

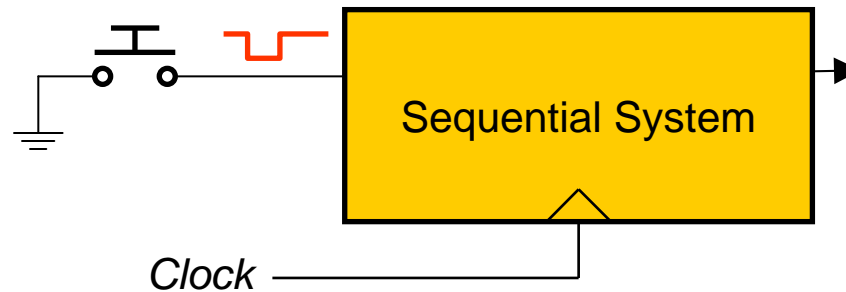
L6: FSMs and Synchronization



Lecture material courtesy of Rex Min

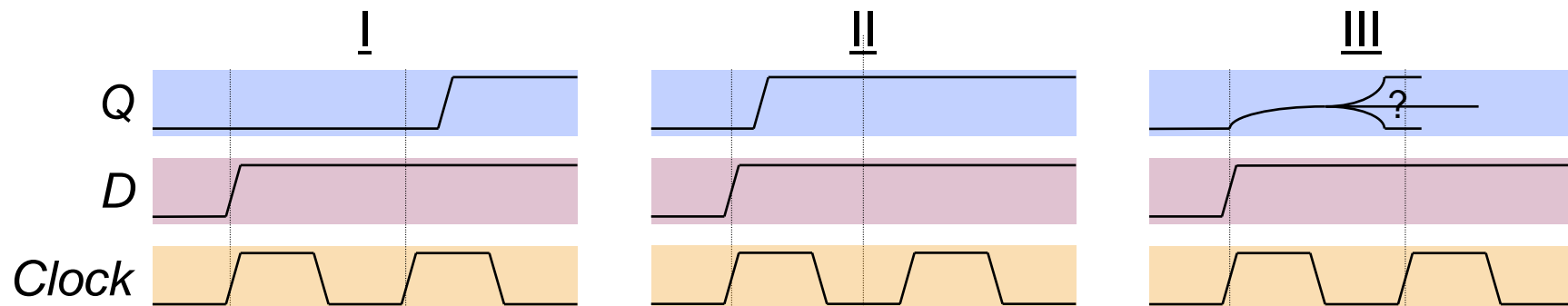
Lecture notes prepared by Professor Anantha Chandrakasan

What about external signals?



Can't guarantee setup and hold times will be met!

When an asynchronous signal causes a setup/hold violation...



Transition is missed on first clock cycle, but caught on next clock cycle.

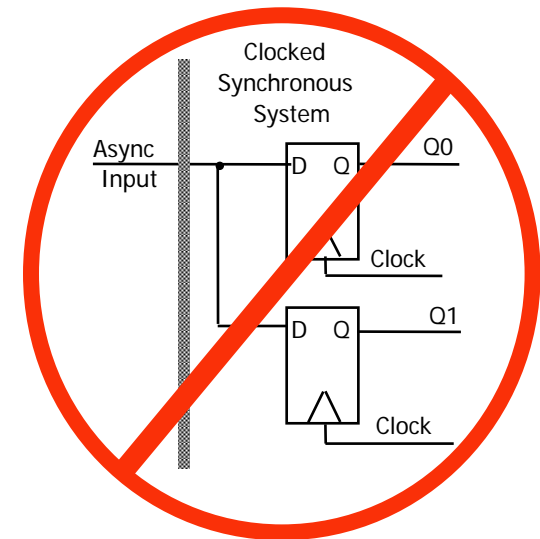
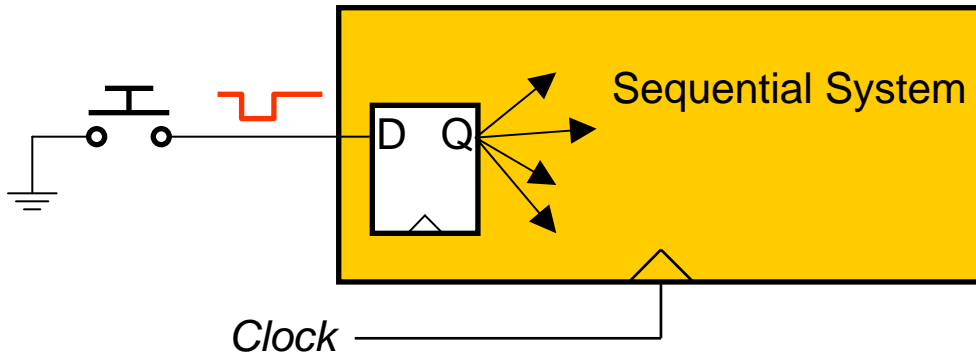
Transition is caught on first clock cycle.

Output is metastable for an indeterminate amount of time.

Q: Which cases are problematic?

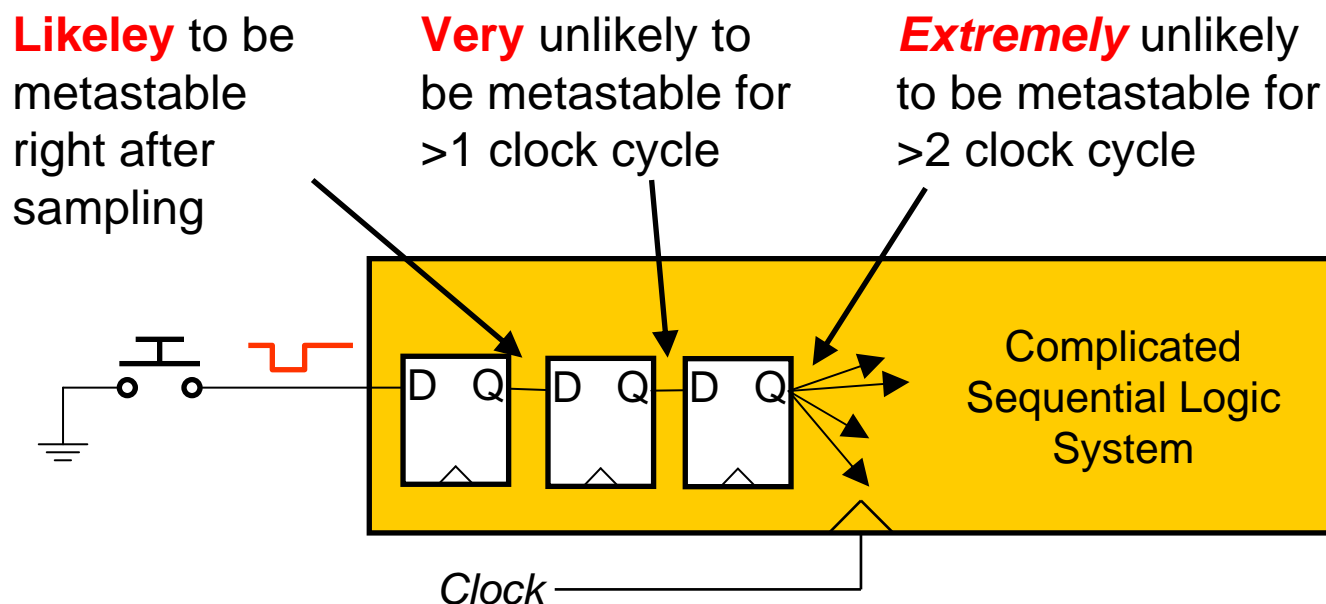
All of them can be, if more than one happens simultaneously within the same circuit.

Idea: ensure that external signals directly feed exactly one flip-flop



This prevents the possibility of I and II occurring in different places in the circuit, but what about metastability?

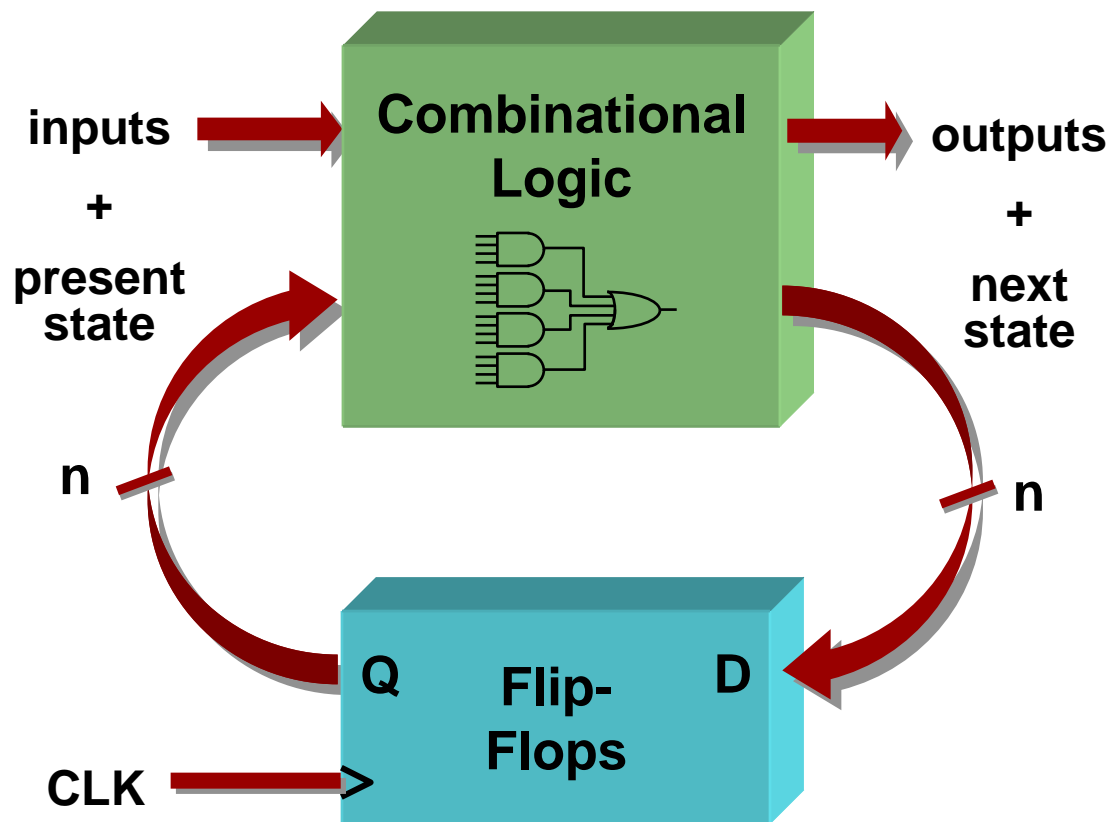
- Preventing metastability turns out to be an impossible problem
- High gain of digital devices makes it likely that metastable conditions will resolve themselves quickly
- Solution to metastability: allow time for signals to stabilize



How many registers are necessary?

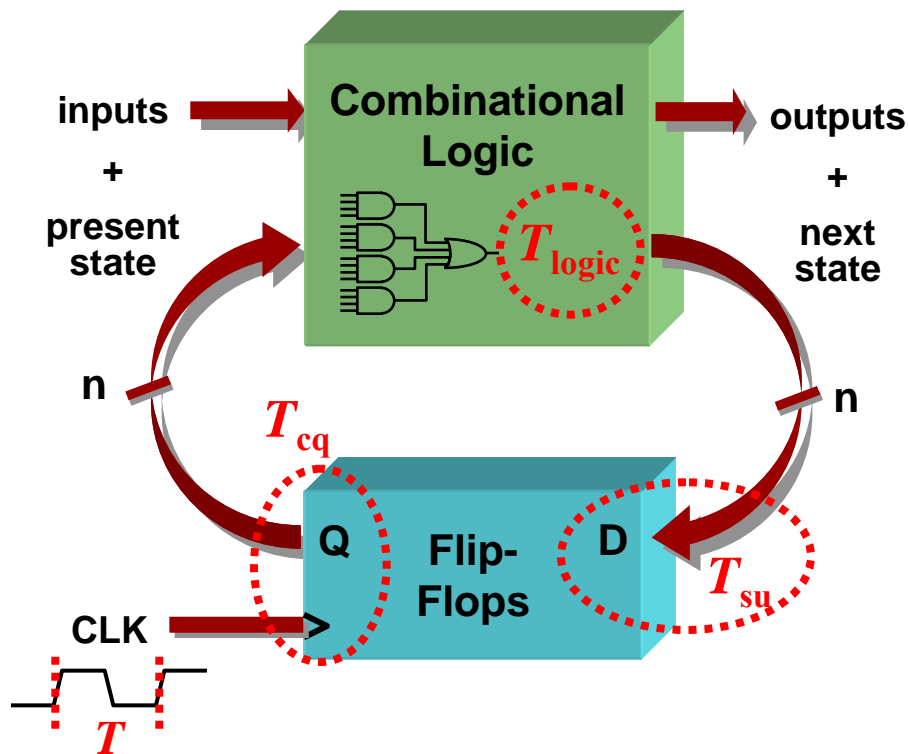
- Depends on many design parameters (clock speed, device speeds, ...)
- In 6.111, one or maybe two synchronization registers is sufficient

- 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*



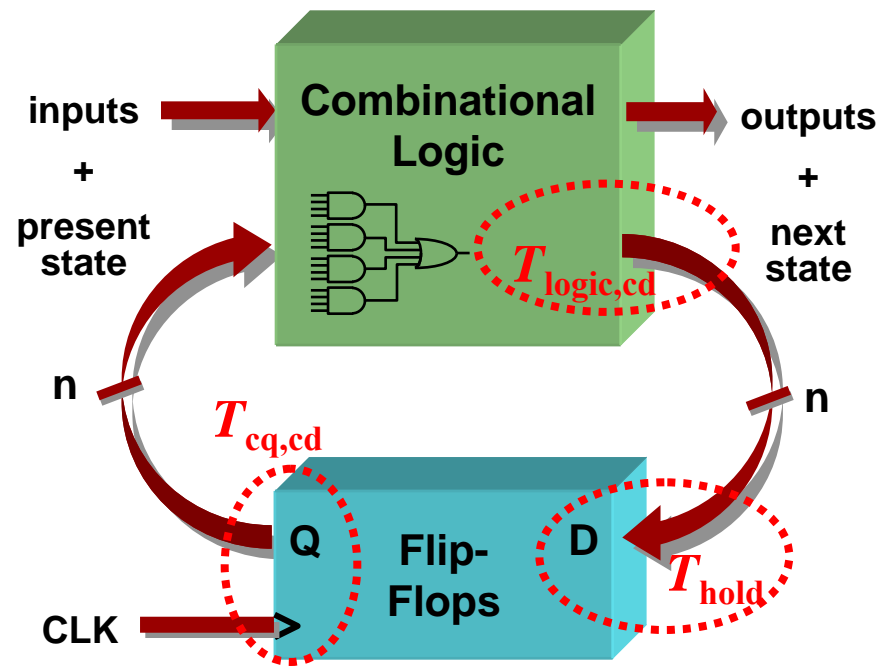
- Timing requirements for FSM are identical to any generic sequential system with feedback

Minimum Clock Period



$$T > T_{cq} + T_{logic} + T_{su}$$

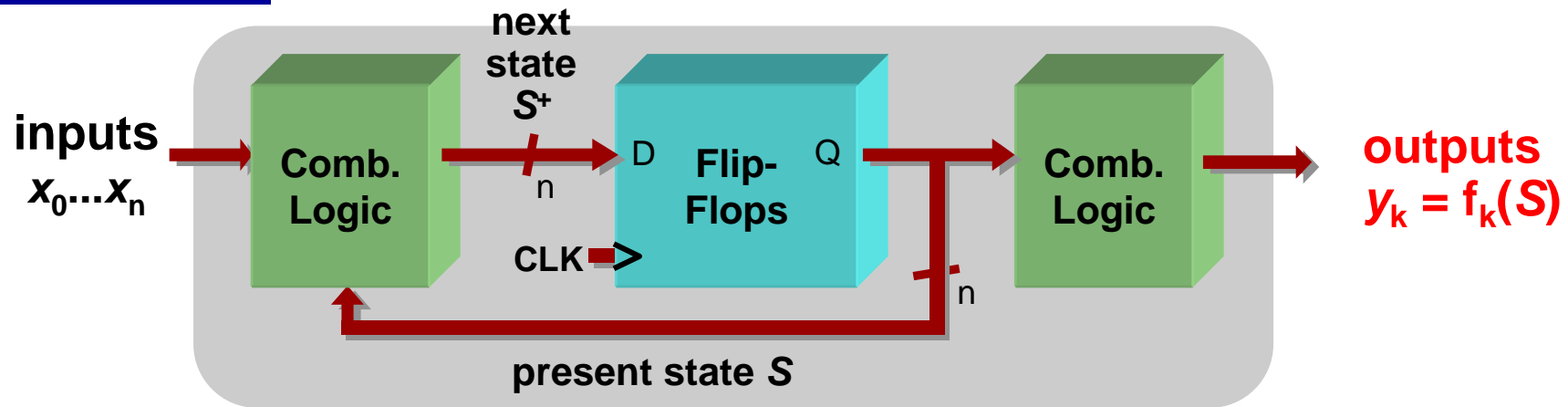
Minimum Delay



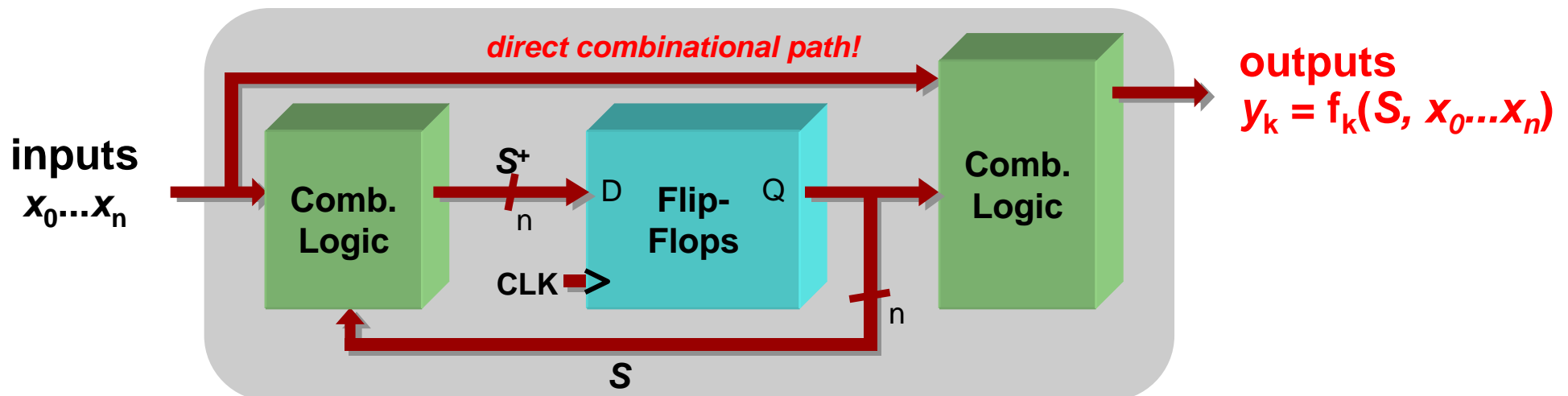
$$T_{cq,cd} + T_{logic,cd} > T_{hold}$$

Moore and Mealy FSMs are distinguished by their output generation

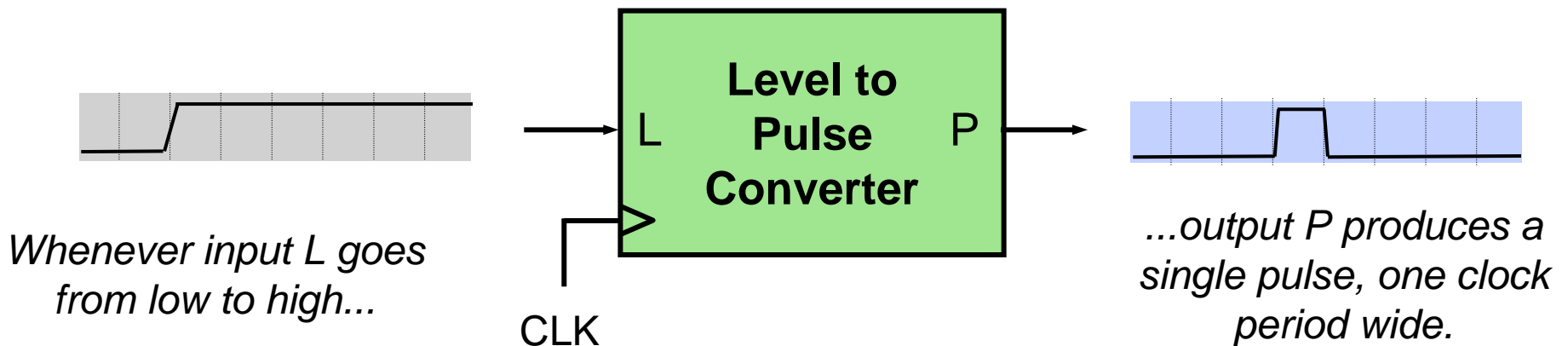
Moore FSM:



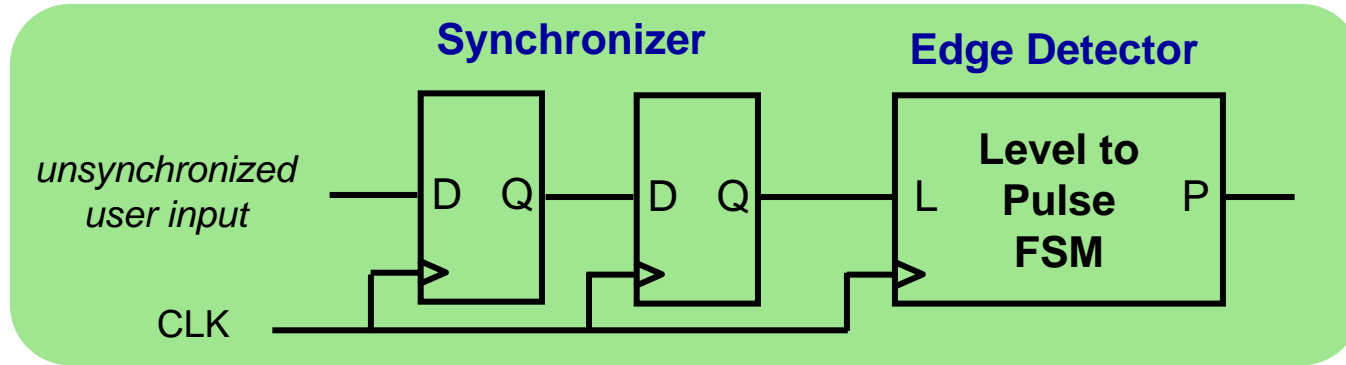
Mealy FSM:



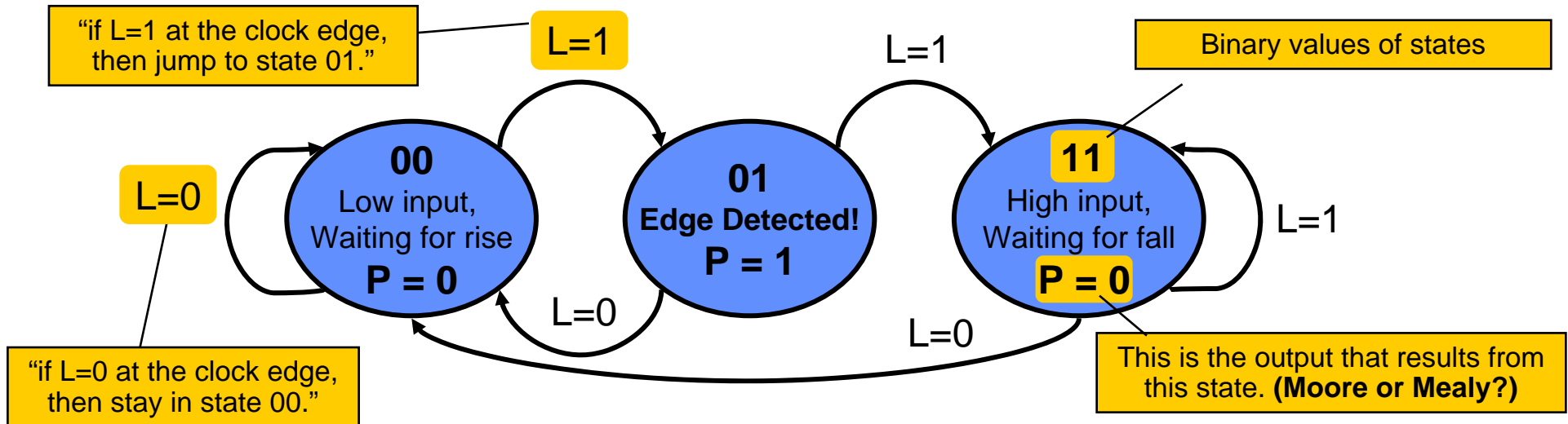
- A **level-to-pulse converter** produces a single-cycle pulse each time its input goes high.
- In other words, it's a synchronous rising-edge detector.
- Sample uses:
 - Buttons and switches pressed by humans for arbitrary periods of time
 - Single-cycle enable signals for counters



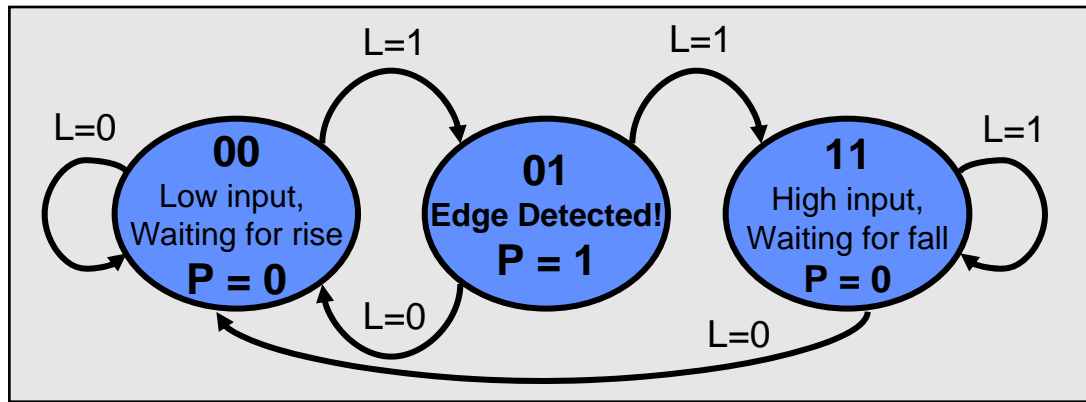
- Block diagram of desired system:



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

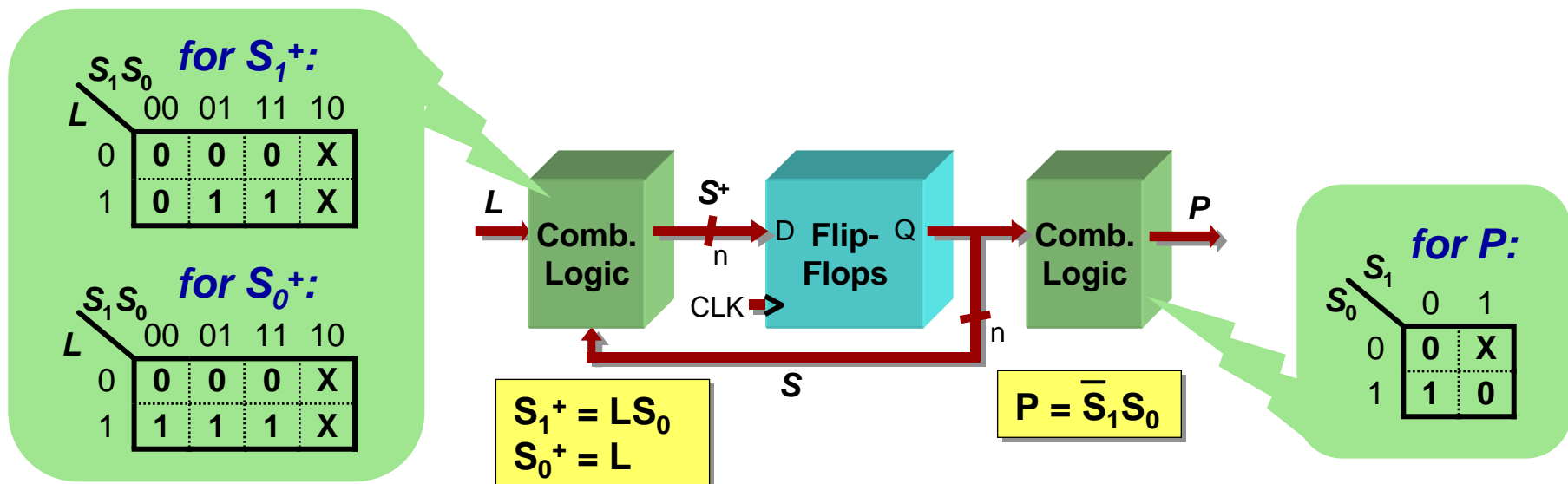


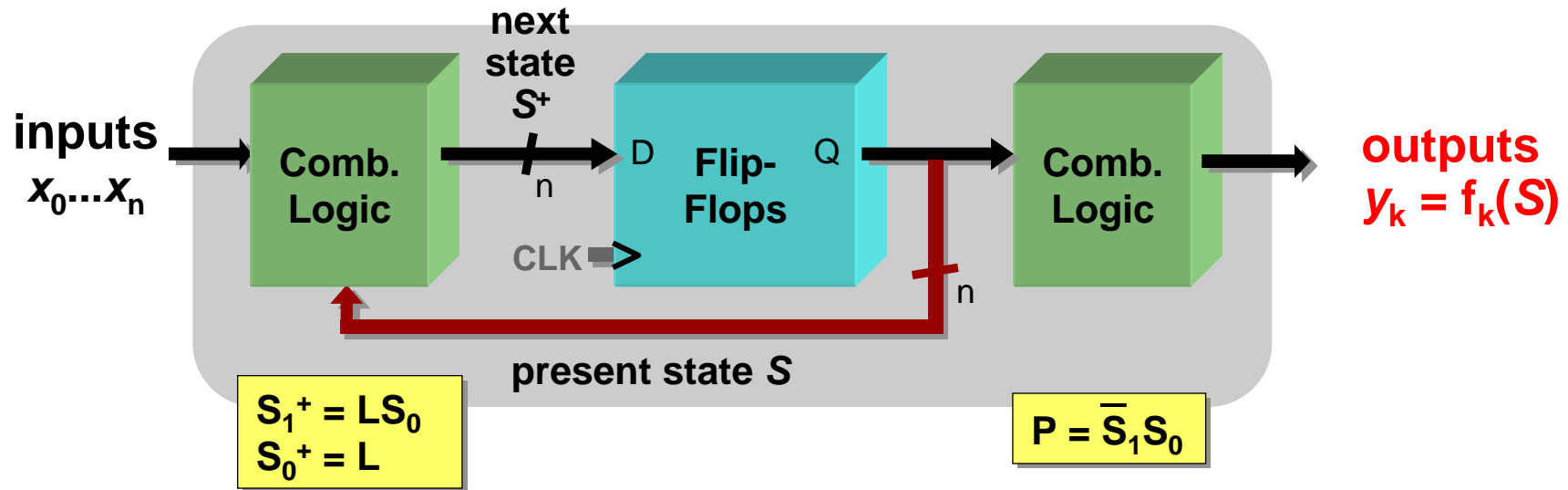
- Transition diagram is readily converted to a state transition table (just a truth table)



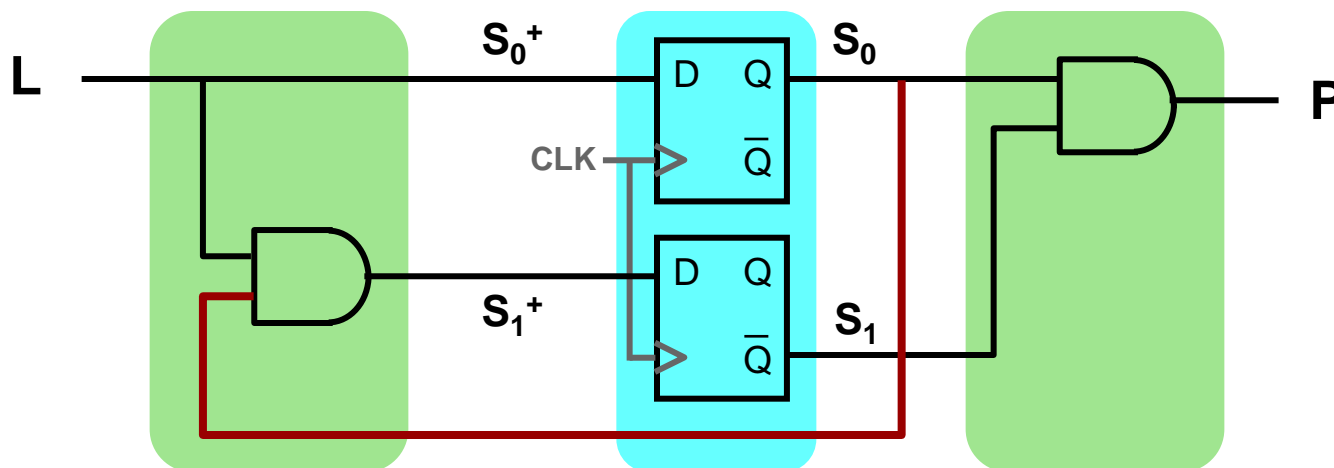
Current State		In	Next State		Out
S_1	S_0	L	S_1^+	S_0^+	P
0	0	0	0	0	0
0	0	1	0	1	0
0	1	0	0	0	1
0	1	1	1	1	1
1	1	0	0	0	0
1	1	1	1	1	0

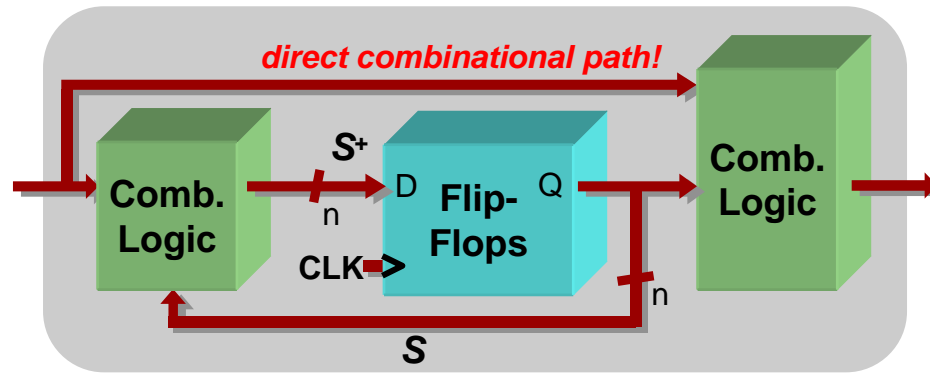
- Combinational logic may be derived by Karnaugh maps





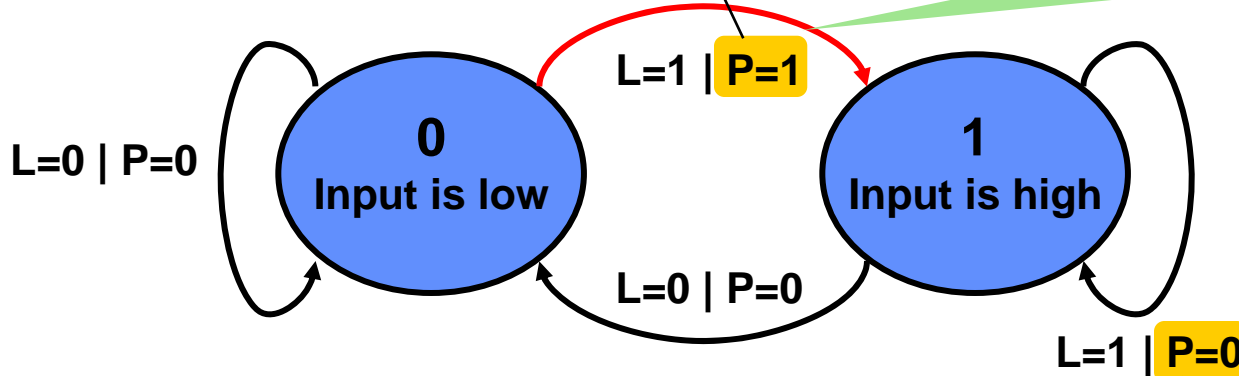
Moore FSM circuit implementation of level-to-pulse converter:



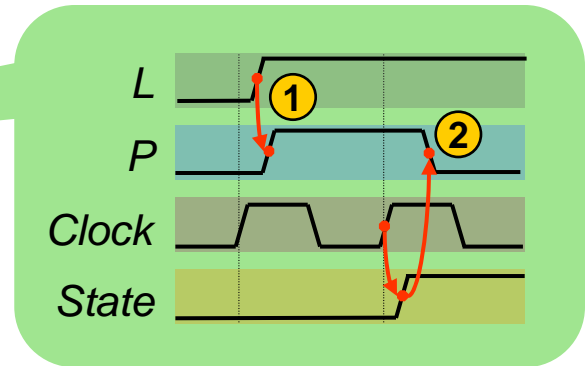


- Since outputs are determined by state *and* inputs, Mealy FSMs may need fewer states than Moore FSM implementations

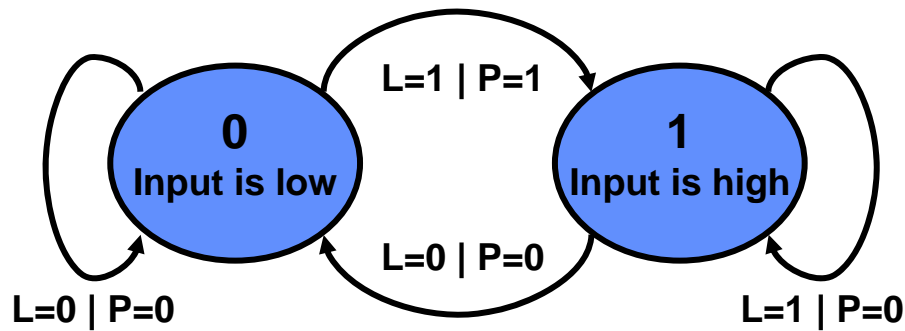
1. When $L=1$ and $S=0$, this output is asserted **immediately** and **until** the state transition occurs (or L changes).



2. After the transition to $S=1$ and as long as L remains at 1, this output is 0.

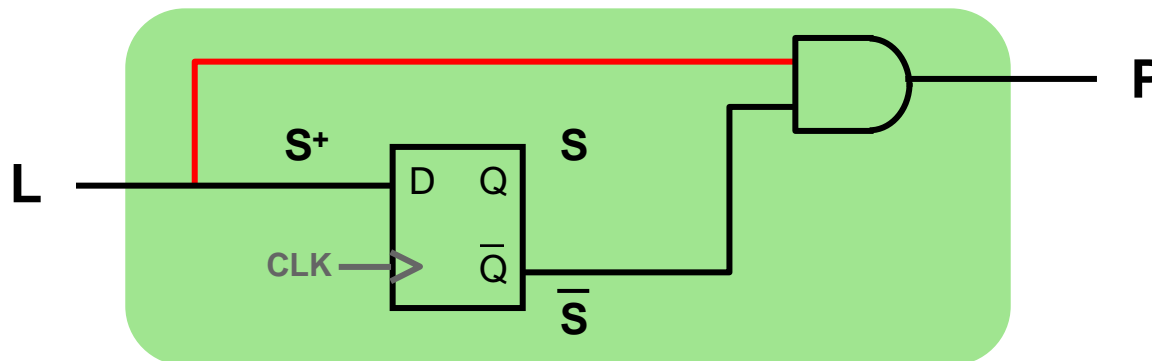


Output transitions immediately.
State transitions at the clock edge.



Pres. State	In	Next State	Out
S	L	S⁺	P
0	0	0	0
0	1	1	1
1	0	0	0
1	1	1	0

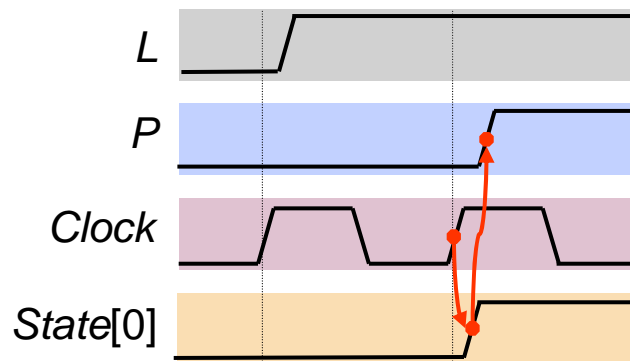
Mealy FSM circuit implementation of level-to-pulse converter:



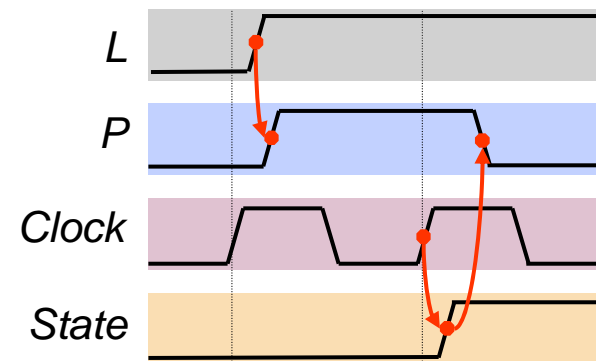
- FSM's state simply remembers the previous value of L
- Circuit benefits from the Mealy FSM's implicit single-cycle assertion of outputs during state transitions

- Remember that the difference is in the output:
 - Moore outputs are based on state only
 - Mealy outputs are based on state *and* input
 - Therefore, Mealy outputs generally occur one cycle earlier than a Moore:

Moore: delayed assertion of P



Mealy: immediate assertion of P



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

- 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



- A starting (idle) state:



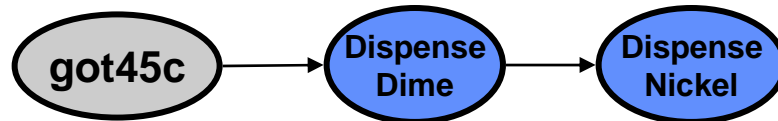
- A state for each possible amount of money captured:



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

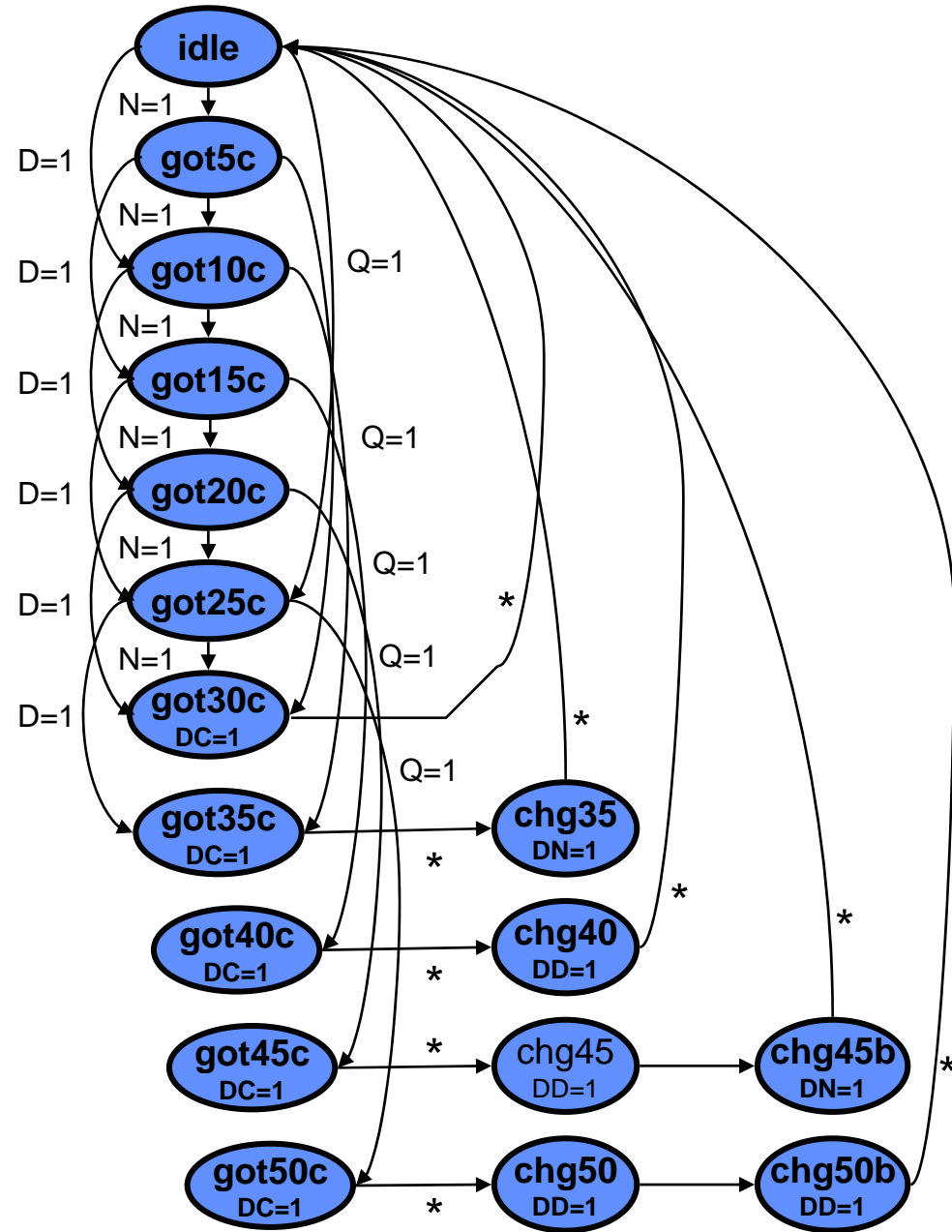


- States to dispense change (one per coin dispensed):



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

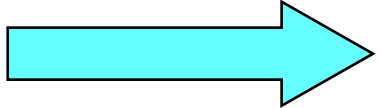
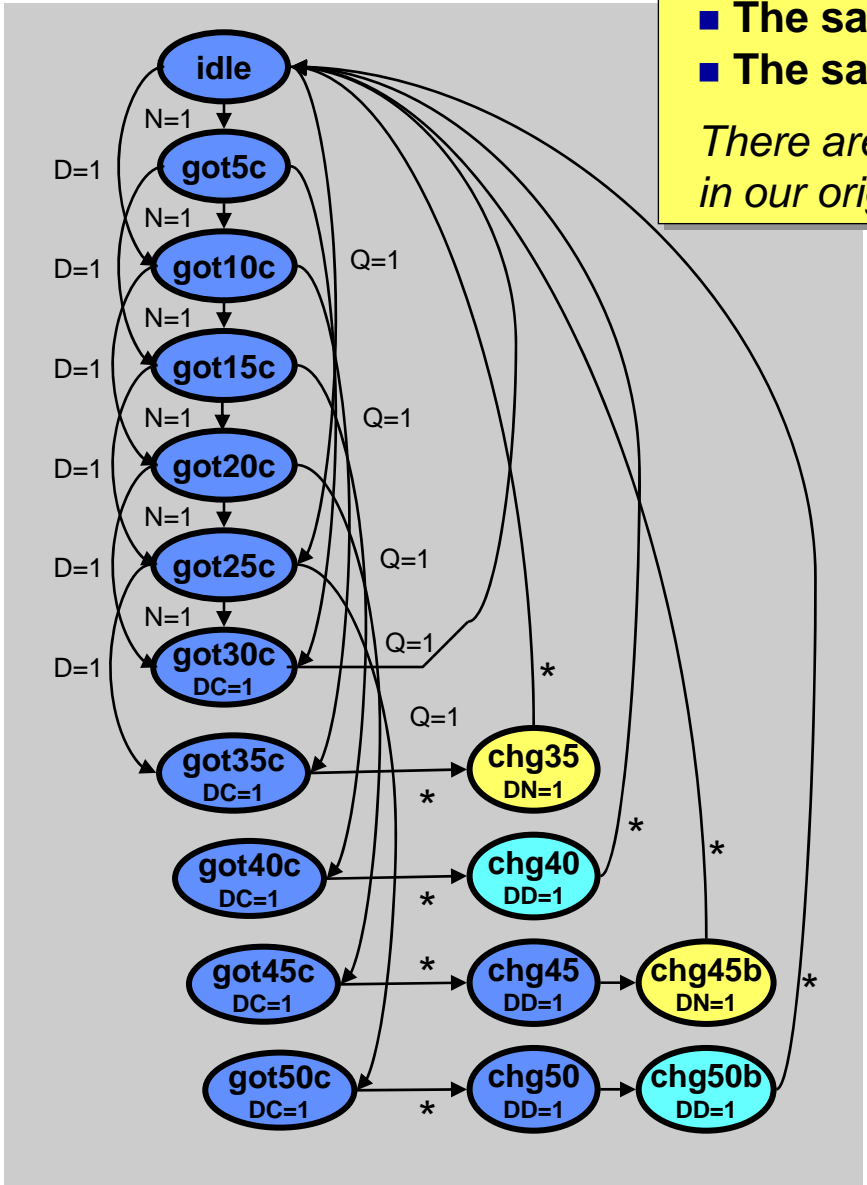
See a better way?
So do we.
Don't go away...



Duplicate states have:

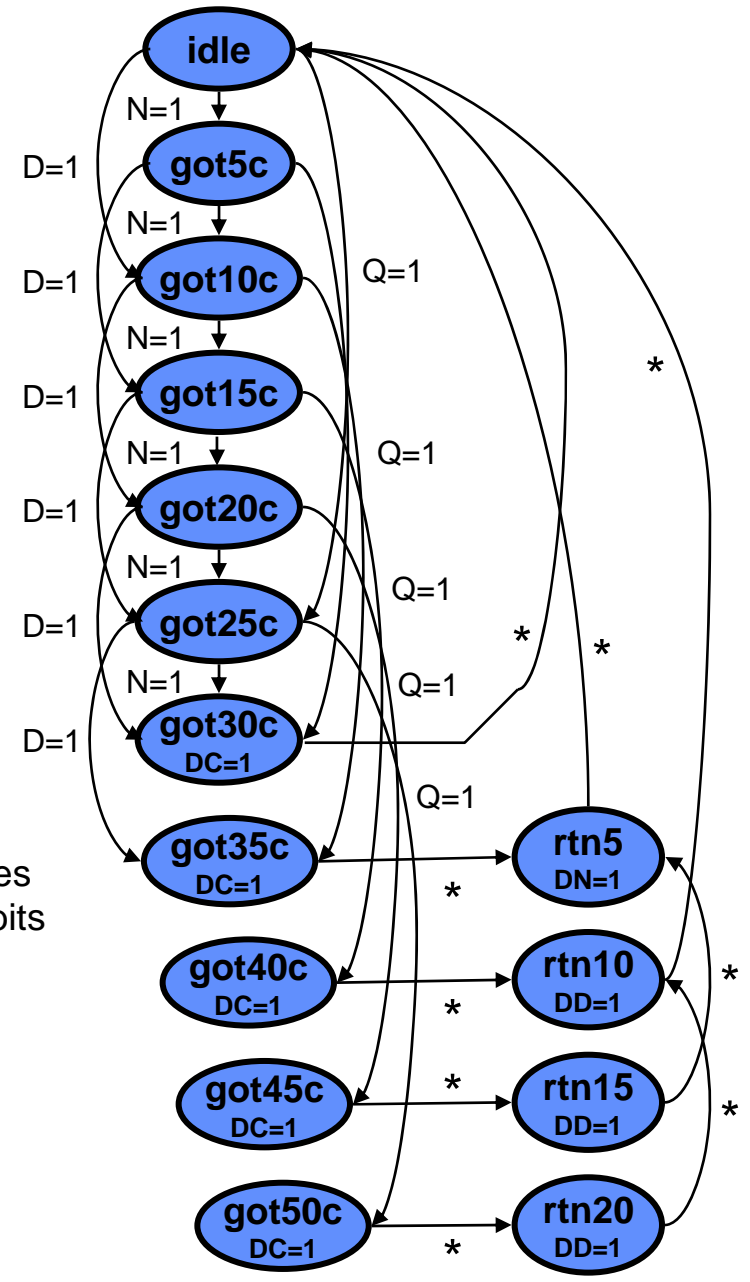
- The same outputs, and
- The same transitions

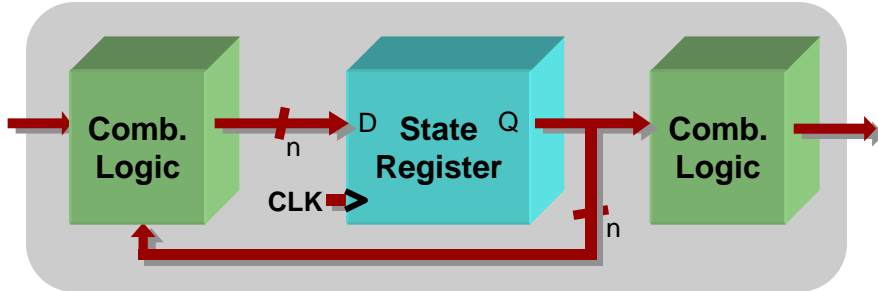
There are two duplicates in our original diagram.



17 states
5 state bits

15 states
4 state bits





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

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;
    endcase
end

```

```

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

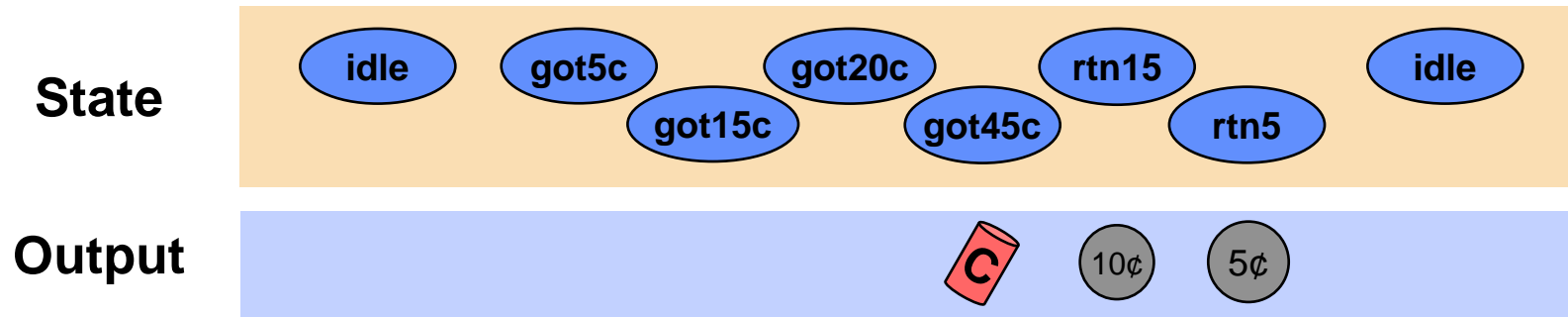
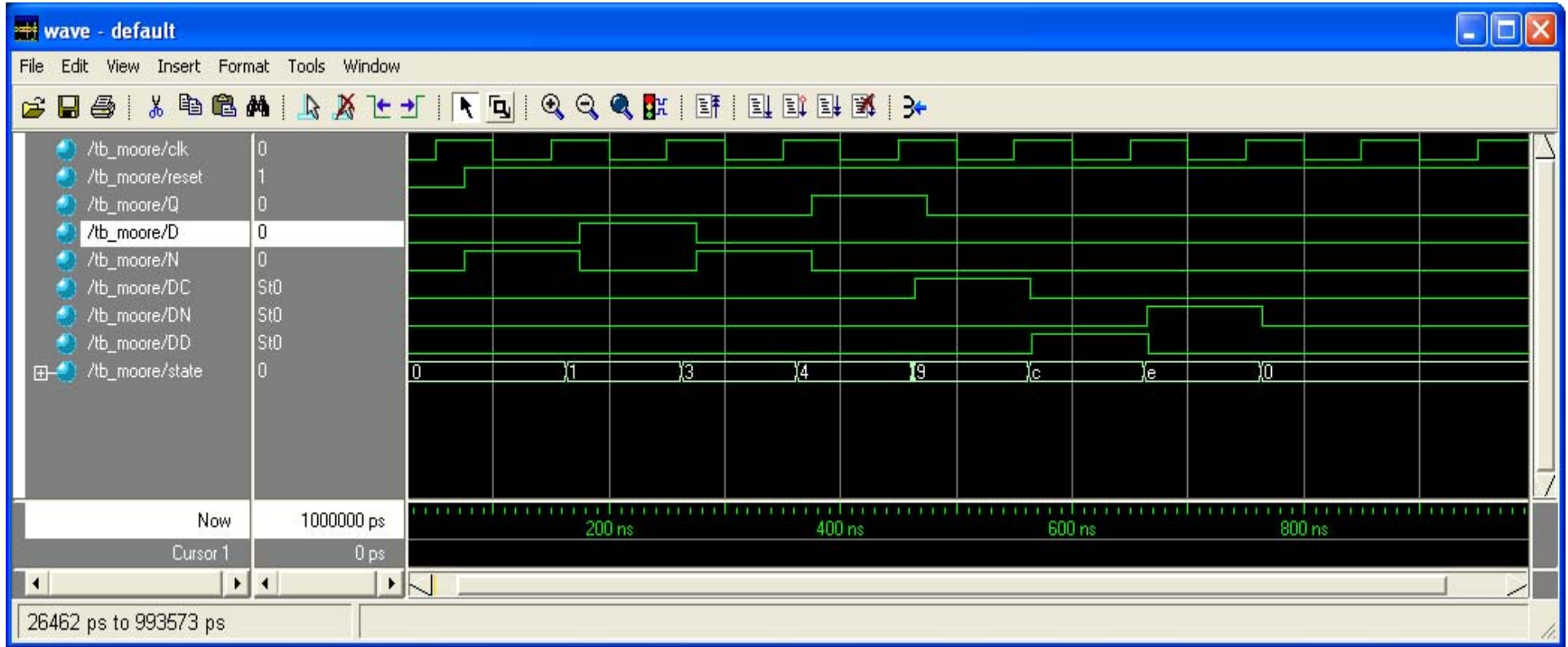
```

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

```



Next-state and output logic combined into a single always block

```
always @ (state or N or D or Q) begin
```

```
    DC = 0; DD = 0; DN = 0; // defaults
```

```
    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: begin
                    DC = 1; next = IDLE;
                end
```

```
        GOT_35c: begin
                    DC = 1; next = RETURN_5c;
                end
```

```
        GOT_40c: begin
                    DC = 1; next = RETURN_10c;
                end
```

```
        GOT_45c: begin
                    DC = 1; next = RETURN_15c;
                end
```

```
        GOT_50c: begin
                    DC = 1; next = RETURN_20c;
                end
```

```
        RETURN_20c: begin
                    DD = 1; next = RETURN_10c;
                end
```

```
        RETURN_15c: begin
                    DD = 1; next = RETURN_5c;
                end
```

```
        RETURN_10c: begin
                    DD = 1; next = IDLE;
                end
```

```
        RETURN_5c:  begin
                    DN = 1; next = IDLE;
                end
```

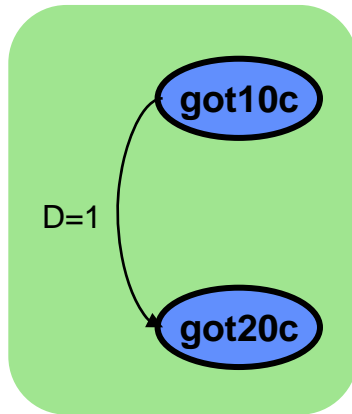
```
        default: next = IDLE;
```

```
    endcase
```

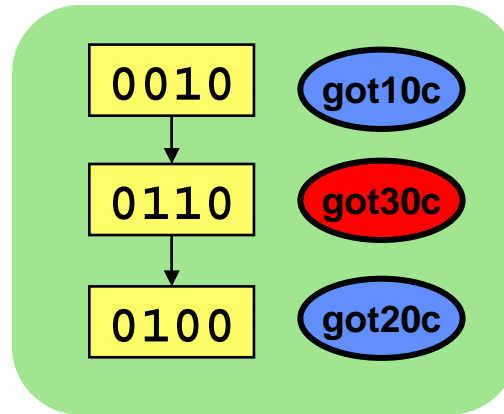
```
end
```

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

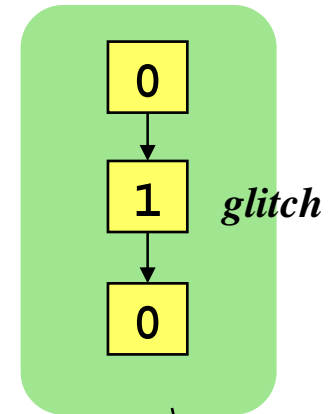
during this state transition...



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



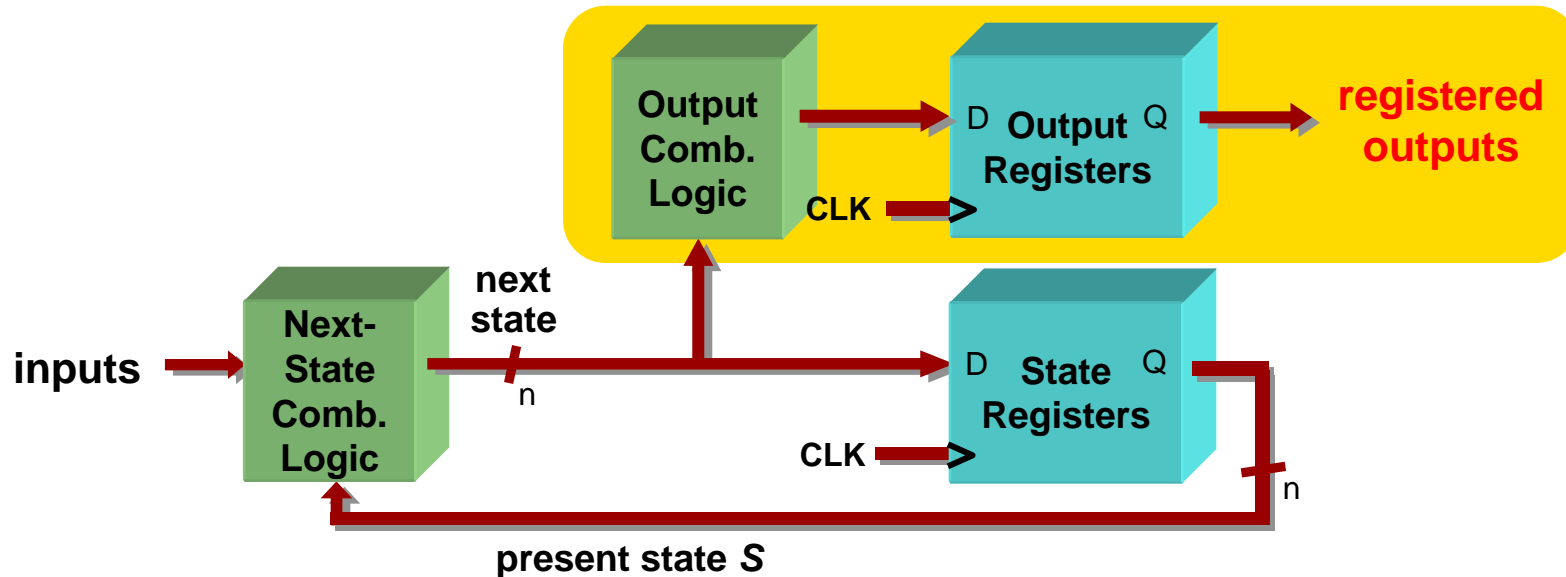
...causing the DC output to **glitch** like this!



```

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!



- **Move output generation into the sequential always block**
- **Calculate outputs based on next state**

```
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;
```

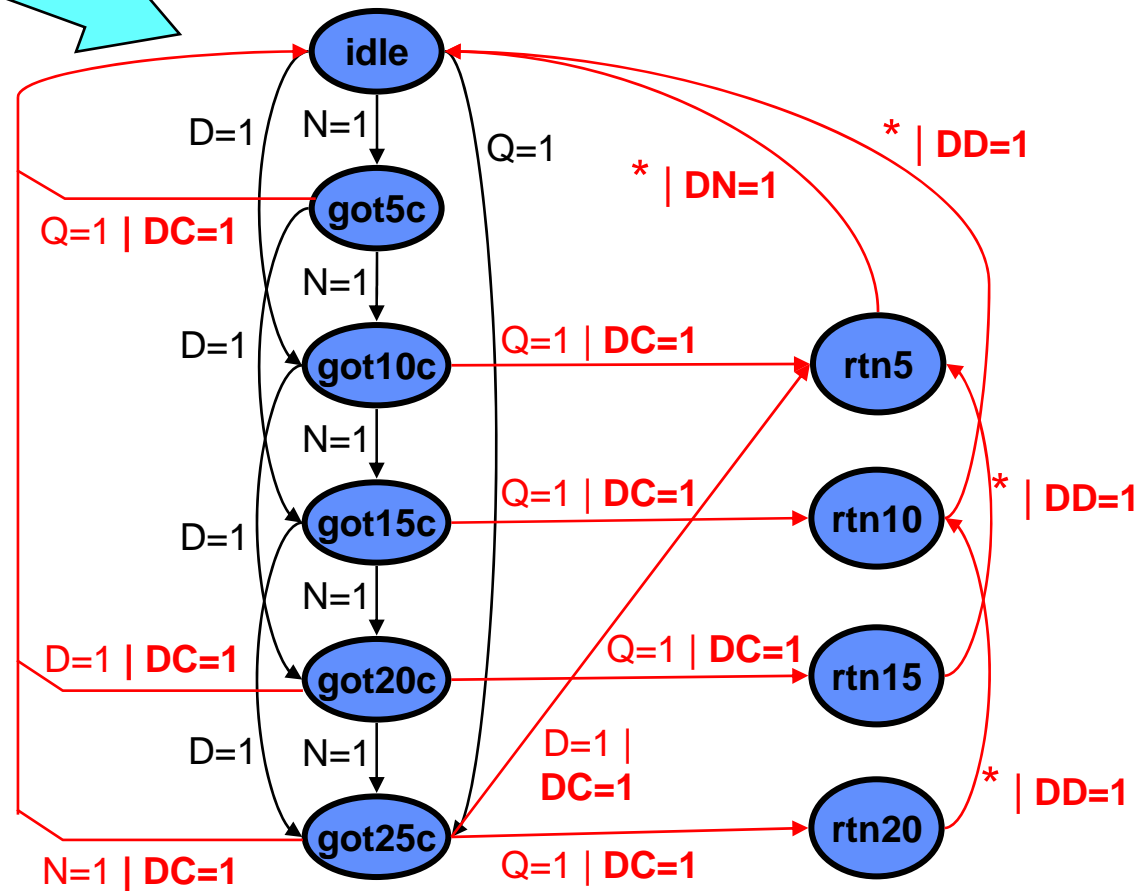
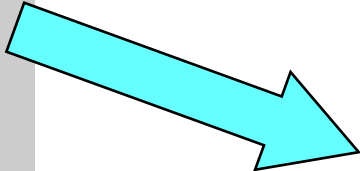
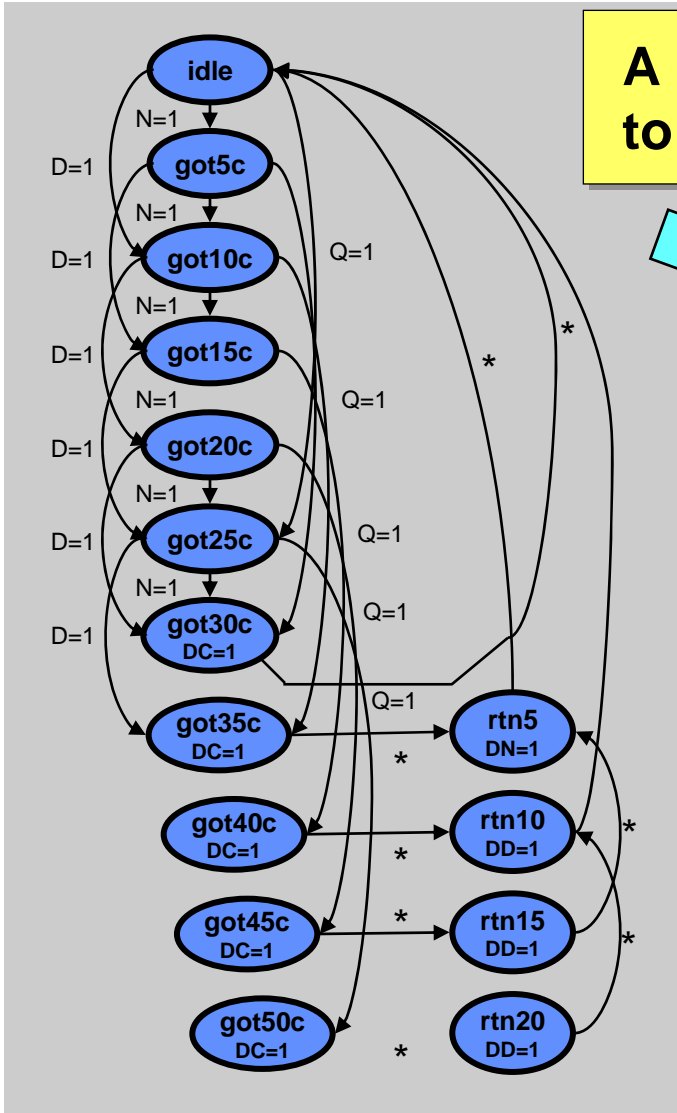
```
    DC <= (next == GOT_30c || next == GOT_35c ||
           next == GOT_40c || next == GOT_45c ||
           next == GOT_50c);
```

```
    DN <= (next == RETURN_5c);
```

```
    DD <= (next == RETURN_20c || next == RETURN_15c ||
           next == RETURN_10c);
```

```
end
```


A Mealy machine can eliminate states devoted solely to holding an output value.



```
module mealyVender (N, D, Q, DC, DN, DD, clk, reset, state);
  input N, D, Q, clk, reset;
  output DC, DN, DD;
  reg DC, DN, DD;

  output [3:0] state;
  reg [3:0] state, next;

  parameter IDLE = 0;
  parameter GOT_5c = 1;
  parameter GOT_10c = 2;
  parameter GOT_15c = 3;
  parameter GOT_20c = 4;
  parameter GOT_25c = 5;
  parameter RETURN_20c = 6;
  parameter RETURN_15c = 7;
  parameter RETURN_10c = 8;
  parameter RETURN_5c = 9;

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

```

always @ (state or N or D or Q) begin

    DC = 0; DN = 0; DD = 0;    // defaults

    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) begin
                       DC = 1; next = IDLE;
                   end
                   else if (D) next = GOT_15c;
                   else if (N) next = GOT_10c;
                   else next = GOT_5c;

        GOT_10c:   if (Q) begin
                       DC = 1; next = RETURN_5c;
                   end
                   else if (D) next = GOT_20c;
                   else if (N) next = GOT_15c;
                   else next = GOT_10c;

        GOT_15c:   if (Q) begin
                       DC = 1; next = RETURN_10c;
                   end
                   else if (D) next = GOT_25c;
                   else if (N) next = GOT_20c;
                   else next = GOT_15c;

        GOT_20c:   if (Q) begin
                       DC = 1; next = RETURN_15c;
                   end
                   else if (D) begin
                       DC = 1; next = IDLE;
                   end
                   else if (N) next = GOT_25c;
                   else next = GOT_20c;
    endcase
end

```

For state GOT_5c, output DC is only asserted if Q=1

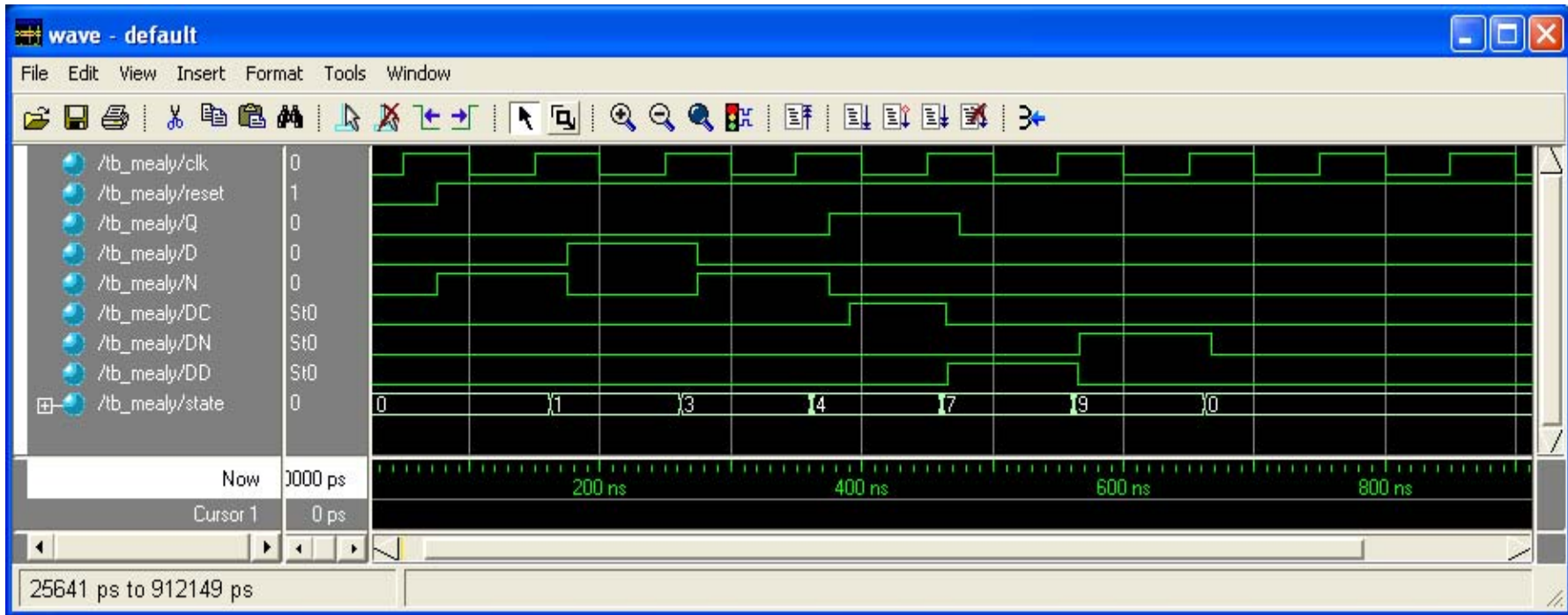
```

        GOT_25c:   if (Q) begin
                       DC = 1; next = RETURN_20c;
                   end
                   else if (D) begin
                       DC = 1; next = RETURN_5c;
                   end
                   else if (N) begin
                       DC = 1; next = IDLE;
                   end
                   else next = GOT_25c;

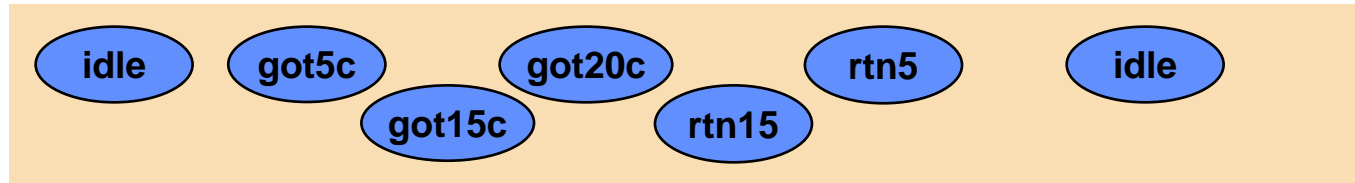
        RETURN_20c: begin
                       DD = 1; next = RETURN_10c;
                   end
        RETURN_15c: begin
                       DD = 1; next = RETURN_5c;
                   end
        RETURN_10c: begin
                       DD = 1; next = IDLE;
                   end
        RETURN_5c:  begin
                       DN = 1; next = IDLE;
                   end

        default: next = IDLE;
    endcase
end
endmodule

```



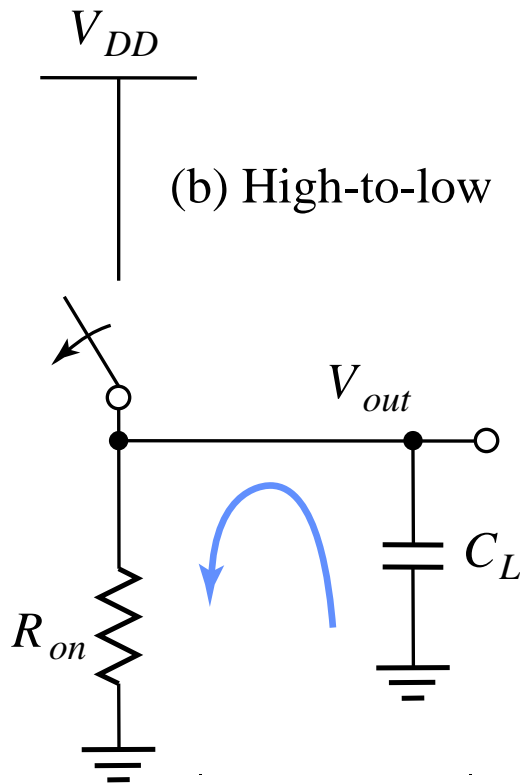
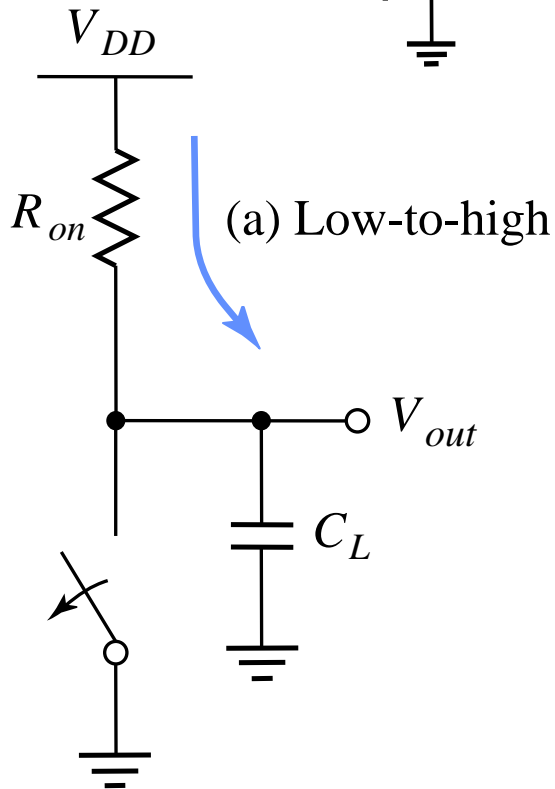
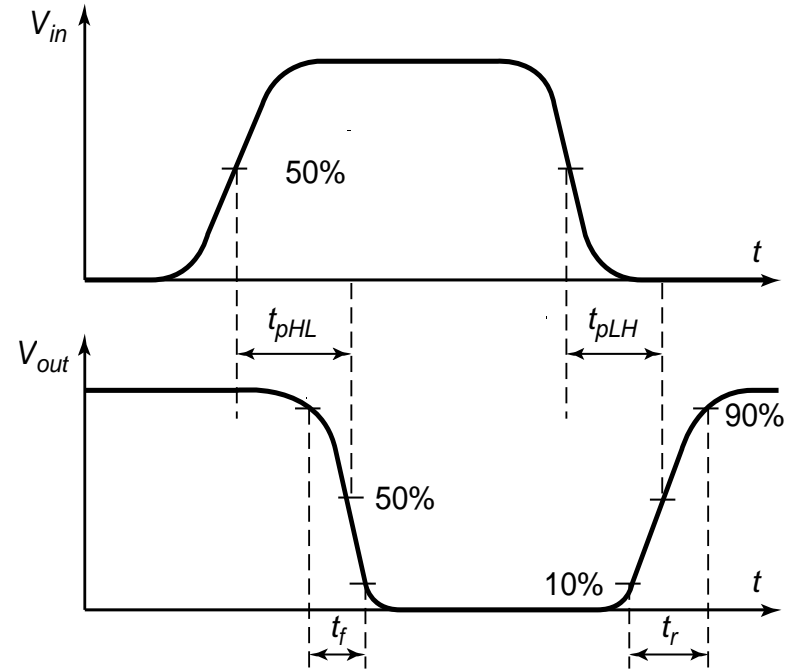
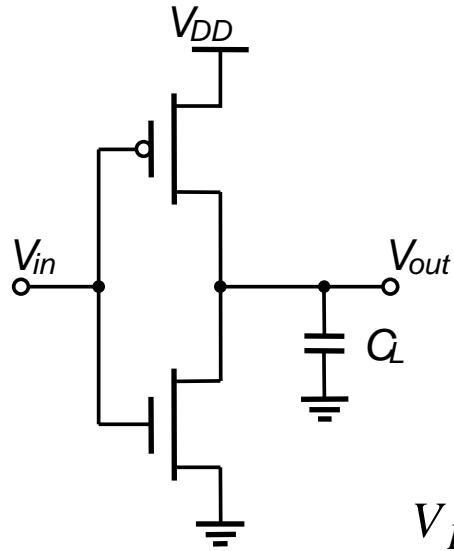
State



Output



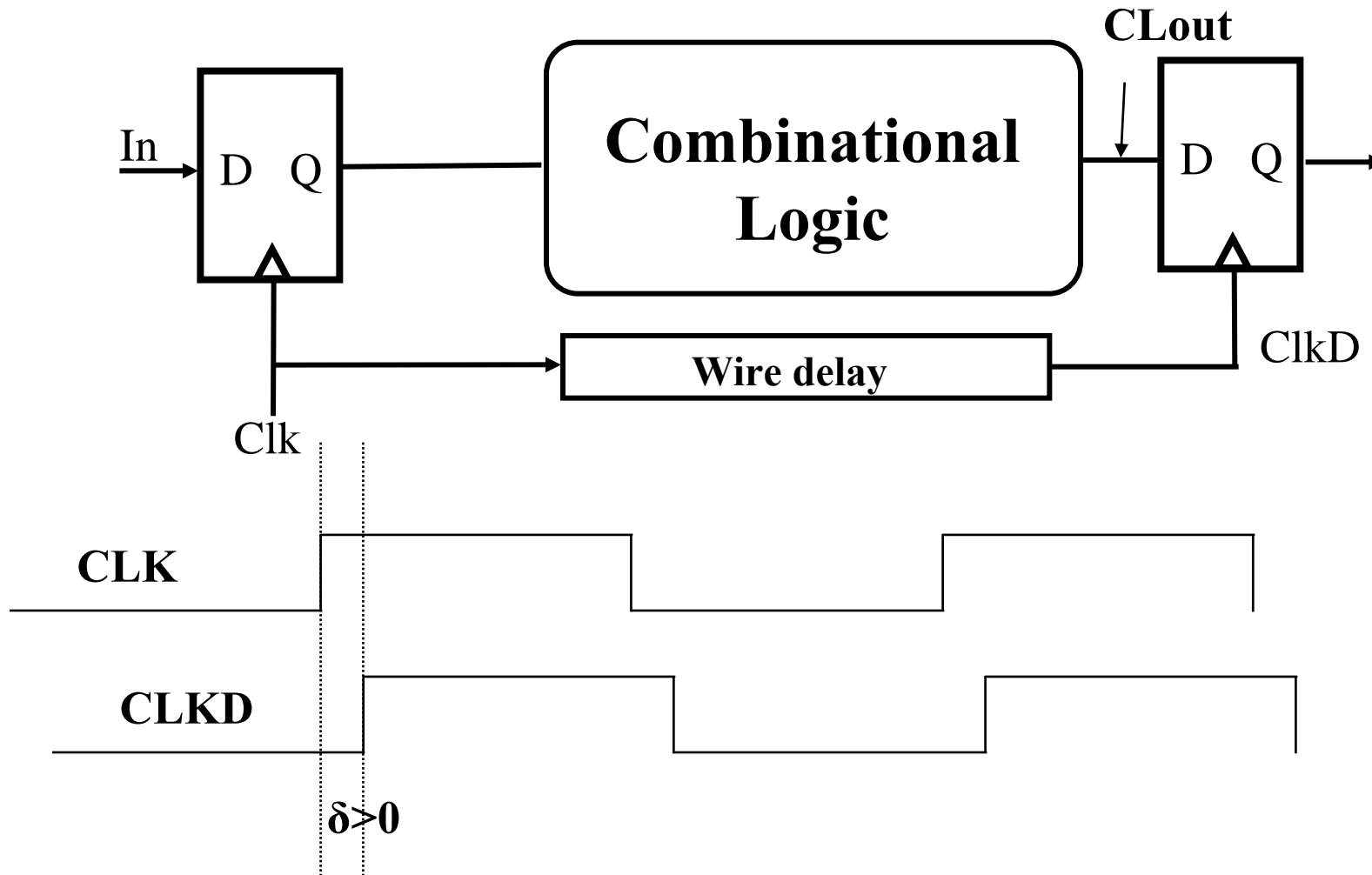
(note: outputs should be registered)



review

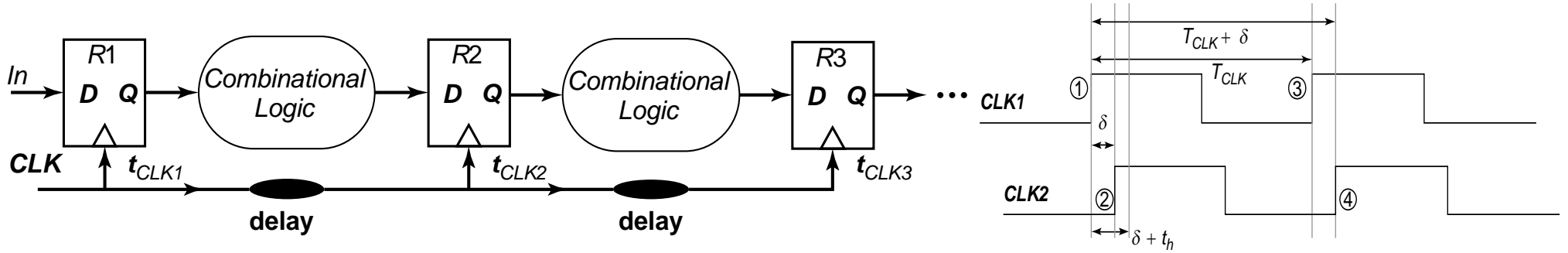
$$v_{out}(t) = (1 - e^{-t/\tau}) V$$

$$t_p = \ln(2) \tau = 0.69 RC$$



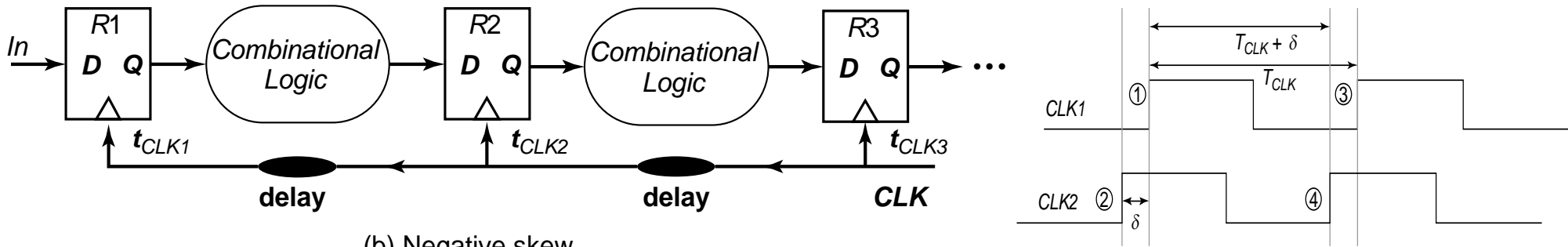
$$T > T_{cq} + T_{logic} + T_{su} - \delta$$

$$T_{cq,cd} + T_{logic,cd} > T_{hold} + \delta$$



(a) Positive skew

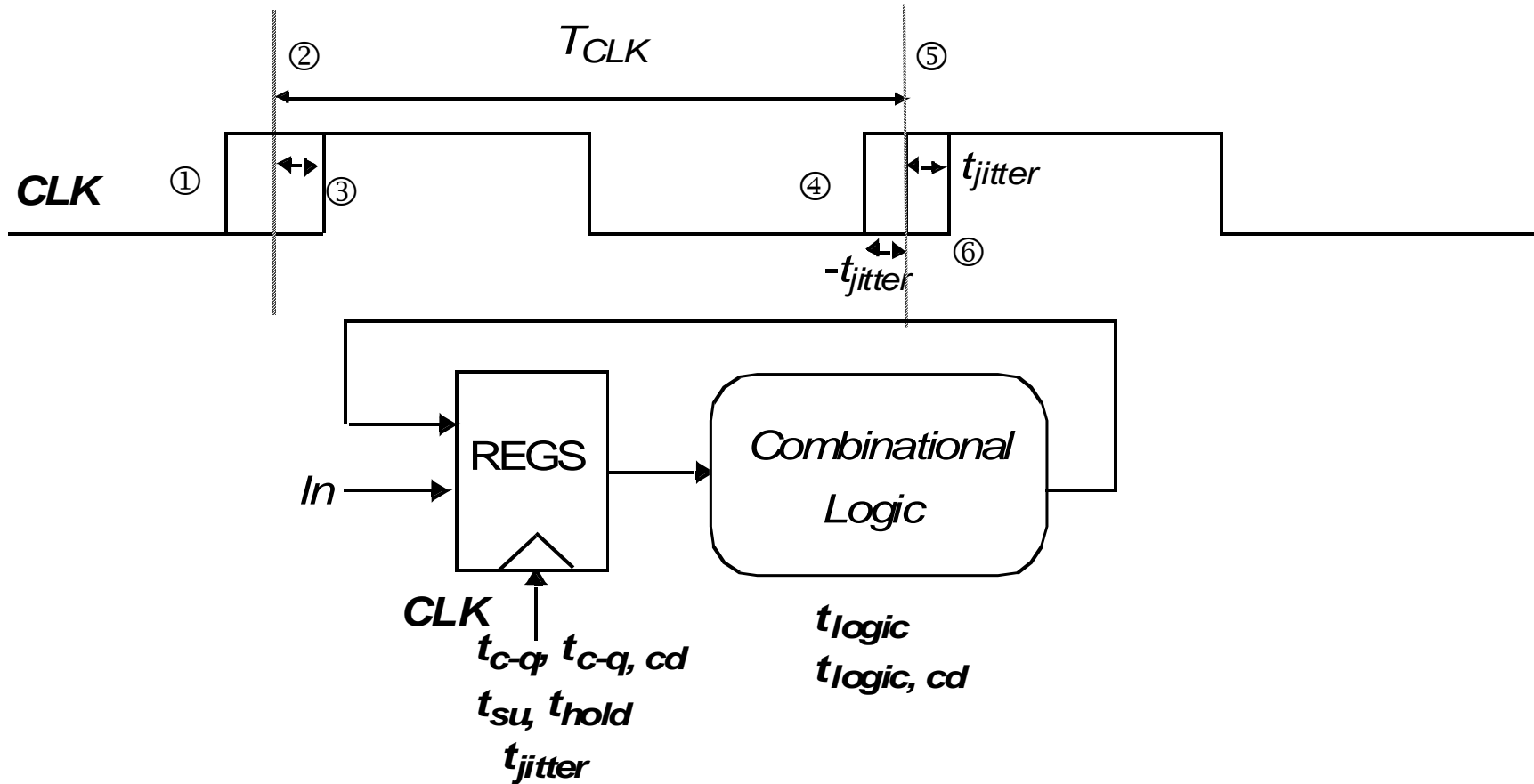
Launching edge arrives before the receiving edge



(b) Negative skew

Receiving edge arrives before the launching edge

➤ Adapted from J. Rabaey, A. Chandrakasan, B. Nikolic, “Digital Integrated Circuits: A Design Perspective”
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$$T_{CLK} - 2t_{jitter} > t_{c-q} + t_{logic} + t_{su}$$

or

$$T > t_{c-q} + t_{logic} + t_{su} + 2t_{jitter}$$

- **Synchronize all asynchronous inputs**
 - Use two back to back registers
- **Two types of Finite State Machines introduced**
 - **Moore** – outputs are a function of current state
 - **Mealy** – outputs a function of current state and input
- **A standard template can be used for coding FSMs**
- **Register outputs of combinational logic for critical control signals**
- **Clock skew and jitter are important considerations**