ECEN 325
Electronics

Operational Amplifiers

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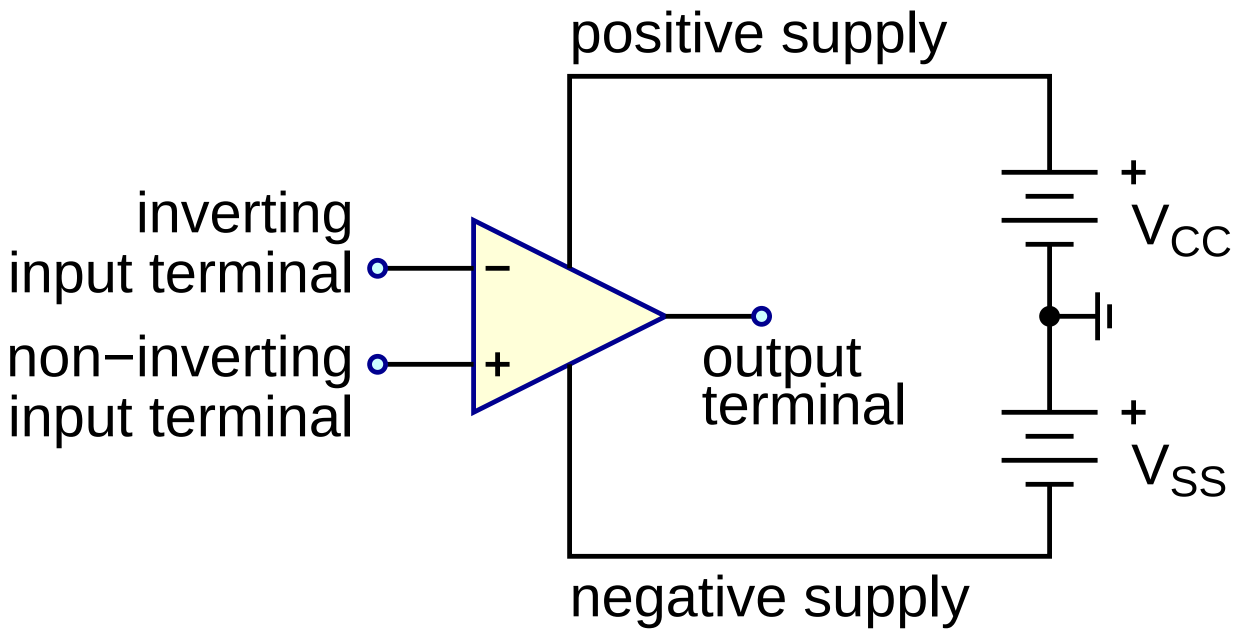
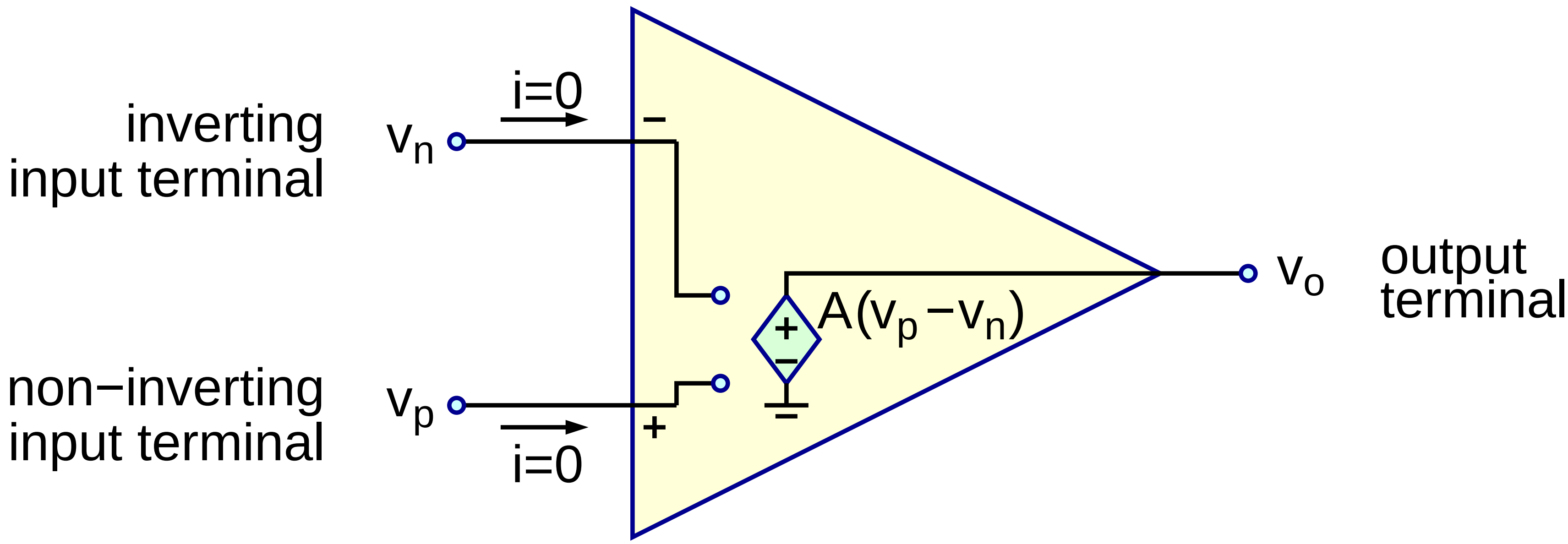
Texas A&M University
Department of Electrical and Computer Engineering

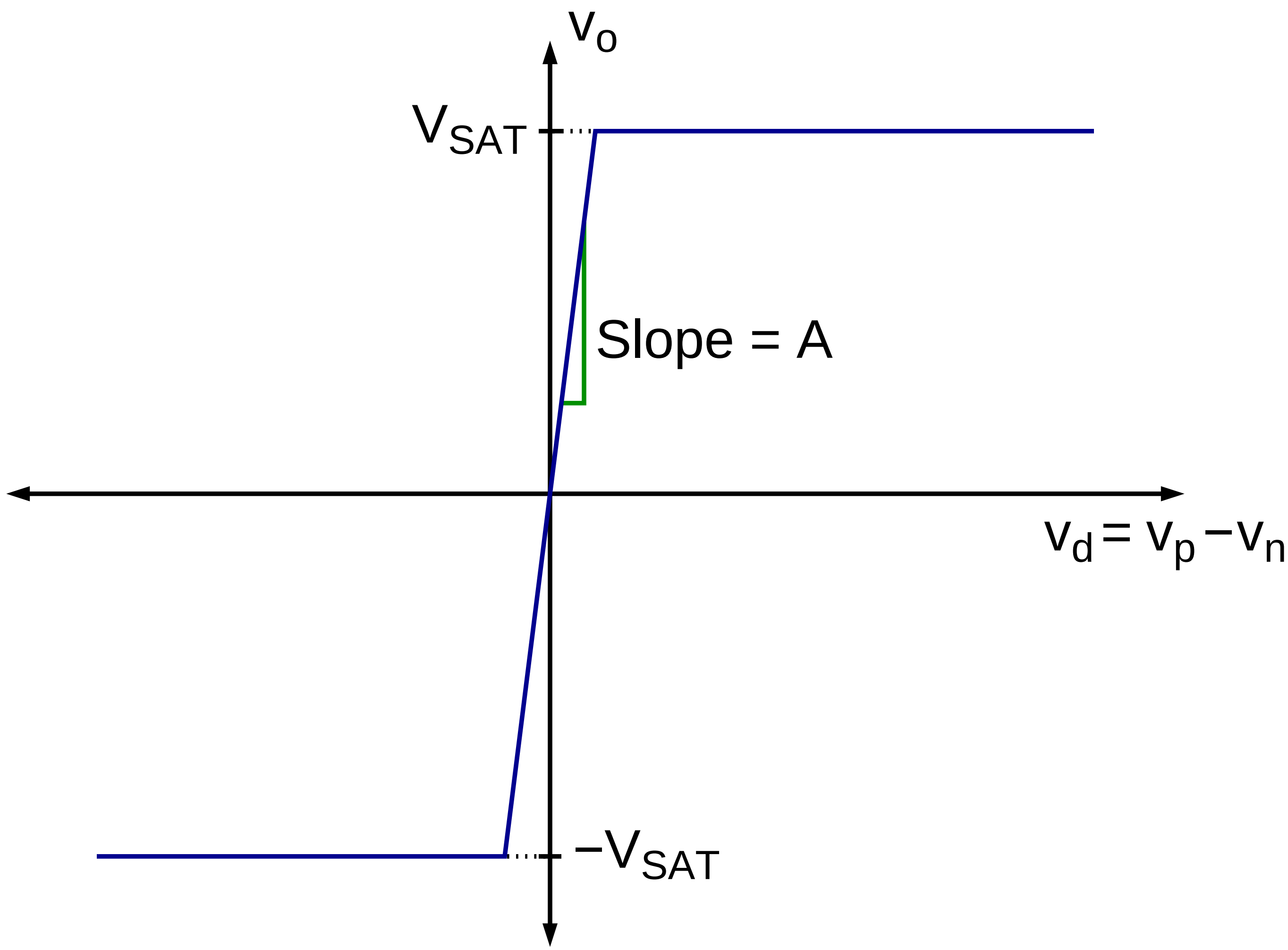
Opamp Terminals



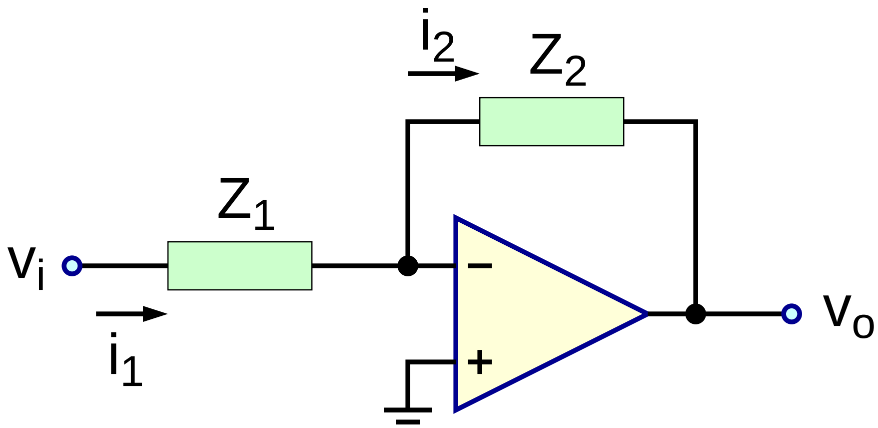
Equivalent Circuit



v_o vs. v_d



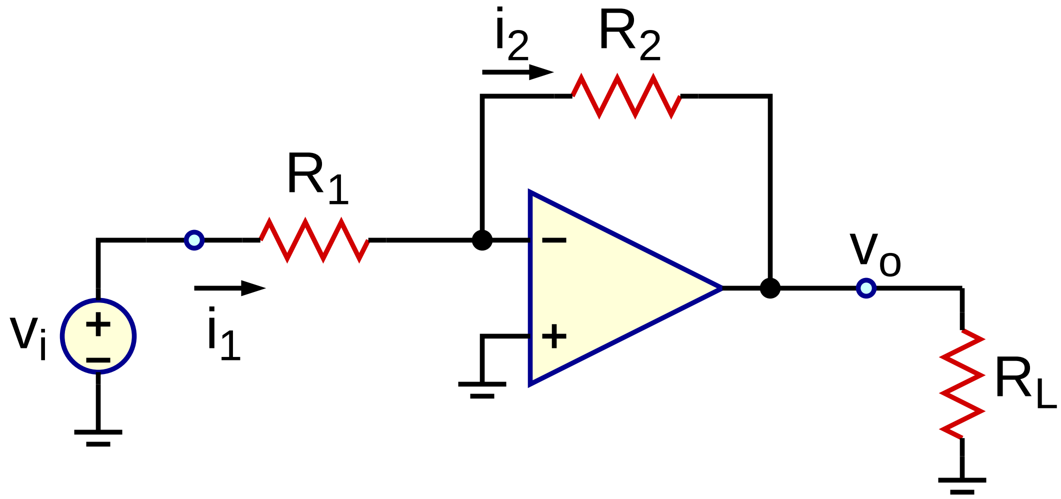
Inverting Configuration



$$\frac{v_o}{v_i} = \frac{-\dfrac{Z_2}{Z_1}}{1 + \dfrac{\left(1 + \dfrac{Z_2}{Z_1}\right)}{A}}$$

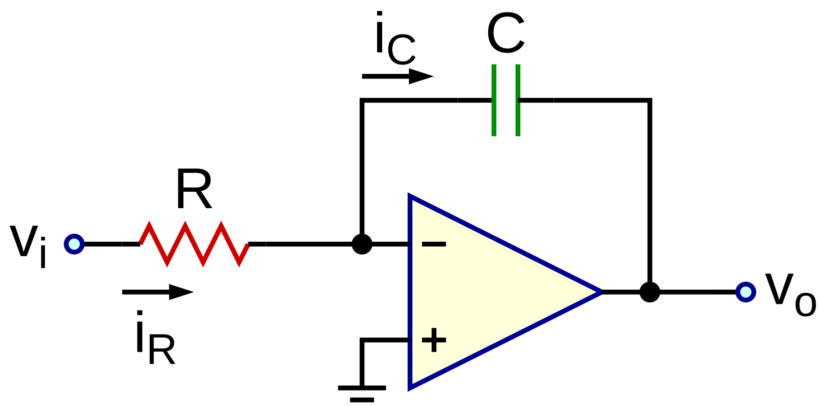
$$A \rightarrow \infty \quad \Rightarrow \quad \frac{v_o}{v_i} = -\frac{Z_2}{Z_1}$$

Inverting Amplifier



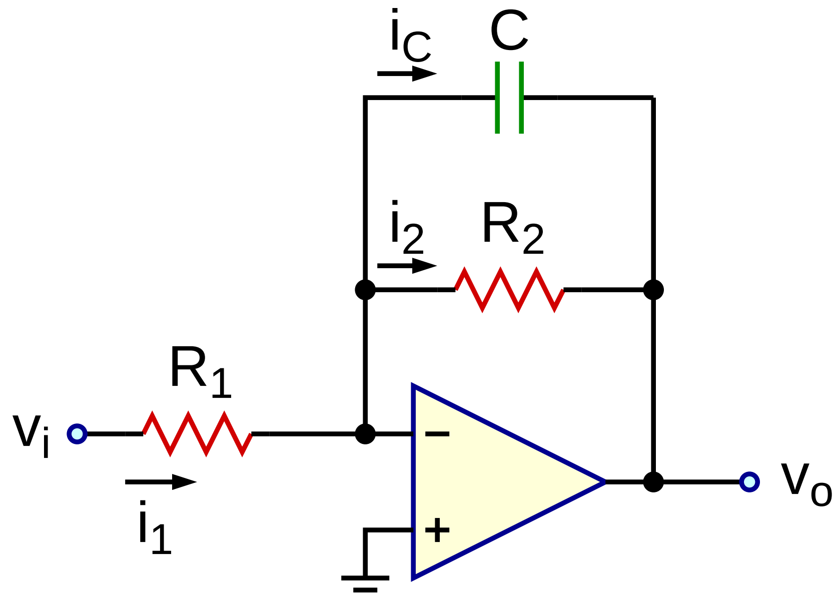
$$\frac{v_o}{v_i} = -\frac{R_2}{R_1}$$

Inverting Integrator



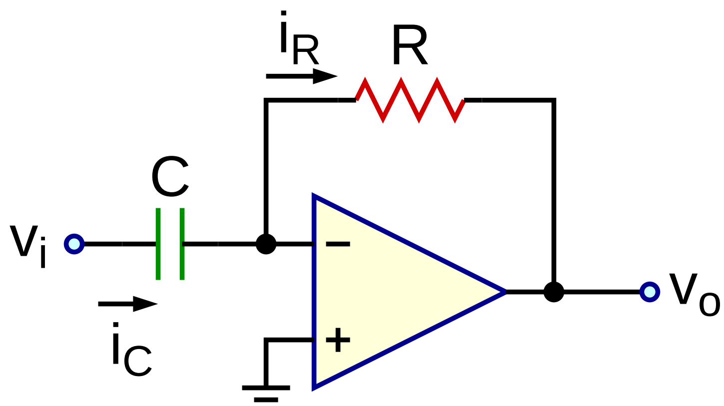
$$\frac{v_o}{v_i} = -\frac{1}{sRC}$$

Inverting Lossy Integrator



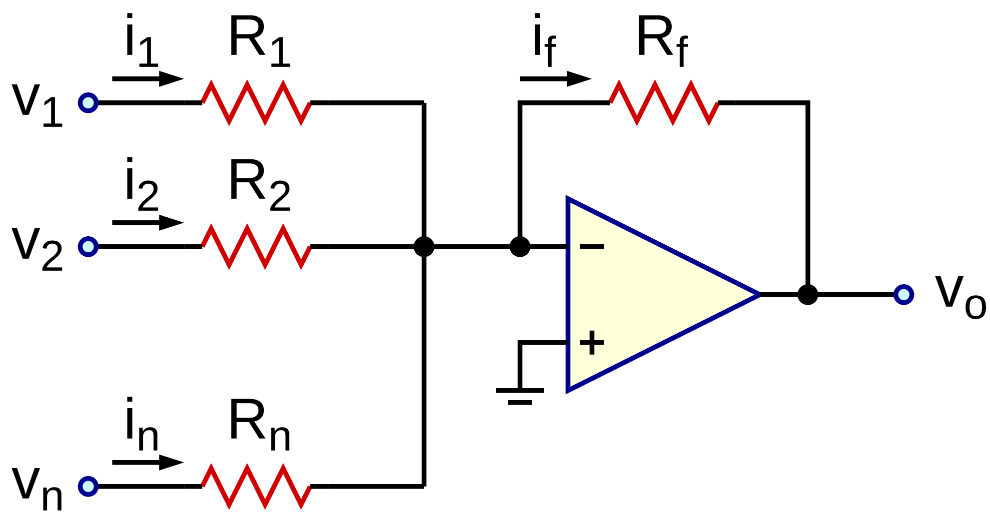
$$\frac{v_o}{v_i} = -\frac{\frac{R_2}{R_1}}{sR_2C + 1} = \frac{K}{\frac{s}{\omega_o} + 1}\,, \quad \omega_o = \frac{1}{R_2C}\,, \quad K = -\frac{R_2}{R_1}$$

Inverting Differentiator



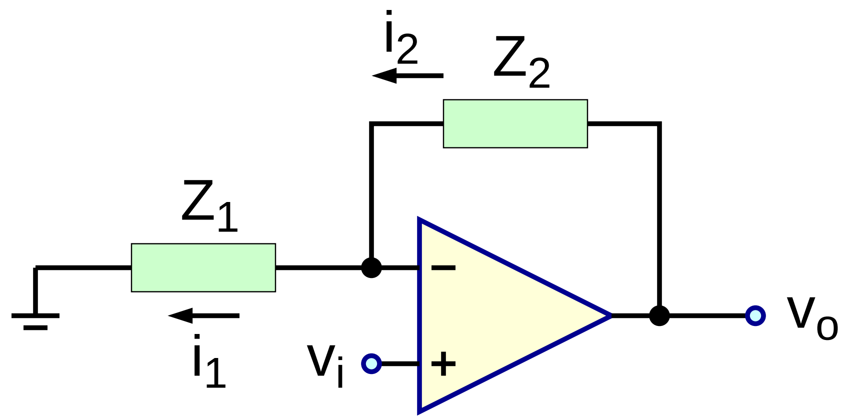
$$\frac{v_o}{v_i} = -sRC$$

Inverting Summer



$$v_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \cdots + \frac{R_f}{R_n}v_n\right)$$

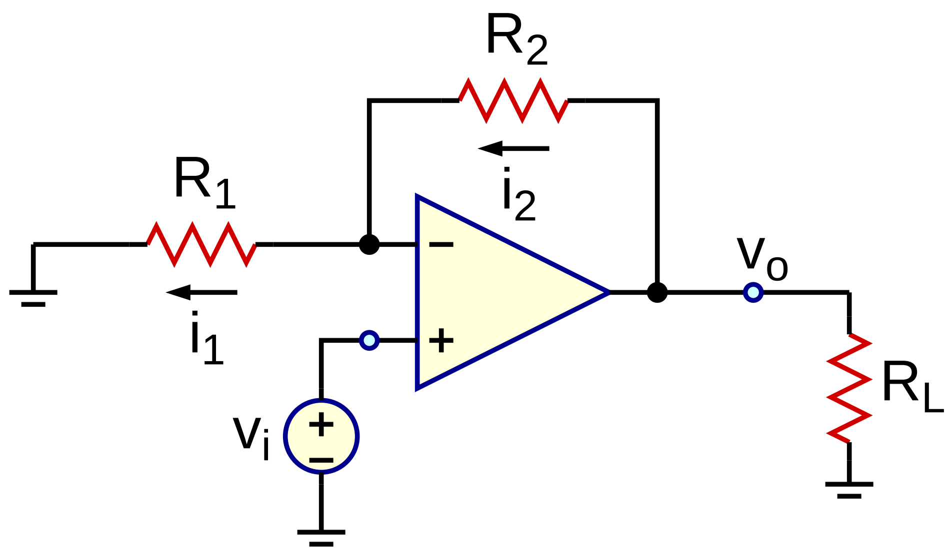
Non-Inverting Configuration



$$\frac{v_o}{v_i} = \frac{1+\dfrac{Z_2}{Z_1}}{1+\dfrac{\left(1+\dfrac{Z_2}{Z_1}\right)}{A}}$$

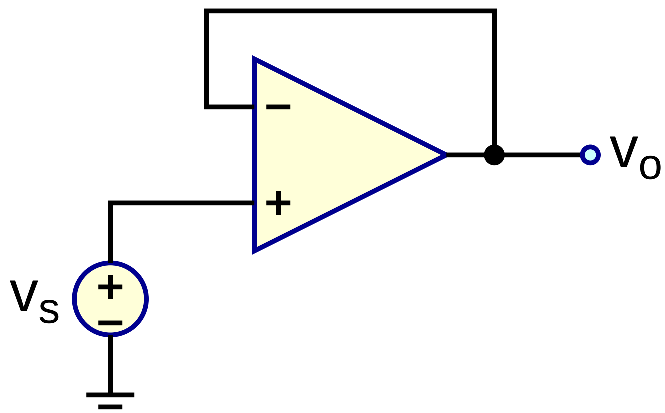
$$A \to \infty \quad \Rightarrow \quad \frac{v_o}{v_i} = 1 + \frac{Z_2}{Z_1}$$

Non-Inverting Amplifier



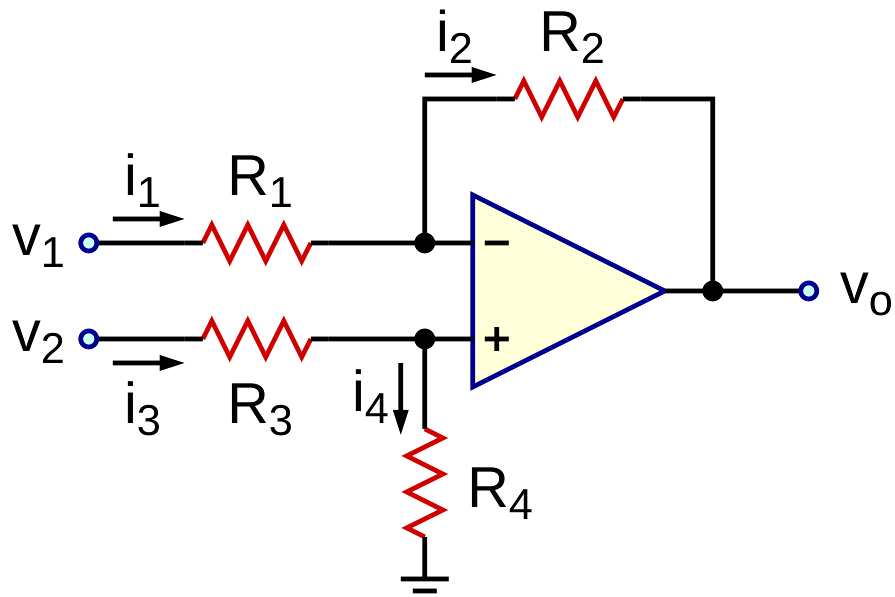
$$\frac{v_O}{v_I} = 1 + \frac{R_2}{R_1}$$

Unity-Gain Buffer



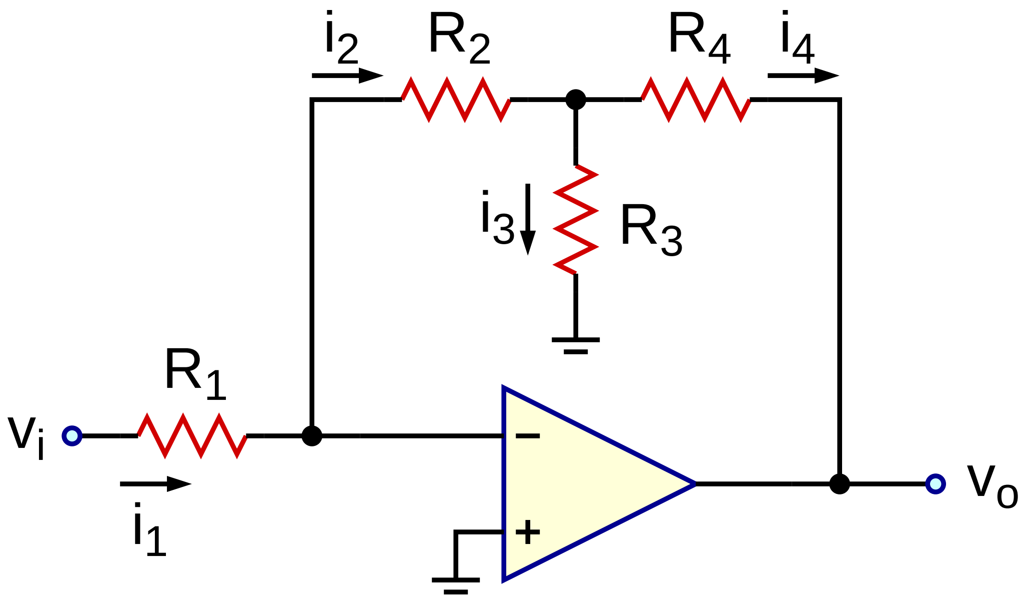
$$v_O = v_S$$

Difference Amplifier

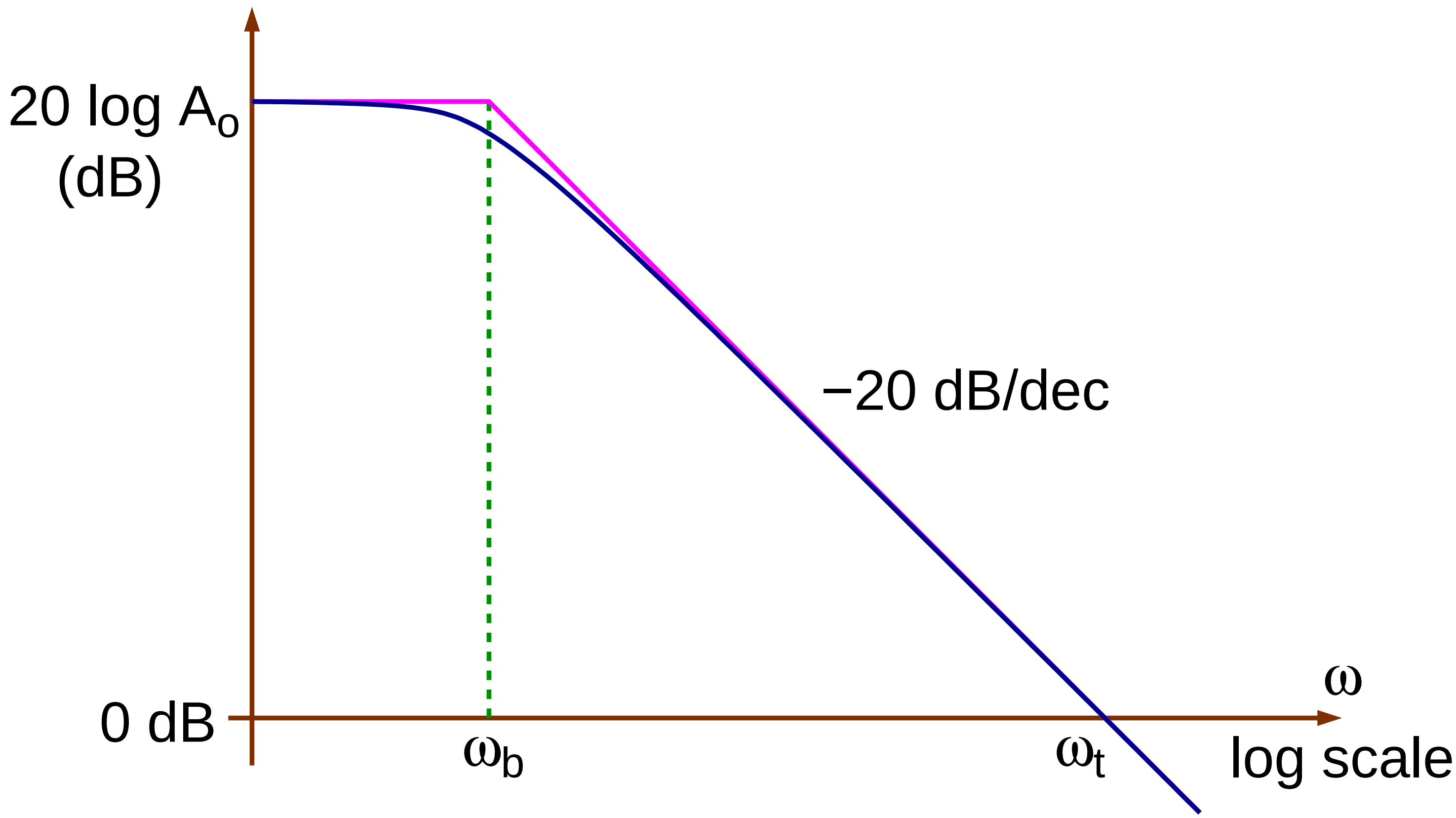


$$v_o = \frac{1 + \frac{R_2}{R_1}}{1 + \frac{R_3}{R_4}} v_2 - \frac{R_2}{R_1} v_1$$

Example



Frequency Dependence



$$\mathbf{A(s)} = \frac{\mathbf{A_o}}{\mathbf{1} + \frac{\mathbf{s}}{\omega_\mathbf{b}}} \qquad |\mathbf{A(j\omega)}| = \frac{\mathbf{A_o}}{\left|\mathbf{1} + \frac{\mathbf{j}\omega}{\omega_\mathbf{b}}\right|}$$

Gain-Bandwidth Product

$$\omega \gg \omega_b \quad \Rightarrow \quad |A(j\omega)| \approx \frac{A_o}{\left|\frac{j\omega}{\omega_b}\right|}$$

$$|A(j\omega)|_{\omega=\omega_t} = 1 \quad \Rightarrow \quad \omega_t = A_o\omega_b$$

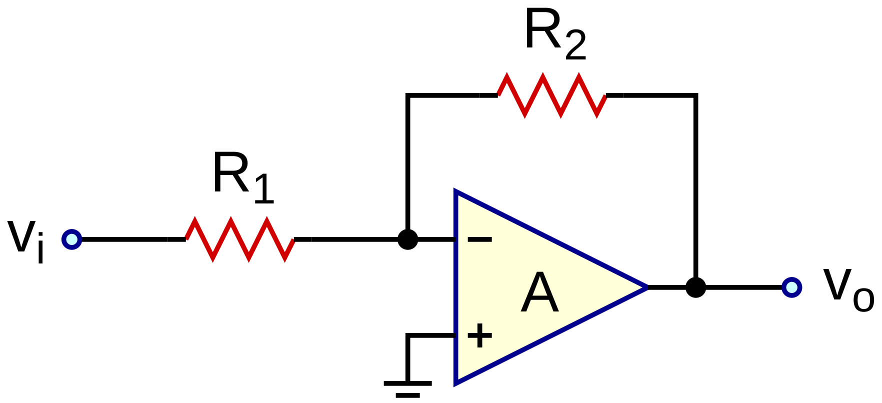
$A_o\omega_b$: Gain-Bandwidth (GBW) Product

ω_t : Unity-gain frequency

ω_b : Bandwidth

A_o : DC gain

Closed-Loop Gain



$$\frac{v_o}{v_i} = \frac{-\dfrac{R_2}{R_1}}{1 + \dfrac{\left(1 + \dfrac{R_2}{R_1}\right)}{A(s)}} \qquad A(s) = \frac{A_o}{1 + \dfrac{s}{\omega_b}}$$

Substitute $\mathbf{A(s)}$ into $\mathbf{v_o/v_i}$,

$$\frac{v_o}{v_i} = \frac{-\dfrac{R_2}{R_1}}{1 + \dfrac{\left(1 + \dfrac{s}{\omega_b}\right)}{A_o}\left(1 + \dfrac{R_2}{R_1}\right)}$$

$$= \frac{-\dfrac{R_2}{R_1}}{1 + \underbrace{\dfrac{1}{A_o}\left(1 + \dfrac{R_2}{R_1}\right)} + s\dfrac{1}{\omega_b A_o}\left(1 + \dfrac{R_2}{R_1}\right)}$$

$$\approx 0 \text{ if } A_o \gg \left(1 + \frac{R_2}{R_1}\right)$$

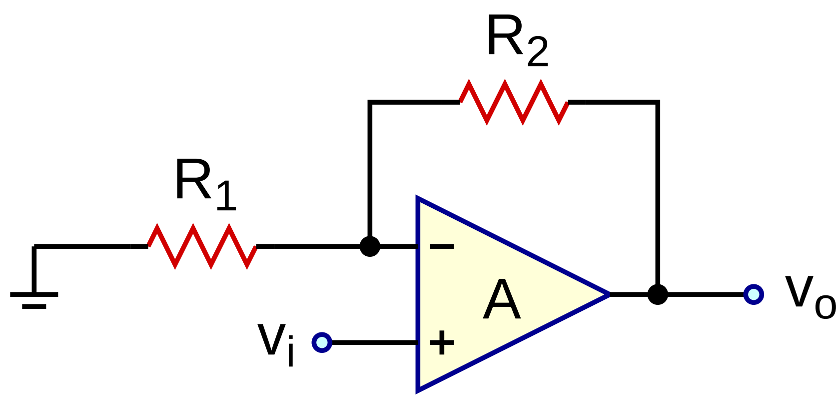
Closed-Loop Gain

$$\frac{v_o}{v_i} \approx \frac{-\dfrac{R_2}{R_1}}{1 + \dfrac{s}{\dfrac{A_o\omega_b}{1+\dfrac{R_2}{R_1}}}} = \frac{-\dfrac{R_2}{R_1}}{1 + \dfrac{s}{\omega_o}}$$

$$\omega_o = \frac{A_o\omega_b}{1+\dfrac{R_2}{R_1}} = \frac{\omega_t}{1+\dfrac{R_2}{R_1}}$$

$$\left(1+\frac{R_2}{R_1}\right)\omega_o = \omega_t$$ (GBW product or unity-gain freq)

Closed-Loop Gain



$$\frac{v_o}{v_i} = \frac{1 + \dfrac{R_2}{R_1}}{1 + \dfrac{\left(1 + \dfrac{R_2}{R_1}\right)}{A(s)}} \qquad A(s) = \frac{A_o}{1 + \dfrac{s}{\omega_b}}$$

Closed-Loop Gain

Substitute $\mathbf{A(s)}$ into $\mathbf{v_o/v_i}$,

$$\frac{v_o}{v_i} = \frac{1+\frac{R_2}{R_1}}{1+\frac{\left(1+\frac{s}{\omega_b}\right)}{A_o}\left(1+\frac{R_2}{R_1}\right)}$$

$$= \frac{1+\frac{R_2}{R_1}}{1+\underbrace{\frac{1}{A_o}\left(1+\frac{R_2}{R_1}\right)}+s\frac{1}{\omega_b A_o}\left(1+\frac{R_2}{R_1}\right)}$$

$$\approx 0 \text{ if } A_o \gg \left(1+\frac{R_2}{R_1}\right)$$

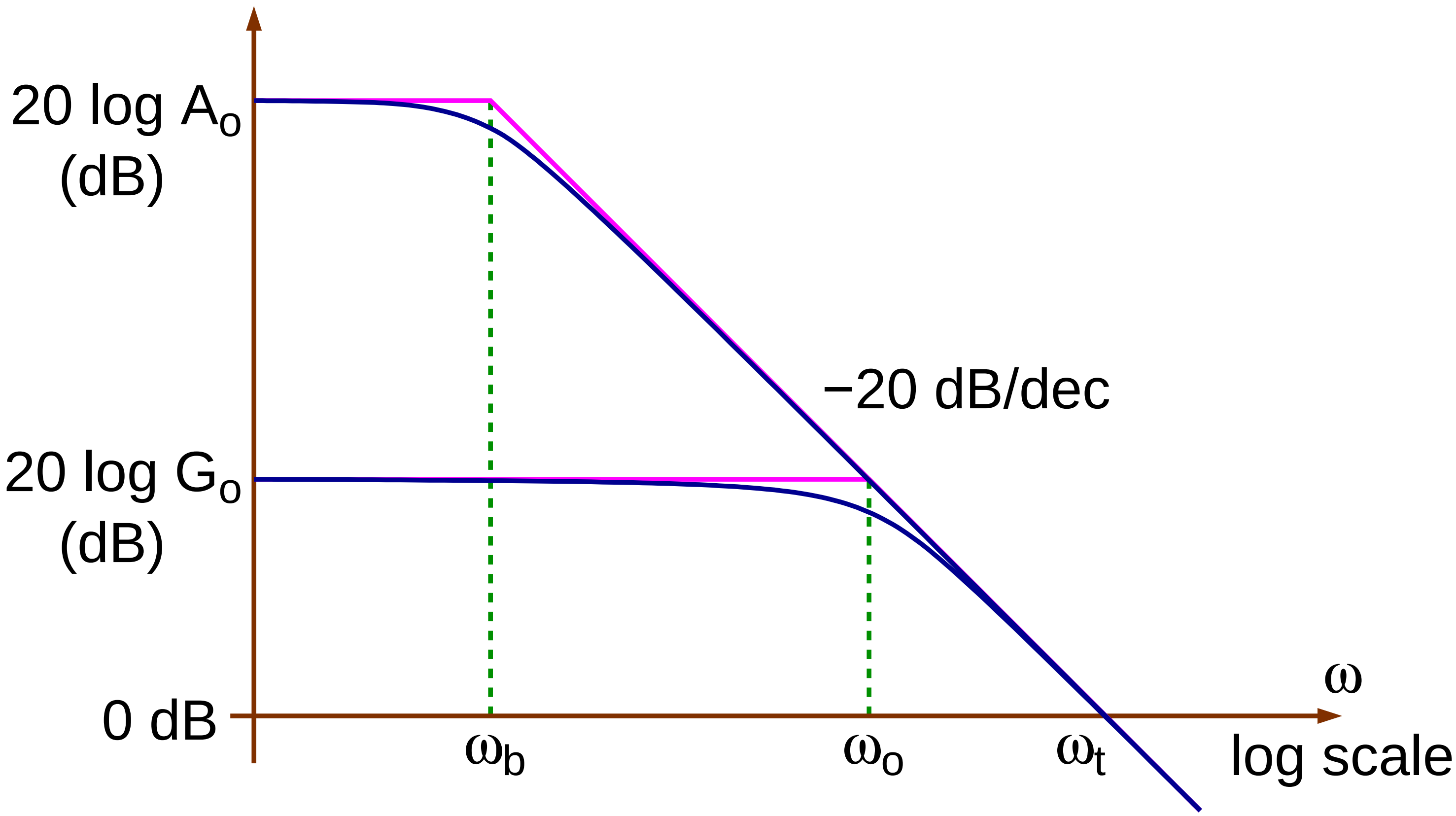
Closed-Loop Gain

$$\frac{v_o}{v_i} \approx \frac{1+\frac{R_2}{R_1}}{1+\frac{s}{\left(\frac{A_o\omega_b}{1+\frac{R_2}{R_1}}\right)}} = \frac{1+\frac{R_2}{R_1}}{1+\frac{s}{\omega_o}} = \frac{G_o}{1+\frac{s}{\omega_o}}$$

$$\omega_o = \frac{A_o\omega_b}{1+\frac{R_2}{R_1}} = \frac{\omega_t}{1+\frac{R_2}{R_1}}$$

$$\left(1+\frac{R_2}{R_1}\right)\omega_o = \omega_t$$ (GBW product or unity-gain freq)

Open & Closed Loop Gain



Slew Rate

Slew rate: Maximum rate of change possible at the output of an opamp

- Find the time-domain output voltage, $\mathbf{v_O(t)}$
- Find the maximum value of rate of change at the output

$$\left.\frac{dv_O}{dt}\right|_{max}$$

- To avoid distortion due to slew-rate limitation, the following should be satisfied

$$\left.\frac{dv_O}{dt}\right|_{max} \leq SR$$

where SR is the slew rate usually specified in the opamp data sheet in units of $V/\mu s$.

In an amplifier circuit, the op-amp has the following slew rate and output voltage:

- SR = 100 V/μs
- $\mathbf{v_O(t) = A \sin(\omega t)}$

Then

- $$\frac{dv_O}{dt} = A\omega \cos(\omega t) \Rightarrow \left.\frac{dv_O}{dt}\right|_{max} = A\omega \cos(\omega t)|_{max} = A\omega$$
- To avoid distortion due to slew-rate limitation, the following should be satistifed

$$A\omega \leq 100 \text{ V}/\mu\text{s}$$

In an amplifier circuit, $\mathbf{v_O/v_i}$ is given as

$$\frac{v_O}{v_i}(s) = \frac{G_O}{1 + \frac{s}{\omega_O}}$$

where $\mathbf{v_I(t) = A_i \sin(\omega_i t)}$ and $\mathbf{v_O}$ is the output of the opamp.

$$v_O(t) = \frac{G_O}{\sqrt{1 + \left(\frac{\omega_i}{\omega_O}\right)^2}} A_i \sin(\omega_i t)$$

To avoid distortion,

$$\left.\frac{dv_O}{dt}\right|_{max} = \frac{G_O \omega_i A_i}{\sqrt{1 + \left(\frac{\omega_i}{\omega_O}\right)^2}} \leq SR$$