Operational Amplifiers

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ME 475: Mechatronics

Operational Amplifier (Op-Amp)

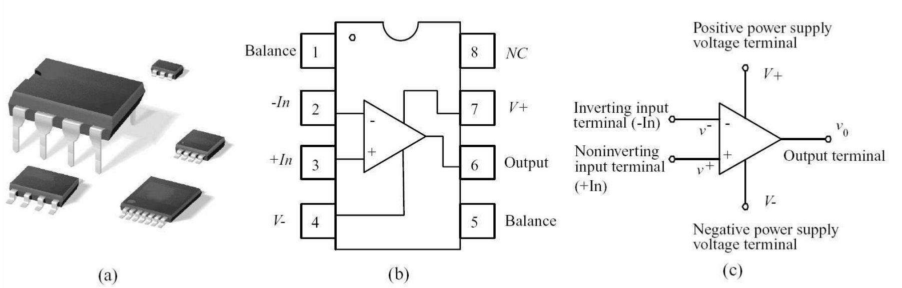
The OP-Amp is a low-cost and versatile IC (Integrated Circuit) consisting of many internal transistors, resistors, and capacitors. These are basic building blocks for:

- Amplifiers
- Integrators and Differentiators
- Summers
- Comparators
- A/D and D/A converters
- Active filters
- Sample and Hold circuits
- . . . etc.

OP-Amp: Components

The OP-Amp has **Single Output** and **Two Inputs**:

1. Noninverting input [+]: output is in phase with input.
2. Inverting input [-]: output is 180^o out of phase with input.



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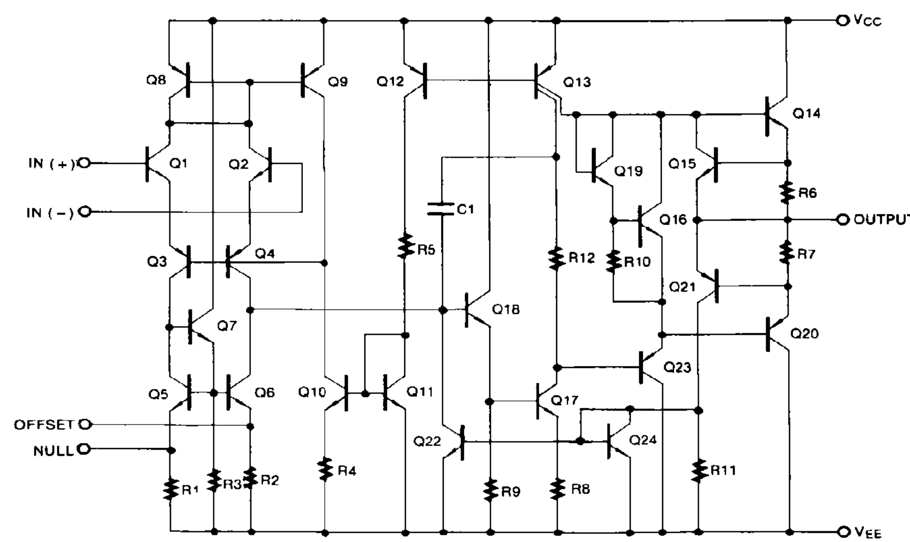
Internal Design of LM741



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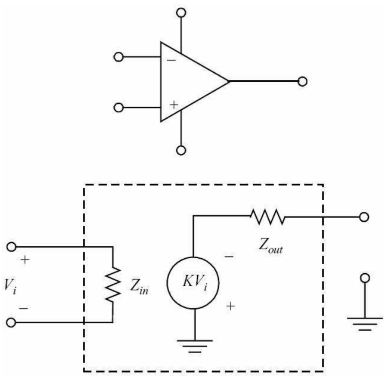
OP-Amp: Equivalent Circuit

Rule 1. Infinite input impedance, $Z_{in} = \infty \implies I_+ = I_- = 0$;
Rule 2. Infinite gain, $\implies E_+ = E_-$;
Rule 3. Zero output impedance, $Z_{out} = 0 \implies E_o \neq f(I_o)$.



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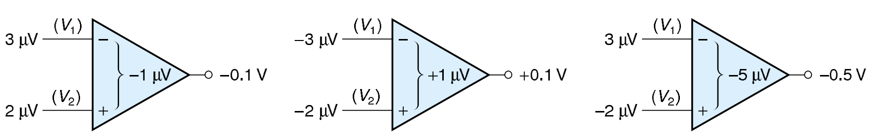
OP-Amp: Characteristics

Characteristics	Ideal Value	Typical real-world value
Open-loop gain	∞	$10^5 V/V$
Offset voltage	0	$\pm 1mV$
Bias currents	0	$10^{-6} - 10^{-14} A$
Input impedance	∞	$10^5 - 10^{11}\Omega$
Output impedance	0	$1 - 10\Omega$

- Ideal op-amps rejects inputs common to both inputs (common mode rejection).
- Actual Common Mode Rejection Ratio, $CMRR = \frac{E_o/E_i}{E_o/E_{cm}} \geq 10^6$ the larger the CMRR, the better the amplifier.

OP-Amp: Examples



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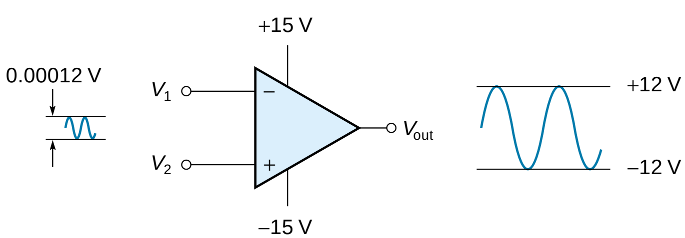

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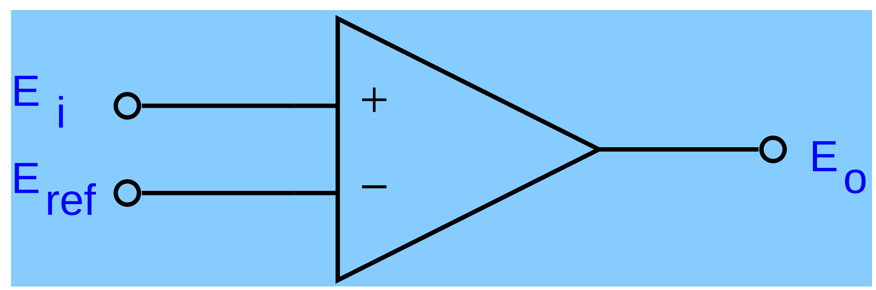
OP-Amp: Voltage Comparator



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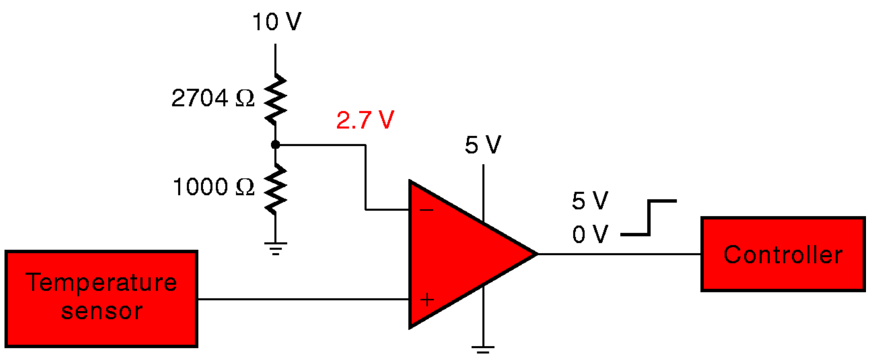
In comparator circuit, there is no negative feedback, hence the circuit exhibits infinite gain and the op-amps will saturate, i.e. the output remains at the most positive or most negative output value. Hence,

$$E_o = \begin{cases} +E_{sat} & E_i > E_{\text{ref}} \\ -E_{sat} & E_i < E_{\text{ref}} \end{cases}$$

Comparator Circuit: Application



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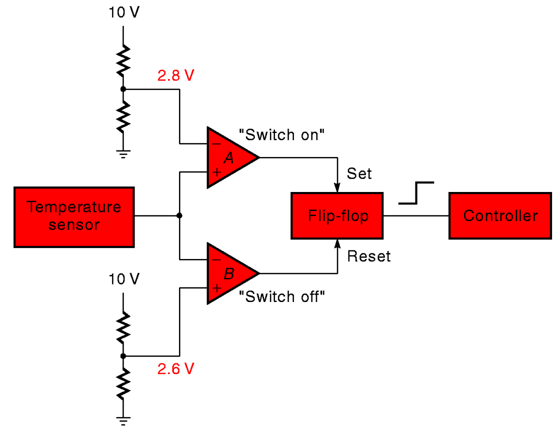
Chatter is a practical problem, output voltage oscillates back-and-forth when input voltage is near to the threshold.

Window Comparator Circuit



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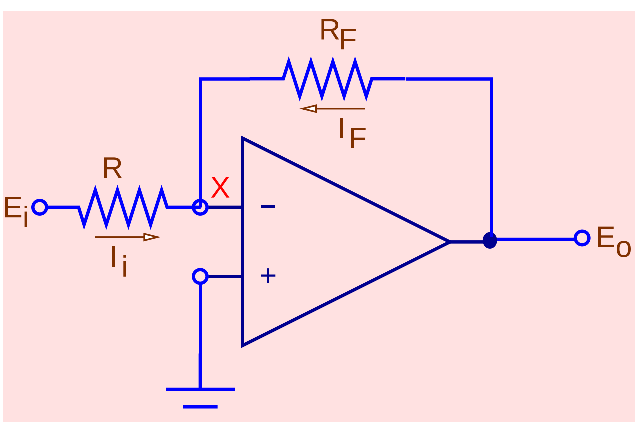
Window Comparator is with inbuilt hysteresis; hysteresis means that switch-on voltage is greater than switch-off voltage.

OP-Amp: Inverting Amplifier



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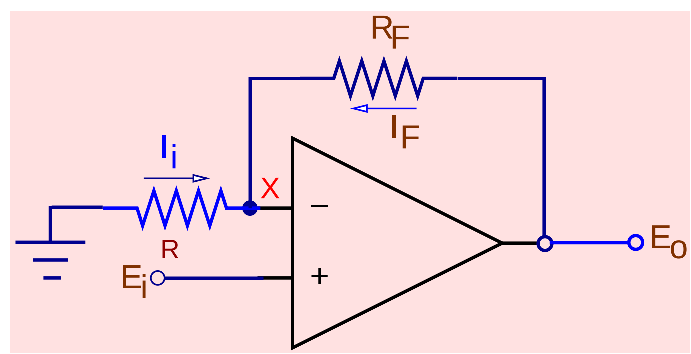
- At X, $I_i + I_F = 0$ (KCL & Rule 1), & $E_X = 0$ (Rule 2);
- $I_i \left(\equiv \frac{E_i - E_X}{R}\right) = -I_F \left(\equiv \frac{E_o - E_X}{R_F}\right) \implies \boxed{\text{gain, } G = \frac{E_o}{E_i} = -\frac{R_F}{R}}$

OP-Amp: Noninverting Amplifier



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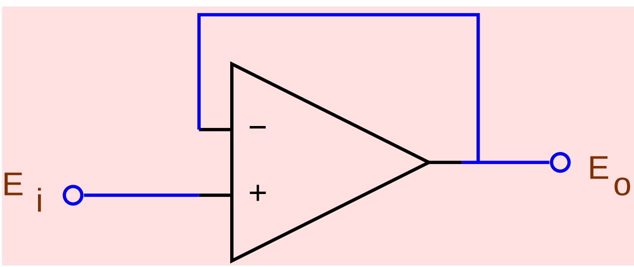
- At X, $I_i + I_F = 0$ (KCL & Rule 1), & $E_X = E_i$ (Rule 2);
- $I_i \left(\equiv \frac{-E_X}{R}\right) = -I_F \left(\equiv \frac{E_o - E_X}{R_F}\right) \implies \boxed{G = 1 + \frac{R_F}{R}}$

OP-Amp: Follower/Buffer

- In a noninverting amplifier with $R = \infty$ & $R_F = 0$, gain, G is unity and there is no voltage amplification. This circuit is known as a *buffer* or *follower*.
- It has a high input impedance and low output impedance. The high input impedance effectively isolates the source from the rest of the circuit.



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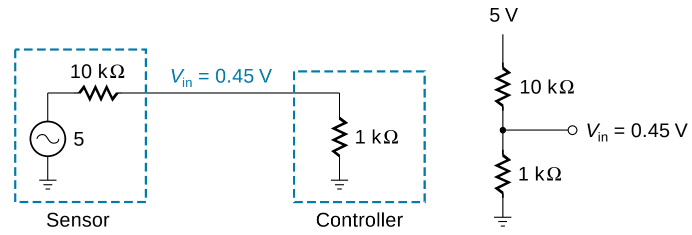
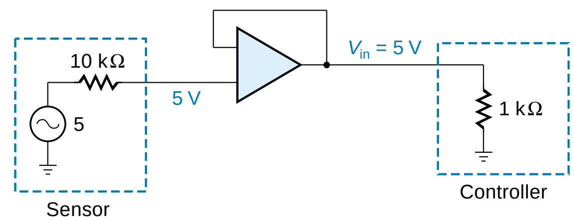
Op-Amp: Voltage Follower Application

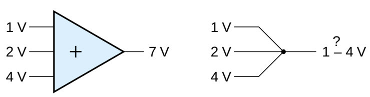


(a) Signal experiences voltage drop (b) Equivalent circuit



(c) No signal voltage drop

Op-Amp: Summing Amplifier



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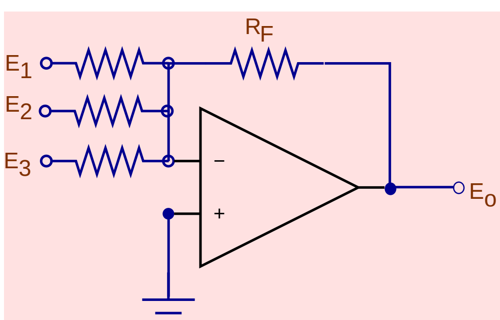

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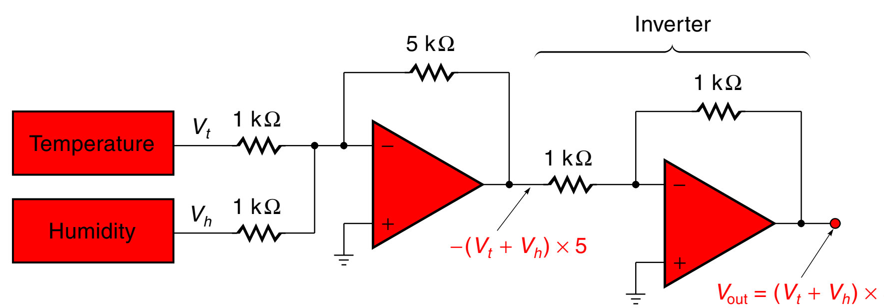
$$E_o = -R_F\left[\frac{E_1}{R_1} + \frac{E_2}{R_2} + \frac{E_3}{R_3}\right]$$

Summing Amplifier: Application

Example: Interface circuit for an air conditioning system

- when the sum of the voltages of temperature and humidity sensors goes above 1.0 V, &
- a threshold circuit in air conditioner require 5.0 V.



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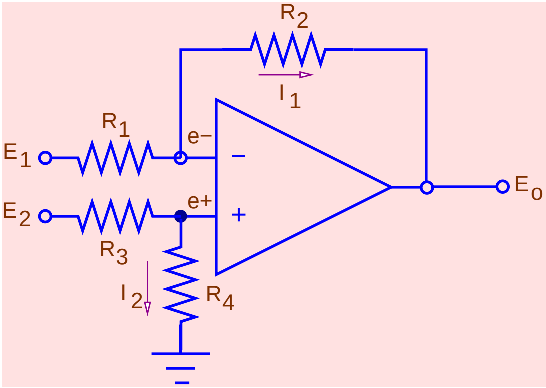
OP-Amp: Differential Amplifier



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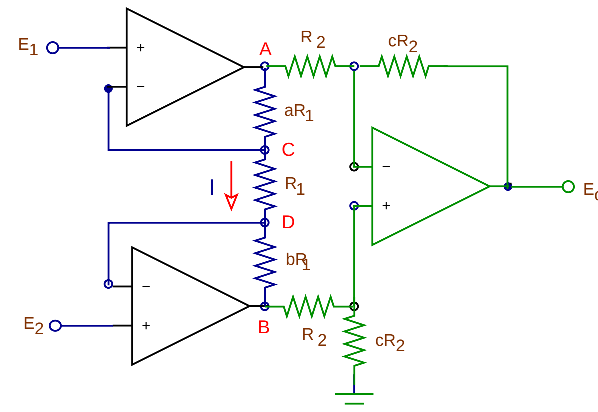
$$e^- = e^+ \implies E_1\left[\frac{R_2}{R_1+R_2}\right] + E_o\left[\frac{R_1}{R_1+R_2}\right] = E_2\left[\frac{R_4}{R_3+R_4}\right]$$
$$E_o = E_2\left[\frac{R_4}{R_3+R_4}\cdot\frac{R_1+R_2}{R_1}\right] - E_1\left[\frac{R_2}{R_1}\right]$$
$$E_o = (E_2 - E_1)\left[\frac{R_2}{R_1}\right] = c(E_2 - E_1) \text{ if } \frac{R_2}{R_1} = \frac{R_4}{R_3} = c$$

Instrument Amplifier



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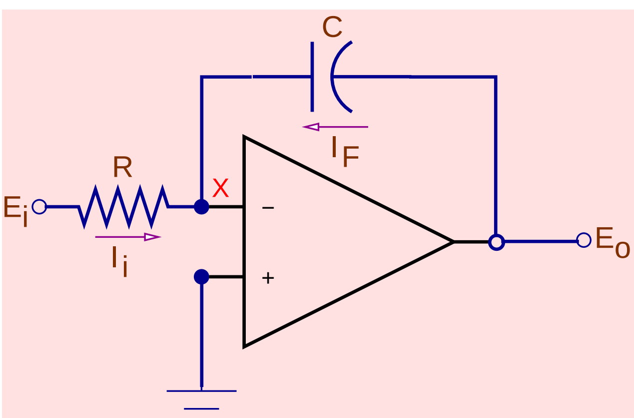
$$I = \frac{E_c - E_D}{R_1} = \frac{E_1 - E_2}{R_1} = \frac{E_A - E_B}{aR_1 + R_1 + bR_1}; \ \& \ E_o = c(E_A - E_B)$$
$$\boxed{G = \frac{E_o}{E_2 - E_1} = c(1 + a + b)}$$

OP-Amp: Integrator



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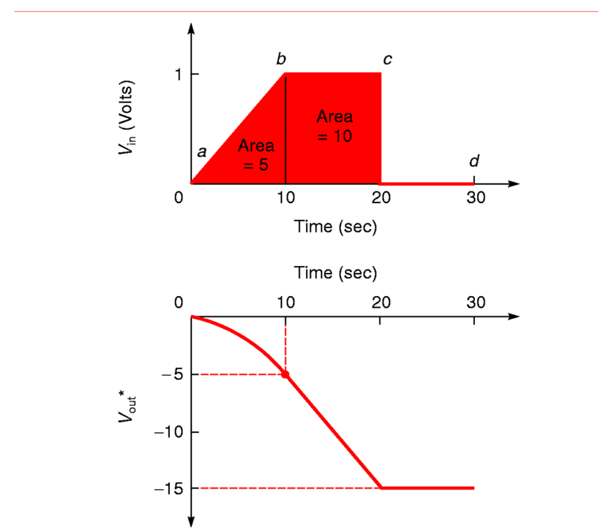
$$I_i = C\frac{E_i}{R}, \quad I_F = c\frac{dE_o}{dt} \ \& \ I_i + I_F = 0(KCL)$$
$$\boxed{E_o = -\frac{1}{RC}\int E_i(\tau)d\tau}$$

Output of an Integrator Circuit ($RC = 1$)



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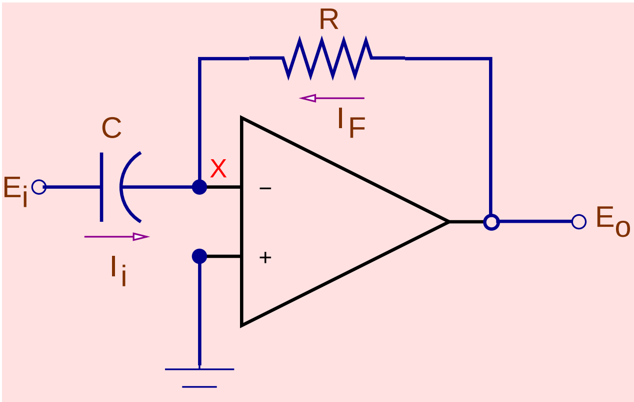
OP-Amp: Differentiator



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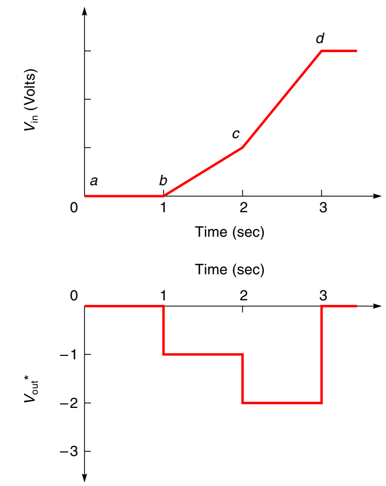
$$I_i = C\frac{dE_i}{dt}, \quad I_F = c\frac{E_o}{R} \;\&\; I_i + I_F = 0(KCL)$$

$$\boxed{E_o = -RC\ \frac{dE_i}{dt}}$$

Output of a Differentiator Ckt. ($RC = 1$)



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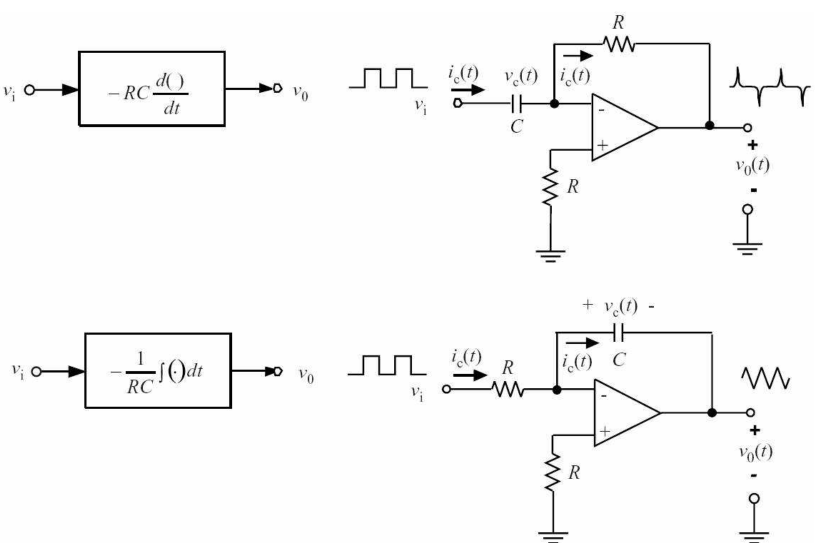
OP-Amp: Differentiator & Integrator



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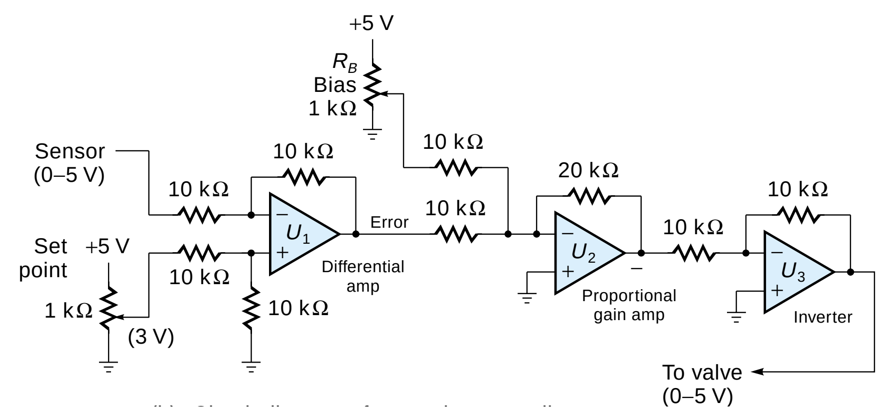
OP-Amp: Proportional Controller



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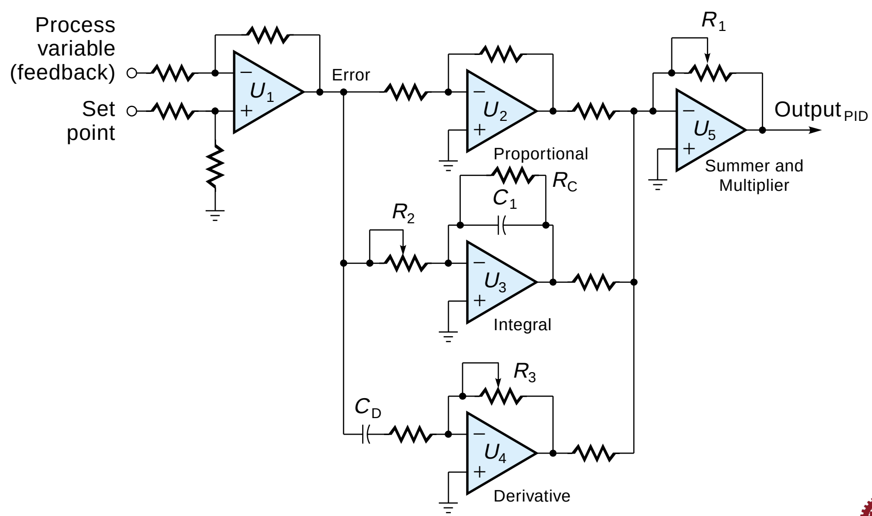
OP-Amp: PID Controller



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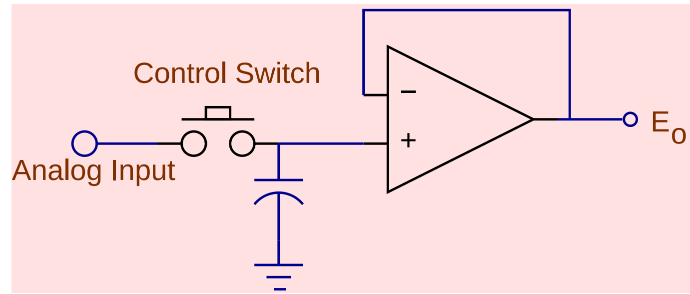
OP-Amp: Sample and Hold Circuit



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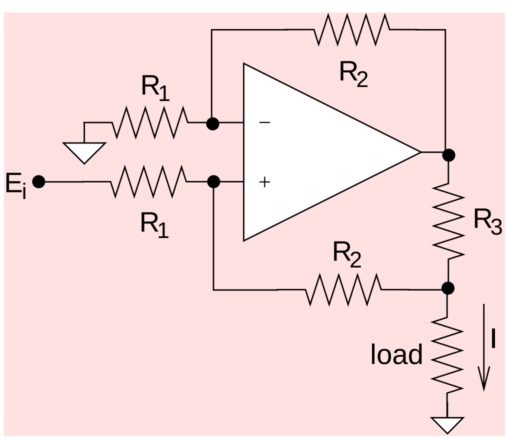
- S/H amplifier holds an analog value, until an A/D converter is ready to convert it to digital.
- The basis circuit consists of an electronic switch to the sample, with a capacitor for the hold and an op-amp voltage follower.

OP-Amps: Current Source



$I = E_i \left(\frac{R_2}{R_1 R_3}\right)$
if $R_2 >> \text{load}$.

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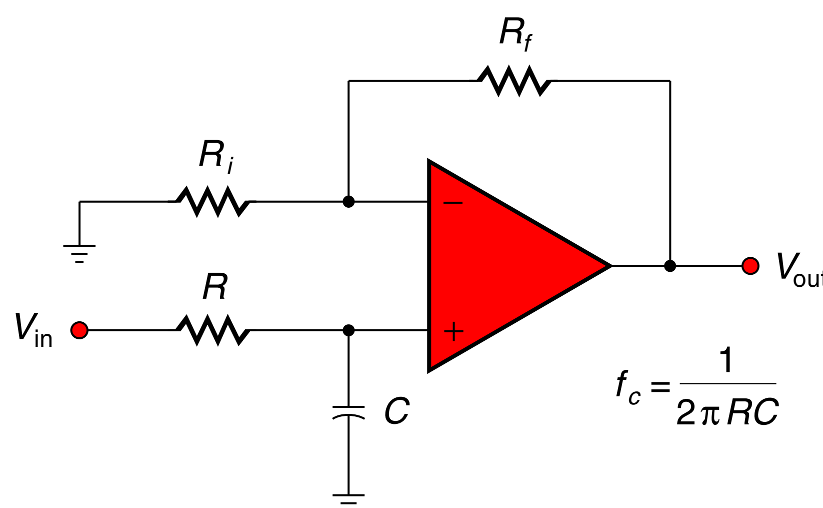
Low-Pass Filter Circuit



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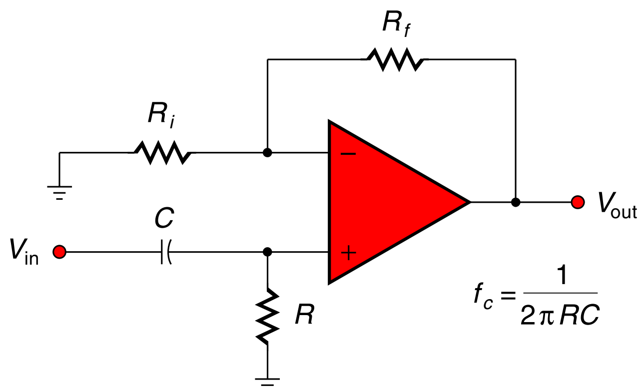
High-Pass Filter Circuit



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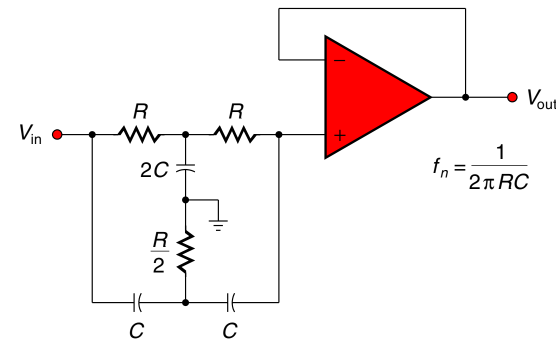
Band-Pass/Band-Reject Filter Circuits

- **Band-Pass Filter** - A band-pass filter can be built by cascading a low-pass filter and a high-pass filter together. The cut-off frequency of the low-pass filter must be higher than the cut-off frequency of the high-pass filter.
- **Band-Reject Filter** -



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