Op-Amps

- An **operational amplifier (op-amp)** is a high-gain linear amplifier.
- Op-amps are usually packaged in IC form (one to four op-amps per IC) and are relatively cheap.
- Characteristics
  1. Very high open-loop gain: A = 100,000+, but unpredictable
  2. Very high input resistance: R_{in} > 1 MΩ
  3. Low output resistance: R_{out} = 50-75 ohm

- It has two inputs (V_1 and V_2) and one output (V_{out}).
- two power-supply inputs, which are typically +12 V and –12 V.

$$V_{out} = A(V_2 - V_1)$$

- The **open-loop gain** (A) is the raw unmodified gain of the op-amp;
  - it is high, typically 100,000 or more.

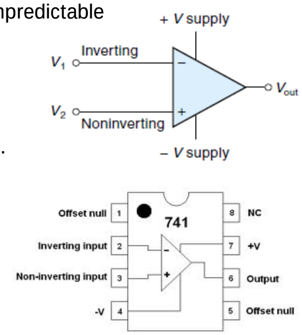


Figure 7.1 The op-amp.

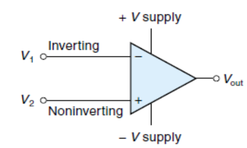
Op-Amps

noninverting input

- *The output is in phase with the noninverting input*
  - when the noninverting input goes positive, V_{out} goes positive;
  - when the noninverting input goes negative, V_{out} goes negative.
- The noninverting input is identified by the + sign in the symbol of Op-amp.

inverting input

- *The output will be out of phase with the signal at the inverting input*
  - when the inverting input goes more positive, the output will go more negative, and vice versa.
- The inverting input is identified by the – sign in the symbol.



Op-Amps

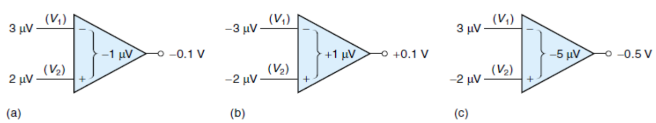


Figure 7.2 Various input voltage combinations (A = 100,000).

- In Figure 7.2(a), both inputs are positive, yet the output is negative. Why?
  - The – input has the larger magnitude, so the quantity ($V_2 – V_1$) is negative (2 μV – 3 μV = –1 μV).
  - From the op-amp equation, $V_{out} = A(V_2 – V_1)$, we see that if ($V_2 – V_1$) is negative, V_{out} will be negative.
- In Figure 7.2(b). The inputs are both negative, yet the output is positive.
  - In this case, [–2 μV – (–3 μV)] = +1 μV, which is positive.
- In Figure 7.2(c), (V2 – V1) = (–2 μV – 3 μV) = –5 μV, which is clearly negative.

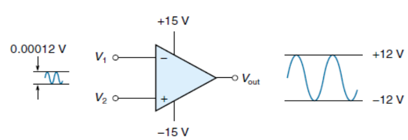


Figure 7.3 Op-Amp (A = 100,000).

Op-Amps: Voltage follower/buffer

- very useful circuit, can boost the current of a signal without increasing the voltage.
- It can transform a high-impedance signal (easily loaded down) into a robust low-impedance signal.
- It has a voltage gain of 1, with a high R_{in} and a low R_{out}.
- the basic op-amp equation:

$$V_{out} = A(V_2 - V_1)$$

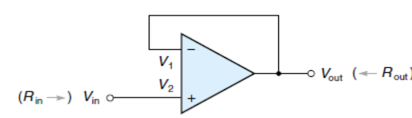


Figure 7.4 A voltage follower circuit.

In the circuit, V_{out} is connected to V_1

thus, $V_{out} = V_1$.

Substituting in V_{out} and expanding,

$$V_{out} = (AV_2) - (AV_{out})$$

Solving for V_{out}, we get $V_{out} = \frac{AV_2}{1+A} \approx V_2$

Voltage follower/buffer: example

- The voltage follower is a simple and very useful circuit.
- Consider the situation shown in Figure 7.5(a). In this case, a high-impedance sensor (10 kΩ), is connected directly to a controller with a 1 kΩ input resistance. The sensor generates 5 V internally, but this is reduced by the voltage drop across the 10 kΩ internal resistance. $V_{in} = \frac{1\ k\Omega \times 5\ V}{1\ k\Omega + 10\ k\Omega} = 0.45\ V$
- This shows that only 0.45 V of the 5 V signal makes it to the controller.
- We could amplify the signal at the controller to make up for the attenuation, but that would amplify noise as well as the signal.

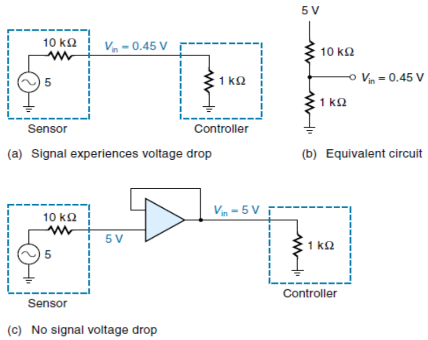


Figure 7.5 Using a voltage follower to prevent load down.

- A better solution is to insert a voltage follower near the sensor, as shown in Figure 7.5(c). Because the op-amp draws no signal current, there is no voltage drop across the 10 kΩ resistor, and the full 5 V enters the voltage follower and appears at its output. The 1 kΩ input resistance of the controller is so much higher than the output resistance of the op-amp that almost all of the 5 V will appear across the controller terminals.

Inverting Amplifier

- The **inverting amplifier** is probably the most common op-amp configuration.
- The circuit requires just two resistors, R_i and R_f.
- R_i is the input resistor, and R_f is the feedback resistor that feeds part of the output signal back to the input.

$$A_V = \frac{-R_f}{R_i}$$

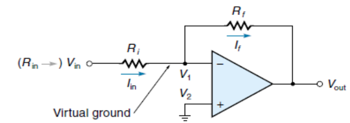


Figure 7.6 The inverting amplifier circuit.

where

A_V = voltage gain of the inverting amp
R_f = value of the feedback resistor
R_i = value of the input resistor

- the voltage gain of the inverting amp is simply the ratio of the two resistors R_f and R_i.
- The minus sign reminds us that the output is inverted.
- Another important point is that the input impedance for the entire inverting amp is approximately R_i (*not* infinite as one might think).
- Figure 7.6 shows this: The right end of R_i is at virtual ground; therefore, the entire V_{in} is "dropped" across R_i.

Non-Inverting

- Many situations call for an amplifier that does not invert the output. For example, the output of a temperature sensor might be such that as the temperature goes up, the voltage goes up.
- If this is the same relationship that the controller wants, we don't want the amplifier to invert it.
- The circuit for the **noninverting amplifier** is shown in Figure 7.7
- It is similar to the inverting amp except the input signal Vin now goes directly to the noninverting input and Ri is grounded.
- Notice that the noninverting amp has an almost infinite input impedance (R_i) because V_{in} connects only to the opamp input.

$$A_V = \frac{R_f}{R_i} + 1$$

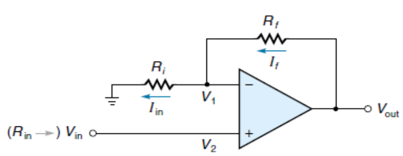


Figure 7.7 The non-inverting amplifier circuit.

Summing Amplifier

- The **summing amplifier** has an output voltage that is the sum of any number of input voltages.

$$V_{out} = -\left(\frac{R_f}{R_a}V_a + \frac{R_f}{R_b}V_b + \frac{R_f}{R_c}V_c\right)$$

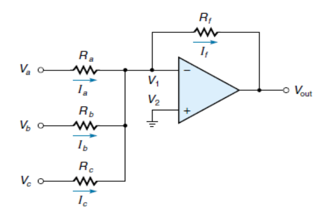


Figure 7.8 The summing amplifier circuit.

If $R_a = R_b = R_c = R_i$,

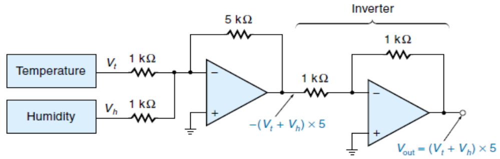
$$V_{out} = -\frac{R_f}{R_i}(V_a + V_b + V_c)$$

Summing Amplifier: example

According to a comfort scale, the air conditioning in a building should come on when the sum of the temperature and humidity sensor voltages goes above 1 V.

A threshold circuit in the air conditioner requires 5 V for turn-on. Design an interface circuit to connect the two sensors to the air conditioning unit.

Figure 7.9 A summing amplifier circuit.



- This circuit requires a summing amplifier with two inputs and a gain of 5.
- By specifying both input resistors to be the same (at 1 kΩ),

$A = \frac{R_f}{R_i} = 5$ $R_f = 5 \times R_i$, When R_f = 1 kΩ, R_f = 5 × 1 kΩ = 5 kΩ

- Figure 7.9 shows the completed circuit. Notice that an inverting amp with a gain of 1 ($R_i = R_f$) was added to make the final output positive.

Differential Amplifiers

- A **differential amplifier** amplifies the difference between two input voltages.
- If $R_a = R_b$ and $R_f = R_g$, which is usually the case, then the equation for V_{out} is

$$V_{out} = \frac{R_f}{R_a}(V_b - V_a)$$

$$\frac{V_{out}}{(V_b - V_a)} = \frac{R_f}{R_a}$$

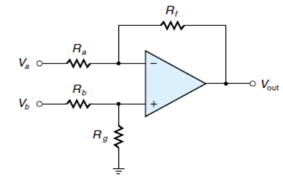


Figure 7.10 The differential amplifier circuit.

- $V_{out}/(V_b - V_a)$ is output/input,

which is a gain, so

$$A_V = \frac{R_f}{R_a}$$

where

A_V = voltage gain of the differential amp
R_f = value of Rf and Rg
R_a = value of input resistors, Ra and Rb

Differential Amplifiers: example

A differential amp is needed to amplify the voltage difference between two temperature sensors. The sensors have an internal resistance of 5 kΩ, and the maximum voltage difference between the sensors will be 2 V. Design the differential amp circuit to have an output of 12 V when the difference the inputs is 2 V.

$A_V = V_{out}/V_{in} = 12/2 = 6$

By letting $R_a = R_b$ and $R_f = R_g$,
Noting that the sensor impedance is 5 kΩ,
we would like the input resistance of the amp to be at least ten times 5 kΩ.
Therefore, if we select Ra = 50 kΩ,
Then, $A_V = R_f/R_a = 6$
solving for R_f

$R_f = R_a \times 6$ = 50 kΩ × 6 = 300 kΩ

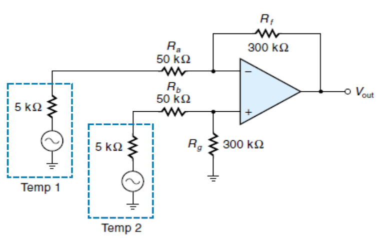


Figure 7.11 The differential amplifier circuit.

Instrumentation Amplifiers

- An **instrumentation amplifier** is a differential amp that has its inputs buffered with voltage followers.
- Voltage follower circuits on the inputs perform three desirable functions:
  - (1) They increase the input resistance so that the source (such as a sensor) will never be loaded down,
  - (2) they make both input resistances equal, and
  - (3) they isolate the gain-defining resistors (R_f, R_i, etc.) from the signal source. This last quality means that instrumentation amps can be prebuilt to have a specific gain.

Applications

- where signals of vastly different voltages are digitized by the same ADC (analog-to-digital converter).
- In such a system, the digital controller could switch to the appropriate gain for each different signal level.

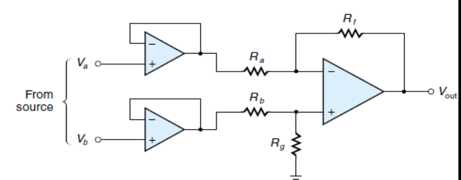


Figure 7.12 The instrumentation amplifier circuit.

Integrators

- The integrator gives an output voltage (V_{out}) that is proportional to the total area under a curve traced out by the input voltage waveform (the horizontal axis being time).
- the feedback element is a capacitor.

$$V_{out} = -\frac{1}{RC} \times (\text{area under } V_{in} \cdot \textit{time} \text{ curve})$$

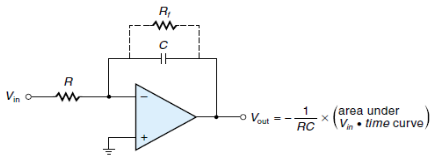


Figure 7.13 An integrator circuit.

- The integrator circuit works by converting V_{in} into a constant current source that forces the capacitor (C) to charge at a linear rate, thus building up the voltage across C.

Integrators

- The integrator concept can be explained by the sample waveforms shown in the Figure 7.14 (which assumes RC = 1).
- Notice that the integrator input voltage (V_{in}) rises from 0 to 1 V in the first 10 s.
- The triangular area under that portion of the curve (a-b) is 5 V·s, so the output (V_{out}) of the integrator goes from 0 to –5 V during the same time.
- In other words, the output voltage ends up being the same magnitude as the area under the curve, in this case 5 (the minus sign appears because it is an inverting amp).
- From time b to c, V_{in} remains at 1 V, so the new area added is 10 V · s.
- Consequently, the magnitude of V_{out} increases by 10 to become –15 V at time c. Then, V_{in} returns to 0 V.
- Because no new area is added between c and d, V_{out} remains at –15 V.

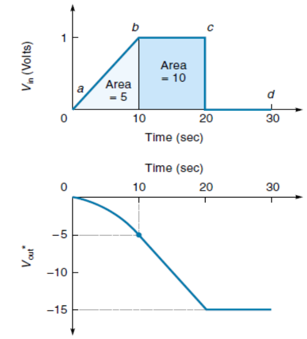


Figure 7.14 The voltage waveform of an integrator circuit. (V_{out} = –V·s in this case because RC = 1.)

Integrators

- Integrators can be useful because they keep a record of what has gone on before.

Note:

- The simple integrator circuit shown is not practical, because any offset voltage (and there is always some) will eventually cause the output to build up and saturate at the power supply voltage.
- One solution is to put a resistor (R_f) across the capacitor to provide some dc feedback.
- If the value of R_f is at least 10 times greater than R, the circuit performance will usually not be adversely affected.

Differentiators

- The differentiator gives an output voltage that is proportional to the rate of change (slope) of the input voltage

$$V_{out} = -\frac{1}{RC} \times \frac{\Delta V_{in}}{\Delta t}$$

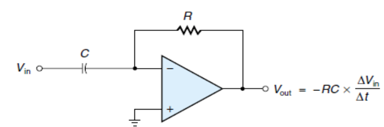


Figure 7.15 A differentiator circuit

- Differentiators can tell us how fast a variable is changing.
- In practice, however, they suffer from the problem that even a small amount of noise in the input will be accentuated, giving a very "noisy" output.

Differentiators

- The differentiator concept is illustrated in the Figure 7.16 (which assumes RC = 1).
- From time a to b, the input voltage (V_{in}) is 0 V, and because it is not changing, the output voltage (V_{out}) is 0 V.
- During the time period b-c, Vin increases at a constant rate of 1 V/s, so the Vout curve reflects this by staying at a constant –1 V (it is negative because the inverting input is used).
- From time c to d, the slope of V_{in} increases to 2 V/s, so V_{out} jumps to –2 V.
- After time d, V_{in} stays at 3 V, and because it is not changing, V_{out} is 0.

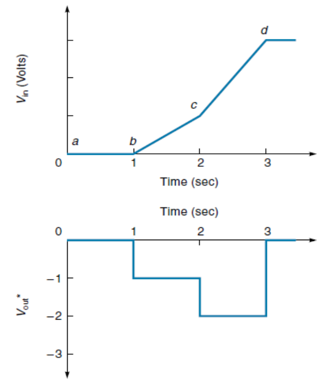
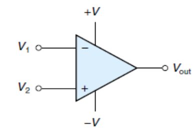
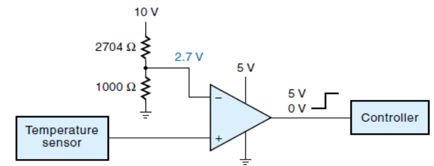


Figure 7.16 Voltage waveforms of a differentiator. (V_{out} = -V_{in} this case because *RC* = 1.)

Comparators

- A typical situation in a control system is a slow-moving analog signal from a sensor being used to trigger some event. Such an interface requires a threshold detector circuit that will switch from off to on when a specified input voltage level is reached.
- A **comparator** is such a circuit (Figure 7.17).
- Comparators are usually operated open-loop so that if V_2 is even slightly more positive than V_1, the tremendous gain will amplify the small difference and drive the output into positive saturation (close to +V). On the other hand, if V_1 is slightly more positive than V_2, the output will go to negative saturation (–V).
- The output is essentially digital in nature – either on or off depending on a very small change in the inputs.





(a) Comparator circuit for example 3.10

Figure 7.17 Comparator circuits.

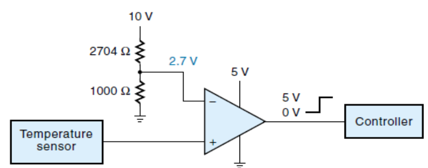
Comparators

The blower on a hot-air solar panel should come on when the temperature reaches 100°F. An analog temperature sensor in the solar panel needs to be interfaced to a digital controller such that the controller receives a 5 V switch on signal when the sensor voltage reaches 2.7 V. Design the interface circuit.

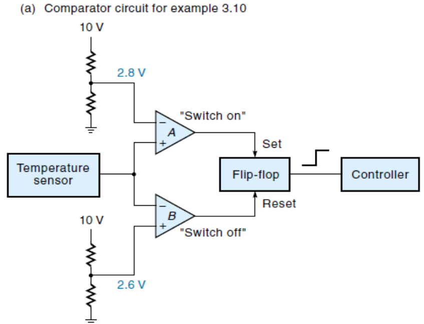
•Figure (a) shows the interface circuit. The signal from the sensor is connected to the noninverting input of the comparator. The inverting input comes from a voltage divider that yields a precise reference voltage of 2.7 V. Notice also that the supply voltages of the comparator are 5 V and ground.

•As long as the sensor voltage is below 2.7 V, the reference voltage at the inverting input predominates, and the output will try to go negative.

•In this case, the output will go to about 0 V because that is what the negative supply voltage is. When the sensor voltage goes only slightly above 2.7 V, the noninverting input becomes positive compared with the inverting input, and the output saturates positive, which is about 5 V. The switch-on point can easily be adjusted by changing the reference voltage resistors.



(a) Comparator circuit for example 3.10



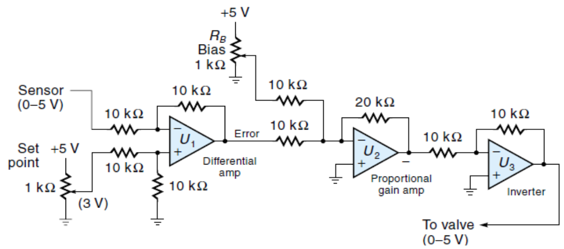
(b) Window comparator circuit

Comparators

- One practical problem with comparators is known as **chatter,** the condition that occurs when the output (V_{out}) oscillates back-and-forth when V_{in} is near the threshold.
- Chatter is caused by noise on the V_{in} signal or some sort of undesirable feedback, say, through the power supply. Practical circuits overcome chatter by using a **window comparator** [Figure (b)], a comparator with built-in hysteresis.
- *hysteresis* means that the switch-on voltage will be greater than the switch-off voltage.

Op-Amp: Proportional controller

Figure 7.19 An analog Proportional controller.



- The analog controller circuit, consists of three op-amps.
- The first op-amp (U_1) is acting as a differential amplifier with a gain of 1, subtracting the sensor feedback signal from the set point to create the error voltage.
- The output of U_1 (error signal) is fed into op-amp U_2, a simple (inverting) summing-type amplifier whose purpose is to provide the proportional gain (K_P).
- The output of U_2 must be inverted to make the output positive; this is done with U_3, which is a simple inverting amplifier with unity gain.

Op-Amp: PID controller

- an analog PID controller uses five differential amplifiers.
- The first differential amplifier (U_1) subtracts the feedback from the set point to produce the error signal.
- Op-amps U_2, U_3, and U_4 are configured to be unit gain, integrator, and differentiator amplifiers, respectively.
- They produce the values for the three terms within the brackets in the PID equation.
- The final amplifier (U_5) sums the three terms and multiplies the sum by K_P to produce the output.
- The capacitor C_I on the integrator accumulates the error in the form of charge, and the capacitor C_D of the differentiator passes only the change in error.
- The constants K_P, K_I, and K_D are selected by adjusting R_1, R_2, and R_3, respectively.

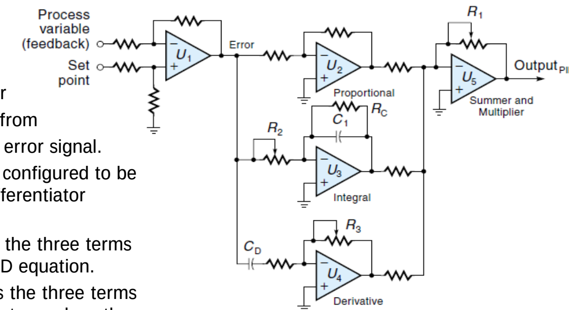


Figure 7.20 An analog PID controller.

$$Output_{PID} = Kp \{ E + K_I \Sigma E \Delta t + K_D \Delta E/\Delta t \}$$

Sample and Hold circuit

- A **sample-and-hold circuit (SHC)** can read in, or sample, a voltage and then remember, or hold, it for a period of time.
- Example: Consider a system, where three analog signals were interfaced to a digital controller. But there is a constraint that all three sensors be read at exactly the same time. Assuming that just one ADC is available, the only way to meet this requirement is to include three **SHCs** as shown.
- By command from the controller, all three **SHCs** will take voltage readings and store the results.
- Then at the convenience of the system, these values can be read one-at-a-time by the controller.
- another reason:
- For the ADC to give an accurate output, the analog input should be constant during the read-in time. If the analog signal is changing too fast, the **SHC** can be used to "freeze" the input voltage during the conversion.

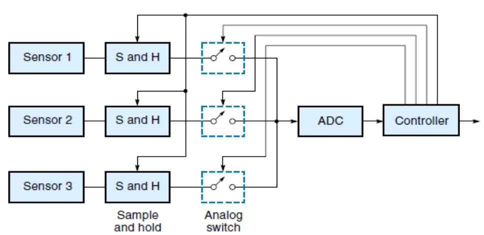


Figure 7.21 An example of using sample-and-hold circuits.

Sample and Hold circuit: working principle

- SHC consists of an analog switch, a capacitor, and a voltage follower amplifier.
- To take a sample, the analog switch is closed for a period of time long enough for the capacitor to charge up to V_{in}; then the switch is opened.
- The signal voltage is trapped on the capacitor because (theoretically) it can't discharge through either the op-amp or analog switch.
- The voltage can be read anytime via the output of the voltage follower.
  - Recall that the gain of a voltage follower is 1.
- For the **SHC** to work, certain conditions must be met.
  - First, the switch must be closed long enough for the capacitor to charge up to the full value of V_{in}. The time required depends on the sizes of Rs (source resistance) and *C*, according to the Equation $\mathbf{t = 5 R_s C}$, where t is the time for C to charge to 99% of V_{in}.
  - Eventually the charge will leak off, so the controller must read the capacitor voltage within a certain time.

The trade-off:

- A larger capacitor will hold the charge longer, But it will increase the read-in time because it takes longer to be charged up. As always, some compromise value of C is selected.

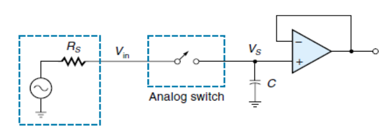


Figure 7.22 A sample-and-hold circuits.

Current Loop

- Most signals are voltage signals, which means that the information being conveyed is proportional to the voltage.
- Two potential problems with this can arise:
  - Susceptibility to electrical noise increases (which is usually in the form of voltage spikes), and
  - Any resistance in the signal wire causes a voltage drop.
- For short distances, wire can usually be effectively shielded from noise, and voltage drops are not a problem.
- For longer cable runs with numerous connectors, such as might be found in a process control system in a large factory, noise and total cable resistance may become significant.
- Figure 7.23 illustrates this situation.
- Notice that the signal from the sensor has been greatly diminished by the cable resistance.

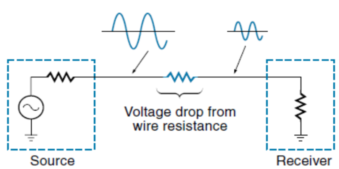


Figure 7.23 Signal voltage is reduced from wire resistance.

Current Loop

- One solution to the problems of noise and signal attenuation is to use current instead of voltage to convey the information.
- This is effective because current, unlike voltage, is not as susceptible to noise and does not drop when it goes through a resistance. As Kirchhoff 's current law tells us, whatever current goes into a branch, comes out.
- Op-amps can be used to implement as the transmitter in a current-loop system.
- This circuit converts a voltage signal (V_{in}) into an output current (I_{out}), which is proportional to V_{in}.
- The op-amp circuit causes the output current to be independent of any resistance in the line.
- It accomplishes this by automatically increasing or decreasing its output voltage (V_{out}) in response to any increasing or decreasing line resistance.
- The current-loop technique is one of the industry standard methods of connecting controllers to sensors and/or actuators.

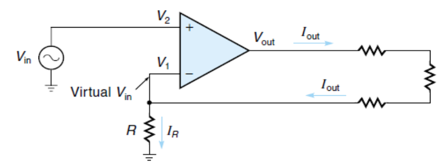


Figure 7.24 The op-amp as a current-loop transmitter.

Filters

- Filter circuits either pass or stop signals, depending on frequency.

Low pass filter:

allows only frequencies below the **cutoff frequency** (f_c) to pass. Frequencies above f_c are attenuated.

- The actual cutoff frequency is defined as the frequency where the gain drops to 0.707 (–3 db) of its pass-band value.
- The steepness of the attenuation depends on the type of filter.

High-pass filter: tends to reject signals with frequencies below the cutoff frequency and pass those above.

Band-pass filter: passes signals with a range of frequencies between fc_1 and fc_2 and rejects all others.

Notch filter:

rejects only a narrow range of frequencies and passes all others.

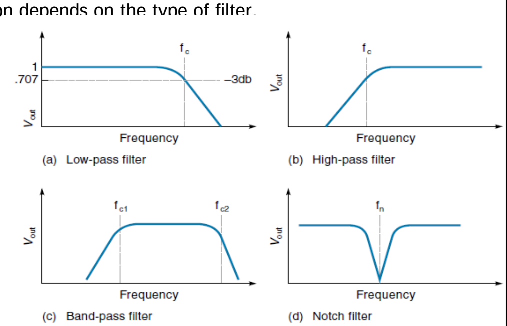


Figure 7.25 Basic filter responses..

Filters

Low pass filter:

- basically a noninverting amp with an *R-C* filter connected to the input

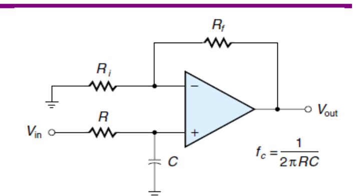


Figure 7.26 A low-pass filter circuit.

High-pass filter:

- It is similar to the low-pass filter but the positions of the R and C are reversed

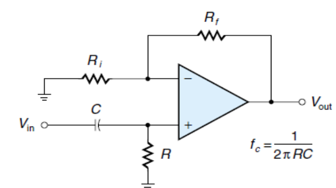


Figure 7.27 A high-pass filter circuit.

Filters

Band-pass filter:

- A band-pass filter can be built by cascading a low-pass filter and a high-pass filter together.
- The cutoff frequency of the low-pass filter (fc_2) must be higher than the cutoff frequency of the high-pass filter (fc_1),

Notch filter:

- The filter itself is a Wein Bridge type.
- The gain of the signal is 1 at all frequencies except near the notch.

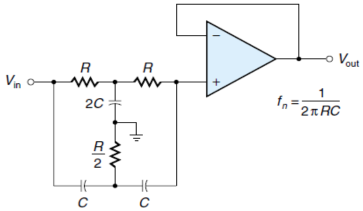


Figure 7.28 A Wein Bridge notch filter circuit.