

DIGITAL LOGIC

Chapter 5 part1: Latches and Flip-flops

2024 Fall

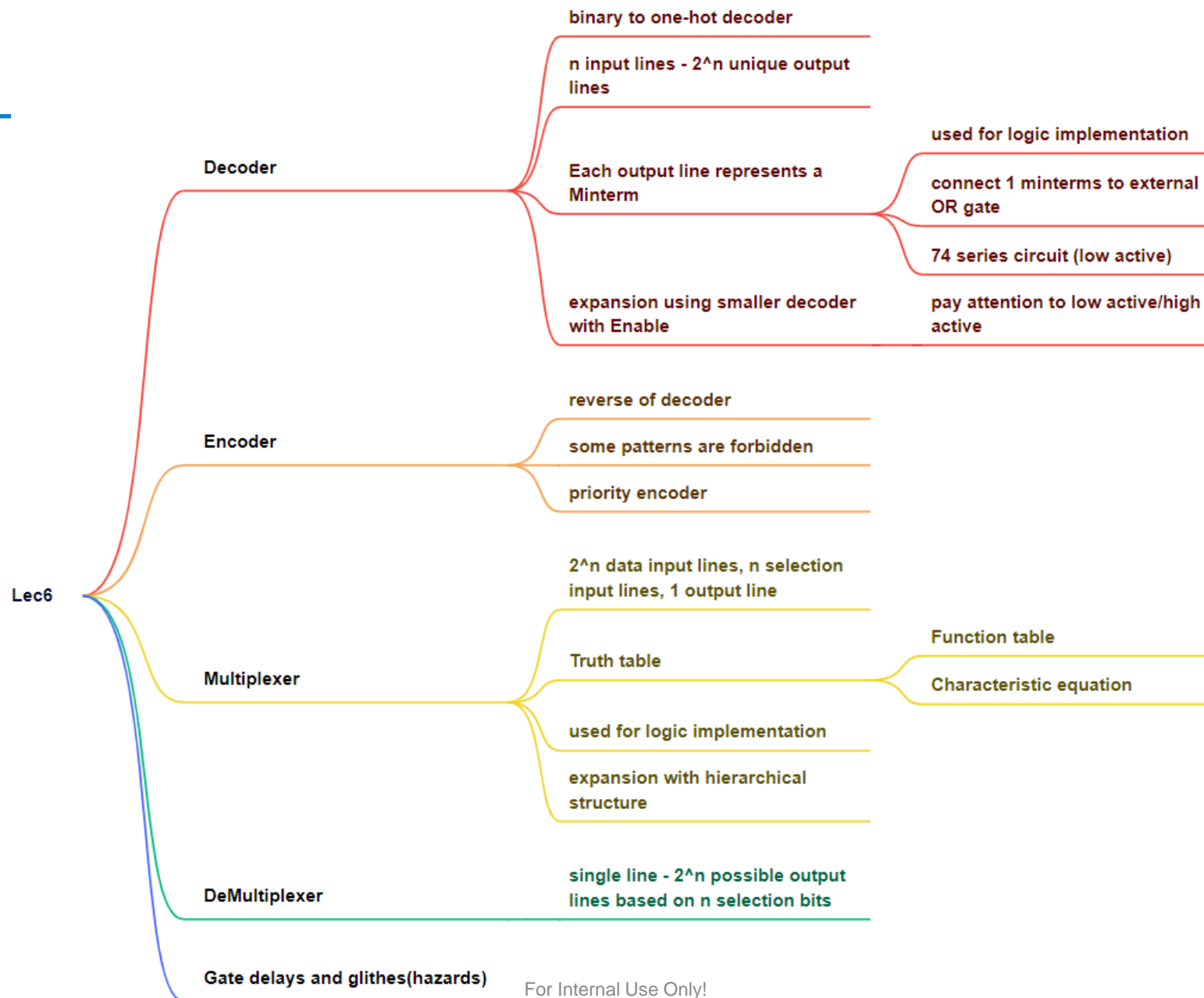
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Today's Agenda

- Recap
- Context
 - Latches
 - Flip-Flops
- Reading: Textbook, Chapter 5.1-5.4

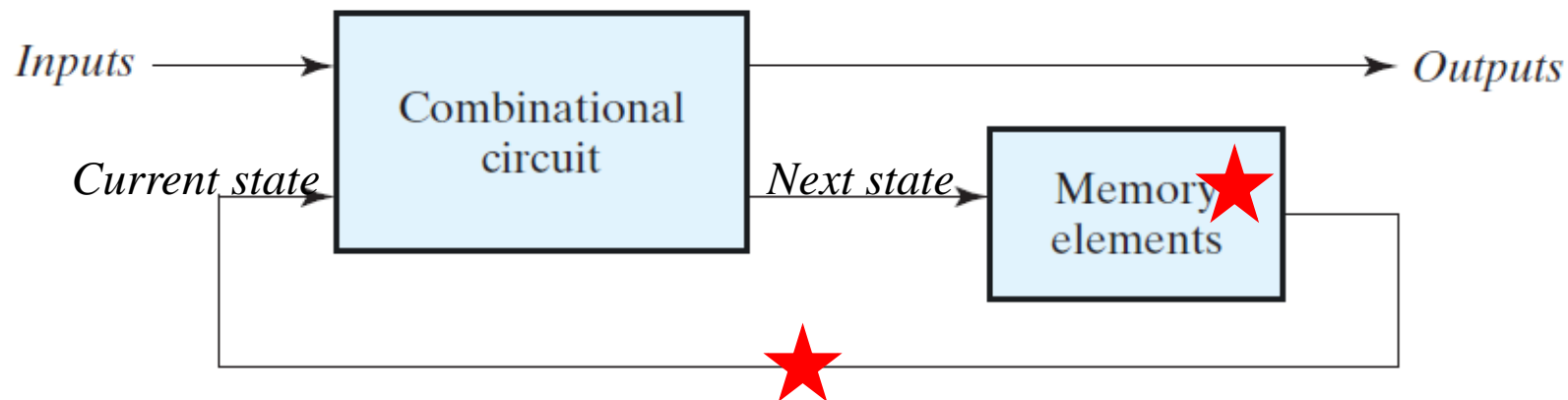


Recap



Sequential Circuits

- A sequential circuit consists of a combinational circuit to which storage elements are connected to form a feedback path.
 - The binary information stored in the memory elements at any given time defines the state of the sequential circuit.
 - (inputs, current state) \Rightarrow (outputs, next state)– The behavior is specified by a time sequence of inputs and internal states.

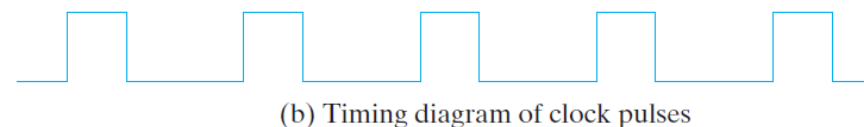
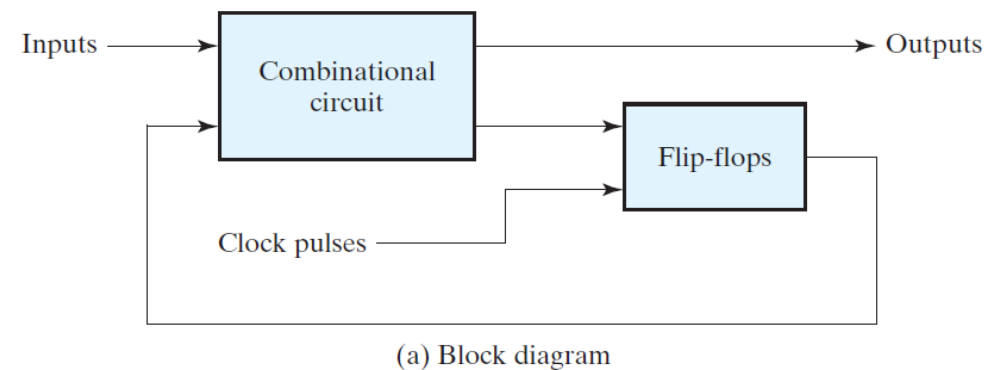
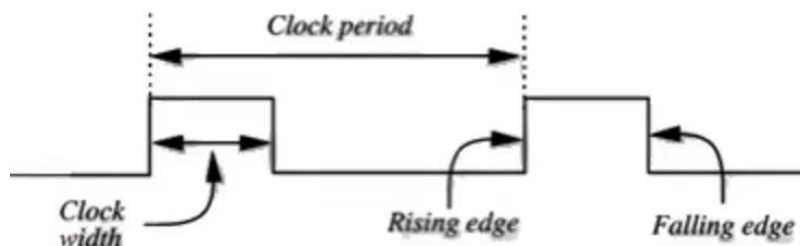


Synchronous vs. Asynchronous Sequential Circuits

- Sequential circuits are broadly classified into two main categories depending on the timing of their signals.
 - **Synchronous sequential circuit** (同步时序电路): A system whose behavior can be defined from the knowledge of its signals at discrete instants of time.
 - **Asynchronous sequential circuit** (异步时序电路): A system whose behavior depends upon input signals at any instant of time and the order in which the inputs change.
- Asynchronous circuit properties
 - Commonly used storage devices are time-delay devices, and the propagation delay of the logic gates (time-delay devices) provides the required storage.
 - Can be viewed as combinational circuit with feedback—May unstable at times

Synchronous Sequential Circuits

- Synchronization usually is achieved by a timing device: clock generator.
 - The outputs are affected only with the application of a clock pulse.
- Clock generator generates a periodic train of clock pulses distributed throughout the system to trigger the memory elements



Storage Elements

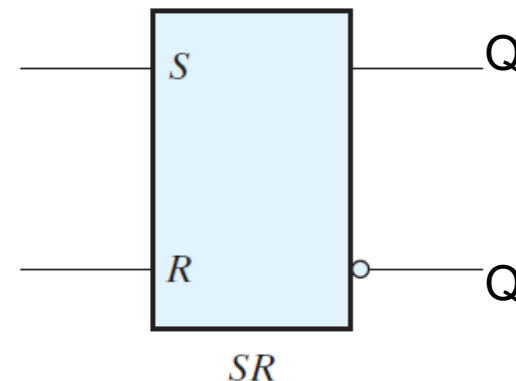
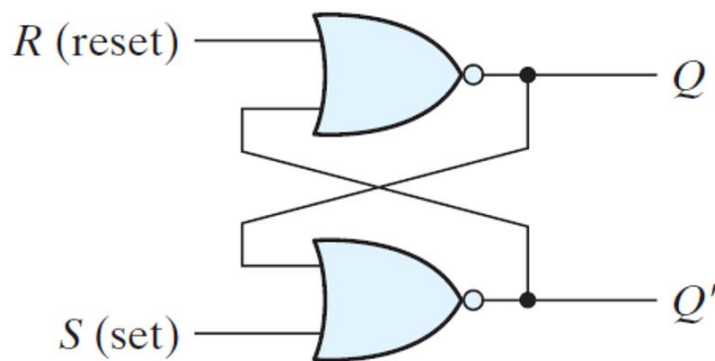
- Some definitions:
 - State: all the information about a circuit necessary to explain its future behavior
 - Latches and flip-flops: state elements that store one bit of state
 - SR Latch (SR锁存器)
 - D Latch (D锁存器)
 - D Flip-flop (DFF, D触发器)

Outline

- **Latches**
- FlipFlops

SR (Set/Reset) Latch

- Latch is an asynchronous sequential circuit (state changes whenever inputs change).
- SR latch is a basic memory element which can store one bit of information
 - Consists of two cross-coupled NOR gates or two cross-coupled NAND gates
 - Two input signals: set (S)/reset(R)
 - Two output signals: Q/Q'
 - Two useful states: set state ($Q=1, Q'=0$)/reset state ($Q=0, Q'=1$)



Basic SR Latch with NOR Gate

- Consider the four possible cases:

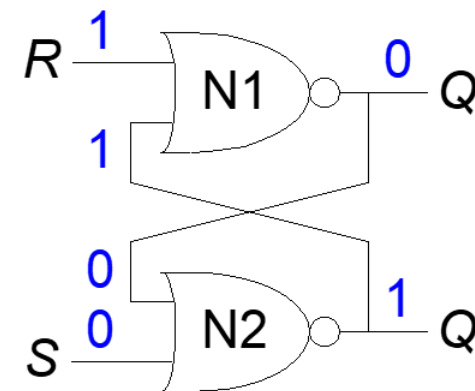
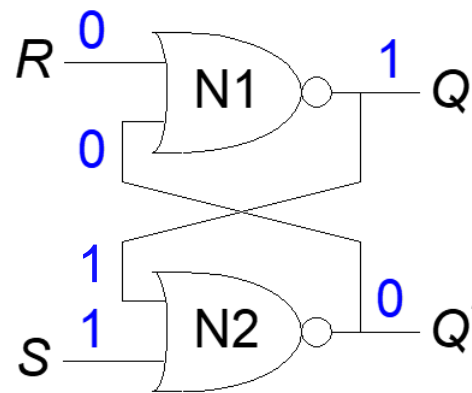
1. $S = 1, R = 0$
2. $S = 0, R = 1$
3. $S = 0, R = 0$
4. $S = 1, R = 1$

- 1. $S = 1, R = 0$:

- then $Q = 1$ and $Q' = 0$
- **Set the output**

- 2. $S = 0, R = 1$:

- then $Q = 0$ and $Q' = 1$
- **Reset the output**



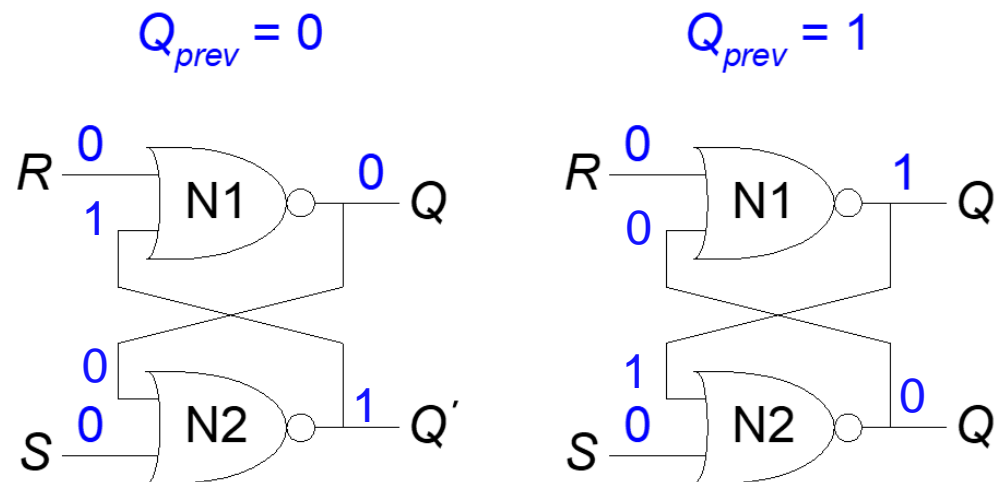
Basic SR Latch with NOR Gate

- Consider the four possible cases:

1. $S = 1, R = 0$
2. $S = 0, R = 1$
3. $S = 0, R = 0$
4. $S = 1, R = 1$

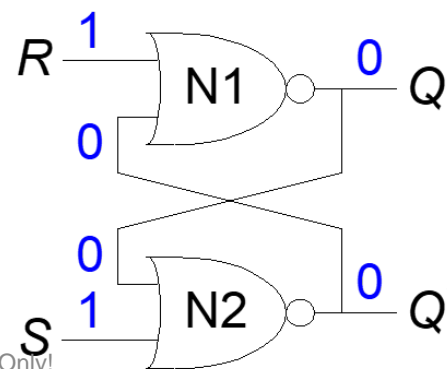
- 3. $S = 0, R = 0$:

- then $Q = Q_{prev}$
- **Memory!**



- 4. $S = 1, R = 1$:

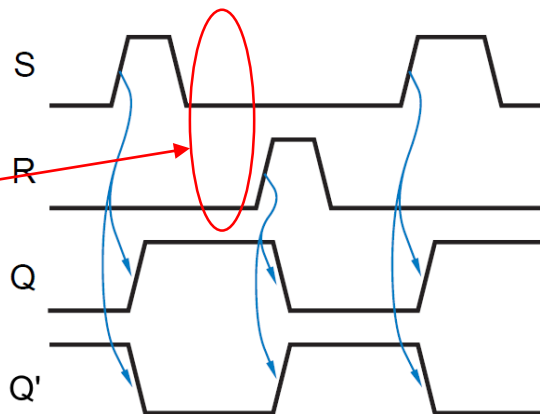
- then $Q = 0$ and $Q' = 0$
- **Invalid State!**
- **$Q' \neq \text{NOT } Q$**



Function Table of SR Latch

- SR Latch's functionality:
 - S is active \rightarrow Set
 - R is active \rightarrow Reset
 - S,R are inactive \rightarrow Memory
 - S,R are active \rightarrow Forbidden

(S,R) must go back to (0,0) before any other change to avoid the occurrence of the undefined state



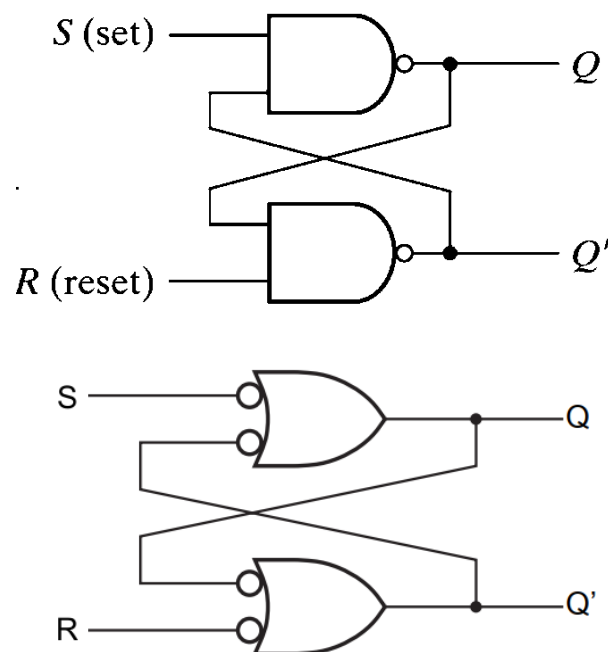
S	R	Q	Q'	
0	0	last Q	last Q'	no change
0	1	0	1	reset state
1	0	1	0	set state
1	1	0	0	forbidden

Function table

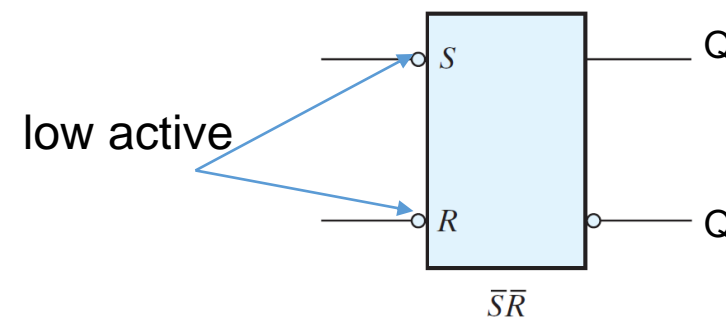
S'R' Latch with NAND Gates

• Low Active Set/Reset inputs

- S is active \rightarrow Set
- R is active \rightarrow Reset
- S,R are inactive \rightarrow Memory
- S,R are active \rightarrow Forbidden



S	R	Q	Q'	
0	0	1	1	forbidden
0	1	1	0	set state
1	0	0	1	reset state
1	1	last Q	last Q'	no change

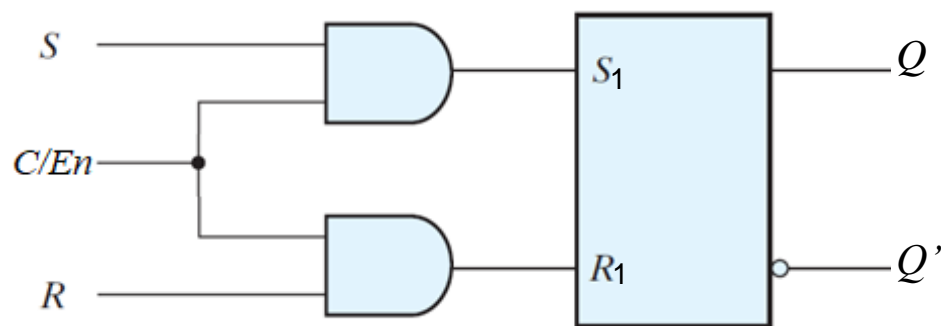


graphic symbol or S'R' Latch

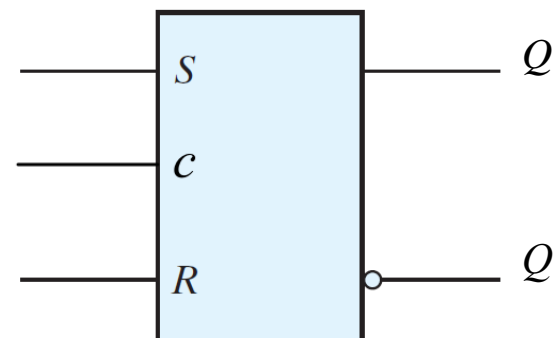
Clocked SR Latch

- Use Clock (or En) to enable/disable the SR latch
 - $C=0$, no change (disabled)
 - $C=1$, operates as normal SR latch (enabled)
- Level sensitive SR Latch
 - However, undefined state when $C = S = R = 1$
- Question:
 - draw the detailed logic diagram of SR latch
 - if AND gate is changed to NAND, how about the SR latch?

C	S	R	Q	Q'	
0	X	X	last Q	last Q'	no change
1	0	0	last Q	last Q'	no change
1	0	1	0	1	reset state
1	1	0	1	0	set state
1	1	1	0	0	forbidden



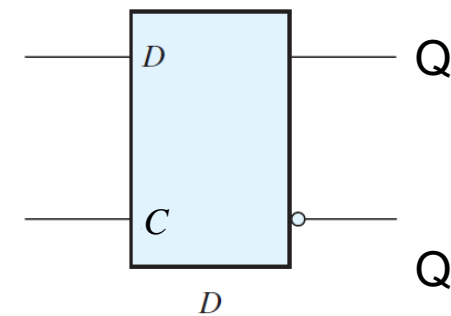
logic diagram



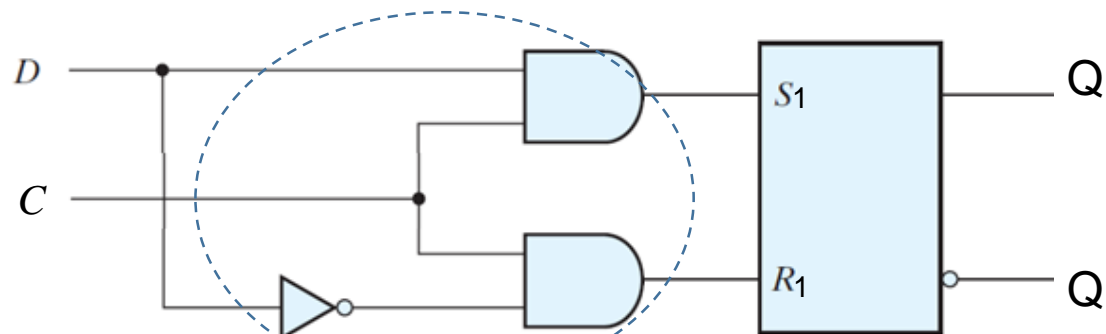
graphic symbol

D Latch

- D latch's inputs: Clk(En), D (only one data input)
 - Clk(En): controls when the output changes
 - D (the data input): controls what the output changes to
 - Constructed from a gated SR latch by connecting the D input to S input and D' to R.
 - Avoiding undesirable condition ($S=R=1$)



D Latch symbols



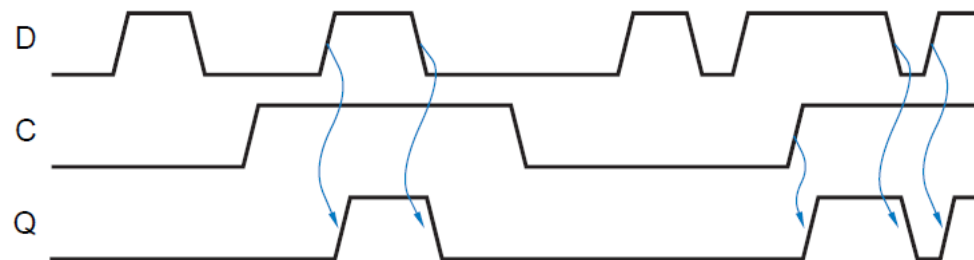
This make sure
S and R differs

C	D	Q	Q'	
0	X	last Q	last Q'	no change
1	0	0	1	Q follows D
1	1	1	0	Q follows D

D Latch

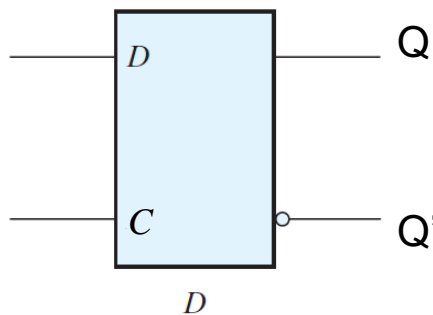
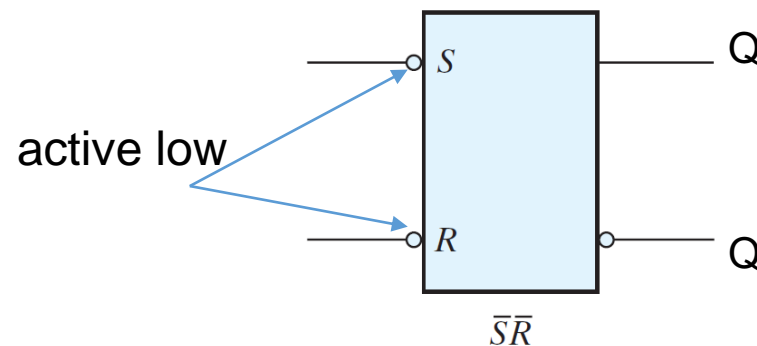
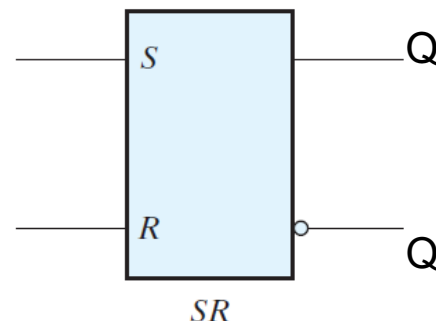
- D latch is also called Transparent Latch
- Level sensitive D Latch
 - When CLK = 1,
 - D passes through to Q (transparent)
 - When CLK = 0,
 - Q holds its previous value (opaque)
 - Can avoid invalid case when
 - $Q' \neq \text{NOT } Q$

C	D	Q	Q'	
0	X	last Q	last Q'	no change
1	0	0	1	Q follows D
1	1	1	0	Q follows D



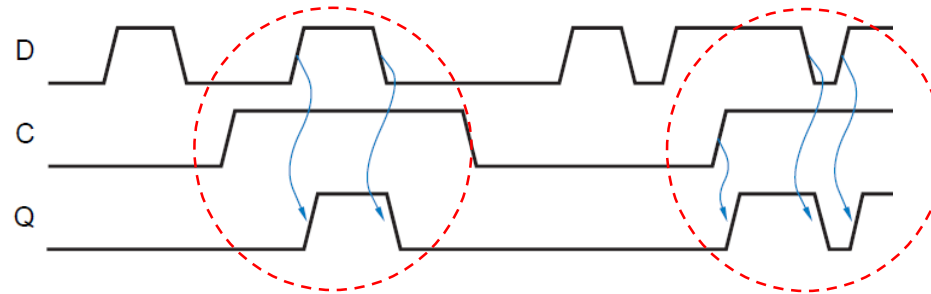
Latch Summary

- SR Latch with NOR gate (SR)
 - Set: Make the output 1
($S = 1, R = 0, Q = 1$)
 - Reset: Make the output 0
($S = 0, R = 1, Q = 0$)
 - Memory: $S=R=0$
- S'R' Latch with NAND gate (S'R')
 - Set: Make the output 1
($S = 0, R = 1, Q = 1$)
 - Reset: Make the output 0
($S = 1, R = 0, Q = 0$)
 - Memory: $S=R=1$
- D Latch (D)
 - Make D passes through to Q



Latches Pros and Cons

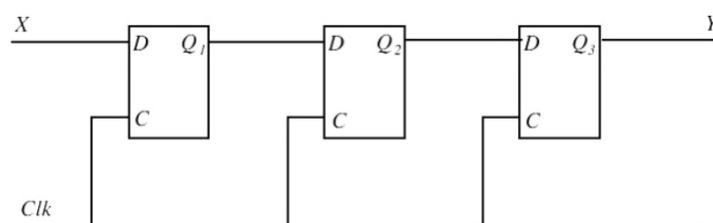
- A latch is enabled whenever $C=1$. (level-sensitive)
 - At any point during $C=1$, any input changes will propagate to the output (with some small delay)



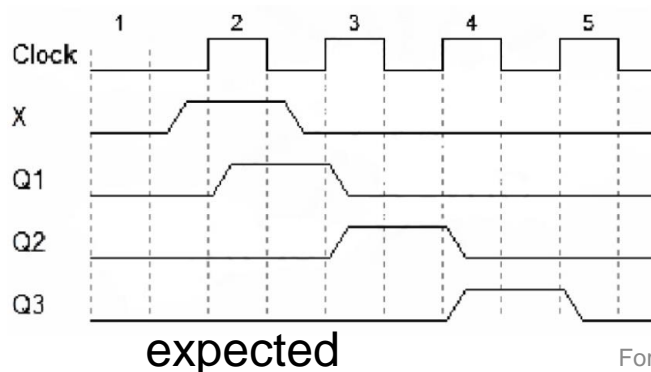
- Pros
 - Useful for level-sensitive applications
 - Latches are faster because they have fewer gates and less delay.
 - Latches are simpler which means they require less hardware to implement and consume less power.

Latches Pros and Cons

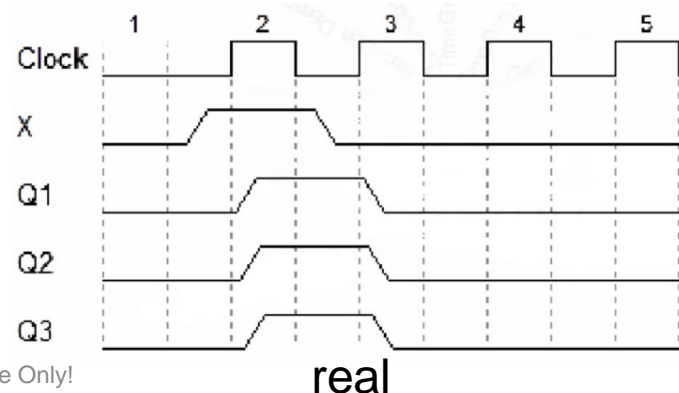
- A latch is enabled whenever $C=1$. (level-sensitive)
 - At any point during $C=1$, any input changes will propagate to the output (with some small delay)
- Cons
 - Difficult to retain value
 - Causing erroneous shifting



Unable to shift Q_2 and Q_3 with clock cycles delay



For Internal Use Only!



Outline

- Latches
- **FlipFlops**

Flip-Flops (FF)

- Latch or Flip-Flop(FF) state changes by a control input.
 - The event is called trigger.
- A Flip-Flop is a more advanced storage element, typically constructed using two D latches or more complex circuitry.
- Example: D Flip Flop
 - Inputs: CLK, D
 - For a Positive-edge triggered D Flip Flop:
 - 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

Trigger

- Trigger
 - The state of a latch or flip-flop is switched by a change of the control input
- Level sensitive (level-triggered) (latches)
 - The state transition starts as soon as the clock is during logic 1 (positive level-sensitive) or logic 0 (negative level-sensitive) level
- Edge-triggered (flip-flops)
 - The state transition starts only at positive (positive edge-triggered) or negative edge (negative edge-triggered) of the clock signal



(a) Response to positive level

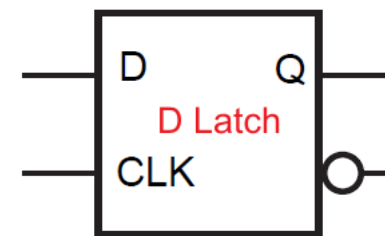


(b) Positive-edge response

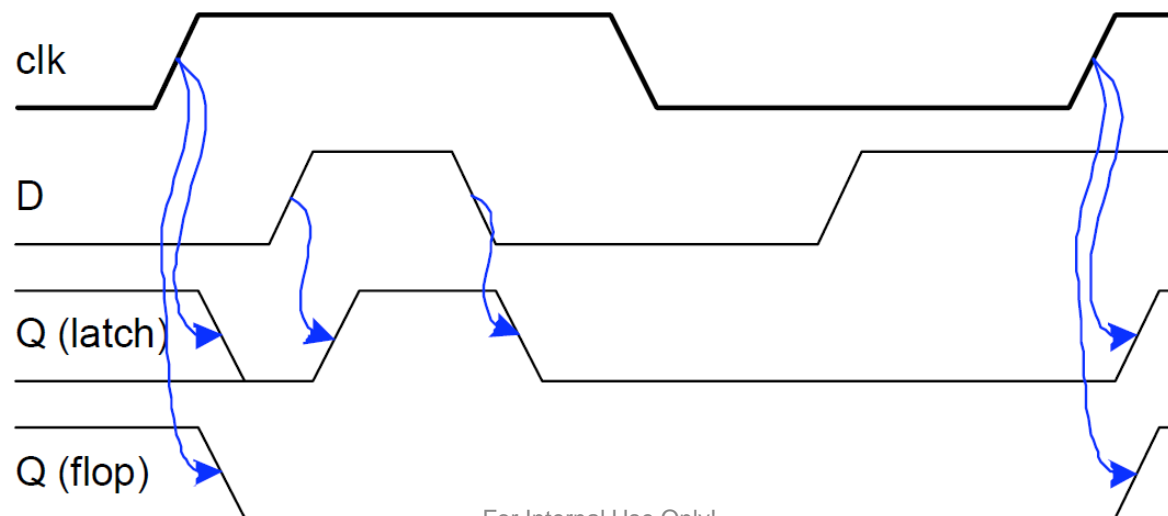
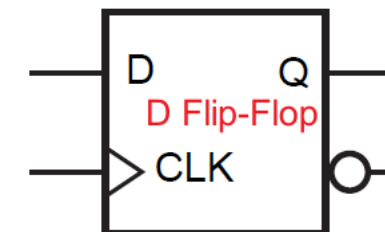
Level-Sensitive vs. Edge-Triggered



(a) Response to positive level

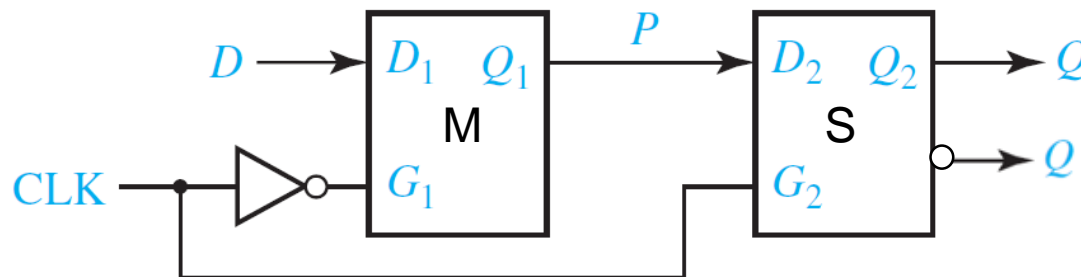


(b) Positive-edge response



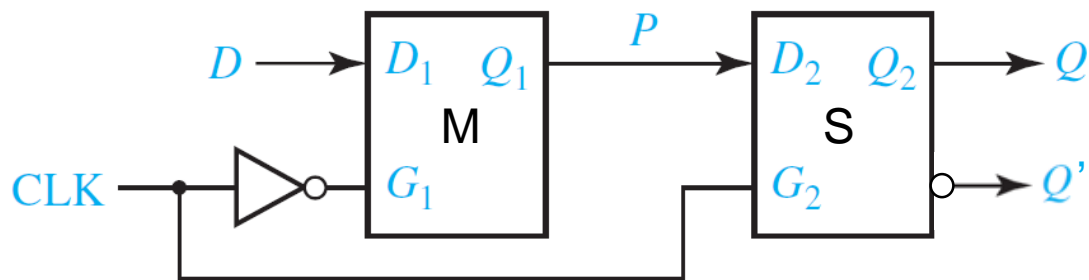
DFF Structure

- A D flip-flop is formed by two separate latches
 - A master D latch (negative level sensitive)
 - A slave D latch (positive level sensitive)
- Positive-edge-triggered D flip-flop
 - When $CLK = 0$
 - master is transparent
 - slave is opaque
 - D passes through to Y
 - When $CLK = 1$
 - master is opaque
 - slave is transparent
 - Y passes through to Q
 - Thus, on the rising edge of the clock (CLK rises from 0→1)
 - D passes through to Q

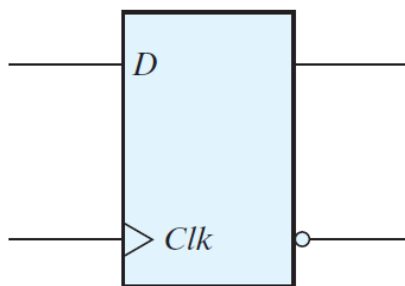


Function Table of DFF

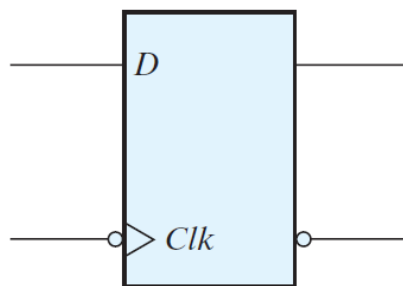
- Function table



C	D	Q	Q'	
0	X	last Q	last Q'	no change
1	X	last Q	last Q'	no change
\uparrow	0	0	1	Q follows D
\uparrow	1	1	0	Q follows D



(a) Positive-edge



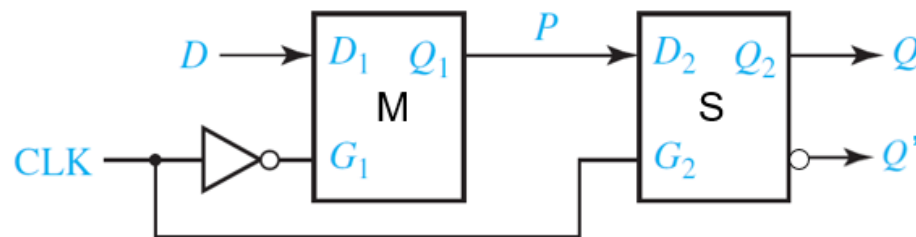
(a) Negative-edge

D Flip-Flop Symbols

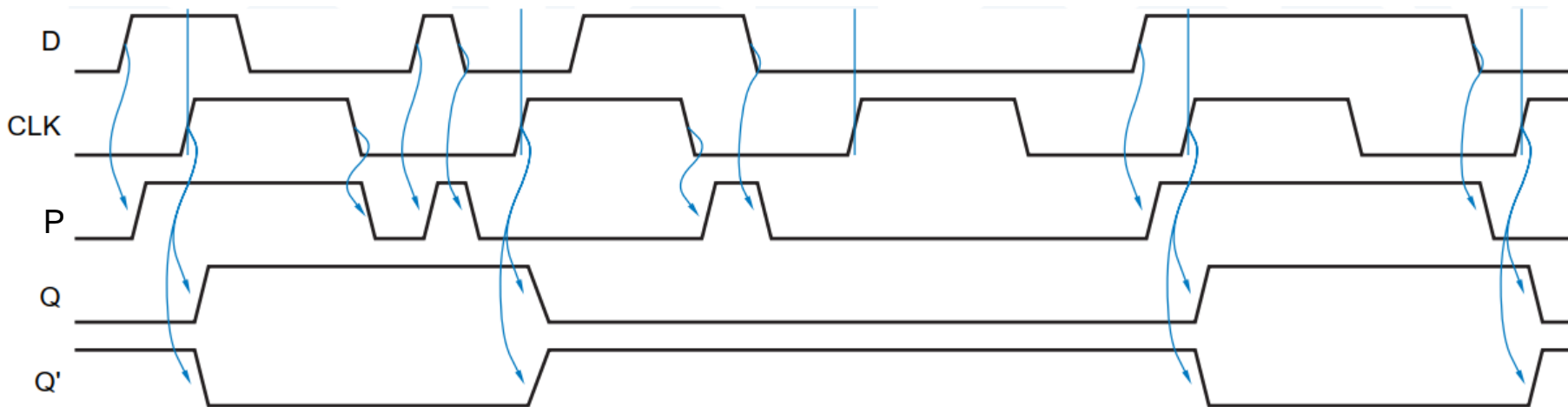
Question: How to design Negative-edge-triggered flip-flop (refer to textbook)

Timing Graph of DFF

- Positive-edge-triggered DFF
 - Q stays stable between two rising edges of the clock signal

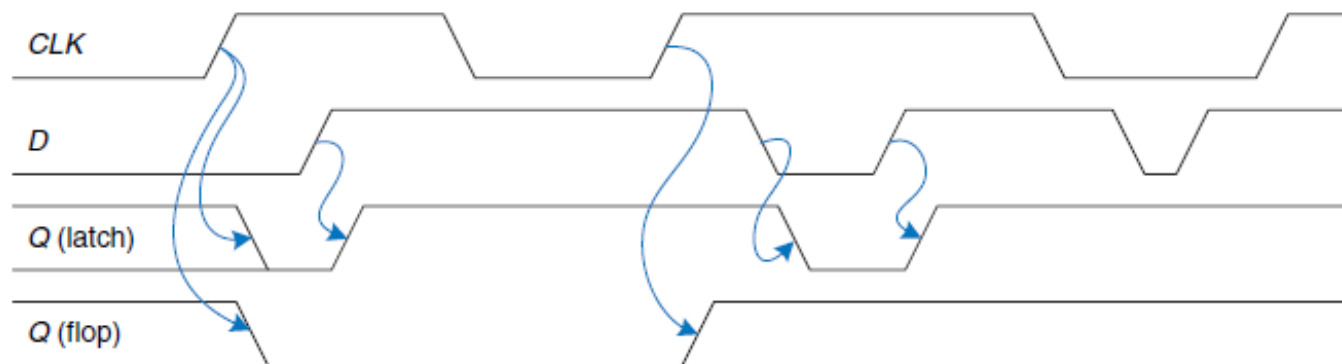
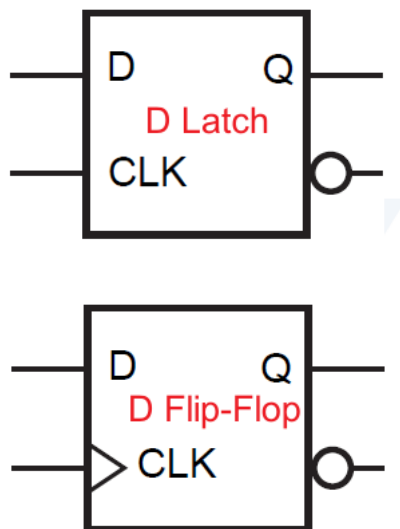


C	D	Q	Q'	
0	X	last Q	last Q'	no change
1	X	last Q	last Q'	no change
\uparrow	0	0	1	Q follows D
\uparrow	1	1	0	Q follows D



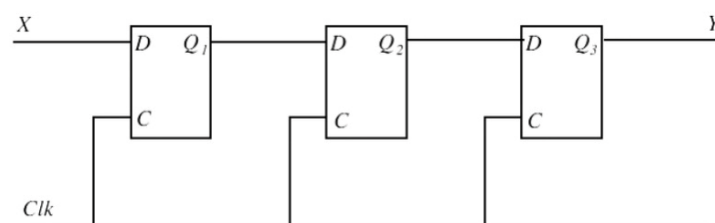
Flip-flop and Latch Comparison

- Apply the D and CLK inputs to a D latch and a D flip-flop, determine the output, Q, of each device.

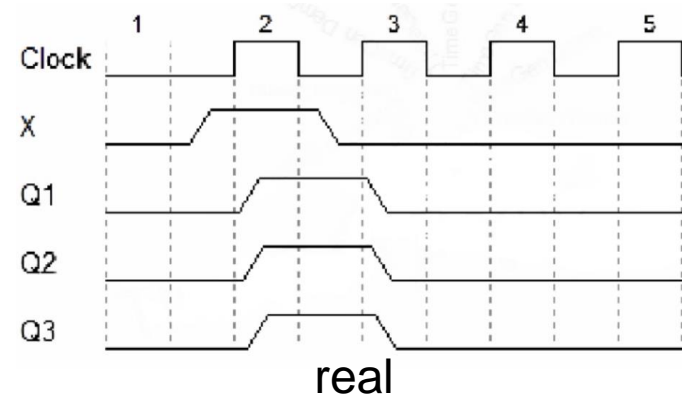
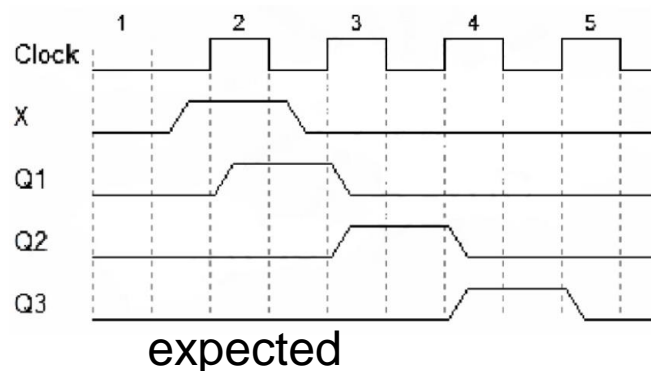


Shifting

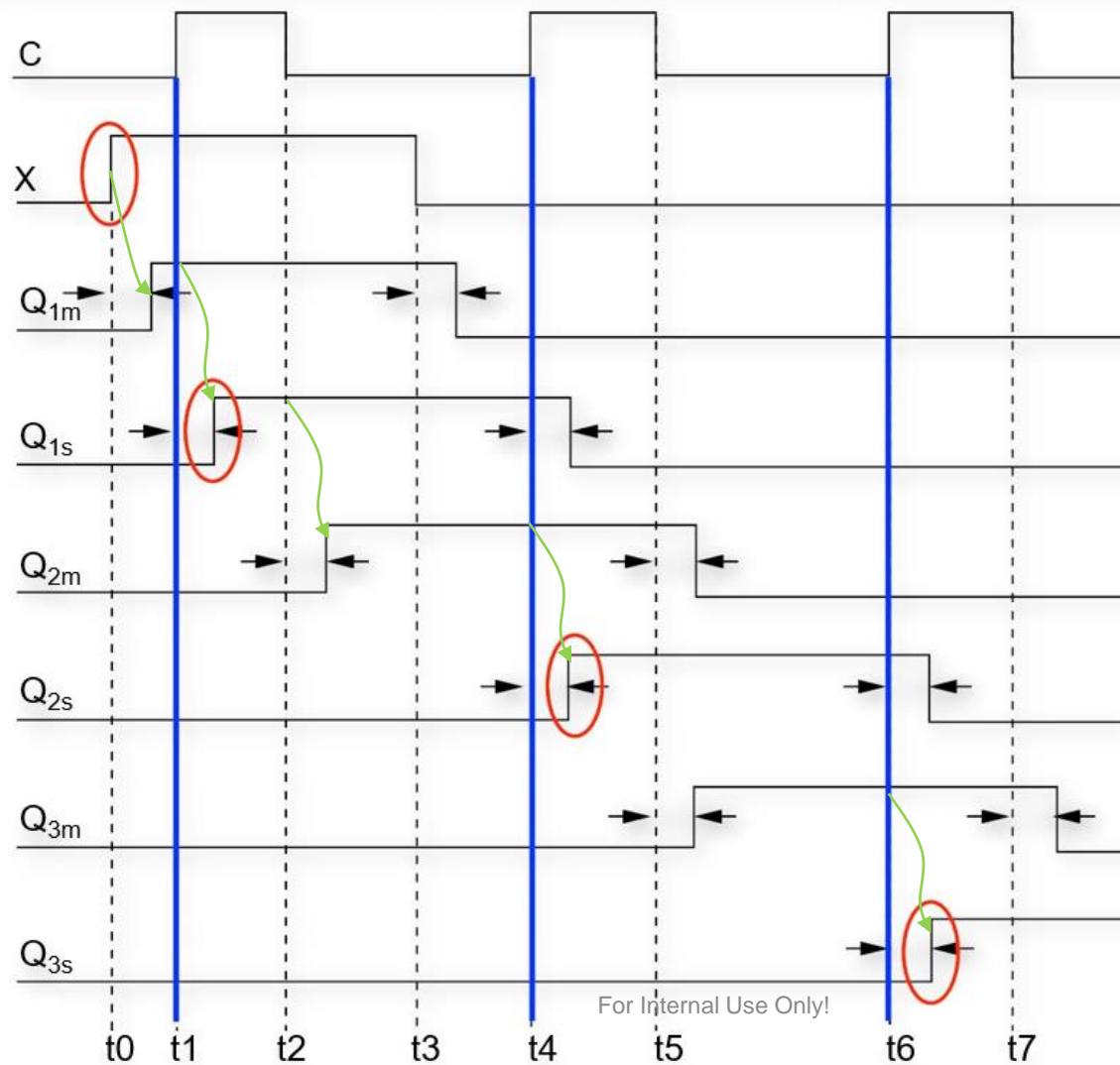
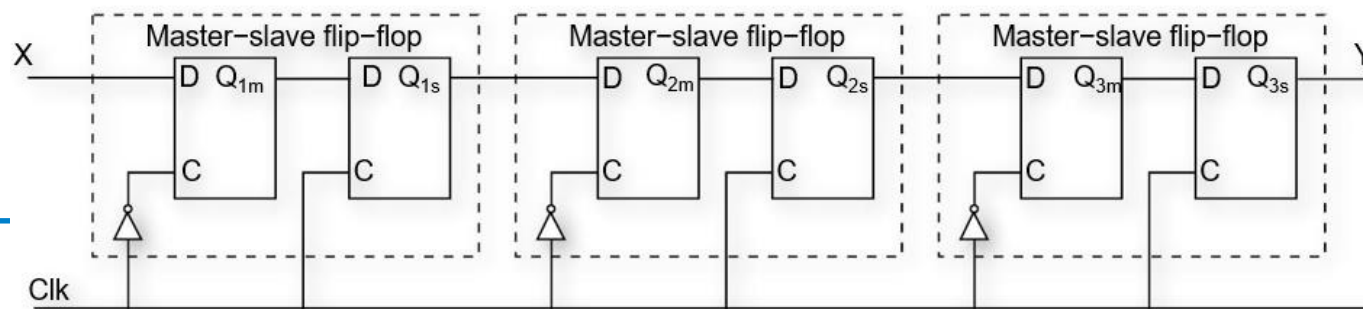
- Remember we wanted to shift input with clock cycles delay, but latches didn't work out



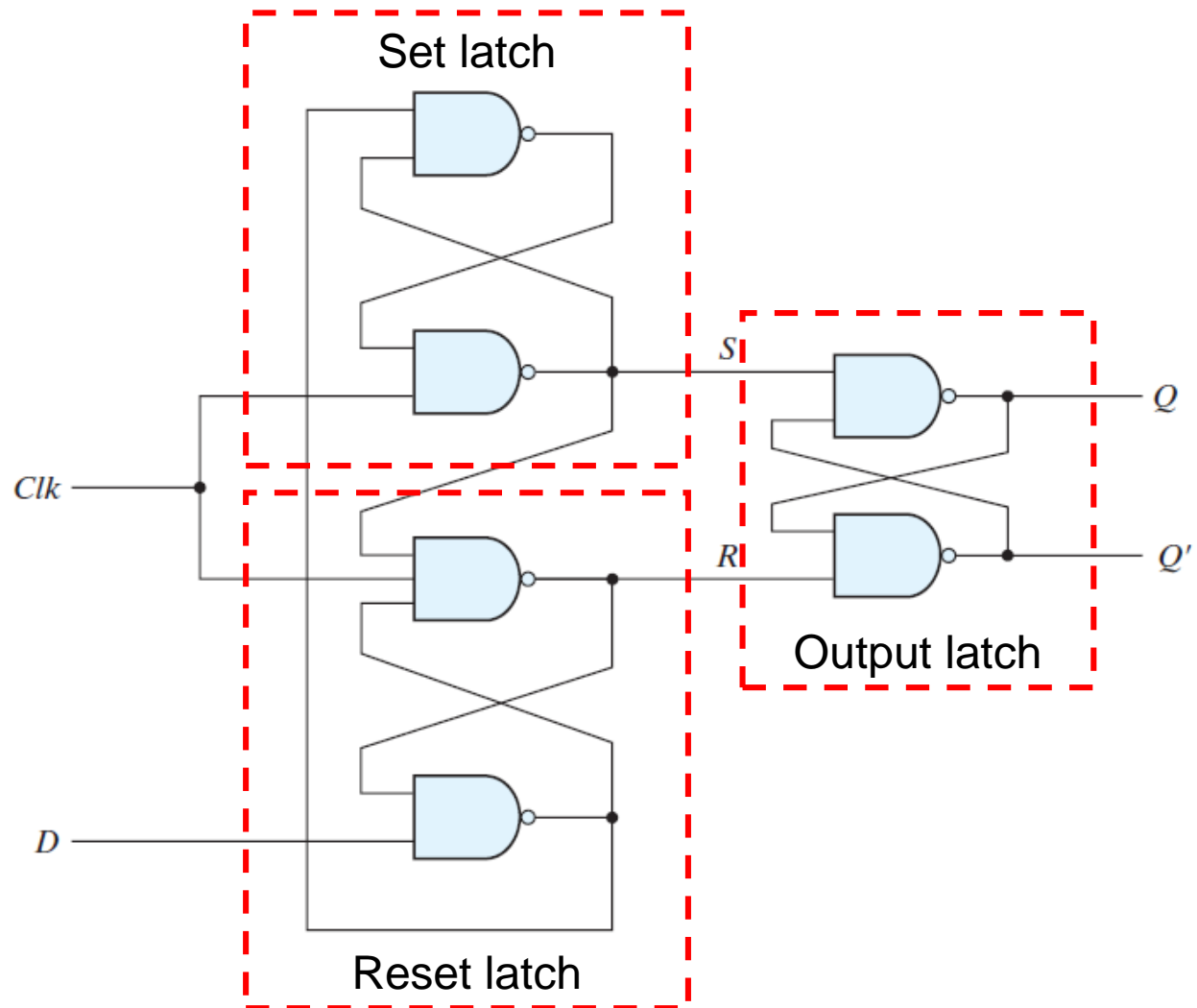
Unable to shift Q_2 and Q_3 with clock cycles delay



- Now we can use FlipFlops



DFF with three SR Latches

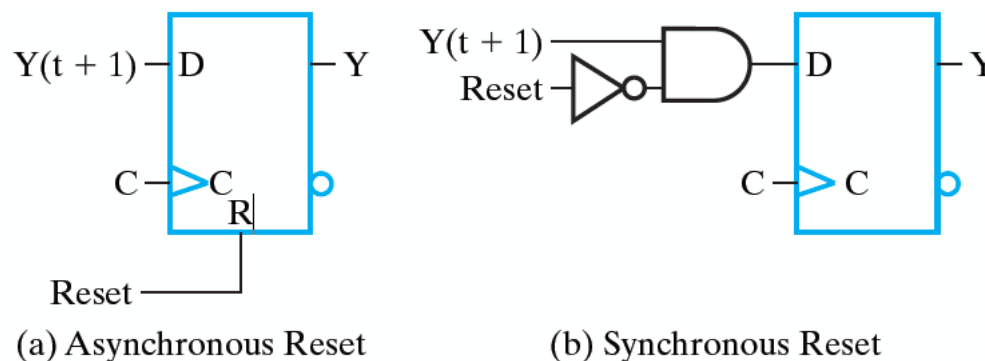


Positive-edge-triggered D flip-flop

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DFF with Reset

- The state of FFs are unknown when power is on. A direct input can force the FFs to a known state before the system starts.
 - E.g. when Reset = 1, FF's output is forced to 0
- Synchronous vs. asynchronous resettable Flip Flop
 - Asynchronous: resets immediately when Reset = 1
 - Synchronous: resets at the clock edge only

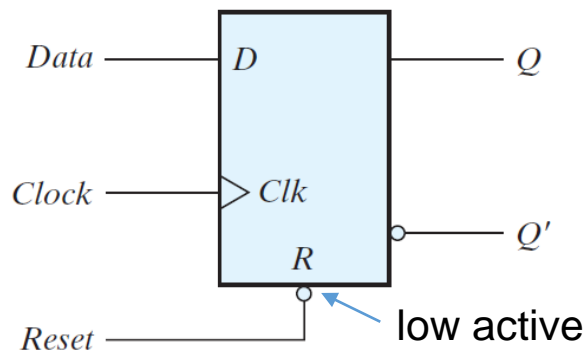


DFF with Asynchronous Reset

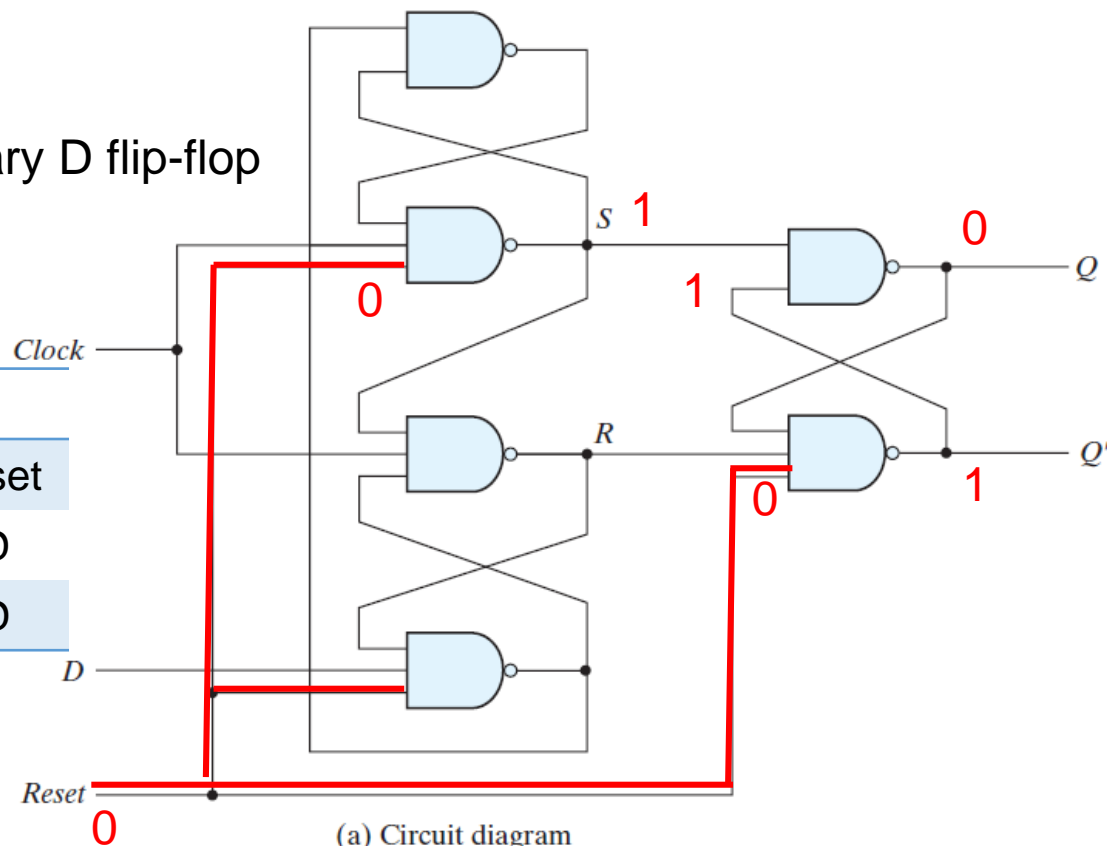
- Active low reset
 - Reset = 0: Q is forced to 0
 - Reset = 1: flip-flop behaves as ordinary D flip-flop

Function table

R	C	D	Q	Q'	
0	X	X	0	1	power on reset
1	\uparrow	0	0	1	Q follows D
1	\uparrow	1	1	0	Q follows D

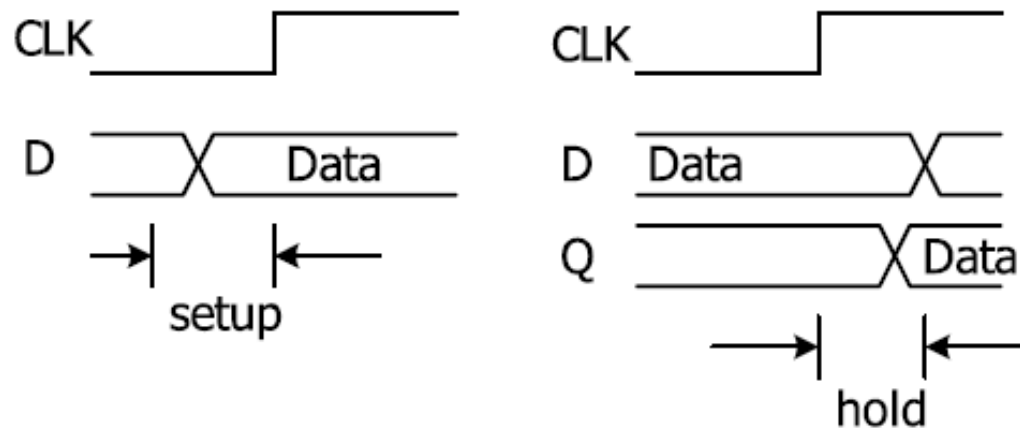


(b) Graphic symbol



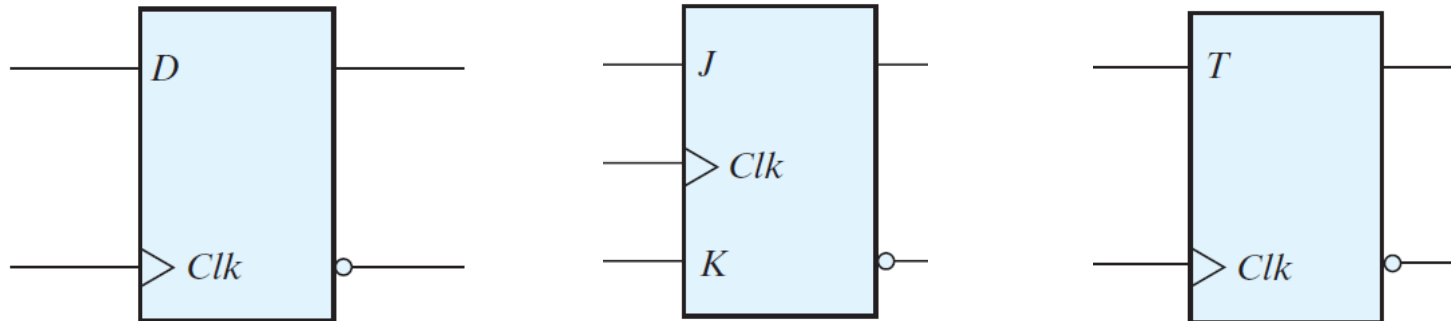
Setup Time/Hold Time

- Setup time
 - D input must be maintained at a constant value prior to the application of the positive Clk pulse
- Hold time
 - Data input must not change after the application of the positive Clk pulse



Types of Flip-Flops

- Flip-flops are more suitable for synchronous sequential circuits and are often used as the basic memory elements, since they only respond to a transition on a clock input.
- Other types of flip-flops can be constructed by using the DFF and external logic.
- Major FFs
 - D(data), JK, T (toggle) FFs
 - Assume only positive-edge-triggered FFs, block diagram are as follow



Characteristic Table

- **Characteristic table:** describe the behavior of a flip-flop based on its input and current state $Q(t)$ just before the rising edge of the clock, and the resulting next state $Q(t+1)$ after the clock transition.

Function table

Clk	D	Q	Q'	
0	X	last Q	last Q'	no change
1	X	last Q	last Q'	no change
\uparrow	0	0	1	Q follows D
\uparrow	1	1	0	Q follows D

Characteristic table of DFF



Characteristic table
D Flip-Flop

D	$Q(t + 1)$
0	0 Reset
1	1 Set

- **Characteristic equation:** derived from the characteristic table using the map method
 - Characteristic equation of DFF:

$$Q_{t+1} = D$$

J-K Flip-Flop

- Positive edge-triggered JKFF





- At rising edge of clock

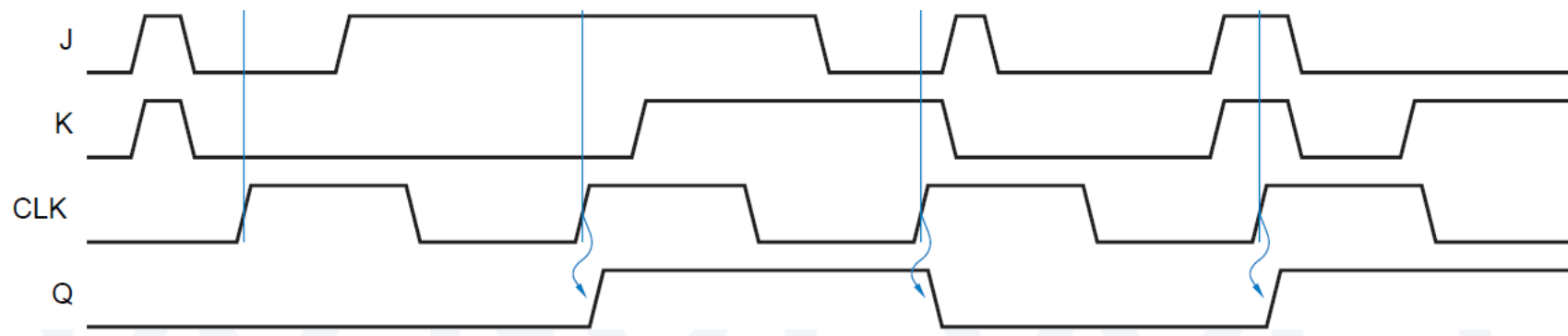
- $J = K = 0$, Q is unchanged
 - $J = K = 1$, Q toggles
 - $J = 1, K = 0$, Q is set to 1
 - $J = 0, K = 1$, Q is reset to 0

- At level of clock

- Q is unchanged

Function Table

Clk	J	K	Q	Q'
0	x	x	last Q	last Q'
1	x	x	last Q	last Q'
	0	0	last Q	last Q'
	0	1	0	1
	1	0	1	0
	1	1	last Q'	last Q



J-K Flip-Flop

Characteristic table

<i>J/K</i> Flip-Flop			
<i>J</i>	<i>K</i>	<i>Q(t + 1)</i>	
0	0	<i>Q(t)</i>	No change
0	1	0	Reset
1	0	1	Set
1	1	<i>Q'(t)</i>	Complement

Derive the Truth table



<i>J</i>	<i>K</i>	<i>Q(t)</i>	<i>Q(t+1)</i>
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	0
1	0	0	1
1	0	1	1
1	1	0	1
1	1	1	0

Characteristic equation of JKFF

$$Q(t+1) = JQ(t)' + K'Q(t)$$

• Algebraically:

$Q(t+1)$

$$= J'K'Q(t) + J'K \cdot 0 + JK' \cdot 1 + JKQ(t)'$$

$$= J'K'Q(t) + JK' + JKQ(t)'$$

$$= J'K'Q(t) + JK'Q(t) + JK'Q(t)' + JKQ(t)'$$

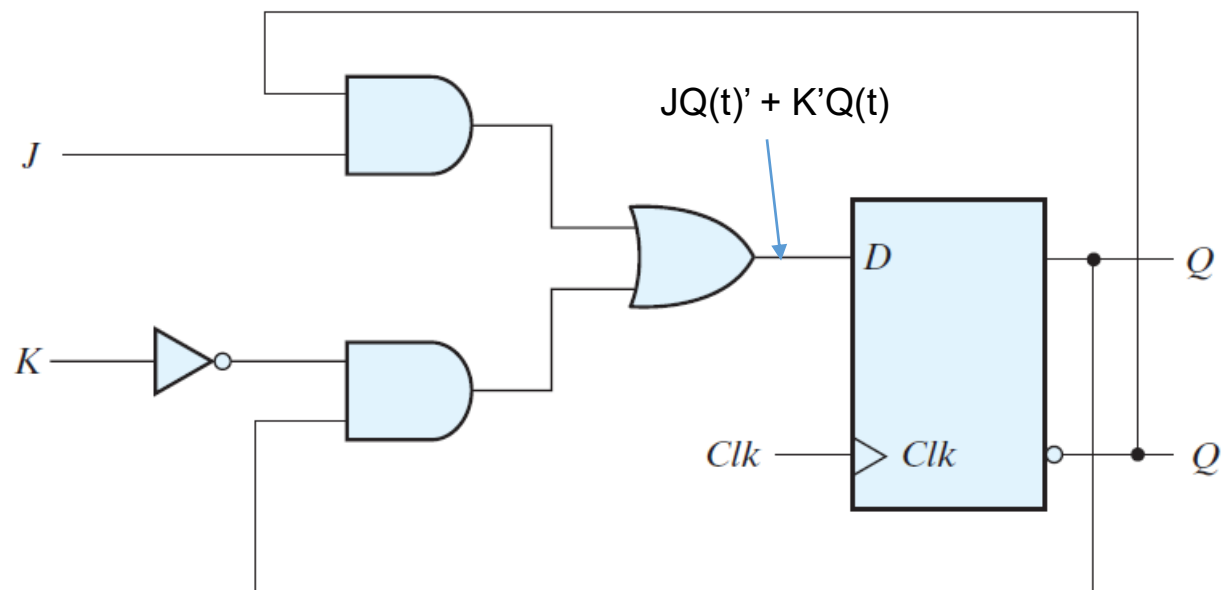
$$= JQ(t)' + K'Q(t)$$

• K-Map

		<i>k</i>			
		00	01	11	10
<i>J</i>	0	<i>m</i> ₀ 0	<i>m</i> ₁ 1	<i>m</i> ₃ 0	<i>m</i> ₂ 0
	1	<i>m</i> ₄ 1	<i>m</i> ₅ 1	<i>m</i> ₇ 0	<i>m</i> ₆ 1
		<i>Q(t)</i>			

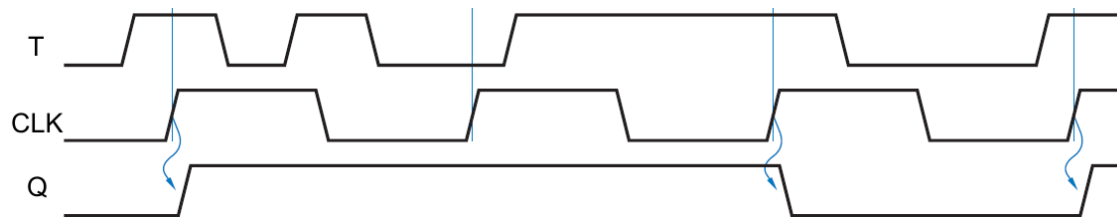
J-K Flip-Flop

- Implement JKFF using DFF
 - Because in DFF, $Q_{t+1} = D$
 - Thus, according to JKFF's characteristic equation, $Q(t+1) = JQ(t)' + K'Q(t)$, we can derive $D = JQ(t)' + K'Q(t)$



T Flip-Flop

- T: Toggle



T Flip-Flop

T	$Q(t + 1)$
0	$Q(t)$ No change
1	$Q'(t)$ Complement

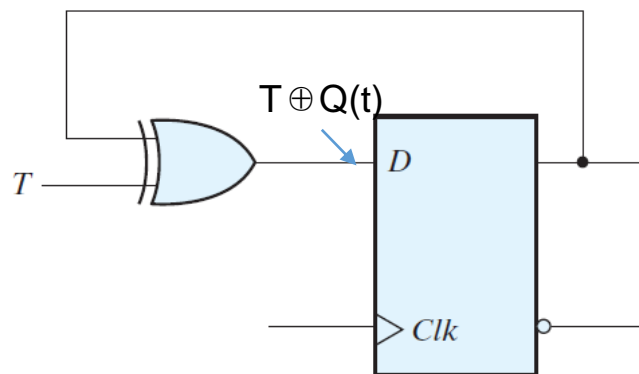


T	Q(t)	Q(t+1)
0	0	0
0	1	1
1	0	1
1	1	0

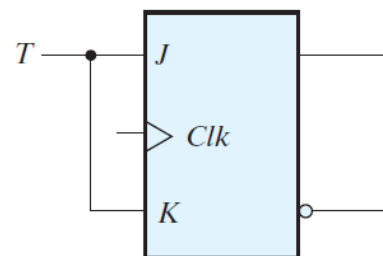
Characteristic equation of TFF

$$Q(t+1) = T'Q(t) + TQ(t)'$$

$$= T \oplus Q(t)$$



From D flip-flop



From JK flip-flop