



CprE 281: Digital Logic

Instructor: Alexander Stoytchev

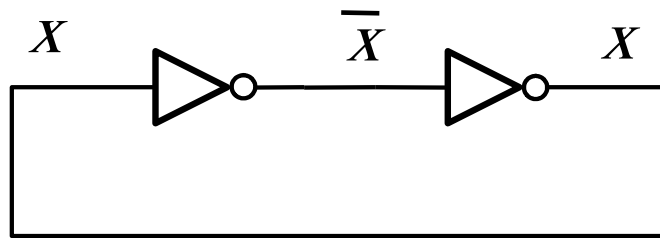
<http://www.ece.iastate.edu/~alexs/classes/>

D Flip-Flops

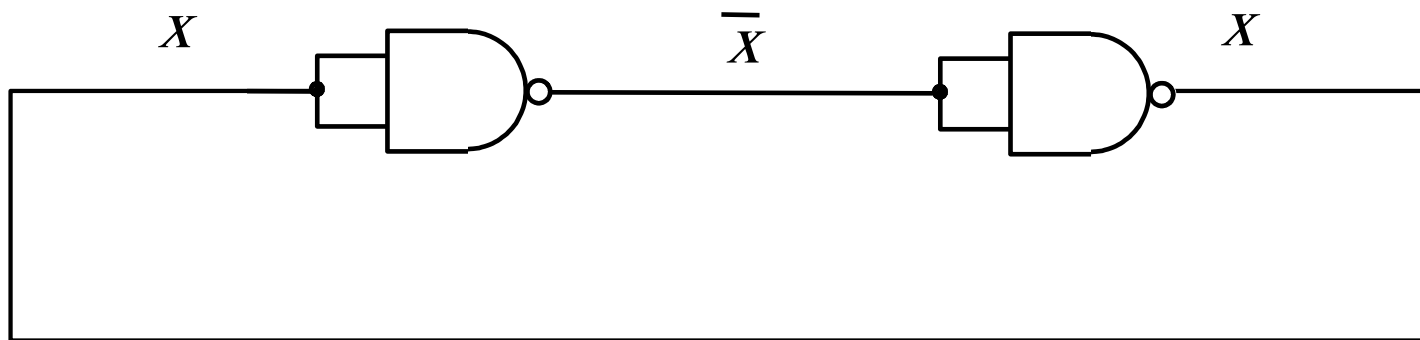
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Quick Review

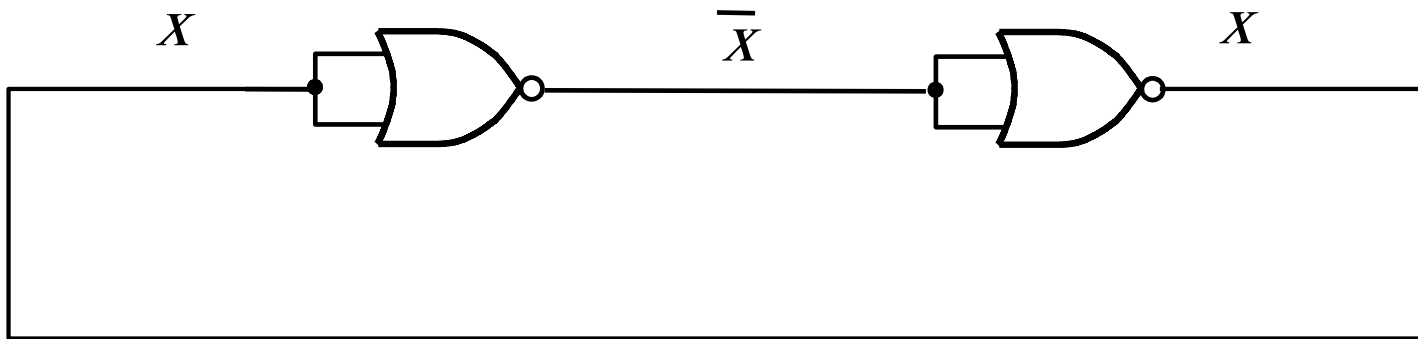
A simple memory element with NOT Gates



A simple memory element with NAND Gates

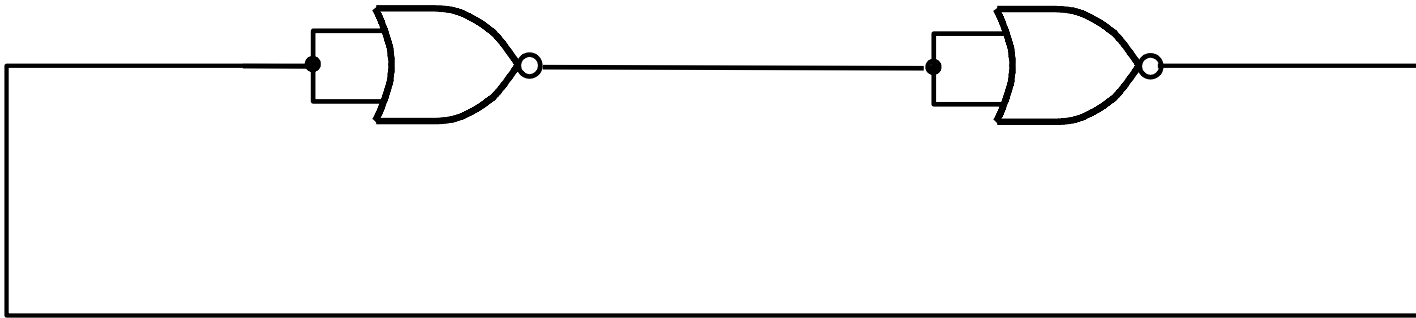


A simple memory element with NOR Gates

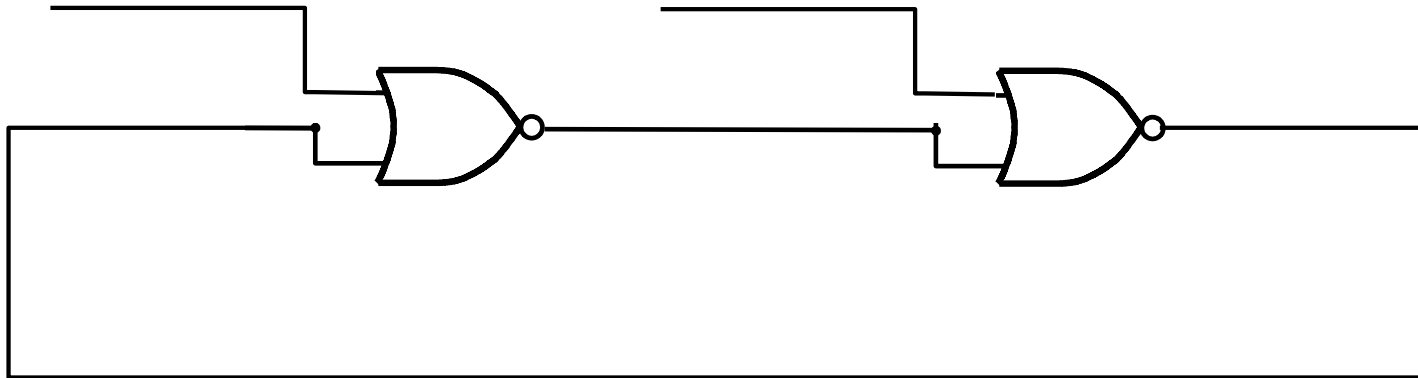


Basic Latch

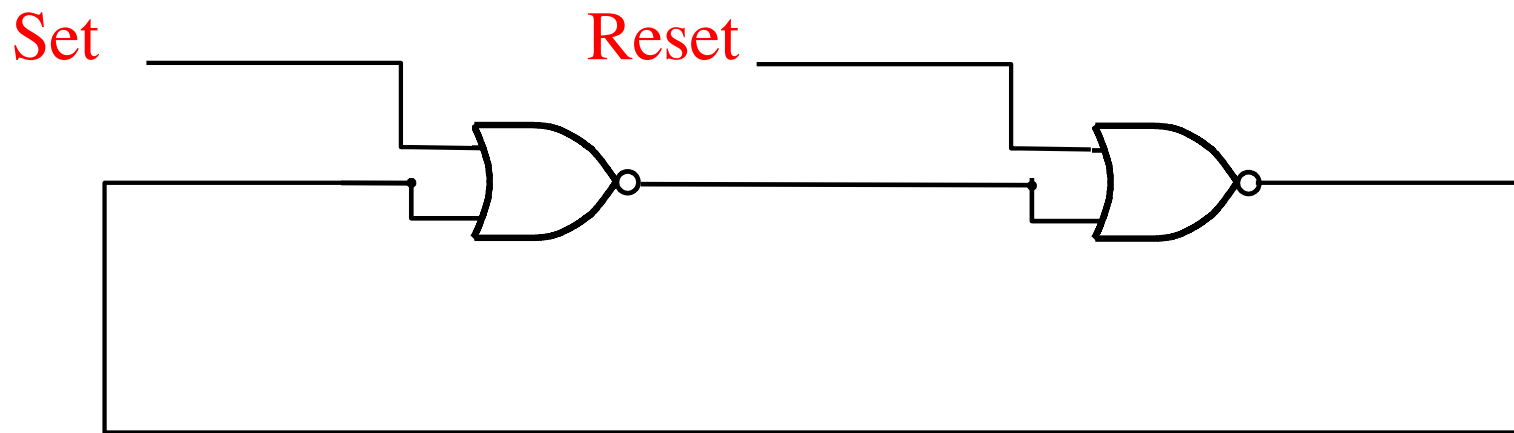
A simple memory element with NOR Gates



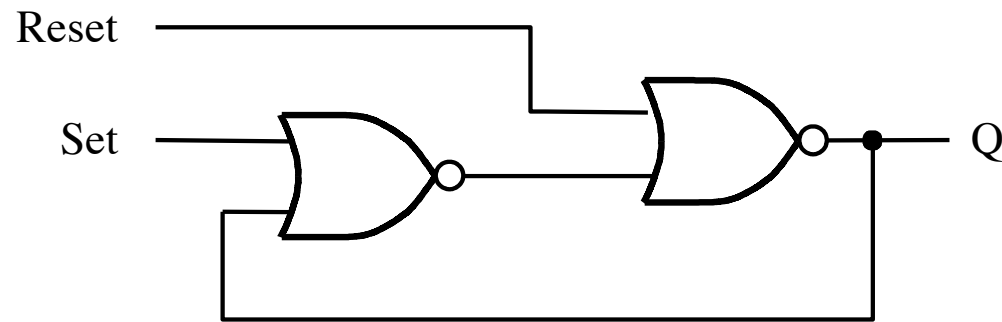
A simple memory element with NOR Gates



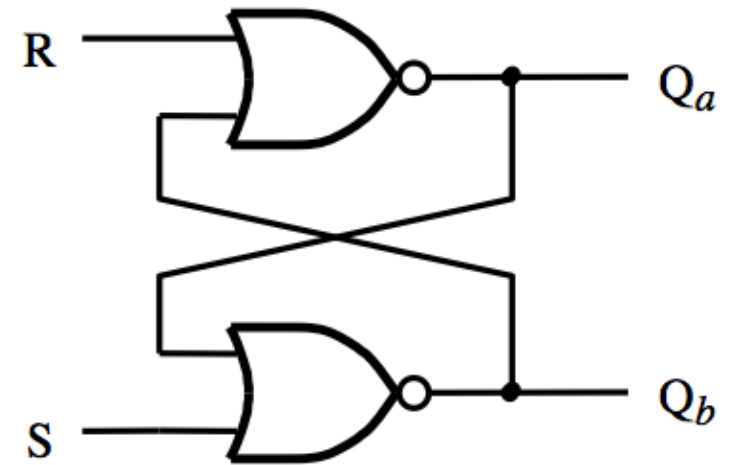
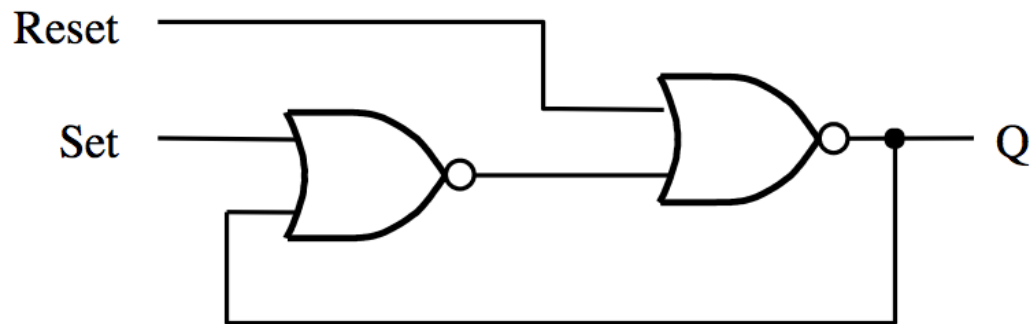
A simple memory element with NOR Gates



A memory element with NOR gates



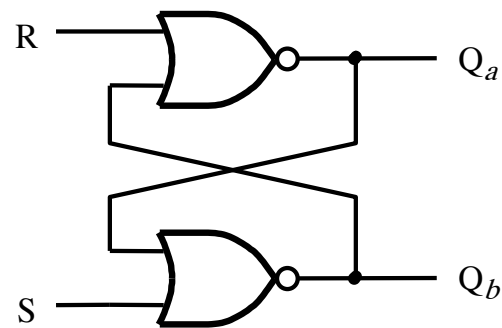
Two Different Ways to Draw the Same Circuit



[Figure 5.3 & 5.4 from the textbook]

Circuit and Characteristic Table for the Basic Latch

Note that Q_a and Q_b are inverses of each other!



(a) Circuit

S	R	Q_a	Q_b	
0	0	0/1	1/0	(no change)
0	1	0	1	
1	0	1	0	
1	1	0	0	

(b) Characteristic table

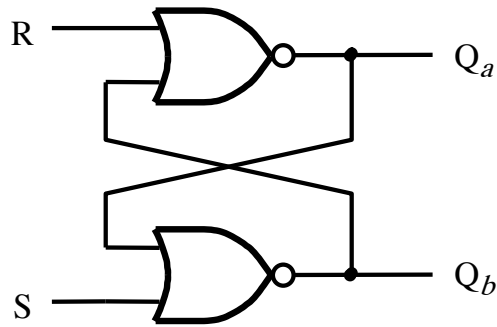
Oscillations and Undesirable States

- **When $S=1$ and $R=1$ both outputs of the latch are equal to 0, i.e., $Q_a=0$ and $Q_b=0$.**
- **Thus, the two outputs are no longer complements of each other.**
- **This is undesirable as many of the circuits that we will build later with these latches rely on the assumption that the two outputs are always complements of each other.**
- **(This is obviously not the case for the basic latch, but we will patch it later to eliminate this problem).**

Oscillations and Undesirable States

- An even bigger problem occurs when we transition from $S=R=1$ to $S=R=0$.
- When $S=R=1$ we have $Q_a=Q_b=0$. After the transition to $S=R=0$, however, we get $Q_a=Q_b=1$, which would immediately cause $Q_a=Q_b=0$, and so on.
- If the gate delays and the wire lengths are identical, then this oscillation will continue forever.
- In practice, the oscillation dies down and the output settles into either $Q_a=1$ and $Q_b=0$ or $Q_a=0$ and $Q_b=1$.
- The problem is that **we can't predict** which one of these two it will settle into.

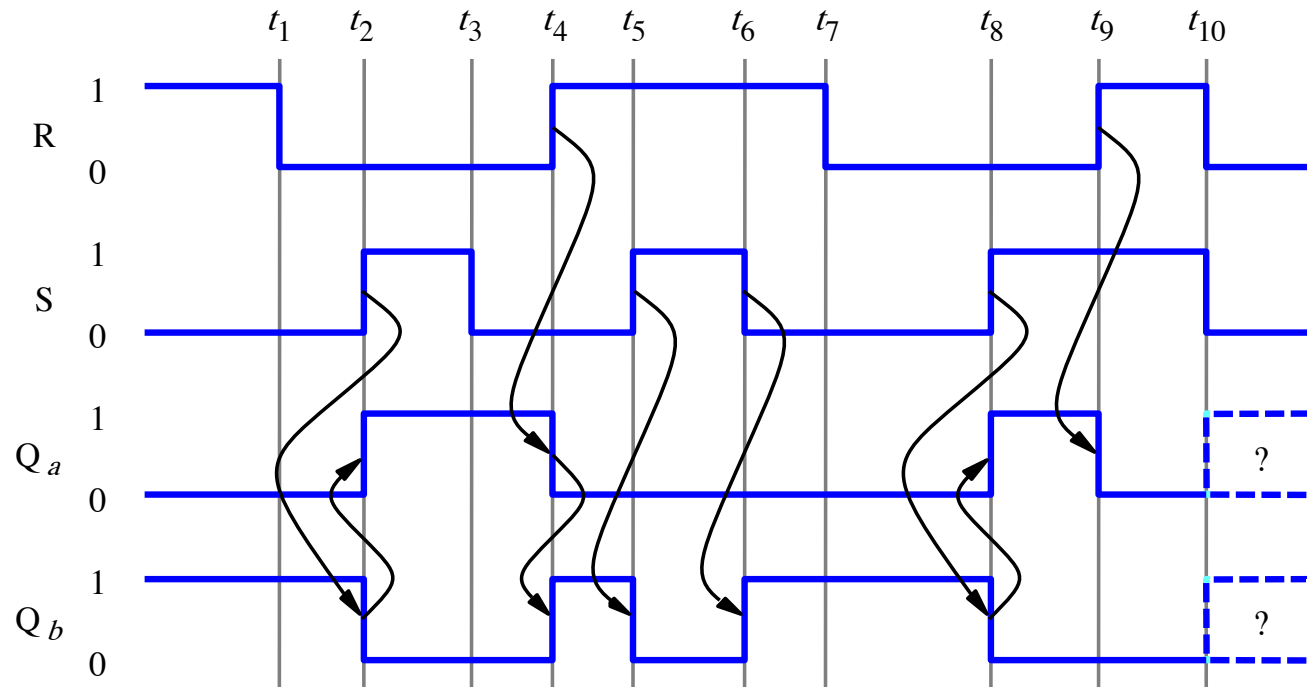
Timing Diagram for the Basic Latch with NOR Gates



(a) Circuit

S	R	Q_a	Q_b
0	0	0/1	1/0 (no change)
0	1	0	1
1	0	1	0
1	1	0	0

(b) Characteristic table

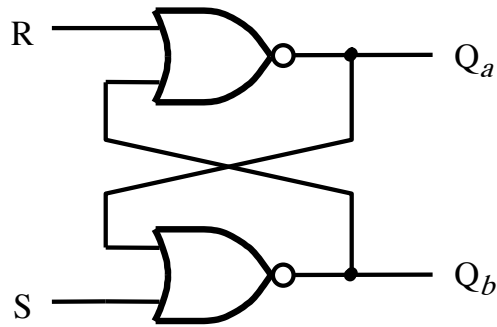


→ Time

(c) Timing diagram

[Figure 5.4 from the textbook]

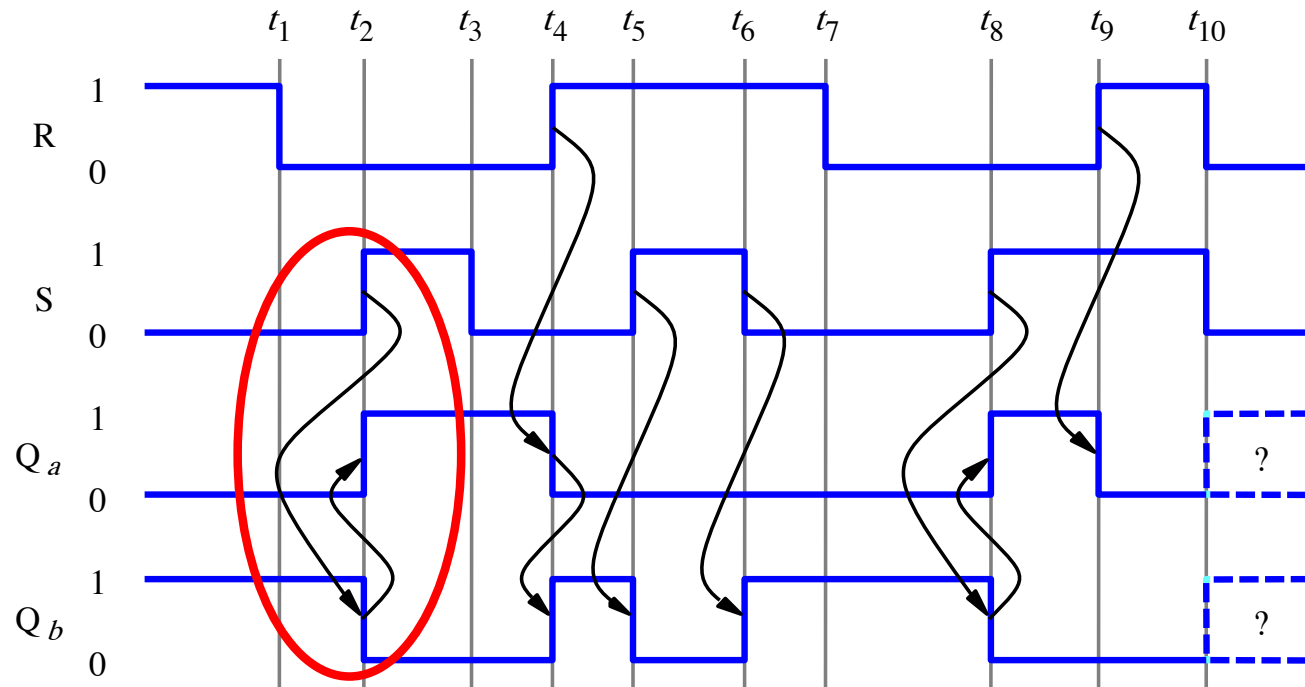
Timing Diagram for the Basic Latch with NOR Gates



(a) Circuit

S	R	Q_a	Q_b
0	0	0/1	1/0 (no change)
0	1	0	1
1	0	1	0
1	1	0	0

(b) Characteristic table

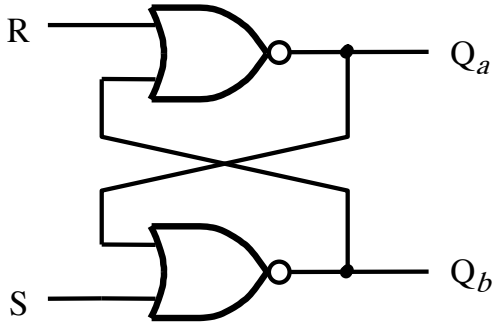


→ Time

(c) Timing diagram

[Figure 5.4 from the textbook]

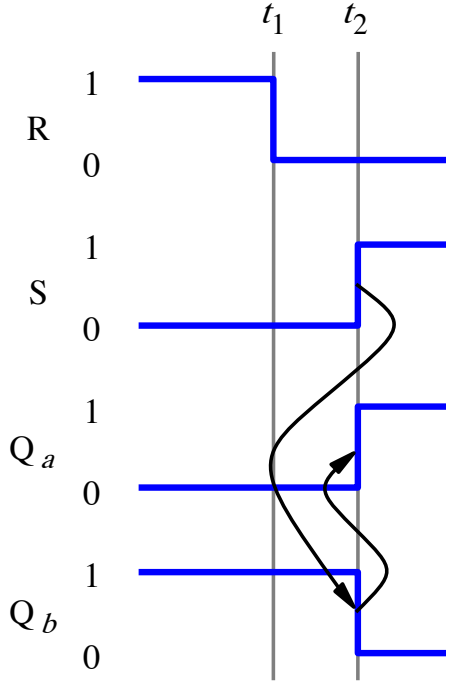
Timing Diagram for the Basic Latch with NOR Gates



(a) Circuit

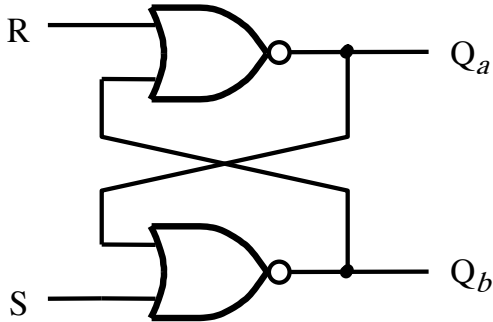
S	R	Q_a	Q_b
0	0	0/1	1/0 (no change)
0	1	0	1
1	0	1	0
1	1	0	0

(b) Characteristic table



(c) Timing diagram

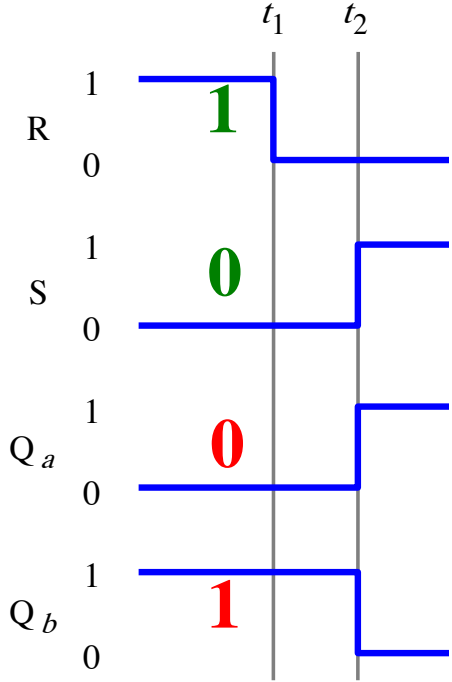
Timing Diagram for the Basic Latch with NOR Gates



(a) Circuit

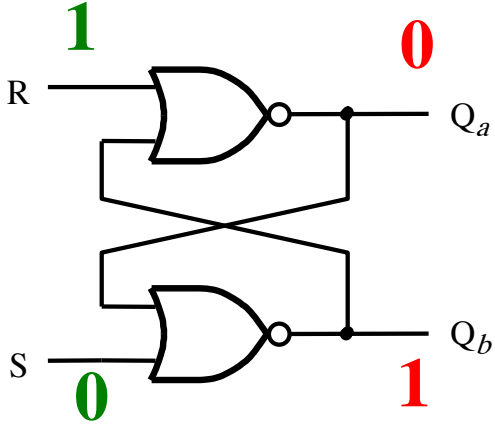
S	R	Q_a	Q_b
0	0	0/1	1/0 (no change)
0	1	0	1
1	0	1	0
1	1	0	0

(b) Characteristic table



(c) Timing diagram

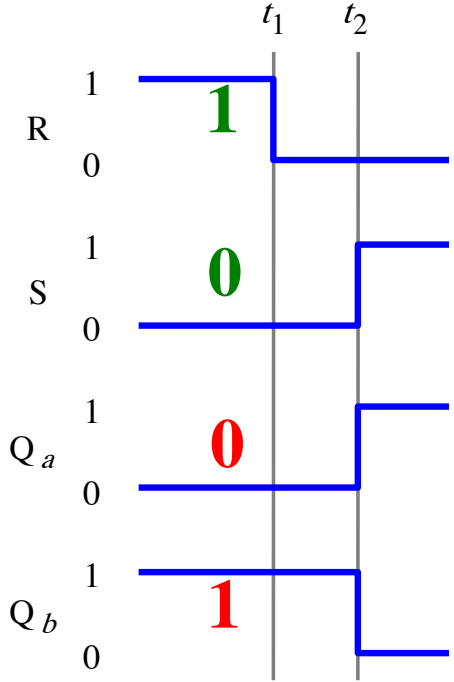
Timing Diagram for the Basic Latch with NOR Gates



(a) Circuit

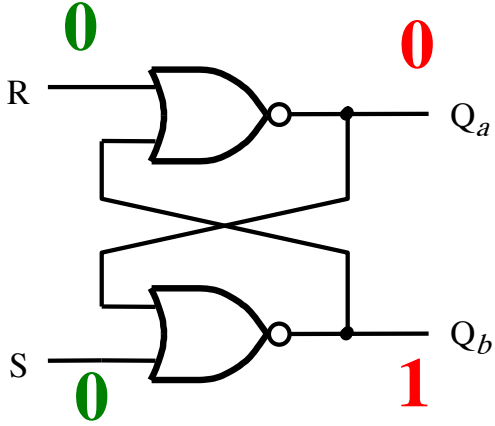
S	R	Q_a	Q_b	
0	0	0/1	1/0	(no change)
0	1	0	1	
1	0	1	0	
1	1	0	0	

(b) Characteristic table



(c) Timing diagram

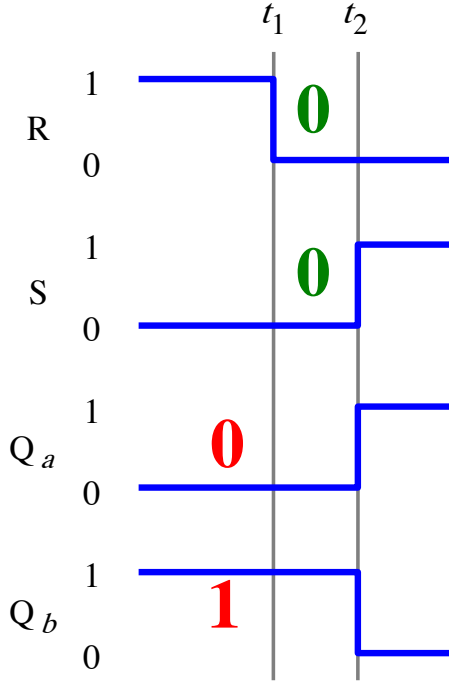
Timing Diagram for the Basic Latch with NOR Gates



(a) Circuit

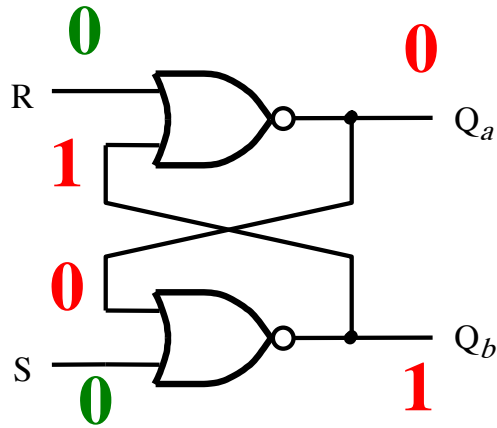
S	R	Q _a	Q _b	
0	0	0/1	1/0	(no change)
0	1	0	1	
1	0	1	0	
1	1	0	0	

(b) Characteristic table



(c) Timing diagram

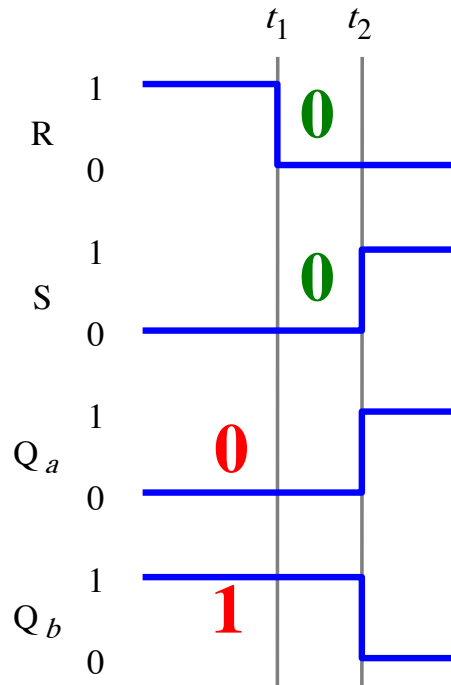
Timing Diagram for the Basic Latch with NOR Gates



(a) Circuit

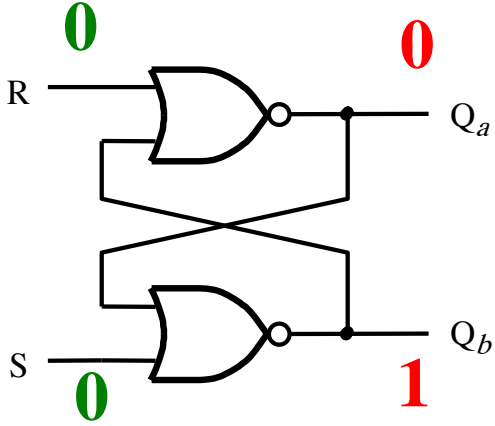
S	R	Q _a	Q _b	
0	0	0/1	1/0	(no change)
0	1	0	1	
1	0	1	0	
1	1	0	0	

(b) Characteristic table



(c) Timing diagram

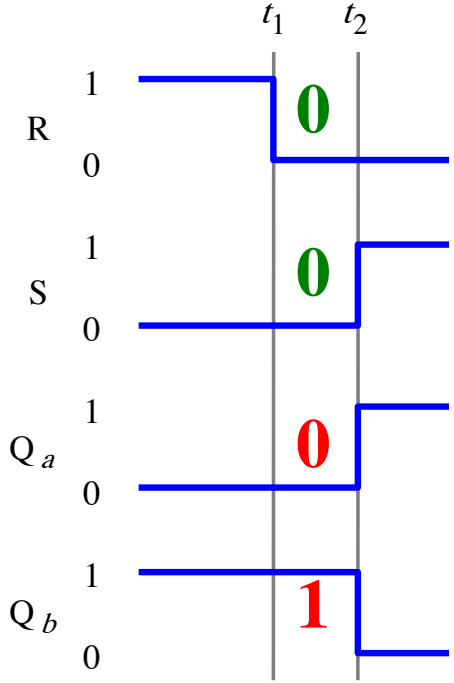
Timing Diagram for the Basic Latch with NOR Gates



(a) Circuit

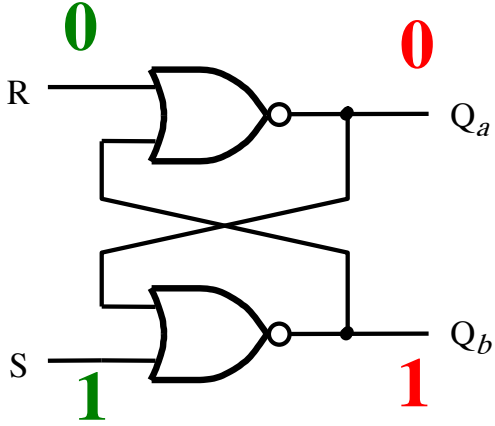
S	R	Q _a	Q _b	
0	0	0/1	1/0	(no change)
0	1	0	1	
1	0	1	0	
1	1	0	0	

(b) Characteristic table



(c) Timing diagram

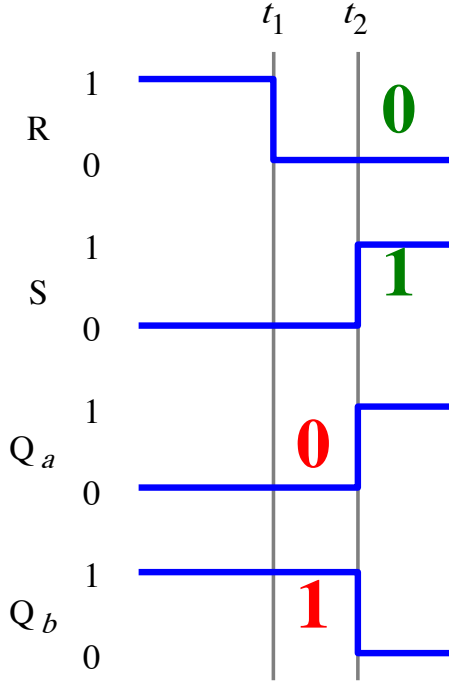
Timing Diagram for the Basic Latch with NOR Gates



(a) Circuit

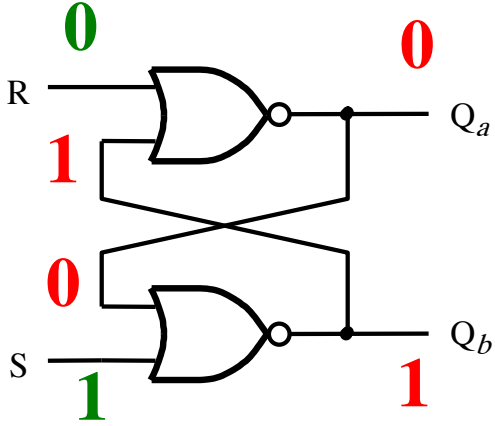
S	R	Q _a	Q _b	
0	0	0/1	1/0	(no change)
0	1	0	1	
1	0	1	0	
1	1	0	0	

(b) Characteristic table



(c) Timing diagram

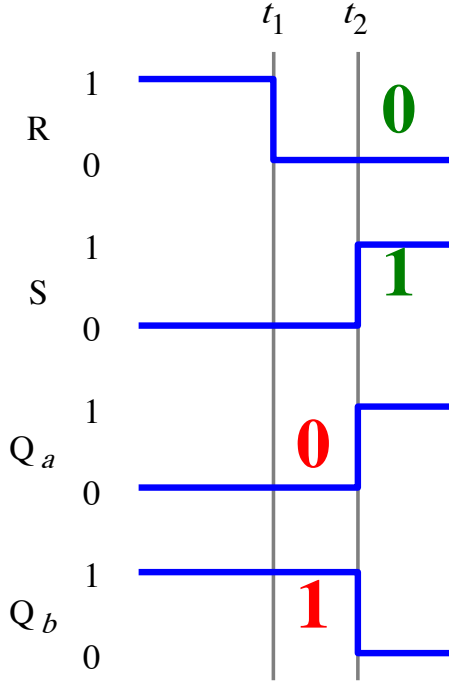
Timing Diagram for the Basic Latch with NOR Gates



(a) Circuit

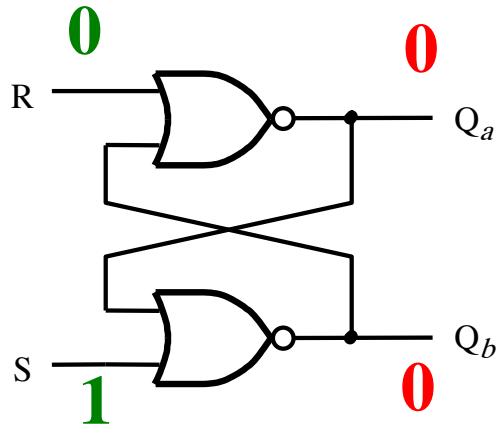
S	R	Q _a	Q _b	
0	0	0/1	1/0	(no change)
0	1	0	1	
1	0	1	0	
1	1	0	0	

(b) Characteristic table



(c) Timing diagram

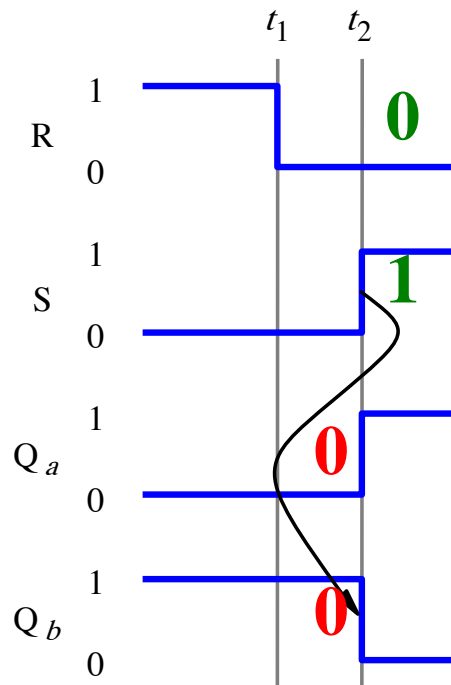
Timing Diagram for the Basic Latch with NOR Gates



(a) Circuit

S	R	Q _a	Q _b	
0	0	0/1	1/0	(no change)
0	1	0	1	
1	0	1	0	
1	1	0	0	

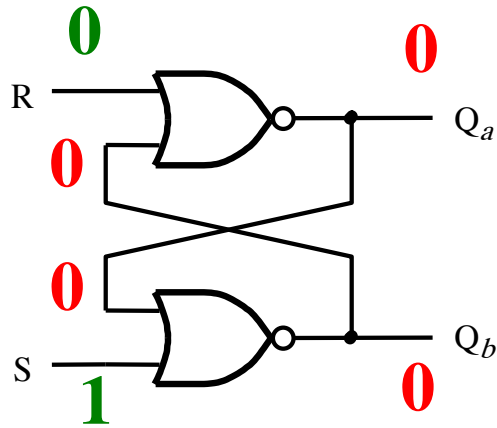
(b) Characteristic table



(c) Timing diagram

For a brief moment the latch goes through the undesirable state $Q_a=0$ and $Q_b=0$.

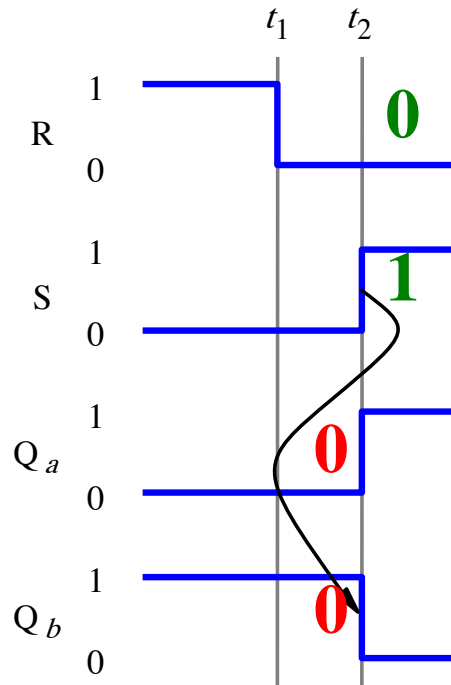
Timing Diagram for the Basic Latch with NOR Gates



(a) Circuit

S	R	Q _a	Q _b	
0	0	0/1	1/0	(no change)
0	1	0	1	
1	0	1	0	
1	1	0	0	

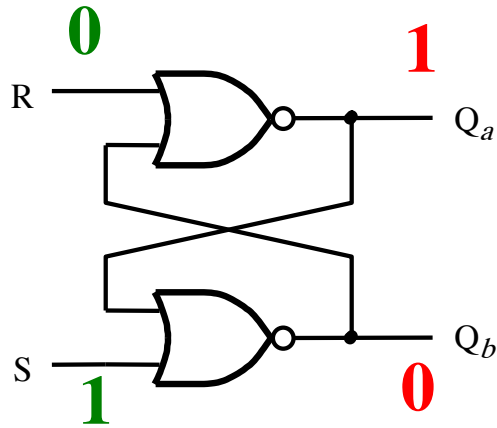
(b) Characteristic table



(c) Timing diagram

But these zeros loop around ...

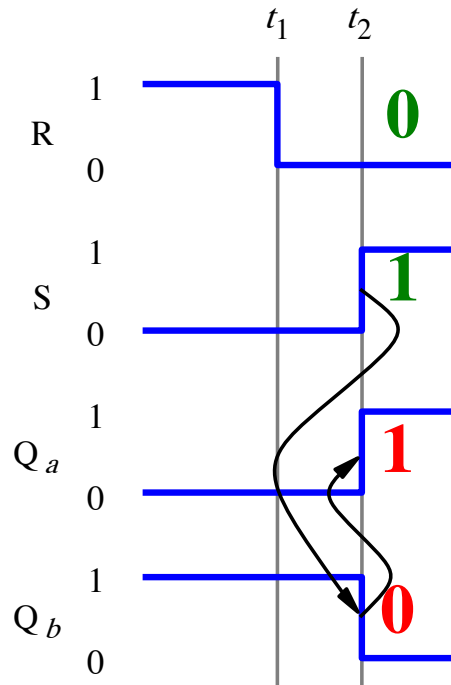
Timing Diagram for the Basic Latch with NOR Gates



(a) Circuit

S	R	Q _a	Q _b	
0	0	0/1	1/0	(no change)
0	1	0	1	
1	0	1	0	
1	1	0	0	

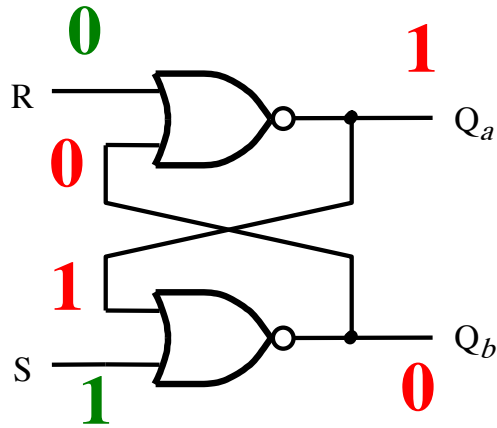
(b) Characteristic table



(c) Timing diagram

... and set it to $Q_a=1$ and $Q_b=0$.

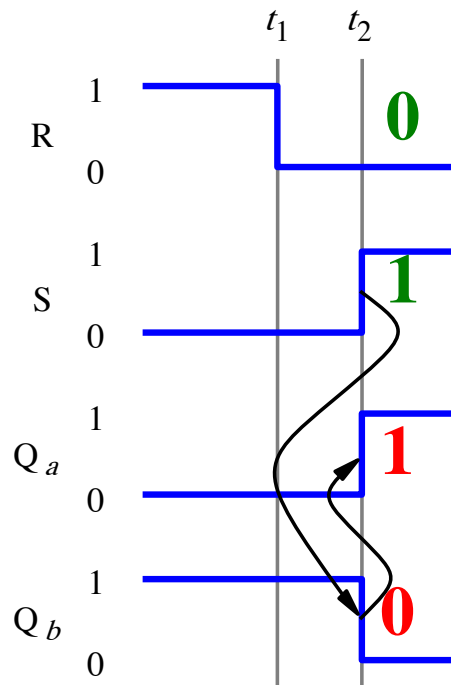
Timing Diagram for the Basic Latch with NOR Gates



(a) Circuit

S	R	Q _a	Q _b	
0	0	0/1	1/0	(no change)
0	1	0	1	
1	0	1	0	
1	1	0	0	

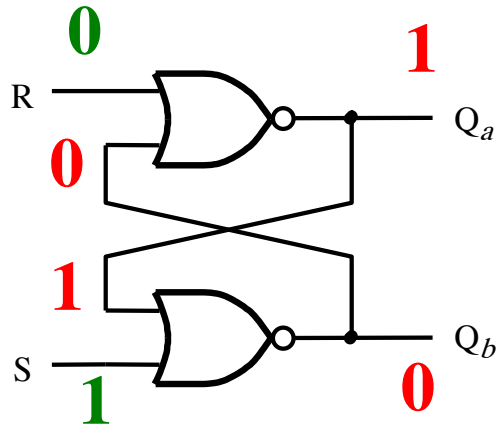
(b) Characteristic table



(c) Timing diagram

The new values also loop around ...

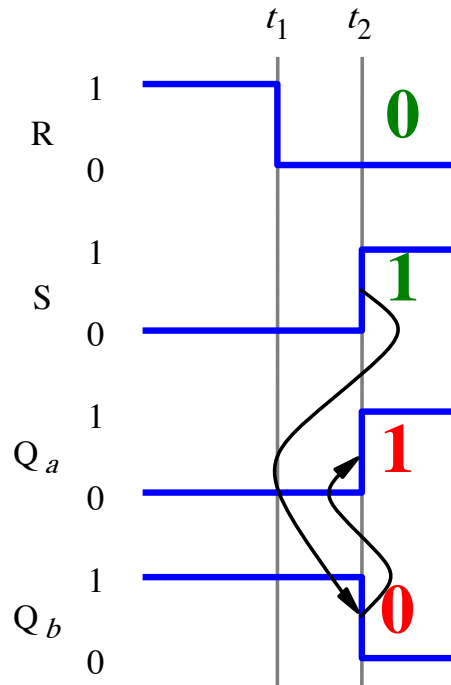
Timing Diagram for the Basic Latch with NOR Gates



(a) Circuit

S	R	Q _a	Q _b	
0	0	0/1	1/0	(no change)
0	1	0	1	
1	0	1	0	
1	1	0	0	

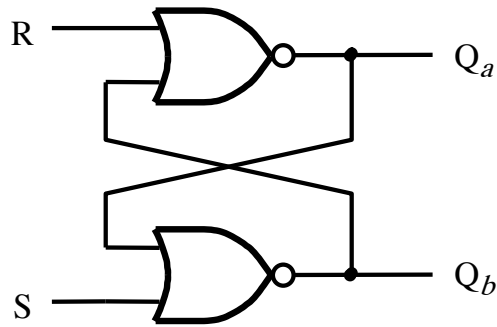
(b) Characteristic table



(c) Timing diagram

... but they leave the outputs the same.

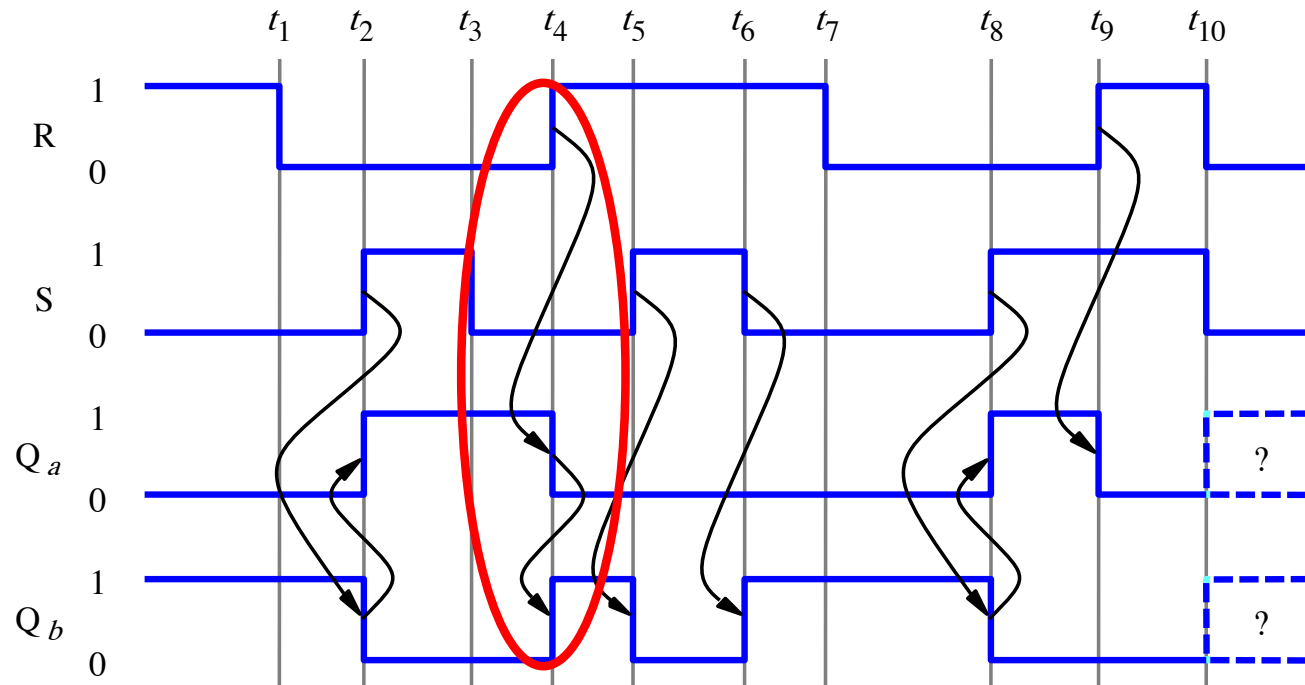
Timing Diagram for the Basic Latch with NOR Gates



(a) Circuit

S	R	Q_a	Q_b
0	0	0/1	1/0 (no change)
0	1	0	1
1	0	1	0
1	1	0	0

(b) Characteristic table

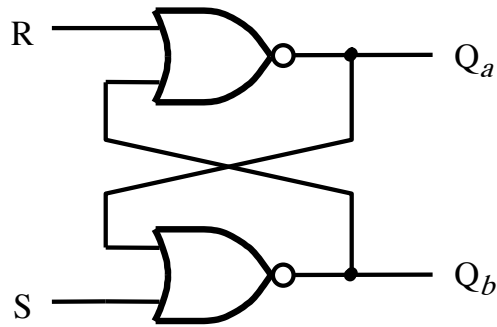


→ Time

(c) Timing diagram

[Figure 5.4 from the textbook]

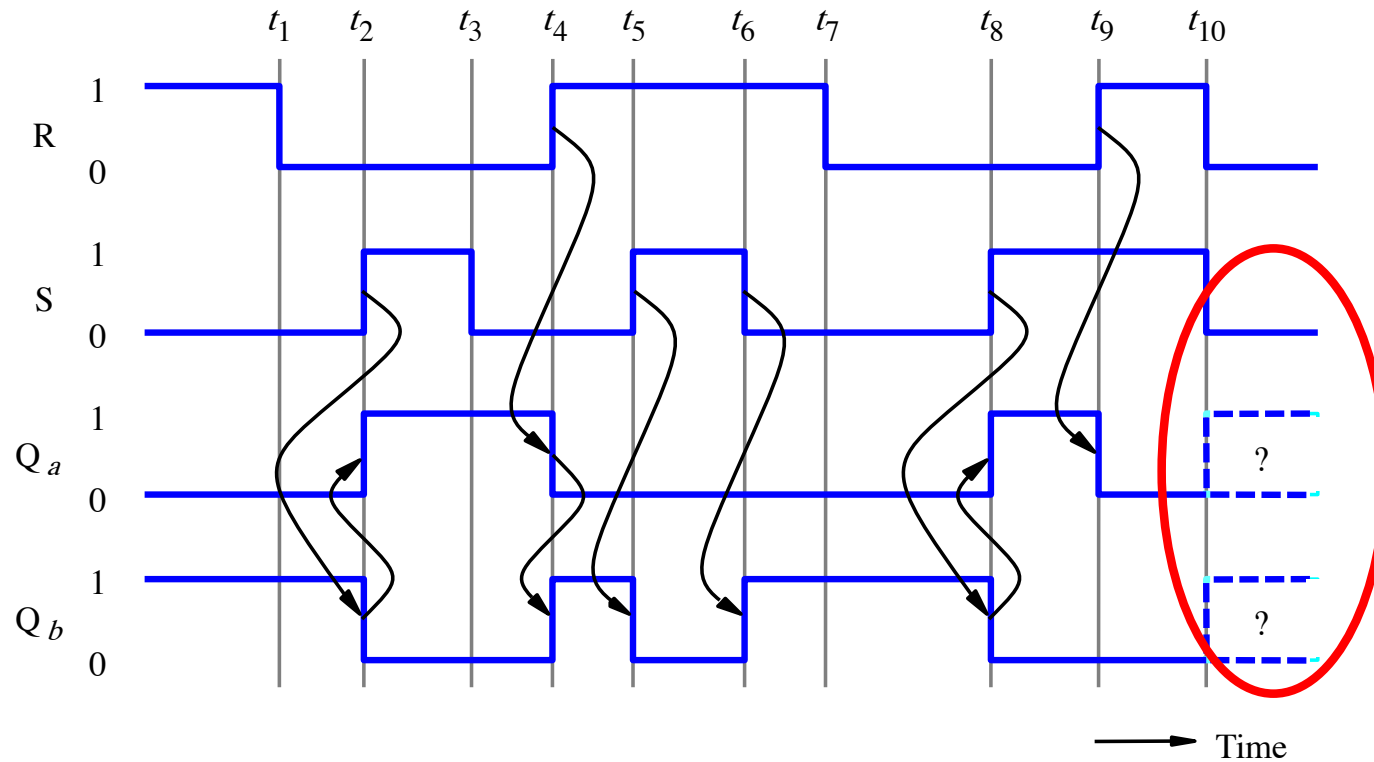
Timing Diagram for the Basic Latch with NOR Gates



(a) Circuit

S	R	Q_a	Q_b
0	0	0/1	1/0 (no change)
0	1	0	1
1	0	1	0
1	1	0	0

(b) Characteristic table

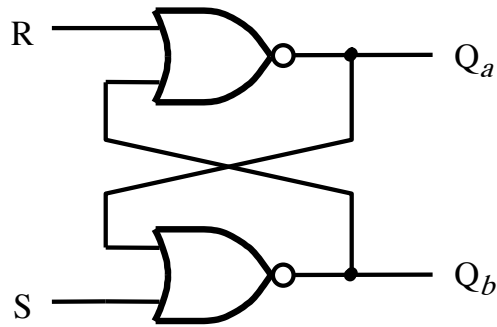


(c) Timing diagram

→ Time

[Figure 5.4 from the textbook]

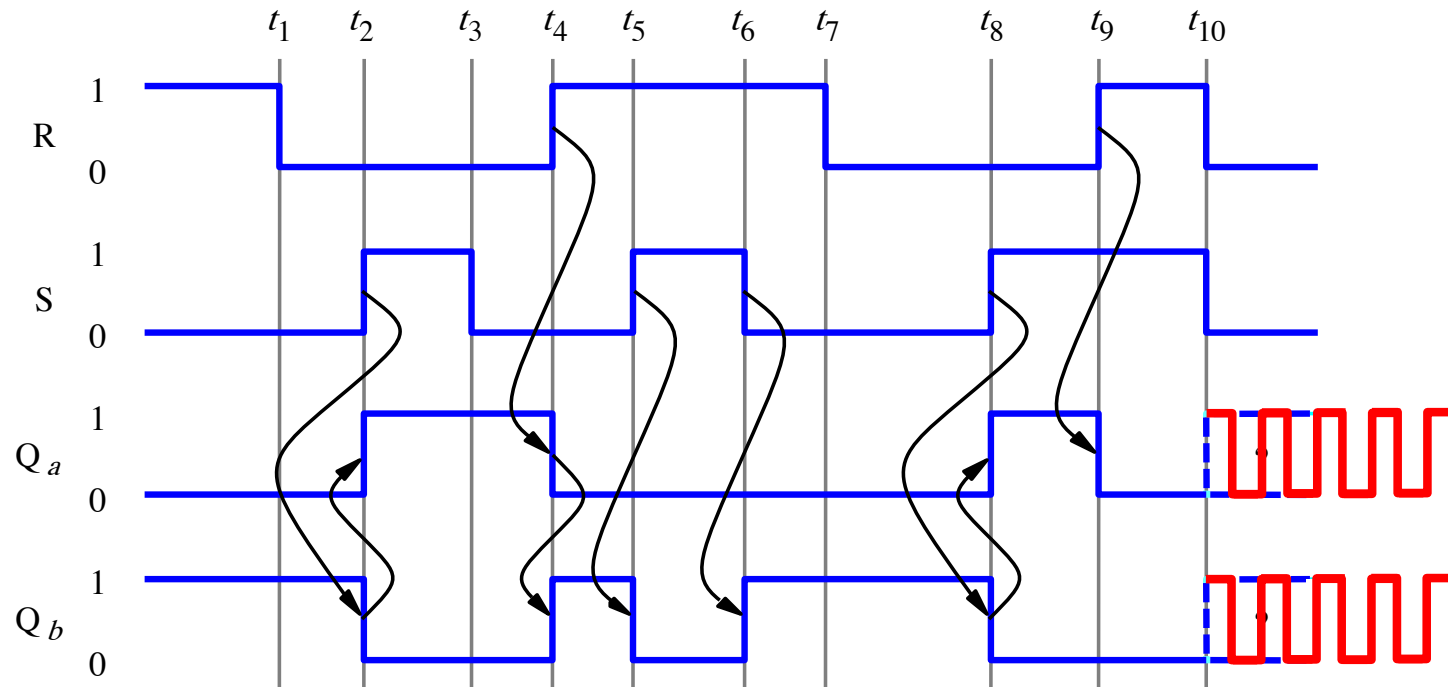
Timing Diagram for the Basic Latch with NOR Gates



(a) Circuit

S	R	Q_a	Q_b
0	0	0/1	1/0 (no change)
0	1	0	1
1	0	1	0
1	1	0	0

(b) Characteristic table

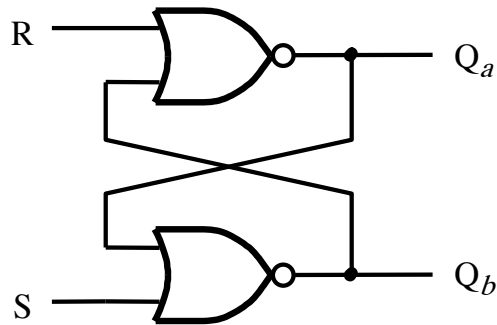


→ Time

(c) Timing diagram

[Figure 5.4 from the textbook]

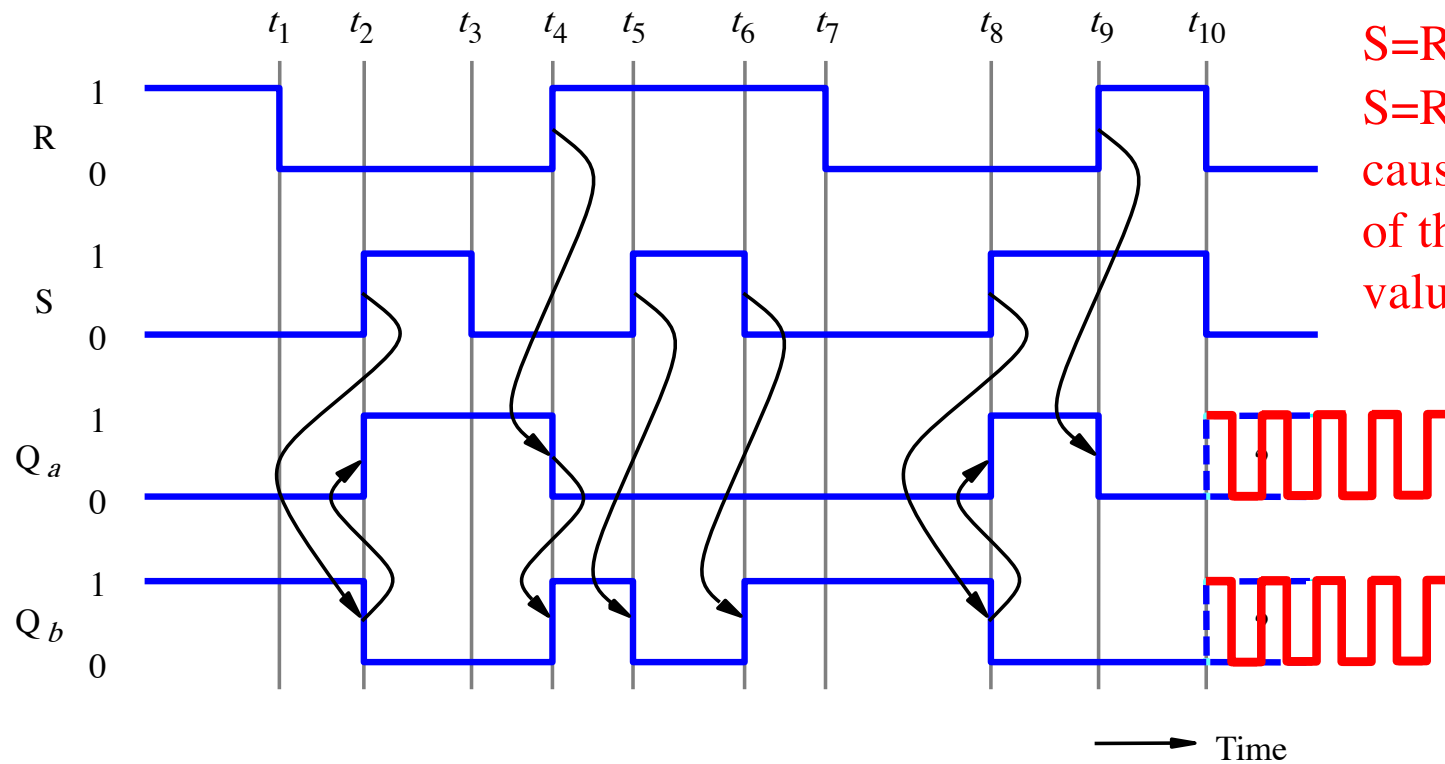
Timing Diagram for the Basic Latch with NOR Gates



(a) Circuit

S	R	Q_a	Q_b
0	0	0/1	1/0 (no change)
0	1	0	1
1	0	1	0
1	1	0	0

(b) Characteristic table



A transition from $S=R=1$ to $S=R=0$ causes oscillations of the two output values Q_a and Q_b .

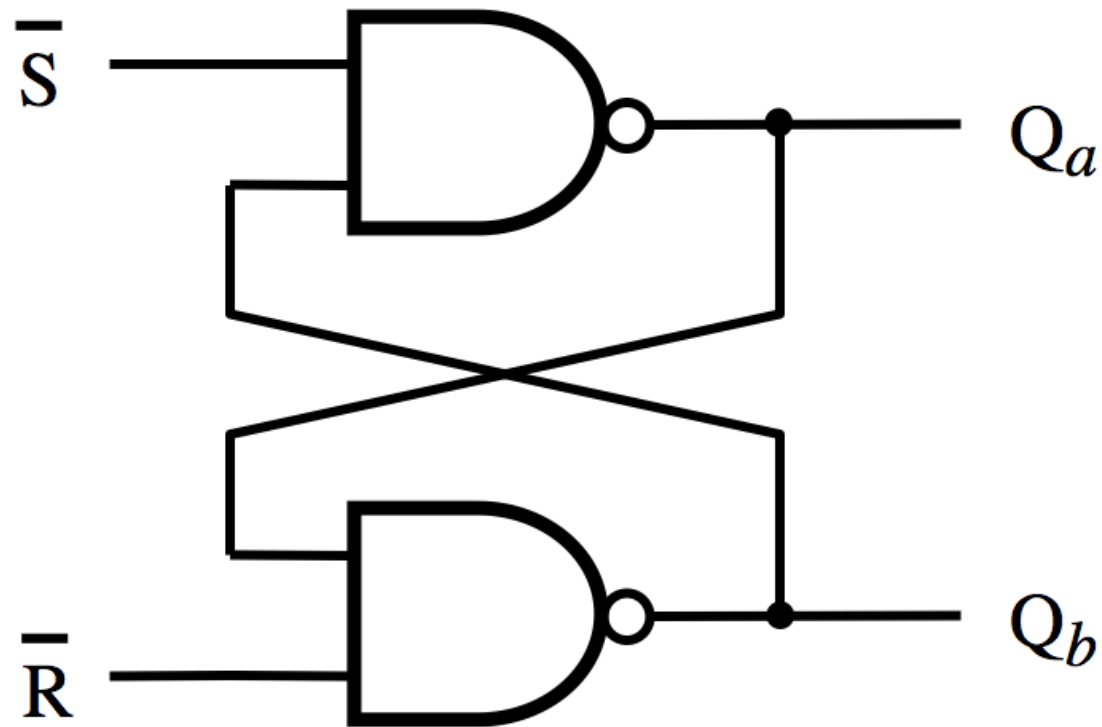
(c) Timing diagram

→ Time

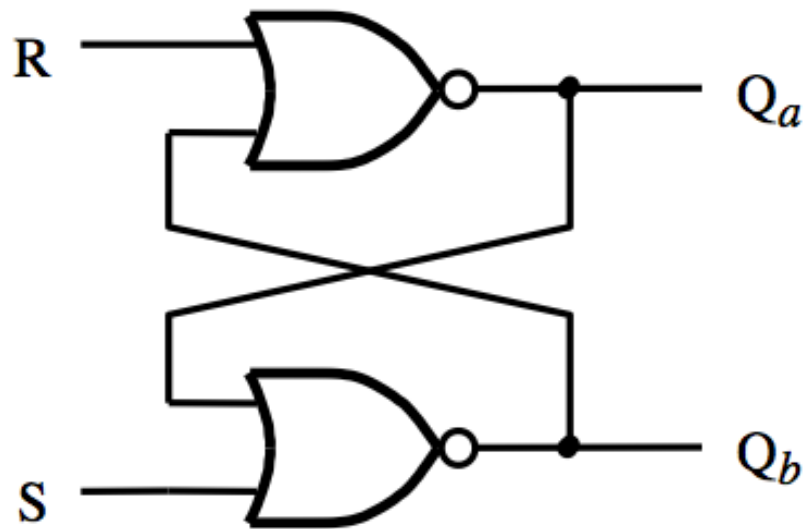
[Figure 5.4 from the textbook]

Basic Latch with NAND Gates

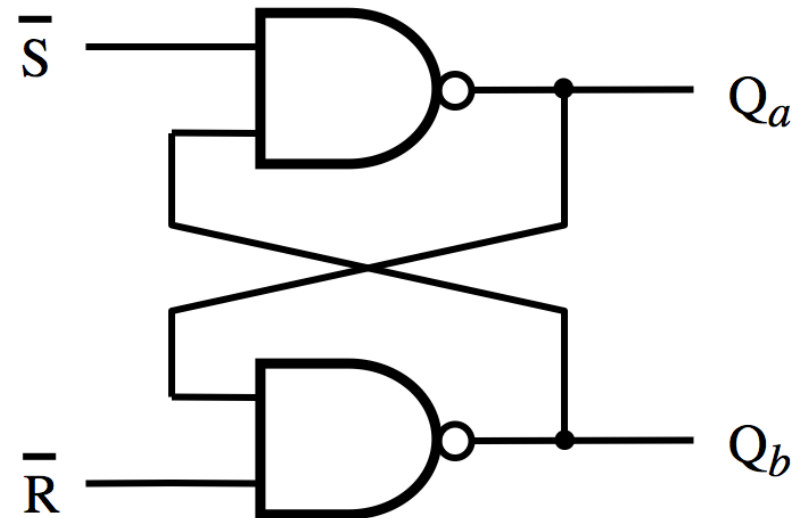
Circuit for the Basic Latch with NAND Gates



Basic Latch (with NOR Gates)



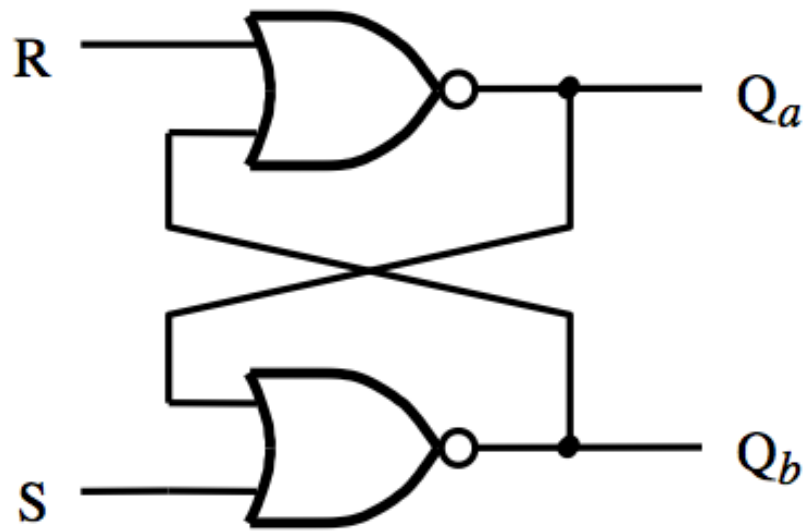
Basic Latch (with NAND Gates)



Notice that in the NAND case the two inputs are swapped and negated.

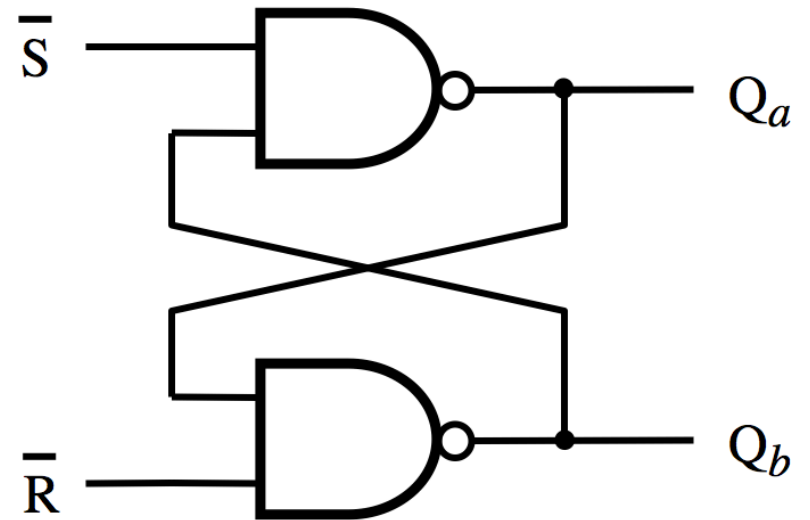
The labels of the outputs are the same in both cases.

Basic Latch (with NOR Gates)



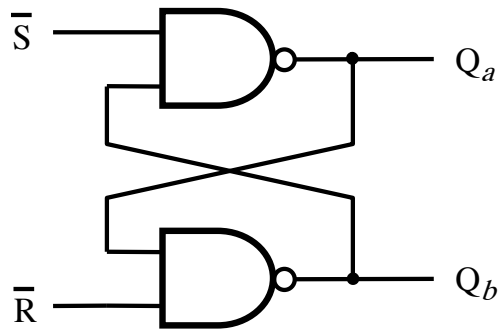
SR Latch

Basic Latch (with NAND Gates)



$\bar{S}\bar{R}$ Latch

Circuit and Characteristic Table



(a) Circuit

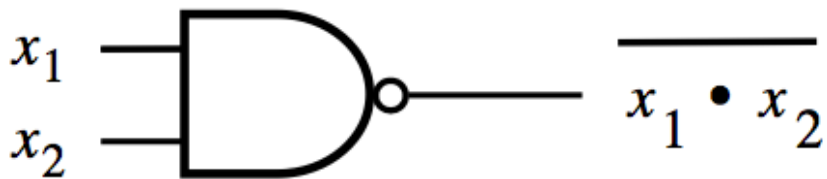
\bar{S}	\bar{R}	Q_a	Q_b
0	0	1	1
0	1	1	0
1	0	0	1
1	1	0/1	1/0 (no change)

(b) Characteristic table (version 1)

S	R	Q_a	Q_b
0	0	0/1	1/0 (no change)
0	1	0	1
1	0	1	0
1	1	1	1

(c) Characteristic table (version 2)

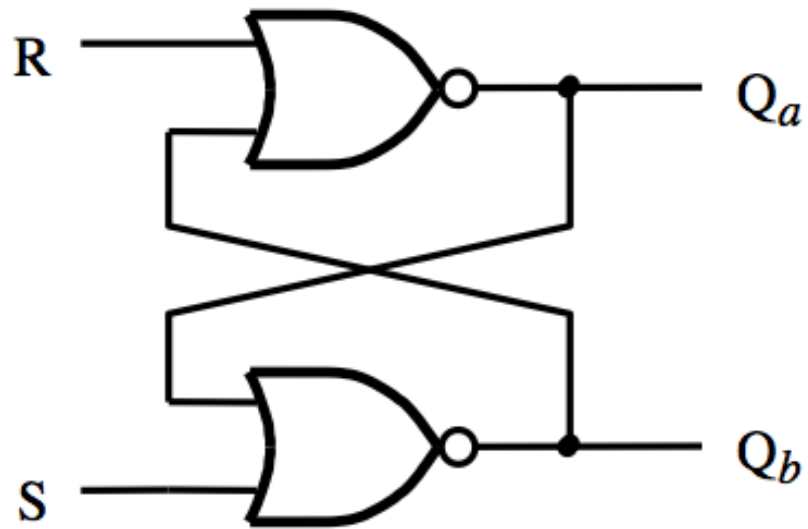
NAND Gate



NAND Gate Truth table

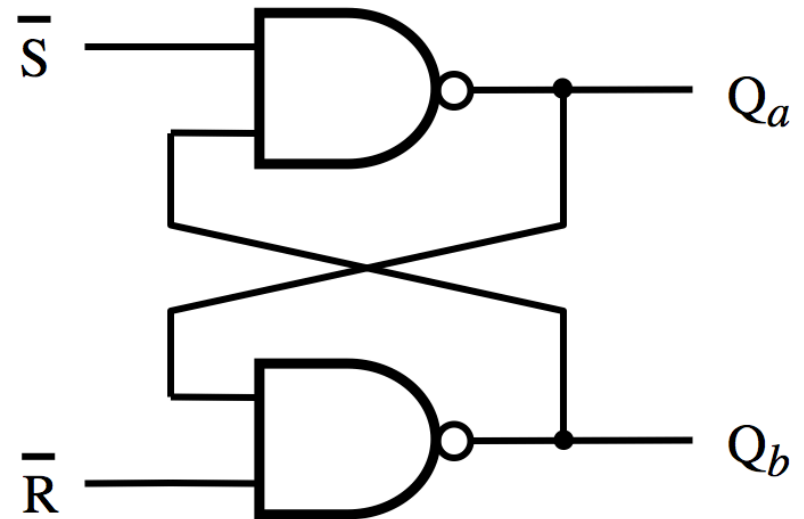
x_1	x_2	f
0	0	1
0	1	1
1	0	1
1	1	0

Basic Latch (with NOR Gates)



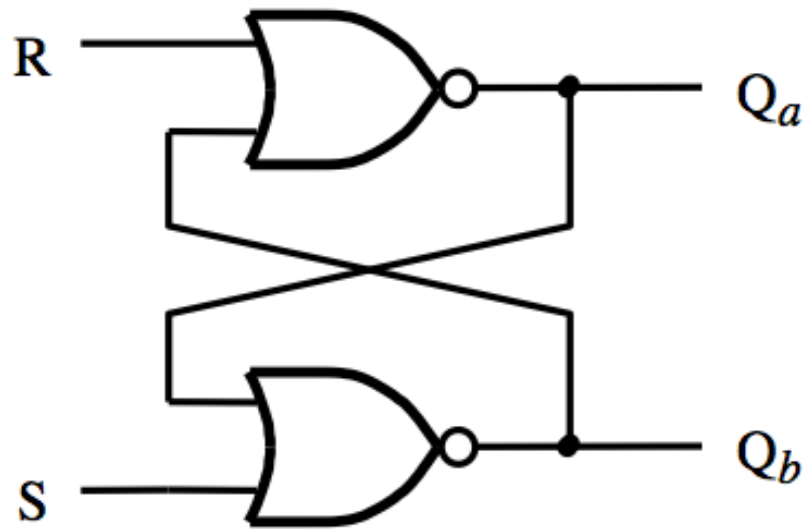
S	R	Q_a	Q_b	
0	0	0/1	1/0	(no change)
0	1	0	1	
1	0	1	0	
1	1	0	0	

Basic Latch (with NAND Gates)



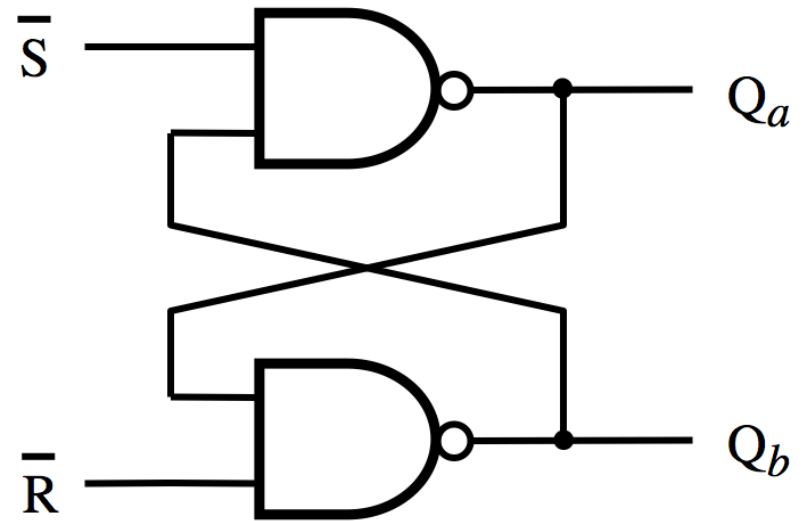
S	R	Q_a	Q_b	
0	0	0/1	1/0	(no change)
0	1	0	1	
1	0	1	0	
1	1	1	1	

Basic Latch (with NOR Gates)



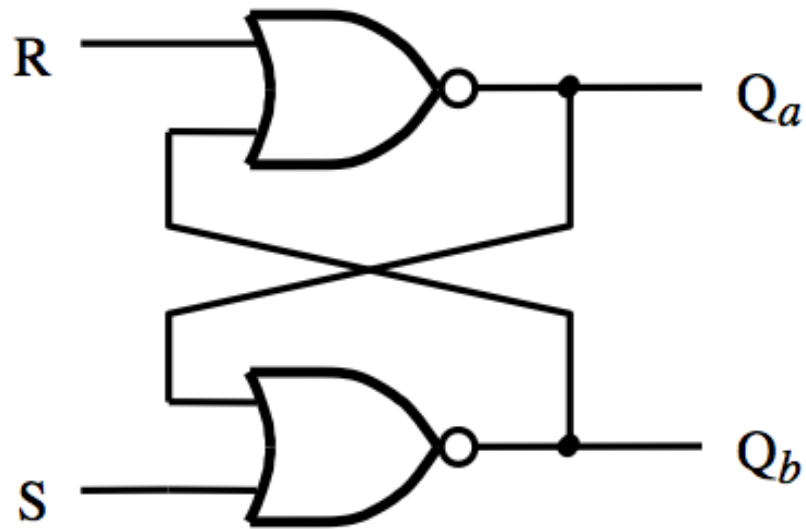
S	R	Q_a	Q_b	
0	0	0/1	1/0	(no change) Latch
0	1	0	1	Reset
1	0	1	0	Set
1	1	0	0	Undesirable

Basic Latch (with NAND Gates)



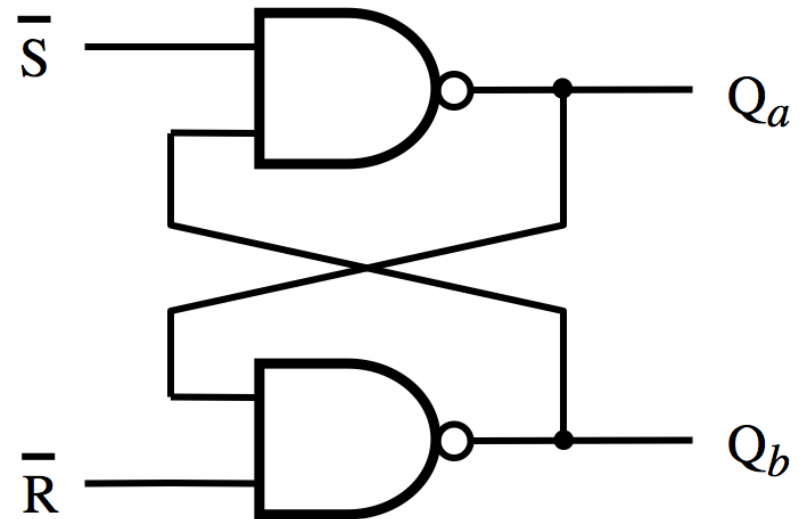
S	R	Q_a	Q_b	
0	0	0/1	1/0	(no change) Latch
0	1	0	1	Reset
1	0	1	0	Set
1	1	1	1	Undesirable

Basic Latch (with NOR Gates)



S	R	Q_a	Q_b	
0	0	0/1	1/0	(no change) Latch
0	1	0	1	Reset
1	0	1	0	Set
1	1	0	0	Undesirable

Basic Latch (with NAND Gates)



S	R	Q_a	Q_b	
0	0	0/1	1/0	(no change) Latch
0	1	0	1	Reset
1	0	1	0	Set
1	1	1	1	Undesirable

The two characteristic tables are the same
(except for the last row, which is the undesirable configuration).

Oscillations and Undesirable States

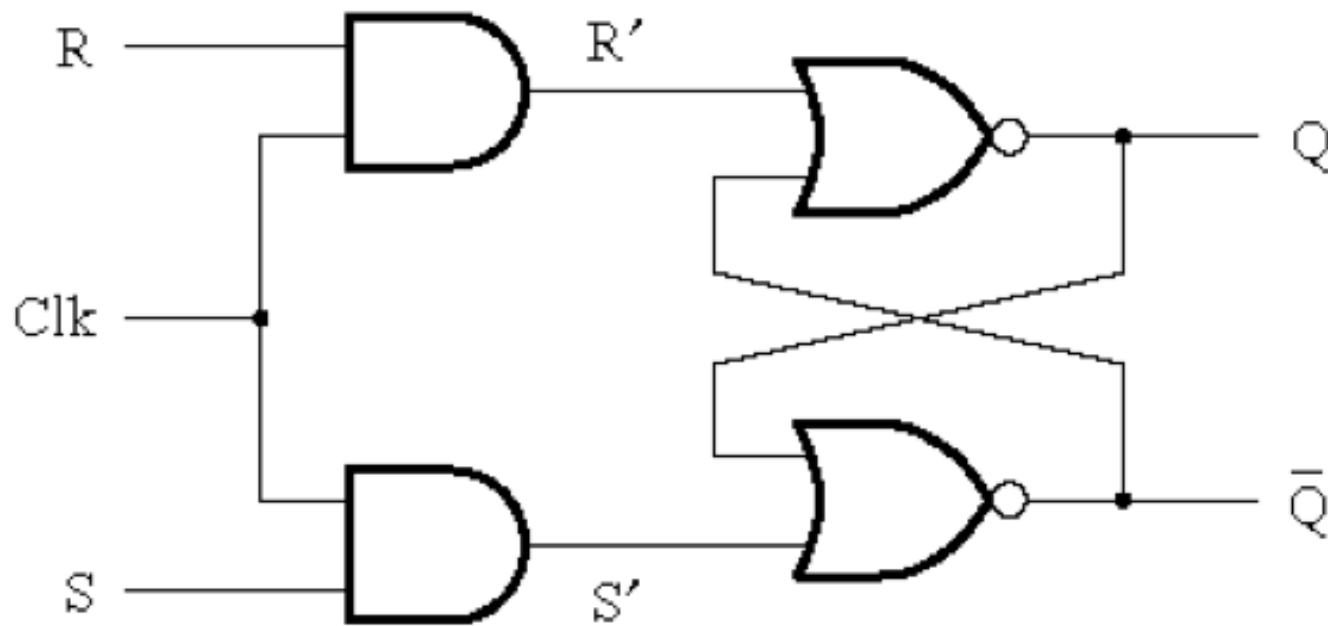
- **The basic latch with NAND gates also suffers from oscillation problems, similar to the basic latch implemented with NOR gates.**
- **Try to do this analysis on your own.**

Gated SR Latch

Motivation

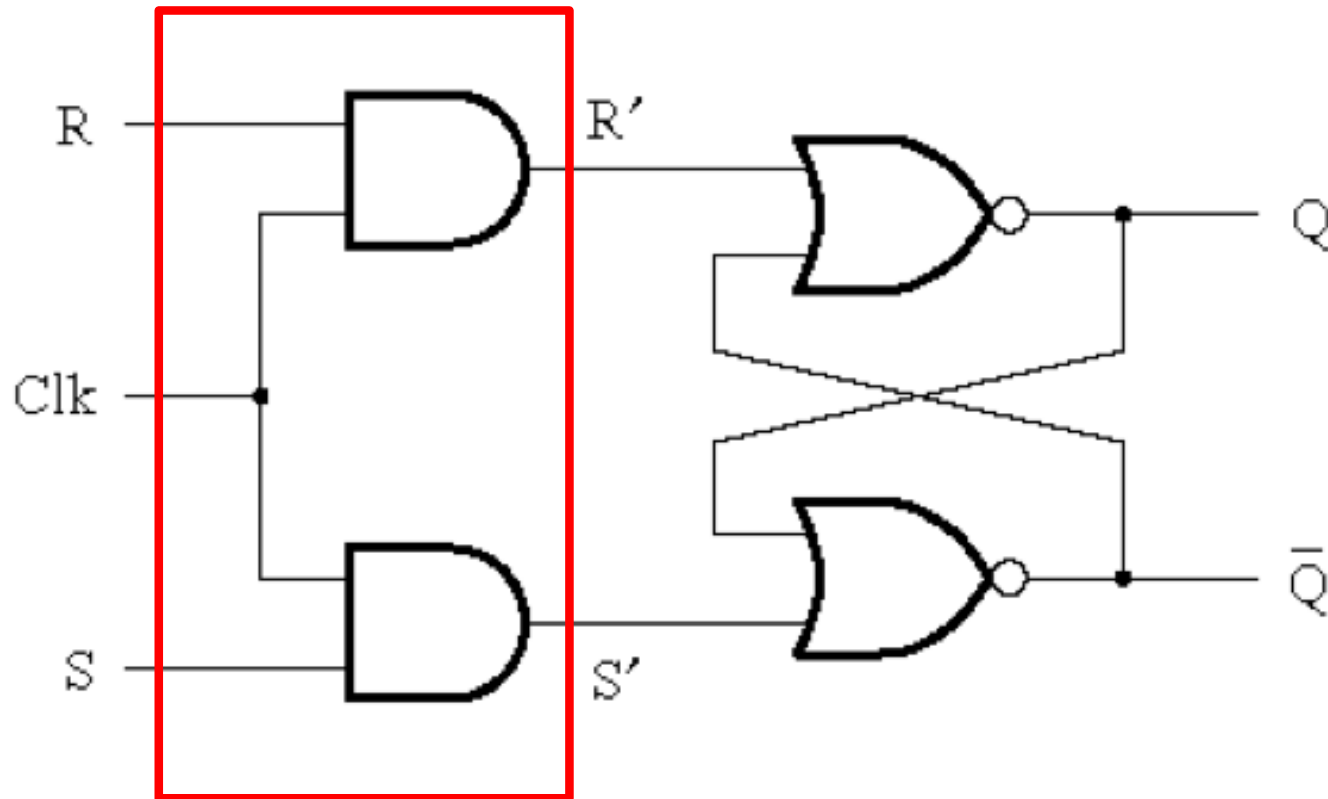
- **The basic latch changes its state when the input signals change**
- **It is hard to control when these input signals will change and thus it is hard to know when the latch may change its state.**
- **We want to have something like an Enable input.**
- **In this case it is called the “Clock” input because it is desirable for the state changes to be synchronized.**

Circuit Diagram for the Gated SR Latch



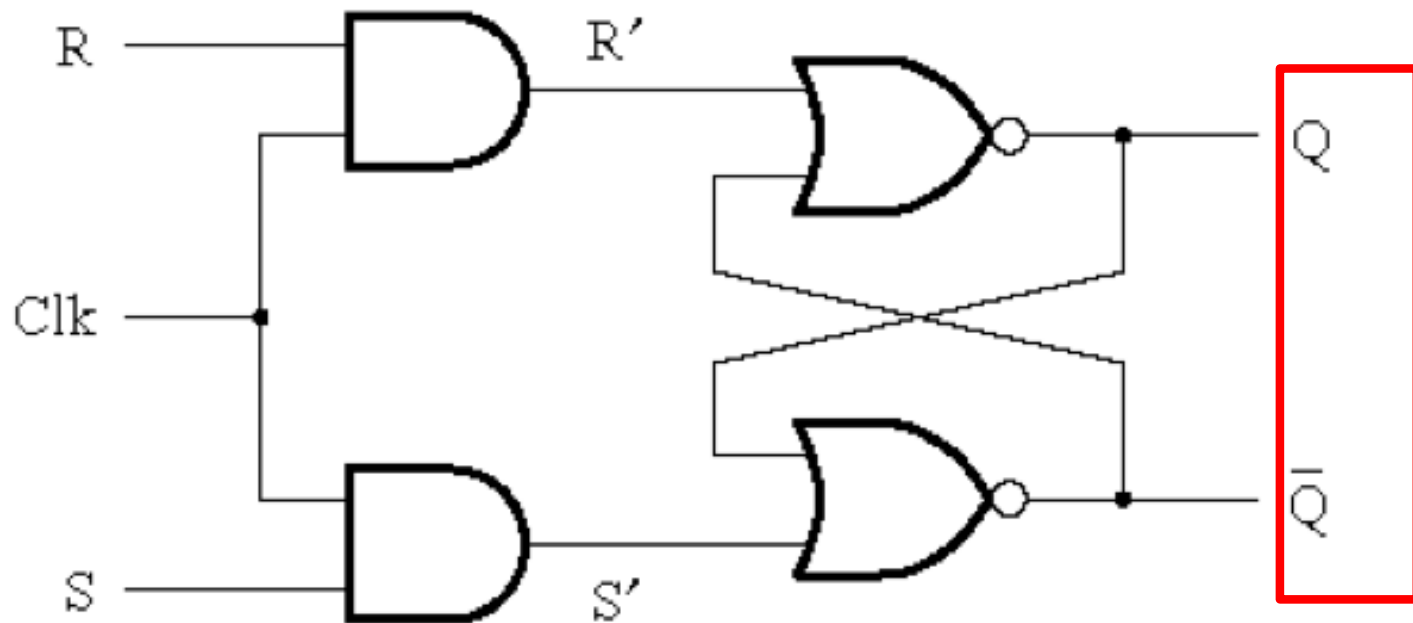
[Figure 5.5a from the textbook]

Circuit Diagram for the Gated SR Latch



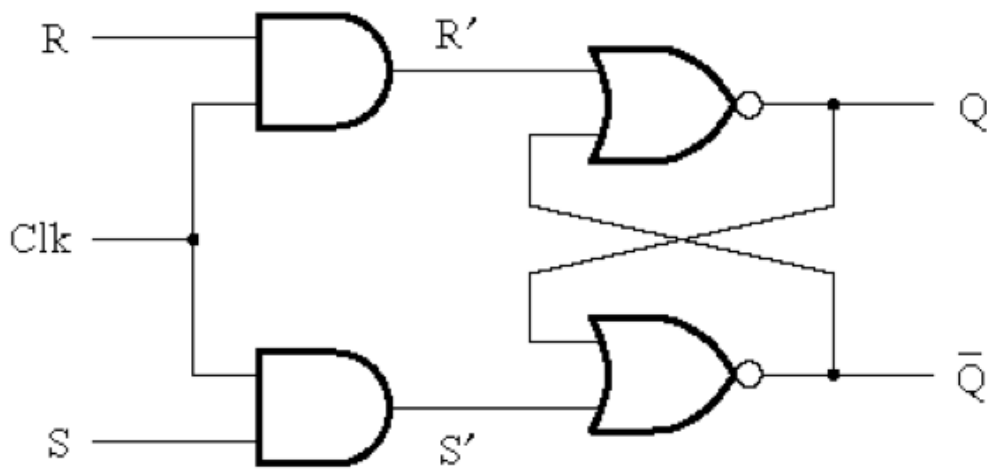
This is the “gate”
of the gated latch

Circuit Diagram for the Gated SR Latch



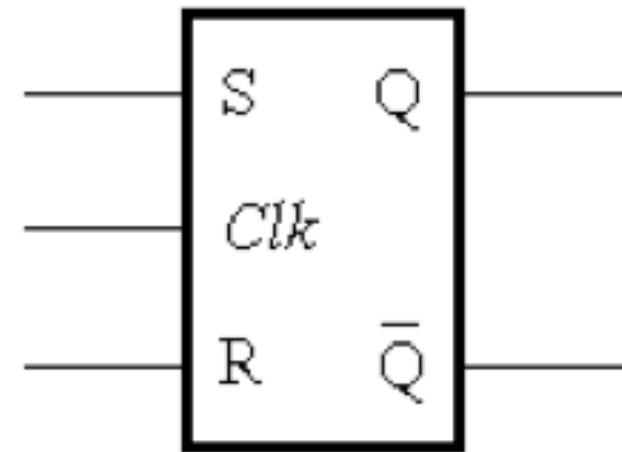
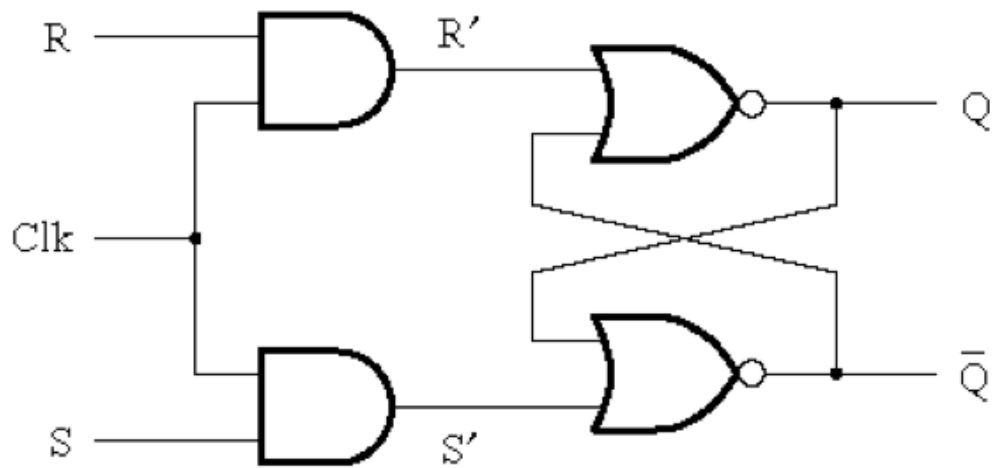
Notice that these are complements of each other

Circuit Diagram and Characteristic Table for the Gated SR Latch

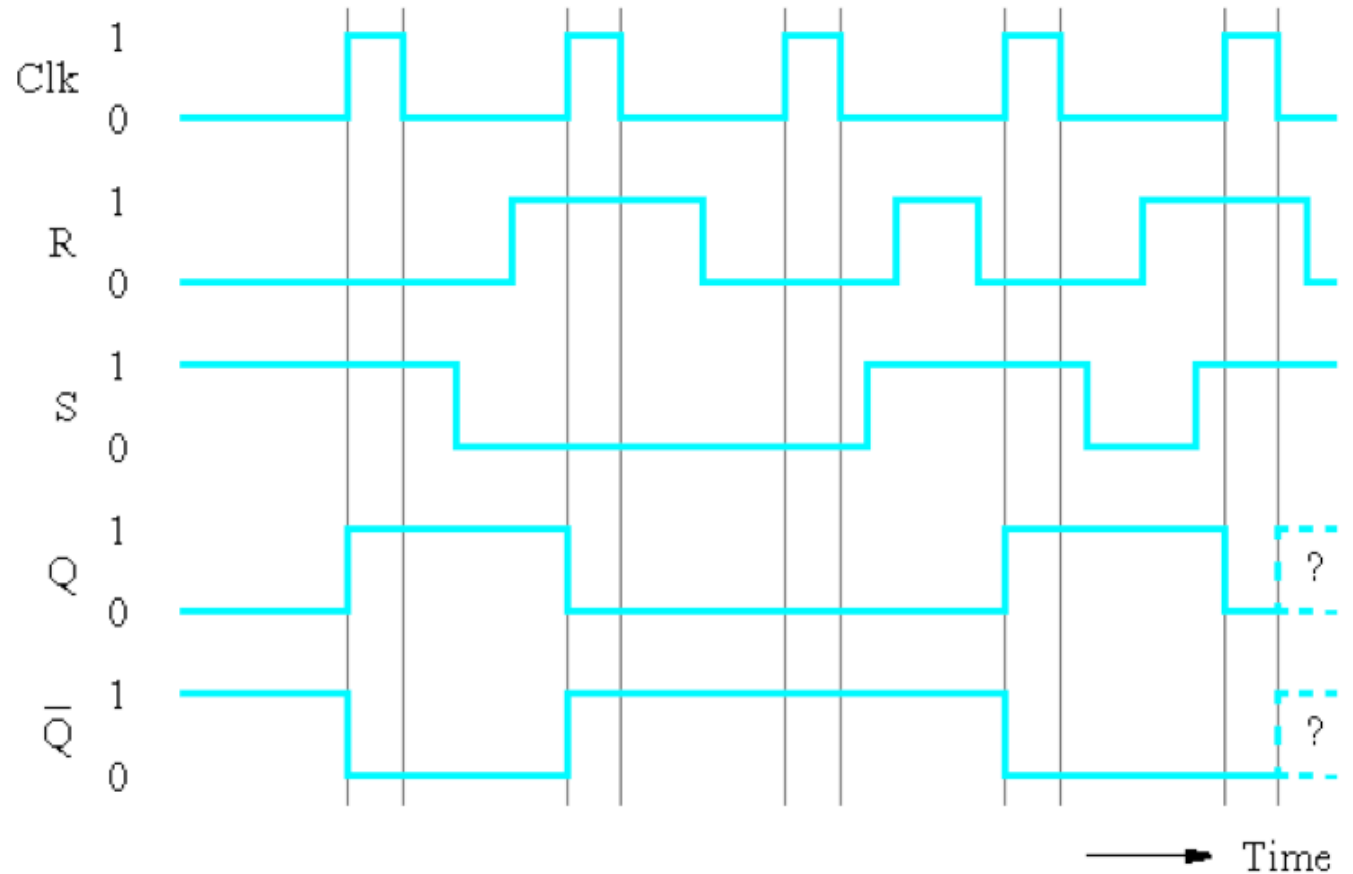
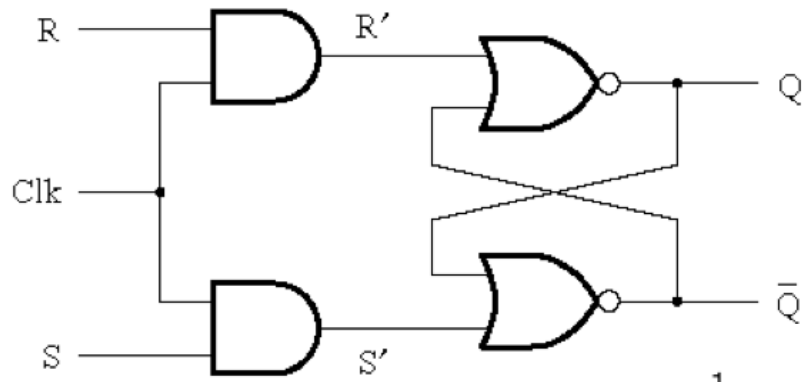


Clk	S	R	Q(t + 1)
0	x	x	Q(t) (no change)
1	0	0	Q(t) (no change)
1	0	1	0
1	1	0	1
1	1	1	x

Circuit Diagram and Graphical Symbol for the Gated SR Latch

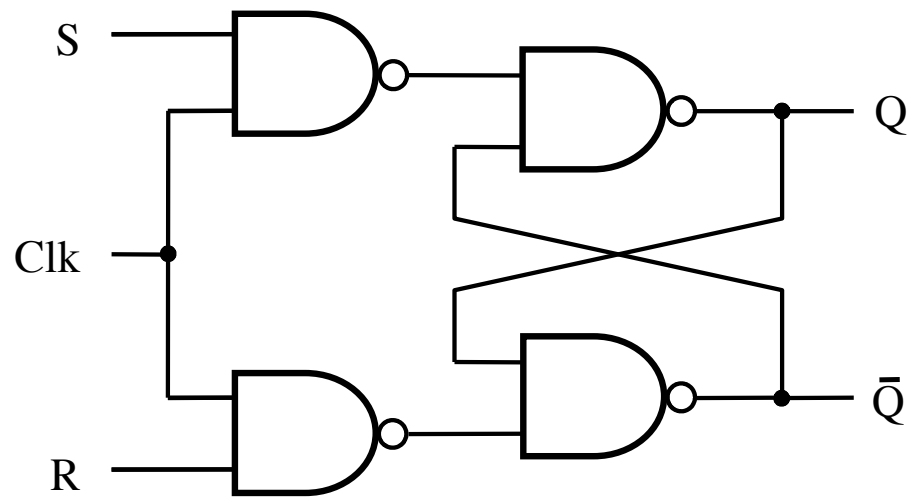


Timing Diagram for the Gated SR Latch

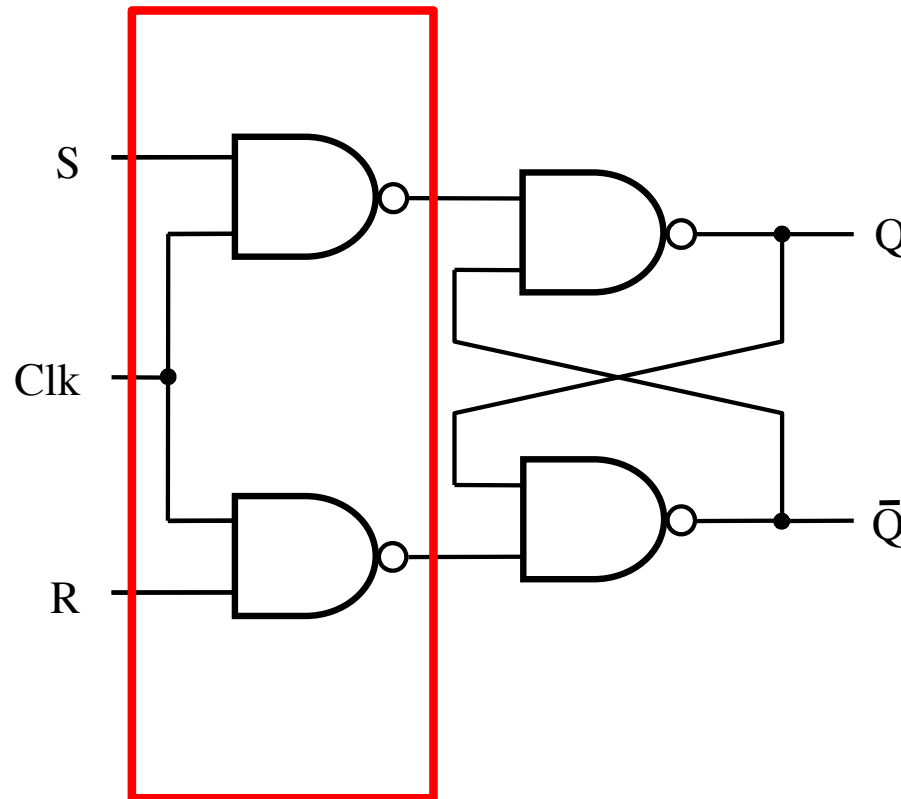


[Figure 5.5c from the textbook]

Gated SR latch with NAND gates

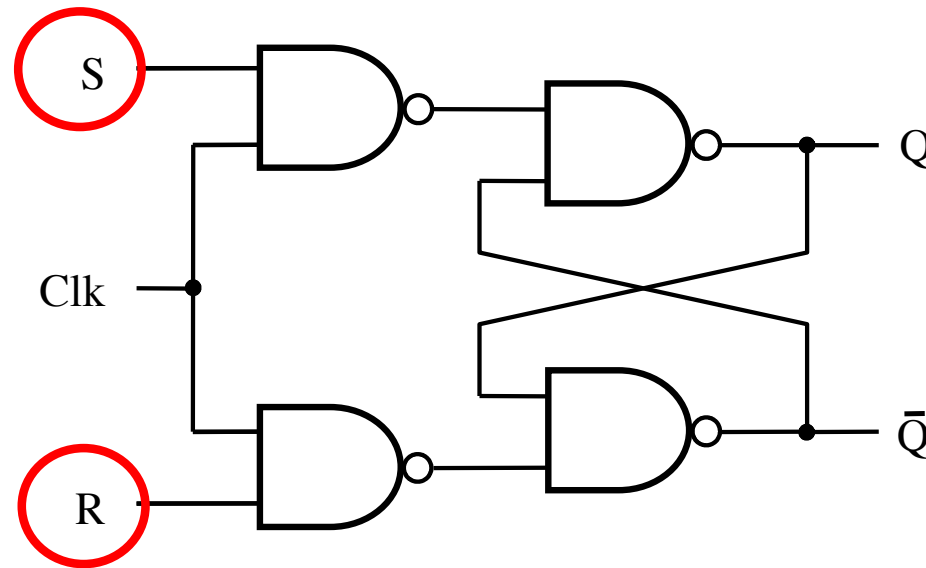


Gated SR latch with NAND gates



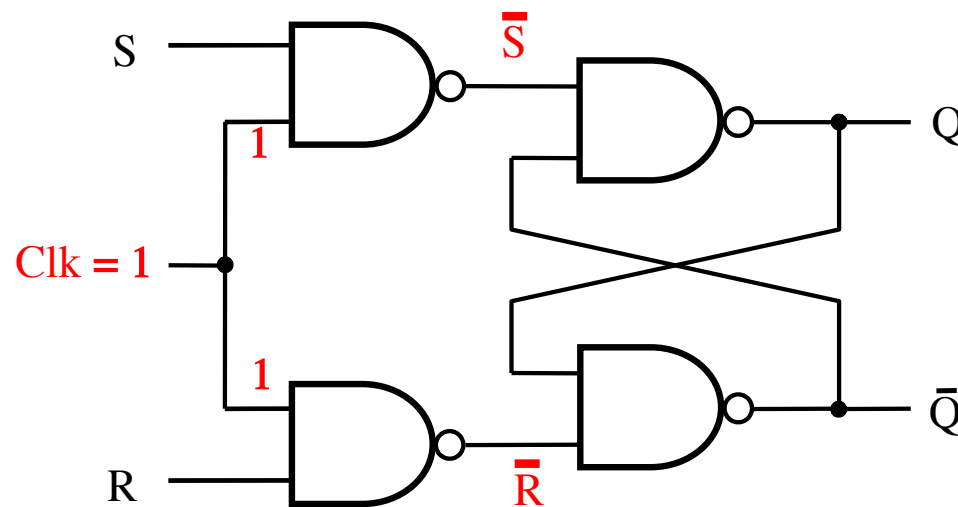
In this case the “gate” is constructed using NAND gates! Not AND gates.

Gated SR latch with NAND gates



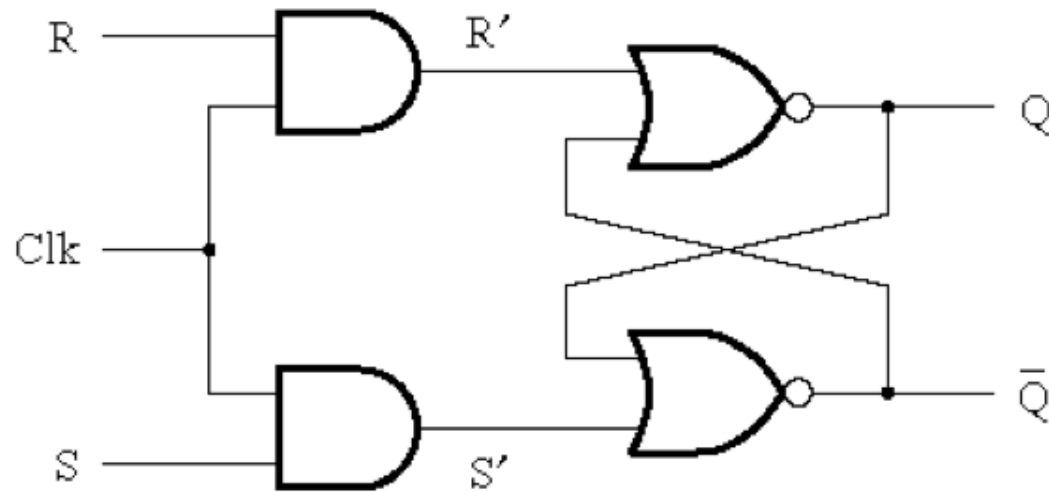
Also, notice that the positions of S and R are now swapped.

Gated SR latch with NAND gates

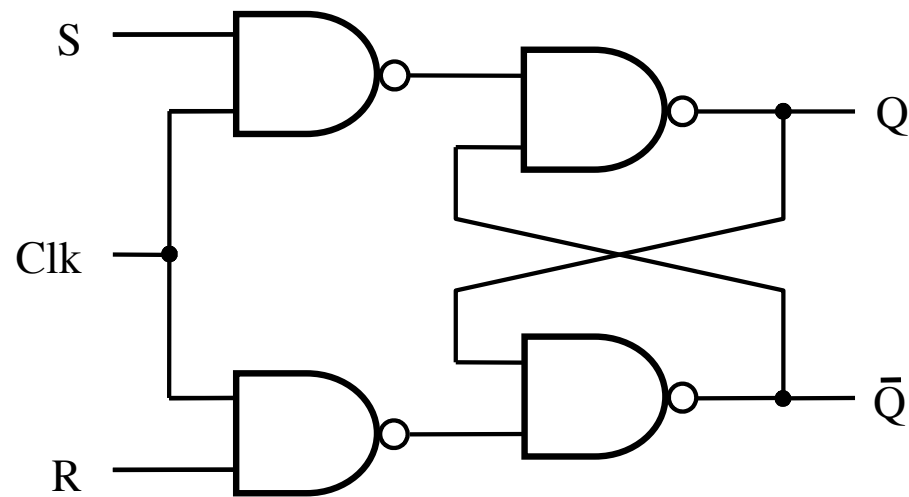


Finally, notice that when $\text{Clk}=1$ this turns into the basic latch with NAND gates, i.e., the $\bar{S}\bar{R}$ Latch.

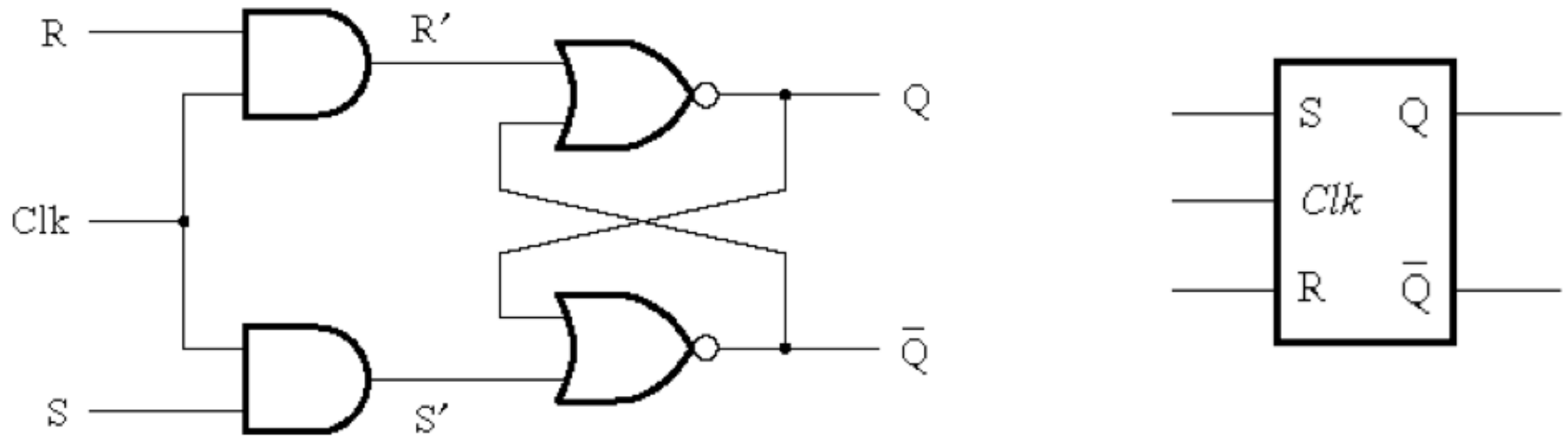
Gated SR latch with NOR gates



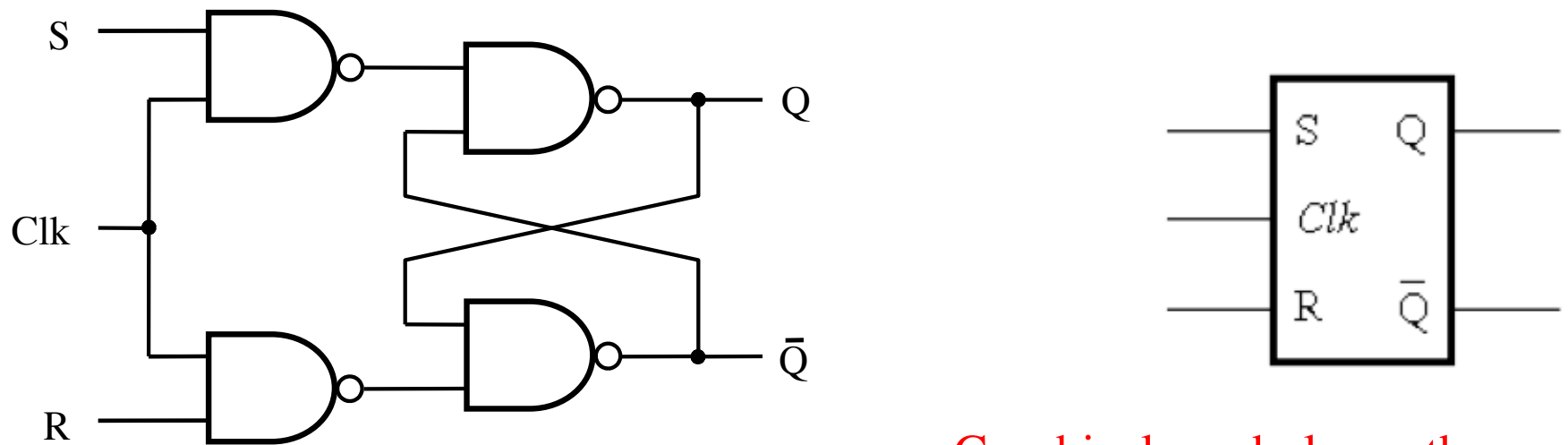
Gated SR latch with NAND gates



Gated SR latch with NOR gates

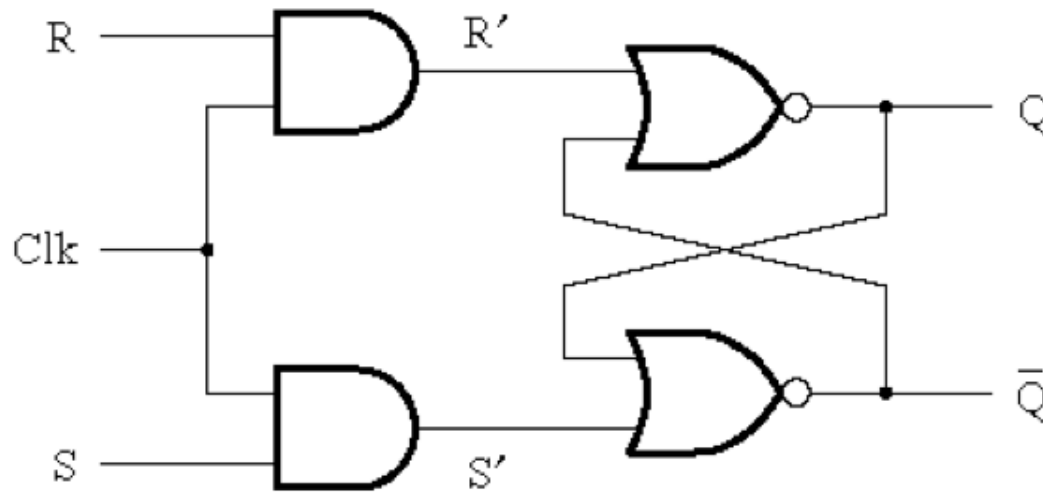


Gated SR latch with NAND gates



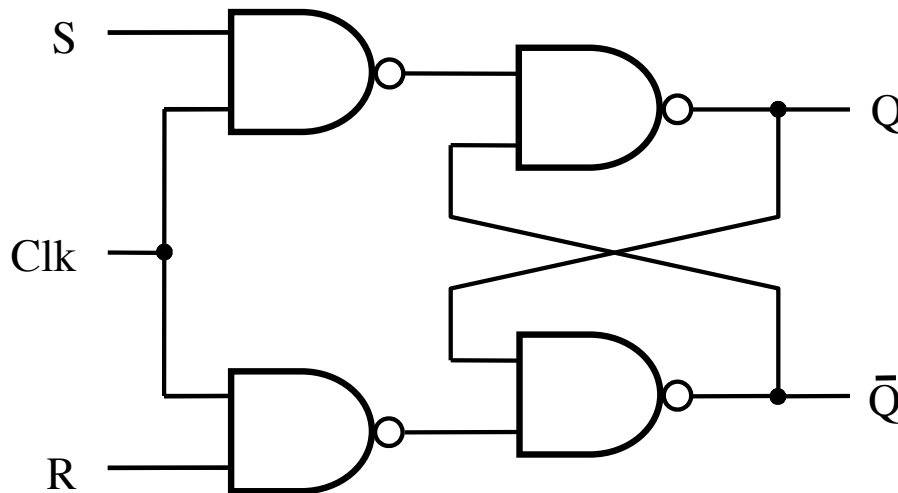
Graphical symbols are the same

Gated SR latch with NOR gates



Clk	S	R	$Q(t+1)$
0	x	x	$Q(t)$ (no change)
1	0	0	$Q(t)$ (no change)
1	0	1	0
1	1	0	1
1	1	1	x (undesirable)

Gated SR latch with NAND gates



Clk	S	R	$Q(t+1)$
0	x	x	$Q(t)$ (no change)
1	0	0	$Q(t)$ (no change)
1	0	1	0
1	1	0	1
1	1	1	x (undesirable)

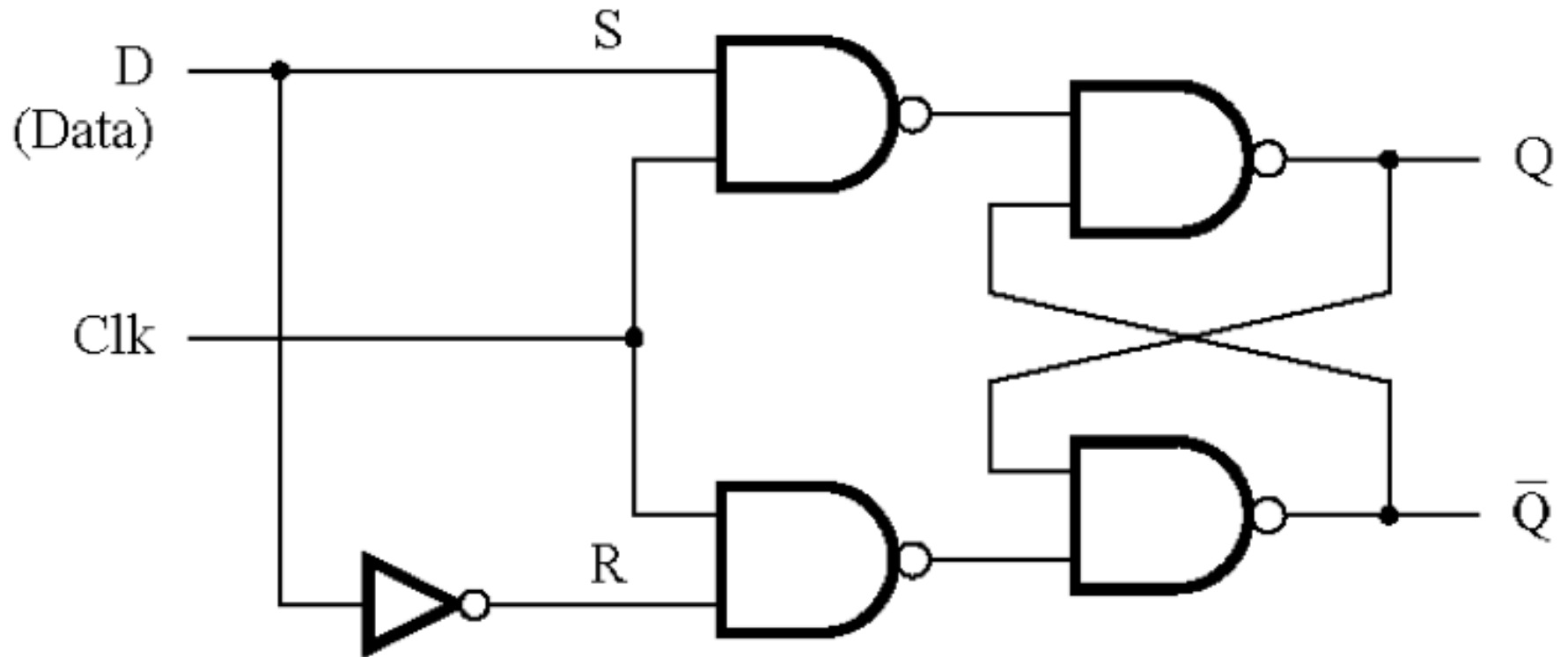
Characteristic tables are the same

Gated D Latch

Motivation

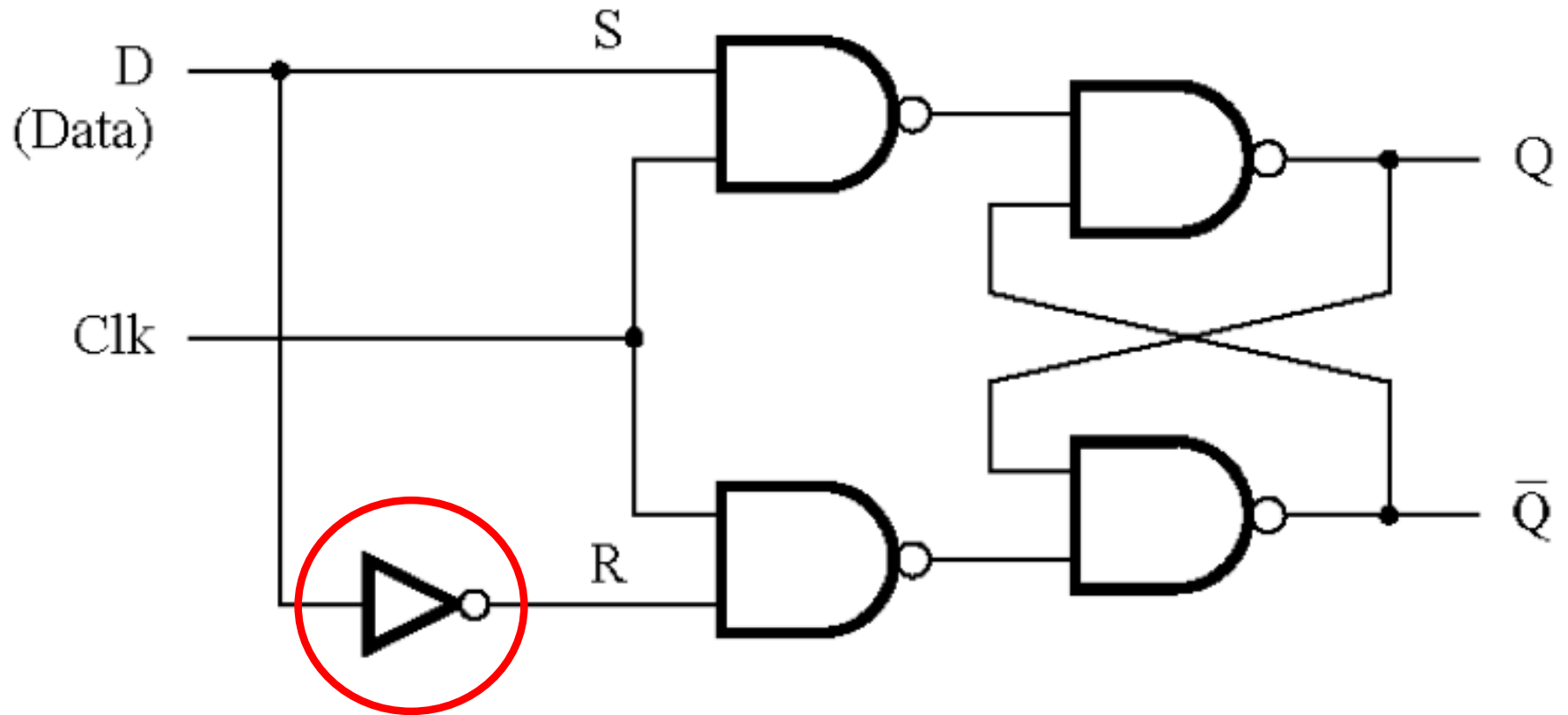
- **Dealing with two inputs (S and R) could be messy. For example, we may have to reset the latch before some operations in order to store a specific value but the reset may not be necessary depending on the current state of the latch.**
- **Why not just have one input and call it D.**
- **The D latch can be constructed using a simple modification of the SR latch.**

Circuit Diagram for the Gated D Latch



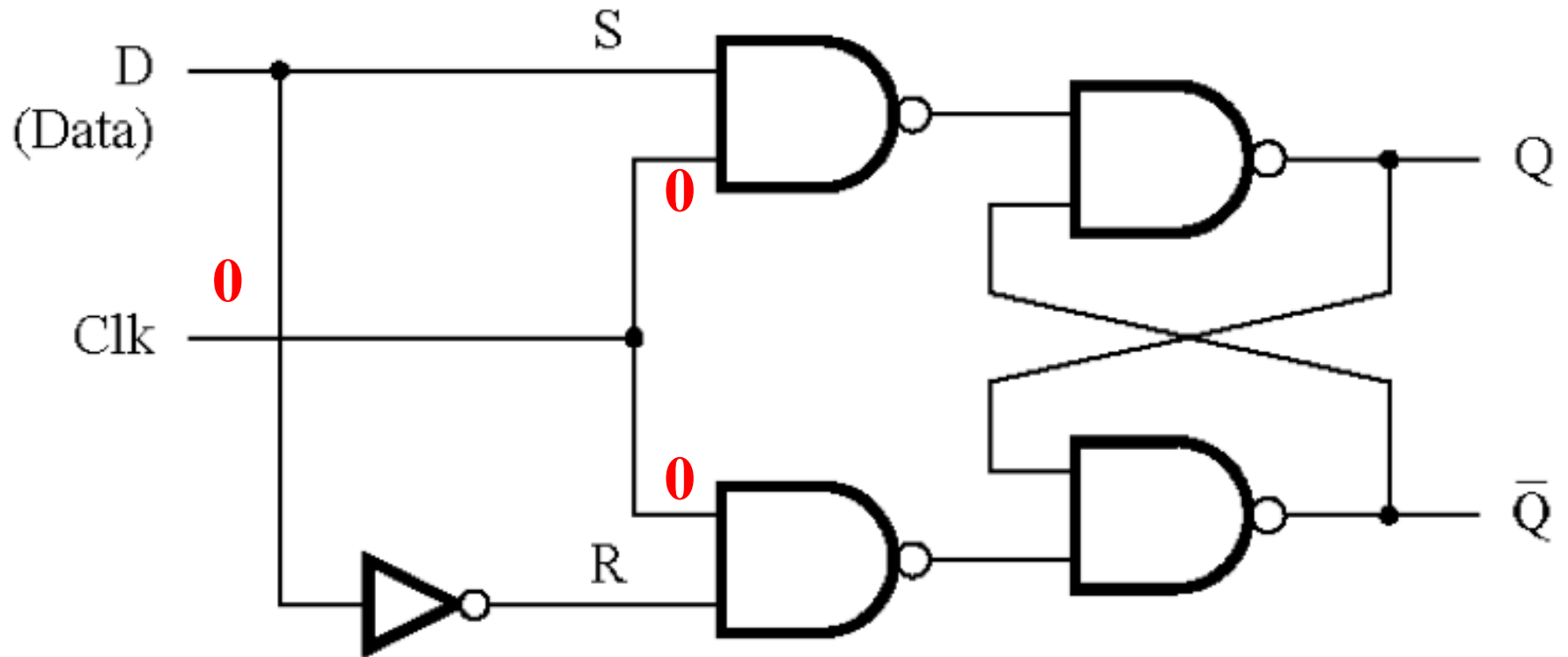
[Figure 5.7a from the textbook]

Circuit Diagram for the Gated D Latch



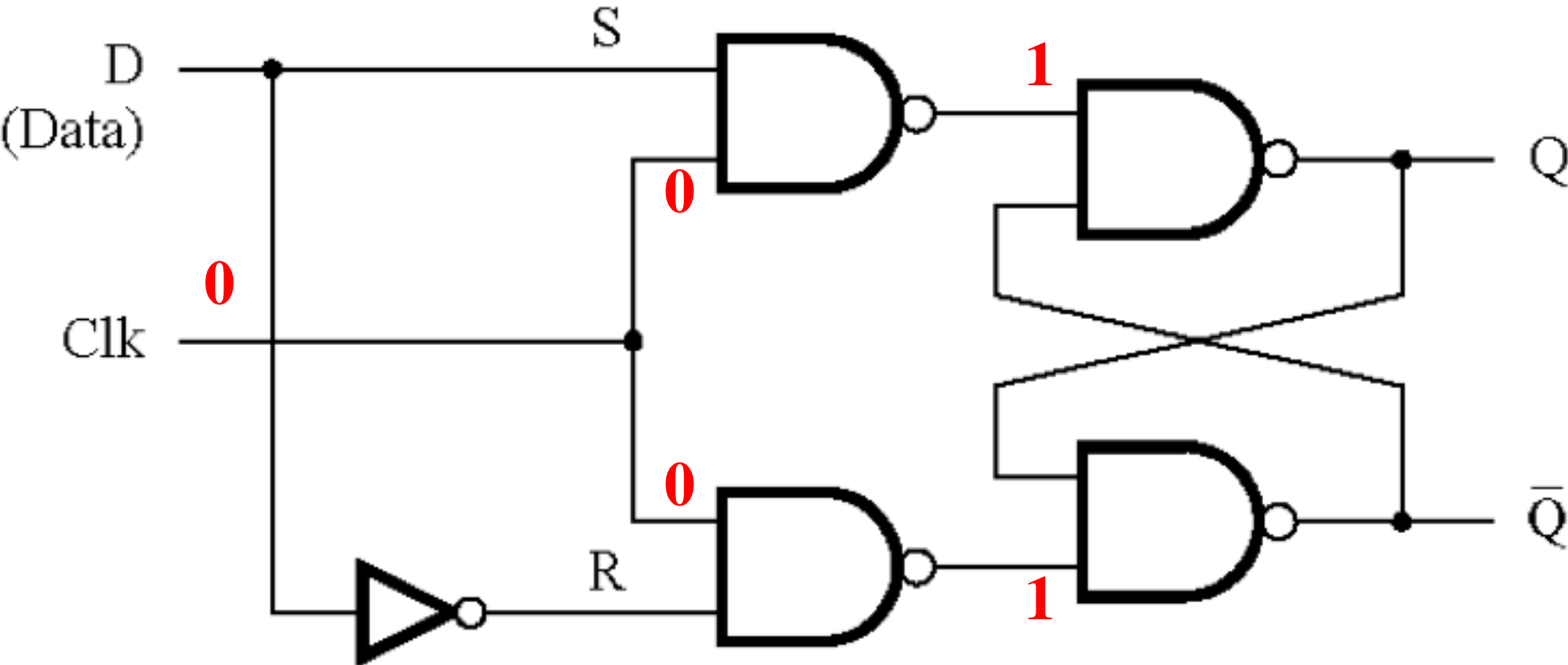
This is the only new thing here.

Circuit Diagram for the Gated D Latch



[Figure 5.7a from the textbook]

Circuit Diagram for the Gated D Latch

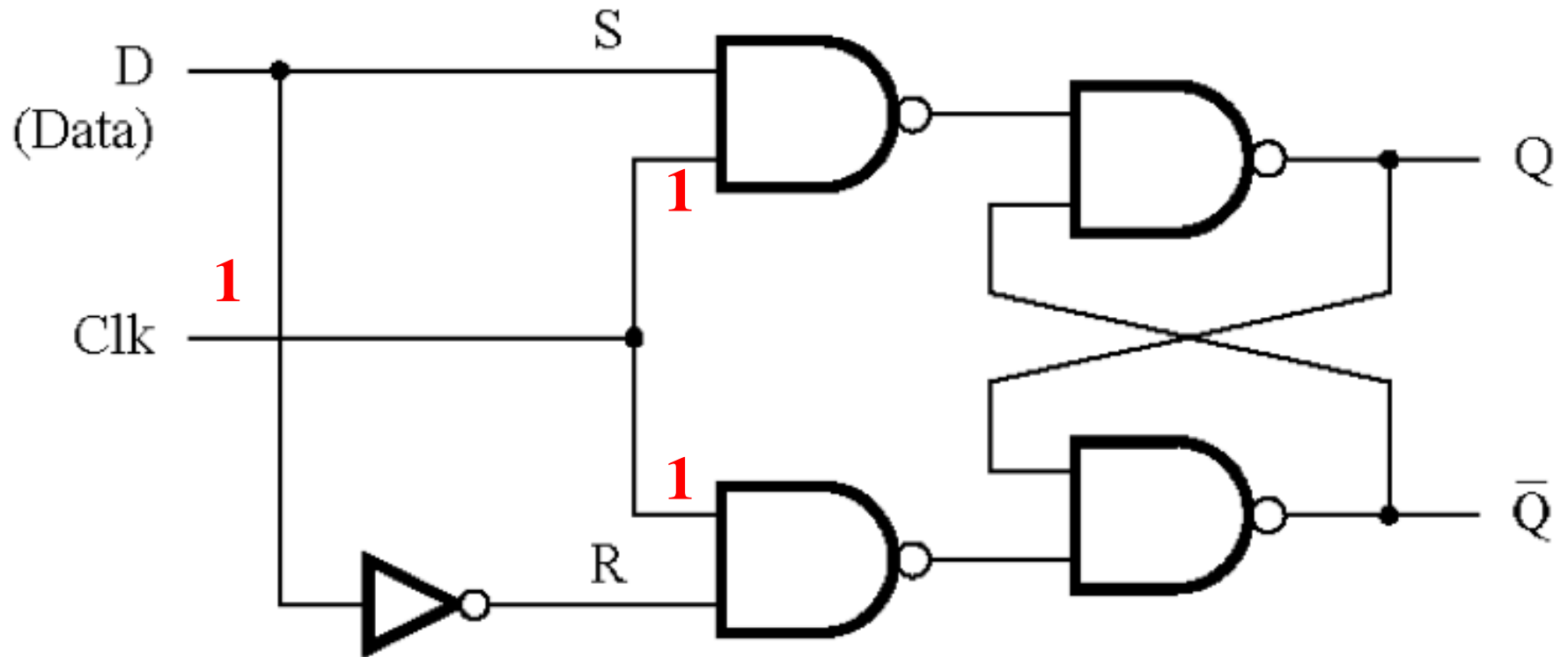


\bar{S}	\bar{R}	Q_a	Q_b
0	0	1	1
0	1	1	0
1	0	0	1
1	1	0/1	1/0

(no change)

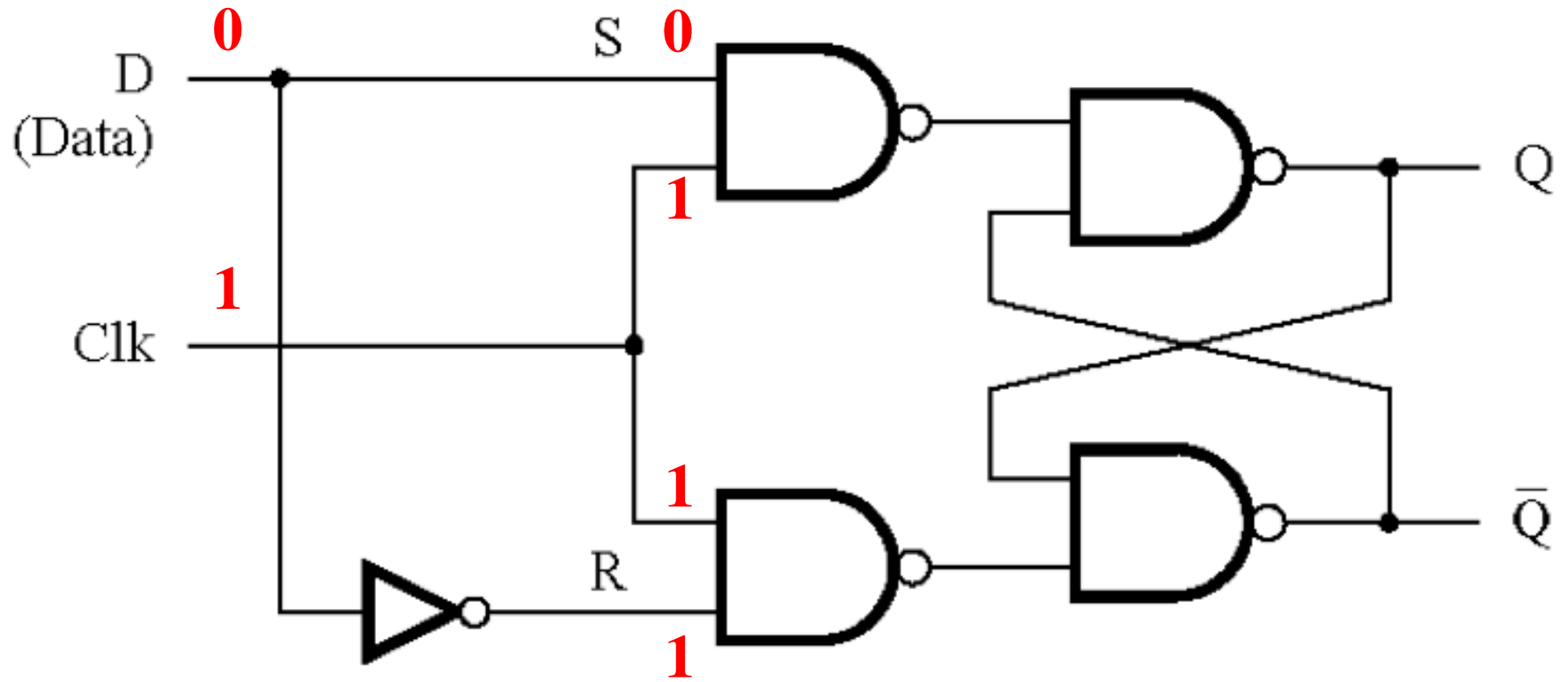
[Figure 5.7a from the textbook]

Circuit Diagram for the Gated D Latch



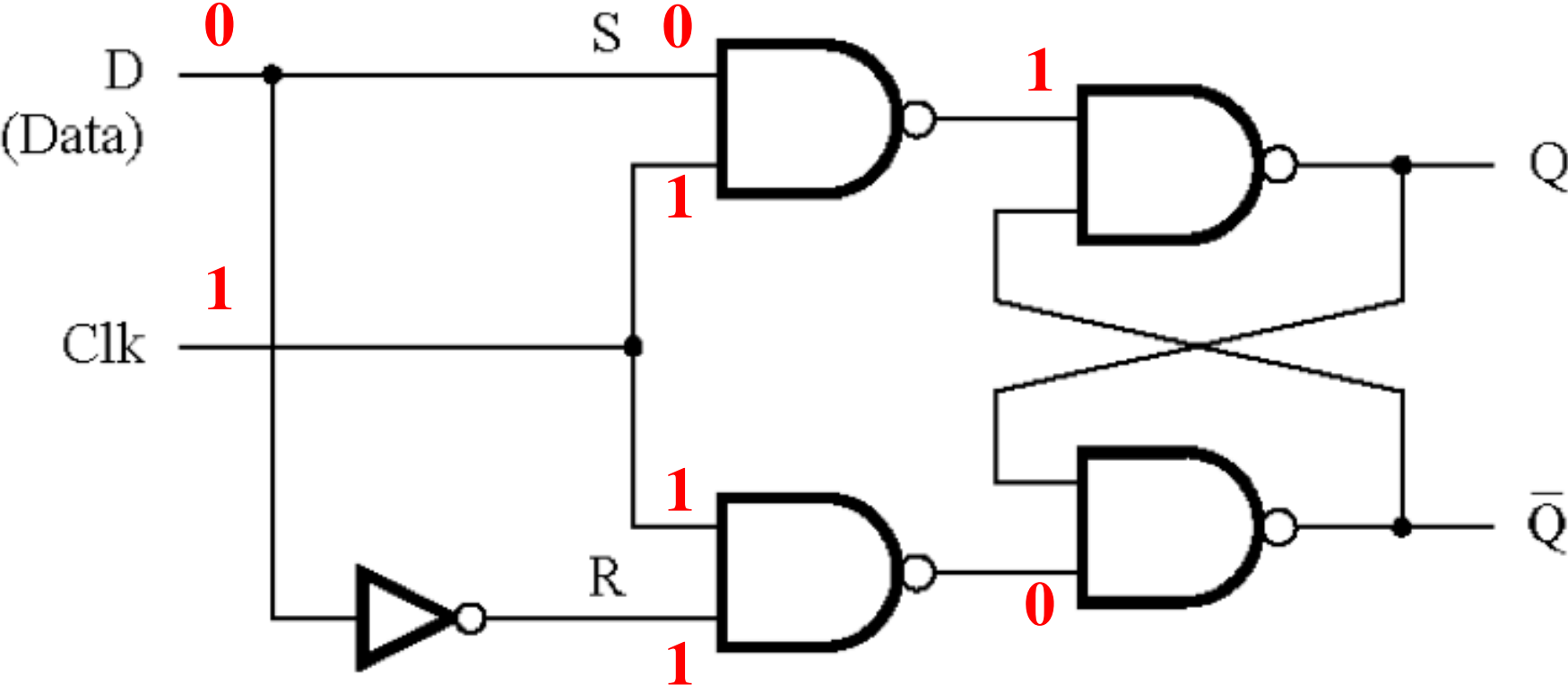
[Figure 5.7a from the textbook]

Circuit Diagram for the Gated D Latch



[Figure 5.7a from the textbook]

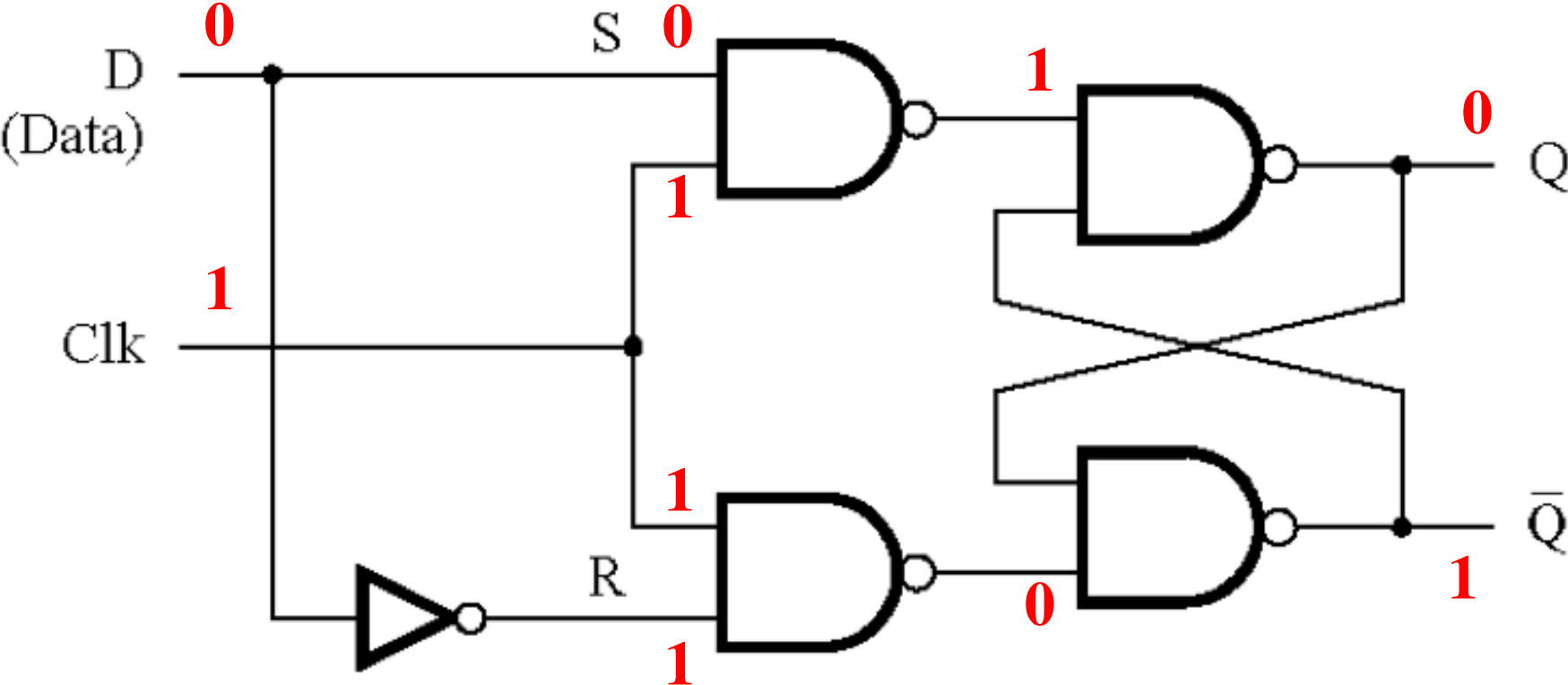
Circuit Diagram for the Gated D Latch



\bar{S}	\bar{R}	Q_a	Q_b
0	0	1	1
0	1	1	0
1	0	0	1
1	1	0/1	1/0 (no change)

[Figure 5.7a from the textbook]

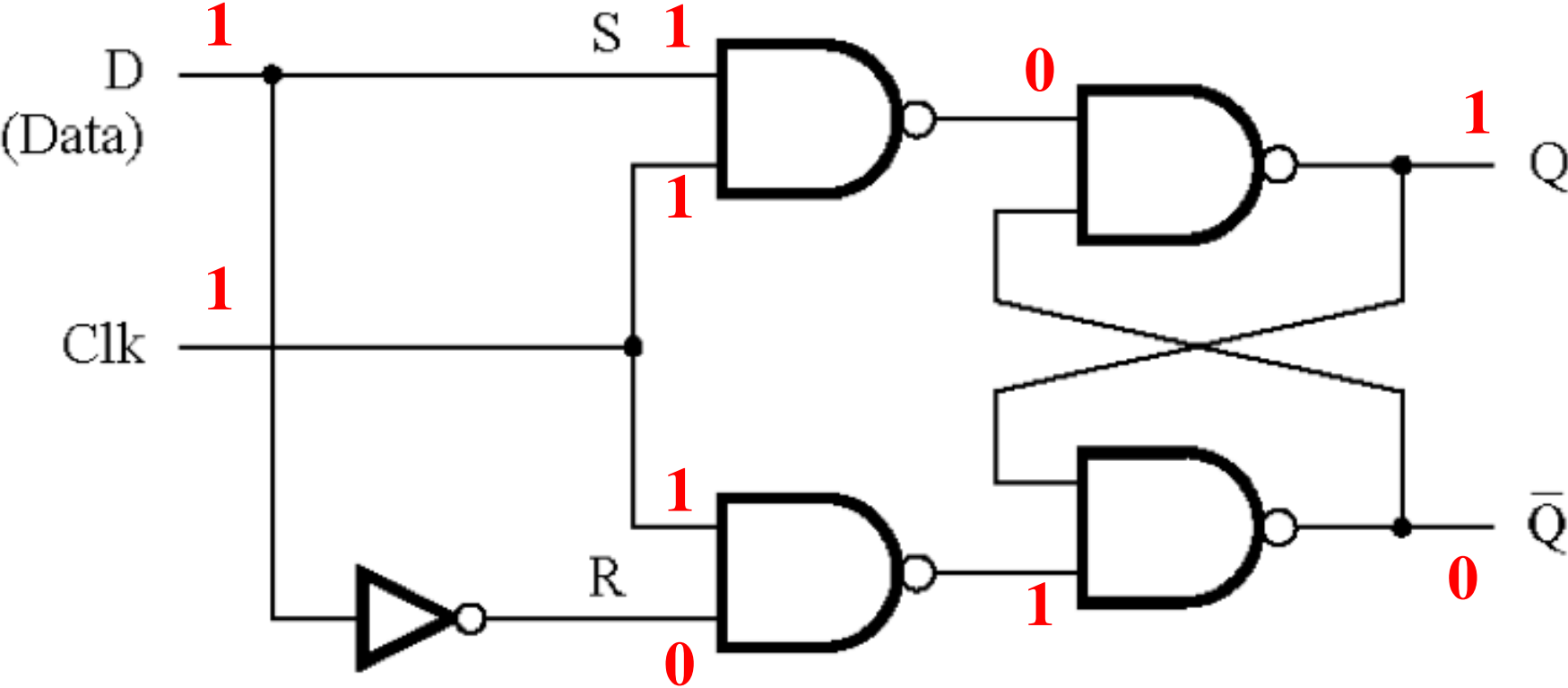
Circuit Diagram for the Gated D Latch



\bar{S}	\bar{R}	Q_a	Q_b
0	0	1	1
0	1	1	0
1	0	0	1
1	1	0/1	1/0 (no change)

[Figure 5.7a from the textbook]

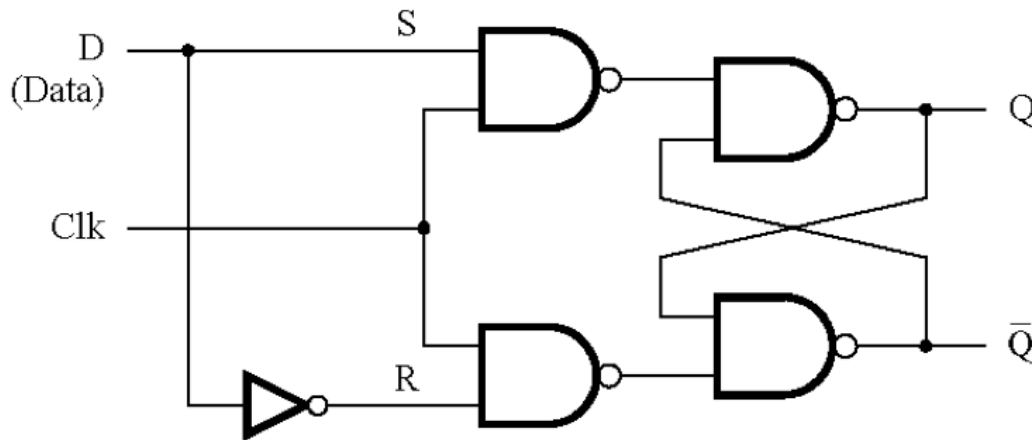
Circuit Diagram for the Gated D Latch



\bar{S}	\bar{R}	Q_a	Q_b
0	0	1	1
0	1	1	0
1	0	0	1
1	1	0/1	1/0 (no change)

[Figure 5.7a from the textbook]

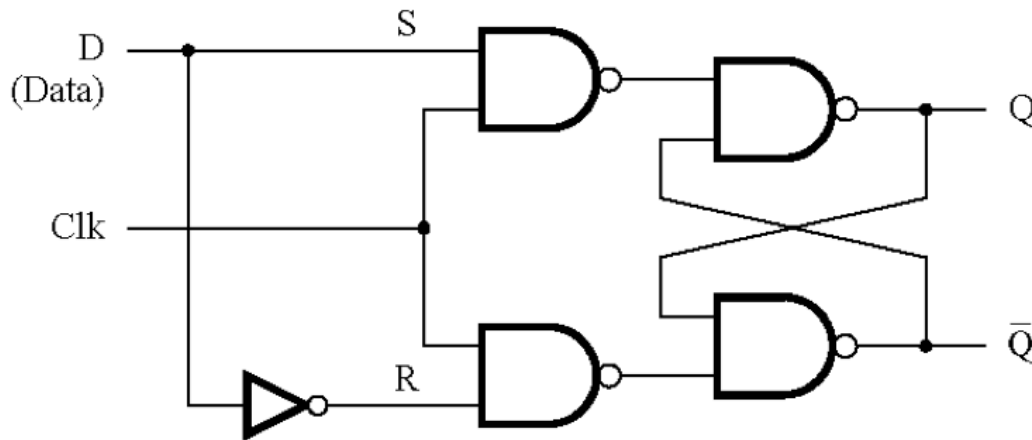
Circuit Diagram and Characteristic Table for the Gated D Latch



Clk	D	$Q(t+1)$
0	x	$Q(t)$
1	0	0
1	1	1

Note that it is now impossible to have $S=R=1$.

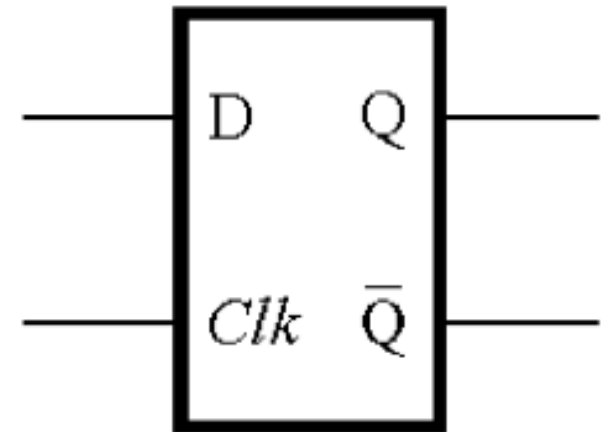
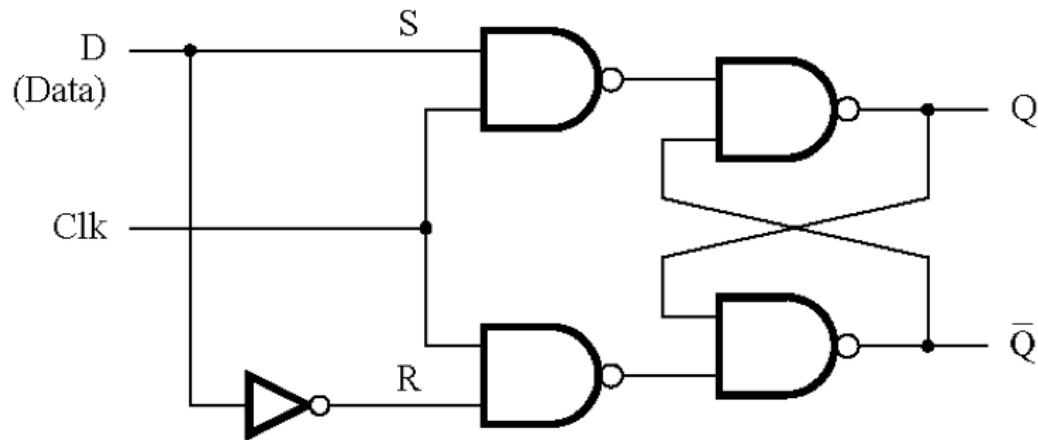
Circuit Diagram and Characteristic Table for the Gated D Latch



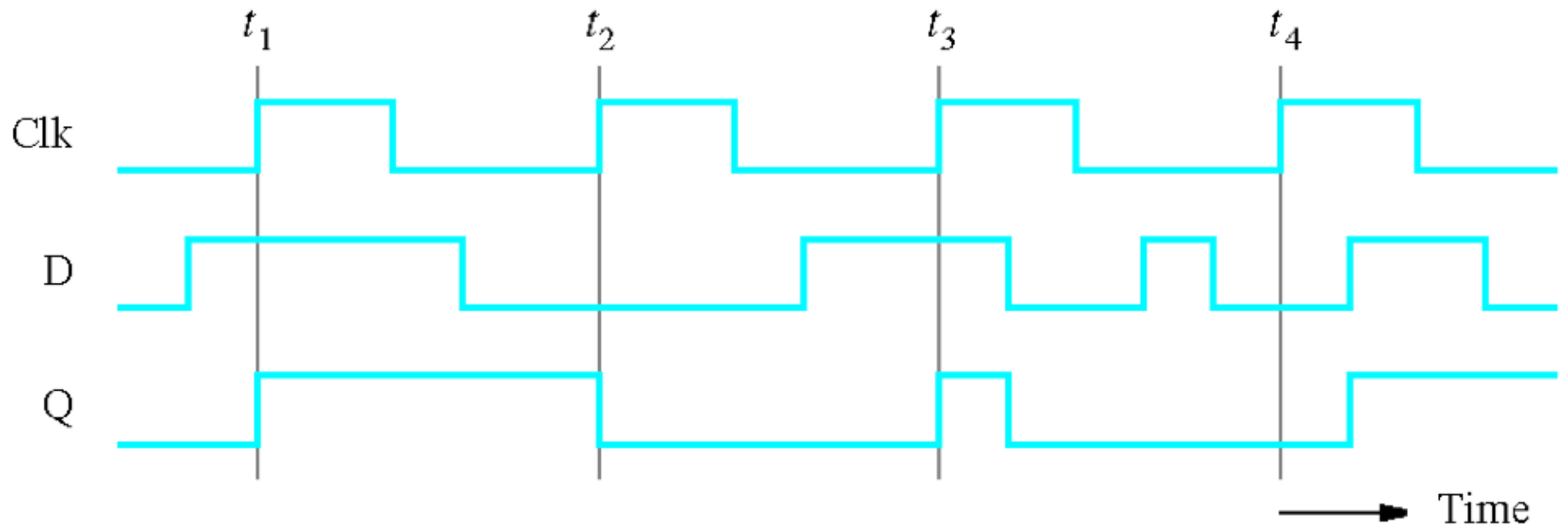
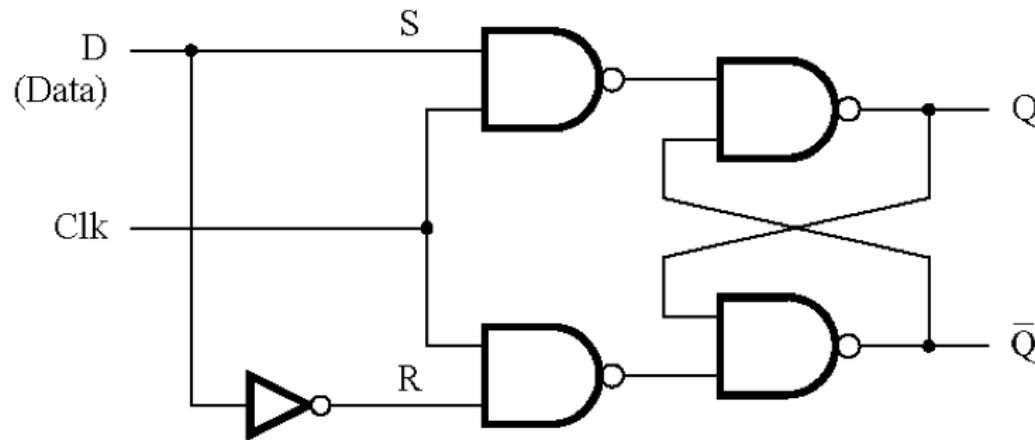
Clk	D	$Q(t+1)$
0	x	$Q(t)$
1	0	0
1	1	1

When Clk=1 the output follows the D input.
When Clk=0 the output cannot be changed.

Circuit Diagram and Graphical Symbol for the Gated D Latch

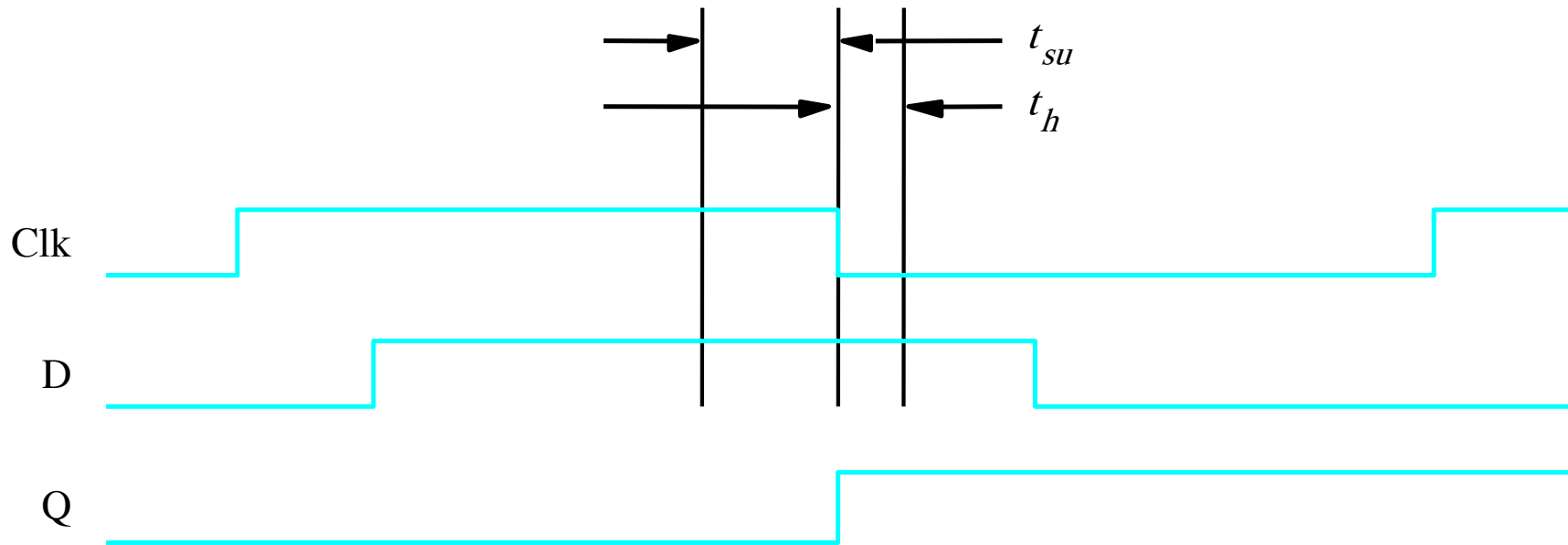


Timing Diagram for the Gated D Latch



[Figure 5.7d from the textbook]

Setup and hold times



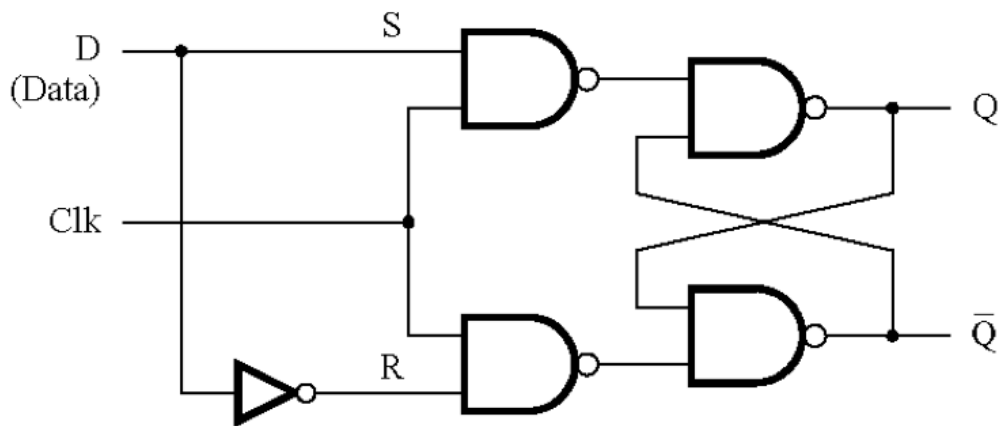
Setup time (t_{su}) – the minimum time that the D signal must be stable prior to the the negative edge of the Clock signal.

Hold time (t_h) – the minimum time that the D signal must remain stable after the the negative edge of the Clock signal.

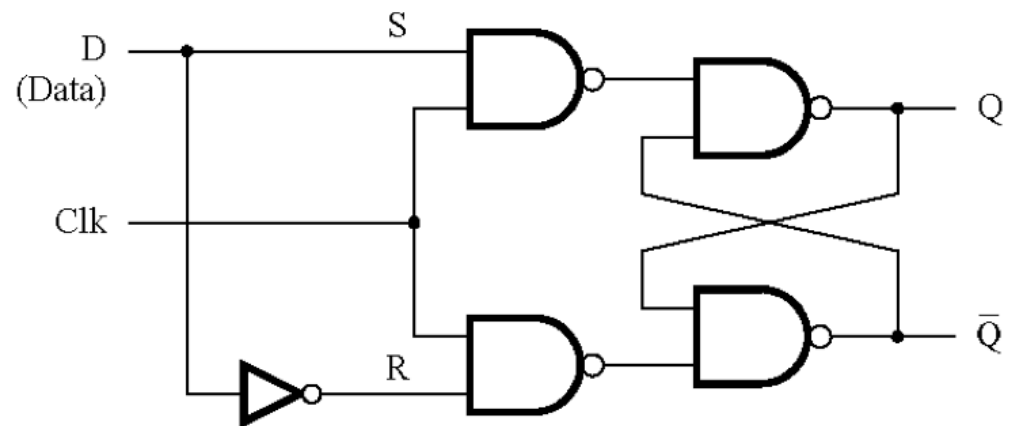
Master-Slave D Flip-Flop

Constructing a Master-Slave D Flip-Flop From Two D Latches

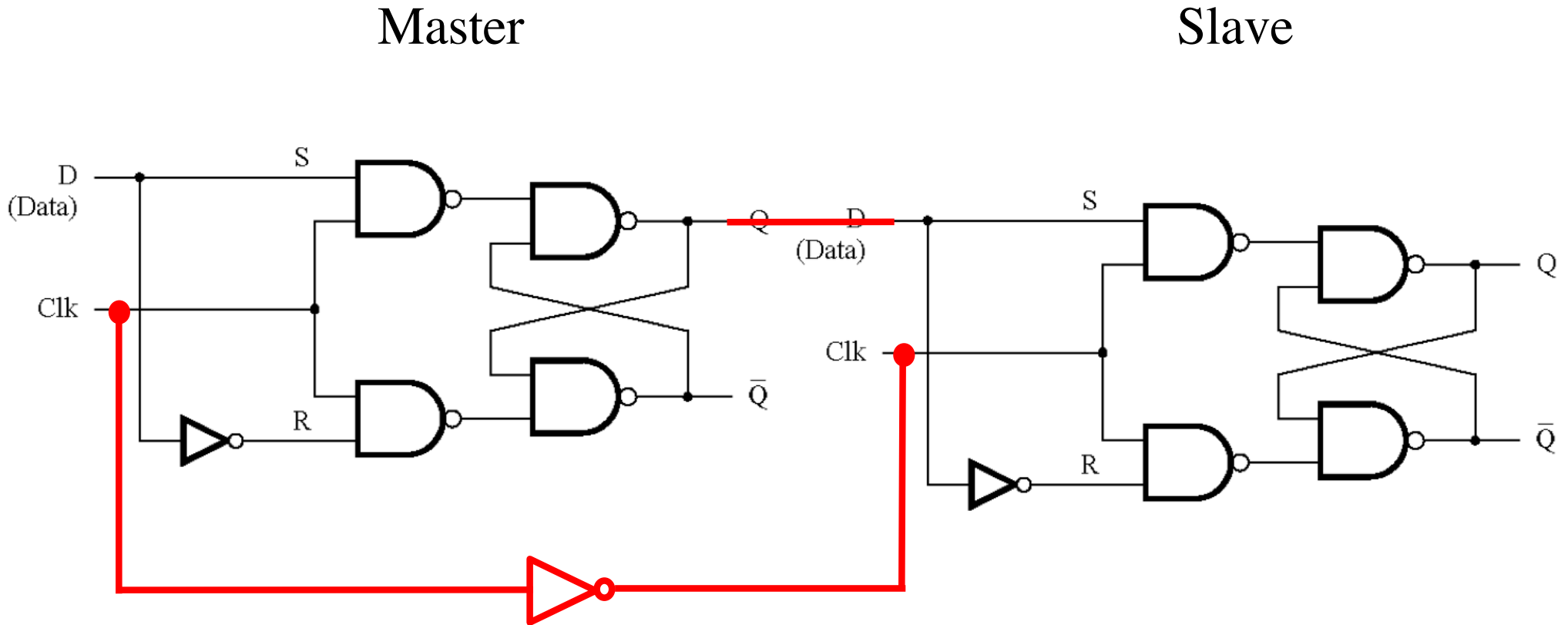
Master



Slave



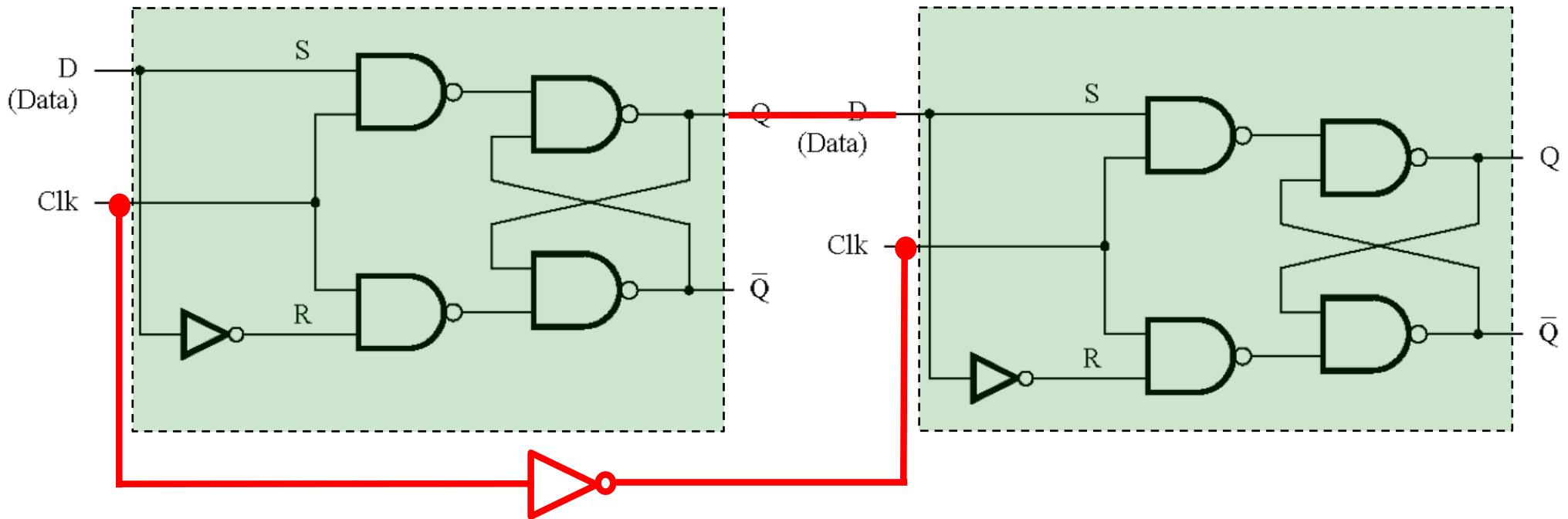
Constructing a Master-Slave D Flip-Flop From Two D Latches



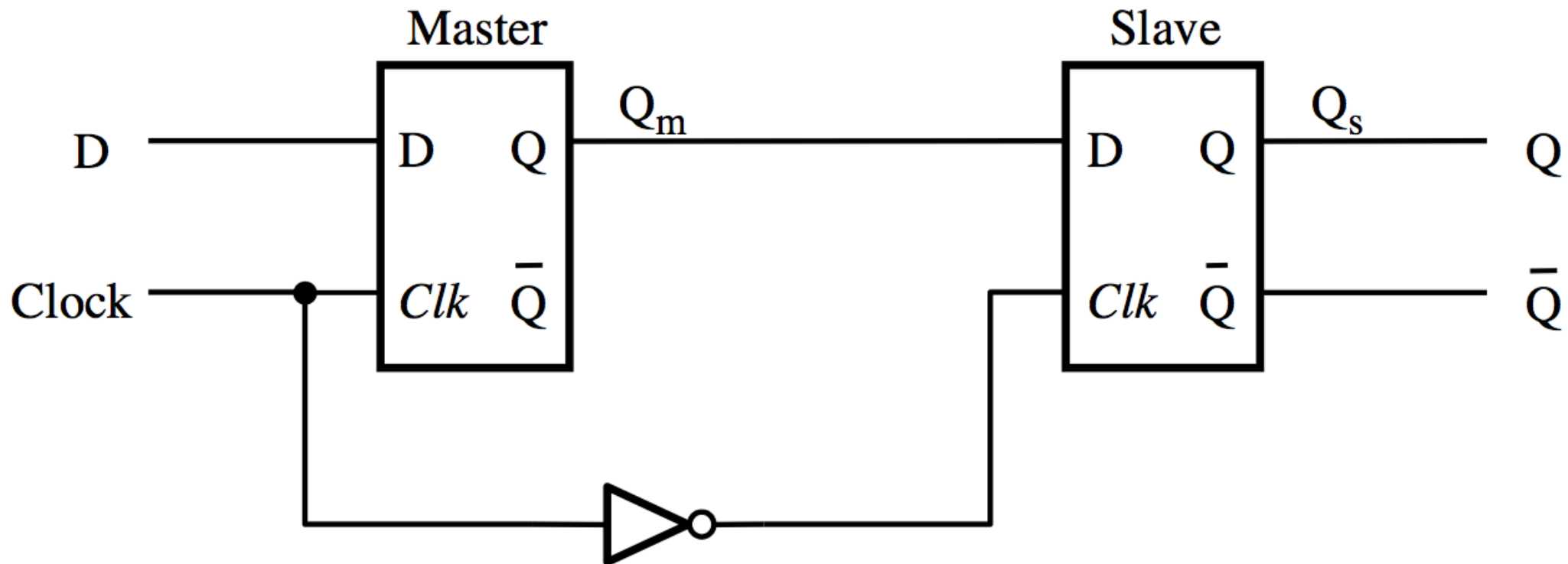
Constructing a Master-Slave D Flip-Flop From Two D Latches

Master

Slave



Constructing a Master-Slave D Flip-Flop From Two D Latches

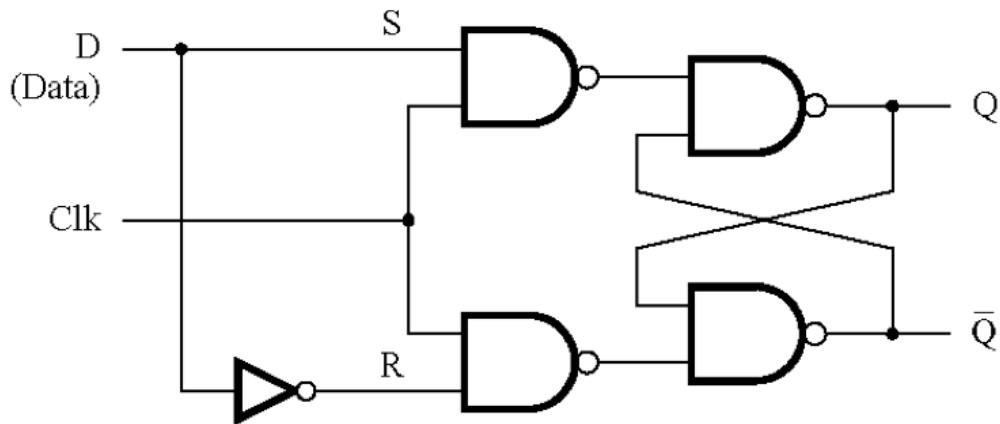


[Figure 5.9a from the textbook]

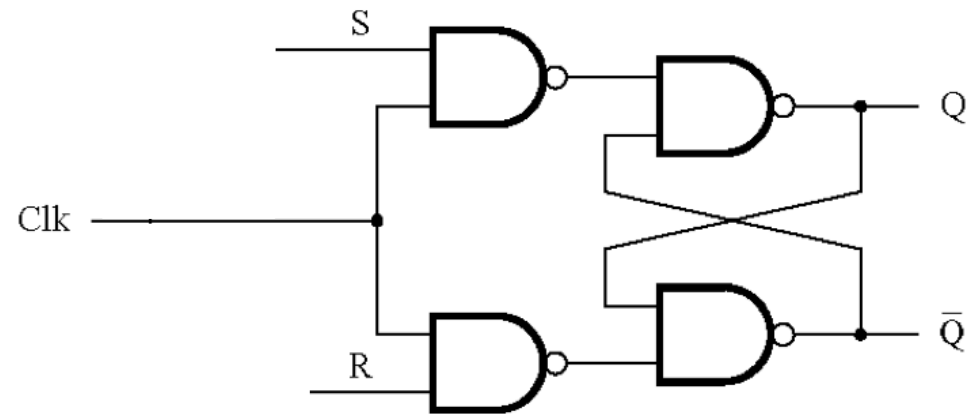
Constructing a Master-Slave D Flip-Flop From one D Latch and one Gated SR Latch

(This version uses one less NOT gate)

Master

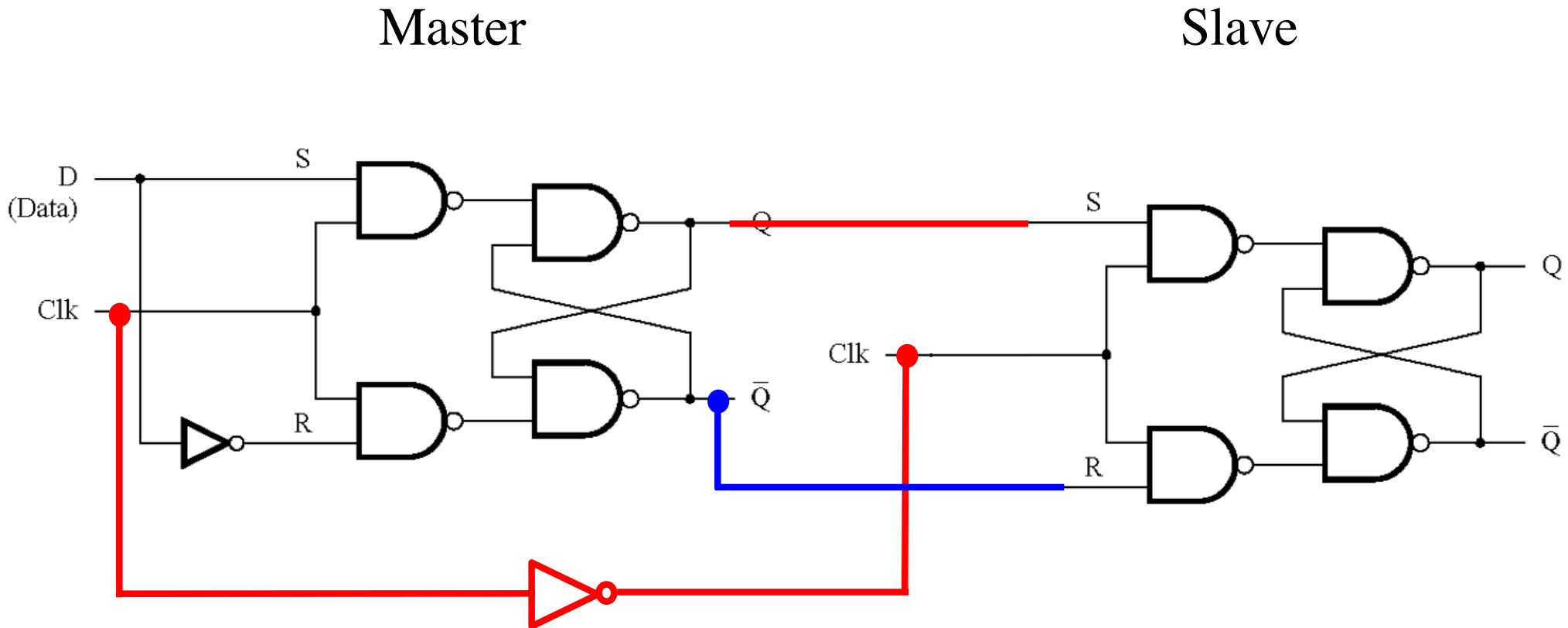


Slave



Constructing a Master-Slave D Flip-Flop From one D Latch and one Gated SR Latch

(This version uses one less NOT gate)

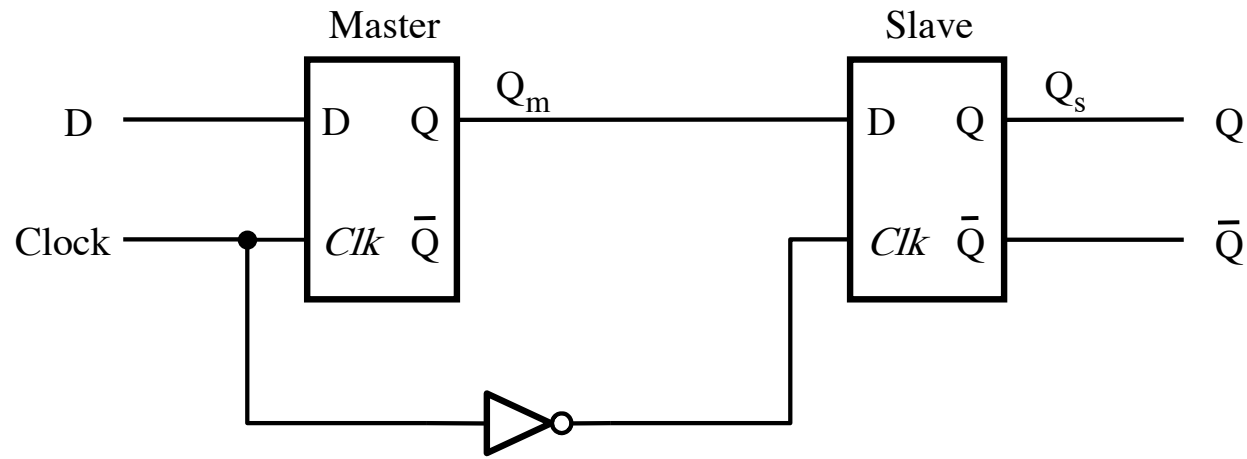


Edge-Triggered D Flip-Flops

Motivation

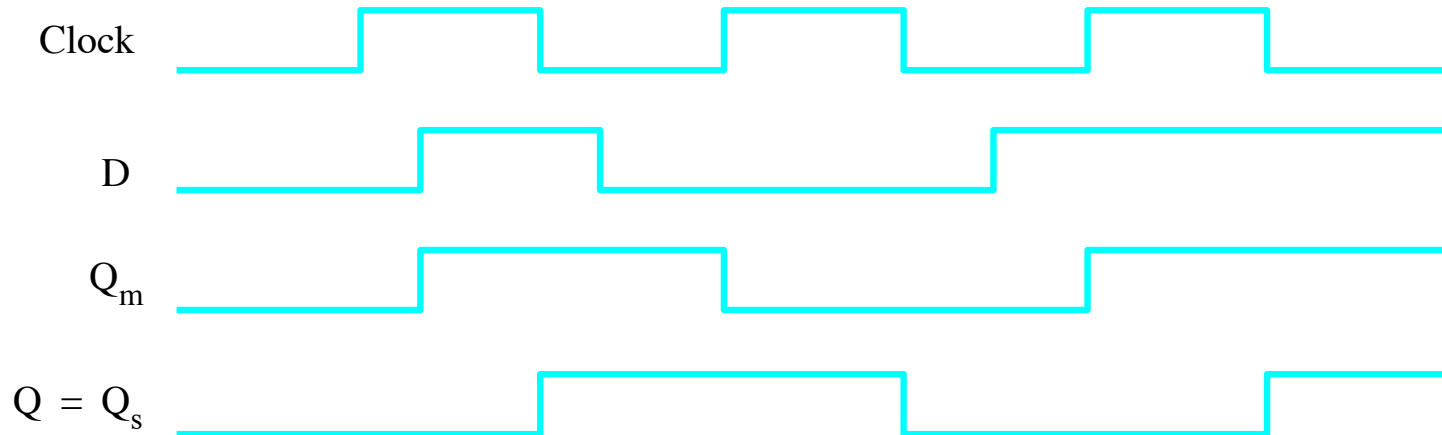
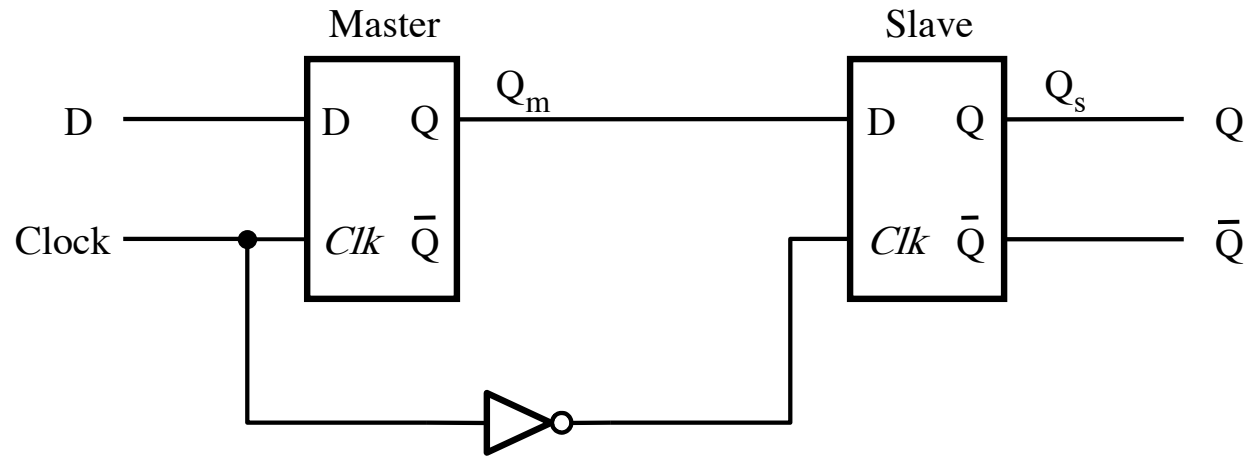
In some cases we need to use a memory storage device that can change its state no more than once during each clock cycle.

Master-Slave D Flip-Flop



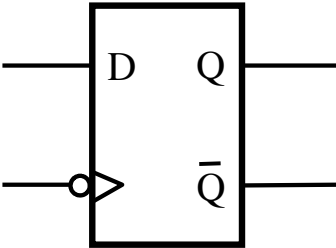
(a) Circuit

Timing Diagram for the Master-Slave D Flip-Flop



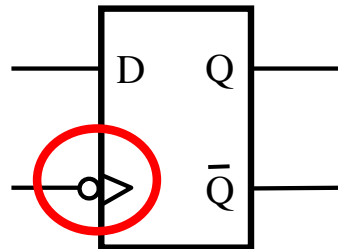
[Figure 5.9a,b from the textbook]

Graphical Symbol for the Master-Slave D Flip-Flop



[Figure 5.9c from the textbook]

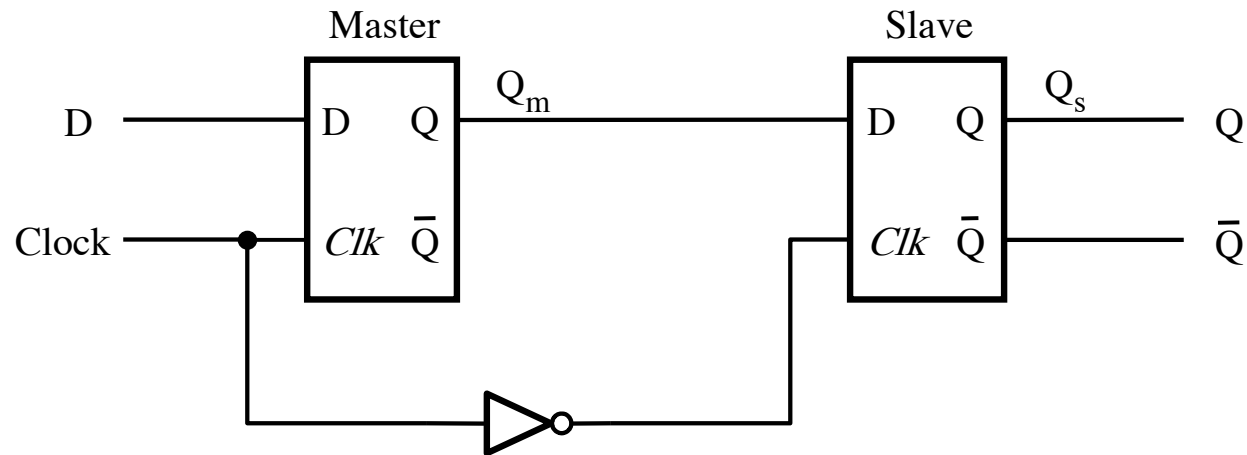
Graphical Symbol for the Master-Slave D Flip-Flop



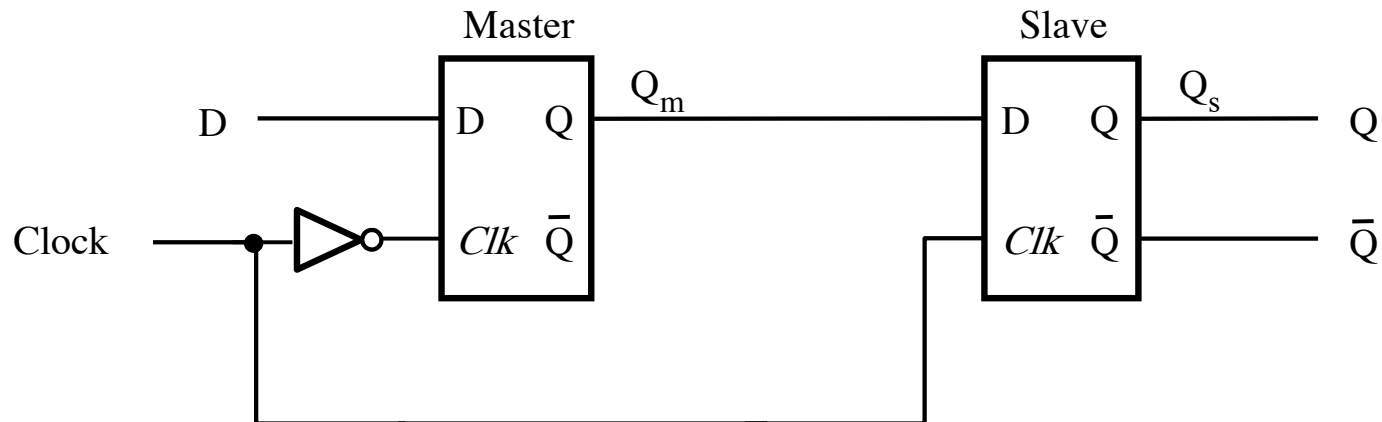
The \triangleright means that this is edge-triggered

The small circle means that it is the negative edge

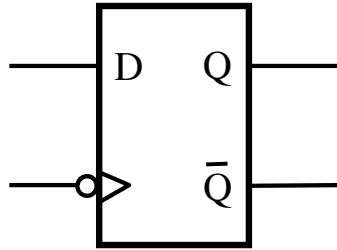
Negative-Edge-Triggered Master-Slave D Flip-Flop



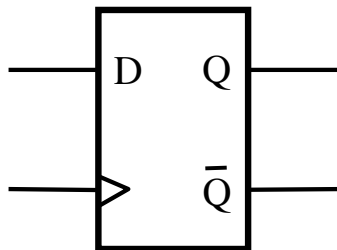
Positive-Edge-Triggered Master-Slave D Flip-Flop



Negative-Edge-Triggered Master-Slave D Flip-Flop

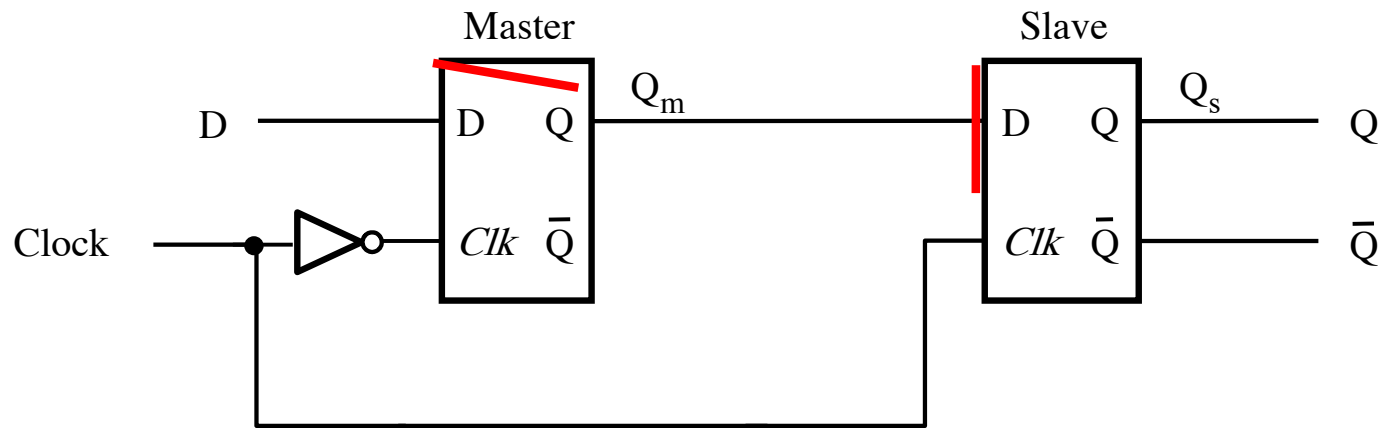


Positive-Edge-Triggered Master-Slave D Flip-Flop

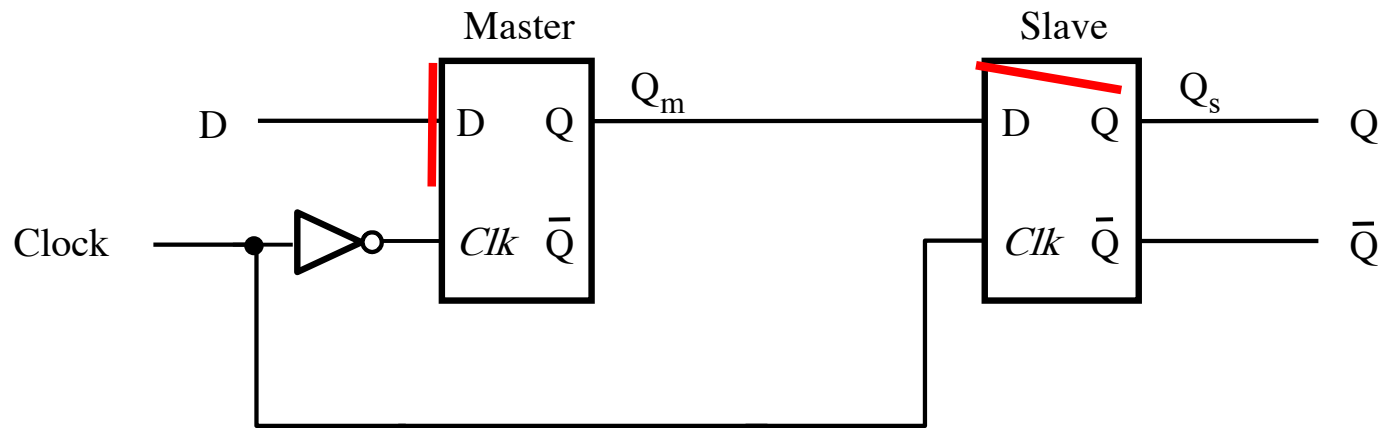


D Flip-Flop: A Double Door Analogy

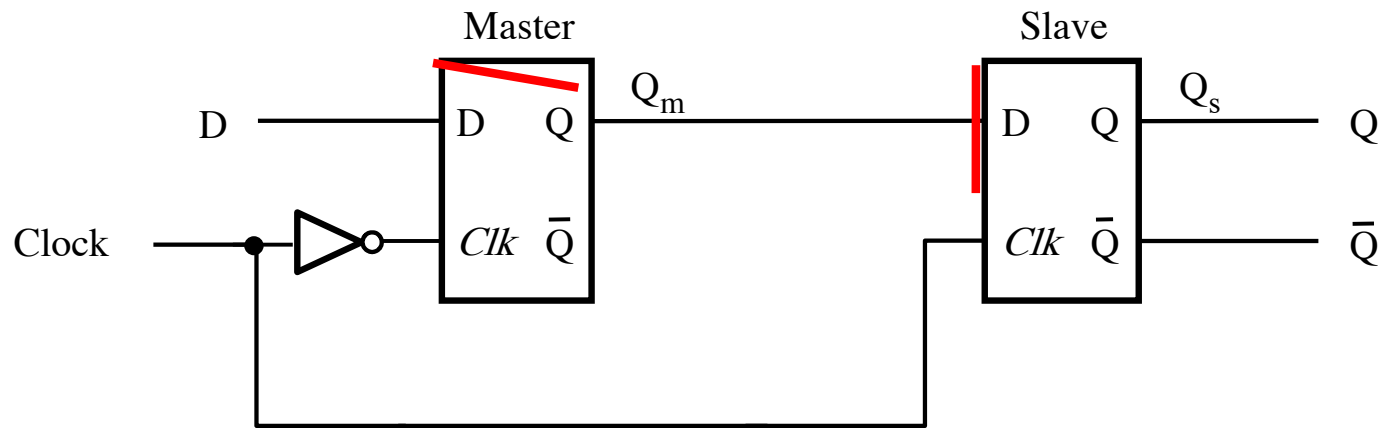
Positive-Edge-Triggered Master-Slave D Flip-Flop



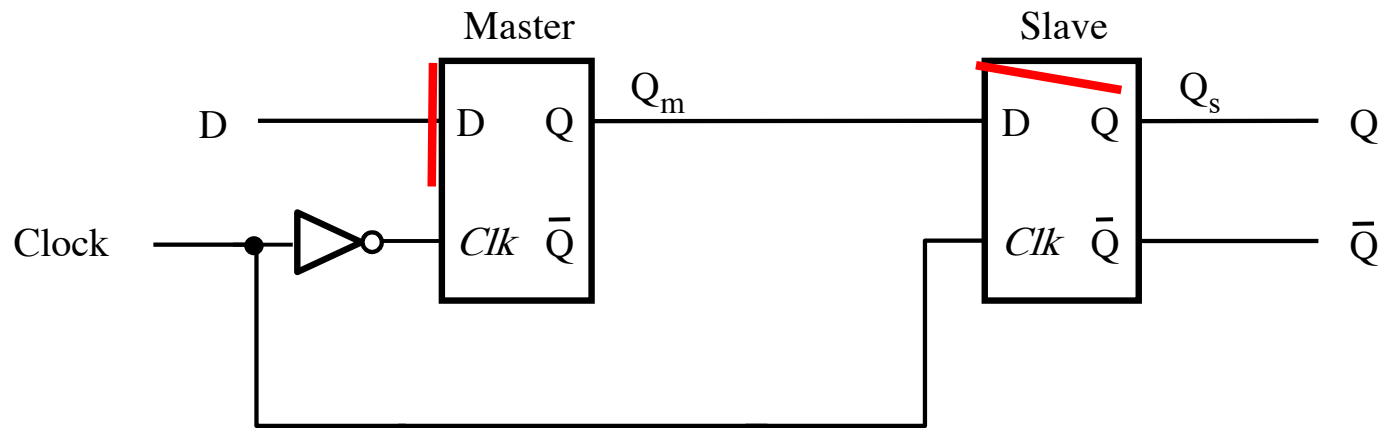
Positive-Edge-Triggered Master-Slave D Flip-Flop



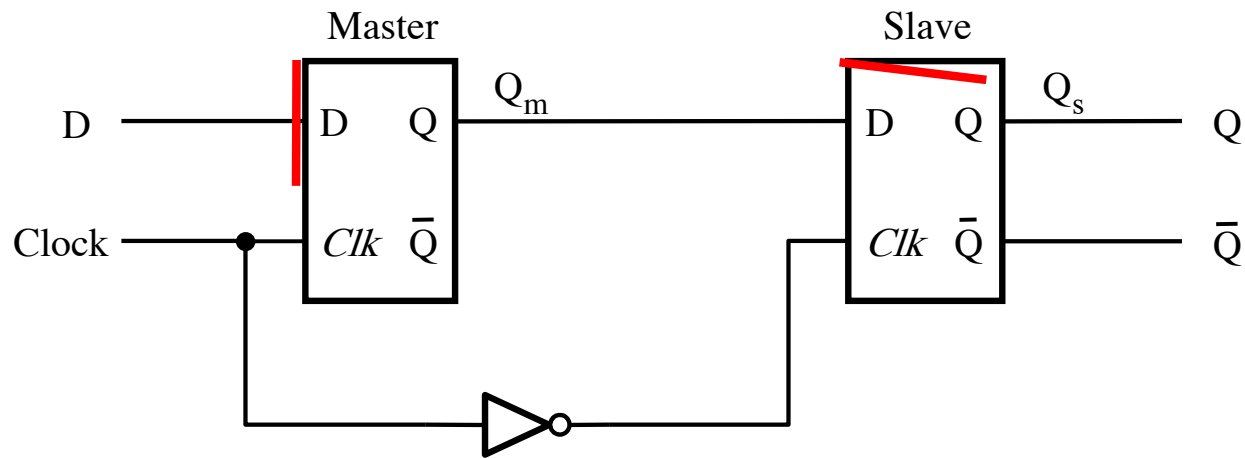
Positive-Edge-Triggered Master-Slave D Flip-Flop



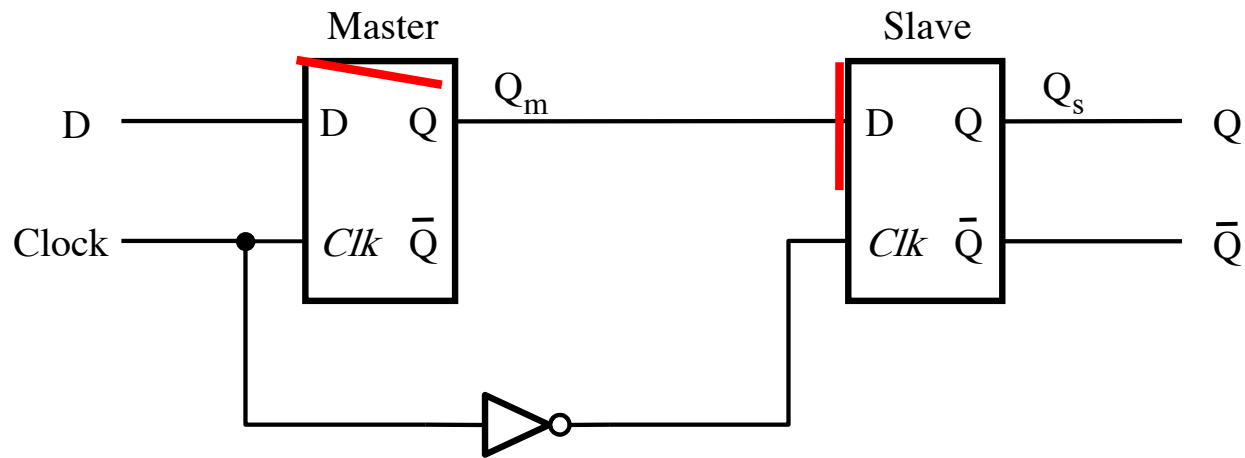
Positive-Edge-Triggered Master-Slave D Flip-Flop



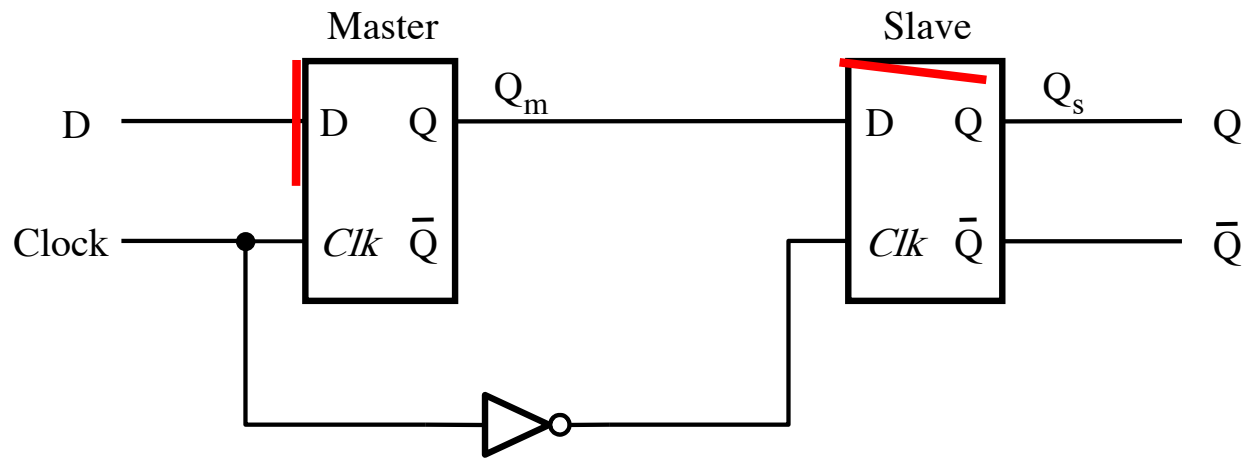
Negative-Edge-Triggered Master-Slave D Flip-Flop



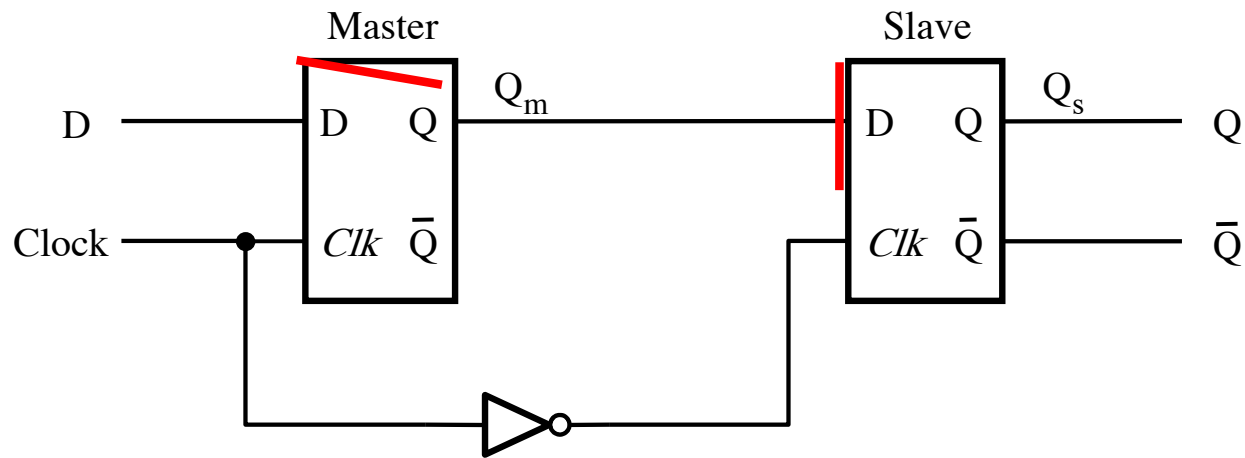
Negative-Edge-Triggered Master-Slave D Flip-Flop



Negative-Edge-Triggered Master-Slave D Flip-Flop

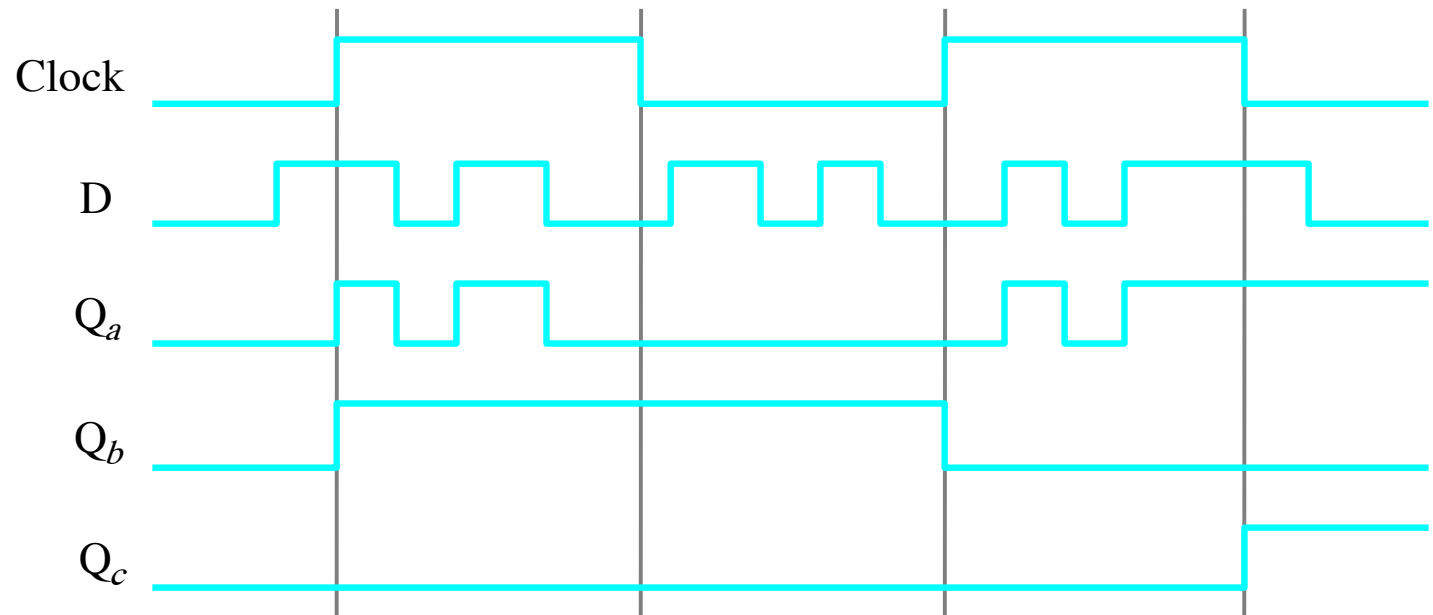
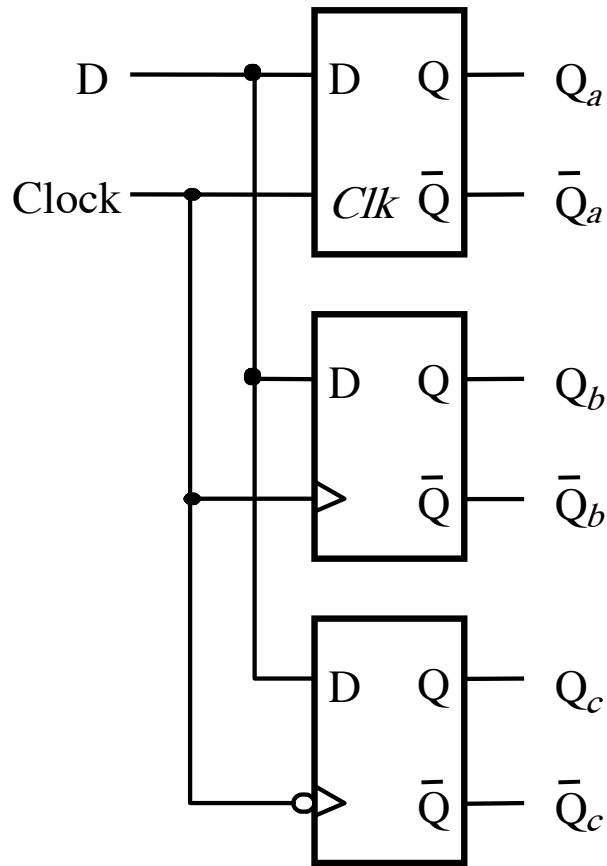


Negative-Edge-Triggered Master-Slave D Flip-Flop

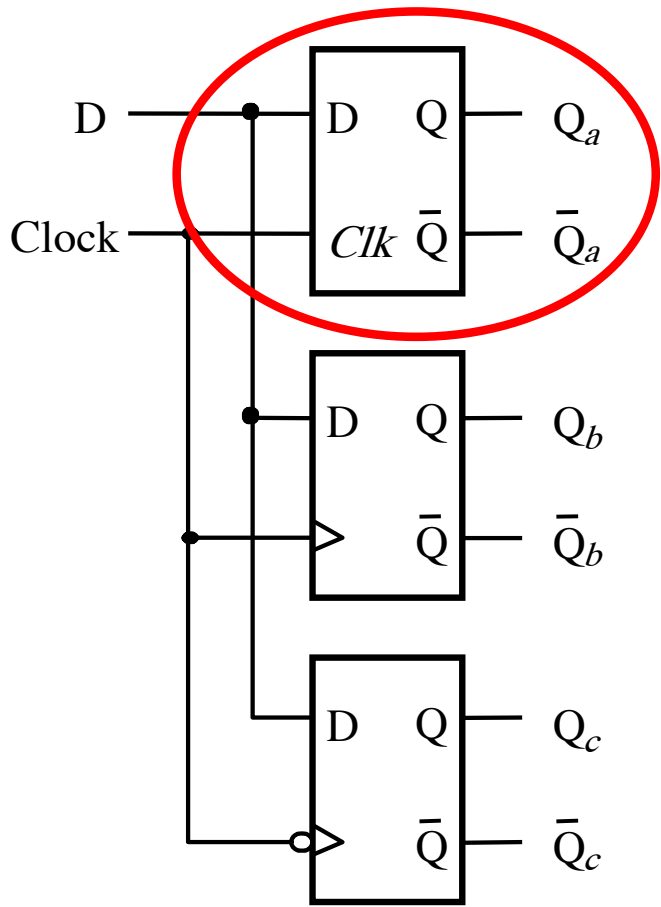


Other Types of Edge-Triggered D Flip-Flops

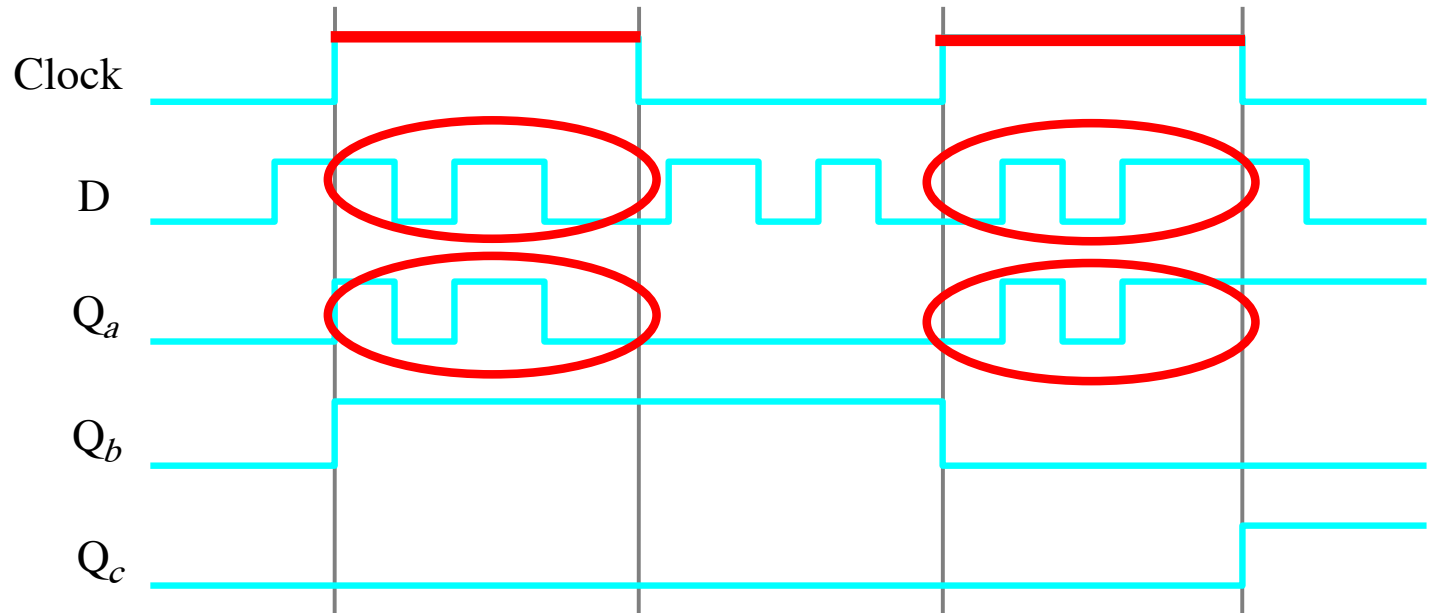
Comparison of level-sensitive and edge-triggered D storage elements



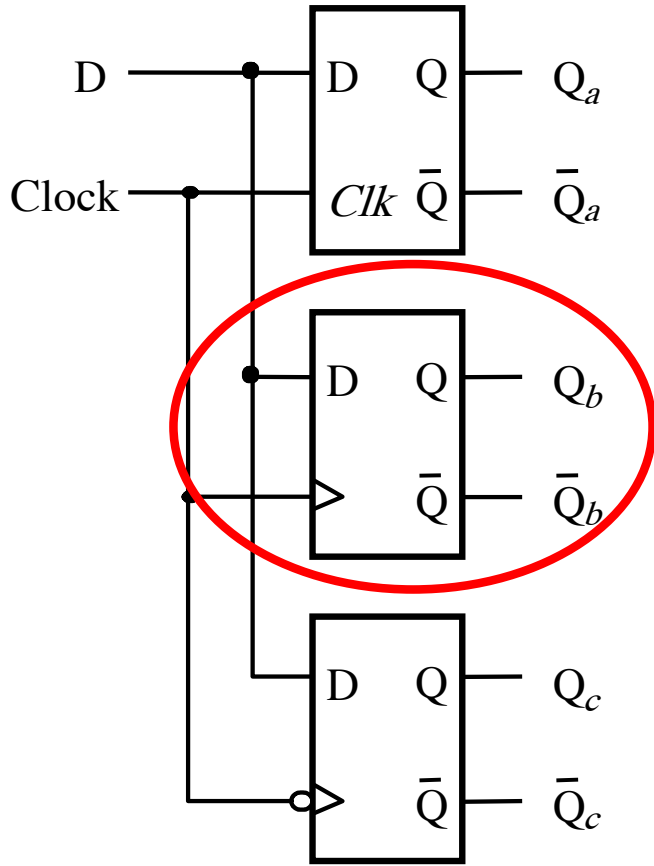
Comparison of level-sensitive and edge-triggered D storage elements



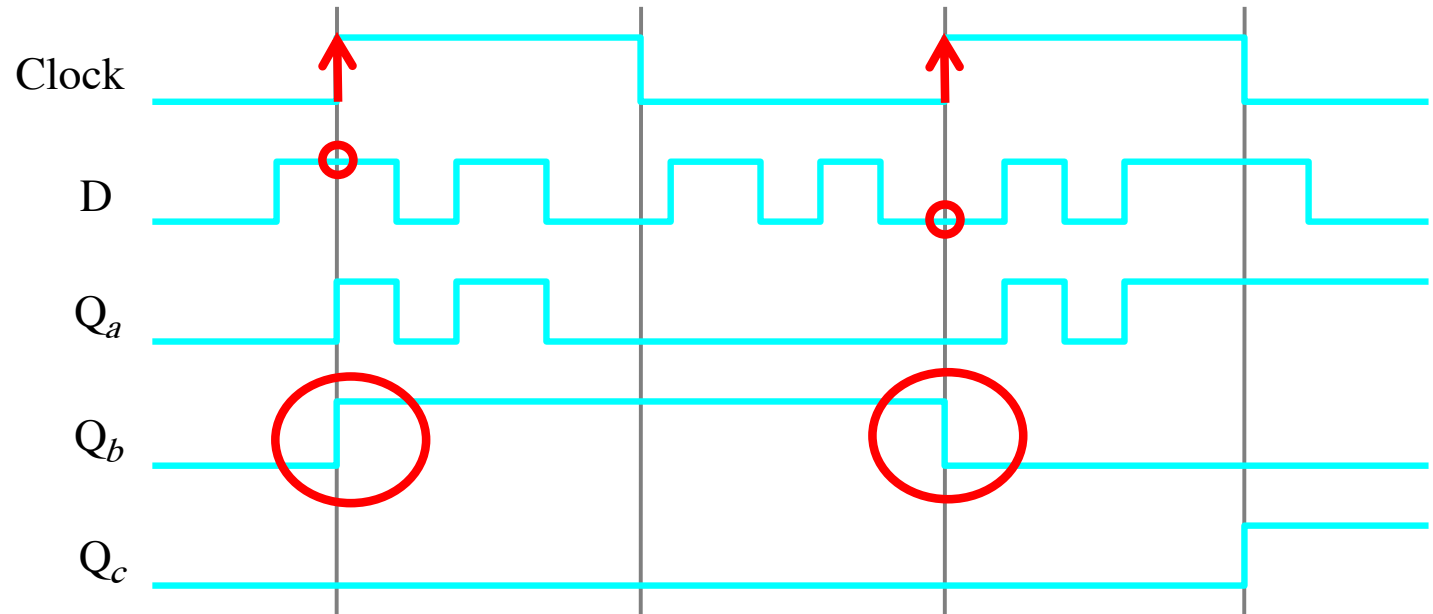
Level-sensitive
(the output mirrors the D input when Clk=1)



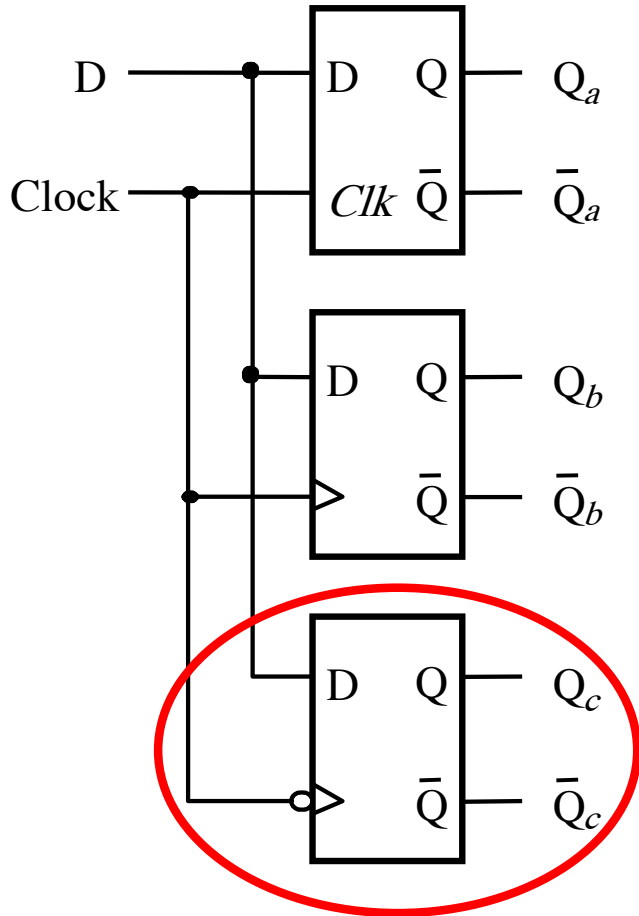
Comparison of level-sensitive and edge-triggered D storage elements



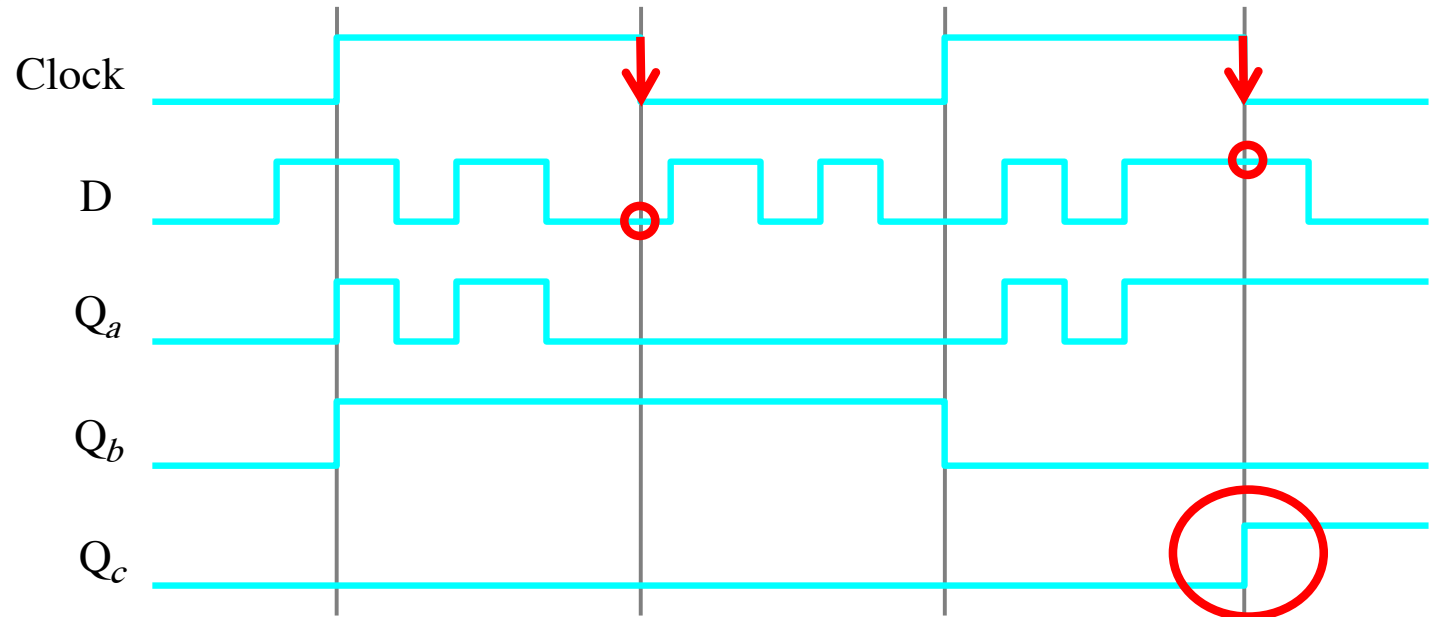
Positive-edge-triggered



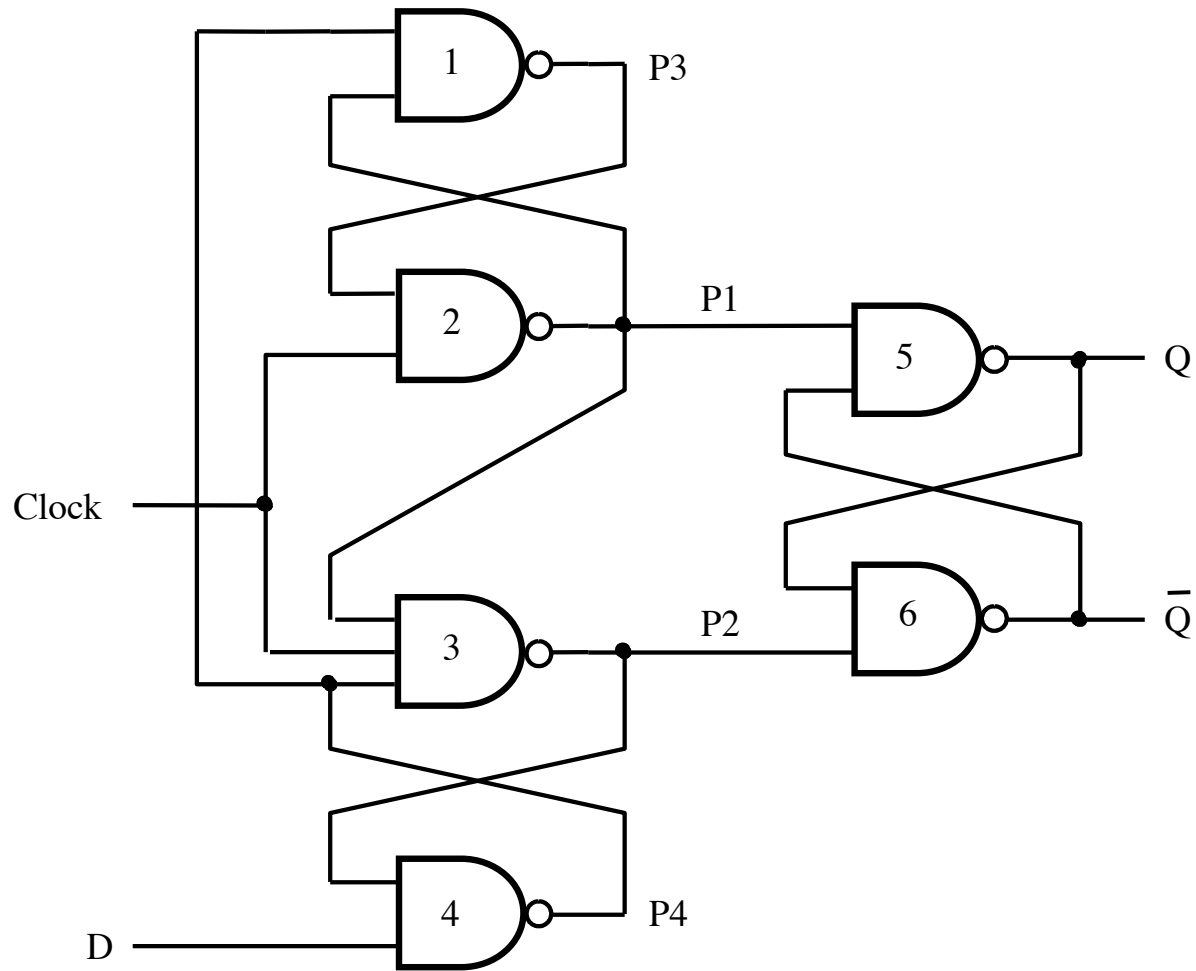
Comparison of level-sensitive and edge-triggered D storage elements



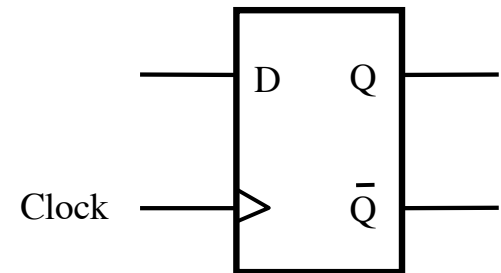
Negative-edge-triggered



A positive-edge-triggered D flip-flop



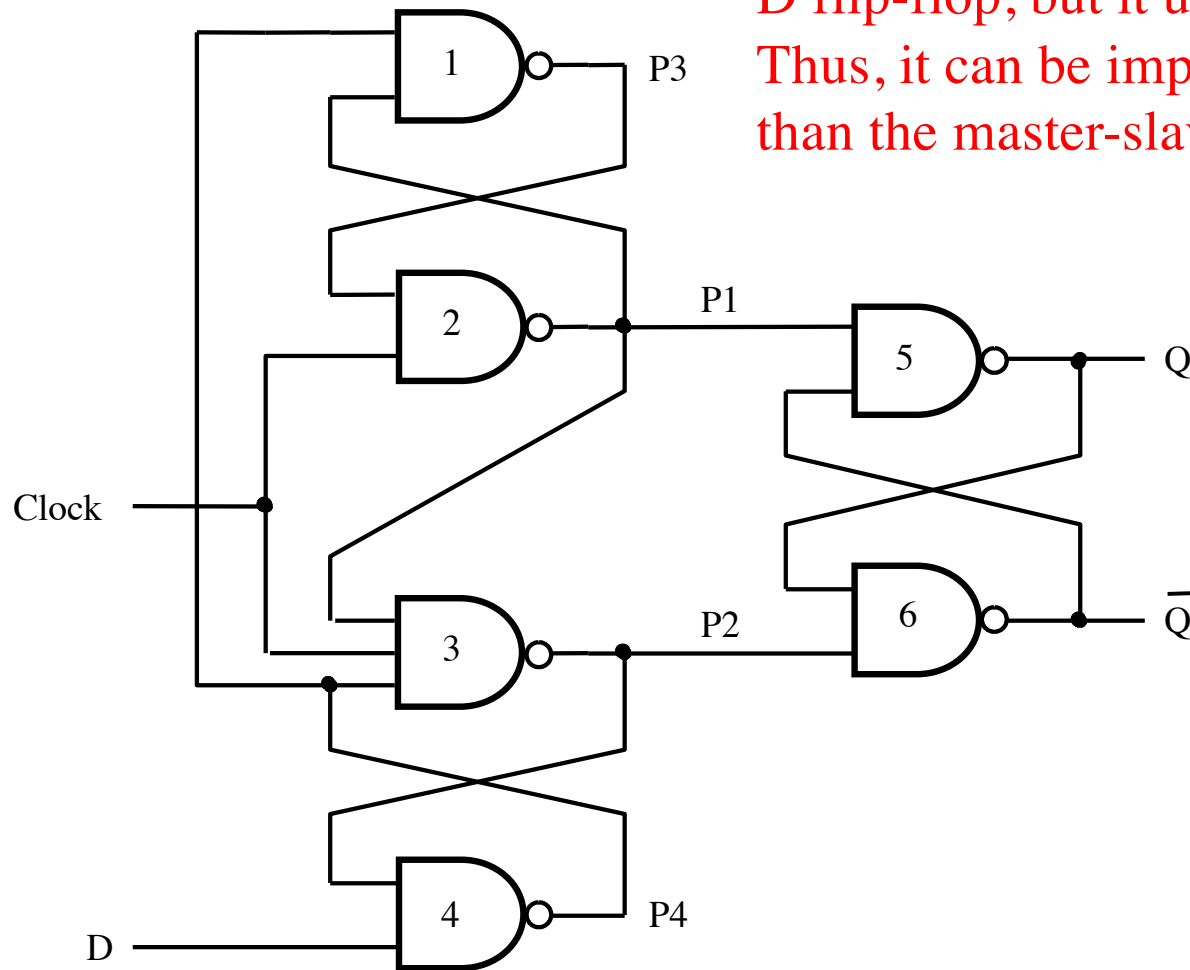
(a) Circuit



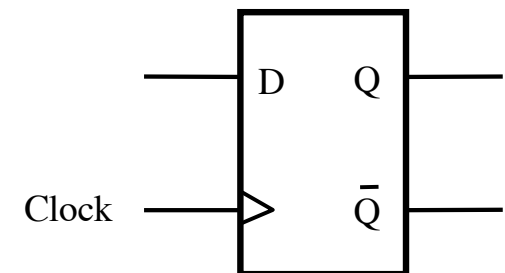
(b) Graphical symbol

A positive-edge-triggered D flip-flop

This circuit behaves like a positive-edge-triggered D flip-flop, but it uses only 6 NAND gates. Thus, it can be implemented with fewer transistors than the master-slave D flip-flop.

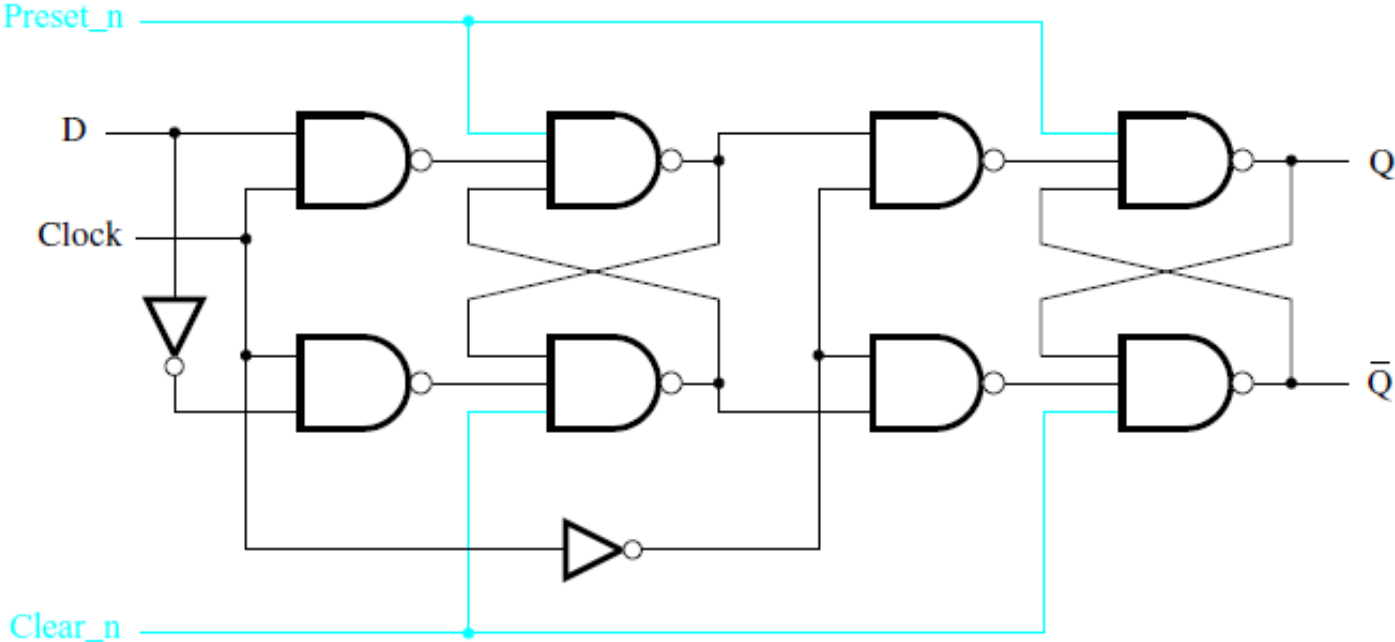


(a) Circuit

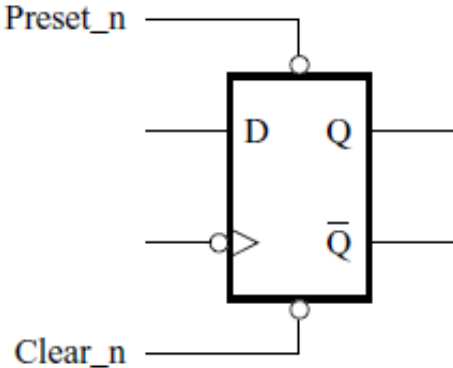


(b) Graphical symbol

Master-slave D flip-flop with Clear and Preset



(a) Circuit

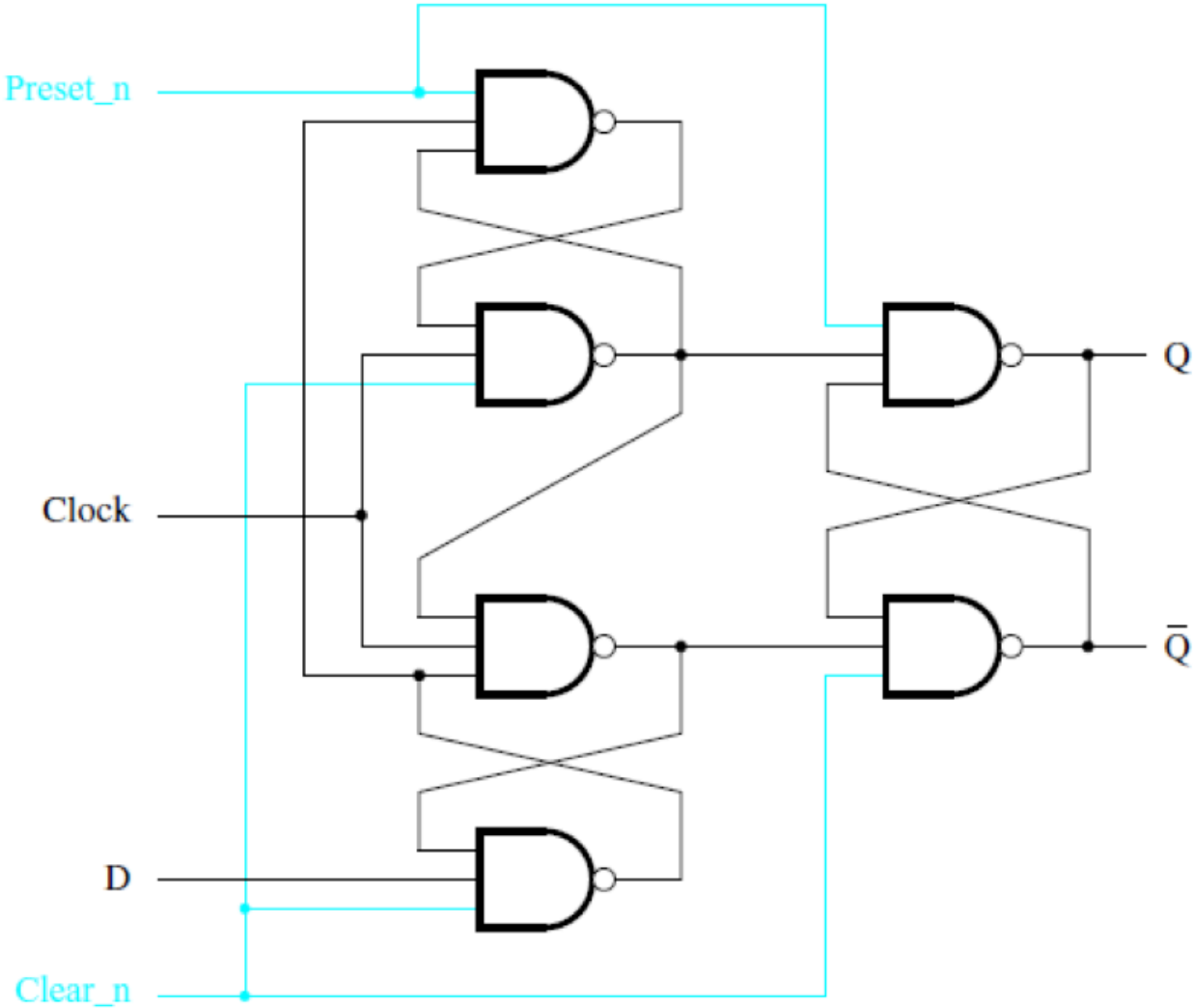


(b) Graphical symbol

[Figure 5.12 from the textbook]

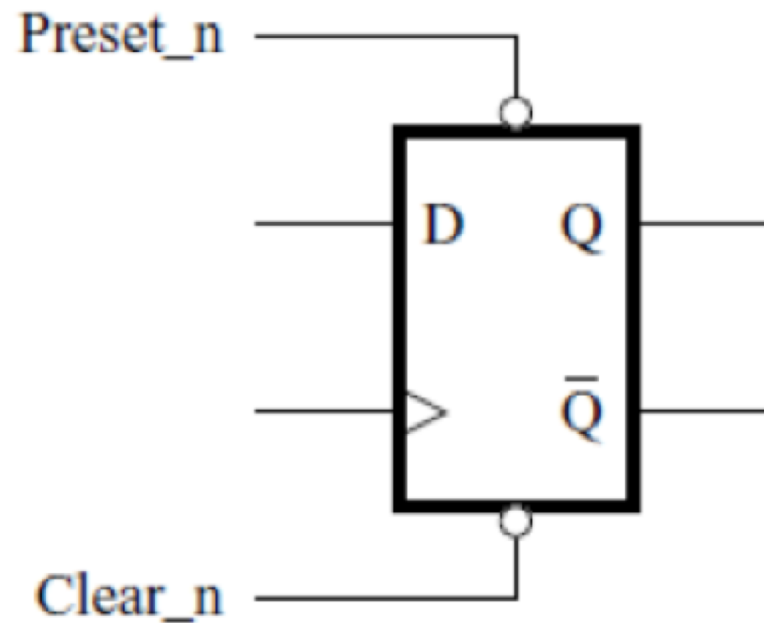
Positive-edge-triggered D flip-flop with Clear and Preset

Positive-edge-triggered D flip-flop with Clear and Preset



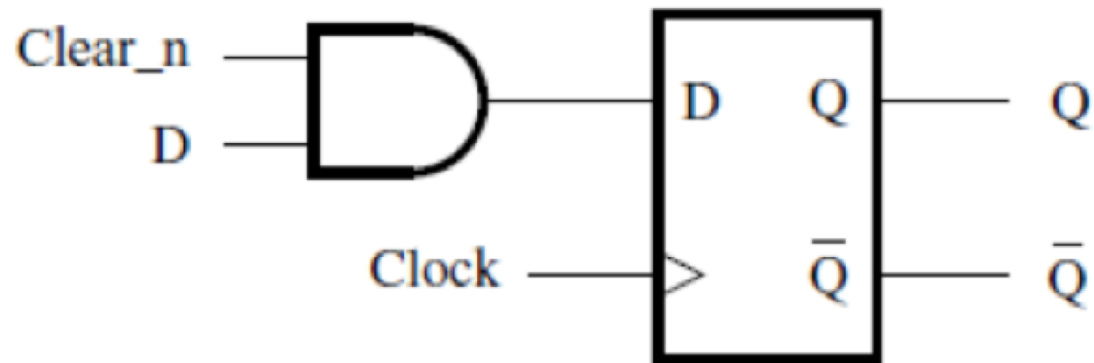
[Figure 5.13a from the textbook]

Positive-edge-triggered D flip-flop with Clear and Preset



(b) Graphical symbol

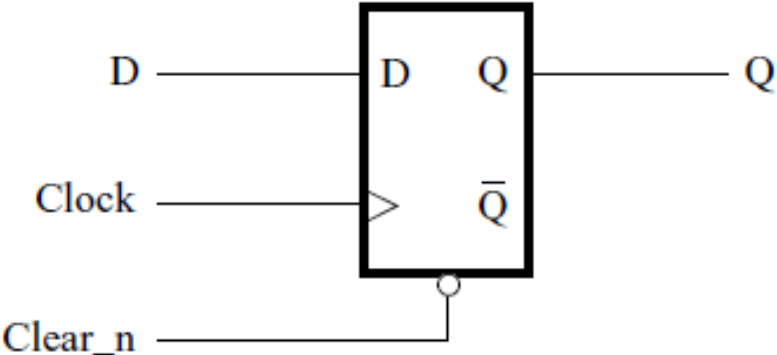
Positive-edge-triggered D flip-flop with Synchronous Clear



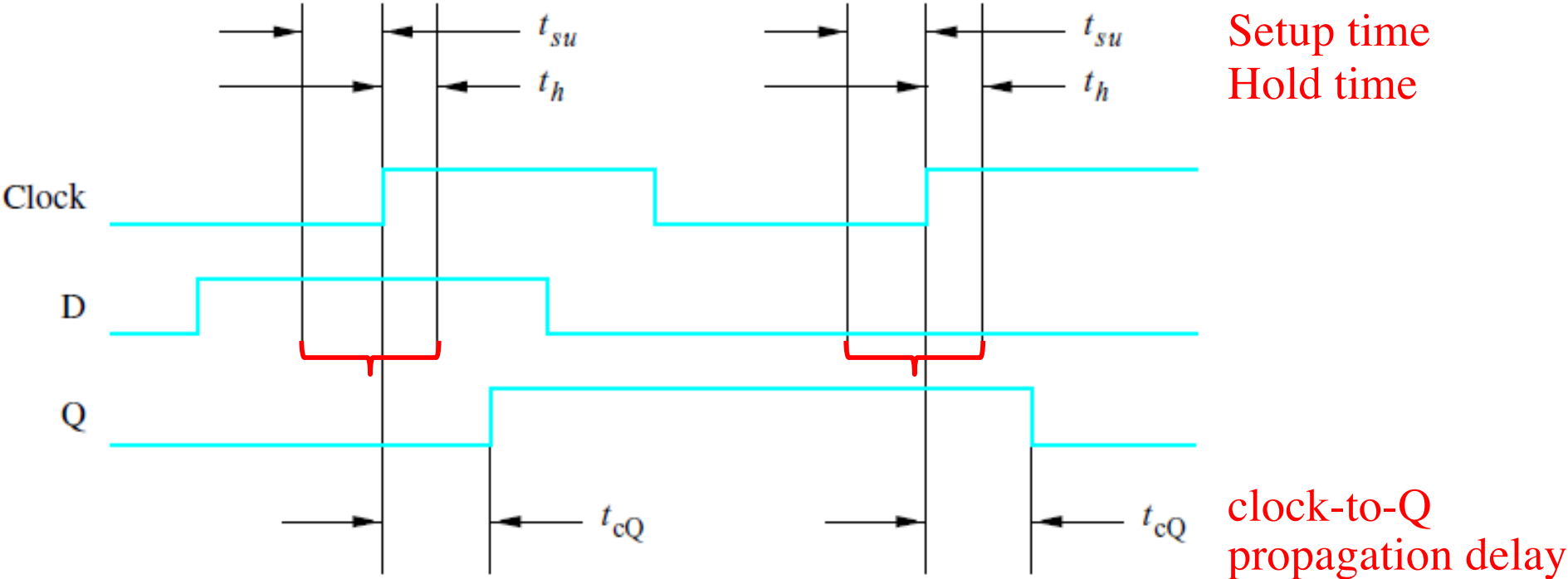
(c) Adding a synchronous clear

The output Q can be cleared only on the positive clock edge.

Flip-Flop Timing Parameters



(a) D flip-flop with asynchronous clear



[Figure 5.14 from the textbook]

(b) Timing diagram

Terminology

- **Basic Latch** – is a feedback connection of two NOR gates or two NAND gates, which can store one bit of information. It can be set using the S input and reset to 0 using the R input.
- **Gated Latch** – is a basic latch that includes input gating and a control input signal. The latch retains its existing state when the control input is equal to 0. Its state may be changed when the control signal is equal to 1.

Terminology

- **Two types of gated latches**
(the control input is the clock):
- **Gated SR Latch** – uses the S and R inputs to set the latch to 1 or reset it to 0.
- **Gated D Latch** – uses the D input to force the latch into a state that has the same logic value as the D input.

Terminology

- **Flip-Flop** – is a storage element that can have its output state changed only on the edge of the controlling clock signal.
- **Positive-edge triggered** – if the state changes when the clock signal goes from 0 to 1.
- **Negative-edge triggered** – if the state changes when the clock signal goes from 1 to 0.

Terminology

The word ***latch*** is mainly used for storage elements, while clocked devices are described as ***flip-flops***.

A **latch** is level-sensitive, whereas a **flip-flop** is edge-sensitive. That is, when a latch is enabled it becomes transparent, while a flip flop's output only changes on a single type (positive going or negative going) of clock edge.

Questions?

THE END