THE ART OF ELECTRONICS

PAUL HOROWITZ
WINFIELD HILL

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THE ART OF ELECTRONICS

Second Edition

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TO CAROL, JACOB, MISHA, AND GINGER

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```
**  Expanded Product Terms **

D0 =>
    a & b & c & d & !e & g
  # a & b & c & !e & f & g
  # a & c & d & !e & f & g
  # b & c & !d & !e & !f & !g
  # !a & !b & c & d & e & f & g
  # a & !b & !c & !d & e & f & g
  # !a & b & c & d & e & !f & g

D1 =>
    a & !b & !c & e & f & g
  # !b & c & d & e & f & g
  # a & b & c & !d & e & f & g
  # a & b & !c & d & e & !f & g
  # a & b & c & d & !e & !f & g
  # a & b & c & !d & !e & !f & !g

D2 =>
    a & !b & !c & d & e & f
  # a & !b & c & d & f & g
  # a & !b & !c & e & f & g
  # !a & b & c & !d & !e & f & g
  # !a & b & c & d & e & !f & g
  # !a & !b & !c & d & e & !f & g
  # a & b & c & !d & !e & !f & !g

D3 =>
    a & b & c & f & g
  # a & !b & !c & d & e & f
  # a & !b & !c & e & f & g
  # !a & !b & c & d & e & f & g
  # !a & b & c & d & e & !f & g
  # !a & !b & !c & d & e & !f & g

D0.oe  => 1
D1.oe  => 1
D2.oe  => 1
D3.oe  => 1
```

Figure 8.78. 7-segment-to-hex encoder: minimized product terms.

CUPL example: vending machine (sequential). An arbitrary state machine (Section 8.18) has a set of *states* and a set of *transition rules* for moving between those states at each clock edge. In general, the transition rules depend both on the present state and on the particular combination of input levels present at the next clock edge. You can implement a state machine in programmable logic containing registers if (a) there are enough register bits to represent all possible states (e.g., with 4 registers you could have up to 16 states) and (b) there are enough inputs and logic gates to implement the transition rules.

As an example, let's design a registered PAL for the state diagram of Figure 8.80. It's a vending machine, and it is supposed to disgorge a bottle of fizzy sweet liquid when 25 cents (or more) has been deposited. There is some sort of coin interface that gobbles up and recognizes money and sends to our PAL a 2-bit input (C1, C0), valid for one clock edge, indicating the coin just deposited (01 = nickel, 10 = dime, 11 = quarter, 00 = slug or no coin).

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```
** Fuse Plot **

Pin #19
 0000 --------------------------------
 0032 x-x-x-----------x---x-----------
 0064 -xx--x--x---x---x---------------
 0096 -xx--x------x---x---x-----------
 0128 -x-xx---x---x---x---x-----------
 0160 x--xx---x---x----x--x-----------
 0192 -x-x-x--x---x----x--x-----------
 0224 xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx

Pin #18
 0256 --------------------------------
 0288 -xx--x--x---x---x---------------
 0320 -xx-x---x-------x---x-----------
 0352 -xx--x------x---x---x-----------
 0384 x--xx----x---x--x---x-----------
 0416 x--xx---x---x----x--x-----------
 0448 -x-x-x--x---x----x--x-----------
 0480 x-x-x----x---x---x---x----------

Pin #17
 0512 --------------------------------
 0544 -xx--x------x---x---x-----------
 0576 -x--x---x---x---x---x-----------
 0608 x-x-x----x--x---x---x-----------
 0640 x-x--x--x---x----x--x-----------
 0672 x-x-x---x----x---x--x-----------
 0704 x-x-x----x---x---x---x----------
 0736 xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx

Pin #16
 0768 --------------------------------
 0800 x-x-x---x----x------x-----------
 0832 x-x-x--------x--x---x-----------
 0864 --x-x---x----x--x---x-----------
 0896 x---x----x---x---x---x----------
 0928 -x-xx---x---x---x---x-----------
 0960 -xx--x---x--x---x---x-----------
 0992 x--xx---x---x----x--x-----------

LEGEND     X : fuse not blown
           - : fuse blown
```

Figure 8.79. 7-segment-to-hex encoder: fuse map.

The state machine's job is to add up the total deposited and generate an output called *bottle* when there's enough money.

Figure 8.81 shows the specification, in CUPL's state-machine syntax. As before, we begin by defining input and output pins. Note that we've added a *reset* input so that you can initialize to the state S0 (no money). Next we define the states, then the rules for moving between them. If any outputs, either registered or combinational, need to be generated during states or transitions between states, they are specified at the same time. In this example, for instance, the output *bottle* has been specified as a separate output register, so that no output state decoding is needed. In fact, this is the only output needed, and the state-machine bits Q0–2 could by implemented in internal registers that don't generate outputs directly; some programmable logic devices have such

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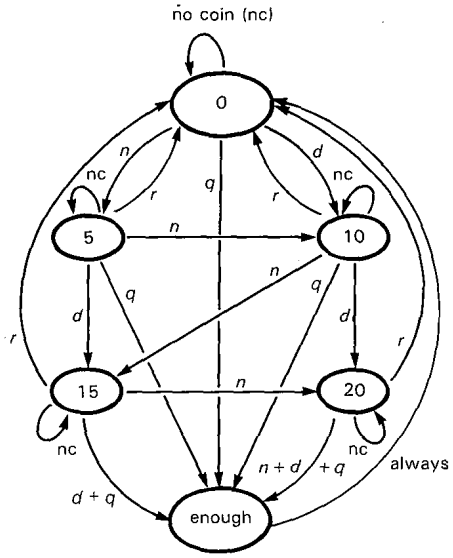

Figure 8.80. Vending machine state diagram.

"buried" registers, in addition to the usual output registers.

Note that you have to specify explicitly the transition from a state to itself, as we have done here for the input *nocoin*. An unspecified condition implicitly resets the state to all zeros. That is because these conditionals are compiled into combinational logic to assert the D inputs of the registers, and thus if the condition is not met, the corresponding D input is not asserted.

Figure 8.82 shows the output from CUPL. There is nothing obvious or simple about the logic, because both the machine state (S0–S5) and the input variable (C0–1) are specified as binary numbers, whereas the logic operates on individual

```
/**  Inputs  **/

Pin  1  = clk    ;  /* clock -- positive edge  */
Pin  3  = c0     ;  /* coin type -- low bit    */
Pin  4  = c1     ;  /* coin type -- high bit   */
Pin  6  = reset  ;  /* reset input             */


/**  Outputs  **/

Pin  18  = !Q0     ;  /* bit 0 of state variable   */
Pin  17  = !Q1     ;  /* bit 1                     */
Pin  16  = !Q2     ;  /* bit 2                     */
Pin  15  = !bottle ;  /* bottle disgorge command   */

/* Define machine states with symbolic names;
      "enough" = 25 cents or more */

$define S0     'b'000
$define S5     'b'001
$define S10    'b'010
$define S15    'b'011
$define S20    'b'100
$define ENOUGH 'b'101

/* define intermediate variables */

nocoin = !c0 & !c1 & !reset;
nickel =  c0 & !c1 & !reset;
dime =   !c0 &  c1 & !reset;
quarter = c0 &  c1 & !reset;

/* Define state bit variable field */

field statebit = [Q2..0] ;
```

Figure 8.81. Vending machine specification (CUPL). (*Continued on next page.*)

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```
/* Transition rules for vending machine */

sequence statebit {
   present S0    if nocoin     next S0;
                 if nickel     next S5;
                 if dime       next S10;
                 if quarter    next ENOUGH   out bottle;

   present S5    if nocoin     next S5;
                 if nickel     next S10;
                 if dime       next S15;
                 if quarter    next ENOUGH   out bottle;

   present S10   if nocoin     next S10;
                 if nickel     next S15;
                 if dime       next S20;
                 if quarter    next ENOUGH   out bottle;

   present S15   if nocoin     next S15;
                 if nickel     next S20;
                 if dime       next ENOUGH   out bottle;
                 if quarter    next ENOUGH   out bottle;

   present S20   if nocoin     next S20;
                 if nickel     next ENOUGH   out bottle;
                 if dime       next ENOUGH   out bottle;
                 if quarter    next ENOUGH   out bottle;

   present ENOUGH              next S0;    }
```

Figure 8.81. (*cont.*)

bits. Thus, the resulting logic does not bear much relation to the original state description (Fig. 8.81). In fact, the particular choice of states (ascending binary, 0–5) could have been chosen differently, completely changing the resulting logic. In this case, this example fits easily within the constraints of the 16R6 PAL (8 product terms per register); if it had not, we could have tried redefining the states, which often leads to a simpler logic realization. Note that the *reset* input acts by an overriding disassertion of all D inputs, which we forced by our definition of the intermediate variables *nocoin*, *nickel*, etc.

EXERCISE 8.30

Verify that the finished logic equations are correct, by checking a few transition rules. You might try all the transitions from 00, or a nickel or dime from some other state.

EXERCISE 8.31

Good vending machines give change. Redraw the state diagram (Fig. 8.80) so that there are states (how many?) for each possible amount of change. Modify the transition rules accordingly. Make sure your modified vending machine still does its primary job – dispensing bottles.

EXERCISE 8.32

Draw a state diagram and transition rules for an electronic combination lock: It should open only if four digits are entered in the correct order. Any error should reset it.

Hints for using programmable logic devices (PLDs)

For certain jobs, PLDs really hit the spot. Here are the most important uses and advantages of PLDs:

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