EE101: Digital circuits (Part 4)

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* The digital circuits we have seen so far (gates, multiplexer, demultiplexer, encoders, decoders) are *combinatorial* in nature, i.e., the output(s) depends only on the *present* values of the inputs and *not* on their past values.

Sequential circuits

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* In *sequential* circuits, the "state" of the circuit is crucial in determining the output values. For a given input combination, a sequential circuit may produce different output values, depending on its previous state.

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* In *sequential* circuits, the "state" of the circuit is crucial in determining the output values. For a given input combination, a sequential circuit may produce different output values, depending on its previous state.
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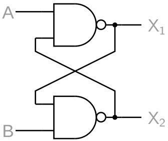
* In other words, a sequential circuit has a *memory* (of its past state) whereas a combinatorial circuit has no memory.
* Sequential circuits (together with combinatorial circuits) make it possible to build several useful applications, such as counters, registers, arithmetic/logic unit (ALU), all the way to microprocessors.

NAND latch (RS latch)



A	B	X_1	X_2

- A, B: inputs, X_1, X_2: outputs

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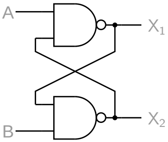

A	B	X_1	X_2

- A, B: inputs, X_1, X_2: outputs
- Consider $A = 1$, $B = 0$.

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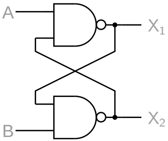

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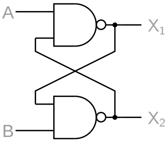

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  Overall, we have $X_1 = 0$, $X_2 = 1$.

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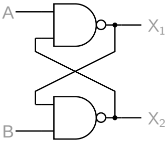

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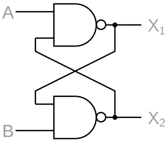

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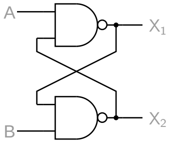

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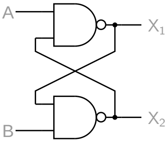

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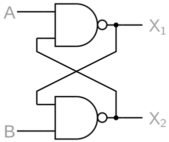

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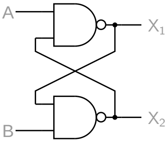

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  If $X_1=1$, $X_2=0$ previously, the circuit continues to "hold" that state.
  Similarly, if $X_1=0$, $X_2=1$ previously, the circuit continues to "hold" that state.

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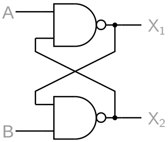

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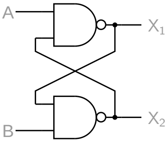

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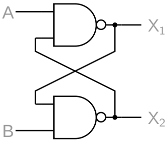

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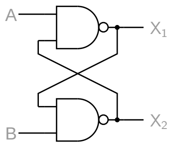

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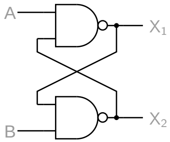

A	B	X_1	X_2
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0	0	invalid	

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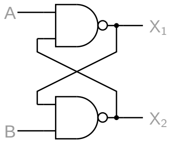

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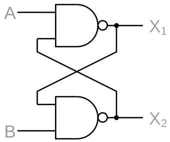

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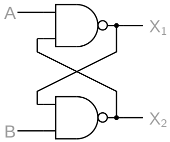

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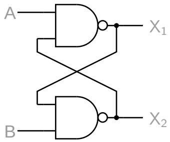

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* In other words,
  $A=1$, $B=0 \longrightarrow$ latch gets reset to 0.
  $A=0$, $B=1 \longrightarrow$ latch gets set to 1.
* The A input is therefore called the RESET (R) input, and B is called the SET (S) input of the latch.

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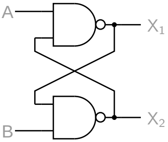

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* The A input is therefore called the RESET (R) input, and B is called the SET (S) input of the latch.
* X_1 is denoted by Q, and X_2 (which is $\overline{X_1}$ in all cases except for $A=B=0$) is denoted by $\overline{Q}$.

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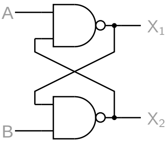

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1	1	previous	
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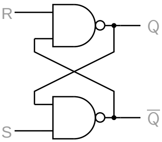

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
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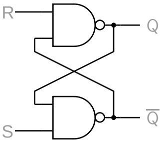

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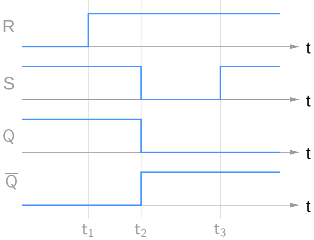

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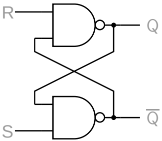

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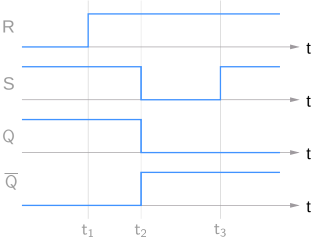

* Up to $t = t_1$, $R = 0$, $S = 1 \rightarrow Q = 1$.

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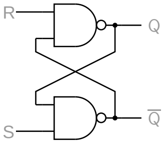

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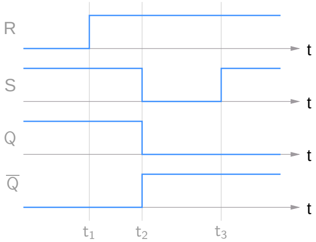
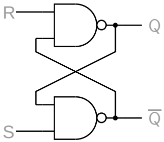


* Up to $t = t_1$, $R = 0$, $S = 1 \rightarrow Q = 1$.
* At $t = t_1$, R goes high $\rightarrow R = S = 1$, and the latch holds its previous state $\rightarrow$ no change at the output.



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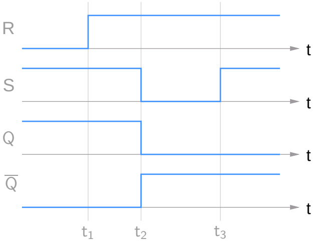
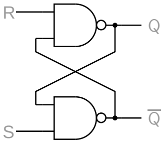
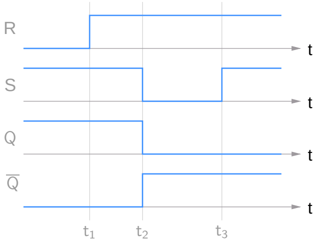


- Up to $t = t_1$, $R = 0$, $S = 1 \rightarrow Q = 1$.
- At $t = t_1$, R goes high $\rightarrow R = S = 1$, and the latch holds its previous state $\rightarrow$ no change at the output.
- At $t = t_2$, S goes low $\rightarrow R = 1$, $S = 0 \rightarrow Q = 0$.

NAND latch (RS latch)

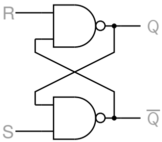


R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

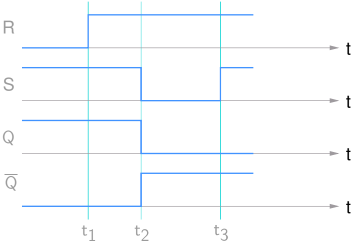


- Up to $t = t_1$, $R = 0$, $S = 1 \rightarrow Q = 1$.
- At $t = t_1$, R goes high $\rightarrow R = S = 1$, and the latch holds its previous state $\rightarrow$ no change at the output.
- At $t = t_2$, S goes low $\rightarrow R = 1$, $S = 0 \rightarrow Q = 0$.
- At $t = t_3$, S goes high $\rightarrow R = S = 1$, and the latch holds its previous state $\rightarrow$ no change at the output.

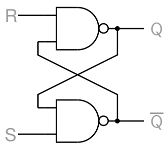
NAND latch (RS latch)



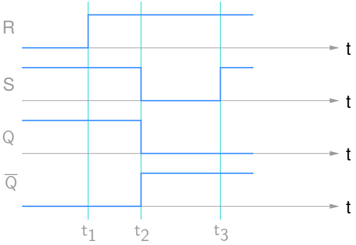
R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	1	1



NAND latch (RS latch)

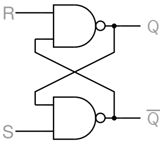


R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	1	1



* Why not allow $R = S = 0$?

NAND latch (RS latch)



R	S	Q	$\overline{Q}$
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1	1	previous	
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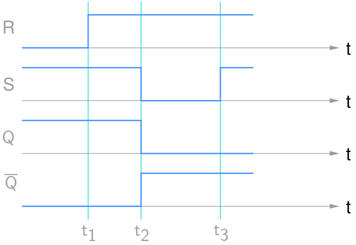

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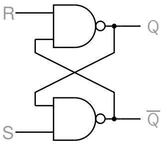
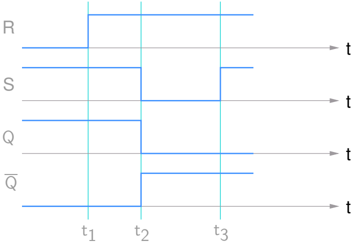


R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	1	1



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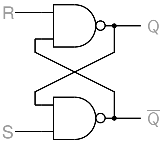
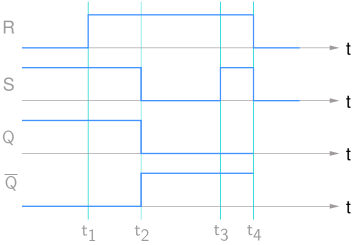


R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	1	1



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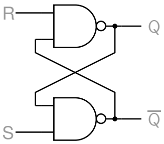
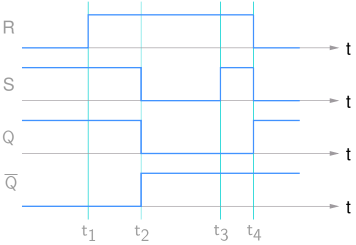


R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	1	1



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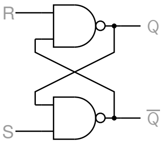
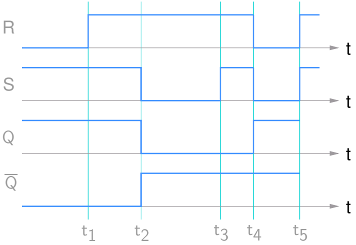


R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	1	1



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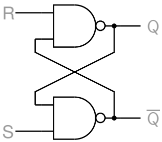
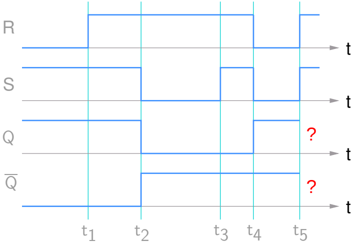


R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	1	1



* Why not allow $R = S = 0$?
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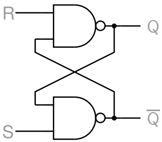
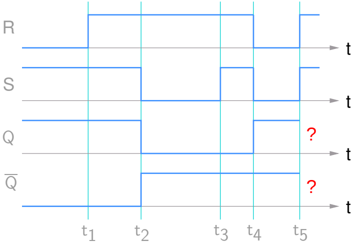


R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	1	1



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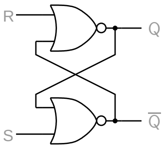
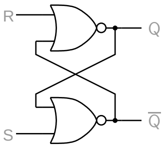
* We surely don't want any question marks in digital electronics!

NOR latch (RS latch)



R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
0	0	previous	
1	1	invalid	

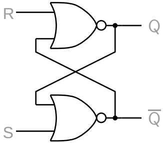
NOR latch (RS latch)



R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
0	0	previous	
1	1	invalid	

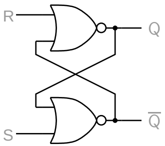
* The NOR latch is similar to the NAND latch:
  When $R = 1$, $S = 0$, the latch gets *reset* to $Q = 0$.
  When $R = 0$, $S = 1$, the latch gets *set* to $Q = 1$.

NOR latch (RS latch)



R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
0	0	previous	
1	1	invalid	

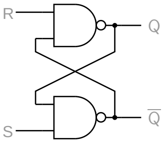
* The NOR latch is similar to the NAND latch:
  When $R=1$, $S=0$, the latch gets *reset* to $Q=0$.
  When $R=0$, $S=1$, the latch gets *set* to $Q=1$.
* For $R=S=0$, the latch retains its previous state (i.e., the previous values of Q and $\overline{Q}$).



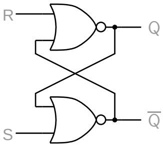
R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
0	0	previous	
1	1	invalid	

* The NOR latch is similar to the NAND latch:
  When $R=1$, $S=0$, the latch gets *reset* to $Q=0$.
  When $R=0$, $S=1$, the latch gets *set* to $Q=1$.
* For $R=S=0$, the latch retains its previous state (i.e., the previous values of Q and $\overline{Q}$).
* $R=S=1$ is not allowed for reasons similar to those discussed in the context of the NAND latch.

Comparison of NAND and NOR latches

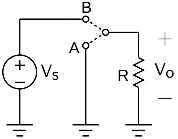


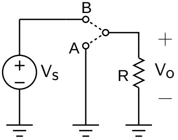
R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	



R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
0	0	previous	
1	1	invalid	

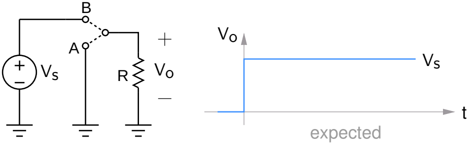
Chatter (bouncing) due to a mechanical switch





* When the switch is thrown from A to B, V_o is expected to go from 0 V to V_s (say, 5 V).

Chatter (bouncing) due to a mechanical switch



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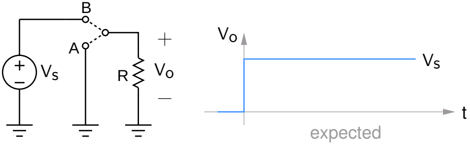
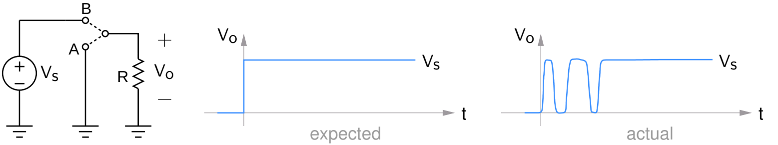


* When the switch is thrown from A to B, V_o is expected to go from 0 V to V_s (say, 5 V).
* However, mechanical switches suffer from “chatter” or “bouncing,” i.e., the transition from A to B is not a single, clean one. As a result, V_o oscillates between 0 V and 5 V before settling to its final value (5 V).

Chatter (bouncing) due to a mechanical switch



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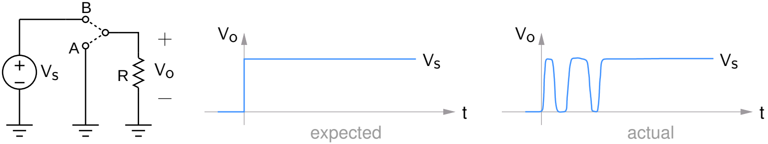
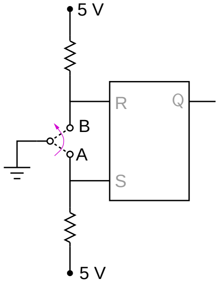
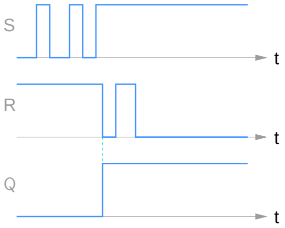


* When the switch is thrown from A to B, V_o is expected to go from 0 V to V_s (say, 5 V).
* However, mechanical switches suffer from "chatter" or "bouncing," i.e., the transition from A to B is not a single, clean one. As a result, V_o oscillates between 0 V and 5 V before settling to its final value (5 V).
* In some applications, this chatter can cause malfunction → need a way to remove the chatter.

Chatter (bouncing) due to a mechanical switch



R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	



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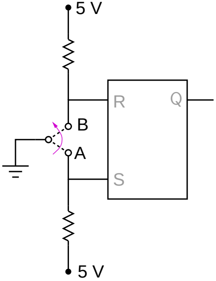
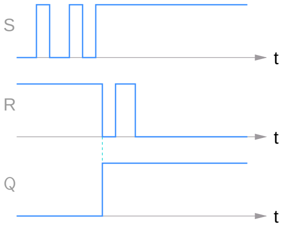
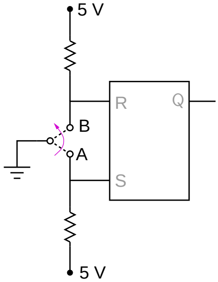


R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

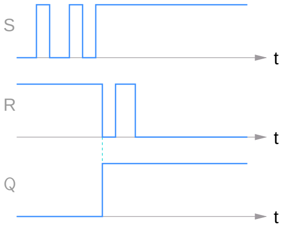


* Because of the chatter, the S and R inputs may have multiple transitions when the switch is thrown from A to B.

Chatter (bouncing) due to a mechanical switch



R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	



* Because of the chatter, the S and R inputs may have multiple transitions when the switch is thrown from A to B.
* However, for $S = R = 1$, the previous value of Q is retained, causing a *single* transition in Q, as desired.

The "clock"

* Complex digital circuits are generally designed for *synchronous* operation, i.e., transitions in the various signals are synchronised with the *clock*.

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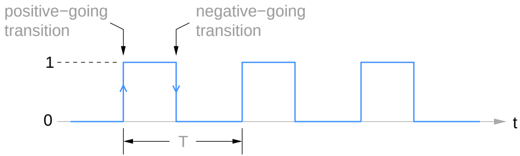
* A clock is a periodic signal, with a positive-going transition and a negative-going transition.



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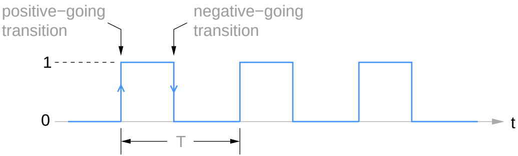
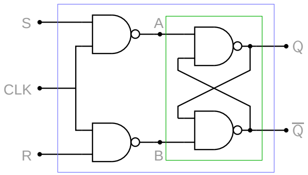


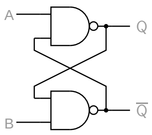
* The clock frequency determines the overall speed of the circuit. For example, a processor that operates with a 1 GHz clock is 10 times faster than one that operates with a 100 MHz clock.

Clocked RS latch



Clocked RS latch

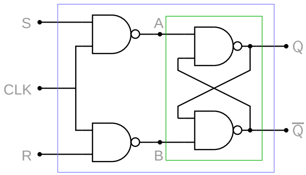
CLK	R	S	Q	$\overline{Q}$
0	X	X	previous	
1	1	0	0	1
1	0	1	1	0
1	0	0	previous	
1	1	1	invalid	



NAND RS latch

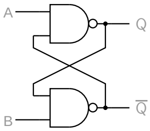
A	B	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Clocked RS latch



Clocked RS latch

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

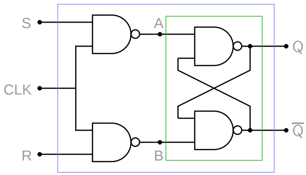


NAND RS latch

A	B	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

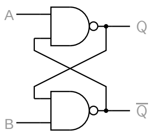
* When clock is inactive (0), $A = B = 1$, and the latch holds the previous state.

Clocked RS latch



Clocked RS latch

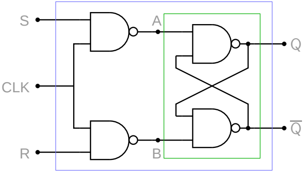
CLK	R	S	Q	$\overline{Q}$
0	X	X	previous	
1	1	0	0	1
1	0	1	1	0
1	0	0	previous	
1	1	1	invalid	



NAND RS latch

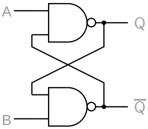
A	B	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

* When clock is inactive (0), $A = B = 1$, and the latch holds the previous state.
* When clock is active (1), $A = \overline{S}$, $B = \overline{R}$. Using the truth table for the NAND RS latch (right), we can construct the truth table for the clocked RS latch.



Clocked RS latch

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

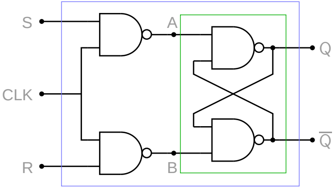


NAND RS latch

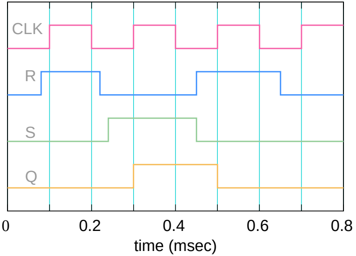
A	B	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

* When clock is inactive (0), $A = B = 1$, and the latch holds the previous state.
* When clock is active (1), $A = \overline{S}$, $B = \overline{R}$. Using the truth table for the NAND RS latch (right), we can construct the truth table for the clocked RS latch.
* Note that the above table is sensitive to the *level* of the clock (i.e., whether CLK is 0 or 1).

Clocked RS latch



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



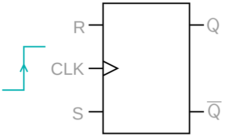
(SEQUEL file: ee101_rs_1.sqproj)

* The clocked RS latch seen previously is *level-sensitive*, i.e., if the clock is active (CLK = 1), the flip-flop output is allowed to change, depending on the R and S inputs.

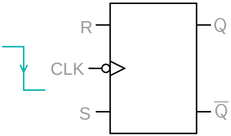
* The clocked RS latch seen previously is *level-sensitive*, i.e., if the clock is active (CLK = 1), the flip-flop output is allowed to change, depending on the R and S inputs.
* In an *edge-sensitive* flip-flop, the output can change only at the active clock *edge* (i.e., CLK transition from 0 to 1 or from 1 to 0).

Edge-triggered flip-flops

* The clocked RS latch seen previously is *level-sensitive*, i.e., if the clock is active (CLK = 1), the flip-flop output is allowed to change, depending on the R and S inputs.
* In an *edge-sensitive* flip-flop, the output can change only at the active clock *edge* (i.e., CLK transition from 0 to 1 or from 1 to 0).
* Edge-sensitive flip-flops are denoted by the following symbols:



positive edge−triggered flip−flop

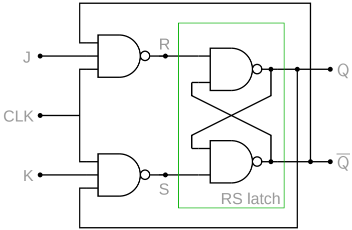


negative edge−triggered flip−flop

JK flip-flop

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

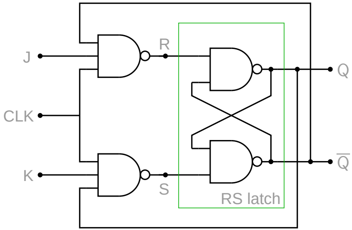
Truth table for RS latch



JK flip-flop

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch

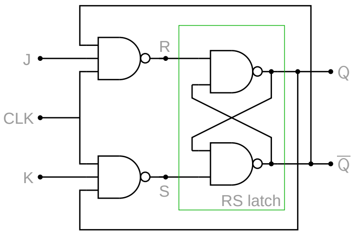


* When CLK $= 0$, we have $R = S = 1$, and the RS latch holds the previous Q. In other words, nothing happens as long as CLK $= 0$.

JK flip-flop

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)

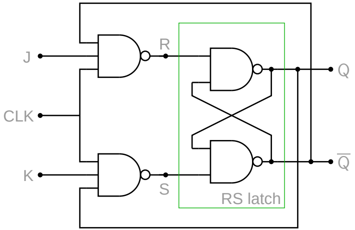
Truth table for JK flip–flop

* When CLK $=0$, we have $R=S=1$, and the RS latch holds the previous Q. In other words, nothing happens as long as CLK $=0$.

JK flip-flop

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)

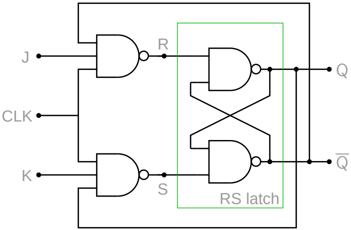
Truth table for JK flip–flop

* When CLK = 0, we have $R = S = 1$, and the RS latch holds the previous Q. In other words, nothing happens as long as CLK = 0.
* When CLK = 1:

JK flip-flop

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)

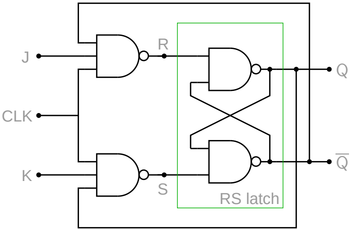
Truth table for JK flip–flop

* When CLK = 0, we have $R = S = 1$, and the RS latch holds the previous Q. In other words, nothing happens as long as CLK = 0.
* When CLK = 1:
  - $J = K = 0 \rightarrow R = S = 1$, RS latch holds previous Q, i.e., $Q_{n+1} = Q_n$, where n denotes the n^{th} clock pulse (This notation will become clear shortly).

JK flip-flop

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)

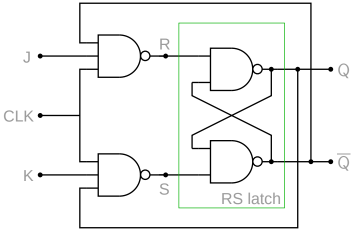
Truth table for JK flip–flop

* When CLK $=0$, we have $R=S=1$, and the RS latch holds the previous Q. In other words, nothing happens as long as CLK $=0$.
* When CLK $=1$:
  - $J=K=0 \rightarrow R=S=1$, RS latch holds previous Q, i.e., $Q_{n+1}=Q_n$, where n denotes the n^{th} clock pulse (This notation will become clear shortly).

JK flip-flop

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)

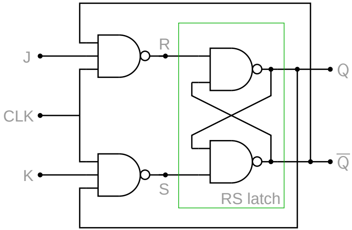
Truth table for JK flip–flop

* When CLK $= 0$, we have $R = S = 1$, and the RS latch holds the previous Q. In other words, nothing happens as long as CLK $= 0$.
* When CLK $= 1$:
  - $J = K = 0 \rightarrow R = S = 1$, RS latch holds previous Q, i.e., $Q_{n+1} = Q_n$, where n denotes the n^{th} clock pulse (This notation will become clear shortly).
  - $J = 0,\ K = 1 \rightarrow R = 1,\ S = \overline{Q_n}$.

JK flip-flop

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)

Truth table for JK flip–flop

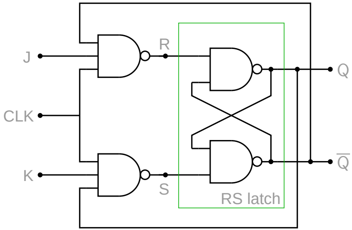
* When CLK = 0, we have $R = S = 1$, and the RS latch holds the previous Q. In other words, nothing happens as long as CLK = 0.
* When CLK = 1:
  - $J = K = 0 \rightarrow R = S = 1$, RS latch holds previous Q, i.e., $Q_{n+1} = Q_n$, where n denotes the n^{th} clock pulse (This notation will become clear shortly).
  - $J = 0,\ K = 1 \rightarrow R = 1,\ S = \overline{Q_n}$.

    Case (i): $Q_n = 0 \rightarrow S = 1$ (i.e., $R = S = 1$) $\rightarrow Q_{n+1} = Q_n = 0$.

JK flip-flop

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)

Truth table for JK flip−flop

* When CLK = 0, we have $R = S = 1$, and the RS latch holds the previous Q. In other words, nothing happens as long as CLK = 0.
* When CLK = 1:
  - $J = K = 0 \rightarrow R = S = 1$, RS latch holds previous Q, i.e., $Q_{n+1} = Q_n$, where n denotes the n^{th} clock pulse (This notation will become clear shortly).
  - $J = 0,\ K = 1 \rightarrow R = 1,\ S = \overline{Q_n}$.

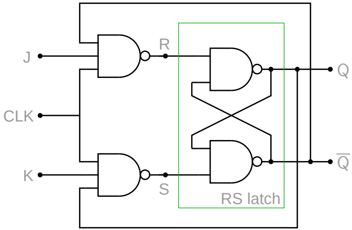
    Case (i): $Q_n = 0 \rightarrow S = 1$ (i.e., $R = S = 1$) $\rightarrow Q_{n+1} = Q_n = 0$.

    Case (ii): $Q_n = 1 \rightarrow S = 0$ (i.e., $R = 1,\ S = 0$) $\rightarrow Q_{n+1} = 0$.

JK flip-flop

R	S	Q	$\overline{\text{Q}}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)

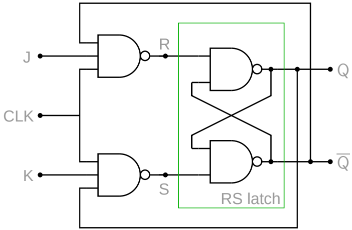
Truth table for JK flip–flop

* When CLK $=0$, we have $R=S=1$, and the RS latch holds the previous Q. In other words, nothing happens as long as CLK $=0$.
* When CLK $=1$:
  - $J=K=0 \rightarrow R=S=1$, RS latch holds previous Q, i.e., $Q_{n+1}=Q_n$, where n denotes the n^{th} clock pulse (This notation will become clear shortly).
  - $J=0,\ K=1 \rightarrow R=1,\ S=\overline{Q_n}$.
    Case (i): $Q_n=0 \rightarrow S=1$ (i.e., $R=S=1$) $\rightarrow Q_{n+1}=Q_n=0$.
    Case (ii): $Q_n=1 \rightarrow S=0$ (i.e., $R=1,\ S=0$) $\rightarrow Q_{n+1}=0$.
    In either case, $Q_{n+1}=0 \rightarrow$ For $J=0,\ K=1,\ Q_{n+1}=0$.

JK flip-flop

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)
1	0	1	0

Truth table for JK flip–flop

* When CLK = 0, we have $R = S = 1$, and the RS latch holds the previous Q. In other words, nothing happens as long as CLK = 0.
* When CLK = 1:
  - $J = K = 0 \rightarrow R = S = 1$, RS latch holds previous Q, i.e., $Q_{n+1} = Q_n$, where n denotes the n^{th} clock pulse (This notation will become clear shortly).
  - $J = 0,\ K = 1 \rightarrow R = 1,\ S = \overline{Q_n}$.

    Case (i): $Q_n = 0 \rightarrow S = 1$ (i.e., $R = S = 1$) $\rightarrow Q_{n+1} = Q_n = 0$.

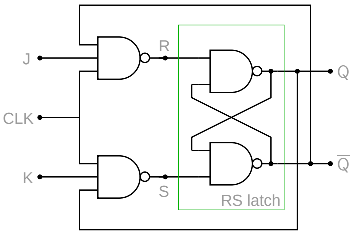
    Case (ii): $Q_n = 1 \rightarrow S = 0$ (i.e., $R = 1,\ S = 0$) $\rightarrow Q_{n+1} = 0$.

    In either case, $Q_{n+1} = 0 \rightarrow$ For $J = 0,\ K = 1,\ Q_{n+1} = 0$.

JK flip-flop

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



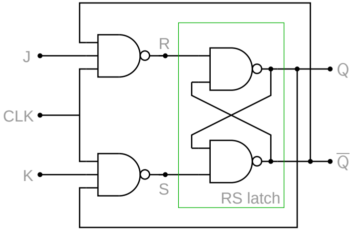
CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)
1	0	1	0

Truth table for JK flip–flop

JK flip-flop

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)
1	0	1	0

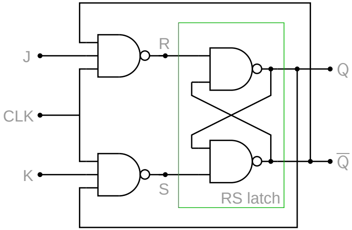
Truth table for JK flip−flop

* When CLK = 1:
  - Consider $J = 1,\ K = 0 \rightarrow S = 1,\ R = \overline{\overline{Q_n}} = Q_n$.

JK flip-flop

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)
1	0	1	0

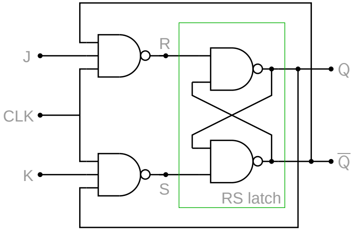
Truth table for JK flip−flop

* When CLK $= 1$:
  - Consider $J = 1$, $K = 0 \rightarrow S = 1$, $R = \overline{\overline{Q_n}} = Q_n$.
    Case (i): $Q_n = 0 \rightarrow R = 0$ (i.e., $R = 0$, $S = 1$) $\rightarrow Q_{n+1} = 1$.

JK flip-flop

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)
1	0	1	0

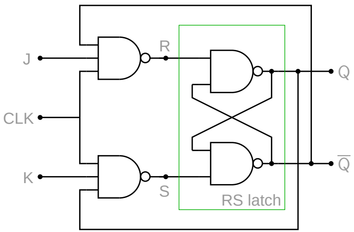
Truth table for JK flip−flop

* When CLK $=1$:
  - Consider $J=1,\ K=0 \rightarrow S=1,\ R=\overline{\overline{Q_n}}=Q_n$.
    Case (i): $Q_n=0 \rightarrow R=0$ (i.e., $R=0,\ S=1$) $\rightarrow Q_{n+1}=1$.
    Case (ii): $Q_n=1 \rightarrow R=1$ (i.e., $R=1,\ S=1$) $\rightarrow Q_{n+1}=Q_n=1$.

JK flip-flop

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)
1	0	1	0

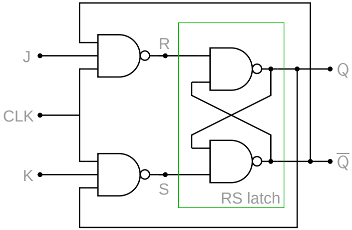
Truth table for JK flip−flop

* When CLK $=1$:
  - Consider $J=1,\ K=0 \longrightarrow S=1,\ R=\overline{\overline{Q_n}}=Q_n$.
    Case (i): $Q_n=0 \longrightarrow R=0$ (i.e., $R=0,\ S=1) \longrightarrow Q_{n+1}=1$.
    Case (ii): $Q_n=1 \longrightarrow R=1$ (i.e., $R=1,\ S=1) \longrightarrow Q_{n+1}=Q_n=1$.
    $\longrightarrow$ For $J=1,\ K=0,\ Q_{n+1}=1$.

JK flip-flop

R	S	Q	$\overline{\text{Q}}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)
1	0	1	0
1	1	0	1

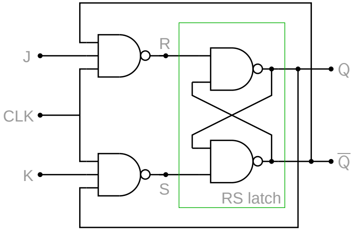
Truth table for JK flip−flop

* When CLK = 1:
  - Consider $J=1,\ K=0 \longrightarrow S=1,\ R=\overline{\overline{Q_n}}=Q_n$.
    Case (i): $Q_n=0 \longrightarrow R=0$ (i.e., $R=0,\ S=1) \longrightarrow Q_{n+1}=1$.
    Case (ii): $Q_n=1 \longrightarrow R=1$ (i.e., $R=1,\ S=1) \longrightarrow Q_{n+1}=Q_n=1$.
    $\longrightarrow$ For $J=1,\ K=0,\ Q_{n+1}=1$.

JK flip-flop

R	S	Q	$\overline{\text{Q}}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)
1	0	1	0
1	1	0	1

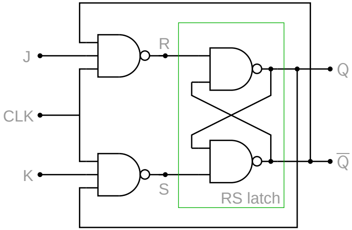
Truth table for JK flip−flop

* When $\text{CLK} = 1$:
  - Consider $J=1,\ K=0 \rightarrow S=1,\ R=\overline{\overline{Q_n}}=Q_n$.
    Case (i): $Q_n=0 \rightarrow R=0$ (i.e., $R=0,\ S=1) \rightarrow Q_{n+1}=1$.
    Case (ii): $Q_n=1 \rightarrow R=1$ (i.e., $R=1,\ S=1) \rightarrow Q_{n+1}=Q_n=1$.
    $\rightarrow$ For $J=1,\ K=0,\ Q_{n+1}=1$.
  - Consider $J=1,\ K=1 \rightarrow R=Q_n,\ S=\overline{Q_n}$.

JK flip-flop

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)
1	0	1	0
1	1	0	1

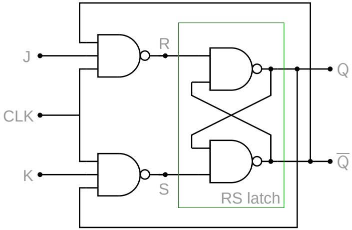
Truth table for JK flip−flop

* When CLK = 1:
  - Consider $J=1,\ K=0 \rightarrow S=1,\ R=\overline{\overline{Q_n}}=Q_n$.
    Case (i): $Q_n=0 \rightarrow R=0$ (i.e., $R=0,\ S=1$) $\rightarrow Q_{n+1}=1$.
    Case (ii): $Q_n=1 \rightarrow R=1$ (i.e., $R=1,\ S=1$) $\rightarrow Q_{n+1}=Q_n=1$.
    $\rightarrow$ For $J=1,\ K=0,\ Q_{n+1}=1$.
  - Consider $J=1,\ K=1 \rightarrow R=Q_n,\ S=\overline{Q_n}$.
    Case (i): $Q_n=0 \rightarrow R=0,\ S=1 \rightarrow Q_{n+1}=1$.

JK flip-flop

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)
1	0	1	0
1	1	0	1

Truth table for JK flip−flop

* When CLK = 1:
  - Consider $J=1,\ K=0 \rightarrow S=1,\ R=\overline{\overline{Q_n}}=Q_n$.
    Case (i): $Q_n=0 \rightarrow R=0$ (i.e., $R=0,\ S=1$) $\rightarrow Q_{n+1}=1$.
    Case (ii): $Q_n=1 \rightarrow R=1$ (i.e., $R=1,\ S=1$) $\rightarrow Q_{n+1}=Q_n=1$.
    $\rightarrow$ For $J=1,\ K=0,\ Q_{n+1}=1$.
  - Consider $J=1,\ K=1 \rightarrow R=Q_n,\ S=\overline{Q_n}$.
    Case (i): $Q_n=0 \rightarrow R=0,\ S=1 \rightarrow Q_{n+1}=1$.
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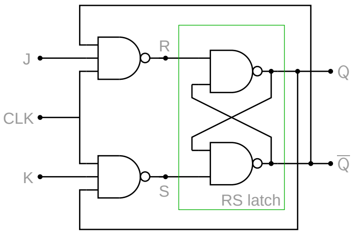
JK flip-flop

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)
1	0	1	0
1	1	0	1

Truth table for JK flip−flop

* When CLK $= 1$:
  - Consider $J=1,\ K=0 \rightarrow S=1,\ R=\overline{\overline{Q_n}}=Q_n$.
    Case (i): $Q_n=0 \rightarrow R=0$ (i.e., $R=0,\ S=1$) $\rightarrow Q_{n+1}=1$.
    Case (ii): $Q_n=1 \rightarrow R=1$ (i.e., $R=1,\ S=1$) $\rightarrow Q_{n+1}=Q_n=1$.
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    Case (i): $Q_n=0 \rightarrow R=0,\ S=1 \rightarrow Q_{n+1}=1$.
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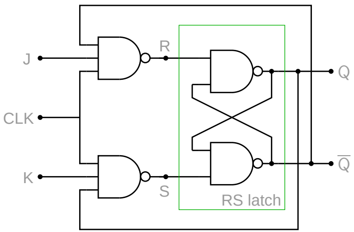
    $\rightarrow$ For $J=1,\ K=1,\ Q_{n+1}=\overline{Q_n}$.

JK flip-flop

R	S	Q	$\overline{Q}$
1	0	0	1
0	1	1	0
1	1	previous	
0	0	invalid	

Truth table for RS latch



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)
1	0	1	0
1	1	0	1
1	1	1	toggles ($\overline{Q_n}$)

Truth table for JK flip−flop

* When CLK = 1:
  - Consider $J=1,\ K=0 \rightarrow S=1,\ R=\overline{\overline{Q_n}}=Q_n$.
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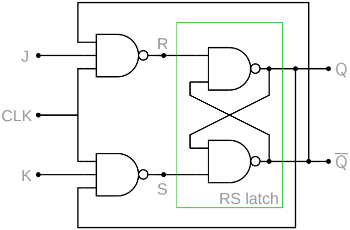
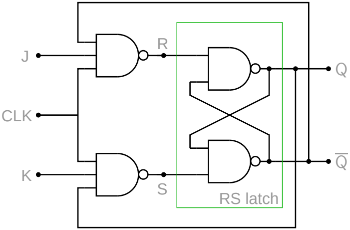


CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)
1	0	1	0
1	1	0	1
1	1	1	toggles ($\overline{Q_n}$)

Truth table for JK flip−flop

Consider $J = K = 1$ and CLK $= 1$.



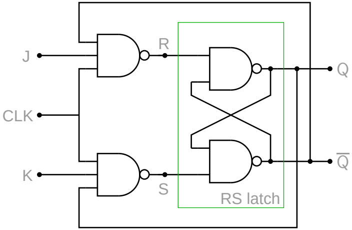
CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)
1	0	1	0
1	1	0	1
1	1	1	toggles ($\overline{Q_n}$)

Truth table for JK flip−flop

Consider $J = K = 1$ and CLK $= 1$.

As long as CLK $= 1$, Q will keep toggling! (The frequency will depend on the delay values of the various gates).

JK flip-flop



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)
1	0	1	0
1	1	0	1
1	1	1	toggles ($\overline{Q_n}$)

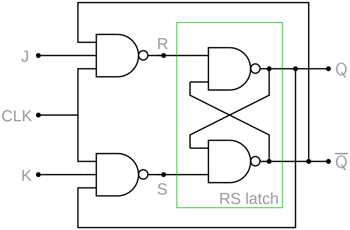
Truth table for JK flip−flop

Consider $J = K = 1$ and CLK $= 1$.

As long as CLK $= 1$, Q will keep toggling! (The frequency will depend on the delay values of the various gates).

When CLK changes from 1 to 0, the toggling will stop. However, the final value of Q is not known; it could be 0 or 1.

JK flip-flop



CLK	J	K	Q (Q_{n+1})
0	X	X	previous (Q_n)
1	0	0	previous (Q_n)
1	0	1	0
1	1	0	1
1	1	1	toggles ($\overline{Q_n}$)

Truth table for JK flip–flop

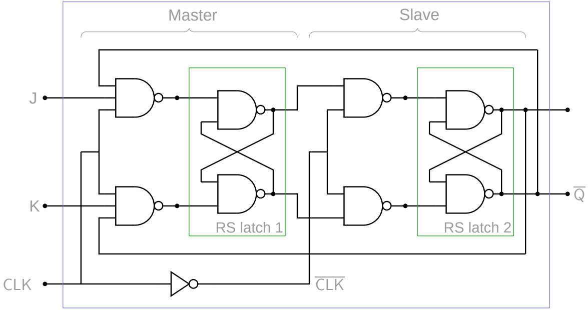
Consider $J = K = 1$ and CLK $= 1$.

As long as CLK $= 1$, Q will keep toggling! (The frequency will depend on the delay values of the various gates).

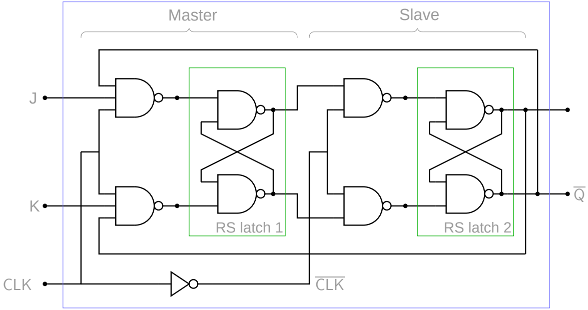
When CLK changes from 1 to 0, the toggling will stop. However, the final value of Q is not known; it could be 0 or 1.

$\rightarrow$ Use the "Master-slave" configuration.

JK flip-flop (Master-Slave)

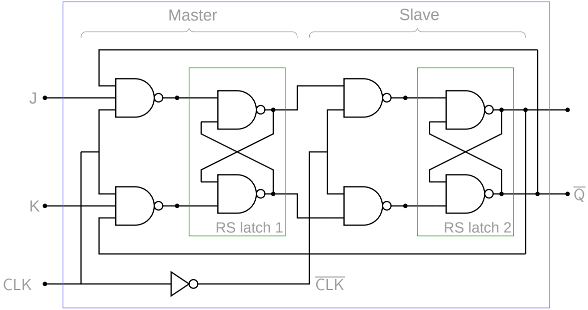


JK flip-flop (Master-Slave)



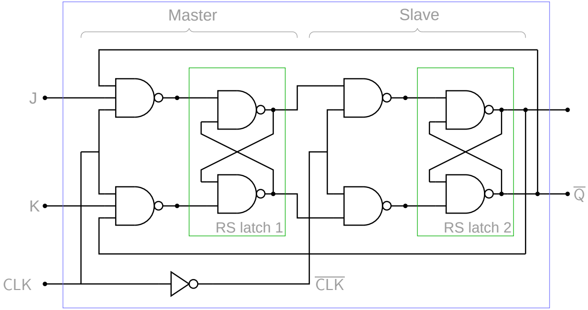
* When CLK goes high, only the first latch is affected; the second latch retains its previous value (because $\overline{\text{CLK}} = 0 \rightarrow R_2 = S_2 = 1$).

JK flip-flop (Master-Slave)



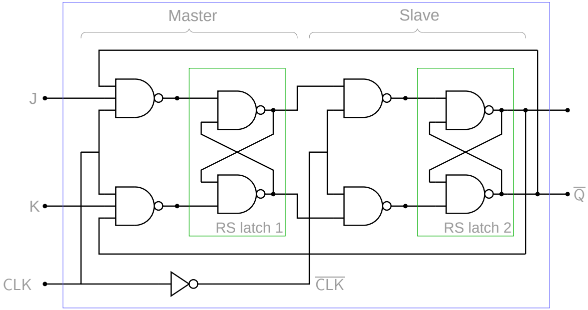
* When CLK goes high, only the first latch is affected; the second latch retains its previous value (because $\overline{\text{CLK}} = 0 \rightarrow R_2 = S_2 = 1$).
* When CLK goes low, the output of the first latch (Q_1) is retained (since $R_1 = S_1 = 1$), and Q_1 can now affect Q.

JK flip-flop (Master-Slave)



* When CLK goes high, only the first latch is affected; the second latch retains its previous value (because $\overline{\text{CLK}} = 0 \rightarrow R_2 = S_2 = 1$).
* When CLK goes low, the output of the first latch (Q_1) is retained (since $R_1 = S_1 = 1$), and Q_1 can now affect Q.
* In other words, the effect of any changes in J and K appears at the output Q only when CLK makes a transition from 1 to 0.
  This is therefore a negative edge-triggered flip-flop.

JK flip-flop (Master-Slave)



CLK	J	K	Q_{n+1}
$\downarrow$	0	0	Q_n
$\downarrow$	0	1	0
$\downarrow$	1	0	1
$\downarrow$	1	1	$\overline{Q_n}$

* When CLK goes high, only the first latch is affected; the second latch retains its previous value (because $\overline{\text{CLK}} = 0 \rightarrow R_2 = S_2 = 1$).
* When CLK goes low, the output of the first latch (Q_1) is retained (since $R_1 = S_1 = 1$), and Q_1 can now affect Q.
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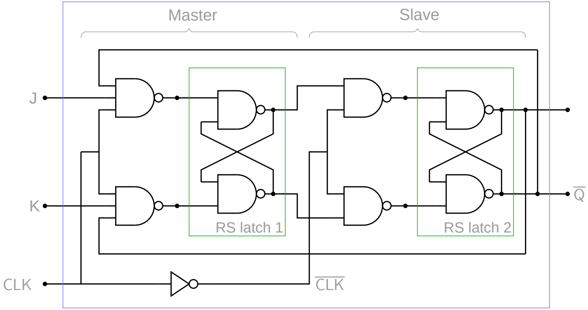
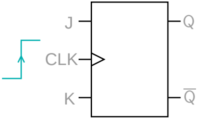


CLK	J	K	Q_{n+1}
↓	0	0	Q_n
↓	0	1	0
↓	1	0	1
↓	1	1	$\overline{Q_n}$

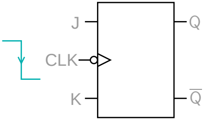
* When CLK goes high, only the first latch is affected; the second latch retains its previous value (because $\overline{\text{CLK}} = 0 \rightarrow R_2 = S_2 = 1$).
* When CLK goes low, the output of the first latch (Q_1) is retained (since $R_1 = S_1 = 1$), and Q_1 can now affect Q.
* In other words, the effect of any changes in J and K appears at the output Q only when CLK makes a transition from 1 to 0.
  This is therefore a negative edge-triggered flip-flop.
* Note that, unlike the RS NAND latch which does not allow one of the combinations of R and S (viz., $R = S = 0$), the JK flip-flop allows all four combinations.

JK flip-flop



CLK	J	K	Q_{n+1}
$\uparrow$	0	0	Q_n
$\uparrow$	0	1	0
$\uparrow$	1	0	1
$\uparrow$	1	1	$\overline{Q_n}$

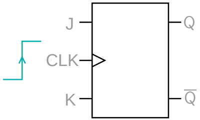
positive edge−triggered JK flip−flop



CLK	J	K	Q_{n+1}
$\downarrow$	0	0	Q_n
$\downarrow$	0	1	0
$\downarrow$	1	0	1
$\downarrow$	1	1	$\overline{Q_n}$

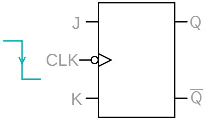
negative edge−triggered JK flip−flop

JK flip-flop



CLK	J	K	Q_{n+1}
$\uparrow$	0	0	Q_n
$\uparrow$	0	1	0
$\uparrow$	1	0	1
$\uparrow$	1	1	$\overline{Q_n}$

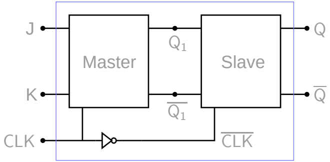
positive edge−triggered JK flip−flop

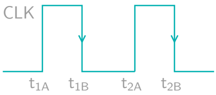


CLK	J	K	Q_{n+1}
$\downarrow$	0	0	Q_n
$\downarrow$	0	1	0
$\downarrow$	1	0	1
$\downarrow$	1	1	$\overline{Q_n}$

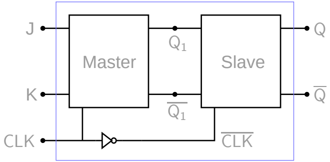
negative edge−triggered JK flip−flop

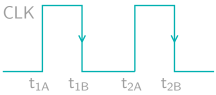
* Both negative (e.g., 74101) and positive (e.g., 7470) edge-triggered JK flip-flops are available as ICs.





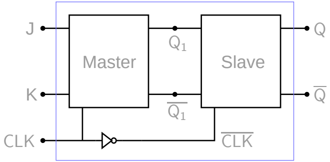
Consider a negative edge-triggered JK flip-flop.

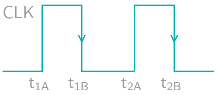




Consider a negative edge-triggered JK flip-flop.

* As seen earlier, when CLK is high (i.e., $t_{1A} < t < t_{1B}$, etc.), the input J and K determine the Master latch output Q_1.
  During this time, *no change* is visible at the flip-flop output Q.





Consider a negative edge-triggered JK flip-flop.

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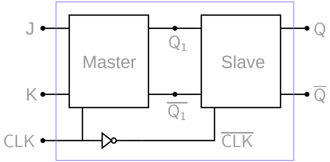
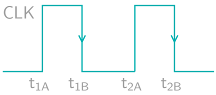
* When the clock goes low, the Slave flip-flop becomes active, making it possible for Q to change.

JK flip-flop





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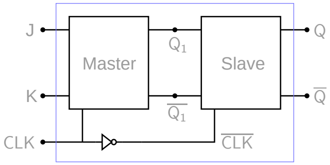
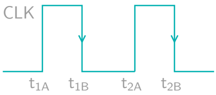
  During this time, *no change* is visible at the flip-flop output Q.
* When the clock goes low, the Slave flip-flop becomes active, making it possible for Q to change.
* In short, although the flip-flop output Q can only change *after* the active edge, (t_{1B}, t_{2B}, etc.), the new Q value is determined by J and K values just *before* the active edge.

JK flip-flop





Consider a negative edge-triggered JK flip-flop.

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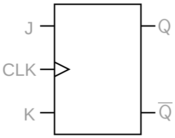
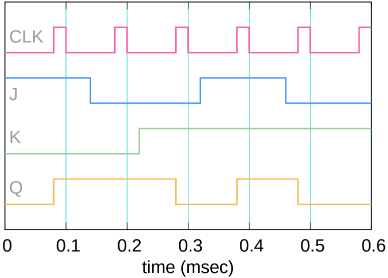
  During this time, *no change* is visible at the flip-flop output Q.
* When the clock goes low, the Slave flip-flop becomes active, making it possible for Q to change.
* In short, although the flip-flop output Q can only change *after* the active edge, (t_{1B}, t_{2B}, etc.), the new Q value is determined by J and K values just *before* the active edge.
  This is a very important point!

JK flip-flop

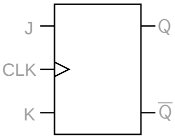


CLK	J	K	Q_{n+1}
↑	0	0	Q_n
↑	0	1	0
↑	1	0	1
↑	1	1	$\overline{Q_n}$

positive edge−triggered JK flip−flop

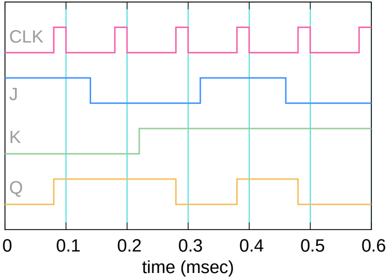


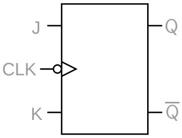
JK flip-flop



CLK	J	K	Q_{n+1}
$\uparrow$	0	0	Q_n
$\uparrow$	0	1	0
$\uparrow$	1	0	1
$\uparrow$	1	1	$\overline{Q_n}$

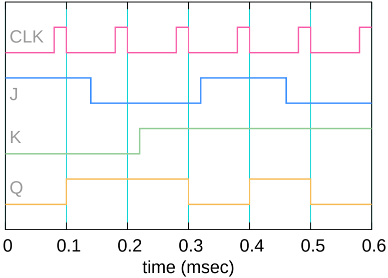
positive edge−triggered JK flip−flop





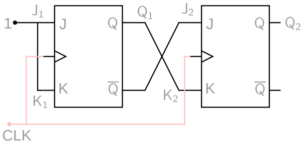
CLK	J	K	Q_{n+1}
$\downarrow$	0	0	Q_n
$\downarrow$	0	1	0
$\downarrow$	1	0	1
$\downarrow$	1	1	$\overline{Q_n}$

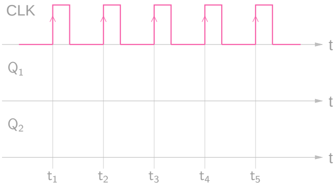
negative edge−triggered JK flip−flop



JK flip-flop

$J_1 = K_1 = 1$. Assume $Q_1 = Q_2 = 0$ initially.





JK flip-flop

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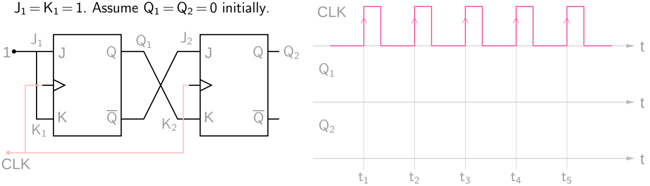

* Since $J_1 = K_1 = 1$, Q_1 toggles after every active clock edge.

JK flip-flop

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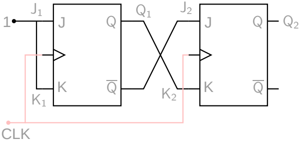

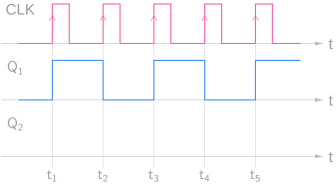

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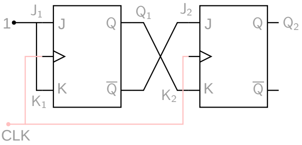
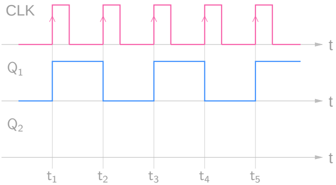
JK flip-flop

$J_1 = K_1 = 1$. Assume $Q_1 = Q_2 = 0$ initially.





* Since $J_1 = K_1 = 1$, Q_1 toggles after every active clock edge.
* $J_2 = \overline{Q_1}$, $K_2 = Q_1$. We need to look at J_2 and K_2 values *just before* the active edge, to determine the next value of Q_2.

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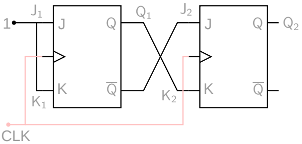

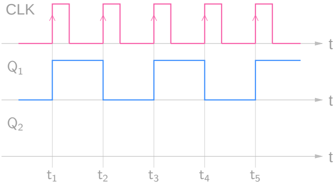

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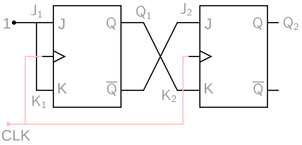

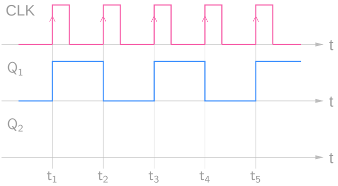

t	$J_2\,(t=t_k^-)$	$K_2\,(t=t_k^-)$	$Q_2\,(t=t_k^+)$
t_1	1	0	1
t_2	0	1	0
t_3	1	0	1
t_4	0	1	0
t_5	1	0	1

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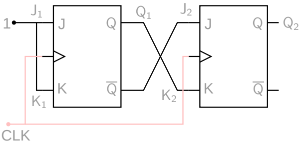

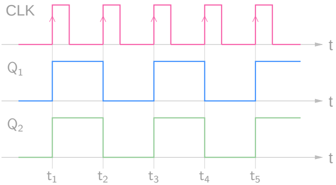

t	$J_2\,(t = t_k^-)$	$K_2\,(t = t_k^-)$	$Q_2\,(t = t_k^+)$
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t_2	0	1	0
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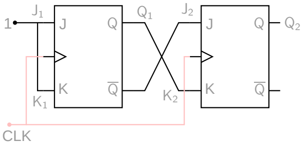

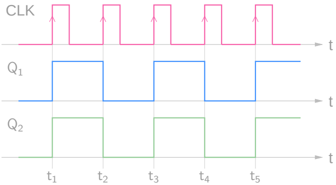

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* It is convenient to construct a table listing J_2 and K_2 to figure out the next Q_2 value.
* Note that the circuit is not doing much, apart from taxing our minds!
  But hold on, some useful circuits will appear soon.