## OBJECTIVES

Upon completion of this chapter, you will be able to:

- Analyze the operation of systems made of several components that have been covered earlier in this textbook.
- Describe an entire project with one HDL file.
- Describe the process of hierarchical project management.
- Understand how to break a project into manageable pieces.
- Use MAX+PLUS II or Quartus II software tools to implement a hierarchical modular project.
- Plan ways to test the operation of the circuits you build.


## - INTRODUCTION

Throughout the first nine chapters of this book, we have explained the fundamental building blocks of digital systems. Now that we have taken out each block and looked it over, we do not want to put them all away and forget them; it is time to build something with the blocks. Some of the examples we have used to demonstrate the operation of individual circuits are really digital systems in their own right, and we have studied how they work. In this chapter, we want to focus more on the building process.

Surveys of graduates show us that most of the professionals in the electrical and computer engineering and technology field have the responsibility of project management. Experience with students has also shown us that the most efficient way to manage a project is not intuitively obvious to everyone, which explains why so many of us end up attending the school of hard knocks (learning through trial and error). This chapter is intended to give you a strategic plan for managing projects while learning about digital systems and the modern tools used to develop them. The principles here are not limited to digital or even electronic projects in general. They could apply to building a house or building your own business. They will definitely improve your success rate and reduce the frustration factor.

Hardware description languages were really created for the purpose of managing large digital systems: for documentation, simulation testing, and the synthesis of working circuits. Likewise, the Altera software tools are specifically designed to work with managing projects that go far beyond the scope of this text. We will describe some of the features of the Altera software packages as we go through the steps of developing these small projects. This concept of modular project development, which was introduced in Chapter 4, will be demonstrated here through a series of examples.

## 10-1 SMALL-PROJECT MANAGEMENT

The first projects described here are relatively small systems that consist of a small number of building blocks. These projects can be developed in separate modules, but this approach would only add to the complexity. They are small enough that it makes sense to implement the entire project in a single HDL design file. This does not mean, however, that a structured process should not be followed to complete the project. In fact, most of the same steps that should be employed in a large modular project are also applicable in these examples. The steps that should be followed are (1) overall definition, (2) strategic planning to break the project into small pieces, (3) synthesis and testing of each piece, and (4) system integration and testing.

## Definition

The first step in any project is the thorough definition of its scope. In this step, the following issues should be determined:

- How many bits of data are needed?
- How many devices are controlled by the outputs?
- What are the names of each input and output?
- Are the inputs and outputs active-HIGH or active-LOW?
- What are the speed requirements?
- Do I understand fully how this device should operate?
- What will define successful completion of this project?

From this step should come a complete and thorough description of the overall project's operation, a definition of its inputs and outputs, and complete numeric specifications that define its capabilities and limitations.

## Strategic Planning

The second step involves developing a strategy for dividing this overall project into manageable pieces. The requirements of the pieces are:

- A way to test each piece must be developed.
- Each piece must fit together to make up the whole system.

■ We must know the nature of all the signals that connect the pieces.

- The exact operation of each block must be thoroughly defined and understood.
- We must have a clear vision of how to make each block work.

This last requirement might seem obvious, but it is amazing how many projects are planned around one central block that involves a not-yet-discovered technical miracle or violates silly little laws like conservation of energy. In this stage, each subsystem (section block) becomes somewhat of a project in and of itself, with the possibility of additional subsystems defined within its boundaries. This is the concept of hierarchical design.

## Synthesis and Testing

Each subsystem should be built starting at the simplest level. In the case of a digital system designed using HDL, it means writing pieces of code. It also
means developing a plan for testing that code to make sure it meets all the criteria. This is often accomplished through some sort of simulation. When a circuit is simulated on a computer, the designer must create all the different scenarios that will be experienced by the actual circuit and must also know what the proper response to those inputs should be. This testing often takes a great deal of thought and is not an area that should be overlooked. The worst mistake you can make is to conclude that a fundamental block works perfectly, only to find later those few situations where it fails. This predicament often forces you to rethink many of the other blocks, thus nullifying much of your work.

## System Integration and Testing

The last step is to put the blocks together and test them as a unit. Blocks are added and tested at each stage until the entire project is working. This area is often trivialized but rarely goes smoothly. Even if you took care of all the details you thought about, there are always the "gotchas" that nobody thought about.

Some aspects of project planning and management go beyond the scope of this text. One is the selection of a hardware platform that will best fit your application. In Chapter 13, we will explore the broad field of digital systems and look specifically at the capabilities and limitations of PLDs in various categories. Another very critical dimension in project management is time Your boss will give you only a certain amount of time to complete your project, and you must plan your work (and effort) to meet this deadline. We will not be able to cover time management in this text, but as a general rule you will find that most facets of the project will actually take two to three times longer than you think they will when you begin.

1. Name the steps of project management.
2. At what stage should you decide how to measure success?

## 10-2 STEPPER MOTOR DRIVER PROJECT

The purpose of this section is to demonstrate a typical application of counters combined with decoding circuits. A digital system often contains a counter that cycles through a specified sequence and whose output states are decoded by a combinational logic circuit, which in turn controls the operation of the system. Many applications also have external inputs that are used to put the system into various modes of operation. This section discusses all these features to control a stepper motor.

In a real project, the first step of definition often involves some research on the part of the project manager. In this section (or project), it is vital that we understand what a stepper motor is and how it works before we try to create a circuit that is supposed to control it. In Section 7-10, we showed you how to design a simple synchronous counter that could be used to drive a stepper motor. The sequence demonstrated in that section is called the fullstep sequence. As you recall, it involved two flip-flops and their $Q$ and $\bar{Q}$ outputs driving the four coils of the motor. The full-step sequence always has two coils of the stepper motor energized in any state of the sequence and typically causes $15^{\circ}$ of shaft rotation per step. Other sequences, however, will
also cause a stepper to rotate. If you look at the full-step sequence, you will notice that each state transition involves turning off one coil and simultaneously turning on another coil. For example, look at the first state (1010) in the full-step sequence of Table 10-1. When it switches to the second state in the sequence, coil 1 is turned off and coil 0 is turned on. The half-step sequence is created by inserting a state with only one coil energized between full steps, as shown in the middle column of Table 10-1. In this sequence, one coil is de-energized before the other is energized. The first state is 1010 and the second state is 1000 , meaning that coil 1 is turned off for one state before coil 0 is turned on. This intermediate state causes the stepper shaft to rotate half as far $\left(7.5^{\circ}\right)$ as it would in the full-step sequence $\left(15^{\circ}\right)$. The half-step sequence is used when smaller steps are desirable and more steps per revolution are acceptable. As it turns out, the stepper motor will rotate in a manner similar to the full-step sequence ( $15^{\circ}$ per step) if you apply only the sequence of intermediate states with one coil energized at a time. This sequence, called the wave-drive sequence, has less torque but operates more smoothly than the full-step sequence at moderate speeds. The wave-drive sequence is shown in the right-hand column of Table 10-1.

TABLE 10-1 Stepper motor coil drive sequences.

| Full-Step | Half-Step | Wave-Drive |
| :---: | :---: | :---: |
| 1010 | 1010 |  |
|  | 1000 | 1000 |
| 1001 | 1001 |  |
|  | 0001 | 0001 |
| 0101 | 0101 |  |
|  | 0100 | 0100 |
| 0110 | 0110 |  |
|  | 0010 | 0010 |

## Problem Statement

A microprocessor laboratory needs a universal interface to drive a stepper motor. In order to experiment with microcontrollers driving stepper motors, it would be useful to have a single universal interface IC wired to the stepper motor. This circuit needs to accept any of the typical forms of stepper drive signals from a microcontroller and activate the windings of the motor to make it move in the desired manner. The interface needs to operate in one of four modes: decoded full-step, decoded half-step, decoded wave-drive, or nondecoded direct drive. The mode is selected by controlling the logic levels on the M1, M0 input pins. In the first three modes, the interface receives just two control bits-a step pulse and a direction control bit-from the microcontroller. Each time it sees a rising edge on the step input, the circuit must cause the motor to move one increment of motion clockwise or counterclockwise, depending on the level present on the direction bit. Depending on the mode that the IC is in, the outputs will respond to each step pulse by changing state according to the sequences shown in Table 10-1. The fourth mode of operation of this circuit must allow the microcontroller to control each winding of the motor directly. In this mode, the circuit accepts four control bits from the microcontroller and passes these logic levels directly to its outputs, which are used to energize the stepper coils. The four modes are summarized in Table 10-2.

TABLE 10-2

| Mode | M1 M0 | Input Signals | Output |  |
| :---: | :---: | :---: | :--- | :--- |
| 0 | 0 | 0 | Step, direction | Full-step count sequence |
| 1 | 0 | 1 | Step, direction | Wave-drive count sequence |
| 2 | 1 | 0 | Step, direction | Half-step count sequence |
| 3 | 1 | 1 | Four control inputs | Direct drive from control inputs |

In modes 0,1 , and 2 , the outputs count through the corresponding count sequence on each rising edge of the step input. The direction input determines whether the sequence moves forward or backward through the states in Table 10-1, thus moving the motor clockwise or counterclockwise. From this description, we can make some decisions about the project.

> Inputs
> step: rising edge trigger
> direction: $0=$ backward through table, $1=$ forward through table cin0, cin1, cin2, cin3, $m 1, m 0$ : active-HIGH control inputs

Outputs<br>cout0, cout1, cout2, cout3: active-HIGH control outputs

## Strategic Planning

This project has two key requirements. It requires a sequential counter circuit that will control the outputs in three of the modes. In the last mode, the output does not follow a counter but rather follows the control inputs. While there are many ways to divide this project and still fulfill these requirements, we will choose to have a simple up/down binary counter that responds to the step and direction inputs. A separate combinational logic circuit will translate (decode) the binary count into the appropriate output state, depending on the mode input setting. This circuit will also ignore the counter inputs and pass the control inputs directly to the outputs when the mode is set to 3 . The circuit diagram is shown in Figure 10-1.

Breaking this problem into manageable pieces is also fairly straightforward. The first step is to build an up/down counter. This counter should be tested on a simulator using only the direction and step inputs. Next, try to make each decoded sequence work individually with the counter. Then try to get the mode inputs to select one of the decoder sequences and add the direct-drive option (which is fairly trivial). When the circuit can follow the states shown in Table 10-1 in either direction, for each mode sequence, and pass the four cin signals directly to cout in mode 3, we will be successful.

## Synthesis and Testing

The code in Figures 10-2 and 10-3 shows the first stage of development: designing and testing an up/down counter. We will use an intermediate integer variable for the counter value and test it by outputting the count directly to $q$. To test this part of the design, we simply need to make sure it can count up and down through the eight states. Figure 10-4 shows the simulation results. We only need to provide the clock pulses and make up a direction control signal, and the simulator demonstrates the counter's response.


FIGURE 10-1 A universal stepper motor interface circuit.

```
SUBDESIGN fig10_2
(
        step, dir :INPUT;
        q[2..0] :OUTPUT;
)
VARIABLE
count[2..0] : DFF;
BEGIN
    count[].clk = step;
    IF dir THEN count[].d = count[].q + 1;
    ELSE count[].d = count[].q - 1;
    END IF;
    q[] = count[].q;
END;
```

```
ENTITY fig10_3 IS
PORT( step, dir :IN BIT;
    q :OUT INTEGER RANGE 0 TO 7);
END fig10_3;
ARCHITECTURE vhdl OF fig10_3 IS
BEGIN
    PROCESS (step)
    VARIABLE count :INTEGER RANGE 0 TO 7;
    BEGIN
        IF (step'EVENT AND step = '1') THEN
                IF dir = '1' THEN count := count + 1;
                ELSE count := count - 1;
                END IF;
        END IF;
        q <= count;
    END PROCESS;
END vhdl;
```

FIGURE 10-2 AHDL MOD-8.
FIGURE 10-3 VHDL MOD-8.


FIGURE 10-4 Simulation testing of a basic MOD-8.

The next step is to add one of the decoded outputs and test it, which will require adding the four-bit cout output specification. The $q$ output bits of the MOD-8 counter are kept for the sake of continuity. Figure $10-5$ shows the AHDL code for this stage of testing, and Figure 10-6 shows the VHDL code for the same stage of testing. Notice that a CASE construct is used to decode the counter and drive the outputs. In the VHDL code, the cout outputs have been declared as bit_vector type because we now want to assign binary bit patterns to them. Figure 10-7 shows the simulated test of its operation with enough clock cycles included to test an entire counter cycle up and down.

The other count sequences are simply variations of the code we just tested. It is probably not necessary to test each one independently, so now is a good time to bring in the mode selector inputs ( $m$ ) and direct-drive coil control inputs (cin). Notice that the new inputs have been defined in Figures 10-8 (AHDL) and 10-9 (VHDL). Because the mode control has four possible states and we want to do something different for each state, another CASE construct works best. In other words, we have chosen to use a CASE structure to select the mode and a CASE structure within each mode to select the

```
SUBDESIGN fig10_5
l
    step, dir :INPUT;
    q[2..0] :OUTPUT;
    cout[3..0] :OUTPUT;
)
VARIABLE
    count[2..0]: DFF;
BEGIN
    count[].clk = step;
    IF dir THEN count[].d = count[].q + 1;
    ELSE count[].d = count[].q - 1;
    END IF;
    q[] = count[].q;
    CASE count[] IS
        WHEN B"000" => cout[] = B"1010";
            WHEN B"001" => cout[] = B"1001";
            WHEN B"010" => cout[] = B"0101";
            WHEN B"011" => cout[] = B"0110";
            WHEN B"100" => cout[] = B"1010";
            WHEN B"101" => cout[] = B"1001";
            WHEN B"110" => cout[] = B"0101";
            WHEN B"111" => cout[] = B"0110";
    END CASE;
END;
```

FIGURE 10-5 AHDL full-step sequence decoder.

```
ENTITY fig10_6 IS
PORT ( step, dir :IN BIT;
    q :OUT INTEGER RANGE 0 TO 7;
    cout :OUT BIT_VECTOR (3 downto 0));
END fig10_6;
ARCHITECTURE vhdl OF fig10_6 IS
BEGIN
    PROCESS (step)
    VARIABLE count :INTEGER RANGE 0 TO 7;
    BEGIN
        IF (step'EVENT AND step = '1') THEN
            IF dir = '1' THEN count := count + 1;
            ELSE count := count - 1;
            END IF;
            q <= count;
        END IF;
            CASE count IS
                WHEN 0 => cout <= B"1010";
                WHEN 1 => cout <= B"1001";
                WHEN 2 => cout <= B"0101";
                WHEN 3 => cout <= B"0110";
                WHEN 4 => cout <= B"1010";
                WHEN 5 => cout <= B"1001";
                WHEN 6 => cout <= B"0101";
                WHEN 7 => cout <= B"0110";
            END CASE;
        END PROCESS;
END vhdl;
```

FIGURE 10-6 VHDL full-step sequence decoder.


FIGURE 10-7 Simulation testing of decoded sequence.

FIGURE 10-8 AHDL stepper driver.

```
SUBDESIGN fig10_8
(
    step, dir :INPUT;
    m[1..0], cin[3..0] :INPUT;
    cout[3..0], q[2..0] :OUTPUT;
)
VARIABLE
    count[2..0] : DFF;
BEGIN
    count[].clk = step;
    IF dir THEN count[].d = count[].q + 1;
    ELSE count[].d = count[].q - 1;
    END IF;
    q[] = count[].q;
    CASE m[] IS
    WHEN 0 =>
                CASE count[] IS -- FULL STEP
                WHEN B"OOO" => cout[] = B"1010";
                WHEN B"001" => cout[] = B"1001";
                WHEN B"010" => cout[] = B"0101";
                WHEN B"011" => cout[] = B"0110";
                WHEN B"100" => cout[] = B"1010";
                WHEN B"101" => cout[] = B"1001";
                WHEN B"110" => cout[] = B"0101";
                WHEN B"111" => cout[] = B"0110";
                END CASE;
```

    WHEN 1 =>
                CASE count[] IS -- WAVE DRIVE
                WHEN B"OOO" => cout[] = B"1000";
                WHEN B"001" => cout[] = B"0001";
                WHEN B"010" => cout[] = B"0100";
                WHEN B"011" => cout[] = B"0010";
                WHEN B"100" => cout[] = B"1000";
                WHEN B"101" => cout[] = B"0001";
                WHEN B"110" => cout[] = B"0100";
                WHEN B"111" => cout[] = B"0010";
                END CASE;
    WHEN 2 =>
    
END CASE;
WHEN 3 => cout[] = cin[]; -- Direct Drive
END CASE;
END;

FIGURE 10-9 VHDL stepper driver.

```
ENTITY fig10_9 IS
PORT ( step, dir :IN BIT;
    m :IN BIT_VECTOR (1 DOWNTO 0);
    cin :IN BIT_VECTOR (3 DOWNTO 0);
    q :OUT INTEGER RANGE 0 TO 7;
    cout :OUT BIT_VECTOR (3 DOWNTO 0));
```

END fig10_9;
ARCHITECTURE vhdl OF fig10_9 IS
BEGIN
PROCESS (step)
VARIABLE count :INTEGER RANGE 0 TO 7;
BEGIN
IF (step'EVENT AND step = '1') THEN
IF dir = '1' THEN count := count + 1;
ELSE count := count - 1;
END IF;
END IF;
q <= count;
CASE m IS
WHEN "OO" => -- FULL STEP
CASE count IS
WHEN $0 \quad=>$ cout <= "1010";
WHEN 1 => cout <= "1001";
WHEN 2 => cout <= "0101";
WHEN 3 => cout <= "0110";
WHEN 4 => cout <= "1010";
WHEN 5 => cout <= "1001";
WHEN 6 => cout <= "0101";
WHEN 7 => cout <= "0110";
END CASE;
WHEN "01" =>
-- WAVE DRIVE
CASE count IS
WHEN $0 \quad=>$ cout <= "1000";
WHEN 1 => cout <= "0001";
WHEN 2 => cout <= "0100";
WHEN 3 => cout <= "0010";
WHEN 4 => cout <= "1000";
WHEN 5 => cout <= "0001";
WHEN 6 => cout <= "0100";
WHEN 7 => cout <= "0010";
END CASE;
WHEN "10" => -- HALF STEP
CASE count IS
WHEN $0 \quad=>$ cout <= "1010";
WHEN 1 => cout <= "1000";
WHEN 2 => cout <= "1001";
WHEN 3 => cout <= "0001";
WHEN 4 => cout <= "0101";
WHEN 5 => cout <= "0100";
WHEN 6 => cout <= "0110";
WHEN 7 => cout <= "0010";
END CASE;
WHEN "11" => cout <= cin;--Direct Drive
END CASE;
END PROCESS;
END vhdl; ;
proper output. Using one construct inside another is known as nesting. The use of indentation is very important to show the structure and logic of the code, especially when nesting is used.

The simulations of Figure $10-10$ verify that the circuit seems to be working properly. Figure 10-10(a) shows each state decoding in mode 0 (full-step) and completing the cycle in both directions. Notice that after the mode $(m)$ changes to $01_{2}$, the output (cout) is decoded as the wave-drive sequence. Figure $10-10$ (b) shows the wave-drive (mode 1) sequence in both directions and then changes the mode to $10_{2}$, resulting in the half-step sequence being decoded from the MOD-8 counter. Finally, Figure 10-10(c) shows the half-step mode cycling up and starting back down. It then switches to mode 3 (direct-drive) at 7.5 ms , showing that the data on cin is transferred asynchronously to the outputs. Notice that the values chosen for cin ensure that each bit can go HIGH and LOW.

Final integration and testing should involve more than just simulation. A real stepper motor and current driver should be connected to the circuit and tested. In this case, the step rate that the simulation used would probably be faster than the actual stepper motor could handle and would need to be slowed down for a real hardware functional test.


FIGURE 10-10 Simulation testing of the complete stepper driver.

1. What are the four modes of operation for this stepper motor driver?
2. What are the inputs for the direct-drive mode?
3. What are the inputs for the wave-drive mode?
4. How many states are in the half-step sequence?

## 10-3 KEYPAD ENCODER PROJECT

Another important skill that we are trying to reinforce is circuit analysis. That may sound like something out of an analog textbook, but we really need to be able to analyze and understand how existing digital circuits operate. In this section, we present a circuit and analyze how it operates. Then we use the skills we have acquired to redesign this circuit and write the code for it in HDL.

## Problem Analysis

To reinforce the encoding concepts of Chapter 9, we present a very useful digital circuit that encodes a hexadecimal (16-key) keypad into a four-bit binary output. Encoders such as this generally have a strobe output that indicates when someone presses and releases a key. Because keypads are often interfaced to a microcomputer's bus system, the encoded outputs should have tristate enables. Figure 10-11 shows the block diagram of the keypad encoder.

The priority encoder method shown in Chapter 9, Figure 9-15, is effective for small keypads. However, large keyboards such as those found on personal computers must use a different technique. In these keyboards, each key is not an independent switch to $V_{C C}$ or ground. Instead, each key switch is used

FIGURE 10-11 Keypad encoder block diagram.

to connect a row to a column in the keyboard matrix. When keys are not pressed, there are no connections between the rows and columns. The trick of knowing which key is pressed is accomplished by activating (pulling LOW) one row at a time and then checking to see if any of the columns have gone LOW. If one of the columns has a LOW on it, then the key being pressed is at the intersection of the activated row and the column that is currently LOW. If no columns are LOW, we know that no keys in the activated row are being pressed and we can check the next row by pulling it LOW. Sequentially activating rows is called scanning the keyboard. The advantage of this method is the reduction in connections to the keypad. In this case, 16 keys can be encoded using eight inputs/outputs.

Each key represents a unique combination of a row number and a column number. By strategically numbering the rows and columns, we can combine the binary row and column numbers to create the binary value of the hexadecimal keys as shown in Figure 10-12. In this figure, row $1\left(01_{2}\right)$ is pulled LOW and the data on the column encoder is $10_{2}$ so the button at row 1, column 2 is evidently pressed. The NAND gate in Figure $10-11$ is used to determine if any column is LOW, indicating that a key is pressed in the currently active row. The output of this gate is named FREEZE because when a key is pressed, we want to freeze the ring counter and quit scanning until the key is released. As the encoders go through their propagation delay and the tristate buffers become enabled, the data outputs are in a transient state. On the next rising edge of the clock, the D flip-flop will transfer a HIGH from FREEZE to the DAV output, indicating that a key is being pressed and the valid data is available.

A shift register counter (ring counter), as we studied in Chapter 7, is used to generate the sequential scan of the four rows. The count sequence uses four states, each state having a different bit pulled LOW. When a key press is detected, the ring counter must hold in its current state (freeze) until the key is released. Figure 10-13 shows the state transition diagram. Each state of this counter must be encoded to generate a two-bit binary row num-


FIGURE 10-12 Encoder operation when pressing the " 6 " key.

FIGURE 10-13 Row drive ring counter state diagram.

ber. Each column value must also be encoded to generate a two-bit binary column number. The system will require the following inputs and outputs.

| 4 | Row drive outputs | $R_{0}-R_{3}$ |
| :--- | :--- | :--- |
| 4 | Column read inputs | $C_{0}-C_{3}$ |
| 4 | Encoded data outputs | $D_{0}-D_{3}$ |
| 1 | Data available strobe output | $D A V$ |
| 1 | Tristate enable input | $O E$ |
| 1 | Clock input | $C L K$ |

## Strategic Planning

This circuit is already structured so that we can easily write pieces of HDL code to emulate each section of the system. The major blocks are as follows:

A ring counter with active-LOW outputs.
Two encoders for the row and column numbers.
Key-press detection and tristate enable circuits.
Because these circuits have been explored in previous chapters, we will not show the development and testing of each block here. The solutions that follow jump directly to the integration and testing phase of the project.

## AHDL SOLUTION

The inputs and outputs (see Figure 10-14) are defined on lines 3-8 and follow the description obtained from analyzing the schematic. The VARIABLE section defines several features of this encoder circuit. The freeze bit detects when a key is pressed. The data node is used to combine the row and column encoder data. The ts bit array (line 13) represents a tristate buffer, as we studied in Chapter 9. Recall that each bit of this buffer has an input, (ts[].IN), an output (ts.OUT), and an output enable (ts[].OE). The data_avail bit (line 14) represents a D flip-flop with inputs data_avail.CLK, data_avail.D, and output data_avail.Q.

```
SUBDESIGN fig10_14
(
    clk :INPUT;
    col[3..0] :INPUT;
    oe :INPUT; --tristate output enable
    row[3..0] :OUTPUT;
    d[3.0.0] :OUTPUT;
    dav :OUTPUT; --data available
)
VARIABLE
freeze :NODE;
data[3..0] :NODE;
ts[3.00] :TRI;
data_avail :DFF;
ring: MACHINE OF BITS (row[3..0])
WITH STATES (s1 = B"1110", s2 = B"1101", s3 = B"1011", s4 = B"0111",
                                    % s = ring states %
                f1 = B"0001", f2 = B"0010", f3 = B"0011", f4 = B"0100",
                f5 = B"0101", f6 = B"0110", f7 = B"1000", f8 = B"1001",
                f9 = B"1010", fa = B"1100", fb = B"1111", fc = B"0000");
                        % f = unused states --> self-correcting design %
BEGIN
    ring.CLK = clk;
    ring.ENA = !freeze;
    data_avail.CLK = clk;
    data_avail.D = freeze;
    dav = data_avail.Q;
    ts[].OE = oe & freeze;
    ts[].IN = data[];
    d[] = ts[].OUT;
    CASE ring IS
        WHEN s1 => ring = s2; data[3..2] = B"00";
        WHEN s2 => ring = s3; data[3..2] = B"01";
        WHEN s3 => ring = s4; data[3..2] = B"10";
        WHEN s4 => ring = s1; data[3..2] = B"11";
        WHEN OTHERS => ring = s1;
    END CASE;
    CASE col[] IS
        WHEN B"1110" => data[1..0] = B"00"; freeze = VCC;
        WHEN B"1101" => data[1..0] = B"01"; freeze = VCC;
        WHEN B"1011" => data[1..0] = B"10"; freeze = VCC;
        WHEN B"0111" => data[1..0] = B"11"; freeze = VCC;
        WHEN OTHERS => data[1..0] = B"00"; freeze = GND;
        END CASE;
END;
```

FIGURE 10-14 AHDL scanning keypad encoder.

Lines 15-20 demonstrate a powerful feature of AHDL that allows us to define a state machine, with each state made up of the bit pattern we need. On line 15, the name ring was given to this state machine because it acts like a ring counter. The bits that make up this ring counter machine are the four row bits that were defined on line 6 . These states are labeled s1-s4 and have their bit patterns assigned to them so that one bit of the four is LOW for each state, like an active-LOW ring counter. The other twelve states are specified by an arbitrary label that starts with $f$ to indicate they are not valid states. Lines 23 through 30 essentially connect all the components as shown in the circuit drawing of Figure 10-11. Both the ring count sequence and the encoding of the row value are described on lines 32-38. For each PRESENT state value of ring, the NEXT state is defined as well as the proper output of the row encoder (data[3..2]). Line 37 ensures that this counter will self-start by sending it to $s 1$ from any state other than s1-s4. The encoding of the column value is described on lines $40-46$. Notice that the generation of the freeze signal in this design does not follow the diagram of Figure 10-11 exactly. In this design, rather than NANDing the columns, the CASE structure activates freeze only when one (and only one) column is LOW. Thus, if multiple keys in the same row were pressed, the encoder would not recognize any as a valid key press and would not activate dav.

## VHDL SOLUTION

Compare the VHDL description in Figure 10-15 with the circuit drawing of Figure 10-11. The inputs and outputs are defined on lines 5-9 and follow the description obtained from analyzing the schematic. Two SIGNALs are defined on lines 13 and 14 for this design. The freeze bit detects when a key is pressed. The data signal is used to combine the row and column encoder data to make a four-bit value representing the key that was pressed. The ring counter is implemented using a PROCESS that responds to the clk input. Line 26 ensures that this counter will self-start by sending it to state " 1110 " from any state other than those in the ring sequence. Notice that on line 20, the status of freeze is checked before a CASE is used to assign a NEXT state to ring. This is the way the count enable is implemented in this design. On line 29, the data available output (dav) is updated synchronously with the value of freeze. It is synchronous because it is within the IF structure (lines 19-30) that detects the active clock edge. The remaining statements (lines 31-52) do not depend on the active clock edge but describe what the circuit will do on either edge of the clock.

The encoding of the row value is described on lines 33-39. For each PRESENT state value of ring, the output of the row encoder data(3 DOWNTO 2) is defined. The encoding of the column value is described on lines 41-47. Notice that the generation of the freeze signal in this design does not follow the diagram of Figure 10-11 exactly. In this design, rather than NANDing the columns, the CASE structure activates freeze only when one (and only one) column is LOW. Thus, if multiple keys in the same row were pressed, the encoder would not recognize any as a valid key press and would not activate dav.

FIGURE 10-15
VHDL scanning 1 keypad encoder.

```
LIBRARY ieee;
USE ieee.std_logic_1164.all;
ENTITY fig10_15 IS
PORT ( clk :IN STD_LOGIC;
    col :IN STD_LOGIC_VECTOR (3 DOWNTO 0);
    row :OUT STD_LOGIC_VECTOR (3 DOWNTO 0);
    d :OUT STD_LOGIC_VECTOR (3 DOWNTO 0);
    dav :OUT STD_LOGIC );
END fig10_15;
ARCHITECTURE vhdl OF fig10_15 IS
SIGNAL freeze :STD_LOGIC;
SIGNAL data :STD_LOGIC_VECTOR (3 DOWNTO 0);
BEGIN
    PROCESS (clk)
    VARIABLE ring :STD_LOGIC_VECTOR (3 DOWNTO 0);
    BEGIN
        IF (clk'EVENT AND clk = '1') THEN
            IF freeze = '0' THEN
                CASE ring IS
                    WHEN "1110" => ring := "1101";
                    WHEN "1101" => ring := "1011";
                    WHEN "1011" => ring := "0111";
                    WHEN "0111" => ring := "1110";
                WHEN OTHERS => ring := "1110";
            END CASE;
            END IF;
            dav <= freeze;
        END IF;
        row <= ring;
        CASE ring IS
            WHEN "1110" => data(3 DOWNTO 2) <= "00";
            WHEN "1101" => data(3 DOWNTO 2) <= "01";
            WHEN "1011" => data(3 DOWNTO 2) <= "10";
            WHEN "0111" => data(3 DOWNTO 2) <= "11";
            WHEN OTHERS => data(3 DOWNTO 2) <= "00";
        END CASE;
        CASE col IS
            WHEN "1110" => data(1 DOWNTO 0) <= "00"; freeze <= '1';
            WHEN "1101" => data(1 DOWNTO 0) <= "01"; freeze <= '1';
            WHEN "1011" => data(1 DOWNTO 0) <= "10"; freeze <= '1';
            WHEN "0111" => data(1 DOWNTO 0) <= "11"; freeze <= '1';
            WHEN OTHERS => data(1 DOWNTO 0) <= "00"; freeze <= '0';
        END CASE;
        IF freeze = '1' THEN d <= data;
        ELSE d <= "ZZZZ";
        END IF;
    END PROCESS;
END vhdl;
```



FIGURE 10-16 Simulation of the scanning keypad encoder.

The simulation of the project is shown in Figure 10-16. The column values ( col ) are entered by the designer as a test input that simulates the value being read from the columns of the keypad as the rows are being scanned. As long as all columns are HIGH (i.e., the hex value F is on col), the ring counter is enabled and counting, dav is LOW, and the $d$ outputs are in the Hi-Z state. Just before the $3.0-\mathrm{ms}$ mark, a 7 is simulated as a col input, which means that one of the columns went LOW. This simulates a key being detected in the most significant column (C3) of the keypad matrix. Notice that as a result of the column going LOW, on the next active (rising) clock edge, the dav line goes HIGH and the ring counter does not change state. It is disabled from going to its NEXT state as long as the key is pressed. At this point, the row value is E hex $\left(1110_{2}\right)$, which means that the least significant row (R0) is being pulled LOW by the ring counter. The row encoder translates this into the binary row number (00). The key located at the intersection of the least significant row $\left(0_{2}\right)$ and the most significant column (112) is the 3 key (see Figure 10-12). At this point, the $d$ outputs hold the encoded key value of 3 ( $0011_{2}$ ). Just after the 4-ms mark, the simulation imitates the release of the key by changing the column value back to F hex, which causes the $d$ output to go into its Hi-Z state. On the next rising clock edge, the dav line goes LOW and the ring counter resumes its count sequence.

1. How many rows on the scanned keyboard are activated at any point in time?
2. If two keys in the same column are pressed simultaneously, which key will be encoded?
3. What is the purpose of the $D$ flip-flop on the DAV pin?
4. Will the time between the key being pressed and DAV going HIGH always be the same?
5. When are the data output pins in the Hi-Z state?

## 10-4 DIGITAL CLOCK PROJECT

One of the most common applications of counters is the digital clock-a time clock that displays the time of day in hours, minutes, and sometimes seconds. In order to construct an accurate digital clock, a closely controlled basic clock frequency is required. For battery-operated digital clocks or watches, the basic frequency is normally obtained from a quartz-crystal oscillator. Digital clocks operated from the ac power line can use the $60-\mathrm{Hz}$ power frequency as the basic clock frequency. In either case, the basic frequency must


FIGURE 10-17 Block diagram for a digital clock.
be divided to a frequency of 1 Hz or 1 pulse per second (pps). Figure 10-17 shows the basic block diagram for a digital clock operating from 60 Hz .

The $60-\mathrm{Hz}$ signal is sent through a Schmitt-trigger circuit to produce square pulses at the rate of 60 pps . This 60 -pps waveform is fed into a MOD60 counter that is used to divide the 60 pps down to 1 pps . The 1 -pps signal is used as a synchronous clock for all of the counter stages, which are synchronously cascaded. The first stage is the SECONDS section, which is used to count and display seconds from 0 through 9 . The $B C D$ counter advances one count per second. When this stage reaches 9 seconds, the BCD counter activates its terminal count output ( $t c$ ), and on the next active clock edge, it recycles to 0 . The BCD terminal count enables the MOD-6 counter and causes it to advance by one count at the same time that the BCD counter recycles. This process continues for 59 seconds, at which point the MOD-6 counter is at the 101 (5) count and the BCD counter is at 1001 (9) so that the display reads 59 s and tc of the MOD-6 is HIGH. The next pulse recycles the BCD counter and the MOD-6 counter to zero (remember, the MOD-6 counts from 0 through 5).

The tc output of the MOD-6 counter in the SECONDS section has a frequency of 1 pulse per minute (i.e, the MOD-6 recycles every 60 s). This signal is fed to the MINUTES section, which counts and displays minutes from 0 through 59. The MINUTES section is identical to the SECONDS section and operates in exactly the same manner.

The tc output of the MOD-6 counter in the MINUTES section has a frequency of 1 pulse per hour (i.e., the MOD-6 recycles every 60 min ). This signal is fed to the HOURS section, which counts and displays hours from 1 through 12. This HOURS section is different from the SECONDS and MINUTES sections because it never goes to the 0 state. The circuitry in this section is sufficiently unusual to warrant a closer investigation.

Figure $10-18$ shows the detailed circuitry contained in the HOURS section. It includes a BCD counter to count units of hours and a single FF (MOD2) to count tens of hours. The BCD counter is a 74160 , which has two activeHIGH inputs, ENT and ENP, that are ANDed together internally to enable the


FIGURE 10-18 Detailed circuitry for the HOURS section.
count. The ENT input also enables the active-HIGH ripple carry out (RCO) that detects the BCD terminal count of 9. The ENT input and RCO output can therefore be used for synchronous counter cascading. The ENP input is tied HIGH so that the counter will increment whenever ENT is HIGH.

The hours counter is enabled by the minutes and seconds stages for only one clock pulse every hour. When this condition occurs, ENT is HIGH, which means that the minutes:seconds stages are at 59:59. For example, at 9:59:59, the tens of hours flip-flop holds a 0 , the 74160 holds $1001_{2}$ (9), and the RCO output is HIGH, putting the tens of hours flip-flop in the SET mode. The two display digits for the hours show 09. On the next rising clock edge, the BCD counter advances to its natural NEXT state of $0000_{2}$, RCO goes LOW, and the tens of hours flip-flop advances to 1 so that the hours display digits now show 10.

When it is 11:59:59, AND gate 1 detects that the tens of hours is 1 and the enable input is active (previous stages are at 59:59). AND gate 3 combines the conditions of AND gate 1 and the condition that the BCD counter is in the state $0001_{2}$. The output of AND gate 3 will be HIGH only at 11:59:59 in the hours count sequence. On the next clock pulse, the AM/PM flip-flop toggles, indicating noon (HIGH) or midnight (LOW). At the same time, the BCD counter advances to 2 and the minutes:seconds stages roll over to 00:00, resulting in a BCD display of 12:00:00. At 12:59:59, AND gate 1 detects that the tens digit is 1 and it is time to advance the hours. AND gate 2 detects that the BCD counter is at 2 . The output of AND gate 2 prepares to do two tasks on the next clock edge: reset the tens of hours flip-flop, and load the 74160 counter with the value 00012. After the next clock pulse, it is 01:00:00 o'clock.

The operation of counter circuits should make sense now, and you should have a good grasp on how you can connect MSI chips to make this digital clock.

Notice that it is really made up of several small and relatively simple circuits that are strategically interconnected to make the clock. Recall that in Chapter 4, we mentioned briefly the concept of modular, hierarchical design and development of digital systems. Now it is time to apply these principles to a project that is within your scope of understanding using the MAX + PLUS II or Quartus II development system from Altera. You must understand the operation of the circuits that have just been described before proceeding with the design of this clock using HDL. Take some time to review this material.

## Top-Down Hierarchical Design

Top-down design means that we want to start at the highest level of complexity in the hierarchy, or that the entire project is considered to exist in a closed, dark box with inputs and outputs. The details regarding what is in the box are not yet known. We can only say at this point how we want it to behave. The digital clock was chosen because everyone is familiar with the end result of the operation of this device. An important aspect of this stage of the design process is establishing the scope of the project. For example, this digital clock is not going to have a way to set the time, set an alarm time, shut off the alarm, snooze, or incorporate other features that you may find on the clock beside your bed. To add all these features now would only clutter the example with unnecessary complexity for our immediate purpose. We are also not going to include the signal conditioning that transforms a $60-\mathrm{Hz}$ sine wave into a 60-pulse-per-second digital waveform, or the decoder/display circuits. The project we are tackling has the following specifications:

Inputs: 60 pps CMOS compatible waveform (accuracy dependent on line frequency)
Outputs: BCD Hours: 1 bit TENS 4 bits UNITS BCD Minutes: 3 bits TENS 4 bits UNITS BCD Seconds: 3 bits TENS 4 bits UNITS PM indicator

Minutes and Seconds sequence: BCD MOD 60
00-59 (decimal representation of BCD)
Hours sequence BCD MOD 12
01-12 (decimal representation of BCD)
Overall range of display
01:00:00-12:59:59
AM/PM indicator toggles at 12:00:00
A hierarchy is a group of objects arranged in rank order of magnitude, importance, or complexity. A block diagram of the overall project (highest level of the hierarchy) is shown in Figure 10-19. Notice that there are four bits for each of the BCD units outputs and only three bits for each of the

FIGURE 10-19 The top level block of the hierarchy.


FIGURE 10-20 The section level of the hierarchy.

minute and second BCD tens outputs. Because the most significant BCD digit for the tens place is $5\left(101_{2}\right)$, only three bits are needed. Notice also that the tens place for the hours (HR_TENS) is only one bit. It will never have a value other than 0 or 1 .

The next phase is to break this problem into more manageable sections. First, we need to take the $60-\mathrm{pps}$ input and transform it into a 1 -pulse-persecond timing signal. A circuit that divides a reference frequency to a rate required by the system is called a prescaler. Next, it makes sense to have individual sections for a seconds counter, minutes counter, and hours counter. So far, the hierarchy diagram looks like Figure 10-20, which shows the project broken into four subsections.

The entire purpose of the frequency prescaler section is to divide the 60pps input to a frequency of one pulse every second. This requires a MOD-60 counter, and the sequence of the count does not really matter. In this example, the minutes and seconds sections both require MOD-60 counters that count from 00-59 in BCD. Looking for similarities like this is very important in the design process. In this case, we can use the exact same circuit design to implement the frequency prescaler, the minutes counter, and the seconds counters.

A MOD-60 BCD counter can be made quite easily from a MOD-10 (decade) counter cascaded to a MOD-6 BCD counter, as we saw in the diagram of Figure 10-17. This means that inside each of these MOD-60 blocks, we would find a diagram similar to Figure 10-21. The hierarchy of the project now appears as shown in Figure 10-22.


FIGURE 10-21 The blocks inside the MOD-60 section.


FIGURE 10-22 The complete hierarchy of the clock project.

The final design decision is whether or not to break down the MOD-12 section for Hours into two stages, as shown in Figure 10-18. One option is to connect the macrofunctions of these standard parts from the HDL library, as we have discussed in previous chapters. Because this circuit is rather unusual, we have decided instead to describe the MOD-12 hours counter using a single HDL module. We will also describe the MOD- 6 and MOD- 10 building blocks using HDL. The entire clock circuit can then be built using these three basic circuit descriptions. Of course, even these blocks can be broken down into smaller flip-flop blocks and designed using the schematic entry, but it will be much easier using HDL at this level.

## Building the Blocks from the Bottom Up

Each of the basic blocks are presented here in both AHDL and VHDL. We present the MOD-6 as a simple modification of the MOD-5 synchronous counter descriptions presented earlier in Chapter 7 (see Figures 7-39 and $7-40$ ). Then we modify this code further to create the MOD-10 counter and finally design the MOD-12 Hours counter from the ground up. We construct the entire clock from these three basic blocks.

## MOD-6 COUNTER AHDL

The only additional features that this design needs that are not covered in Figure 7-39 are the count enable input and terminal count ( $t$ c) output shown in Figure 10-23. Notice that the extra input (enable, line 3) and output (tc, line 4) are included in the I/O definition. A new line (line 11) in the architecture description tests enable before deciding how to update the value of

```
SUBDESIGN fig10_23
(
    clock, enable :INPUT; -- synch clock and enable.
    q[2..0], tc :OUTPUT; -- 3-bit counter
)
VARIABLE
    count[2..0] :DFF; -- declare a register of D flip-flops.
BEGIN
    count[].clk = clock; -- connect all clocks to synchronous source
    IF enable THEN
            IF count[].q < 5 THEN
            count[].d = count[].q + 1; -- increment current value by one
            ELSE count[].d = 0; -- recycle,force unused states to 0
            END IF;
        ELSE count[].d = count[].q; -- not enabled: hold at this count
        END IF;
        tc = enable & count[].q == 5; -- detect maximum count if enabled
        q[] = count[].q; -- connect register to outputs
END;
```

FIGURE 10-23 The MOD-6 design in AHDL.
count (lines 12-15). If enable is LOW, the same value is held on count at every clock edge by the ELSE branch (line 16). Remember always to match an IF with an END IF, as we did on lines 15 and 17 . Terminal count ( $t c$, line 18) will be HIGH when it is true that count $==5$ AND enable is active. Notice the use of double equal signs $(==)$ to evaluate equality in AHDL.

## MOD-6 COUNTERVHDL

The only additional features that this design needs that are not covered in Figure 7-40 are the count enable input and terminal count (tc) output shown in Figure 10-24. Notice that the extra input (enable, line 2) and output ( $t c$, line 4) are included in the I/O definition. A new line (line 15) in the architecture description tests enable before deciding how to update the value of count (lines $16-20$ ). In the case that enable is LOW, the current value is held in the variable count and does not count up. Remember always to match an IF with an END IF, as we did on lines 20-22. The terminal count indicator ( $t c$, lines 23 and 24) will be HIGH when it is true that count $=5$ AND enable is active.

```
ENTITY fig10_24 IS
PORT( clock, enable :IN BIT ;
            q :OUT INTEGER RANGE O TO 5;
            tc :OUT BIT
    );
END fig10_24;
ARCHITECTURE a OF fig10_24 IS
BEGIN
        PROCESS (clock) -- respond to clock
    VARIABLE count :INTEGER RANGE O TO 5;
    BEGIN
        IF (clock = '1' AND clock'event) THEN
            IF enable = '1' THEN -- synchronous cascade input
            IF count < 5 THEN -- < max (terminal) count?
                        count := count + 1;
            ELSE
                count := 0;
            END IF;
            END IF;
        END IF;
        IF (count = 5) AND (enable = '1') THEN -- synch cascade output
            tc <= '1'; -- indicate terminal ct
        ELSE tc <= '0';
        END IF;
        q <= count; -- update outputs
    END PROCESS;
END a;
```

FIGURE 10-24 The MOD-6 design in VHDL.


FIGURE 10-25 Simulation of the MOD-6 counter.

The simulation testing of the MOD-6 counter in Figure 10-25 verifies that it counts $0-5$ and that it responds to the count enable input by ignoring the clock pulses and freezing the count whenever enable is LOW. It also generates the $t c$ output when it is enabled at its maximum count of 5 .

## MOD-10 COUNTER AHDL

The MOD-10 counter varies only slightly from the MOD-6 counter that was described in Figure 10-23. The only changes that are necessary involve changing the number of bits in the output port and the register (in the VARIABLE section) along with the maximum value that the counter should reach before rolling over. Figure 10-26 presents the MOD-10 design.

```
(
    clock, enable :INPUT; -- synch clock and enable.
    q[3..0], tc :OUTPUT; -- 4-bit Decade counter
)
VARIABLE
    count[3..0] :DFF; -- declare a register of D flip flops.
BEGIN
    count[].clk = clock; -- connect all clocks to synchronous source
    IF enable THEN
        IF count[].q < 9 THEN
            count[].d = count[].q + 1; -- increment current value by one
            ELSE count[].d = 0; -- recycle,force unused states to 0
        END IF;
    ELSE count[].d = count[].q; -- not enabled: hold at this count
    END IF;
    tc = enable & count[].q == 9; -- detect maximum count
    q[] = count[].q; -- connect register to outputs
END;
```

SUBDESIGN fig10_26

FIGURE 10-26 The MOD-10 design in AHDL.

## MOD-10 COUNTER VHDL

The MOD-10 counter varies only slightly from the MOD-6 counter that was described in Figure 10-24. The only changes that are necessary involve changing the number of bits in the output port and the variable count (using INTEGER RANGE) along with the maximum value that the counter should reach before rolling over. Figure 10-27 presents the MOD-10 design.

```
ENTITY fig10_27 IS
PORT( clock, enable :IN BIT ;
            q :OUT INTEGER RANGE O TO 9;
            tc :OUT BIT
    );
END fig10_27;
ARCHITECTURE a OF fig10_27 IS
BEGIN
    PROCESS (clock) -- respond to clock
    VARIABLE count :INTEGER RANGE 0 TO 9;
    BEGIN
        IF (clock = '1' AND clock'event) THEN
            IF enable = '1' THEN -- synchronous cascade input
                        IF count < 9 THEN -- decade counter
                count := count + 1;
                        ELSE
                        count := 0;
            END IF;
                END IF;
        END IF;
        IF (count = 9) AND (enable = '1') THEN -- synch cascade output
            tc <= '1';
        ELSE tc <= '0';
        END IF;
        q <= count; -- update outputs
        END PROCESS;
END a;
```

FIGURE 10-27 The MOD-10 design in VHDL.

## MOD 12 Design

We have already decided that the hours counter is to be implemented as a single design file using HDL. It must be a MOD-12 BCD counter that follows the hours sequence of a clock ( $1-12$ ) and provides the AM/PM indicator. Recall from the initial design step that the BCD outputs need to be a four-bit array for the low-order digit and a single bit for the high-order digit. To design this counter circuit, consider how it needs to operate. Its sequence is:

$$
01020304050607080910111201 \ldots
$$

By observing this sequence, we can conclude that there are four critical areas that define the operations needed to produce the proper NEXT state:

1. When the value is 01 through 08 , increment the low digit and keep the high digit the same.
2. When the value is 09 , reset the low digit to 0 and force the high digit to 1 .
3. When the value is 10 or 11 , increment the low digit and keep the high digit the same.
4. When the value is 12 , reset the low digit to 1 and the high digit to 0 .

Because these conditions need to evaluate a range of values, it is most appropriate to use an IF/ELSIF construct rather than a CASE construct. There
is also a need to identify when it is time to toggle the AM/PM indicator. This time occurs when the hour state is 11 and the enable is HIGH, which means that the lower-order counters are at their maximum (59:59).

## MOD-12 COUNTER IN AHDL

The AHDL counter needs a bank of four D flip-flops for the low-order BCD digit and only a single D flip-flop for the high-order BCD digit because its value will always be 0 or 1 . A flip-flop is also needed to keep track of A.M. and p.m. These primitives are declared on lines 7-9 of Figure 10-28. Also note that in this design, the same names are used for the output ports. This is a convenient feature of AHDL. When the enable input (ena) is active, the circuit evaluates the IF/ELSE statements of lines 16-28 and performs the proper

```
SUBDESIGN fig10_28
(
    clk, ena :INPUT;
    low[3..0], hi, pm :OUTPUT;
)
VARIABLE
    low[3..0] :DFF;
    hi :DFF;
    am_pm :JKFF;
    time :NODE;
BEGIN
    low[].clk = clk; -- synchronous clocking
    hi.clk = clk;
    am_pm.clk = clk;
    IF ena THEN -- use enable to count
            IF low[].q < 9 & hi.q == 0 THEN
                low[].d = low[].q + 1; --inc lo digit
                hi.d = hi.q; -- hold hi digit
        ELSIF low[].q == 9 THEN
            low[].d = 0;
            hi.d = VCC;
        ELSIF hi.q == 1 & low[].q < 2 THEN
                    low[].d = low[].q + 1;
                    hi.d = hi.q;
        ELSIF hi.q == 1 & low[].q == 2 THEN
                    low[].d = 1;
                    hi.d = GND;
            END IF;
    ELSE
        low[].d = low[].q;
        hi.d = hi.q;
    END IF;
    time = hi.q == 1 & low[3..0].q == 1 & ena; -- detect 11:59:59
    am_pm.j = time; -- toggle am/pm at noon and midnight
    am_pm.k = time;
    pm = am_pm.q;
END;
```

FIGURE 10-28 The MOD-12 hours counter in AHDL.
operation on the high and low nibble of the BCD number. Whenever the enable input is LOW, the value remains the same, as shown on lines 30 and 31. Line 33 detects when the count reaches 11 while the counter is enabled. This signal is applied to the $J$ and $K$ inputs of the am_pm flip-flop to cause it to toggle at 11:59:59.

## MOD-12 COUNTER INVHDL

The VHDL counter of Figure 10-29 needs a four-bit output for the low-order BCD digit and a single output bit for the high-order BCD digit because its

```
ENTITY fig10_29 IS
PORT( clk, ena :IN BIT ;
    low :OUT INTEGER RANGE 0 TO 9;
    hi :OUT INTEGER RANGE 0 TO 1;
    pm :OUT BIT );
END fig10_29;
ARCHITECTURE a OF fig10_29 IS
BEGIN
    PROCESS (clk) -- respond to clock
    VARIABLE am_pm :BIT;
    VARIABLE ones :INTEGER RANGE 0 TO 9; -- 4-bit units signal
    VARIABLE tens :INTEGER RANGE 0 TO 1; -- 1-bit tens signal
    BEGIN
        IF (clk = '1' AND clk'EVENT) THEN
            IF ena = '1' THEN -- synchronous cascade input
            IF (ones = 1) AND (tens = 1) THEN -- at 11:59:59
                am_pm := NOT am_pm; -- toggle am/pm
            END IF;
            IF (ones < 9) AND (tens = 0) THEN -- states 00-08
                ones := ones + 1; -- increment units
            ELSIF ones = 9 THEN -- state 09...set to 10:00
                ones := 0; -- units reset to zero
                tens := 1; -- tens bump up to 1
            ELSIF (tens = 1) AND (ones < 2) THEN-- states 10, 11
                ones := ones + 1; -- increment units
            ELSIF (tens = 1) AND (ones = 2) THEN -- state 12
                ones := 1; -- set to 01:00
                tens := 0;
            END IF;
    -- This space is the alternate location for updating am/pm
    -----------------------------------------------------------------
        END IF;
            END IF;
            pm <= am_pm;
            low <= ones; -- update outputs
            hi <= tens;
    END PROCESS;
END a;
```

FIGURE 10-29 The MOD-12 hours counter in VHDL.
value will always be 0 or 1 . These outputs (lines 3 and 4) and also the variables that will produce the outputs (lines 12 and 13) are declared as integers because this makes "counting" possible by simply adding 1 to the variable value. On each active edge of the clock, when the enable input is active, the circuit needs to decide what to do with the BCD units-of-hours counter, the single bit tens-of-hours flip-flop, and also the AM/PM flip-flop.

This example is an excellent opportunity to point out some of the advanced features of VHDL that allow the designer to describe precisely the operation of the final hardware circuit. In previous chapters, we discussed the issue of statements within a PROCESS being evaluated sequentially. Recall that statements outside the PROCESS are considered concurrent, and the order in which they are written in the design file has no effect on the operation of the final circuit. In this example, we must evaluate the current state to decide whether to toggle the AM/PM indicator and also advance the counter to the NEXT state. The issues involved include the following:

1. How do we "remember" the current count value in VHDL?
2. Do we evaluate the current count to see if it is 11 (to determine if we need to toggle the AM/PM flip-flop) and then increment to 12 , or do we increment the counter's state from 11 to 12 and then evaluate the count to see if it is 12 (to know we need to toggle the AM/PM flip flop)?

Regarding the first issue, there are two ways to remember the current state of a counter in VHDL. Both SIGNALs and VARIABLEs hold their value until they are updated. Generally, SIGNALs are used to connect nodes in the circuit like wires, and VARIABLEs are used like a register to store data between updates. Consequently, VARIABLEs are generally used to implement counters. The major differences are that VARIABLEs are local to the PROCESS in which they are declared and SIGNALs are global. Also, VARIABLEs are considered to be updated immediately within a sequence of statements in a PROCESS, whereas SIGNALs referred to in a PROCESS are updated when the PROCESS suspends. In this example, we have chosen to use VARIABLEs, which are local to the PROCESS that describes what should happen when the active clock edge occurs.

For the second issue, either of these strategies will work, but how do we describe them using VHDL? If we want the circuit to toggle A.M. and P.M. by detecting 11 prior to the counter updating (like a synchronous cascade), then the test must occur in the code before the VARIABLEs are updated. This test is demonstrated in the design file of Figure 10-29 on lines 17-19. On the other hand, if we want the circuit to toggle A.M. and P.M. by detecting when the hour 12 has arrived after the clock edge (more like a ripple cascade), then the VARIABLEs must be updated prior to testing for the value 12. To modify the design in Figure 10-29 to accomplish this task, the IF construct of lines 17-19 can be moved to the blank area of lines 31-33 and edited as shown in bold below:

```
IF (ones = 2) AND (tens = 1) THEN -- at 12:00:00
    am_pm := NOT am_pm; -- toggle am/pm
    END IF;
```

The order of the statements and the value that is decoded makes all the difference in how the circuit operates. On lines $36-38$, the $a m \_p m$ VARIABLE is connected to the pm port, the units BCD digit is applied to the lower four bits of the output (low), and the tens digit (a single-bit variable) is applied to the
most significant digit (hi) of the output port. Because all these VARIABLEs are local, these statements must occur prior to END PROCESS on line 39.

After the design is compiled, it must be simulated to verify its operation, especially at the critical areas. Figure $10-30$ shows an example of a simulation to test this counter. On the left side of the timing diagram, the counter is disabled and is holding the hour 11 because the hi digit is at 1 and the low[] digit is at 1 . On the rising edge of the clock, after the enable goes HIGH, the hour goes from 11 to 12 and causes the PM indicator to go HIGH, which means it is noon. The next active edge causes the count to roll over from 12 to 01 . On the right half of the timing, the same sequence is simulated, showing that there would actually be many clock pulses between the times the hour increments. On the clock cycle before it must increment, the enable is driven HIGH by the terminal count of the previous stage.


FIGURE 10-30 Simulation of the MOD-12 hours counter.

## Combining Blocks Graphically

The building blocks of the project have been defined, created, and individually simulated to verify that they work correctly. Now it is time to combine the blocks to make sections and to combine the sections to make the final product. Altera's software offers several ways to accomplish the integration of all the pieces of a project. In Chapter 4, we mentioned that all different types of design files (AHDL, VHDL, VERILOG, Schematic) can be combined graphically. This technique is made possible by a feature that allows us to create a "symbol" to represent a particular design file. For example, the MOD-6 counter design file that was written in the VHDL design file fig10_24 can be represented in the software as the circuit block, as shown in Figure 10-31(a). The MAX+PLUS II or Quartus II software creates this symbol at the click of a button. From that point, it will recognize the symbol as operating according to the design specified in the HDL code. The symbol of Figure 10-31(b) was created from the AHDL file for the MOD-10 counter of Figure 10-26, and the symbol of Figure 10-31(c) was created from the VHDL file for the MOD-12 counter of Figure 10-29. (The reason these blocks are named by figure number is simply to make it easier to locate the design files on the enclosed CD. In a design environment [rather than in a textbook], they should be named according to their purpose, with names like MOD6, MOD10, and CLOCK_HOURS.)


FIGURE 10-31 Graphic block symbols generated from HDL design files: (a) MOD-6 from VHDL; (b) MOD-10 from AHDL; (c) MOD-12 from VHDL.


FIGURE 10-32 Graphically combining HDL blocks to make a MOD-60.

Following the design hierarchy that we established, the next step is


FIGURE 10-33 The MOD-60 counter. to combine the MOD-6 and MOD-10 counters to make a MOD-60 block. MAX+PLUS II software uses graphic design files (.gdf) to integrate the block symbols by drawing lines that connect the input ports, symbols, and output ports. Quartus II software provides the same feature but uses block design files (.bdf). The result is shown in Figure 10-32, which represents a GDF file in MAX+PLUS II or a BDF file in Quartus II. This graphic or block design file can be compiled and used to simulate the operation of the MOD60 counter. When the design has been verified as working properly, the MAX+PLUS II or Quartus II system allows us to take this circuit and create a block symbol for it, as shown in Figure 10-33.

The MOD-60 symbol can be used repeatedly along with the MOD-12 symbol to create the system-level block symbol diagram shown in Figure 10-34. Even this system-level diagram can be represented by a block symbol for the entire project, as shown in Figure 10-35.


FIGURE 10-34 The complete clock project connected using block symbols.

FIGURE 10-35 The entire clock represented by one symbol.


## Combining Blocks Using Only HDL

The graphic approach works well as long as it is available and adequate for the purpose at hand. As we mentioned previously, HDL was developed to provide a convenient way to document complex systems and to store the
information in a more timeless and software-independent manner. It is reasonable to assume that with AHDL, the option of graphic integration of subdesigns will always be available with the tools from Altera; however, this assumption is not reasonable for users of VHDL. Many VHDL development systems do not offer any equivalent to the graphic block integration of Altera, which is why it is important to address the same concept of modular, hierarchical development and project integration using only text-based language tools. Our coverage of AHDL integration will not be as in-depth as our coverage of VHDL because the graphic method is generally preferred.

## AHDL MODULE INTEGRATION

Let's go back to the two AHDL files for the MOD-6 and MOD-10 counters. How do we combine these files into a MOD-60 counter using only text-based AHDL? The method is really very similar to that of graphic integration. Instead of creating a "symbol" representation of the MOD-6 and MOD-10 files, a new kind of file called an "INCLUDE" file is created. It contains all the important information about the AHDL file it represents. To describe a MOD-60 counter, a new TDF file, shown in Figure 10-36, is opened. The building block files are "included" at the top, as shown on lines 1 and 2 . Next, the names that were used for the building blocks are used like library components or primitives to define the nature of a variable. On line 10, the variable mod10 is now used to represent the MOD-10 counter in the other module (fig10_26). MOD10 now has all the attributes (inputs, outputs, functional operation) described in fig10_26.tdf. Likewise, on line 11, the variable mod6 is given the attributes of the MOD-6 counter of fig10_23.tdf. Lines 13-19 accomplish the exact same task as drawing lines on the GDF or BDF file to connect the components to one another and to the input/output ports.

```
INCLUDE "fig10_26.inc"; -- mod-10 counter module
INCLUDE "fig10_23.inc"; -- mod-6 counter module
SUBDESIGN fig10_36
l
    clk, ena :INPUT;
    ones[3..0], tens[2..0], tc :OUTPUT;
)
VARIABLE
    mod10 :fig10_26; -- mod-10 for units
    mod6 :fig10_23; -- mod-6 for tens
BEGIN
    mod10.clock = clk; -- synchronous clocking
    mod6.clock = clk;
    mod10.enable = ena;
    mod6.enable = mod10.tc; -- cascade
    ones[3..0] = mod10.q[3..0]; -- 1s
    tens[2..0] = mod6.q[2..0]; -- 10s
    tc = mod6.tc; -- Make terminal count at 59
END;
```

FIGURE 10-36 The MOD-60 made from MOD-10 and MOD-6 in AHDL.

This file (FIG10_36.TDF) can be translated into an "include" file (fig10_ 36.inc) by the compiler and then used in another tdf file that describes the interconnection of major sections to make up the system. Each level of the hierarchy refers back to the constituent modules of the lower levels.

## VHDL MODULE INTEGRATION

Let's go back to the two VHDL files for the MOD-6 and MOD-10 counters, which were shown in Figures 10-24 and 10-27, respectively. How do we combine these files into a MOD-60 counter using only text-based VHDL? The method is really very similar to that of graphic integration. Instead of creating a "symbol" representation of the MOD-6 and MOD-10 files, these design files are described as a COMPONENT, like we studied in Chapter 5. It contains all the important information about the VHDL file it represents. To describe a MOD-60 counter, a new VHDL file, shown in Figure 10-37, is opened. The building block files are described as "components," as shown on lines

```
ENTITY fig10_37 IS
PORT( clk, ena :IN BIT ;
    tens :OUT INTEGER RANGE O TO 5;
    ones :OUT INTEGER RANGE O TO 9;
    tc :OUT BIT );
END fig10_37;
ARCHITECTURE a OF fig10_37 IS
SIGNAL cascade_wire :BIT;
COMPONENT fig10_24 -- MOD-6 module
PORT( clock, enable :IN BIT ;
    q :OUT INTEGER RANGE O TO 5;
    tc :OUT BIT);
END COMPONENT;
COMPONENT fig10_27 -- MOD-10 module
PORT( clock, enable :IN BIT ;
        q :OUT INTEGER RANGE O TO 9;
        tc :OUT BIT);
END COMPONENT;
BEGIN
        mod10:fig10_27
        PORT MAP( clock => clk,
        enable => ena,
        q => ones,
        tc => cascade_wire);
    mod6:fig10_24
        PORT MAP( clock => clk,
            enable => cascade_wire,
                q => tens,
                tc => tc);
END a;
```

FIGURE 10-37 The MOD-60 made from MOD-10 and MOD-6 in VHDL.

```
ENTITY fig10_38 IS
PORT( pps_60 :IN BIT ;
    hour_tens :OUT INTEGER RANGE O TO 1;
    hour_ones, min_ones, sec_ones :OUT INTEGER RANGE O TO 9;
    min_tens, sec_tens :OUT INTEGER RANGE 0 to 5;
    pm :OUT BIT );
END fig10_38;
ARCHITECTURE a OF fig10_38 IS
SIGNAL cascade_wire1, cascade_wire2, cascade_wire3 :BIT;
SIGNAL enabled
:BIT;
COMPONENT fig10_37 -- MOD-60
PORT( clk, ena :IN BIT ;
    tens :OUT INTEGER RANGE 0 TO 5;
    ones :OUT INTEGER RANGE O TO 9;
    tc
    :OUT BIT );
END COMPONENT;
COMPONENT fig10_29 -- MOD-12
PORT( clk, ena :IN BIT ;
    low :OUT INTEGER RANGE 0 TO 9;
    hi :OUT INTEGER RANGE 0 TO 1;
    pm :OUT BIT );
END COMPONENT;
BEGIN
    enabled <= '1';
    prescale:fig10_37 -- MOD-60 prescaler
        PORT MAP( clk => pps_60,
            ena => enabled,
            tc => cascade_wire1);
    second:fig10_37 -- MOD-60 seconds counter
        PORT MAP( clk => pps_60,
            ena => cascade_wire1,
            ones => sec_ones,
            tens => sec_tens,
            tc => cascade_wire2);
    minute:fig10_37 -- MOD-60 minutes counter
        PORT MAP( clk => pps_60,
            ena => cascade_wire2,
            ones => min_ones,
            tens => min_tens,
            tc => cascade_wire3);
    hour:fig10_29
                            -- MOD12 Hours Counter
        PORT MAP( clk => pps_60,
            ena => cascade_wire3,
            low => hour_ones,
            hi => hour_tens,
            pm => pm);
```

END a;

FIGURE 10-38 The complete clock in VHDL.

10-14 and lines 15-19 in the architecture description. Next, the names that were used for the building blocks (components) are used along with the PORT MAP keywords to describe the interconnection of these components. The information in the PORT MAP sections describes the exact same operations as drawing wires on a schematic diagram in a GDF file or BDF file.

Finally, the VHDL file that represents the block at the top of the hierarchy is created using components from Figure 10-37 (MOD-60) and Figure 10-29 (MOD-12). This file is shown in Figure 10-38. Notice that the general form is as follows:

Define I/O: lines 1-7
Define signals: lines 10-11
Define components: lines 12-23
Instantiate components and connect them together: lines 27-52

## REVIEW QUESTIONS

1. What is being defined at the top level of a hierarchical design?
2. Where does the design process start?
3. Where does the building process start?
4. At which stage(s) should simulation testing be done?

## 10-5 FREQUENCY COUNTER PROJECT

The project in this section demonstrates the use of counters and other standard logic functions to implement a system called a frequency counter, which is similar to the piece of test equipment that you have probably used in the laboratory. The theory of operation will be described in terms of conventional MSI logic devices and then related to the building blocks that can be developed using HDL. As with most projects, this example consists of several circuits that we have studied in earlier chapters. They are combined here to form a digital system with a unique purpose. First, let us define a frequency counter.

A frequency counter is a circuit that can measure and display the frequency of a signal. As you know, the frequency of a periodic waveform is simply the number of cycles per second. Shaping each cycle of the unknown frequency into a digital pulse allows us to use a digital circuit to count the cycles. The general idea behind measuring frequency involves enabling a counter to count the number of cycles (pulses) of the incoming waveform during a precisely specified period of time called the sampling interval. The length of the sampling interval determines the range of frequencies that can be measured. A longer interval provides improved precision for low frequencies but will overflow the counter at high frequencies. A shorter sample interval provides a less precise measurement of low frequencies but can measure a much higher maximum frequency without exceeding the upper limit of the counter.

Assume that a frequency counter uses a four-digit BCD counter. Determine the maximum frequency that can be measured using each of the following sample intervals:
(a) 1 second
(b) 0.1 second
(c) 0.01 second

## Solution

(a) With a sampling interval of 1 second, the four-digit counter can count up to 9999 pulses. The frequency is 9999 pulses per second or 9.999 kHz .
(b) The counter can count up to 9999 pulses within the sampling interval of 0.1 second. This translates into a frequency of 99,990 pulses per second or 99.99 kHz .
(c) The counter can count up to 9999 pulses within the sampling interval of 0.01 second. This translates into a frequency of 999,900 pulses per second or 999.9 kHz .

## EXAMPLE 10-2

FIGURE 10-39 Basic frequency counter block diagram.

If a frequency of 3792 pps is applied to the input of the frequency counter, what will the counter read under each of the following sample intervals?
(a) 1 second
(b) 0.1 second
(c) 10 ms

## Solution

(a) During a sampling interval of 1 second, the counter will count 3792 cycles. The frequency will read 3.792 kpps .
(b) During a sampling interval of 0.1 second, the number of pulses that will be counted is 379 or 380 cycles, depending on where the sample interval begins. The frequency will read 03.79 kpps or 03.80 kpps .
(c) During a sampling interval of 0.01 second, the number of pulses that will be counted is 37 or 38 cycles, depending on where the sample interval begins. The frequency will read 003.7 kpps or 003.8 kpps .

One of the most straightforward methods for constructing a frequency counter is shown as a block diagram in Figure 10-39. The major blocks are the counter, the display register, the decoder/display, and the timing and control unit. The counter block contains several cascaded BCD counters that are used to count the number of pulses produced by the unknown signal applied to the clock input. The counter block has count enable and clear controls. The time period for counting (sample interval) is controlled by an enable signal that is produced by the timing and control block. The length

of time for the BCD counters to be enabled can be selected with the range select input to the timing and control block. This allows the user to select the desired frequency range to be measured and effectively determines the location of the decimal point in the digital readout. The pulse width of the enable signal (sample interval) is critical for taking an accurate frequency measurement. The counter must be cleared before it is enabled for a new frequency measurement of the unknown signal. After a new count has been taken, the counter is disabled, and the most recent frequency measurement is stored in the display register. The output of the display register is input to the decoder and display block, where the BCD values are converted into decimal for the display readout. Using a separate display register allows the frequency counter to take a new measurement in the background so that the user does not watch the counter while it is totaling the number of pulses for a new reading. The display is instead updated periodically with the last frequency reading.

The accuracy of this frequency counter depends almost entirely on the accuracy of the system clock frequency, which is used to create the proper pulse width for the counter enable signal. A crystal-controlled clock generator is used in Figure 10-39 to produce an accurate system clock for the timing and control block.

A pulse shaper block is needed to ensure that the unknown signal whose frequency is to be measured will be compatible with the clock input for the counter block. A Schmitt-trigger circuit may be used to convert "nonsquare" waveforms (sine, triangle, etc.) as long as the unknown input signal is of satisfactory amplitude. If the unknown signal might have a larger or smaller amplitude than is compatible with a given Schmitt trigger, then additional analog signal conditioning circuitry, such as an automatic gain control, will be required for the pulse shaper block.

The timing diagram for the control of the frequency counter is shown in Figure $10-40$. The control clock is derived from the system clock signal by frequency dividers contained in the control and timing block. The period of the control clock signal is used to create the desired enable pulse width. A recycling control counter inside the control and timing block is clocked by the control clock signal. It has selected states decoded to produce the repeating


FIGURE 10-40 Frequency counter timing diagram.


FIGURE 10-41 Timing and control block for frequency counter.
control signal sequence (clear, enable, and store). The counter (cascaded BCD stages) is first cleared. Then the counter is enabled for the proper sample interval to count the digital pulses, which have the same frequency as the unknown signal. After disabling the counter, the new count is stored in the display register.

The counter, display register, and decoder/display sections are straightforward and are not described any further here. The timing and control block provides the "brains" for our frequency counter and deserves a little more discussion to explain its operation. Figure 10-41 shows the sub-blocks within the timing and control block. For our example design, we will assume that the clock generator produces a $100-\mathrm{kHz}$ system clock signal. The system clock frequency is divided by a set of five decade counters (MOD-10). This gives the user six different frequencies that can be selected by the multiplexer for the control clock frequency using the range select control. Because the period of the control clock is the same as the pulse width of the counter enable, this setup allows the frequency counter to have six different frequency measurement ranges. The control counter is a MOD-6 counter that has three selected states decoded by the control signal generator to produce the clear, enable, and store control signals.

Assume that the BCD counter in Figure 10-39 consists of three cascaded BCD stages and their associated displays. If the unknown frequency is between 1 kpps and 9.99 kpps , which range (sample interval) should be selected using the MUX of Figure 10-41?

## Solution

With three BCD counters, the total capacity of the counter is 999. A 9.99-kpps frequency produces a count of 999 if a 0.1 -s sample interval were used. Thus, in order to use the full capacity of the counter, the MUX should select the $0.1-\mathrm{s}$ clock period ( 10 Hz ). If a 1 -s sampling interval were used, the counter capacity would always be exceeded for frequencies in the specified range. If a shorter sample interval were used, the counter would count only between 1 and 99, which would give a reading to only two significant figures and would be a waste of the counter's capacity.

1. What is the purpose of running the unknown signal through a pulse shaper?
2. What are the units of a frequency measurement?
3. What does the display show during the sample interval?

## SUMMARY

1. Successful project management can be accomplished by the following steps: overall project definition; breaking the project into small, strategic pieces; synthesis and testing of each piece; and system integration.
2. Small projects like the stepper motor driver can be completed in a single design file, even though these projects are developed modularly.
3. Projects that consist of several simple building blocks, like the keypad encoder, can produce very useful systems.
4. Larger projects like the digital clock can often take advantage of standard common modules that can be used repeatedly in the overall design.
5. Projects should be built and tested in modules starting at the lowest levels of hierarchy.
6. Preexisting modules can easily be combined with new custom modules using both graphical and text-based description methods.
7. Modules can be combined and represented as a single block in the next higher level of the hierarchy using the Altera design tools.

## IMPORTANT TERMS

| nesting | prescaler | sampling interval |
| :--- | :--- | :--- |
| hierarchy | frequency counter |  |

## PROBLEMS

## SECTION 10-1

10-1. The security monitoring system of Section 9-8 in Chapter 9 can be developed as a project.
(a) Write a project definition with specifications for this system.
(b) Define three major blocks of this project.
(c) Identify the signals that interconnect the blocks.
(d) ${ }^{\star}$ At what frequency must the oscillator run for a $2.5-\mathrm{Hz}$ flash rate?
(e)^Why is it reasonable to use only one current limiting resistor for all eight LEDs?

## SECTION 10-2

Problems 10-2 through 10-7 refer to stepper motors described in Section 10-2.
B 10-2. How many full steps must occur for a complete revolution?
B 10-3. How many degrees of rotation result from one compete cycle through the full-step sequence in Table 10-1?
B 10-4. How many degrees of rotation result from one complete cycle through the half-step sequence in Table 10-1?
B 10-5. The cout lines of Figure $10-1$ started at 1010 and have just progressed through the following sequence: $1010,1001,0101,0110$.
(a)^How many degrees has the shaft rotated?
(b) What sequence will reverse the rotation and return the shaft to its original position?
B 10-6. Describe a method to test the stepper driver in:
(a) Full-step mode
(b) Half-step mode
(c) Wave-drive mode
(d) Direct-drive mode

D, H 10-7. Rewrite the stepper driver design file of Figure 10-8 or 10-9 without using a CASE statement. Use your favorite HDL.
D, H 10-8. Modify the stepper design file of Figure $10-8$ or $10-9$ to add an enable input that puts the outputs in the $\mathrm{Hi}-\mathrm{Z}$ state (tristate) when enable $=0$.

## SECTION 10-3

B 10-9. Write the state table for the ring counter shown in Figure 10-11 and described in Figure 10-13.
B $10-10 .^{\star}$ With no keys pressed, what is the value on $\mathrm{c}[3 . .0]$ ?
B 10-11. Assume that the ring counter is in state 0111 when someone presses the 7 key. Will the ring counter advance to the NEXT state?
B 10-12. Assume the 9 key is pressed and held until DAV $=1$.
(a) ${ }^{\star}$ What is the value on the ring counter?
(b) What is the value encoded by the row encoder?
(c) What is the value encoded by the column encoder?
(d) What binary number is on the $\mathrm{D}[3 . .0]$ lines?

B 10-13.*In Problem 10-12, will the data be valid on the falling edge of DAV?
B, D 10-14. If you wanted to latch data from the keypad into a 74174 register, which signal from the keypad would you connect to the clock of the register? Draw the circuit.
T 10-15.*The keypad is connected to a 74373 octal transparent latch as shown in Figure 10-42. The output is correct as long as a key is held. However, it is unable to latch data between key presses. Why will this circuit not work correctly?

[^0]

FIGURE 10-42 Problem 10-15.

## SECTION 10-4

B $10-16$. Assume a $1-\mathrm{Hz}$ clock is applied to the seconds stage of the clock in Figure 10-17. The MOD-10 units of seconds counter's terminal count (tc) output is shown in Figure 10-43. Draw a similar diagram showing the number of clock cycles between the tc output pulses of each of the following:
(a)^Tens of seconds counter
(b) Units of minutes counter
(c) Tens of minutes counter


FIGURE 10-43 Problem 10-16.

B $10-17$. . How many cycles of the $60-\mathrm{Hz}$ power line will occur in a 24 -hour period? What problem do you think will result if we attempt to simulate the operation of the entire clock circuit?
D 10-18. ${ }^{\star}$ Many digital clocks are set by simply making them count faster while a push button is held down. Modify the design to add this feature.
D, H 10-19. Modify the hours stage of Figure 10-18 to keep military time (00-23 hours).

## SECTION 10-5

B 10-20. Draw the hierarchy diagram for the frequency counter project.
D, H 10-21. Write the HDL code for the MOD-6 control counter and control signal generator in Figure 10-41.
D, H 10-22.* Write the HDL code for the MUX of Figure 10-41.
D 10-23. Use graphic design techniques and the BCD counter described in Figure 10-31, the MUX, and the control signal generator design to create the entire timing and control block for the frequency counter project.
D, H 10-24. Write the HDL code for the timing and control section of the frequency counter.

## ANSWERS TO SECTION REVIEW QUESTIONS

## SECTION 10-1

1. Definition, strategic planning, synthesis and testing, system integration and testing 2. The definition stage

## SECTION 10-2

1. Full-step, half-step, wave-drive, and direct-drive $\quad$ 2. $\operatorname{cin}_{0}-\operatorname{cin}_{3}$ [mode selector switches set to $(1,1)$ ] 3 . Step, direction [mode selector switches set to $(0,1)$ ]
2. Eight states

## SECTION 10-3

1. Only one $\quad$ 2. The first one scanned after being pressed (usually the first one pressed) 3. To make DAV go HIGH after the data stabilizes 4. No, it goes HIGH on the next clock after the key is pressed. 5. Whenever OE is LOW or when no keys are pressed

## SECTION 10-4

1. The overall operating specifications and the system inputs and outputs.
2. At the top of the hierarchy 3. At the bottom, building the simplest blocks first
3. At each stage of modular implementation

## SECTION 10-5

1. To change the shape of the analog signal into a digital signal of the same frequency 2. Cycles per second (Hz) or pulses per second (pps) 3. The display shows the frequency measured during the previous sample interval.

[^0]:    *Answers to problems marked with an asterisk can be found in the back of the text.

