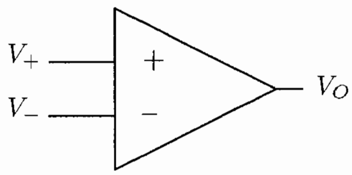
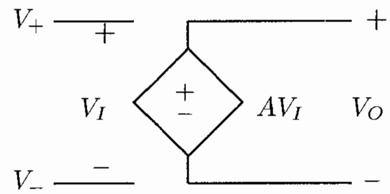
Circuit Figure:



Circuit Model:



−: **Inverting** input. **Point** (of triangle): **Output** of op-amp.
+: **Non-Inverting** input. **Not shown:** Power supply connections.

$$V_O = \begin{cases} A(V_+ - V_-) & \text{if } |A(V_+ - V_-)| < 12V \\ 12V & \text{if } A(V_+ - V_-) > 12V \\ -12V & \text{if } A(V_+ - V_-) < -12V \end{cases}$$

Dependent source is linear only over a limited input range

A: *Open-loop gain* $A \approx 200,000$! But output actually *clips* at $\pm 12V$.
R_{IN} : Assume $R_{IN} \to \infty$ (actually $\approx 2M\Omega$); $R_{OUT} = 0$ (actually $\approx 70\Omega$)
210: We assume **negative feedback**: $\exists$connection between output and V_-

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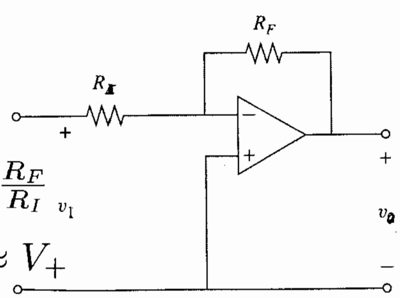
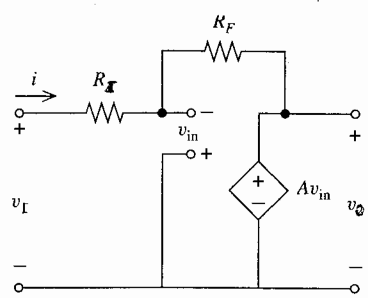
EX: Inverting amplifier:

Node: $\frac{V_- - V_I}{R_I} + \frac{V_- - V_O}{R_F} = 0$ at V_-
Device: $V_O = A(V_+ - V_-) = -AV_-$
Combine: $\frac{V_O}{V_I} = -\frac{R_F}{R_I}\frac{1}{1+\frac{1}{A}(1+\frac{R_F}{R_I})} \simeq -\frac{R_F}{R_I}$
Also: $V_- = -\frac{V_O}{A} \approx 0 = V_+ : V_- \approx V_+$





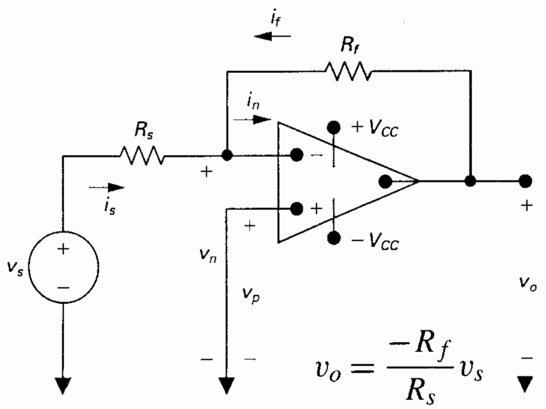
"Golden Rules" for Ideal Op-Amp Circuits with Negative Feedback:

- $I_+ = I_- = 0$ (input currents=0). Note *output* current$\neq 0$!
  KCL does *not* apply to ideal op-amp: no power supply connections!
- $V_+ = V_-$ (virtual short at input). Actually differ by few mV.

Note: Input looks like both open and short circuit simultaneously!

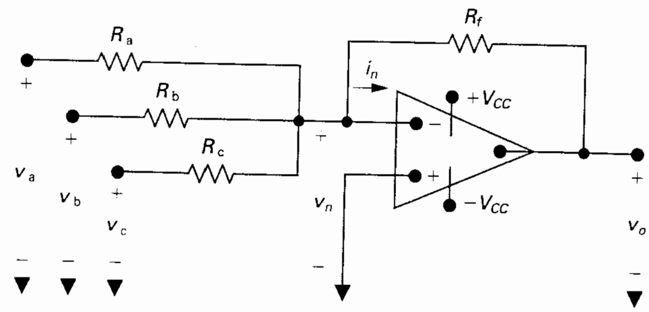
EX: Redo inverting amplifier circuit above using golden rules:
Node: $V_- = V_+ = 0$. $I_- = 0 \to I = \frac{V_I}{R_I} = -\frac{V_O}{R_F} \to \frac{V_O}{V_I} = -\frac{R_F}{R_I}$. Easier!

See: Overleaf for: Non-inverting amp; follower; summer; differential amp.
Note: **All** of these assume op-amp $|V_O| < 12V$; if not, V_O clips at $\pm 12V$.
Note: For analysis with finite R_{IN} and nonzero R_{OUT}, see pp. 206-208.
CMRR: Differential amp Common-Mode Rejection Ratio=$\frac{\text{differential mode gain}}{\text{commonmode gain}}$.



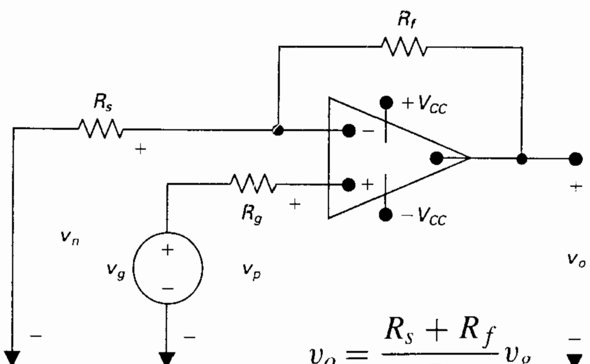
$$v_o = \frac{-R_f}{R_s} v_s$$

An inverting-amplifier circuit.



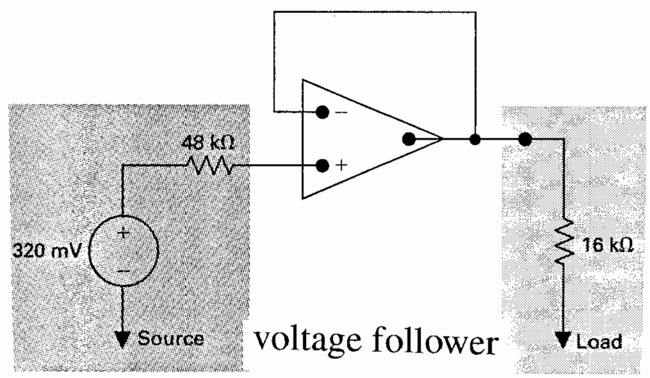
A summing amplifier.

$$v_o = -\left(\frac{R_f}{R_a} v_a + \frac{R_f}{R_b} v_b + \frac{R_f}{R_c} v_c \right)$$

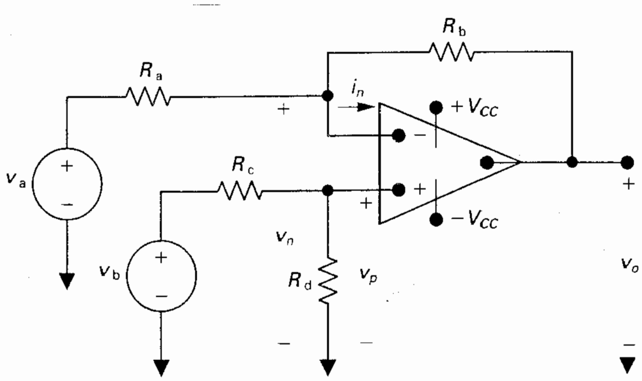


$$v_o = \frac{R_s + R_f}{R_s} v_g$$

A noninverting amplifier.

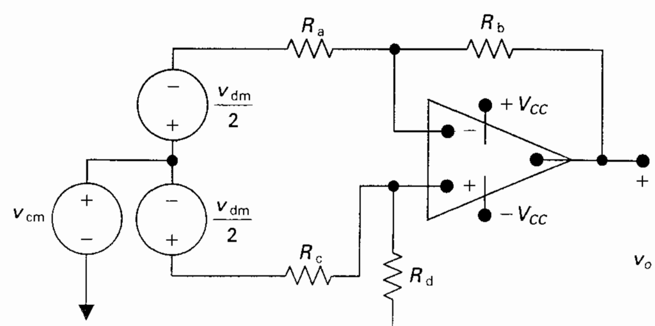


voltage follower



A difference amplifier.

$$v_o = \frac{R_d(R_a + R_b)}{R_a(R_c + R_d)} v_b - \frac{R_b}{R_a} v_a$$



$v_{cm} = (v_a + v_b)/2 \qquad v_{dm} = v_b - v_a$

$$v_o = \left[\frac{R_a R_d - R_b R_c}{R_a(R_c + R_d)} \right] v_{cm} + \left[\frac{R_d(R_a + R_b) + R_b(R_c + R_d)}{2R_a(R_c + R_d)} \right] v_{dm},$$

$$= A_{cm} v_{cm} + A_{dm} v_{dm},$$

Now, substitute $R_c = R_a$ and $R_d = R_b$.

$$v_o = (0) v_{cm} + \left(\frac{R_b}{R_a} \right) v_{dm}$$