EE 220

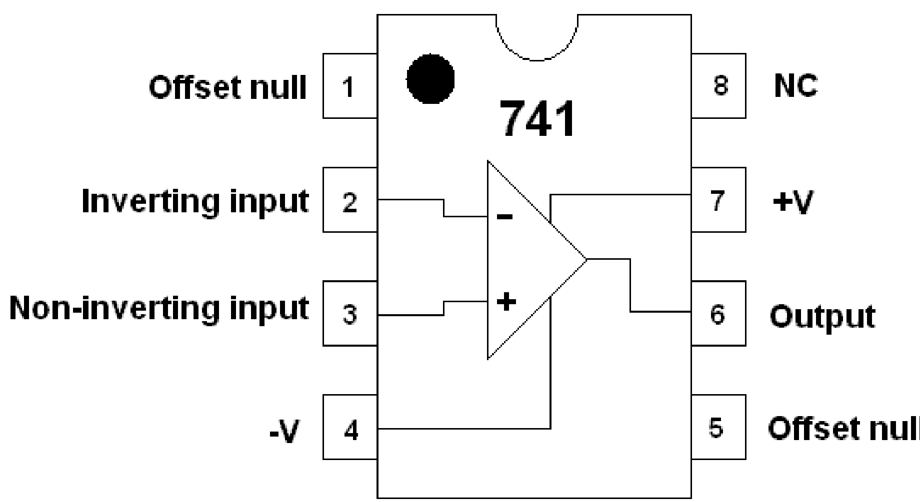
Operational Amplifiers

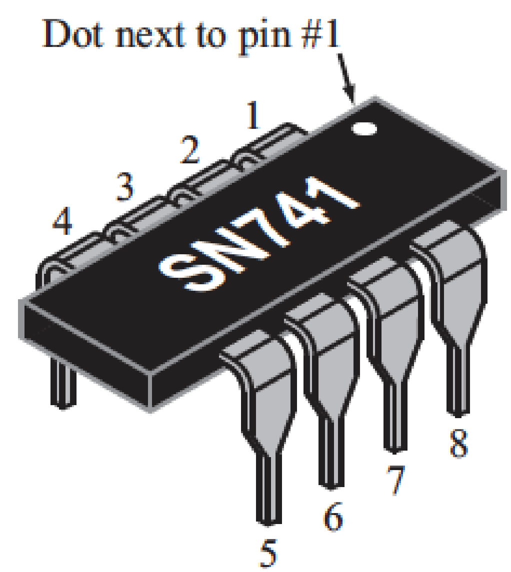
Operational Amplifiers (Op Amps)

1. Op Amp Characteristics
2. Ideal Op Amp
3. Inverting Amplifier
4. Non-Inverting Amplifier
5. Summing Amplifier
6. Difference Amplifier
7. Voltage Follower
8. Cascaded Op Amps
9. MOSFET

What is an Op Amp?

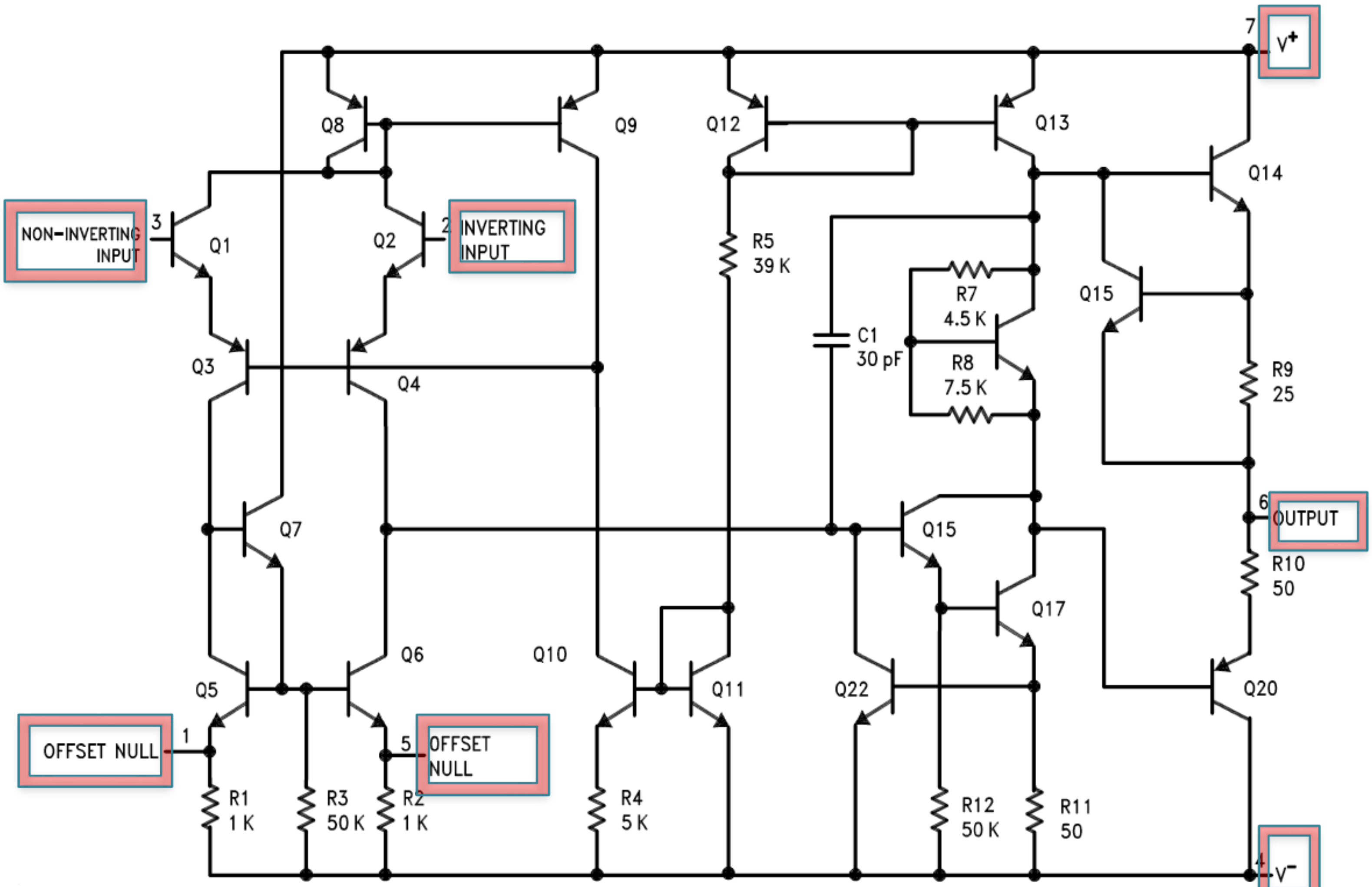
- It is an electronic circuit that behaves like a voltage-controlled voltage source.
- It is often used to perform mathematical operations such as *inversion*, *addition*, *subtraction*, *multiplication*, *division*, *differentiation* and *integration*.





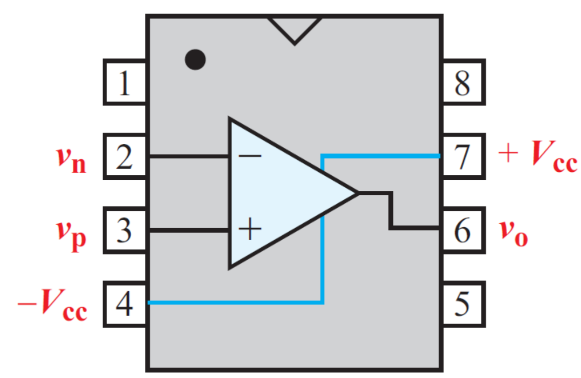
Inside The Op Amp

Schematic Diagram



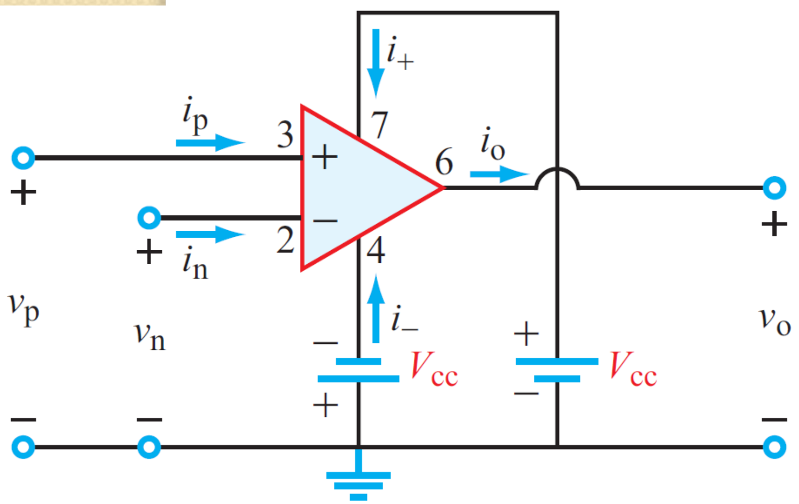
Operational Amplifier

- Two input terminals, positive (non-inverting) and negative (inverting)
- One output
- Power supply $+V_{cc}$ and $-V_{cc}$

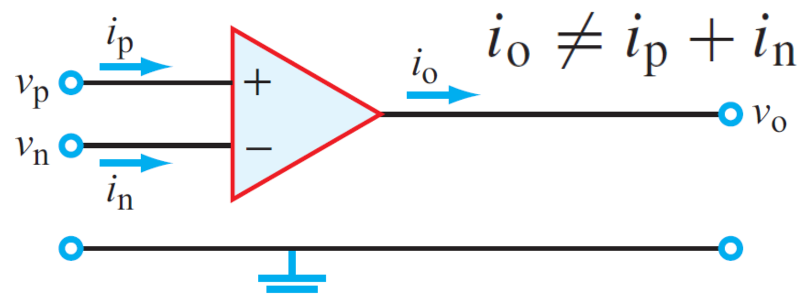


(b) Pin diagram

Op Amp showing power supply



Op Amp with power supply not shown (which is how we usually display op amp circuits)



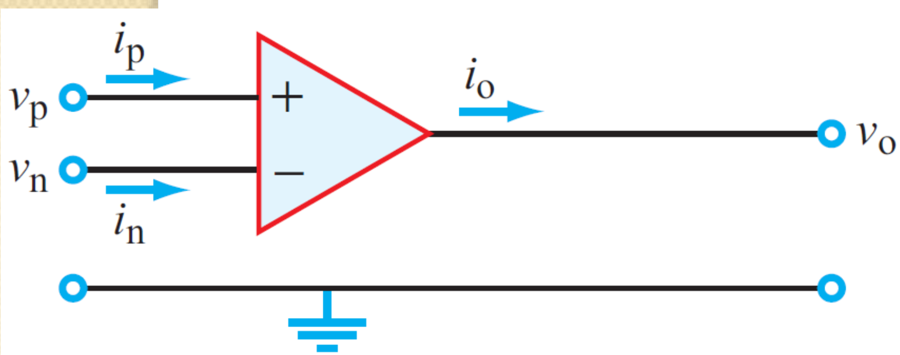
$$i_o \neq i_p + i_n$$

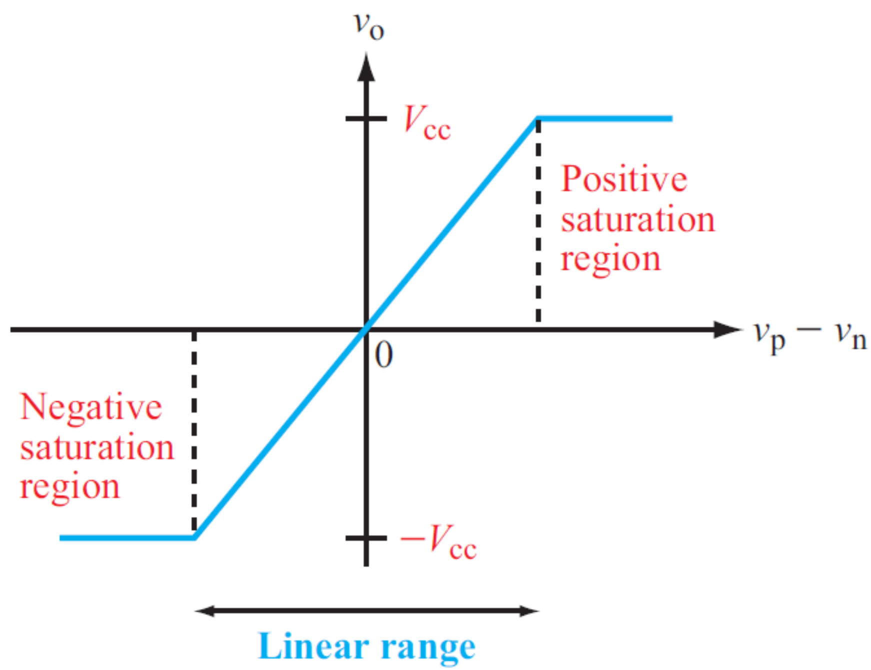
Op Amp Gain

- Key important aspect of op amp: high voltage gain output,

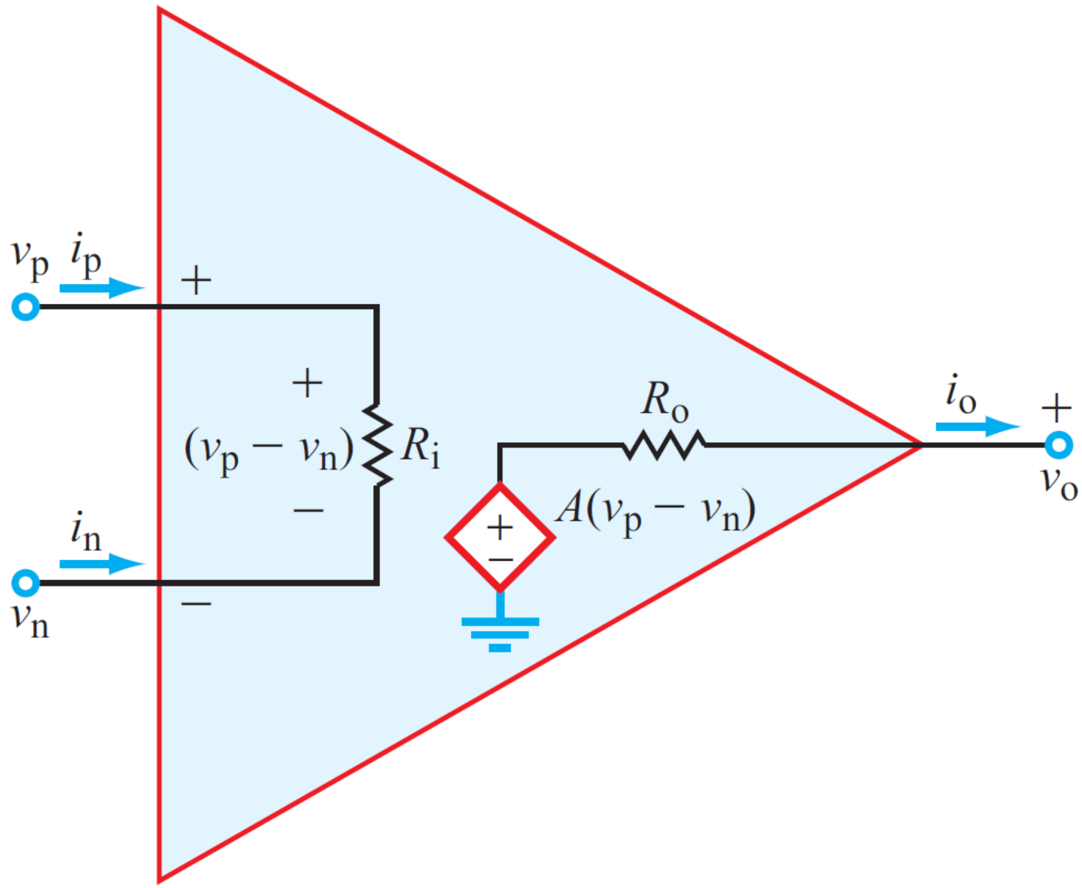
$$v_o = A(v_p - v_n)$$

  - A is the op-amp gain (or open-loop gain)
  - Linear response



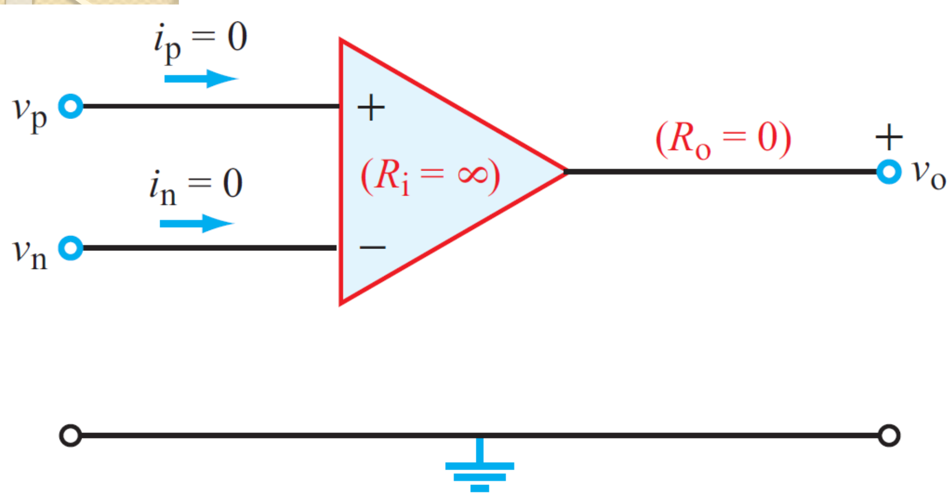


Op Amp Equivalent Circuit



Op-Amp Characteristics	Parameter	Typical Range	Ideal Op Amp
• Linear input–output response	Open-loop gain A	10^4 to 10^8 (V/V)	∞
• High input resistance	Input resistance R_i	10^6 to 10^{13} Ω	∞ Ω
• Low output resistance	Output resistance R_o	1 to 100 Ω	0 Ω
• Very high gain	Supply voltage V_{cc}	5 to 24 V	As specified by manufacturer

Circuit Analysis With Ideal Op-Amps



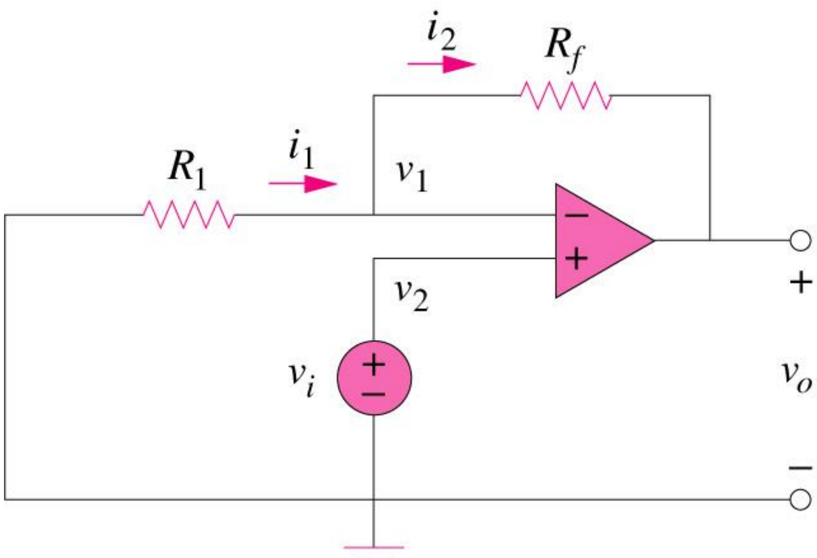
Ideal Op Amp

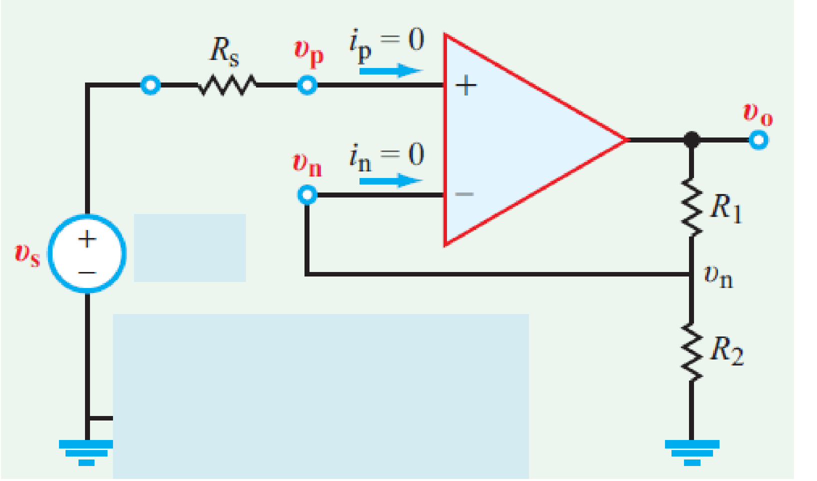
- Current constraint $i_p = i_n = 0$
- Voltage constraint $v_p = v_n$
- $A = \infty$ $R_i = \infty$ $R_o = 0$

- Use nodal analysis as before.
- $v_p = v_n$ (Ideal op-amp model).
- $i_p = i_n = 0$ (Ideal op-amp model).
- Do not apply KCL at op amp output

Non-Inverting Amplifier

- Non-inverting amplifier is designed to produce positive voltage gain.





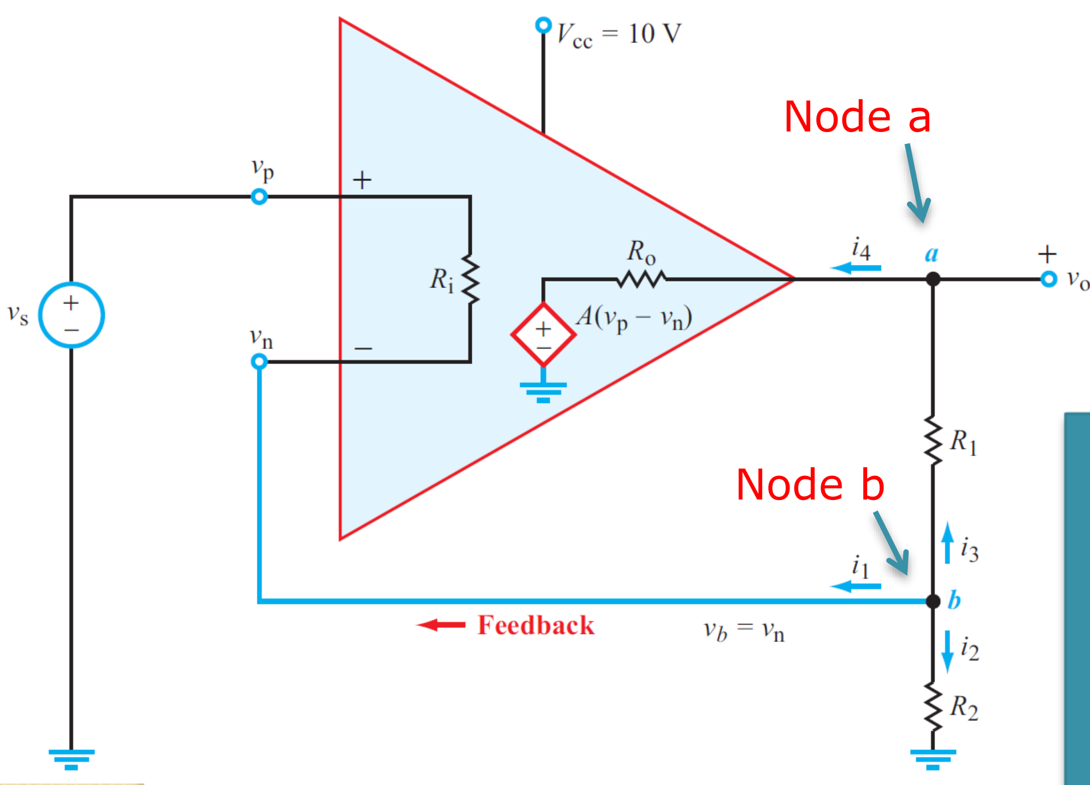
$$v_o = \left(1 + \frac{R_f}{R_1}\right) v_{in}$$

$$V_o = (1+R_1/R_2)v_s$$

Non-Inverting Amplifier

Example 1:

For $V_{cc} = 10$ V, $A = 10^6$, $R_i = 10^7$ Ω, $R_o = 10$ Ω, $R_1 = 80$ kΩ, and $R_2 = 20$ kΩ,



KCL at Node a:

$$\frac{v_n - v_o}{R_1} = \frac{v_o - A(v_p - v_n)}{R_o}$$

KCL at Node b:

$$\frac{v_n - v_p}{R_i} + \frac{v_n}{R_2} + \frac{v_n - v_o}{R_1} = 0$$

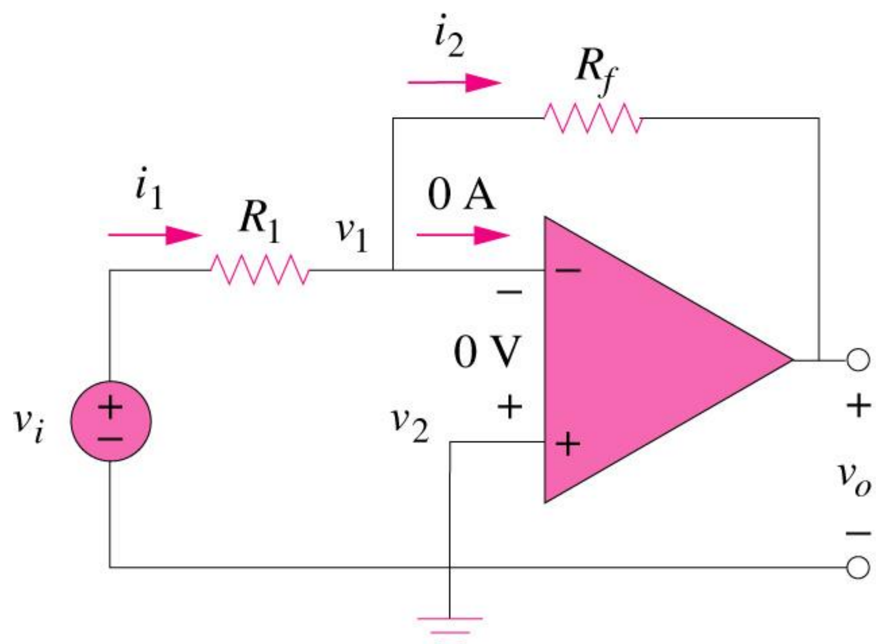
For infinite *A*:

$$G = \frac{v_0}{v_s} = \frac{R_1 + R_2}{R_2} = 5$$

$$G = \frac{v_o}{v_s} = \frac{[AR_i(R_1 + R_2) + R_2R_o]}{AR_2R_i + R_o(R_2 + R_i) + R_1R_2 + R_i(R_1 + R_2)} = 4.999975$$

Inverting Amplifier

- An inverting amplifier reverses the polarity of the input signal while amplifying it.

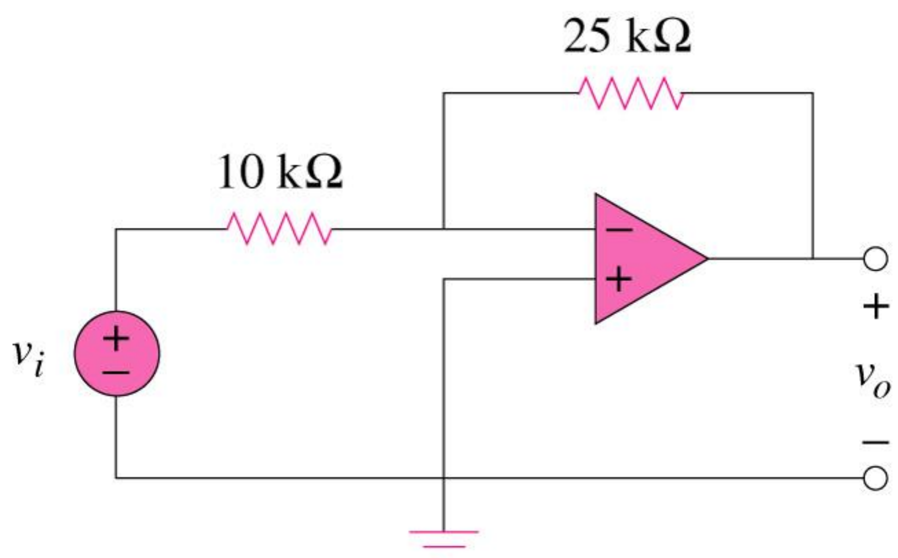


$$v_o = -\frac{R_f}{R_1} v_i$$

Inverting Amplifier

Example 2:

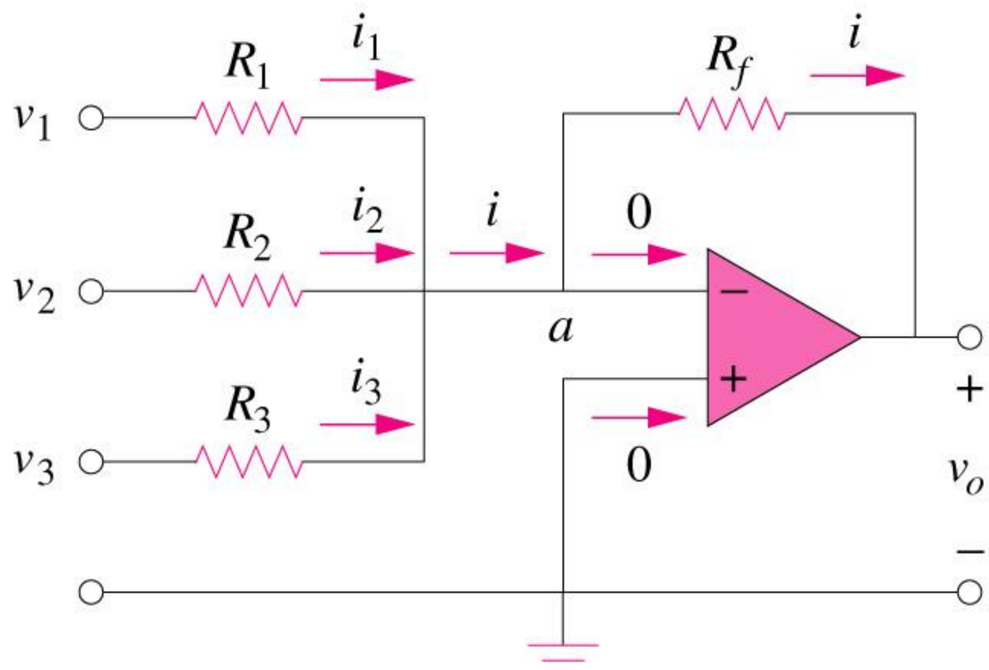
Refer to the op amp circuit below. If v_i = 0.5V, calculate the output voltage v_o and the current in the 10 kΩ resistor.



Answer: (a) -1.25V; (b) 50μA

Summing Amplifier

- Summing Amplifier is an op amp circuit that combines several inputs and produces an output that is equal to the weighted sum of the inputs.

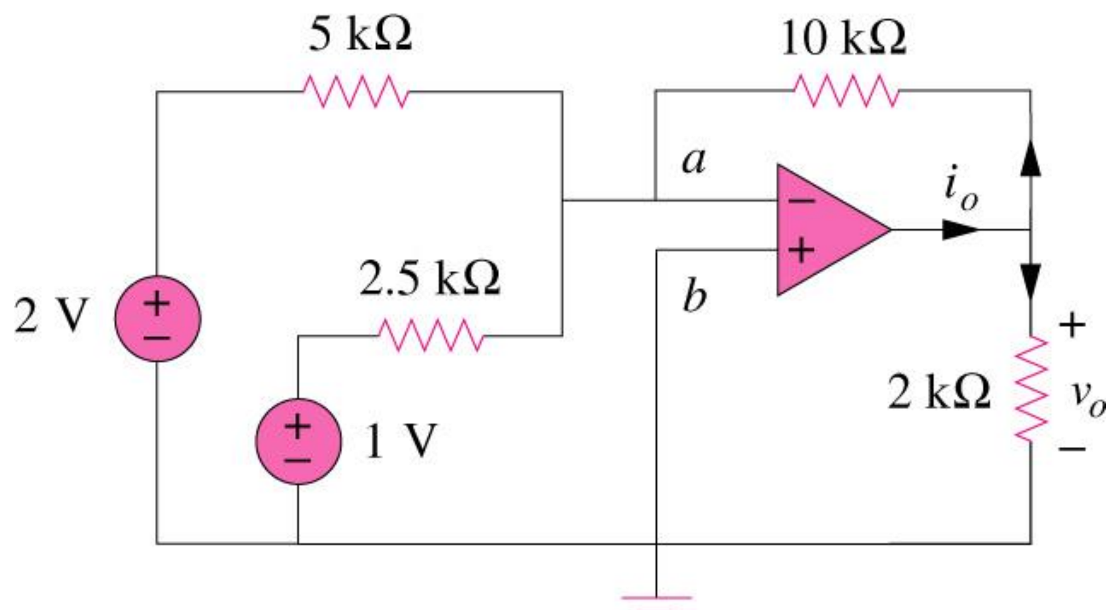


$$v_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right)$$

Summing Amplifier

<u>Example 3:</u>

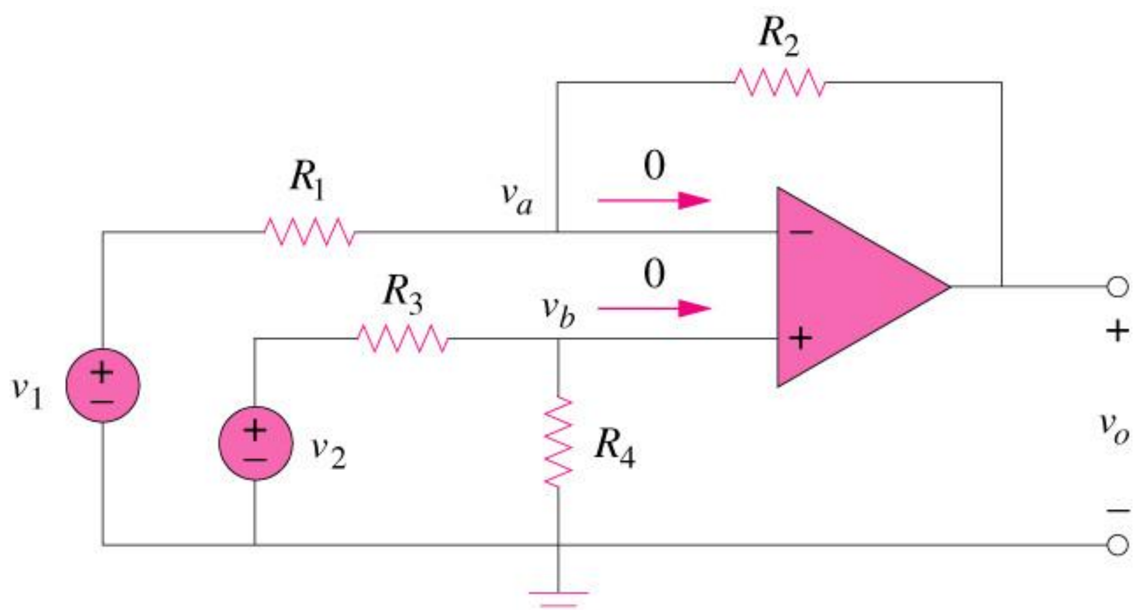
Calculate v_o and i_o in the op amp circuit shown below.



Answer: -3.8V, -1.425mA

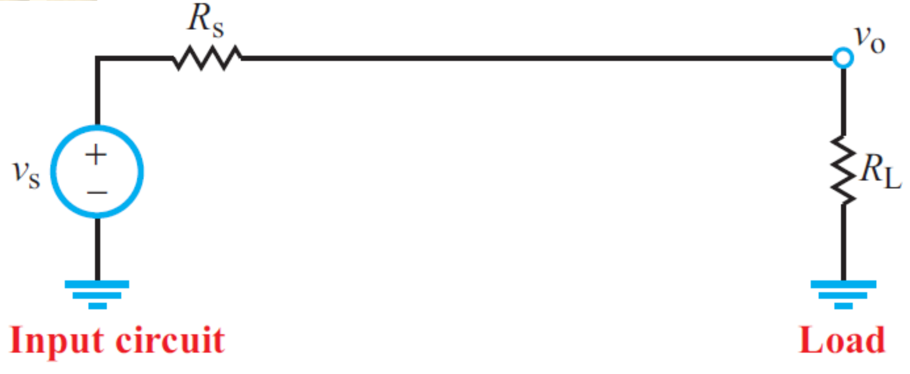
Difference Amplifier

- Difference amplifier is a device that amplifies the difference between two weighted inputs.



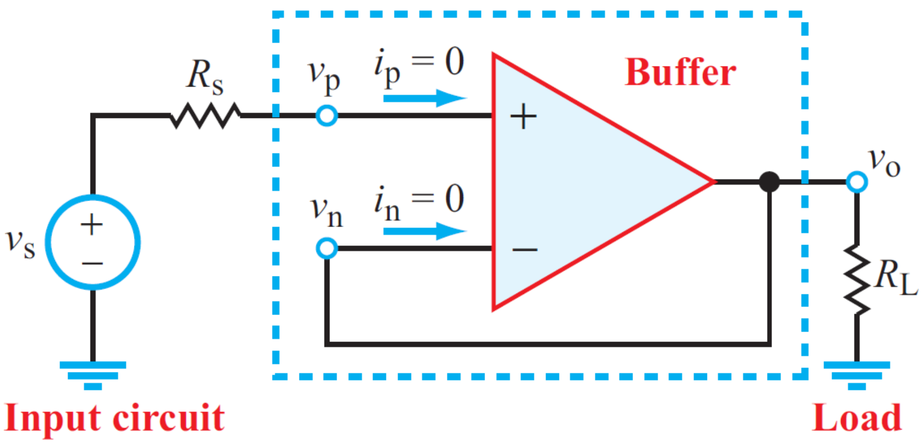
$$v_o = \frac{R_2(1 + R_1/R_2)}{R_1(1 + R_3/R_4)} v_2 - \frac{R_2}{R_1} v_1 \Rightarrow v_o = v_2 - v_1 \text{, if } \frac{R_2}{R_1} = \frac{R_3}{R_4} = 1$$

Voltage Follower/Buffer



$$v_o = \frac{v_s R_L}{R_s + R_L} \qquad \text{(without voltage follower)}$$

v_o depends on load resistor.

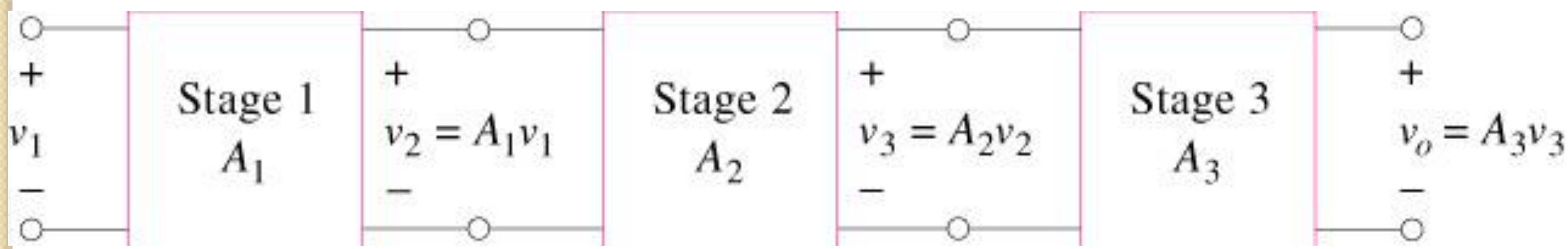


$$v_o = v_p = v_s \qquad \text{(with voltage follower)}$$

v_o is immune to load resistor.

Cascaded Op Amps

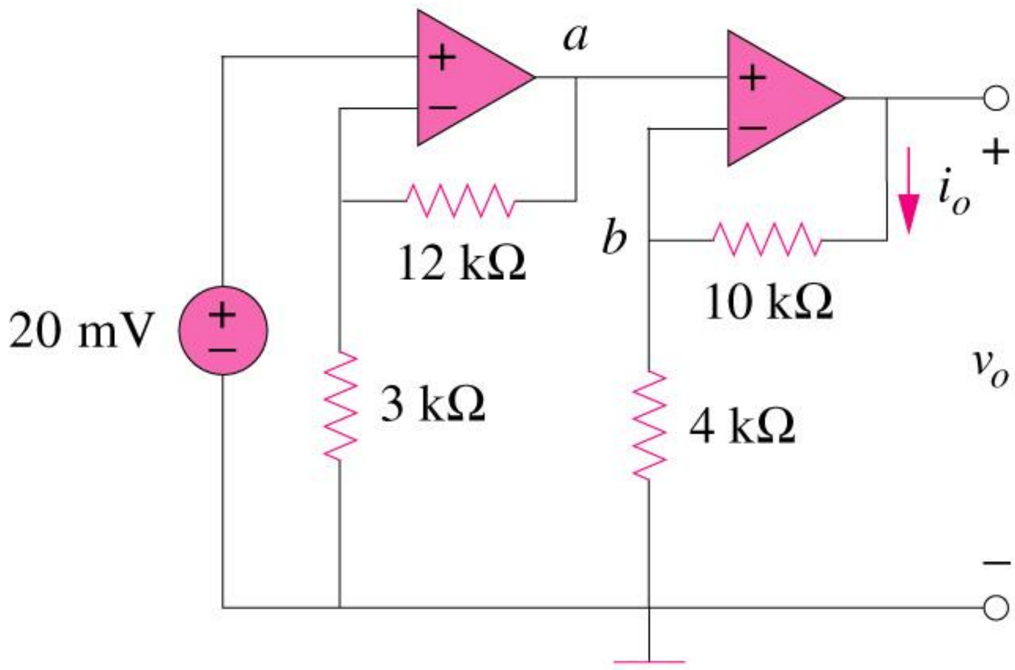
- It is a head-to-tail arrangement of two or more op amp circuits such that the output to one is the input of the next.



Cascaded Op Amps

<u>Example 4:</u>

Find v_o and i_o in the circuit shown below.

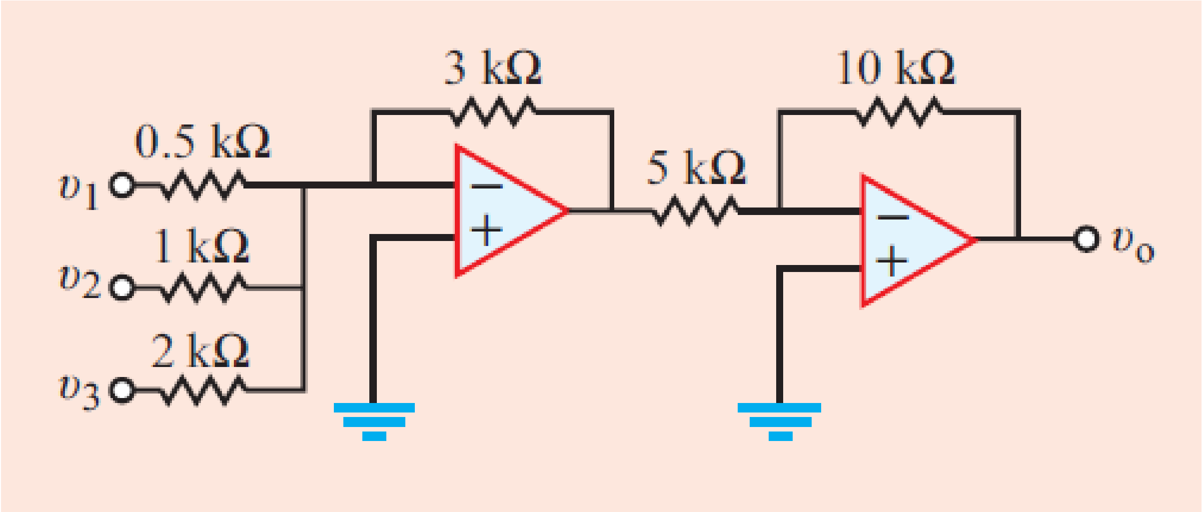


Answer: 350mV, 25μA

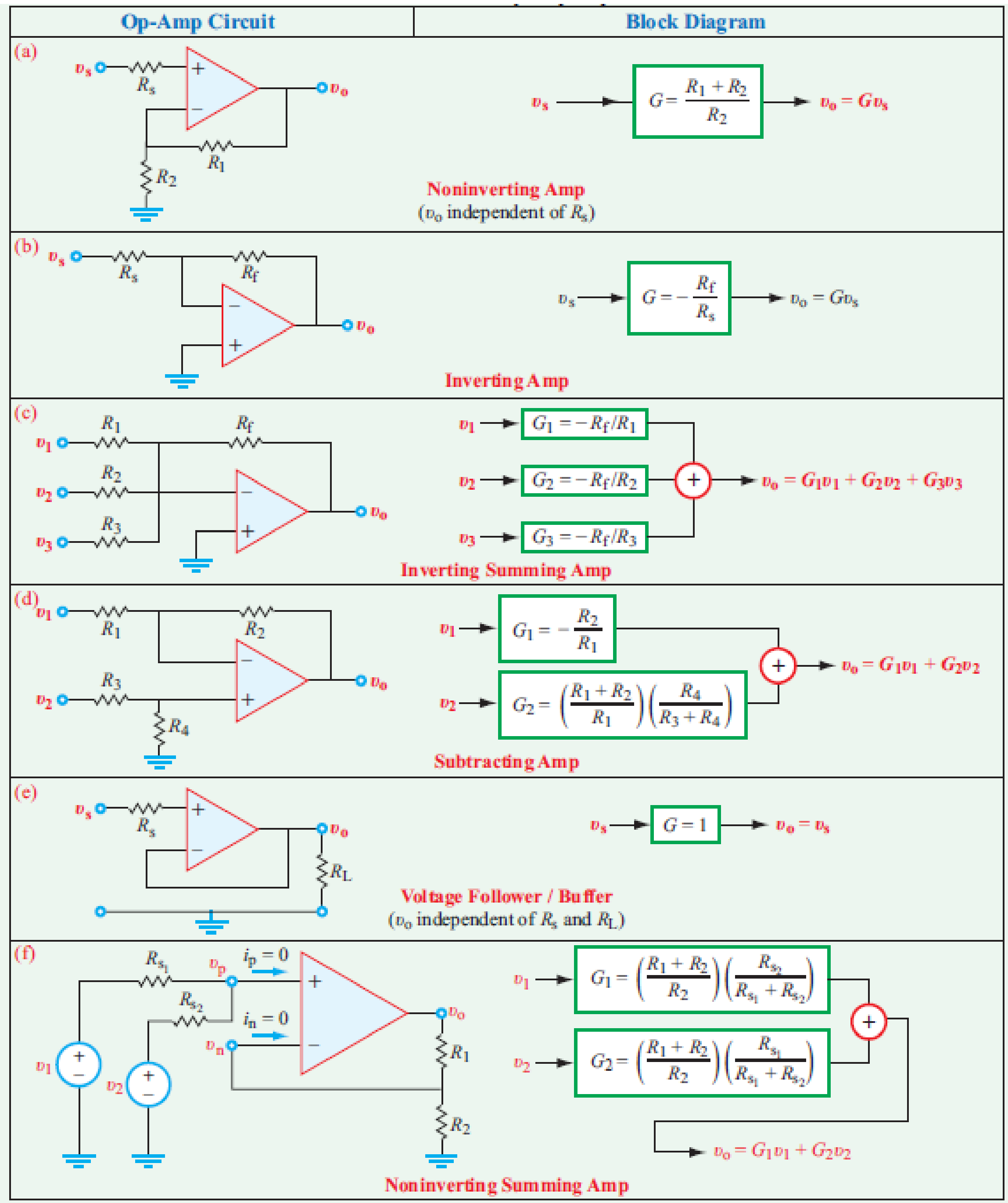
Cascaded Op Amps

<u>Example 5:</u>

Find v_o in terms of v_1, v_2 and v_3.



Answer: $v_o = 12v_1 + 6v_2 + 3v_3$.

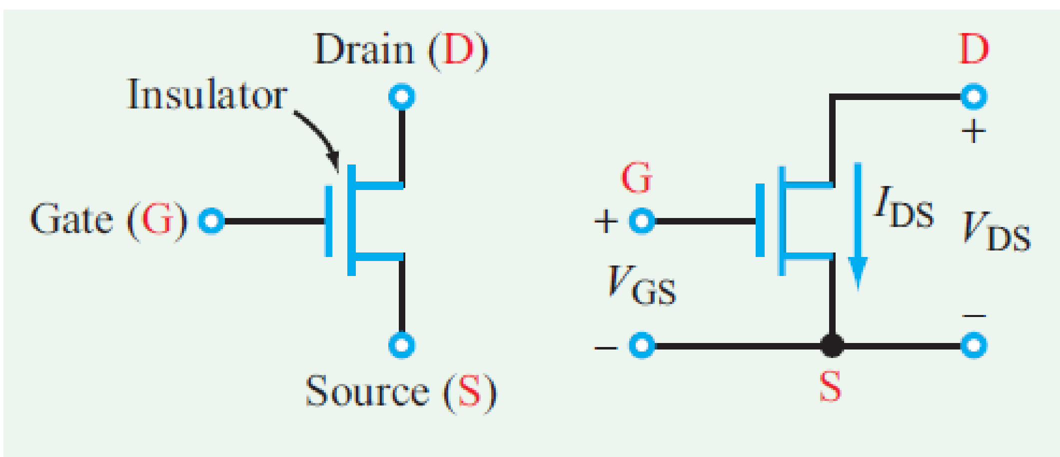

Op-Amp Circuit
Block Diagram
(a)
G = (R1 + R2)/R2
vo = Gvs
Noninverting Amp
(vo independent of Rs)
(b)
G = − Rf/Rs
vo = Gvs
Inverting Amp
(c)
G1 = −Rf/R1
G2 = −Rf/R2
G3 = −Rf/R3
vo = G1v1 + G2v2 + G3v3
Inverting Summing Amp
(d)
G1 = − R2/R1
G2 = ((R1 + R2)/R1)(R4/(R3 + R4))
vo = G1v1 + G2v2
Subtracting Amp
(e)
G = 1
vo = vs
Voltage Follower / Buffer
(vo independent of Rs and RL)
(f)
ip = 0
in = 0
G1 = ((R1 + R2)/R2)(Rs2/(Rs1 + Rs2))
G2 = ((R1 + R2)/R2)(Rs1/(Rs1 + Rs2))
vo = G1v1 + G2v2
Noninverting Summing Amp

Practice Problems (Chap. 4)

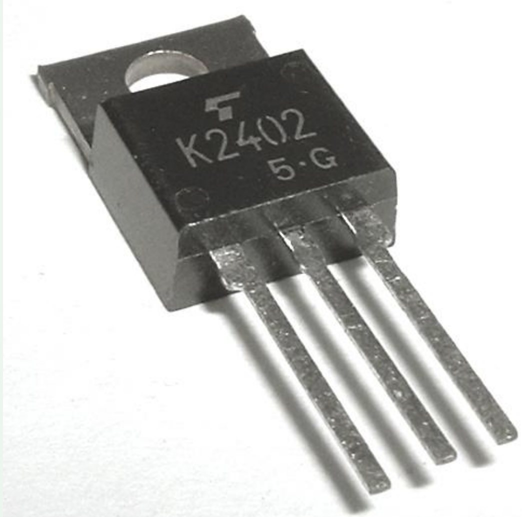
- Solve the following problems: 4, 8, 12, 16, 20, …, 52.

Another Transistor: the MOSFET

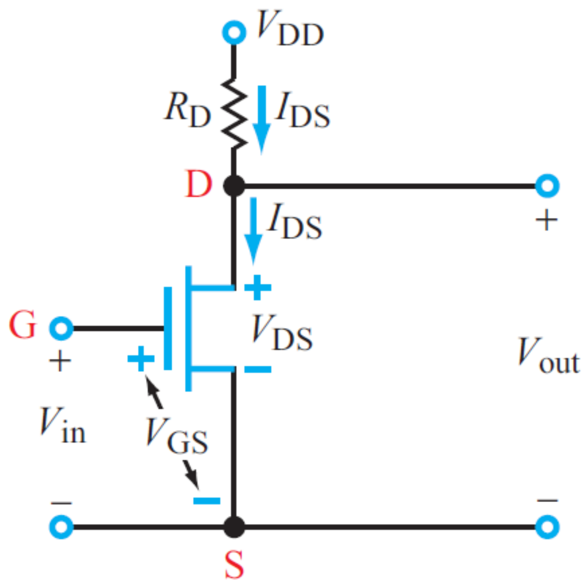
- A MOSFET (metal-oxide semiconductor field-effect transistor) is a voltage-controlled electronic switch.
- A MOSFET has three terminals: the ***gate*** (G), the ***source*** (S), and the ***drain*** (D).
- Because the gate G is separated from the rest of the transistor by the thin insulating layer, no dc current can flow from G to either D or S.

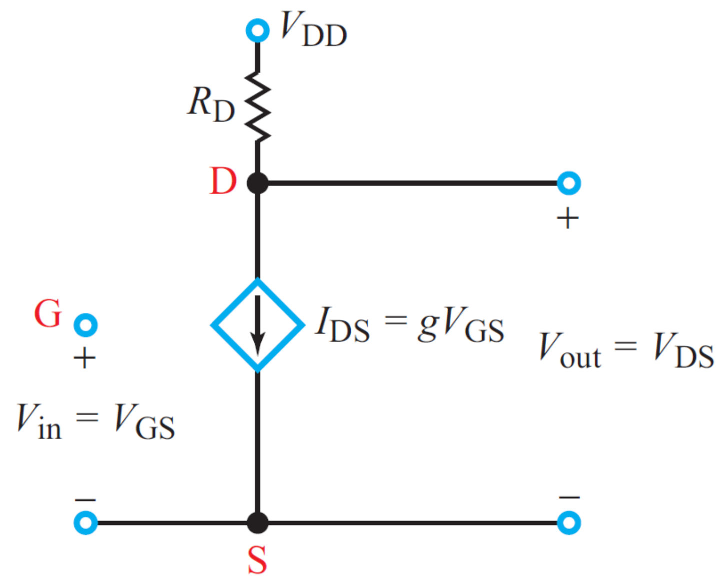


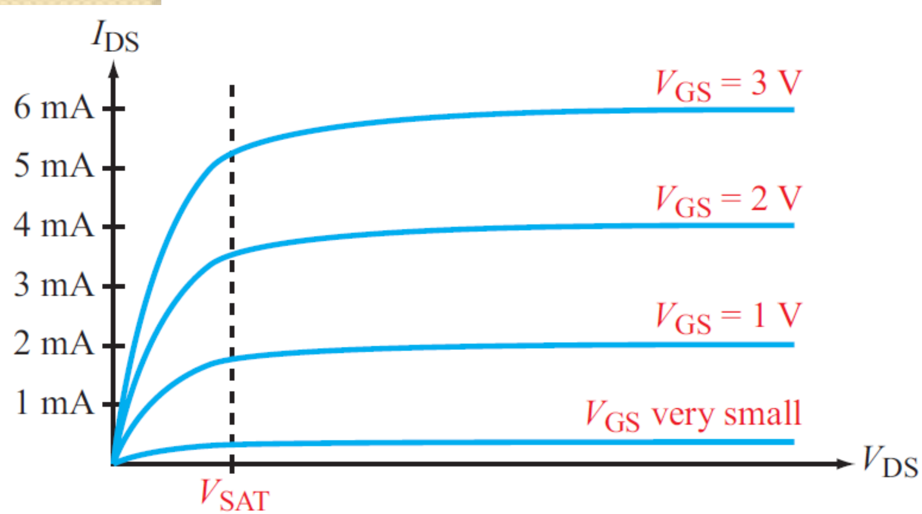
(a) MOSFET symbol (b) Voltages



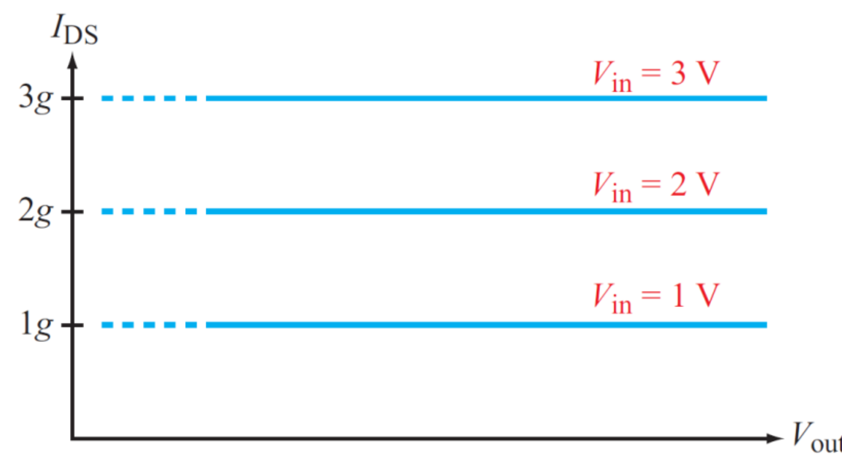
MOSFET Equivalent Circuit





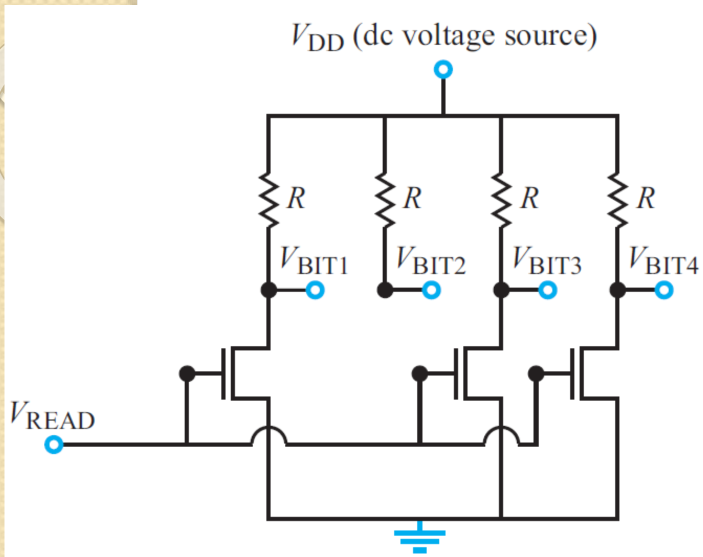


Characteristic curves

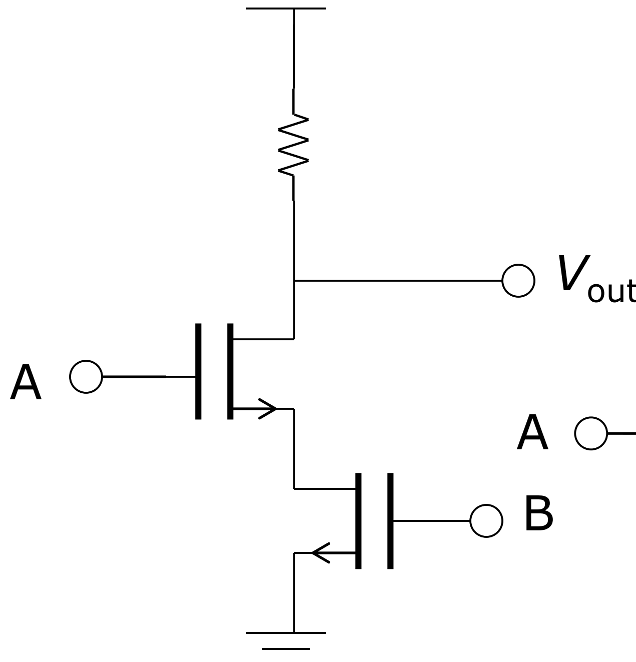


Idealized response

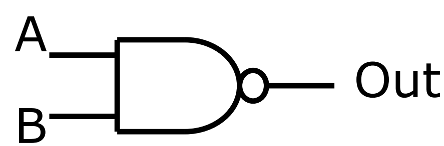
MOSFETs in Digital Circuits

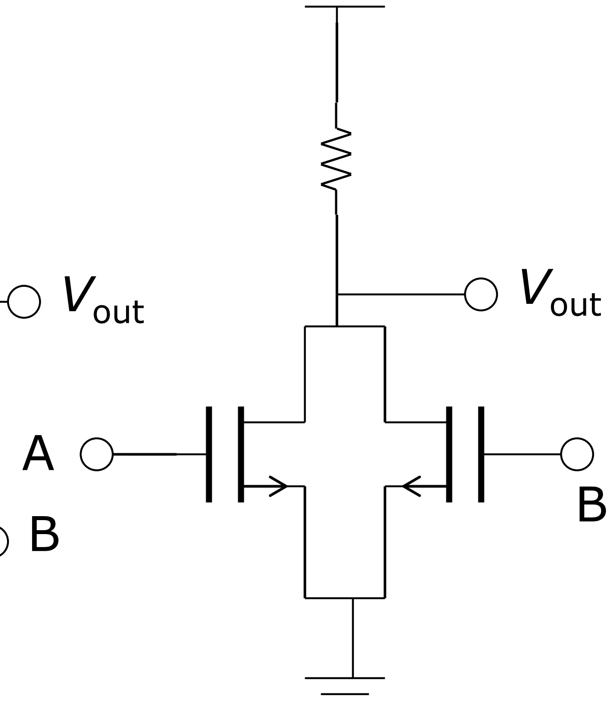


4-bit ROM



NAND Gate





NOR Gate