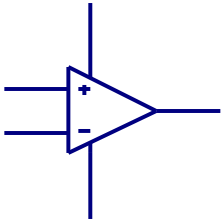# OP-AMP Basics

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).

理想运算放大器有无限增益

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
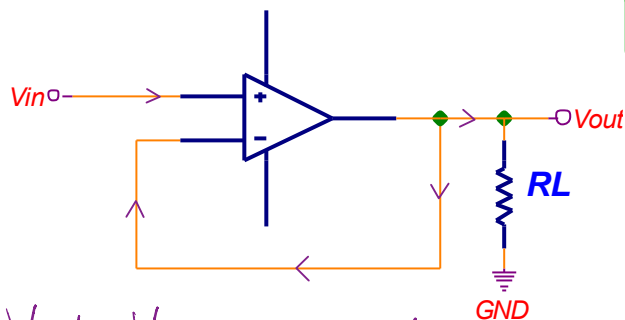
$$Vout = Vin, \quad gain = 1$$

Voltage Follower:

No current flows into the input, **Rin** = ∞
The output is fed back to the inverting input. Since the output adjusts to make the inputs the same voltage **Vout = Vin** (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 10-100Ω).

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.

Vin 与 Vin^- 虚短: $Vin = Vin^-$
电路虚断: $I_{R_1} = I_{R_2} \Rightarrow$ [diagram] $I = \dfrac{Vout}{R_1+R_2}$

$Vin^- = IR_1 = Vin$

$$\frac{Vin}{R_1} = \frac{Vout}{R_1+R_2} = Vout = \frac{R_1+R_2}{R_1}\,Vin.$$

Non-inverting Amplifier: 同相放大器
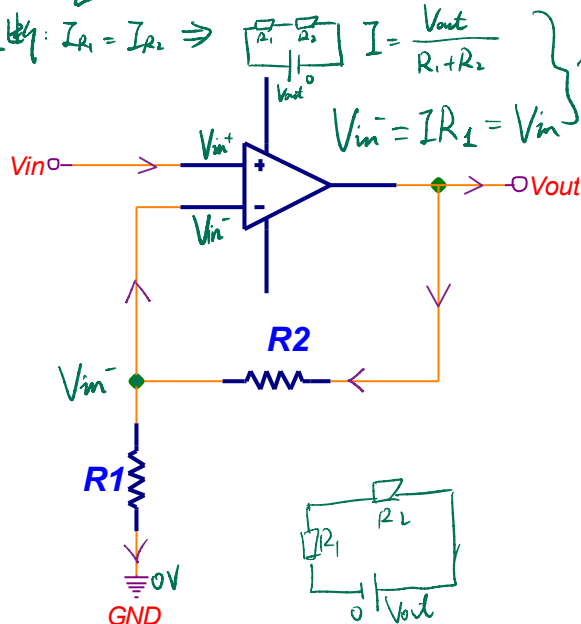
No current flows into the input, **Rin = ∞**
The output adjusts to bring Vin- to the same voltage as Vin+. Therefore **Vin- = Vin** and since no current flows into Vin- the same current must flow through R1 & R2. Vout is therefore VR1 + VR2 = Vin- + IR2 = Vin- + (Vin/R1)R2. **Vout = Vin (1+ R2/R1)**.

$$gain = 1 + \frac{R_2}{R_1}$$

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).
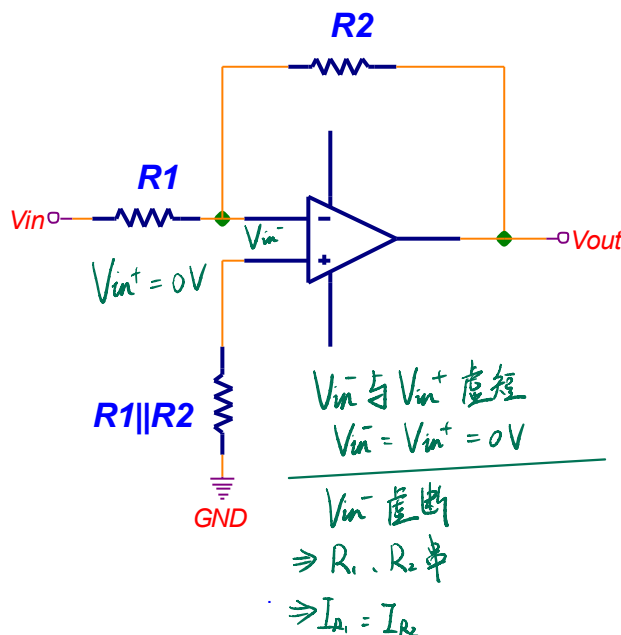

Inverting Amplifier: 反相放大器

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

Vin^- 与 Vin^+ 虚短
$Vin^- = Vin^+ = 0V$

Vin^- 虚断
$\Rightarrow R_1 、 R_2$ 串
$\Rightarrow I_{R_1} = I_{R_2}$

Application hint: Why not connect Vin+ 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.
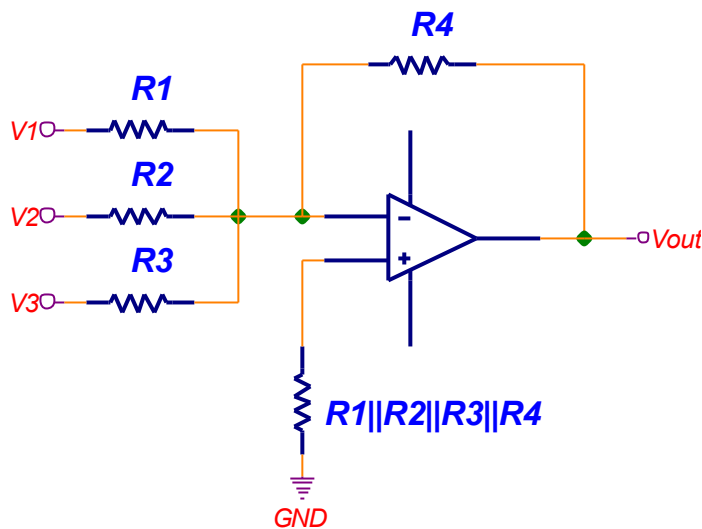
反放:
[diagram] $Vin \quad Vin^- = 0$
[diagram] $Vin^- = 0 \quad Vout$
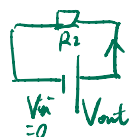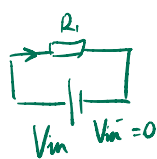
$$I_{R_1} = \frac{Vin}{R_1}$$
$$I_{R_2} = I_{R_1}$$
$$I_{R_2} = \frac{-Vout}{R_2}$$

$$\frac{Vin}{R_1} = \frac{-Vout}{R_2}$$
$$\Rightarrow Vout = -\frac{R_2}{R_1}Vin$$

Summing amplifier: 加法放大器

Since Vin- is a vertual ground adding V2 and R2 (and V3 & R3) doesn't change the current flowing through R1 from V1. Each input contributes to the output using the following equation:

Vout = -V1(R4/R1) - V2(R4/R2) - V3(R4/R3).
The input impedance for the V1 input is still R1, similarly V2's input impedance is R2 and V3's is R3. Most of the time the parallel combination of R1-R4 isn't used and Vin+ 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).
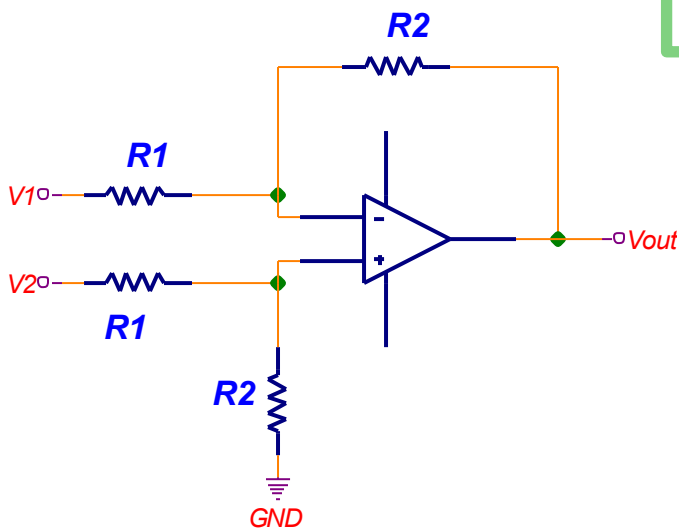
Difference Amplifier: 差分放大器
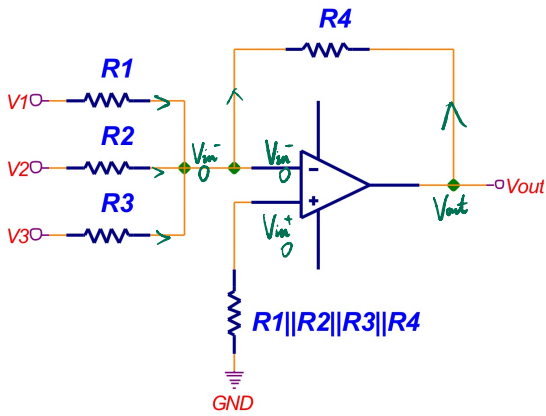
You can work out the gain as before using the two rules (no current flows into the inputs, and the output will adjust to bring Vin- to Vin+). The result is **Vout = (V2-V1)*(R2/R1).** Also, **Rin(-) = R1, Rin(+) = R1 + R2**.

Application hint: Use precision resistors. If the two R2 resistors differ by 1% you're difference will be off by 1%. Same goes for the R1 resistors. Assume V1 = V2. 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).

Top circuit (summing amplifier):

Labels: R4, R1, R2, R3, V1, V2, V3, V_{in}^-, V_{in}^-, V_{in}^+, Vout, R1||R2||R3||R4, GND

$$V_{in}^- = V_{in}^+ = 0\ V$$

$$\left. \begin{array}{l} I_{R_1} = \dfrac{V_1}{R_1} \\[6pt] I_{R_2} = \dfrac{V_2}{R_2} \\[6pt] I_{R_3} = \dfrac{V_3}{R_3} \end{array} \right\} \quad \begin{array}{l} I_{R_4} = -\left(I_{R_1} + I_{R_2} + I_{R_3}\right) \\[10pt] \qquad = \dfrac{V_{out}}{R_4} \end{array}$$

$$V_{out} = -\frac{R_4}{R_1} V_1 - \frac{R_4}{R_2} V_2 - \frac{R_4}{R_3} V_3$$

Bottom circuit (difference amplifier):

Labels: R2, R1, V1, R1, V2, V_{in}^-, V_{in}^+, Vout, R2, GND, I
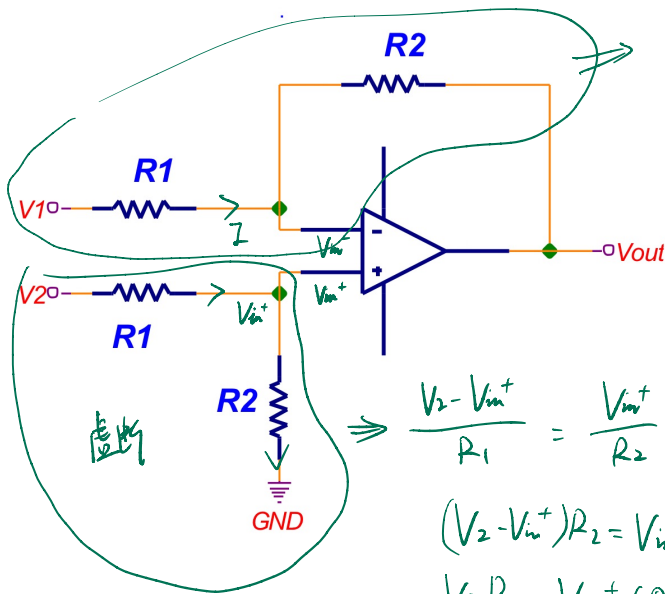
$$\frac{V_1 - V_{in}^-}{R_1} = \frac{V_{in}^- - V_{out}}{R_2}$$

$$V_{out} = V_{in}^- - \frac{R_2}{R_1}\left(V_1 - V_{in}^-\right)$$

$$= \left(1 + \frac{R_2}{R_1}\right)V_{in}^- - \frac{R_2}{R_1} V_1$$

$$= \frac{R_1 + R_2}{R_1} \times \frac{R_2}{R_1 + R_2} V_2 - \frac{R_2}{R_1} V_1$$

$$= \frac{R_2}{R_1}\left(V_2 - V_1\right)$$

$$\frac{V_2 - V_{in}^+}{R_1} = \frac{V_{in}^+}{R_2}$$

$$\left(V_2 - V_{in}^+\right)R_2 = V_{in}^+ \times R_1$$

$$V_2 R_2 = V_{in}^+ \left(R_1 + R_2\right)$$

$$V_{in}^+ = \frac{R_2}{R_1 + R_2} V_2$$