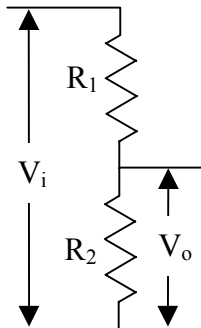


Electronic Circuits and Feedback

These notes give a short introduction to analog circuits. If you like to learn more about electronics (a good idea if you are thinking of becoming an experimental physicist), you can take a class offered in the summer (PHY-557). An excellent general reference is “The Art of Electronics” by Horowitz and Hill (Cambridge press).

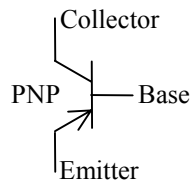
1. Resistive divider (hopefully a review)



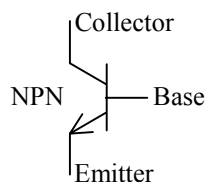
$$V_o = R_2 / (R_1 + R_2) V_i$$

To show this consider a current $I = V_i / (R_1 + R_2)$ flowing through both resistors and use Ohm's law. Note that the current is assumed to be the same in both resistors and the current flowing to the output is assumed to be negligible. Therefore, one has to avoid “loading” the divider with any resistance comparable to R_2

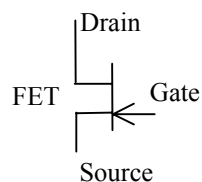
2. Transistors



Without going into details of the semiconductor physics you can think of a transistor as a valve. The base (gate) controls the current that flows through the collector-emitter (drain-source) circuit. Transistors come in a number of flavors. The two main types are bipolar transistors and field-effect transistors.



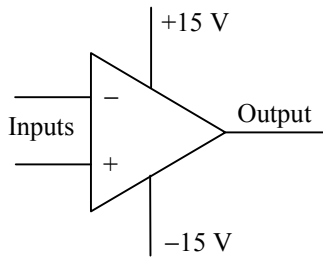
Bipolar transistors, the two top diagrams on the left, can be either PNP with the current flowing from the emitter to the collector or NPN with the current flowing in the opposite direction. The arrow on the emitter indicates the direction of current flow. The current through the collector-emitter circuit is amplified relative to base-emitter current by the gain coefficient $\beta \sim 100$. Another practical thing to remember is that the voltage between the base and the emitter is always about 0.7 V when any current flows through the transistor. This is a property of silicon that is used in nearly all transistors.



Field effect transistors (FET) also come in several types, only one is shown on the left. The main difference from the bipolar transistors is that they are controlled by a voltage on the gate instead of a current. The gate current of FET transistors is extremely small.

In modern electronic circuits transistors are rarely used except when the output power is relatively large. For example, a typical stereo contains mostly integrated circuits except for the output transistors driving the speakers.

3. Operational Amplifiers

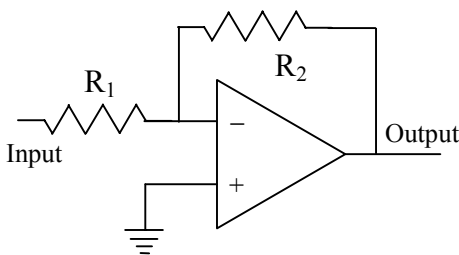


Operational amplifiers (op-amps) are the simplest and most commonly used analog integrated circuit. The circuit basically amplifies the voltage difference between the two inputs by a very large factor, 10^6 – 10^7 . Op-amps typically require ± 15 V power supplies, but can run almost as well with any supply voltage between ± 5 V and ± 20 V. In circuit diagrams the power supply lines are usually not shown explicitly.

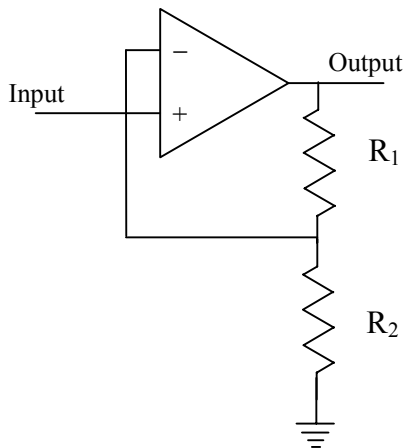
Operational amplifiers are almost never used without a feedback, an additional circuit that sets the gain of the amplifier to a smaller and well-defined value. The behavior of op-amp circuits with feedback can be understood by following two simple rules:

1. The output of the amplifier changes in a way to make the voltage difference between the two amplifier inputs equal to zero.
2. The current flowing into the amplifier inputs is equal to zero.

The first rule assumes that the gain of the amplifier is essentially infinite and the second rule is a consequence of the amplifier internal design.

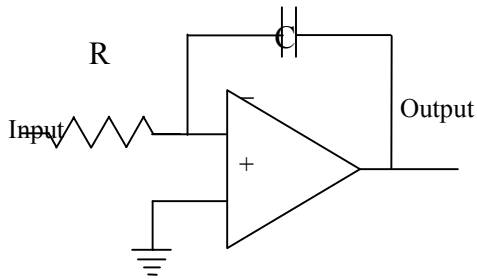


The circuit on the left is an inverting amplifier. Its analysis proceeds as follows. Suppose a voltage V_i is applied to the input. Since the “+” input of the op-amp is at ground, the “–” input must also be at zero voltage following the first op-amp rule. Therefore the current flowing through resistor R_1 is $I = V_i/R_1$. The current going into the amplifier input is zero, therefore the same current I must flow through the resistor R_2 , where it creates a voltage drop $I R_2$. Since one end of R_2 is at ground, the output voltage (relative to ground) is $V_o = -R_2/R_1 V_i$. One drawback of this circuit is that it has a low input impedance, i.e. draws a potentially significant current $I = V_i/R_1$ from the input terminal.

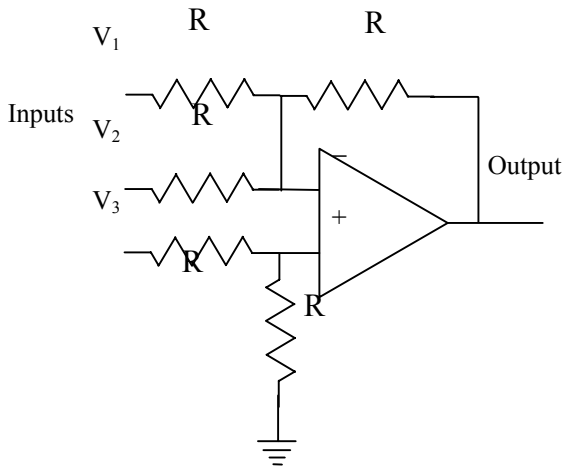


The next circuit is a non-inverting amplifier. The voltage on the “–” terminal must be equal to the input voltage, therefore the output voltage $V_o = (1 + R_1/R_2) V_i$. This circuit has a gain ≥ 1 . Its input impedance is equal to the input impedance of the op-amp, typically in the $G\Omega$ range, and it draws virtually no current from the input.

You might have noticed that it’s the “–” terminal that is always connected to the output through some type of circuit. This is necessary to obtain a “negative feedback”, such that if a finite voltage difference develops between the inputs, the amplifier output will drive it back to zero.



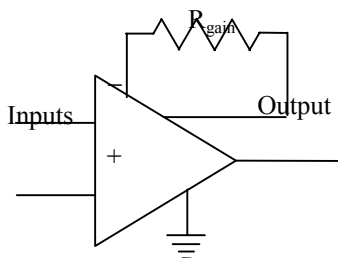
Another example of an op-amp circuit is an integrator shown on the left. You can show that the output voltage of the circuit is given by $V_o = R/C \int V_i(t) dt$. Of course, this relationship is satisfied only if the output remains within the output voltage range of the amplifier, typically 1-2 V smaller than the power supply voltage. Also note that the output current of op-amps is typically limited to 10-30 mA.



The final example is a sum/difference amplifier. For all equal resistors after a little algebra you can show that the output voltage is $V_o = -(V_1 + V_2 - V_3)$. Such circuit can be used to take a sum/difference of any number of voltage inputs.

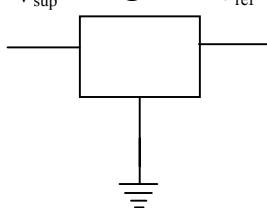
Because of practical limitations of the op-amps, such as a limited output current and a large, but finite, input resistance, the resistor values in the above circuits should be chosen in the range 1 kΩ to 10 MΩ.

4. Instrumentation amplifier



The difference amplifier above has a drawback that it draws a significant current from the inputs. It turns out that a difference amplifier with high input impedance requires at least 3 op-amps. Such circuits are commonly packaged into a single chip called an instrumentation amplifier. The output is given by $V_o = G(V_+ - V_-)$, where the gain G is set using an external resistor. Instrumentation amplifiers are useful for measuring small voltages because they cancel common-mode noise.

5. Voltage Reference



Whenever a constant voltage is needed in a circuit, a voltage reference chip is usually used. They are available with output voltages of 2.5, 5 or 10 V, which remains constant for a very wide range of supply voltages.

Many other more specialized chips are easily available, such as analog multipliers/dividers, comparators, variable-gain amplifiers, oscillators, dc-dc voltage converters, etc.

Feedback and Control

Let's consider the subject of feedback in more detail since it is used not only in op-amps but also in a wide variety of experimental arrangements.

Suppose we have a physical property a that can be measured and can be changed by varying a parameter b . For example, a is the temperature in the room and b is the power going to an electric heater. For simplicity assume that a is proportional to b , $a = Fb$. It is desired to maintain a at a specific *set point* a_0 . We introduce an *error signal* $e = (a - a_0)$ that we like to make as small as possible. Imagine we setup a *control loop* that adjusts b in response to changes in e . We consider the simplest, but very common, *proportional* feedback that sets $b = -G e$, where G is the gain of the control loop. Note the minus sign, we need *negative* feedback to arrive at the set point. After a little manipulation we find

$$e = a - a_0 = -\frac{a_0}{1 + GF}$$

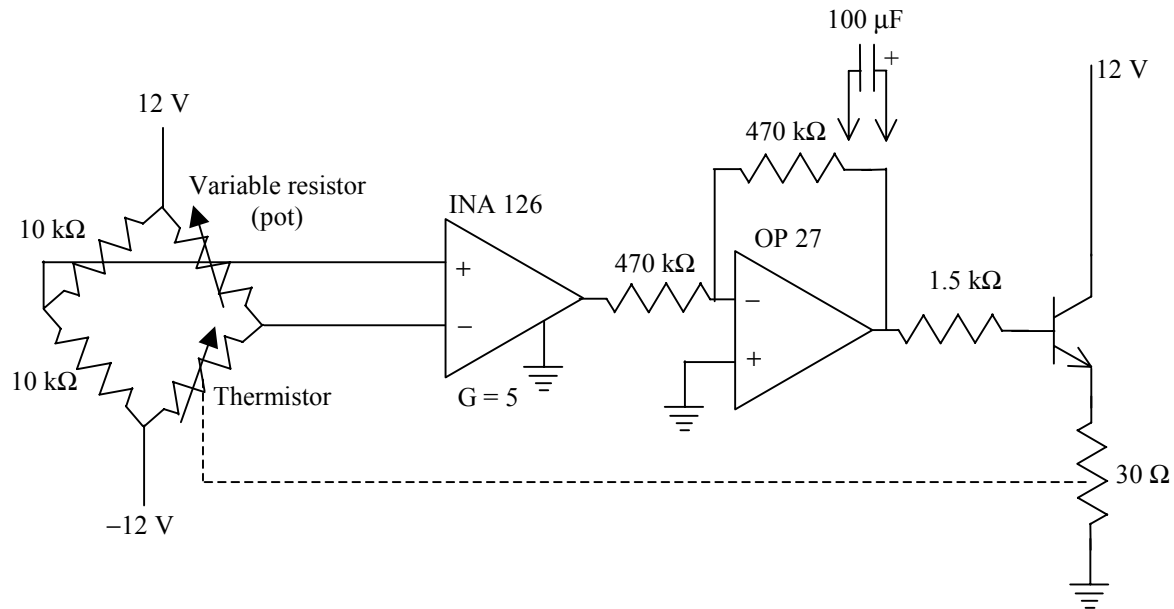
Thus, to maintain a close to a_0 we need a large gain G and we can never get the error signal exactly to zero using proportional feedback. It simply follows from the fact that to get a finite output b we need a finite input e .

A common way to get around this problem is to add *integral* feedback for which the output $b = -G \int e(t) dt$. With integral feedback even a small error signal if it persists for a long time will eventually integrate to produce a large output signal. With integral feedback one can ensure that the error signal is on average equal to zero. Finally, one can add *derivative* feedback to improve the performance of the control loop. For example, if you see the temperature in the room raising very fast and approaching the desired temperature, you might want to turn down the heater before the temperature reaches the set point to avoid a large overshoot.

This discussion only scratches the surface of the control theory since in practice the measured variable a responds to changes in b in a complicated way. If you turn on the heater in the room the temperature will not increase immediately, but will take some time to reach equilibrium. One can show that near the set point any control system behaves as a simple harmonic oscillator, i.e. it can be underdamped, overdamped or critically damped. We will not dwell on the control theory further, interested students can consult numerous books and courses in the EE department. Most practical feedback systems use some combination of proportional and integral feedback. The parameters are adjusted to achieve the fastest approach to the set point without excessive overshoot and oscillations.

Temperature Control Circuit

In the lab you will build a temperature control circuit shown below and experiment with different feedback parameters.



The circuit consists of the following main parts:

Thermistor glued to a power resistor. The thermistor is a temperature sensor whose resistance drops very quickly with increasing temperature. It is based on an undoped semiconductor. At room temperature the resistance is about $10\text{ k}\Omega$ and it drops about $5\%/^{\circ}\text{C}$. The power resistor will be used to heat the thermistor and maintain it at a desired temperature.

Wheatstone Bridge. This arrangement allows a precision comparison of the thermistor resistance to the resistance of the potentiometer. Adjusting the potentiometer changes the set point. The bridge arrangement cancels noise from the power supply.

Instrumentation amplifier. We need to make a differential measurement and cannot load the resistance bridge. Hence an instrumentation amplifier is needed. The output of the instrumentation amplifier gives the error signal.

Operational Amplifier. The proportional feedback is implemented using an inverting amplifier. Adding the capacitor in series gives a combination of proportional and integral feedback. Different values of the feedback resistor would give different behavior of the control loop.

Power Transistor. Since we need several watts to heat the power resistor well above room temperature, a power transistor is necessary to increase the current capacity of the op-amp.