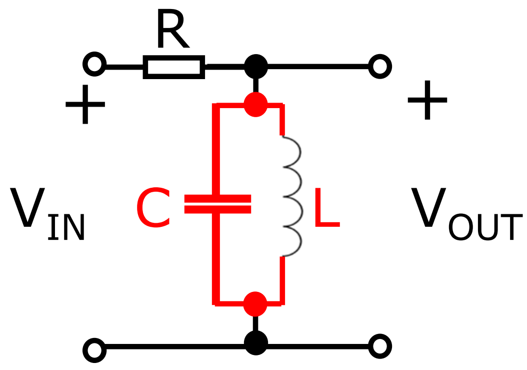
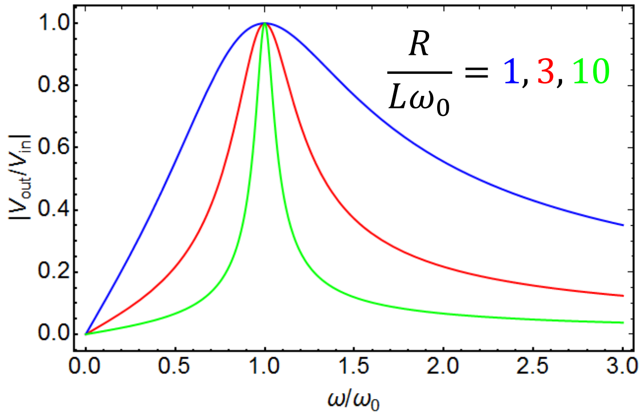
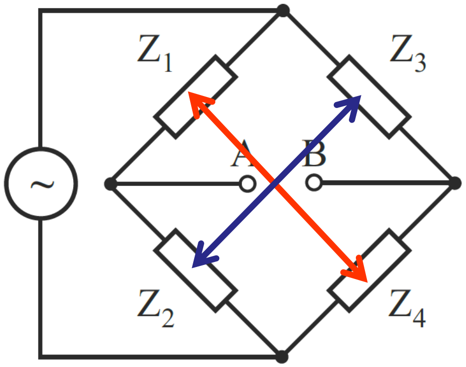
Recap

- Band pass filter





- Bridge circuits



Balanced when

$$Z_1 Z_4 = Z_2 Z_3$$

- Power dissipation in AC circuits

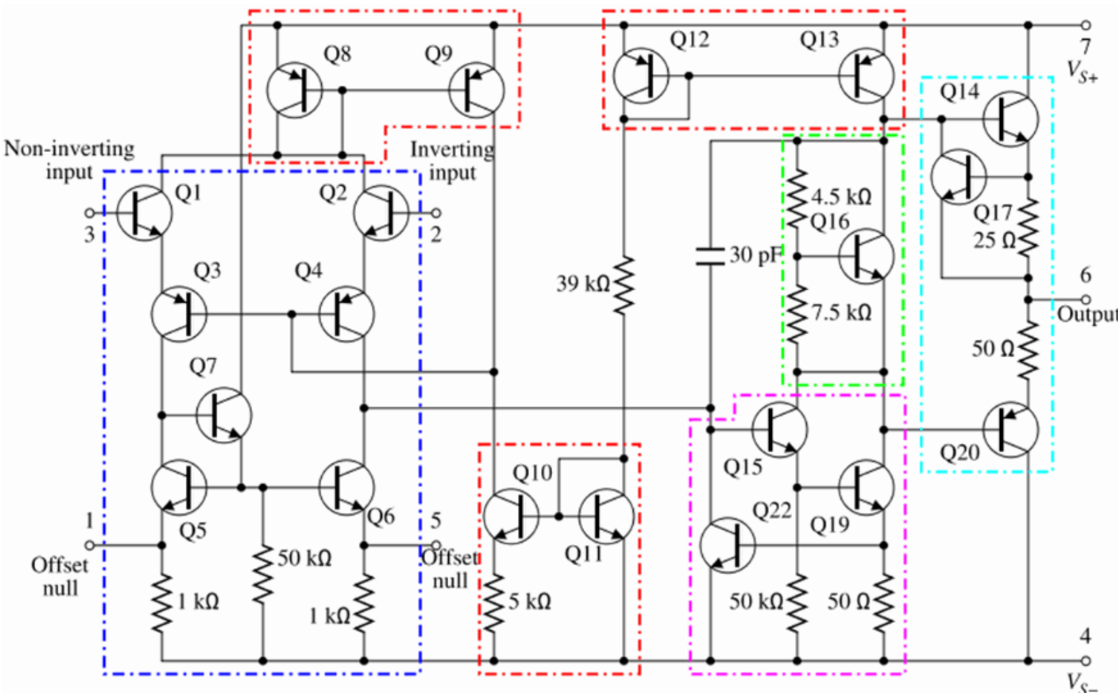
$$\langle P \rangle = \frac{1}{2} I_0^2 \mathrm{Re}(Z) = \frac{1}{2} V_0 I_0 \cos(\phi) = V_{\mathrm{rms}} I_{\mathrm{rms}} \cos(\phi)$$

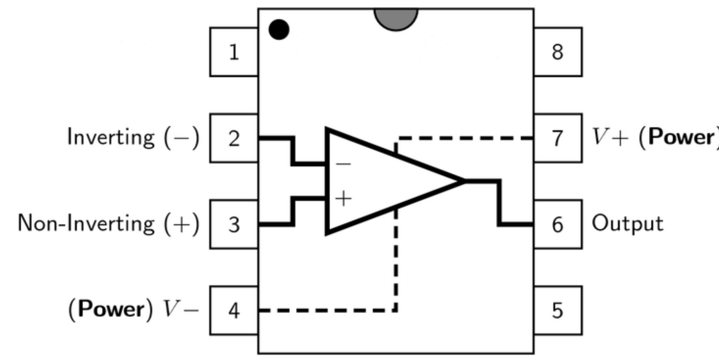
$$Z = |Z| e^{i\phi}$$

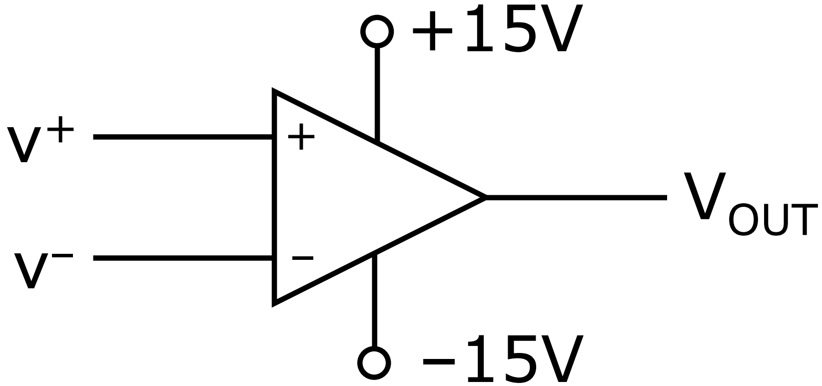
Today

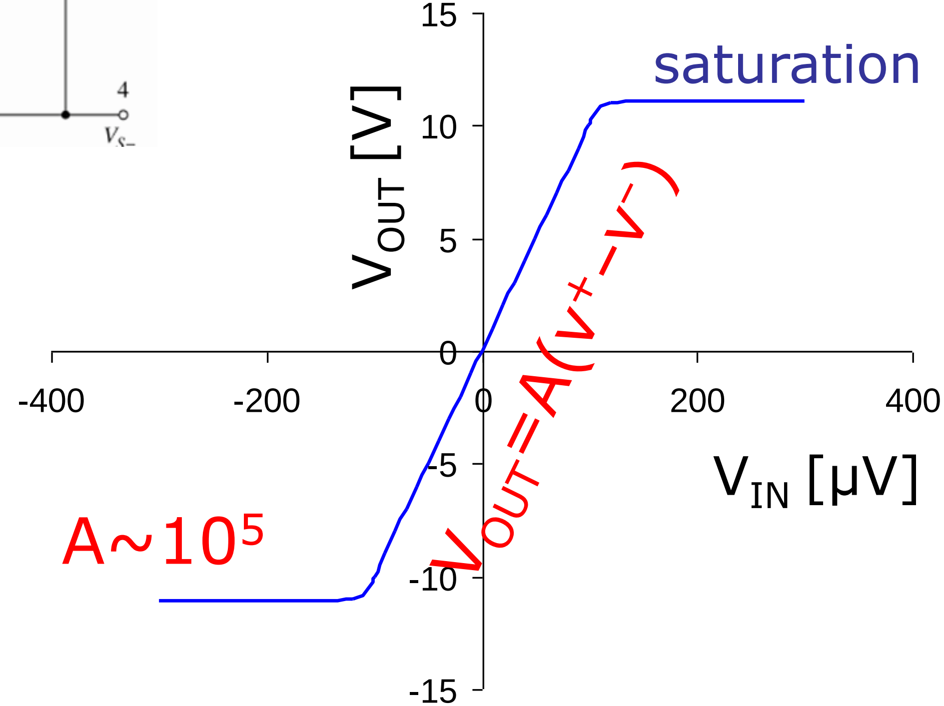
- Op-amps

Operational amplifiers (op-amps)

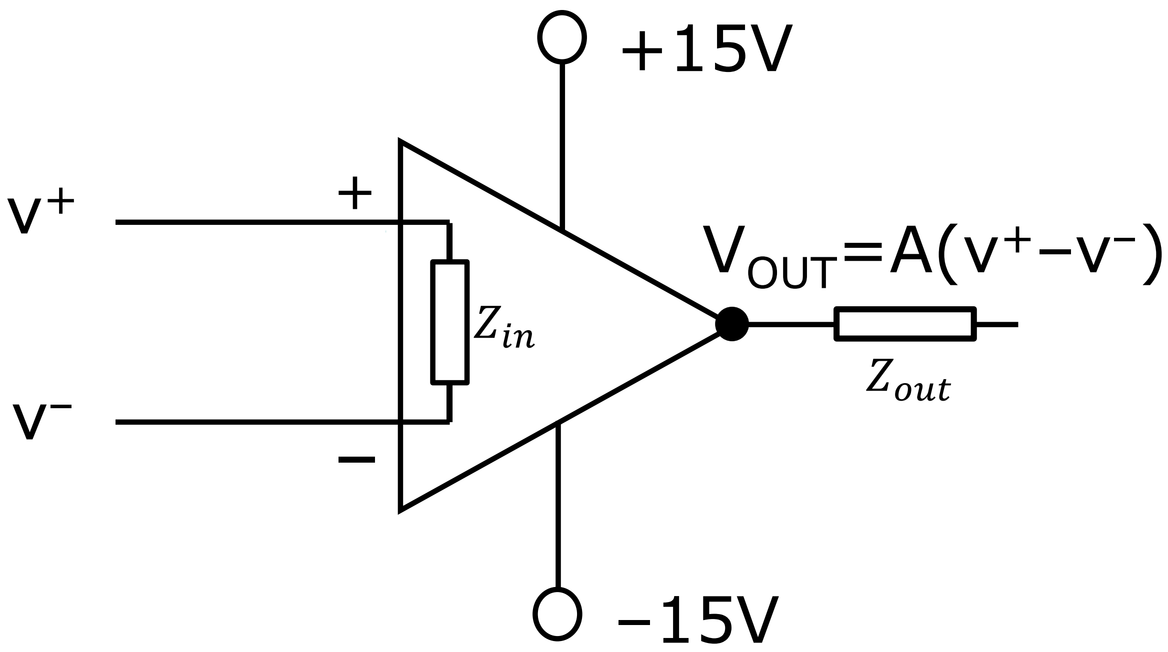








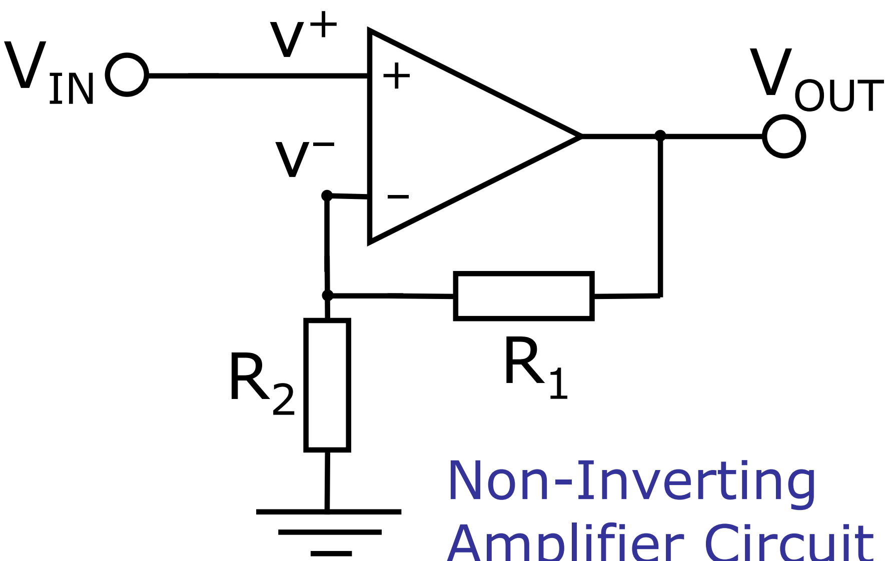
The ideal op-amp



Real		Ideal	
$Z_{in} \sim 10^8\ \Omega$		$Z_{in} = \infty$	(draws no current)
$Z_{out} \sim 100\ \Omega$		$Z_{out} = 0$	(supplies unlimited current)
$A \sim 10^5$		$A = \infty$	$(v_+ = v_-)$

Need feedback

Op-amp Feedback



Non-Inverting Amplifier Circuit

$$V_{OUT} = A\left(v^+ - v^-\right)$$

$$V_{OUT} = A\left(V_{IN} - V_{OUT}\frac{R_2}{R_1 + R_2}\right)$$

$$V_{OUT}\left(1 + A\frac{R_2}{R_1 + R_2}\right) = AV_{IN}$$

$$\frac{V_{OUT}}{V_{IN}} = \frac{A}{1 + \frac{AR_2}{R_1 + R_2}} \approx \frac{R_1 + R_2}{R_2}$$

But feedback must be negative

Op-amp golden rules

- Golden Rule #1: the inputs draw no current

  Because $Z_{in} = \infty$

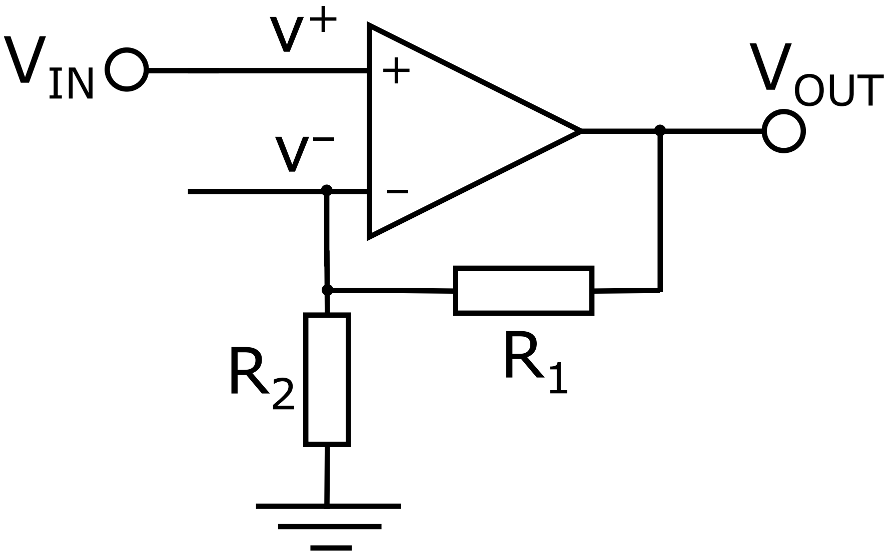
- Golden Rule #2: $V_+ = V_-$

  Because $A = \infty$

  This requires negative feedback

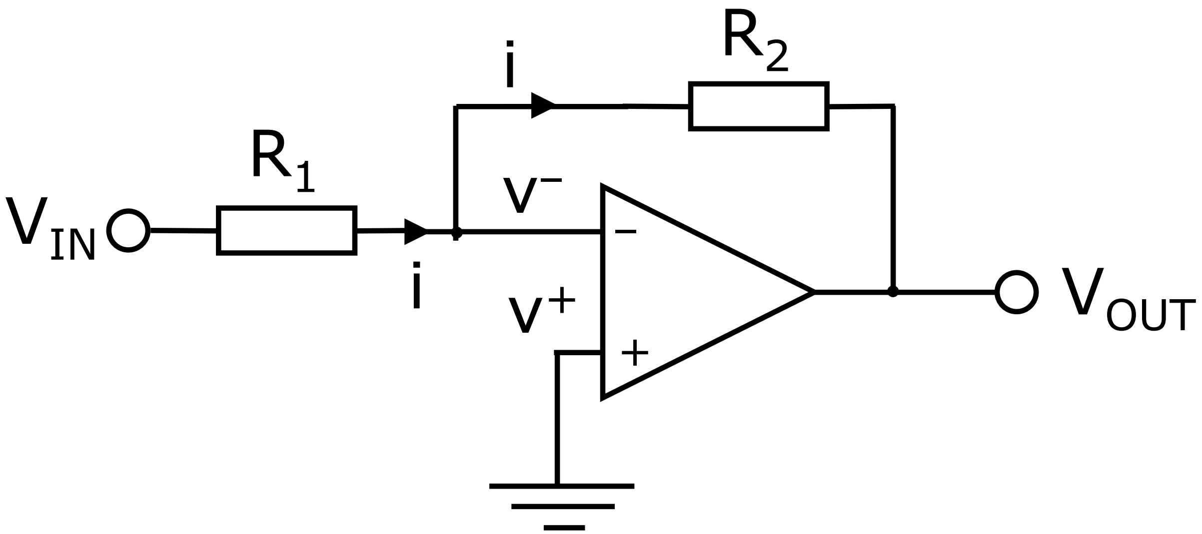
Applying these means you can analyse a circuit containing an op-amp without knowing anything about the details of the op-amp

Non-Inverting Amplifier



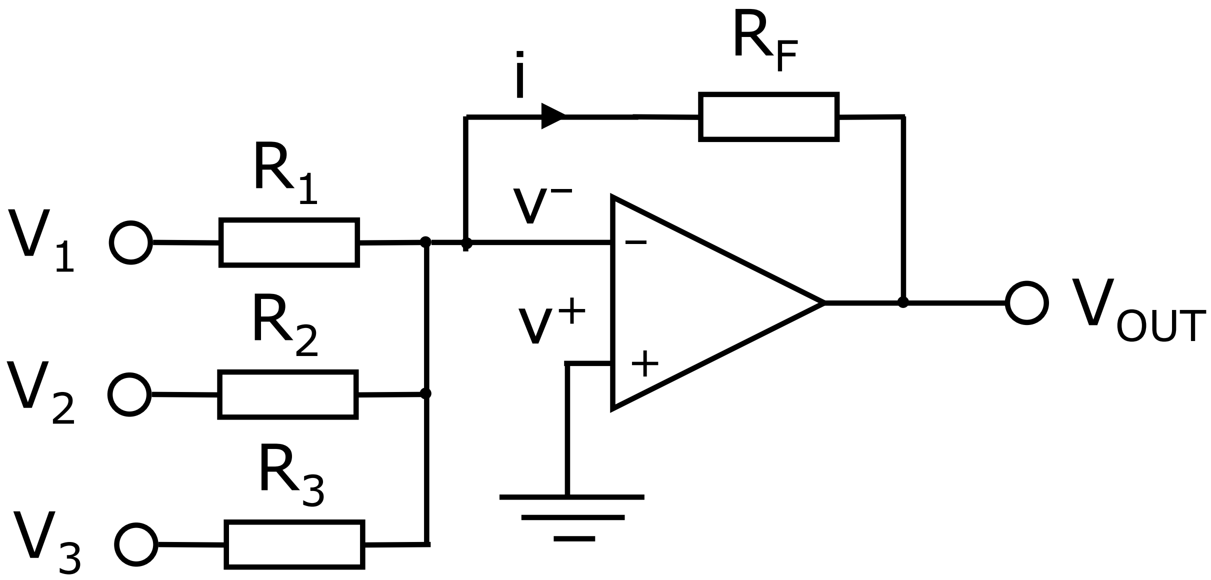
$$\frac{V_{out}}{V_{in}} = \frac{R_1 + R_2}{R_2}$$

Inverting Amplifier



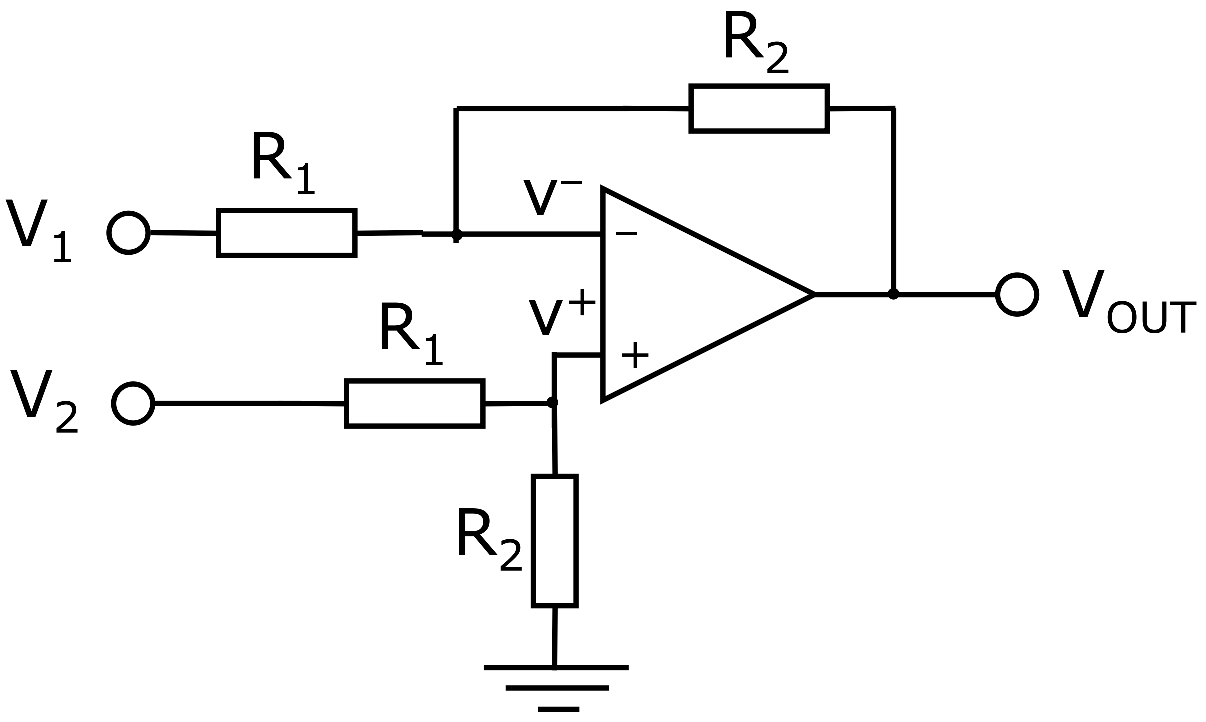
$$\frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}$$

Summing Amplifier



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

Difference amplifier



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