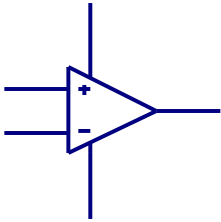


OP-AMP Basics

Operational amplifiers are convenient building blocks that can be used to build amplifiers, filters, and even an analog computer. Op-amps are integrated circuits composed of many transistors & resistors such that the resulting circuit follows a certain set of rules. The most common type of op-amp is the voltage feedback type and that's what we'll use.

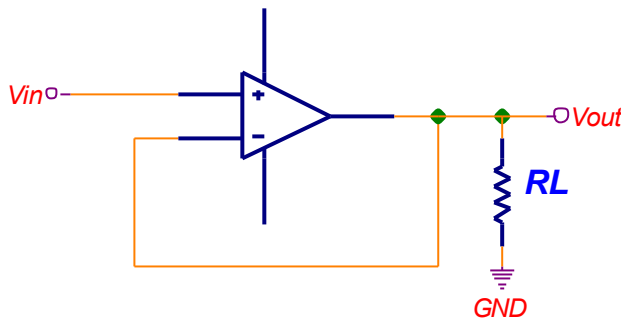


The schematic representation of an op-amp is shown to the left. There are two input pins (non-inverting and inverting), an output pin, and two power pins. The ideal op-amp has infinite gain. It amplifies the voltage difference between the two inputs and that voltage appears at the output. Without feedback this op-amp would act like a comparator (i.e. when the non-inverting input is at a higher voltage than the inverting input the output will be high, when the inputs are reversed the output will be low).

Two rules will let you figure out what most simple op-amp circuits do:

1. **No current flows into the input pins (i.e. infinite input impedance)**
2. **The output voltage will adjust to try and bring the input pins to the same voltage (this rule is valid for the circuits shown below)**

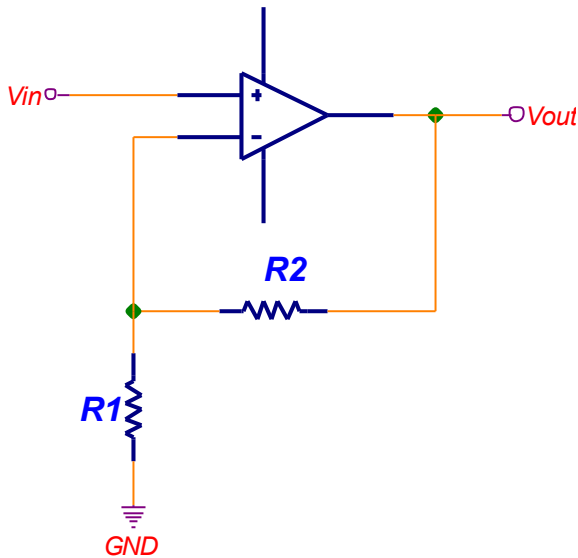
Simple OP-AMP circuits



Voltage Follower:

No current flows into the input, $R_{in} = \infty$
The output is fed back to the inverting input. Since the output adjusts to make the inputs the same voltage $V_{out} = V_{in}$ (i.e. a voltage follower, gain = 1).
This circuit is used to buffer a high impedance source (note: the op-amp has low output impedance 10-100 Ω).

Application hint: The input impedance on some CMOS amplifiers is so high that without any input the non-inverting input can float around to different voltages (i.e. the input pin picks up signals like an antenna). In cases where the input could be disconnected (such as when coming from an external sensor) it's a good idea to tie the input to ground via a high value resistor (1M-10M Ω). This keeps the input at ground potential if the wire to the sensor becomes disconnected and still has high input impedance.

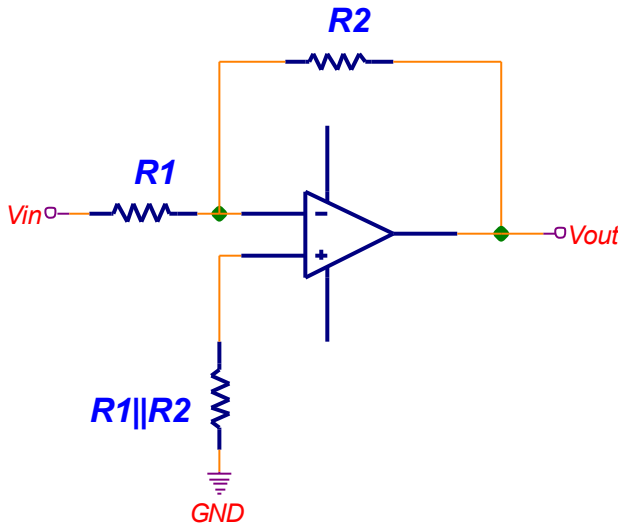


Non-inverting Amplifier:

No current flows into the input, $R_{in} = \infty$
 The output adjusts to bring V_{in-} to the same voltage as V_{in+} . Therefore $V_{in-} = V_{in}$ and since no current flows into V_{in-} the same current must flow through $R1$ & $R2$. V_{out} is therefore $V_{R1} + V_{R2} = V_{in-} + IR2 = V_{in-} + (V_{in}/R1)R2$.
 $V_{out} = V_{in} (1 + R2/R1)$.

Application hint: When dealing with larger signals keep in mind that the output can't exceed the power supply voltage (i.e. if the op-amp is powered from +/- 15V and you have a one volt input and a gain of 20 you won't get 20V on the output. The output will most likely stop a few volts below the supply rail (around 13V). There are special op-amps designed to handle inputs and outputs that go all

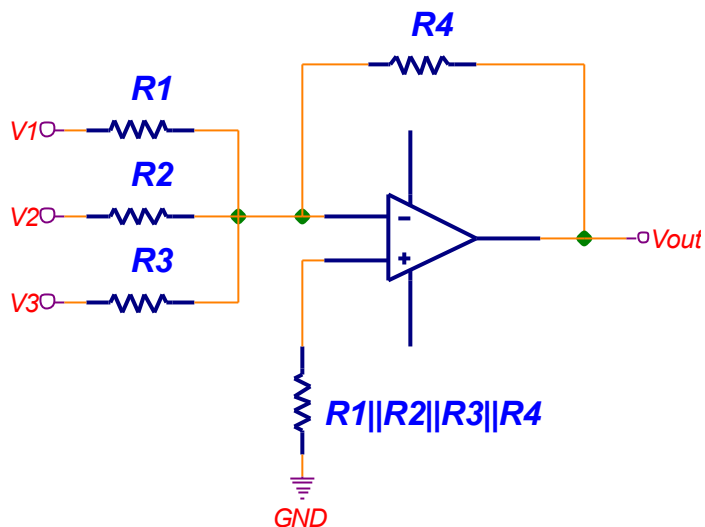
the way to the power supply rail but these op-amps usually only operate at lower voltages (i.e. 0-5V).



Inverting Amplifier:

Because no current flows into the input pins there can't be a voltage drop across $R1 || R2$. V_{in+} is therefore at 0V (this is called a virtual ground). The output will adjust such that V_{in-} is at zero volts. This makes $R_{in} = R1$ (not ∞). The current through $R1$ & $R2$ have to be the same since no current goes into the input pins. Therefore $I = V_{in}/R1$. $V_{out} = V_{in+} - IR2 = 0 - (V_{in}/R1)R2$. Therefore **$V_{out} = -V_{in}(R2/R1)$** . Note: The negative sign is because the current flows from the input to the output whereas in the earlier examples the current flows from the output to the input.

Application hint: Why not connect V_{in+} directly to ground? Actually, many people do and the circuit works fine. The reason to have $R1 || R2$ is because real op-amps aren't perfect and draw a small bias current into both inputs. By adding $R1 || R2$ the voltage drop at the + input is offset by the same amount as the voltage drop at the - input. This is called input offset voltage.



Summing amplifier:

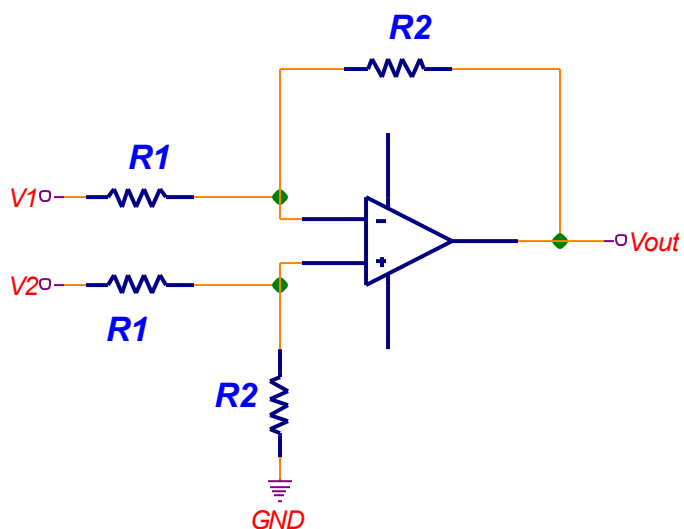
Since V_{in-} is a virtual ground adding V_2 and R_2 (and V_3 & R_3) doesn't change the current flowing through R_1 from V_1 . Each input contributes to the output using the following equation:

$$V_{out} = -V_1(R_4/R_1) - V_2(R_4/R_2) - V_3(R_4/R_3).$$

The input impedance for the V_1 input is still R_1 , similarly V_2 's input impedance is R_2 and V_3 's is R_3 . Most of the time the parallel combination of R_1 - R_4 isn't used and V_{in+} is grounded.

Application hint: Some op-amps have null pins that allow you to add a potentiometer and null (remove) the input offset error (Ex: The LM741:

<http://media.digikey.com/pdf/Data%20Sheets/Fairchild%20PDFs/LM741.pdf>). Some newer op-amps (Ex: LTC1151: <http://cds.linear.com/docs/en/datasheet/1151fa.pdf>) are chopper stabilized (i.e. they measure the offset and null it automatically many times a second). Chopper stabilized op-amps work best with slow moving inputs (temperature for example, something well below the rate at which the offset is measured and nulled).



Difference Amplifier:

You can work out the gain as before using the two rules (no current flows into the inputs, and the output will adjust to bring V_{in-} to V_{in+}). The result is $V_{out} = (V_2 - V_1) * (R_2/R_1)$. Also,

$$R_{in(-)} = R_1, R_{in(+)} = R_1 + R_2.$$

Application hint: Use precision resistors. If the two R_2 resistors differ by 1% you're difference will be off by 1%. Same goes for the R_1 resistors. Assume $V_1 = V_2$. If the resistors aren't matched the output won't be zero. Actually, it's better to buy a difference amplifier or an instrumentation amplifier instead of building the difference amp

from an op-amp and discrete resistors. By using a difference amp with the resistors on the IC they can be laser trimmed to better than 0.01% (Ex: LT1190: <http://cds.linear.com/docs/en/datasheet/1190fa.pdf>, or LT1168: <http://cds.linear.com/docs/en/datasheet/1168fa.pdf>).