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

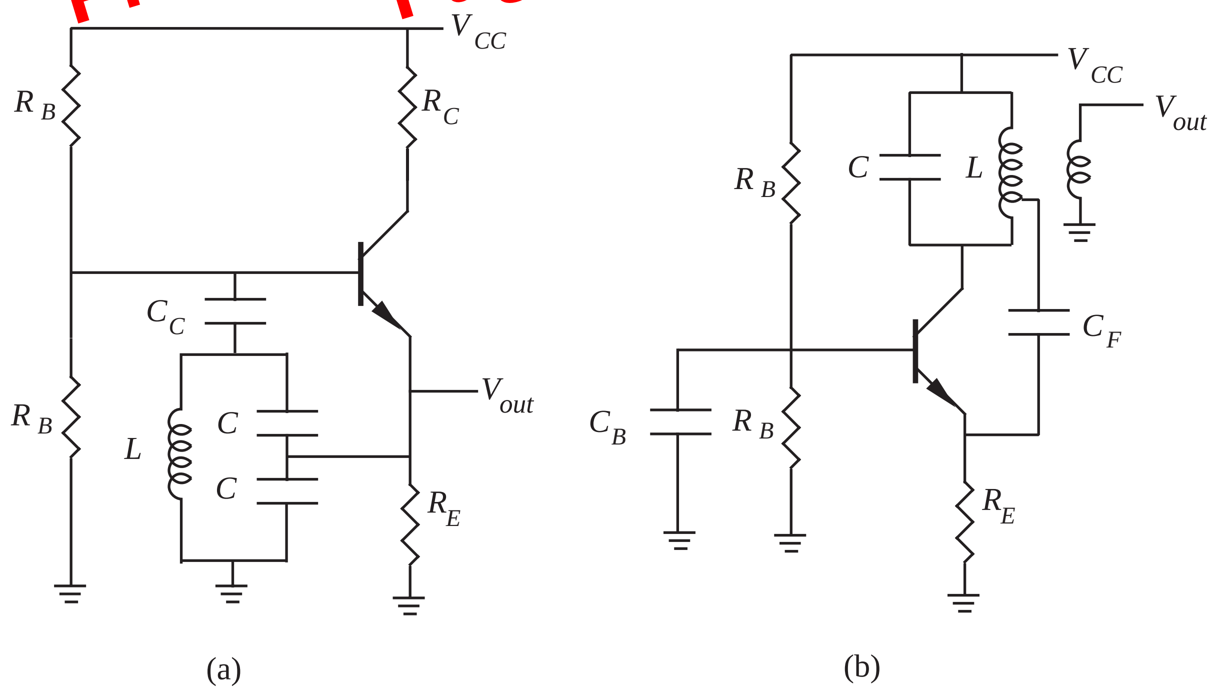
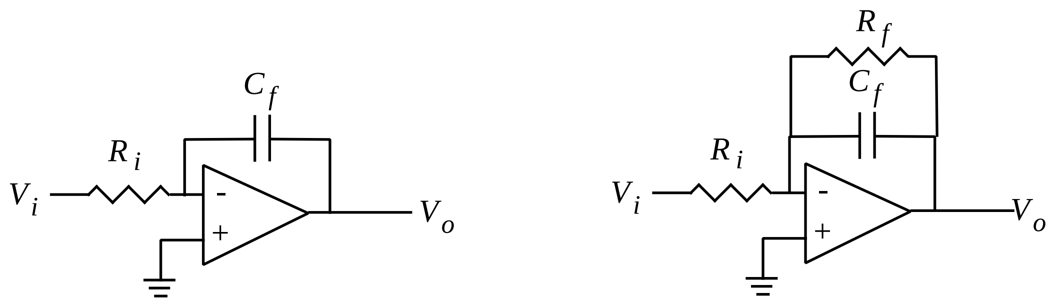


Fig 10. Single-transistor oscillator circuits: (a) Colpitts, (b) Hartley



(a) (b)

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

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

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

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

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

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

This equation can be integrated to yield