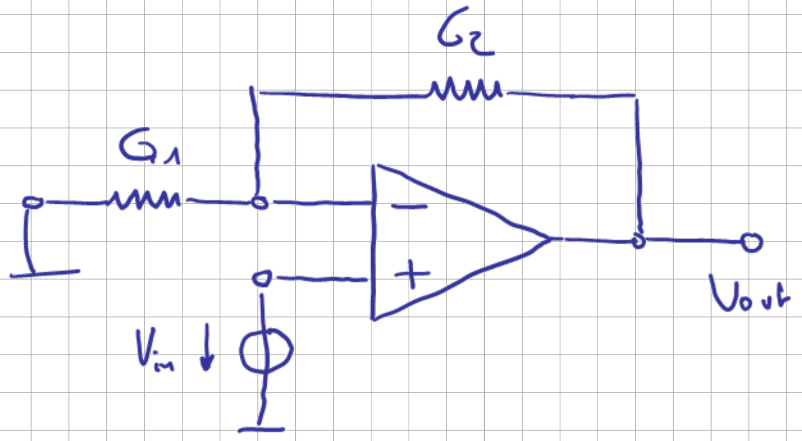
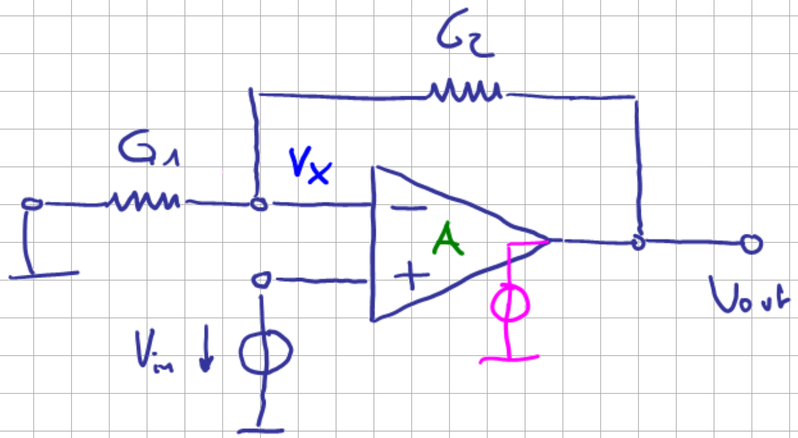
Simple amplifier with an OpAmp: complete analysis

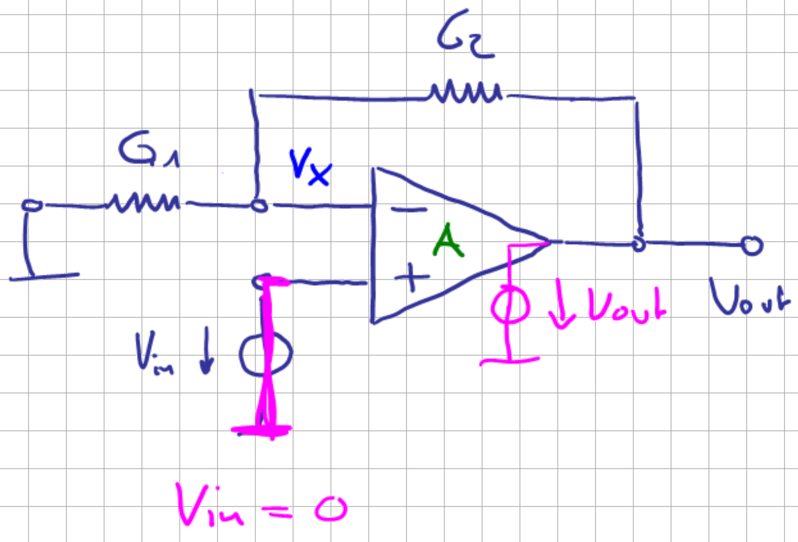


I will assume that you know Mason's gain rule (→ teaching videos)

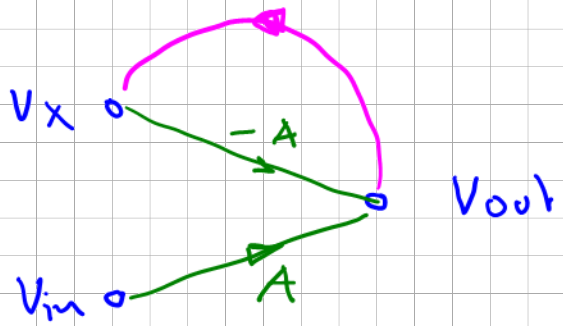
- Analysis with conventional SFG
- Loop gain, open-loop gain, closed-loop gain
- Analysis with driving-point SFG
- Positive vs. negative input
- Bandwidth, gain-bandwidth product
- Stability and phase margin
- Output resistance
- Noise analysis (resistor and amplifier noise)
- Slew rate constraints
- SFG for an amplifier with the AD812 CFB OpAmp



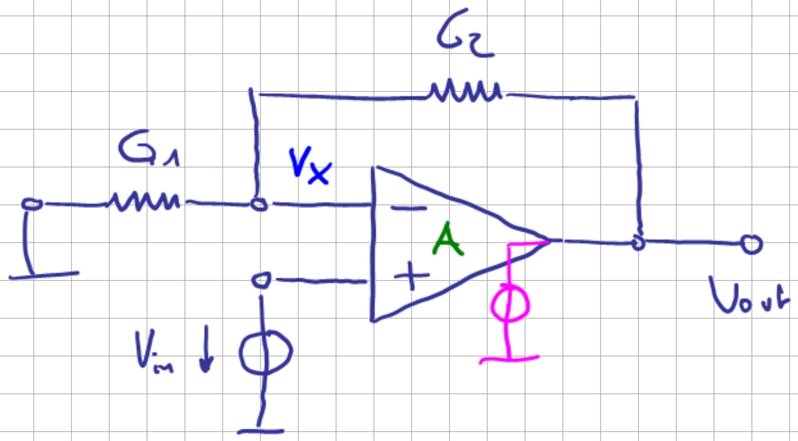
G2
G1
Vx
A
Vin
Vout

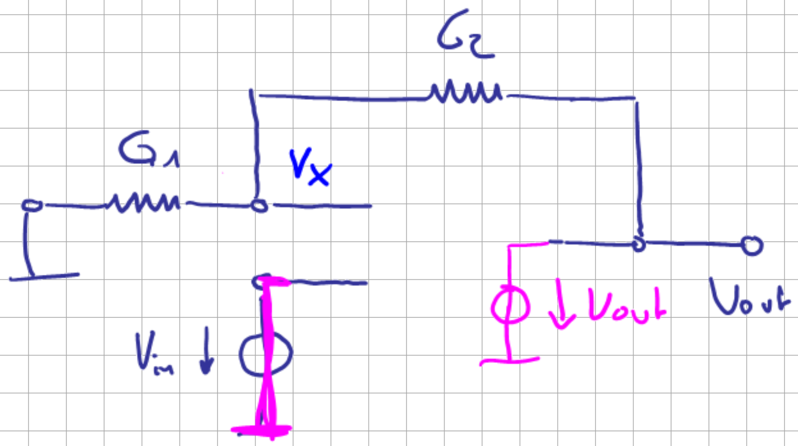


G2
G1
Vx
A
Vin
Vout
Vout
Vin = 0

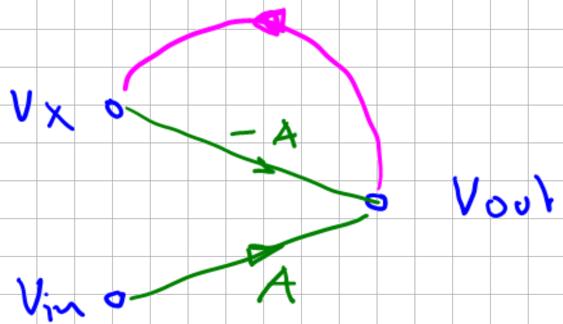


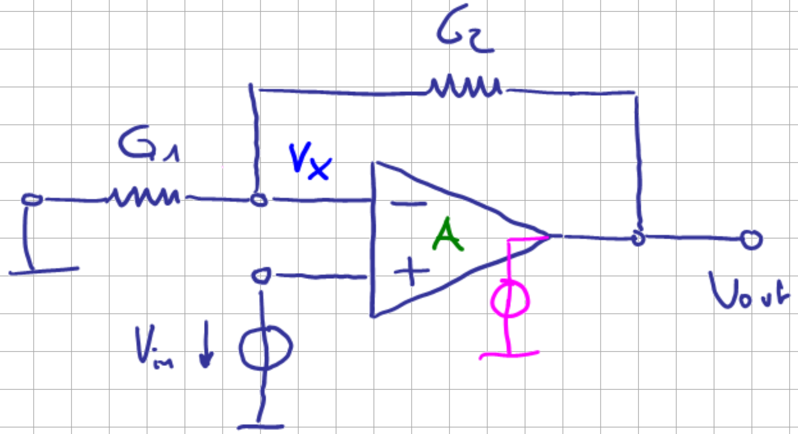
Vx
-A
Vout
Vin
A

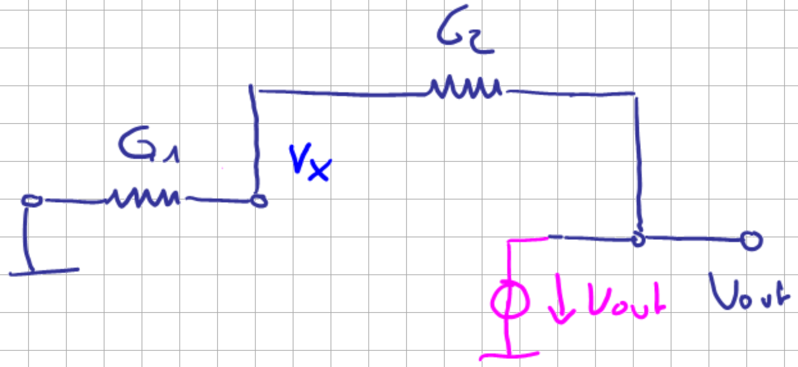




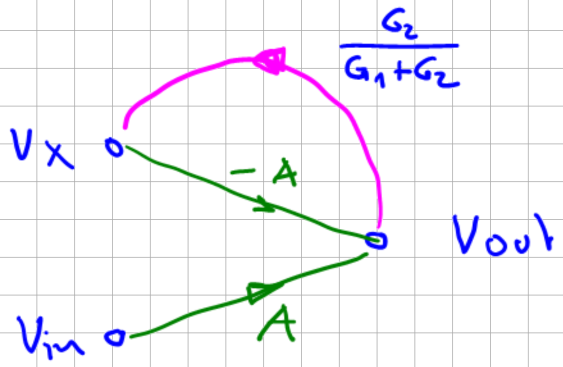
$V_{in} = 0$

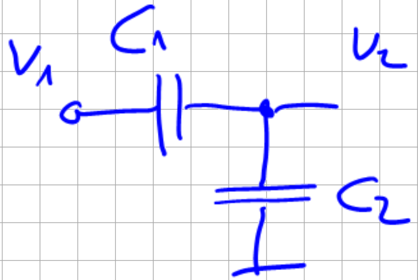




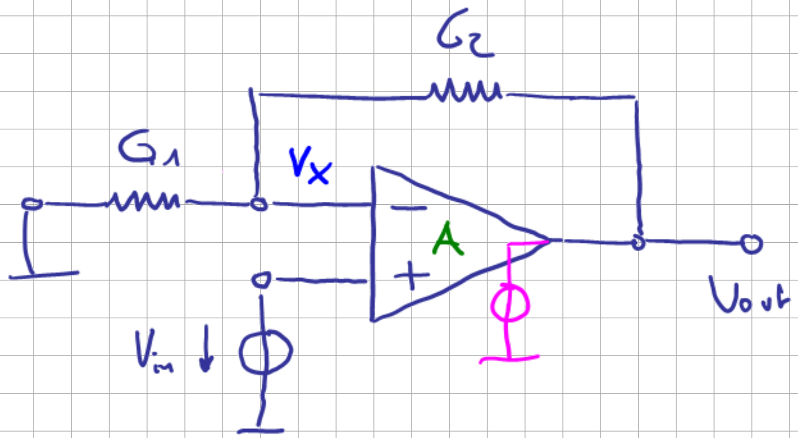


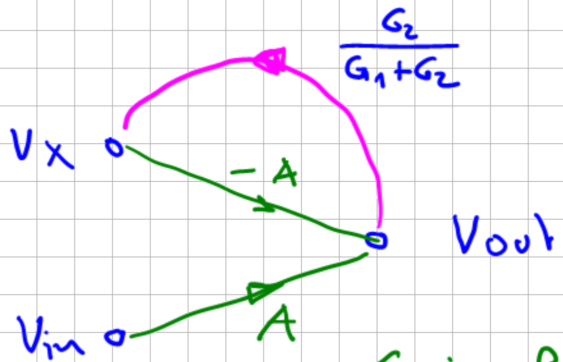
$$\frac{V_x}{V_{out}} = \frac{G_2}{G_1 + G_2}$$

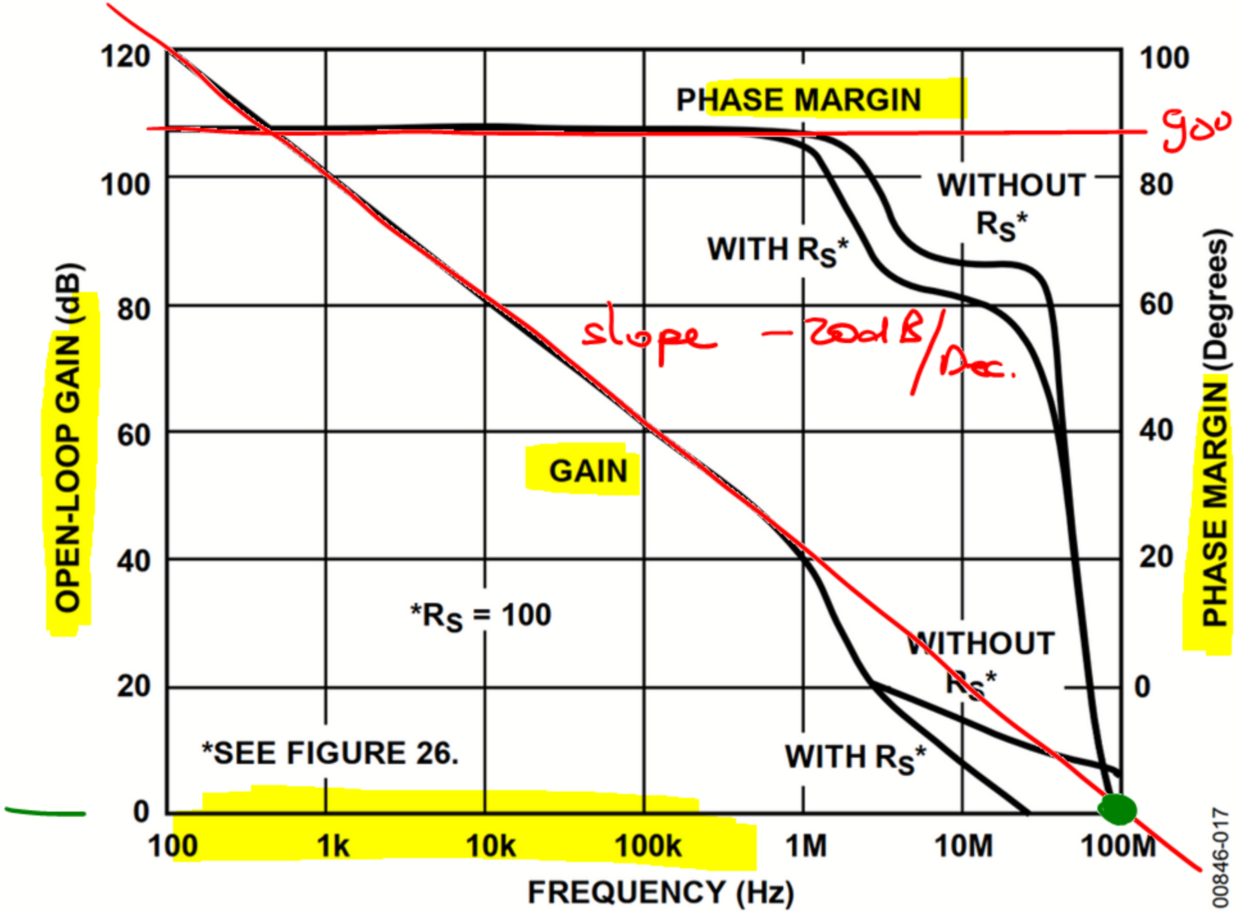




$$\frac{V_2}{V_1} = \frac{Y_{C1}}{Y_{C1} + Y_{C2}} = \frac{j\omega C_1}{j\omega C_1 + j\omega C_2}$$







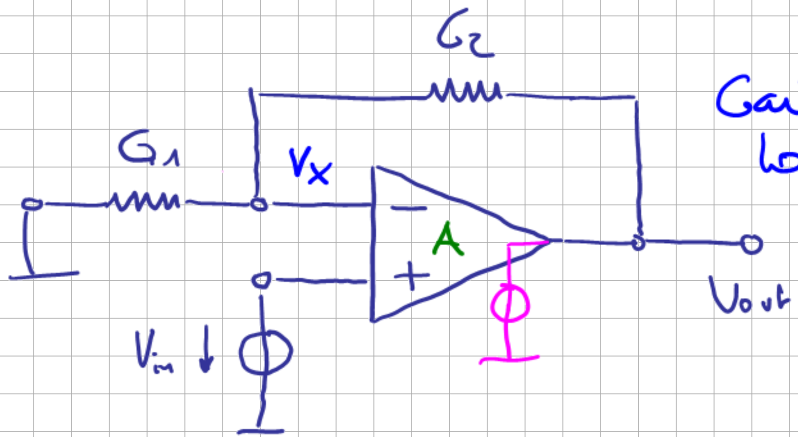
Gain-BW-Product $\cong$ 100 MHz $\cdot 2\pi$

Figure 16. Open-Loop Gain and Phase Margin vs. Frequency

Phase $= -90°$

$$\Rightarrow A \approx \frac{\omega_t}{s}$$

$$PM = \text{Phase} + 180°$$



$A \approx \frac{\omega_1}{s}$ Open-loop gain (OpAmp)

Gain of the loop

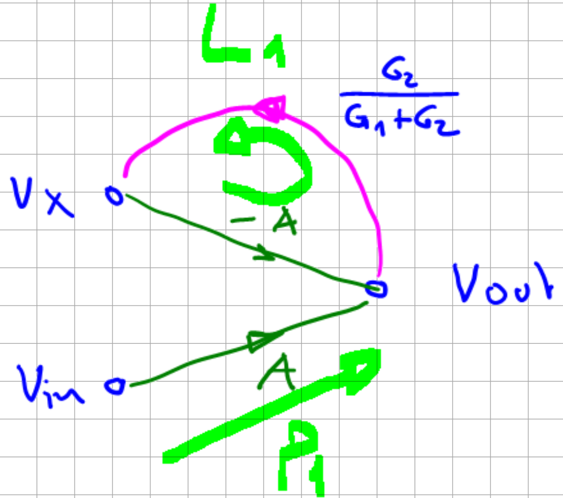
$$\boxed{L_1 = -A \cdot \frac{G_2}{G_1+G_2}}$$ Loop gain

$$\Delta = 1 - L_1 = 1 + A \frac{G_2}{G_1+G_2}$$

$$(G_1+G_2)\,\Delta = G_1+G_2+A\,G_2$$

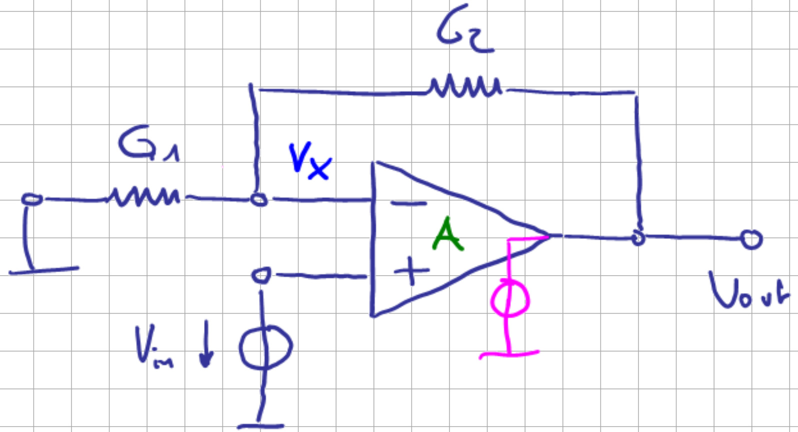
$$P_1 = A \qquad \Delta_1 = 1$$

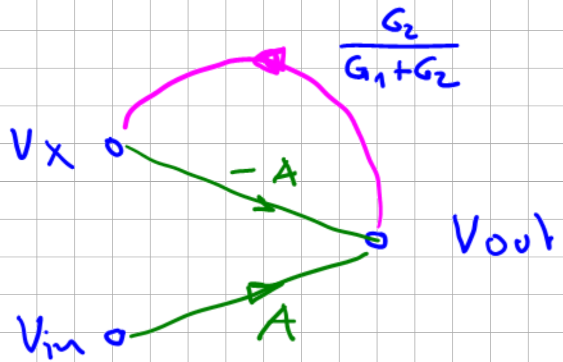
$$(G_1+G_2)\,P_1\,\Delta_1 = A\,(G_1+G_2)$$

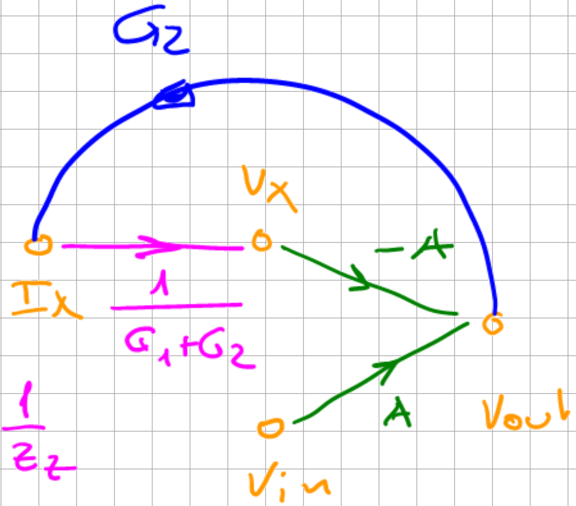


$$\frac{V_{out}}{V_{in}} = \frac{A\,(G_1+G_2)}{G_1+G_2+A\,G_2}$$

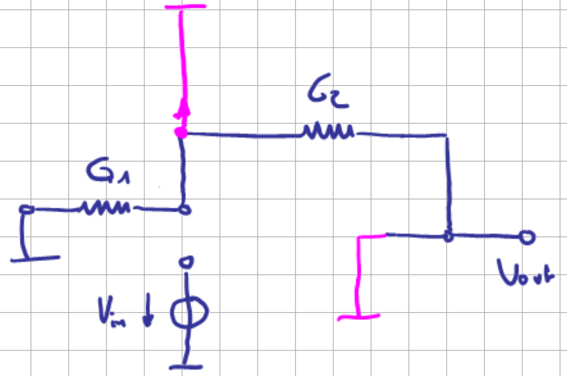
Closed-loop gain
(result Mason)

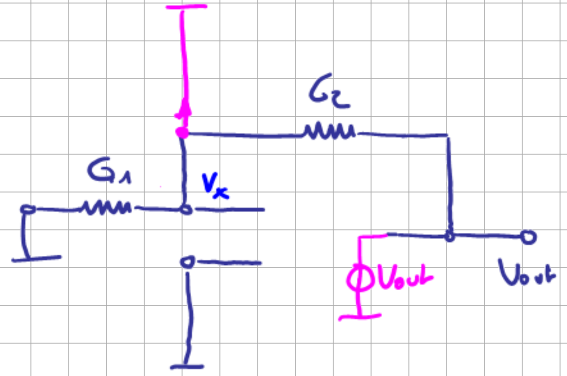


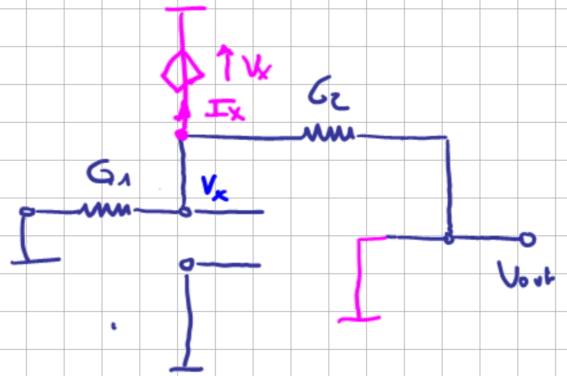




$$Y_x = \frac{1}{Z_z} = G_1 + G_2$$

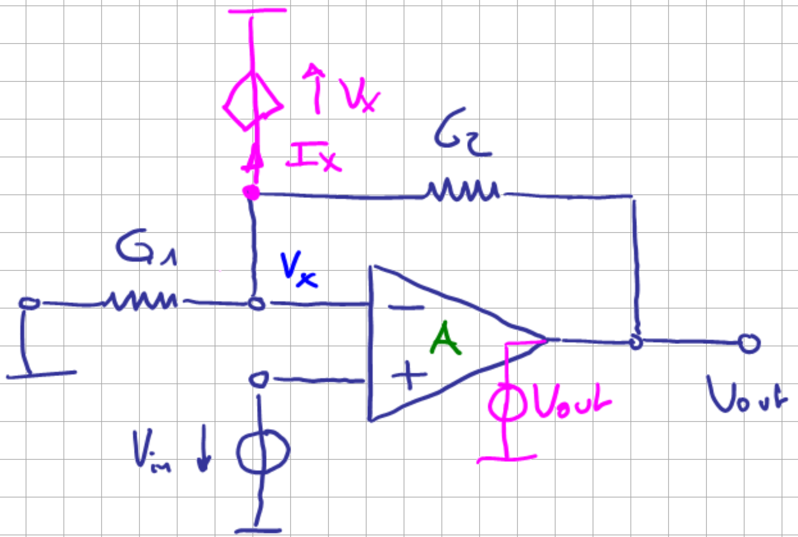

G2
G1
Vout
Vin

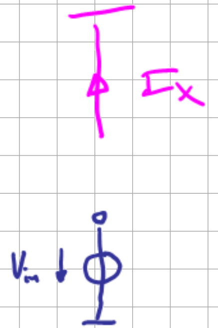

G2
G1
Vx
Vout
Vout

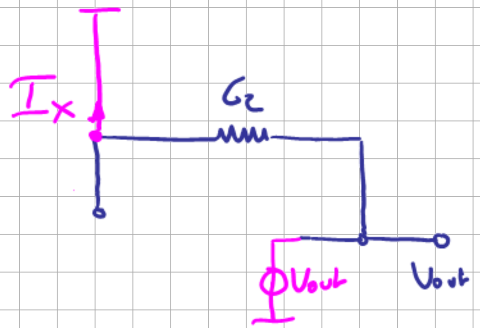

Vx
Ix
G2
G1
Vx
Vout

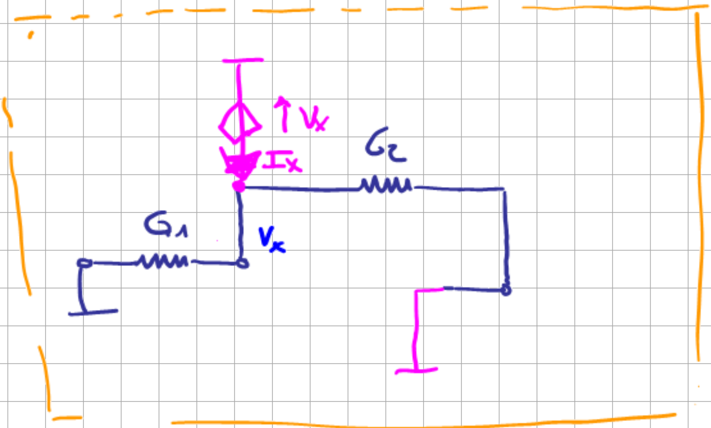
V_{in} ?

$V_{out} = V_x = 0$


Vx
Ix
G2
G1
Vx
−
A
+
Vout
Vout
Vin







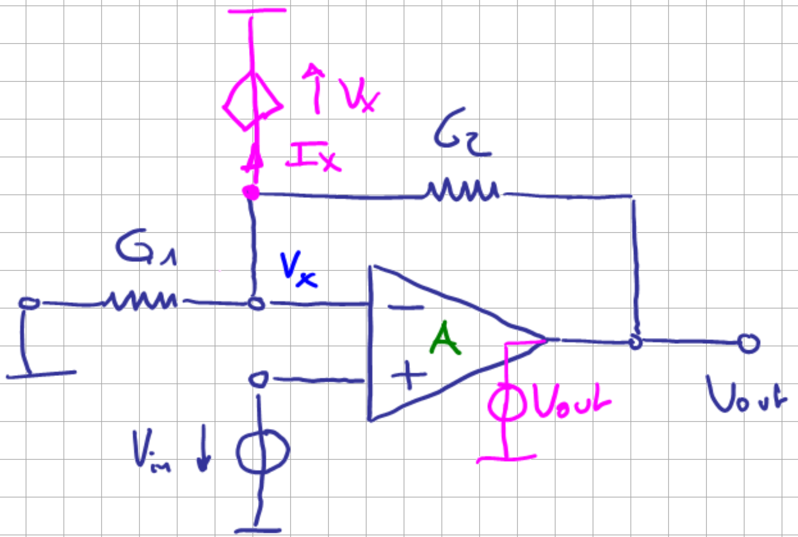
V_{in} ?

$V_{out} = V_x = 0$

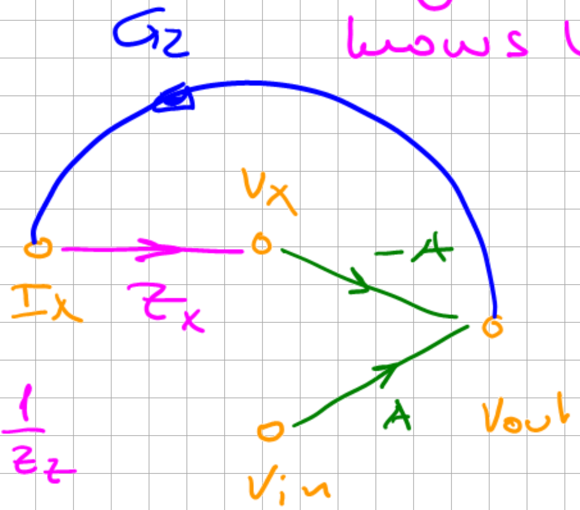
I_x in Graph is for

$V_x = 0$

short-circuit current

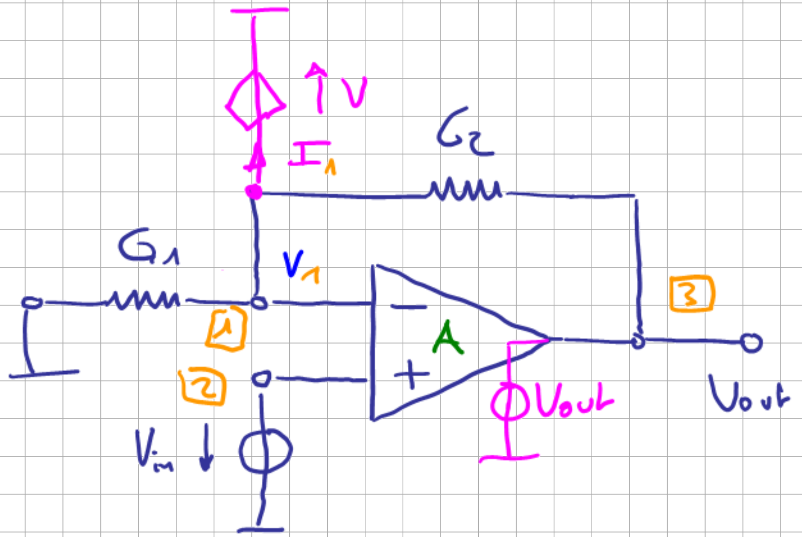


Magic Source: it already knows V_x, $\rightarrow$ $\underline{\underline{I_x = 0}}$



$Y_x = \frac{1}{Z_x}$

$= G_1 + G_2$



10000

Gain : 1000 60dB

100 40dB

10 20dB

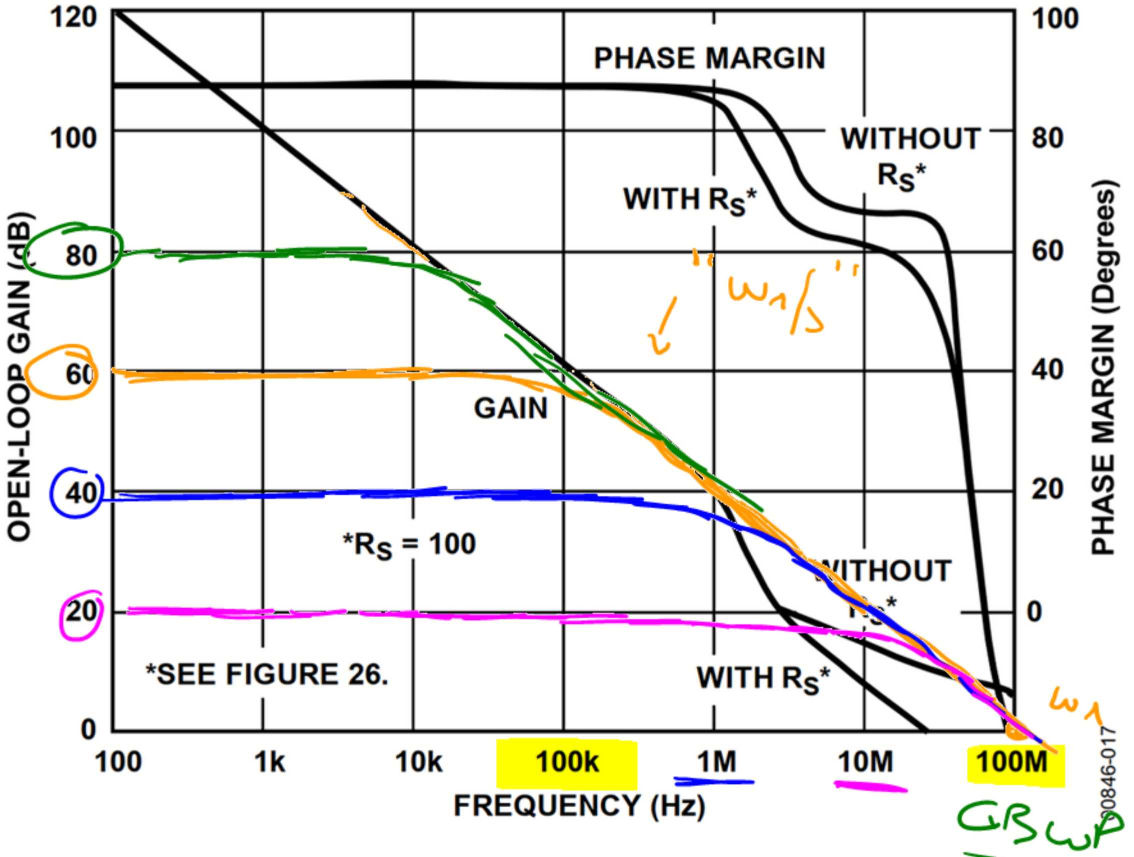
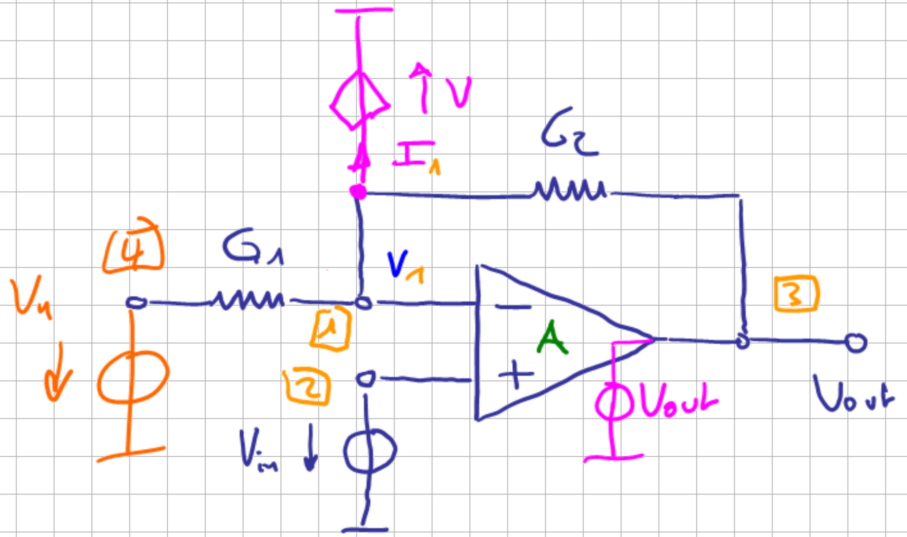


Figure 16. Open-Loop Gain and Phase Margin vs. Frequency



10000

Gain : 1000 60dB

100 40dB

10 20dB

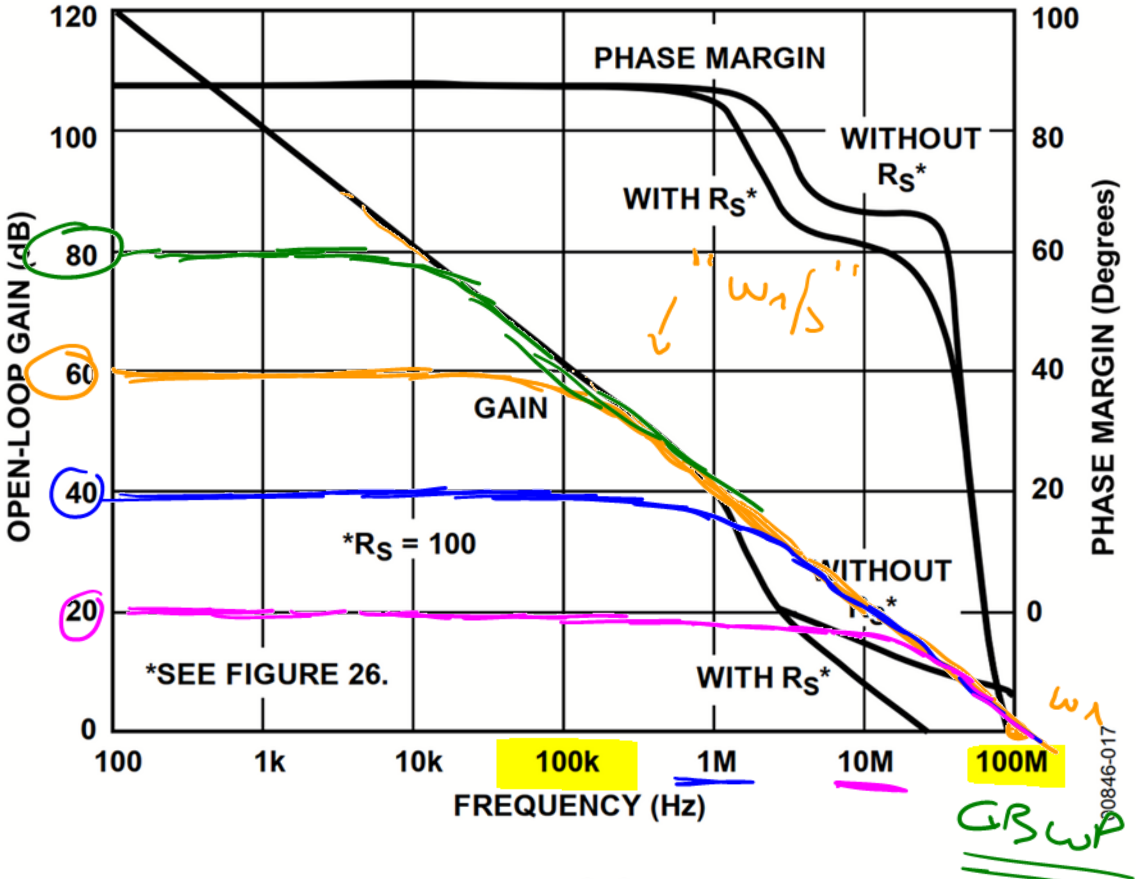


Figure 16. Open-Loop Gain and Phase Margin vs. Frequency

Phase Margin

Loop gain: find the phase at gain 1 and check the distance to the point $-180°$

$$\text{Loop Gain} = \frac{\text{Open-loop gain}}{\text{Closed-loop gain}}$$

$$= \frac{A}{\frac{G_1+G_2}{G_2}} \qquad \frac{G_1+G_2}{G_2} = 1 \ (0\,\text{dB})$$

$$= \frac{G_2 A}{G_1+G_2} \qquad \text{(for this circuit)}$$

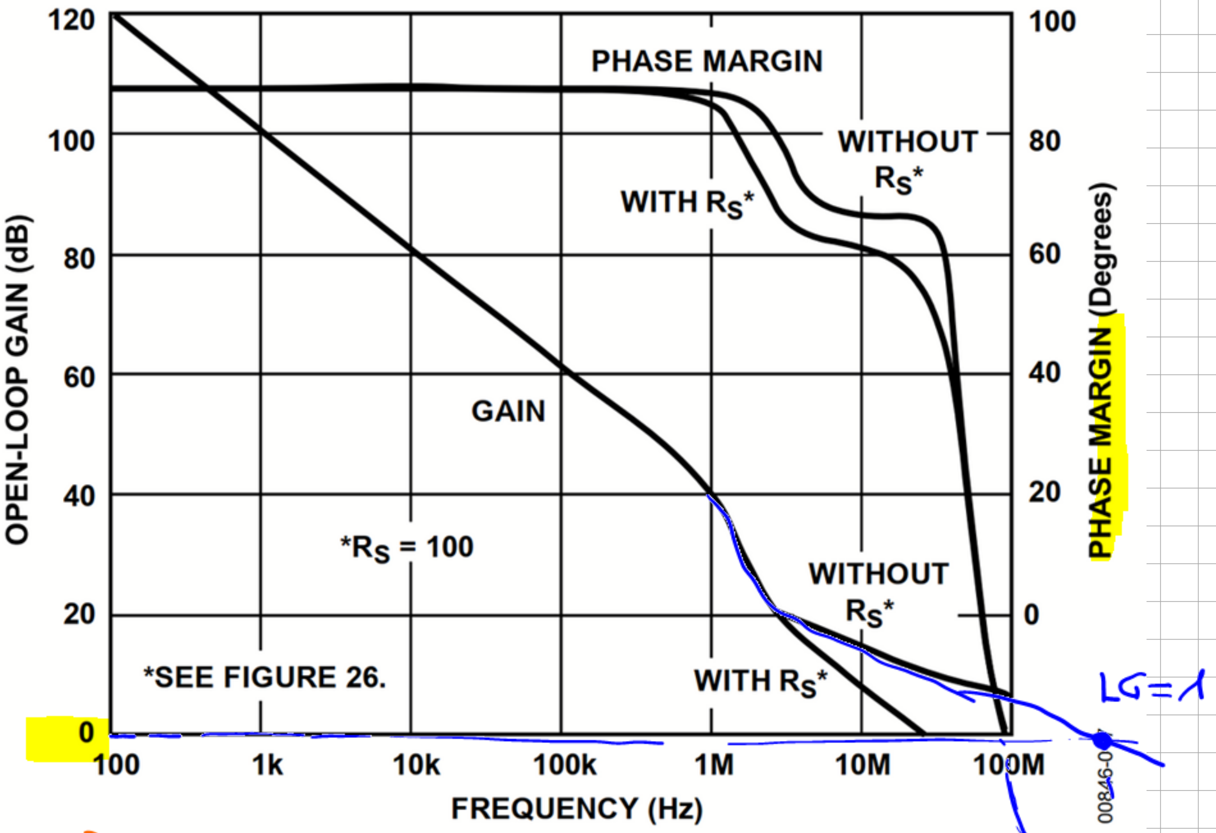


Figure 16. Open-Loop Gain and Phase Margin vs. Frequency

unstable!

Phase Margin

Loop gain: find the phase at gain 1 and check the distance to the point $-180°$

$$\text{Loop Gain} = \frac{\text{Open-loop gain}}{\text{Closed-loop gain}}$$

$$= \frac{A}{\frac{G_1+G_2}{G_2}}$$

$$\frac{G_1+G_2}{G_2} = 10 \quad (20\,\text{dB})$$

$$= \frac{G_2 A}{G_1+G_2}$$

(for this circuit)

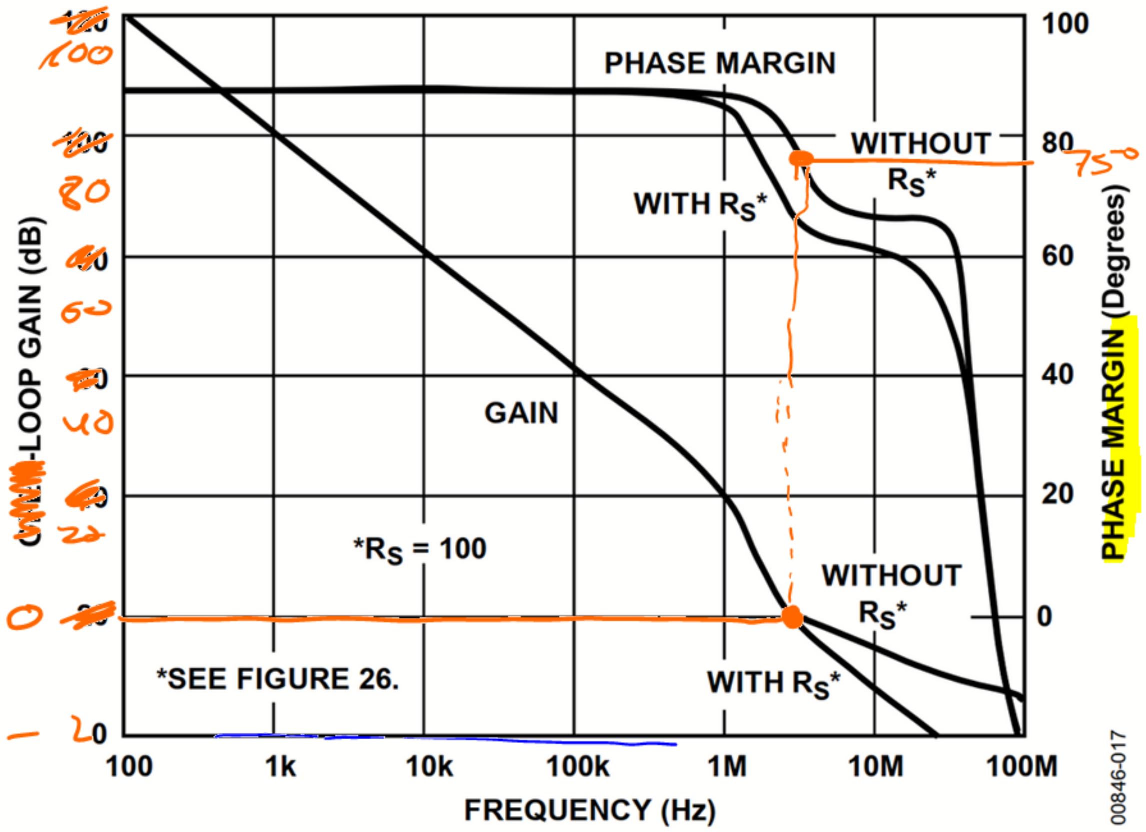


Figure 16. Open-Loop Gain and Phase Margin vs. Frequency

Phase Margin

Loop gain: find the phase at gain 1 and check the distance to the point $-180°$

$$\text{Loop Gain} = \frac{\text{Open-loop gain}}{\text{Closed-loop gain}} = \frac{A}{\frac{G_1+G_2}{G_2}} = \frac{G_2 A}{G_1+G_2}$$

(for this circuit)

50 dB ?

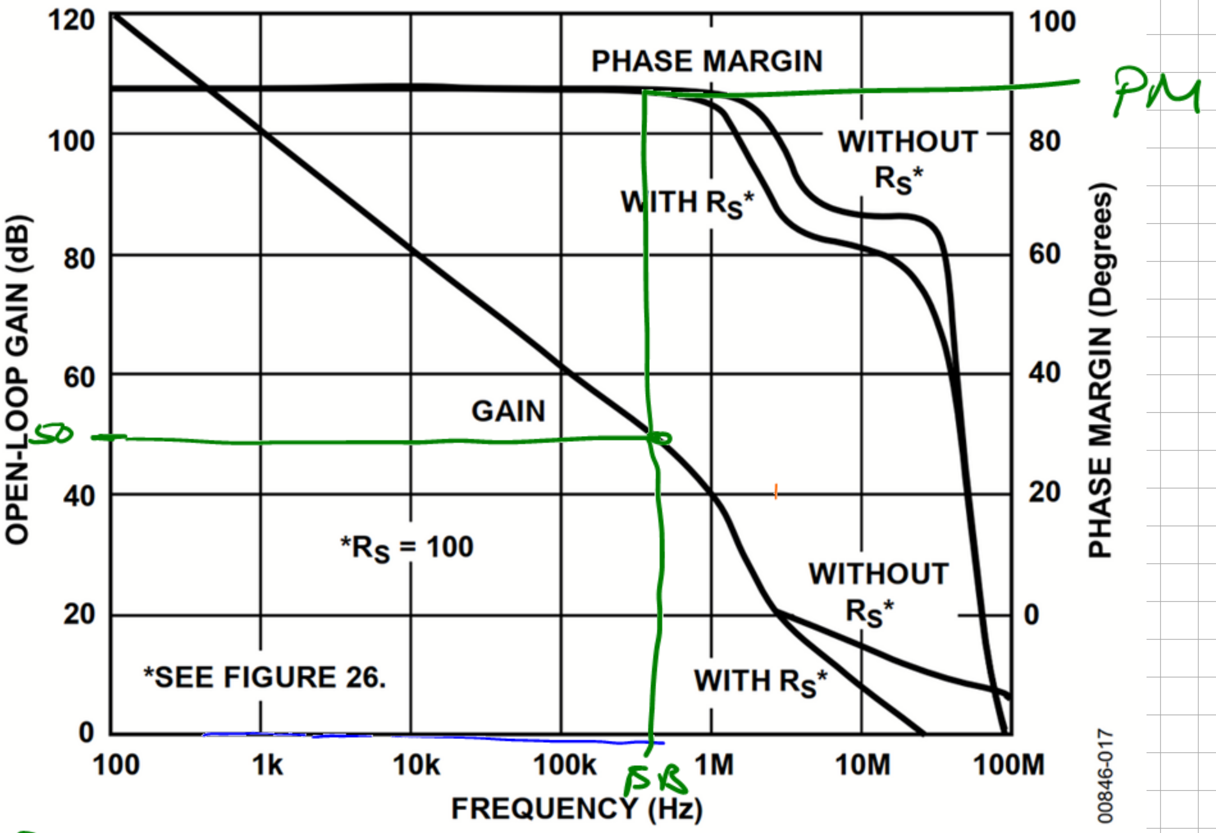
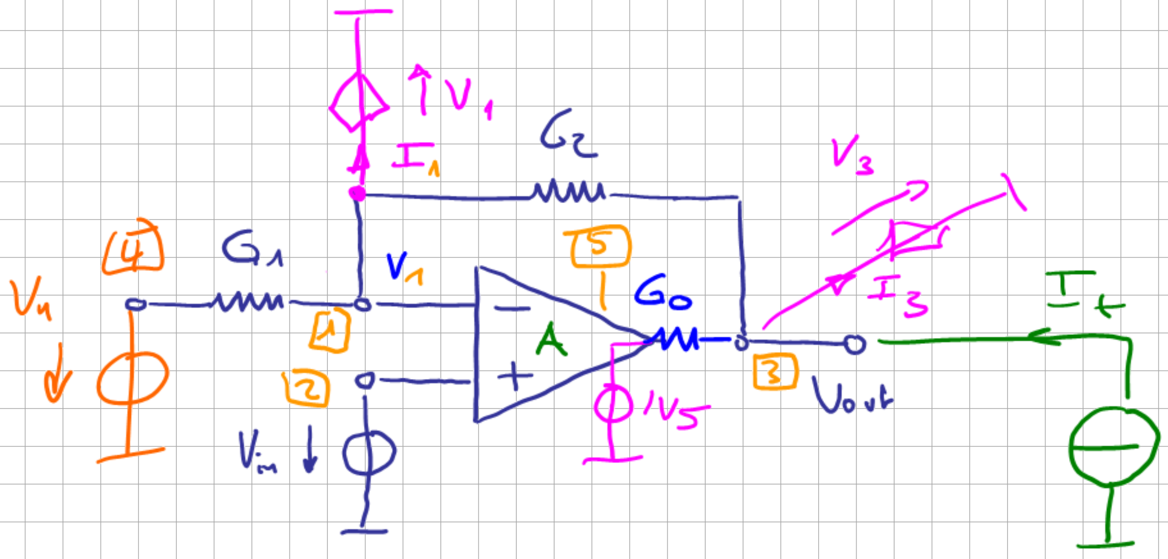


Figure 16. Open-Loop Gain and Phase Margin vs. Frequency

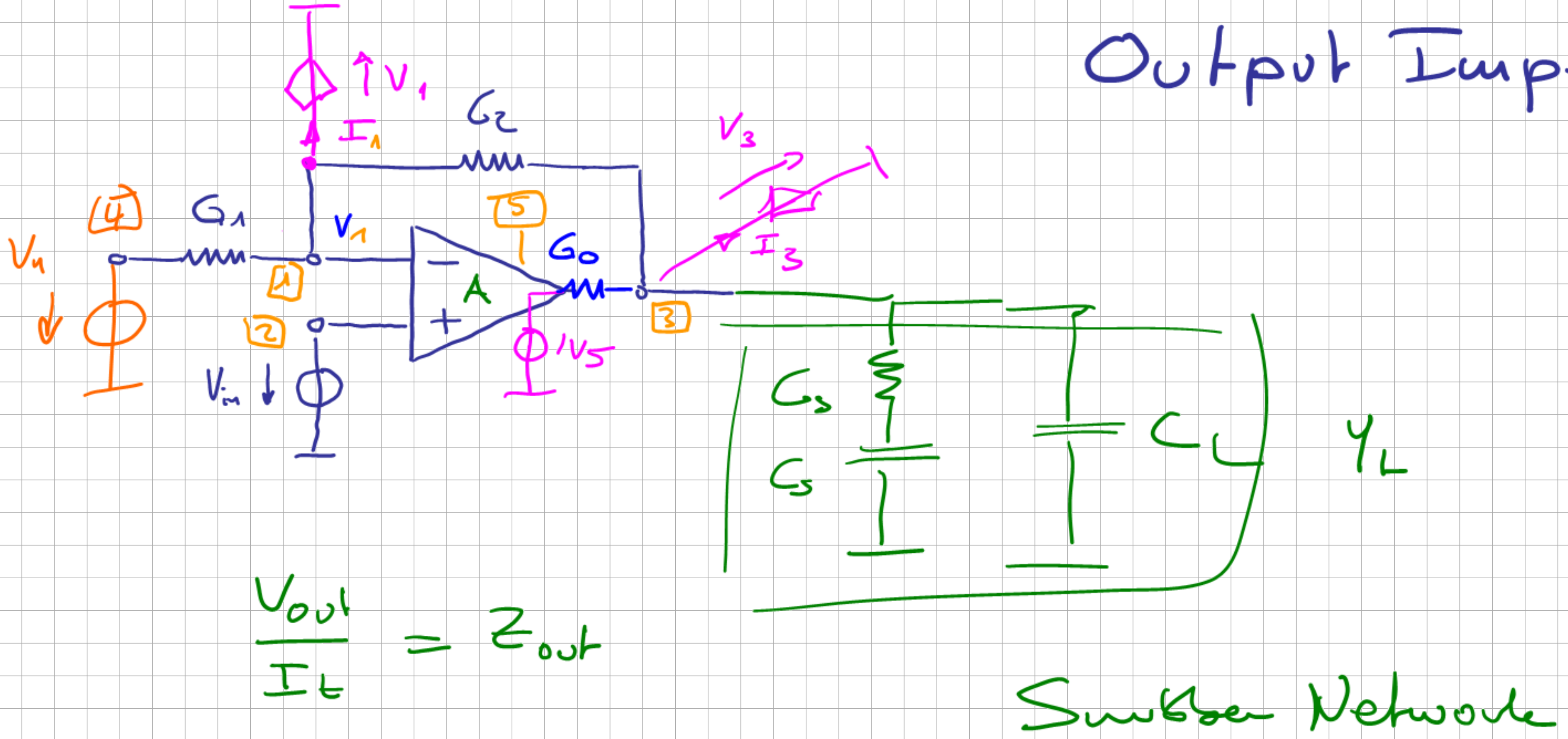
A

Output Impedance?

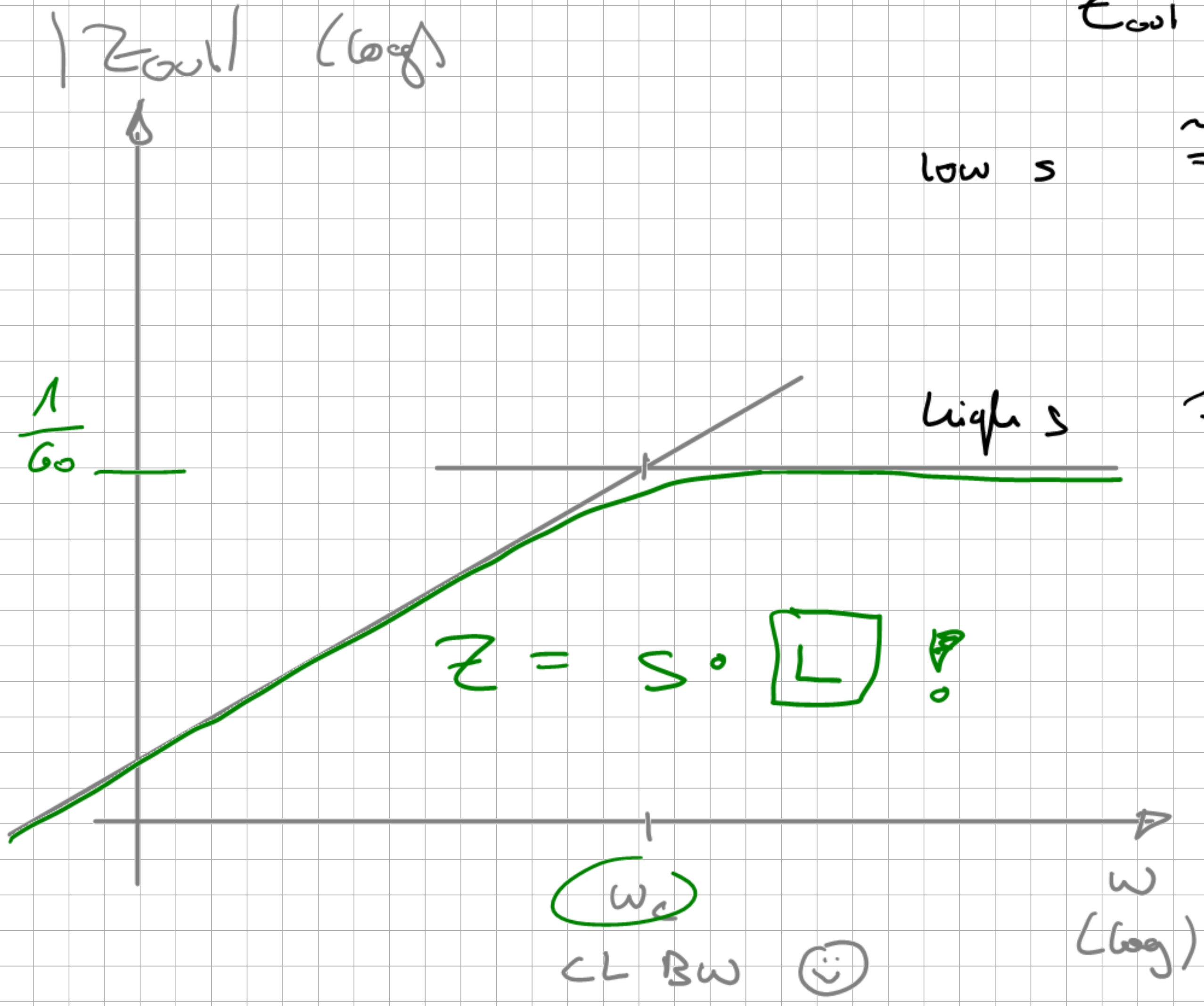


$$\frac{V_{out}}{I_t} = Z_{out}$$

Output Impedance?



$$\frac{V_{out}}{I_t} = Z_{out}$$



$$Z_{out} = \frac{s\,(G_1 + G_2)}{G_0 G_2 \omega_1 + s\,(G_0 + G_2)(G_1 + G_2)}$$

low s

$$\simeq \underbrace{\frac{s\,(G_1+G_2)}{\omega_1 \, G_2}}_{\text{closed-loop gain}} \cdot \boxed{\frac{1}{G_0}}$$

high s

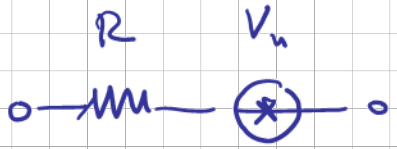
$$\simeq \frac{\cancel{s}\,\cancel{(G_1+G_2)}}{\cancel{s}\,(G_0+G_2)\cancel{(G_1+G_2)}} = \frac{1}{G_0+G_2}$$

$$\approx \frac{1}{G_0}$$

(Snubber Network)

Boltzman constant $1.38 \cdot 10^{-23}$ J/K

Temp. 300 K



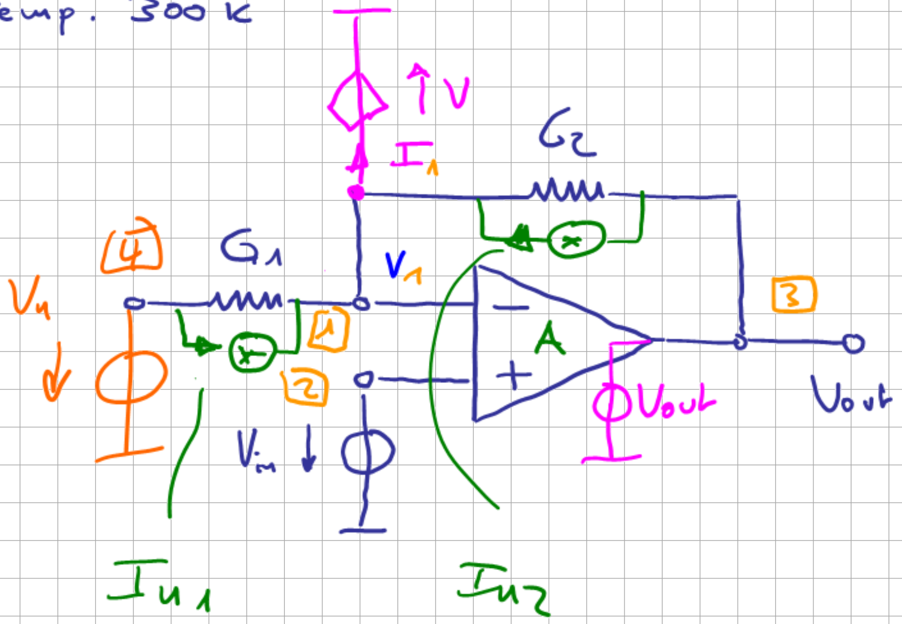
$$V_n^2 = 4kTR$$

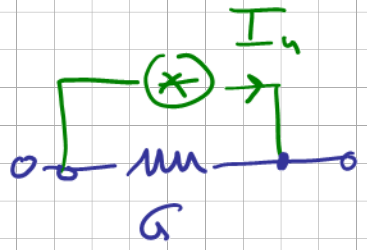
300K

1 kΩ

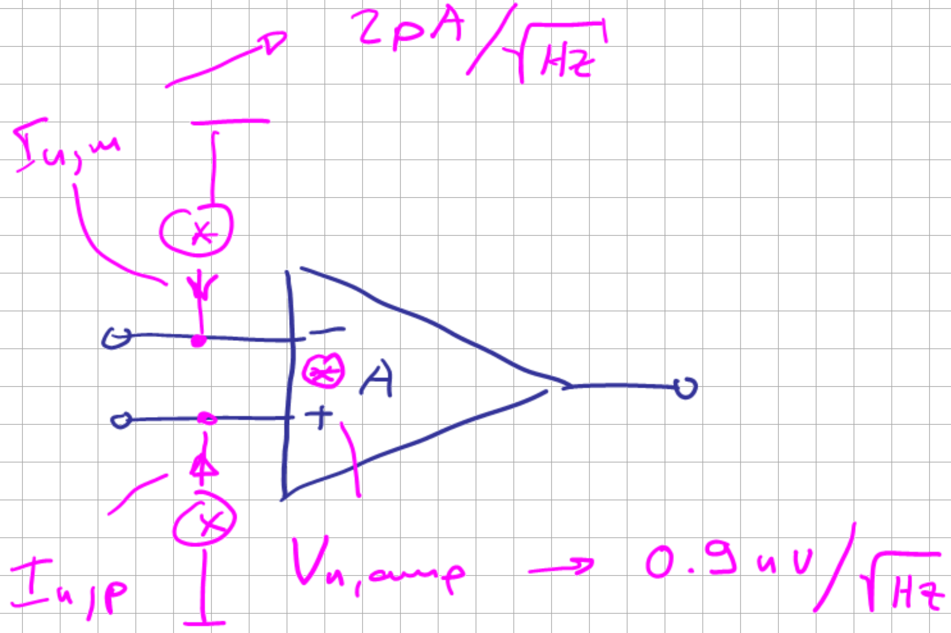
$$\sqrt{V_n^2} = \sqrt{4kTR}$$

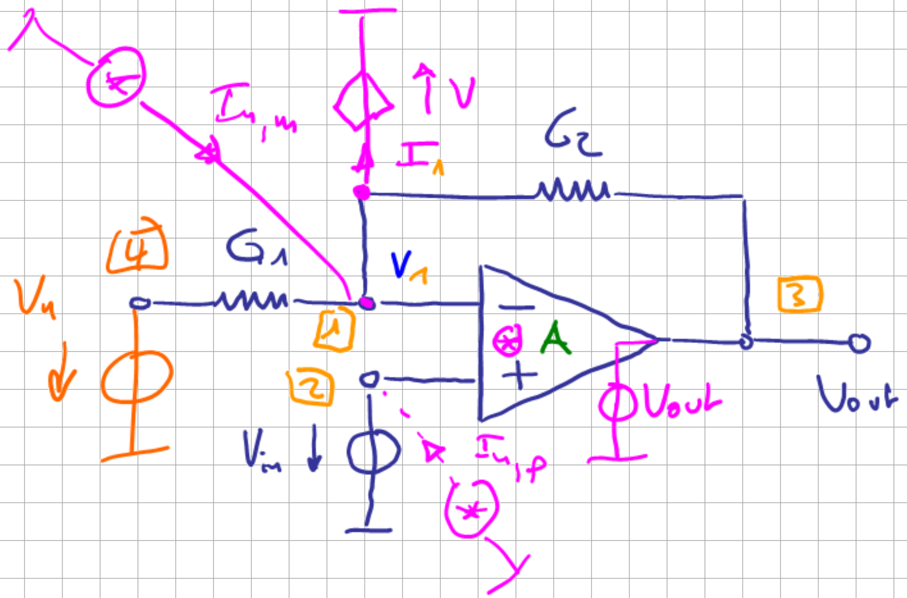
$$\simeq 4\ uV/\sqrt{Hz}$$





$$I_n^2 = 4kTG$$





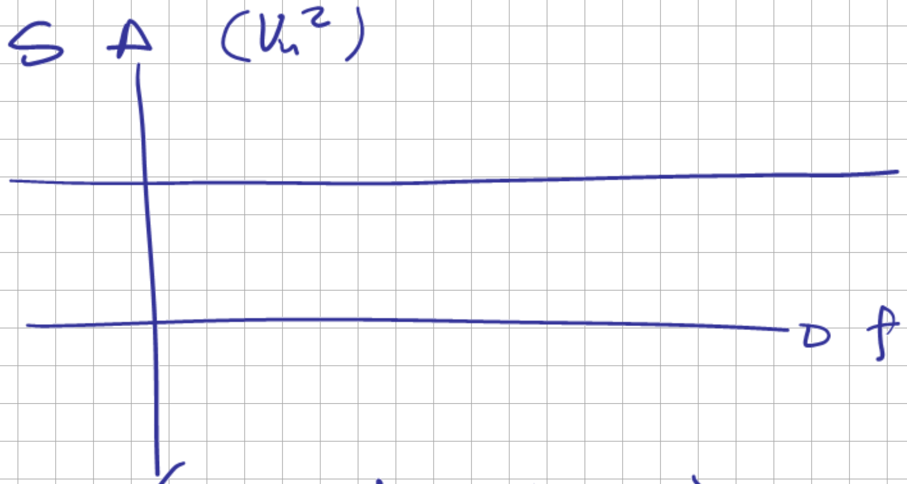
$$V_{n,out}^2 = V_{n,amp}^2 \cdot |T_{n,amp}|^2 + I_{n,m}^2 \, |T_{n,m}|^2$$

$$\left(V/\sqrt{Hz}\right)^2 \qquad + I_{n1}^2 \, |T_{n1}|^2 + I_{n2}^2 \cdot |T_{n2}|^2$$

$$T_{n,amp} \cong \frac{G_1+G_2}{G_2} \qquad T_{n,m} = T_{n1} = T_{n2} = -\frac{1}{G_2}$$

for low s

White noise



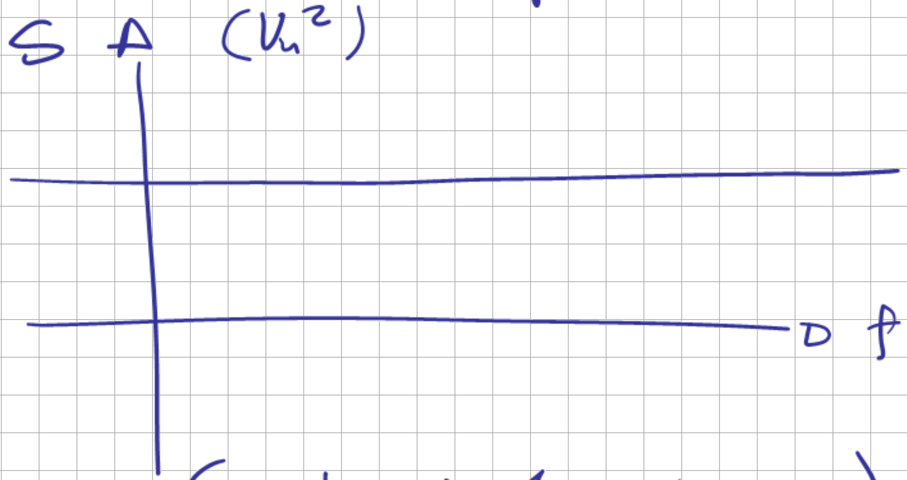
(random phase)

add power!

X, Y not correlated

$$\mathrm{Var}[X+Y] = \mathrm{Var}[X] + \mathrm{Var}[Y] + \cancel{2\,\mathrm{Cov}(X,Y)} = 0$$

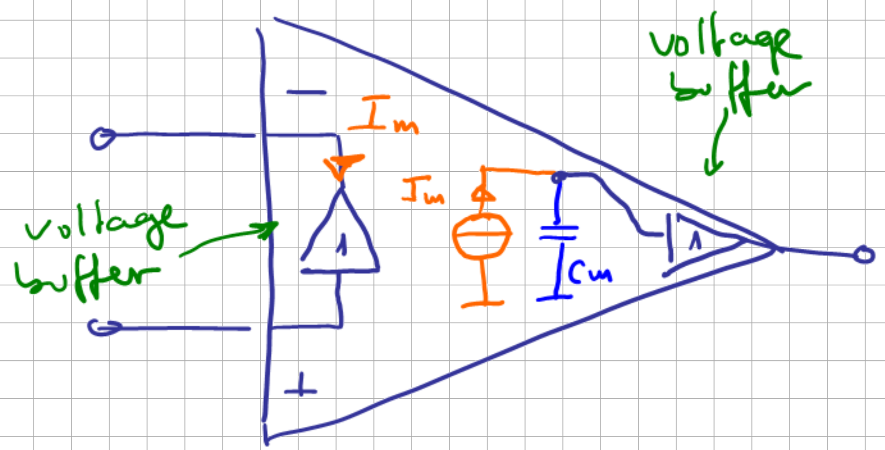
Dirac Impulse

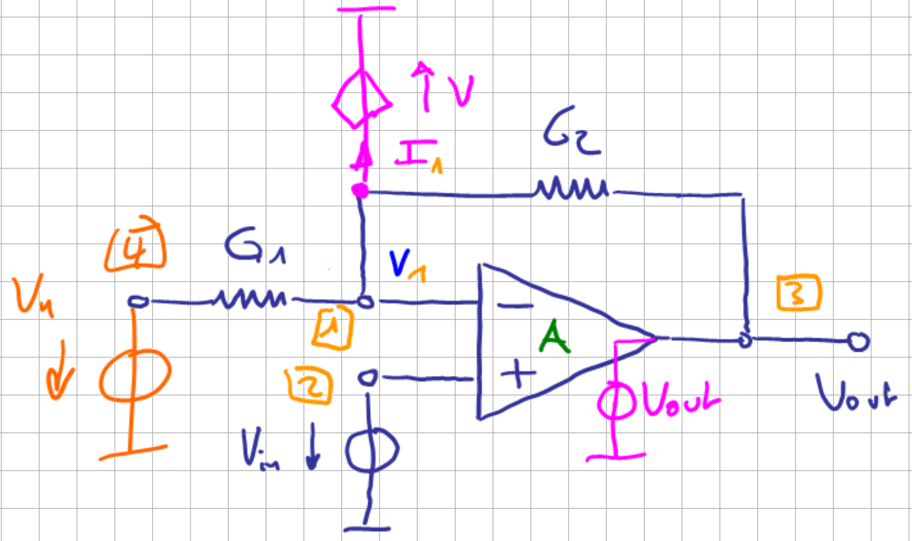


(deterministic phase)

add amplitude!

AD 812 CFB OpAmp



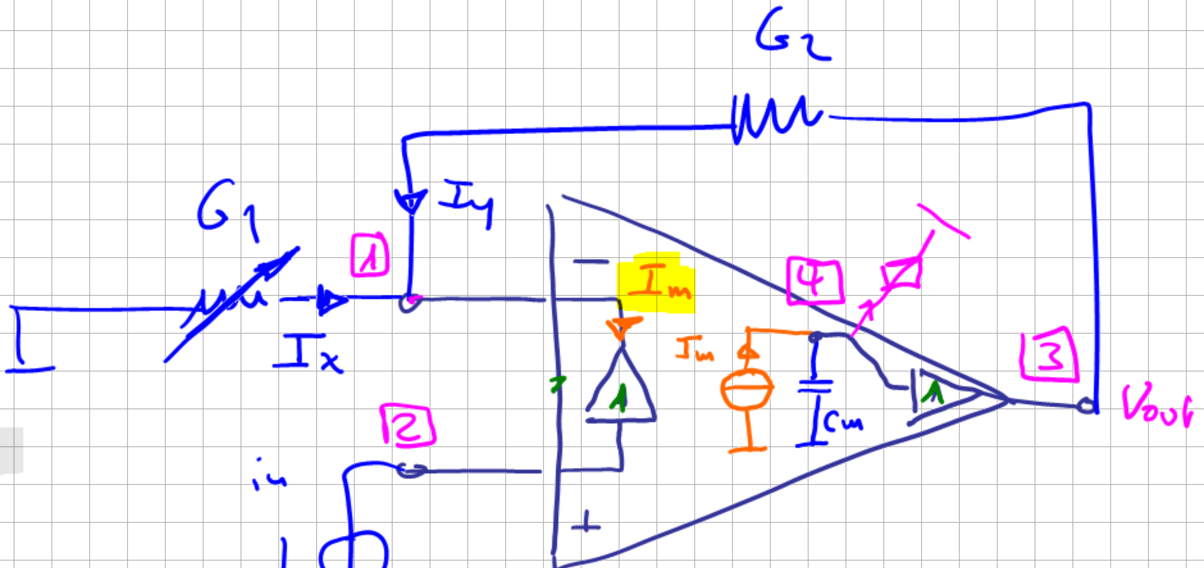


AD 812 CFB OpAmp

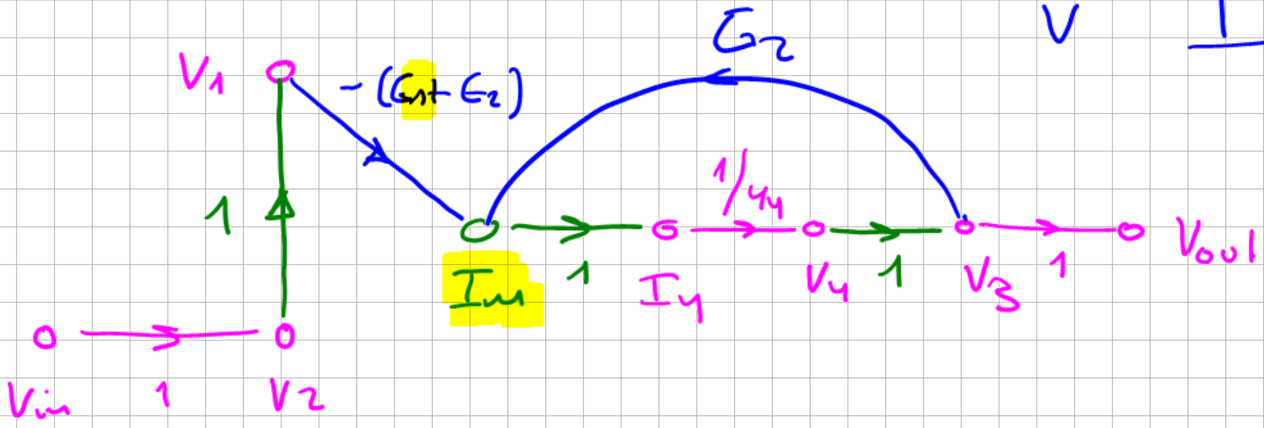
$$I_m = I_x + I_y \quad \text{(Kirchhoff)}$$

$$= -V_1 G_1 + (V_3 - V_1)\cdot G_2$$

$$= V_1\cdot(-G_1 - G_2) + V_3\cdot G_2$$



$$y_4 = s\cdot C_m$$



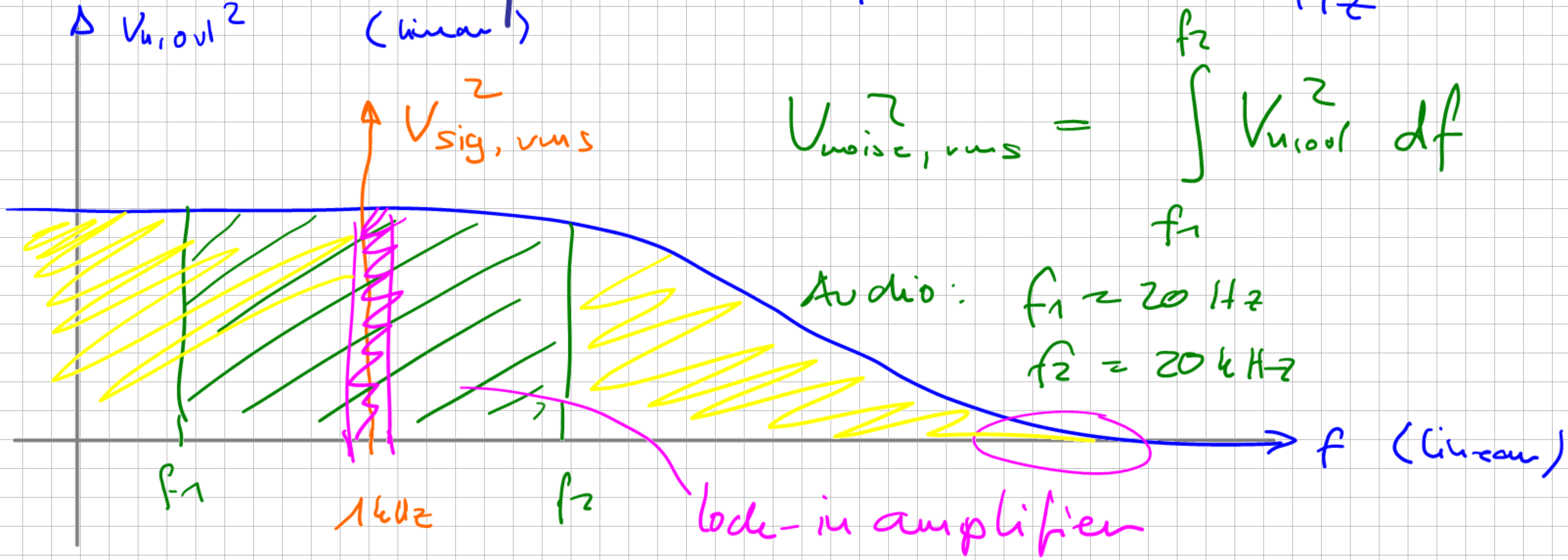
Noise Density

$V_{n,out}^2$ Unit $\frac{V^2}{Hz}$

$$V_{noise,rms}^2 = \int_{f_1}^{f_2} V_{n,out}^2 \, df$$

Audio: $f_1 = 20\ Hz$

$f_2 = 20\ kHz$



$$SNR = \frac{V_{sig,rms}^2}{V_{noise,rms}^2}$$