bases are created by exploiting the resonant properties of *piezoelectric* crystals cut to specific sizes. Piezoelectricity is the property found in certain crystals whereby slight changes in the crystalline structure result in a small electric field, and vice versa; exposing the crystal to an electric field causes slight deformation of its structure. Quartz is the most common piezoelectric crystal in use for oscillators, but other such crystals, both natural and synthetic, have this property. A solid object's natural resonant frequency is a function of its physical dimensions and its composition. A crystal such as quartz or certain ceramics has a predictable resonant frequency that can be finely adjusted by varying the size of the crystal slab. Furthermore, the resonant frequency is largely insensitive to variations in temperature and voltage.

A piezoelectric crystal of known resonant frequency can be incorporated with an inverting amplifier to yield an accurate clock. The amplifier drives one end of the crystal, and the other end feeds back to the amplifier's input. With proper circuit design, the crystal begins to resonate as it is driven and quickly settles into a continuous oscillation that both stimulates and is maintained by the amplifier. A generic crystal oscillator circuit found in many digital ICs is shown in Fig. 16.1. Note the crystal's graphical representation. The IC contains an internal crystal driver, which is a specialized inverter. Externally, a crystal and load capacitors are required. The load capacitors form an LC resonant circuit in concert with the crystal that is made to appear inductive. Manufacturers specify crystals with a particular load capacitance requirement for proper oscillation. The two capacitors are typically selected to be the same value, C. When this is done, the overall load capacitance, C_L, is 0.5 C plus any stray capacitance, C_S, in the circuit. Stray capacitance is often in the may range of several picofarads. A crystal specified with C_L = 18 pF might use 22-pF capacitors assuming $C_S \approx$ 7 pF.

The circuit shown is a digital oscillator, because it emits a square wave binary signal. Analog applications such as RF use a linear amplifier to drive a sine wave instead.

It is rare to find a circumstance these days in which an engineer must design a digital oscillator from scratch. Many embedded microprocessors and microcontrollers contain on-board driver circuits that require the connection of an external crystal, and usually the dual capacitors as well. When an IC does not contain an integrated oscillator, discrete crystal oscillators are the most common solution. A variety of companies, including CTS, ECS, and Ecliptek, manufacture off-the-shelf oscillators that include the crystal and driver circuit in a single package. These components typically have four terminals: power, ground, clock, and an optional clock enable.

Quartz crystals are ubiquitous, because they are inexpensive and provide a relatively high degree of frequency stability over time and temperature. Frequency tolerance between 50 and 100 parts per million (ppm), or better than 0.01 percent, is easily obtained. In contrast, most ceramic crystals, usually called *ceramic resonators,* are less expensive and have tolerances an order of magnitude worse

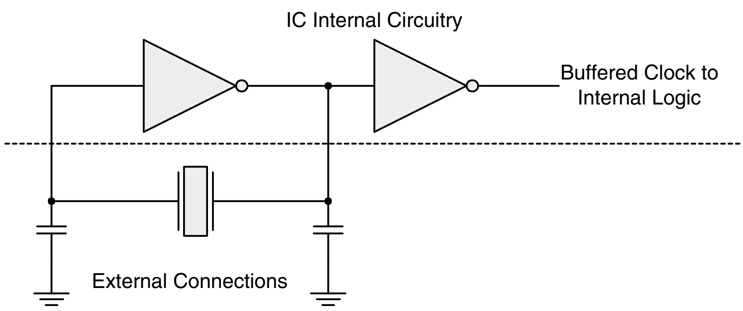

FIGURE 16.1 Digital crystal oscillator.

than common quartz crystals. Ceramic resonators are used in very low-cost applications wherein accuracy is forsaken for small cost savings. Most digital systems use quartz crystals that cost approximately $1.00, because they are reliable, they provide an accurate time base, and the crystal's cost is a small fraction of the overall system cost.

Some applications require tighter tolerances than normal crystal oscillators provide. More precise manufacturing techniques and control over materials can yield tolerances of approximately 1 ppm. Below this level, temperature control becomes a significant factor in frequency stability. So-called *oven-controlled oscillators* are specially designed to maintain the crystal at a stable temperature to greatly reduce temperature as a variable in the crystal's resonant frequency. Using this technique, oscillators are available with tolerances on the order of one part per billion! Conner-Winfield and Vectron International, among others, manufacture these high-accuracy oscillator products.

Most digital systems do not require clock accuracy better than 50 or 100 ppm. However, jitter is another clock stability characteristic of concern. Each oscillator circuit is subject to a certain amount of jitter based on the tolerance of its components. Aside from an oscillator's inherent jitter specification, ambient noise can couple into the oscillator and cause additional jitter. Therefore, it is desirable to attenuate ambient noise on the power supply that might otherwise couple into the oscillator circuit. It is common to find various types of LC filters on the power leads of crystal oscillators. A basic pi-type topology is shown in Fig. 16.2, consisting of a ferrite bead with capacitors on each side to attenuate high frequencies with small capacitors and provide lower frequency response with a larger capacitor. This circuit attenuates differential noise and provides the oscillator with a cleaner power supply relative to its ground reference.

16.2 LOW-SKEW CLOCK BUFFERS

Once a stable clock source has been established, the signal must be distributed to all components that operate on that clock. Clock distribution is critical to a digital system, because synchronous timing analysis assumes the presence of a reliable and consistent clock. Conventional synchronous buses running between ICs require a common clock so that they can work together with a known timing relationship. A single bit on a synchronous bus essentially consists of an output flop on one IC that drives an external wire, possibly passes through some combinatorial logic, and then is sampled at the input of a flop on another IC. Each IC on the bus should ideally see the same clock signal. In reality, there are slight skew variations between these individual clocks. Some clocks arrive a little sooner than others. Skew should be kept to a minimum because, like jitter, it reduces the synchronous timing budget.

Common clock signals are distributed in a low-skew manner by closely matching the delays from the clock source to all loads. Distribution delays are incurred as the clock passes through passive wires and active buffers. Consider the hypothetical clock distribution tree shown in Fig. 16.3. An oscillator drives a clock buffer, which drives five loads. All of the clock signals are point-to-point with

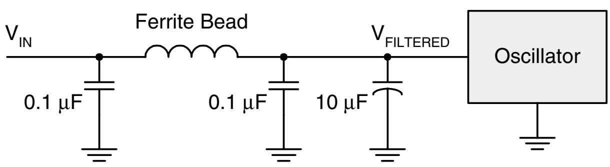

FIGURE 16.2 Oscillator LC pi power filter.