Review Questions

1. Give one application where would you use a relay.
2. Why do we place a driver between the microcontroller and the relay?
3. What is an NC relay?
4. Why are relays that use coils called electromechanical relays?
5. What is the advantage of a solid-state relay over EMR?
6. What is the advantage of an optoisolator over an EM relay?

SECTION 17.2: STEPPER MOTOR INTERFACING

This section begins with an overview of the basic operation of stepper motors. Then we describe how to interface a stepper motor to the 8051. Finally, we use Assembly language programs to demonstrate control of the angle and direction of stepper motor rotation.

Stepper motors

A *stepper motor* is a widely used device that translates electrical pulses into mechanical movement. In applications such as disk drives, dot matrix printers, and robotics, the stepper motor is used for position control. Stepper motors commonly have a permanent magnet *rotor* (also called the *shaft*) surrounded by a *stator* (see Figure 17-7). There are also steppers called variable reluctance *stepper motors* that do not have a PM rotor. The most common stepper motors have four stator windings that are paired with a center-tapped common as shown in Figure 17-8. This type of stepper motor is commonly referred to as a *four-phase* or unipolar stepper motor. The center tap allows a change of current direction in each of

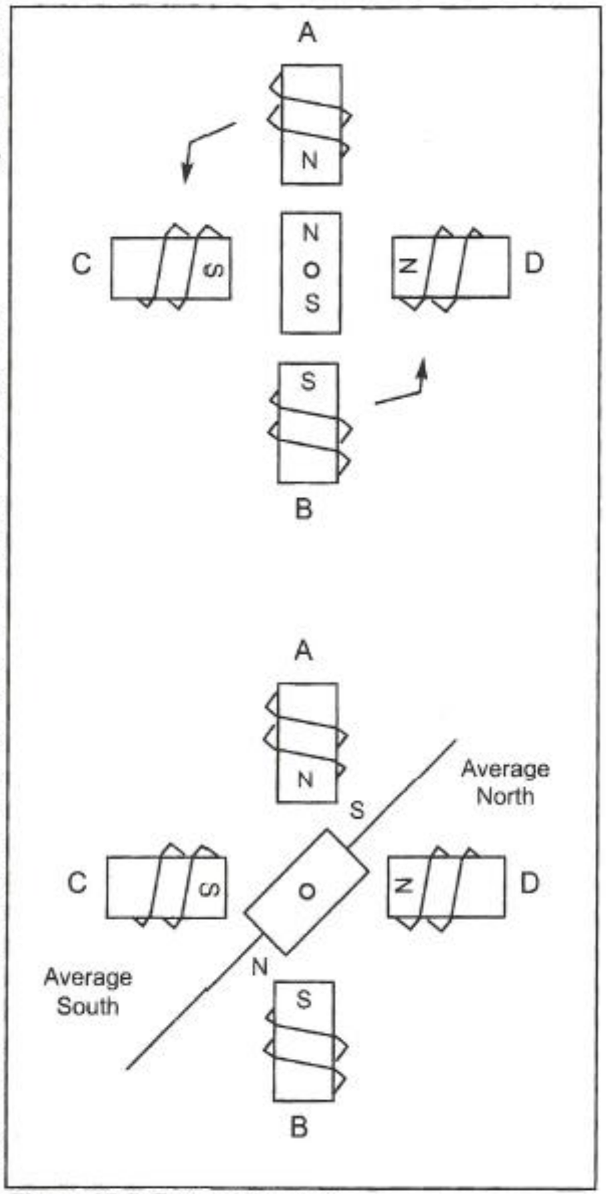


Figure 17-7. Rotor Alignment

two coils when a winding is grounded, thereby resulting in a polarity change of the stator. Notice that while a conventional motor shaft runs freely, the stepper motor shaft moves in a fixed repeatable increment, which allows one to move it to a precise position. This repeatable fixed movement is possible as a result of basic magnetic theory where poles of the same polarity repel and opposite poles attract. The direction of the rotation is dictated by the stator poles. The stator poles are determined by the current sent through the wire coils. As the direction of the current is changed, the polarity is also changed causing the reverse motion of the rotor. The stepper motor discussed here has a total of 6 leads: 4 leads representing the four stator windings and 2 commons for the center-tapped leads. As the sequence of power is applied to each stator winding, the rotor will rotate. There are several widely used sequences where each has a different degree of precision. Table 17-3 shows a 2-phase, 4-step stepping sequence.

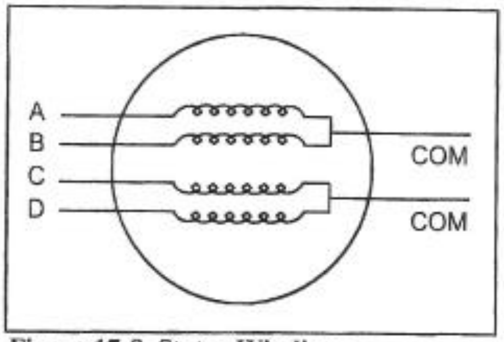


Figure 17-8. Stator Windings Configuration

Table 17-3: Normal 4-Step Sequence

Clockwise	Step #	Winding A	Winding B	Winding C	Winding D	Counter-clockwise
↓	1	1	0	0	1	↑
	2	1	1	0	0	
	3	0	1	1	0	
	4	0	0	1	1	

It must be noted that although we can start with any of the sequences in Table 17-3, once we start we must continue in the proper order. For example, if we start with step 3 (0110), we must continue in the sequence of steps 4, 1, 2, etc.

Step angle

How much movement is associated with a single step? This depends on the internal construction of the motor, in particular the number of teeth on the stator and the rotor. The *step angle* is the minimum degree of rotation associated with a single step. Various motors have different step angles. Table 17-4 shows some step angles for various motors. In Table 17-4, notice the term *steps per revolution*. This is the total number of steps needed to rotate one complete rotation or 360 degrees (e.g., 180 steps × 2 degrees = 360).

It must be noted that perhaps contrary to one's initial impression, a stepper motor does not need more ter-

Table 17-4: Stepper Motor Step Angles

Step Angle	Steps per Revolution
0.72	500
1.8	200
2.0	180
2.5	144
5.0	72
7.5	48
15	24

minal leads for the stator to achieve smaller steps. All the stepper motors discussed in this section have 4 leads for the stator winding and 2 COM wires for the center tap. Although some manufacturers set aside only one lead for the common signal instead of two, they always have 4 leads for the stators. Next we discuss some associated terminology in order to understand the stepper motor further.

Example 17-1

Describe the 8051 connection to the stepper motor of Figure 17-9 and code a program to rotate it continuously.

Solution:

The following steps show the 8051 connection to the stepper motor and its programming.

1. Use an ohmmeter to measure the resistance of the leads. This should identify which COM leads are connected to which winding leads.
2. The common wire(s) are connected to the positive side of the motor's power supply. In many motors, +5 V is sufficient.
3. The four leads of the stator winding are controlled by four bits of the 8051 port (P1.0 - P1.3). However, since the 8051 lacks sufficient current to drive the stepper motor windings, we must use a driver such as the ULN2003 to energize the stator. Instead of the ULN2003, we could have used transistors as drivers, as shown in Figure 17-9. However, notice that if transistors are used as drivers, we must also use diodes to take care of inductive current generated when the coil is turned off. One reason that using the ULN2003 is preferable to the use of transistors as drivers is that the ULN2003 has an internal diode to take care of back EMF.

```
         MOV  A,#66H     ;load step sequence
BACK:    MOV  P1,A       ;issue sequence to motor
         RR   A          ;rotate right clockwise
         ACALL DELAY     ;wait
         SJMP BACK       ;keep going

         ...
DELAY
         MOV  R2,#100
H1:      MOV  R3,#255
H2:      DJNZ R3,H2
         DJNZ R2,H1
         RET
```

Change the value of DELAY to set the speed of rotation.
We can use the single-bit instructions SETB and CLR instead of RR A to create the sequences.

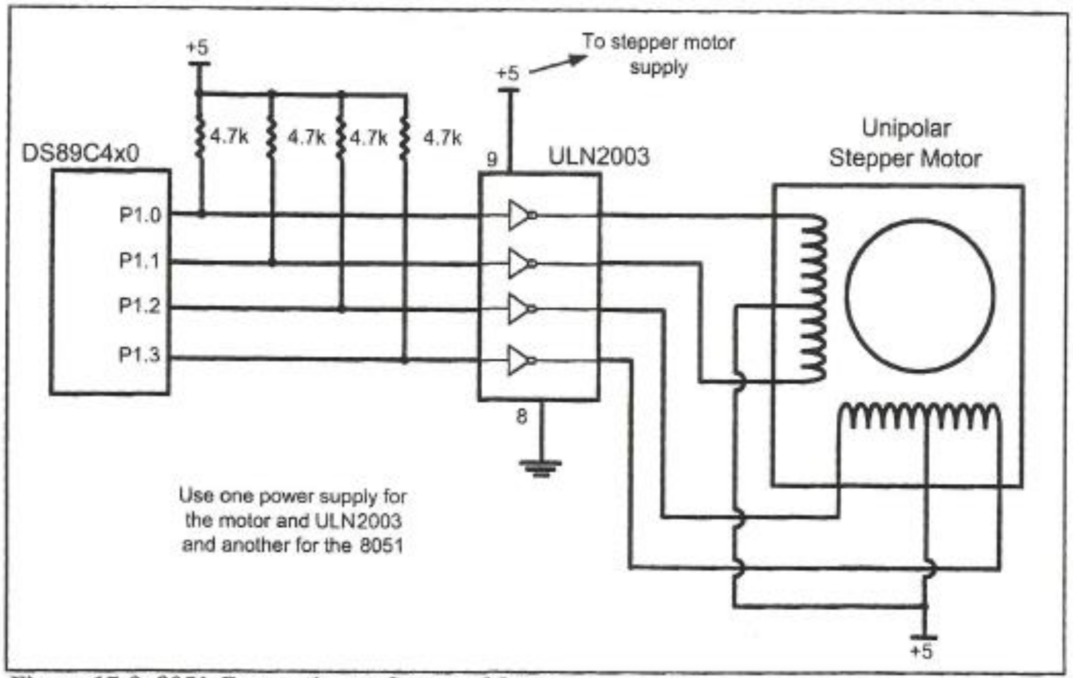


Figure 17-9. 8051 Connection to Stepper Motor

Steps per second and rpm relation

The relation between rpm (revolutions per minute), steps per revolution, and steps per second is as follows.

$$\text{Steps per second} = \frac{\text{rpm} \times \text{Steps per revolution}}{60}$$

The four-step sequence and number of teeth on rotor

The switching sequence shown earlier in Table 17-3 is called the 4-step switching sequence since after four steps the same two windings will be "ON". How much movement is associated with these four steps? After completing every four steps, the rotor moves only one tooth pitch. Therefore, in a stepper motor with 200 steps per revolution, the rotor has 50 teeth since $4 \times 50 = 200$ steps are needed to complete one revolution. This leads to the conclusion that the minimum step angle is always a function of the number of teeth on the rotor. In other words, the smaller the step angle, the more teeth the rotor passes. See Example 17-2.

Example 17-2

Give the number of times the four-step sequence in Table 17-3 must be applied to a stepper motor to make an 80-degree move if the motor has a 2-degree step angle.

Solution:

A motor with a 2-degree step angle has the following characteristics:

Step angle:	2 degrees	Steps per revolution:	180
Number of rotor teeth:	45	Movement per 4-step sequence:	8 degrees

To move the rotor 80 degrees, we need to send 10 consecutive four-step sequences, since 10 × 4 steps × 2 degrees = 80 degrees.

Looking at Example 17-2, one might wonder what happens if we want to move 45 degrees, since the steps are 2 degrees each. To allow for finer resolutions, all stepper motors allow what is called an *8-step* switching sequence. The 8-step sequence is also called *half-stepping,* since in the 8-step sequence each step is half of the normal step angle. For example, a motor with a 2-degree step angle can be used as a 1-degree step angle if the sequence of Table 17-5 is applied.

Table 17-5: Half-Step 8-Step Sequence

Clockwise	Step #	Winding A	Winding B	Winding C	Winding D	Counter-clockwise
↓	1	1	0	0	1	↑
	2	1	0	0	0	
	3	1	1	0	0	
	4	0	1	0	0	
	5	0	1	1	0	
	6	0	0	1	0	
	7	0	0	1	1	
	8	0	0	0	1	

Motor speed

The motor speed, measured in steps per second (steps/s), is a function of the switching rate. Notice in Example 17-1 that by changing the length of the time delay loop, we can achieve various rotation speeds.

Holding torque

The following is a definition of holding torque: "With the motor shaft at standstill or zero rpm condition, the amount of torque, from an external source, required to break away the shaft from its holding position. This is measured with rated voltage and current applied to the motor." The unit of torque is ounce-inch (or kg-cm).

Wave drive 4-step sequence

In addition to the 8-step and the 4-step sequences discussed earlier, there is another sequence called the wave drive 4-step sequence. It is shown in Table 17-6. Notice that the 8-step sequence of Table 17-5 is simply the combination of the wave drive 4-step and normal 4-step normal sequences shown in Tables 17-6 and 17-3, respectively. Experimenting with the wave drive 4-step is left to the reader.

Table 17-6: Wave Drive 4-Step Sequence

Clockwise	Step #	Winding A	Winding B	Winding C	Winding D	Counter-clockwise
↓	1	1	0	0	0	↑
	2	0	1	0	0	
	3	0	0	1	0	
	4	0	0	0	1	

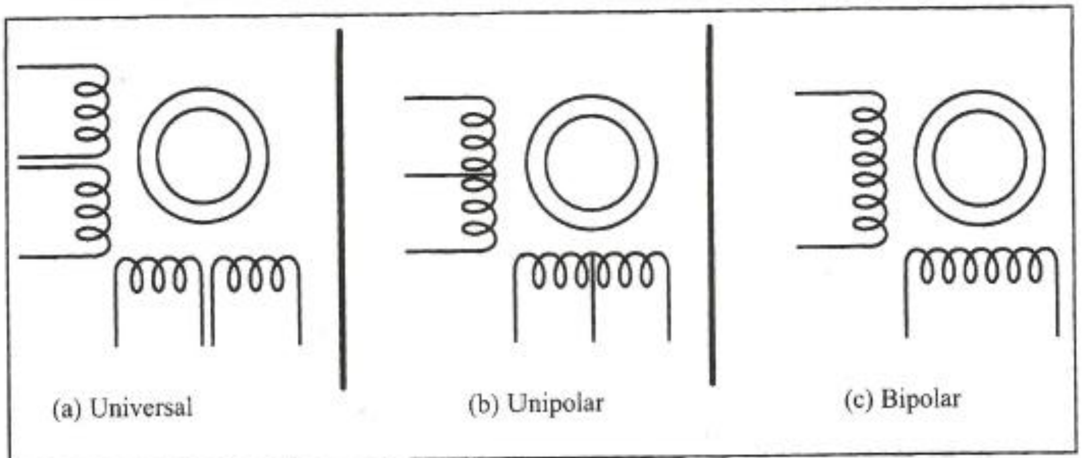
Table 17-7: Selected Stepper Motors Characteristics (www.Jameco.com)

Part No.	Step Angle	Drive System	Volts	Phase Resistance	Current
151861CP	7.5	unipolar	5 V	9 ohms	550 mA
171601CP	3.6	unipolar	7 V	20 ohms	350 mA
164056CP	7.5	bipolar	5 V	6 mA	800 mA

Unipolar versus bipolar stepper motor interface

There are three common types of stepper motor interfacing: universal, unipolar, and bipolar. They can be identified by the number of connections to the motor. A universal stepper motor has eight, while the unipolar has six and the bipolar has four. The universal stepper motor can be configured for all three modes, while the unipolar can be either unipolar or bipolar. Obviously the bipolar cannot be configured for universal nor unipolar mode. Table 17-7 shows selected stepper motor characteristics. Figure 17-10 shows the basic internal connections of all three type of configurations.

Unipolar stepper motors can be controlled using the basic interfacing shown in Figure 17-11, whereas the bipolar stepper requires H-Bridge circuitry. Bipolar stepper motors require a higher operational current than the unipolar; the advantage of this is a higher holding torque.


(a) Universal

(b) Unipolar

(c) Bipolar

Figure 17-10. Common Stepper Motor Types

Using transistors as drivers

Figure 17-11 shows an interface to a unipolar stepper motor using transistors. Diodes are used to reduce the back EMF spike created when the coils are energized and de-energized, similar to the electromechanical relays discussed earlier. TIP transistors can be used to supply higher current to the motor. Table 17-8 shows the common industrial Darlington transistors. These transistors can accommodate higher voltages and currents.

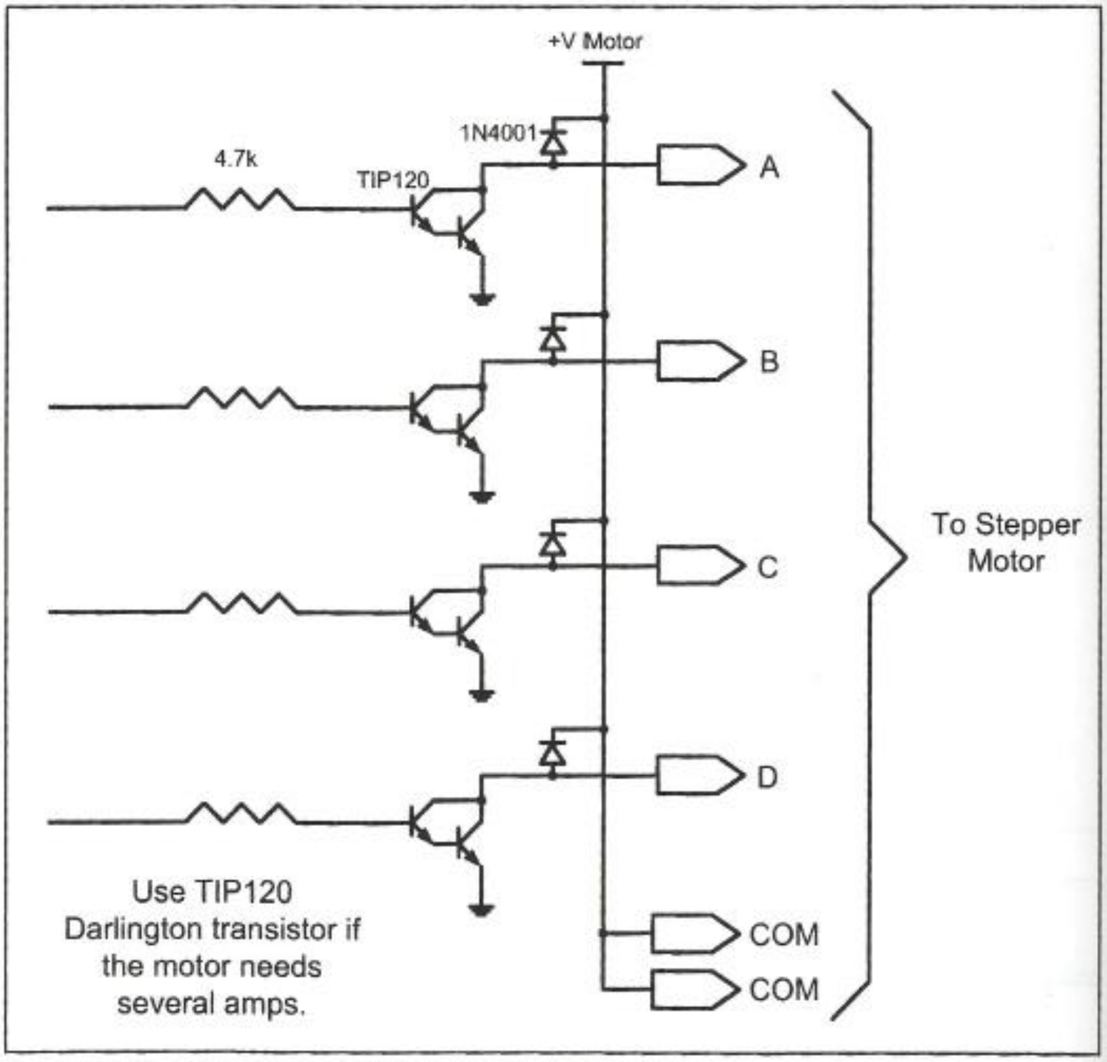


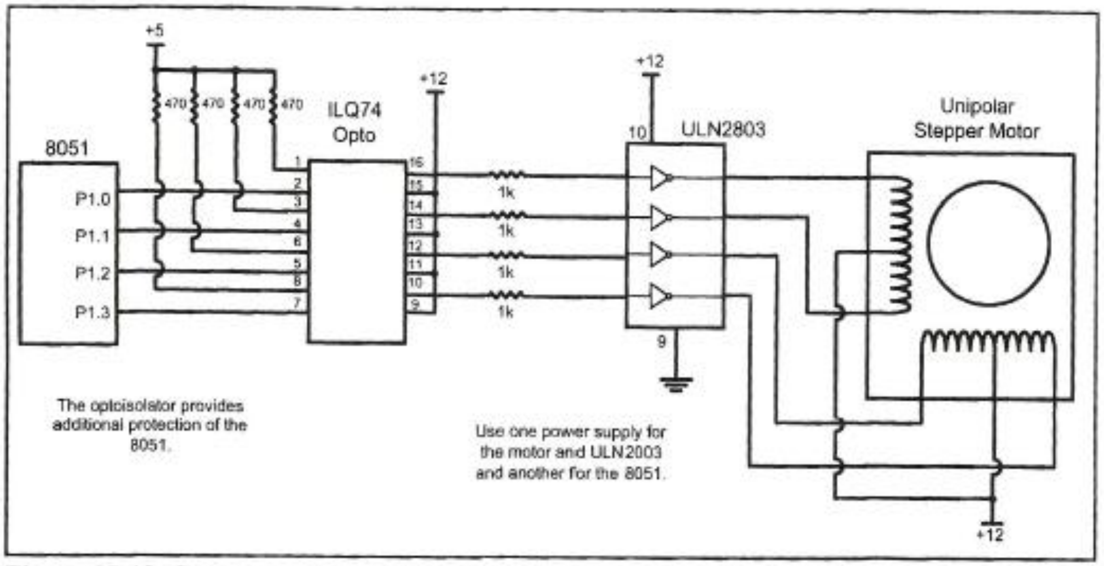
Figure 17-11. Using Transistors for Stepper Motor Driver

Table 17-8: Darlington Transistor Listing

NPN	PNP	Vceo (volts)	Ic (amps)	hfe (common)
TIP110	TIP115	60	2	1000
TIP111	TIP116	80	2	1000
TIP112	TIP117	100	2	1000
TIP120	TIP125	60	5	1000
TIP121	TIP126	80	5	1000
TIP122	TIP127	100	5	1000
TIP140	TIP145	60	10	1000
TIP141	TIP146	80	10	1000
TIP142	TIP147	100	10	1000

Controlling stepper motor via optoisolator

In the first section of this chapter we examined the optoisolator and its use. Optoisolators are widely used to isolate the stepper motor's EMF voltage and keep it from damaging the digital/microcontroller system. This is shown in Figure 17-12.



The optoisolator provides additional protection of the 8051.

Use one power supply for the motor and ULN2003 and another for the 8051.

Figure 17-12. Controlling Stepper Motor via Optoisolator

Example 17-3

A switch is connected to pin P2.7. Write a program to monitor the status of SW and perform the following:

(a) If SW = 0, the stepper motor moves clockwise.

(b) If SW = 1, the stepper motor moves counterclockwise.

Solution:

```
      ORG    0H              ;starting address
MAIN: SETB   P2.7            ;make an input
      MOV    A, #66H         ;starting phase value
      MOV    P1, A           ;send value to port
TURN:
      JNB    P2.7, CW        ;check switch result
      RR     A               ;rotate right
      ACALL  DELAY           ;call delay
      MOV    P1,A            ;write value to port
      SJMP   TURN            ;repeat
CW:   RL     A               ;rotate left
      ACALL  DELAY           ;call delay
      MOV    P1,A            ;write value to port
      SJMP   TURN            ;repeat

DELAY:
      MOV    R2, #100
H1:   MOV    R3, #255
H2:   DJNZ   R3, H2
      DJNZ   R2,H1
      RET
      END
```

Stepper motor control with 8051 C

The 8051 C version of the stepper motor control is given below. In this program we could have used << (shift left) and >> (shift right) as was shown in Chapter 7.

```
#include <reg51.h>
void main()
  {
    while(1)
      {
        P1 = 0x66;
        MSDelay(100);
        P1 = 0xCC;
        MSDelay(100);
        P1 = 0x99;
        MSDelay(100);
        P1 = 0x33;
        MSDelay(100);
      }
  }
```

Example 17-4

A switch is connected to pin P2.7. Write a C program to monitor the status of SW and perform the following:

(a) If SW = 0, the stepper motor moves clockwise.

(b) If SW = 1, the stepper motor moves counterclockwise.

Solution:

```
#include <reg.h>
sbit SW=P2^7;

void main()
  {
    SW = 1;
    while(1)
      {
        if(SW == 0)
          {
            P1 = 0x66;
            MSDelay(100);
            P1 = 0xCC;
            MSDelay(100);
            P1 = 0x99;
            MSDelay(100);
            P1 = 0x33;
            MSDelay(100);
          }
        else
          {
            P1 = 0x66;
            MSDelay(100);
```

Example 17-4 Cont.

```
              P1 = 0x33;
              MSDelay(100);
              P1 = 0x99;
              MSDelay(100);
              P1 = 0xCC;
              MSDelay(100);
           }
       }
   }

void MSDelay(unsigned int value)
   {
     unsigned int x, y;
     for(x=0;x<1275;x++)
       for(y=0;y<value;y++);
   }
```

Review Questions

1. Give the 4-step sequence of a stepper motor if we start with 0110.
2. A stepper motor with a step angle of 5 degrees has ____ steps per revolution.
3. Why do we put a driver between the microcontroller and the stepper motor?

SECTION 17.3: DC MOTOR INTERFACING AND PWM

This section begins with an overview of the basic operation of DC motors. Then we describe how to interface a DC motor to the 8051. Finally, we use Assembly and C language programs to demonstrate the concept of pulse width modulation (PWM) and show how to control the speed and direction of a DC motor.

DC motors

A direct current (DC) motor is another widely used device that translates electrical pulses into mechanical movement. In the DC motor we have only + and – leads. Connecting them to a DC voltage source moves the motor in one direction. By reversing the polarity, the DC motor will move in the opposite direction. One can easily experiment with the DC motor. For example, small fans used in many motherboards to cool the CPU are run by DC motors. By connecting their leads to the + and – voltage source, the DC motor moves. While a stepper motor moves in steps of 1 to 15 degrees, the DC motor moves continuously. In a stepper motor, if we know the starting position we can easily count the number of steps the motor has moved and calculate the final position of the motor. This is not possible in a DC motor. The maximum speed of a DC motor is indicated in rpm and is given in the data sheet. The DC motor has two rpms: no-load and loaded. The manufacturer's data sheet gives the no-load rpm. The no-load rpm can be from a few thousand to tens of thousands. The rpm is reduced when moving a load and it decreases as the load is increased. For example, a drill turning a screw has a much lower rpm speed than when it is in the no-load situation. DC motors also