

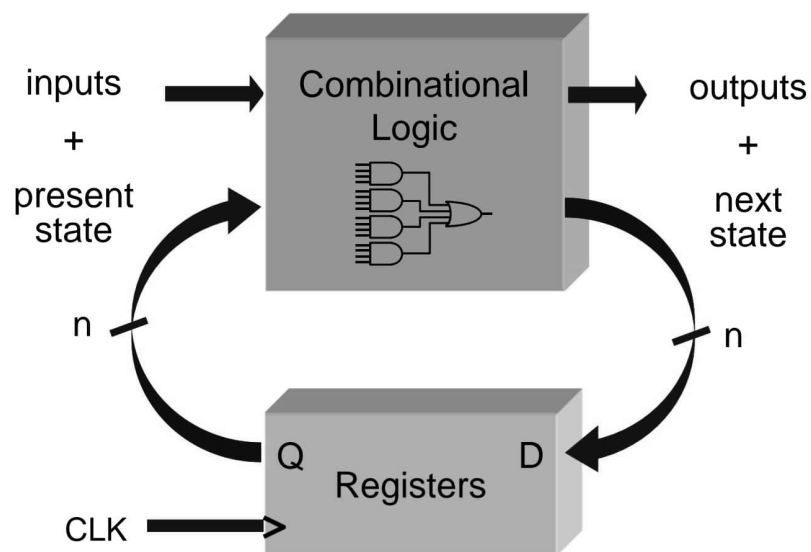


Finite State Machines

- Design methodology for sequential logic
 - identify distinct states
 - create state transition diagram
 - choose state encoding
 - write combinational Verilog for next-state logic
 - write combinational Verilog for output signals
- Lots of examples

Finite State Machines

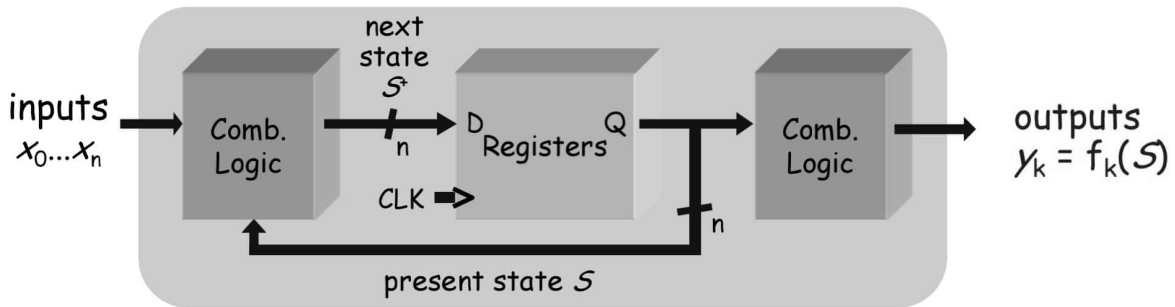
- Finite State Machines (FSMs) are a useful abstraction for *sequential circuits with centralized "states" of operation*
- At each clock edge, combinational logic computes *outputs* and *next state* as a function of *inputs* and *present state*



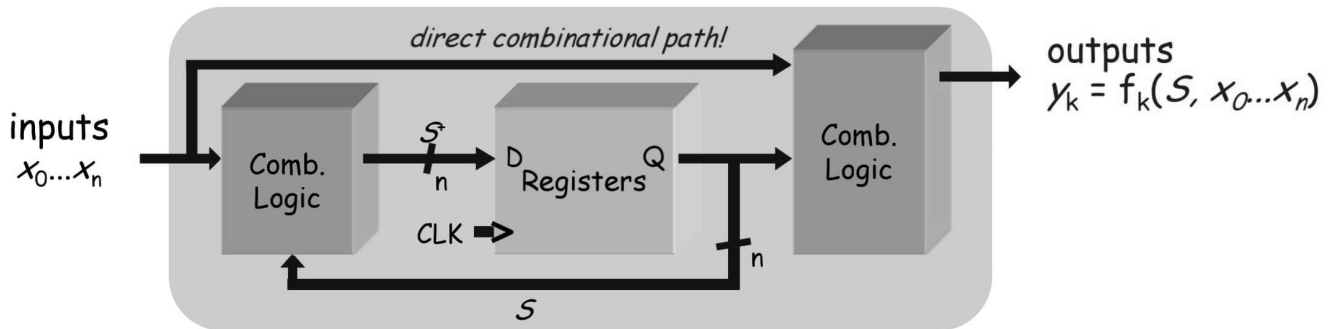
Two Types of FSMs

Moore and Mealy FSMs : different output generation

- Moore FSM:

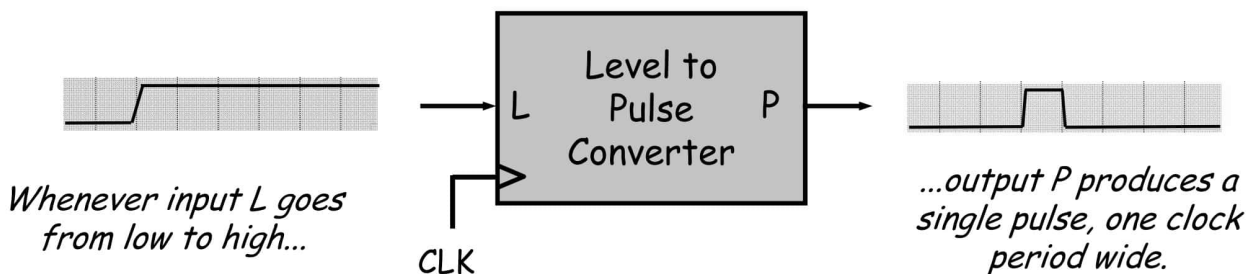


- Mealy FSM:



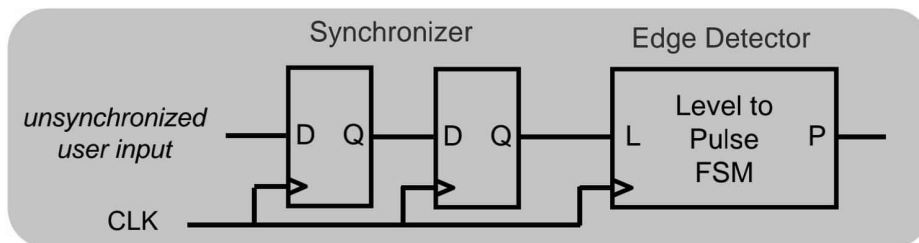
Design Example: Level-to-Pulse

- A level-to-pulse converter produces a single-cycle pulse each time its input goes high.
- It's a synchronous rising-edge detector.
- Sample uses:
 - Buttons and switches pressed by humans for arbitrary periods of time
 - Single-cycle enable signals for counters

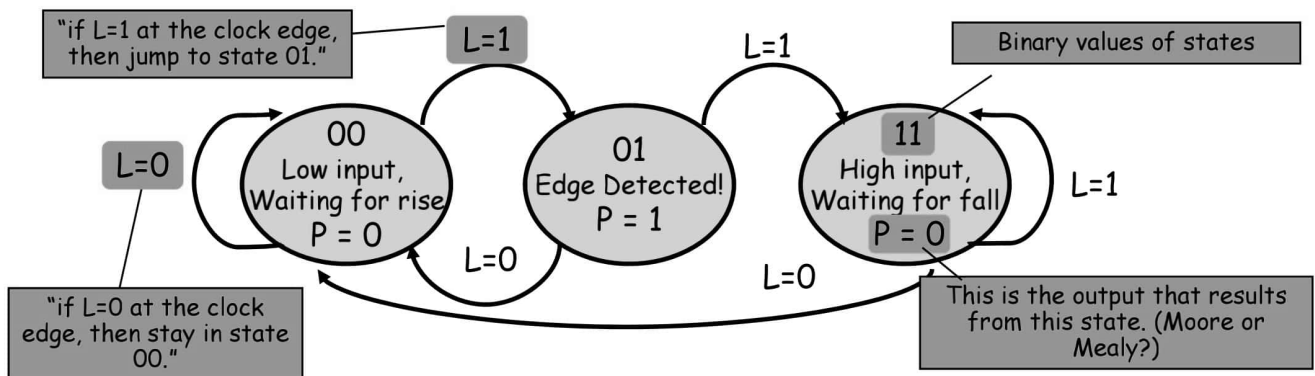


Step 1: State Transition Diagram

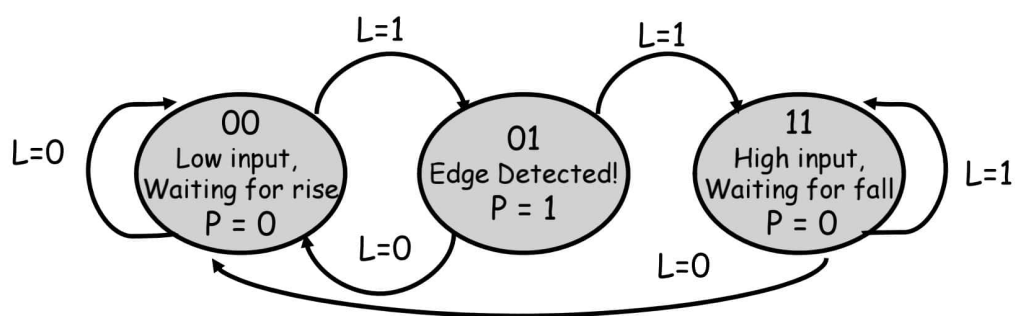
- Block diagram of desired system:



- State transition diagram is a useful FSM representation and design aid:



Valid State Transition Diagrams



- Arcs leaving a state are mutually exclusive, i.e., for any combination input values there's at most one applicable arc
- Arcs leaving a state are collectively exhaustive, i.e., for any combination of input values there's at least one applicable arc
- So for each state: for any combination of input values there's exactly one applicable arc
- Often a starting state is specified
- Each state specifies values for all outputs (Moore)

Choosing State Representation

Choice #1: binary encoding

For N states, use $\text{ceil}(\log_2 N)$ bits to encode the state with each state represented by a unique combination of the bits.

Tradeoffs: most efficient use of state registers, but requires more complicated combinational logic to detect when in a particular state.

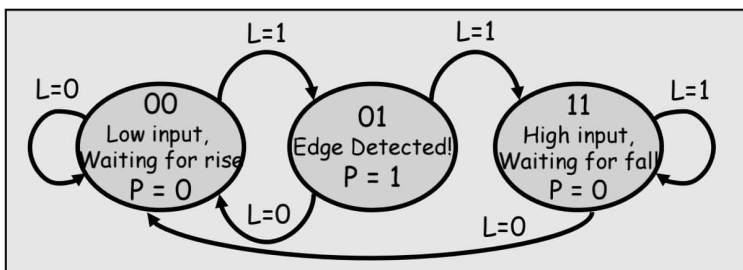
Choice #2: "one-hot" encoding

For N states, use N bits to encode the state where the bit corresponding to the current state is 1, all the others 0.

Tradeoffs: more state registers, but often much less combinational logic since state decoding is trivial.

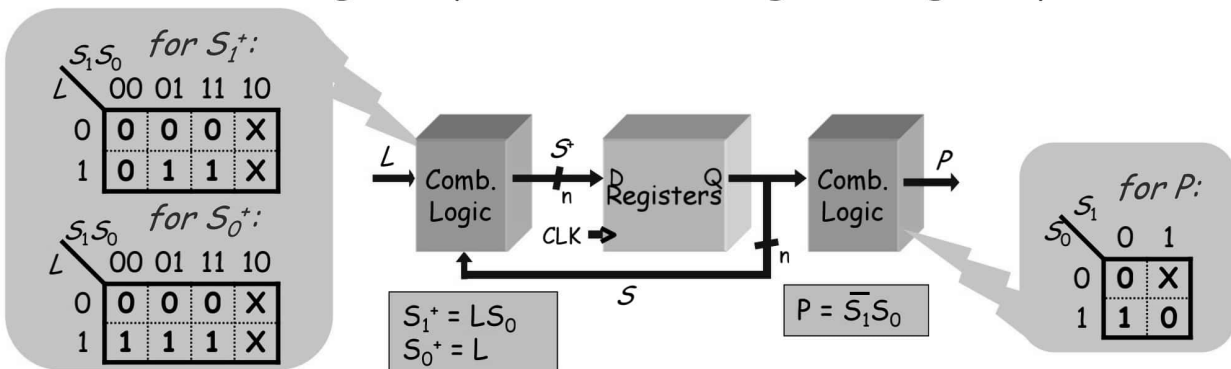
Step 2: Logic Derivation

Transition diagram is readily converted to a state transition table (just a truth table)

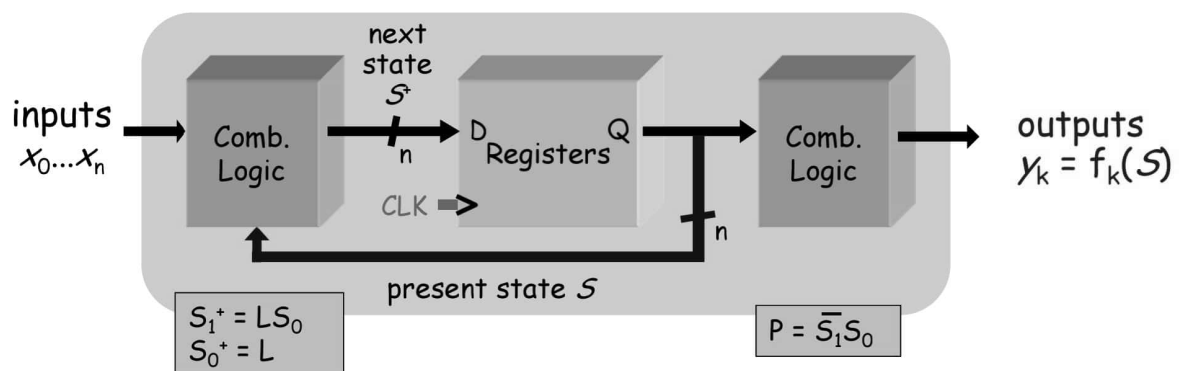


Current State		In	Next State		Out
S_1	S_0	L	S_1^+	S_0^+	P
0	0	0	0	0	0
0	0	1	0	1	0
0	1	0	0	0	1
0	1	1	1	1	1
1	1	0	0	0	0
1	1	1	1	1	0

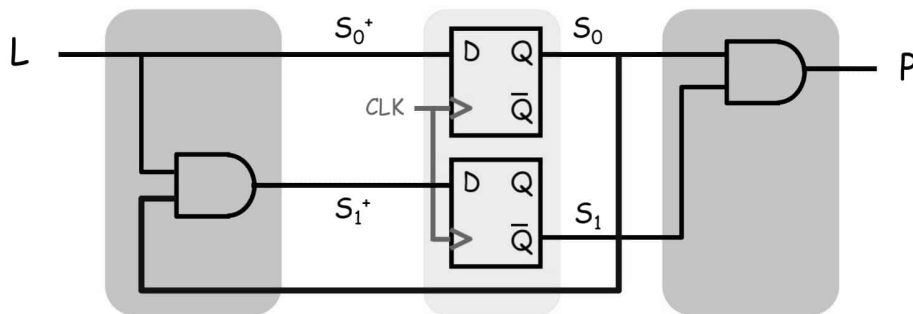
- Combinational logic may be derived using Karnaugh maps



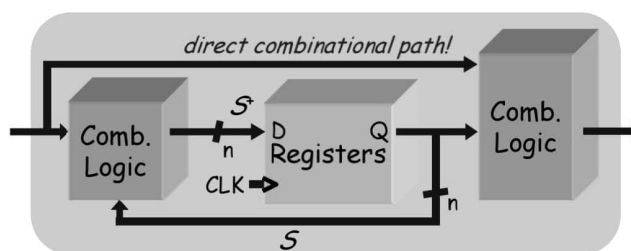
Moore Level-to-Pulse Converter



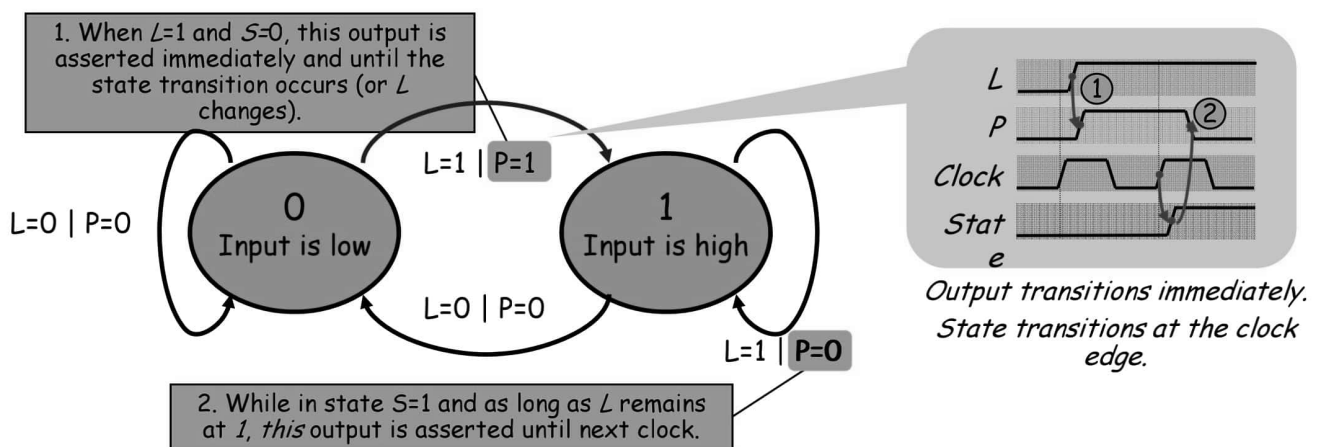
Moore FSM circuit implementation of level-to-pulse converter:



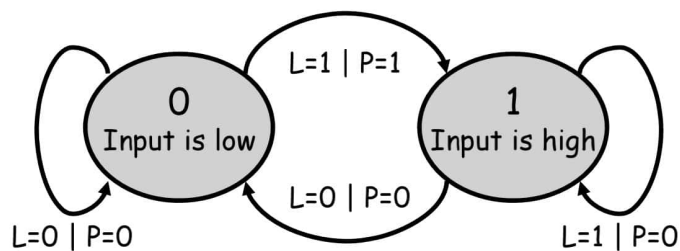
Design of a Mealy Level-to-Pulse



- Since outputs are determined by state *and* inputs, Mealy FSMs may need fewer states than Moore FSM implementations

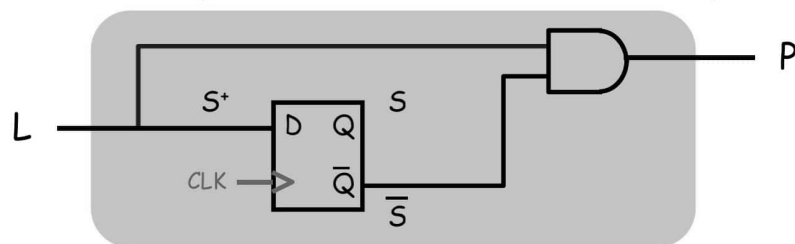


Mealy Level-to-Pulse Converter



Pres. State	In	Next State	Out
S	L	S^*	P
0	0	0	0
0	1	1	1
1	1	1	0
1	0	0	0

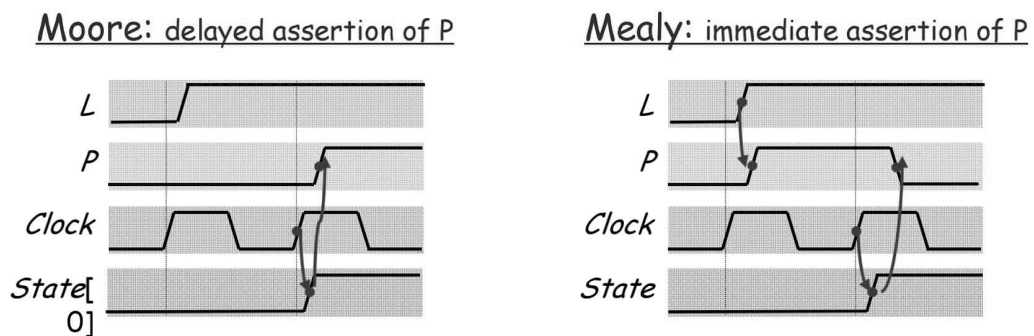
Mealy FSM circuit implementation of level-to-pulse converter:



- FSM's state simply remembers the previous value of L
- Circuit benefits from the Mealy FSM's implicit single-cycle assertion of outputs during state transitions

Moore/Mealy Trade-Offs

- How are they different?
 - Moore: outputs = $f(\text{state})$ only
 - Mealy outputs = $f(\text{state and input})$
 - Mealy outputs generally occur one cycle earlier than a Moore:



- Compared to a Moore FSM, a Mealy FSM might...
 - Be more difficult to conceptualize and design
 - Have fewer states

Example: Intersection Traffic Lights

- Design a controller for the traffic lights at the intersection of two streets - two sets of traffic lights, one for each of the streets.
- Step 1: Draw starting state transition diagram. Just handle the usual green-yellow-red cycle for both streets. How many states? Well, how many different combinations of the two sets of lights are needed?
- Step 2: add support for a walk button and walk lights to your state transition diagram.
- Step 3: add support for a traffic sensor for each of the streets - when the sensor detects traffic the green cycle for that street is extended.

Example to be worked collaboratively on the board...

FSM Example

GOAL:

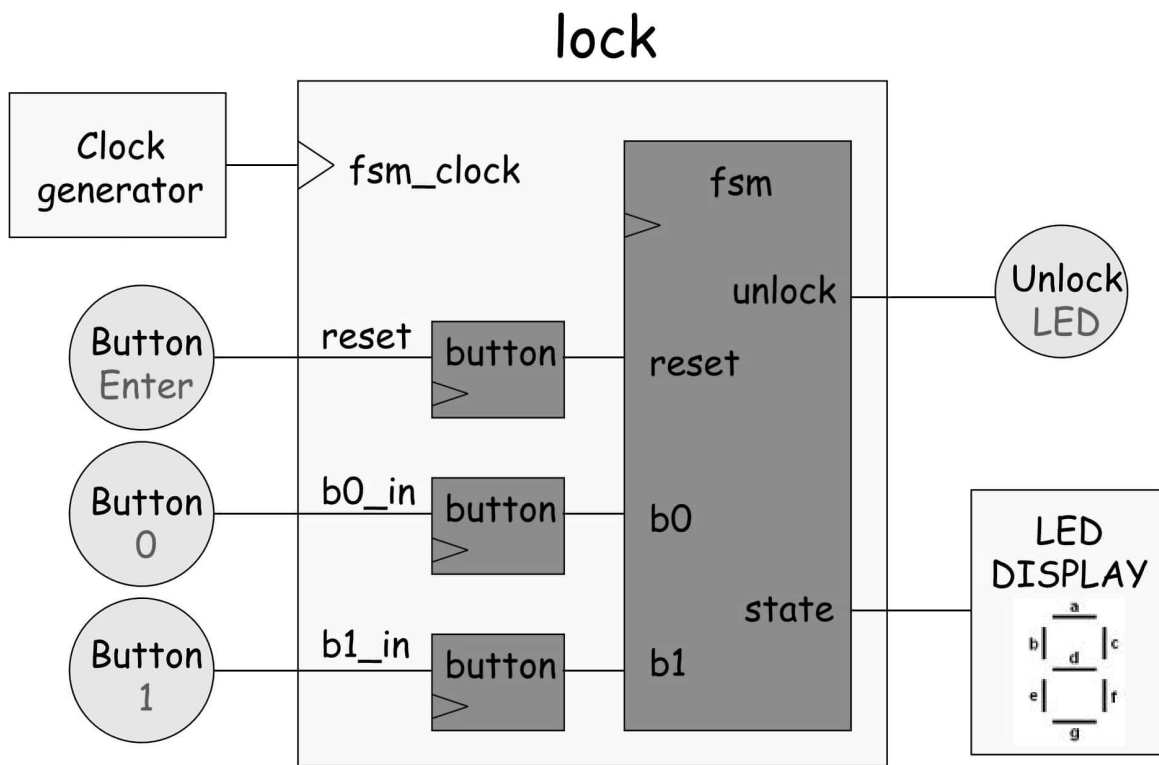
Build an electronic combination lock with a reset button, two number buttons (0 and 1), and an unlock output. The combination should be 01011.



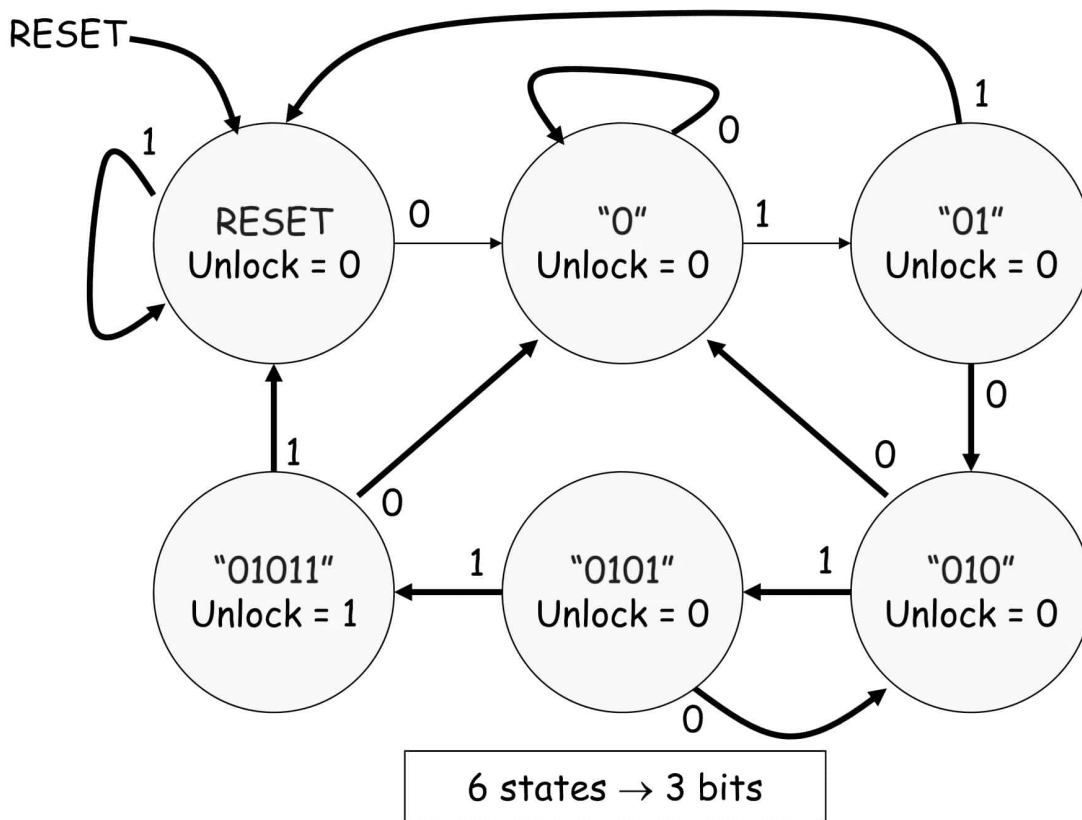
STEPS:

1. Design lock FSM (block diagram, state transitions)
2. Write Verilog module(s) for FSM

Step 1A: Block Diagram



Step 1B: State transition diagram



Step 2: Write Verilog

```
module lock(input clk,reset_in,b0_in,b1_in,  
            output out);
```

```
    // synchronize push buttons, convert to pulses
```

```
    // implement state transition diagram  
    reg [2:0] state,next_state;  
    always @(*) begin  
        // combinational logic!  
        next_state = ???;  
    end  
    always @(posedge clk) state <= next_state;
```

```
    // generate output  
    assign out = ???;
```

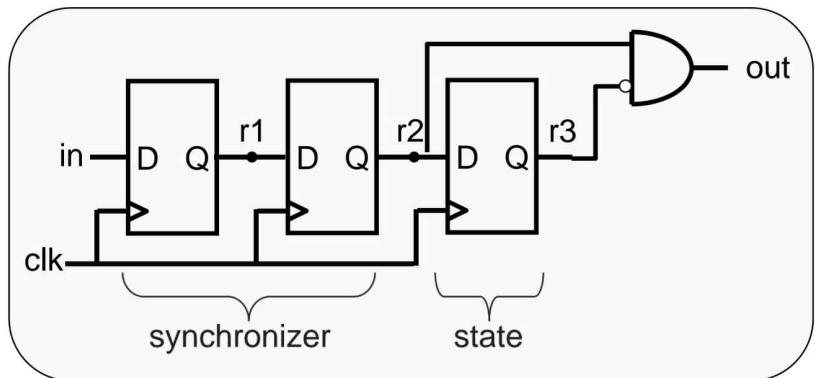
```
    // debugging?  
endmodule
```

Step 2A: Synchronize buttons

```
// button
// push button synchronizer and level-to-pulse converter
// OUT goes high for one cycle of CLK whenever IN makes a
// low-to-high transition.
```

```
module button(
  input clk,in,
  output out
);
  reg r1,r2,r3;
  always @(posedge clk)
  begin
    r1 <= in;    // first reg in synchronizer
    r2 <= r1;    // second reg in synchronizer, output is in sync!
    r3 <= r2;    // remembers previous state of button
  end

  // rising edge = old value is 0, new value is 1
  assign out = ~r3 & r2;
endmodule
```



Step 2B: state transition diagram

```

parameter S_RESET = 0; // state assignments
parameter S_0 = 1;
parameter S_01 = 2;
parameter S_010 = 3;
parameter S_0101 = 4;
parameter S_01011 = 5;

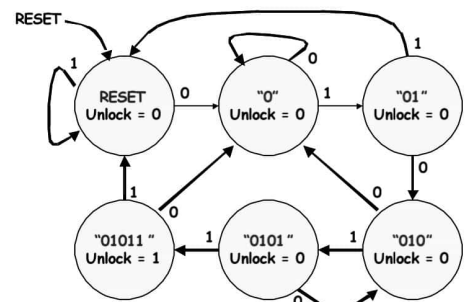
```

```

reg [2:0] state, next_state;
always @(*) begin
    // implement state transition diagram
    if (reset) next_state = S_RESET;
    else case (state)
        S_RESET: next_state = b0 ? S_0 : b1 ? S_RESET : state;
        S_0:      next_state = b0 ? S_0 : b1 ? S_01 : state;
        S_01:     next_state = b0 ? S_010 : b1 ? S_RESET : state;
        S_010:    next_state = b0 ? S_0 : b1 ? S_0101 : state;
        S_0101:  next_state = b0 ? S_010 : b1 ? S_01011 : state;
        S_01011: next_state = b0 ? S_0 : b1 ? S_RESET : state;
        default: next_state = S_RESET; // handle unused states
    endcase
end

always @(posedge clk) state <= next_state;

```



Step 2C: generate output

```
// it's a Moore machine! Output only depends on current state
assign out = (state == S_01011);
```

Step 2D: debugging?

```
// hmmm. What would be useful to know? Current state?
// hex_display on labkit shows 16 four bit values
assign hex_display = {6'b0, 1'b0, state[2:0]};
```

Step 2: final Verilog implementation

```
module lock(input clk,reset_in,b0_in,b1_in,
            output out, output [3:0] hex_display);

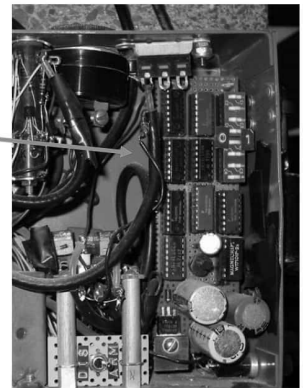
    wire reset, b0, b1; // synchronize push buttons, convert to pulses
    button b_reset(clk,reset_in,reset);
    button b_0(clk,b0_in,b0);
    button b_1(clk,b1_in,b1);

    parameter S_RESET = 0; parameter S_0 = 1; // state assignments
    parameter S_01 = 2; parameter S_010 = 3;
    parameter S_0101 = 4; parameter S_01011 = 5;

    reg [2:0] state,next_state;
    always @(*) begin // implement state transition diagram
        if (reset) next_state = S_RESET;
        else case (state)
            S_RESET: next_state = b0 ? S_0 : b1 ? S_RESET : state;
            S_0: next_state = b0 ? S_0 : b1 ? S_01 : state;
            S_01: next_state = b0 ? S_010 : b1 ? S_RESET : state;
            S_010: next_state = b0 ? S_0 : b1 ? S_0101 : state;
            S_0101: next_state = b0 ? S_010 : b1 ? S_01011 : state;
            S_01011: next_state = b0 ? S_0 : b1 ? S_RESET : state;
            default: next_state = S_RESET; // handle unused states
        endcase
    end
    always @ (posedge clk) state <= next_state;

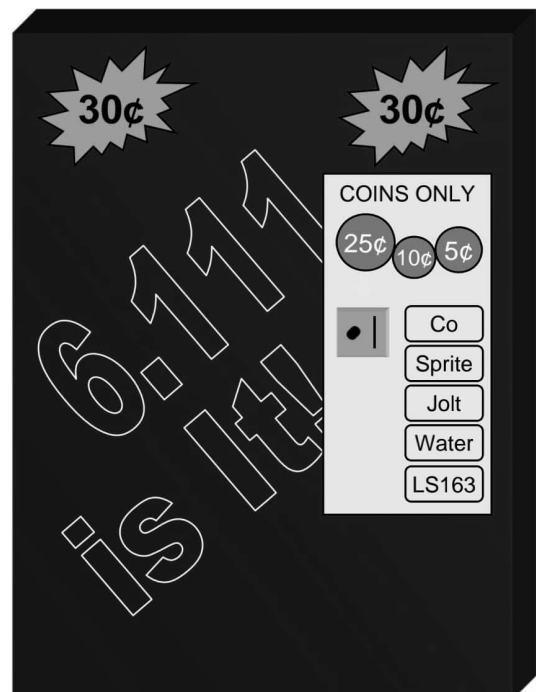
    assign out = (state == S_01011); // assign output: Moore machine
    assign hex_display = {1'b0,state}; // debugging
endmodule
```

Real FSM Security System



The 6.111 Vending Machine

- Lab assistants demand a new soda machine for the 6.111 lab. You design the FSM controller.
- All selections are \$0.30.
- The machine makes change. (Dimes and nickels only.)
- Inputs: limit 1 per clock
 - Q - quarter inserted
 - D - dime inserted
 - N - nickel inserted
- Outputs: limit 1 per clock
 - DC - dispense can
 - DD - dispense dime
 - DN - dispense nickel



What States are in the System?

- A starting (idle) state:

idle

- A state for each possible amount of money captured:

got5c got10c got15c ...

- What's the maximum amount of money captured before purchase?
25 cents (just shy of a purchase) + one quarter (largest coin)

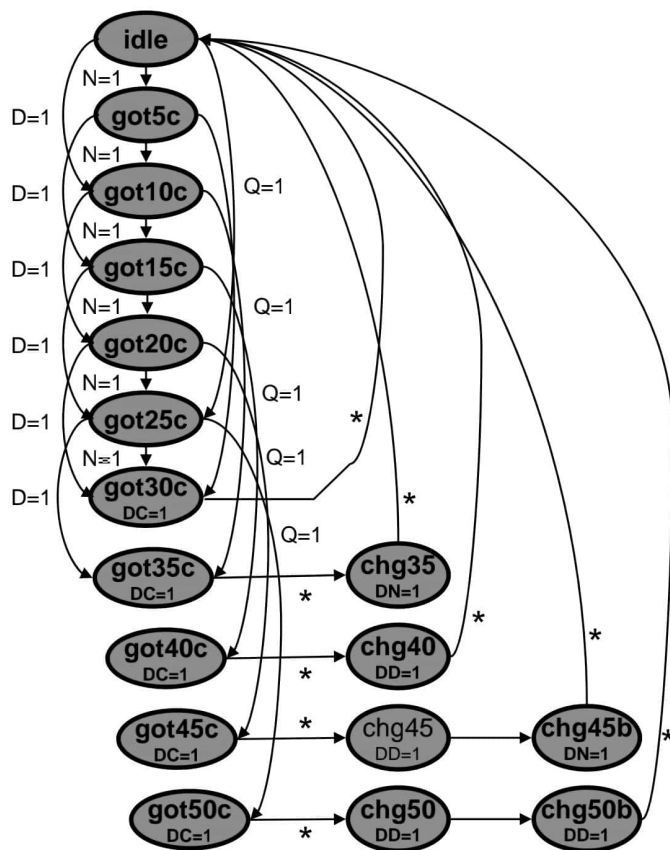
... got35c got40c got45c got50c

- States to dispense change (one per coin dispensed):

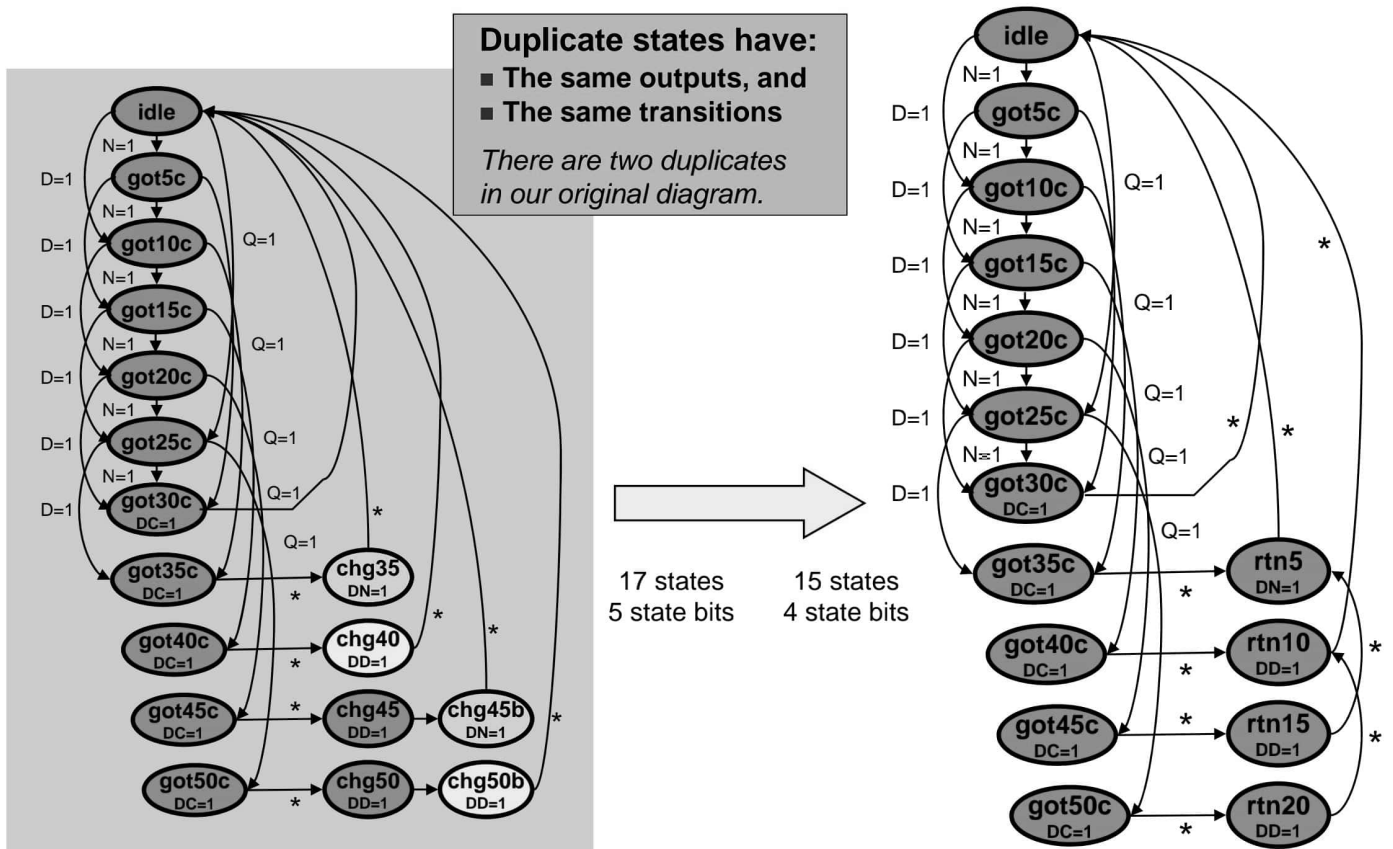


A Moore Vender

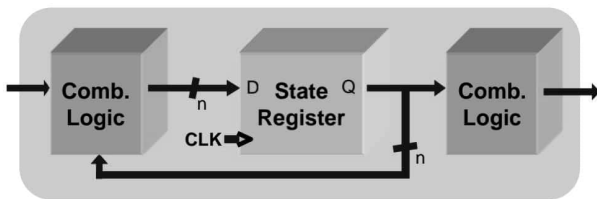
Here's a first cut at the state transition diagram.



State Reduction



Verilog for the Moore Vender



**FSMs are easy in Verilog.
Simply write one of each:**

- **State register**
(sequential always block)
- **Next-state combinational logic**
(comb. always block with case)
- **Output combinational logic block**
(comb. always block *or* assign statements)

```
module mooreVender (
    input N, D, Q, clk, reset,
    output DC, DN, DD,
    output reg [3:0] state);

    reg next;
```

States defined with parameter keyword

```
parameter IDLE = 0;
parameter GOT_5c = 1;
parameter GOT_10c = 2;
parameter GOT_15c = 3;
parameter GOT_20c = 4;
parameter GOT_25c = 5;
parameter GOT_30c = 6;
parameter GOT_35c = 7;
parameter GOT_40c = 8;
parameter GOT_45c = 9;
parameter GOT_50c = 10;
parameter RETURN_20c = 11;
parameter RETURN_15c = 12;
parameter RETURN_10c = 13;
parameter RETURN_5c = 14;
```

State register defined with sequential always block

```
always @ (posedge clk or negedge reset)
    if (!reset) state <= IDLE;
    else state <= next;
```

Verilog for the Moore Vender

Next-state logic within a combinational always block

```
always @ (state or N or D or Q) begin
  case (state)
    IDLE:    if (Q) next = GOT_25c;
             else if (D) next = GOT_10c;
             else if (N) next = GOT_5c;
             else next = IDLE;

    GOT_5c:  if (Q) next = GOT_30c;
             else if (D) next = GOT_15c;
             else if (N) next = GOT_10c;
             else next = GOT_5c;

    GOT_10c: if (Q) next = GOT_35c;
             else if (D) next = GOT_20c;
             else if (N) next = GOT_15c;
             else next = GOT_10c;

    GOT_15c: if (Q) next = GOT_40c;
             else if (D) next = GOT_25c;
             else if (N) next = GOT_20c;
             else next = GOT_15c;

    GOT_20c: if (Q) next = GOT_45c;
             else if (D) next = GOT_30c;
             else if (N) next = GOT_25c;
             else next = GOT_20c;
```

```
GOT_25c:  if (Q) next = GOT_50c;
           else if (D) next = GOT_35c;
           else if (N) next = GOT_30c;
           else next = GOT_25c;

GOT_30c:  next = IDLE;
GOT_35c:  next = RETURN_5c;
GOT_40c:  next = RETURN_10c;
GOT_45c:  next = RETURN_15c;
GOT_50c:  next = RETURN_20c;

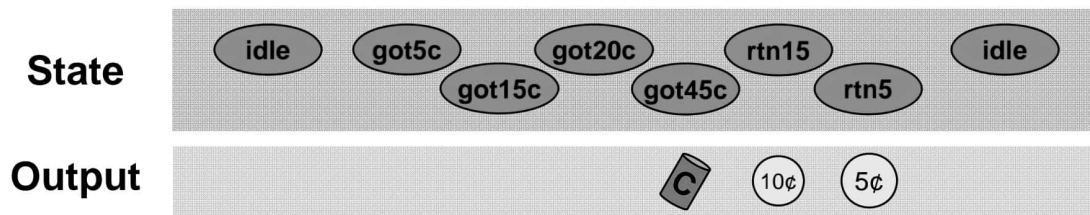
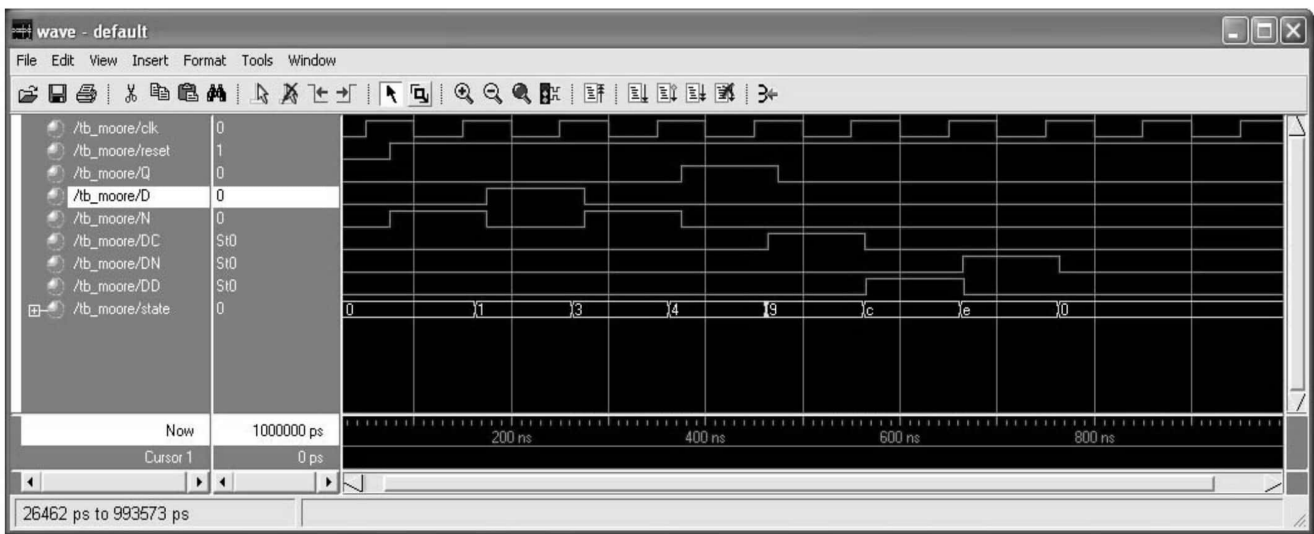
RETURN_20c: next = RETURN_10c;
RETURN_15c: next = RETURN_5c;
RETURN_10c: next = IDLE;
RETURN_5c:  next = IDLE;

  default: next = IDLE;
endcase
end
```

Combinational output assignment

```
assign DC = (state == GOT_30c || state == GOT_35c ||
             state == GOT_40c || state == GOT_45c ||
             state == GOT_50c);
assign DN = (state == RETURN_5c);
assign DD = (state == RETURN_20c || state == RETURN_15c ||
             state == RETURN_10c);
endmodule
```

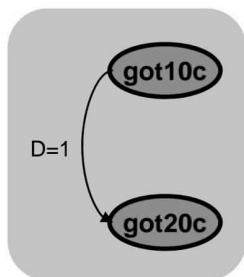
Simulation of Moore Vender



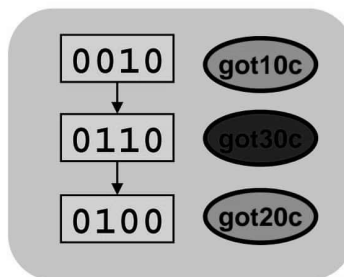
FSM Output Glitching

- FSM state bits may not transition at precisely the same time
- Combinational logic for outputs may contain hazards
- Result: your FSM outputs may glitch!

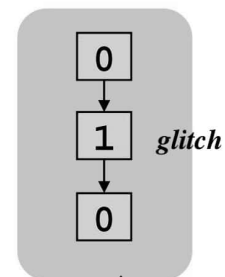
during this state transition...



...the state registers may transition like this...



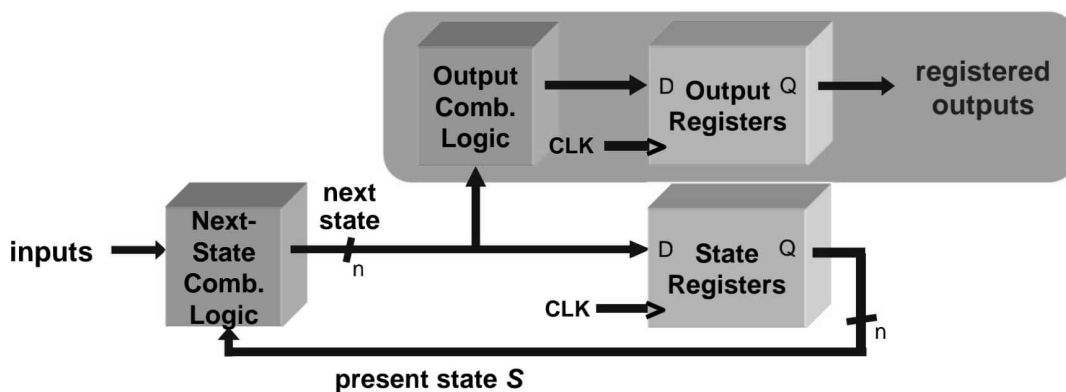
...causing the DC output to **glitch** like this!



```
assign DC = (state == GOT_30c || state == GOT_35c ||
             state == GOT_40c || state == GOT_45c ||
             state == GOT_50c);
```

If the soda dispenser is glitch-sensitive, your customers can get a 20-cent soda!

Registered FSM Outputs are Glitch-Free



- Move output generation into the sequential always block
- Calculate outputs based on next state
- Delays outputs by one clock cycle. Problematic in some application.

```

reg DC, DN, DD;

// Sequential always block for state assignment
always @ (posedge clk or negedge reset) begin
    if (!reset) state <= IDLE;
    else if (clk) state <= next;

    DC <= (next == GOT_30c || next == GOT_35c ||
           next == GOT_40c || next == GOT_45c ||
           next == GOT_50c);
    DN <= (next == RETURN_5c);
    DD <= (next == RETURN_20c || next == RETURN_15c ||
           next == RETURN_10c);
end
    
```

Where should CLK come from?

- Option 1: external crystal
 - Stable, known frequency, typically 50% duty cycle
- Option 2: internal signals
 - Option 2A: output of combinational logic



- No! If inputs to logic change, output may make several transitions before settling to final value → several rising edges, not just one! Hard to design away output glitches...
- Option 2B: output of a register
 - Okay, but timing of CLK2 won't line up with CLK1

