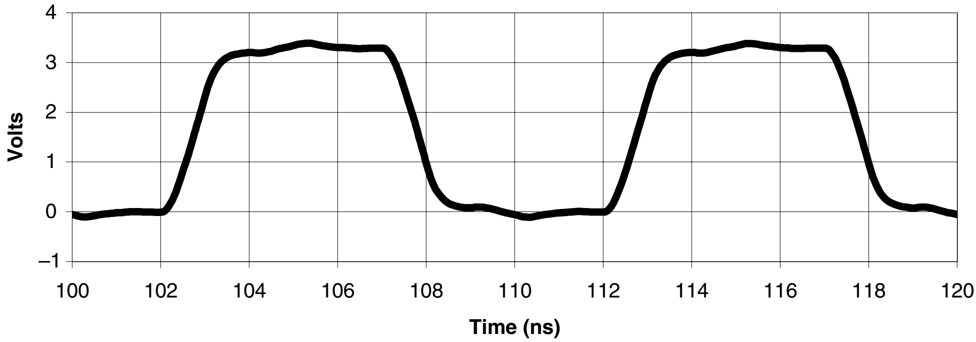

FIGURE 19.18 Transmission line with $R_T = 47\ \Omega$.

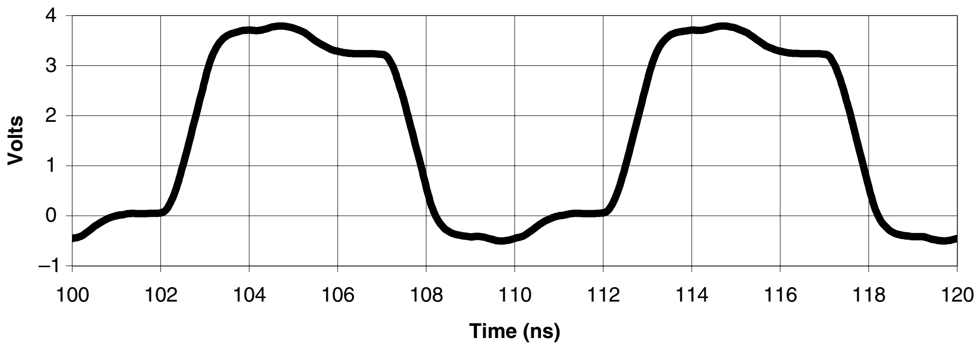

FIGURE 19.19 Transmission line with $R_T = 33\ \Omega$.

tion. As expected, there is greater distortion, because the transmission line is not as well terminated. Approximately 0.5 V of overshoot and undershoot are observed.

The preceding examples provide a brief glimpse of what is possible with Spice. In addition to passive circuits, semiconductors and active components can be modeled, enabling detailed simulations of analog amplifiers and digital circuits. Spice enables simulation to the desired level of resolution without forcing undue complexity. Small, quick simulations suffice for circuits with significant margins. More complex and detailed simulations that use highly accurate models are called for when operating near the limits of technology where margins for errors are very small.

19.9 TEST EQUIPMENT

Test equipment needs vary, depending on the complexity of a project. There are general types of test equipment used to debug and measure wide varieties of circuits, and there are very specialized tools designed for niche applications. This section provides a brief introduction to the more common pieces of test equipment found in typical engineering laboratories. As with any equipment, costs and capabilities vary widely. A 25-MHz analog oscilloscope may cost several hundred dollars, whereas a

1-GHz digital oscilloscope can cost tens of thousands of dollars. Both oscilloscopes perform the same basic function, but one performs that function at much higher frequencies and with more powerful measurement features. The following companies are among those who manufacture some or all of the test equipment mentioned in the following text: Agilent Technologies, B&K Precision, Fluke, Kenwood, LeCroy, and Tektronix.

Perhaps the most basic test tool is the *multimeter*, available in analog and digital varieties. A digital multimeter is called a *DMM*. Multimeters measure voltage, resistance, current, and sometimes capacitance, inductance, and diode forward voltages. Measuring voltage and current are passive functions, but the other capabilities require injecting current into a component under test to discern its voltage or other properties. DMMs are very common because of their low cost and ease of use.

Another relatively inexpensive test device is called a *logic probe* and is useful for engineers on a budget. A logic probe is placed onto a digital signal, and its indicators, visual and/or audible, tell whether a logic 0 or logic 1 is present and whether the line is clocking or pulsing high or low. Very basic debugging can be done with a logic probe in the absence of an oscilloscope. A logic probe, for example, can determine if a chip-select is being asserted to a device on a microprocessor's bus. Unfortunately, a logic probe cannot provide other useful information such as pulse duration and the relative timing of multiple signals.

Oscilloscopes have been mentioned in various contexts thus far. Their basic function is to display a time-domain view of voltage over very narrow time spans. Traditionally, oscilloscopes were fully analog instruments with cathode-ray tubes (CRTs) that required constant scanning to maintain a visible image. As such, a traditional analog oscilloscope is most useful with repetitive signals that could continually retrigger the trace moving across the CRT. Digital oscilloscopes, or digital storage oscilloscopes (DSOs), are hybrid analog and digital devices that sample an analog input and then load the digitized data stream into a buffer where it can be manipulated as a computer graphic. This memory feature allows digital oscilloscopes to capture single-shot events and display them indefinitely. Most oscilloscopes have at least two channels, allowing two signals to be displayed simultaneously and correlated with one another. More expensive oscilloscopes have four or more channels.

Once a waveform is displayed, analog and digital oscilloscopes enable various measurements to be taken, including frequency, amplitude, and relative timing between channels. Low-budget analog oscilloscopes may have only grid markings on the screen from which measurements can be manually estimated. More expensive oscilloscopes have built-in marker functions that automate the measurement process to varying extents.

The bandwidth of an oscilloscope is an important characteristic that indicates the frequency handling capabilities of its amplification and sampling circuits. An oscilloscope cannot be expected to provide meaningful observations when operated near the limits of its specified bandwidth. Keep in mind that digital signals contain high-frequency components created by sharp transition edges. A 100-MHz clock signal represents more than 100 MHz of bandwidth. Using an oscilloscope with greater bandwidth enables observations with less attenuation of higher frequencies. Rules of thumb vary on bandwidth versus actual signal frequency. Accepting an order-of-magnitude difference between a digital signal frequency and oscilloscope bandwidth yields good results. If this appears too expensive, a trade-off must be made between cost and the accuracy of measurements.

DSOs have another important defining characteristic: sampling rate. Sampling rate effects differ, depending on the capabilities of the oscilloscope and on whether the signal being measured is a single-shot event or repetitive, such as a clock. Some DSOs treat these two classes of signals differently. Single-shot events must be sampled in a single pass and are subject to a Nyquist limit imposed by the sampling rate. Measuring a signal with frequencies too near the Nyquist frequency (one-half the sampling rate) results in unacceptable distortion of the signal. Good results are attainable when measuring signal frequencies that are less than one-fifth to one-tenth of the sampling rate. Some DSOs are able to sample higher-frequency repetitive signals by combining the samples from many