Electronics – 96032

POLITECNICO DI MILANO

Closed-loop Gain and Impedances

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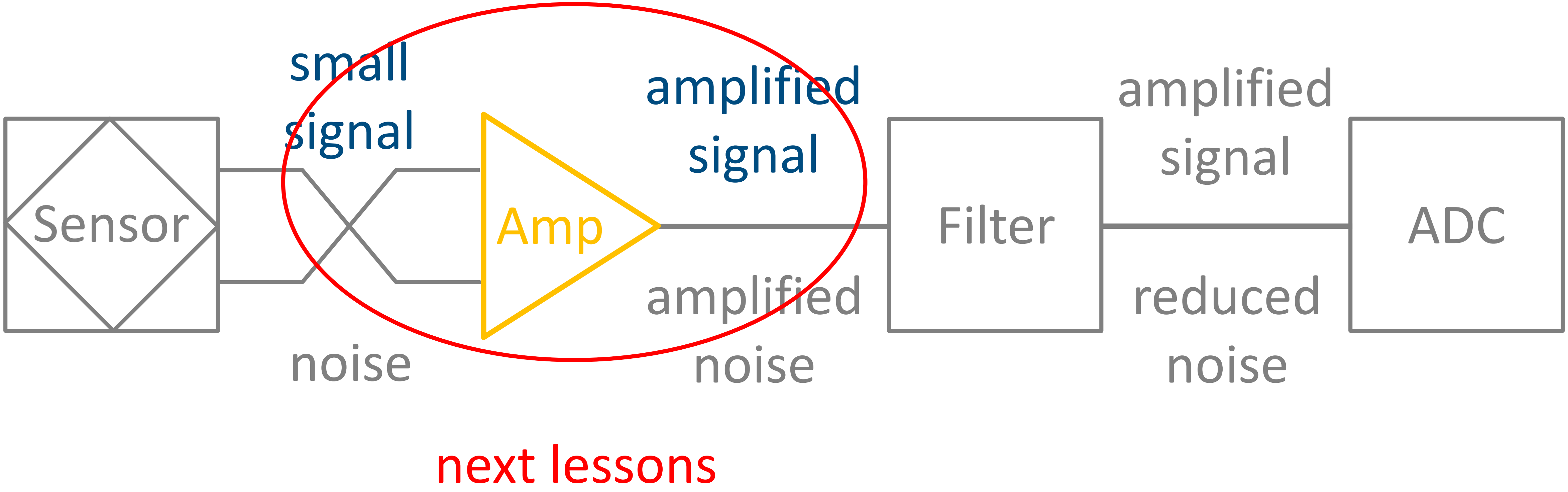
Disclaimer

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

Acquisition chain



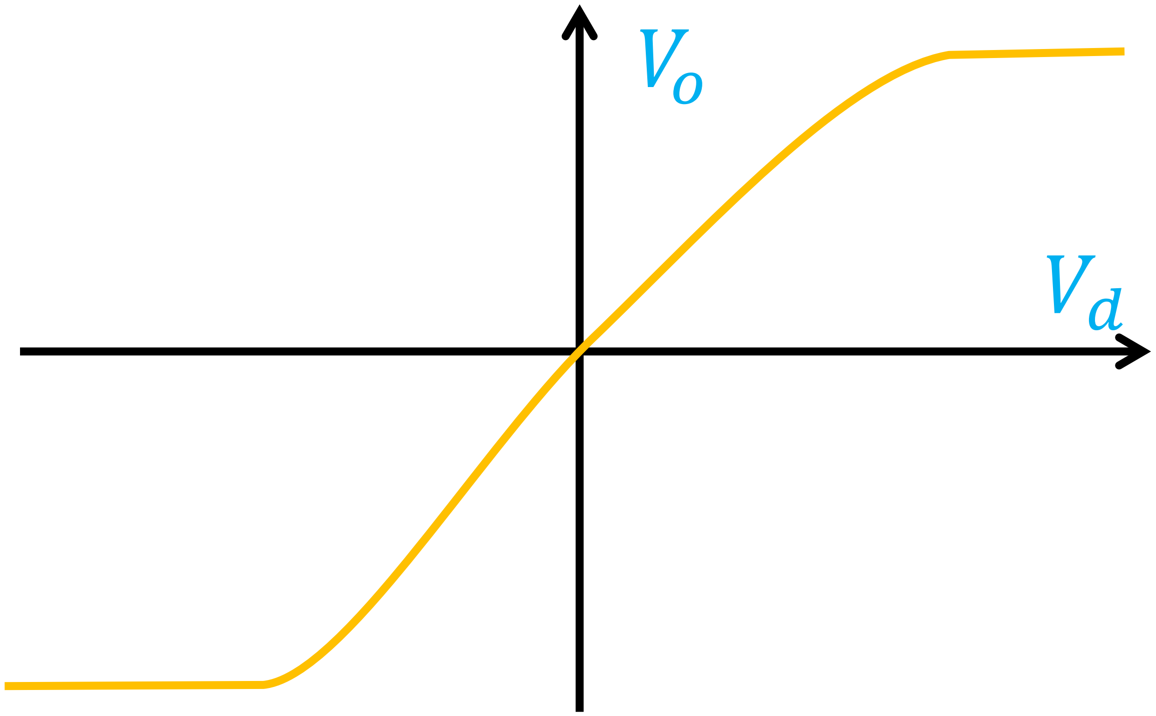
Purpose of the lesson

- 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 (this lesson)
  - Stability of feedback amplifiers
  - Instrumentation amplifiers and OpAmp parameters

Outline

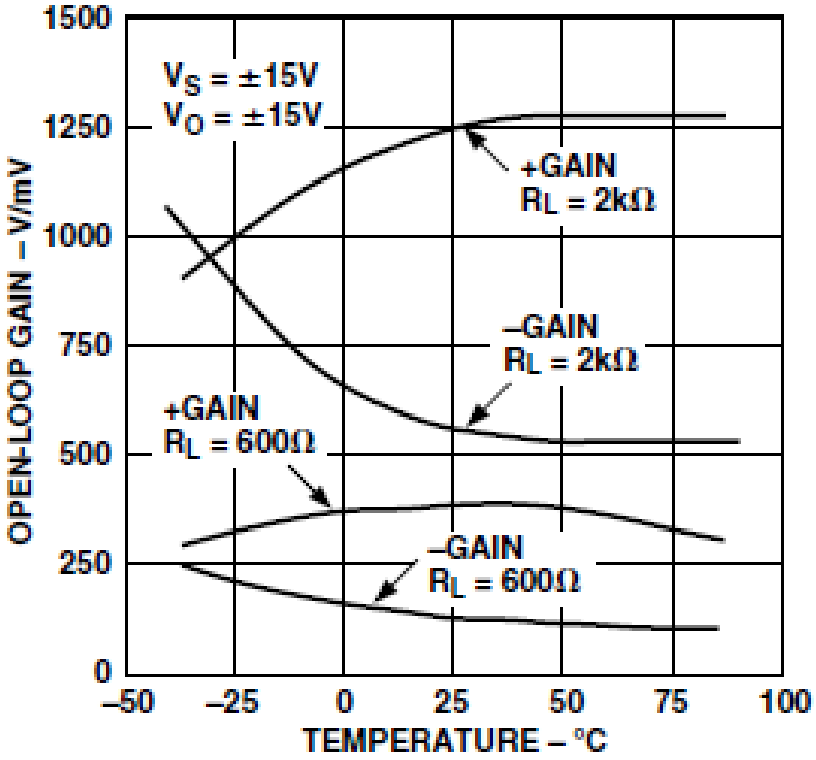
- Loop gain and closed-loop gain calculation
- Input/output impedances

OA parameter: large-signal voltage gain

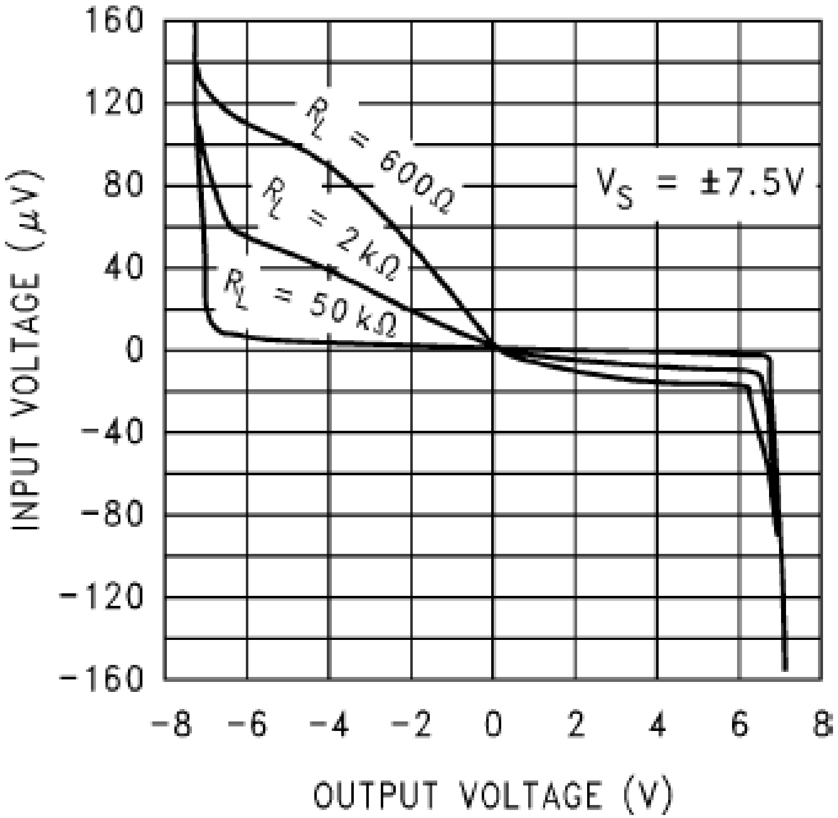


- I/O characteristic is non-linear $\Rightarrow$ gain A_V is the slope of the linear interpolation
- Typical values are $80 - 120$ dB (sometimes expressed in V/mV), but dependent on V_{cc}, R_L, T,…

Actual values from datasheets

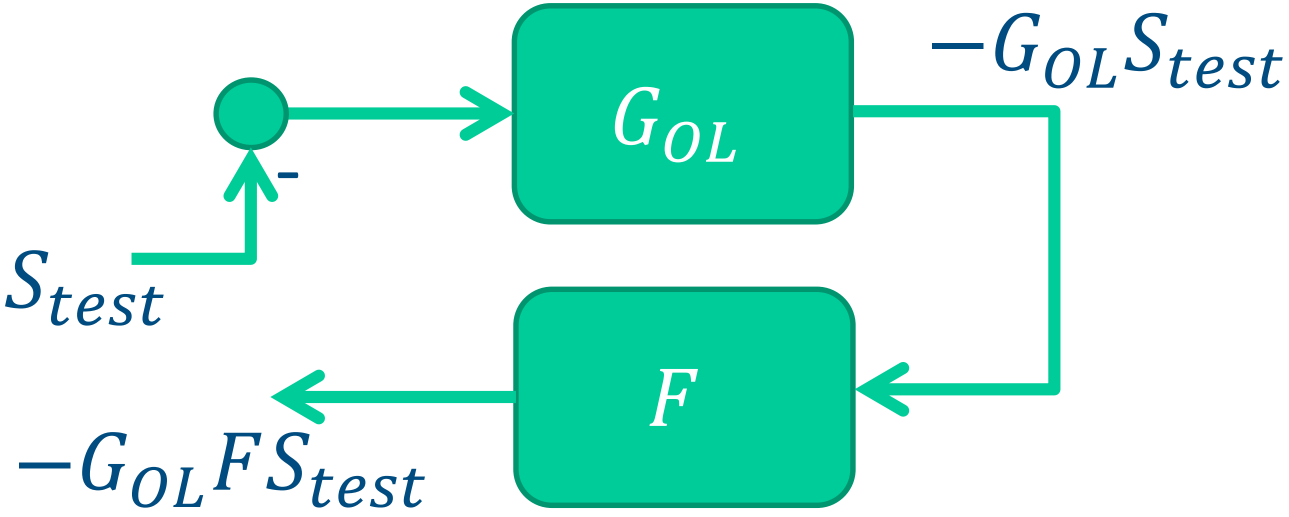


Dependence on T and R_L (note the asymmetry of the gain)

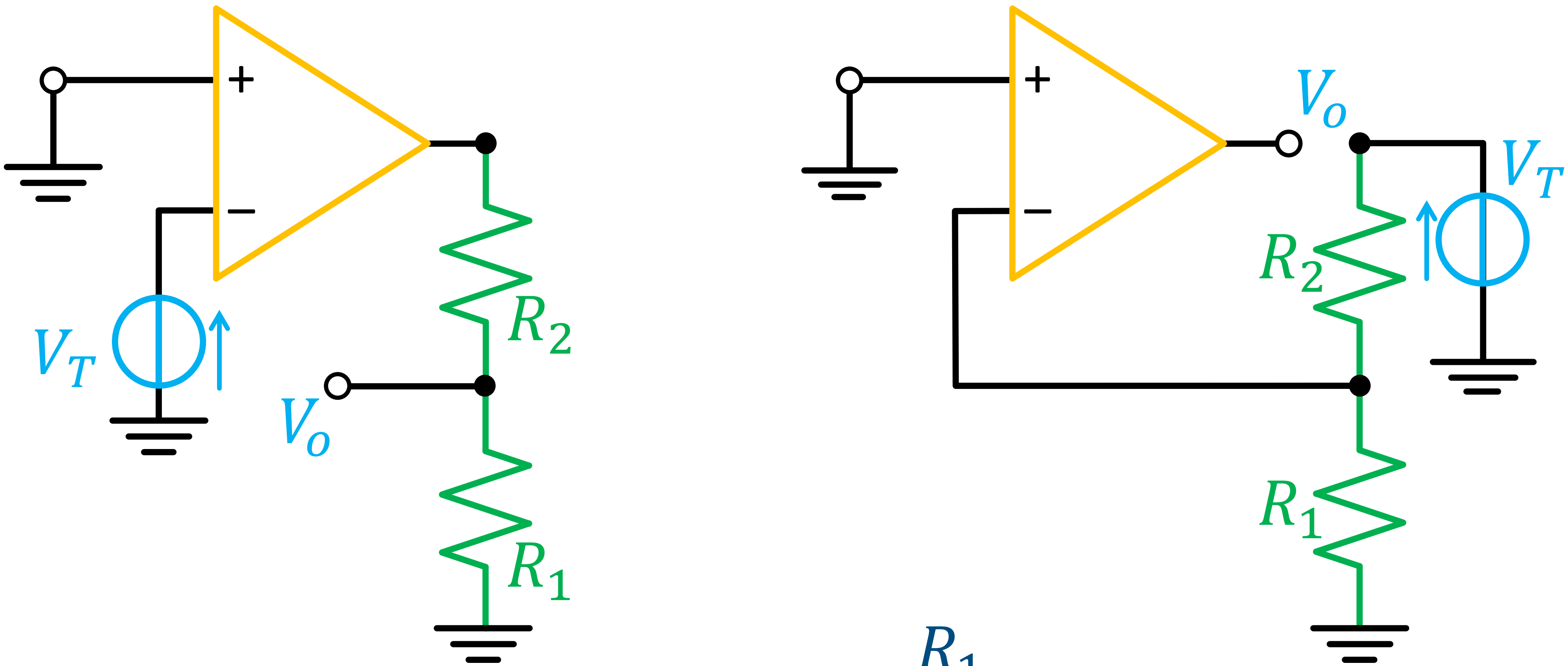


(low-power CMOS OA)

Loop gain calculation (concept)

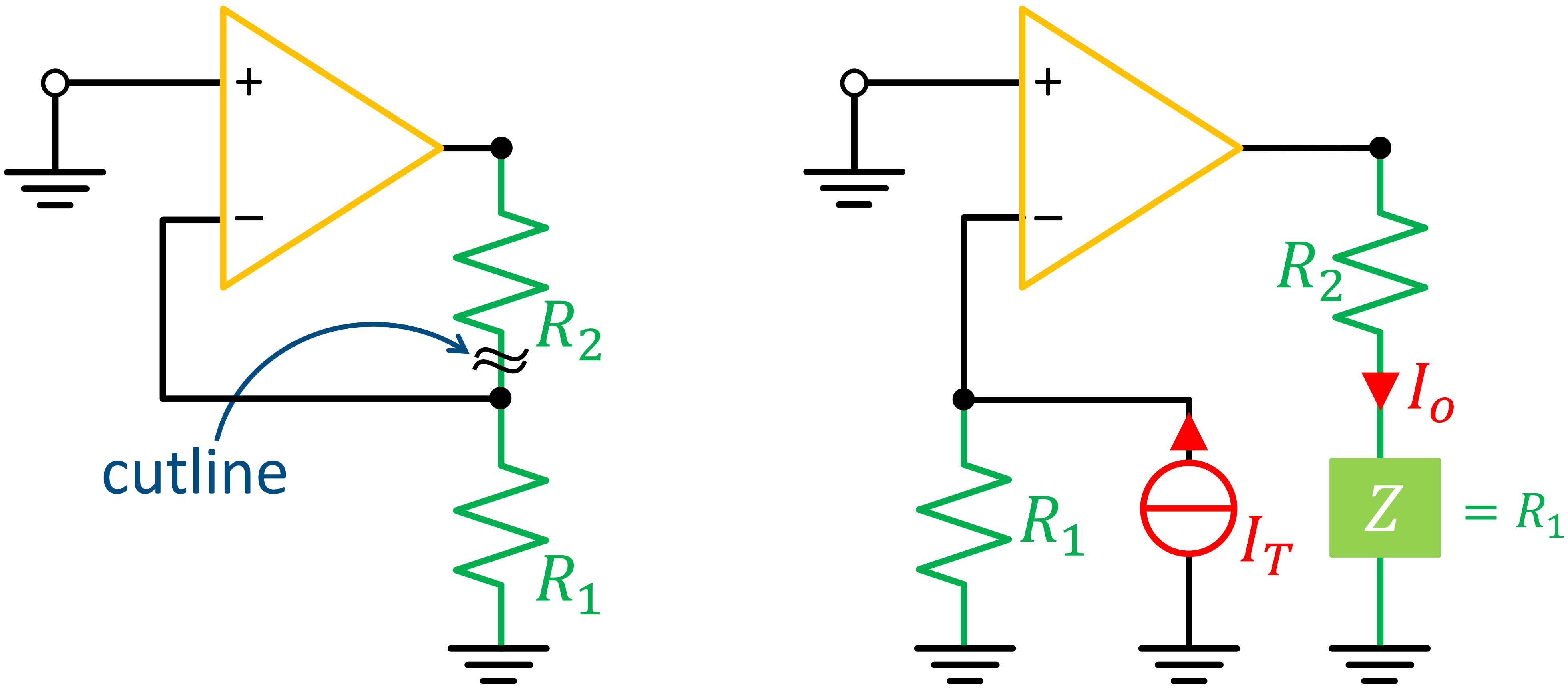


Loop gain calculation

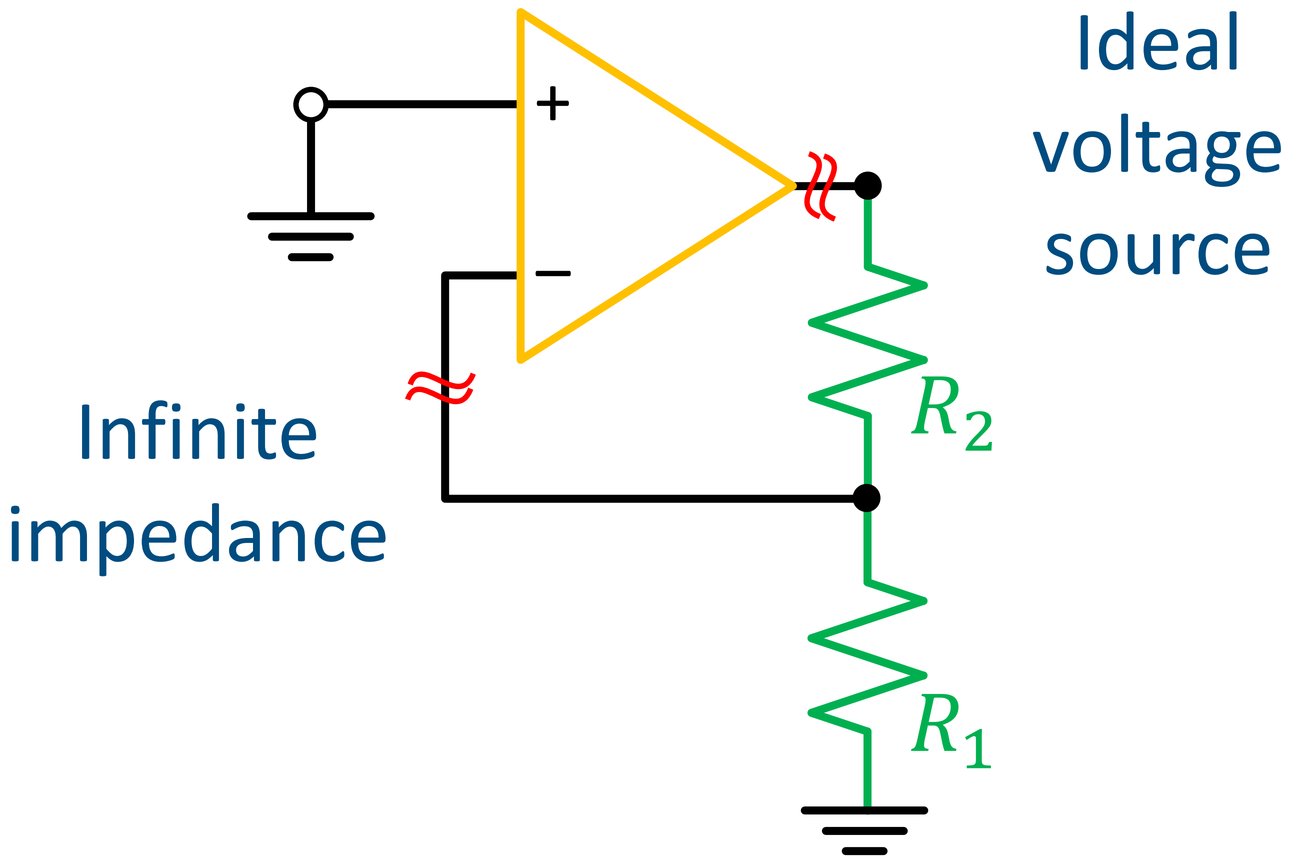


$$G_{loop} = -A\frac{R_1}{R_1 + R_2}$$

Impedance reconstruction



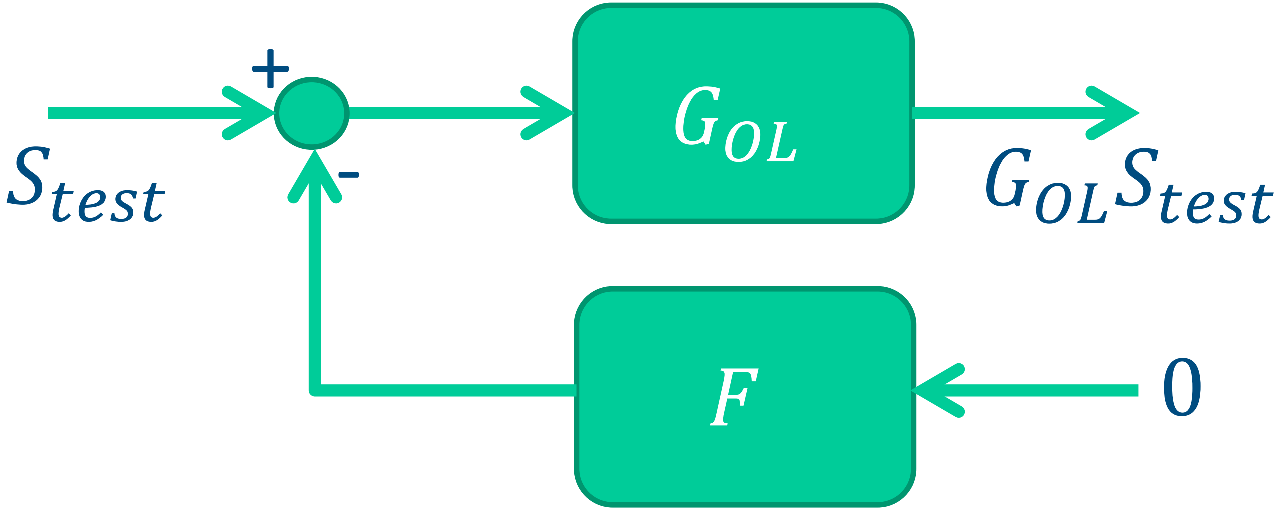
Smart cutpoints



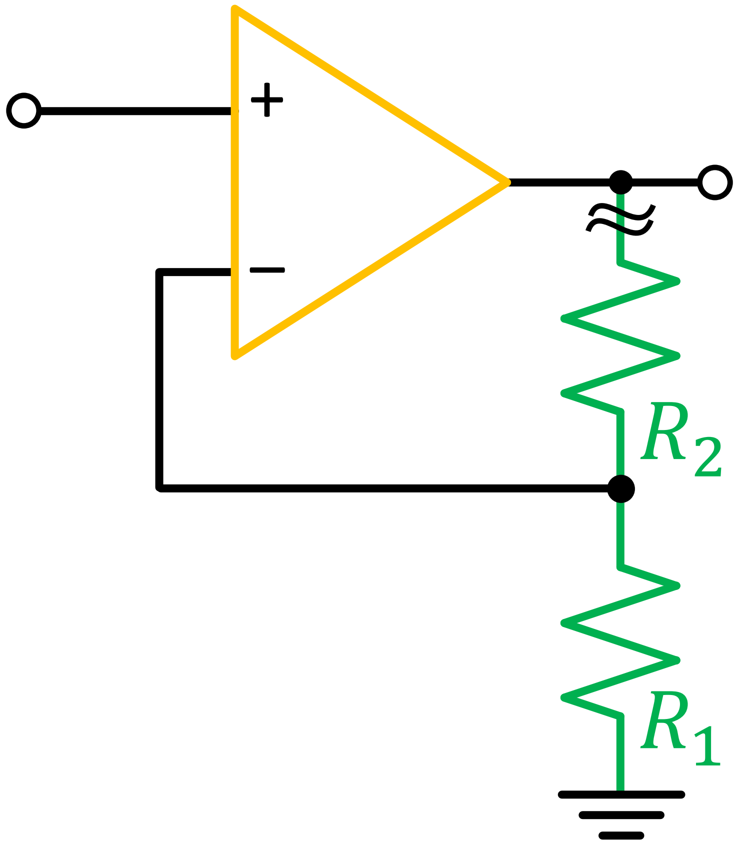
Closed-loop gain

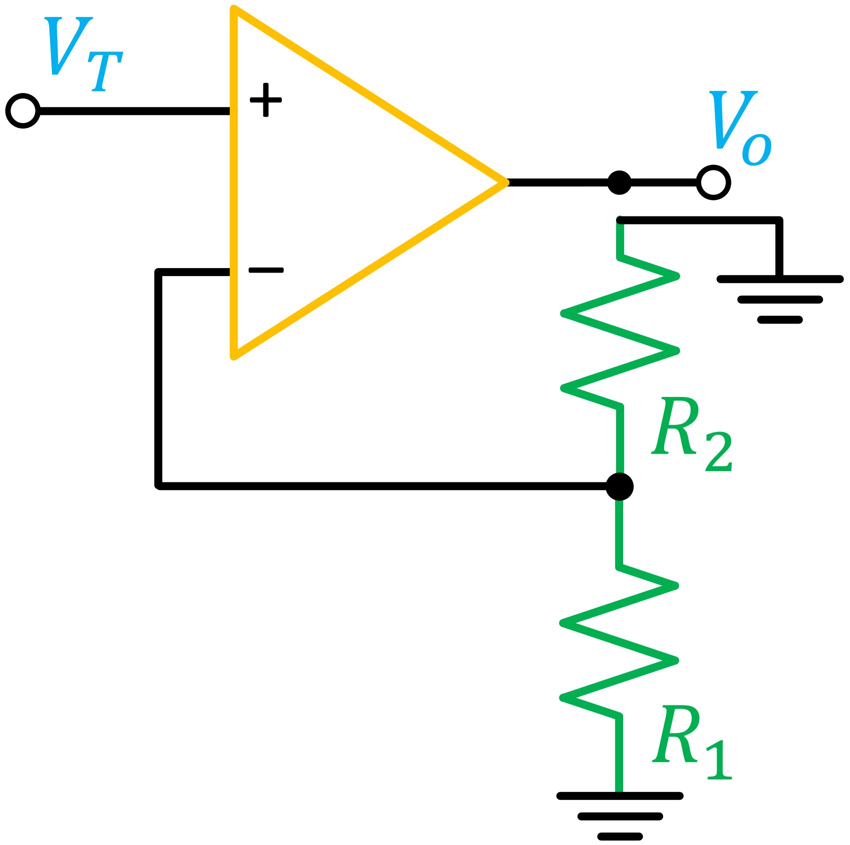
$$G = \frac{V_o}{V_i} = \frac{G_{id}}{1 - \frac{1}{G_{loop}}} = \frac{\frac{R_1 + R_2}{R_1}}{1 + \frac{R_1 + R_2}{AR_1}} = \frac{A}{1 + \frac{AR_1}{R_1 + R_2}} = \frac{G_{OL}}{1 - G_{loop}}$$

Open-loop gain calculation (concept)



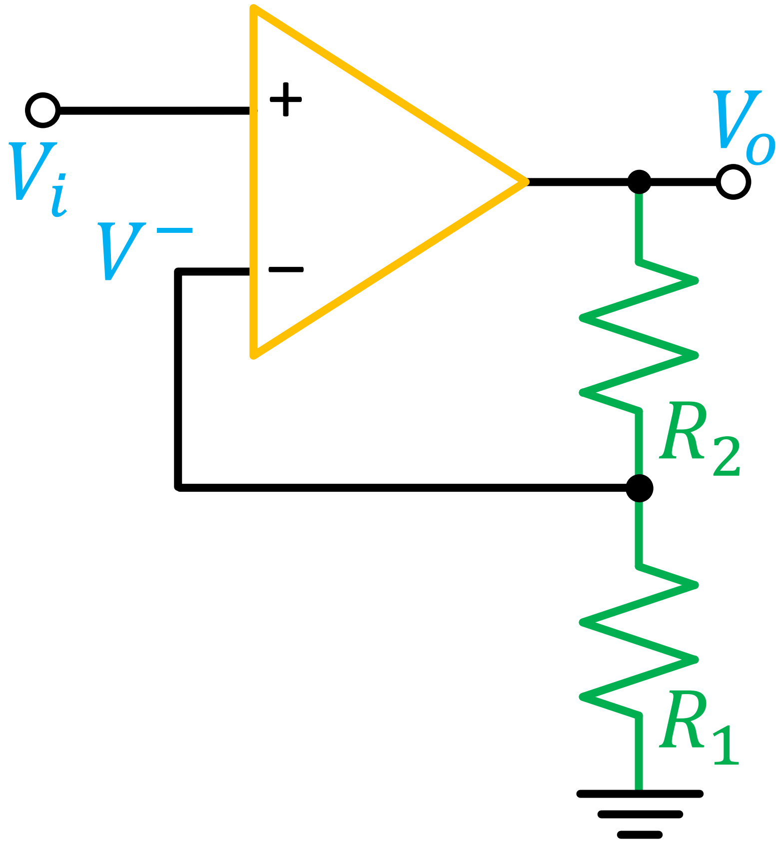
Open-loop gain calculation





$$G_{OL} = A$$

Direct calculation (no feedback theory)

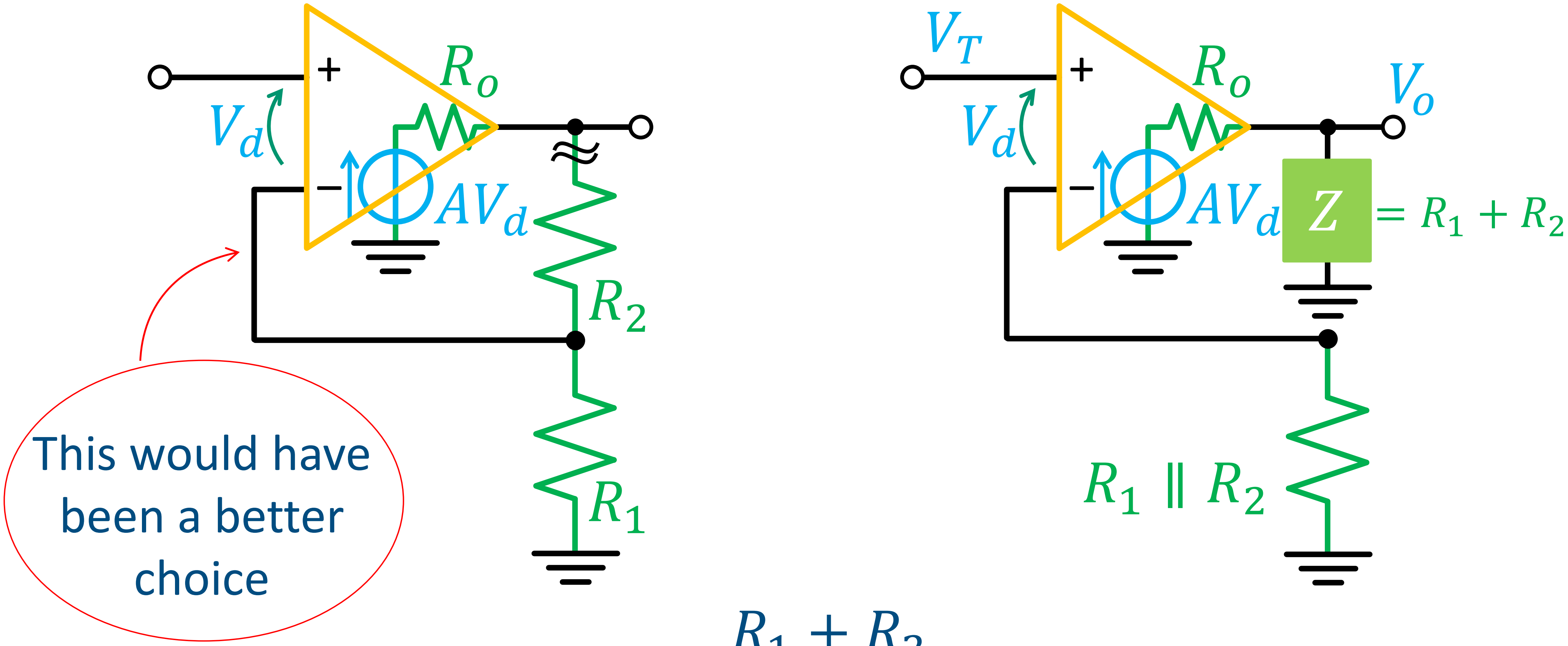


$$V^- = V_o \frac{R_1}{R_1 + R_2}$$

$$V_o = A(V^+ - V^-) = A(V_i - V^-)$$

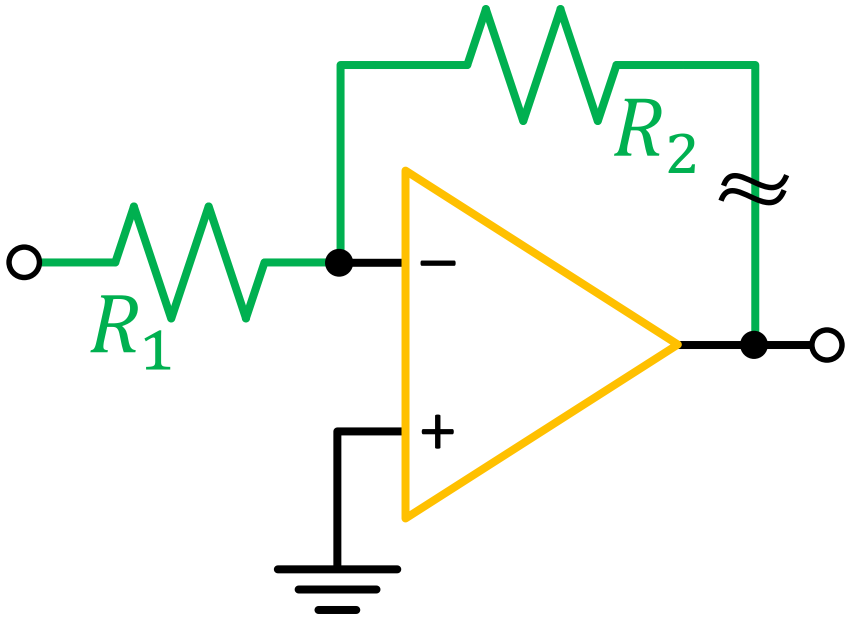
$$\frac{V_o}{V_i} = \frac{A}{1 + \frac{AR_1}{R_1 + R_2}}$$

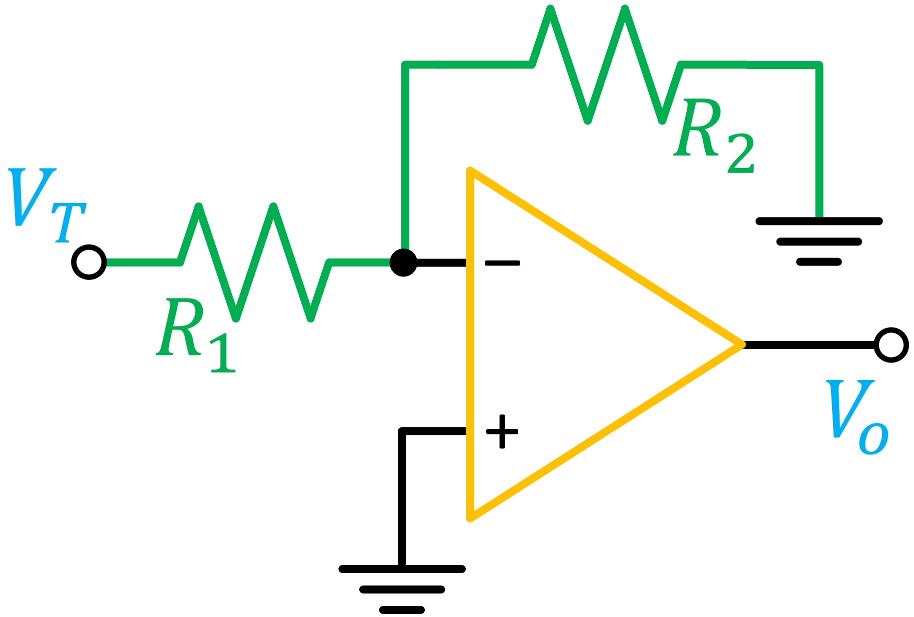
Impedance reconstruction



$$G_{OL} = A \frac{R_1 + R_2}{R_1 + R_2 + R_o} \qquad G_{loop} = ?$$

Inverting amplifier case





$$G_{OL} = -A\frac{R_2}{R_1 + R_2}$$

Closed-loop gain

$$G = \frac{V_o}{V_i} = \frac{G_{id}}{1 - \frac{1}{G_{loop}}} = \frac{-\frac{R_2}{R_1}}{1 + \frac{R_1 + R_2}{AR_1}} = \frac{-A\frac{R_2}{R_1 + R_2}}{1 + \frac{AR_1}{R_1 + R_2}} = \frac{G_{OL}}{1 - G_{loop}}$$

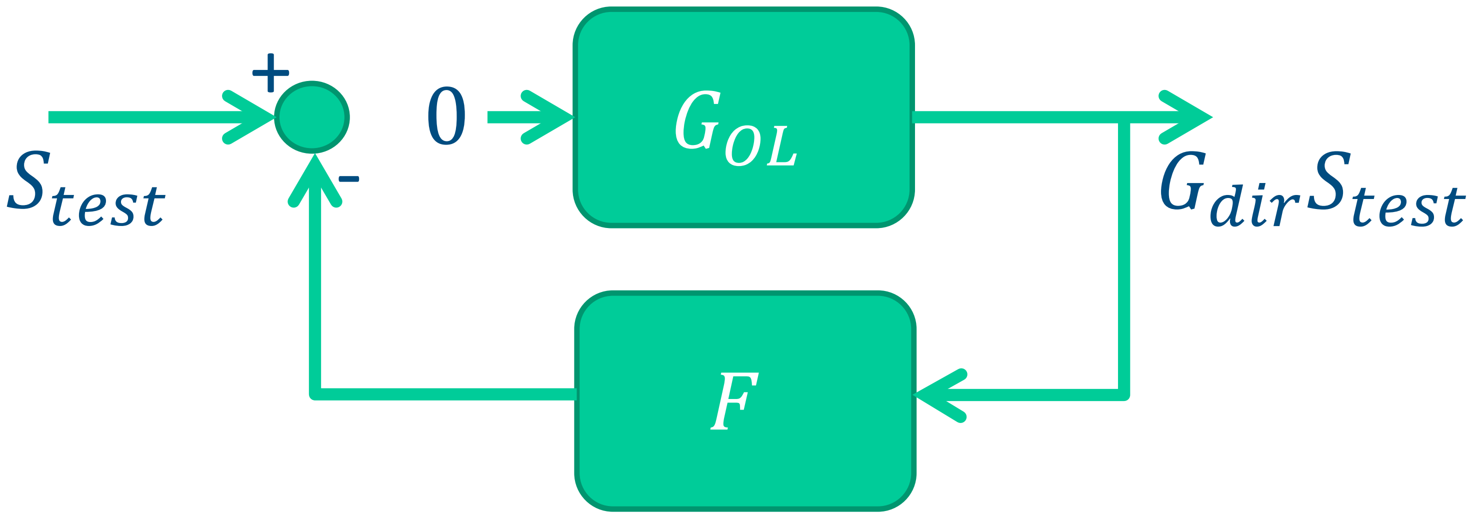
A few notes

- Always remember to reconstruct the impedance in non-ideal cases
- In any case, G_{OL} can always be calculated as

$$G_{OL} = -G_{loop} G_{id}$$

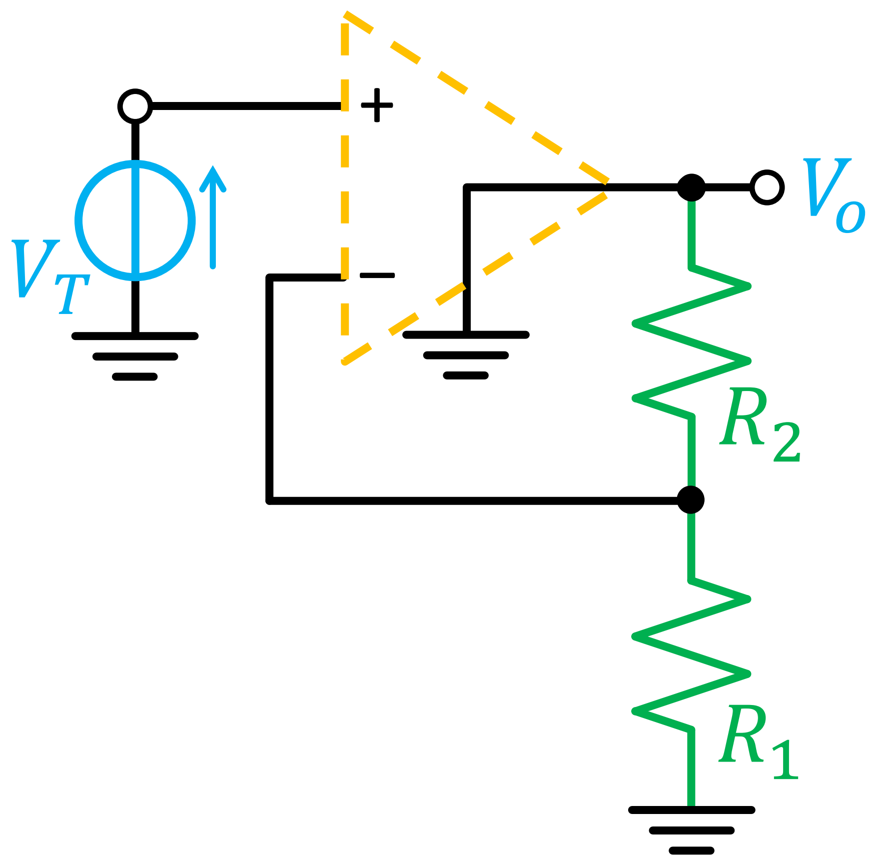
- The closed-loop gain may contain an additional term (called *direct gain* or *feedthrough gain*) due to direct transfer through the feedback network. This term is usually (but not always) small and neglected

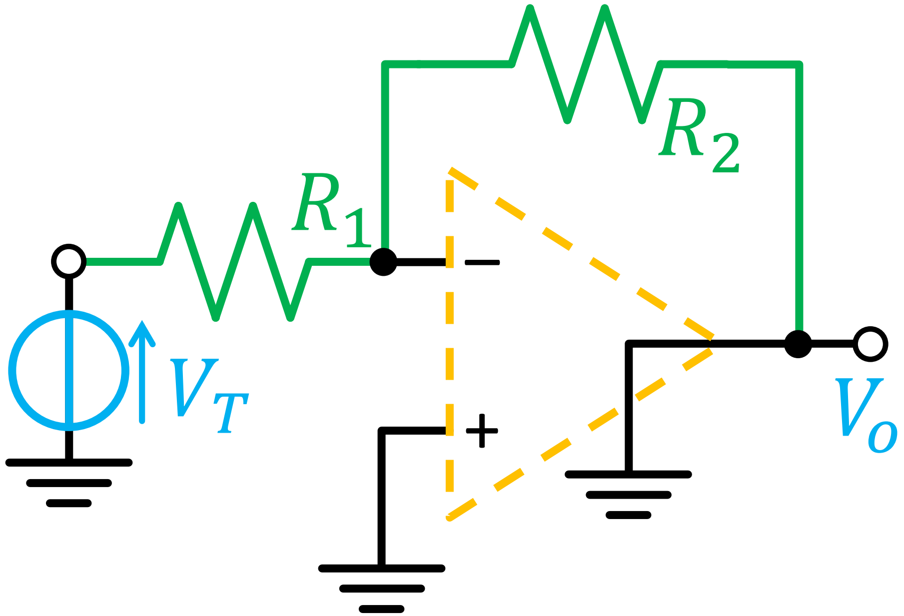
Direct gain calculation (concept)



$G_{dir} = 0$ is expected

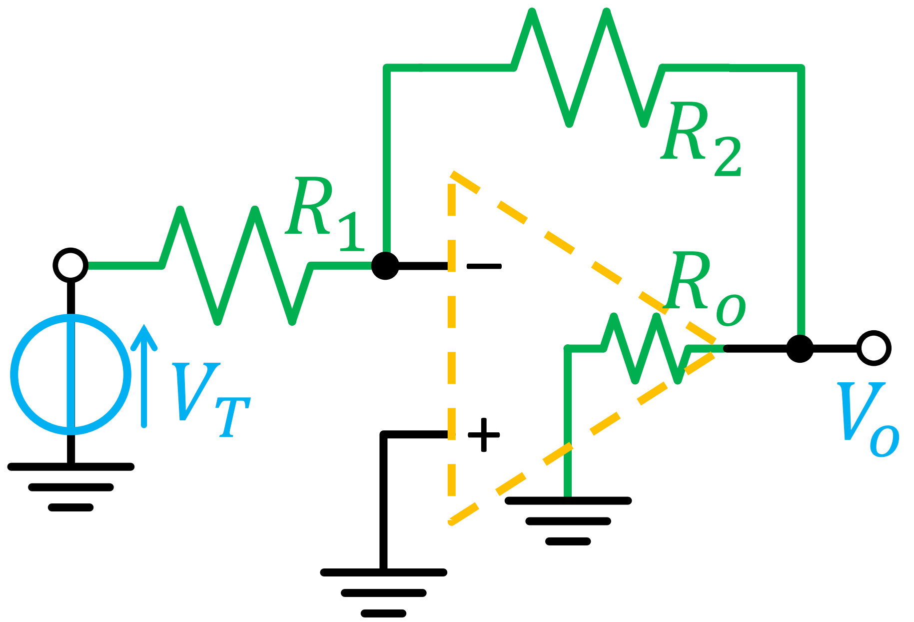
Direct gain calculation (simple cases)





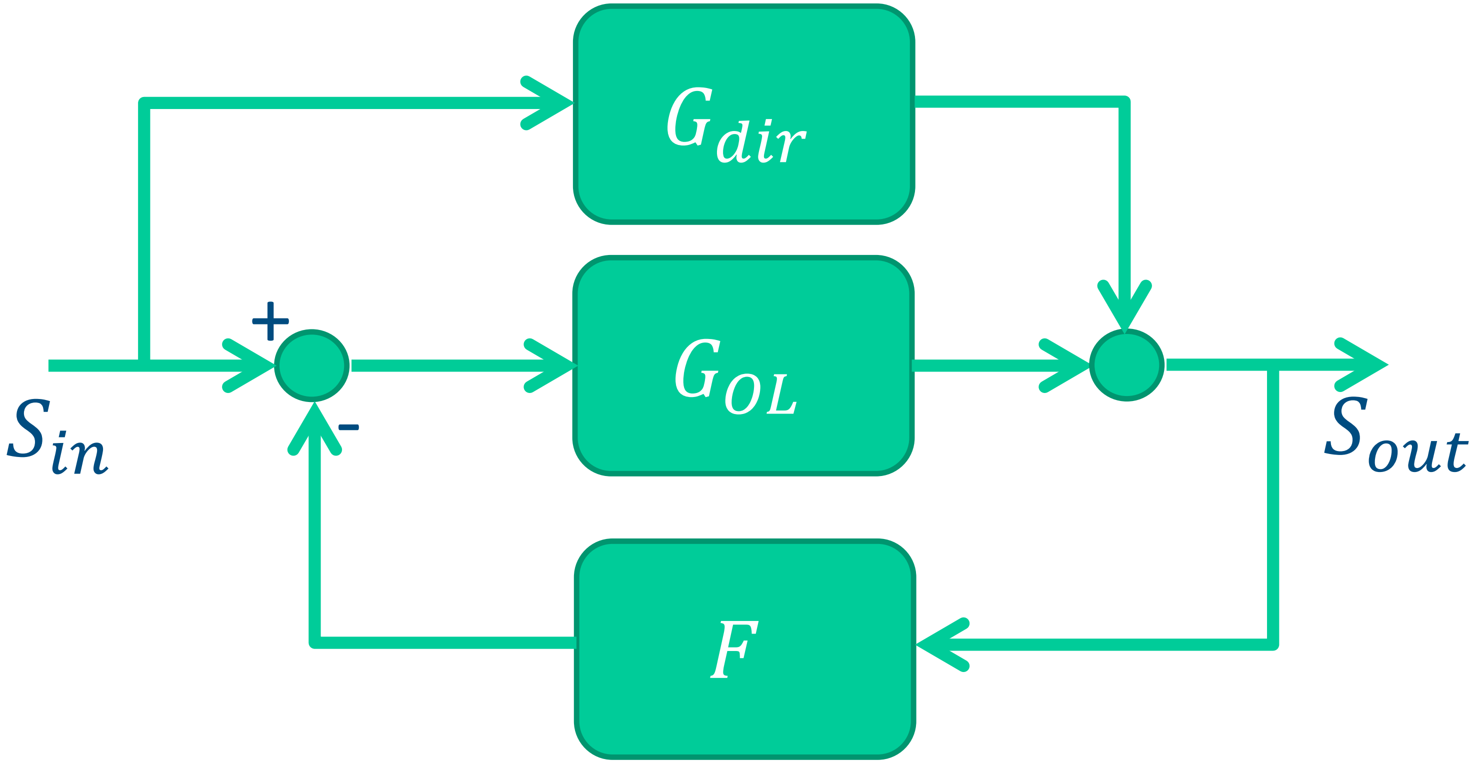
$G_{dir} = 0$ is obtained

Direct gain calculation (with R_o)



$$G_{dir} = \frac{R_o}{R_o + R_1 + R_2}$$

Block scheme

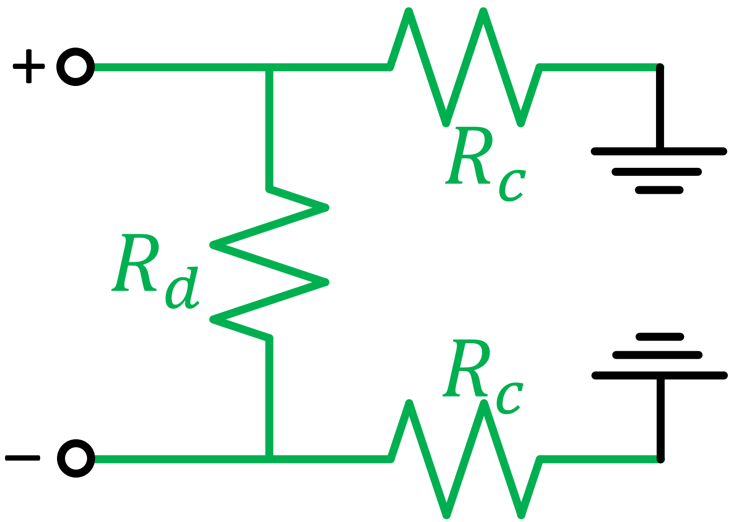


$$G = \frac{G_{OL} + G_{dir}}{1 - G_{loop}}$$

Outline

- Loop gain and closed-loop gain calculation
- Input/output impedances

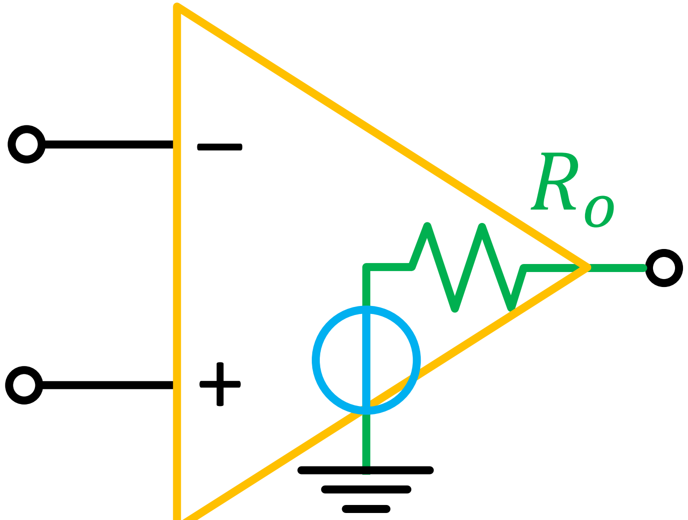
OA parameter: input resistance



- Usually $R_c \gg R_d$
- An input capacitance of a few pF must also be considered at high frequencies

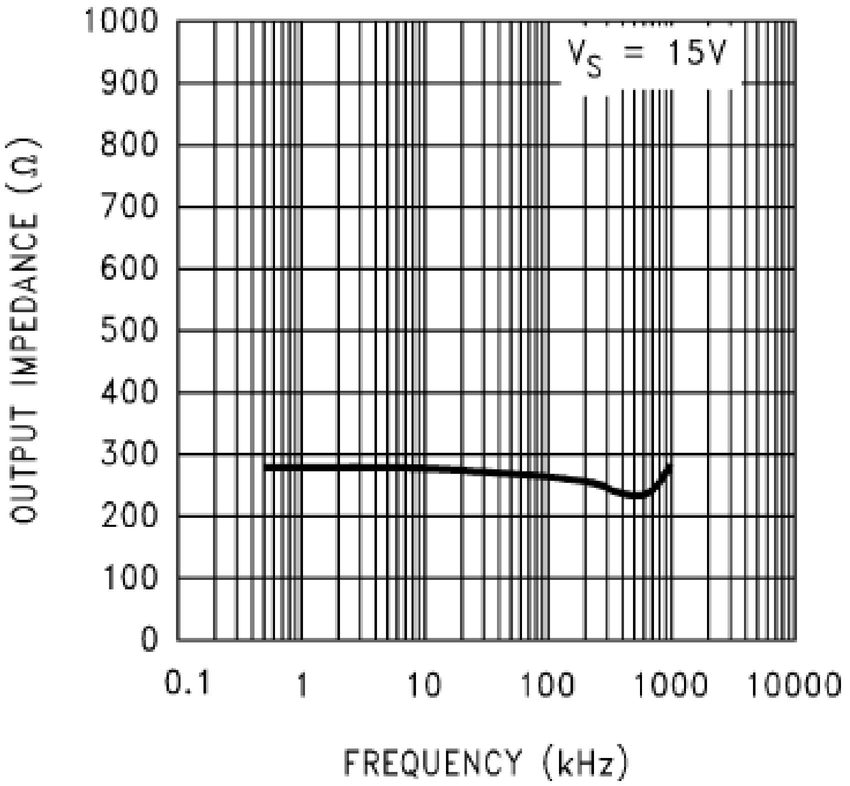
- Typ. BJT OA: $10^5 - 10^8\ \Omega$
- Typ. JFET OA: $10^9 - 10^{10}\ \Omega$
- Typ. CMOS OA: $10^{12}\ \Omega$

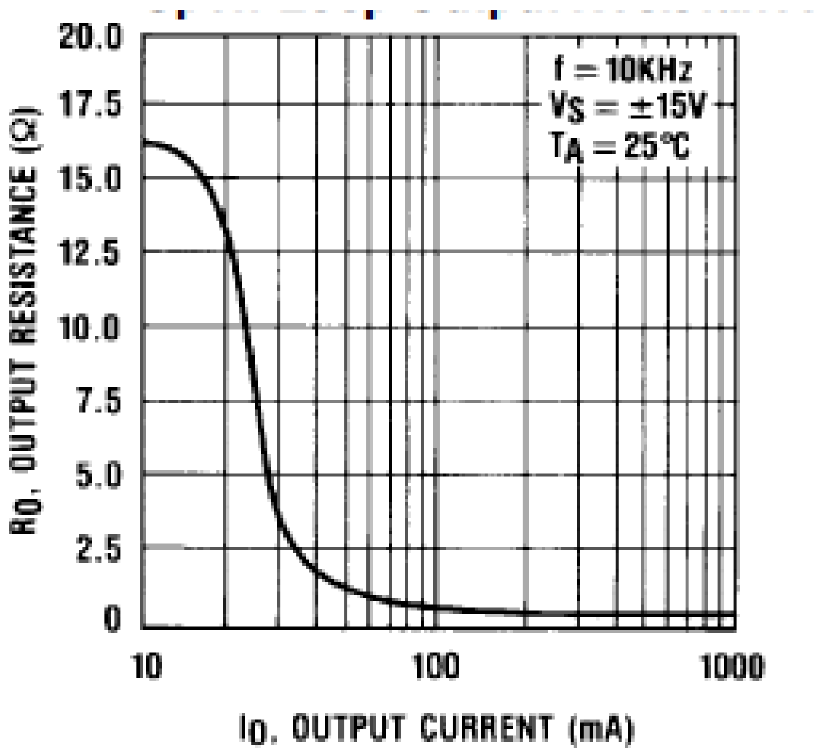
OA parameter: output resistance



- Typically smaller than 100 Ω
- A bit higher in CMOS OA

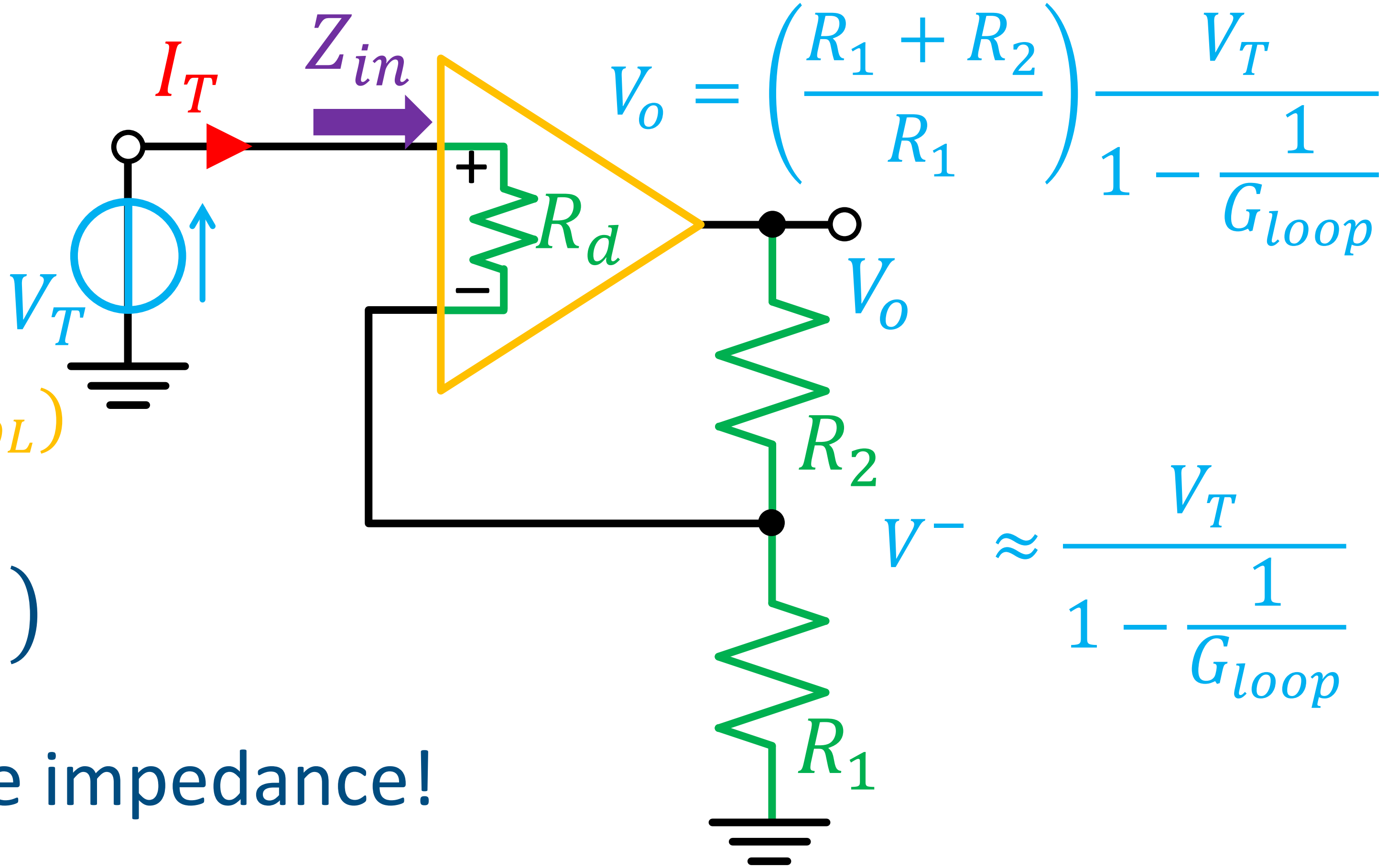
Actual values from datasheets





Power OA

Input impedance ($R_d \gg R_1 \parallel R_2$)



Impedance for $G_{loop} = 0$ (Z_{OL})

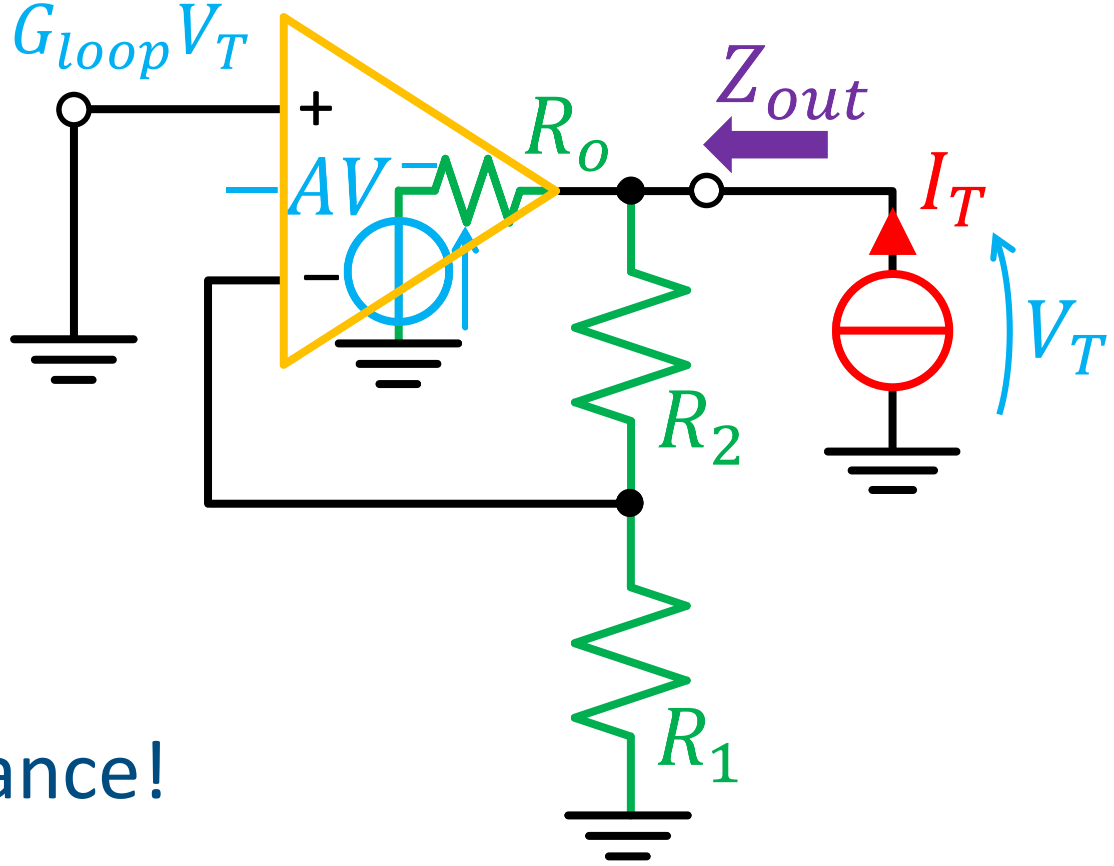
$$Z_{in} = \frac{V_T}{I_T} \approx R_d (1 - G_{loop})$$

Feedback has changed the impedance!

For $|G_{loop}| = \infty$ (ideal case), we get $Z_{in} = \infty$

Output impedance ($R_o \ll R_1 + R_2$)

$$-AV^- = -A\frac{R_1}{R_1+R_2}V_T \approx G_{loop}V_T$$



Impedance for $G_{loop} = 0$ (Z_{OL})

$$Z_{out} = \frac{V_T}{I_T} \approx \frac{R_o}{1-G_{loop}}$$

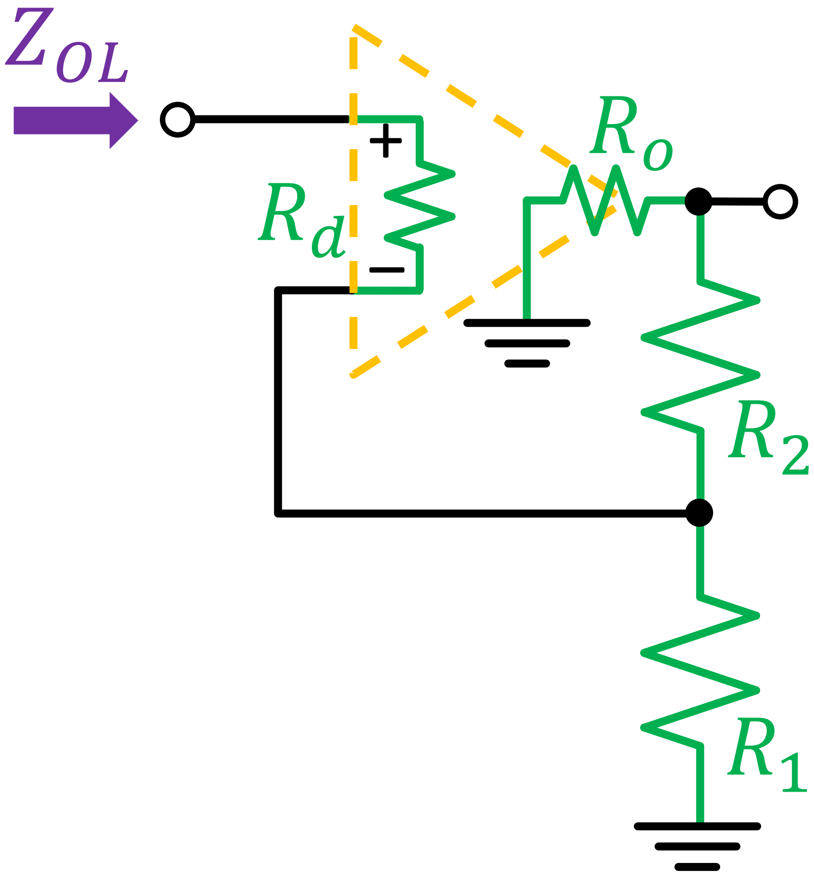
Feedback has changed the impedance!

For $|G_{loop}| = \infty$ (ideal case), we get $Z_{out} = 0$

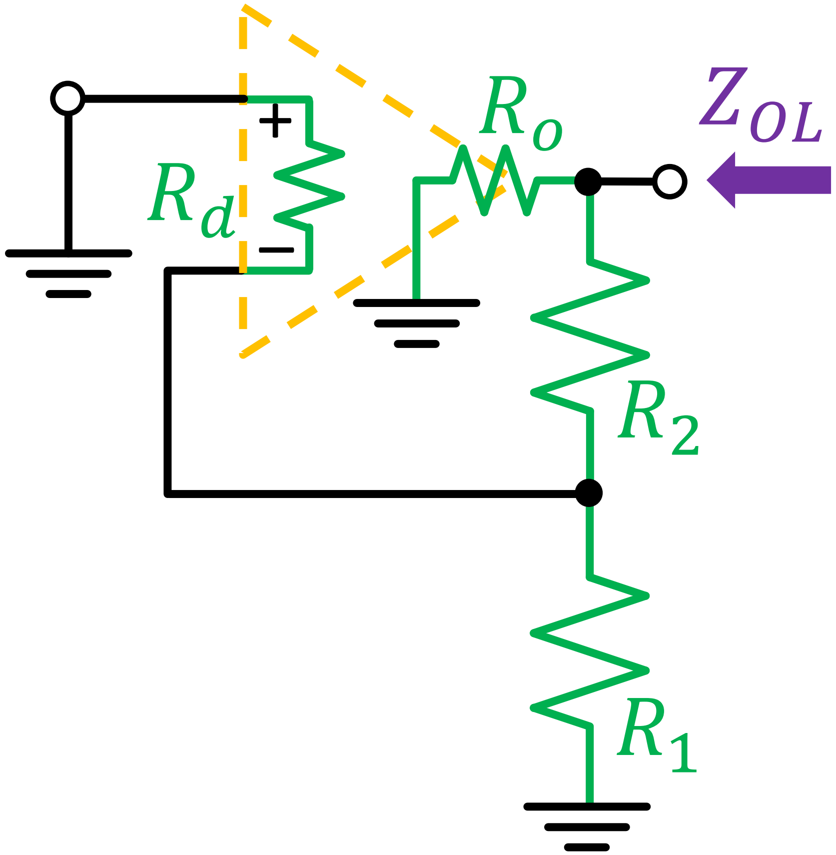
Procedure

1. Compute $Z_{in/out}$ in the ideal case
2. If $Z_{ideal} = \infty \Rightarrow Z = Z_{OL}\left(1 - G_{loop}\right)$
   If $Z_{ideal} = 0 \Rightarrow Z = Z_{OL}/(1 - G_{loop})$
3. Compute terms

Z_{OL} calculation

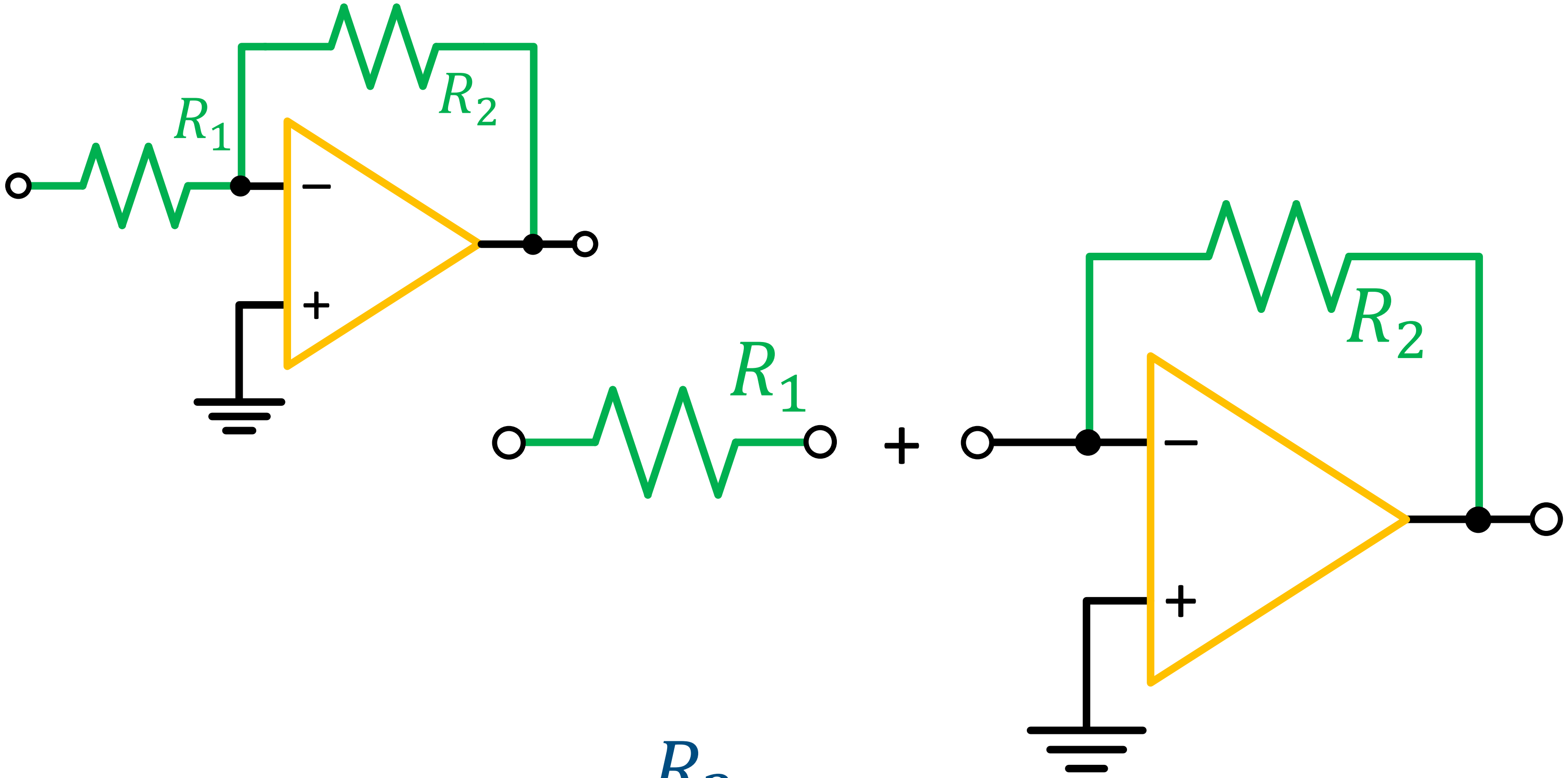


$$Z_{OL} = R_d + R_1 \parallel (R_2 + R_o)$$



$$Z_{OL} = R_o \parallel (R_2 + R_1 \parallel R_d)$$

The inverting case



$$Z_{in} = R_1 + \frac{R_2}{1 + A}$$

Closed-loop output impedance