Chapter 3 Inputs and Outputs.

All digital circuits require inputs and generate outputs. If the inputs don't come from other digital circuits, it is usually necessary to condition or convert them to make them into valid digital signals. Likewise, if the outputs are not destined to become inputs of another digital circuit, they must be conditioned to light indicators, actuate motors, drive speakers, etc. This chapter provides an overview of a few basic input and output signal conditioning techniques. It is not intended to be a thorough treatment of the subject, but it should provide enough detail to put the design of digital circuits in context.

3.1 Switches

One of the most common input devices (particularly when human interaction is involved) is the switch. Switches come in all shapes and sizes (Figure 3-1). There are pushbuttons, keypads, slide switches, toggle switches and limit switches. There are switches that are activated by acceleration, temperature, pressure or magnetic field. Electrically, however, all switches behave the same. When a switch is *open*, no charge can flow through its terminals, but when it is *closed*, the terminals act like a single conductor and charge flows freely.

Figure 3-1 Various Switches.

How can we turn a switch closure into a voltage level change? To answer that, we need to know a little more about electrical current and resistance. Recall from Section 1.1 that (positive) charge at one electrical potential will flow to a lower potential if it is allowed to. This movement of charge is called current and it is measured in Amperes (abbreviated A). An Ampere (or Amp) is equivalent to one Coulomb per second.

We never want the charge to move all at once. If it did, the electric potential of the voltage source could not be maintained (and it may melt some wire along the way). We need something to limit the current flow, and that something is called a *resistor*.

When a resistor is in an electrical circuit, the current through the resistor, *I*, is proportional to the voltage, *V*, across it. The resistance, *R*, is the constant of proportionality:

$$V = IR \tag{3.1}$$

This relationship is known as Ohm's law, named after the 19th century German physicist, Georg Ohm. Not surprisingly, resistance is measured in Ohms (abbreviated Ω). Solving Ohm's law for the current we get:

$$I = \frac{V}{R} \tag{3.2}$$

Note that if the voltage across a resistor is limited to *V*, the current it will draw from the voltage source is limited to *V*/*R*.

What has all this to do with digital signals and switches? The answer is that a digital signal can be produced by connecting a resistor and a switch to a voltage source, usually V_{CC} (or V_{DD}). To illustrate this circuit, we will use a schematic diagram (Figure 3-2).

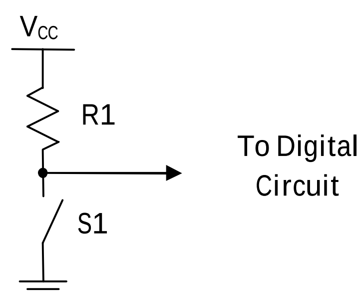

Figure 3-2 Using a Switch and V_{CC} to Generate a Digital Signal.

The symbols denoted by R1 and S1 represent the resistor and the switch respectively. If the switch is closed, the signal is *low* because it is electrically connected to ground. (By definition, ground is 0 Volts, which is *low* for most digital technologies.) While the switch is closed, the current through R1, I_{R1}, is V_{CC}/R1, but it has no bearing on the digital signal. If the switch is open, the digital signal is *high*. This is because there is no current flowing through R1 (except a tiny amount flowing into the digital circuit). Ohm's law tells us that the voltage drop across R1 is $V_{R1} = I_{R1} \cdot \text{R1} \approx 0$, which means that the signal voltage is essentially V_{CC}, a potential that is generally considered to be *high*.

The only question that remains is what value of resistance should we use for R1? If the resistance is too small, too much current will flow when the switch is closed, and that might destroy the voltage source or affect battery life. If the resistor is too large, it may not be able to conduct enough current to drive the input(s) of the digital circuit high. For CMOS (complementary metal-oxide-semiconductor) digital circuits, resistances in the range 10kΩ to 100kΩ usually work well. For TTL, smaller resistances work better, typically in the range 1kΩ to 5kΩ.

Example 1.15. A battery-operated digital circuit has $V_{DD} = 3.3V$. A pushbutton and a 50kΩ resistor are used to produce a digital signal. What is the current through the resistor when the pushbutton switch is closed?

Solution: When the pushbutton switch is closed, the voltage across the resistor is 3.3V. Using Ohm's law,

$$I = \frac{V}{R} = \frac{3.3}{50{,}000} = 66\mu A$$

The current through the resistor is 66 microamperes.

Note: The resistor and switch may be exchanged in CMOS circuits but not in TTL circuits. This is because TTL inputs require much more current when they are driven low than they do when they are driven high.

3.2 Phototransistors

Another device that is commonly used for digital input signals is the phototransistor. This device acts like a (one-way) switch that closes when it detects light of a particular wavelength. These devices are often paired with an LED (light emitting diode) to detect a blockage in the line of sight between them. (Many garage doors have a safety feature that works in this way.)

Figure 3-3 LED and Matching Phototransistor.

Another popular application of LEDs and phototransistors is the *shaft encoder* (Figure 3-4). A simple shaft encoder can be made by attaching a slotted wheel to a shaft and positioning a phototransistor in such a way that as the shaft turns, light from an LED is alternately blocked and unblocked. Digital circuitry then counts the pulses to determine how far the shaft has turned. If another phototransistor is added slightly offset from the first, the digital circuitry can also know which way the shaft is turning.

Figure 3-4 Shaft Encoders.

One other common application of phototransistors is the opto-isolator (or optocoupler). This device is simply an LED and a phototransistor in a single package, but it is surprisingly useful when a signal comes from circuitry that does not share the same ground. The opto-isolator makes it possible for anything that can turn on an LED to be converted into a digital signal.

Whether a phototransistor is used in an opto-isolator or to detect light, the technique for generating the digital signal is the same. Connect a resistor, R1, to a phototransistor, Q1 as shown in Figure 3-5. This is the same approach that we used for switches, except now it is necessary to consult the datasheet for the phototransistor (or opto-isolator) to choose a value for R1.

When light strikes the phototransistor, current flows and causes the signal voltage to drop to a low voltage. When the light stops, the current stops as well and the signal returns to its high voltage.

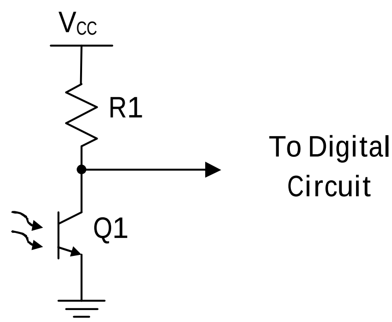

Figure 3-5 Using a Phototransistor to Generate a Digital Signal.

3.3 Analog to Digital Converters

One application of digital circuits that has become popular over the past few decades is digital signal processing. Typically this involves processing a real-world signal (such as the sound carried to a microphone) in the digital realm. To do this, the real-world signal must first be converted to an analog electrical signal using a microphone, sensor, transducer, etc. From there, the signal must be converted to binary (or two's complement) with enough bits to provide the needed precision. This conversion is accomplished with a device called an *Analog to Digital Converter* (also known as an A/D Converter or ADC). The output of the ADC is then fed directly to the digital processing circuit (Figure 3-6).

The number of data bits that an ADC generates is called its *resolution*. Most ADCs have 8 to 12 bits of resolution, but 18-bit ADCs are available. Some ADCs generate bits continuously, while others produce valid data only after a conversion process. Some ADCs have multiple analog inputs that can be selected; others do not. For more information on Analog to Digital Conversion, refer to [TBD].

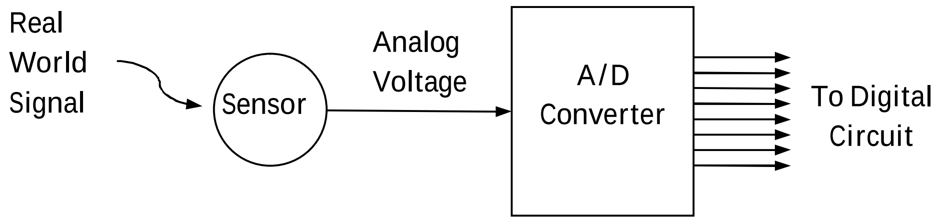

Figure 3-6 Conditioning a Real-World Signal for Digital Processing.

3.4 Comparitors

Sometimes, we only need to know whether or not a real-world signal has exceeded some limit or *threshold*. For example, suppose a digital circuit has the job of opening a refrigeration valve if the temperature is too warm and it's not in a defrost cycle. We can convert the temperature to digital with an ADC and compare it to a setpoint digitally, but it's not necessary to know the temperature, only that it is too warm. A simpler approach is use a *comparator*, a device that compares two analog signals and generates a digital result. Figure 3-7 shows a simple comparator circuit with an adjustable setpoint. If the analog voltage reaches the threshold voltage set by the *potentiometer* (variable resistor) R1, the output of the comparator will be high. Otherwise, it will be low.

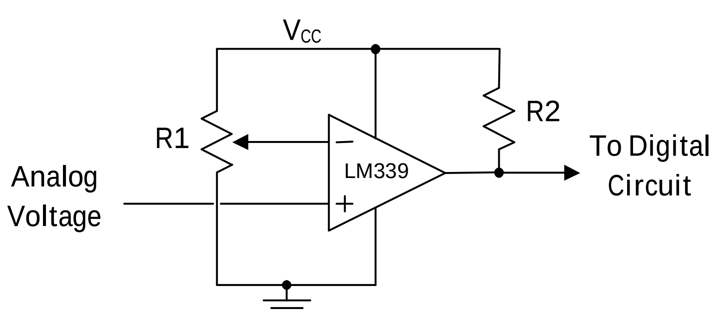

Figure 3-7 Using a Comparator to Generate a Digital Signal.

Resistor R2 is often necessary because many comparators are only capable of driving the signal low (much like the switches and phototransistors discussed earlier).

> **Threshold**
>
> The term threshold dates back to the twelfth century when straw was placed on the floor to provide warmth and cushioning. A small raised strip, the threshold, was placed under the doorway presumably to keep the straw from spilling out when the door was open. But if too much straw piled up near the door, it would reach the threshold and start to spill out.
>
> In electronics, threshold has come to mean the voltage (or current) at which a certain characteristic begins to appear.

3.5 Light Emitting Diodes (LEDs)

One very common thing to do with a digital signal is to use it to light an LED. LEDs are used as indicator lights and segments of the familiar seven-segment display. They are sometimes used for large video screens and moving signs. LEDs that generate infrared wavelengths are also popular for TV remotes, and opto-isolators.

An LED is a device that emits light when current, I_f, flows through it in one direction. The amount of current varies from one type of LED to another, but many LEDs will light with very little current. If that current is less than what the digital output can *sink* (we'll see how to find that in Chapter 6), the LED can be driven directly from a digital signal with a single resistor (Figure 3-8).

Current Sources and Sinks

A digital output becomes low by establishing a current path to ground, and when current flows through that path, we say that the output is *sinking* the current.

Likewise, when an output is high it establishes a current path from V_{CC}. When current flows through this path we say that the output is *sourcing* the current.

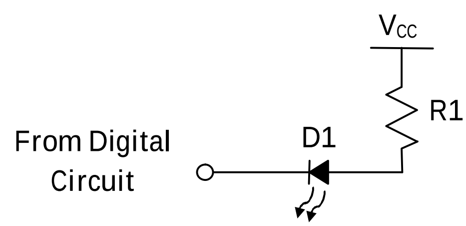

Figure 3-8 Driving an LED. A Low Signal Lights the LED.

When the output is low, the LED is lit because current flows from V_{CC}, through R1 and D1 and into the digital output. When the output is high, no current flows and the LED turns off.

A serious analysis of this circuit to find the value of R1 requires an understanding of microelectronics that is beyond the scope of this text, but as a rule of thumb, the voltage drop across an LED when it is *forward biased* (lit) is about 2.0 Volts, and the voltage of a low digital output is about 0.5V. This leaves V_{CC}-2.5 Volts across the resistor, and by Ohm's law,

$$R1 = \frac{V_{CC} - 2.5}{I_f}$$

For CMOS circuits, the LED can also be configured as shown in Figure 3-9. In this case, the digital output is sourcing the current for the LED. This configuration has the perceived advantage that a high (rather than a low) output voltage turns on the LED.

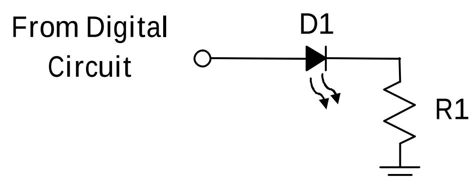

Figure 3-9 Driving an LED, A High Signal Lights the LED (CMOS only).

If the LED current is greater than the output's ability to source or sink, it will be necessary to *buffer* the signal. A buffer is a digital device that is designed to boost the output current of a digital signal. Buffers will be covered in more detail in Chapter 5.

3.6 Solid State Relays

Sometimes the output of a digital circuit needs to drive a load such as an AC motor or fluorescent light. One popular way to do this is to use a *Solid State Relay* (SSR), which is essentially an isolated switch controlled by an input voltage (Figure 3-10).

Figure 3-10 Solid State Relay.

When the voltage on the input exceeds the *pick-up voltage*, the switch closes and current flows to the load. It is not unusual for an SSR to have an input resistance of 700-1000Ω and a pickup voltage as low as 3 Volts, which means that it can be driven by practically any digital signal. Figure 3-11 shows two ways that a digital signal can control and SSR. Note that option (b) is not available for TTL signals because they cannot source enough current.

Solid state relays are also available for DC loads.

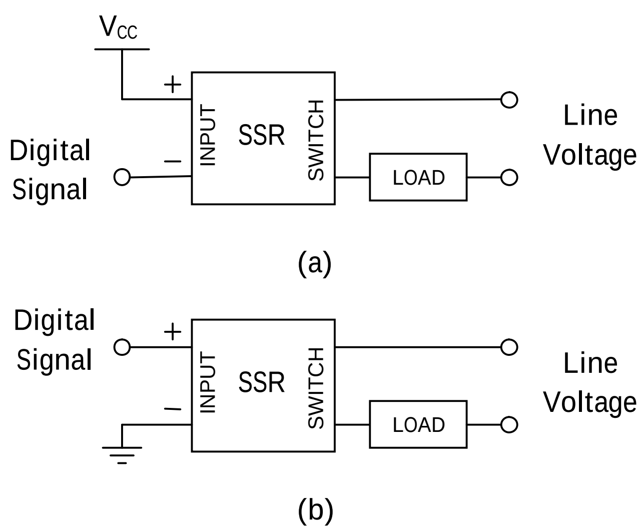

Figure 3-11 SSR Interface. (a) Low Signal Closes Switch. (b) High Signal Closes Switch.

3.7 Digital to Analog Converters

Often, particularly in digital signal processing applications, it is necessary to convert a multi-bit digital signal to an analog signal. The analog signal might drive a speaker, dim a light or control the speed of a motor. The conversion is handled by a device called a *Digital to Analog Converter* (or D/A Converter or DAC). A DAC is a relatively simple device: a multi-bit digital signal that represents a binary (or two's complement) number is presented to the DAC, and the DAC generates an analog voltage or current that is proportional to the number. (See Figure 3-12.)

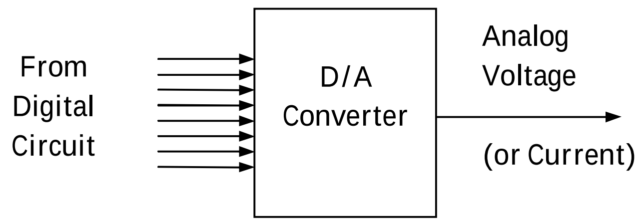

Figure 3-12 Conditioning a Real-World Signal for Digital Processing.

Like an ADC, the resolution of the DAC is equal to the number of bits in the binary (or two's complement) number. DACs with 8 to 16 of resolution-bits are common, but larger DACs are available. The internal construction of the DAC is beyond the scope of this text, but more information on the subject can be found in [TBD].

Exercises

1. Find at least one digital input device other than the ones mentioned in the text.
2. Find at least one digital output device other than the ones mentioned in the text.
3. Find and print the datasheet for (a) an opto-isolator, (b) an A/D converter, (c) a comparator, (d) a seven-segment LED, (e) a solid state relay and (f) a D/A converter

Bibliography

Voltmeter – Northern Tool & Equipment
Logic Probe – BK Precision
Logic Analyzer – Test Equity

Most digital circuits require inputs, and it is often necessary to condition input signals so that they fall into the valid voltage range for digital signals. In order to do this properly, it is necessary to understand the input characteristics of digital devices.

The characteristics of every digital device available for purchase are documented in its datasheet. Datasheets can range in size from a few pages to several hundred pages. The datasheet provides electrical characteristics, the functional description and packaging options. The input characteristics of a device are largely defined by the four parameters, V_{IL}, V_{IH}, I_{IL} and I_{IH}.

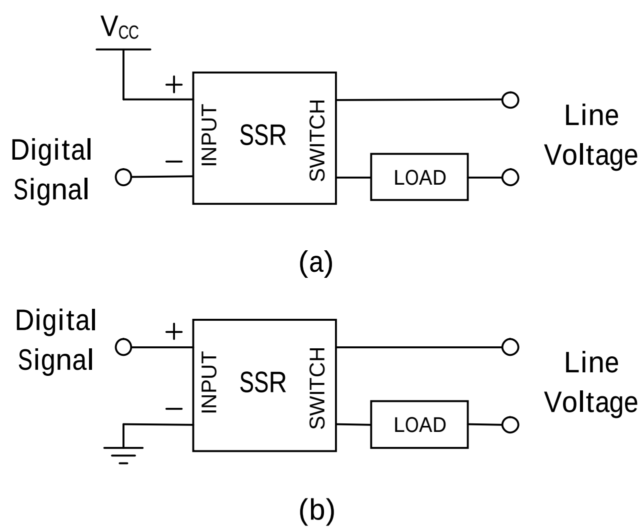

Figure 1-15 SSR Interface. (a) Low Signal Closes Switch. (b) High Signal Closes Switch.