Chapter 5

- OUTLINE
  - Op-Amp from 2-Port Blocks
  - Op-Amp Model and its Idealization
  - Negative Feedback for Stability
  - Components around Op-Amp define the Circuit Function

The Operational Amplifier

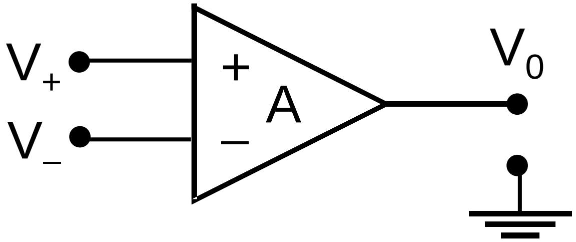
- The ***operational amplifier*** ("***op amp***") is a basic building block used in analog circuits.
  - Its behavior is modeled using a dependent source.
  - When combined with resistors, capacitors, and inductors, it can perform various useful functions:
    - **amplification/scaling** of an input signal
    - **sign changing** (inversion) of an input signal
    - **addition** of multiple input signals
    - **subtraction** of one input signal from another
    - **integration** (over time) of an input signal
    - **differentiation** (with respect to time) of an input signal
    - **analog filtering**
    - **nonlinear functions** like exponential, log, sqrt, etc
  - Isolate input from output; allow cascading

High Quality Dependent Source In an Amplifier

AMPLIFIER SYMBOL

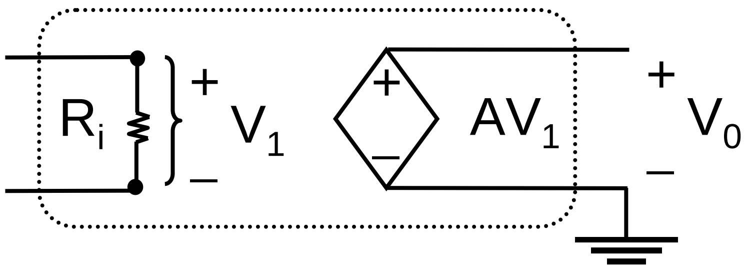
Differential Amplifier

$$V_0 = A(V_+ - V_-)$$



AMPLIFIER MODEL

Circuit Model *in linear region*

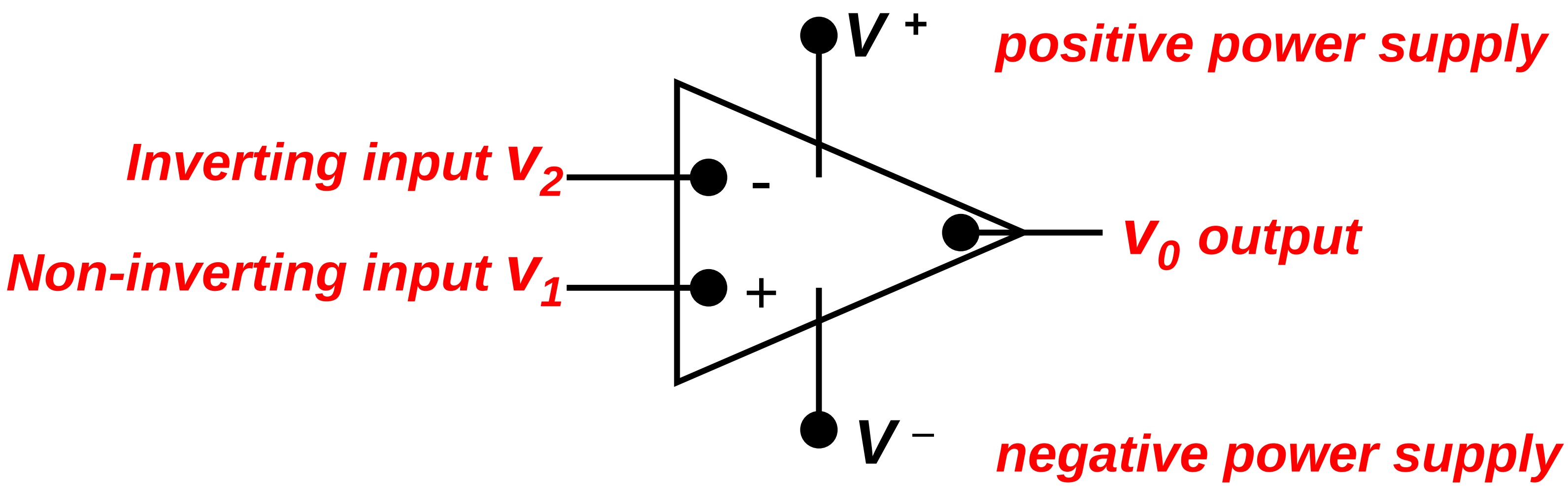


V_0 depends only on input $(V_+ - V_-)$

See the utility of this: this Model when used correctly mimics the behavior of an amplifier but omits the complication of the many many transistors and other components.

Op Amp Terminals

- 3 signal terminals: 2 inputs and 1 output
- IC op amps have 2 additional terminals for DC power supplies
- Common-mode signal= $(v_1+v_2)/2$
- Differential signal = v_1-v_2



Model for Internal Operation

- A is differential gain or open loop gain
- Ideal op amp

$$A \to \infty$$

$$R_i \to \infty$$

$$R_o = 0$$

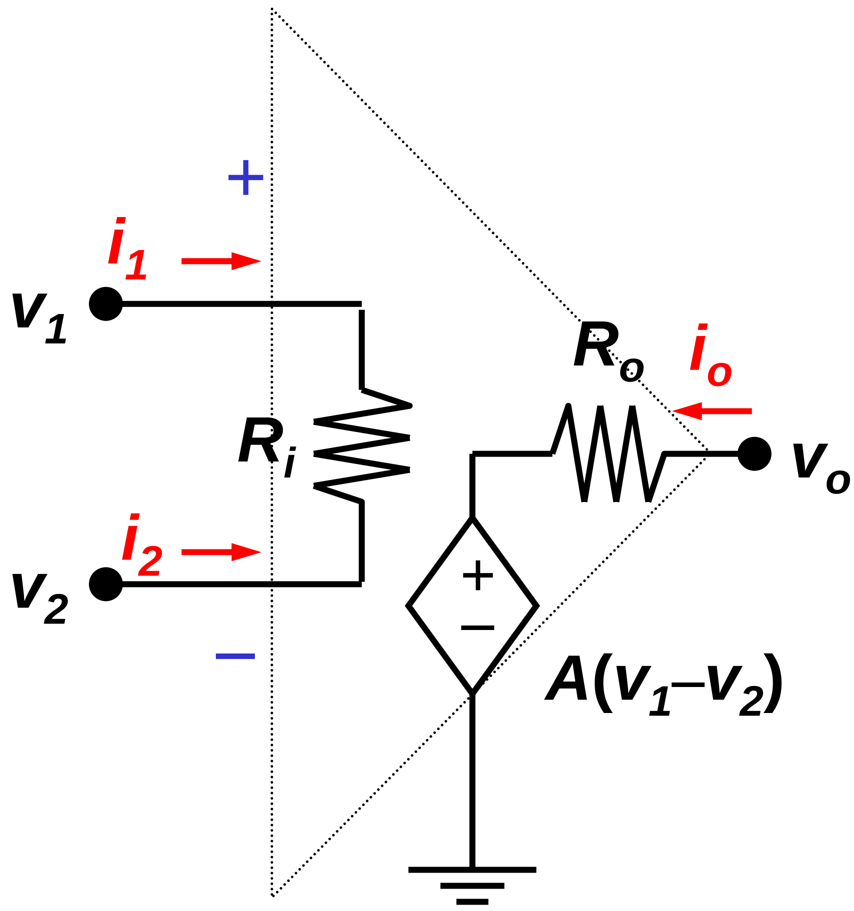
  – Common mode gain = 0

$$v_{cm} = \frac{(v_1 + v_2)}{2} \quad , v_d = v_1 - v_2$$

$$v_o = A_{cm} v_{cm} + A_d v_d$$

$$Since \quad v_o = A(v_1 - v_2) \quad , A_{cm} = 0$$

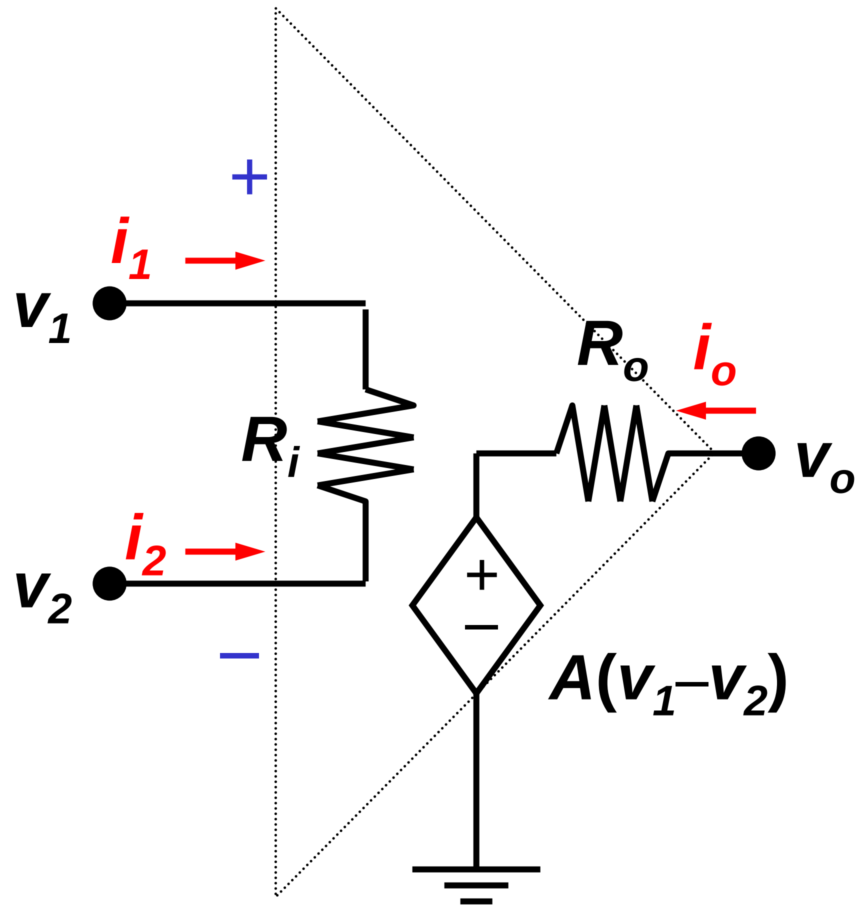
- Circuit Model



Model and Feedback

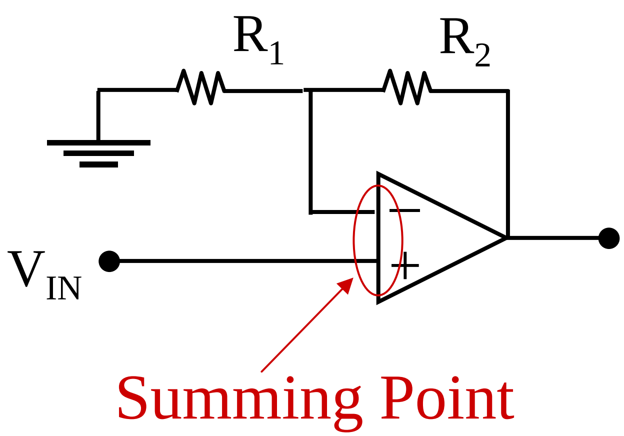
- Negative feedback
  - connecting the output port to the negative input (port 2)
- Positive feedback
  - connecting the output port to the positive input (port 1)
- Input impedance: R looking into the input terminals
- Output impedance: Impedance in series with the output terminals

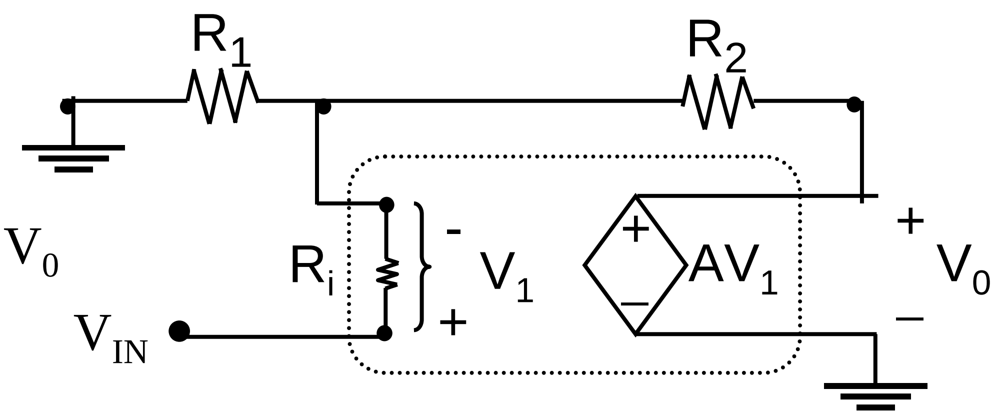
- Circuit Model



Op-Amp and Use of Feedback

A very high-gain differential amplifier can function in an extremely linear fashion as an operational amplifier by using negative feedback.





Circuit Model

Negative feedback $\Rightarrow$ **Stabilizes** the output

Hambley Example pp. 644 for Power Steering

We can show that that for $A \rightarrow \infty$ and $R_i \rightarrow \infty$,

$$V_0 \cong V_{IN} \cdot \frac{R_1 + R_2}{R_1}$$

Stable, finite, and independent of the properties of the OP AMP !

Summing-Point Constraint

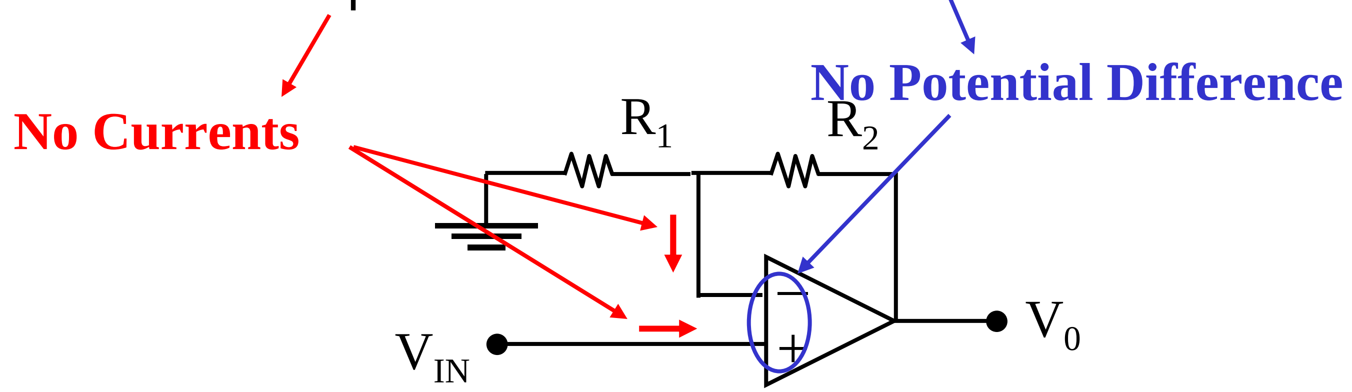
- Check if under negative feedback
  - Small v_i result in large v_o
  - Output v_o is connected to the inverting input to reduce v_i
  - Resulting in $v_i=0$
- Summing-point constraint
  - $v_1= v_2$
  - $i_1 = i_2 =0$
- Virtual short circuit
  - Not only voltage drop is 0 (which is short circuit), input current is 0
  - This is different from short circuit, hence called “virtual” short circuit.

Ideal Op-Amp Analysis Technique

Applies only when Negative Feedback is present in circuit!

Assumption 1: The potential between the op-amp input terminals, $v_{(+)} - v_{(-)}$, equals zero.

Assumption 2: The currents flowing into the op-amp's two input terminals both equal zero.



EXAMPLE

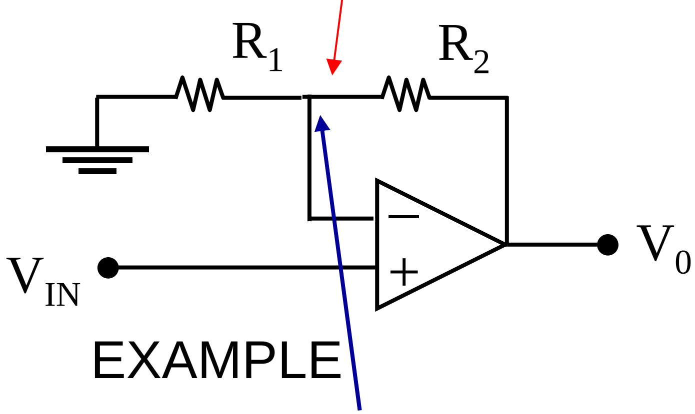
Ideal Op-Analysis: Non-Inverting Amplifier

Yes Negative Feedback is present in this circuit!

Assumption 1: The potential between the op-amp input terminals, $v_{(+)} - v_{(-)}$, equals zero.

Assumption 2: The currents flowing into the op-amp's two input terminals both equal zero.

KCL with currents in only two branches



V_{IN} appears here

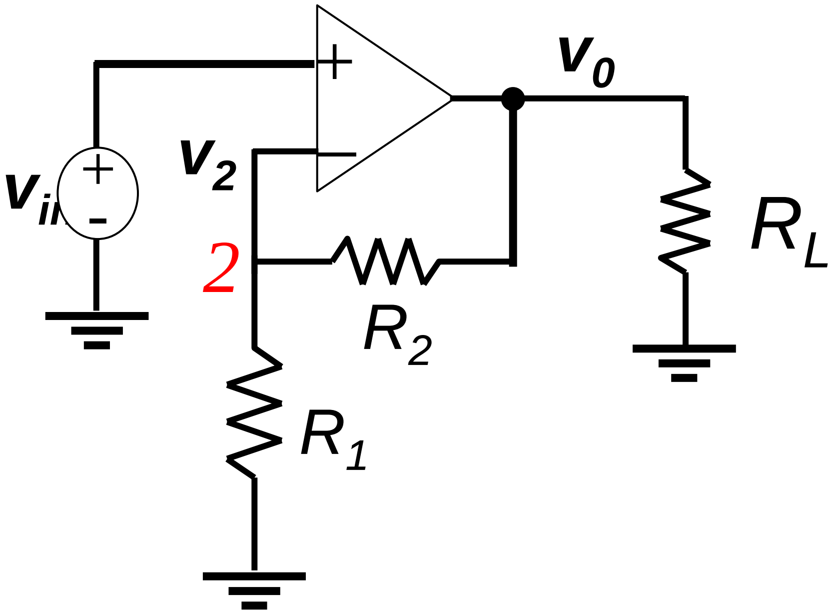
$$\frac{v_{in}}{R_1} + \frac{v_{in} - v_{out}}{R_2} = 0$$

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

Non-inverting Amplifier

Non-Inverting Amplifier

- Ideal voltage amplifier



$$Closed\ \ loop\ \ gain = A_v = \frac{v_o}{v_{in}}$$

$$v_1 = v_2 = v_{in}\ \ , i_1 = i_2 = 0$$

$$Use\ \ KCL\ \ At\ \ Node\ \ 2.$$

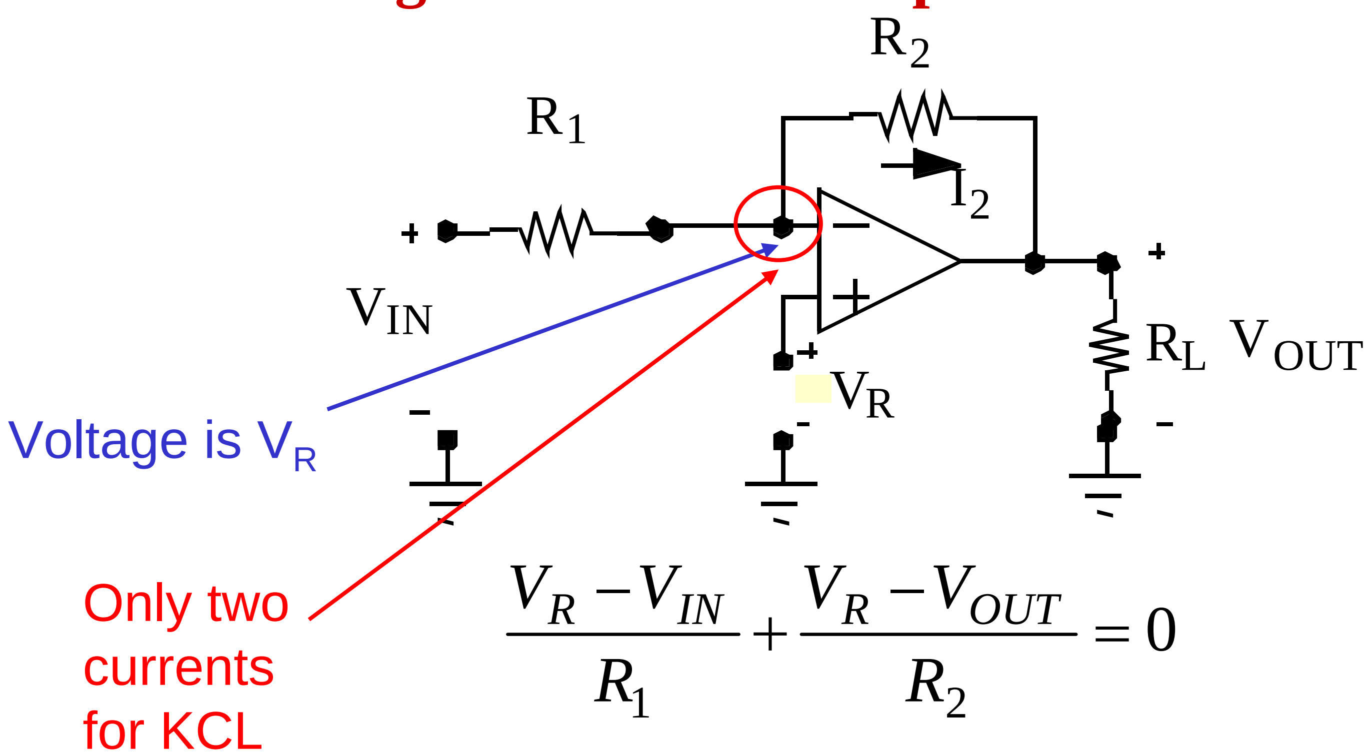
$$i = \frac{(v_0 - v_2)}{R_2} = \frac{(v_2 - 0)}{R_1}$$

$$A = \frac{v_o}{v_{in}} = \frac{(R_1 + R_2)}{R_1}$$

$$Input\ \ impedance = \frac{v_{in}}{i} \to \infty$$

Ideal Op-Amp Analysis: Inverting Amplifier

Yes Negative Feedback is present in circuit!



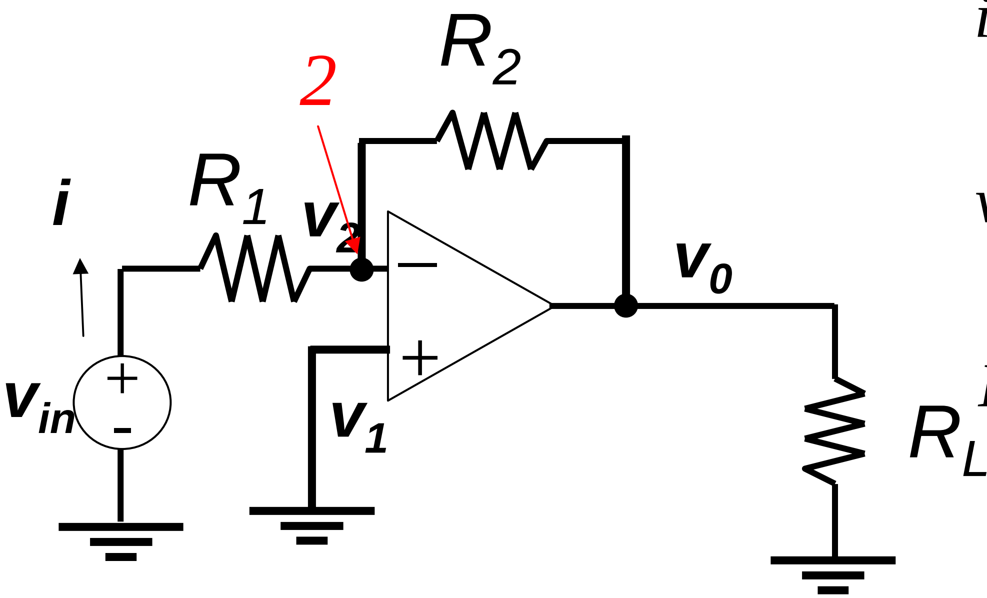
$$\frac{V_R - V_{IN}}{R_1} + \frac{V_R - V_{OUT}}{R_2} = 0$$

$$V_{OUT} = V_R - \frac{R_2}{R_1}\left(V_{in} - V_R\right)$$

Inverting Amplifier with reference voltage

Inverting Amplifier

- Negative feedback → checked
- Use summing-point constraint



$$Closed\ \ loop\ \ gain = A_v = \frac{v_o}{v_{in}}$$

$$v_1 = v_2 = 0\ \ , i_1 = i_2 = 0$$

$$Use\ \ KCL\ \ At\ \ Node\ \ 2.$$

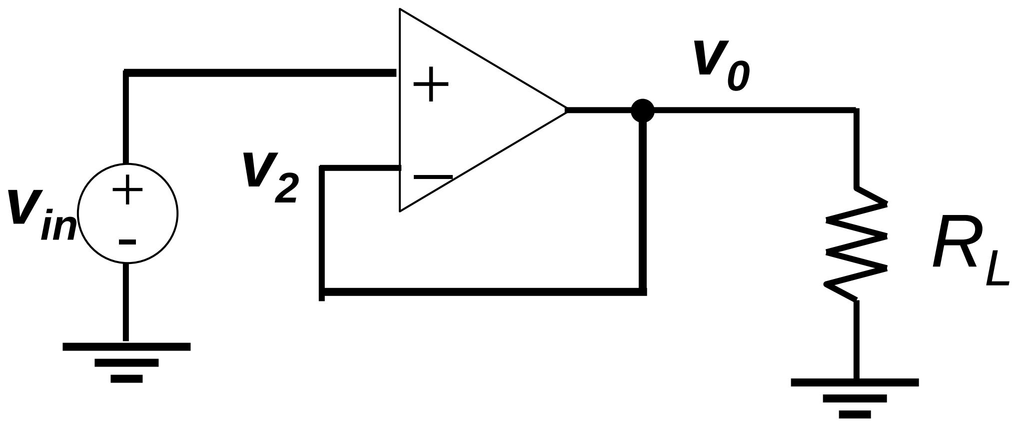
$$i = \frac{(v_{in} - v_2)}{R_1} = \frac{(v_{out} - v_2)}{R_2}$$

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

$$Input\ \ impedance = \frac{v_{in}}{i} = R_1$$

Ideal voltage source – independent of load resistor

Voltage Follower



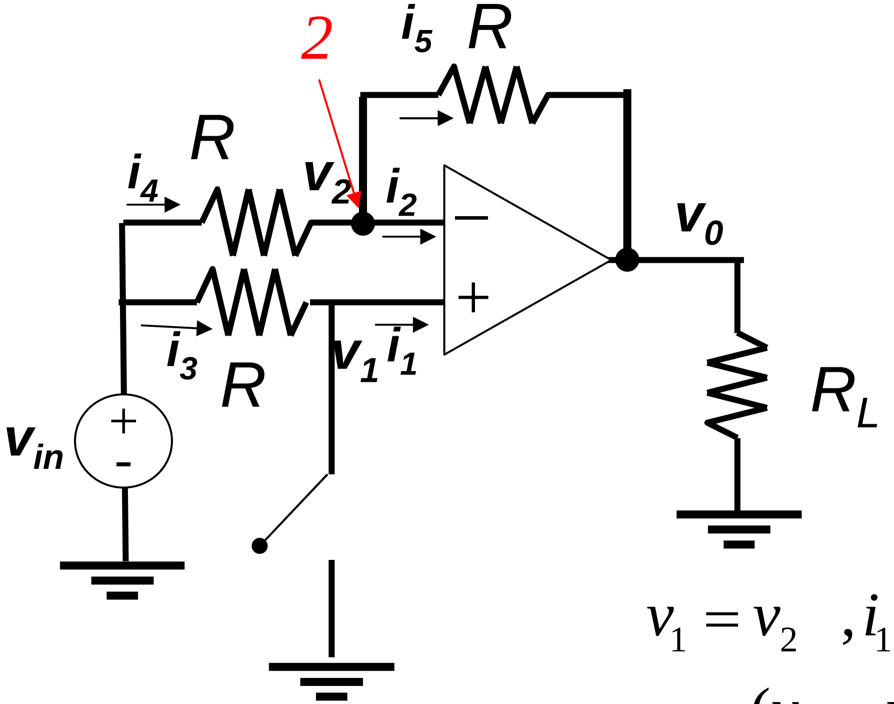
$$R_2 = 0$$

$$R_1 \to \infty$$

$$i = \frac{(v_0 - v_2)}{R_2} = \frac{(v_2 - 0)}{R_1}$$

$$A = \frac{v_o}{v_{in}} = \frac{(R_1 + R_2)}{R_1} = 1 + \frac{R_2}{R_1} = 1$$

Example 1



- Switch is open

$$v_1 = v_2 \quad , i_1 = 0 \rightarrow i_3 = 0$$

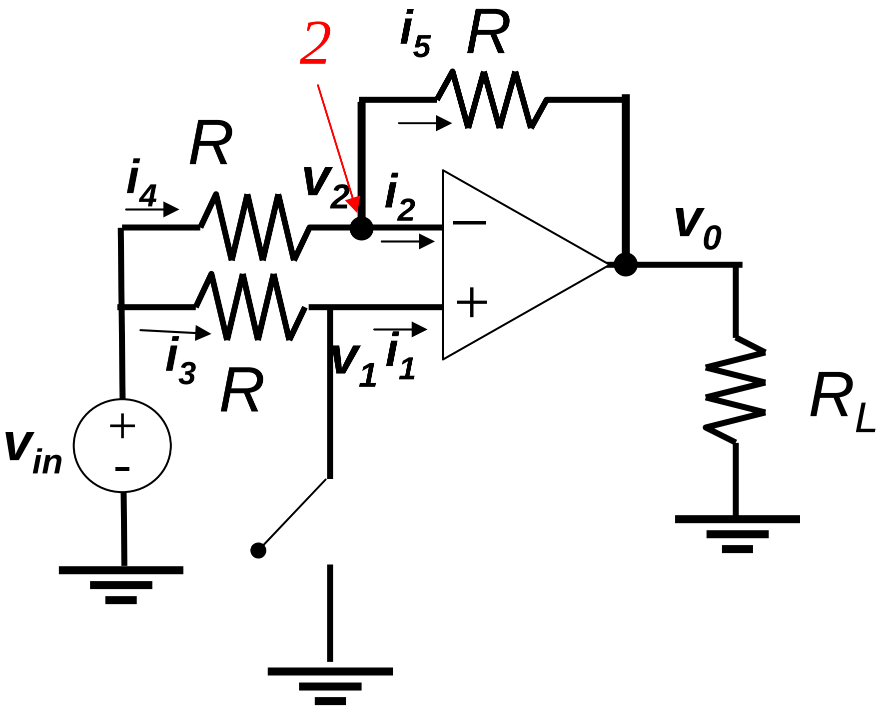
$$i_3 = \frac{(v_{in} - v_1)}{R} \rightarrow v_1 = v_2 = v_{in} \rightarrow i_4 = 0 \rightarrow i_5 = 0$$

$$i_5 = \frac{(v_0 - v_2)}{R} \rightarrow v_0 = v_2 = v_{in}$$

$$A = \frac{v_o}{v_{in}} = 1 \quad , R_{in} \rightarrow \infty$$

Example 1

- Switch is closed



$$v_1 = v_2 = 0 \quad , i_1 = 0 \rightarrow i_3 = 0$$

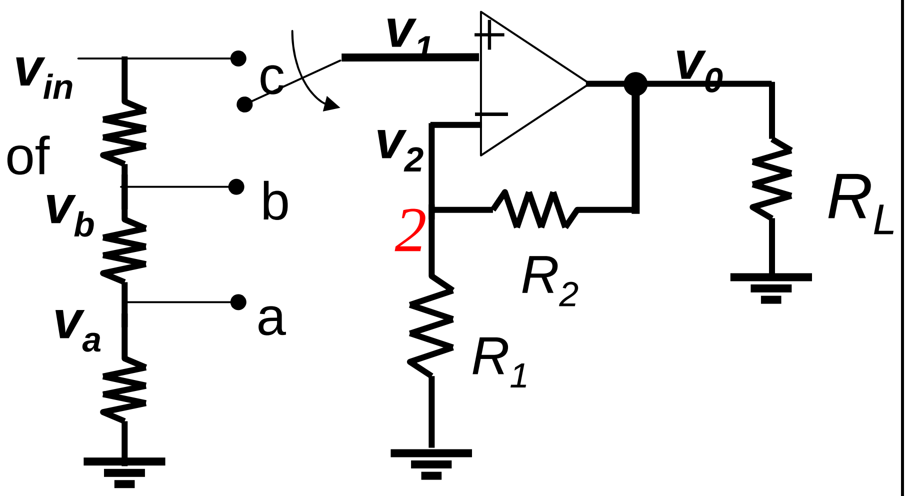
$$i_4 = \frac{(v_{in} - v_2)}{R} = i_5 = -\frac{(v_0 - v_2)}{R}$$

$$v_0 = -v_{in}$$

$$A = \frac{v_o}{v_{in}} = -1 \quad , R_{in} = R/2$$

Example 2

- Design an analog front end circuit to an instrument system
  - Requires to work with 3 full-scale of input signals (by manual switch): $0 \sim \pm 1, 0 \sim \pm 10, 0 \sim \pm 100$ V
  - For each input range, the output needs to be $0 \sim \pm 10$ V
  - The input resistance is 1MΩ



$$v_o = (1 + \frac{R_2}{R_1}) v_1$$

$$v_1 = v_{in} \quad Switch \ \ at \ \ c$$

$$v_1 = \frac{R_a + R_b}{R_a + R_b + R_c} v_{in} \quad Switch \ \ at \ \ b$$

$$v_1 = \frac{R_a}{R_a + R_b + R_c} v_{in} \quad Switch \ \ at \ \ a$$

Example 2 (cont'd)

$$R_{in} = R_a + R_b + R_c = 1M\Omega$$

$$Max\ A_v = 10 = (1 + \frac{R_2}{R_1})\quad Switch\ \ at\ \ c$$

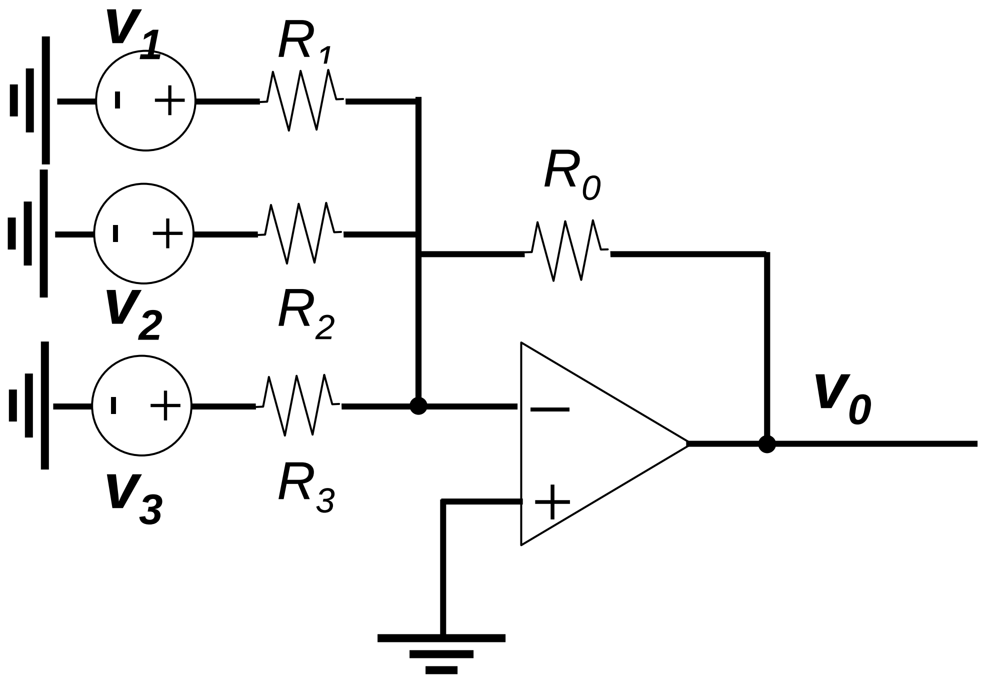
$$A_v = 1 = \frac{R_a + R_b}{R_a + R_b + R_c}(1 + \frac{R_2}{R_1})\quad Switch\ \ at\ \ b \therefore \frac{R_a + R_b}{R_a + R_b + R_c} = 0.1$$

$$A_v = 0.1 = \frac{R_a}{R_a + R_b + R_c}(1 + \frac{R_2}{R_1})\quad Switch\ \ at\ \ a \therefore \frac{R_a}{R_a + R_b + R_c} = 0.01$$

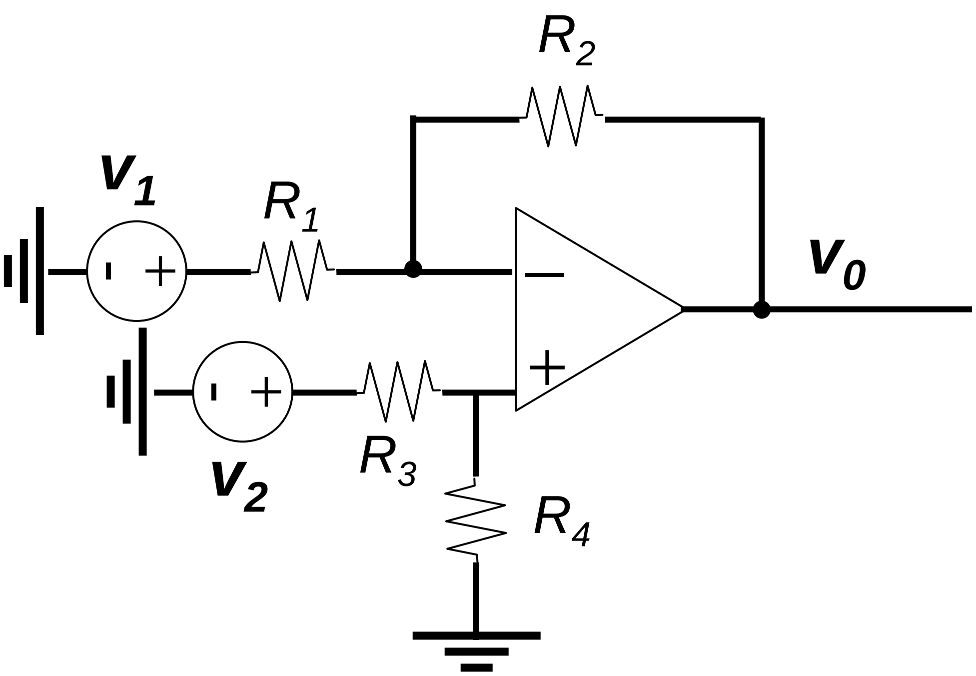
$$\therefore R_a = 10k\Omega, R_b = 90k\Omega, R_c = 900k\Omega$$

$$R_2 = 9R_1$$

Summing Amplifier

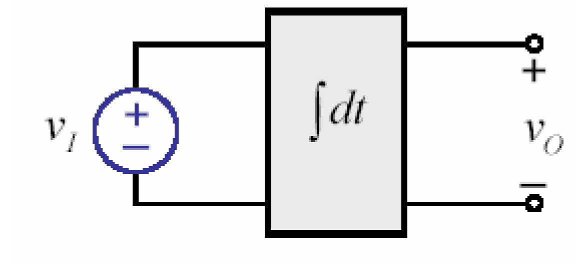


Difference Amplifier

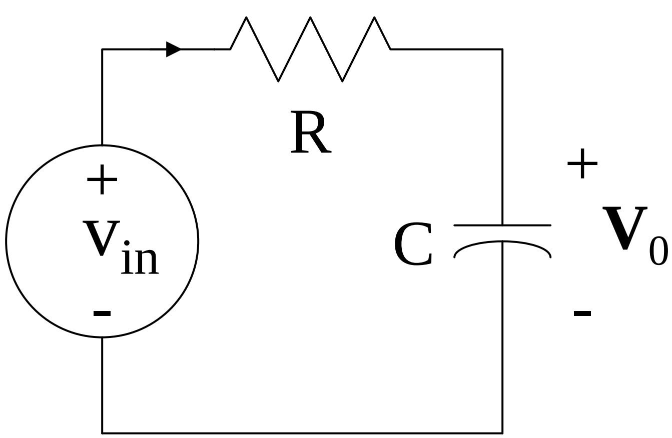


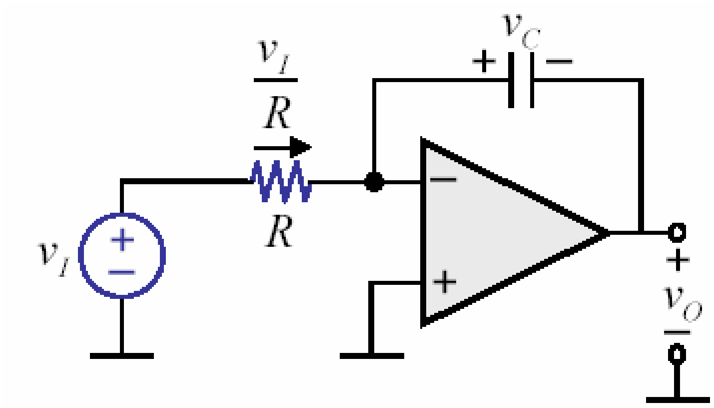
Integrator

- Want $v_o = K\int v_{in}dt$



- What is the difference between:



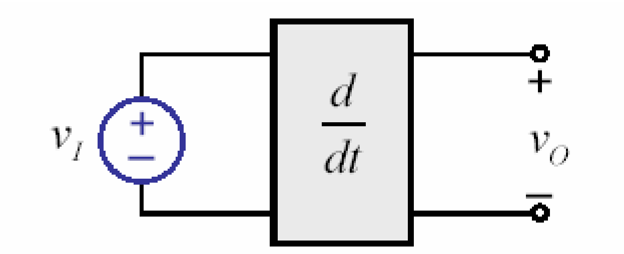


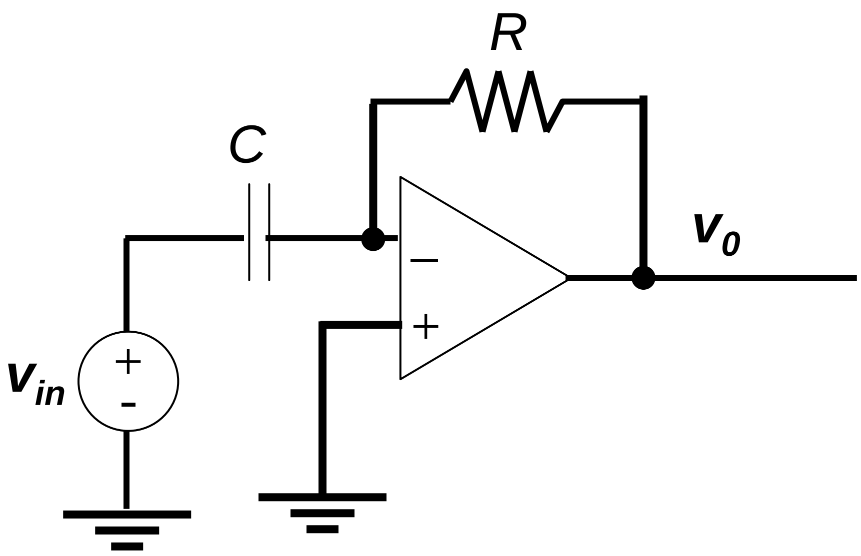
$$v_O \approx \frac{1}{RC}\int_{-\infty}^{t} v_I\, dt$$

$$v_O = -\frac{1}{C}\int_{-\infty}^{t}\frac{v_I}{R}dt$$

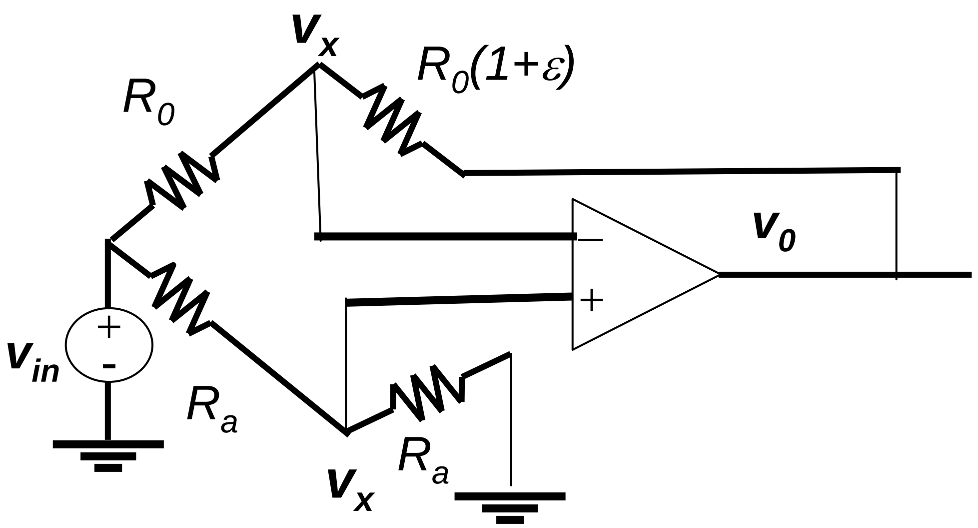
Differentiator

- Want





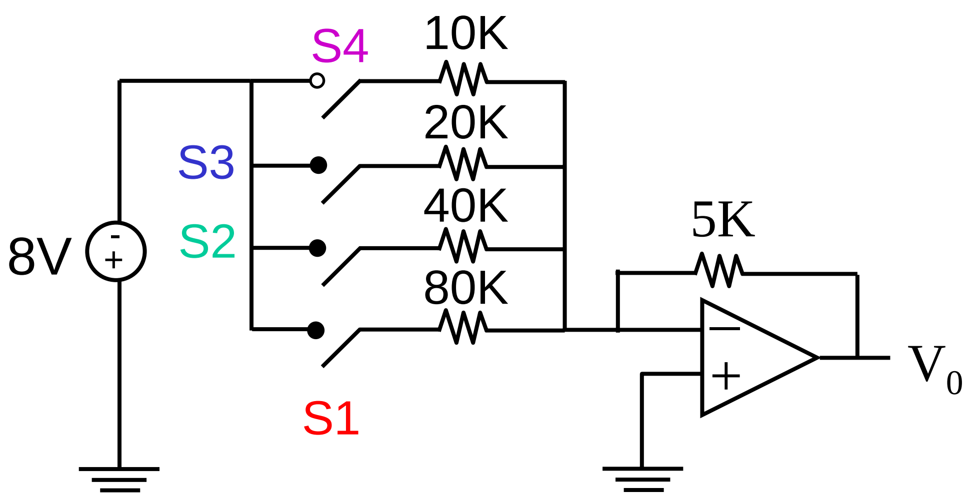
Bridge Amplifier



Application: Digital-to-Analog Conversion

A DAC can be used to convert the digital representation of an audio signal into an analog voltage that is then used to drive speakers -- so that you can hear it!

“Weighted-adder D/A converter”



4-Bit D/A

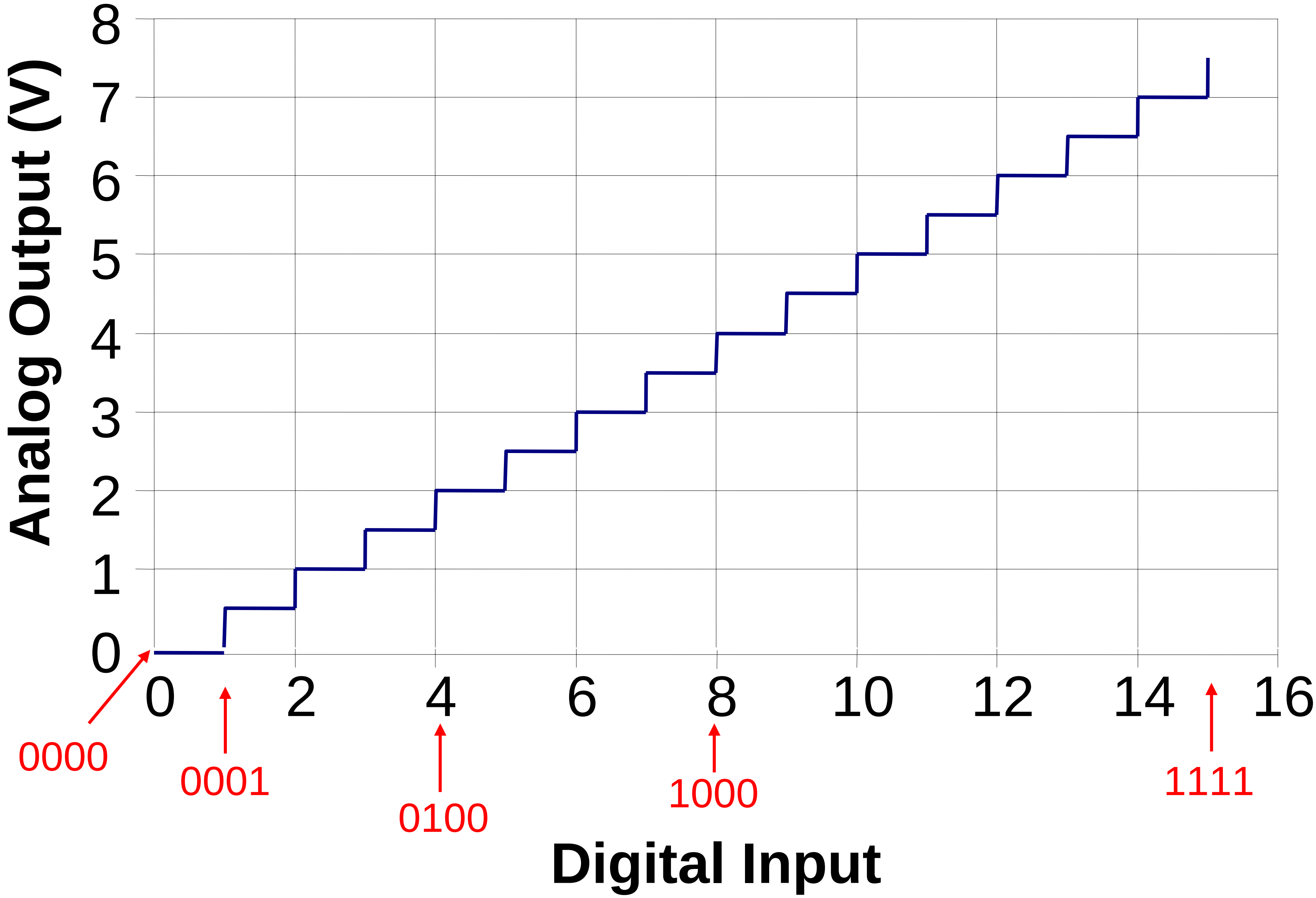
S1 closed if LSB =1
S2 " if next bit = 1
S3 " if " " = 1
S4 " if MSB = 1

(Transistors are used as electronic switches)

Binary number	Analog output (volts)
0 0 0 0	0
0 0 0 1	.5
0 0 1 0	1
0 0 1 1	1.5
0 1 0 0	2
0 1 0 1	2.5
0 1 1 0	3
0 1 1 1	3.5
1 0 0 0	4
1 0 0 1	4.5
1 0 1 0	5
1 0 1 1	5.5
1 1 0 0	6
1 1 0 1	6.5
1 1 1 0	7
1 1 1 1	7.5

↑ MSB ↑ LSB

Characteristic of 4-Bit DAC



Nonlinear Opamp Circuits

- Start reading through online notes: "Introduction to nonlinear circuit analysis".
- Outline:
  - Differences between positive and negative feedback.
  - Oscillator circuit.