Chapter 1 Digital Signals.

Before we can design any kind of digital circuit or system, it is crucial to understand the concept of a digital signal. This chapter explains what digital signals are, how to measure them and what circuitry we can use to create them.

1.1 Voltage

Electrons and protons are charged particles. The electrons are negative and the protons are positive. Charge is measured in *Coulombs*; one Coulomb is equivalent to the charge of 6.2415×10^{18} protons.

When positively charged particles and negatively charged particles are separated, they are attracted to each other and have the potential to do work. This *electric potential* is measured in *Volts*, and it tells us how much work a Coulomb of positive charge will do to get back to the negative charge.

For example, each Coulomb of charge that travels from the positive terminal of a twelve-volt battery to the negative terminal will do twelve Joules of work. (In actual fact, the negatively charged electrons travel from the negative terminal to the positive terminal, and the electrons that arrive at the positive terminal are not necessarily the ones that left the negative terminal. But it's just easier, and mathematically equivalent, to think of the positive charge as the one that moves.)

All voltages are relative. This means that you can't tell what absolute voltage is on the negative terminal or the positive terminal of the battery. All you can say is that the positive terminal is twelve volts higher than the negative terminal. (Your Physics professor will disagree. He will say the electric potential is zero at a point infinitely far away, but since we can't very well measure anything at that distance, it's not particularly useful.)

Benjamin Franklin

In 1751, scientists had identified two types of electricity: resinous and vitreous. Benjamin Franklin was the first to label these as positive and negative. Resinous electricity became negative and vitreous electricity became positive. He had no idea that electrons are the principal charge carriers and that his arbitrary choice just made them all negative. This made things confusing when the electron was discovered in 1897 because the electrons flow in the opposite direction of the current.

It just gives credence to the old adage that if there is a 50% chance of getting it right, there's a 90% chance of getting it wrong.

Since the voltages are all relative, we simply choose one (usually the negative terminal of a battery or power supply) and call it ground (i.e. declare its potential to be zero volts). All voltages thereafter are measured relative to ground.

Insulators are materials whose electrons are tightly bound to their nuclei. This makes it difficult or impossible for charge to move or flow through an insulator. Conductors, on the other hand, have a large number of free electrons. This allows charge to move readily about the conductor, expending very little energy. Since little or no energy is lost, we can assume that the electric potential, or voltage, is the same throughout the entire conductor. This property makes conductors an ideal conduit to convey voltage and charge from one part of a circuit to another.

1.2 High and Low

A signal is any measurable quantity that varies with time (or space). For a digital signal, that measurable quantity is usually the voltage on a conductor, and that voltage is (almost always) restricted to one of two values: *high* and *low*. The meaning of high and low depends on the technology that is being used. For example, an older (but still popular) technology called Transistor-Transistor Logic (TTL) defines to a low value to be 0.8 Volts or less and a high value to be 2.0 Volts or more. The voltages between 0.8 Volts and 2.0 Volts are forbidden. A list of high and low voltage ranges for some other technologies is given in Table 1-1.

Table 1-1 High and Low Voltage Ranges for Some Digital Technologies.

Technology	Voltage Source	Low Voltage Range	High Voltage Range
TTL	5.0V	0.0 – 0.8V	2.0 – 5.0V
6 Volt CMOS	6.0V	0.0 – 1.8V	4.2 – 6.0V
3.3 Volt CMOS	3.3V	0.0 – 1.0V	2.3 – 3.3V
ECL	-5.0V	-2. 0 – -1.35V	-1. 25 – 0V

1.3 Measuring Digital Signals

Sometimes (usually when a circuit is not behaving as intended) it is necessary for us to measure the voltage of a signal and from that determine if it is in a high, low or forbidden voltage range. To do this, many tools are available. If a signal is static (i.e. not changing at the moment), a logic probe or a volt meter is sufficient. If the signal is changing with time, an oscilloscope or logic analyzer is required.

To use the logic probe (Figure 1-1), the black wire (or lead) must first be connected to the ground of the digital circuit and the red lead must be connected to a voltage source (such as a battery or power supply). Usually the same voltage source that powers the digital circuit can also power the probe. When the tip of the logic probe touches a signal, one or more LEDs on the probe light to indicate whether the signal is high, low or changing.

To use the volt meter (Figure 1-2), the black probe must be connected to ground and the meter must be configured for DC Volts. Then, when the red probe touches a signal, the voltage of that signal is displayed on the volt meter. Again, what that voltage means depends on the digital circuit technology.

Figure 1-1 Logic Probe

Figure 1-2 Volt Meter

An oscilloscope is a device that displays the voltage of a signal as a function of time (Figure 1-3). Oscilloscopes typically have 2-4 channels, which means they can display 2-4 signals simultaneously. To use the oscilloscope, connect the black ground lead (of each probe) to the digital circuit ground and connect the probe(s) to the signal(s) of interest. When the oscilloscope is triggered (usually by a voltage change on one of the signals) a waveform for each connected signals is displayed.

Figure 1-3 Oscilloscope

Figure 1-4 Mixed Signal Oscilloscope

Another kind of oscilloscope that is becoming popular is the mixed signal oscilloscope. Most oscilloscopes are designed to display 2-4 analog signals, but a mixed signal oscilloscope can display those analog signals plus multiple (usually 16) digital signals. For complicated digital circuits, the ability to display many signals at once can be a great benefit.

If even more channels are required, it will be necessary to use a logic analyzer (Figure 1-5). A logic analyzer has no analog channels but may have over 200 digital channels.

Figure 1-5 Logic Analyzer

1.4 Generating Digital Signals

So, how can we make a digital signal? One way is to connect two switches to a voltage source. (The voltage must correspond to a *high* digital signal. See Table 1-1.) To illustrate, we will use a *schematic diagram* or simply *schematic* (Figure 1-6). The symbols in the schematic denoted by S1, S2 and V1 represent the two switches and the voltage source respectively. The lines in the schematic represent conductors or wires.

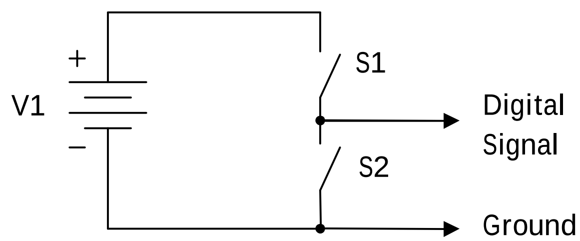


Figure 1-6 Using Switches to Generate a Digital Signal.

A switch is a device that behaves like an insulator or a conductor depending on whether the switch is *open* or *closed*. When a switch is closed, the terminals act like a single conductor and charge can flow from one terminal to the other. When a switch open, it acts like an insulator and no charge can flow. (For many students, the terms *open* and *closed* seem backward when they are applied to switches. This is probably because valves behave in exactly the opposite way.)

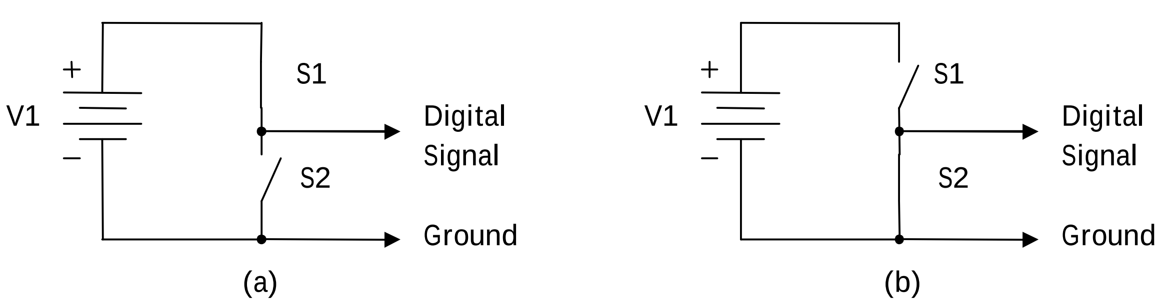


Figure 1-7 Using Switches to Generate (a) a High Signal and (b) a Low Signal.

Consider what happens if S1 is closed and S2 is open (Figure 1-7a). The digital signal is connected to the voltage source and therefore has the same electric potential, so it is *high*. If instead S1 is open and S2 is closed (Figure 1-7b), the digital signal is connected to ground and is therefore *low*.

Generating a digital signal always requires a voltage source, but it is not necessary to use a separate voltage source for each signal. Usually a single voltage source called V_{CC} or V_{DD} is used for all the signals in a circuit (Figure 1-8).

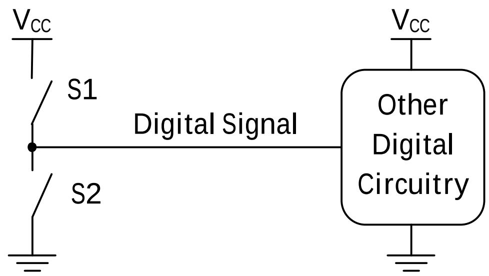
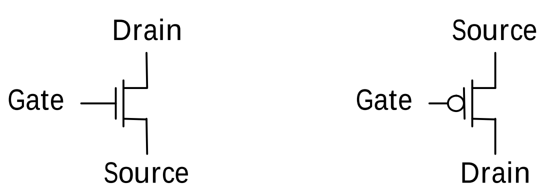


Figure 1-8 Using a common V_{CC}.

Note the use of the ground symbol in Figure 1-8. All points in the schematic that are connected to a ground symbol (⏚) are connected together. Similarly, all points in the schematic that are labeled with the same name (such as V_{CC}) are connected together as well.

Of course, generating digital signals with switches is impractical (unless you have a tiny gnome to actuate them). Instead of switches, we mostly use *metal-oxide semiconductor field effect transistors* (MOSFETs), but not always. The TTL technology, for example, uses *bipolar junction transistors* (BJTs).

It is not necessary to have a detailed understanding of MOSFETs in order to design digital circuits, but it is helpful to understand some basic concepts. The MOSFETs used in digital circuitry come in two flavors, N-channel (or NMOS) and P-channel (or PMOS). The schematic symbols for these devices are shown in Figure 1-9. Each MOSFET has three terminals: *source*, *drain* and *gate*. The source and drain act, to some extent, like a switch that is controlled by the voltage on the gate.



(a) N-Channel (b) P-Channel

Figure 1-9 NMOS and PMOS Transistors.

The behavior of a MOSFET is governed by the relationship between its *gate-to-source voltage*, V_{GS} and its (nearly constant) *threshold voltage*, V_{th}. For NMOS transistors, the source voltage is assumed to be more negative than the gate, so V_{GS} and V_{th} are both positive. For PMOS transistors, the source voltage is more positive than the gate, so V_{GS} and V_{th} are both negative.

If V_{GS} is between zero and V_{th}, the MOSFET is in its *cutoff region* and the source and drain behave like an open switch. A MOSFET is in this state it is said to be *off*. When V_{GS} exceeds V_{th}, the MOSFET is in its linear or saturation region (depending on the drain voltage) and behaves much like a closed switch. A MOSFET in this state is said to be *on*.

To create a digital signal using MOSFETs, we need only replace the switches in Figure 1-8 with MOSFETs (Figure 1-10). Note that the source of the PMOS transistor is connected to V_{CC} and the source of the NMOS transistor is connected to ground. When MOSFETS are connected in this way they are said to be *complementary*.

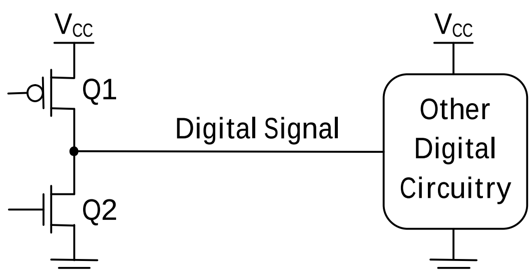


Figure 1-10 Generating a Digital Signal with Complementary MOSFETs.

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 appear.

All that remains is to connect the gates. One simple but surprisingly useful thing to do with the gates is to tie them together and call it an input (See Figure 1-11). When the input is *low*, the PMOS transistor, Q1, is on and the NMOS transistor, Q2 is off. This causes the output signal to go *high*. But when the input is *high*, Q1 is off and Q2 is on, so the output signal goes *low*. This device is called an *inverter* because the output is always the inverse of the input.

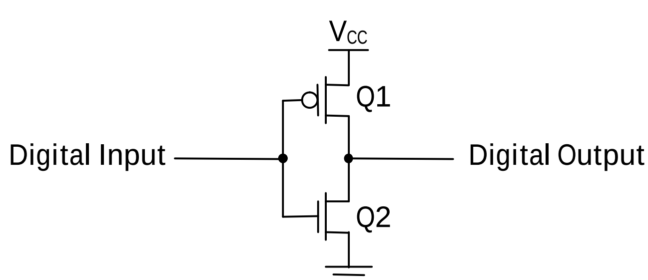
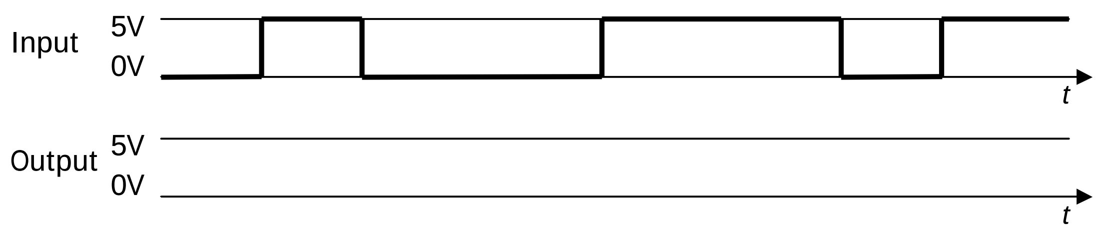


Figure 1-11 CMOS Inverter.

The technique of using complementary MOSFETs to implement digital circuits is the cornerstone of CMOS (*Complementary Metal-Oxide Semiconductor*) technology, which is the most prevalent digital circuit technology today. We will learn how to combine MOSFETs to make other CMOS devices in Chapter 5.

Exercises

1. Electric potential is generated by separating charged particles. Do you think that separating additional particles will lead to higher, lower or the same potential. Explain.
2. Suppose we choose the positive terminal of the voltage source to be ground. What would the voltage ranges for high and low be for (a) TTL and (b) 3.3 Volt CMOS.
3. Under what conditions would (a) the voltmeter give you more information than the logic probe, (b) the oscilloscope give you more information than the voltmeter, (c) the logic analyzer give you more information than the oscilloscope?
4. The input to a CMOS inverter (as a function of time) is shown below. Plot its output.



5. Consider Figure 1-10. (a) If the digital signal goes high (meaning Q1 is on and Q2 is off), does charge flow into or out of the other digital circuitry? (b) Repeat part (a) if the digital signal goes low (meaning Q1 is off and Q2 is on). (Hint. Recall charge flows from higher to lower electric potential.)

Bibliography