *

$R_{eq} = R_s$

$$\rightarrow f_{pole} = \frac{1}{2\pi C R_s}$$

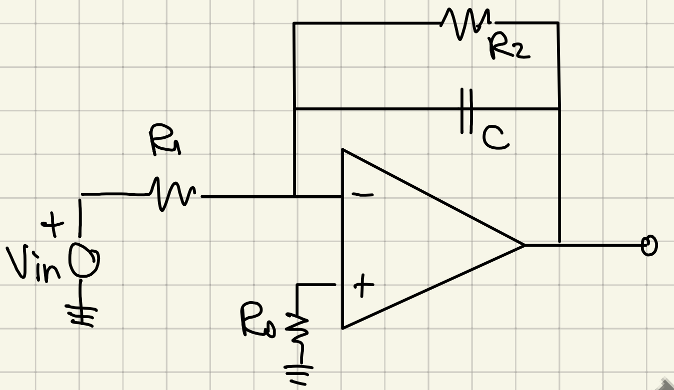






1st AND 2nd ORDER ACTIVE FILTERS

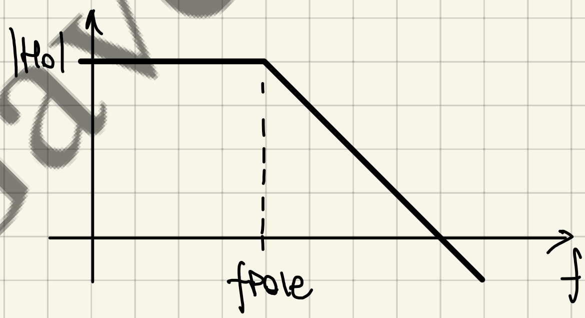
• LOW-PASS FILTER (INTEGRATOR)



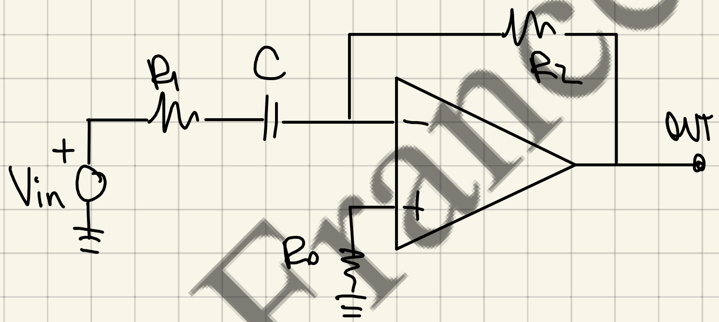
$H_0 = -R_2/R_1$

$H_\infty = 0$

$f_{pole} = \frac{1}{2\pi C R_2}$



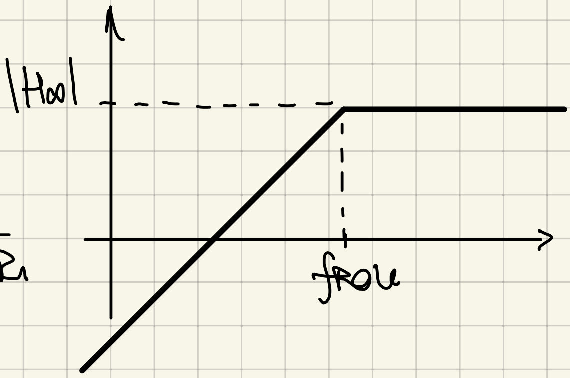
• HIGH-PASS FILTER (DERIVATOR)



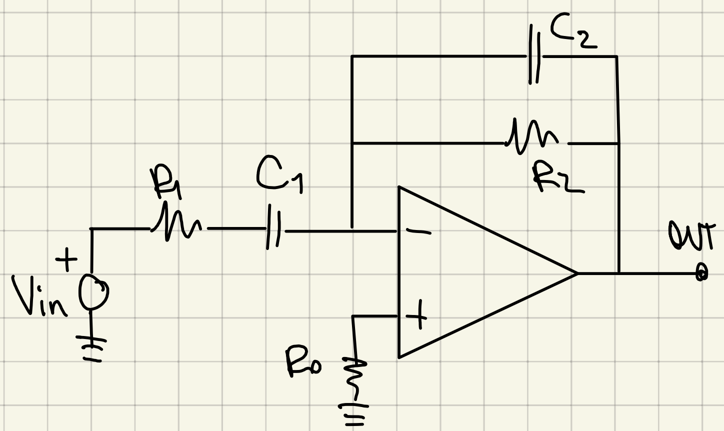
$H_0 = 0$

$H_\infty = -\frac{R_2}{R_1}$

$f_{pole} = \frac{1}{2\pi C R_1}$



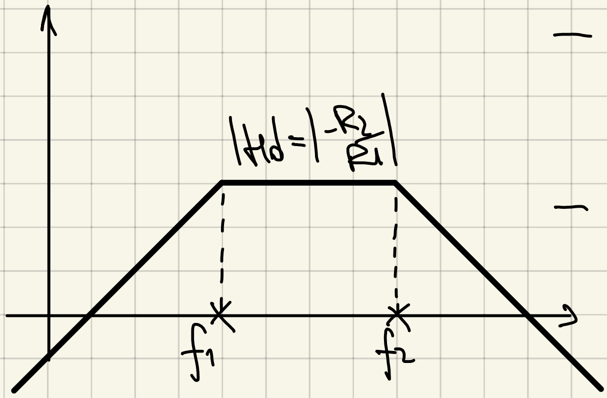
• BAND-PASS FILTER



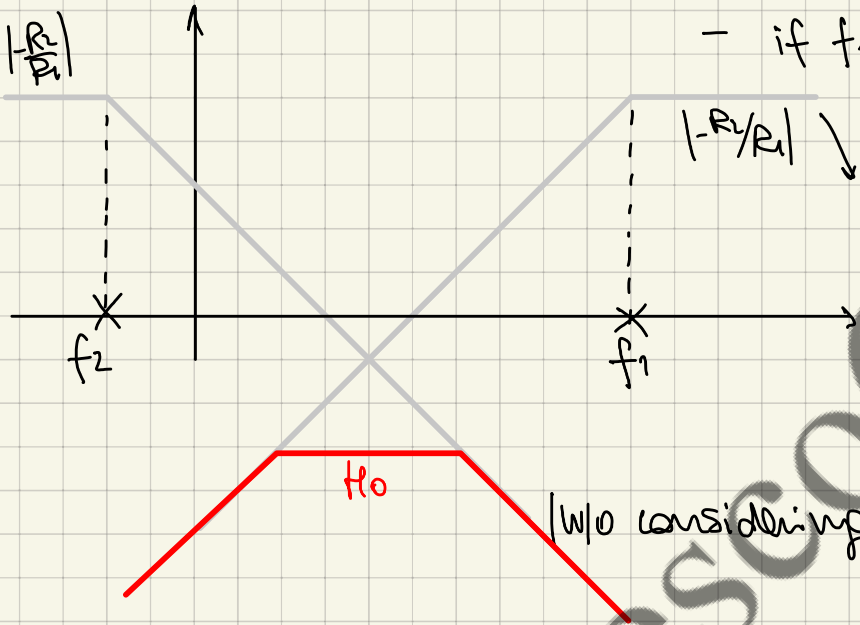
$f_1 = \frac{1}{2\pi C_1 R_1}$

$f_2 = \frac{1}{2\pi C_2 R_2}$

- if $f_1 << f_2 \rightarrow$ BPF $\Rightarrow$
  - if $f < f_1 \rightarrow C_1$ and C_2 are open
  - if $f_1 < f < f_2 \rightarrow C_1$ is short and C_2 is open $\rightarrow H_0 = -R_2/R_1$
  - if $f > f_2 \rightarrow C_1$ and C_2 are short



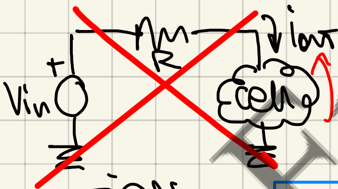
- if $f_1 >> f_2 \rightarrow$ NOTCH $\Rightarrow$
  - if $f < f_2 \rightarrow C_1$ and C_2 are open
  - if $f_1 < f < f_2 \rightarrow C_2$ is short and C_1 is open $\rightarrow H_0 = 0$



$$H_0 = \left|-\frac{R_2}{R_1}\right| \cdot \frac{1}{\frac{\text{Pole, in}}{\text{Pole, out}}}$$

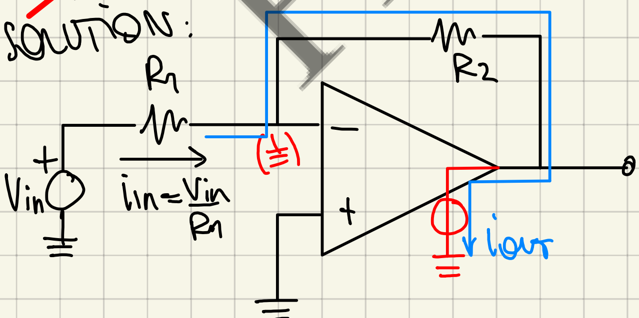
CURRENT AND VOLTAGE CONVERTERS

- VOLTAGE - CURRENT CONVERTER (TRANSCONDUCTANCE AMPLIFIER)

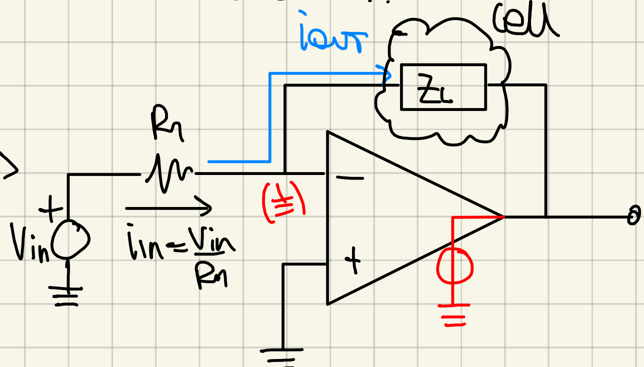


$\Rightarrow$ This is a stupid converter bcs we are pretending that the voltage drop across the cell is zero $\rightarrow$ DON'T USE IT!!

SOLUTION:



$\Rightarrow$

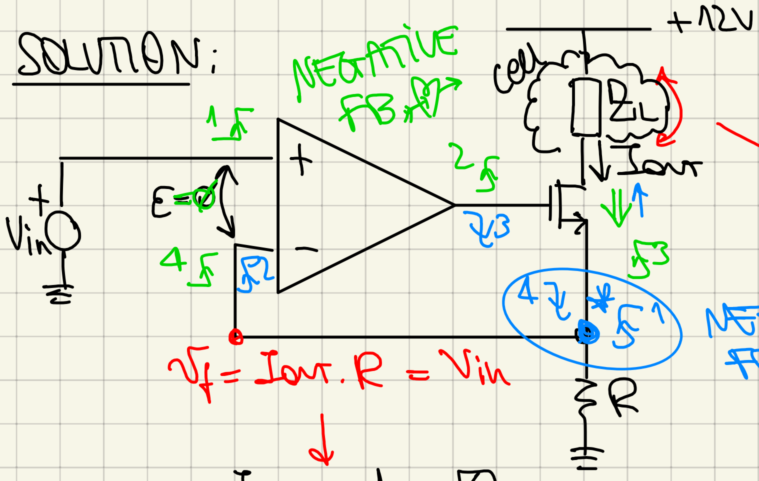


$i_{out} = i_{in} = \frac{V_{in}}{R} \rightarrow \frac{i_{out}}{V_{in}} = \frac{1}{R}$

<u>ISSUE</u>: if I_{in} is very high, then $I_{out,MAX} = I_{in}$, must be very high

$\rightarrow$ if $I_{in} = 100mA \rightarrow I_{out,MAX} = 100mA$ and the OpAmp must drink it, and it may not be able to do that

SOLUTION:



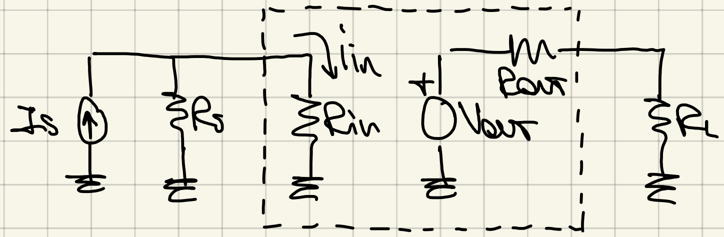
We can check the FB even @ another node inside the loop *

If the voltage across the load changes we don't care, bcz the current flowing through the loop is set by the FB and R

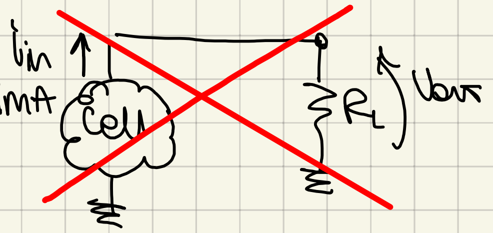
$V_f = I_{OUT} \cdot R = V_{in}$

$$\frac{I_{OUT}}{V_{in}} = \frac{1}{R}$$

• CURRENT-VOLTAGE CONVERTER (TRANSIMPEDANCE AMPLIFIER)



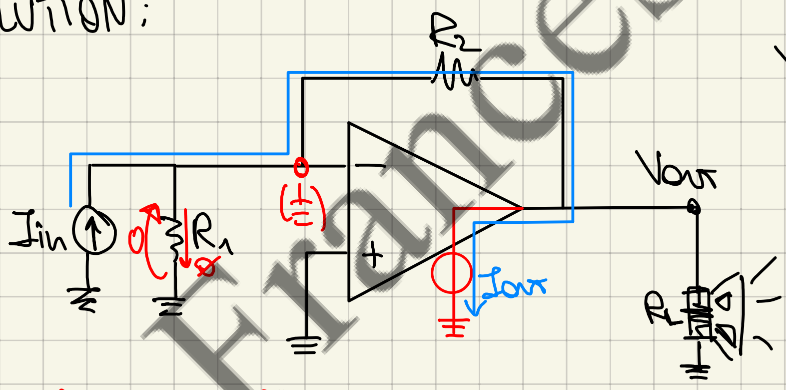
$V_{OUT} = G_R \, i_{in}$



⇒ This is a stupid I-to-V converter, bcz if we used a huge load the voltage drop across the load and so also across the cell would be huge too and the cell could get destroyed

DON'T USE IT!!

SOLUTION:



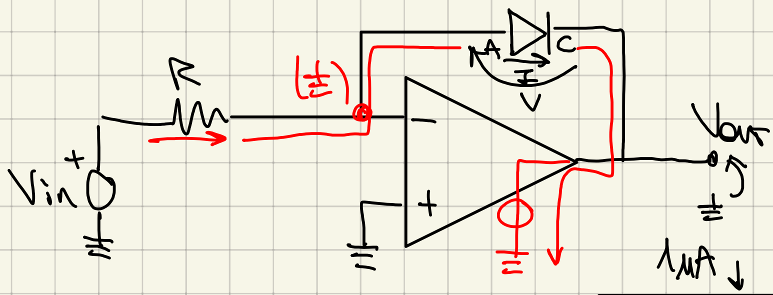
$V_{OUT} = -I_{IN} R_2$

→ we can change R_L as we want bcz it has no effect on V_{OUT}

EXP AND LOG CONVERTER

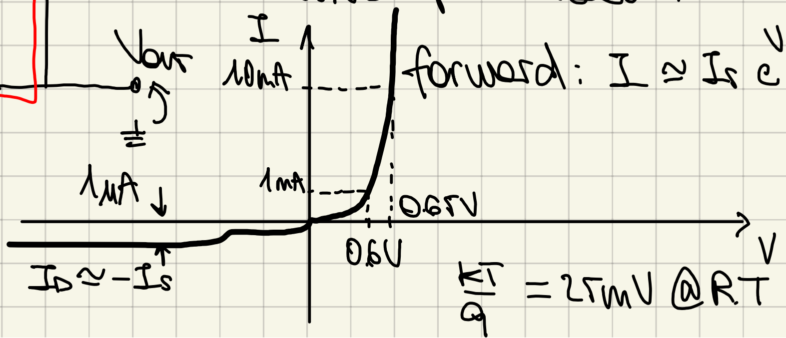
• LOGARITHMIC AMPLIFIER

let's use a non-linear component (ex: a diode)



$$\boxed{I_D = I_s\left(e^{V/kT/q} - 1\right)}$$

I-V curve of a diode:



forward: $I \simeq I_s e^{V/kT/q}$

$\frac{kT}{q} = 25mV$ @ RT (T=300K)

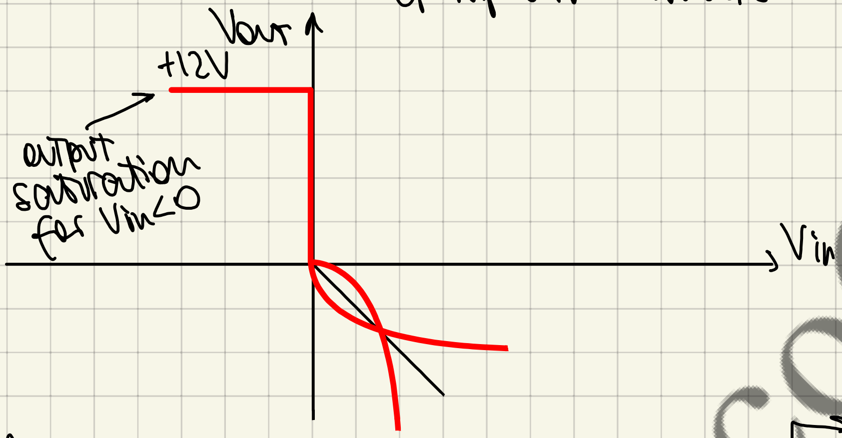
How does the circuit operate?

if the diode is ON → $V = 0.6V$ → $I_D = I_S\left(e^{V/kT/q} - 1\right) \simeq I_S\, e^{V/kT/q}$

$$\begin{cases} I_D = I_{IN} \\ V = -V_{OUT} \end{cases} \Rightarrow \frac{V_{IN}}{R} \simeq I_S\, e^{-V_{OUT}/kT/q} \Rightarrow \boxed{V_{OUT} = -\frac{kT}{q} \ln\left(\frac{V_{in}}{R \cdot I_S}\right)}$$

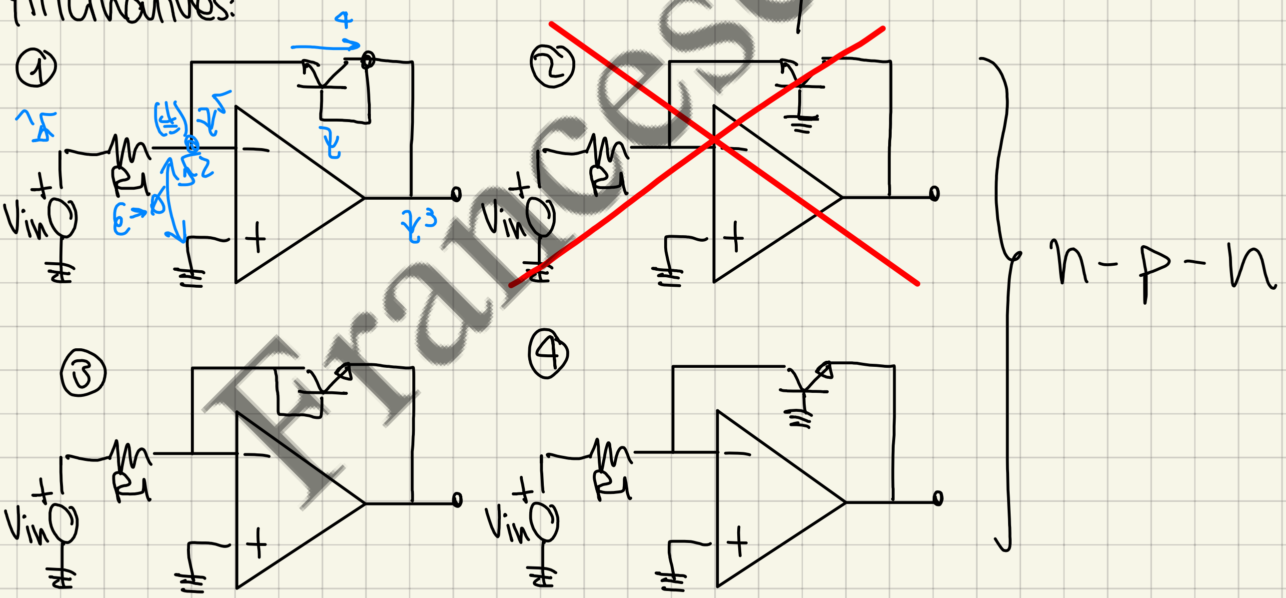
Notice: The output has a logarithmic dependence to what we apply @ the input (V_{in})

Beware: if $V_{in} < 0$ → The diode becomes reverse biased, the current should reverse but it cannot, bc no current can flow in the opposite direction through the diode, or better there is a current but it is almost constant, and the output of the OpAmp will saturate

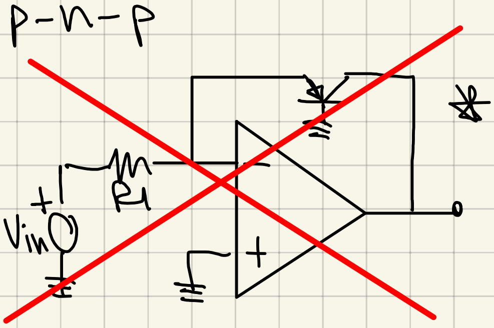


Alternatives:

→ This cannot work too bc ✱ (same reason)



p-n-p

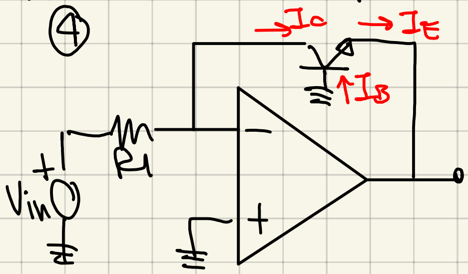


✱ This circuit cannot work bc whenever we apply something at the input, the output moves (and so the collector of the BJT), but the current cannot change. The current of the BJT changes only if we vary the V_{BE}

The best configuration is the 4th: it's preferred to keep the base at ground in such a way we can compensate the approximation on the current ($I_D = I_s(e^{V/kT/q} - 1) \simeq I_s e^{V/kT/q}$)

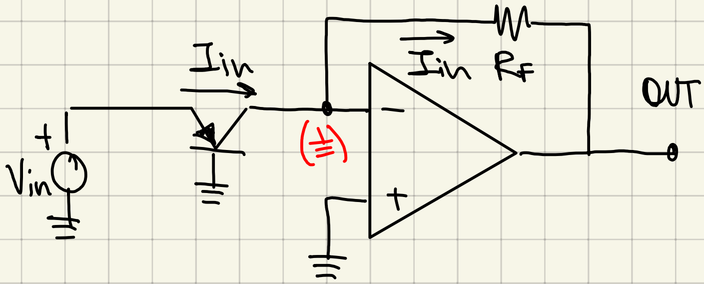
In fact the collector current compared to the emitter one slightly differs, bc there is also a base current: $I_E = I_C + I_B$ and $I_C = \beta I_B$

4



- EXPONENTIAL AMPLIFIER

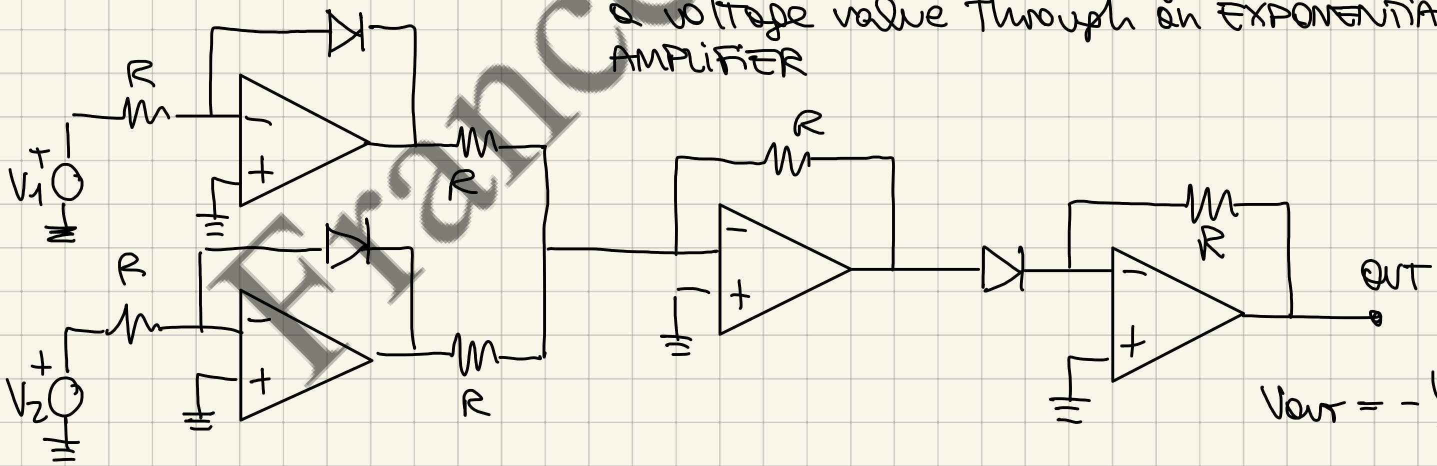
$$\boxed{V_{OUT} = -I_{in} R_F = \cong -R_F I_s e^{V_{BE}/(kT/q)}}$$



VOLTAGE MULTIPLIER = a. we convert the voltages into logarithmics through LOGARITHMIC AMPLIFIERS

b. we sum up the logarithmics through a simple ADDER

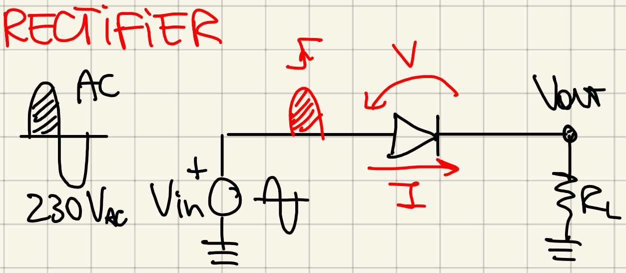
c. we convert again the resulting logarithmic into a voltage value through an EXPONENTIAL AMPLIFIER

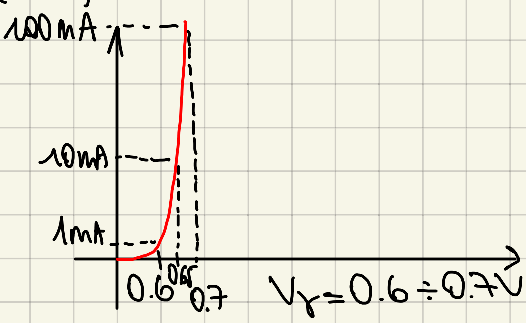


$$V_{OUT} = -\frac{V_1 V_2}{R I_s}$$

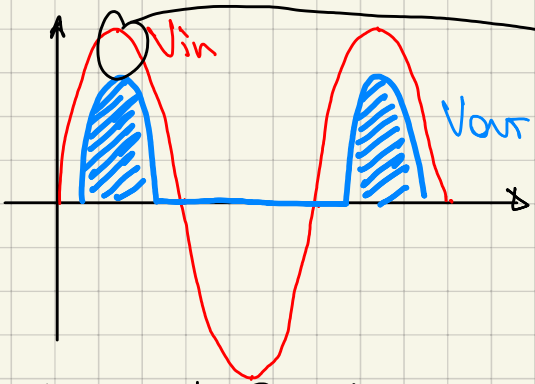
Up to now we considered small signals, but we can also operate these stages w/ large signals (non-DC signals (AC)).

RECTIFIER

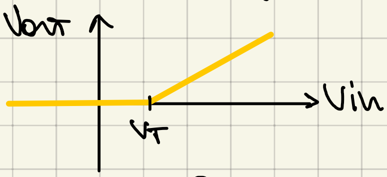




$V_\gamma = 0.6 \div 0.7\,V$

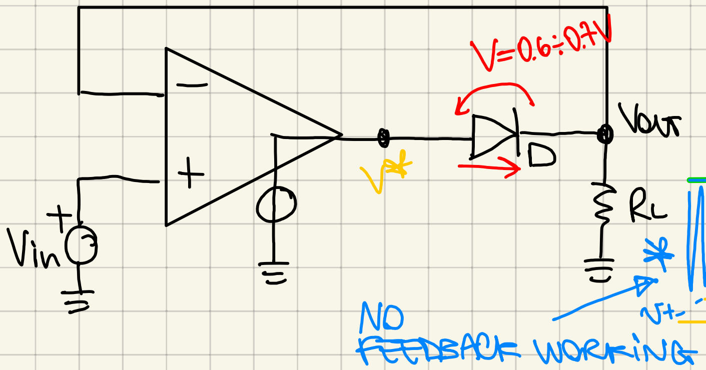


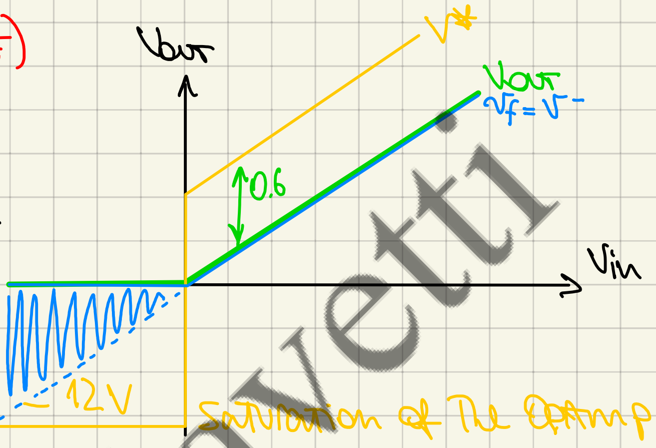
This drop in the OUTPUT signal is due to the 0.6/0.7V drop on the diode
↓
we want a rectifier w/o voltage drop.



The solution to this issue is known as PRECISION RECTIFIER (or SUPER DIODE)

PRECISION RECTIFIER (SUPER DIODE)





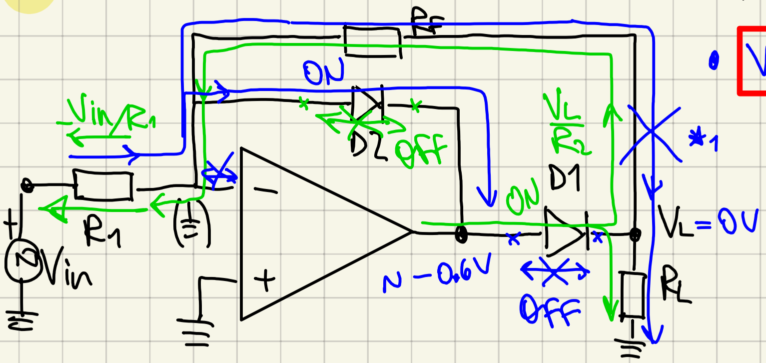
- when $\boxed{V_{in} > 0}$ → D: ON → $\boxed{V_{out} = V_{in} = V_f}$ & $\boxed{V^* = V_{out} + 0.6V}$
- when $\boxed{V_{in} < 0}$ → the diode stops the current flow in the opposite direction (D: OFF) → $\boxed{V_{out} = 0 = V_f}$
  V^* → goes to a very negative value bcz it tries to force the diode to reverse the current (ideally $V^* \to -\infty$), but the current cannot flow to the opposite direction so V^* saturates to the most negative power supply (-12V)
  ⇒ $\boxed{V^* = -12V}$ &

* when Vin<0 there is a voltage diff. btw V^+ and V^- which means that the feedback doesn't work

Notice: it's called super diode bcz the voltage drop btw Vin and V_L is 0V

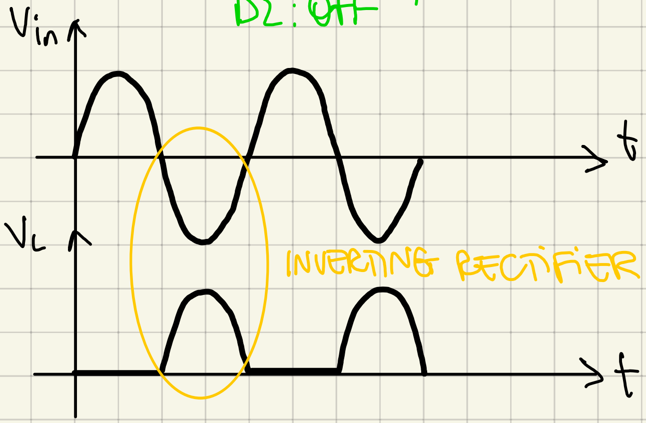
How can we avoid the saturation of the OpAmp?

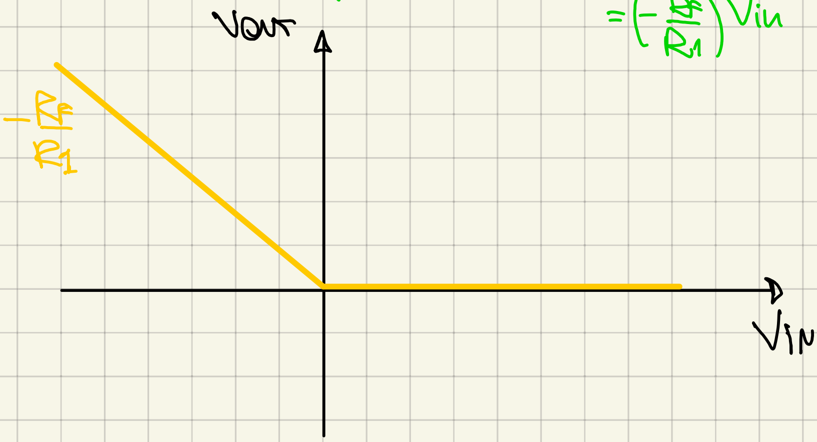
① SUPER DIODE INVERTING RECTIFIER W/O SATURATION OF THE OPAMP



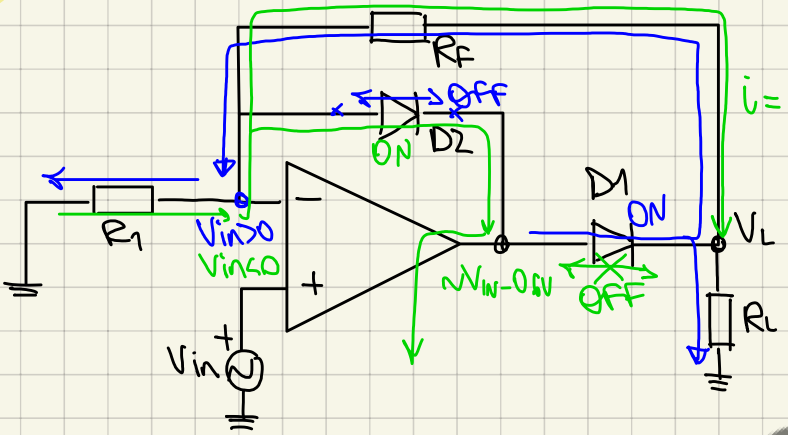
- $\boxed{V_{in} > 0}$ ⇒ D1: OFF, D2: ON ⇒ *1 RF is in series w/ RL but they are btw 2 grounds so no current flows ⇒ $V_L = 0$

• $\boxed{V_{in}<0}$ ⇒ D1: ON, D2: OFF, $G = -R_F/R_{in}$ (classical inverting stage) ⇒ $V_L = G\,V_{in} = \left(-\frac{R_F}{R_1}\right)V_{in}$





② SUPER DIODE NON-INVERTING RECTIFIER W/O SATURATION OF THE OPAMP



• $\boxed{V_{IN}>0}$ ⇒ D1 : ON, D2 : OFF } $V_L = \left(1+\frac{R_F}{R_1}\right)V_{IN}$

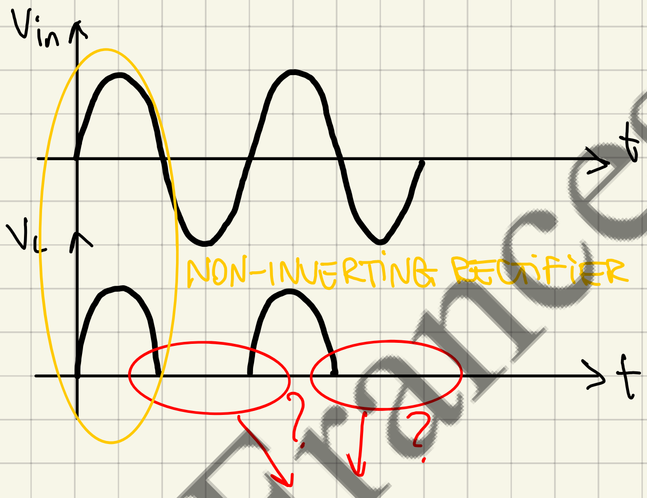
• $\boxed{V_{IN}<0}$ ⇒ D1 : OFF, D2 : ON }

$V_{IN} - V_L = \left(-\frac{V_{IN}}{R_1} - I_s e^{V_T/(KT/q)}\right)\cdot R_F$

→ Something like that maybe ☹ *

↓

The output (V_L) is not zero, but there is something leaking out

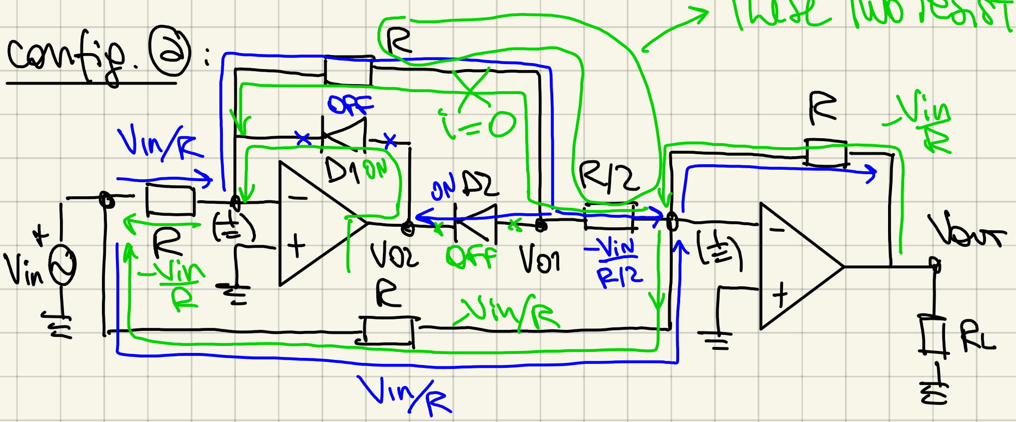


it won't be zero *

③ SUPER DOUBLE-RECTIFIER

config. ②:

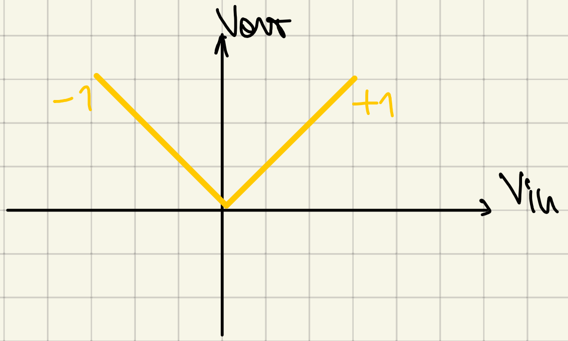
These two resistances are btw 2 grounds

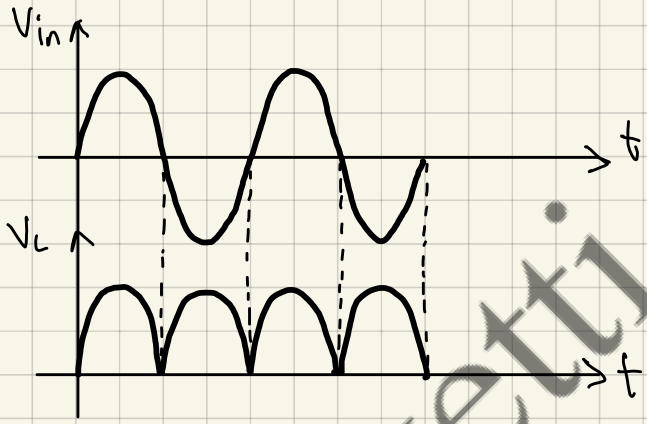


• $V_{in} > 0$: D1: OFF, D2: ON , $V_{O1} = \left(-R/R\right) V_{in} = -V_{in}$, $V_{out} = -\left(-\frac{V_{in}}{R/2} + \frac{V_{in}}{R}\right) R \overset{!}{=} V_{in} R \left(\frac{2}{R} - \frac{1}{R}\right) = V_{in}$

$V_{O2} \cong -V_{in} - 0.6V$

• $V_{in} < 0$: D1: ON, D2: OFF , $V_{O2} \cong -0.6V$, $V_{O1} = 0V$, $V_{out} = \left(-\frac{V_{in}}{R}\right) \cdot R = -V_{in}$





config. (b)

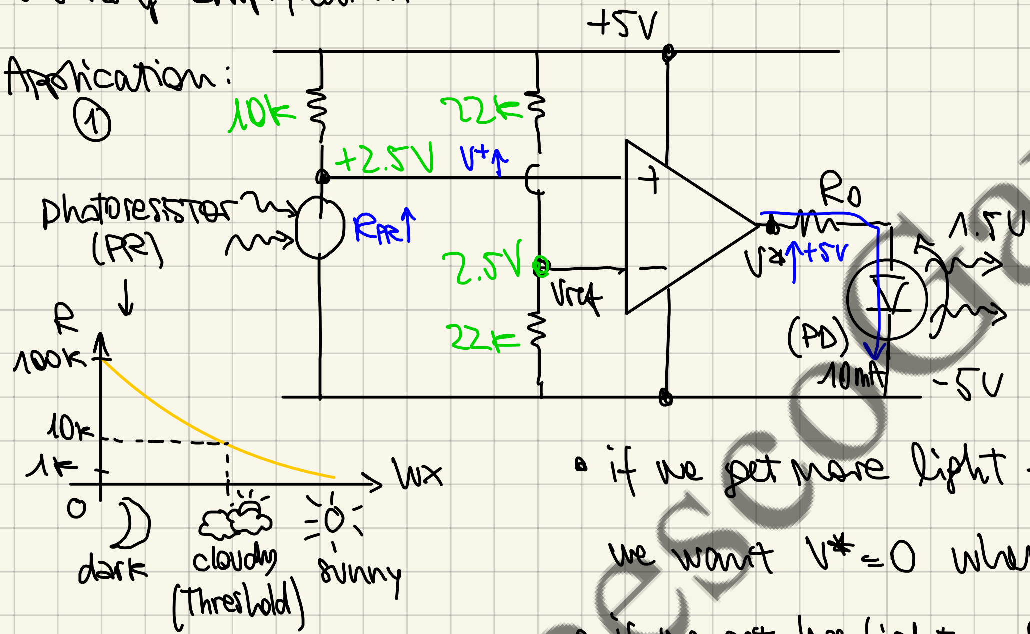
config. (c)

COMPARATORS (DISCRIMINATORS) (NO FEEDBACK)

• ONE-THRESHOLD DISCRIMINATOR (LEVEL DETECTOR)

when V_s is very close to V_r, if we move a little bit V_s compared to V_r we get a strong amplification

Application:
①



• if we get more light → R_{PR}↓ → V^+↓

we want $V^* = 0$ when $V^+ < V_{ref}$

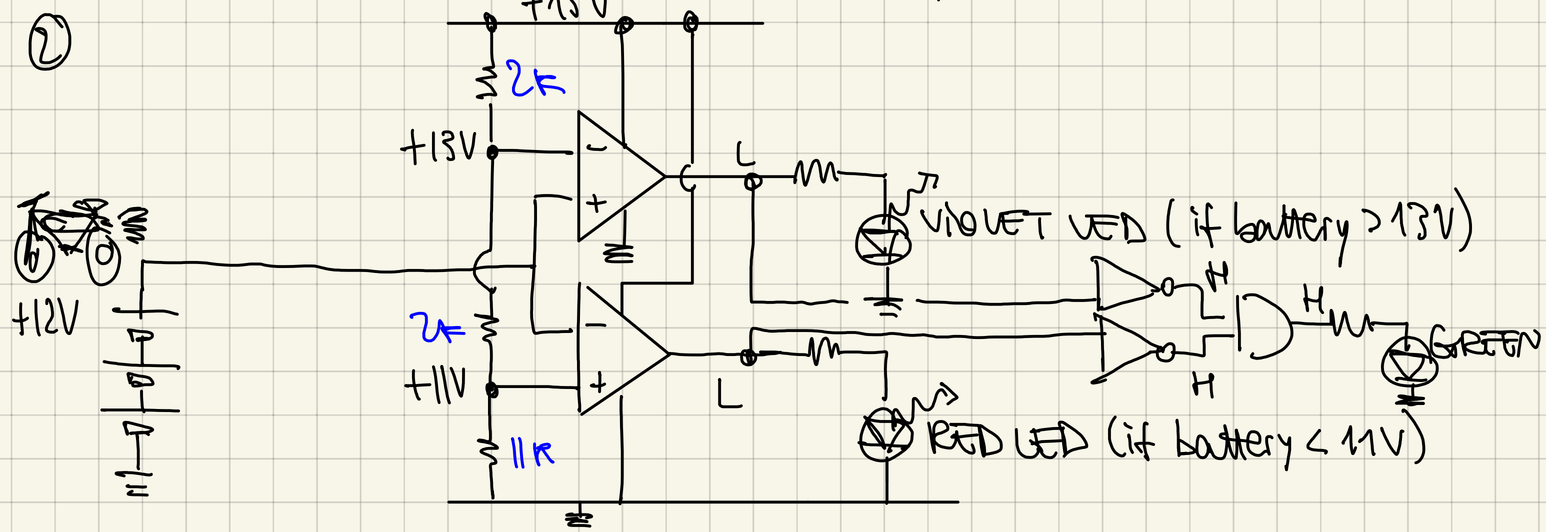
• if we get less light → R_{PR}↑ → V^+↑ → V^*↑

→ we can set R_0 in order to have the proper current we wish:

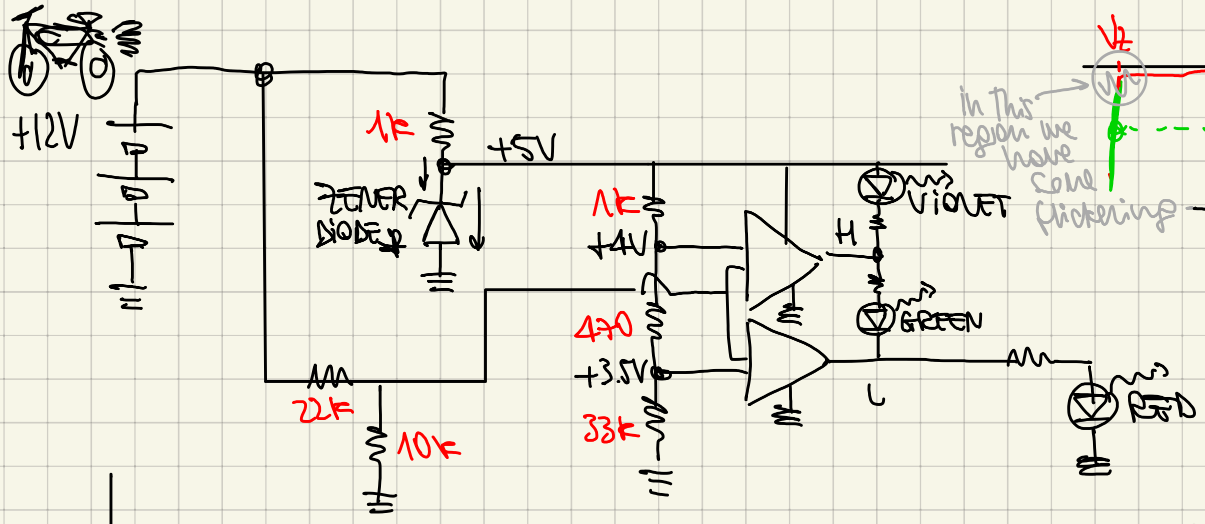
$$R_0 = \frac{5 - 1.5}{10\,mA} = 350\,\Omega$$

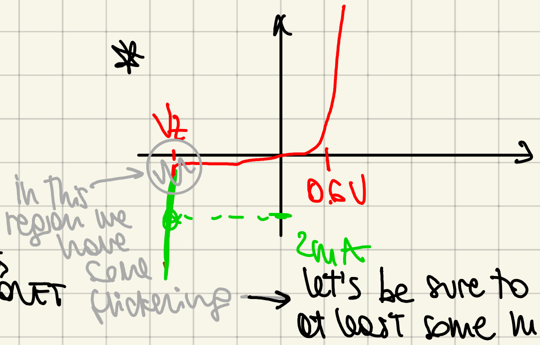
Now let's suppose we want to check the battery's charge level of our motorbike

②



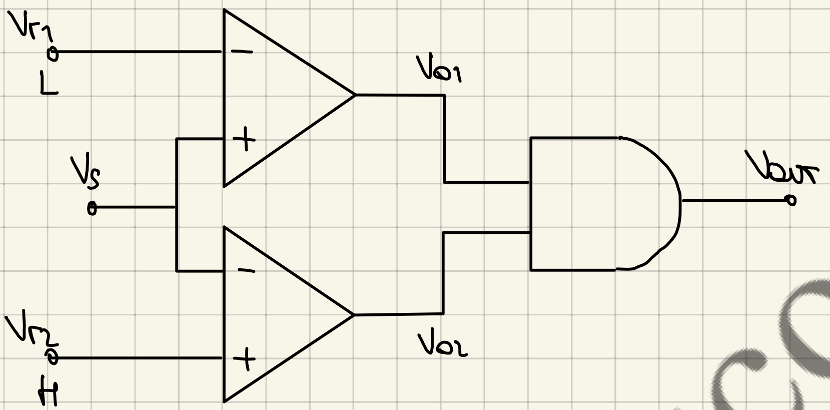
better solution :





let's be sure to have at least some mA across the Zener diode to avoid flickering noise

• TWO-THRESHOLDS DISCRIMINATOR ("WINDOW COMPARATOR")

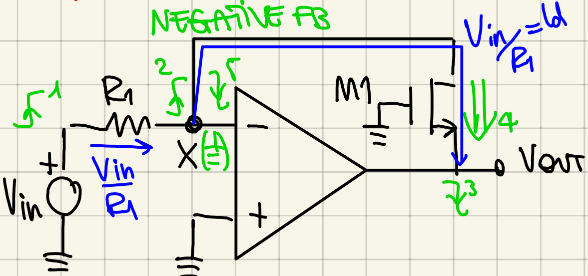


ES03 - OPAMP STAGES (3)

23/09/2021

SQRT AMPLIFIER

$$\left. i_{d,n}\right|_{sat} = \frac{1}{2}\mu_n C'_{ox}\left(\frac{W}{L}\right)_n (V_{GS}-V_{Tn})^2$$



$V_{GS} - V_t = V_{ov}$

$$\begin{cases} \dfrac{V_{in}}{R_1} = i_d \\ i_d = \dfrac{1}{2}\mu_n C'_{ox}\left(\dfrac{W}{L}\right)_1 (V_{GS}-V_{Tn})^2 \\ V_G = 0 \\ V_S = V_{OUT} \end{cases} \Rightarrow \frac{V_{in}}{R_1} = \frac{1}{2}\mu_n C'_{ox}\left(\frac{W}{L}\right)_1 (-V_{OUT}-V_{Tn})^2$$

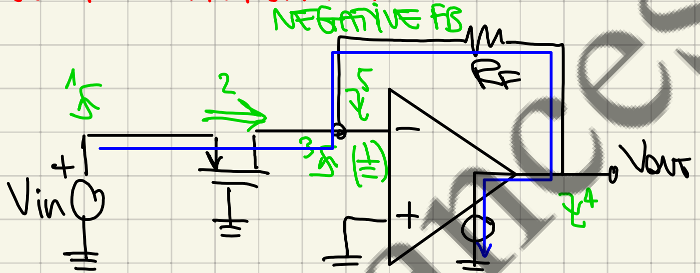
$$V_{OUT}^2 + V_{Tn}^2 - 2V_{Tn}V_{OUT} - \frac{V_{in}}{\frac{1}{2}\mu_n C'_{ox}\left(\frac{W}{L}\right)_1 R_1} = 0$$

$$V_{OUT}^2 - 2V_{Tn}V_{OUT} + V_{Tn}^2 - \frac{V_{in}}{\frac{1}{2}\mu_n C'_{ox}\left(\frac{W}{L}\right)_1 R_1} = 0$$

$$V_{OUT,1/2} = \underbrace{V_{Tn}}_{\text{DC term}} \pm \sqrt{\cancel{V_{Tn}^2} - \cancel{V_{Tn}^2} + \frac{V_{in}}{\frac{1}{2}\mu_n C'_{ox}\left(\frac{W}{L}\right)_1 R_1}}$$

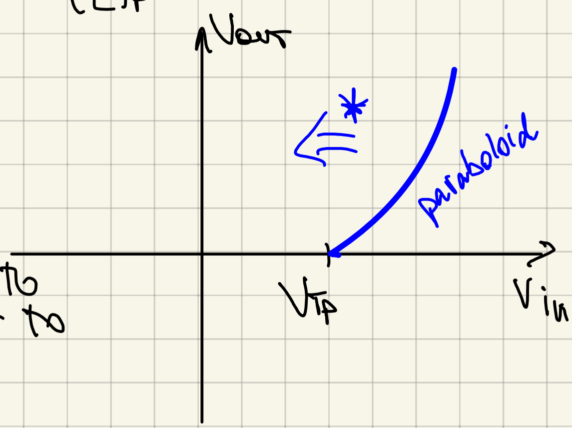
POWER-2 AMPLIFIER

$$\left. i_{d,p}\right|_{sat} = \frac{1}{2}\mu_p C'_{ox}\left(\frac{W}{L}\right)_p (V_{SG}-|V_{Tp}|)^2$$

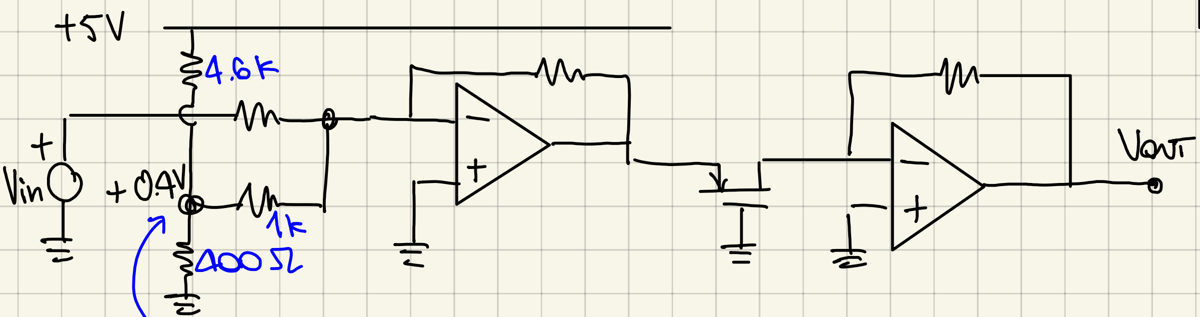


$$V_{OUT} = -i_{d,p}\cdot R_F = -\frac{1}{2}\mu_p C'_{ox}\left(\frac{W}{L}\right)_p (V_{in}-|V_{Tp}|)^2$$

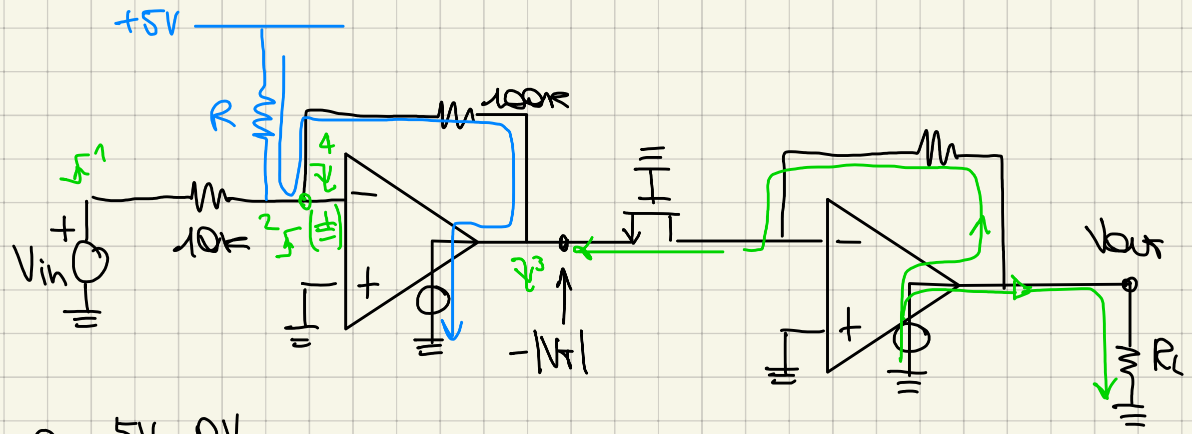
if $|V_{Tp}| = |-0.4|V \rightarrow \underbrace{V_{SG} > |V_{Tp}|}_{\exists \text{ channel condition}} \Rightarrow V_{in} > 0.4V$



* Notice: if we want to bring this paraboloid back to zero, so we have to play some trick in order to make Vin able to be @ 0V



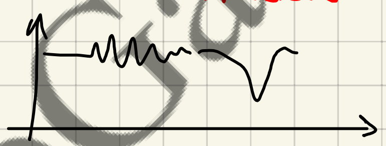
$$5V \cdot \frac{400\Omega // 1k}{400\Omega // 1k + 4.6k} \simeq 0.3\ldots$$

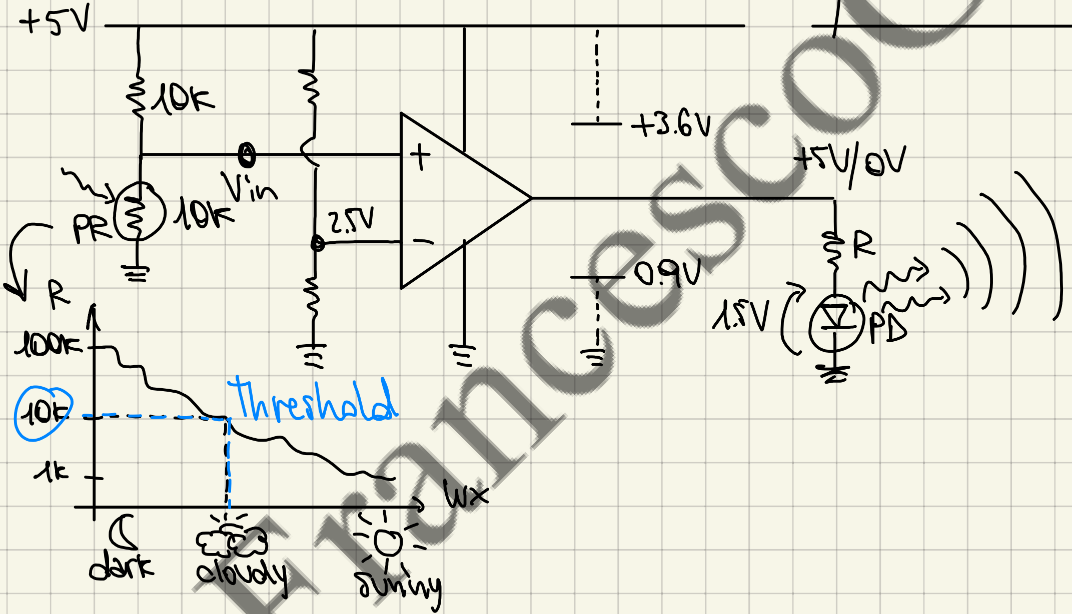


$$R = \frac{5V - 0V}{|V_t| / 100k} =$$

NEED OF HISTERISIS COMPARATOR → SCHMITT TRIGGER

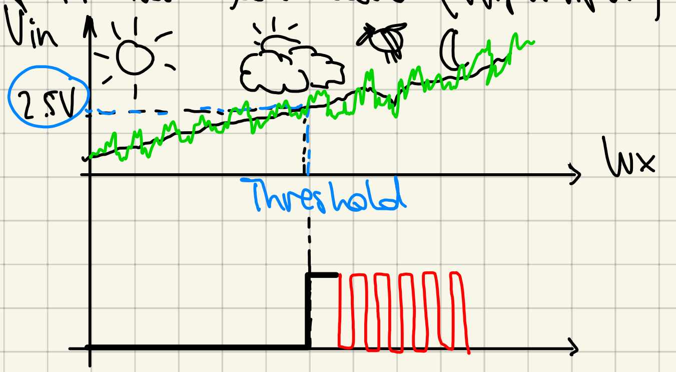
We have previously seen:





All the comparators presented so far suffer of a big issue: they all have a single voltage reference for threshold switching and so they suffer noise and other stuff... let's see!!

if PR has a low value (high light) → the Vin voltage is low too



It may happen that due to noise the Vin signal suffers of variations

The comparator will behave like this:

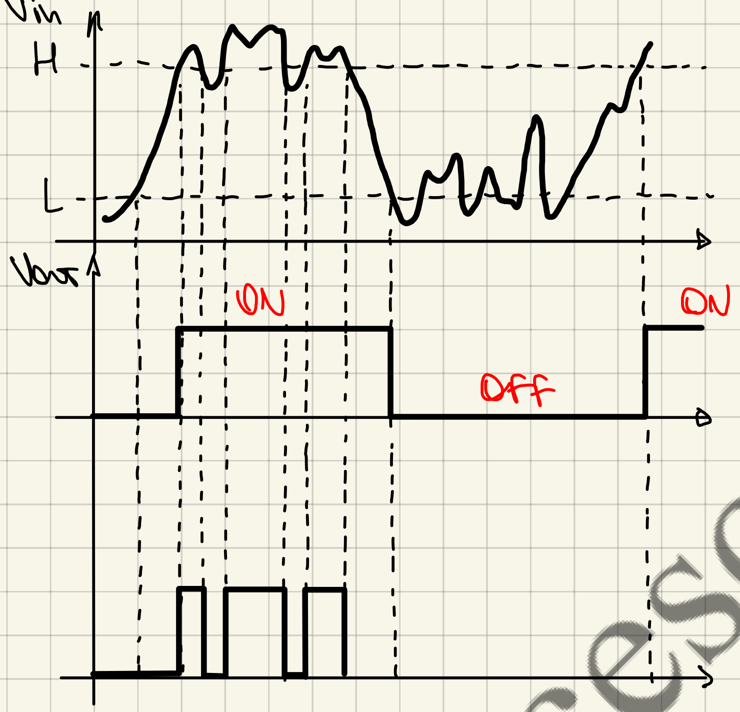
- when Vin < 2.5V → comparator is @ low value
- when Vin > 2.5V → comparator turns on

But if the LED turns on, it produces light and this light could introduce a negative FB to the PR itself

if there is more light → PR decreases its value and so Vin
→ so the comparator turns off
→ the LED turns off
→ PR increases again and so Vin
→ the comparator turns on again

To avoid this undesired effect (undesired commutations) must be avoid and to do so, we should use two thresholds

To avoid flippering "undecisions", let's implement two switching thresholds:



If the input signal passes the high threshold the comparator turns ON and it remains ON till it does not pass the low threshold, at that point it turns OFF

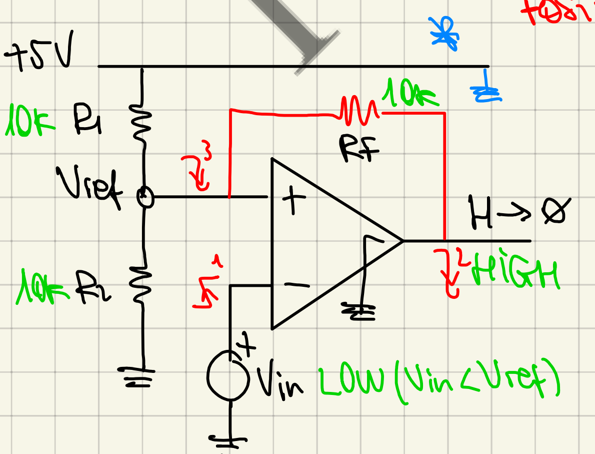
TRIGGER

COMPARATOR

How can we design such a comparator?

Let's get the previous comparator → to add the second threshold we have just to add a positive FB

- INVERTING SCHMITT TRIGGER



$V_{ref} = +5V \dfrac{R_1}{R_1+R_2} = 2.5V$

$V_L = +5V \dfrac{R_2 \| R_F}{R_2 \| R_F + R_1} = 1.7V$ (when output is low ≈ 0)

$V_H = +5V \dfrac{R_2}{R_2 + R_1 \| R_F} = 3.4V$ (when output is high ≈ 5V)

HYSTERESIS $\boxed{H = \Delta = V_H - V_L}$

The hysterisis is caused by the variation of V_{OUT} which varies from $0 \to 5V$

How can we compute it?

$\to$ let's turn off the PS * $\Rightarrow H = 5V \dfrac{R_1 \| R_2}{R_1 \| R_2 + R_F}$

if we decide $\begin{cases} \Delta \ll V_H \\ \Delta \ll V_L \end{cases}$ where $V_H = 2.6V$, $V_L = 2.4V$ $\to \Delta = 0.2V$

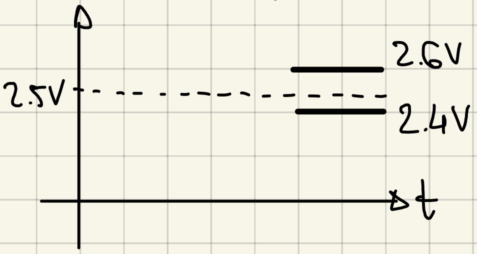
$\to$ if Δ is small $\to R \ll R_1, R_2 \to H = \Delta \simeq 5V \dfrac{R_1 \| R_2}{R}$

$(R \gg R_1 \| R_2)$

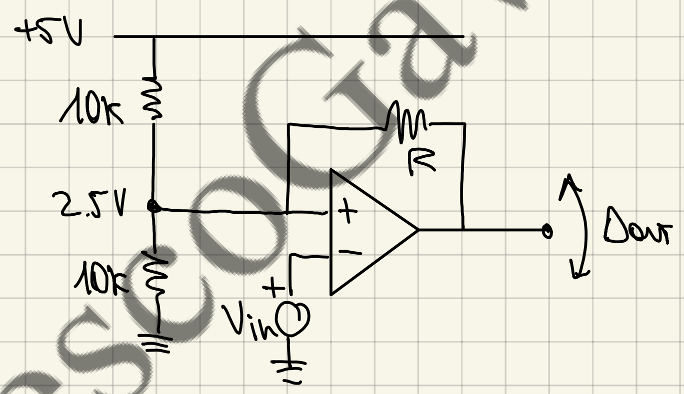
Instead of applying a system w/ 3 unknowns

$\downarrow$

Simplified sizing of the Schmitt Trigger

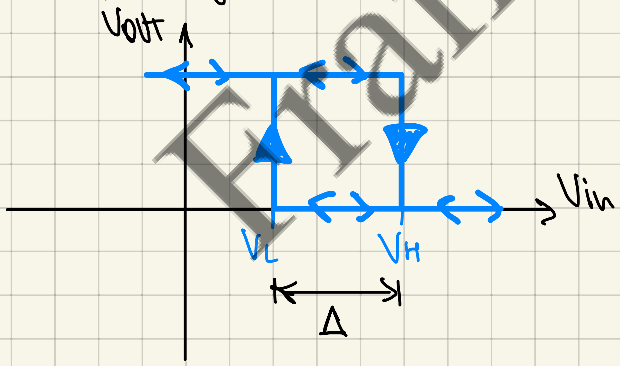


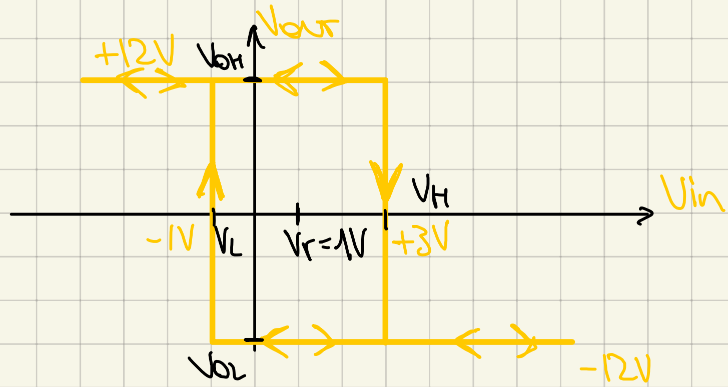
1. Create the threshold
2. Apply the threshold to the positive input of the OpAmp
3. Apply the hysterisis adding R in positive loop
4. The hysterisis we want to apply is:



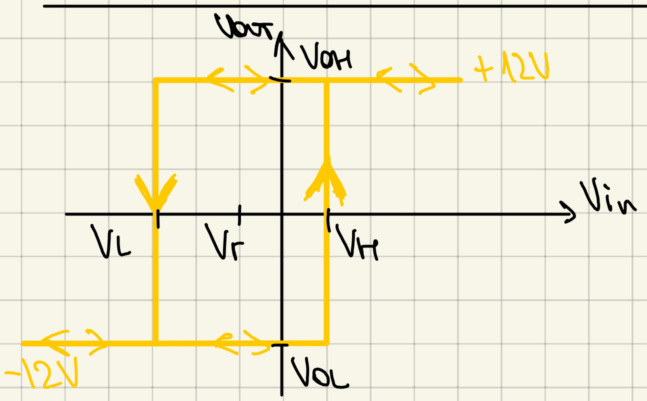
$$\Delta \simeq D_{OUT} \cdot \frac{R_1 \| R_2}{R} \to 0.2 \simeq 5 \cdot \frac{5k}{R} \to R = \frac{5V}{0.2V} \cdot 5k = 125k\Omega$$

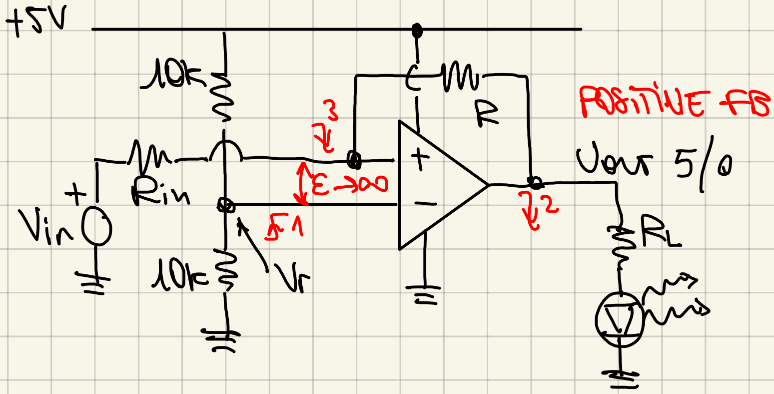
D_{OUT} $\downarrow$ output swing





• NON-INVERTING SCHMITT TRIGGER



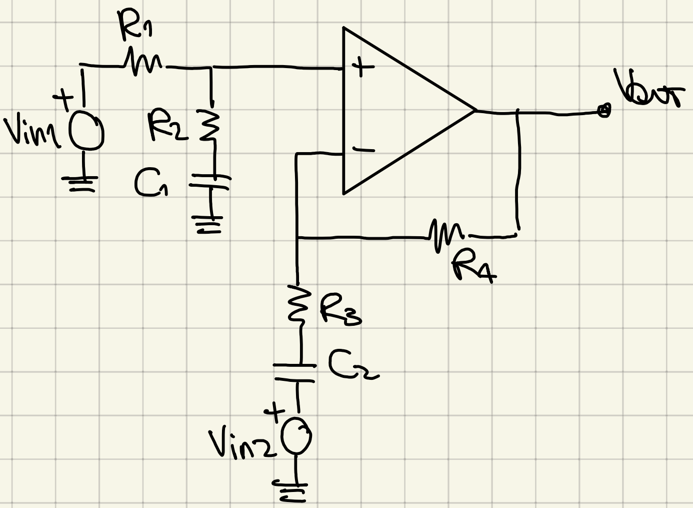


The feedback is positive, but if by chance $V^+ = V_{ref}$:

$$I_{R_{in}} = \frac{V_{in}-V_{ref}}{R_{in}} = I_R = \frac{V_{ref}-V_{out}}{R} \quad \text{where } V_{out} = \begin{cases} 5V \\ 0V \end{cases}$$

- if $V_{out} = 5V \rightarrow \frac{V_{in}-V_{ref}}{R_{in}} = \frac{V_{ref}-5V}{R} \rightarrow V_H =$
- if $V_{out} = 0V \rightarrow \frac{V_{in}-V_{ref}}{R_{in}} = \frac{V_{ref}-0V}{R} \rightarrow V_L =$

EXERCISE 1

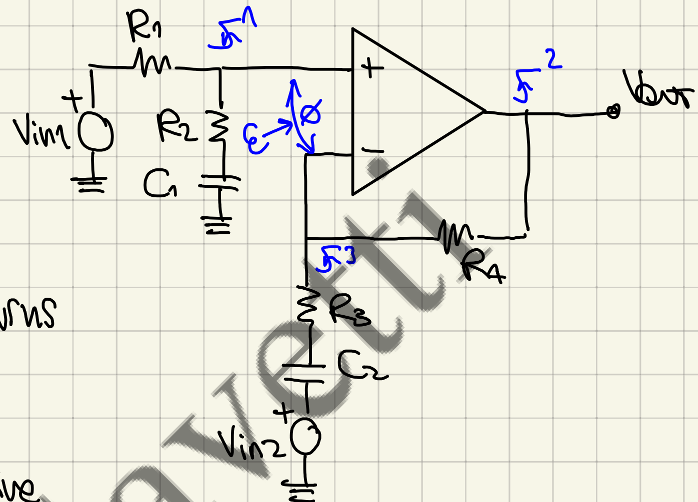


$R_1 = 20k\Omega$, $R_2 = 30k\Omega$, $R_3 = 1k\Omega$, $R_4 = 10k\Omega$

$C_1 = 200nF$, $C_2 = 1nF$

$A_0 = 10^6$ $I_B = 10nA$ $f_0 = 10Hz$

① FEEDBACK CHECK



Notice:
- if in the FB path there are just passive components and it returns to the ⊖ pin
  → the FEEDBACK is NEGATIVE
- if in the FB path there are active components (transistors, opamps, etc) even if the FB path returns to the ⊖ pin
  → we have to check it !!!

In this case it's evident that the FB is NEGATIVE but we can check it anyway

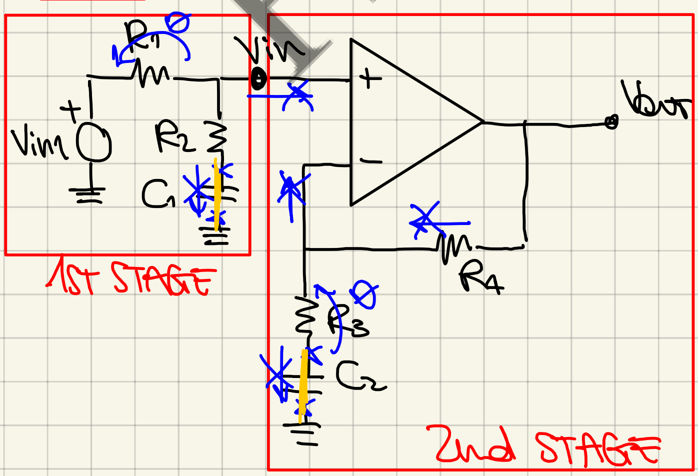
② ASYMPTOTIC ANALYSIS

Notice: we can notice that we have two inputs and that the circuit can be divided in two stages

↓

Let's study the behavior of the circuit considering the two inputs separately

Ⓐ $\boxed{V_{in1}}$ → let's short V_{in2} → then let's study the two stages separately



- 1st STAGE

@DC → C open → $\frac{V_{in}}{V_{in1}}(0) = 1$

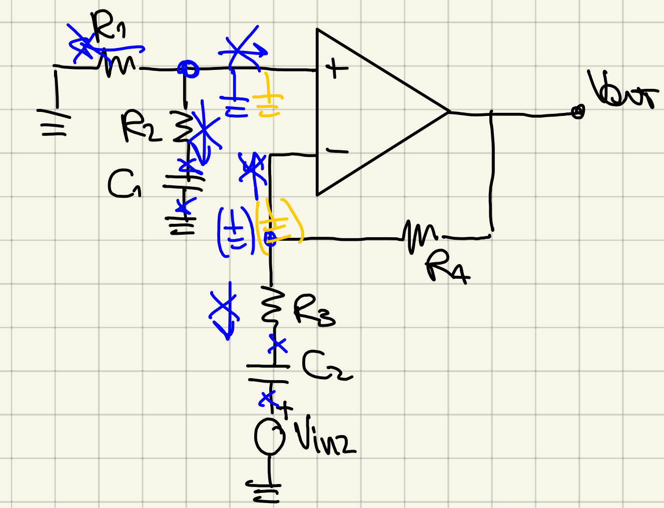
@HF → C short → $\frac{V_{in}}{V_{in1}}(\infty) = \frac{R_2}{R_1+R_2} = 0.6$

- 2nd STAGE

@DC → C open → $\frac{V_{out}}{V_{in}}(0) = 1$

@HF → C short → $\frac{V_{out}}{V_{in}}(\infty) = 1 + \frac{R_4}{R_3} = 11$

B) $\boxed{V_{in2}}$ → let's short V_{in1} → Notice: now there's just one stage to consider



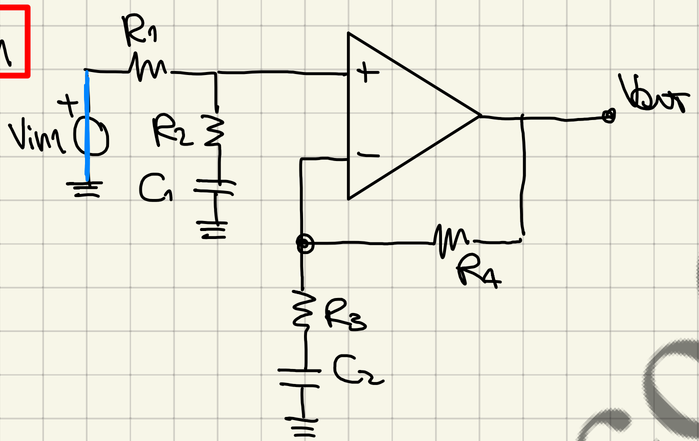
@DC → C open → $\frac{V_{out}}{V_{in2}}(0) = 0$

@HF → C short → INVERTING STAGE

→ $\frac{V_{out}}{V_{in2}}(\infty) = -\frac{R_4}{R_3} = -10$

③ POLES & ZEROS

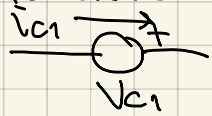
A) $\boxed{V_{in1}}$



- POLES: → × short all the generators

  × compute the equivalent resistance seen by the capacitor

  ↳ so we should replace the capacitor under investigation w/ a test generator ex:



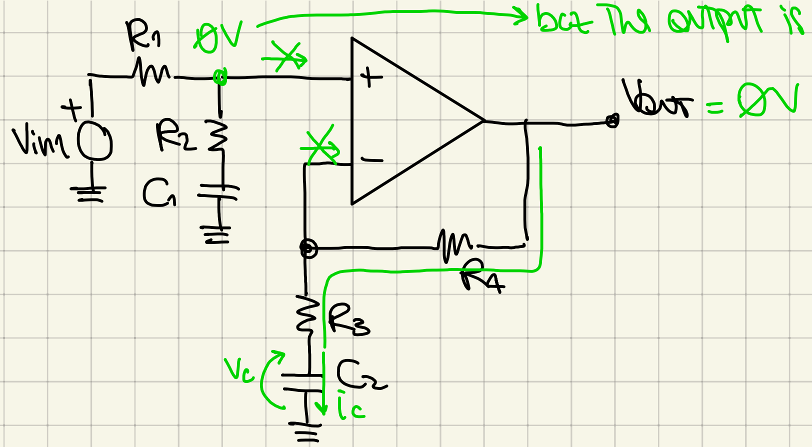
$$f_{p1} = \frac{1}{2\pi C_1(R_1+R_2)} = 16\text{ Hz}$$

$$f_{p2} = \frac{1}{2\pi C_2 R_3} = 160\text{ kHz}$$

- ZEROS:

× METHOD 1 = "BY CALCULUS"

- put the output @ 0V
- keep the signal generator
- replace the capacitor under investigation w/ a test generator and compute the resistance seen by the capacitor / the generator

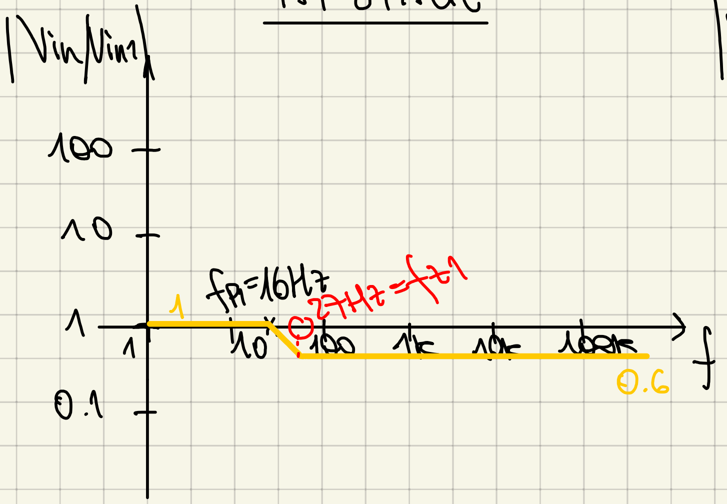


$$f_{z1} = \frac{1}{2\pi C_1 R_2} \simeq 27\ Hz$$

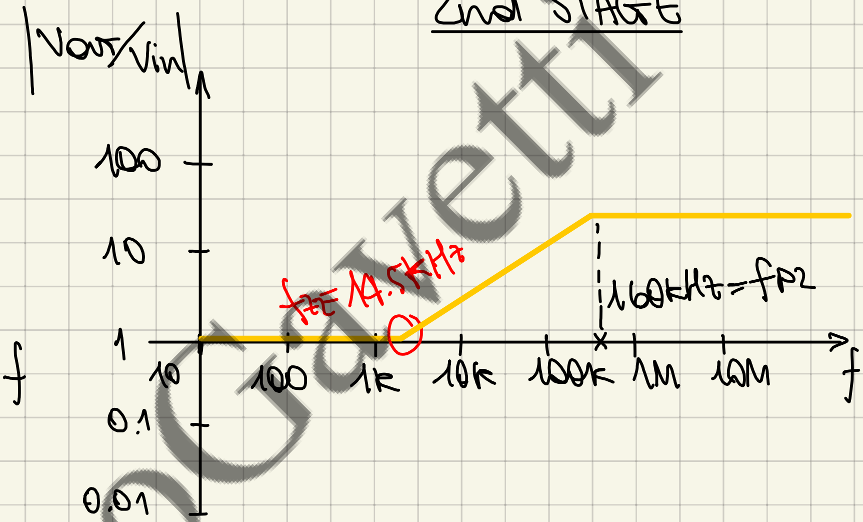
$$f_{z2} = \frac{1}{2\pi C_2 (R_3+R_4)} \simeq 14.5\ kHz$$

× <u>METHOD 2</u> = "GRAPHICALLY"

<u>1st STAGE</u>



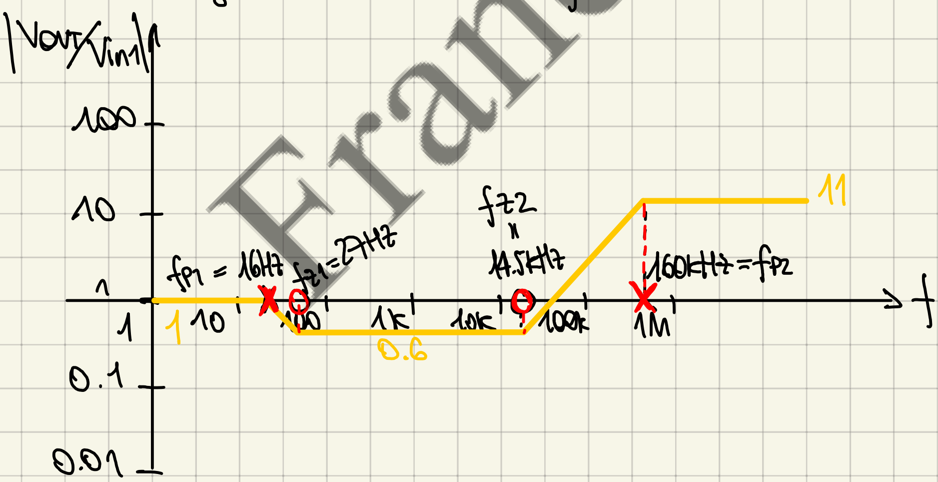
<u>2nd STAGE</u>



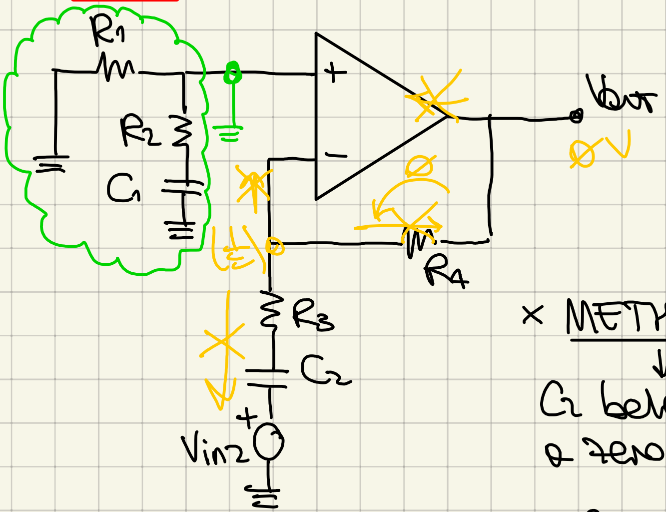
$$\boxed{f_{z1} = f_{p1}/0.6 = 27Hz}$$

$$\boxed{f_{z2} = f_{p2}/11 = 160kHz/11 = 14.5\ kHz}$$

In conclusion for the 1st signal generator we can plot the final Bode diagram in this way:



B $\boxed{V_{in2}}$



• POLES:

$$f_{P2} = \frac{1}{2\pi C_2 R_3} = 160\,kHz$$

• ZEROS:

× METHOD 1 := "THEORETICALLY"

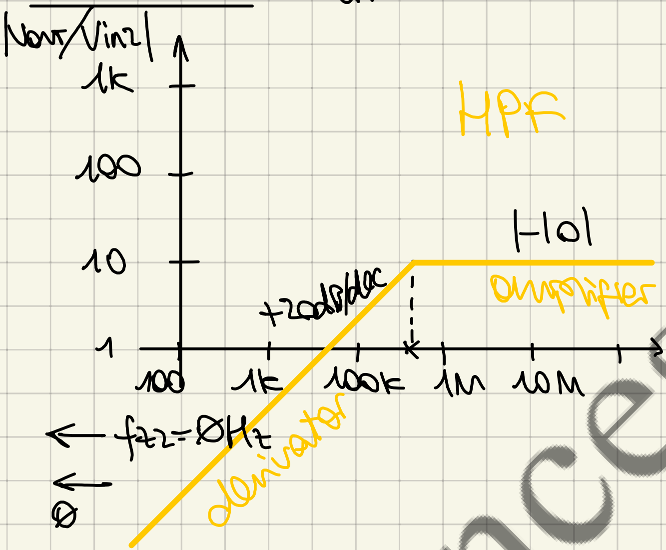
↓

C_2 belongs to the signal path so it introduces a zero @ $f=0$

→ $f_{Z2} = 0\,Hz$

× METHOD 2 := "BY COMPUTATION"

× METHOD 3 = "GRAPHICALLY"



from the graph it's easy to see that there must be a zero @:
$f_{Z2} = \varnothing\,Hz$.

+20dB/dec → GBWP = $f_{P2}/10$ = 160Hz

EXAMPLE 2

Calvin measures his bike's speed s, by employing Hobbe's speedometer ($V_s = s \cdot 50\,mV/m/s + 200\,mV$) and 10V FSR voltmeters

(A) Design a circuit for displaying the speed, up to 40km/h, w/ 3s smoothing.

$S_{FSR} = 40\,km/h \leftrightarrow V_{S,FSR} = 10V$

$$V_s = \left(40\,km/h \cdot 50\frac{mV}{m/s} + \cancel{200}\,mV\right) G = 10V$$

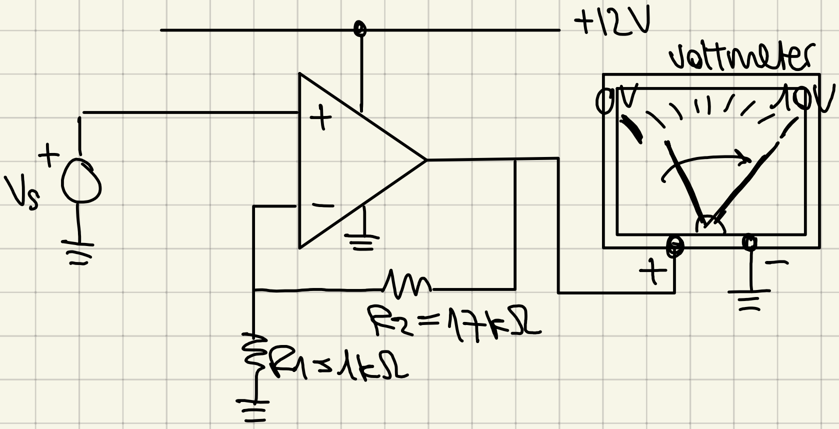
let's neglect this term → we'll design a circuit in order to cancel out this DC term

$$\rightarrow V_s = 40 \cdot \frac{1000\,m}{3600\,s} \cdot \frac{50\,mV}{m/s} = 555\,mV \cdot G = 10V$$

↓

I need an amplification to reach 10V of FSR

$G = \frac{10V}{550mV} \cong 18$ → I need to design an amplifier w/ this gain

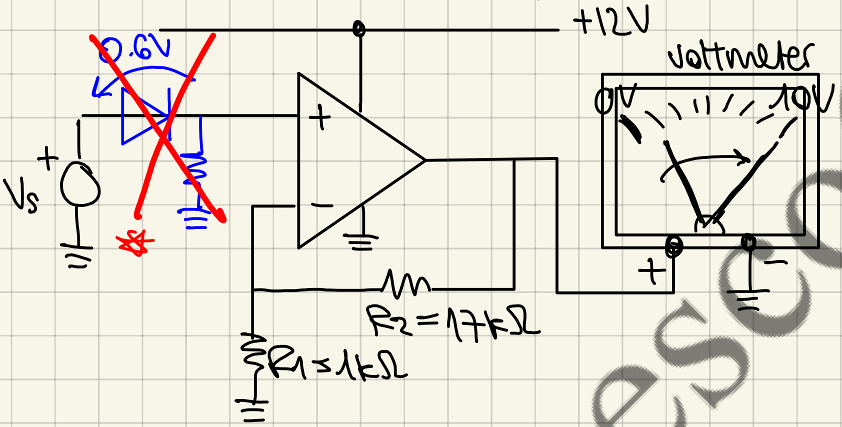


it's a non-inverting stage
↓
$A_0 = 1 + \frac{R_2}{R_1} = 18$

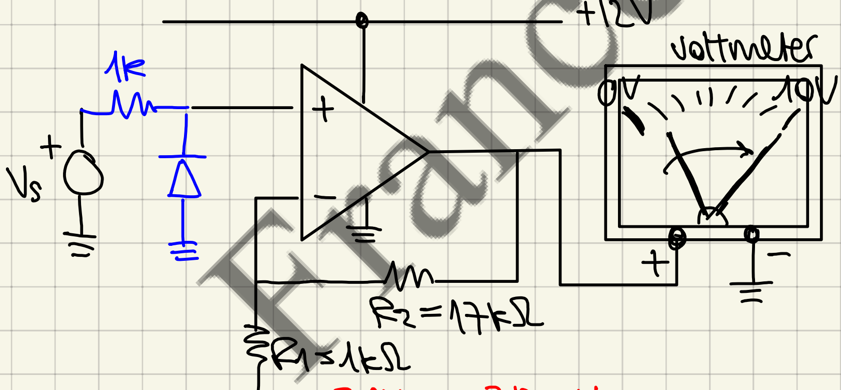
$\rightarrow \frac{R_2}{R_1} = 17 \rightarrow \begin{cases} R_2 = 17k\Omega \\ R_1 = 1k\Omega \end{cases}$

Beware: set the PS btw +12V and ØV, bcz if we set the PS btw [+12V, -12V] we run the risk to burn the OpAmp bcz we apply a voltage which is outside the CMIVR

Can we limit the input in order to not become negative?
↳ let's use a diode → only a positive signal will pass through it



* But we don't like this solution bcz in this way we lose 0.6V and we cannot afford it

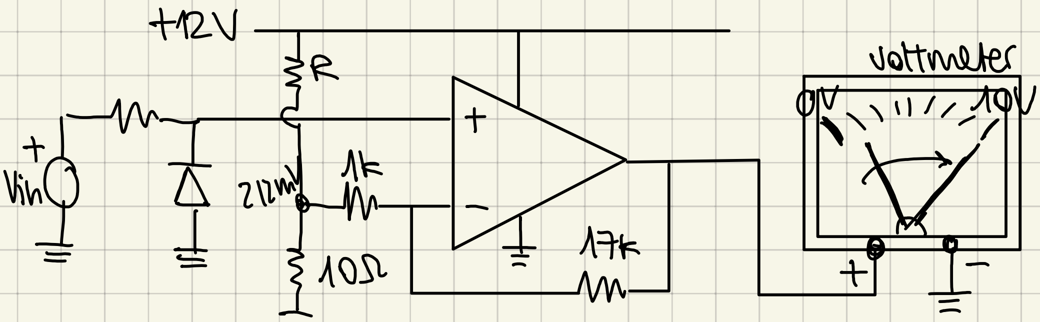


Now we have to find a way to cancel the 200mV DC
↓
$200mV \cdot 18 = 3.6V$
↓
at the output we have to subtract 3.6V in order to remove the 200mV DC value in input

$3.6V / 17 = 212\ mV$

↳ Do we have to use a battery? NO!!

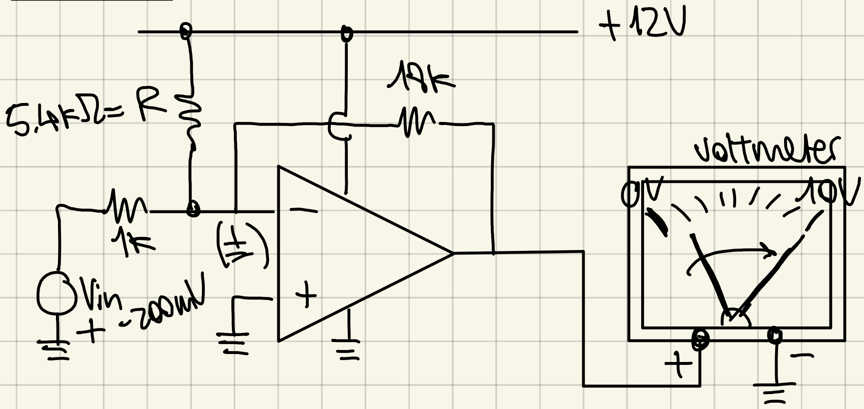
SOLUTION ①



$12 \cdot \frac{10}{10+R} = 0.217$

R =

SOLUTION ②

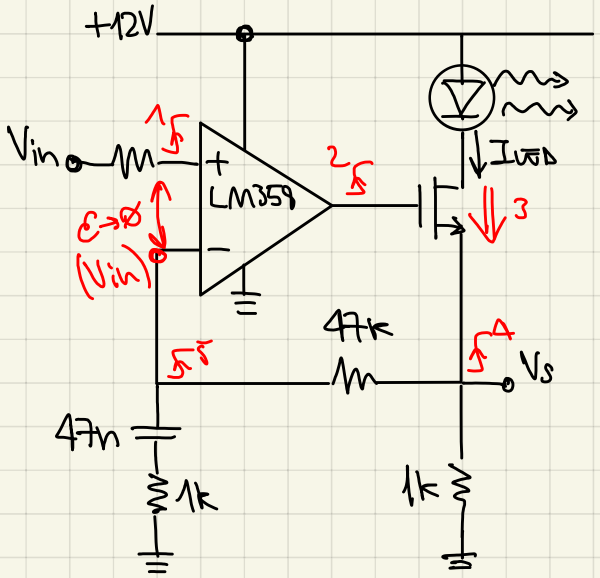


$$\frac{12V - 0V}{R} \cdot 18k = 3.6V$$

$$\downarrow$$

$$R = \frac{3.6}{12} \cdot 18k = 5.4k\Omega$$

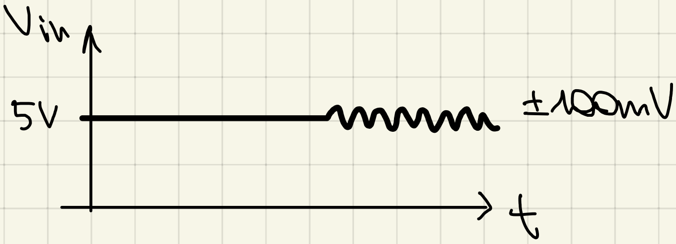
EXAMPLE ③



MOSFET: $V_T = 0.5V$

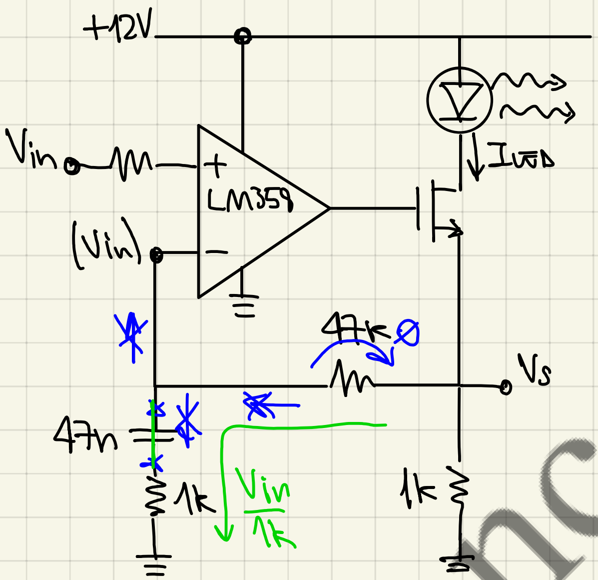
$k = \frac{1}{2}\mu_n C'_{ox}\left(\frac{W}{L}\right)_n = 12\,mA/V^2$

$V_{in}(t)$ has 5V DC + (±100mV) sinusoid



Ⓐ Compute I_{LED}/V_{in} relationship @DC and I_{LED} for $V_{in} = 5V$

NEGATIVE FB → V-to-I converter (If we had a positive feedback it would have been a comparator)



@DC → C open → $V_s = V_{in}$ → $G(0) = 1$

@HF → C short → $V_s = V_{in}\left(1 + \frac{47}{1}\right)$ → $G(\infty) = 48$

$$I_{LED}(0) = \frac{V_s}{1k} = \frac{V_{in}}{1k}$$

$$\rightarrow \frac{I_{LED}(0)}{V_{in}} = 1\,mA/V$$

$$i_{LED}(\infty) = \frac{V_s}{1k} + \frac{V_{in}}{1k} = \frac{1}{1k}\left(48V_{in} + V_{in}\right) = V_{in}\,\frac{49}{1k}$$

$$\frac{i_{LED}}{V_{in}}(\infty) = \frac{49}{1k} = 49\,mA/V$$

$V_{in} = 5V$ DC → $I_{LED}(0) = 1\frac{mA}{V} \cdot 5V = 5mA$