Electronics – 96032

POLITECNICO DI MILANO





OpAmp Circuit Stability and Compensation

Alessandro Spinelli

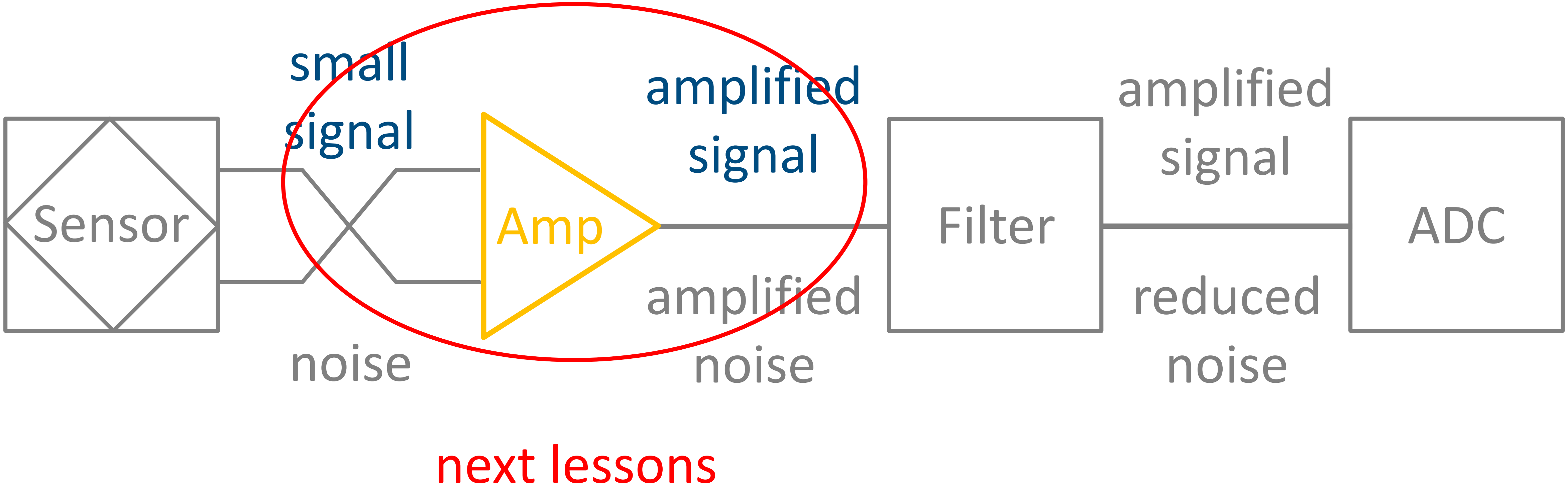
Phone: (02 2399) 4001

alessandro.spinelli@polimi.it spinelli.faculty.polimi.it

Disclaimer

Slides are supplementary material and are NOT a replacement for textbooks and/or lecture notes

Acquisition chain



Purpose of the lesson

- We begin our study with the analysis and design of simple amplifiers
- Next lessons will deal with
  - Basic amplifier principles and the feedback amplifier concept
  - Linear applications of OpAmps
  - Feedback amplifier properties
  - Stability of feedback amplifiers (this lesson)
  - Instrumentation amplifiers and OpAmp parameters

Outline

- Frequency response of feedback amplifiers
- Stability of feedback amplifiers
- Compensation
- Appendix

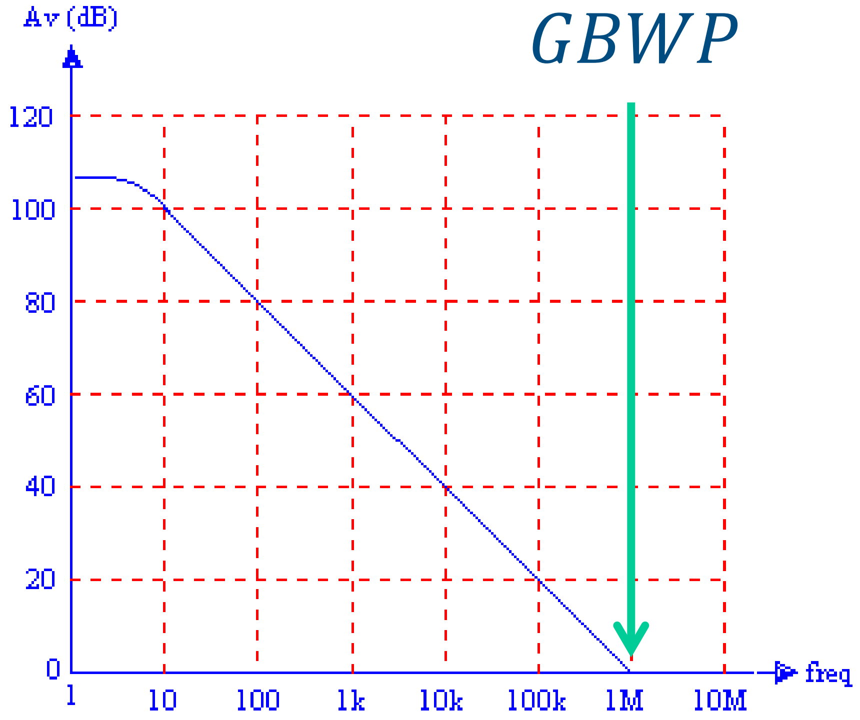
OA parameter: gain-bandwidth product

- Open-loop gain can usually be expressed as

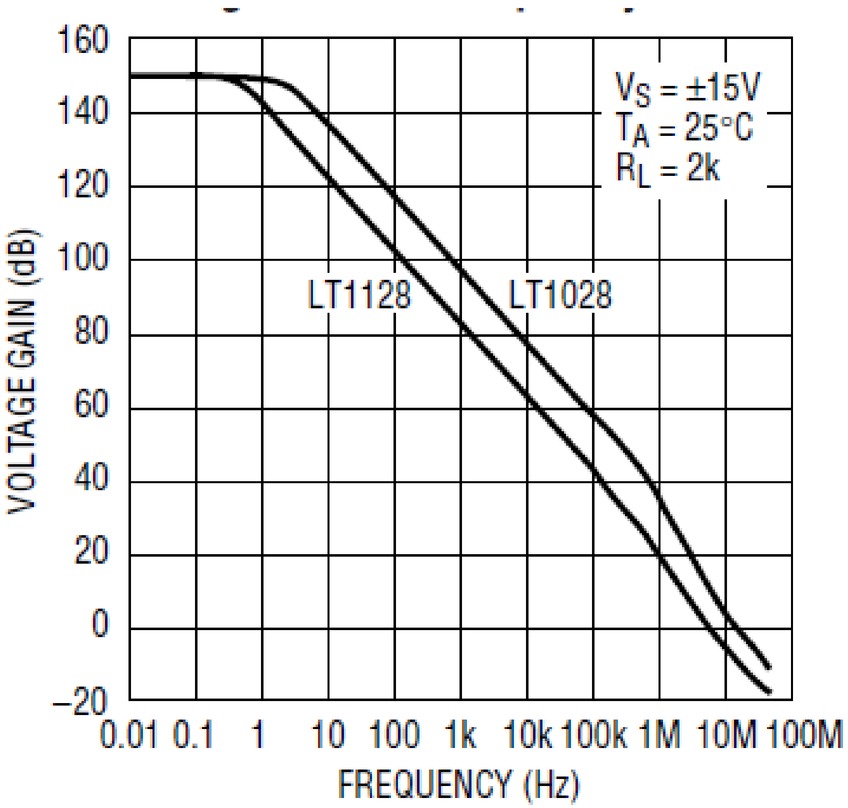
$$A(s) = \frac{A_0}{1 + s\tau}$$

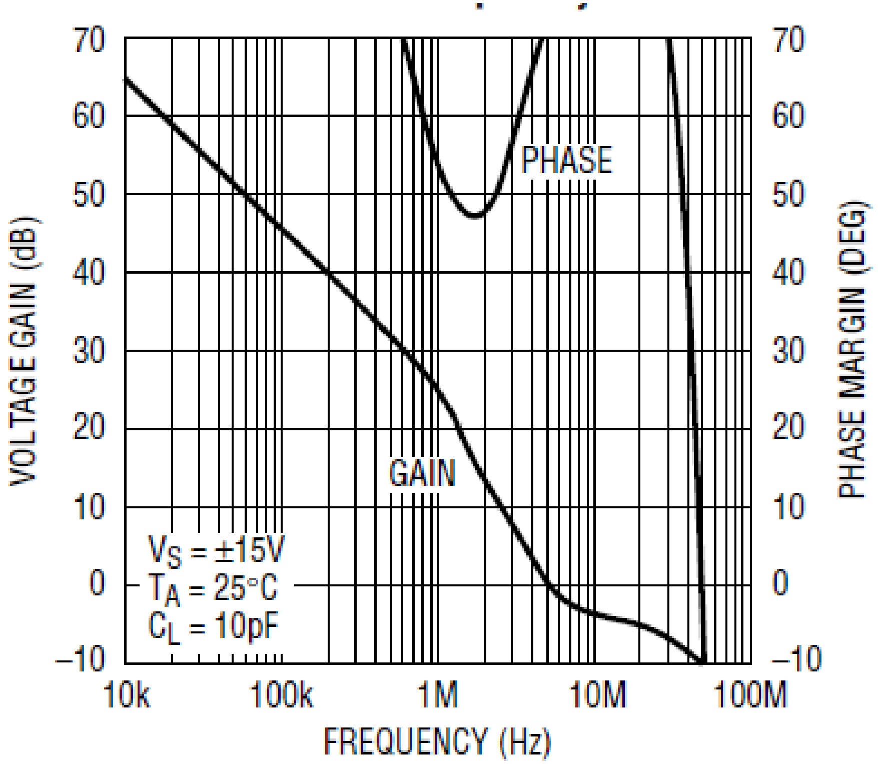
- $GBWP$ is the unity-gain frequency

$$GBWP = \frac{A_0}{2\pi\tau}$$

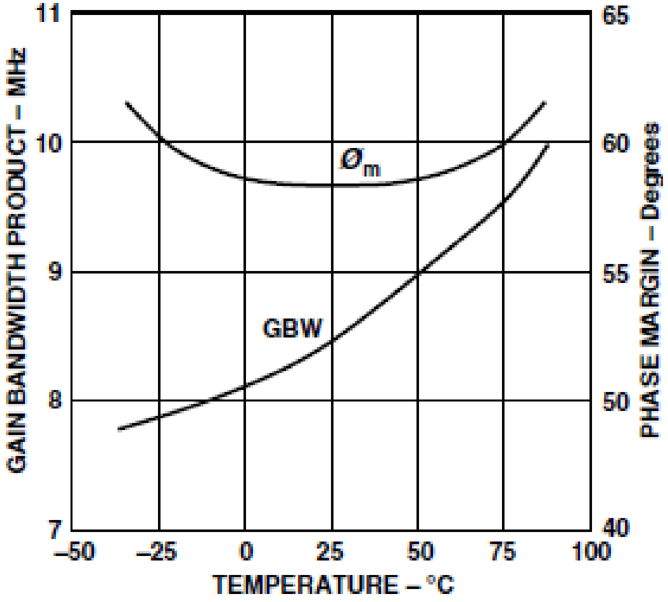


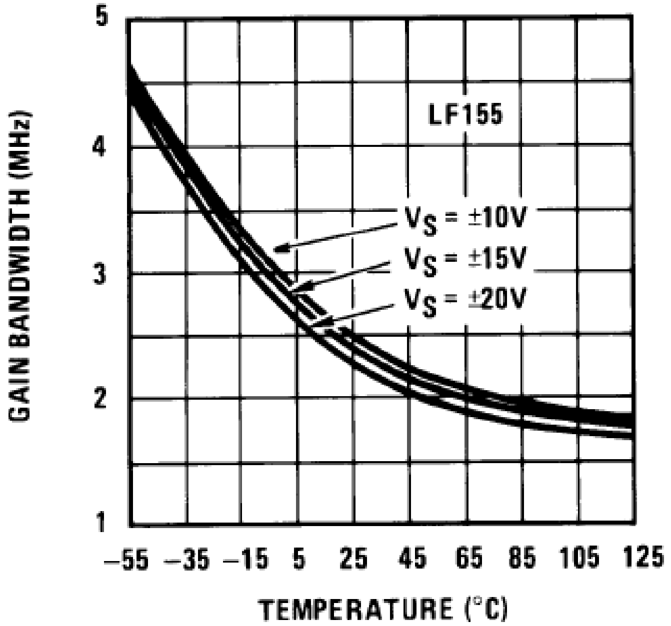
Actual values from datasheets

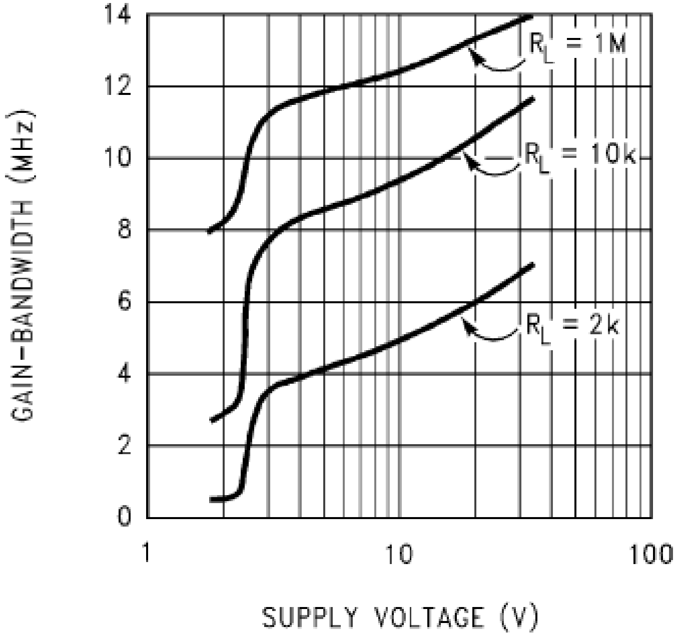




Actual values from datasheets







Dependent on $V_{CC}, R_L, T, \ldots$

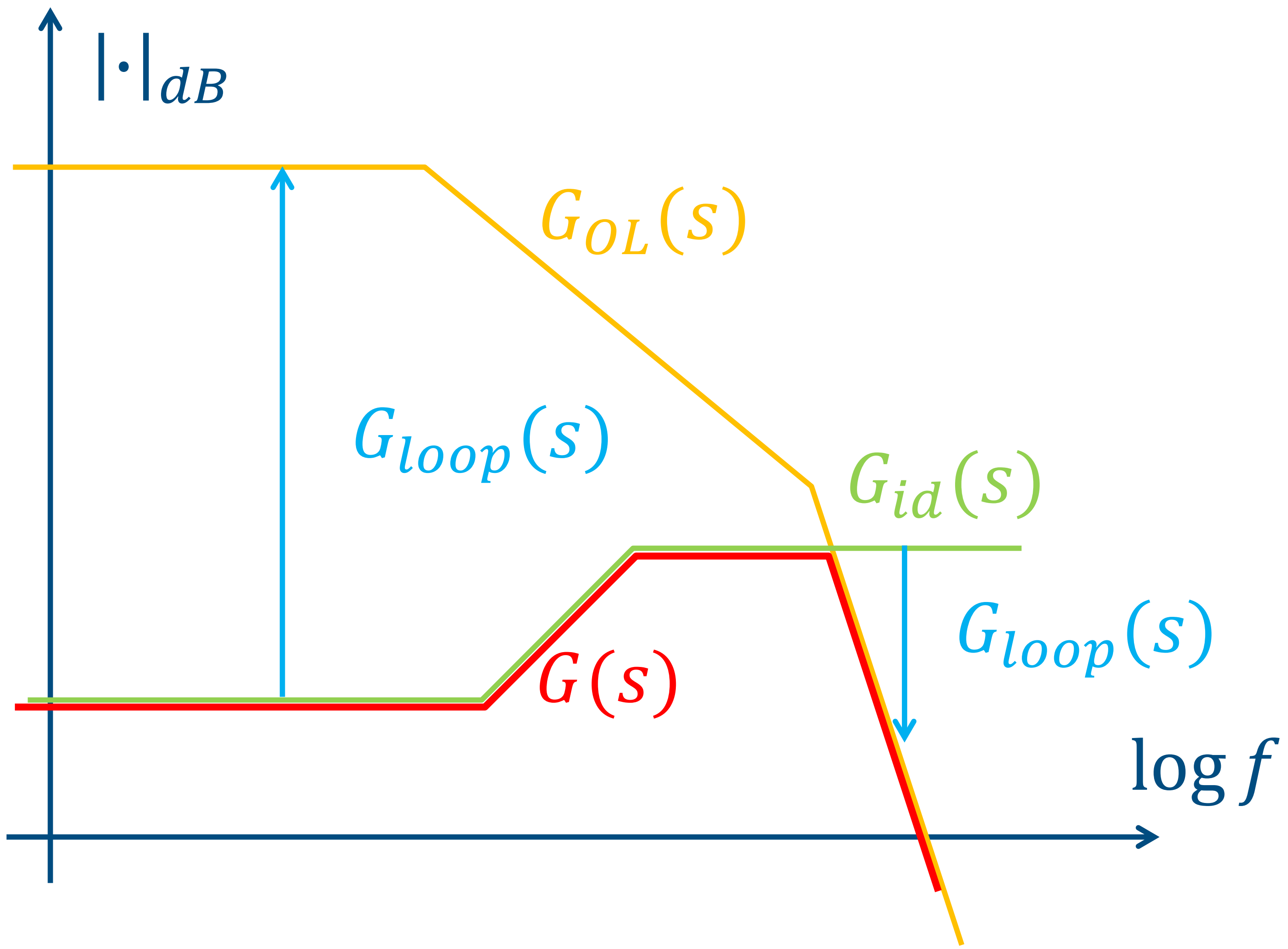
Frequency response

$$G = \frac{G_{OL}(s)}{1 - G_{loop}(s)} = \frac{G_{id}(s)}{1 - 1/G_{loop}(s)} \approx \begin{matrix} G_{id} \ \forall \ |G_{loop}| \gg 1 \\ G_{OL} \ \forall \ |G_{loop}| \ll 1 \end{matrix}$$

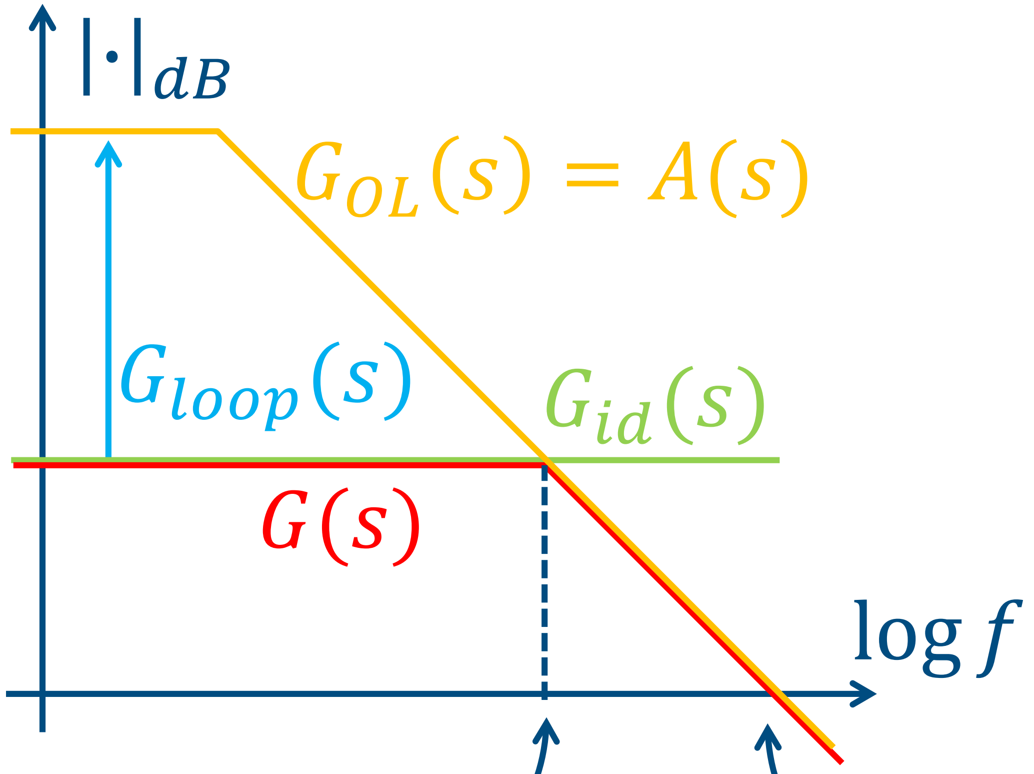
where

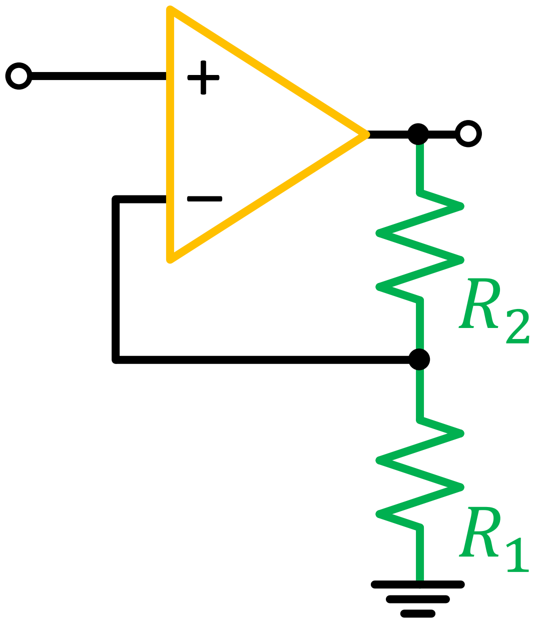
$$G_{loop}(s) = -\frac{G_{OL}(s)}{G_{id}(s)} \Rightarrow \left|G_{loop}(s)\right|_{dB} = |G_{OL}(s)|_{dB} - |G_{id}(s)|_{dB}$$

Bode plot



Example: single-pole amplifier





$$f_T = \frac{GBWP}{G_{id}}$$

$$\frac{A_0}{2\pi\tau} = GBWP$$

Analytical solution

$$G = \frac{G_{id}}{1 - \frac{1}{G_{loop}(s)}} = \frac{G_{id}}{1 + \frac{R_1 + R_2}{A(s) R_1}}$$

The pole position is

$$\frac{(R_1 + R_2)(1 + s\tau)}{A_0 R_1} = -1$$

Open-loop pole

$$s = -\frac{1}{\tau}\left(1 + \frac{A_0 R_1}{R_1 + R_2}\right) = -\frac{1}{\tau}\left(1 - G_{loop}(0)\right) \Rightarrow f_p \approx \frac{A_0}{2\pi\tau}\frac{R_1}{R_1 + R_2}$$

Gain-bandwidth product

- For a non-inverting amplifier we have

$$f_p \approx \frac{A_0}{2\pi\tau}\frac{1}{G_{id}} \Rightarrow f_p G_{id} = \frac{A_0}{2\pi\tau} = GBWP$$

- In an inverting configuration we should write

$$f_p(R_1 + R_2)/R_1 = f_p(1 + |G_{id}|) = GBWP,$$

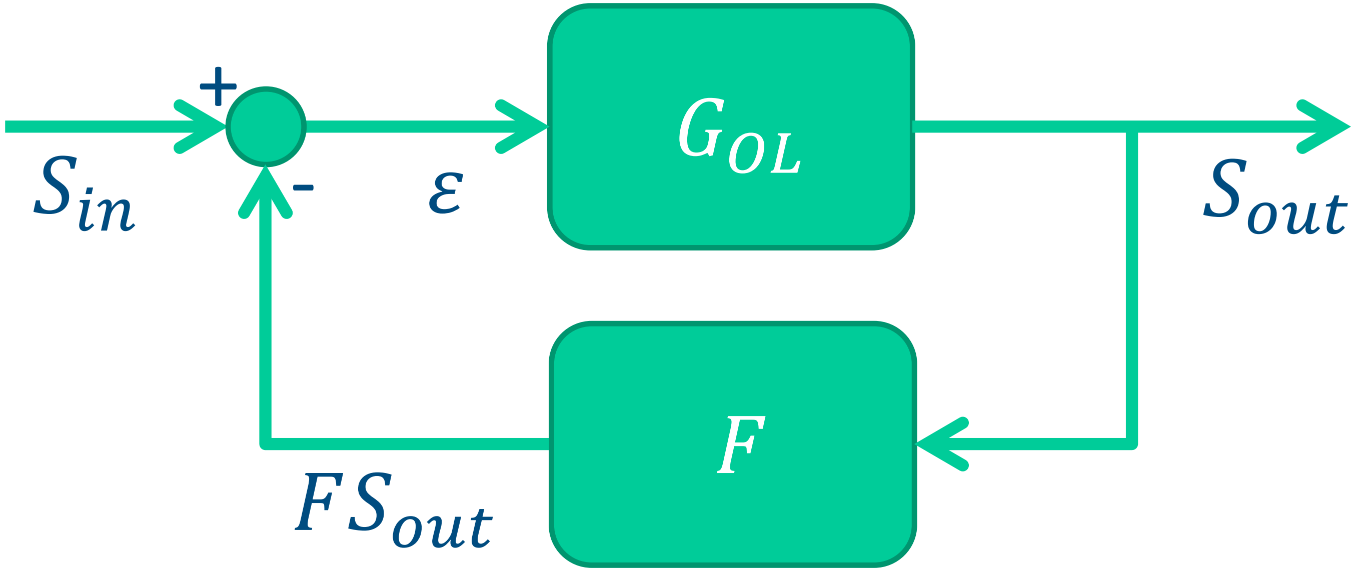
which becomes the same for high gains

- The feedback loop reduces the (open-loop) gain by $1 - G_{loop}(0)$ and widens the bandwidth by the same factor

Outline

- Frequency response of feedback amplifiers
- Stability of feedback amplifiers
- Compensation
- Appendix

Stability of feedback systems

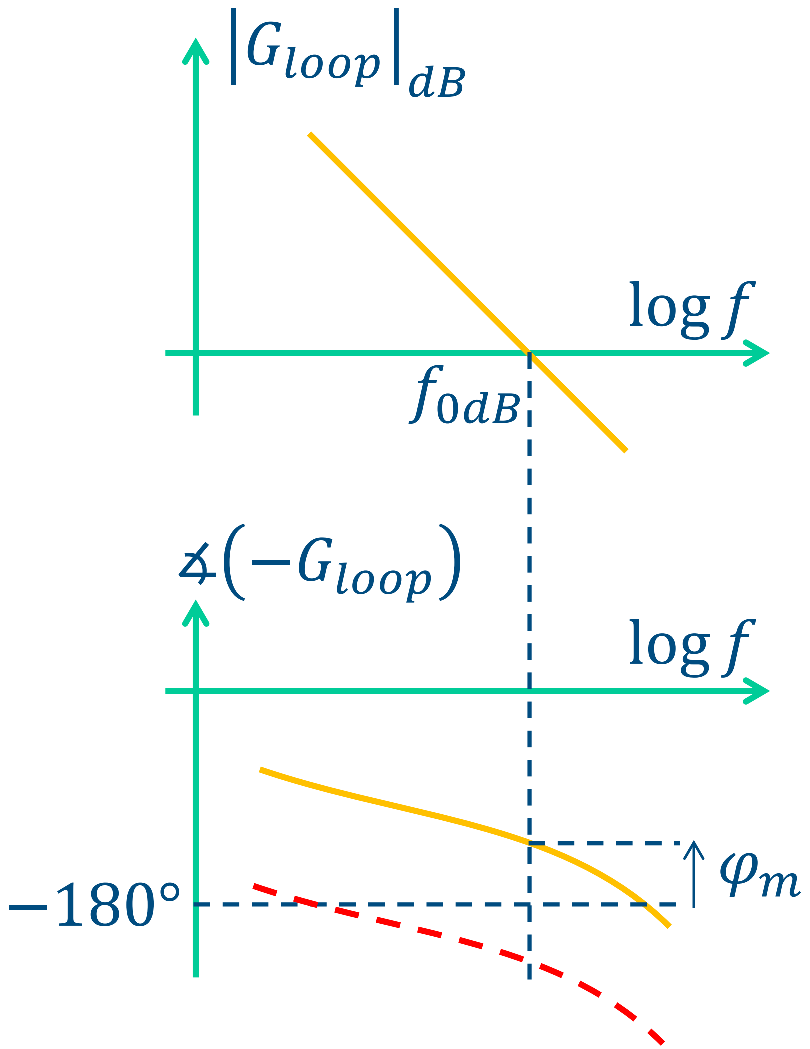


- Stability only depends on G_{loop}
- The critical condition is $G_{loop} = 1$, *i.e.*, $-G_{loop} = -1$

Bode stability criterion (1945)

- If
  - $G_{loop}(s)$ only has poles in LHP (or in $s = 0$)
  - There is only one critical frequency f_{0dB} where the magnitude of $-G_{loop}$ is 0 dB
  - $\measuredangle\left(-G_{loop}(f_{0dB})\right) > -180°$
- Then, the system is stable

Phase margin



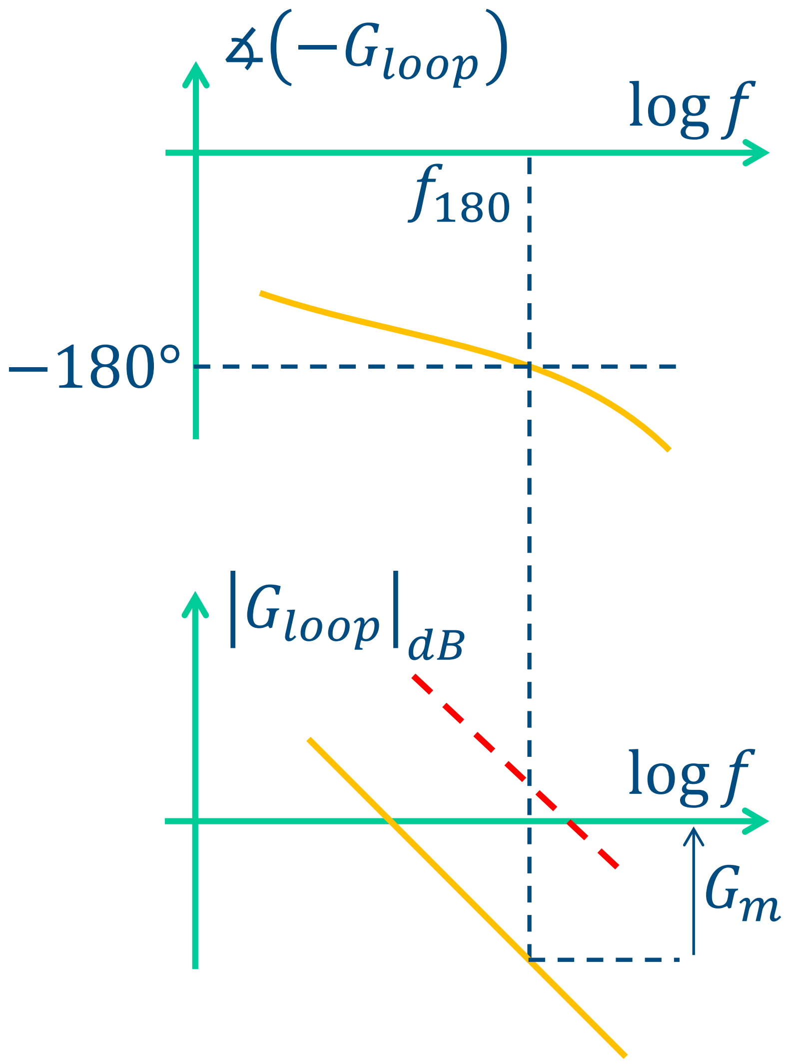
- In real systems, the phase can change because of tolerances and parameter drift
- The phase margin represents how much increase in phase lag the system can withstand before becoming unstable

$$\varphi_m = 180 + \measuredangle\left(-G_{loop}(f_{0dB})\right)$$

An alternative definition

- If
  - $G_{loop}(s)$ only has poles in LHP (or in $s = 0$)
  - There is only one frequency f_{180} where the phase of $-G_{loop}$ is $-180°$ ($\pm$ multiples of $360°$)
  - $\left|G_{loop}(f_{180})\right| < 1$
- Then, the system is stable

Gain margin



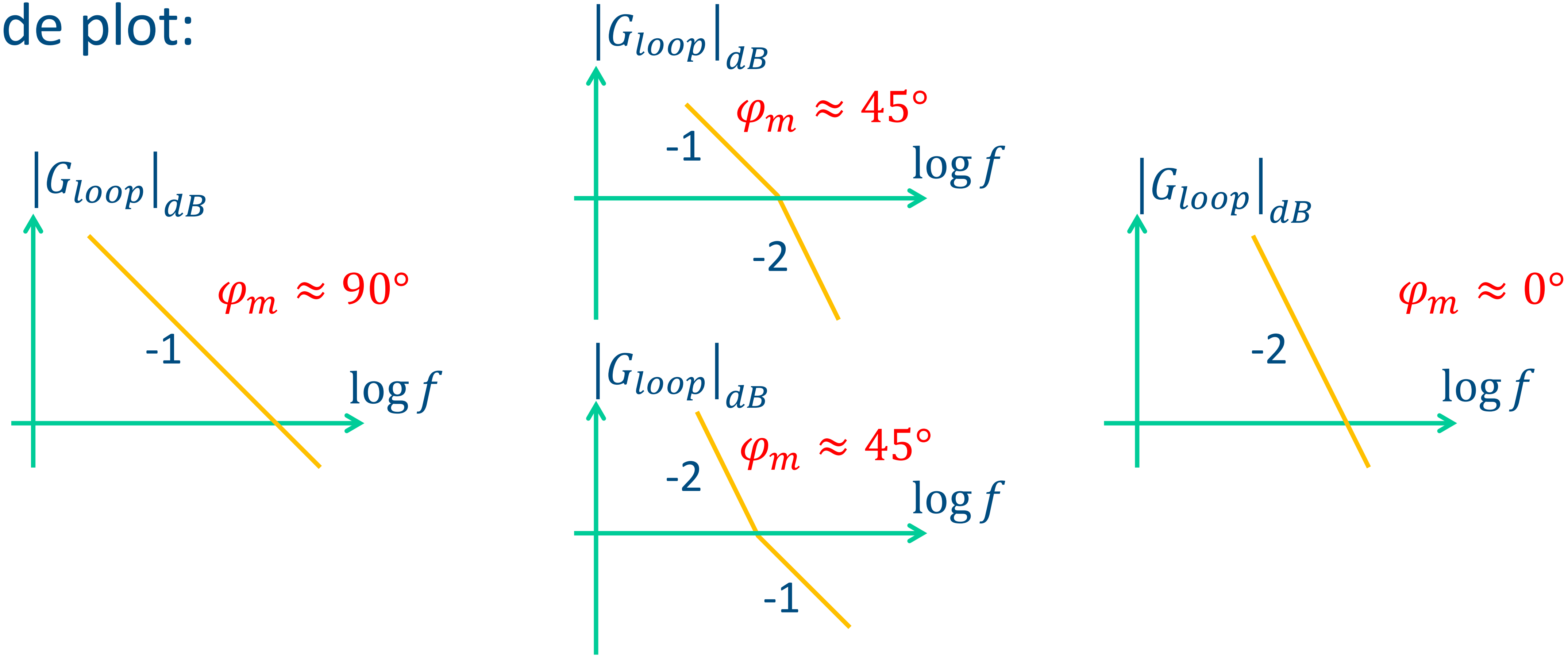
- In real systems, the gain changes because of tolerances and drift
- The gain margin represents how much increase in gain the system can withstand before becoming unstable

$$G_m\Big|_{dB} = -\left|G_{loop}(f_{180})\right|_{dB} \Rightarrow$$

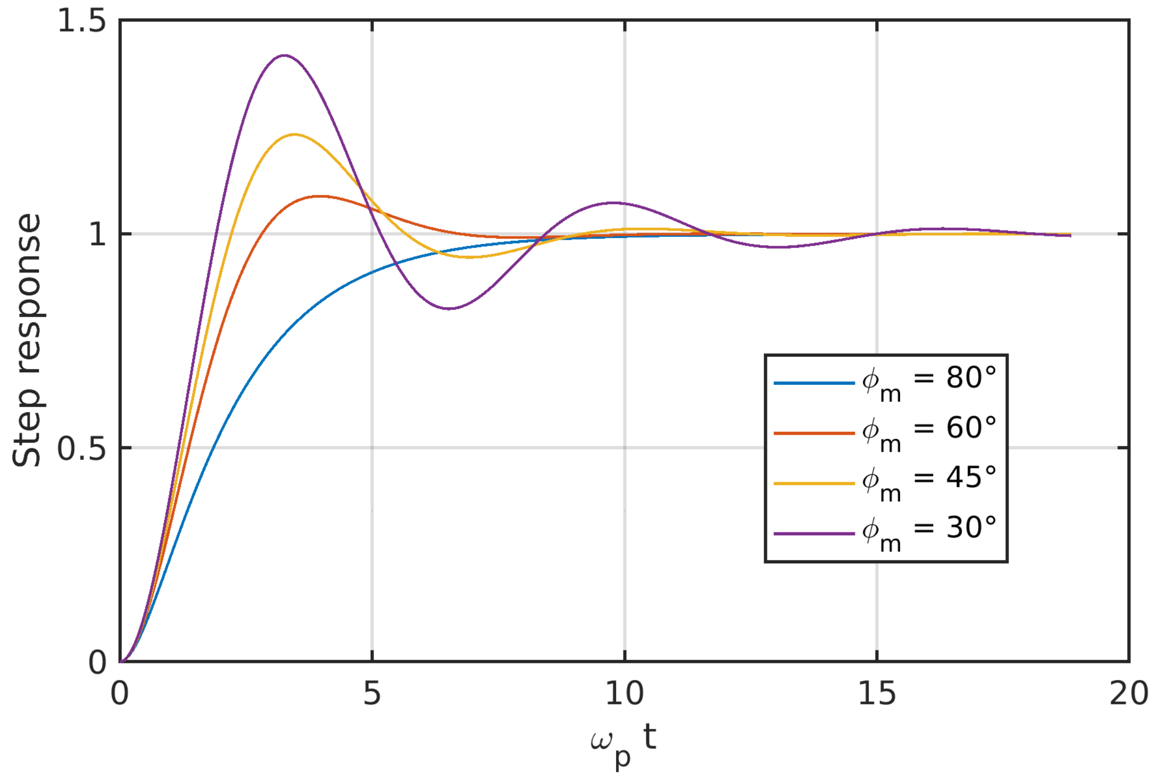
$$G_m = \frac{1}{\left|G_{loop}(f_{180})\right|}$$

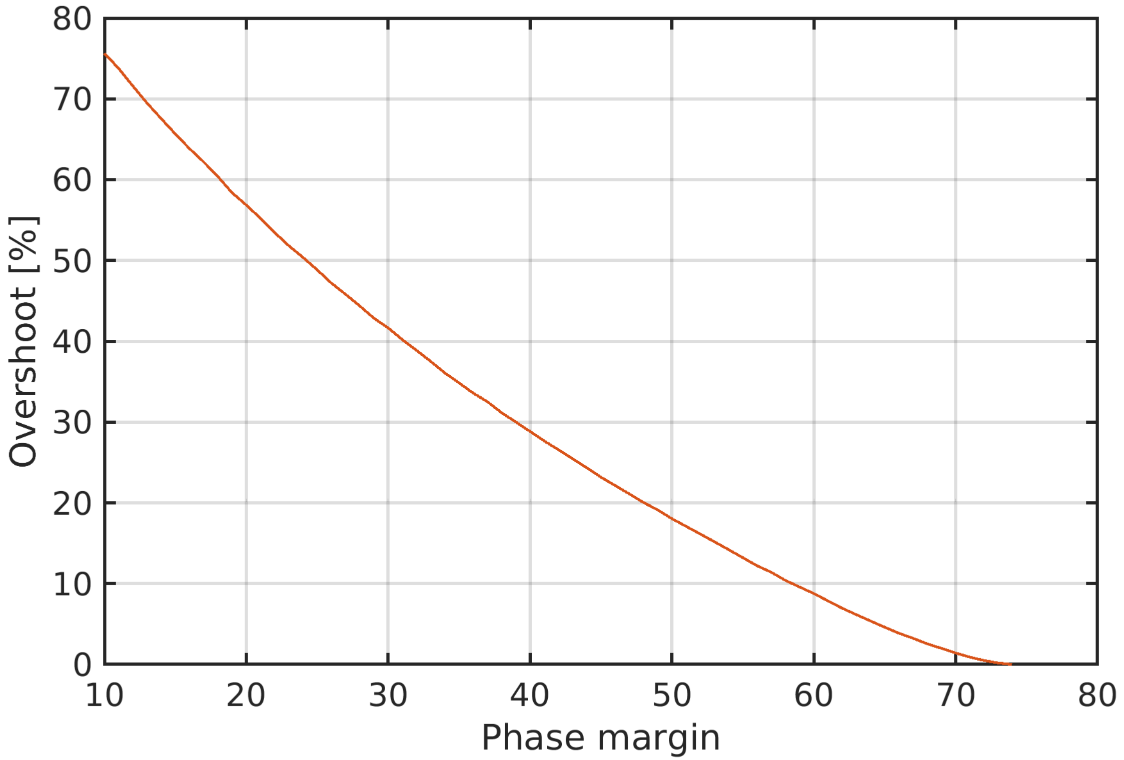
Simplified Bode criterion

If poles and zeros of G_{loop} are in LHP, stability can be inferred from Bode plot:



How much phase margin?





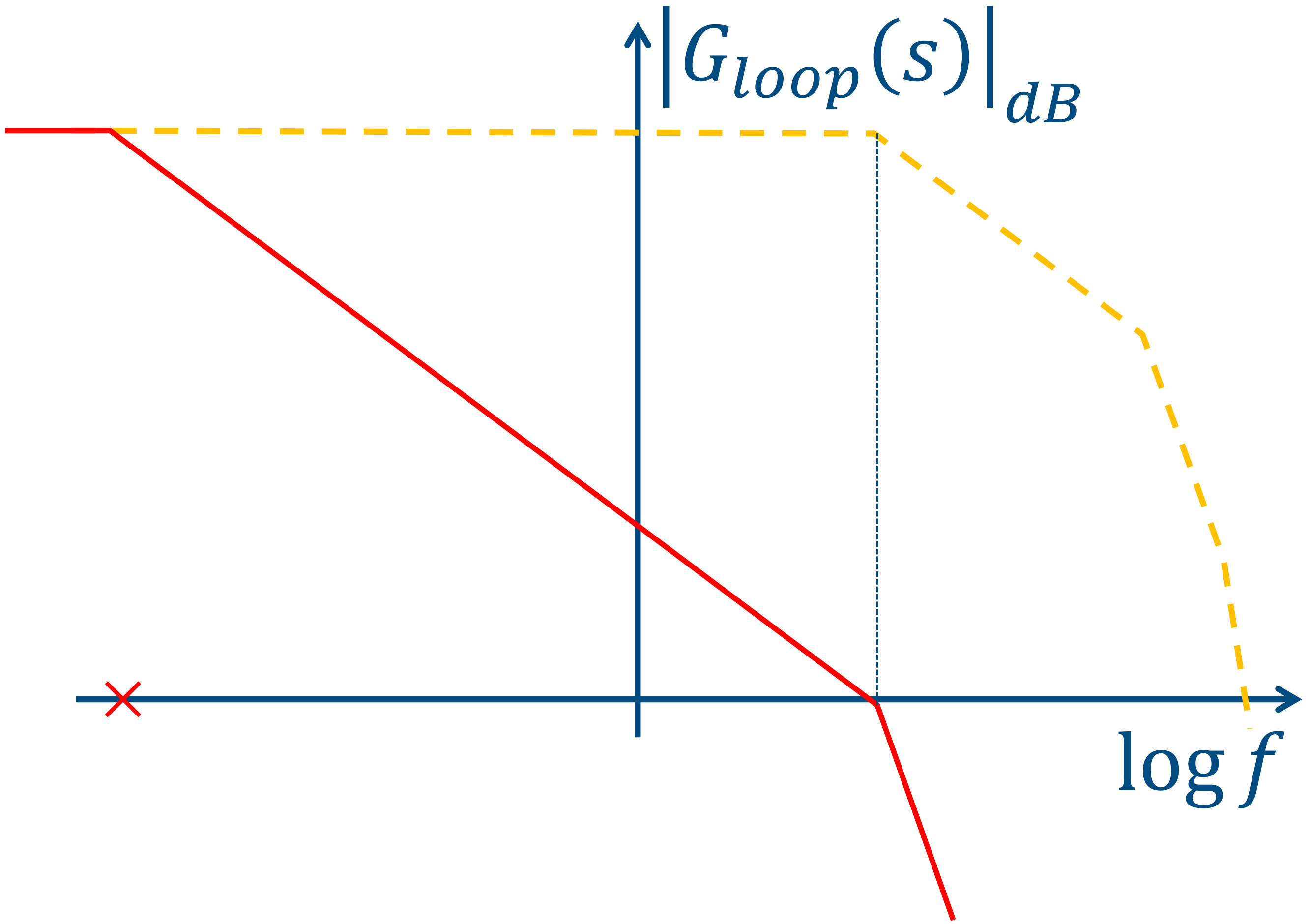
Outline

- Frequency response of feedback amplifiers
- Stability of feedback amplifiers
- Compensation
- Appendix

Frequency compensation of OpAmps

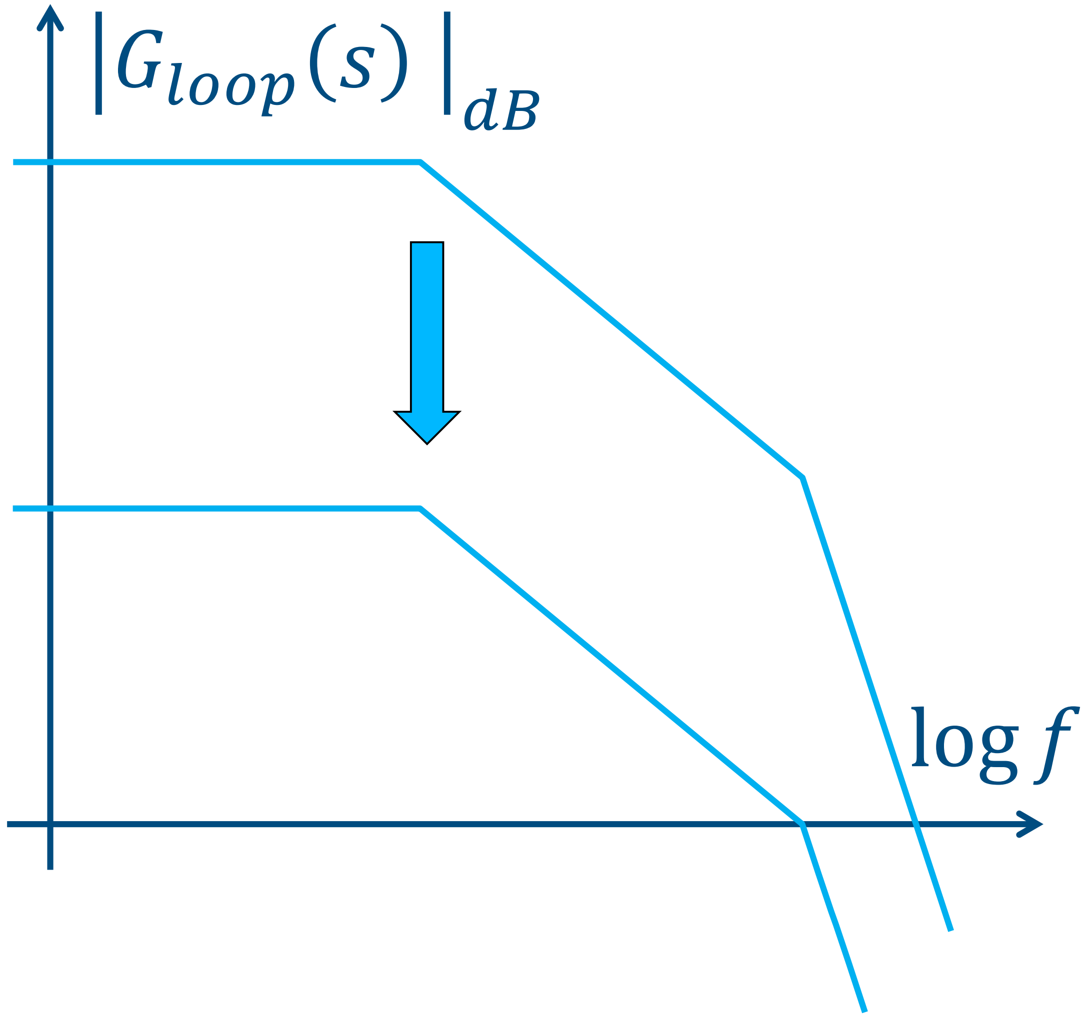
- Is the tailoring of $G_{loop}(s)$ in order to improve the circuit stability
- Most OAs are «internally compensated» to ease their use with resistive feedback, and have a single pole above 0dB
- For frequency-dependent feedback, stability must be checked and compensation applied (if needed)

Dominant pole compensation



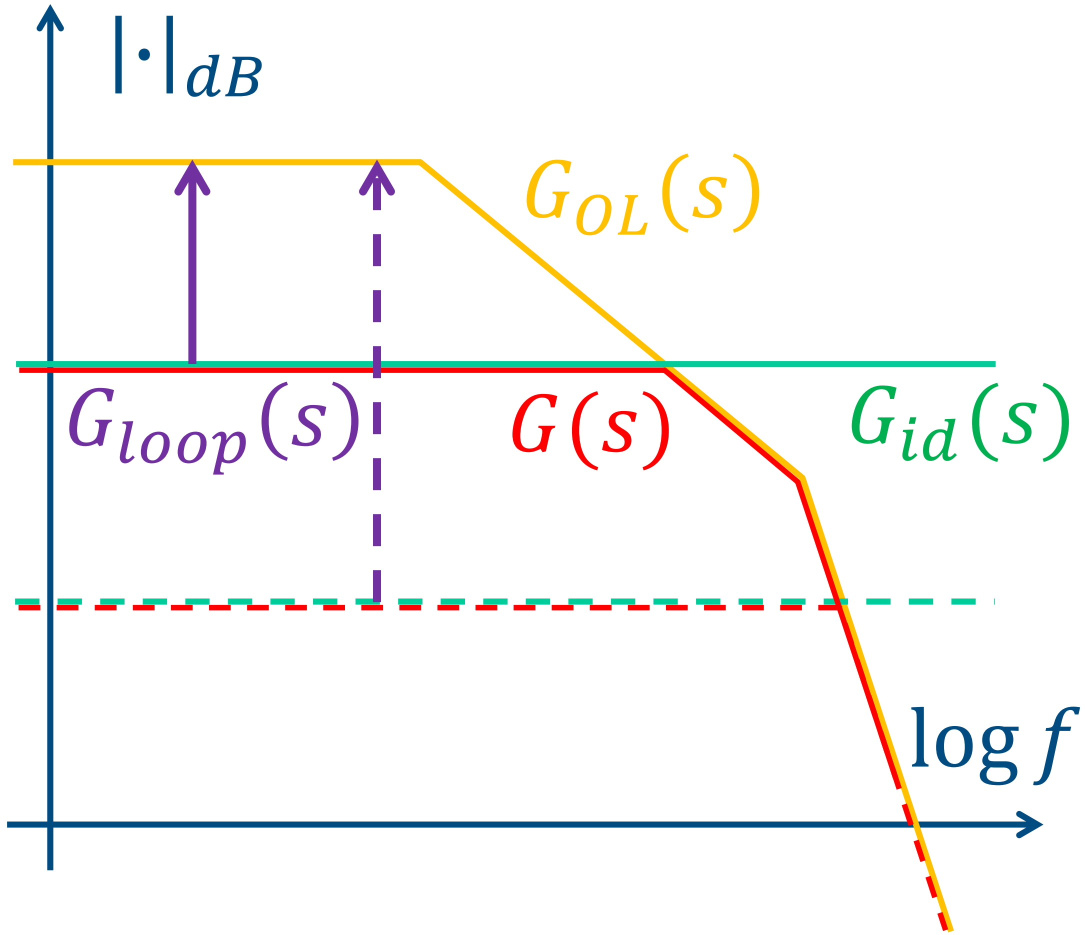
- Used in OA internal compensation
- Put (usually) a large capacitor at the output of the OA
- Big reduction of bandwidth $\Rightarrow$ use only if no other option is available

Gain compensation



- Reduces G_{loop} until sufficient phase margin is achieved
- Useful in uncompensated versions of OAs
- Bandwidth and static precision are reduced $\Rightarrow$ this solution should also be avoided

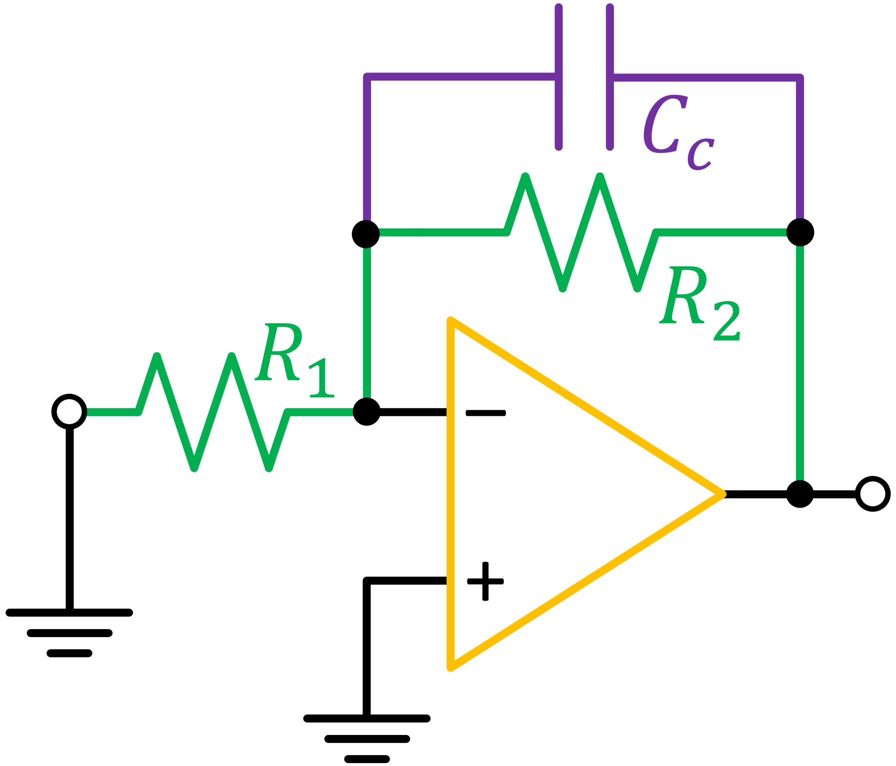
Example: un(or de)compensated OAs

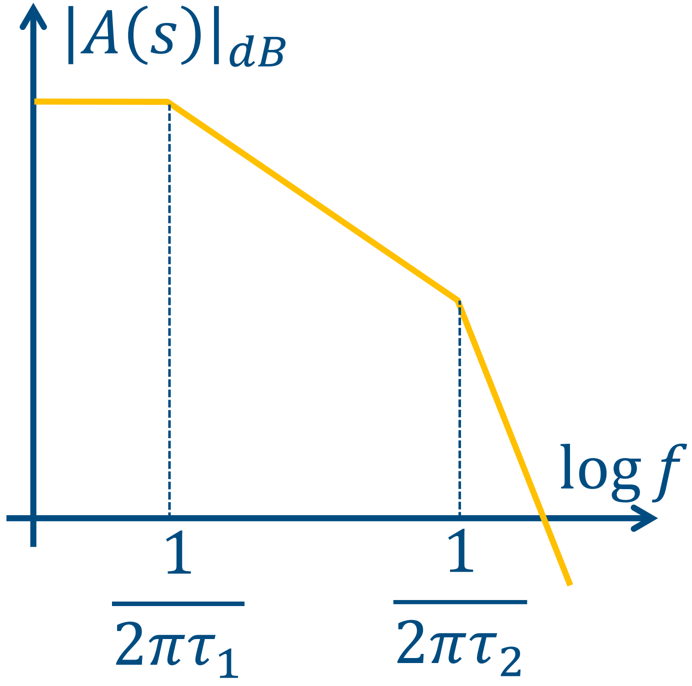


- As $\left|G_{loop}\right|_{dB} = |G_{OL}|_{dB} - |G_{id}|_{dB}$, reduction of $|G_{loop}|$ can be obtained by increasing $|G_{id}|$
- Circuit becomes more stable as gain is increased

See [1] for details

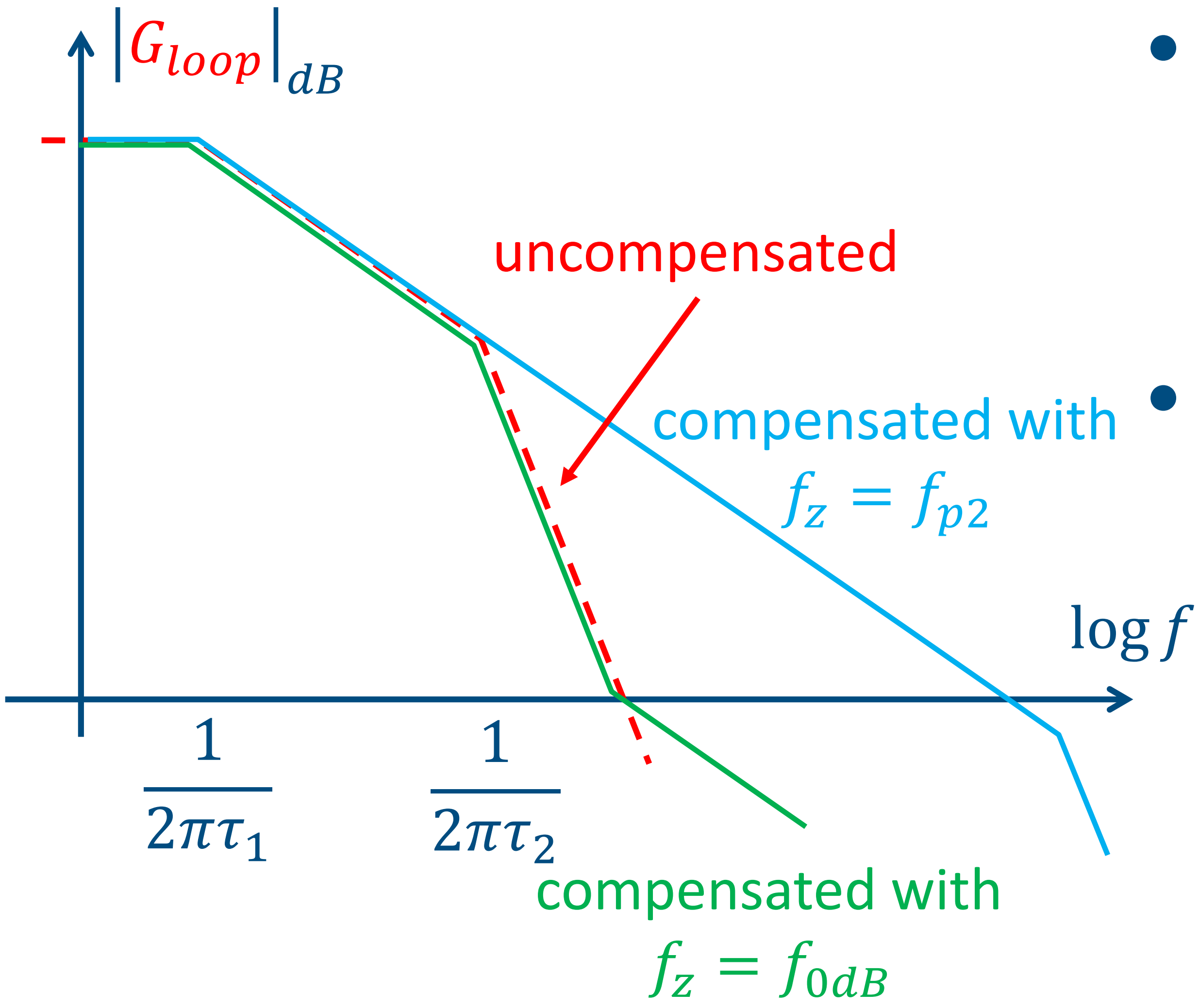
Lead compensation $(f_z < f_p)$





$$G_{loop} = -A(s)\frac{R_1}{R_1 + R_2}\frac{1 + sC_cR_2}{1 + sC_c(R_1 \| R_2)}$$

Resulting loop gain



- The zero can be placed anywhere between the second pole of the OA and f_{0dB}
- The ideal gain is also modified

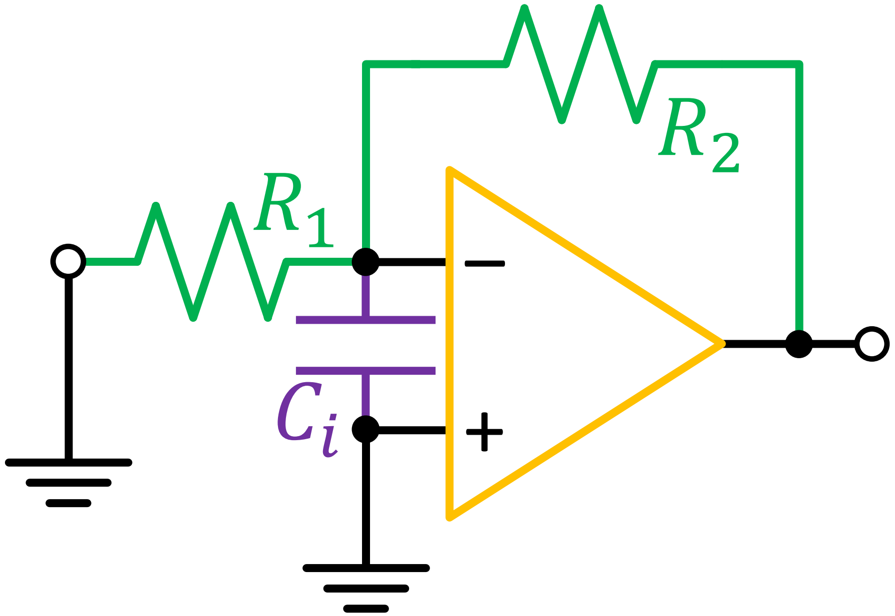
$$G_{id}^{I} = -\frac{R_2}{R_1}\frac{1}{1 + sC_cR_2}$$

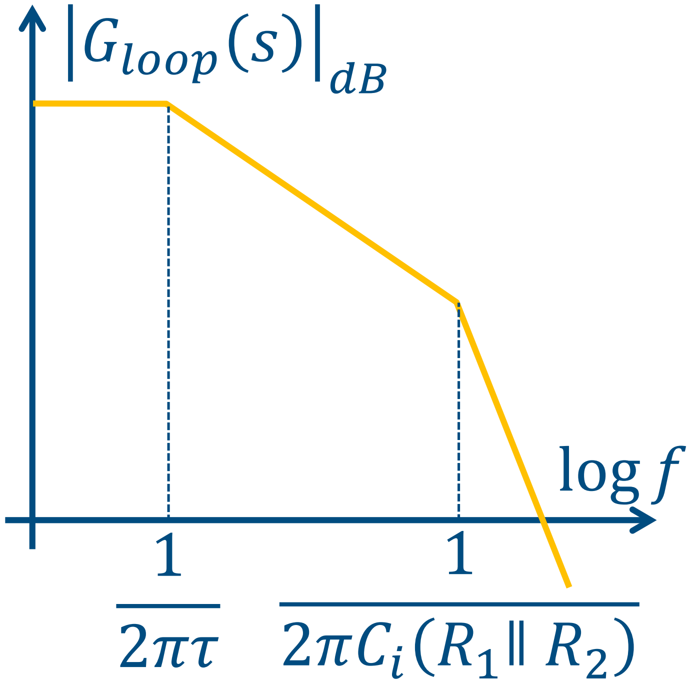
$$G_{id}^{NI} = \frac{R_1 + R_2}{R_1}\frac{1 + sC_c\, R_1 \parallel R_2}{1 + sC_cR_2}$$

Comments

- The closed-loop gain contains a pole at $f_z \Rightarrow$ there is a trade-off between phase margin and bandwidth
- If f_z is lowered too much to increase the phase margin (e.g, $f_z \leq f_{p2}$), high-frequency poles of $A(s)$ must also be considered $\Rightarrow$ increasing f_{0dB} beyond $GBWP$ is not a good idea!

Example: input capacitance

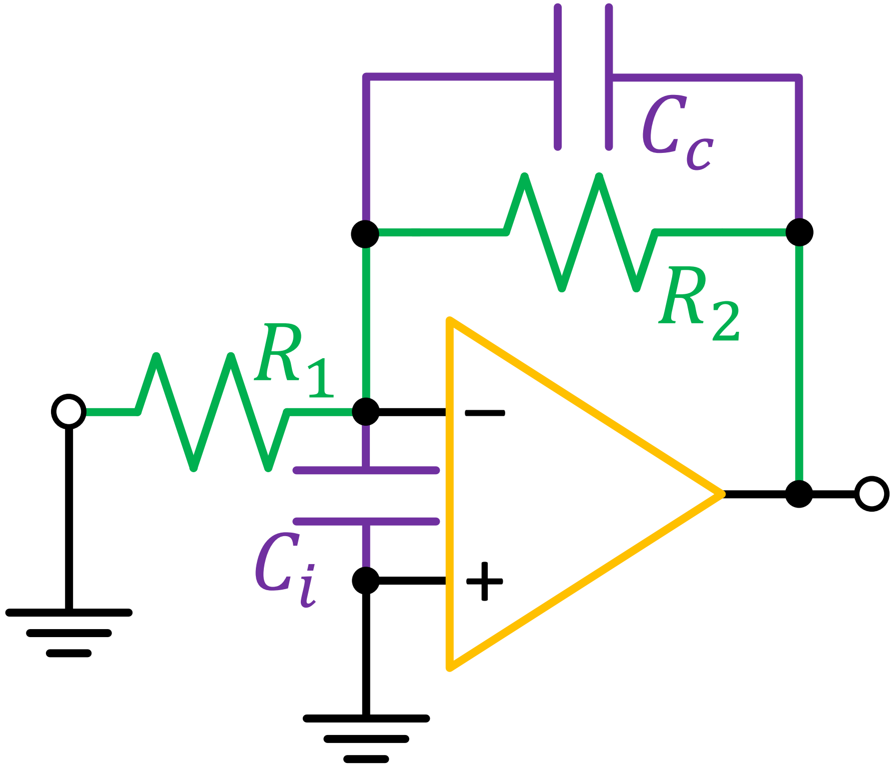




single-pole

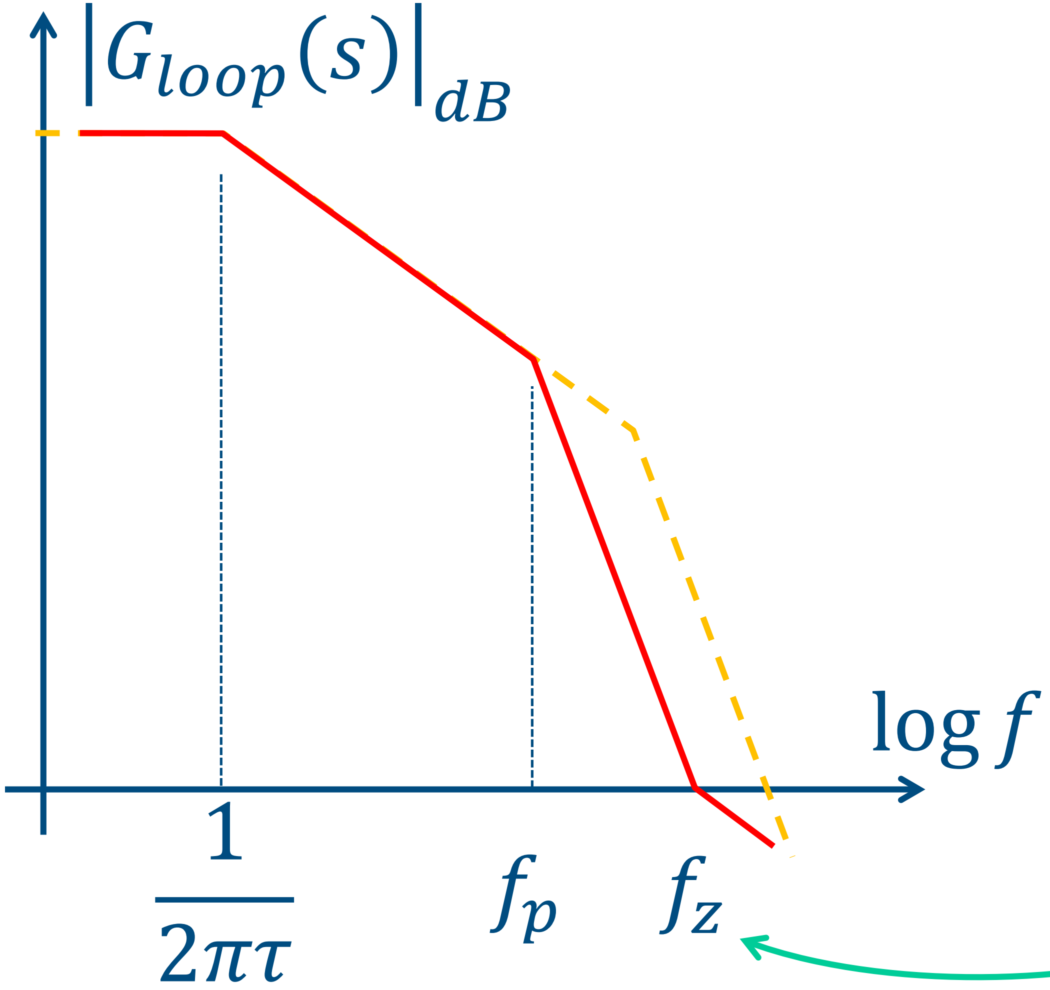
$$G_{loop} = -A(s)\frac{R_1 \parallel Z_C}{R_1 \parallel Z_C + R_2} = -A(s)\frac{R_1}{R_1 + R_2}\frac{1}{1 + sC_i(R_1 \parallel R_2)}$$

Compensation of input capacitance



$$G_{loop} = -A(s)\frac{R_1}{R_1+R_2}\frac{1+sC_cR_2}{1+s(C_i+C_c)(R_1 \parallel R_2)}$$

Resulting loop gain



$$f_p = \frac{1}{2\pi(C_i + C_c)(R_1 \parallel R_2)}$$

$$f_z = \frac{1}{2\pi C_c R_2}$$

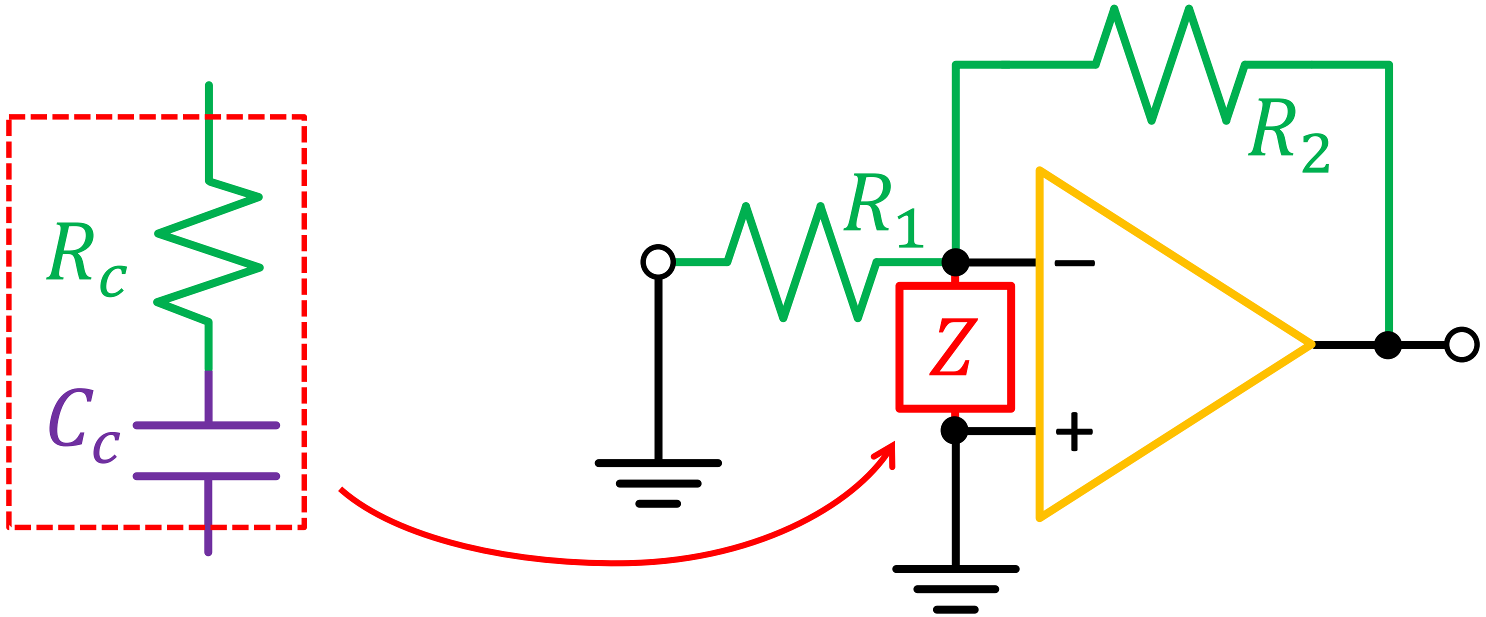
- Small C_c: $f_z > f_p$
- Large C_c: $f_z < f_p$

$f_p < f_z$

Comments

- C_c modifies the closed-loop gain $\Rightarrow$ stability is traded off against bandwidth (now given by f_z)
- Another possibility is $C_c R_2 = C_i R_1$ (pole-zero cancellation), but keep in mind that C_i is never constant in reality…
- In differential amplifiers, use symmetric compensation

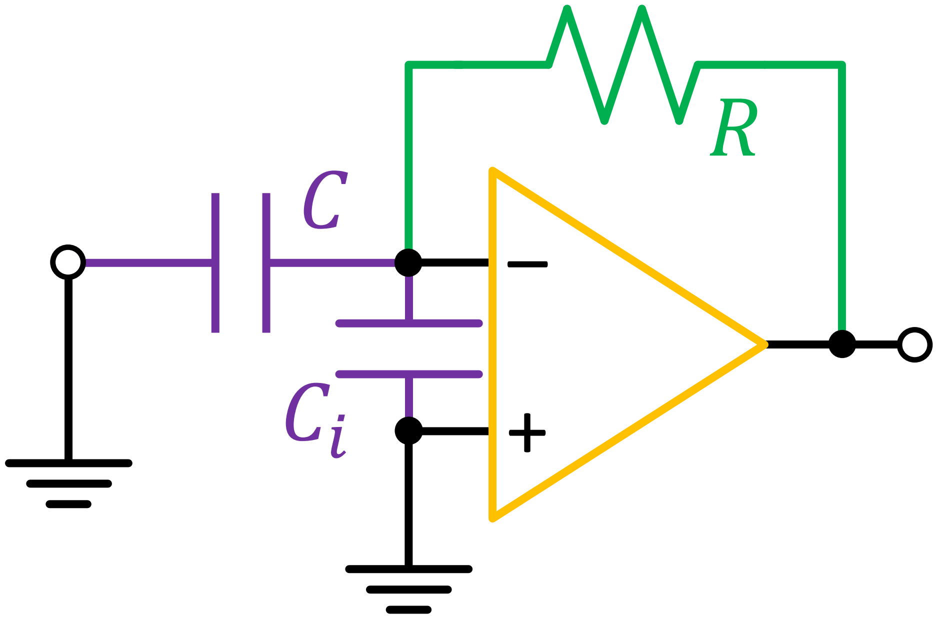
Lag network ($f_p < f_z$)



$$G_{loop} = -A(s)\frac{R_1}{R_1+R_2}\frac{1+sC_cR_c}{1+sC_c(R_c+R_1 \parallel R_2)}$$

Z does not affect G_{id}, but can degrade Z_{in} in NI amplifiers

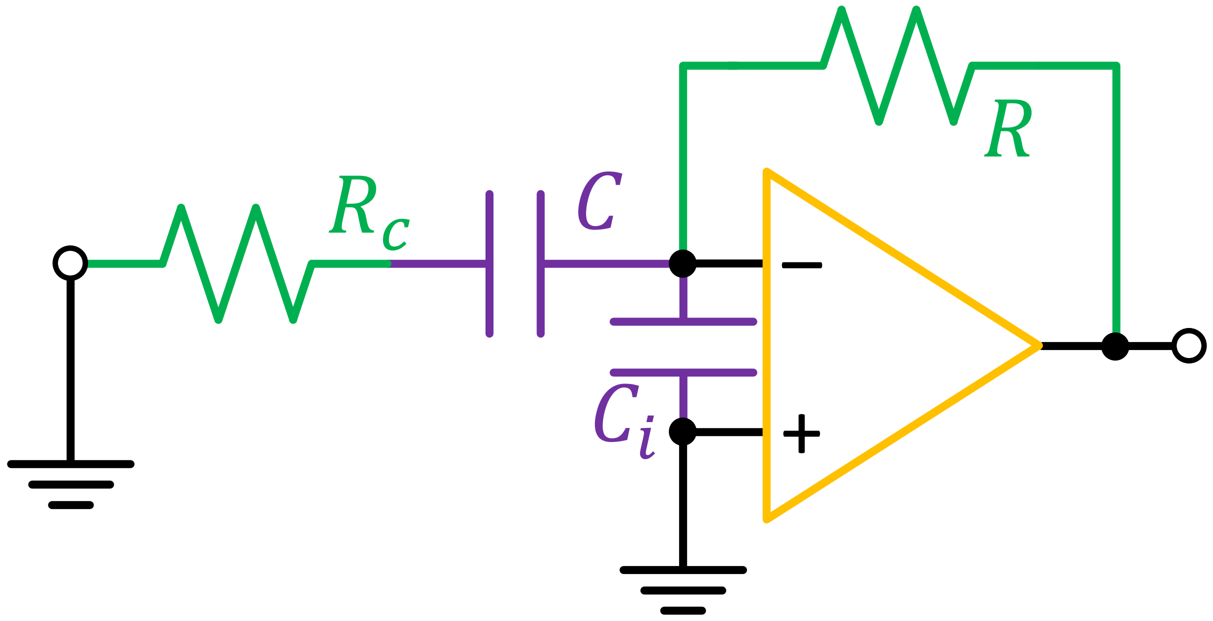
Example: differentiator



$$G_{loop} = -A(s)\frac{1}{1 + sR(C + C_i)}$$

A small resistor R_c between the OA inputs can reduce G_{loop} and provide compensation. However, reducing G_{loop} is usually not a good solution…

Alternative compensation scheme



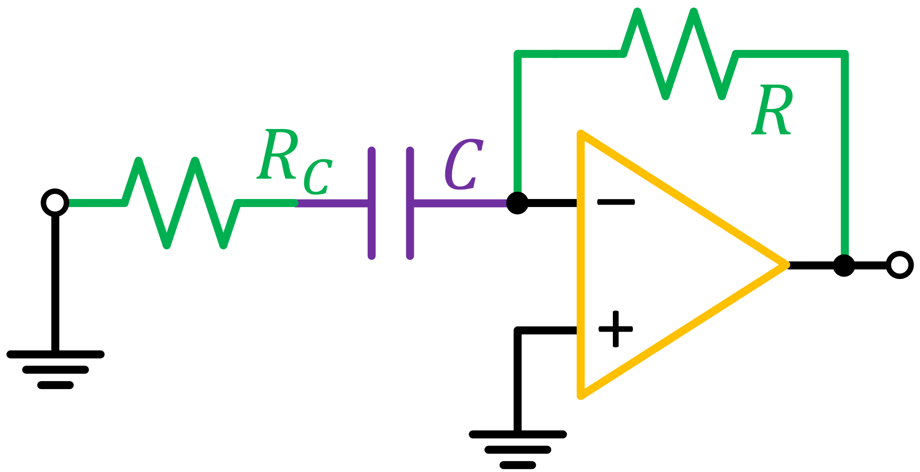
$$G_{loop} = -A(s)\frac{1 + sCR_c}{1 + s(CR_c + CR + C_iR) + s^2CC_iRR_c}$$

LH/HF approximation

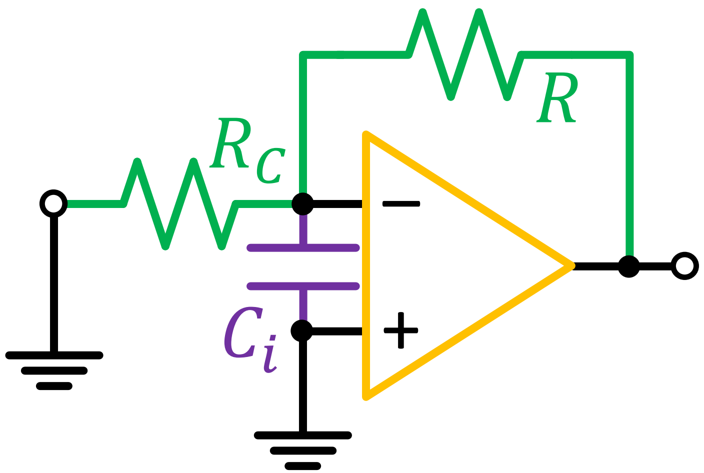
- For frequencies much smaller than its pole/zero, a capacitor can be regarded as an open circuit
- For frequencies much larger than its pole/zero, a capacitor can be regarded as a short-circuit
- Pole/zero frequencies are inversely proportional to the capacitance value
  - C will give LF pole/zero $\Rightarrow$ C_i behaves as an open circuit
  - C_i will give HF pole/zero $\Rightarrow$ C behaves as a short-circuit

Resulting schemes

LF



HF



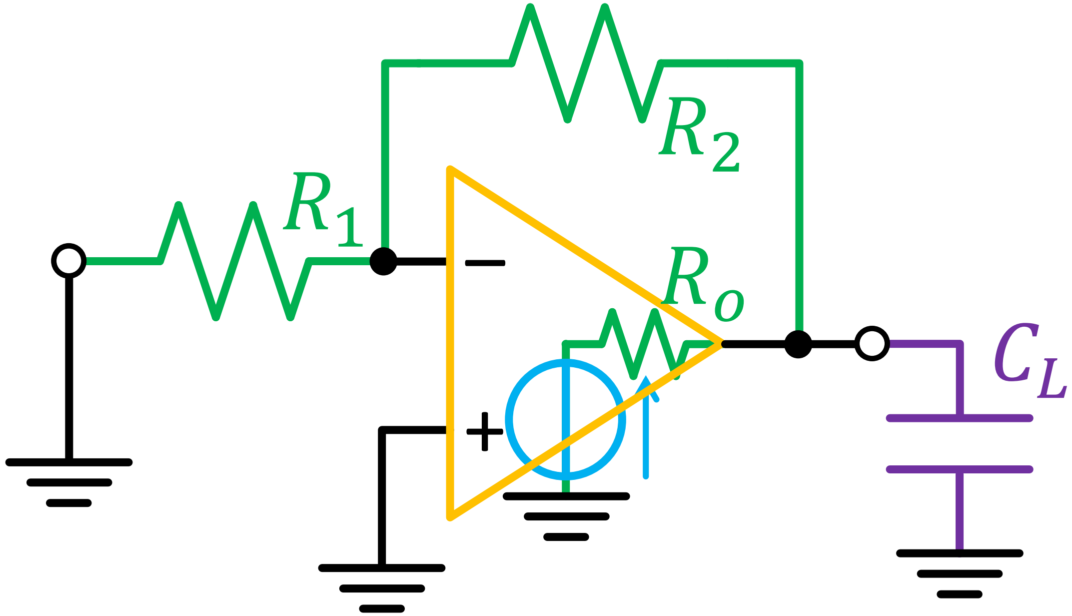
Poles and zeros

LF: $f_z = \dfrac{1}{2\pi C R_c}$ $\quad f_{p1} \approx \dfrac{1}{2\pi C(R_c + R)}$

HF: $\quad f_{p2} \approx \dfrac{1}{2\pi C_i(R_c \| R)}$

- f_{p2} is usually at high frequency and can be neglected
- Lag network ($f_{p1} < f_z$) can be used for compensation
- Closed-loop gain bandwidth limited to $\dfrac{1}{2\pi R_c C}$

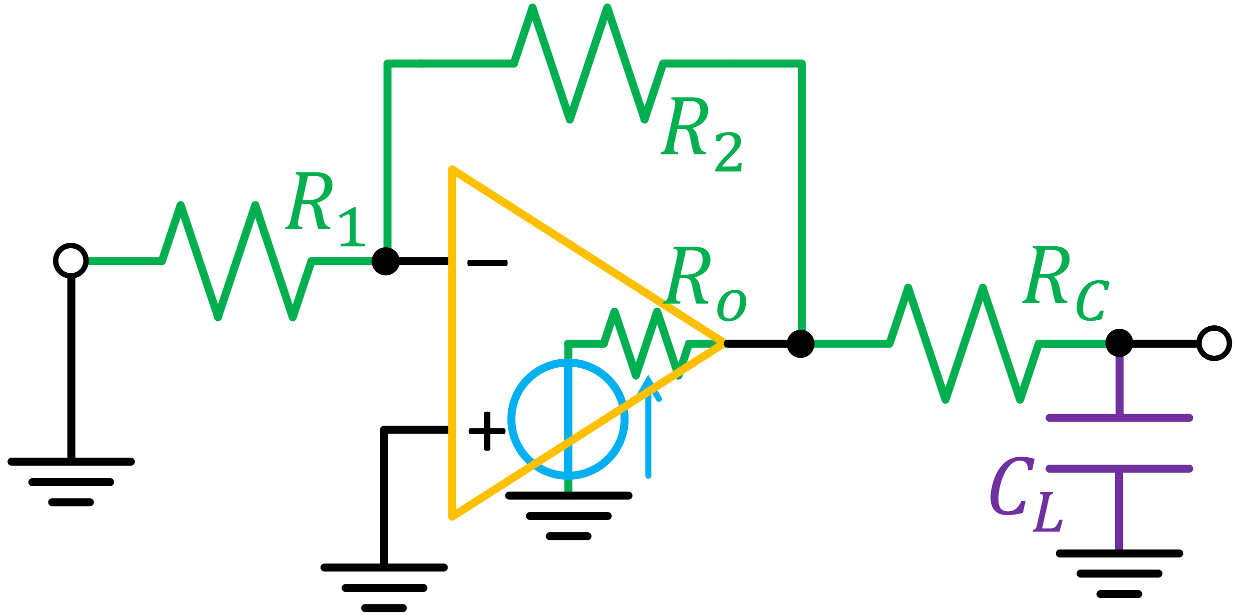
Capacitive load



Additional pole in G_{loop} must be above $GBWP$ (say, 10 $GBWP$) $\Rightarrow$ rough (and conservative) estimate of maximum load capacitance is

$$C_L \approx \frac{1}{2\pi R_o (10\ GBWP)}$$

Compensation – 1



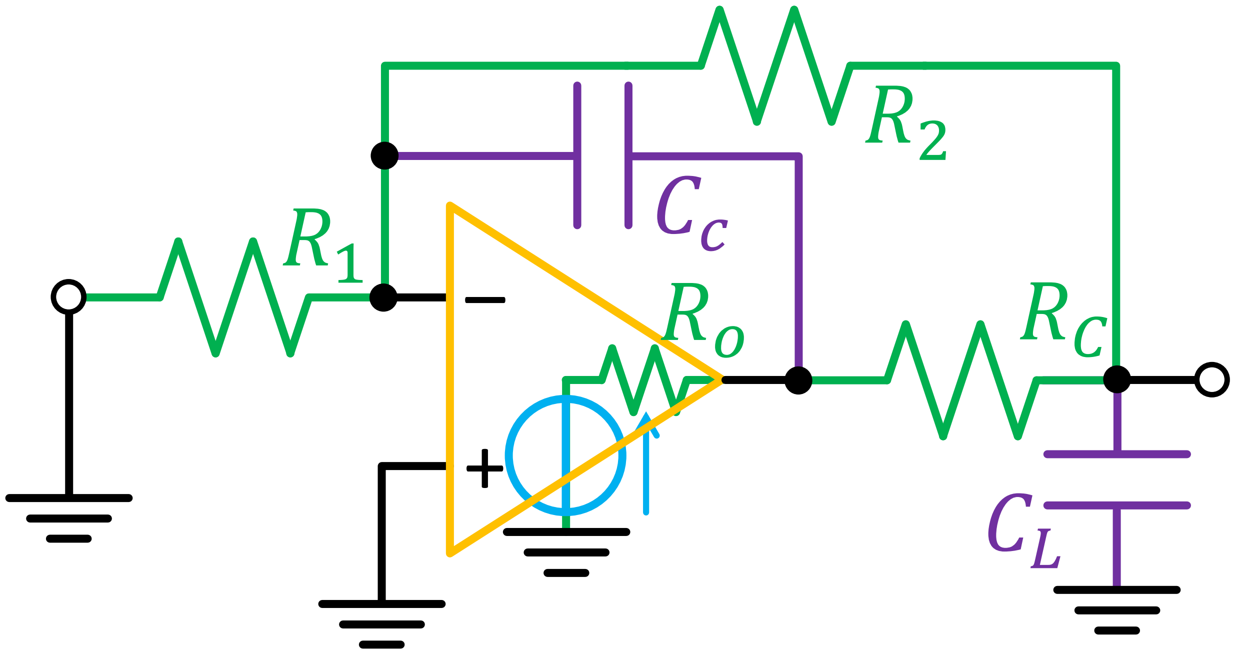
$$f_z = \frac{1}{2\pi C_L R_c} \qquad f_p \approx \frac{1}{2\pi C_L (R_c + R_o)}$$

If $R_1 + R_2 \gg R_o$

Outline

- Frequency response of feedback amplifiers
- Stability of feedback amplifiers
- Compensation
- Appendix

Compensation – 2



See [2] for details

References

1. https://www.ti.com/lit/pdf/snoa486
2. https://www.analog.com/media/en/analog-dialogue/volume-38/number-2/articles/techniques-to-avoid-instability-capacitive-loading.pdf