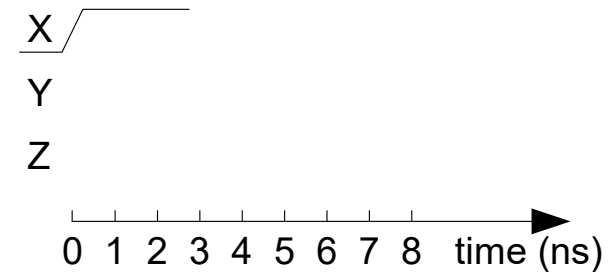
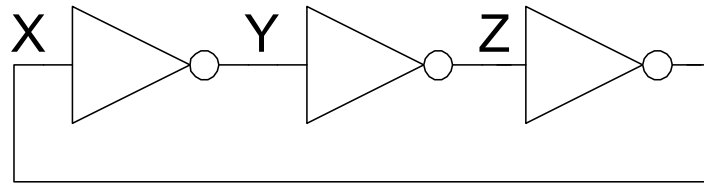


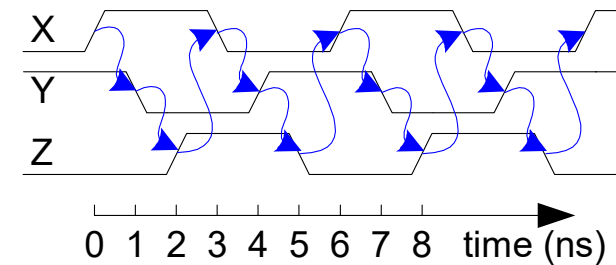
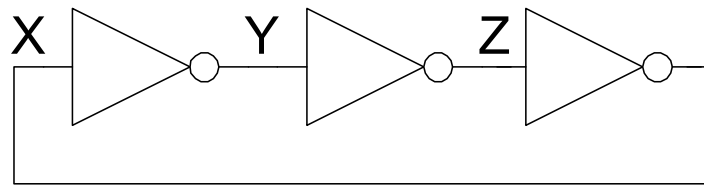
Sequential Logic

- Sequential circuits: all circuits that aren't combinational
- A problematic circuit:



Sequential Logic

- Sequential circuits: all circuits that aren't combinational
- A problematic circuit:



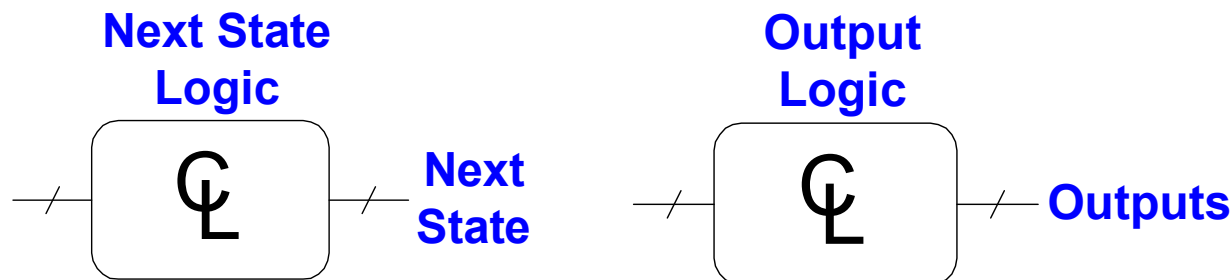
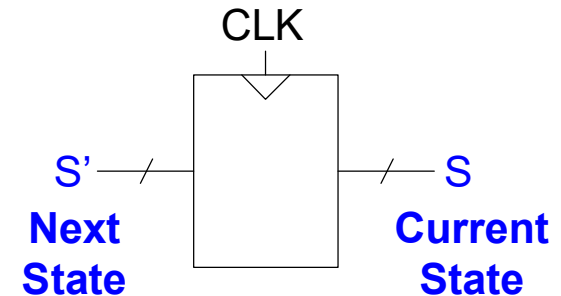
- No inputs and 1-3 outputs
- Astable circuit, oscillates
- Period depends on inverter delay
- It has a *cyclic path*: output fed back to input

Synchronous Sequential Logic Design

- Breaks cyclic paths by **inserting registers**
- Registers contain **state** of the system
- State changes at clock edge: system **synchronized** to the clock
- **Rules** of synchronous sequential circuit composition:
 - Every circuit element is either a register or a combinational circuit
 - At least one circuit element is a register
 - All registers receive the same clock signal
 - Every cyclic path contains at least one register
- Two common synchronous sequential circuits
 - Finite State Machines (FSMs)
 - Pipelines

Finite State Machine (FSM)

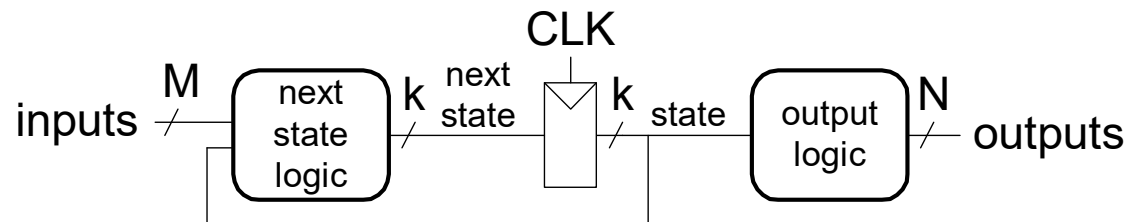
- Consists of:
 - **State register**
 - Stores current state
 - Loads next state at clock edge
 - **Combinational logic**
 - Computes the next state
 - Computes the outputs



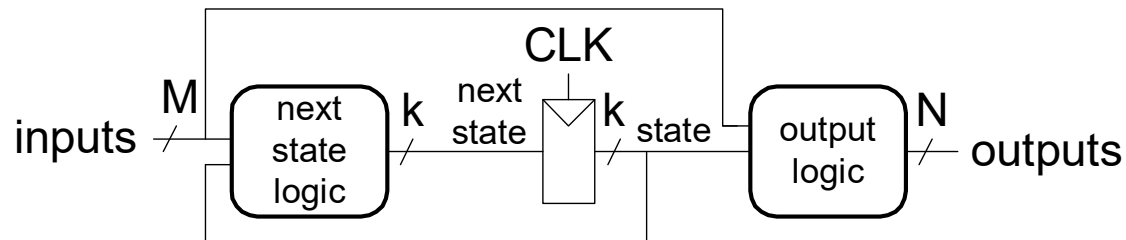
Finite State Machines (FSMs)

- Next state determined by current state and inputs
- Two types of finite state machines differ in output logic:
 - **Moore FSM:** outputs depend only on current state
 - **Mealy FSM:** outputs depend on current state *and* inputs

Moore FSM



Mealy FSM

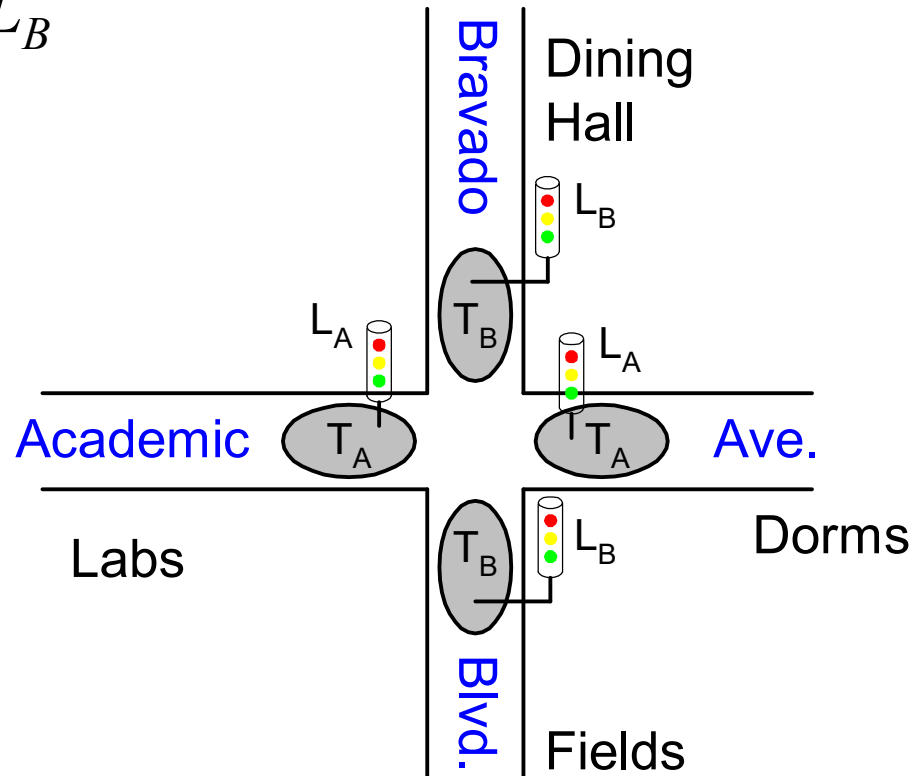


FSM Design Procedure

- Identify inputs and outputs
- Sketch state transition diagram
- Write state transition table
- Select state encodings
- For Moore machine:
 - Rewrite state transition table with state encodings
 - Write output table
- For a Mealy machine:
 - Rewrite combined state transition and output table with state encodings
- Write Boolean equations for next state and output logic
- Sketch the circuit schematic

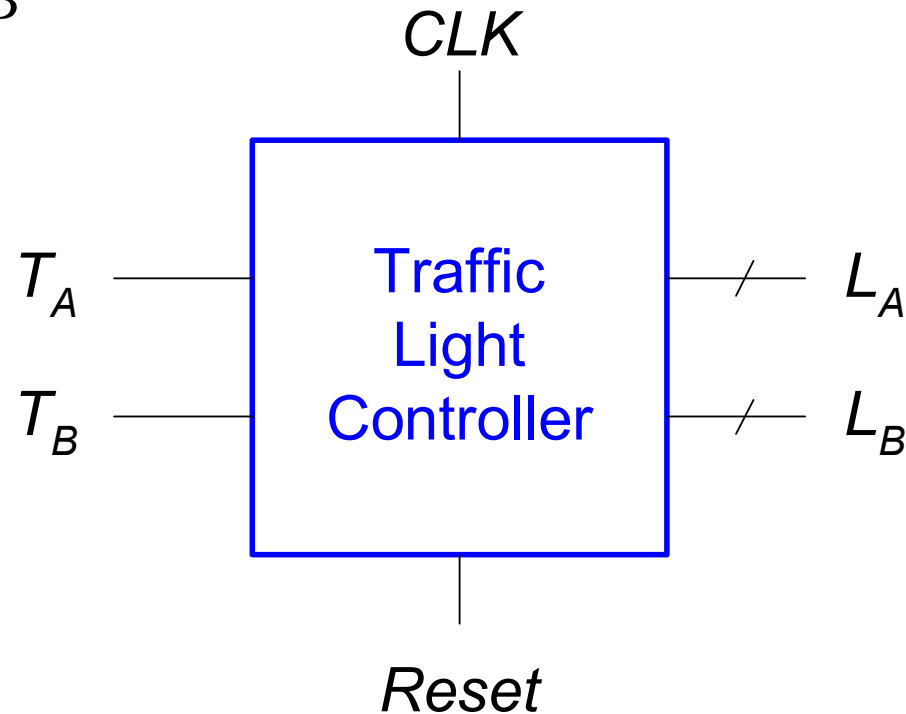
FSM Example

- Traffic light controller
 - Traffic sensors: T_A , T_B (TRUE when there's traffic)
 - Lights: L_A , L_B



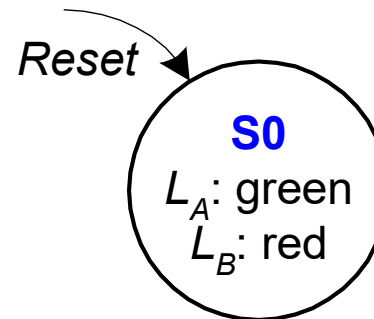
FSM Black Box

- Inputs: CLK , $Reset$, T_A , T_B
- Outputs: L_A , L_B



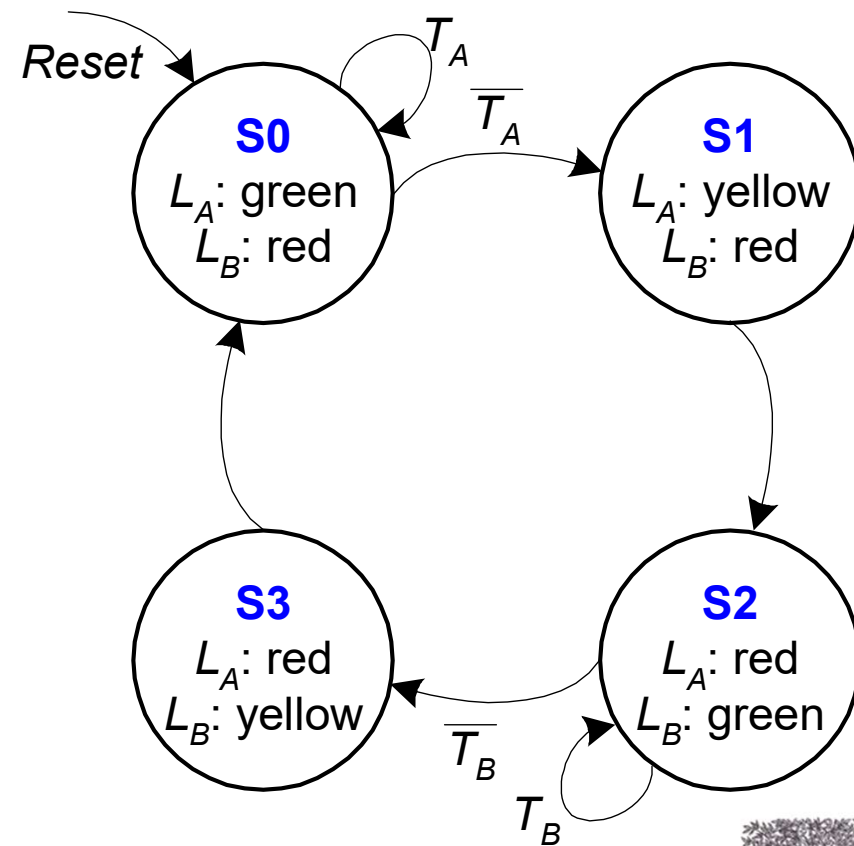
FSM State Transition Diagram

- **Moore FSM:** outputs labeled in each state
- **States:** Circles
- **Transitions:** Arcs



FSM State Transition Diagram

- **Moore FSM:** outputs labeled in each state
- **States:** Circles
- **Transitions:** Arcs



FSM State Transition Table

Current State S	Inputs T_A T_B		Next State S'
S0	0	X	
S0	1	X	
S1	X	X	
S2	X	0	
S2	X	1	
S3	X	X	

FSM State Transition Table

Current State	Inputs		Next State
S	T_A	T_B	S'
S0	0	X	S1
S0	1	X	S0
S1	X	X	S2
S2	X	0	S3
S2	X	1	S2
S3	X	X	S0

FSM Encoded State Transition Table

Current State		Inputs		Next State	
S_1	S_0	T_A	T_B	S'_1	S'_0
0	0	0	X		
0	0	1	X		
0	1	X	X		
1	0	X	0		
1	0	X	1		
1	1	X	X		

State	Encoding
S0	00
S1	01
S2	10
S3	11

FSM Encoded State Transition Table

Current State		Inputs		Next State	
S_1	S_0	T_A	T_B	S'_1	S'_0
0	0	0	X	0	1
0	0	1	X	0	0
0	1	X	X	1	0
1	0	X	0	1	1
1	0	X	1	1	0
1	1	X	X	0	0

State	Encoding
S0	00
S1	01
S2	10
S3	11

$$S'_1 = S_1 \oplus S_0$$

$$S'_0 = \overline{S_1} \overline{S_0} \overline{T_A} + S_1 \overline{S_0} \overline{T_B}$$

FSM Output Table

Current State		Outputs			
S_1	S_0	L_{A1}	L_{A0}	L_{B1}	L_{B0}
0	0				
0	1				
1	0				
1	1				

Output	Encoding
green	00
yellow	01
red	10

FSM Output Table

Current State		Outputs			
S_1	S_0	L_{A1}	L_{A0}	L_{B1}	L_{B0}
0	0	0	0	1	0
0	1	0	1	1	0
1	0	1	0	0	0
1	1	1	0	0	1

Output	Encoding
green	00
yellow	01
red	10

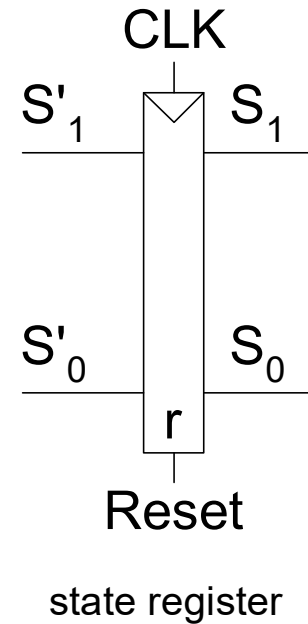
$$L_{A1} = S_1$$

$$L_{A0} = \overline{S_1}S_0$$

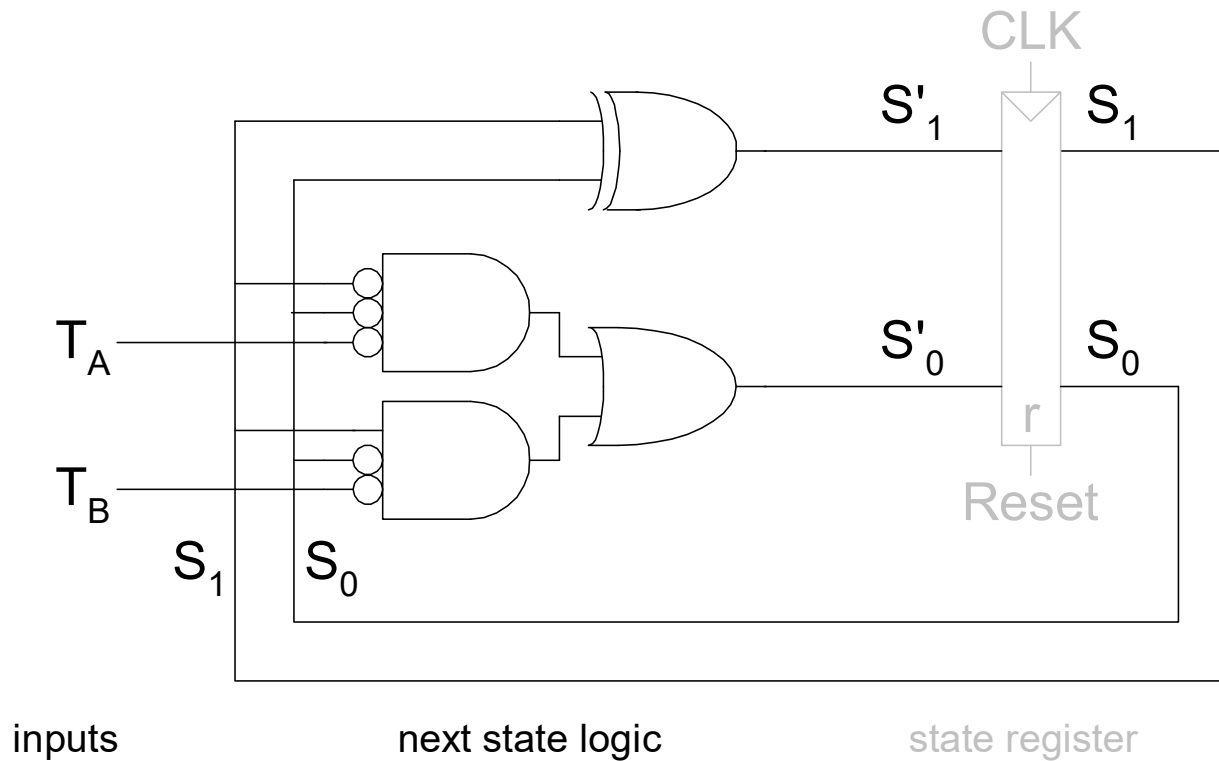
$$L_{B1} = S_1$$

$$L_{B0} = S_1S_0$$

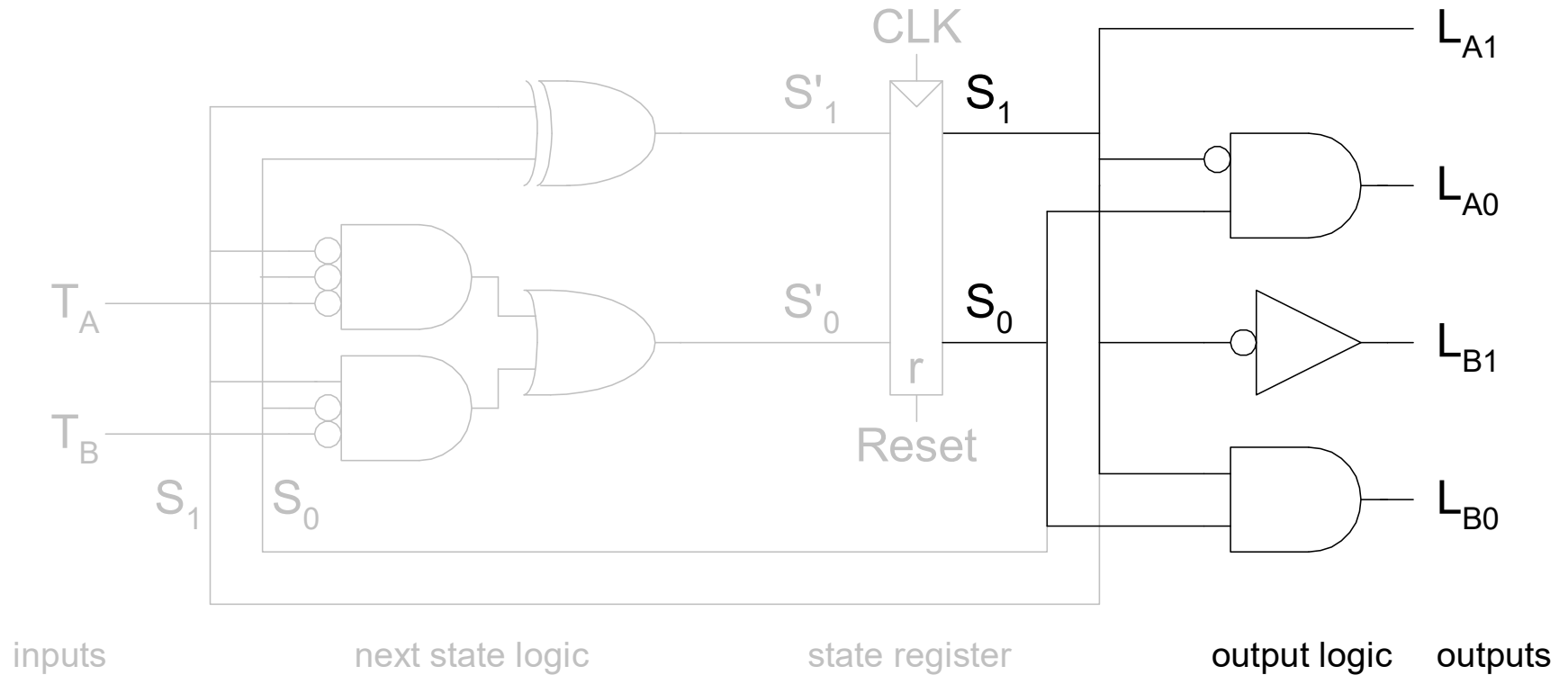
FSM Schematic: State Register



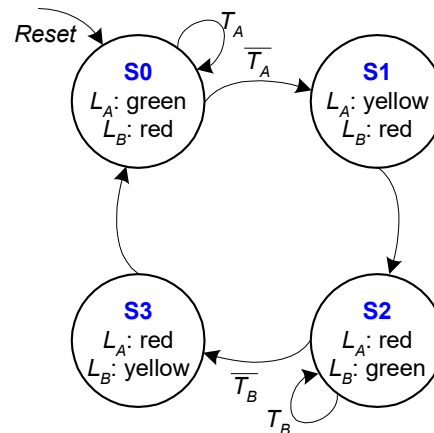
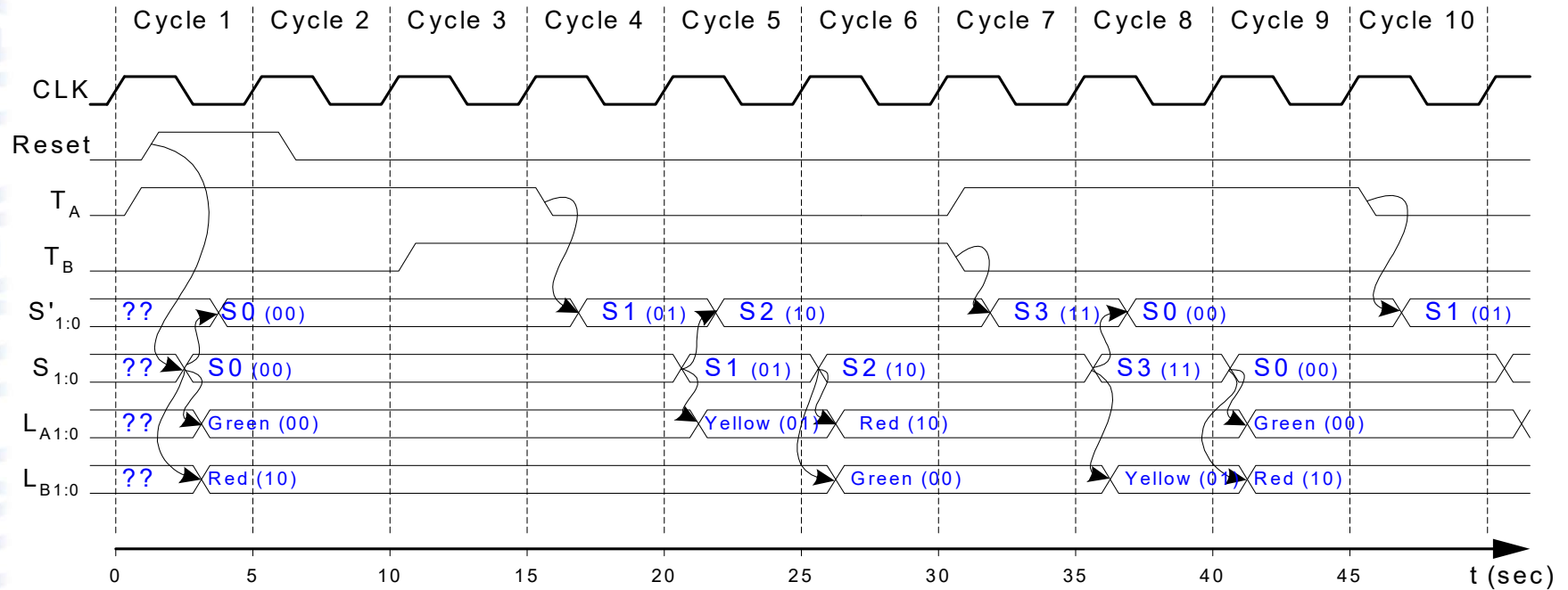
FSM Schematic: Next State Logic



FSM Schematic: Output Logic



FSM Timing Diagram

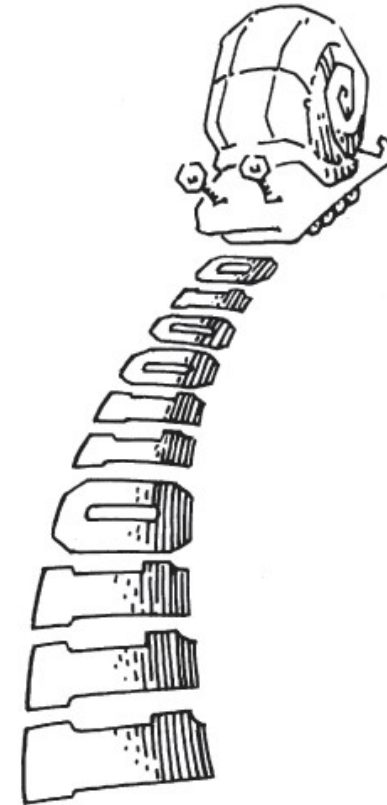


FSM State Encoding

- **Binary** encoding:
 - i.e., for four states, 00, 01, 10, 11
- **One-hot** encoding
 - One state bit per state
 - Only one state bit HIGH at once
 - i.e., for 4 states, 0001, 0010, 0100, 1000
 - Requires more flip-flops
 - Often next state and output logic is simpler

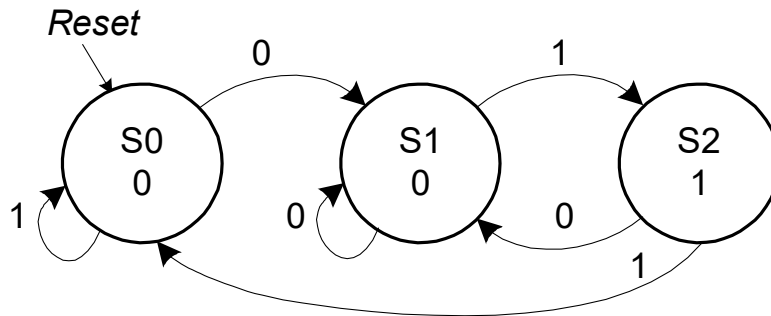
Moore vs. Mealy FSM

- Alyssa P. Hacker has a snail that crawls down a paper tape with 1's and 0's on it. The snail smiles whenever the last two digits it has crawled over are 01. Design Moore and Mealy FSMs of the snail's brain.

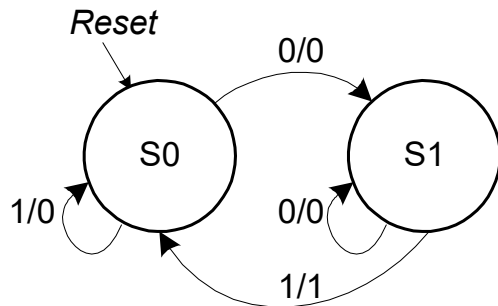


State Transition Diagrams

Moore FSM



Mealy FSM



Mealy FSM: arcs indicate input/output

Moore FSM State Transition Table

Current State		Inputs	Next State	
S_1	S_0		S'_1	S'_0
0	0	0		
0	0	1		
0	1	0		
0	1	1		
1	0	0		
1	0	1		

State	Encoding
S0	00
S1	01
S2	10

Moore FSM State Transition Table

Current State		Inputs	Next State	
S_1	S_0		S'_1	S'_0
0	0	0	0	1
0	0	1	0	0
0	1	0	0	1
0	1	1	1	0
1	0	0	0	1
1	0	1	0	0

State	Encoding
S0	00
S1	01
S2	10

$$S'_1 = S_0 A$$

$$S'_0 = \overline{A}$$

Moore FSM Output Table

Current State		Output
S_1	S_0	Y
0	0	
0	1	
1	0	

$$Y = S_1$$

Moore FSM Output Table

Current State		Output
S_1	S_0	Y
0	0	0
0	1	0
1	0	1

$$Y = S_1$$

Mealy FSM State Transition & Output Table

Current State	Input	Next State	Output
S_0	A	S'_0	Y
0	0		
0	1		
1	0		
1	1		

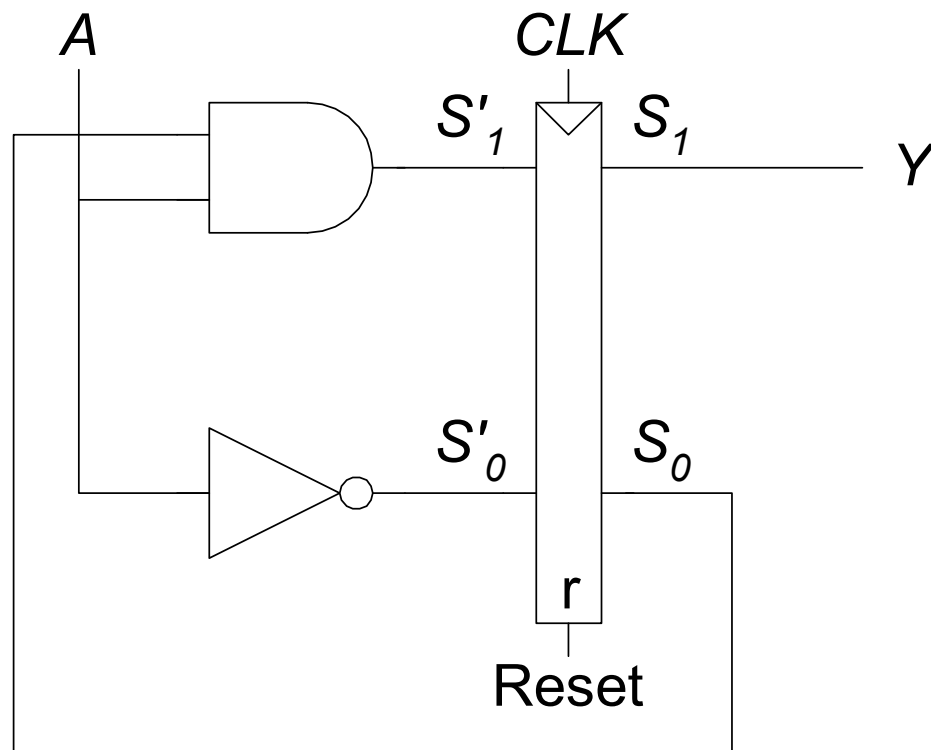
State	Encoding
S0	00
S1	01

Mealy FSM State Transition & Output Table

Current State	Input	Next State	Output
S_0	A	S'_0	Y
0	0	1	0
0	1	0	0
1	0	1	0
1	1	0	1

State	Encoding
S0	00
S1	01

Moore FSM Schematic



Mealy FSM Schematic

