

# DIGITAL LOGIC

## Chapter 6 : Registers & Counters

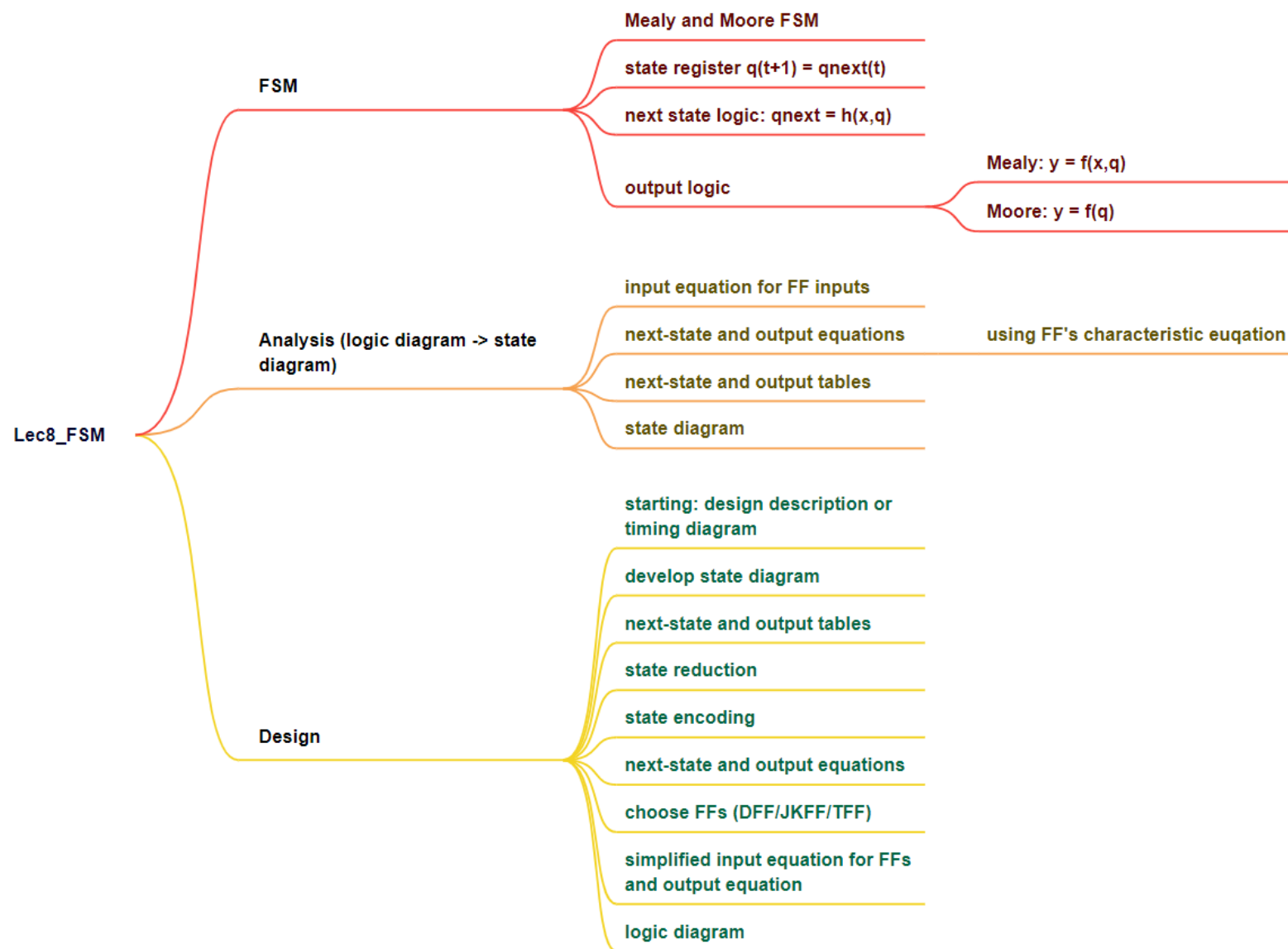
2024 Fall

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# Today's Agenda

- Recap
- Context
  - Registers
  - Design a sequence generator
  - Counters
  - Design a counter
- Reading: Textbook, Chapter 6.1-6.9

# Recap

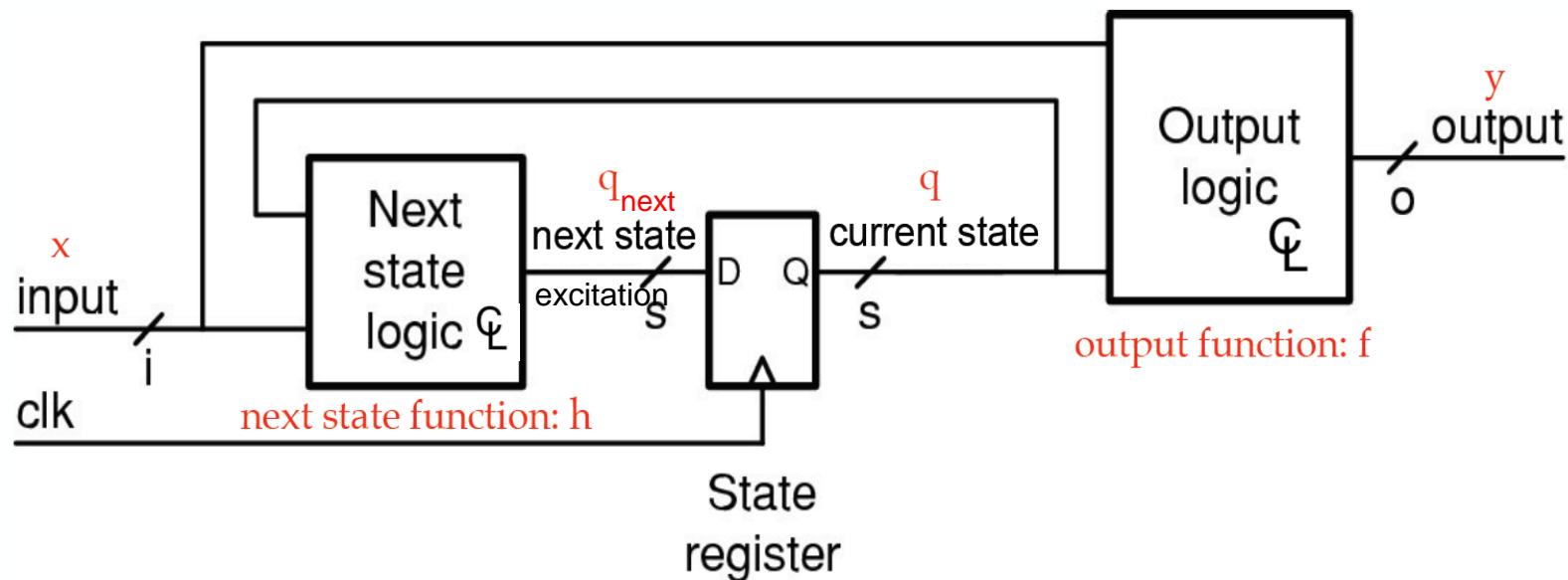


# Outline

- **Various types of registers**
- Sequence generator with shift register
- Asynchronous counter
- Synchronous counter
- Design a synchronous counter

# Clocked Sequential Circuits

- Clocked sequential circuits have flip-flops and combinational gates.
- FFs are essential, otherwise reduce to combinational.
- Circuits that include flip-flops are usually classified by the function they perform rather than by the name of the sequential circuit.
- Two such circuits are **registers** and **counters**.

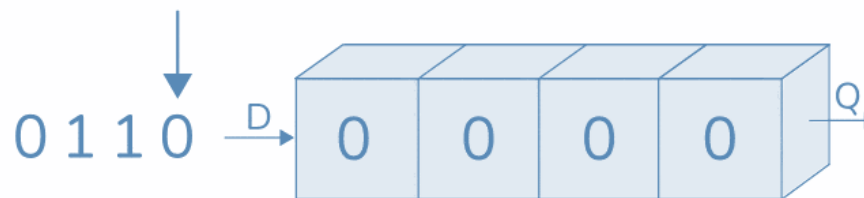


# Registers and Counters

- Register
  - A group of binary cells (FFs) suitable for holding binary data information
  - In addition to the FFs, a register may have combinational gates to control when and how the new information is transferred into the register (MUXes, ...)
- Counter
  - A register that goes through a predetermined sequence of states upon the application of input pulses
  - The gates in a counter are connected in such a way as to produce a pre-described sequence of binary states in the register (arithmetic circuits)

# Shift Register

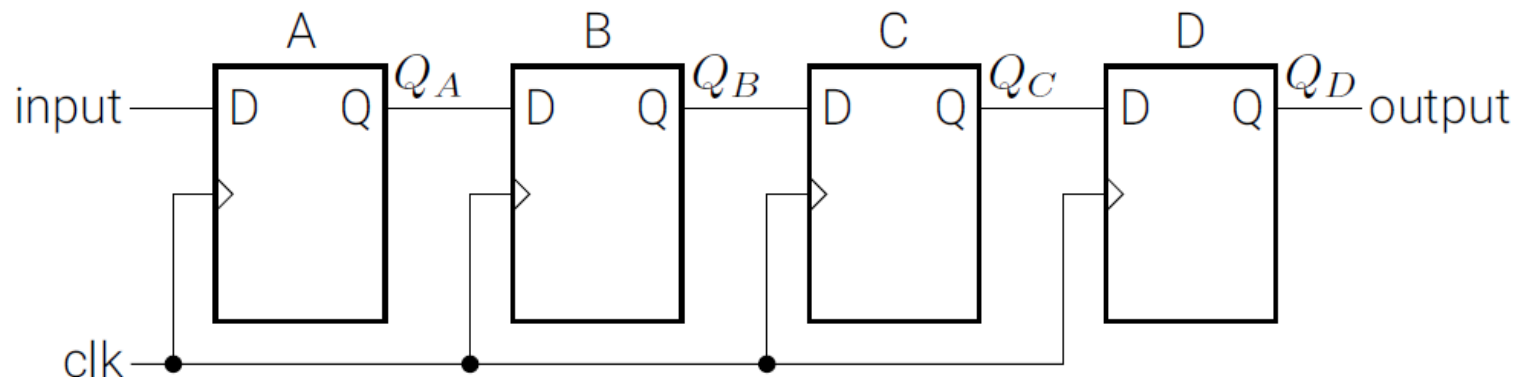
- Register: bitwise extension of a FF.
  - The shift register permits the stored data to move from a particular location to some other location within the register.
  - All the n FFs are driven by the common clock signal
  - sometimes with load control
- Type: Based on input & output
  - Serial-in to Serial-out (SISO)
  - Serial-in to Parallel-out (SIPO)
  - Parallel-in to Serial-out (PISO)
  - Parallel-in to Parallel-out (PIPO)
- Direction
  - Left shift
  - Right shift
  - Rotate (right or left)
  - Bidirectional
- Universal shift register



Bits moving through a SISO shift register

# 4-bit Serial-in to Serial-out

- SISO: the data is shifted serially “IN” and “OUT” of the register, one bit at a time in either a left or right direction under clock control.



- An example of **1011** into the register. (Suppose bits are shifted in from LSB to MSB)

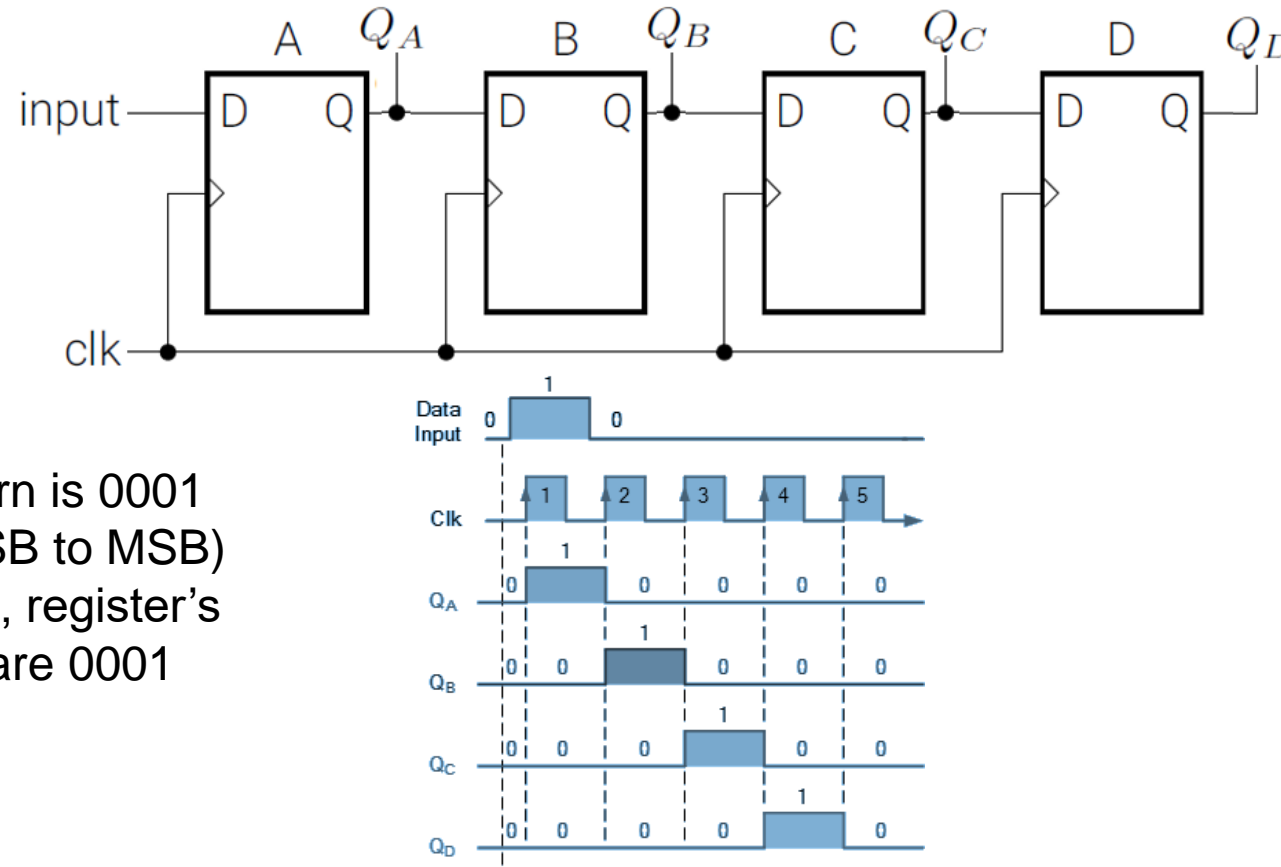
Starting from clock cycle 4, values could be read from  $Q_D$  one by one during each cycle

CLK	$Q_A$	$Q_B$	$Q_C$	$Q_D$ output
initial	0	0	0	0
↑	1	0	0	0
↑	1	1	0	0
↑	0	1	1	0
↑	1	0	1	1



# 4-bit Serial-in to Parallel-out

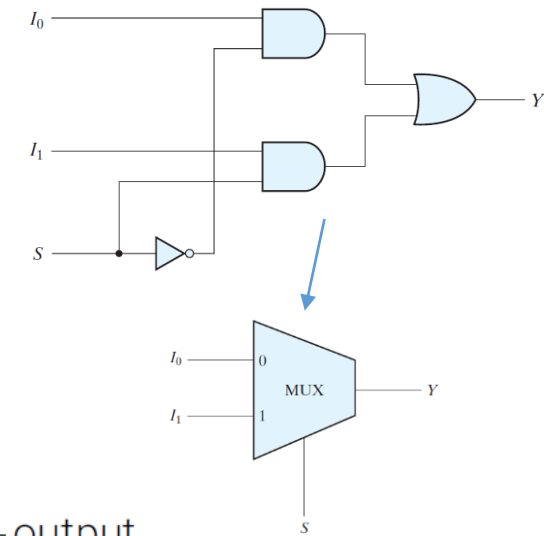
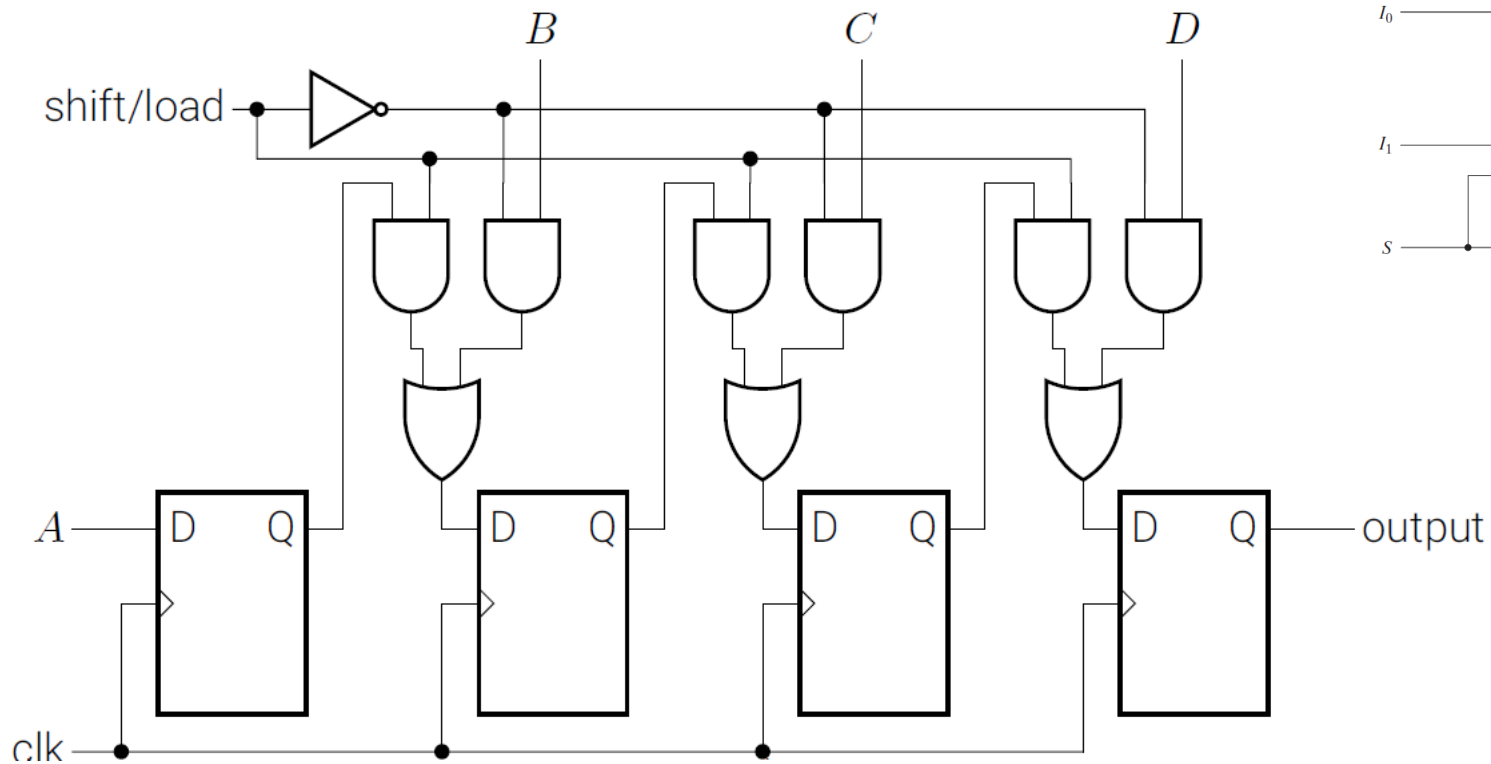
- SIPO: the register is loaded with serial data, one bit at a time, with the stored data being available at the output in parallel form.



Suppose input pattern is 0001  
(values sent from LSB to MSB)  
then at clock cycle 4, register's  
outputs  $Q_A Q_B Q_C Q_D$  are 0001

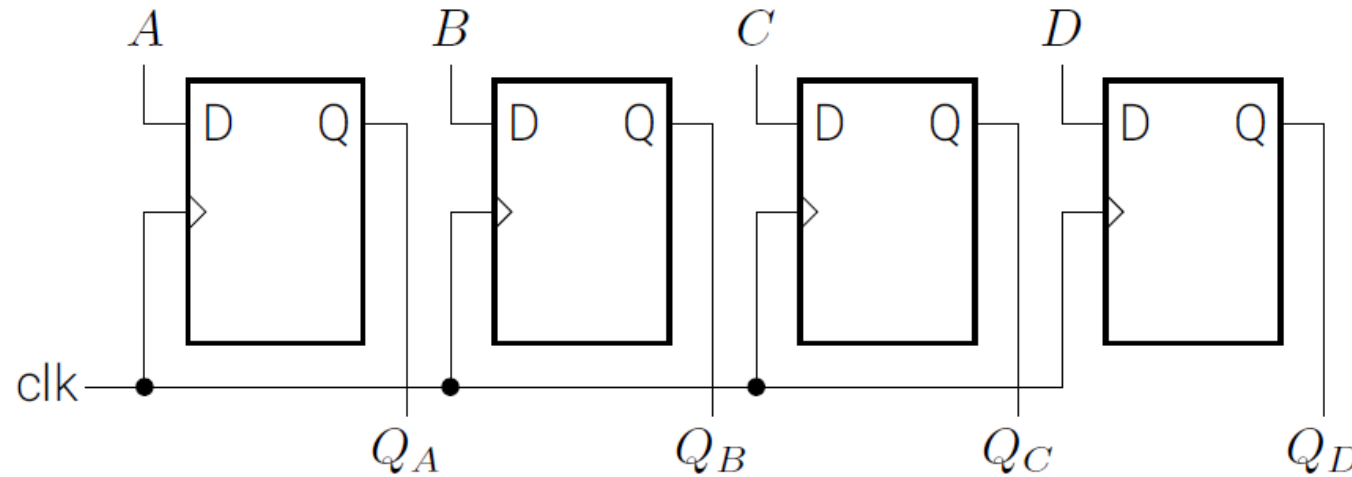
# 4-bit Parallel-in to Serial-out

- PISO: the parallel data is loaded into the register simultaneously and is shifted out of the register serially one bit at a time under clock control.



# 4-bit Parallel-in to Parallel-out

- PIPO: the parallel data is loaded simultaneously into the register, and transferred together to their respective outputs by the same clock pulse.

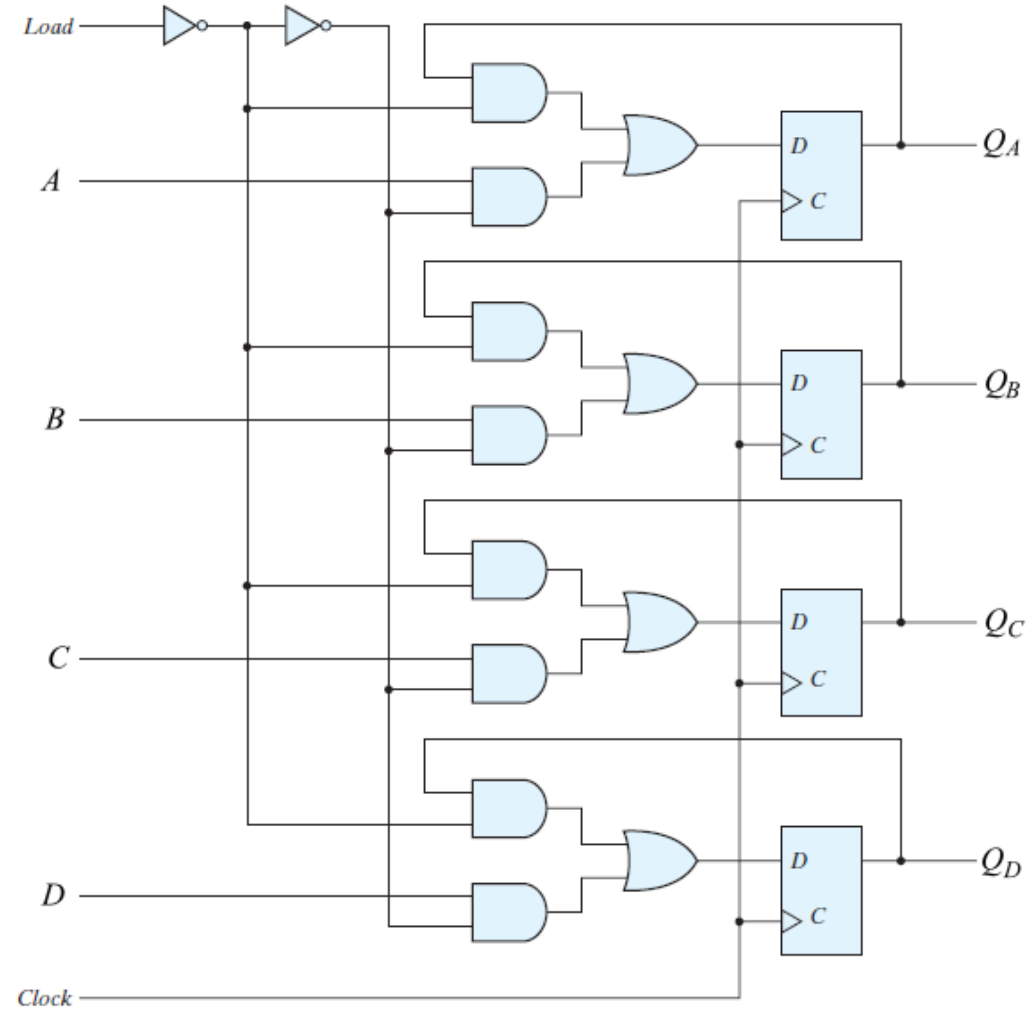


# PIPO with Parallel Load

- 4-bit Parallel-in to Parallel-out Register with Parallel Load Logic diagram

function table

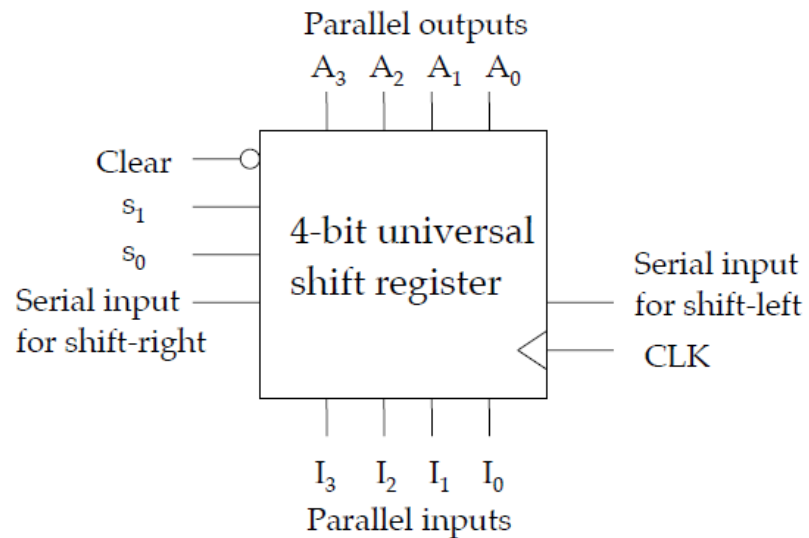
Present state Load	Next state			
	$Q_A$	$Q_B$	$Q_C$	$Q_D$
0	No change			
1	A	B	C	D



# Universal Shift Register

- Universal shift register
  - Capable of both-direction shifting and parallel load/out

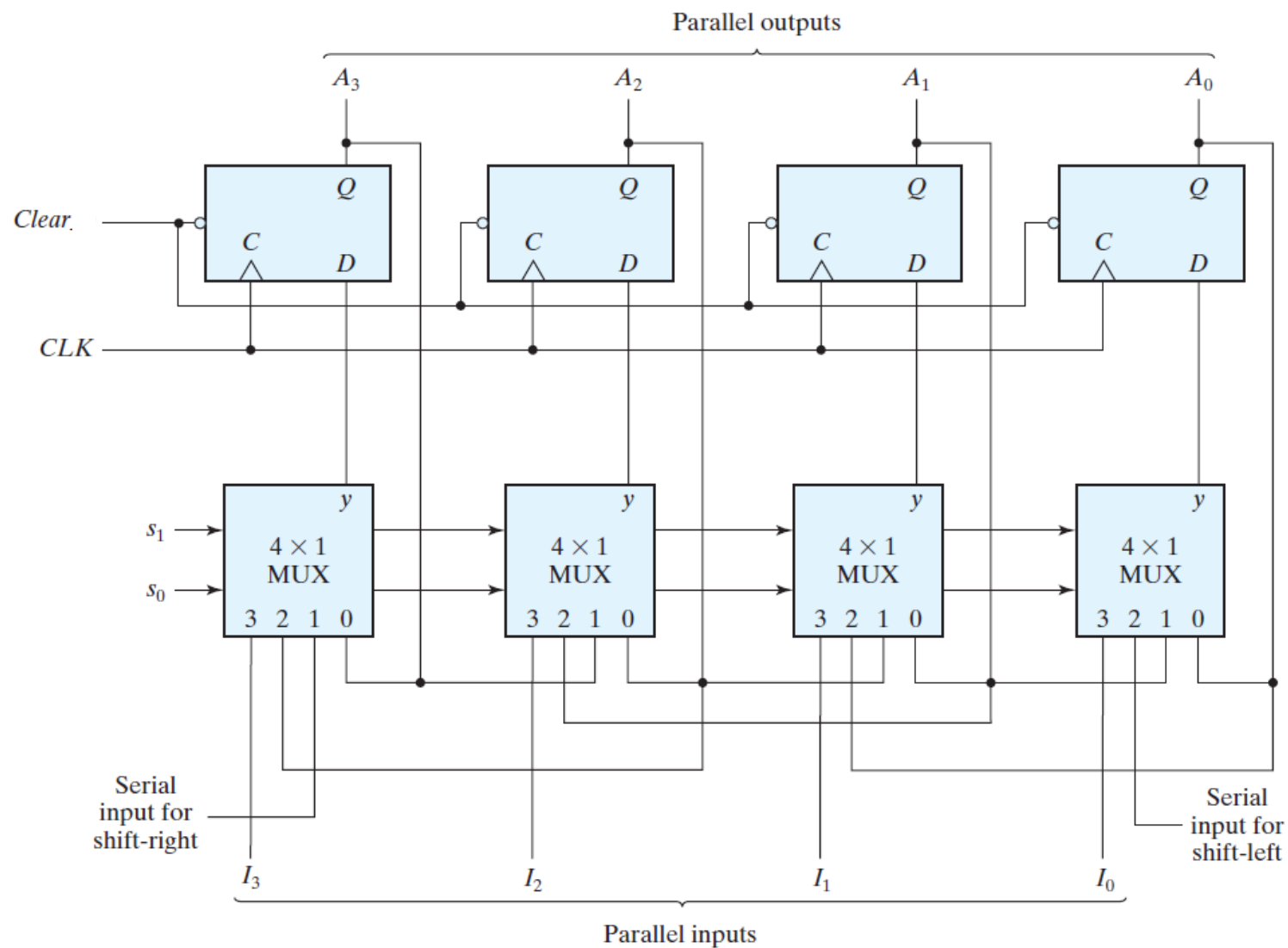
functional table



graphic symbol

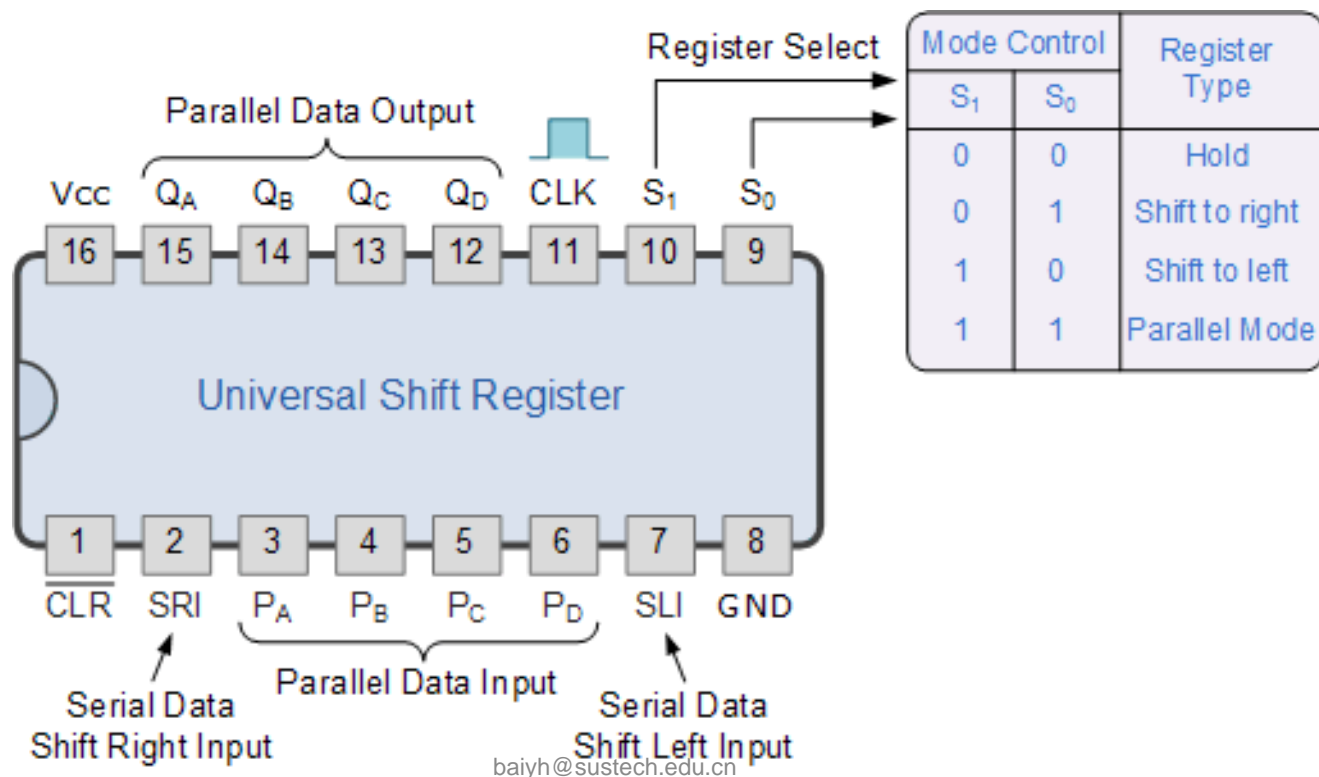
Clear	S <sub>1</sub>	S <sub>0</sub>	A <sub>3</sub> <sup>+</sup>	A <sub>2</sub> <sup>+</sup>	A <sub>1</sub> <sup>+</sup>	A <sub>0</sub> <sup>+</sup>	Operation
0	x	x	0	0	0	0	Clear
1	0	0	A <sub>3</sub>	A <sub>2</sub>	A <sub>1</sub>	A <sub>0</sub>	No change
1	0	1	sri	A <sub>3</sub>	A <sub>2</sub>	A <sub>1</sub>	Shift right
1	1	0	A <sub>2</sub>	A <sub>1</sub>	A <sub>0</sub>	sli	Shift left
1	1	1	I <sub>3</sub>	I <sub>2</sub>	I <sub>1</sub>	I <sub>0</sub>	Parallel load

# Universal Shift Register



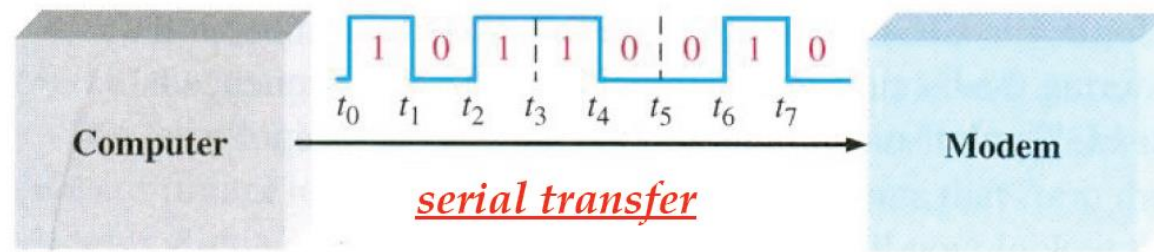
# 74 Series Shift Register

- Some of the IC's available for shift registers
  - 74164 – 8-bit SIPO shift register
  - 74165 – 8-bit PISO shift register
  - 74194 – 4-bit PIPO shift register
  - 74195 – 4-bit Universal shift register (can be used for SISO, SIPO, and PIPO operations)

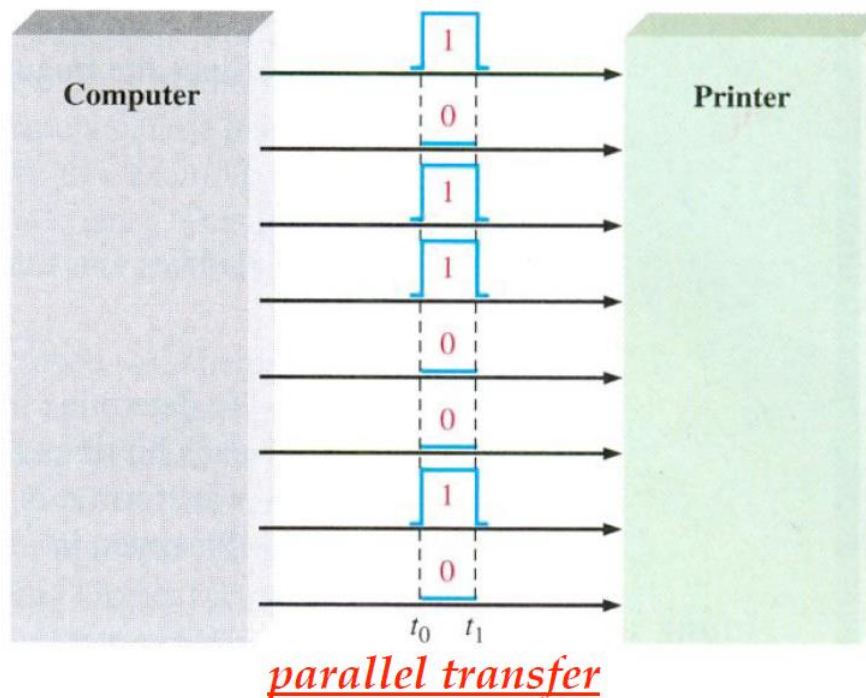


# Serial/Parallel Transfer

- Shifters are useful in serializers and deserialisers that convert data from parallel to serial form and back again



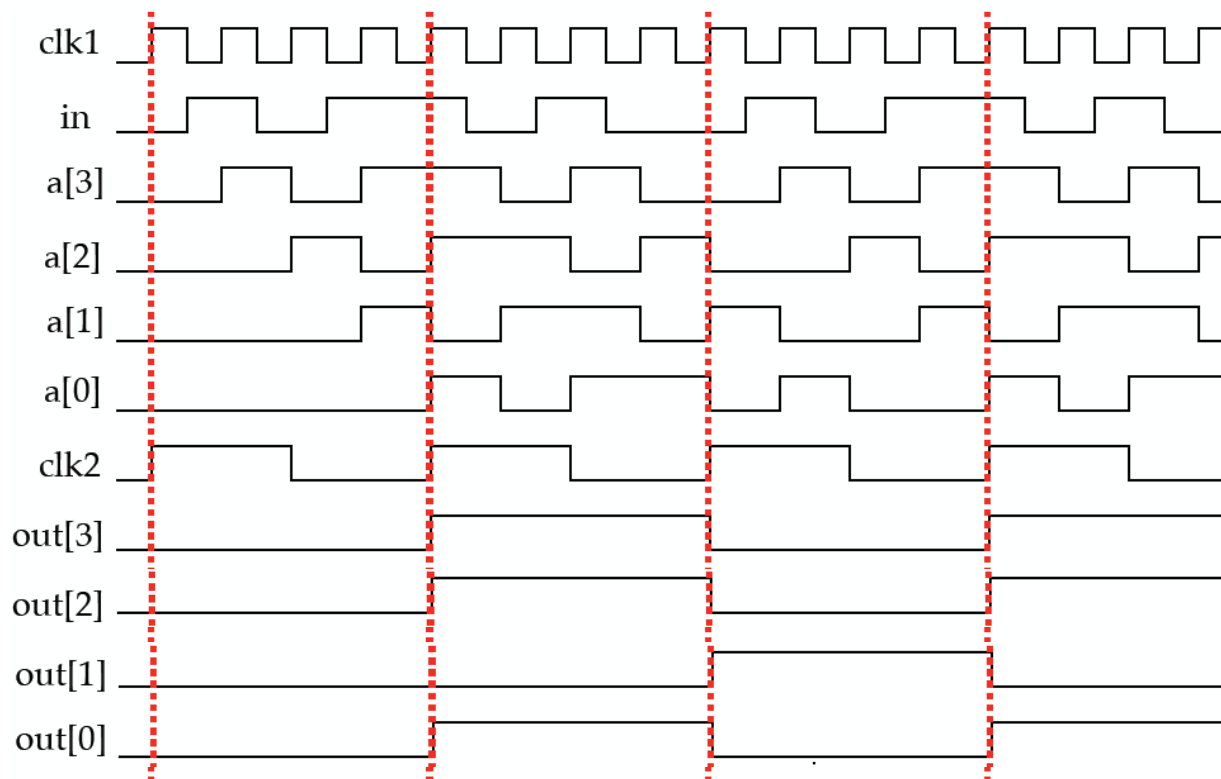
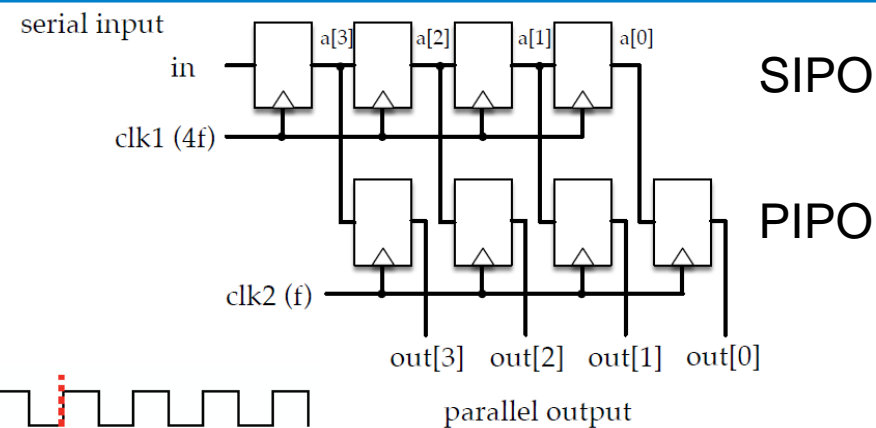
- Serial
  - One bit a time
  - Need more time, low complexity
- Parallel
  - All bits at the same time
  - Transfer faster, higher complexity





# Serial to Parallel Converter

- clk for SIPO is faster

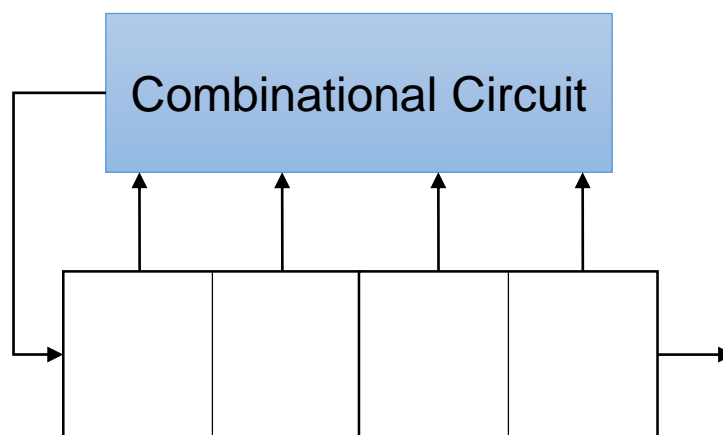


# Outline

- Various types of registers
- **Sequence generator with shift register**
- Asynchronous counter
- Synchronous counter
- Design a synchronous counter

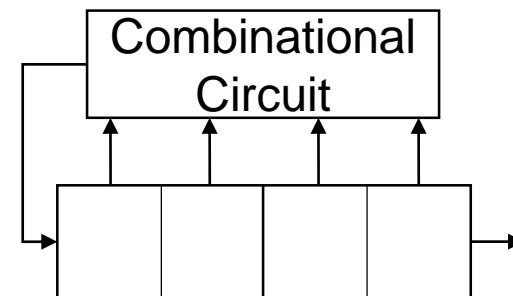
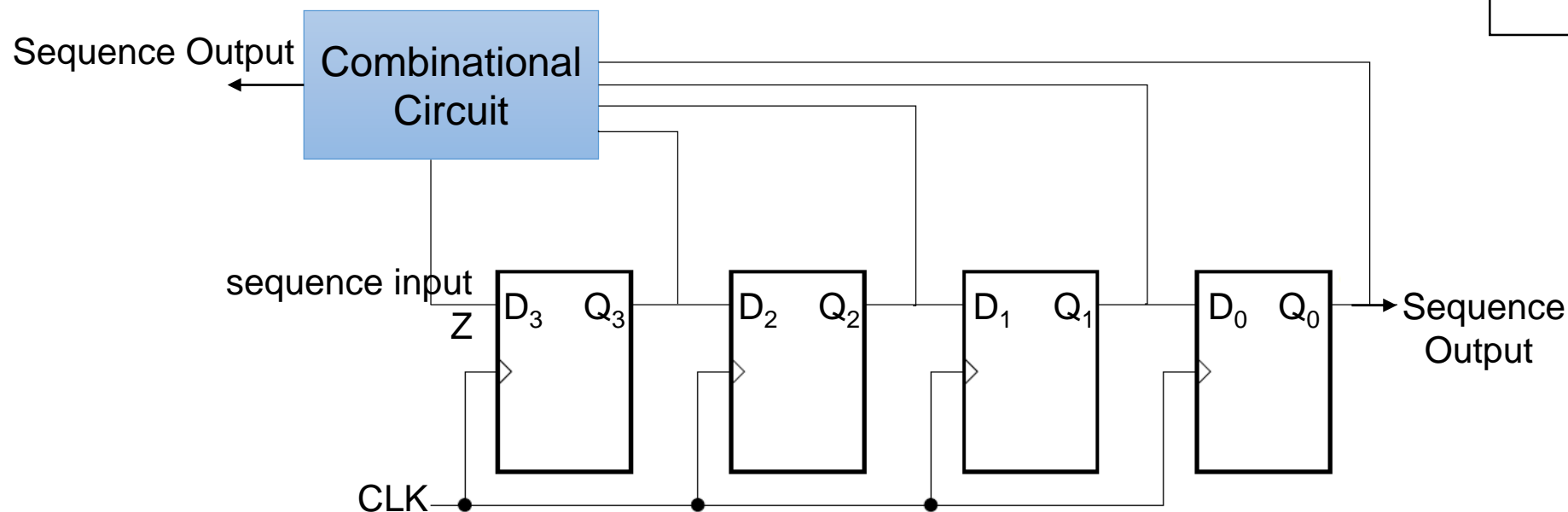
# Sequence Generator

- A sequence generator is a circuit that generates a desired sequence of bits in synchronization with a clock.
- Can be used as a random bit generator, code generator, and prescribed period generator.
- The output of the combinational circuit is a function of the shift register state and is connected to the serial input of the shift register



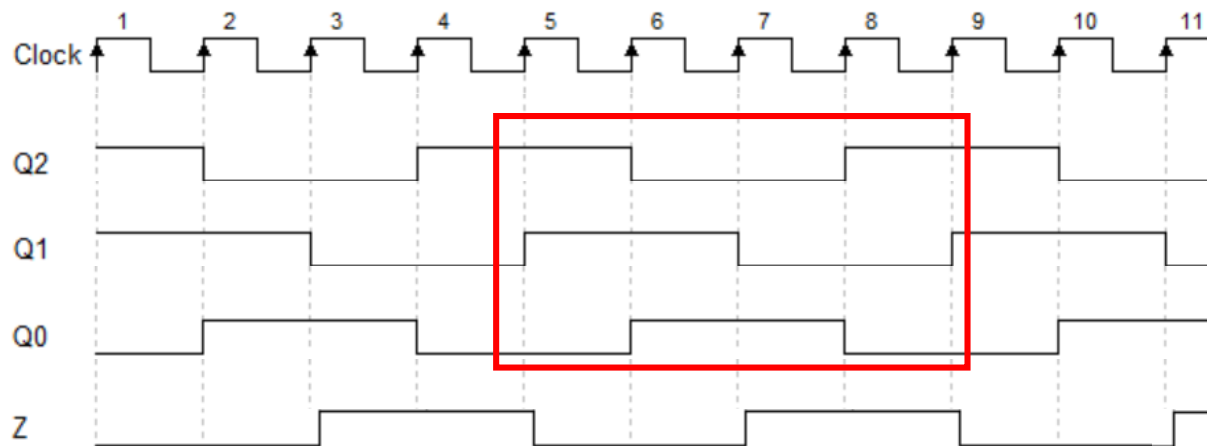
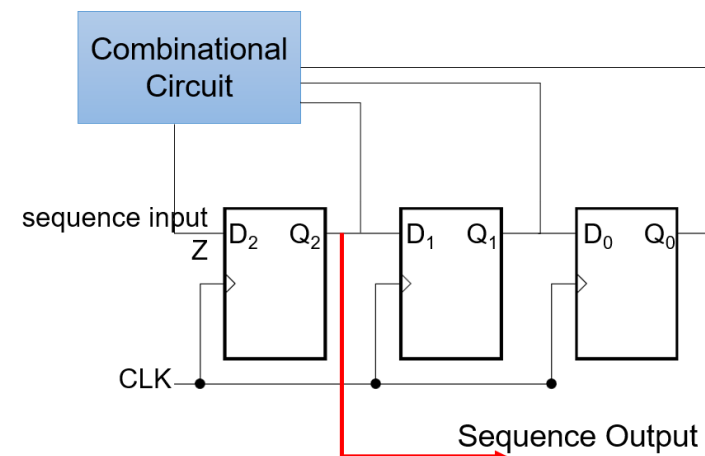
# Sequence Generator

- $n$  FFs can generate a sequence with the length of  $N \leq 2^n - 1$
- The required sequence can be obtained from the output of any FF, or the output of the combinational circuit



# Example: Design a 4-bit Sequence Generator

- Design of a sequence generator to generate a sequence of **1001**. (MSB is first generated)
  - The minimum number of flip-flops required to generate a sequence of length  $N$  is given by  $N \leq 2^n - 1 \rightarrow n = 3$  (3 FFs)
  - Noted all zero's state is excluded to avoid that circuit being stuck in this state.



	FF's outputs			Serial Input
Clk	Q <sub>2</sub>	Q <sub>1</sub>	Q <sub>0</sub>	Z
↑	1	1	0	
↑	0	1	1	
↑	0	0	1	
↑	1	0	0	

# Example: Design a 4-bit Sequence Generator

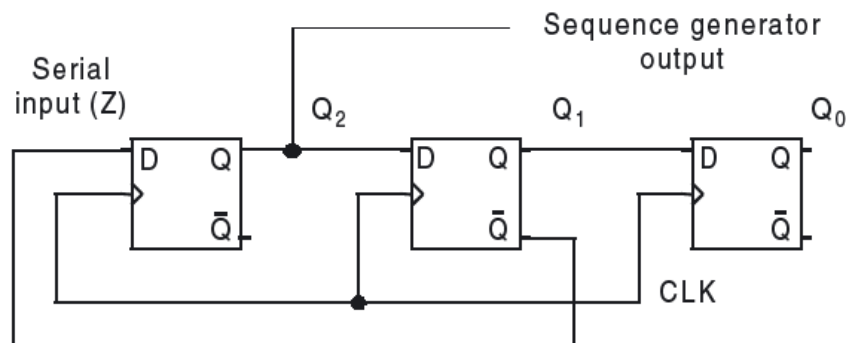
- Design of a sequence generator to generate a sequence of **1001**. (MSB is first generated)
  - The minimum number of flip-flops required to generate a sequence of length  $N$  is given by  $N \leq 2^n - 1 \rightarrow n = 3$  (3 FFs)

CLK	Z	$Q_2$	$Q_1$	$Q_0$
↑	0	1	1	0
↑	0	0	1	1
↑	1	0	0	1
↑	1	1	0	0

CLK	$Q_2$	$Q_1$	$Q_0$	Z
↑	1	1	0	0
↑	0	1	1	0
↑	0	0	1	1
↑	1	0	0	1

$Q_1Q_0$		00	01	11	10
$Q_2$	0	X	1	0	X
	1	1	X	X	0

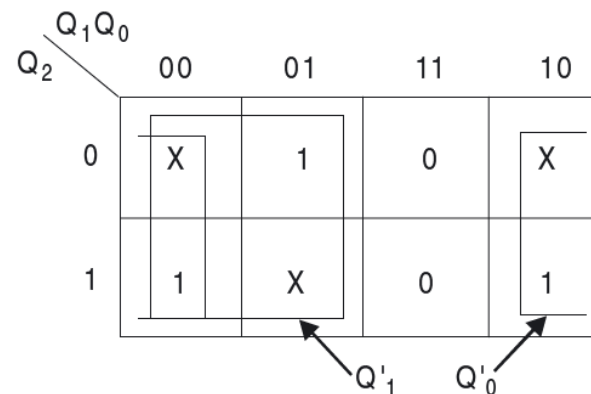
$$Z = Q_1'$$



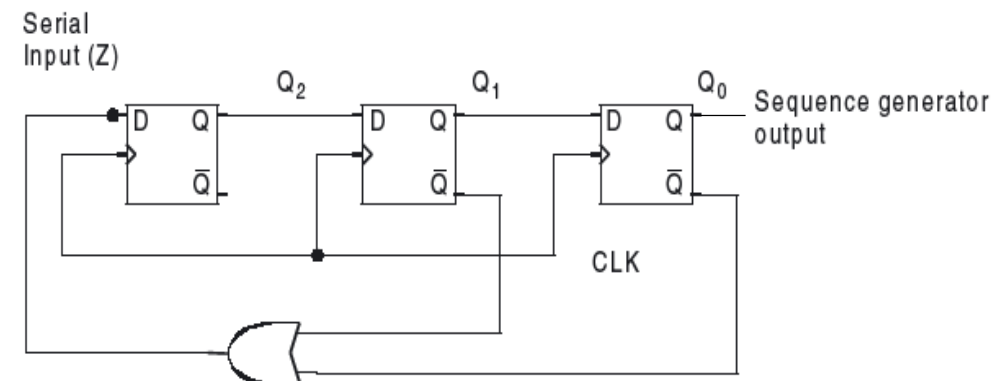
# Example: Design a 5-bit Sequence Generator

- Design of a sequence generator to generate a sequence of **10011**. (MSB is first generated)
  - The minimum number of flip-flops required to generate a sequence of length  $N$  is given by  $N \leq 2^n - 1 \rightarrow n = 3$  (3 FFs)

	FF's outputs			Serial Input
CLK	$Q_2$	$Q_1$	$Q_0$	$Z$
↑	1	1	1	0
↑	0	1	1	0
↑	0	0	1	1
↑	1	0	0	1
↑	1	1	0	1



$$Z = Q_1' + Q_0'$$



# Example: Design a 6-bit Sequence Generator

- Design of a sequence generator to generate a sequence of **110101** (MSB is first generated)
  - The minimum number of flip-flops required to generate a sequence of length  $N$  is given by  $N \leq 2^n - 1$
  - The minimum value of  $n$  to satisfy the above condition is 3.

CLK	$Q_2$	$Q_1$	$Q_0$	Z
↑	1	1	0	
↑	1	1	1	
↑	0	1	1	
↑	1	0	1	
↑	0	1	0	
↑	1	0	1	

State 101 occurs twice!

3 flip-flops are not sufficient to generate the given sequence.



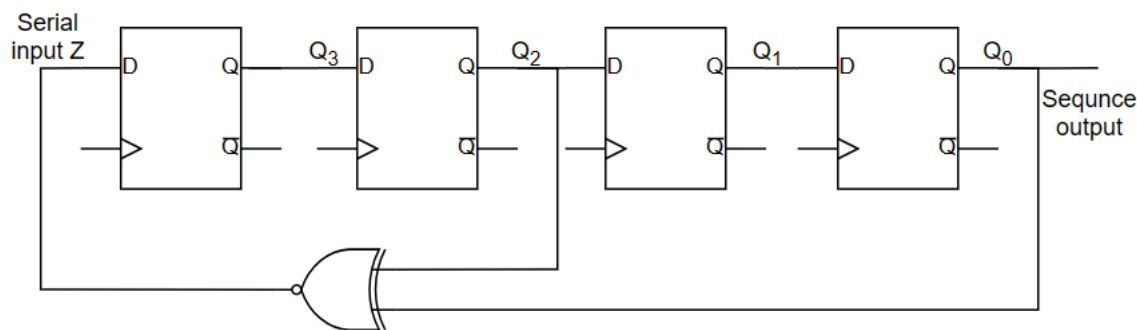
# Example: Design a 6-bit Sequence Generator

- Needs 4 FFs to generate 110101

clk	Q <sub>3</sub>	Q <sub>2</sub>	Q <sub>1</sub>	Q <sub>0</sub>	Z
↑	1	1	0	1	1
↑	1	1	1	0	0
↑	0	1	1	1	1
↑	1	0	1	1	0
↑	0	1	0	1	1
↑	1	0	1	0	1

		Q <sub>1</sub> Q <sub>0</sub>			
		00	01	11	10
Q <sub>3</sub> Q <sub>2</sub>	00	X	X	X	X
	01	X	1	1	X
	11	X	1	X	0
	10	X	X	0	1

$$Z = Q_2Q_0 + Q_2'Q_0' = (Q_2 \oplus Q_0)'$$



# Outline

- Various types of registers
- Sequence generator with shift register
- **Asynchronous counter**
- Synchronous counter
- Design a synchronous counter

# Counters

- A counter is a special type of register that counts upward, downward, or in any pre-specified sequence
  - Ripple counters (asynchronous counter)
    - The output transition of flip-flop serves as a source for triggering other flip-flops
  - Synchronous counters
    - The clock inputs of all flip-flops receive a common clock

# Asynchronous Counters

- aka. Serial or ripple counters
- All the flip-flops are not driven by the same clock pulse.
  - The successive flip-flop is triggered by the output of the previous flip-flop.
  - Hence the counter has cumulative settling time, which limits its speed of operation

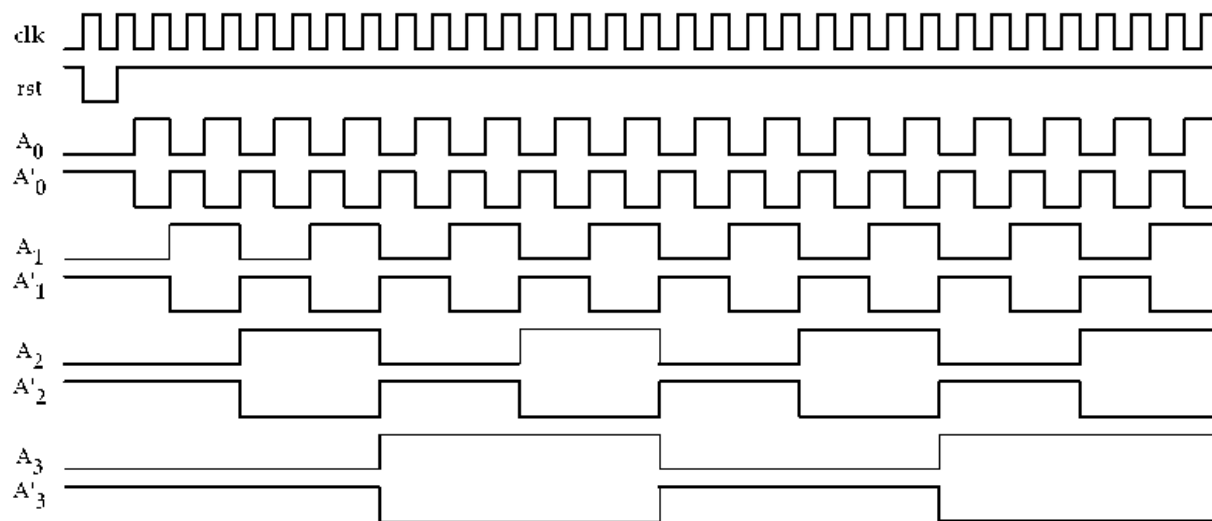


# 4-bit Binary Ripple Counter

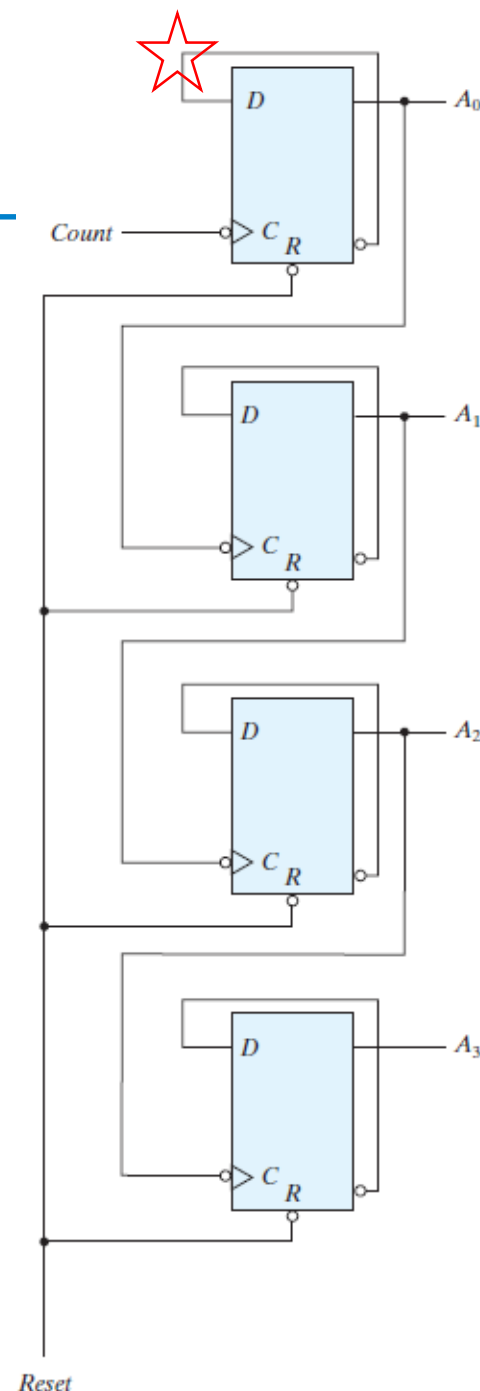
- Binary Up count sequence

$A_3$	$A_2$	$A_1$	$A_0$
0	0	0	0
0	0	0	1
0	0	1	0
0	0	1	1
0	1	0	0
0	1	0	1
0	1	1	0
0	1	1	1
1	0	0	0

- Timing diagram

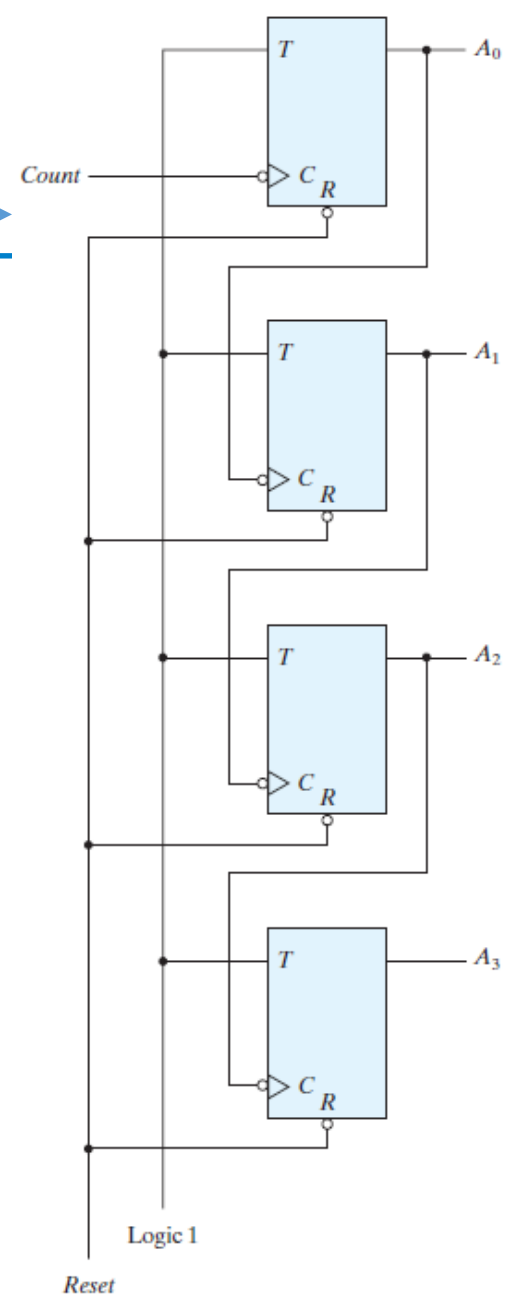
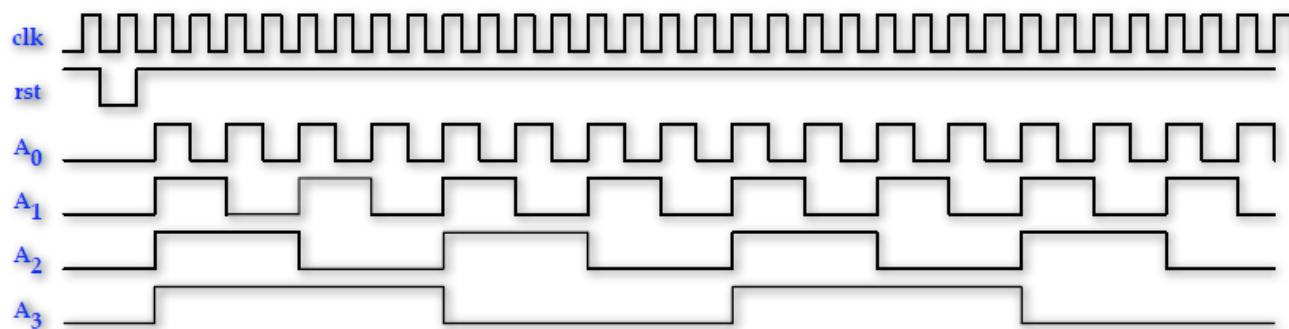


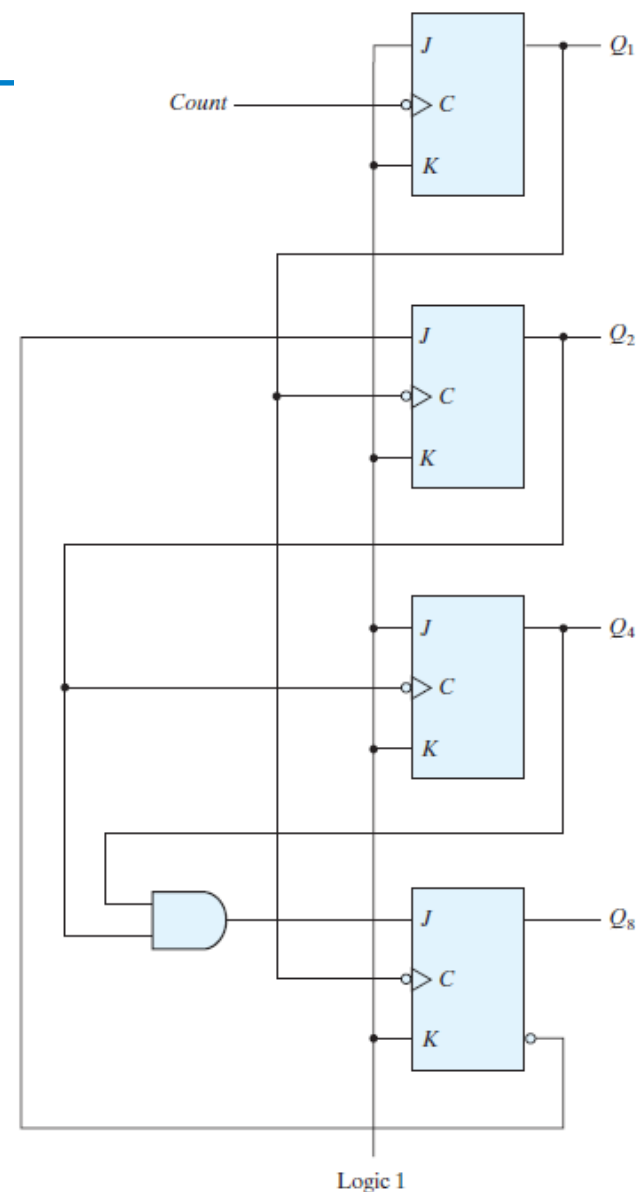
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# 4-bit Binary Ripple Counter

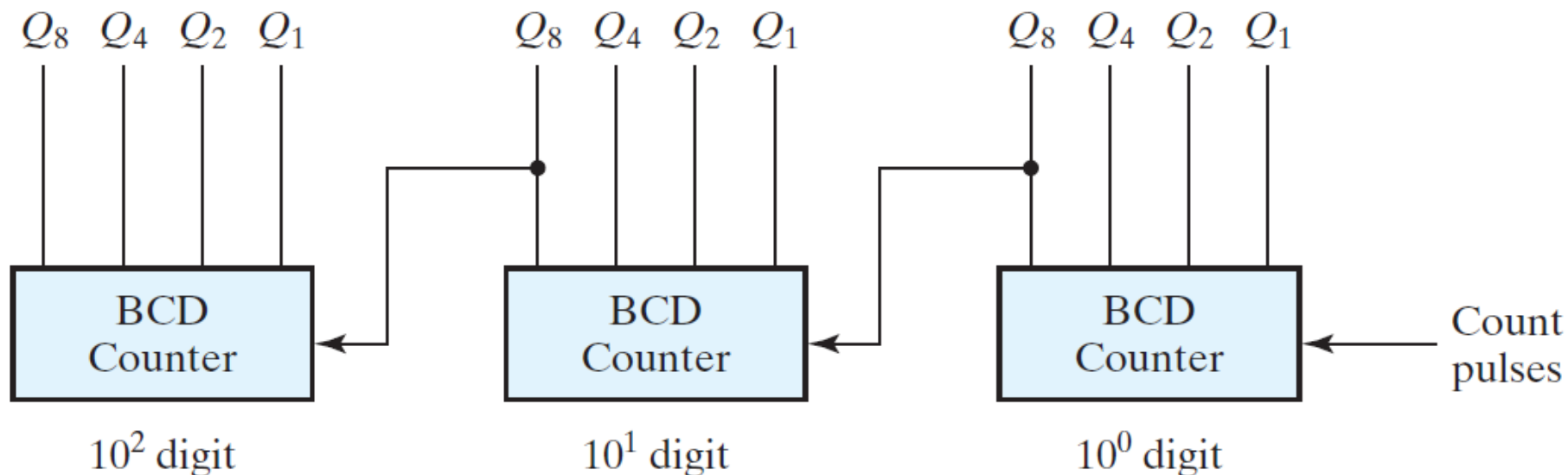
- Binary Up counter using TFF
- What if design a down counter?
  - just replace negative-edge triggered clock with positive-edge triggered clock





# Three-decade BCD Ripple Counter

- When  $Q_8$  in one decade goes from 1 to 0, it triggers the count for the next higher decade while it's own decade goes from 9 to 0.





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- Design a synchronous counter

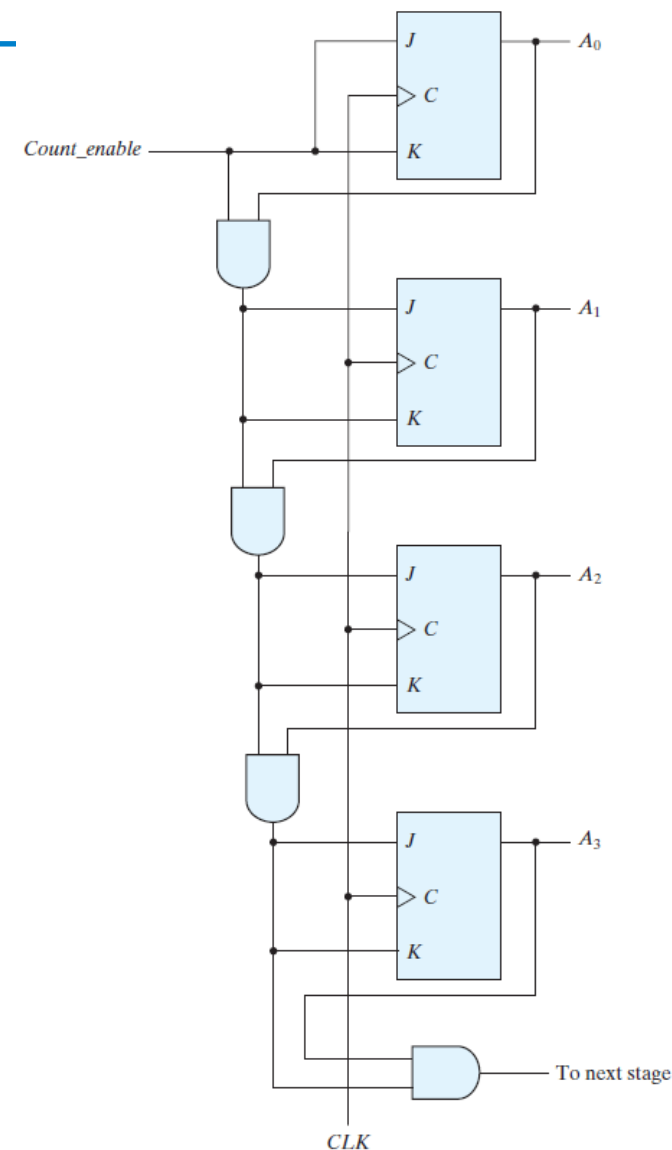
# Synchronous counters

- The ripple or asynchronous counter is the simplest to build, but its highest operating frequency is limited because of ripple action.
  - delay time
  - glitches
- Both of these problems can be overcome, if all the flip-flops are clocked synchronously.
- The resulting circuit is known as a synchronous counter.

# 4-bit Synchronous Binary Counters

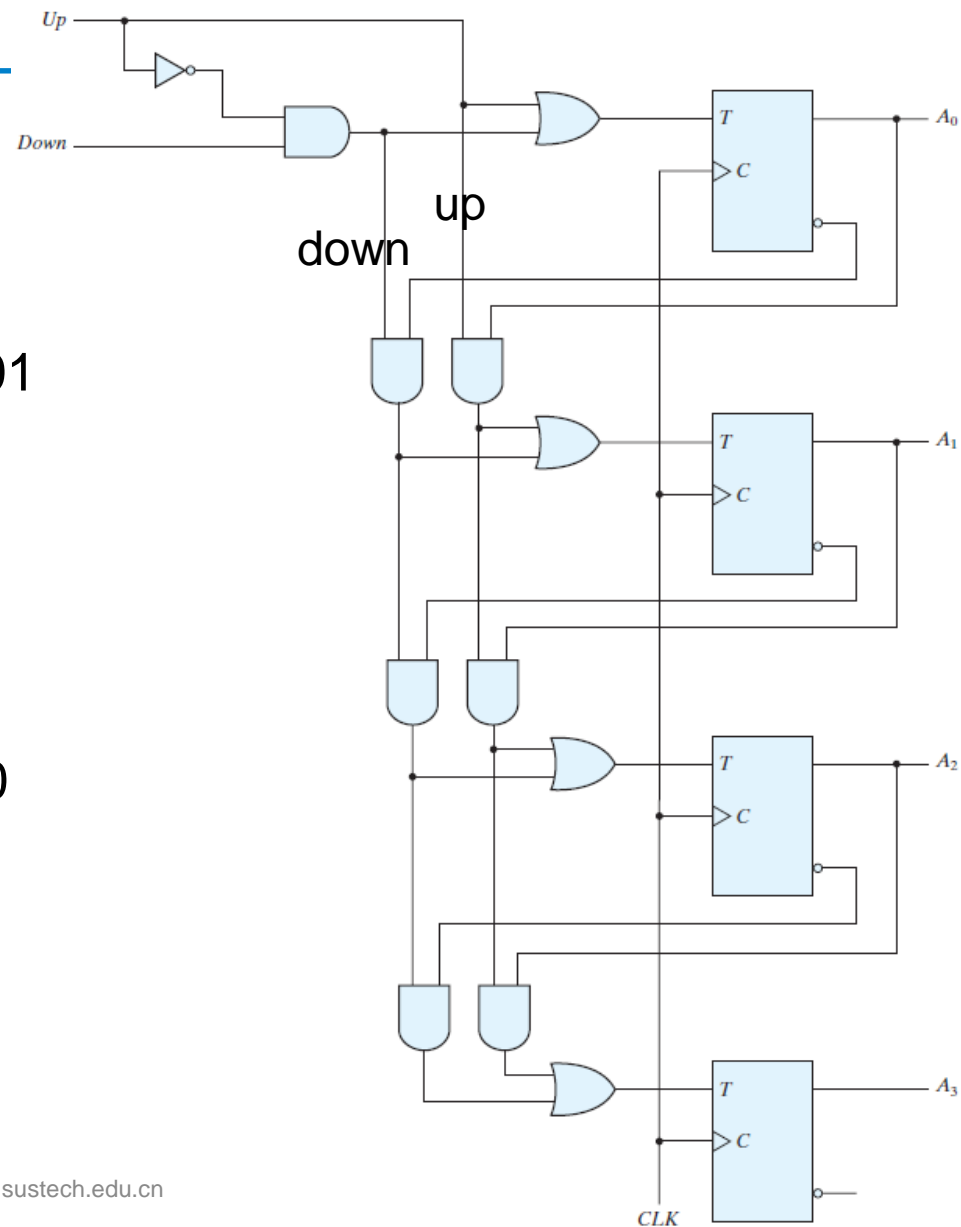
- Count up
  - As the number of stages increases, the number of AND gates also increases, along with the number of inputs for each of those AND gates.

$A_3$	$A_2$	$A_1$	$A_0$
0	0	0	0
0	0	0	1
0	0	1	0
0	0	1	1
0	1	0	0
0	1	0	1
0	1	1	0
0	1	1	1
1	0	0	0



# 4-bit Up/Down Binary Counter

- Up=1, Down=0 =>
  - counting up
  - $A_3A_2A_1A_0$
  - $0000 \rightarrow 0001 \rightarrow 0010 \rightarrow 0011 \rightarrow 0100 \rightarrow 0101$
- Up=0, Down=1 =>
  - counting down
  - $A_3A_2A_1A_0$
  - $1111 \rightarrow 1110 \rightarrow 1101 \rightarrow 1100 \rightarrow 1011 \rightarrow 1010$

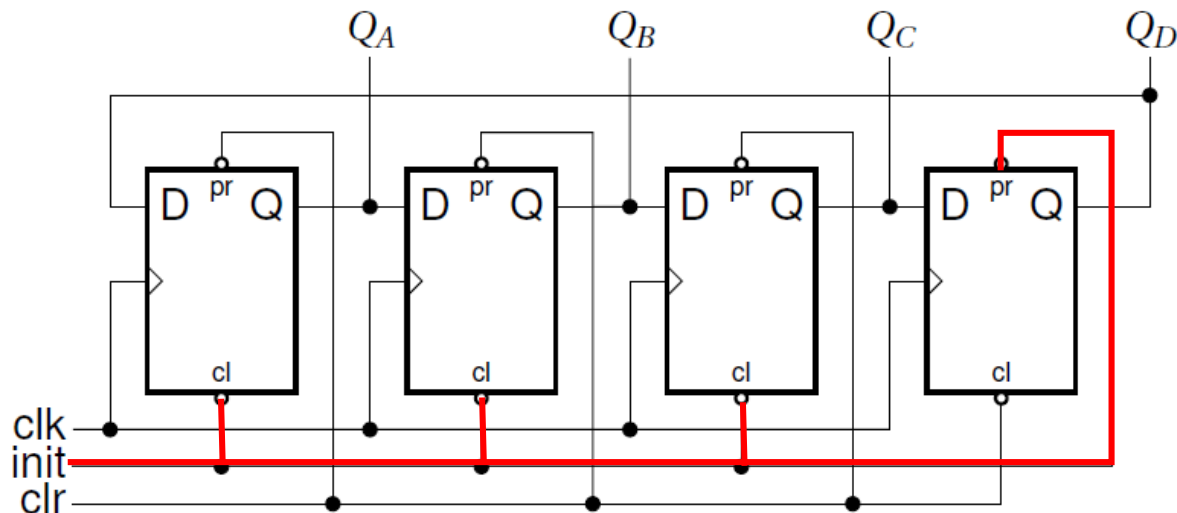


# Shift Register Counters

- Shift registers may be arranged to form different types of counters.
- These shift registers use feedback, where the output of the last flip-flop in the shift register is fed back to the first flip-flop.
- Based on the type of this feedback connection, the shift register counters are classified as
  - ring counter
  - switch-tail ring counter or Johnson counter

# Ring Counter

- A circular shift register with only one flip-flop being set at any particular time, all others are cleared. (initial value 0001 as in example)
- The single bit is shifted from one flip-flop to the next to produce the sequence of timing signals

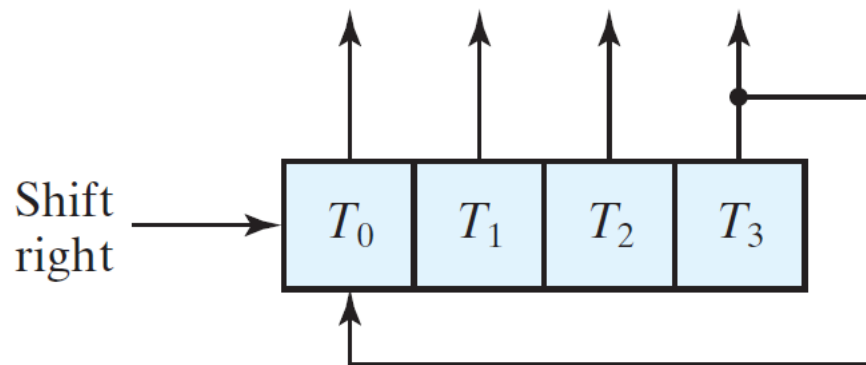


1000 → 0100 → 0010 → 0001

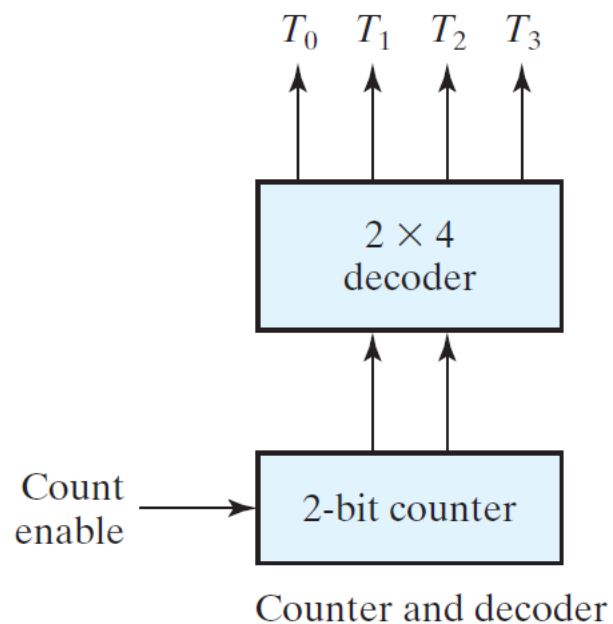
init	clk	$Q_A$	$Q_B$	$Q_C$	$Q_D$
L	X	0	0	0	1
H	↑	1	0	0	0
H	↑	0	1	0	0
H	↑	0	0	1	0
H	↑	0	0	0	1

init	clk	$Q_A$	$Q_B$	$Q_C$	$Q_D$
L	X	0	0	0	1
H	↑	1	0	0	0
H	↑	0	1	0	0
H	↑	0	0	1	0
H	↑	0	0	0	1

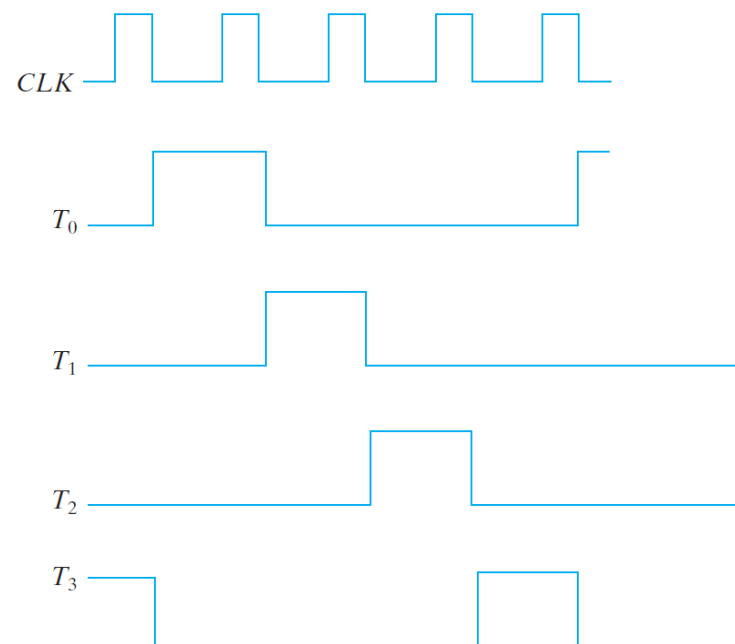
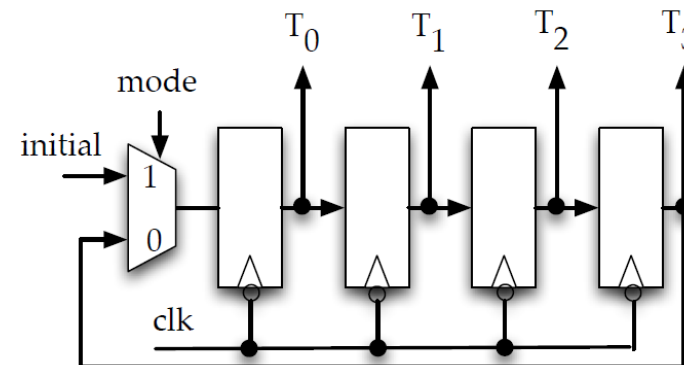
# Ring Counter for Decoder



Ring-counter (initial value = 1000)



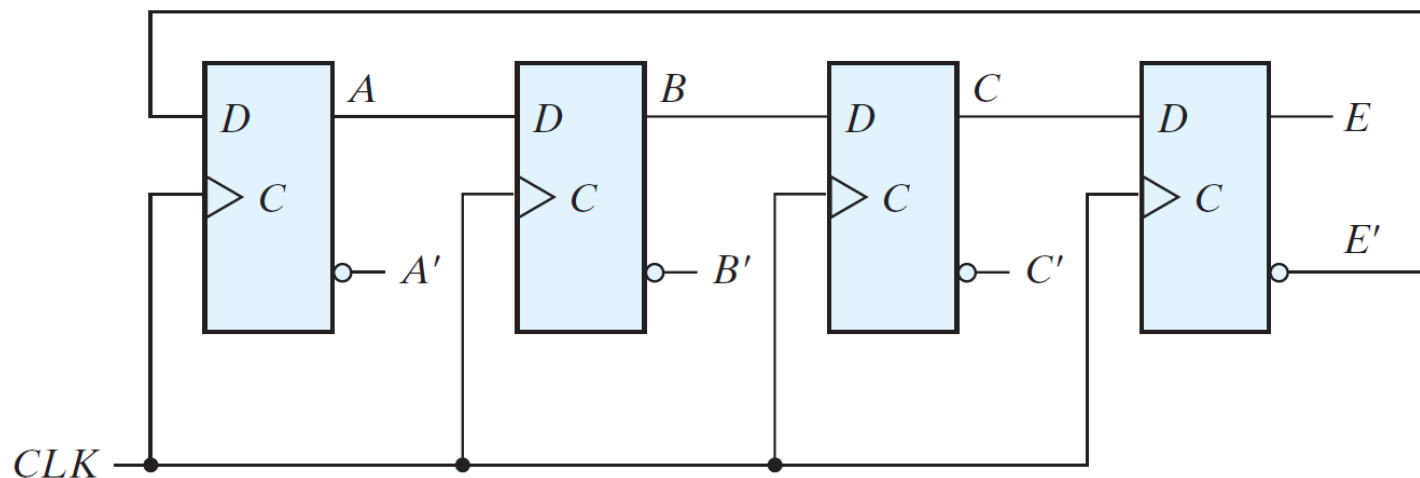
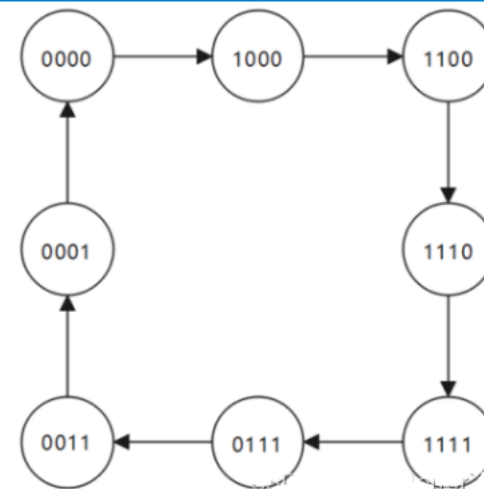
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Sequence of four timing signals

# Johnson counter

- Switch-tail ring counter: a circular shift register with its complement output of the last flip-flop connected to the input of the first flip-flop
- Johnson counter is a k-bit switch-tail ring counter will go through a sequence of  $2k$  distinguishable states (initial value 0000 as in example)

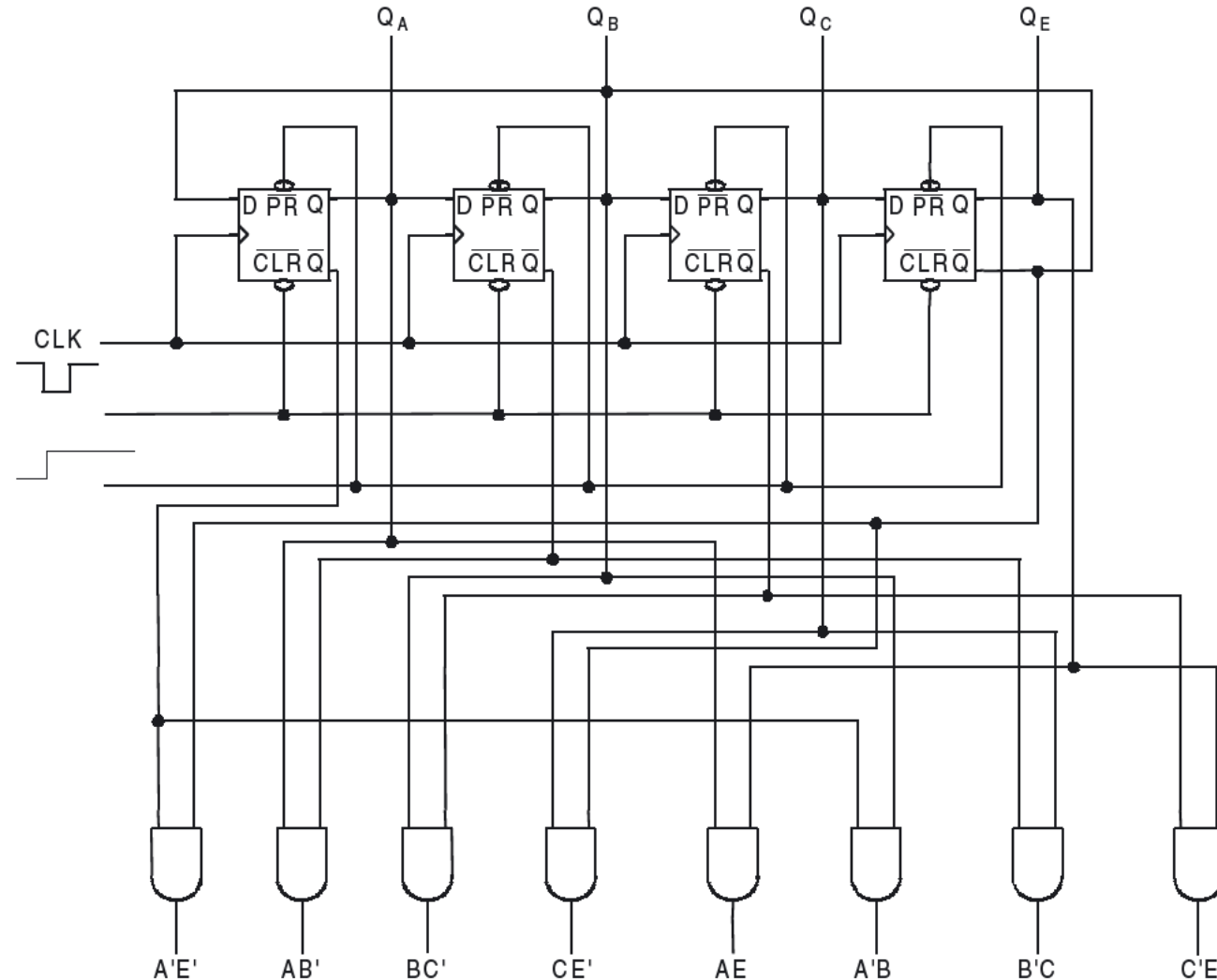


Sequence number	Flip-flop outputs			
	A	B	C	E
1	0	0	0	0
2	1	0	0	0
3	1	1	0	0
4	1	1	1	0
5	1	1	1	1
6	0	1	1	1
7	0	0	1	1
8	0	0	0	1



# Johnson counter for decoder

- Using AND gates for one-hot outputs



AND gate required  
for output

$A'E'$   
 $AB'$   
 $BC'$   
 $CE'$   
 $AE$   
 $A'B$   
 $B'C$   
 $C'E$

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- **Design a synchronous counter**

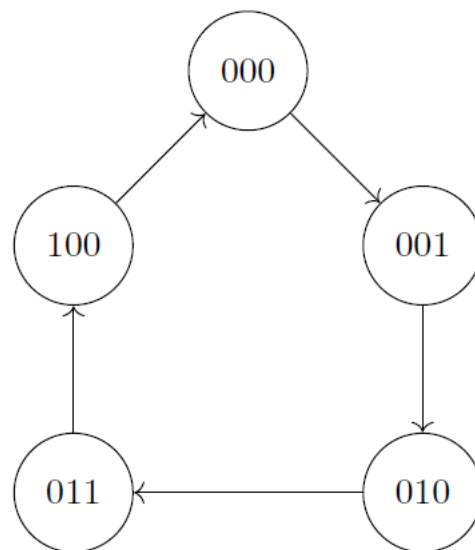
# Design a Synchronous Counter

Recall: Design Procedure of Sequential Circuits

1. Specification: design description or timing diagram
2. Formulation: develop state diagram
3. Generate next-state table in form of count sequence
4. Choose type of Flip-Flop
5. Derive simplified excitation equations of FFs
6. Draw logic diagram

# Modulo-N Counter

- Counters can be designed to generate any desired sequence of states. A divide-by-N counter (also known as a modulo- N counter)
- e.g. mod-5 counter
  - A counter that goes through the following binary repeated sequence: 0, 1, 2, 3, 4, 0, 1, 2, ...

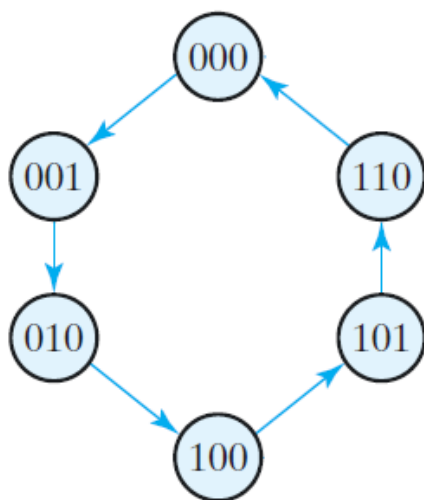


# Counters with Unused States

- $n$  flops  $\Rightarrow 2^n$  states
- Unused states
  - States that are not used in specifying the FSM, may be treated as don't-care conditions or may be assigned specific next states
- Self-correcting counters
  - Ensure that when a circuit enter one of its unused states, it eventually goes into one of the valid states after one or more clock pulses so that it can resume normal operation
  - Analyze the circuit to determine the next state from an unused state after it is designed

# Example: Counters with Unused States

- Design a counter that goes through the following binary repeated sequence:  
0, 1, 2, 4, 5, 6
  - The unused state is 011 & 111, they are considered as don't care conditions.



Present State			Next State			Flip-Flop Inputs					
A	B	C	A	B	C	$J_A$	$K_A$	$J_B$	$K_B$	$J_C$	$K_C$
0	0	0	0	0	1	0	X	0	X	1	X
0	0	1	0	1	0	0	X	1	X	X	1
0	1	0	1	0	0	1	X	X	1	0	X
0	1	1	X	X	X	X	X	X	X	X	X
1	0	0	1	0	1	X	0	0	X	1	X
1	0	1	1	1	0	X	0	1	X	X	1
1	1	0	0	0	0	X	1	X	1	0	X
1	1	1	X	X	X	X	X	X	X	X	X

# Example: Counters with Unused States

$A \backslash BC$	00	01	11	10
0	0	0	$x$	1
1	$x$	$x$	$x$	$x$

$J_A$

$A \backslash BC$	00	01	11	10
0	0	1	$x$	$x$
1	0	1	$x$	$x$

$J_B$

$A \backslash BC$	00	01	11	10
0	1	$x$	$x$	0
1	1	$x$	$x$	0

$J_C$

$A \backslash BC$	00	01	11	10
0	$x$	$x$	$x$	$x$
1	0	0	$x$	1

$K_A$

$A \backslash BC$	00	01	11	10
0	$x$	$x$	$x$	1
1	$x$	$x$	$x$	1

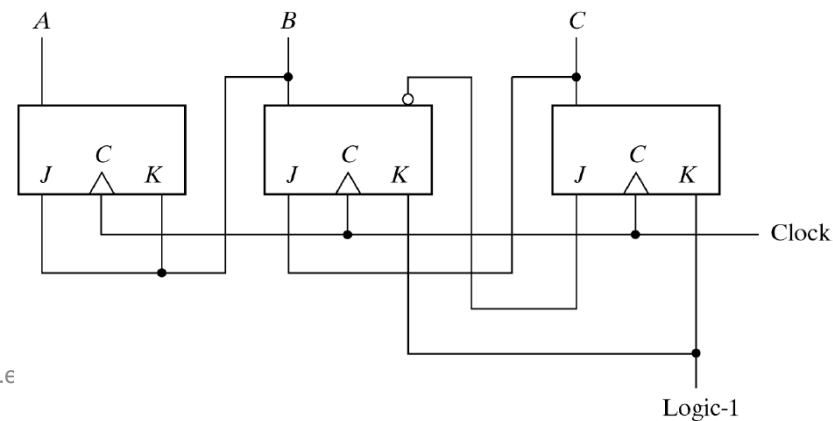
$K_B$

$A \backslash BC$	00	01	11	10
0	$x$	1	$x$	$x$
1	$x$	1	$x$	$x$

$K_C$

- $J_A = B$
- $J_B = C$
- $J_C = B'$

- $K_A = B$
- $K_B = 1$
- $K_C = 1$



# Example: Counters with Unused States

- Unused state & Self-correcting

- What happen if the circuit gets into unused state 011 or 111 because of an error signal?
- Let's analyze the state transition
- $J_A = B$                        $K_A = B$
- $J_B = C$                        $K_B = 1$
- $J_C = B'$                        $K_C = 1$

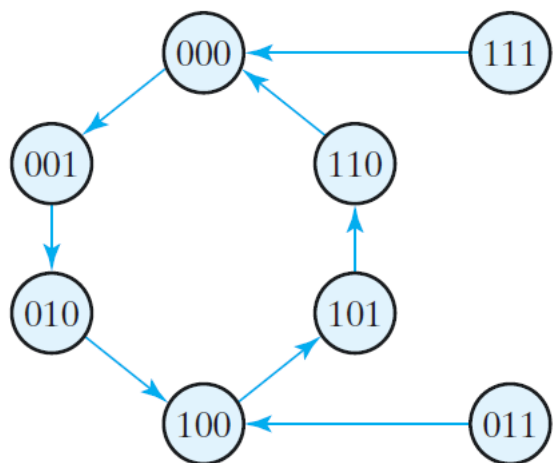
Present Stat			Next State			Flip-Flop Inputs					
A	B	C	A	B	C	$J_A$	$K_A$	$J_B$	$K_B$	$J_C$	$K_C$
0	1	1	1	0	0	1	1	1	1	0	1
1	1	1	0	0	0	1	1	1	1	0	1

- 100 and 000 are valid state, thus this is a self-correcting counter, it eventually reaches the normal count sequence after one or more clock pulses



# Example: Counters with Unused States

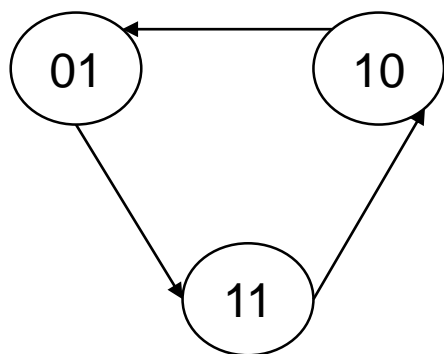
- An alternative design could use additional logic to direct every unused state to a specific next state, to make sure the counter is self-correcting
- To ensure that lock out does not occur, **assuming  $111 \rightarrow 000$ ,  $011 \rightarrow 100$** .



Present State			Next State			Flip-Flop Inputs					
A	B	C	A	B	C	$J_A$	$K_A$	$J_B$	$K_B$	$J_C$	$K_C$
0	0	0	0	0	1	0	X	0	X	1	X
0	0	1	0	1	0	0	X	1	X	X	1
0	1	0	1	0	0	1	X	X	1	0	X
0	1	1	1	0	0	1	X	X	1	X	1
1	0	0	1	0	1	X	0	0	X	1	X
1	0	1	1	1	0	X	0	1	X	X	1
1	1	0	0	0	0	X	1	X	1	0	X
1	1	1	0	0	0	X	1	X	1	X	1

# Lock out problem

- Taking another counter example: It may be possible that the counter might go from one unused state to another and never arrive at a used state.



A(t)	B(t)	A(t+1)	B(t+1)
0	1	1	1
1	1	1	0
1	0	0	1

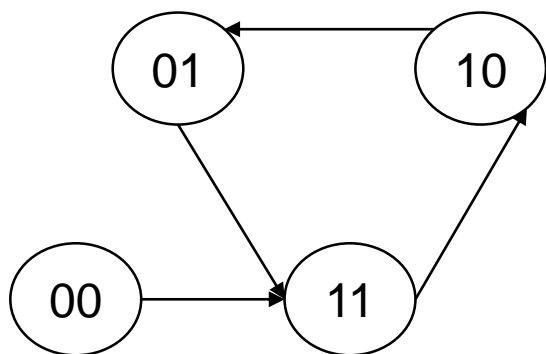
B	0	1
A		
0	x	1
1	0	1

B	0	1
A		
0	x	1
1	1	0

- $D_A = \Sigma(1,3), d = \Sigma(0)$
- $D_B = \Sigma(1,2), d = \Sigma(0)$
- $D_A = B, D_B = A \oplus B$
- If state is 00, then next state is still 00 (stuck at 00)

# Lock out problem

- Thus, the solution is to force state 00 transit to another valid state, for example 11

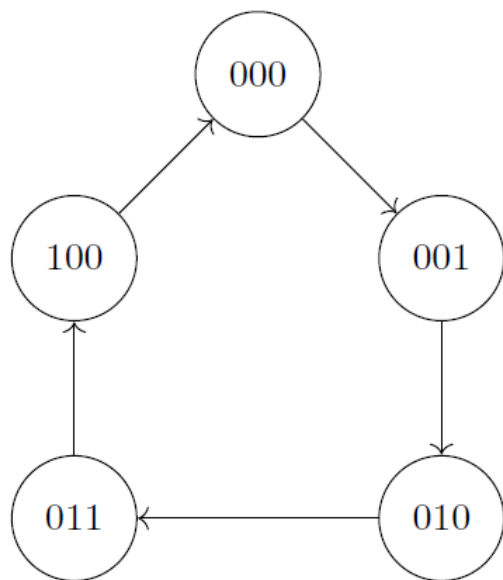


A(t)	B(t)	A(t+1)	B(t+1)
0	1	1	1
1	1	1	0
1	0	0	1
0	0	1	1

- $D_A = ?$ ,  $D_B = ?$

# Exercise: Design a mod-5 Counter

- mod-5 counter
  - A counter that goes through the following binary repeated sequence: 0, 1, 2, 3, 4, 0, 1, 2, ...



Present			Next			Flip-flop Inputs					
$A_2$	$A_1$	$A_0$	$A_2$	$A_1$	$A_0$	$J_{A2}$	$K_{A2}$	$J_{A1}$	$K_{A1}$	$J_{A0}$	$K_{A0}$
0	0	0	0	0	1	0	X	0	X	1	X
0	0	1	0	1	0	0	X	1	X	X	1
0	1	0	0	1	1	0	X	X	0	1	X
0	1	1	1	0	0	1	X	X	1	X	1
1	0	0	0	0	0	X	1	0	X	0	X

# Exercise: Design a mod-5 Counter

$A_2$	$A_1 A_0$			
	00	01	11	10
0			1	
1	X	X	X	X

$$J_{A2} = A_1 A_0$$

$A_2$	$A_1 A_0$			
	00	01	11	10
0		1	X	X
1		X	X	X

$$J_{A1} = A_0$$

$A_2$	$A_1 A_0$			
	00	01	11	10
0	1	X	X	1
1		X	X	X

$$J_{A0} = A_2'$$

$A_2$	$A_1 A_0$			
	00	01	11	10
0	X	X	X	X
1	1	X	X	X

$$K_{A2} = 1$$

$A_2$	$A_1 A_0$			
	00	01	11	10
0	X	X	1	
1	X	X	X	X

$$K_{A1} = A_0$$

$A_2$	$A_1 A_0$			
	00	01	11	10
0	X	1	1	X
1	X	X	X	X

$$K_{A0} = 1$$

# Exercise: Design a mod-5 Counter

- Check the unused state, we confirm that all three unused states results in a valid state after one cycle. It is by nature a self-correcting counter.

Present Stat			Next State			Flip-Flop Inputs					
A2	A1	A0	A2	A1	A0	J <sub>2</sub>	K <sub>2</sub>	J <sub>1</sub>	K <sub>1</sub>	J <sub>0</sub>	K <sub>0</sub>
1	0	1	0	1	0	0	1	1	1	0	1
1	1	0	0	1	0	0	1	0	0	0	1
1	1	1	0	0	0	1	1	1	1	0	1

