

CHAPTER

8

Clock Generation

When one has a task to do, one follows a step by step approach to accomplish that task. A robot works in the same way. It does everything you tell it to do, in the order that you tell it. To keep its commands ordered, the instructions are stored in a memory chip. The robot steps through memory one instruction at a time. A kind of “metronome” or pacer is needed to tell the robot how quickly it should move through the instructions. To accomplish this, we will build a clock circuit that will generate a low frequency periodic signal. On each clock pulse, the robot will advance one instruction forward in its memory.



Background

In the previous lab exercise, we introduced the principle of digital circuits, where we consider the circuits to only have two kinds of output voltages – high and low. A high input would make the LED light and the motor run. A low input will cause neither to happen. In this laboratory exercise, we will introduce a device that uses the high-low concept; the digital inverter (see Fig. 8.1). An inverter decides whether its input voltage is a high or low, and it then sets its output voltage to the opposite. A close-to-0V (low) input will make a close-to-5V (high) output, and vice versa. The *threshold voltage* for an inverter is the value of input that causes the output to change between low and high. In our robot, we will use the CMOS family of logic gates. CMOS refers to a particular technology used to implement the digital circuits. The letters stand for Complementary

Inverters

Metal-Oxide-Semiconductor and refer to the physical construction of the transistors that make up the logic circuits. Almost no current will flow into a CMOS inverter. The output of the inverter acts as a voltage source with a 0V or 5V value.

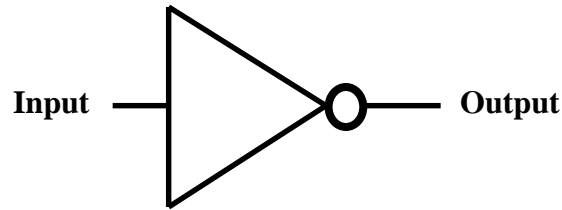


Figure 8.1 Schematic symbol for an inverter.

This is very much like the op amp comparator circuit you studied in the last laboratory exercise except that the positive input terminal is internally connected to a voltage that is approximately halfway between the high and low power supply voltages. For this lab, you will use one of the integrated circuits (IC's) in your robot kit. Find the one that has the number 4069 on it. It is a 14 pin dual-in-line-package (DIP). The pins are numbered sequentially starting with pin 1. Remember that pin 1 is located at the end of the IC with a dot or a semicircular indentation. Hold the indentation upward with the pins pointing away from you. The number of the pin at the top left is 1. The pins are numbered in a counter-clockwise direction. The pin on the bottom left is pin 7, the pin on the bottom right is pin 8, and the pin on the top right is pin 14. All IC's need power to work, and it is standard for digital ICs to make the bottom left pin the ground attachment, and the top right pin the +5V pin. Since this IC has 14 pins, the ground and power are at pins 7 and 14, respectively. The diagram for this chip is shown in Fig. 8.2. Note, these CMOS ICs are particularly sensitive to damage from static electricity. The foam pads that they come in are made of a conducting material and you should keep them in the foam pads whenever you are not using them in your circuit.

Capacitors

Many interesting timing circuits can be derived by combining these inverters with networks containing resistors and components called *capacitors*. A capacitor is a circuit element that stores charge. The total charge is proportional to the voltage: $Q=CV$. The constant of proportionality C is called the capacitance and has units of Farads. The Farad is a very large unit, however, and we will typically use capacitors in the range of pF (10^{-12} F) to F(10^{-6} F). An important property of a capacitor is that the voltage across a capacitor cannot change instantaneously. To see why this is, consider a bathtub anal-

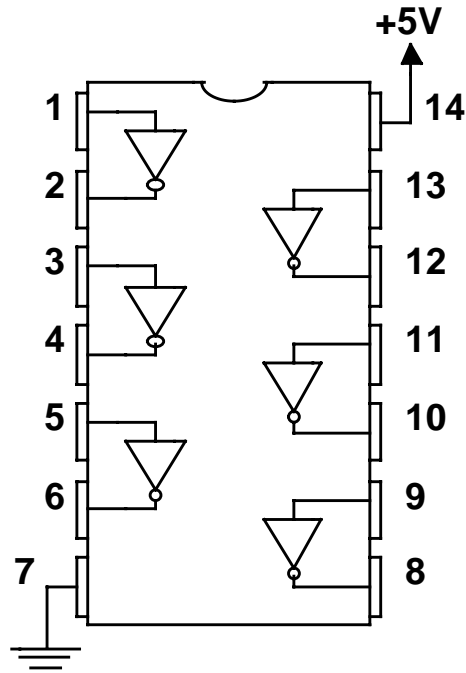


Figure 8.2 Pinout for the 4069 CMOS Inverter.

ogy. The charge is represented by the total amount of water in the bathtub. We can change the level in the bathtub by adding more water or by draining water out, but the level doesn't change instantaneously; it depends on the rate of flow into or out of the tub. In a similar way, the charge (and hence the voltage) cannot change instantaneously across a capacitor. Instead, the rate at which it changes depends on the amount of current flowing into or out of the capacitor. Resistors can be used to control the current flowing into or out of capacitors, and thereby control the rate at which the voltage can change.

Consider the circuit shown in Fig. 8.3. In addition to a resistor (R) and a capacitor (C), this circuit uses an inverter to amplify the output of the RC circuit (node B) back up to a logic signal. In this case we will only consider "ideal" inverters. The voltage at point B in this circuit, for the case when the input is a sudden change in voltage from one level (called the initial voltage) to another level (called the final voltage) at time $t=0$, can be represented by the fol-

Delay Circuit

lowing expression:

$$V_B = V_I \quad t < 0$$

$$V_B = V_I e^{-t/RC} + V_F(1 - e^{-t/RC}) \quad t \geq 0$$

where V_I is the starting voltage and V_F is the final voltage. We call this kind of an input waveform a “step input.” For example, if $V_I=0$ and $V_F=5$ V, the first term vanishes and the second term describes a voltage that rises at a rate determined by the product RC and asymptotically approaches 5 V. Similarly, if $V_I=5$ V and $V_F=0$, the second term vanishes and the voltage decays exponentially to zero at a rate determined by RC . This behavior is illustrated in the lower part of the figure below. In essence, $R1$ and $C4$ act to delay a rising or falling edge by approximately $0.69RC$ (the value of time for which the exponential has a value of 0.5 which is the switching point if we assume that the inverter switches half way between V_I and V_F). Note, because of the properties of the ideal inverter, the waveform at Y is +5V when the waveform at B is below 2.5V and the waveform at Y is 0V when the waveform at B is above 2.5V.

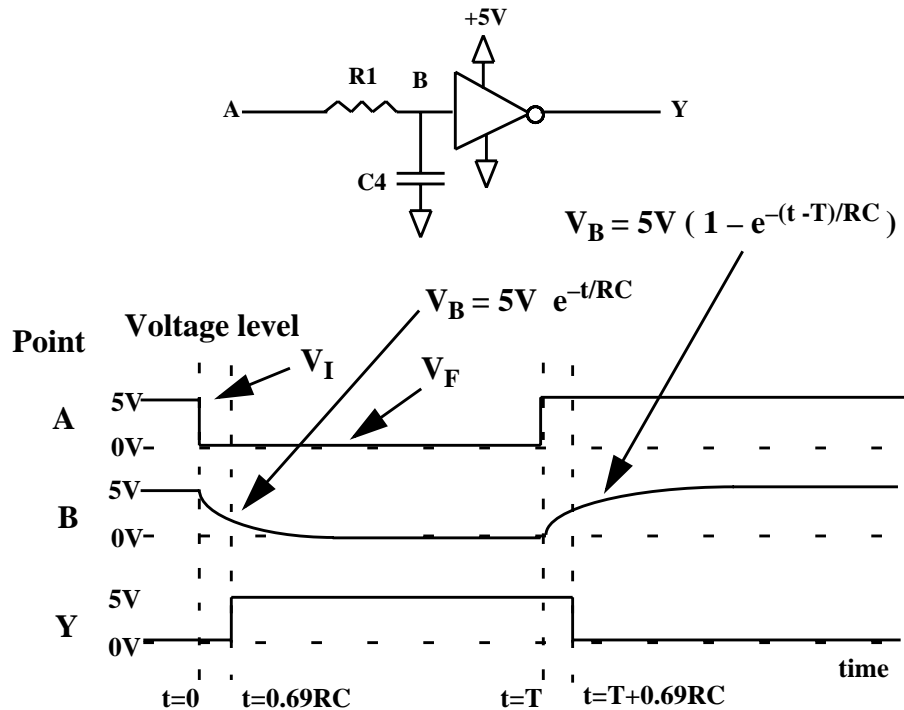


Figure 8.3 A pulse delay circuit constructed using an inverter, a resistor and a capacitor.

Pulse Generator Circuit

There is another type of timing circuit that can be constructed with inverters, resistors, and capacitors (see Fig. 8.4). It is similar to the above delay circuit, except that the capacitor and resistor are interchanged. The function of this circuit is to generate a pulse of short duration from each rising edge of the input waveform.

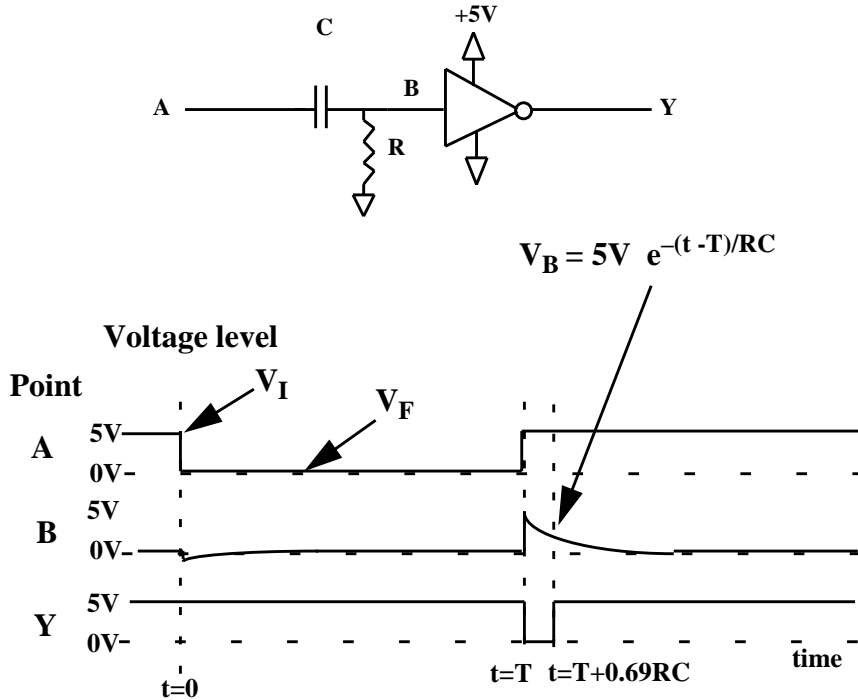


Figure 8.4 A circuit for converting long pulses in to short pulses using an inverter, resistors, and a capacitor.

During the downward going edge of the input waveform shown in Fig. 8.4, the capacitor attempts to maintain itself at the same voltage it was at initially. Unfortunately, since the input was initially at +5V and point B was initially at 0V, then immediately after the input drops to 0V point B should drop to -5V in order to maintain 5V across the capacitor. This does not actually happen because most logic gates do not allow their input voltages to go outside of the power supply voltages (0V–5V in this case). If you look very closely, you will see that the input does go slightly negative, about one V_{D-ON} (0.7V). This is because these CMOS ICs use diodes on the input to keep the input voltage from going more than 0.7V outside of the 0V–5V range.

To see how this works, consider a transition from 0 to 5 V at point A. Initially points A and B are both at zero voltage, so the voltage across the capacitor is zero and no charge is stored. Since the voltage across the capacitor cannot change instantaneously, point B

must suddenly rise to 5 V at the same time that point A makes the transition. However, resistor R_6 completes a circuit from the 5 V at A to ground and allows the capacitor to charge. As the capacitor charges, the voltage at point B exponentially returns to zero. Therefore, this circuit acts to convert a voltage going from low to high (and staying there for some time much longer than RC) into a pulse whose duration is given by $0.69RC$ (the length of time for which the exponential has a value greater than 0.5).

The voltage at point B in this circuit for times following $t=T$ can be represented by the following expression:

$$V_B(t) = 5 \text{ V } e^{-(t-T)/RC}$$

The inverter at the output then goes to 0V at $t=T$ because the voltage at point B jumps up to 5V. Then, as the voltage at point B exponentially decays, the inverter's output goes to +5V when the voltage at point B reaches 2.5V which is at $t = T + 0.69 RC$.

Remember that we said when the input to this circuit is going from high to low we would also expect to couple a transient (in this case going negative by 5V) onto node B. However, most integrated circuit logic gates have a diode connected from each input to ground and a second diode connected from each input to +5V. These diodes are there to keep the input to a gate's input between ground and +5V in order to prevent static electricity from damaging the input. Unfortunately, the instantaneously pulling charge out of a capacitor requires extremely high currents. In order to keep from forcing these high currents through the input protection diodes, we have added R_7 to the circuit (see Fig. 8.5). It serves no purpose in terms of the pulse generator – it is only there to limit the current through the protection diodes. Now when the input voltage goes to 0V and point B only goes to -0.7V, the capacitor can still maintain its 5V charge (instantaneously) by keeping its left hand terminal (see Fig. 8.5) at +4.3V. Instantly following the input downward step, there will be just over 2mA of current flowing into the inverter's input protection diodes. Note, the overall time RC time constant of the circuit is lengthened to $(R_6 + R_7)C$.

Clock Generator

As we will see, many digital circuits require a “clock” signal. That is, a periodic square wave at a controlled frequency. Therefore, the final resistor, capacitor, and inverter circuit that we will consider is the free running oscillator shown in Fig. 8.6. Note, in this circuit

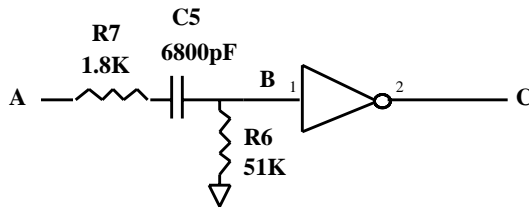


Figure 8.5 A circuit for converting long pulses in to short pulses using an inverter, resistors, and a capacitor. Current limiting resistor included.

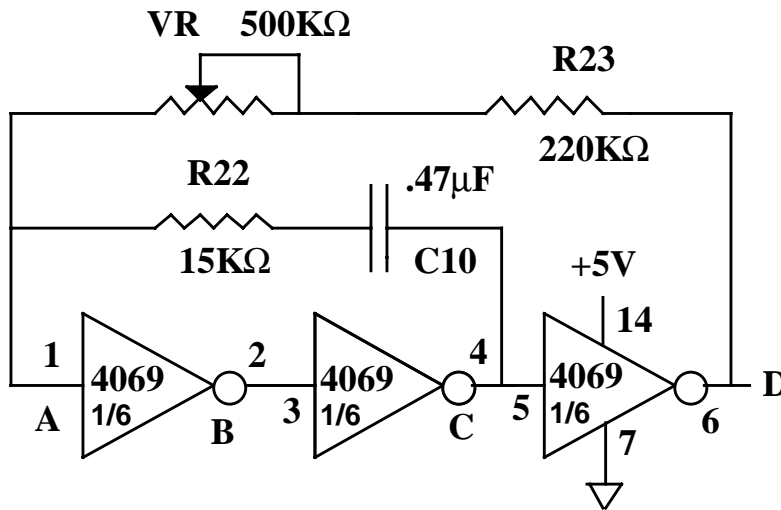


Figure 8.6 A circuit for generating continuous oscillations (a “clock” circuit) constructed using 3 inverters, resistors, and a capacitor.

R_{22} is like R_7 in the previous circuit – it is only added to the circuit in order to limit the currents flowing into the input protection diodes of the inverters. If we further simplify the problem by assuming that the input protection diodes will limit the voltage at all gate inputs to the range $\{-0.7V - +5.7V\}$, we can eliminate this resistor (for analysis purposes only). In addition, we can lump the fixed resistor R_{23} in with the variable resistor RV . By eliminating both R_{22} and R_{23} we end up with the simplified circuit shown in Fig. 8.7.

Let us consider the operation of the circuit shown in Fig. 8.7. The easiest way to understand the operation of a RC + inverter circuit is to assume a given starting state and then simply analyze the operation of the circuit over time. For simplicity, let us assume that $A=0V$, $B=5V$, $C=0V$, and $D=5V$. Note, you can choose any set of starting voltages you wish. However, it is important to pick ones

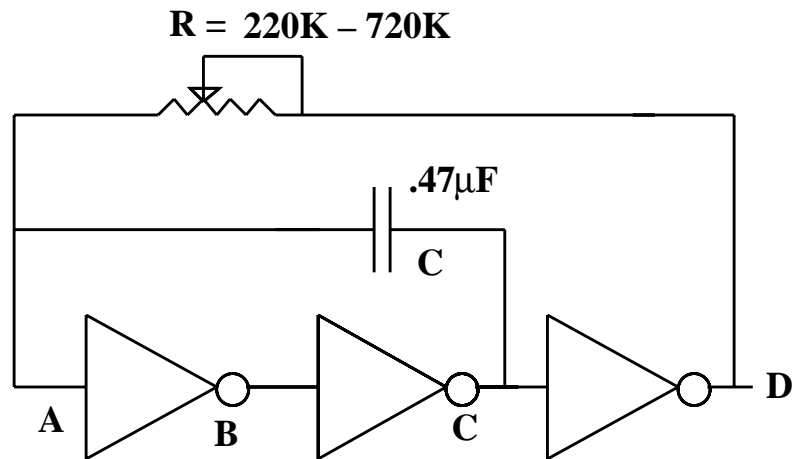


Figure 8.7 A simplified version of the clock circuit eliminating the nonessential resistors.

that are consistent with the inverter's characteristic. Next consider how the circuit will evolve. As long as the voltage at point A remains below 2.5V, then point C will stay at ground. In this case we have an R in series with a C to ground just as we did in Fig. 8.3. The solution for the voltage at point A follows from that derivation and is:

$$V_A = 5V(1 - e^{-t/RC})$$

The first part of the curve for point A in Fig. 8.8 shows this curve. However, as soon as the voltage at point A crosses 2.5V the output at point D will go to 0V and at point C will go to +5V. Since the capacitor keeps the voltage across itself constant, the voltage at point A will try to go to 2.5V+5V=7.5V. However, the input protection diodes will clamp the voltage at point A at 5.7V (see)Fig. 8.8. Because point D is now 0V, the resistor will try to drag point A down to 0V from its starting point at 5.7V. Again, as soon as it crosses 2.5V the outputs of the inverters will all switch. An important question in determining the frequency of oscillation of this clock circuit is how long does it take to go from 5.7V to 2.5V? We know the equation of this line is simply

$$V_A(t) = 5.7V e^{-t/RC} = 2.5V$$

We can set it equal to 2.5V and solve for the value of t. In this case it takes 0.82RC units of time before the inverters switch. Note, the product of resistance and capacitance has units of time. Specifi-

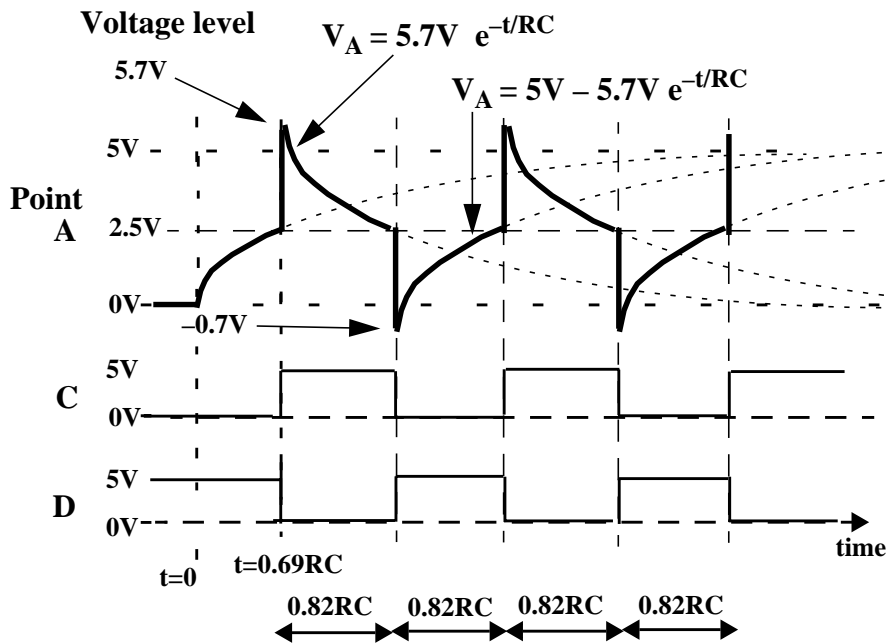


Figure 8.8 Voltage waveforms over time for the RC + inverters clock generator.

cally, 1 farad times 1 ohm is equal to 1 second.

As soon as the voltage at point A crosses 2.5V the output at point D will go to 5V and at point C will go to 0V. Since the capacitor keeps the voltage across itself constant, the voltage at point A will try to go to $+2.5V - 5V = -2.5V$. However, the input protection diodes will clamp the voltage at point A at $-0.7V$ (see) Fig. 8.8. Because point D is now at $+5V$, the resistor will try to drag point A up to $+5V$ from its starting point at $-0.7V$. Again, as soon as it crosses 2.5V the outputs of the inverters will all switch. How long does it take to go from $-0.7V$ to 2.5V? We know the equation of this line is simply

$$V_A(t) = -5.7 \text{ V } e^{-t/RC} + 5V = 2.5V$$

We can set it equal to 2.5V and solve for the value of t. In this case it again takes $0.82RC$ units of time before the inverters switch. Therefore the period of this oscillator is $1.64RC$ seconds and its frequency of oscillation is $1/(1.64RC)$ Hz.



Laboratory Exercises

1. Put the chip in the protoboard. Adjust the +20V part of the power supply to have an output of +5V and connect it to pin 14. Connect pin 7 to the common terminal of the power supply. Don't build the rest of the circuit yet. Adjust the +6V part of the power supply to have an output of +0V and connect it to the input of the first inverter, pin 1. Vary the voltage on pin 1 from 0 volts to 5 volts and measure the voltage on the output, pin 2, for each input voltage.

Test all six inverters in the IC package.

2. Construct the simple pulse delay circuit shown in Fig. 8.3. Adjust your function generator to output a 0V-5V square wave at a frequency of 50 Hz. Note, you will need to use the square wave mode and to add a DC offset of 2.5V. First power up your circuit and then connect the function generator. Connect the scope channel 1 to point A and verify that you have the desired square wave. Trigger the scope on channel 1. Now look at point B with channel 2 of the scope. Does it match the wave form in Fig. 8.3? Finally, move channel 2 to look at the output, node C. Is there a delay?
3. Construct the simple pulse generating circuit shown in Fig. 8.4. Adjust your function generator to output a 0V-5V square wave at a frequency of 100 Hz. First power up your circuit and then connect the function generator. Connect the scope channel 1 to point A and verify that you have the desired square wave. Trigger the scope on channel 1. Now look at point B with channel 2 of the scope. Does it match the wave form in Fig. 8.4? Finally, move channel 2 to look at the output, node C.
4. Now, build the clock circuit shown in Fig. 8.6 on the protoboard. To see that it works, light an LED with the output as shown in Fig. 8.9. Note, you may use a 1K resistor in place of the 330 Ω resistor shown in Fig. 8.9. A working circuit will make the LED flash. Note how you can vary the flashing frequency by varying the potentiometer.

5. Change the value of the capacitor C10 to 0.01 F. This will increase the frequency of the output about 50 times. Instead of observing the LED, look at the points A and C simultaneously with two channels of your oscilloscope. Set the scope to trigger on C. Then look at points C and D simultaneously. Set the scope to trigger on C as before.
6. Finally, solder the circuit onto the robot PC board. Note, switch back to using the 0.47 μ F capacitor for C10 before installing it. IC chips can be damaged by the heat of the soldering iron, so remember to solder all of the components first, before you insert the IC's into their sockets. Set the +20V part of your power supply to +9V and attach it to the +9 V pin of the robot PC board to the right of SW1 (make sure SW1 is on). Attach the power supply common to the GND pin of the robot PC board. Check that the output of your voltage regulator is still +5V. Test the clock generator output by getting an oscilloscope reading from the output of pin 5 of the inverter chip - grab the lead of R23. As always, leave enough component lead sticking out of the PC board to grab with a clip lead or scope probe. Identify any problems that you might have and fix them. If you have a problem ask your TA for help.

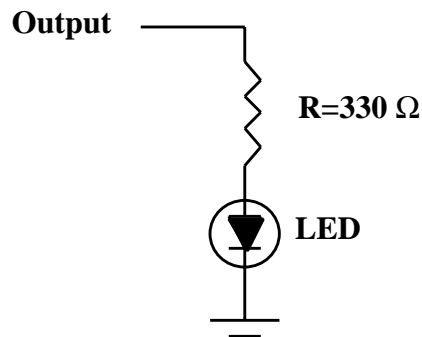


Figure 8.9 Using an LED to construct a digital signal indicator.