

# Chapter 3

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<http://www.ee.unlv.edu/~b1morris/cpe100/>

## CPE100: Digital Logic Design I

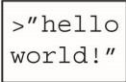


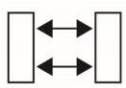
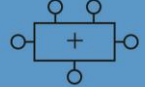
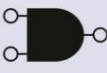
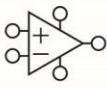

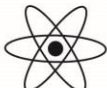
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Section 1004: Dr. Morris  
Sequential Logic Design



# Chapter 3 :: Topics

- Introduction
- Latches and Flip-Flops
- Synchronous Logic Design
- Finite State Machines
- Timing of Sequential Logic
- Parallelism

Application Software	
Operating Systems	
Architecture	
Micro-architecture	
Logic	
Digital Circuits	
Analog Circuits	
Devices	
Physics	

# Introduction

- Previously, Combinational Logic design had outputs only depend on current value of inputs
- Outputs of sequential logic depend on current *and* prior input values – it has **memory**.
- Some definitions:
  - **State:** all the information about a circuit necessary to explain its future behavior
  - **Latches and flip-flops:** state elements that store one bit of state
  - **Synchronous sequential circuits:** combinational logic followed by a bank of flip-flops

# Sequential Circuits

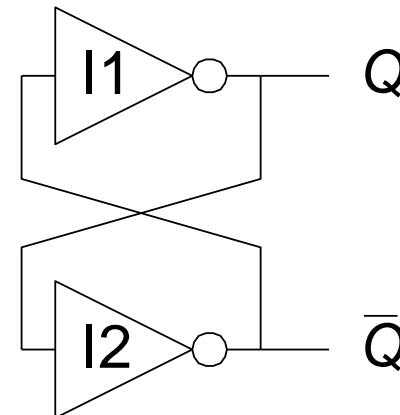
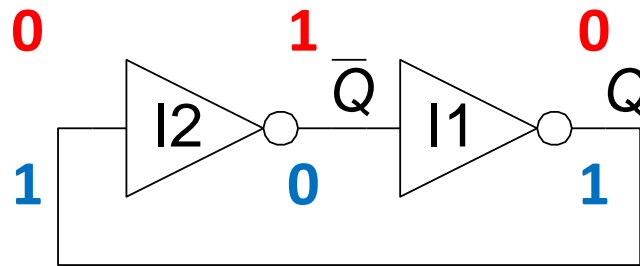
- Give sequence to events (i.e. a notion of time)
- Have memory (short-term)
- Use feedback from output to input to store information
  - Need to “remember” past output

# State Elements

- The state of a circuit influences its future behavior
- State elements store state
  - Bistable circuit
  - SR Latch
  - D Latch
  - D Flip-flop

# Bistable Circuit

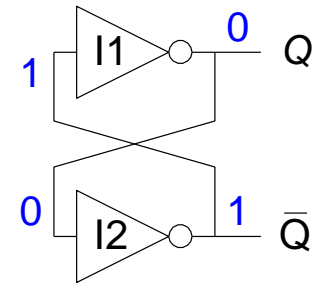
- Fundamental building block of other state elements
- Two outputs:  $Q$ ,  $\bar{Q}$  (state)
- No inputs



Redrawn circuit to  
emphasize symmetry

# Bistable Circuit Analysis

- Consider the two possible cases:
  - $Q = 0$ :  
then  $\bar{Q} = 1$ ,  $Q = 0$  (consistent)

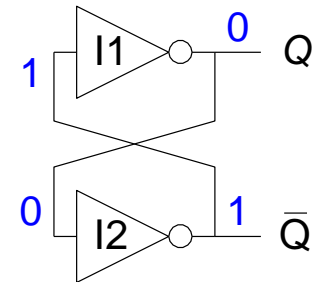


# Bistable Circuit Analysis

- Consider the two possible cases:

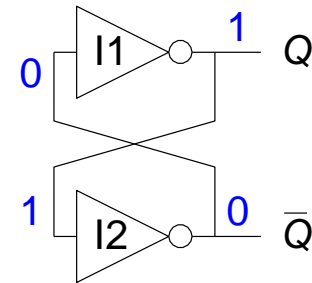
- $Q = 0$ :

then  $\bar{Q} = 1$ ,  $Q = 0$  (consistent)



- $Q = 1$ :

then  $\bar{Q} = 0$ ,  $Q = 1$  (consistent)

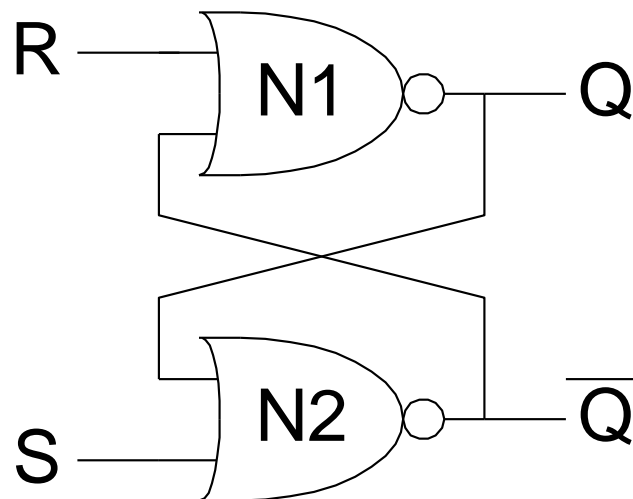


- Stores 1 bit of state in the state variable,  $Q$  (or  $\bar{Q}$ )
- But there are **no inputs to control the state**



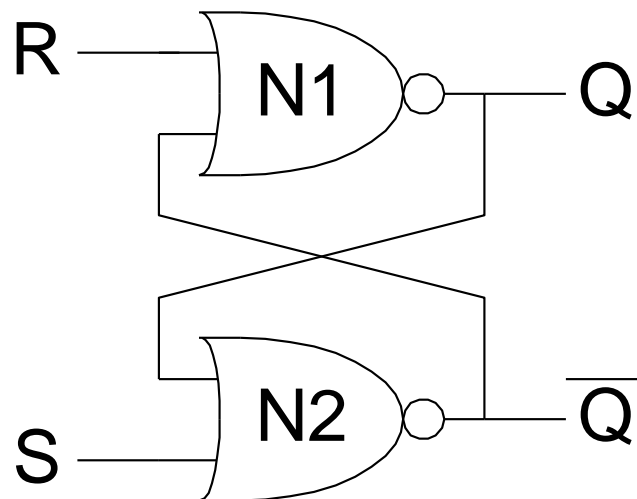
# SR (Set/Reset) Latch

- SR Latch
  - S – set  $Q=1$
  - R – reset  $Q=0$



# SR (Set/Reset) Latch

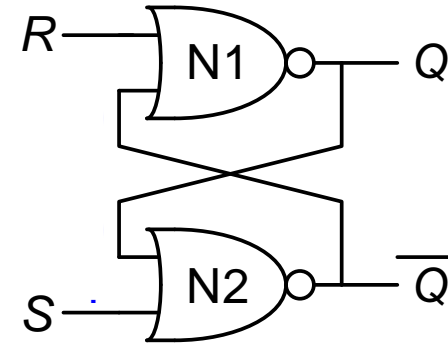
- SR Latch



- Consider the four possible cases:
  - $S = 1, R = 0$
  - $S = 0, R = 1$
  - $S = 0, R = 0$
  - $S = 1, R = 1$

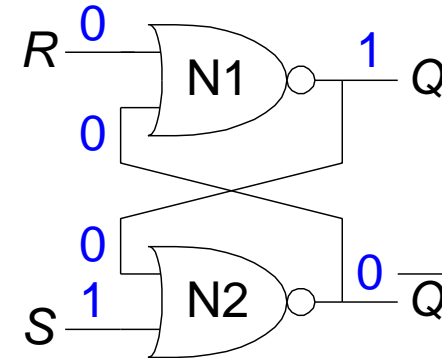
# SR Latch Analysis

- $S = 1, R = 0$ :  
then  $Q = 1$  and  $\bar{Q} = 0$



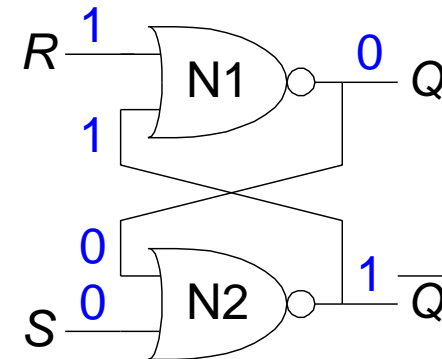
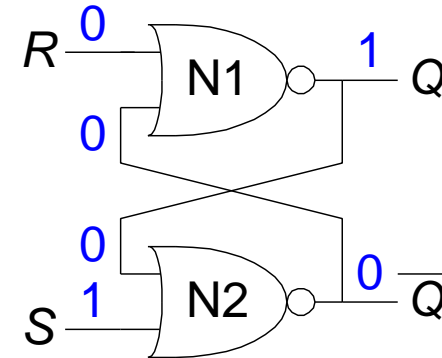
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# SR Latch Analysis

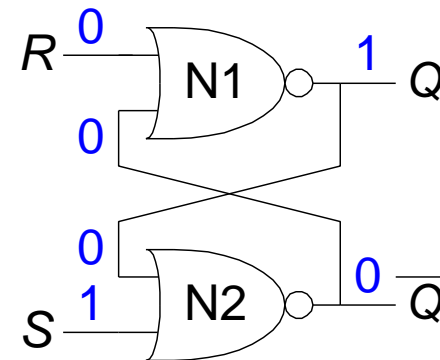
- $S = 1, R = 0$ :  
then  $Q = 1$  and  $\bar{Q} = 0$
- $S = 0, R = 1$ :  
then  $Q = 0$  and  $\bar{Q} = 1$



# SR Latch Analysis

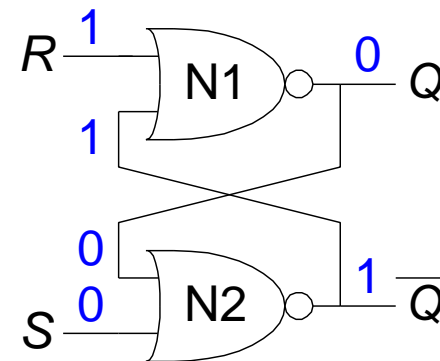
- $S = 1, R = 0$ :  
then  $Q = 1$  and  $\bar{Q} = 0$

**Set the output**



- $S = 0, R = 1$ :  
then  $Q = 0$  and  $\bar{Q} = 1$

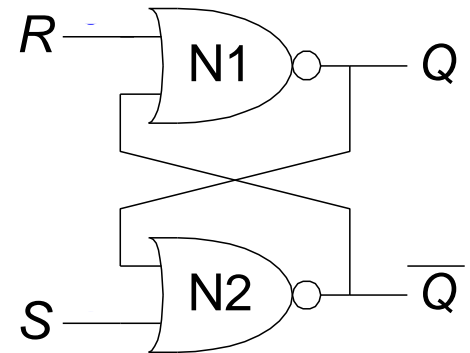
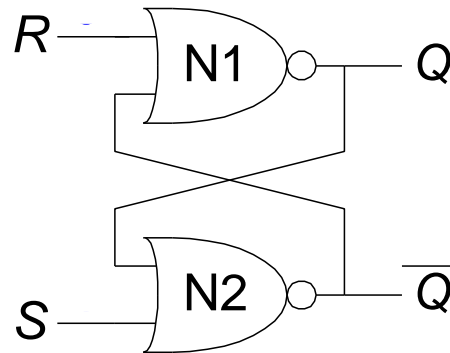
**Reset the output**



# SR Latch Analysis

- $S = 0, R = 0$ :

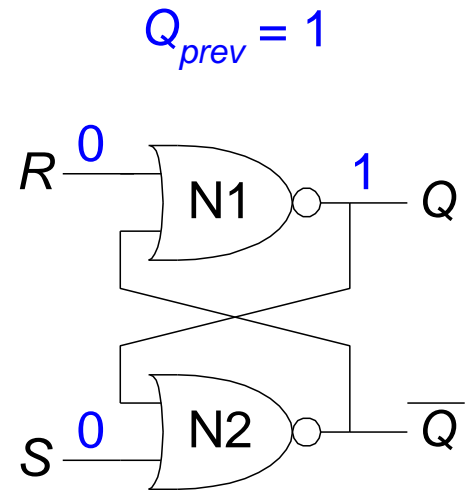
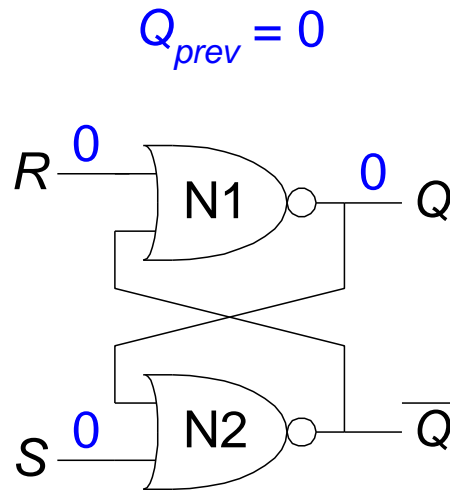
then  $Q = Q_{prev}$



# SR Latch Analysis

- $S = 0, R = 0$ :

then  $Q = Q_{prev}$

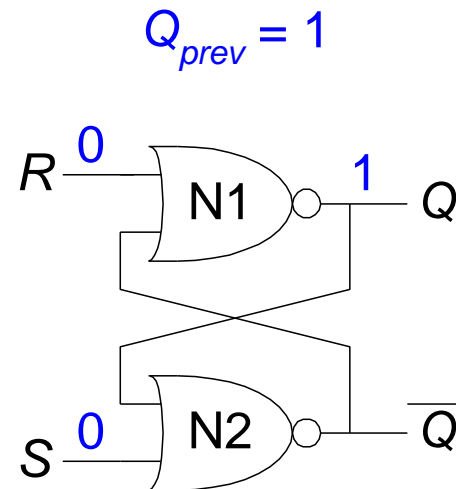
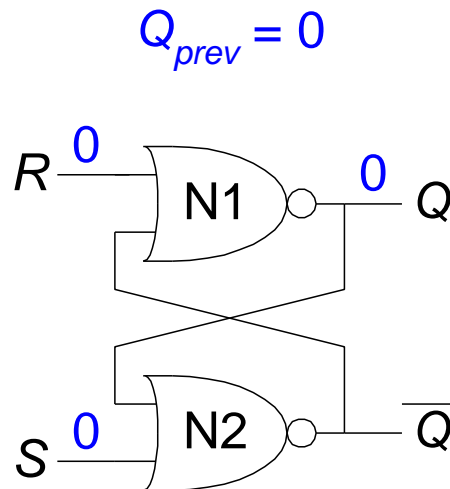




# SR Latch Analysis

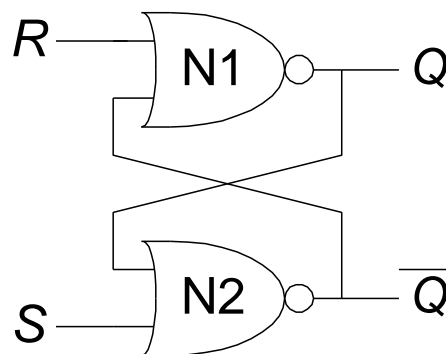
- $S = 0, R = 0:$

then  $Q = Q_{prev}$



- $S = 1, R = 1:$

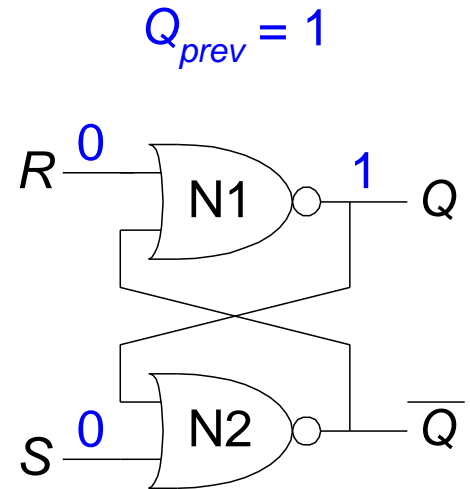
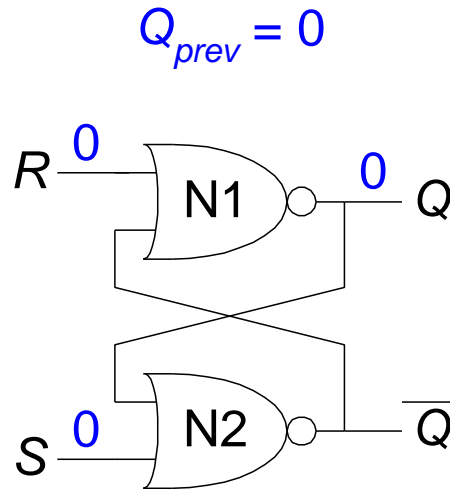
then  $Q = 0, \bar{Q} = 0$



# SR Latch Analysis

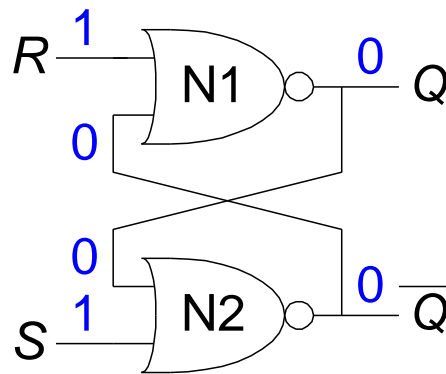
- $S = 0, R = 0$ :

then  $Q = Q_{prev}$



- $S = 1, R = 1$ :

then  $Q = 0, \bar{Q} = 0$

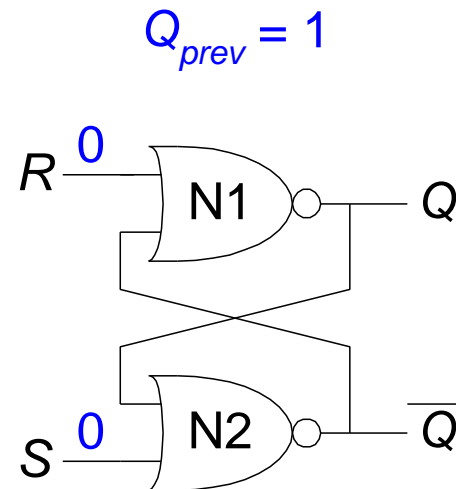
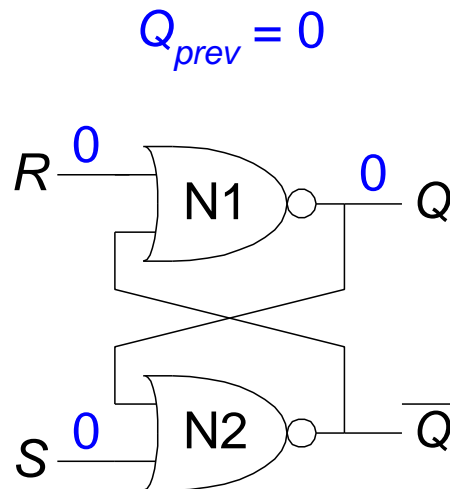


# SR Latch Analysis

- $S = 0, R = 0$ :

then  $Q = Q_{prev}$

**Memory!**

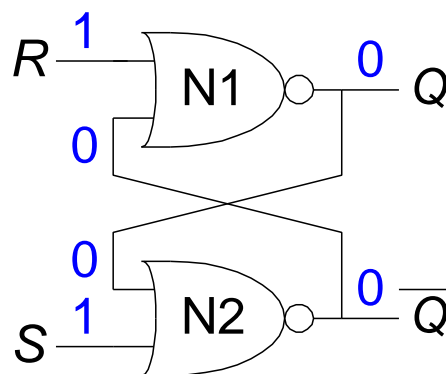


- $S = 1, R = 1$ :

then  $Q = 0, \bar{Q} = 0$

**Invalid State**

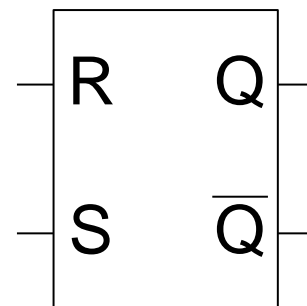
$\bar{Q} \neq \text{NOT } Q$



# SR Latch Symbol

- SR stands for Set/Reset Latch
  - Stores one bit of state ( $Q$ )
- Control what value is being stored with  $S$ ,  $R$  inputs
  - **Set:** Make the output 1  
( $S = 1$ ,  $R = 0$ ,  $Q = 1$ )
  - **Reset:** Make the output 0  
( $S = 0$ ,  $R = 1$ ,  $Q = 0$ )

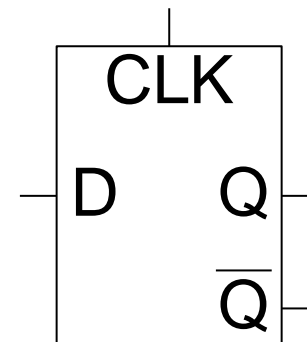
SR Latch  
Symbol



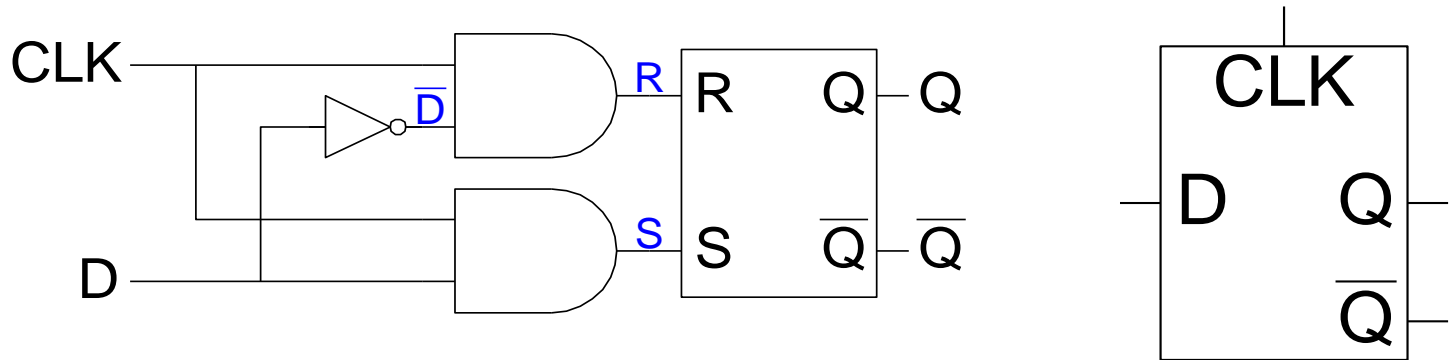
# D Latch

- Two inputs:  $CLK$ ,  $D$ 
  - $CLK$ : controls *when* the output changes
  - $D$  (the data input): controls *what* the output changes to
- Function
  - When  $CLK = 1$ ,  
 $D$  passes through to  $Q$  (*transparent*)
  - When  $CLK = 0$ ,  
 $Q$  holds its previous value (*opaque*)
- Avoids invalid case when  
 $Q \neq \text{NOT } \bar{Q}$

D Latch  
Symbol

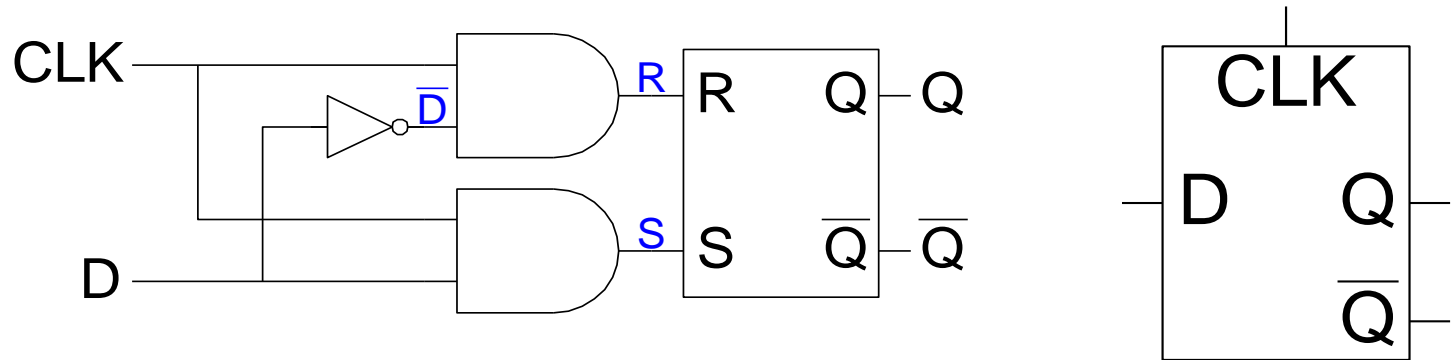


# D Latch Internal Circuit



$CLK$	$D$	$\overline{D}$	$S$	$R$	$Q$	$\overline{Q}$
0	X					
1	0					
1	1					

# D Latch Internal Circuit

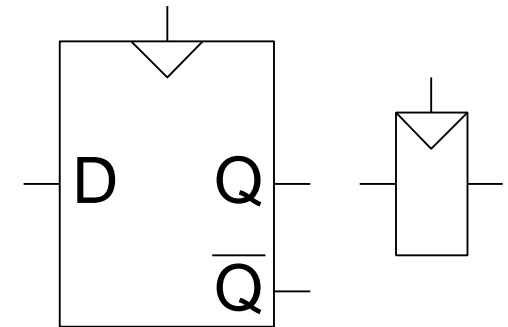


$CLK$	$D$	$\overline{D}$	$S$	$R$	$Q$	$\overline{Q}$
0	X	$\overline{X}$	0	0	$Q_{prev}$	$\overline{Q}_{prev}$
1	0	1	0	1	0	1
1	1	0	1	0	1	0

# D Flip-Flop

- **Inputs:**  $CLK$ ,  $D$
- **Function**
  - Samples  $D$  on rising edge of  $CLK$ 
    - When  $CLK$  rises from 0 to 1,  $D$  passes through to  $Q$
    - Otherwise,  $Q$  holds its previous value
  - $Q$  changes only on rising edge of  $CLK$
- Called *edge-triggered*
- Activated on the clock edge

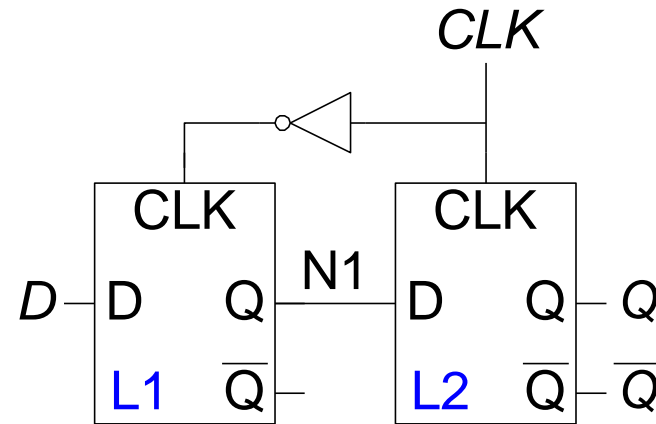
D Flip-Flop Symbols





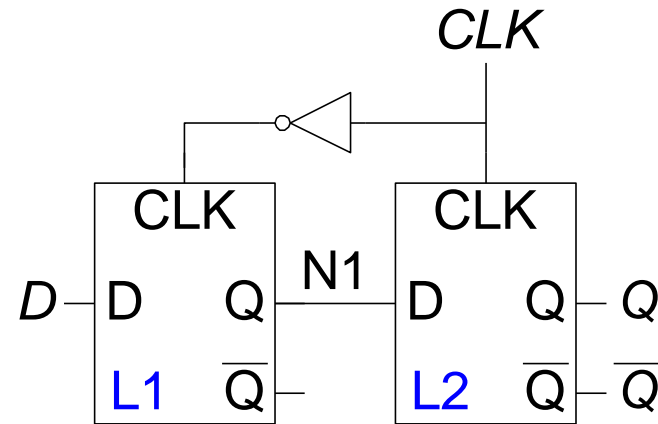
# D Flip-Flop Internal Circuit

- Two back-to-back latches (L1 and L2) controlled by complementary clocks
- When  $CLK = 0$ 
  - L1 is transparent
  - L2 is opaque
  - $D$  passes through to N1



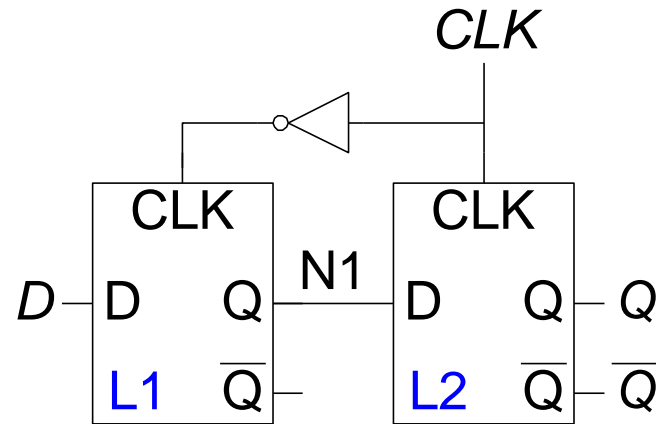
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- Two back-to-back latches (L1 and L2) controlled by complementary clocks
- When  $CLK = 0$ 
  - L1 is transparent
  - L2 is opaque
  - $D$  passes through to N1
- When  $CLK = 1$ 
  - L2 is transparent
  - L1 is opaque
  - N1 passes through to  $Q$

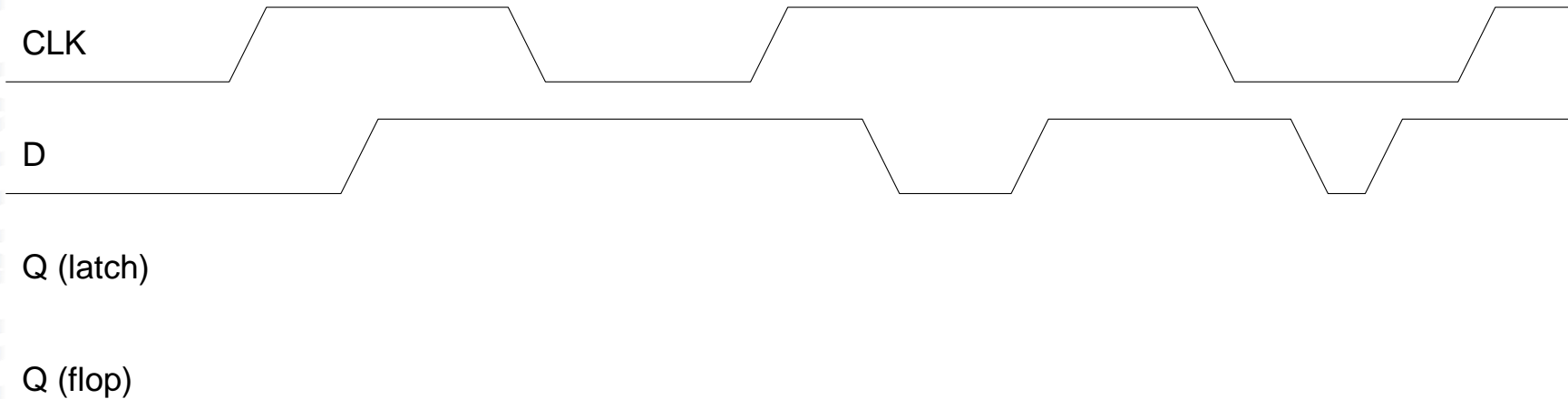
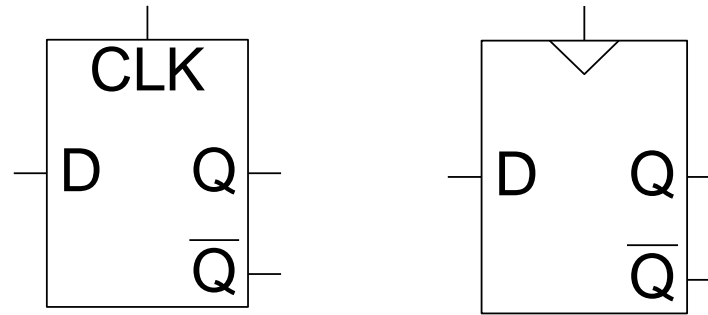


# D Flip-Flop Internal Circuit

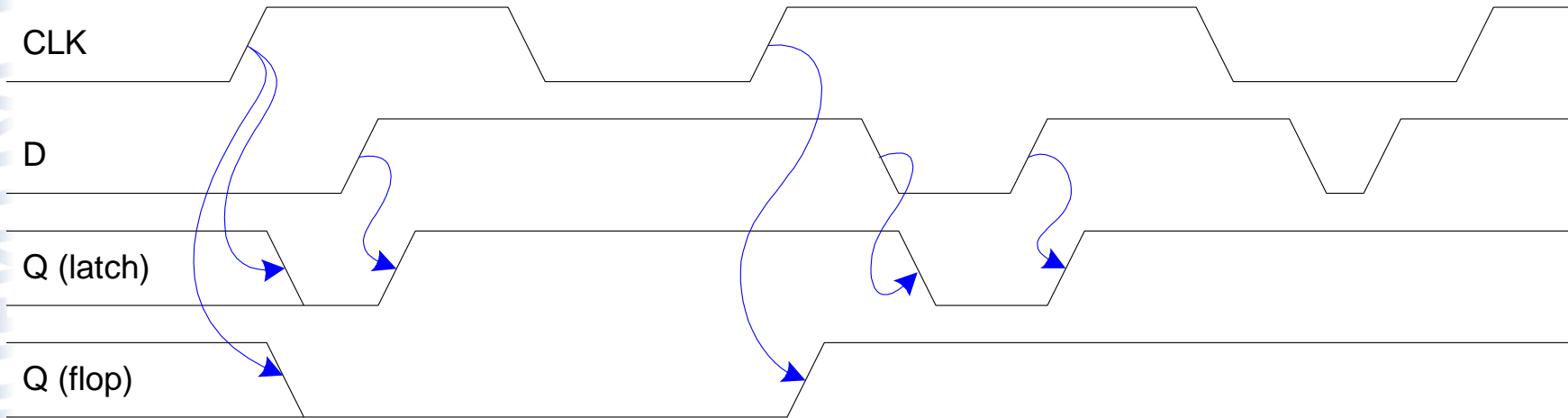
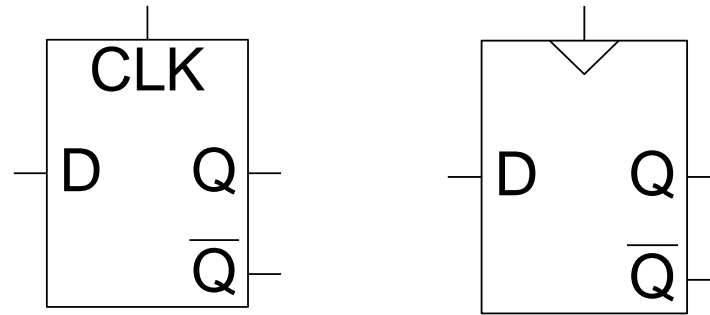
- Two back-to-back latches (L1 and L2) controlled by complementary clocks
- When  $CLK = 0$ 
  - L1 is transparent
  - L2 is opaque
  - $D$  passes through to N1
- When  $CLK = 1$ 
  - L2 is transparent
  - L1 is opaque
  - N1 passes through to  $Q$
- Thus, on the edge of the clock (when  $CLK$  rises from  $0 \rightarrow 1$ )
  - $D$  passes through to  $Q$



# D Latch vs. D Flip-Flop

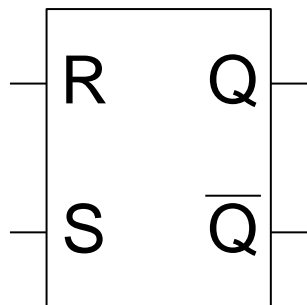


# D Latch vs. D Flip-Flop



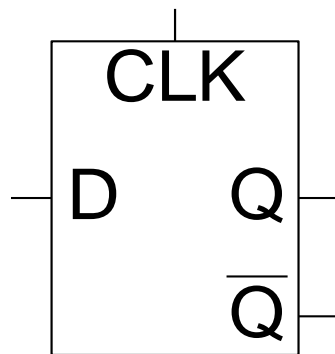
# Review

## SR Latch



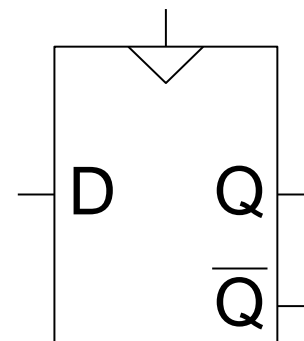
**S = 1, R = 0:**  $Q = 1$   
**S = 0, R = 1:**  $Q = 0$

## D Latch



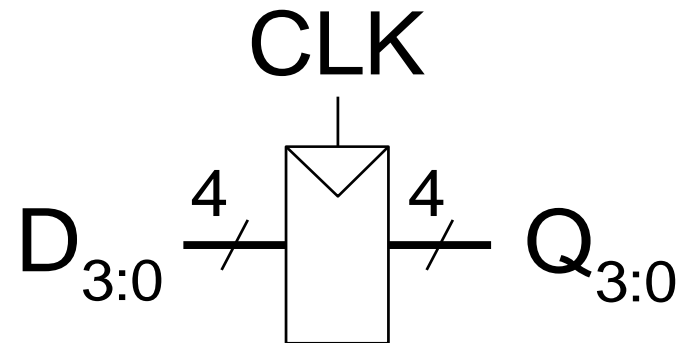
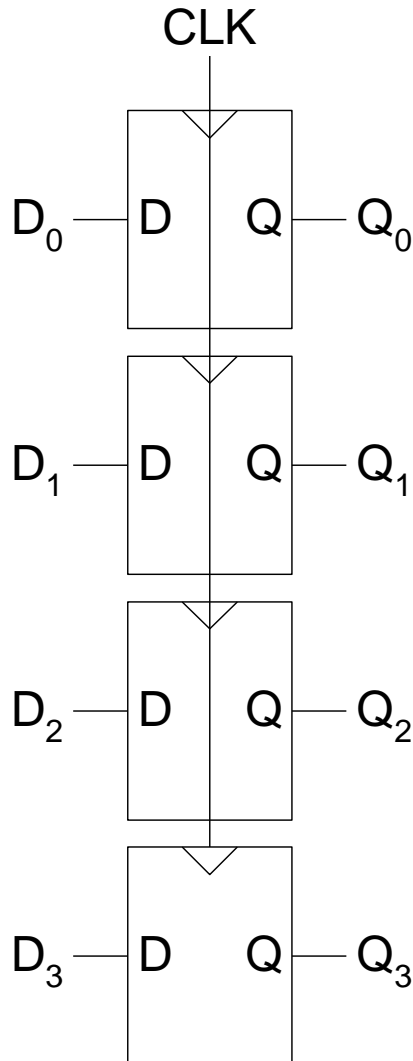
**CLK = 1:**  $Q = D$   
**CLK = 0:**  $Q = Q_{\text{prev}}$

## D Flip-flop



**CLK = 0  $\rightarrow$  1:**  $Q = D$   
**Otherwise:**  $Q = Q_{\text{prev}}$

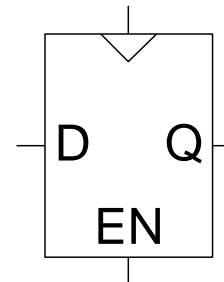
# Registers



# Enabled Flip-Flops

- **Inputs:**  $CLK$ ,  $D$ ,  $EN$ 
  - The enable input ( $EN$ ) controls when new data ( $D$ ) is stored
- **Function**
  - $EN = 1$ :  $D$  passes through to  $Q$  on the clock edge
  - $EN = 0$ : the flip-flop retains its previous state

Symbol

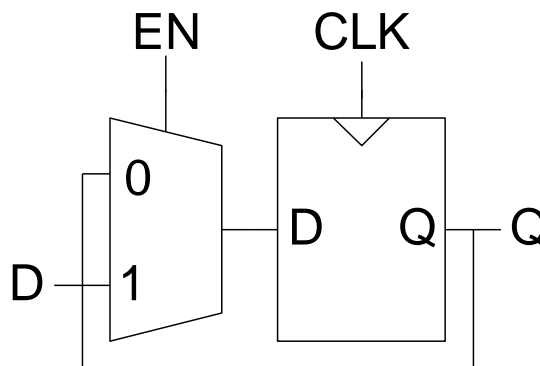




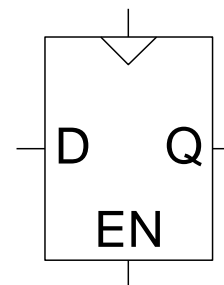
# Enabled Flip-Flops

- **Inputs:**  $CLK$ ,  $D$ ,  $EN$ 
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Internal  
Circuit



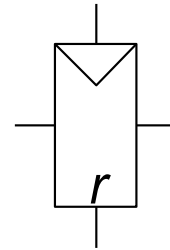
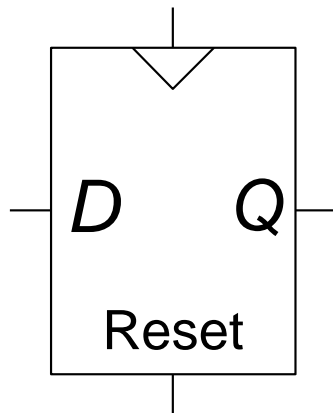
Symbol



# Resettable Flip-Flops

- **Inputs:**  $CLK$ ,  $D$ ,  $Reset$
- **Function:**
  - $Reset = 1$ :  $Q$  is forced to 0
  - $Reset = 0$ : flip-flop behaves as ordinary D flip-flop

## Symbols

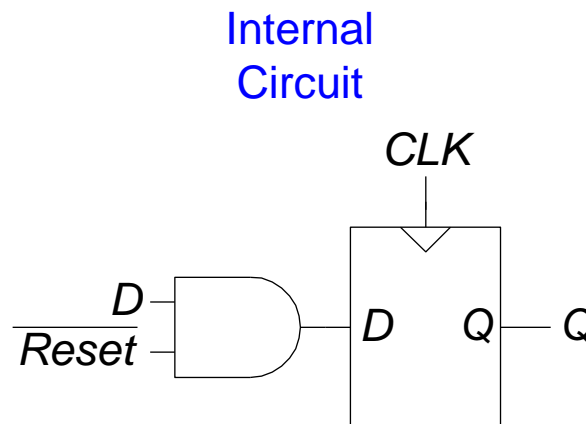


# Resettable Flip-Flops

- Two types:
  - **Synchronous:** resets at the clock edge only
  - **Asynchronous:** resets immediately when  $Reset = 1$
- Asynchronously resettable flip-flop requires changing the internal circuitry of the flip-flop
- Synchronously resettable flip-flop?

# Resettable Flip-Flops

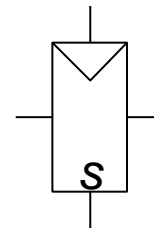
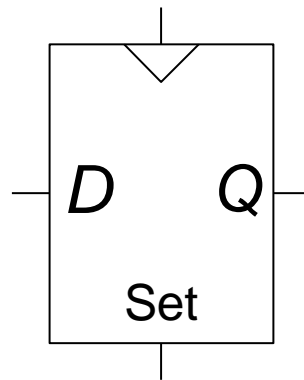
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  - **Synchronous:** resets at the clock edge only
  - **Asynchronous:** resets immediately when  $Reset = 1$
- Asynchronously resettable flip-flop requires changing the internal circuitry of the flip-flop
- Synchronously resettable flip-flop?



# Settable Flip-Flops

- **Inputs:**  $CLK$ ,  $D$ ,  $Set$
- **Function:**
  - $Set = 1$ :  $Q$  is set to 1
  - $Set = 0$ : the flip-flop behaves as ordinary D flip-flop

## Symbols



# Synchronous Sequential Logic Design

- Registers **inserted between combinational logic**
- Registers contain **state** of the system
- State changes at clock edge: system **synchronized** to the clock

# Synchronous Sequential Logic Design

- **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



# Synchronous Sequential Logic Design

- **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



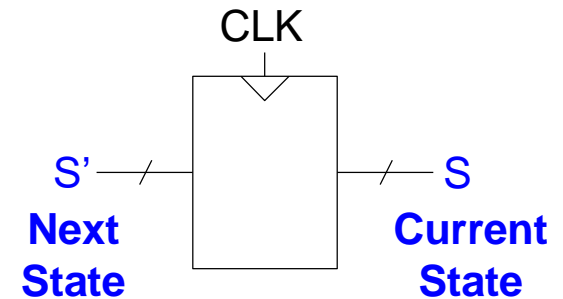


# Finite State Machine (FSM)

- Consists of:

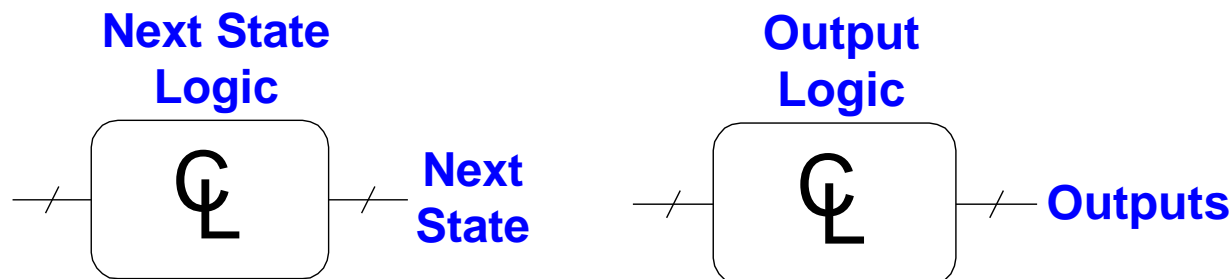
- State register**

- Stores current state
    - Loads next state at clock edge



- Combinational logic**

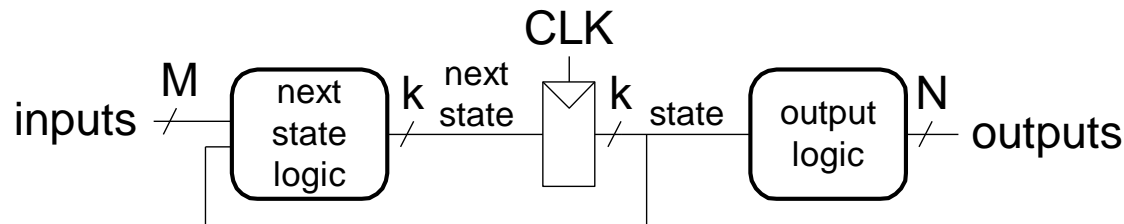
- Computes the next state
    - Computes the outputs



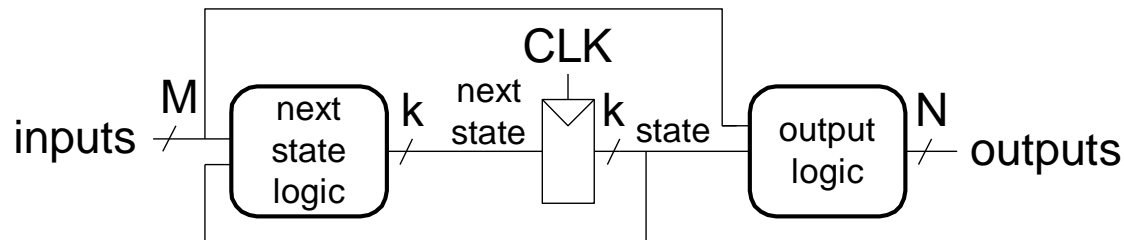
# Finite State Machines (FSMs)

- 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

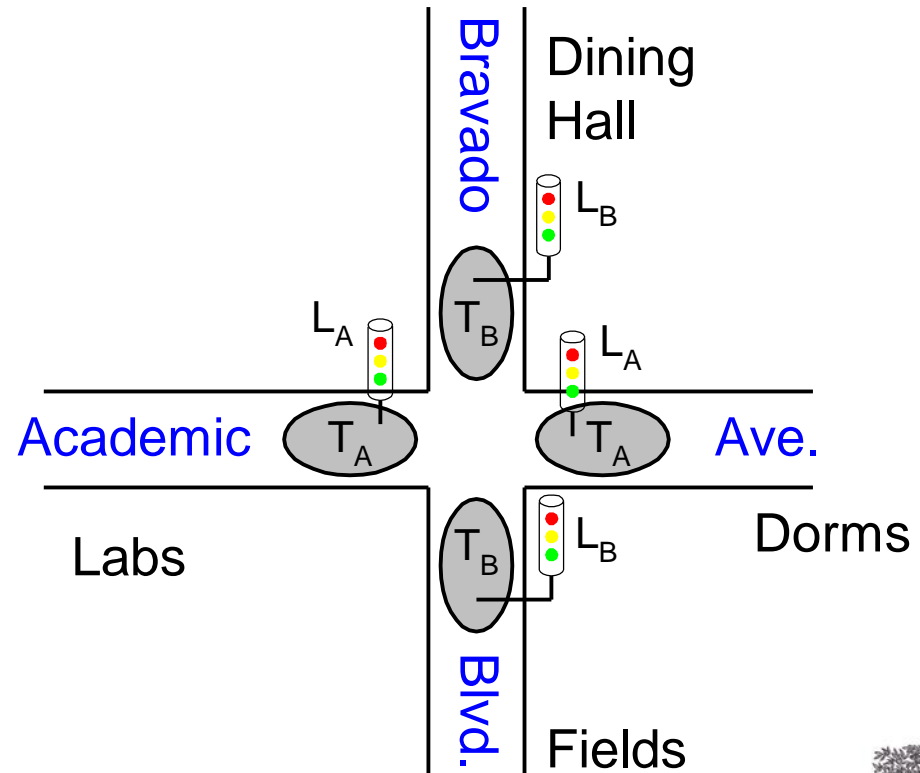


# FSM Design Procedure

1. Identify inputs and outputs
2. Sketch state transition diagram
3. Write state transition table
4. Select state encodings
5. Rewrite state transition table with state encodings
6. Write output table
7. Write Boolean equations for next state and output logic
8. Sketch the circuit schematic

# FSM Example

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

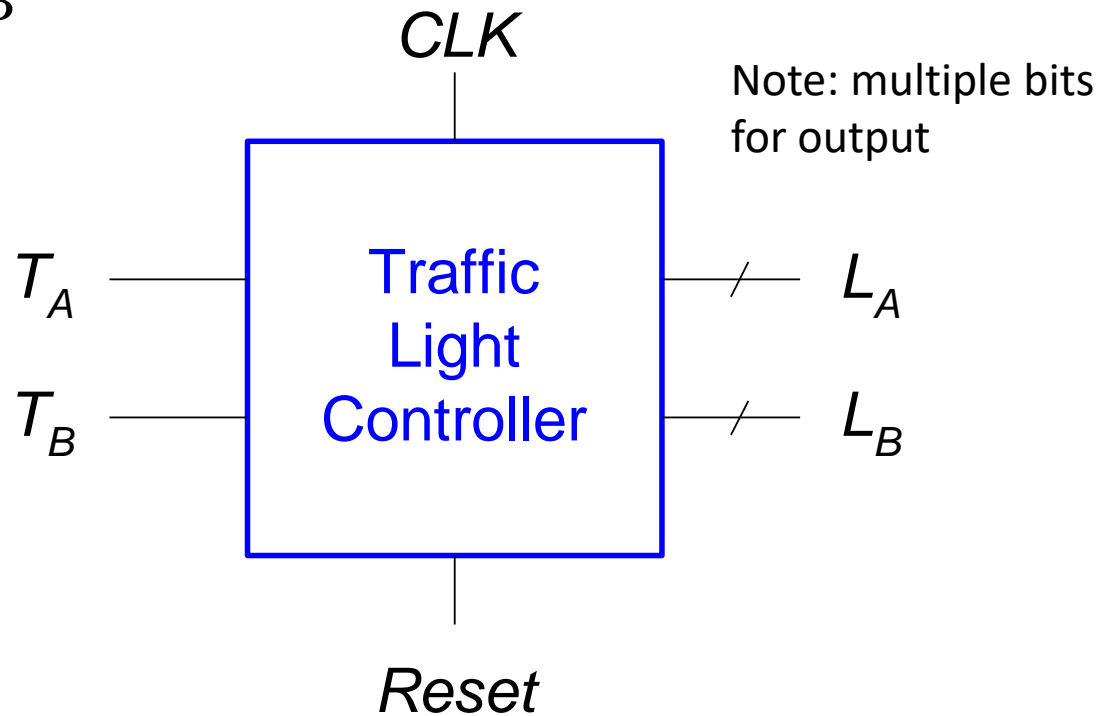


# FSM Design Procedure

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# FSM Black Box

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



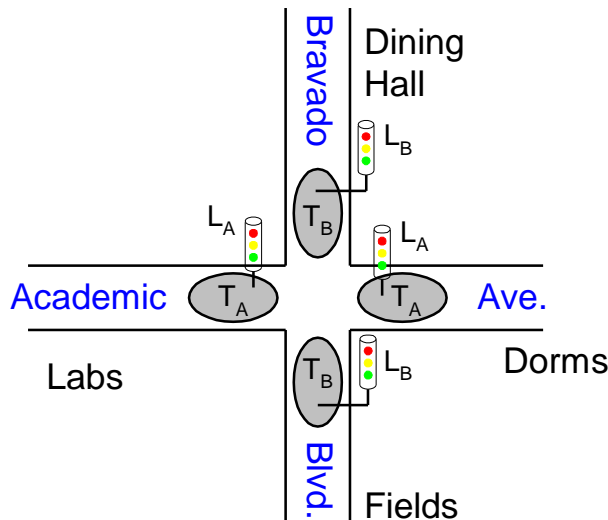
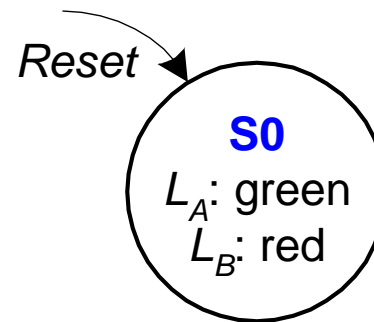
# FSM Design Procedure

1. Identify inputs and outputs
2. **Sketch state transition diagram**
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# FSM State Transition Diagram

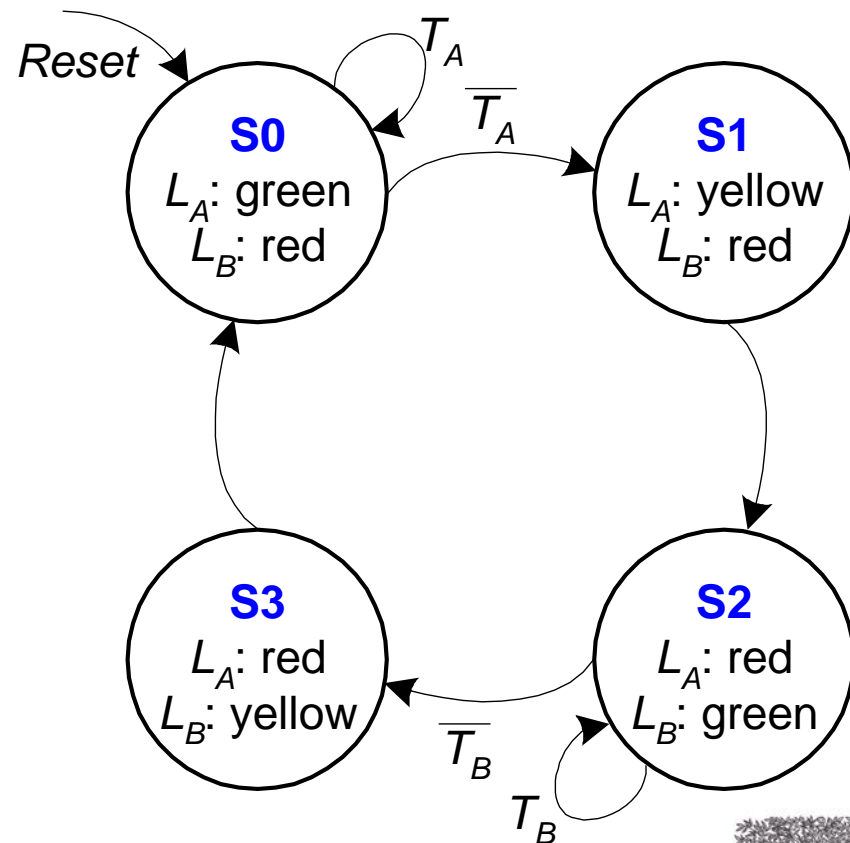
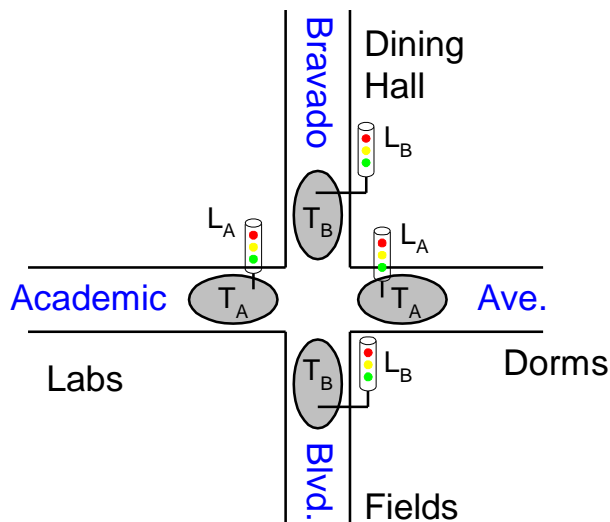
- **Moore FSM:** outputs labeled in each state
- **States:** Circles
- **Transitions:** Arcs





# FSM State Transition Diagram

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



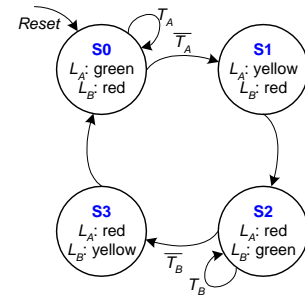
# FSM Design Procedure

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3. **Write state transition table**
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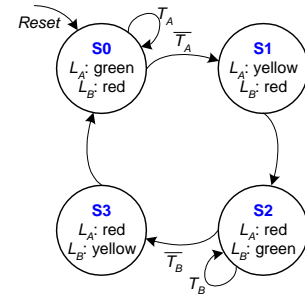
# FSM State Transition Table

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



# FSM State Transition Table

Current State $S$	Inputs		Next State $S'$
	$T_A$	$T_B$	
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 Design Procedure

1. Identify inputs and outputs
2. Sketch state transition diagram
3. Write state transition table
- 4. Select state encodings**
- 5. Rewrite state transition table with state encodings**
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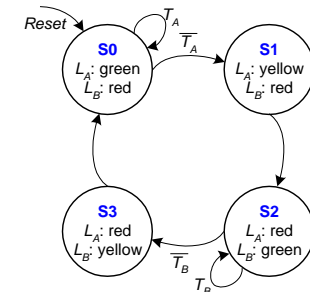


# FSM Encoded State Transition Table

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

Two bits required for 4 states



# FSM Encoded State Transition Table

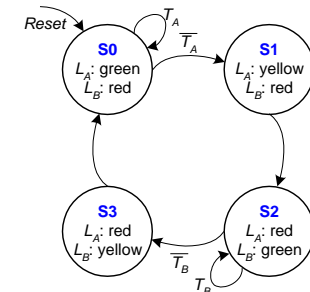
Current State		Inputs		Next State	
$S_1$	$S_0$	$T_A$	$T_B$	$S'_1$	$S'_0$
0	0	0	X	0	1
0	0	1	X	0	0
0	1	X	X	1	0
1	0	X	0	1	1
1	0	X	1	1	0
1	1	X	X	0	0

State	Encoding
S0	00
S1	01
S2	10
S3	11

Two bits required for 4 states

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

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



# FSM Design Procedure

1. Identify inputs and outputs
2. Sketch state transition diagram
3. Write state transition table
4. Select state encodings
5. Rewrite state transition table with state encodings
6. **Write output table**
7. **Write Boolean equations for next state and output logic**
8. Sketch the circuit schematic

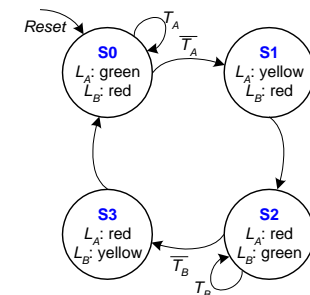


# FSM Output Table

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

Two bits required for 3 outputs



# 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

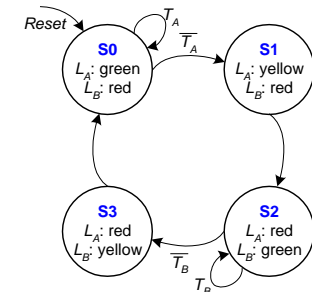
Two bits required for 3 outputs

$$L_{A1} = S_1$$

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

$$L_{B1} = S_1$$

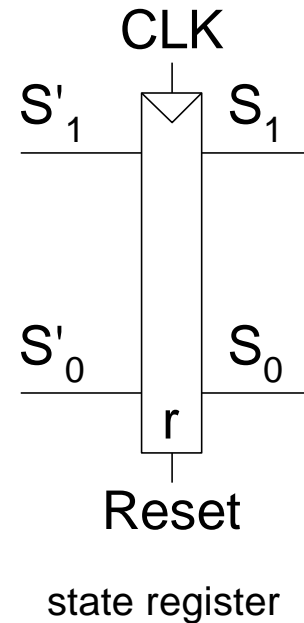
$$L_{B0} = S_1S_0$$



# FSM Design Procedure

1. Identify inputs and outputs
2. Sketch state transition diagram
3. Write state transition table
4. Select state encodings
5. Rewrite state transition table with state encodings
6. Write output table
7. Write Boolean equations for next state and output logic
8. **Sketch the circuit schematic**

# FSM Schematic: State Register



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

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

$$L_{A1} = S_1$$

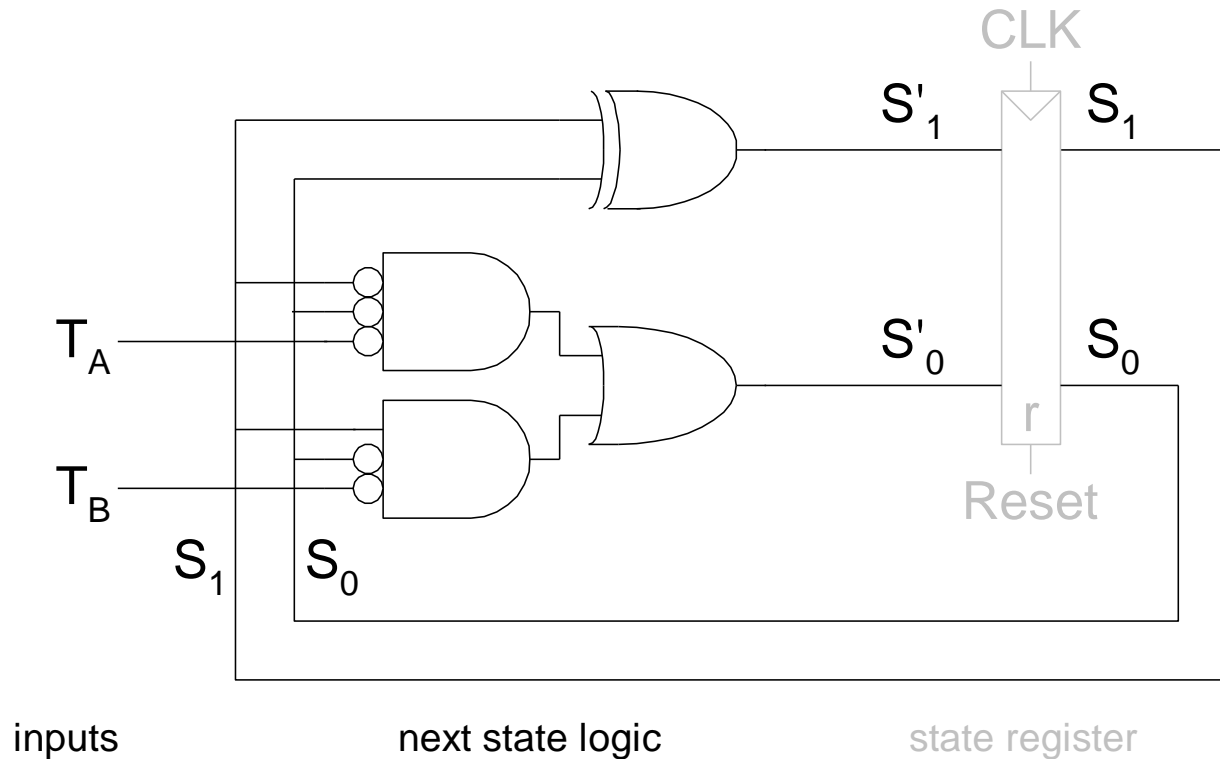
$$L_{A0} = \overline{S_1} S_0$$

$$L_{B1} = \overline{S_1}$$

$$L_{B0} = S_1 S_0$$



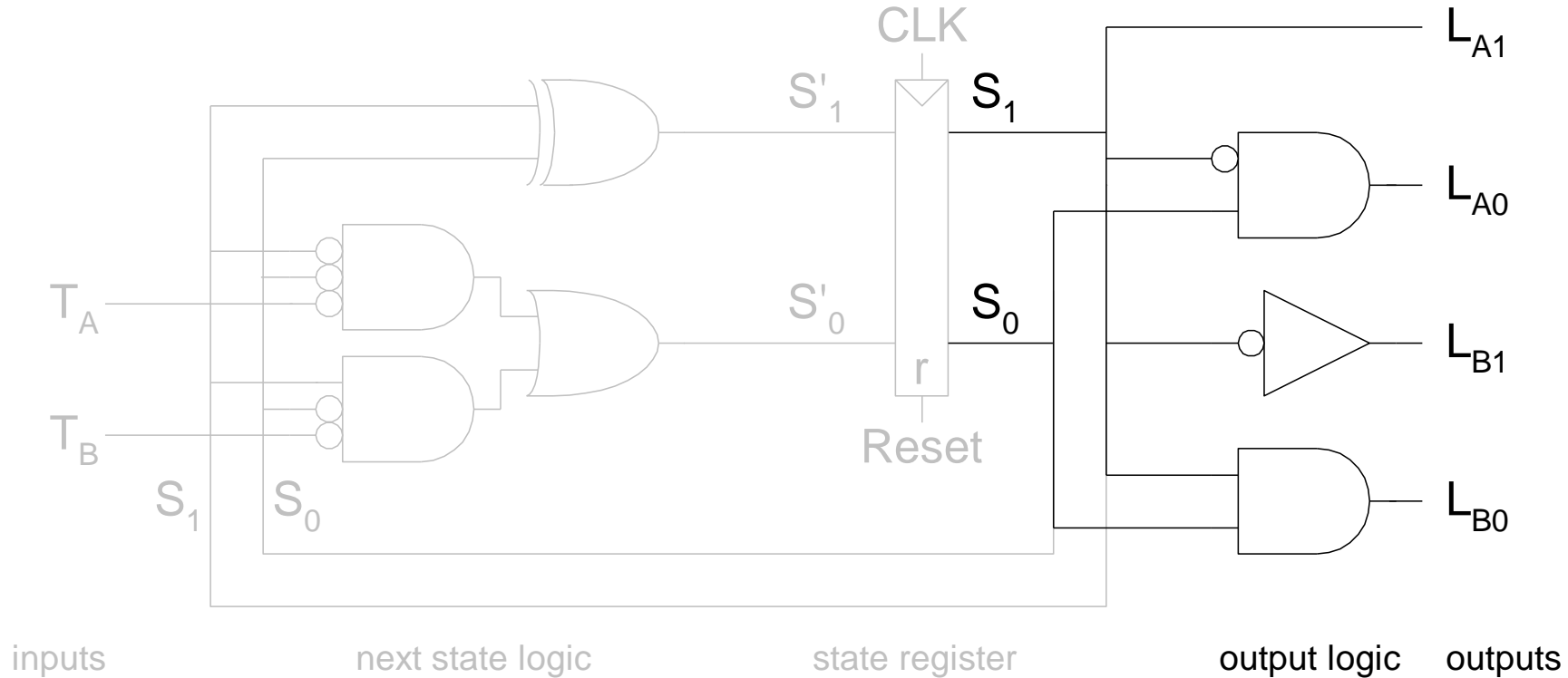
# FSM Schematic: Next State Logic



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

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

# FSM Schematic: Output Logic



$$L_{A1} = S_1$$

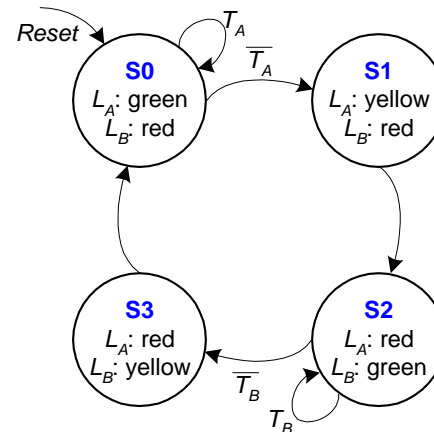
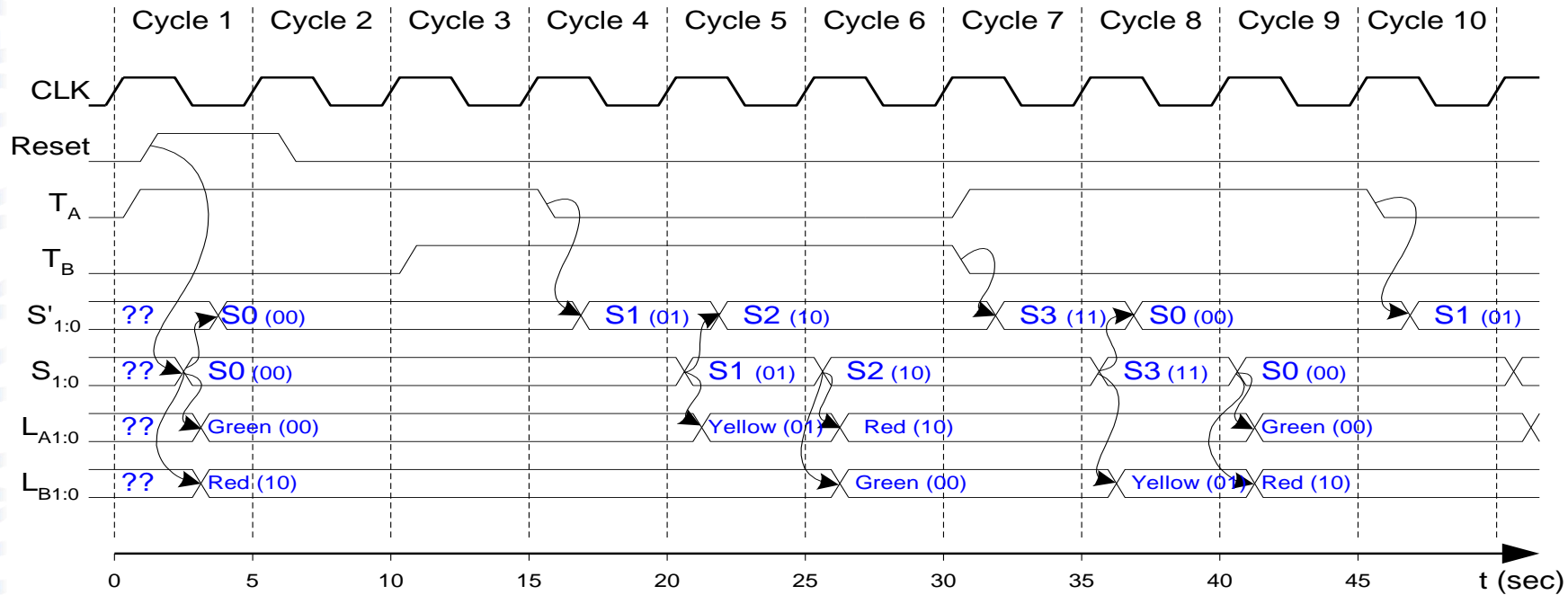
$$L_{A0} = \overline{S_1} S_0$$

$$L_{B1} = \overline{S_1}$$

$$L_{B0} = S_1 S_0$$



# 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



# FSM Design Procedure

1. Identify inputs and outputs
2. Sketch state transition diagram
3. Write state transition table
4. Select state encodings
5. Rewrite state transition table with state encodings
6. Write output table
7. Write Boolean equations for next state and output logic
8. Sketch the circuit schematic

# FSM Problems

1. Design a circuit to detect 3 or more 1's in a row in a bit stream
2. Vending machine: Release an item after receiving 15 cents
  - Single coin slot but tells if you put in dime or nickel
  - No change given

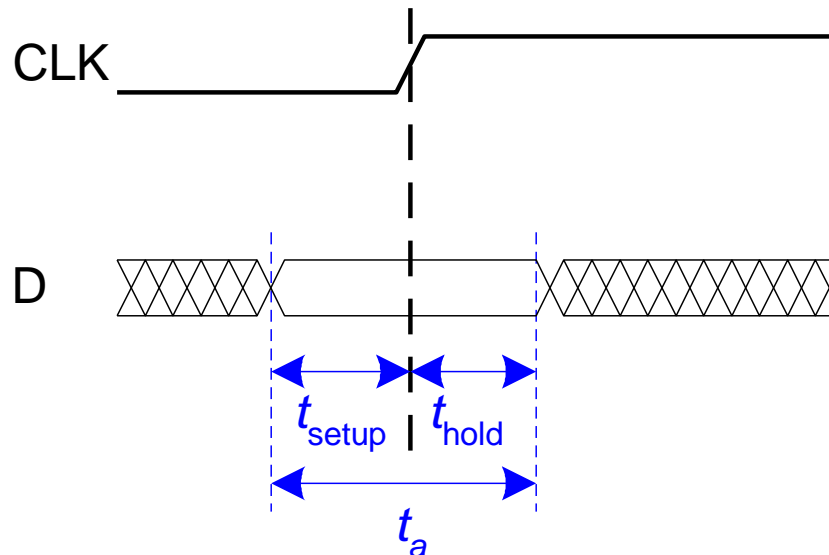
- |  |  |
|--|--|
| 1. Identify inputs and outputs                         | 6. Write output table                                      |
| 2. Sketch state transition diagram                     | 7. Write Boolean equations for next state and output logic |
| 3. Write state transition table                        | 8. Sketch the circuit schematic                            |
| 4. Select state encodings                              |  |
| 5. Rewrite state transition table with state encodings |  |

# Timing

- Flip-flop samples  $D$  at clock edge
- $D$  must be stable when sampled
  - Similar to a photograph,  $D$  must be stable around clock edge
  - Moving right before or after shutter click results in blurry photo
- If not, metastability can occur

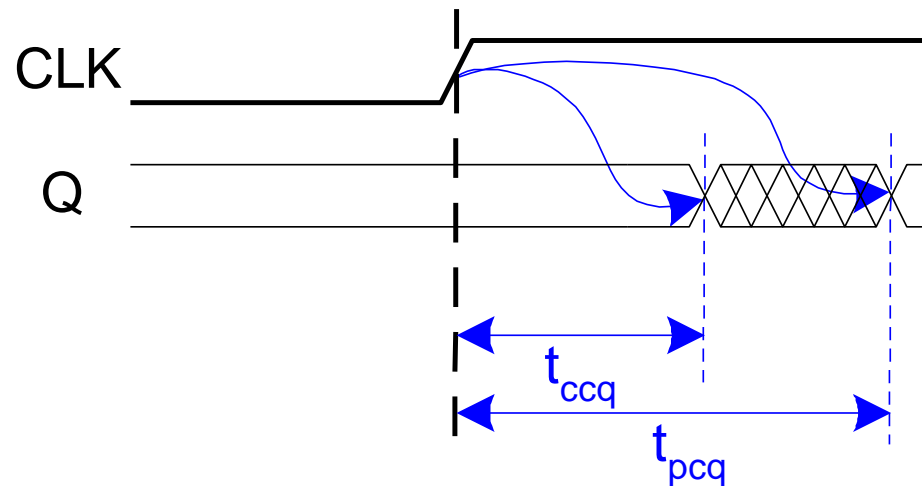
# Input Timing Constraints

- **Setup time:**  $t_{\text{setup}}$  = time *before* clock edge data must be stable (i.e. not changing)
- **Hold time:**  $t_{\text{hold}}$  = time *after* clock edge data must be stable
- **Aperture time:**  $t_a$  = time *around* clock edge data must be stable ( $t_a = t_{\text{setup}} + t_{\text{hold}}$ )



# Output Timing Constraints

- **Propagation delay:**  $t_{pcq}$  = time after clock edge that the output  $Q$  is guaranteed to be stable (i.e., to stop changing)
- **Contamination delay:**  $t_{ccq}$  = time after clock edge that  $Q$  might be unstable (i.e., start changing)



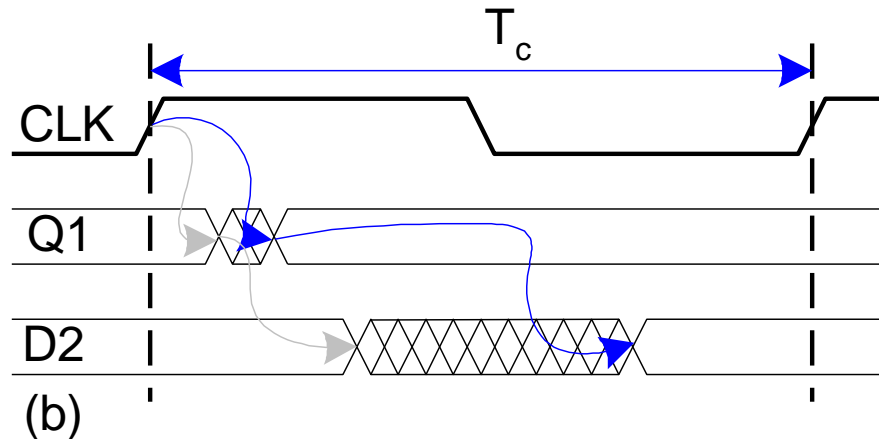
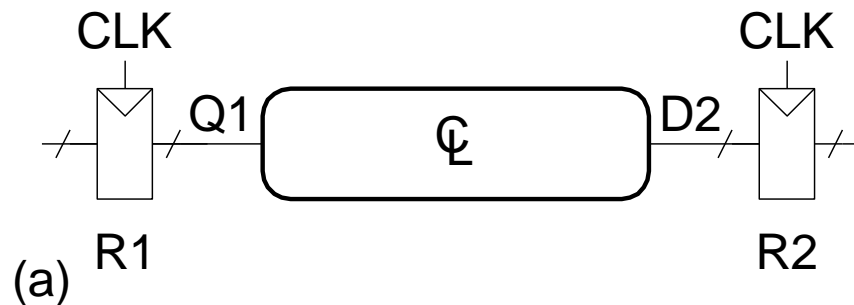
# Dynamic Discipline

- Synchronous sequential circuit inputs must be stable during aperture (setup and hold) time around clock edge
  - Specifically, inputs must be stable:
    - at least  $t_{\text{setup}}$  before the clock edge
    - at least until  $t_{\text{hold}}$  after the clock edge
- Previously, static discipline:
  - With logically valid inputs, every circuit element must produce logically valid outputs



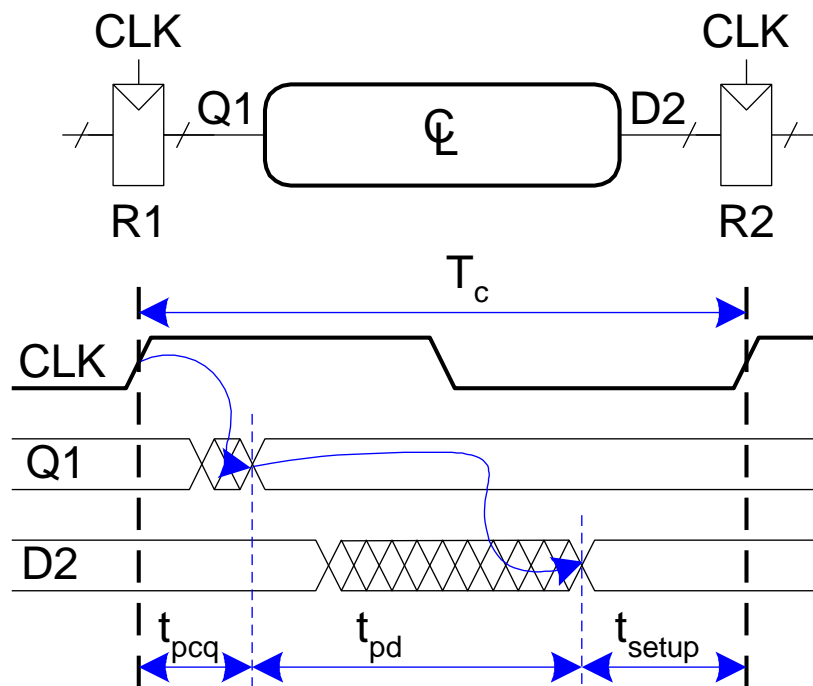
# Dynamic Discipline

- The delay between registers has a **minimum** and **maximum** delay, dependent on the delays of the circuit elements



# Setup Time Constraint

- Depends on the **maximum** delay from register R1 through combinational logic to R2
- The input to register R2 must be stable at least  $t_{\text{setup}}$  before clock edge

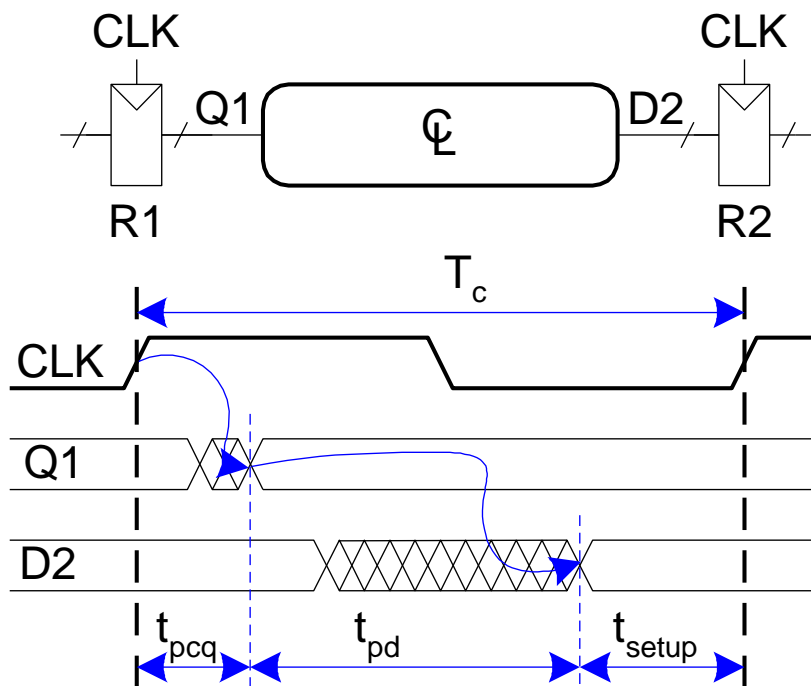


$$T_c \geq$$



# Setup Time Constraint

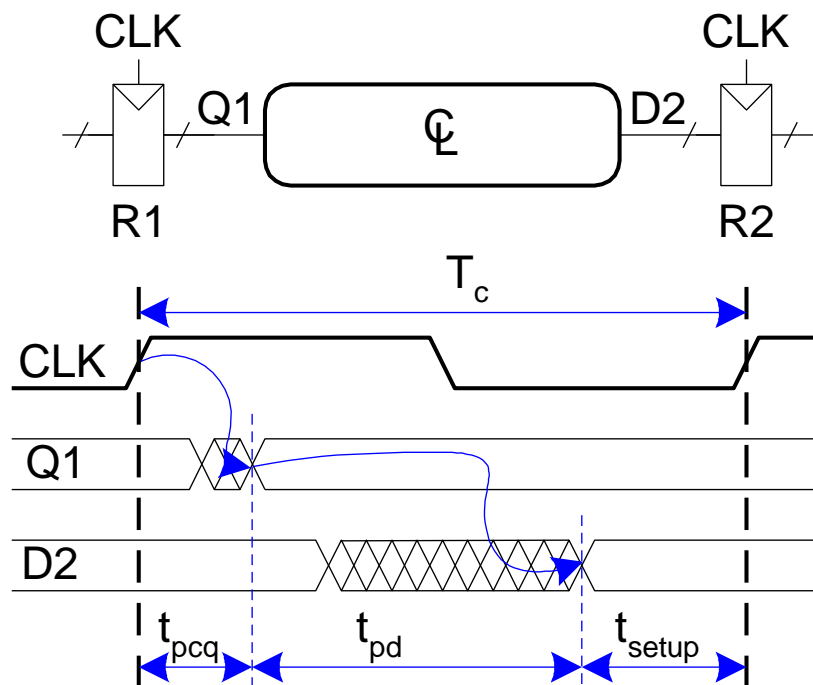
- Depends on the **maximum** delay from register R1 through combinational logic to R2
- The input to register R2 must be stable at least  $t_{\text{setup}}$  before clock edge



$$T_c \geq t_{pcq} + t_{pd} + t_{\text{setup}}$$
$$t_{pd} \leq$$

# Setup Time Constraint

- Depends on the **maximum** delay from register R1 through combinational logic to R2
- The input to register R2 must be stable at least  $t_{\text{setup}}$  before clock edge

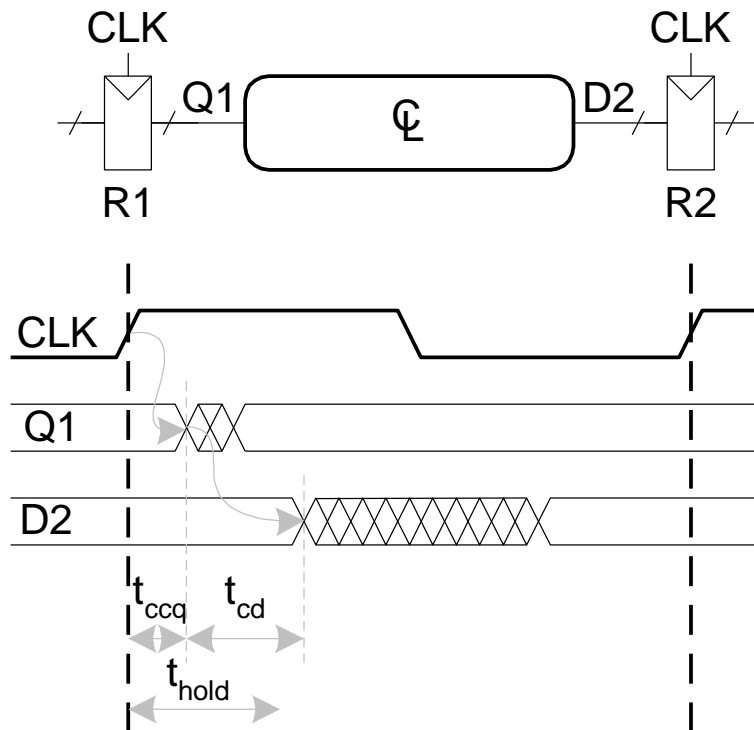


$$T_c \geq t_{pcq} + t_{pd} + t_{\text{setup}}$$
$$t_{pd} \leq T_c - (t_{pcq} + t_{\text{setup}})$$

$(t_{pcq} + t_{\text{setup}})$ : sequencing overhead

# Hold Time Constraint

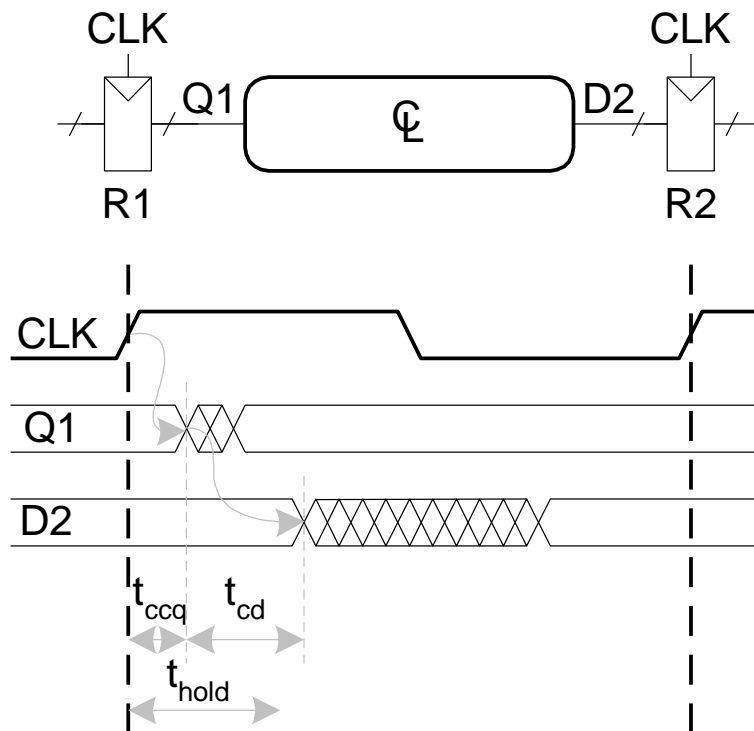
- Depends on the **minimum** delay from register R1 through the combinational logic to R2
- The input to register R2 must be stable for at least  $t_{\text{hold}}$  after the clock edge



$$t_{\text{hold}} <$$

# Hold Time Constraint

- Depends on the **minimum** delay from register R1 through the combinational logic to R2
- The input to register R2 must be stable for at least  $t_{\text{hold}}$  after the clock edge

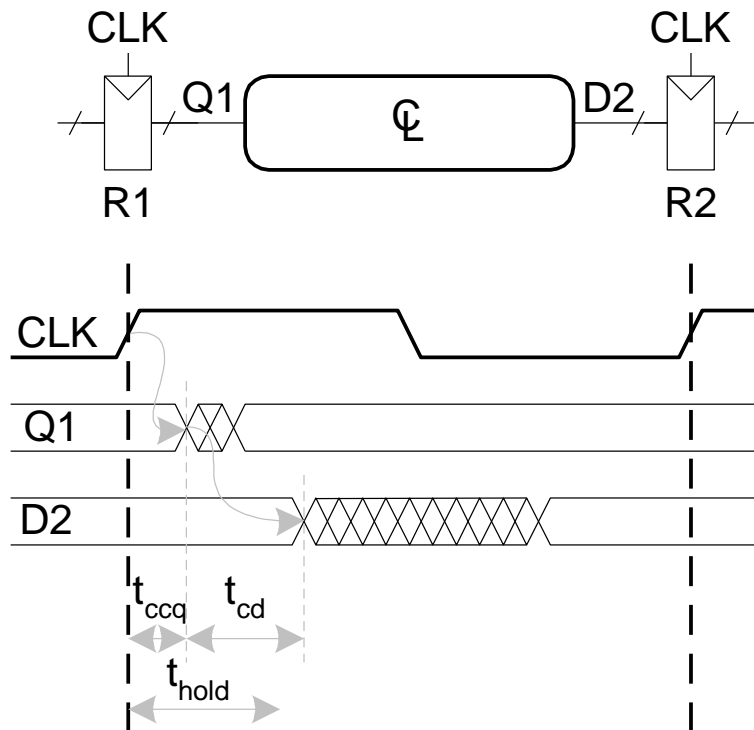


$$t_{\text{hold}} < t_{ccq} + t_{cd}$$

$$t_{cd} >$$

# Hold Time Constraint

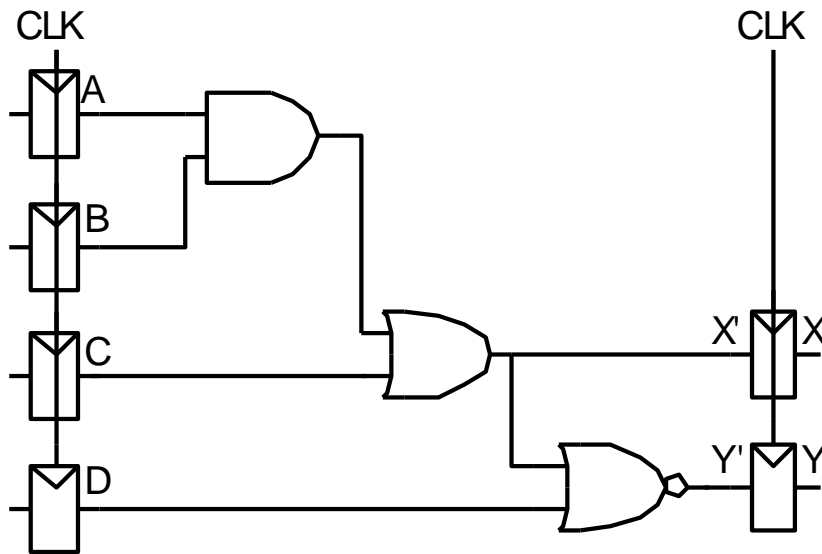
- Depends on the **minimum** delay from register R1 through the combinational logic to R2
- The input to register R2 must be stable for at least  $t_{\text{hold}}$  after the clock edge



$$t_{\text{hold}} < t_{\text{ccq}} + t_{\text{cd}}$$

$$t_{\text{cd}} > t_{\text{hold}} - t_{\text{ccq}}$$

# Timing Analysis



## Timing Characteristics

$$t_{ccq} = 30 \text{ ps}$$

$$t_{pcq} = 50 \text{ ps}$$

$$t_{\text{setup}} = 60 \text{ ps}$$

$$t_{\text{hold}} = 70 \text{ ps}$$

per gate

$$\begin{cases} t_{pd} = 35 \text{ ps} \\ t_{cd} = 25 \text{ ps} \end{cases}$$

$$t_{pd} =$$

$$t_{cd} =$$

Setup time constraint:

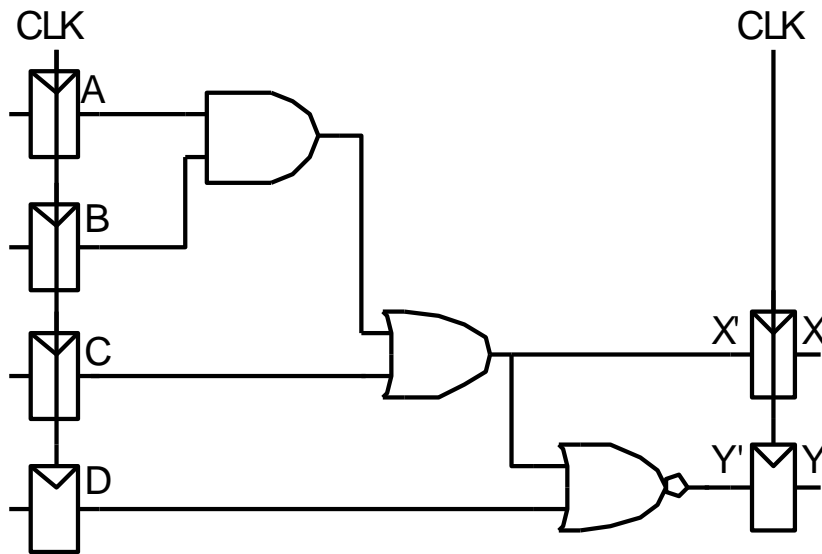
$$T_c \geq$$

$$f_c =$$

Hold time constraint:

$$t_{ccq} + t_{cd} > t_{\text{hold}} ?$$

# Timing Analysis



$$t_{pd} = 3 \times 35 \text{ ps} = 105 \text{ ps}$$

$$t_{cd} = 25 \text{ ps}$$

**Setup time constraint:**

$$T_c \geq (50 + 105 + 60) \text{ ps} = 215 \text{ ps}$$

$$f_c = 1/T_c = 4.65 \text{ GHz}$$

## Timing Characteristics

$$t_{ccq} = 30 \text{ ps}$$

$$t_{pcq} = 50 \text{ ps}$$

$$t_{\text{setup}} = 60 \text{ ps}$$

$$t_{\text{hold}} = 70 \text{ ps}$$

per gate

$$\left[ \begin{array}{ll} t_{pd} & = 35 \text{ ps} \\ t_{cd} & = 25 \text{ ps} \end{array} \right.$$

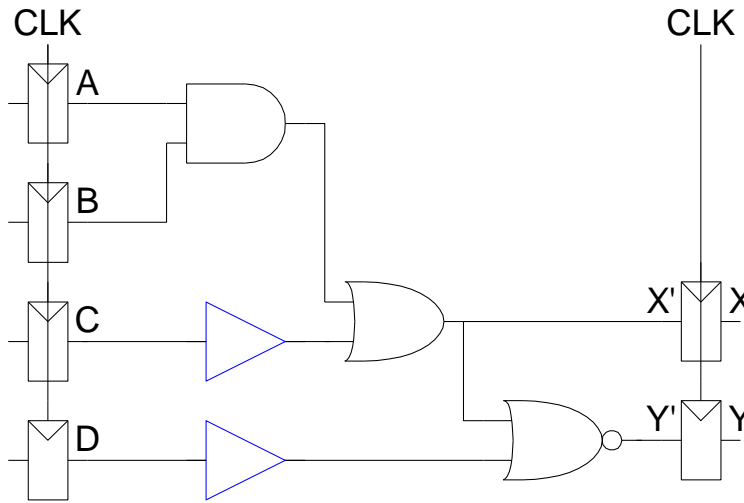
**Hold time constraint:**

$$t_{ccq} + t_{cd} > t_{\text{hold}} ?$$

$$(30 + 25) \text{ ps} > 70 \text{ ps} ? \text{ No!}$$



## Add buffers to the short paths:



$$t_{pd} =$$

$$t_{cd} =$$

## Setup time constraint:

$$T_c \geq$$

$$f_c =$$

## Timing Characteristics

$$t_{ccq} = 30 \text{ ps}$$

$$t_{pcq} = 50 \text{ ps}$$

$$t_{\text{setup}} = 60 \text{ ps}$$

$$t_{\text{hold}} = 70 \text{ ps}$$

$$\text{per gate} \left[ \begin{array}{ll} t_{pd} & = 35 \text{ ps} \\ t_{cd} & = 25 \text{ ps} \end{array} \right.$$

**Hold time constraint:**

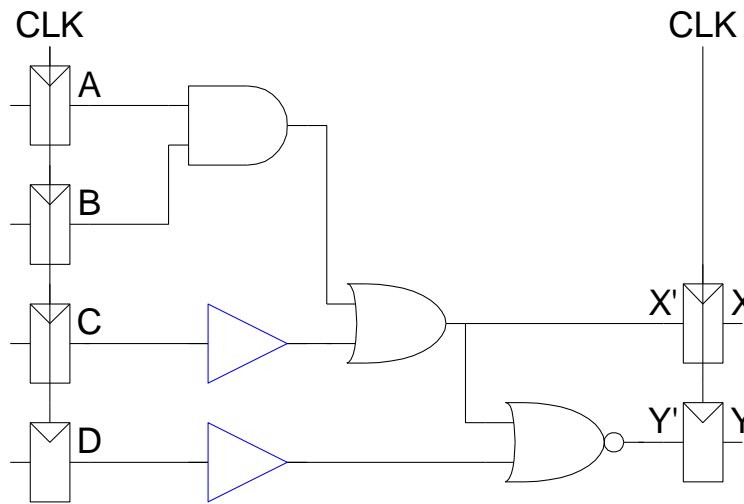
$$t_{ccq} + t_{cd} > t_{hold} ?$$





# Timing Analysis

Add buffers to the short paths:



$$t_{pd} = 3 \times 35 \text{ ps} = 105 \text{ ps}$$

$$t_{cd} = 2 \times 25 \text{ ps} = 50 \text{ ps}$$

Setup time constraint:

$$T_c \geq (50 + 105 + 60) \text{ ps} = 215 \text{ ps}$$

$$f_c = 1/T_c = 4.65 \text{ GHz}$$

## Timing Characteristics

$$t_{ccq} = 30 \text{ ps}$$

$$t_{pcq} = 50 \text{ ps}$$

$$t_{\text{setup}} = 60 \text{ ps}$$

$$t_{\text{hold}} = 70 \text{ ps}$$

$$\text{per gate} \left[ \begin{array}{ll} t_{pd} & = 35 \text{ ps} \\ t_{cd} & = 25 \text{ ps} \end{array} \right.$$

Hold time constraint:

$$t_{ccq} + t_{cd} > t_{\text{hold}} ?$$

$$(30 + 50) \text{ ps} > 70 \text{ ps} ? \text{ Yes!}$$



# Parallelism

- **Two types of parallelism:**
  - **Spatial parallelism**
    - duplicate hardware performs multiple tasks at once
  - **Temporal parallelism**
    - task is broken into multiple stages
    - also called pipelining
    - for example, an assembly line

# Parallelism Definitions

- **Token:** Group of inputs processed to produce group of outputs
- **Latency:** Time for one token to pass from start to end
- **Throughput:** Number of tokens produced per unit time

**Parallelism increases throughput**

# Parallelism Example

- Ben Bitdiddle bakes cookies to celebrate traffic light controller installation
- 5 minutes to roll cookies
- 15 minutes to bake
- What is the latency and throughput without parallelism?

# Parallelism Example

- Ben Bitdiddle bakes cookies to celebrate traffic light controller installation
- 5 minutes to roll cookies
- 15 minutes to bake
- What is the latency and throughput without parallelism?

**Latency** = 5 + 15 = 20 minutes = **1/3 hour**

**Throughput** = 1 tray/ 1/3 hour = **3 trays/hour**

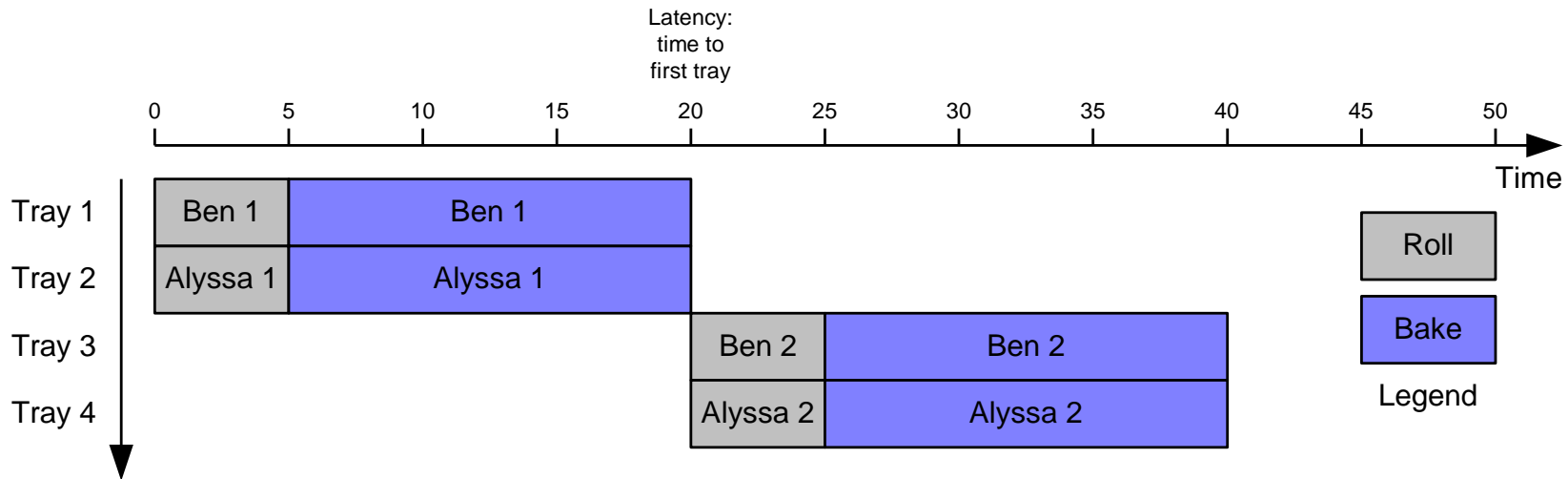
# Parallelism Example

- What is the latency and throughput if Ben uses parallelism?
  - **Spatial parallelism:** Ben asks Allysa P. Hacker to help, using her own oven
  - **Temporal parallelism:**
    - two stages: rolling and baking
    - He uses two trays
    - While first batch is baking, he rolls the second batch, etc.



# Spatial Parallelism

Spatial  
Parallelism



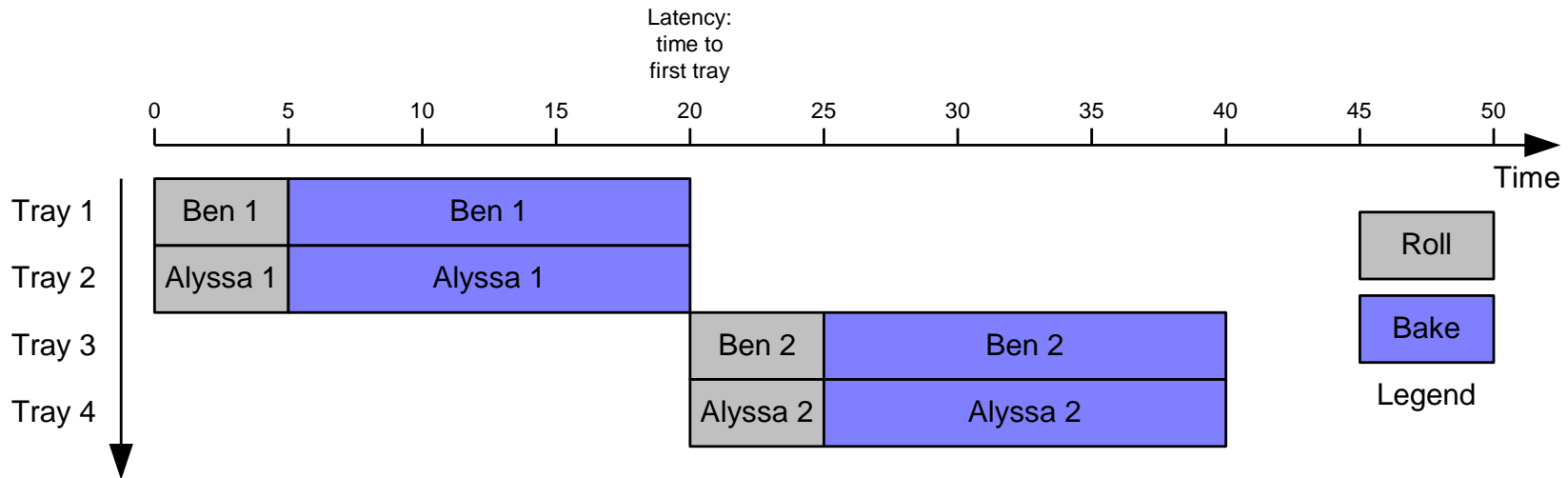
**Latency = ?**

**Throughput = ?**



# Spatial Parallelism

Spatial  
Parallelism



**Latency** = 5 + 15 = 20 minutes = **1/3 hour**

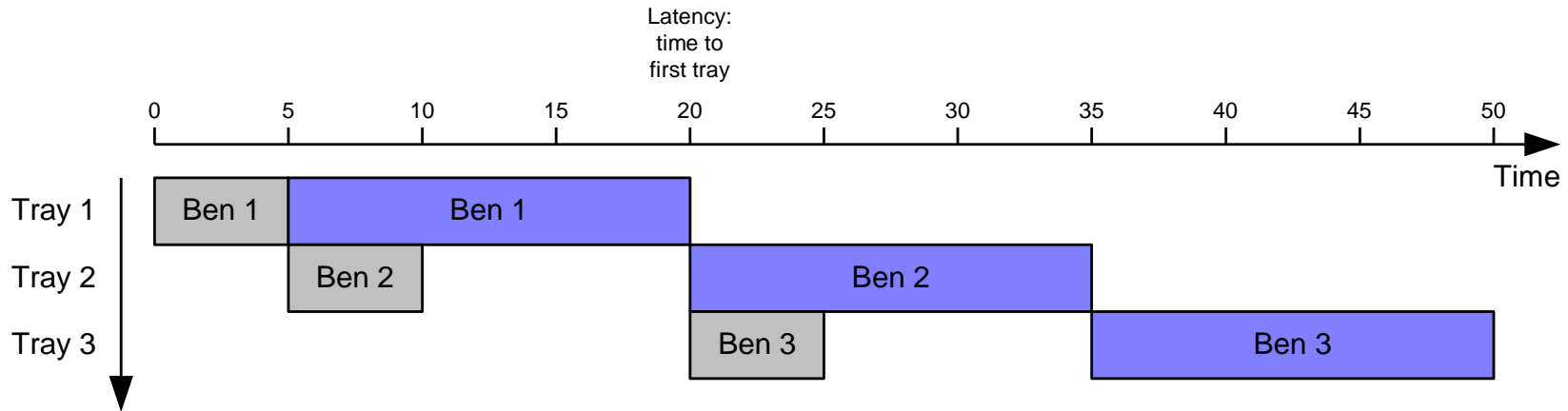
**Throughput** = 2 trays/ 1/3 hour = **6 trays/hour**





# Temporal Parallelism

Temporal  
Parallelism

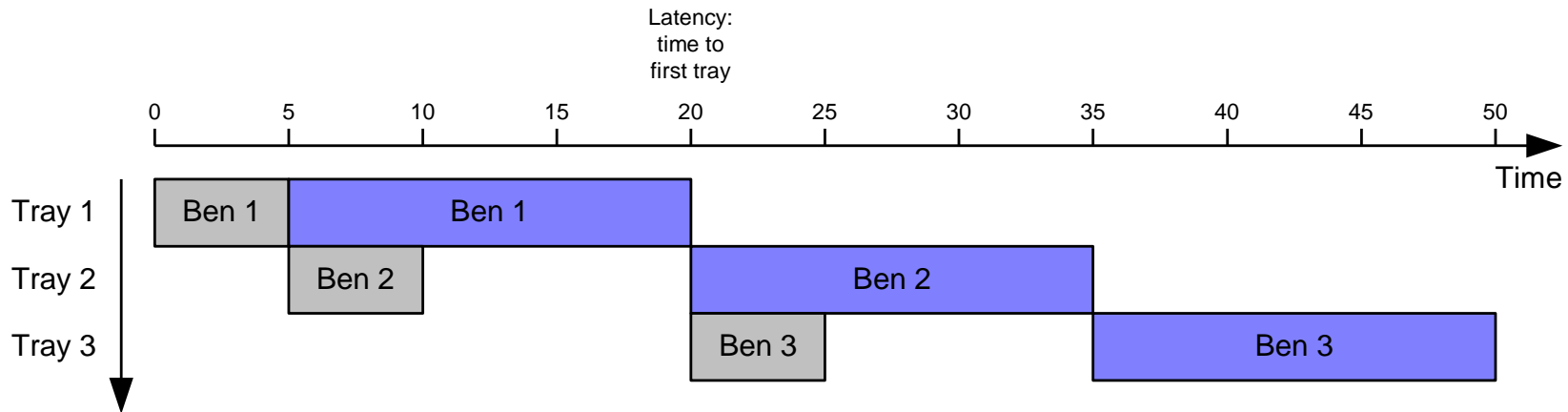


**Latency = ?**

**Throughput = ?**

# Temporal Parallelism

Temporal  
Parallelism



**Latency** = 5 + 15 = 20 minutes = **1/3 hour**

**Throughput** = 1 trays/ 1/4 hour = **4 trays/hour**

Using both spatial and temporal techniques, the throughput would be **8 trays/hour**

