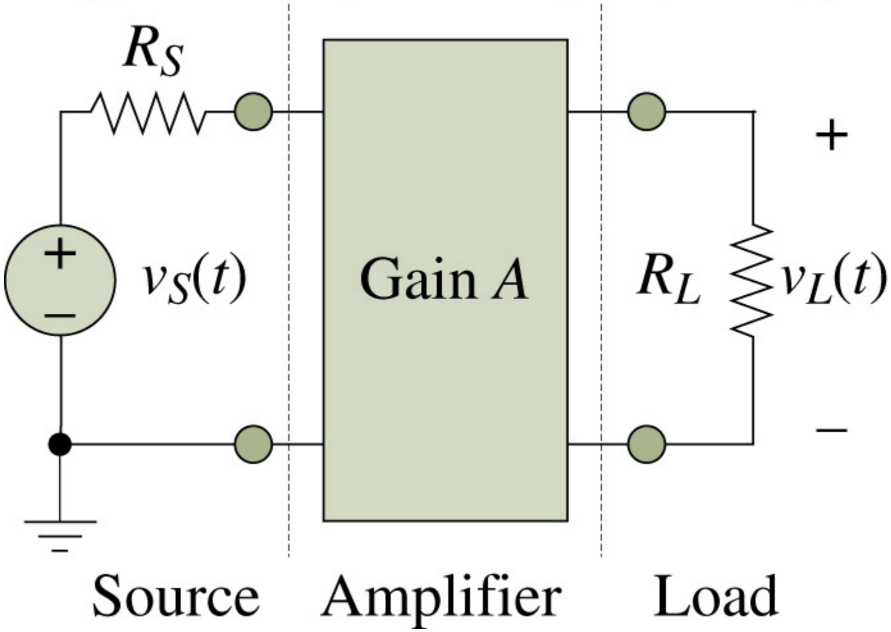
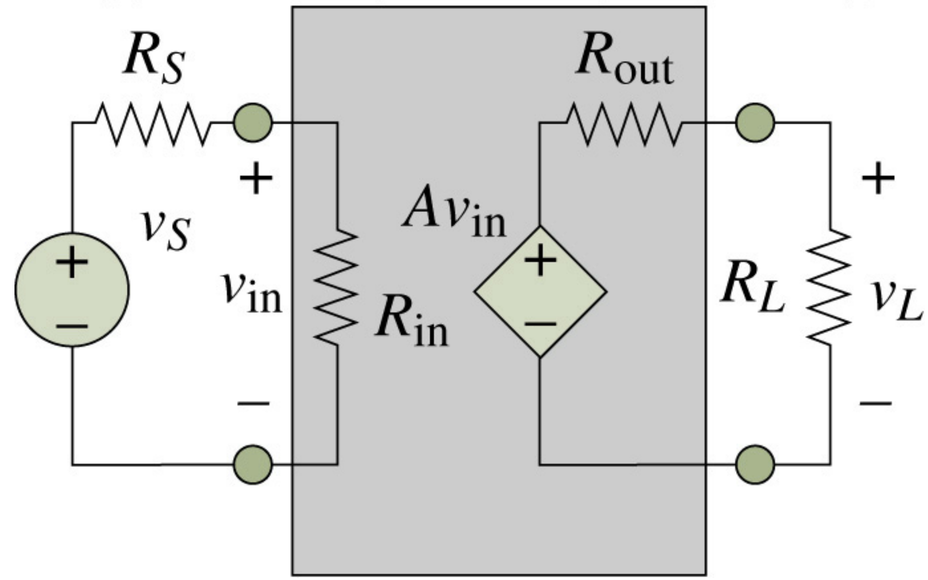
Operational Amplifier

- Operational amplifier is an amplifier whose output voltage is proportional to the negative of its input voltage and that boosts the amplitude of an input signal, many times, i.e., has a very high gain.High-gain amplifiers.
- They were developed to be used in synthesizing mathematical operations in early analog computers, hence their name.
- Typified by the series 741 (The integrated circuit contains 8-pin mini-DIP, 20 transistors and 11 resistors).
- Used for amplifications, as switches, as filters, as rectifiers, and in digital circuits.
- Take advantage of large open-loop gain.
- It is usually connected so that part of the output is fed back to the input.
- Can be used with positive feedback to produce oscillation.

A Voltage Amplifier



Simple Voltage Amplifier Model



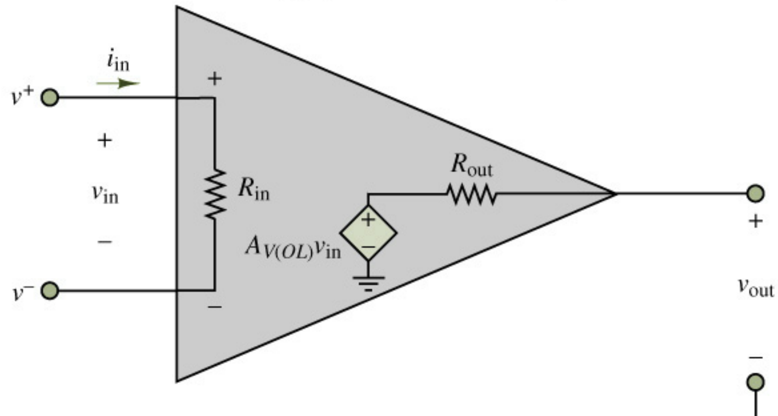
$$v_{in} = \frac{R_{in}}{R_S + R_{in}} v_S ; v_L = A v_{in} \frac{R_L}{R_{out} + R_L}$$

$$v_L = \left(A \frac{R_{in}}{R_S + R_{in}} \frac{R_L}{R_{out} + R_L} \right) v_S ; v_{in} \approx v_S ; v_L = A v_{in}$$

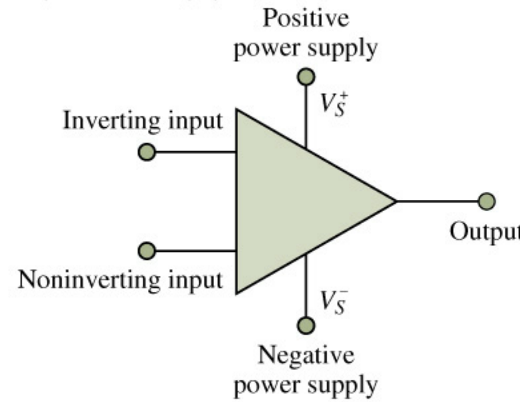
The Operational Amplifier

- The integrated circuit operational amplifier evolved soon after development of the first bipolar integrated circuit.
- The μA-709 was introduced by Fairchild Semiconductor in 1965.
- Since then, a vast array of op-amps with improved characteristics, using both bipolar and MOS technologies, have been designed.
- Most op amps are inexpensive (less than a dollar) and available from a wide range of suppliers.
- There are usually 20 to 30 transistors that make up an op-amp circuit.
- From a signal point of view, the op-amp has two input terminals and one output terminal as shown in the following figures.
- The ideal op-amp senses the difference between two input signals and amplifies the difference to produce an output signal.
- Ideally, the input impedance is infinite, which means that the input current is zero. The output impedance is zero.

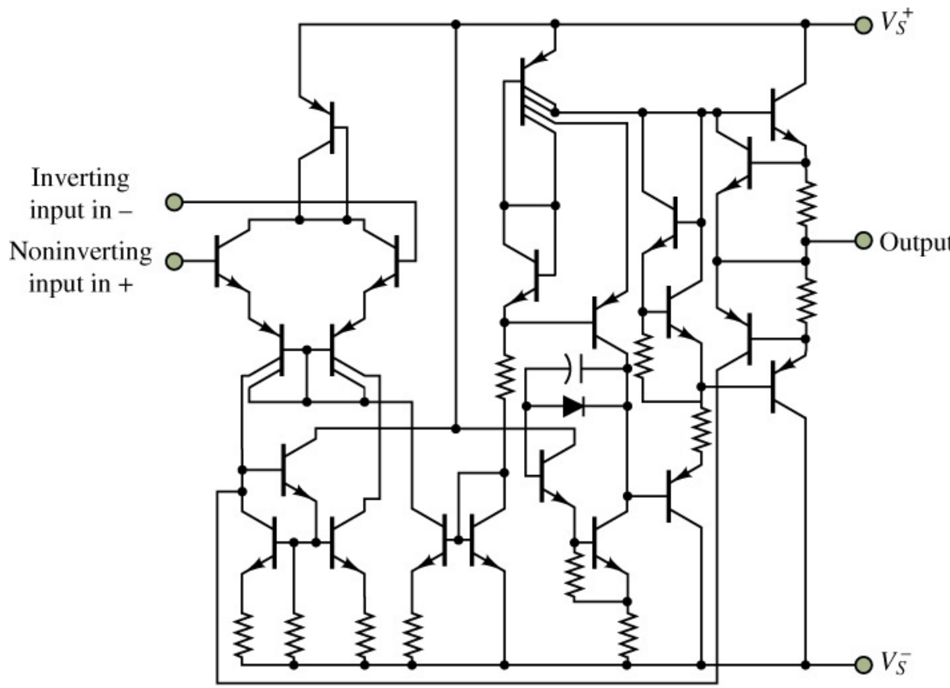
Operational Amplifier Model Symbols and Circuit Diagram



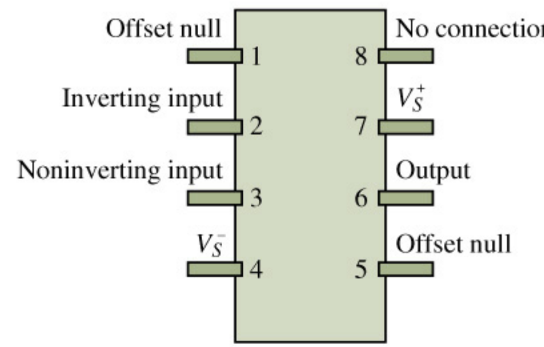
Op-amp model



Simplified circuit symbol



IC op-amp diagram



Integrated-circuit operational amplifier (IC op-amp)

The Ideal and Real Op-Amp

Ideal Amplifier:

- Two Inputs:
  - Inverting.
  - Non-inverting.
- $V_o = A (V_+ - V_-)$
- Gain A is large (∞).
- $V_o = 0$, when $V_+ = V_-$
- Infinite input resistance, which produces no currents at the inputs.
- The output resistance is zero, so it does not affect the output of the amplifier by loading.
- The gain A is independent of the frequency.

Real Amplifier:

- Gain (10^5 - 10^9).
- Input resistance
  - 10^6 for BJTs
  - 10^9 - 10^{12}
- Output resistance: 100-1000 Ω.

Inverting Amplifier

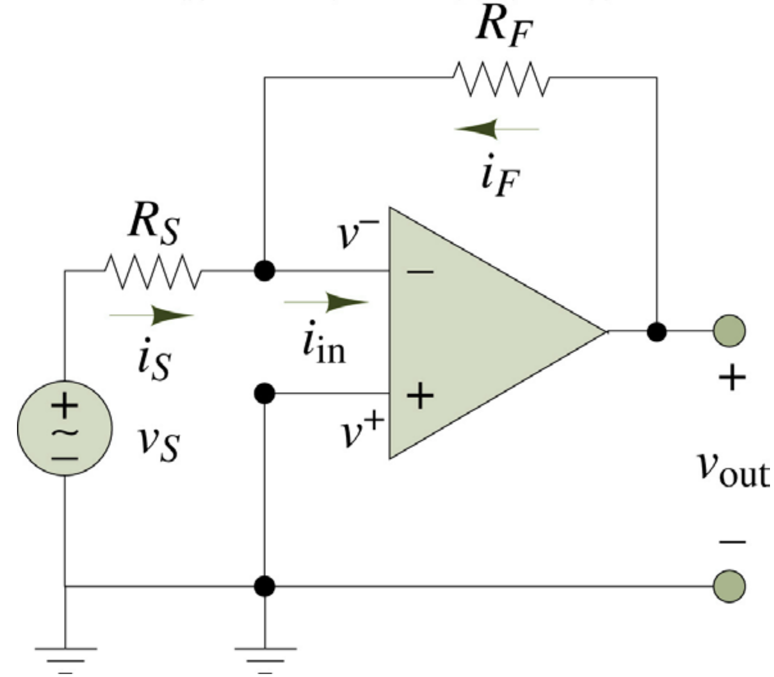
$$i_S + i_F = i_{in}$$

$$i_S = \frac{v_S - v^-}{R_S}; i_F = \frac{v_{out} - v^-}{R_F}; i_{in} = 0$$

$$i_S = -i_F; i_{in} = 0; v^- = v^+$$

$$\frac{v_S}{R_S} + \frac{v_{out}}{A_v R_S} = -\frac{v_{out}}{R_F} - \frac{v_{out}}{A_v R_F}$$

$$v_{out} = -\frac{R_F}{R_S} v_S$$



Design Example: Design an inverting amplifier with a closed loop voltage of A_v = -5. Assume the op-amp is driven by a sinusoidal soorce, $v_s = 0.1 \sin \omega t$ volts, which has a source resistance of $R_{sr} = 1$ kΩ and which supply a maximum current of 5 μA. Assume that the frequency is low.

$$i_s = \frac{v_s}{R_s} (R_s \text{ in this example means two resistances} : R_s = R_1 + R_{sr}.$$

R_{sr} represents the source resistance. Therefore $i_s = \dfrac{v_s}{R_{sr} + R1}$

If $i_s(\max) = 5\mu$A, then we write $R_1(\min) + R_{sr} = \dfrac{v_s(\max)}{i_s(\max)} = \dfrac{0.1}{5\times10^{-6}} = 20\ \text{k}\Omega$

R_1 should be $19\ \text{k}\Omega$ and $A_v = \dfrac{-R_2}{R_{sr} + R_1} = -5.$

Accordingly $R_2 = 5(R_{sr} + R_1) = 5 \times 20 = 100\ \text{k}\Omega$

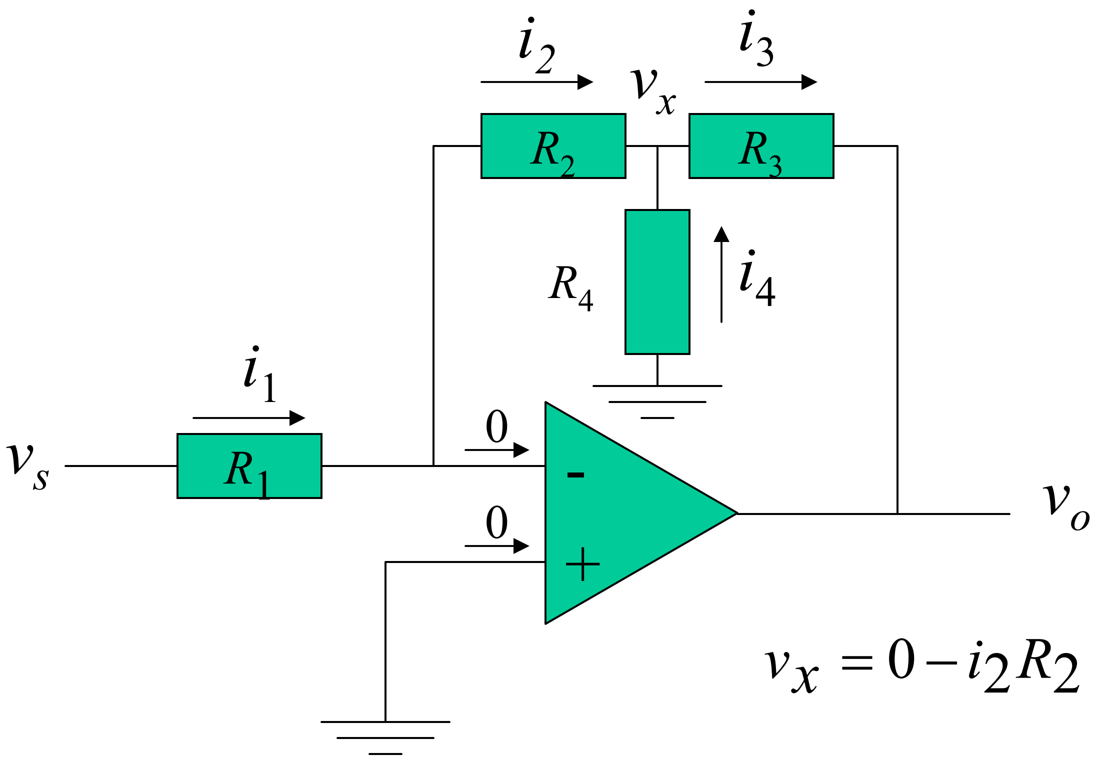
To Solve Ideal Op-Amp Circuit

- If the noninverting terminal of the op-amp is at ground potential, then the inverting terminal is at virtual ground. Sum currents at this point, assuming zero current enters the op-amp itself.

- If the noninverting terminal of the op-amp is not at ground potential, then the inverting terminal voltage is equal to that at the noninverting terminal. Sum currents at the inverting terminal node, assuming zero current enters the op-amp itself.

- For an ideal op-amp circuit, the output voltage is determined from either step 1 or step 2 above and is independent of any load connected to the output terminal.

Amplifier with a T-Network



$$v_x = 0 - i_2 R_2 = -v_s \left(\frac{R_2}{R_1}\right)$$

$$i_2 + i_4 = i_3; -\frac{v_x}{R_2} - \frac{v_x}{R_4} = \frac{v_x - v_o}{R_3}$$

Combing the above equations we get

$$A_v = \frac{v_o}{v_s} = -\frac{R_2}{R_1}\left(1 + \frac{R_3}{R_4} + \frac{R_3}{R_2}\right)$$

Design Example: An op-amp with a T-network is to be used as a preamplifier for a microphone. The maximum microphone output voltage is 12 mV (rms) and the microphone has an output resistance of 1 kΩ. The op-amp circuit is to be designed such that the maximum output voltage is 1.2 V (rms). The input amplifier resistance should be fairly large but all resistance values should be less than 500 kΩ.

$$|A_v| = \frac{1.2}{0.012} = 100$$

$$A_v = -\frac{R_2}{R_1}\left(1+\frac{R_3}{R_4}\right)-\frac{R_3}{R_1}$$

If we choose $\frac{R_2}{R_1} = \frac{R_3}{R_1} = 8$

$$-100 = -8\left(1+\frac{R_3}{R_4}\right)-8; \frac{R_3}{R_4} = 10.5$$

We should include the value of the source resistance in the calculation

If we set $R_1 = 49$ kΩ and $R_{sr} = 1$ kΩ then the total resistance ($R_{1\,effective}$) will be 50 kΩ

$R_2 = R_3 = 400$ kΩ and $R_4 = 38.1$ kΩ

A Practical Application: Why Feedback

- Self-balancing mechanism, which allows the amplifier to preserve zero potential difference between its input terminals.
- A practical example that illustrates a common application of negative feedback is the thermostat. This simple temperature control system operates by comparing the desired ambient temperature and the temperature measured by the thermometer and turning a heat source on and off to maintain the difference between actual and desired temperature as close to zero as possible.

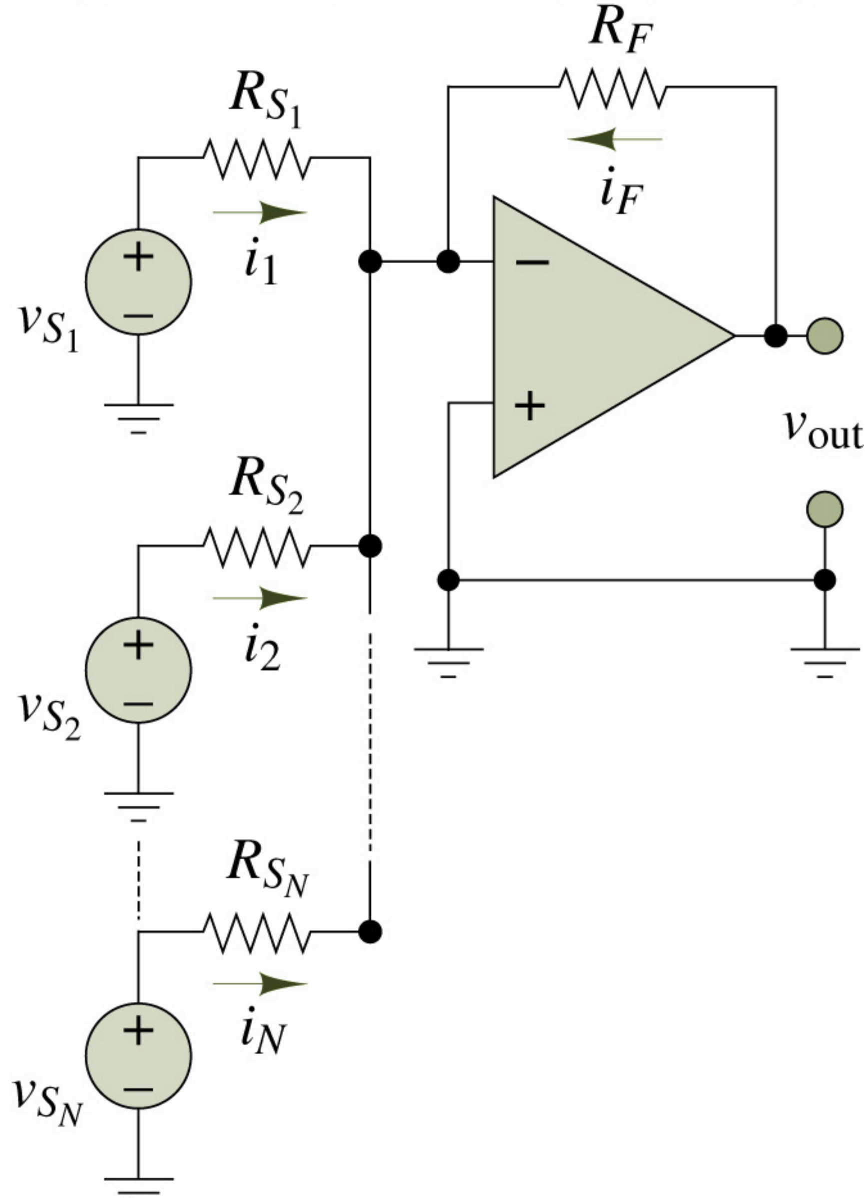
Summing Amplifier

$$i_1 + i_2 + \ldots + i_N = -i_F$$

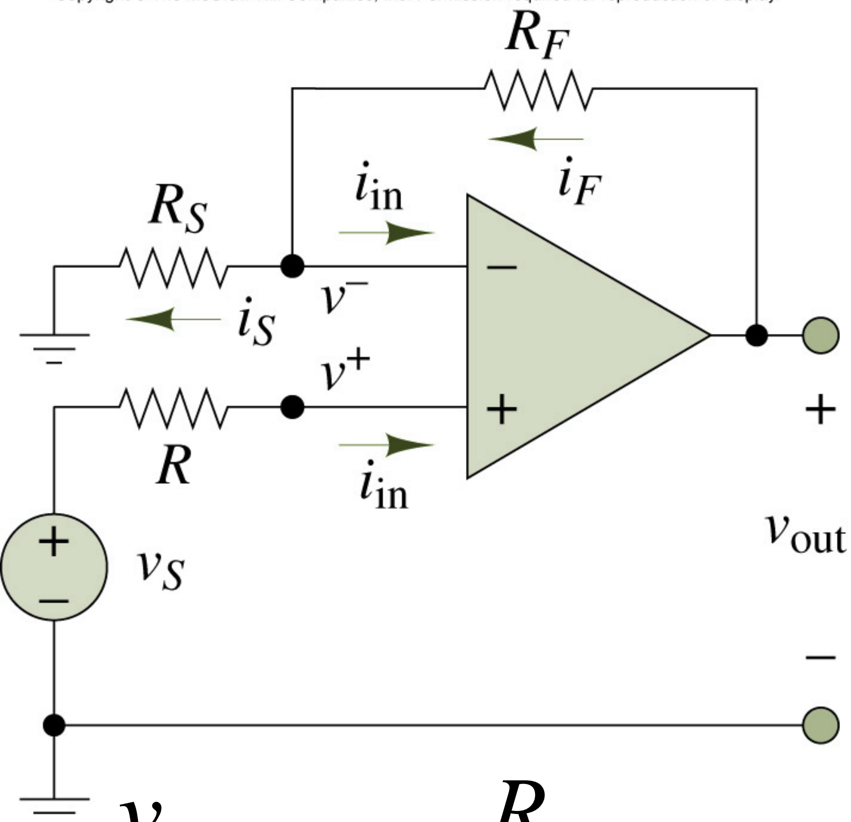
$$i_n = \frac{v_{S_n}}{R_{S_n}} \ldots\ldots n = 1,2,\ldots N$$

$$i_F = \frac{v_{out}}{R_F}$$

$$v_{out} = -\sum_{n=1}^{N} \frac{R_F}{R_{S_n}} v_{S_n}$$

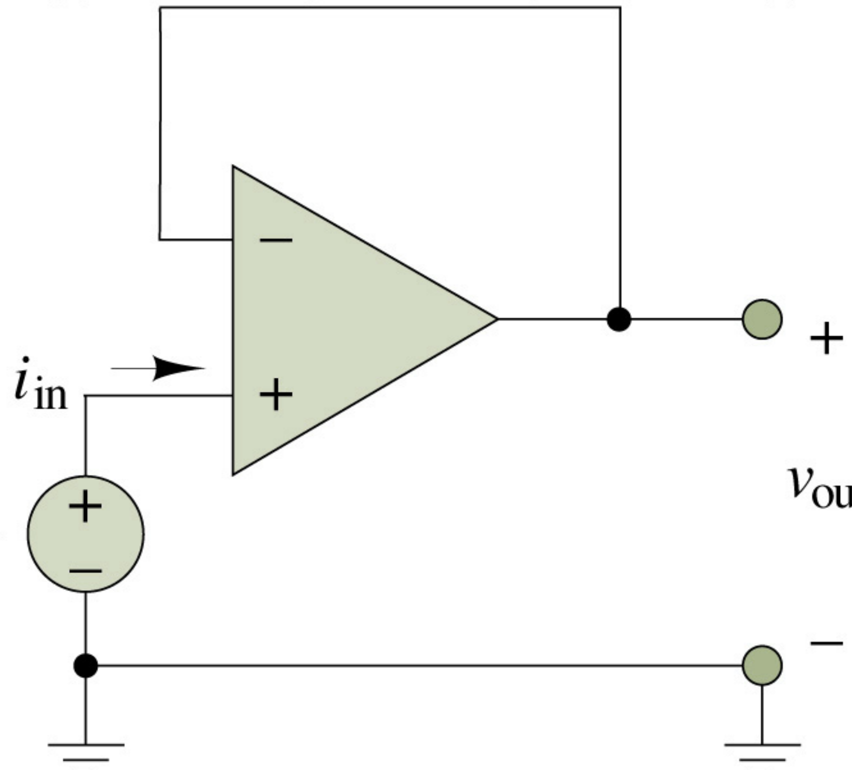


Noninverting Amplifier



$$\frac{v_{out}}{v_S} = 1 + \frac{R_F}{R_S}$$

Voltage Follower



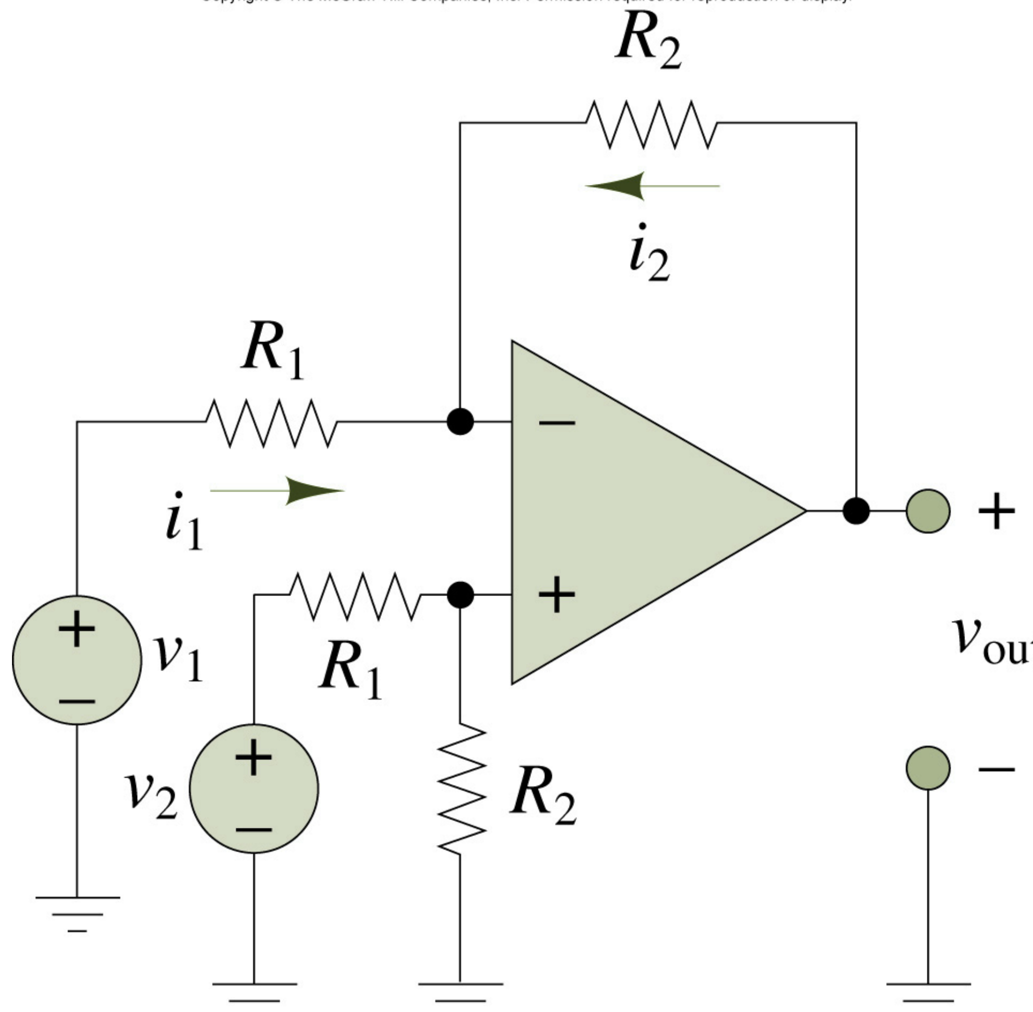
$$v_S = v_{out}$$

Design Example: Design a noninverting amplifier with a closed loop gain of $A_v = 5$. The output voltage is limited to $-10 \text{ V} \leq v_o \leq +10 \text{ V}$ and the maximum current in any resistor is limited to 50 μA

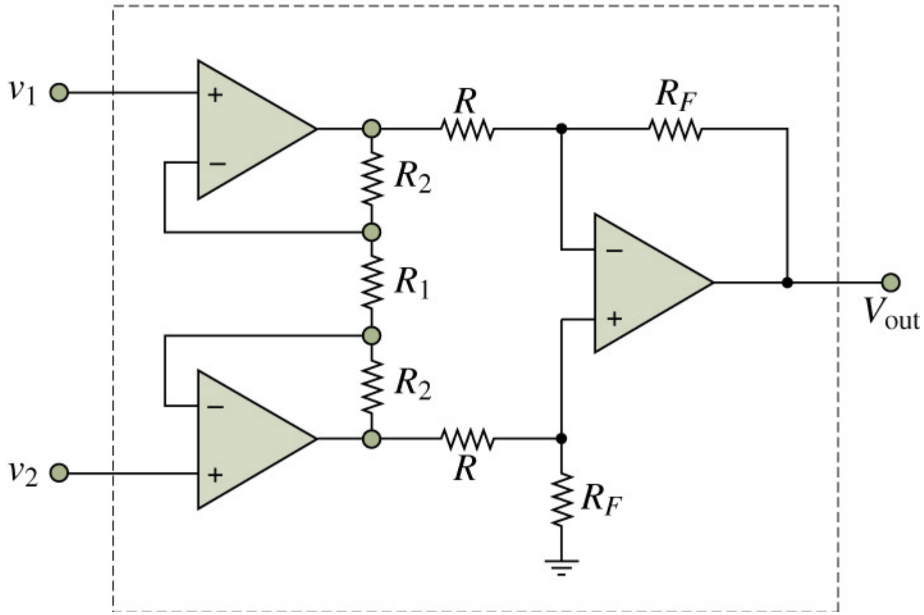
Answer: $R_1 = 40 \text{ k}\Omega$, $R_2 = 160 \text{ k}\Omega$

Differential Amplifier

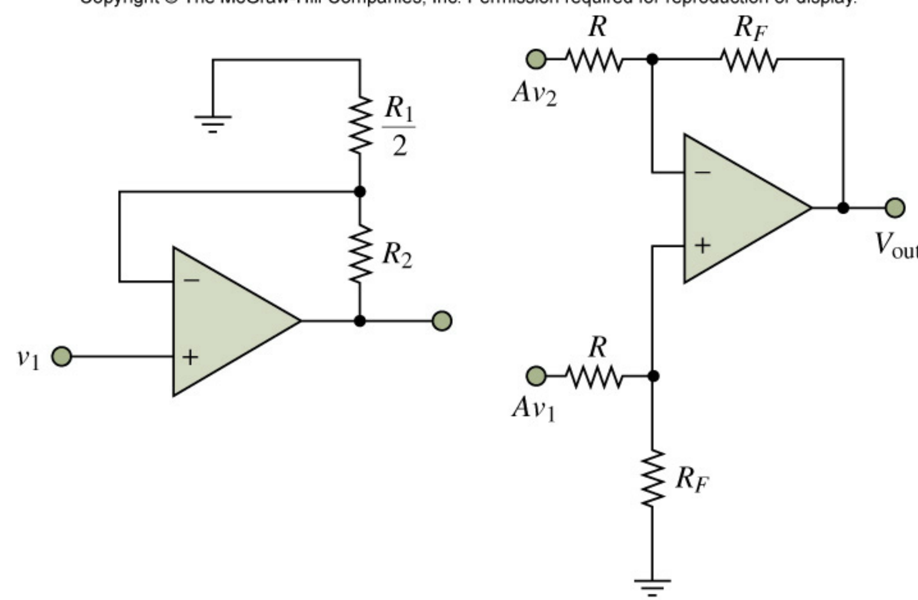
$$v_{out} = \frac{R_2}{R_1}\left(v_2 - v_1\right)$$



Instrumentation Amplifier



Input (a) and output (b) stages of Instrumentation amplifier



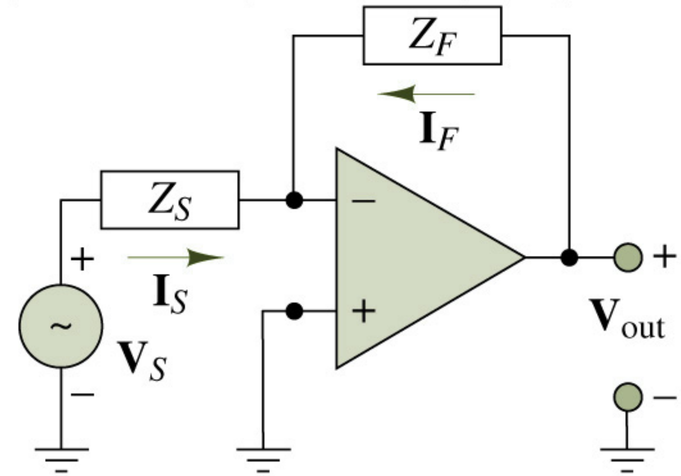
(a) (b)

$$A_V = \frac{v_{out}}{v_1 - v_2} = \frac{R_F}{R}\left(1 + \frac{2R_2}{R_1}\right)$$

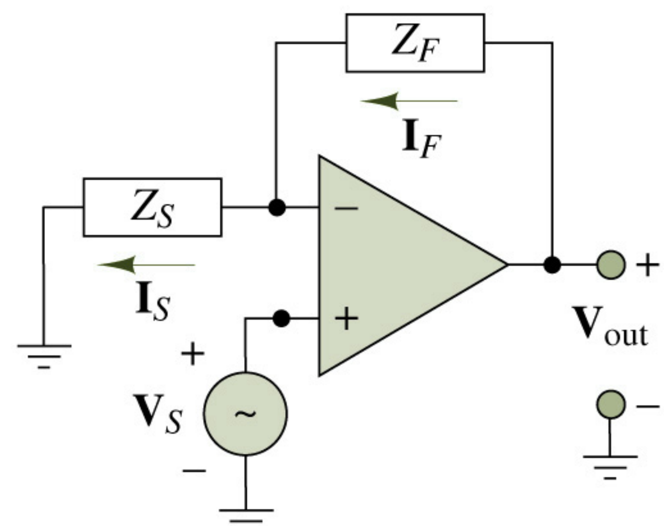
Op-amp Circuits Employing Complex Impedances

$$\frac{V_{out}}{V_S}(j\omega) = -\frac{Z_F}{Z_S}$$

$$\frac{V_{out}}{V_S}(j\omega) = 1 + \frac{Z_F}{Z_S}$$

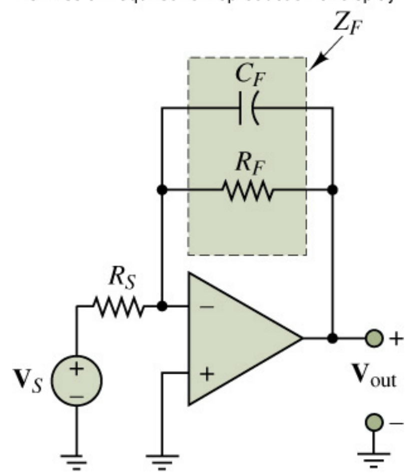


Inverting

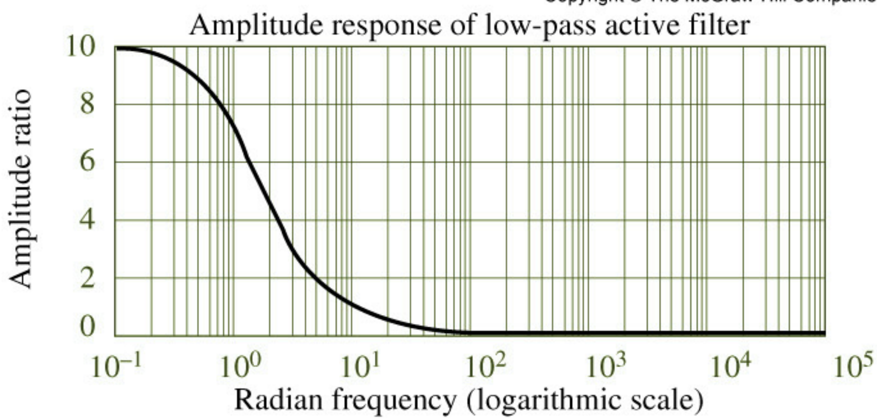


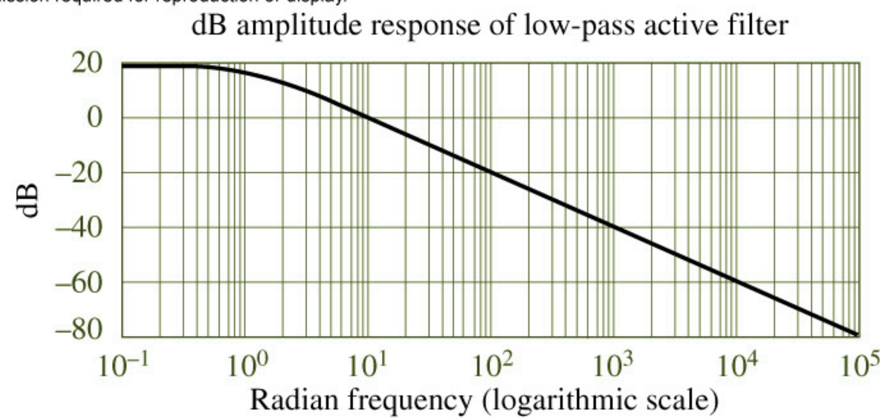
Noninverting

Active Low-Pass Filter

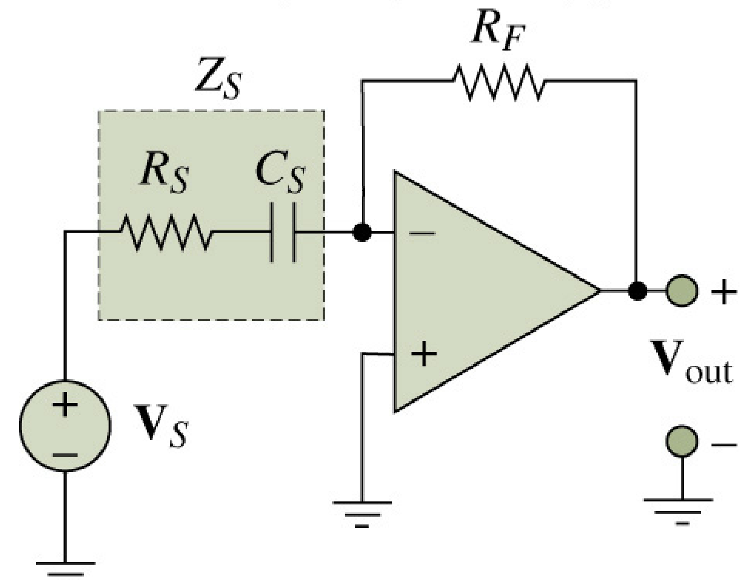


Normalized Response of Active Low-pass Filter

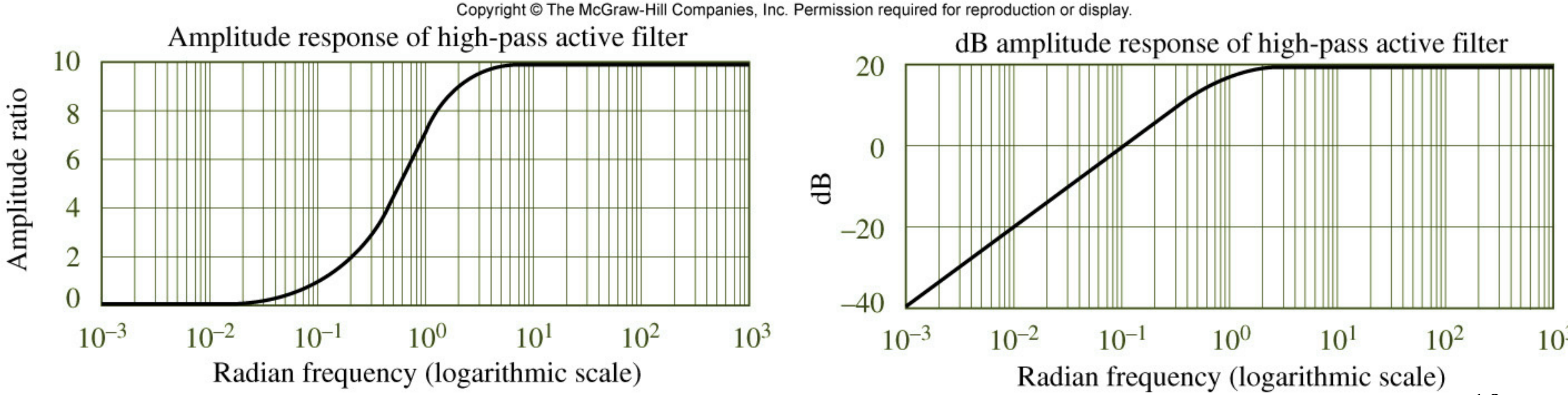




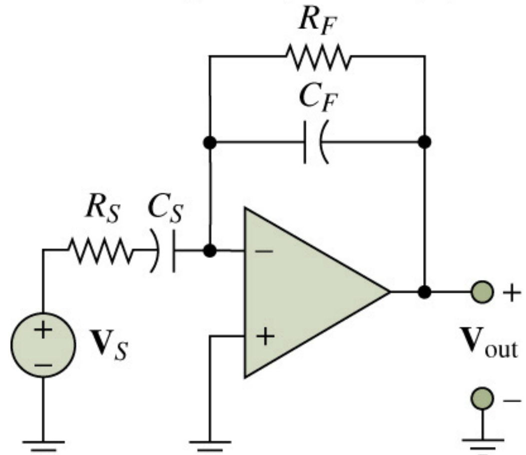
Active High-Pass Filter



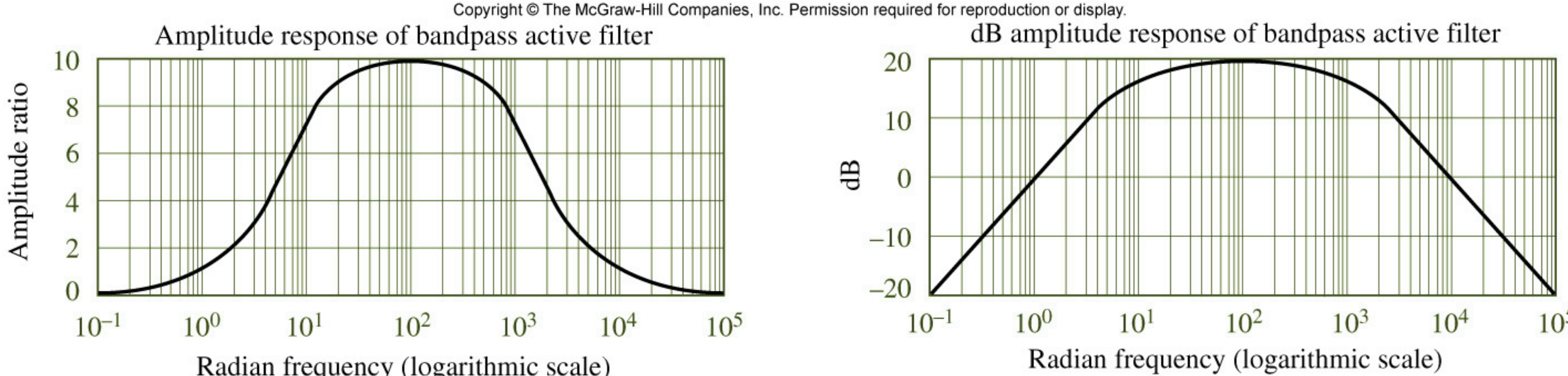
Normalized Response of Active High-pass Filter



Active Band-Pass Filter

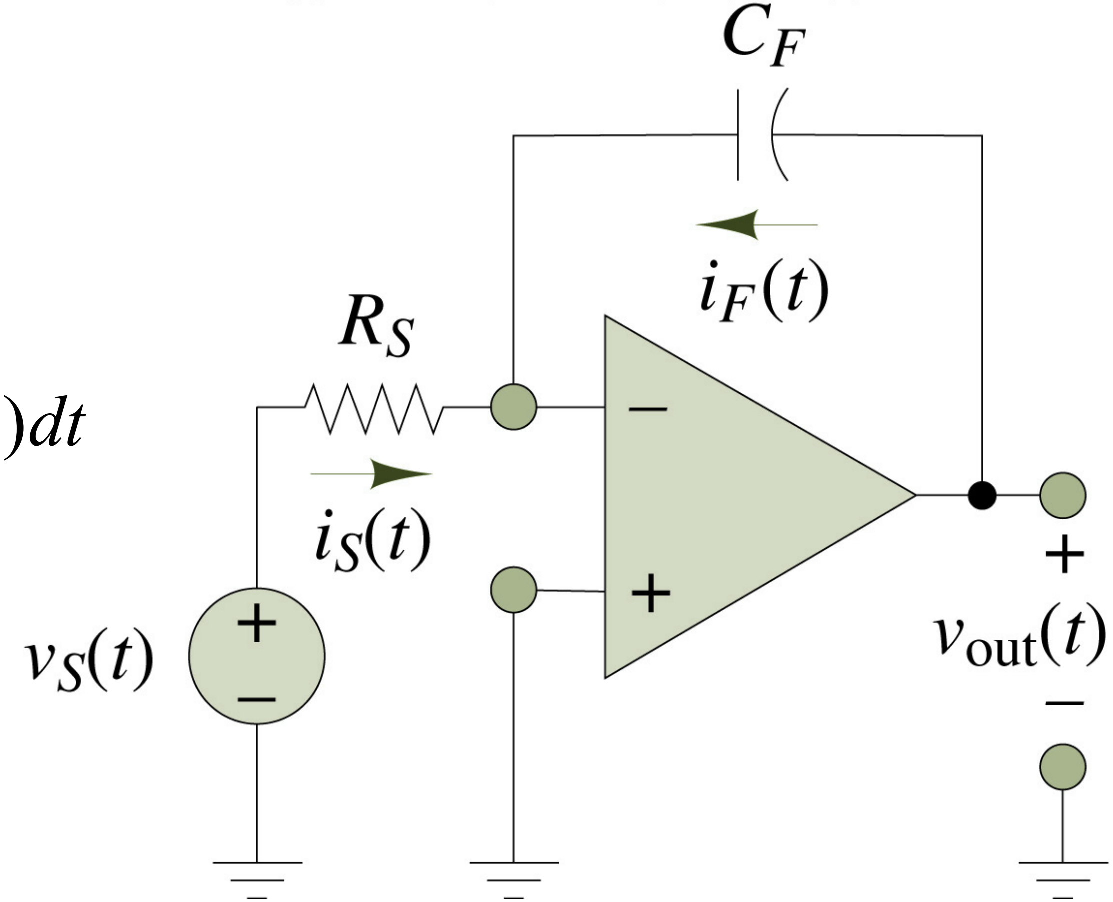


Normalized Amplitude Response of Active Band-pass Filter



Op-amp Integrator

$$v_{out}(t) = -\frac{1}{R_S C_F} \int_{-\infty}^{t} v_S(t)\,dt$$



Op-amp Differentiator

$$v_{out}(t) = -R_F C_S \frac{dv_S(t)}{dt}$$