

Theory

A. Introduction to Sequential Circuits

If we have an AND gate and drive both inputs with 1, the output would be **1**. However, if one of its inputs is 0, the output will be **0**. This behavior is defined by the **truth table** and describes a **combinatorial** circuit, where the **output** is determined **solely by its inputs**.

Sequential circuits are different. They not only rely on the current inputs but **also the previous output**. For example, creating a circuit that flips every time a button is pressed, changing from 0 to 1 or 1 to 0, requires **remembering the previous output**. This type of circuit, where the output is determined by both inputs and the previous output, is called a **sequential circuit**.

B. The Clock Signal

The **clock signal** is a periodic signal used to synchronize digital circuits, analogous to a musical tempo in an orchestra. It pulses at precise intervals to **ensure** sequential circuits remain **in sync**.

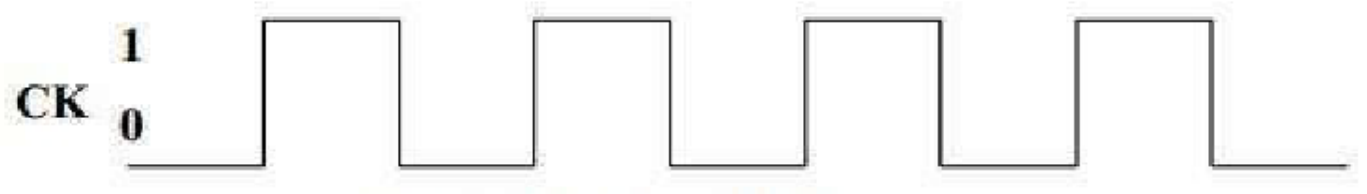


Figure 1-1: Clock Diagram

The clock signal is a square wave, with a **rising edge** (transition from 0 to 1) and a **falling edge** (transition from 1 to 0).

One prominent example is the CPU clock, which pulses in MHz to GHz, controlling instruction execution in processors.

C. Synchronous and Asynchronous Sequential Circuits

Sequential circuits can be either **synchronous** or **asynchronous**. Synchronous circuits are controlled by a clock signal, while asynchronous circuits are not.

There are two types of synchronous circuits:

1. **Positive edge triggered:** Activated on the rising edge of the clock signal.
2. **Negative edge triggered:** Activated on the falling edge of the clock signal.

Synchronous circuits have a triangle symbol at the clock input, and a bubble at the clock input of negative edge-triggered devices.

Below is the picture for the two types of synchronous sequential circuits. The left one is positive edge triggered and the right one is negative edge triggered. Notice the “bubble” at the clock input of the negative edge triggered device.

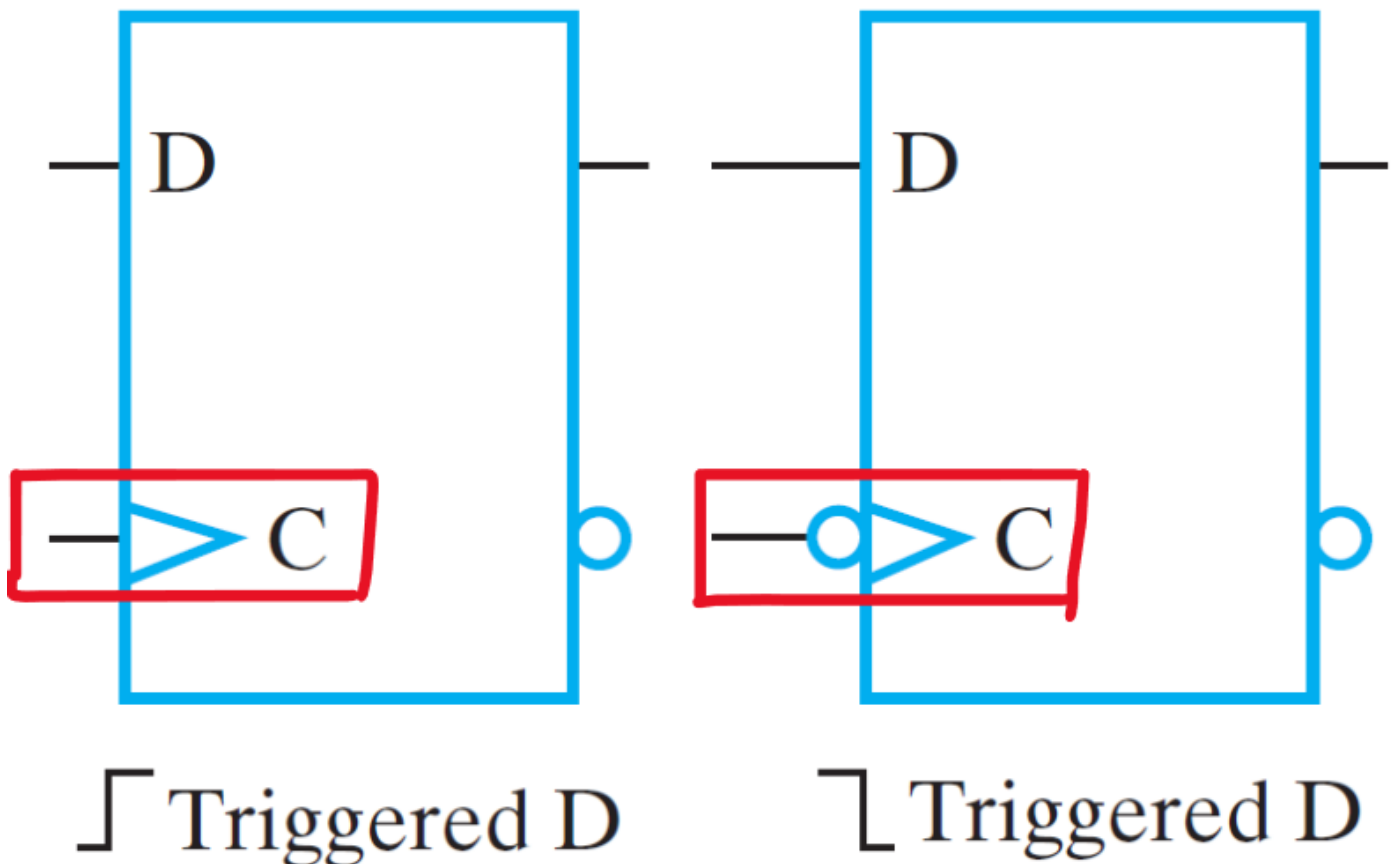


Figure 2-1: Trigger Types

D. Latches and Flip-Flops

Latches and **flip-flops** are the simplest sequential circuits. They store a single bit of data (either 0 or 1) and are essential components in building more complex sequential circuits and memory devices (akin to **logic gates**, but for sequential circuits). The key difference between them is that **latches are asynchronous**, while **flip-flops are synchronous**.

Latches and flip-flops have a characteristic equation that relates the next state (NS/Qnext) to the present state (PS/Q).

1. SR Latch and SR' Latch

An **SR latch** is built from two cross-coupled NOR gates. It has two inputs, **S (set)** and **R (reset)**, and two outputs, **Q** and **Q'**, which are complements of each other.

- When $S = 1$ and $R = 0$, $Q = 1$ (set state).
- When $S = 0$ and $R = 1$, $Q = 0$ (reset state).
- When $S = 0$ and $R = 0$, the latch retains its previous state.

If both $S = 1$ and $R = 1$, the state is **undefined** (forbidden).

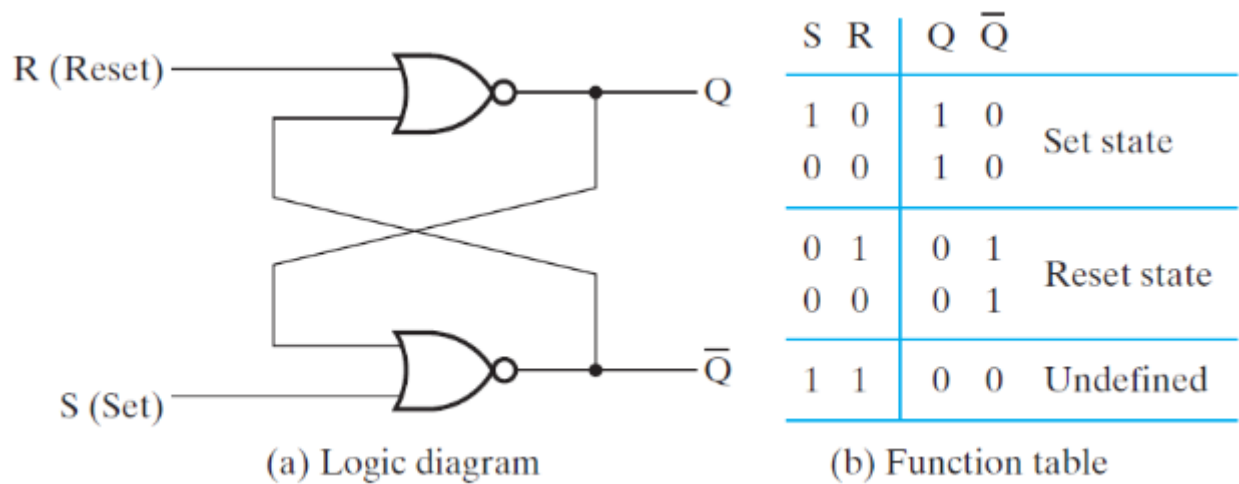


Figure 3-1: SR Latch

The characteristic equation for the SR latch is:

$Q_{next} = S + R'Q$, where $S.R = 0$.

A similar type, the **(SR)' latch** is built from cross-coupled NAND gates. It is activated when inputs are driven low (0), unlike the SR latch.

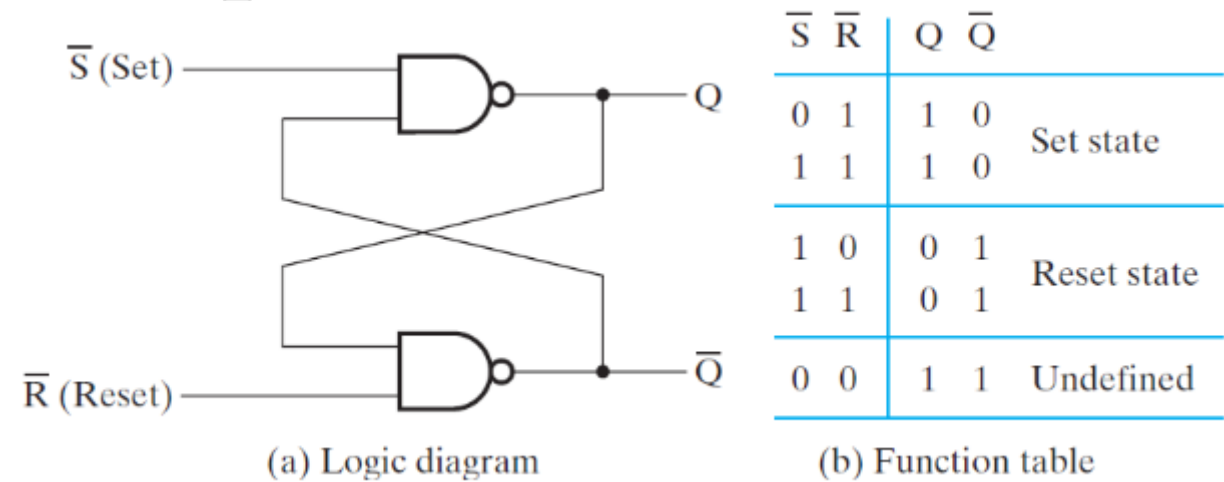


Figure 3-2: (SR)' Latch

2. D Latch

A **D latch** avoids the undefined state by ensuring **S** and **R** are **never both 1** at the same time. The D latch is created by using an inverter to make **S** and **R** complements of each other.

It has two inputs:

- **D (data)**: Determines the next state.
- **C (control)**: Enables or disables state changes.

When **C = 0**, the latch holds its state. When **C = 1**, the output depends on **D**:

- **D = 0** results in a reset state (**Q = 0**).
- **D = 1** results in a set state (**Q = 1**).

The characteristic equation for the D latch is:

$$Q_{\text{next}} = D.$$

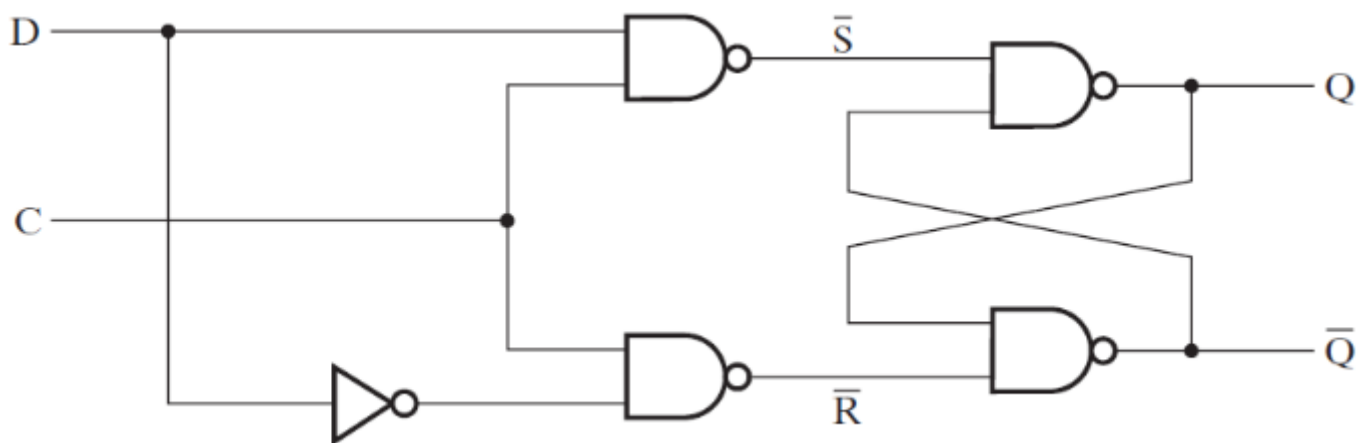


Figure 3-3-1: D Latch

C	D	Next state of Q
0	X	No change
1	0	Q = 0; Reset state
1	1	Q = 1; Set state

Figure 3-3-2: D Latch Truth Table

3. D Flip-Flop

A **D flip-flop** operates like a **D latch** but with a **clock signal instead of an enable signal**. The state changes at the transition of the clock signal (rising or falling edge), depending on **D**.

The D flip-flop can be implemented by using two latches (in this case a D latch and an SR latch) in a configuration as shown below:

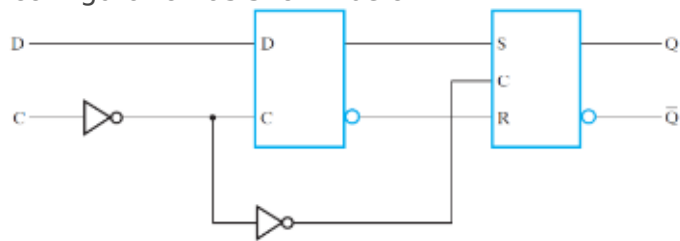


FIGURE 4-10
Positive-Edge-Triggered D Flip-Flop

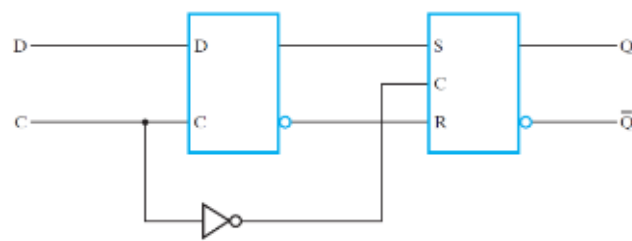


FIGURE 4-9
Negative-Edge-Triggered D Flip-Flop

Figure 3-4: D Flip-Flop

It prevents multiple state changes during a clock cycle by using two latches (a D latch and an SR latch) in a **master-slave configuration**.

4. JK Flip-Flop

The **JK flip-flop** is similar to the SR flip-flop, but when both **J** and **K** are 1, it enters a **toggle state** where the output flips between 0 and 1 on each clock cycle.

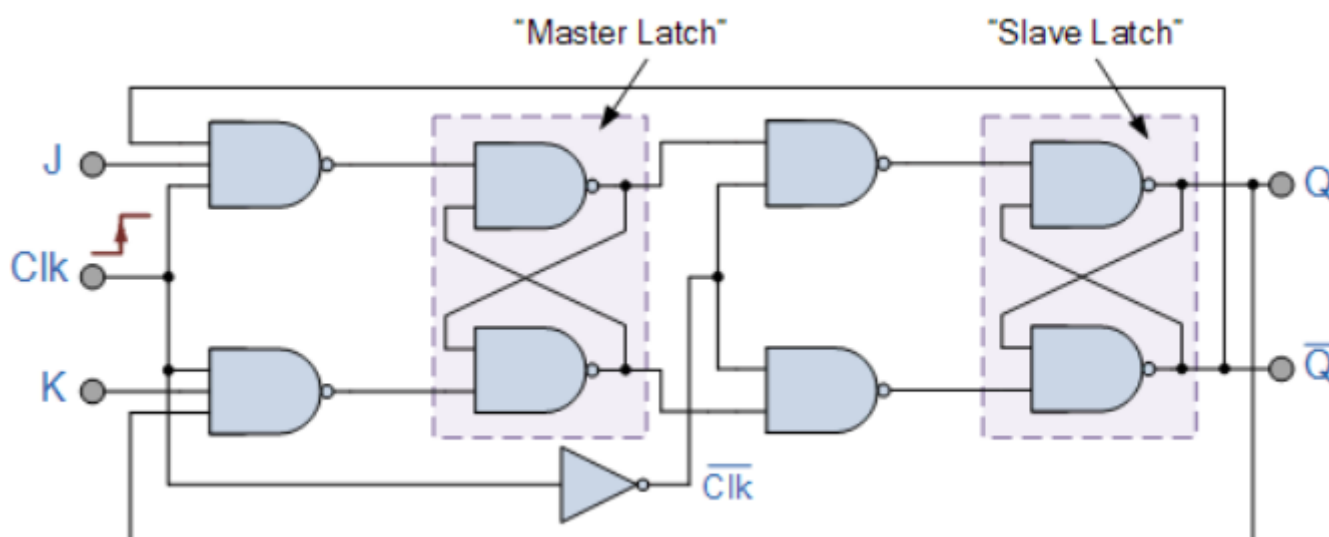


Figure 3-5-1: JK Flip-Flop

J	K	Q_{next}	STATE
0	0	Q	HOLD
0	1	0	RESET
1	0	1	SET
1	1	\overline{Q}	TOGGLE

Figure 3-5-2: JK Truth Table

The characteristic equation for the JK flip-flop is:

$$Q_{next} = JQ' + K'Q$$

5. T Flip-Flop

The **T flip-flop** has two states:

- **Hold** ($T = 0$): Retains the previous state.
- **Toggle** ($T = 1$): Inverts the previous state.

The T flip-flop can be created by connecting a JK flip-flop's **J** and **K** inputs together or using an XOR gate with a D flip-flop.

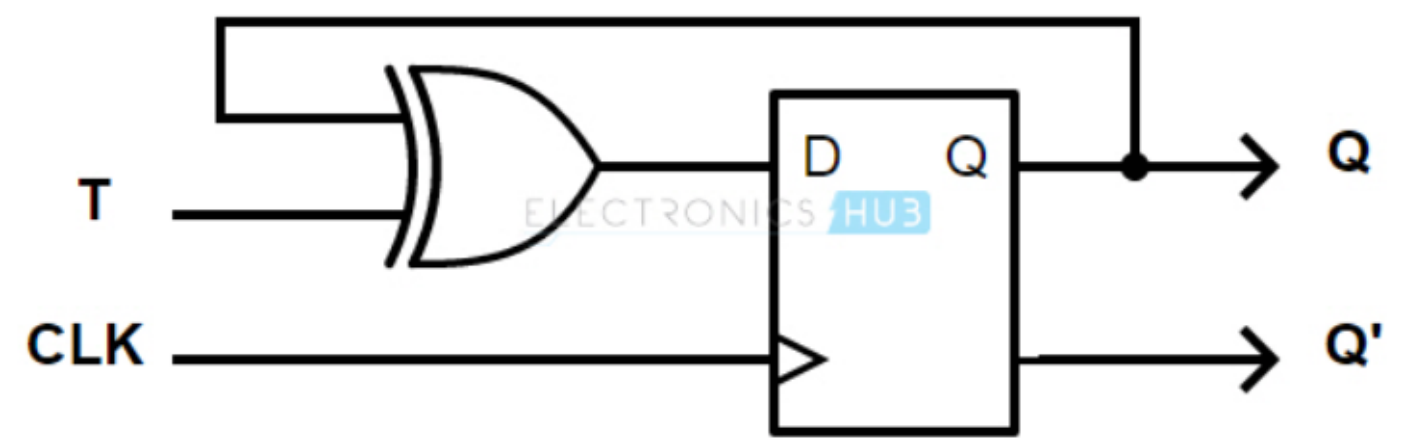


Figure 3-6-1: T Flip-Flop

T	Q _{next}	STATE
0	Q	HOLD
1	\overline{Q}	TOGGLE

Figure 3-6-2: T Flip-Flop Truth Table

The characteristic equation for the T flip-flop is:

$$Q_{next} = T \oplus Q$$