

## PHYS 331: Junior Physics Laboratory I

### Notes on Analog Circuits

Digital circuits deal, in principle, with only two values of voltage, whereas analog circuits process signals with continuous variation of voltage. In fact, of course, no macroscopic signal is truly quantized, so even a digital circuit designer needs some familiarity with analog electronics. These notes will provide a very basic introduction to the capabilities of analog circuitry. You may also need to review the elementary analysis of passive DC and AC circuits as found in a freshman physics text.

#### A. Transistor action

Transistors of various types are essential to most modern electronics. They, in turn, depend upon the ability to fabricate semiconducting materials to very precise specifications. We begin, therefore, by discussing very crudely how bipolar transistors function. Descriptions of other types of transistors and more quantitative treatments can be found in the suggested readings.

Semiconductors, as the name implies, are not insulators but neither do they conduct as well as metals. (Commercially important semiconductors include the elements silicon and germanium, and compounds gallium arsenide and gallium phosphide.) The reason for this is quite simple: there are relatively few mobile charge carriers in a pure semiconductor at room temperature, and none at absolute zero. Semiconductors are technically useful because the density of charge carriers, and hence the conductivity, is exquisitely sensitive to part-per-million levels of impurities, referred to as "dopants". Furthermore, by appropriate choice of the dopant, either positive or negative charge carriers can be introduced. A specimen with predominantly positive charge carriers is referred to as "p-type", while a specimen with negative carriers is "n-type". (The negative carriers are electrons, as in metals. The positive carriers are "holes", empty states in an otherwise filled sea of electrons. The existence of holes with an effective positive charge is a consequence of the Pauli exclusion principle acting in a crystalline lattice. A complete explanation can be found in any solid state physics text.)

A piece of p-type material in intimate electrical contact with a piece of n-type material forms a "pn junction" in the region of contact. If wires are attached to the sandwich, as indicated in Fig. 1, it is found that the current-voltage characteristic is very asymmetric. The resulting device is called a "diode". For circuit use, two features of the diode I-V characteristic are important. First, there is a threshold (about 0.6V in silicon) before significant current flows in the

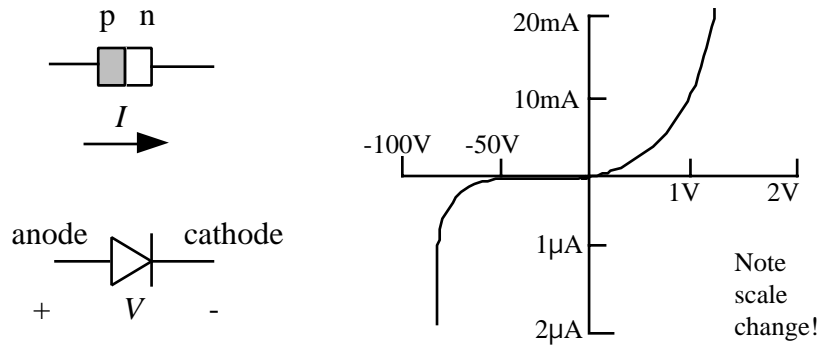


Fig. 1 Junction diode structure, circuit symbol and I-V characteristic.

forward direction. This threshold is the "junction voltage drop" or just "junction drop". For a "forward biased" diode above threshold the current increases very rapidly with little increase in applied voltage. Second, there is a small "leakage current" when the diode is "reverse biased" (n side positive with respect to p side). This phenomenon is usually only a minor nuisance.

A more interesting device can be made by joining three layers as shown in Fig. 2 to create an NPN bipolar transistor. (The term "bipolar" refers to the use of both n and p-type material in the structure. The following description also holds for the analogous PNP transistor if all polarities are reversed. Other designs are possible, but will not be discussed here.) Evidently the base-emitter and base-collector circuits will behave like diodes. The unexpected fact is that if the collector is made positive with respect to the emitter, then a current in the base-emitter circuit can control the current flow across the (reverse biased) collector-base junction. For small base currents the relationship is linear

$$I_C = h_{FE} I_B = \beta I_B \quad (1)$$

where the current gain,  $h_{FE}$  or  $\beta$ , is typically 10-100. This current gain actually represents a power gain, in the sense that a low-power input signal applied to the base can cause a higher-power signal to appear in the collector circuit.

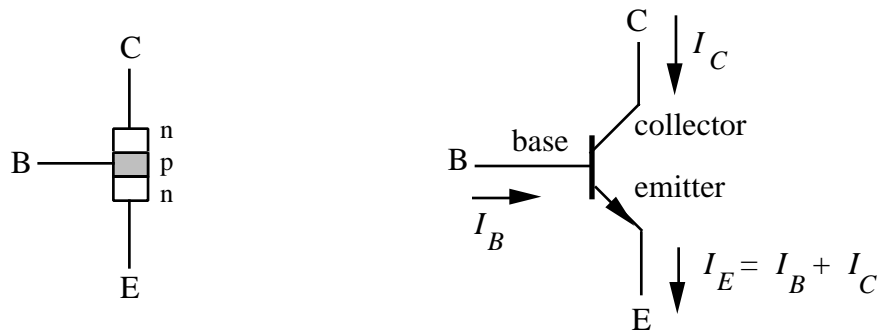


Fig. 2 NPN junction transistor structure and circuit symbol

## B. Gate circuits

As a first example of transistor circuitry, consider Fig. 3, which shows the common-emitter configuration of an NPN transistor. The supply voltage  $V_{CC}$  is taken to be positive. If  $V_{in}$  is zero or negative there will be no base current, hence no collector current, and the transistor is said to be cut off. When  $V_{in}$  is positive and greater than the junction drop (0.6 V for silicon), base current will start to flow, the collector current will increase according to Eq. 1 and  $V_{CE}$  will decrease. For sufficiently large  $I_B$ ,  $V_{CE}$  reaches a minimum (0.1-0.2 V for silicon) and  $I_C$  is limited chiefly by the load resistor  $R_2$ . The transistor is now fully on, and is said to be saturated. The ability to switch between two well defined states is ideal for implementing digital logic.

The common-emitter configuration is itself a possible design for a NOT circuit. Suppose we define logic 0 as a zero-volt signal and logic 1 as  $V_{CC}$ , a positive voltage. Referring again to Fig. 3, when  $V_{in} = 0$  the transistor is cut off and  $V_{out} = V_{CC}$ . Conversely, if we choose  $R_1$  correctly the transistor can be driven to saturation when  $V_{in} = V_{CC}$ .  $V_{out}$  is then nearly zero (actually  $V_{CE}$  at saturation). More simply,  $V_{out}$  is the logical converse of  $V_{in}$ , as claimed.

A NOR circuit can be constructed using two transistors in common emitter configurations, as shown in Fig. 4. A logic high applied to either input (or both) turns on  $Q_1$  or  $Q_2$ , pulling the output low, which is the required function. An OR circuit could be made by driving the NOT circuit just described with the output of the NOR.

The TTL circuits used for the digital exercises also employ transistors as switches, although the circuit configuration is somewhat different to facilitate manufacture. The design rules governing fan-out and logic levels are all determined by the circuit arrangements chosen to implement the various logic functions.

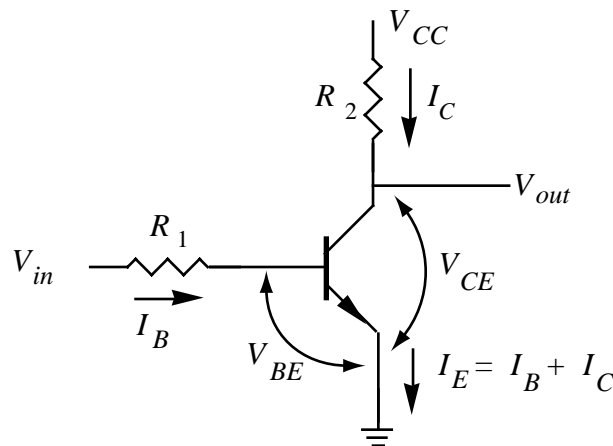


Fig. 3 NPN transistor in common-emitter configuration

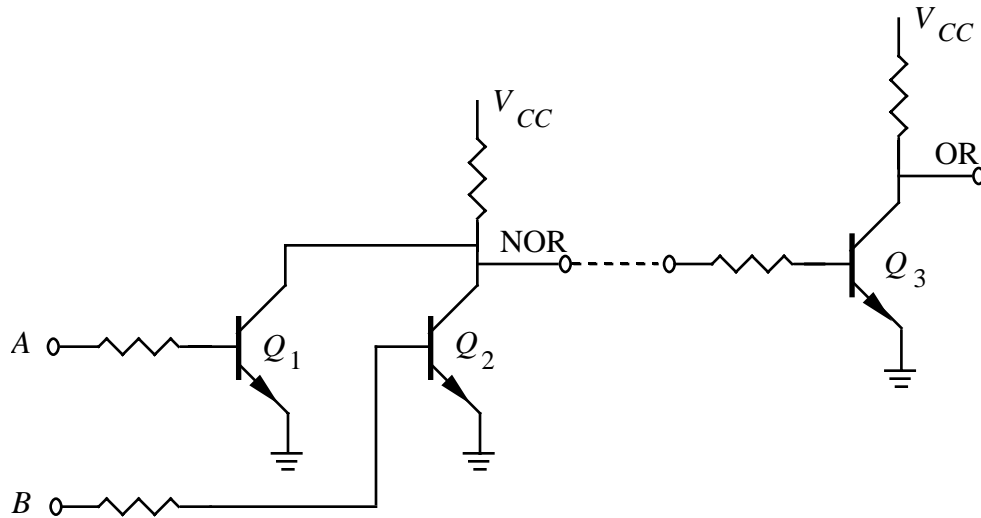


Fig. 4 Two-transistor NOR gate and conversion to OR.

### C. Single-stage amplifiers

The common emitter configuration can be modified to produce an output signal that is linearly proportional to the input, a function known as amplification. The trick is to supply a constant base current, called a bias current, so that the transistor is partially turned on. The signal current is then superimposed on the constant bias current. The resulting collector current will have a DC component, proportional to the bias current, plus a varying component proportional to the signal current. Figure 5 presents the same argument graphically, and Fig. 6 shows a circuit

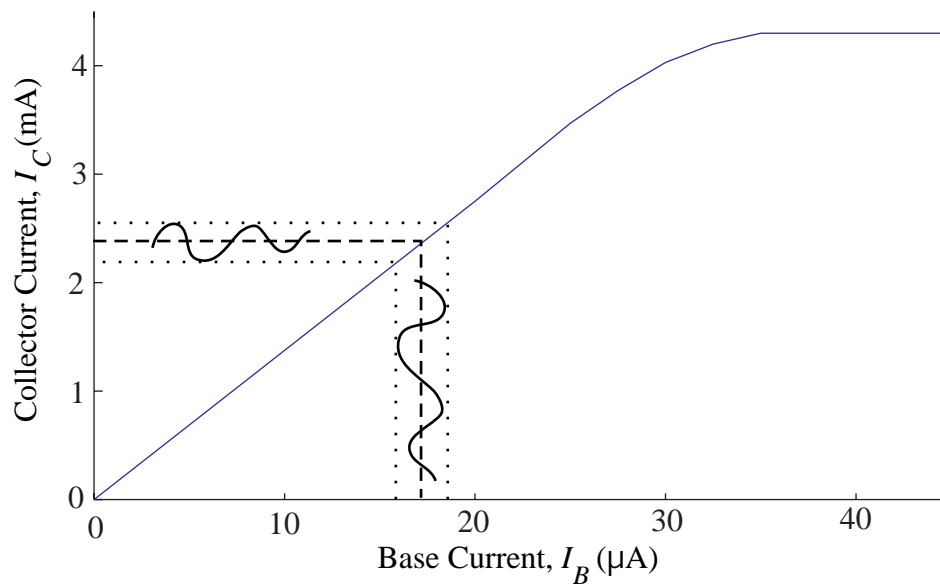


Fig. 5 Plot of collector current vs base current showing effect of bias and signal inputs. The dashed line indicates the bias current input and resulting collector current. Addition of a varying component causes the collector current to follow within the limits shown.

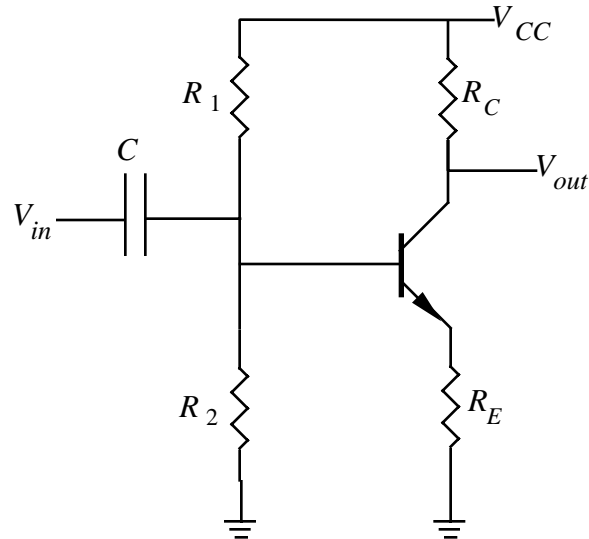


Fig. 6. Biased NPN common-emitter amplifier. A capacitor is used to couple in the AC signal so that the signal source cannot affect the bias current. The same circuit works for a PNP transistor if all polarities are reversed.

implementation. Since the plot is not a straight line there will always be some distortion in the output signal, and signals large enough to drive the transistor into cut-off or saturation will be limited or 'clipped'.

The output voltage of the common emitter amplifier can be substantially larger than the input voltage. With no external signal, some amount of collector current flows, resulting in a voltage drop across the collector resistor which sets the output voltage between  $V_{CC}$  and ground. A small positive signal input will cause additional base current to flow, which causes a much larger increase in the collector current, increasing the voltage drop across the collector resistor and lowering the output voltage. A small negative signal would decrease the base current, thereby increasing the output voltage. The output voltage is therefore an inverted and amplified replica of the input, offset by a DC component due to the bias current. The DC component can be blocked by another capacitor, leaving only the desired signal. A detailed analysis shows that the gain is determined by  $h_{FE}$  and by the effective resistances at input and output.

The emitter resistor  $R_E$  shown in Fig. 6 is not actually essential for circuit function, but it does serve a very useful purpose. The flow of collector current heats the junction because of inevitable losses. The current gain  $h_{FE}$  increases at higher temperatures, resulting in still more collector current for the same bias current, further increasing the temperature. In the absence of an emitter resistor, this succession of events can destroy the device, a phenomenon known as thermal runaway. At best, it will shift the operating point toward saturation and may make the circuit inoperative. An emitter resistor reduces the tendency for thermal runaway by reducing the

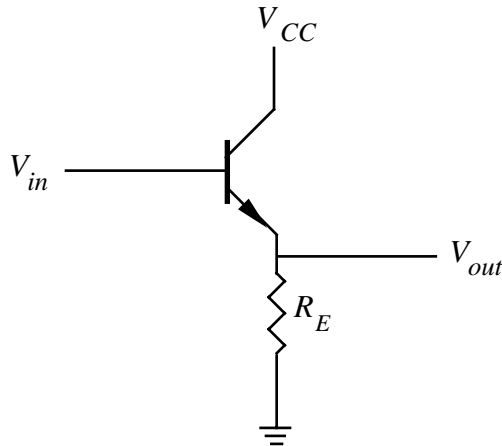


Fig. 7 The emitter-follower circuit.

voltage from base to emitter as the collector current increases. The decrease in  $V_{BE}$  decreases the base current, partially compensating for the increased  $h_{FE}$  and thereby stabilizing the circuit. This is an example of negative feedback, which we will see again later. Practically, an  $R_E$  much smaller than  $R_C$  is usually sufficient for stability.

Sometimes one wants to transfer substantial power to a low resistance load. If the signal source cannot supply the power, the emitter follower circuit in Fig. 7 is useful. A small current from the signal source, applied to the base, can cause a large amount of current to flow through the emitter resistor or a load connected in parallel with it. Note that this amplifier does not invert: An increase in base voltage causes more collector current to flow, increasing the voltage at the emitter. It can be shown that the output voltage is only equal to the input voltage, minus the drop in the base-emitter diode, so there is no voltage gain. The circuit provides power gain, however, because there is a much larger current at the output than the input, and power is the product of current and voltage.

As drawn, the emitter follower can connect the load to the positive supply, but it cannot produce negative output voltages. Like the common emitter amplifier, the follower can be biased to amplify AC signals, but that leads to a steady current flow in the emitter resistor. If the circuit is intended for high power this implies large dissipation in the emitter resistor even in the absence of a signal. A much more interesting possibility is shown in Fig. 8. One transistor is NPN and the other PNP, connected between positive and negative supplies so that  $Q_1$  conducts on positive input swings and  $Q_2$  on negative inputs. With no input there is no collector current and hence no dissipation at all in the absence of a signal. The emitter resistor is shared by  $Q_1$  and  $Q_2$ , and is usually the load to be driven rather than a separate circuit element. This circuit is called a push-pull emitter follower, or a complementary pair, and is widely used as the output stage of relatively high power amplifiers.

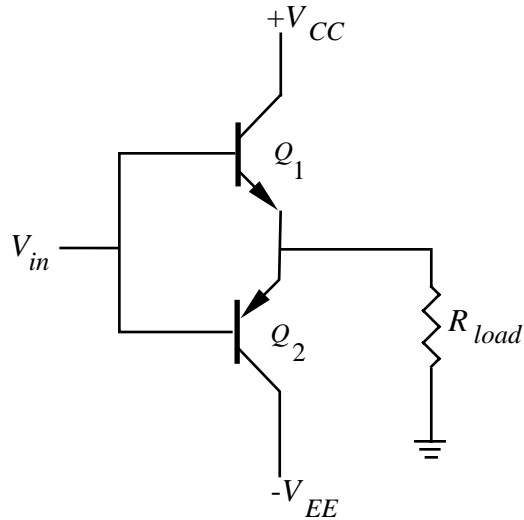


Fig. 8 A simple push-pull circuit, without bias.

Two failings of the push-pull follower are thermal runaway and crossover distortion. As in the common emitter amplifier, thermal runaway can be avoided by a small emitter resistor, typically an ohm or two, in each emitter lead. Crossover distortion occurs because the input signal must be large enough to turn on the base-emitter diode before the transistor will conduct. The circuit does not, therefore, produce an output until the input is bigger than about 0.6V, resulting in a distorted waveform. One cure is to bias the transistors so that they are on the verge

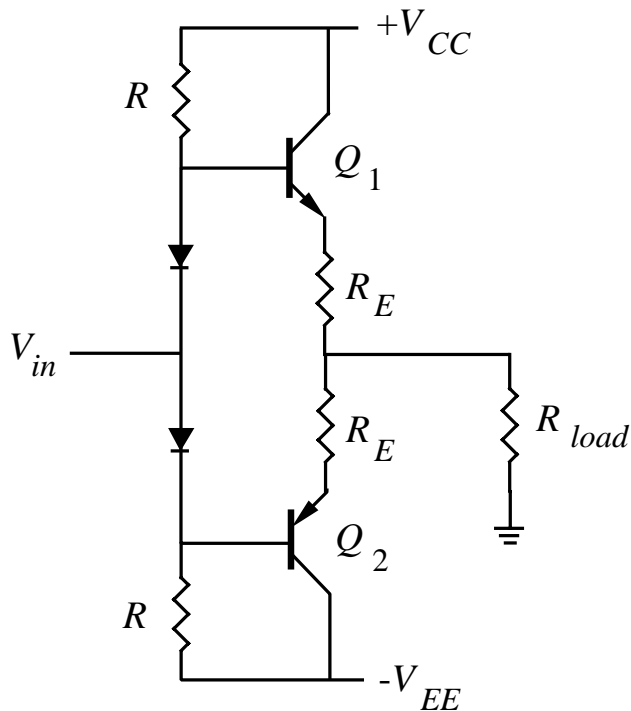


Fig. 9 A push-pull circuit with bias and runaway protection.

of conduction without a signal. This is shown in Fig. 9, where diodes are used to set the base voltage exactly one diode drop above or below zero. An alternative is to use feedback, as we will demonstrate later.

The magnitude of voltage or power gain available from a single stage of amplification is obviously limited, so most practical amplifiers consist of several coupled stages. Further refinements are often added to improve characteristics such as frequency response or distortion for particular applications. Such complex devices are usually purchased, rather than being designed by an experimentalist, so they will not be considered here.

#### D. Oscillators

An oscillator circuit converts DC electrical energy into a periodic signal. One way to accomplish this is to feed part of the output of an amplifier back to the input. If, for some frequency, the feedback is in phase at the input, and if the power gain around the loop is greater than one, the output will be a self-sustaining oscillation at the favored frequency. This can occur deliberately, as in the circuits below, or by accident.

Fig. 10 shows two classic designs, implemented with an NPN transistor as the gain element. The Colpitts circuit is based on a biased emitter follower stage. Part of the output goes to the base through the LC circuit, whose resonant frequency determines the oscillation frequency. Coupling capacitor  $C_C$  is included to block the DC path through the feedback circuit, thereby maintaining the desired bias level. The Hartley circuit is based on a common emitter

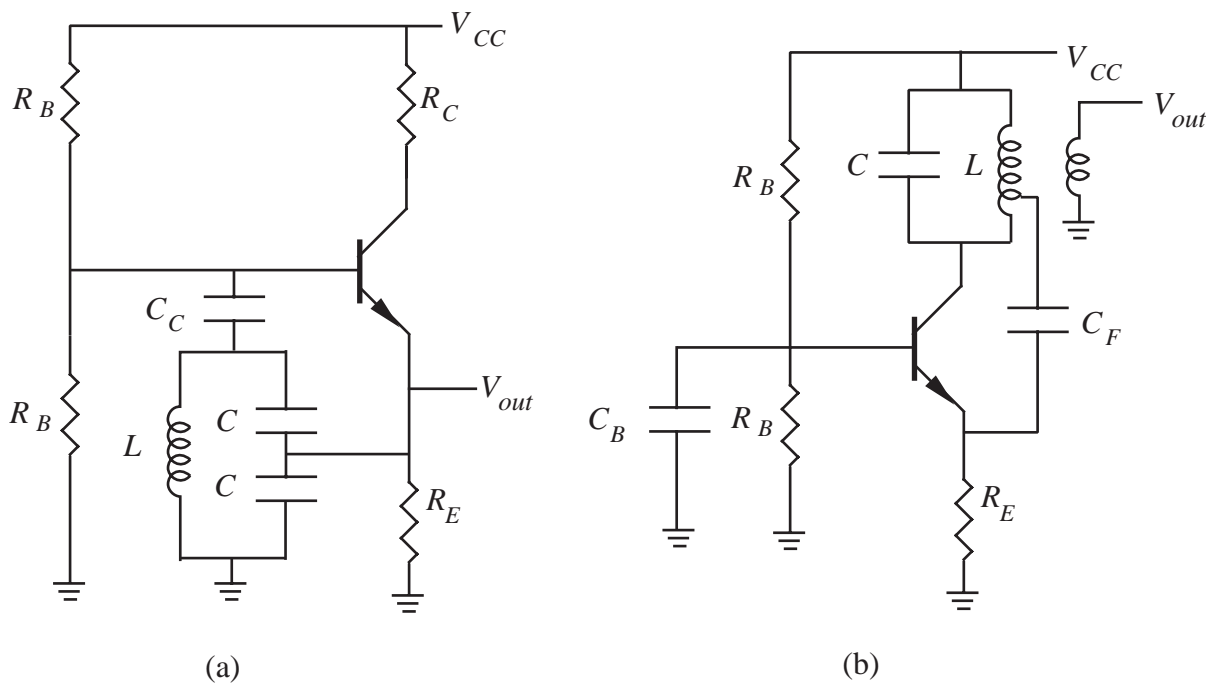


Fig 10. Single-transistor oscillator circuits: (a) Colpitts, (b) Hartley



amplifier, with an LC circuit replacing the collector resistor and with a transformer-coupled output. Without the feedback capacitor  $C_F$  this circuit would have a frequency-dependent gain, maximum at the LC resonant frequency. By coupling some of the output into the emitter circuit,  $C_F$  causes the base-emitter voltage to vary slightly, modulating the base current and sustaining the oscillation at the LC resonant frequency.  $C_B$  holds the bias voltage steady so that the feedback is not cancelled by a changing voltage drop across  $R_B$ .

Any amplifier circuit may become an oscillator if stray inductance or capacitance, perhaps within the transistor structure, in a breadboard or in a power supply, provides positive feedback at any frequency for which the gain is sufficiently large. The cure is to change the layout of the circuit so that unintended capacitances between input and output are reduced, decrease the inductance of power supplies or decouple them with a local capacitor, and decrease the bandwidth of the amplifier as much as possible. At high frequencies it may be necessary to divide the necessary gain across several stages, each of which is carefully isolated from adjacent stages.

## E. Operational Amplifiers

Operational amplifiers are multi-stage differential amplifiers characterized by high gain, high input impedance and wide bandwidth. The ideal op-amp has infinite differential gain, no common mode gain (a signal applied to both inputs is not amplified), infinite input impedance (it draws no current from the input signal), zero output impedance (output voltage is unaffected by load impedance), and the output can change instantaneously to the required value. Op-amps are often used as building blocks to create functions needed by specific experiments in much the same way that packaged gate circuits are used to synthesize digital logic. These low cost, commercially available devices come remarkably close to the ideal, so we assume perfect performance and note the effect of real limitations qualitatively.

General purpose op-amps have two inputs, labeled + and -, and a single output. When the + terminal is positive with respect to the - terminal, the output voltage goes positive, while reversing the input polarity reverses the output polarity. Because of the high gain, a very small difference in voltage at the input terminals will drive the amplifier to full output. Op-amps are, therefore, almost always used with external feedback to obtain the desired function. The effect of an ideal amplifier on the feedback circuit can be understood by applying two rules: (1) The output changes in such a way as to make the voltage difference between the inputs zero; (2) The inputs draw no current.

The circuit of Fig. 11(a) provides a simple example for analysis. Applying the second rule, we find  $I_i = I_f$ . Using Ohm's law to get the individual currents then gives the relation

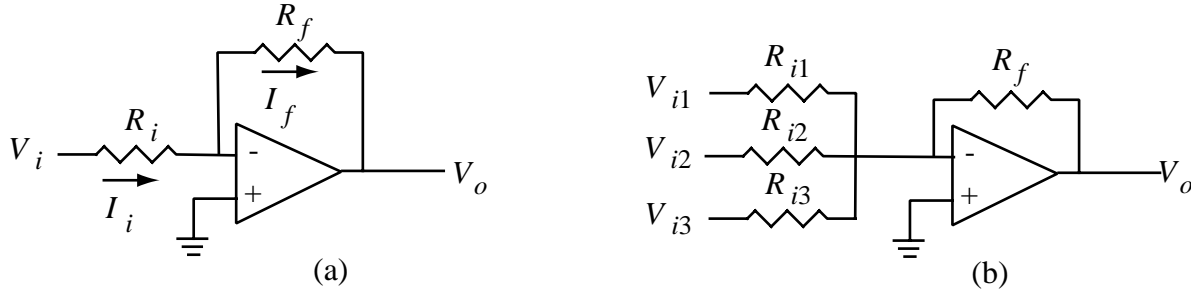


Fig. 11 (a) A simple inverting amplifier and (b) a multi-input inverter or adder.

$$I_i = \frac{V_i - V_-}{R_i} = \frac{V_- - V_o}{R_f} = I_f \quad (2)$$

The first rule requires  $V_- = 0$ , so this simplifies to

$$V_o = -\frac{R_f}{R_i} V_i \quad (3)$$

which tells us that the gain of the circuit is determined by the resistances and not by the amplifier, whose gain may vary from unit to unit. The minus sign indicates that the output is inverted relative to the input.

The same analysis applied to the circuit of Fig. 11(b) yields

$$V_o = -\frac{R_f}{R_{i1}} V_{i1} - \frac{R_f}{R_{i2}} V_{i2} - \frac{R_f}{R_{i3}} V_{i3} \quad (4)$$

so it constitutes a weighted inverting adder. The advantage of this circuit over a passive resistive combiner is that there is no interaction among the input signals. Each input sees a resistor connected to a virtual ground point at zero volts, regardless of the other inputs.

It is also possible to construct a non-inverting circuit, as shown in Fig. 12(a). The voltage at the inverting terminal is determined by the  $R_1, R_2$  voltage divider

$$V_- = \frac{R_2}{R_1 + R_2} V_o \quad (5)$$

Rule 2 requires that the amplifier adjust  $V_o$  until  $V_- = V_p$ , so

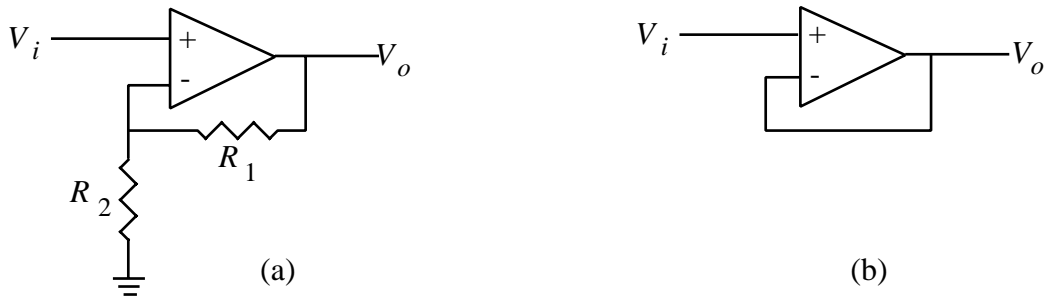


Fig 12 (a) A non-inverting amplifier or follower with gain. (b) A unity-gain follower.

$$V_o = \left(1 + \frac{R_1}{R_2}\right) V_i \quad (6)$$

Again, the voltage gain is determined by a resistance ratio, but there is no inversion. This arrangement can be generalized to several inputs, as with the inverter. Alternatively, if we let  $R_1$  become very small and  $R_2$  become very large, we arrive at the circuit of Fig. 12(b). This is called a follower, because the output voltage 'follows' the input voltage. Followers are used when it is necessary to isolate a signal source from a load or to obtain more power output than the signal source can provide.

A combination adder/subtractor, usually called a differential voltage amplifier, is shown in Fig. 13. Applying the rules, one can show that the output is proportional to the difference between the voltages at the inputs:

$$V_o = \frac{R_2}{R_1} (V_{i2} - V_{i1}) \quad (7)$$

This is useful in situations where the signal source is 'floating', that is when both terminals are at some potential above ground and the desired signal is their voltage difference. A disadvantage of

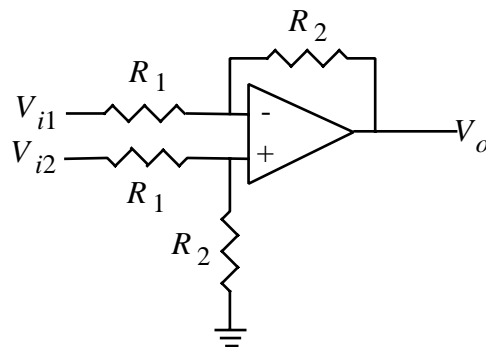


Fig. 13 One implementation of a differential amplifier.

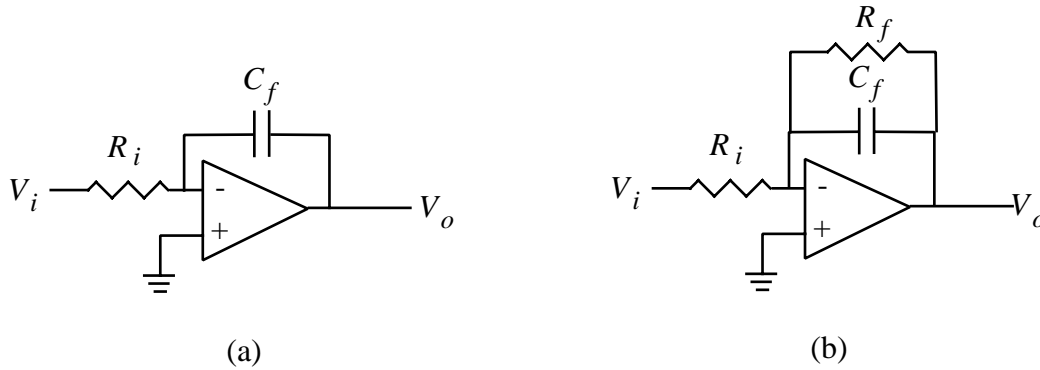


Fig. 14 (a) A pure integrator or low-pass filter. (b) An averager and low-pass filter.

this particular circuit is that it becomes inaccurate if the resistors are not exactly equal as assumed. Better and more complex designs avoid the need for precise resistor matching, and are available as combined units called instrumentation amplifiers.

There are even more interesting possibilities if we allow frequency-dependent feedback. Consider the circuit of Fig. 14(a). The analysis leading to Eq. (3) is applicable, provided we substitute the complex impedance of the feedback capacitor for the simple resistance term. The result is

$$V_o = \frac{j}{\omega R_i C_f} V_i \quad (8)$$

where  $j$  is the square root of  $-1$ . (This usage is conventional in electrical engineering, to avoid confusion with currents.) Evidently the output has a 90 phase shift and the gain varies inversely with the frequency. The circuit is therefore a filter that passes low frequencies and attenuates high frequencies.

A more physical analysis provides a different viewpoint on the same circuit. Start with the fundamental equations for a capacitor

$$CV = Q \quad I = \frac{dQ}{dt} = C \frac{dV}{dt} \quad (9)$$

and then invoke the second rule to equate the input current to the feedback current

$$\frac{V_i}{R_i} = -C_f \frac{dV_o}{dt} \quad (10)$$

This equation can be integrated to yield

$$-\frac{1}{R_i C_f} \int_0^t V_i dt = \Delta V_o \quad (11)$$

which tells us that we have built an integrator. Integrators are not common, but they are used as ramp generators in sweep circuits and in analog to digital converters.

Although the integrator is a low-pass filter, the infinite gain at DC means that any small offset will accumulate until the amplifier saturates. This problem can be avoided by adding a resistor in parallel as in Fig. 14(b). Using complex impedances again, one can show that

$$|V_o| = \frac{1}{[1 + \omega^2 R_f^2 C_f^2]^{1/2}} \frac{R_f}{R_i} V_i \quad (12)$$

At high frequencies the response falls like  $1/\omega$ , just as for the integrator, but at low frequencies the gain is limited to  $R_f/R_i$ , so this arrangement is more practical as a filter. Many other filter circuits with advantageous characteristics for particular applications are possible, but we will not consider them here.

The circuit in Fig. 15(a) is useful with transducers that produce a current, rather than a voltage output. When the photodiode is biased as shown the reverse current is directly proportional to the intensity of the light absorbed near the PN junction. Following the rules, the amplifier adjusts  $V_o$  so that all the current flows through  $R_f$ ,  $V_- = 0$ , and the output voltage is

$$V_o = -R_f I_i \quad (13)$$

Logically the 'gain' of this current to voltage converter would be expressed in ohms, but it is more common and convenient to use volts/amp. The simple resistor of Fig. 15(b) is also a current-voltage converter, but here the voltage drop across the transducer decreases as the current

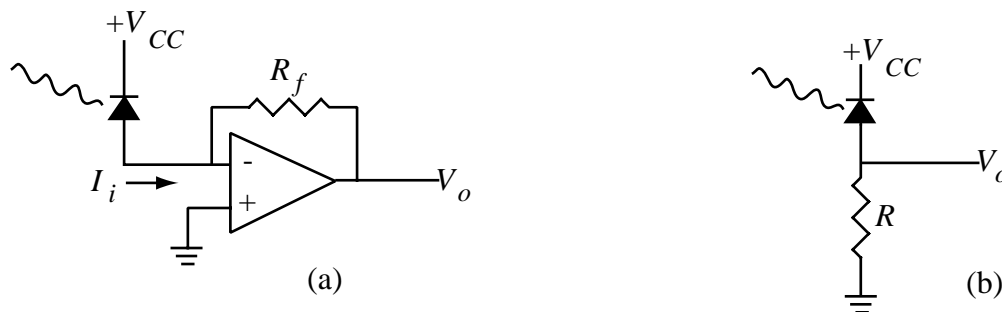


Fig. 15 Two approaches to current-voltage conversion.

increases. This may lead to non-linearities which are avoided in the op-amp circuit because the device always sees a virtual ground at the op-amp input.

A typical integrated-circuit op-amp can produce output currents up to a few milliamps and output voltages to nearly the supply voltages. If this is not sufficient, one can add circuitry to increase the output capability. The push-pull booster shown in Fig. 16 is a typical solution. Note that the feedback for the inverter is taken around the booster, not just the op-amp. This is done to remove the cross-over distortion that would otherwise occur with an unbiased complementary pair.

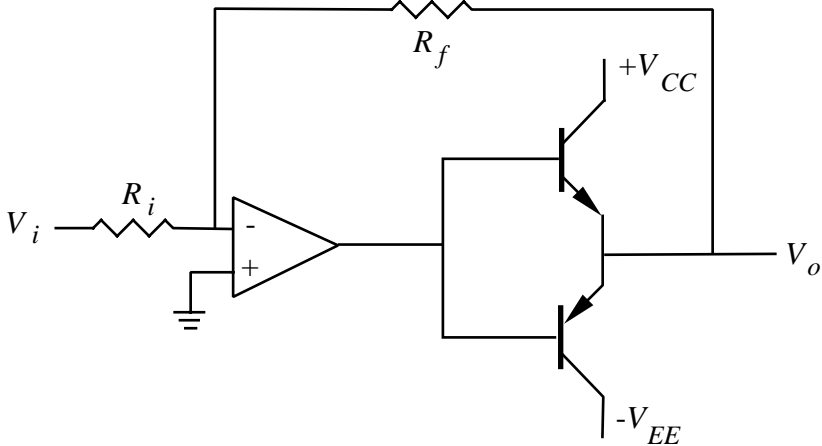


Fig. 16 Op-amp inverter with power booster on the output.