

COMSM1302

Overview of Computer Architecture

Lecture 5

Storage



In this lecture

Foundations

- Data representation, logic, Boolean algebra.

Building blocks

- Transistors, transistor based logic, simple devices, **storage**.

Modules

- Memory, simple controllers, FSMs, processors and execution.

Programming

- Machine code, assembly, high-level languages, compilers.

Wrap-up

- Operating systems, energy aware computing.



Previous lecture

- We can do **basic arithmetic** with a **bunch of NAND gates**!

Imagine if we could **store** the results of that arithmetic.

Today we learn how.



Combinatorial vs. sequential logic



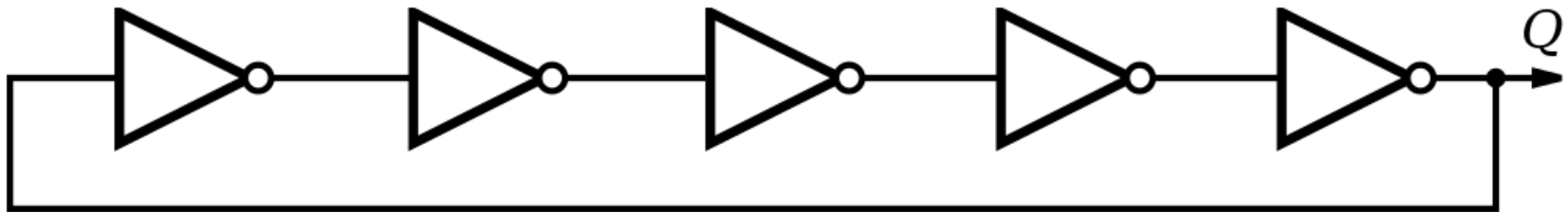
- So far, everything we have done is **combinatorial** logic.
 - Input signals are combined in various ways to produce output signals.
 - By **connecting blocks together** we can build more complex circuits.
- If we **change inputs**, the **outputs change** shortly afterwards.
 - Signals take some (very small) time to propagate.



🔥 Ring Oscillator

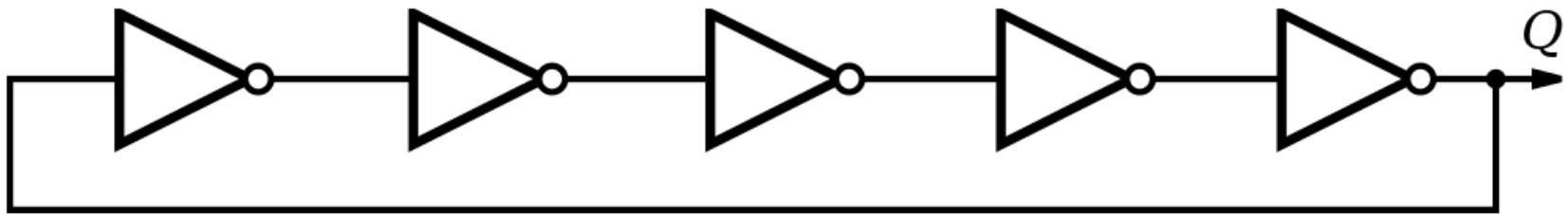


What does the below device do?



🔥 Ring Oscillator

What does the below device do?



A **ring oscillator** is a device composed of an **odd number of NOT gates** in a **ring**. The output oscillates between two voltage levels, representing true and false. The NOT gates, or inverters, in a ring oscillator are **connected in a chain** and the output of the last inverter is fed back into the first, forming a circular chain, or a ring.

Can a circular chain composed of an even number of inverters be used as a ring oscillator?

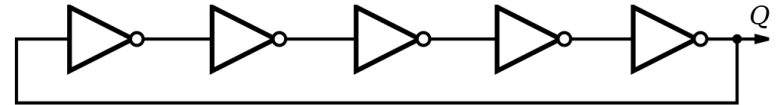


Ring Oscillator

- The output oscillates between 1 and 0.
- How fast?

$$F_{osc} = \frac{1}{N \times 2D_{inv}}$$

- N is the **number of inverters**.



- D_{inv} – the **inverter delay**, is determined by:
 - Wire length
 - Device size
 - Voltage
 - Temperature
 - Material
 - ...



Combinatorial vs. sequential logic

- What if we wanted to perform the following arithmetic:

$$Y = 24 + 15 + 100$$

- But we can only add two numbers together at a time.
- We can create a sequence:

$$X = 24 + 15$$

$$Y = X + 100$$

- We want to take the **output** of our **first addition** and make it one of the **inputs** to our **second addition**.

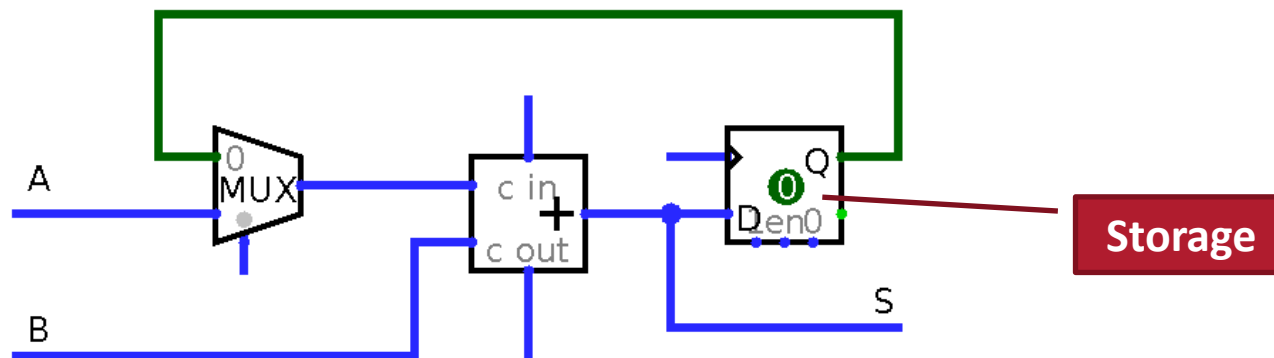
It's not *quite* that simple.



🔥 Combinatorial vs. sequential logic

- To enforce a sequence reliably, we can:
 - Store result values
 - Control when values are stored
- This allows us to build a *sequential* system, combining **storage** and **combinatorial logic**.

Below: A *prototype* we'll explain, develop and complete!

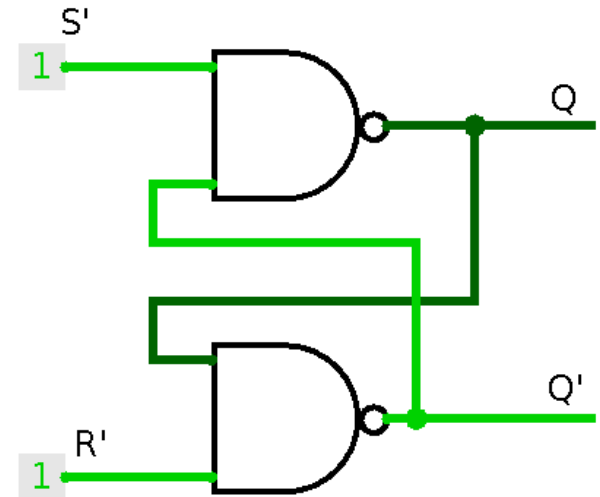


SR-latch



μ

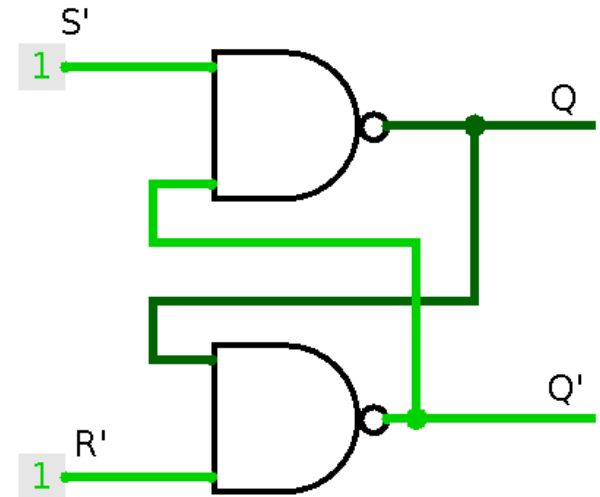
- Two NAND gates
- Input signals are **active-low**.
 - Denoted with top bar or tick, e.g. \overline{S} or S'
 - active high/low tells you what logic value is necessary for you to activate an input
 - **active high** is active when set to 1
 - **active low** is active when set to 0
- Start from $S' = R' = 1$



SR-latch



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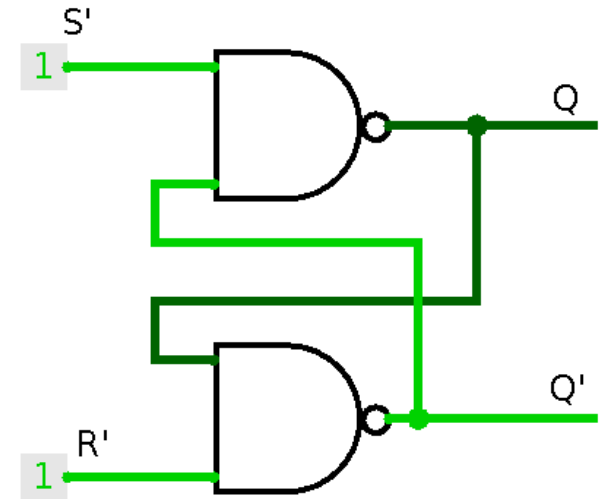


SR-latch



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- **Set the latch**
 - $S' = 0$



A	B	A NAND B
1	1	0
1	0	1
0	1	1
0	0	1

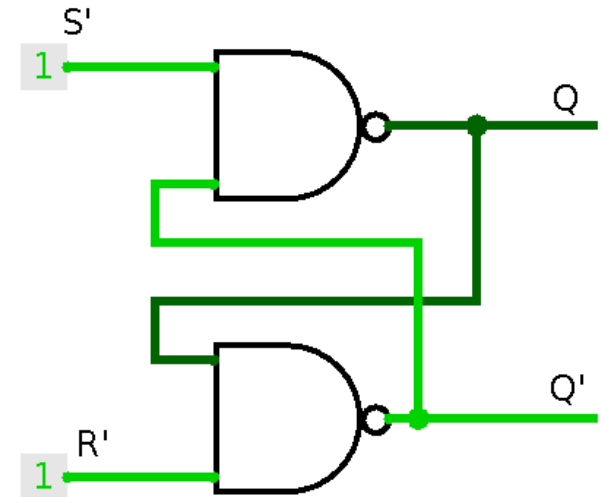


SR-latch



μ

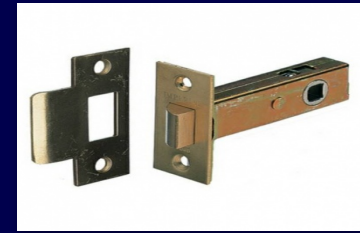
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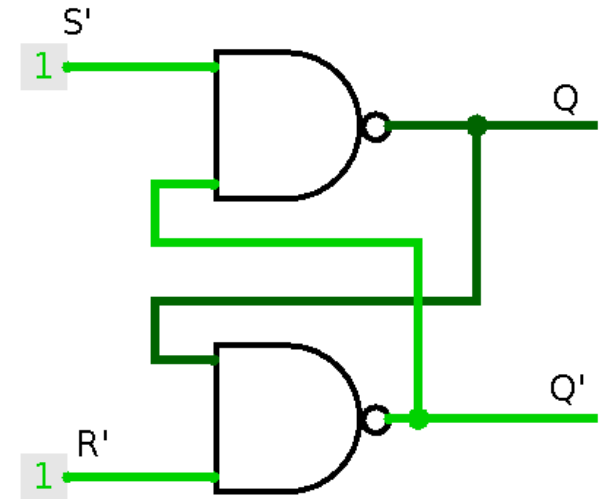
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- Start from $S' = R' = 1$
- **Set the latch**
 - $S' = 0$
- **Reset the latch**
 - $R' = 0$

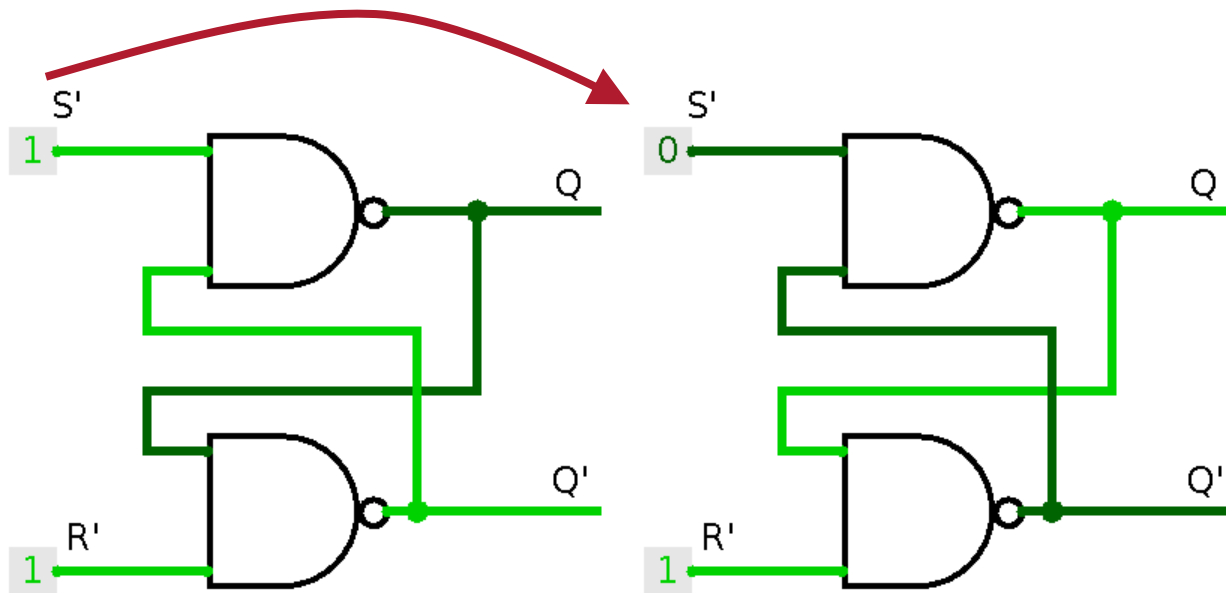


A	B	A NAND B
1	1	0
1	0	1
0	1	1
0	0	1



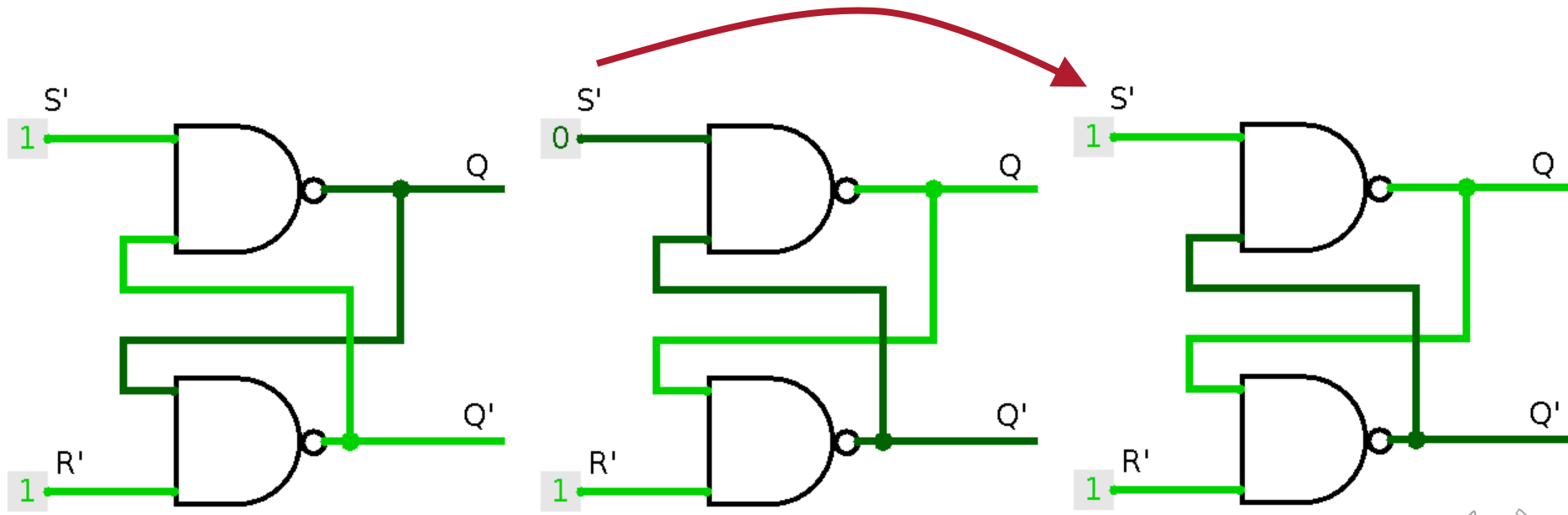
🔥 Setting the latch

- When S' transitions to low, Q is **set high** (and Q' its inverse).



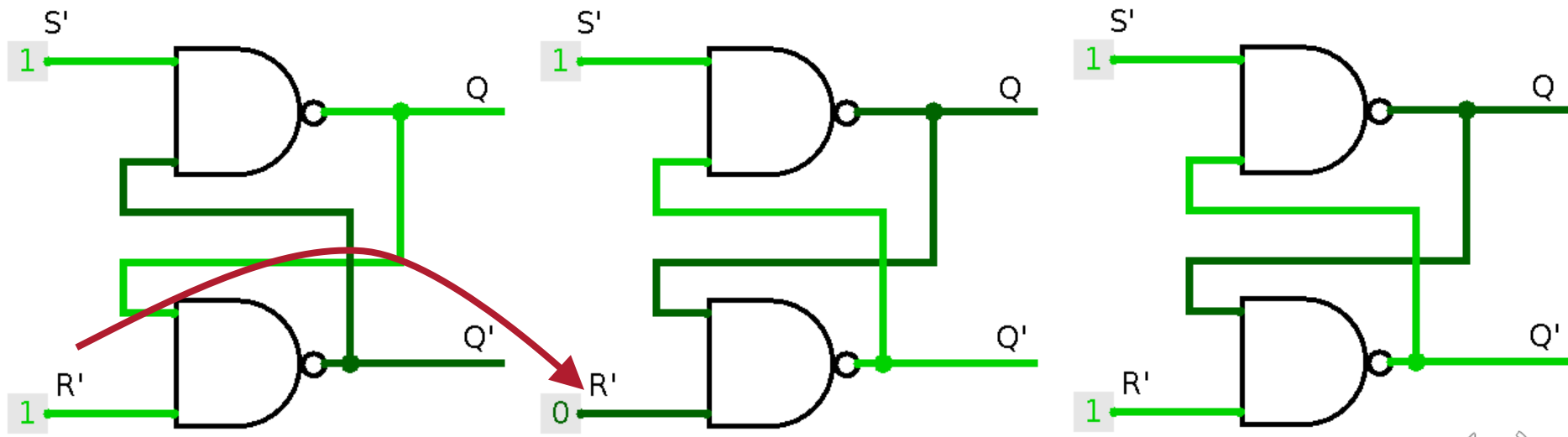
🔥 Setting the latch

- When S' transitions to low, Q is **set high** (and Q' its inverse).
- Upon S' returning to high... Q retains the same high value.



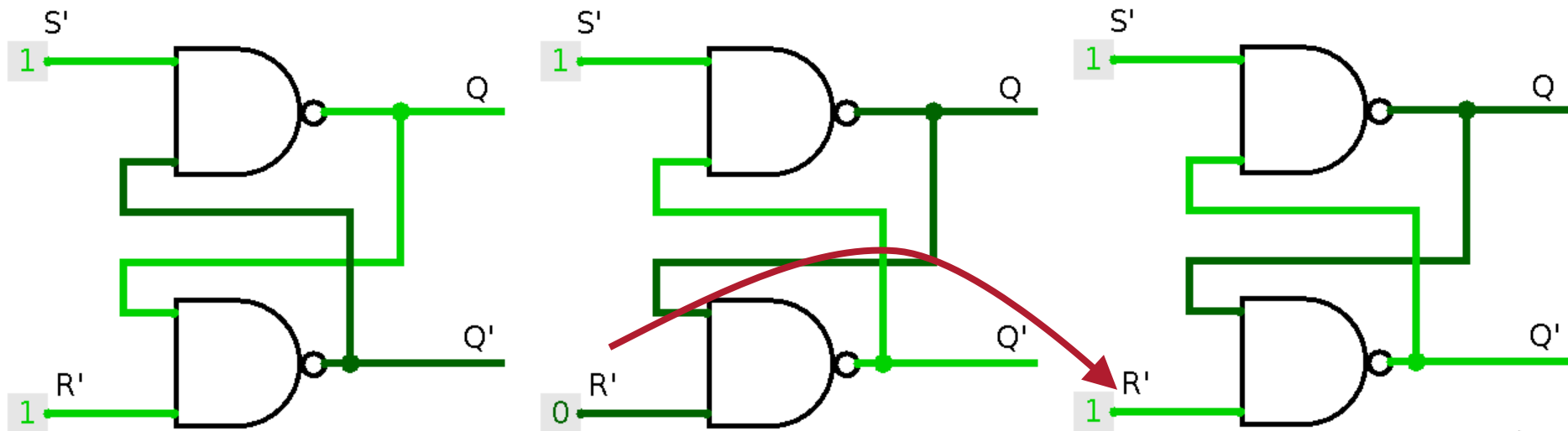
🔥 Resetting the latch

- When R' transitions to low, Q is **reset low**.



🔥 Resetting the latch

- When R' transitions to low, Q is **reset low**.
- Upon R' returning to high... Q retains the same low value.

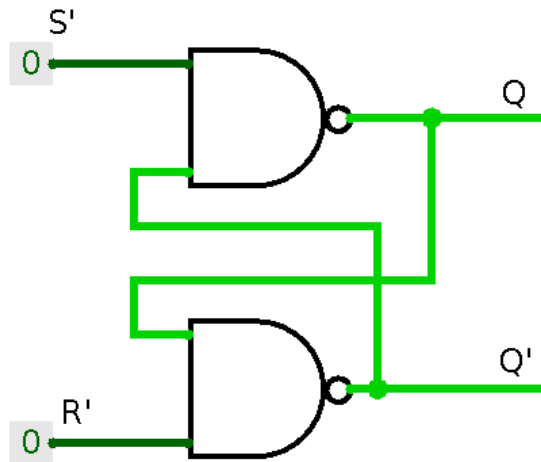


SR inputs

A	B	A NAND B
1	1	0
1	0	1
0	1	1
0	0	1

S'	R'	Q
1	1	Hold
1	0	0
0	1	1
0	0	

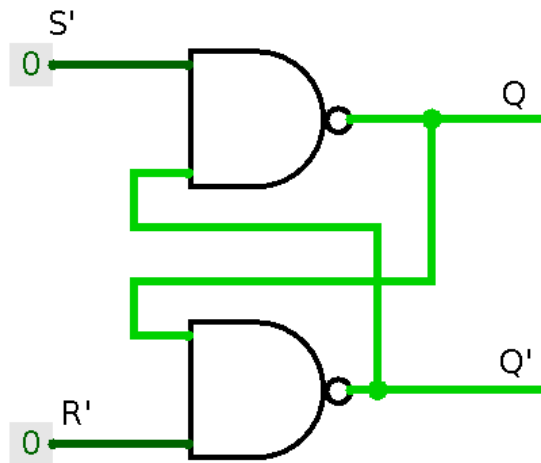
- There are **three valid** combinations of S' and R' for the SR NAND latch.



SR inputs

A	B	A NAND B
1	1	0
1	0	1
0	1	1
0	0	1

S'	R'	Q
1	1	Hold
1	0	0
0	1	1
0	0	Not allowed

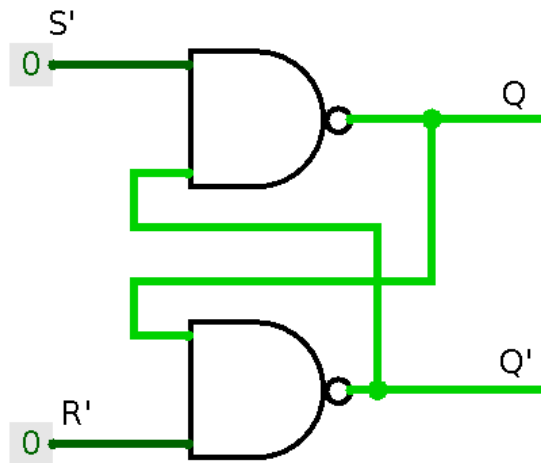


- There are **three valid** combinations of S' and R' for the SR NAND latch.
- Both S' and R' should **not be active** (low) together.

SR inputs

A	B	A NAND B
1	1	0
1	0	1
0	1	1
0	0	1

S'	R'	Q
1	1	Hold
1	0	0
0	1	1
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Why?

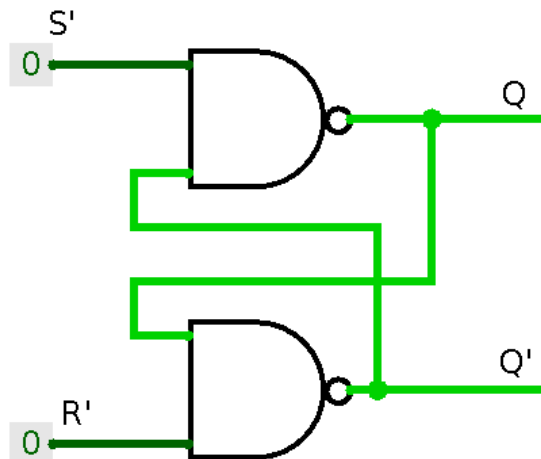


SR inputs

A	B	A NAND B
1	1	0
1	0	1
0	1	1
0	0	1

S'	R'	Q	Q'
1	1	Q_prev	Q'_prev
1	0	0	1
0	1	1	0
0	0		

- If both S' and R' were active at the same time, then the output ...



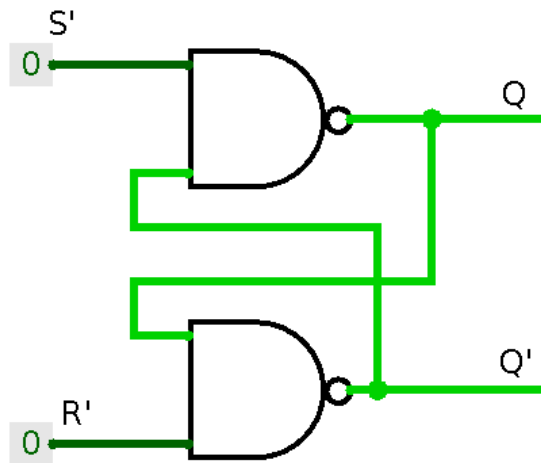
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S'	R'	Q	Q'
1	1	Q_prev	Q'_prev
1	0	0	1
0	1	1	0
0	0		

- If both S' and R' were active at the same time, then the output **would not make any sense**.

$$S' = 0, R' = 0, Q = Q'$$



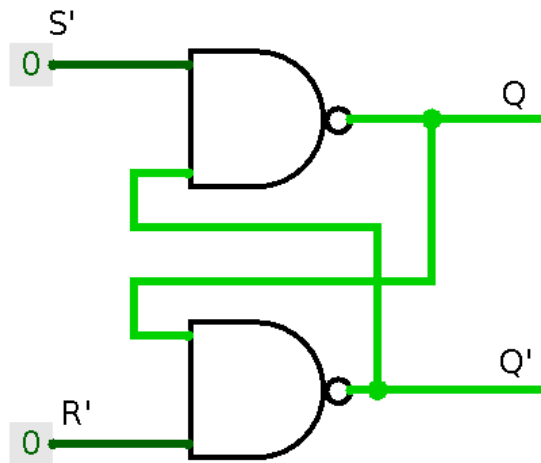
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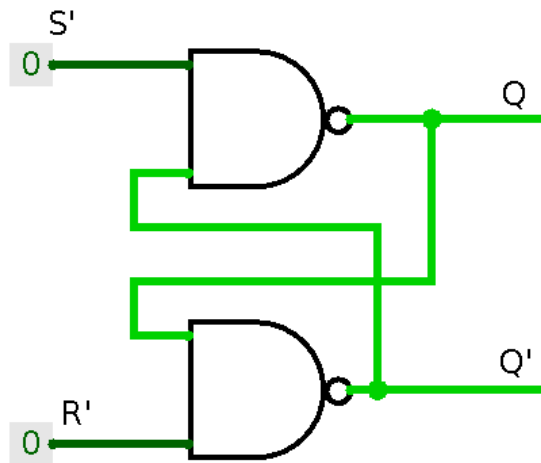
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1	0	0	1
0	1	1	0
0	0	not allowed	

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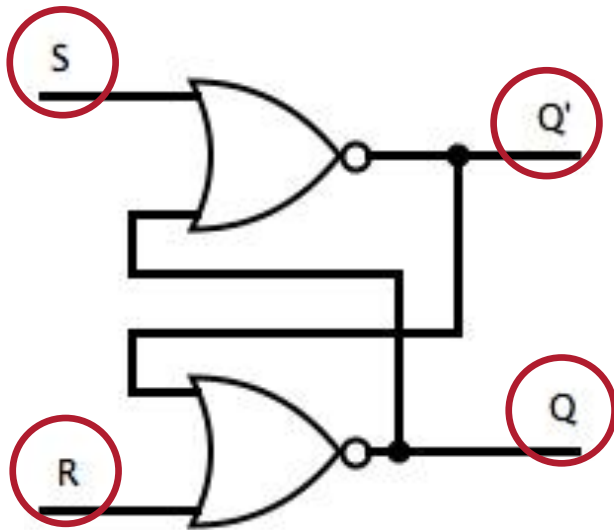
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🔥 Different latch types

- We have seen an SR (Set-Reset) latch using NAND.
 - An SR latch can also be built from NOR gates.

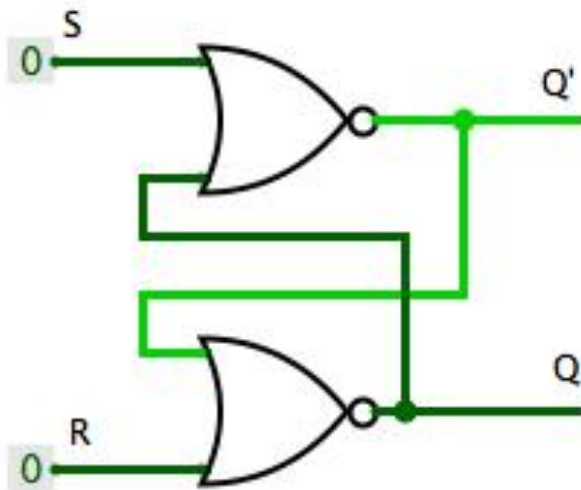
How does this work?



🔥 SR latch with NOR gates

A	B	A NOR B
1	1	0
1	0	0
0	1	0
0	0	1

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How does this work?

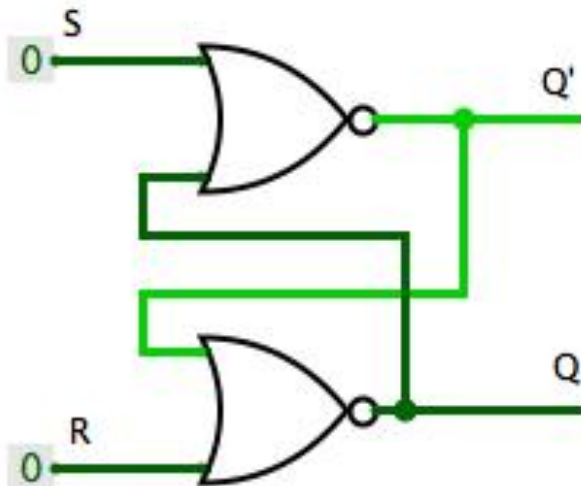
S	R	Q	Q_next	Q'_next
0	0	0		

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1	1	0
1	0	0
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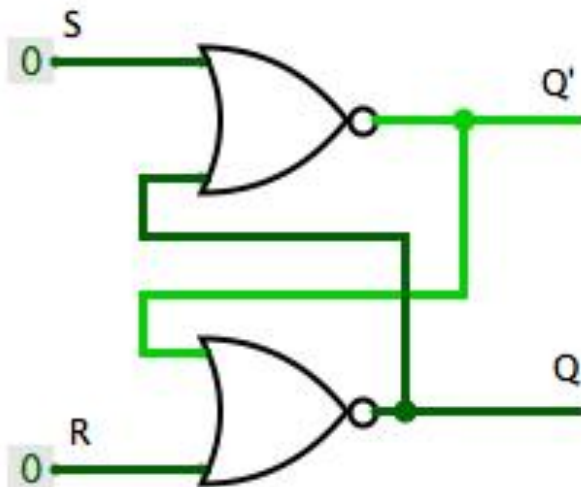


S	R	Q	Q_next	Q'_next
0	0	0	0	1

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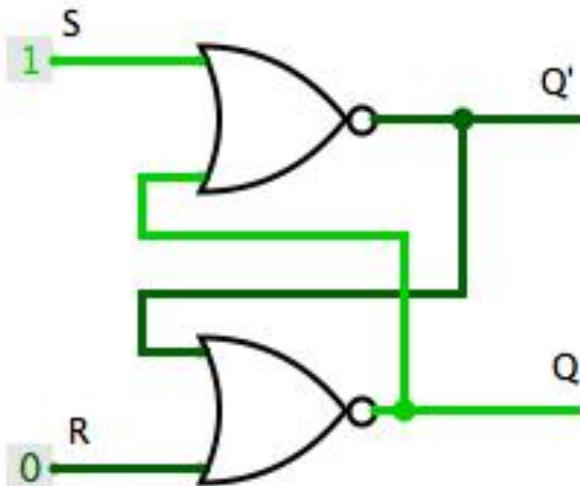
S	R	Q	Q_next	Q'_next
0	0	0	0	1
1	0	0		

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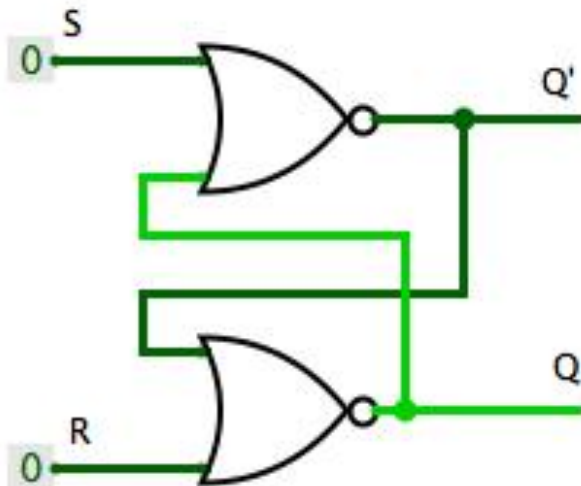
S	R	Q	Q_next	Q'_next
0	0	0	0	1
1	0	0	1	0

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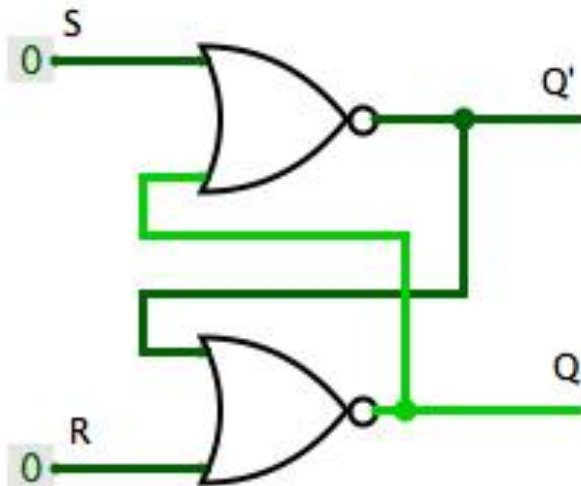
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1	0	0	1	0
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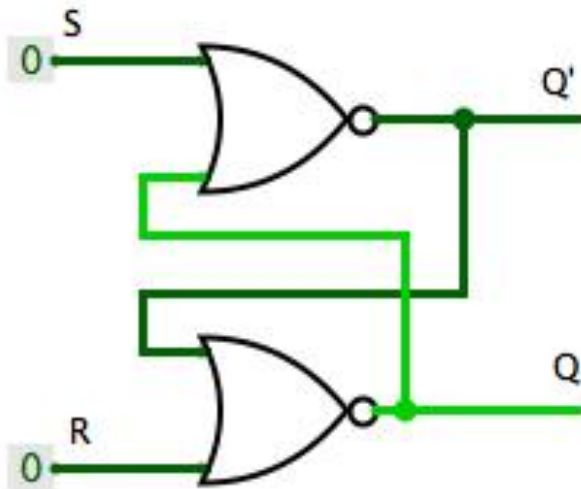
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1	0	0	1	0
0	0	1	1	0

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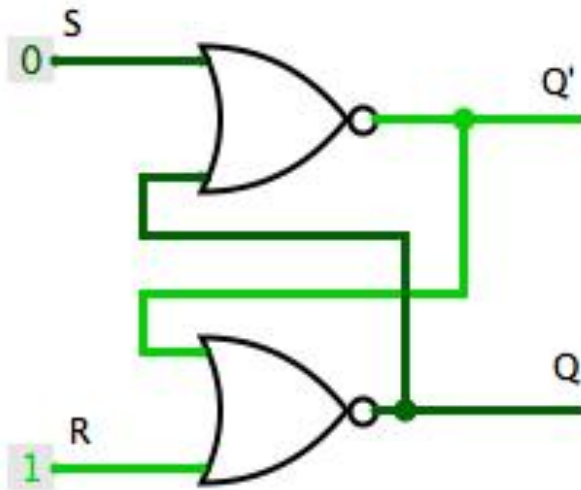
S	R	Q	Q_next	Q'_next
0	0	0	0	1
1	0	0	1	0
0	0	1	1	0
0	1	1		

🔥 SR latch with NOR gates

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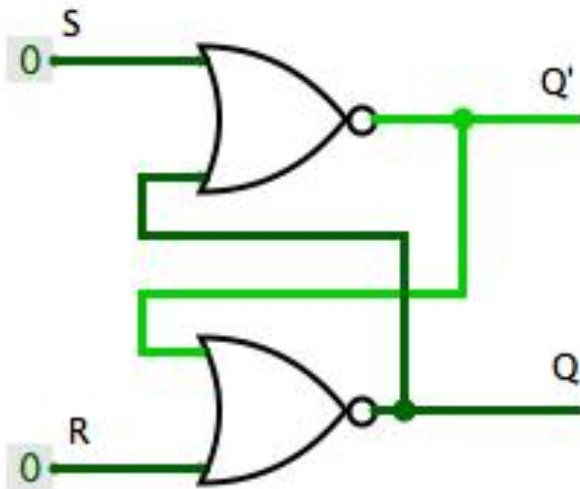
S	R	Q	Q_next	Q'_next
0	0	0	0	1
1	0	0	1	0
0	0	1	1	0
0	1	1	0	1

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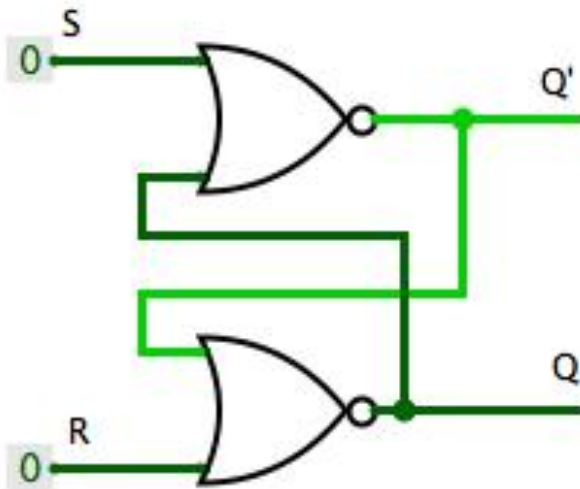
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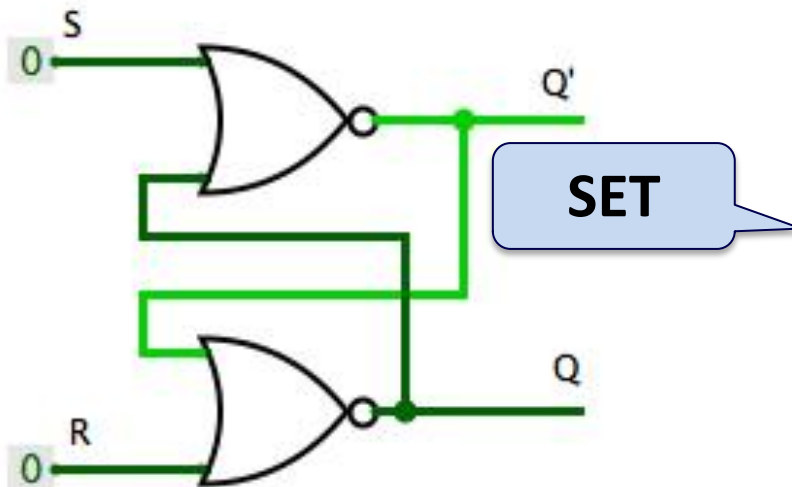
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0	0	0	0	1
1	0	0	1	0
0	0	1	1	0
0	1	1	0	1
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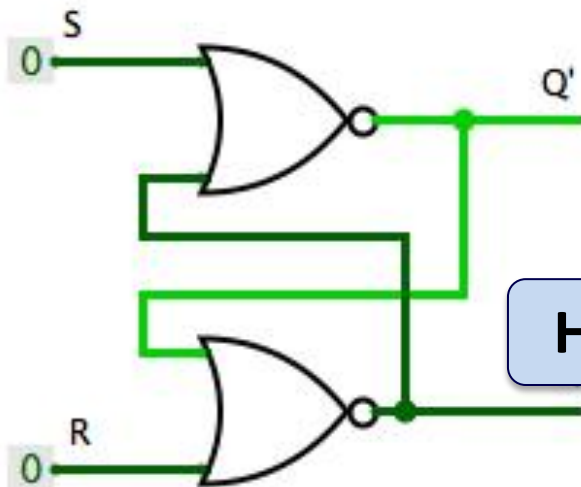
S	R	Q	Q_next	Q'_next
0	0	0	0	1
1	0	0	1	0
0	0	1	1	0
0	1	1	0	1
0	0	0	0	1

🔥 SR latch with NOR gates

A	B	A NOR B
1	1	0
1	0	0
0	1	0
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How does this work?



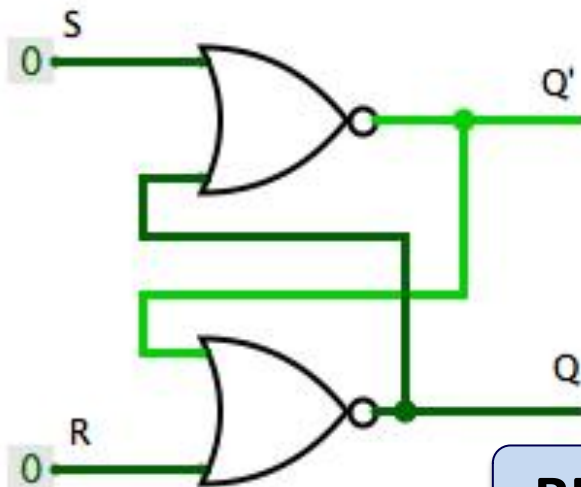
S	R	Q	Q_next	Q'_next
0	0	0	0	1
1	0	0	1	0
0	0	1	1	0
0	1	1	0	1
0	0	0	0	1

🔥 SR latch with NOR gates

A	B	A NOR B
1	1	0
1	0	0
0	1	0
0	0	1

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How does this work?



RESET

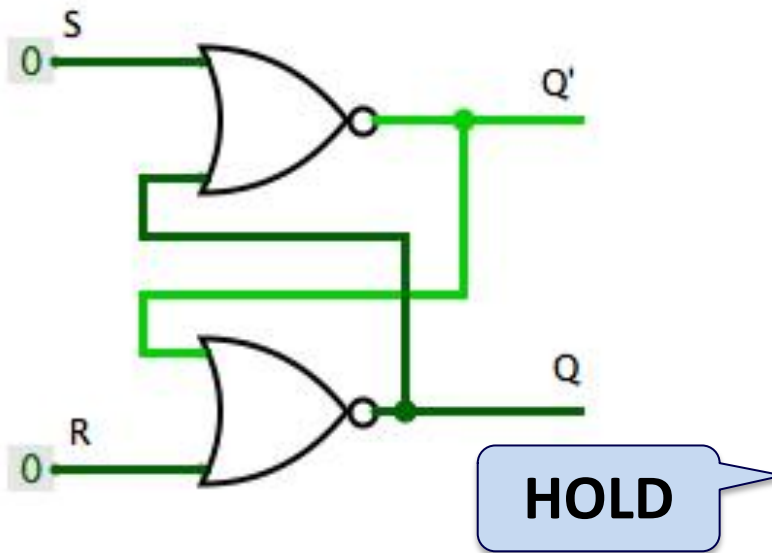
S	R	Q	Q_next	Q'_next
0	0	0	0	1
1	0	0	1	0
0	0	1	1	0
0	1	1	0	1
0	0	0	0	1

🔥 SR latch with NOR gates

A	B	A NOR B
1	1	0
1	0	0
0	1	0
0	0	1

- We have seen an SR (Set-Reset) latch using NAND.
 - An SR latch can also be built from NOR gates.

How does this work?

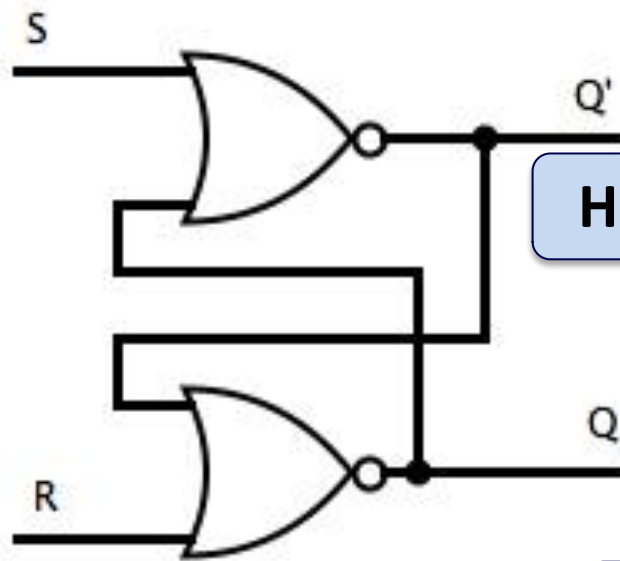


S	R	Q	Q_next	Q'_next
0	0	0	0	1
1	0	0	1	0
0	0	1	1	0
0	1	1	0	1
0	0	0	0	1

🔥 SR latch with NOR gates

A	B	A NOR B
1	1	0
1	0	0
0	1	0
0	0	1

- We have seen an SR (Set-Reset) latch using NAND.
 - An SR latch can also be built from NOR gates.



How does this work?

S	R	Q	Q'
0	0	Q_prev	Q'_prev
0	1	0	1
1	0	1	0
1	1		

HOLD (points to the first row where S=0, R=0)

SET (points to the third row where S=1, R=0)

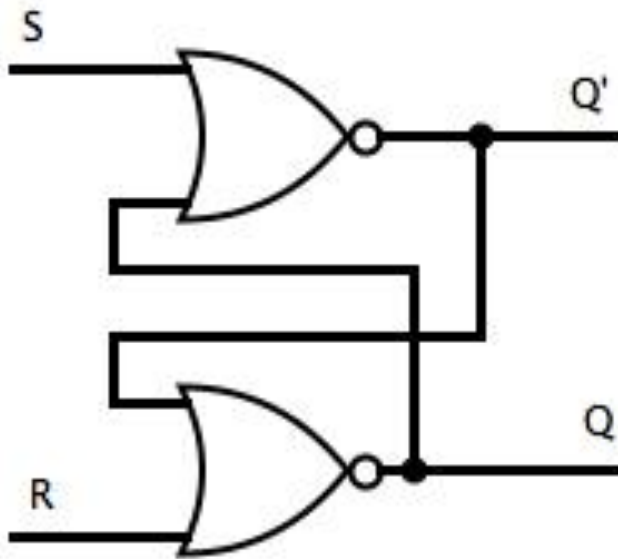
RESET (points to the second row where S=0, R=1)



🔥 SR latch with NOR gates

A	B	A NOR B
1	1	0
1	0	0
0	1	0
0	0	1

- We have seen an SR (Set-Reset) latch using NAND.
 - An SR latch can also be built from NOR gates.



How does this work?

S	R	Q	Q'
0	0	Q_prev	Q'_prev
0	1	0	1
1	0	1	0
1	1	not allowed	

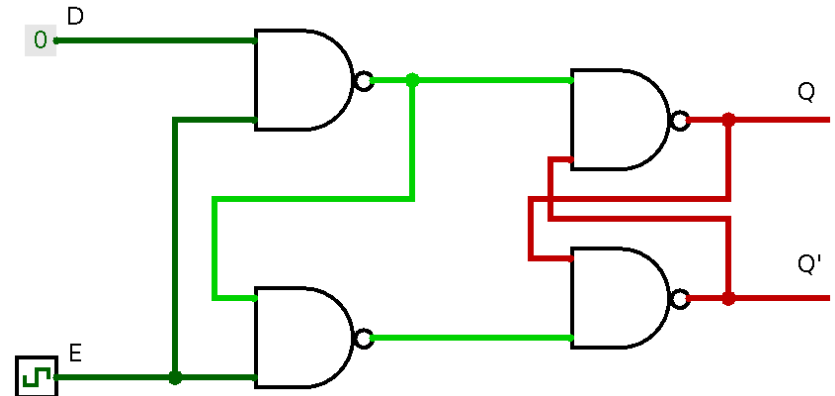
Different latch types

- SR (Set-Reset) latch
 - using NAND gates
 - using NOR gates
- Other latches:
 - **D latch**
 - JK latch

D-latch

- Instead of separate set/reset inputs, one input, **D**, specifies the **data** value, and a second input, **E**, **enables** propagation.
- If E is low, the previous output values are retained.

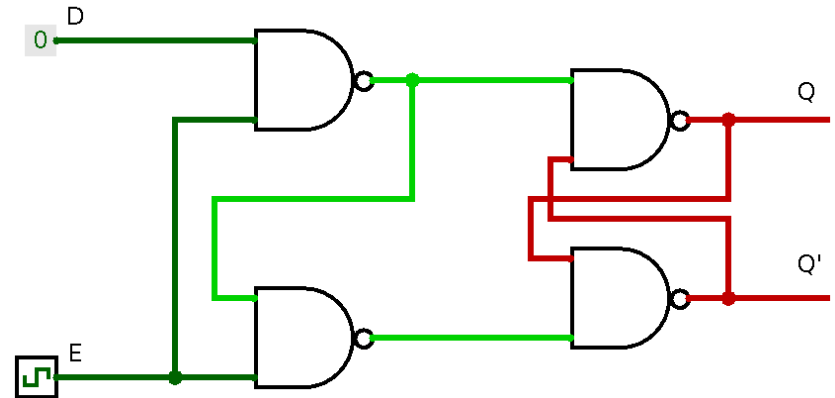
D	E	Q	Q'
0	0	Q_prev	Q'_prev
0	1	0	1
1	0	Q_prev	Q'_prev
1	1	1	0



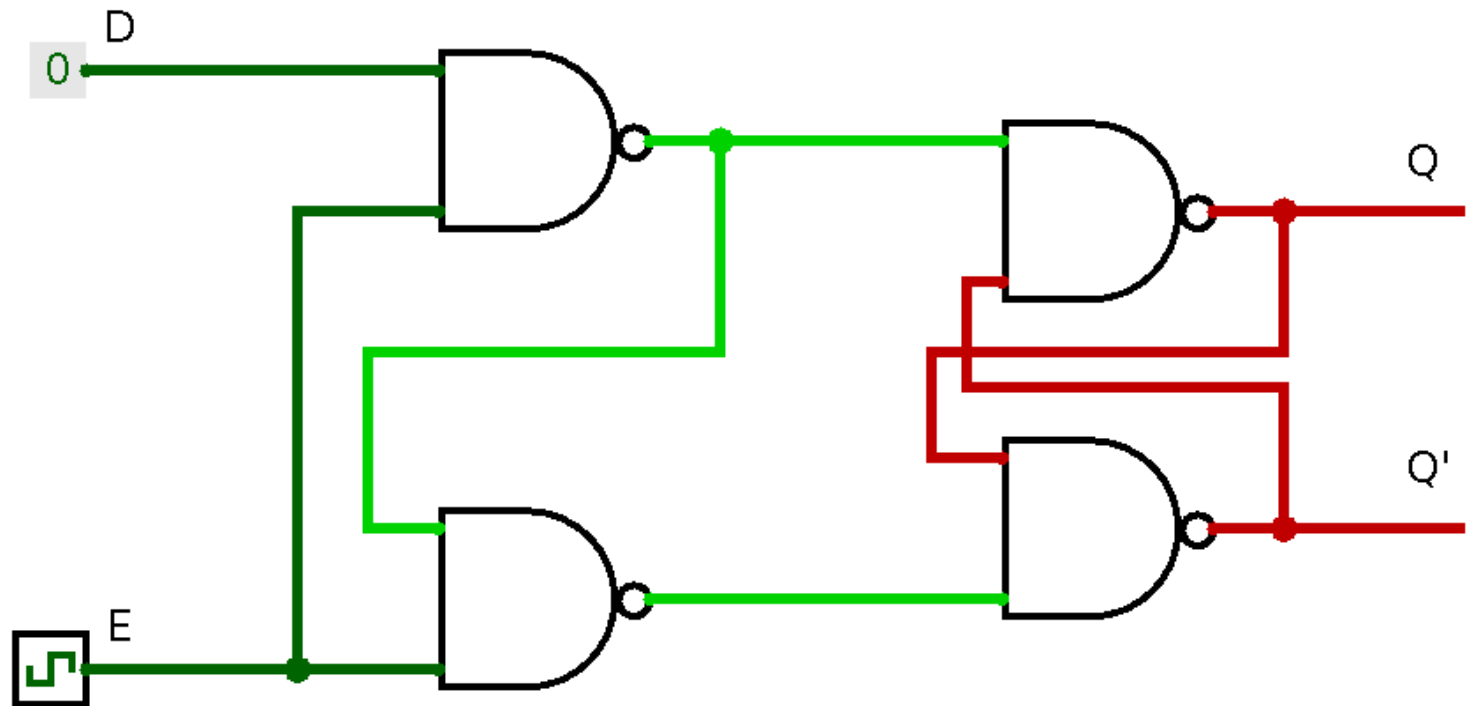
D-latch

- Instead of separate set/reset inputs, one input, **D**, specifies the **data** value, and a second input, **E**, **enables** propagation.
- If E is low, the previous output values are retained.
- No forbidden inputs.
 - Why?

D	E	Q	Q'
0	0	Q_prev	Q'_prev
0	1	0	1
1	0	Q_prev	Q'_prev
1	1	1	0



🔥 D-latch internal signals



🔥 D-latch truth table - I



D	E	\bar{S}	\bar{R}	Q	\bar{Q}
0	0				
0	1				
1	0				
1	1				



🔥 D-latch truth table - II



D	E	\bar{S}	\bar{R}	Q	\bar{Q}
0	0	1	1		
0	1	1	0		
1	0	1	1		
1	1	0	1		



🔥 D-latch truth table - II

S'	R'	Q	Q'
1	1	hold	
1	0	0	1
0	1	1	0
0	0	Not allowed	

D	E	\bar{S}	\bar{R}	Q	\bar{Q}
0	0	1	1		
0	1	1	0		
1	0	1	1		
1	1	0	1		

🔥 D-latch truth table - III

S'	R'	Q	Q'
1	1	hold	
1	0	0	1
0	1	1	0
0	0	Not allowed	

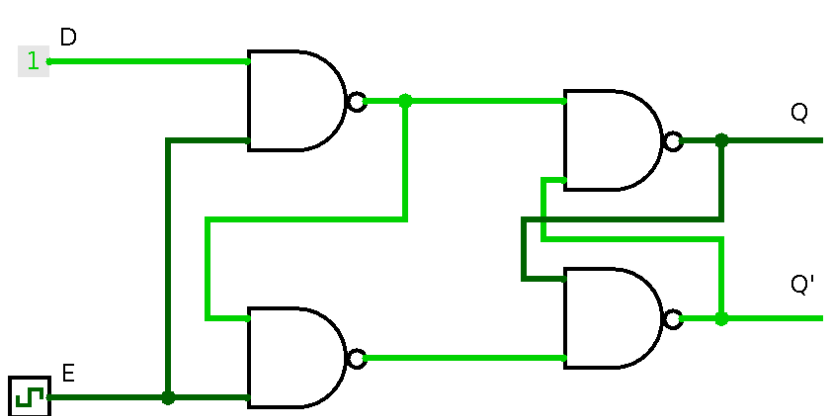
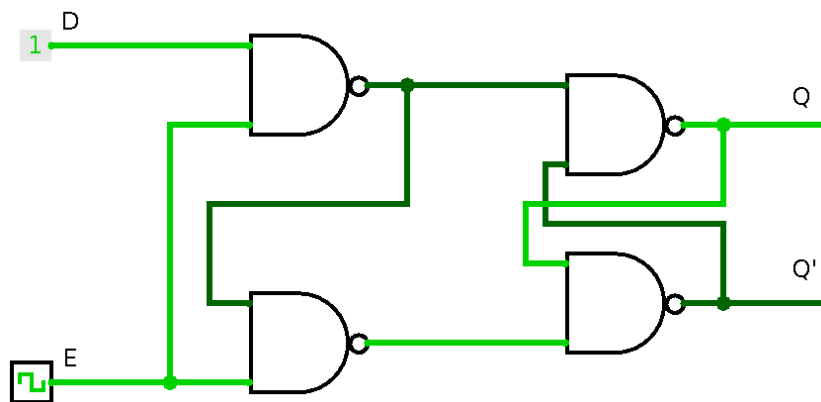
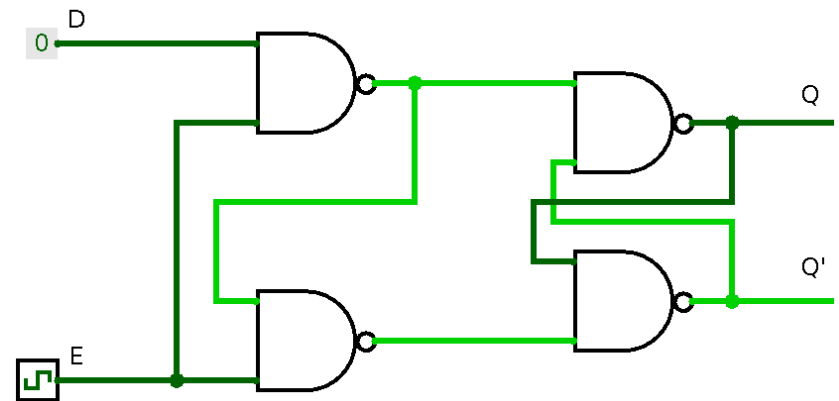
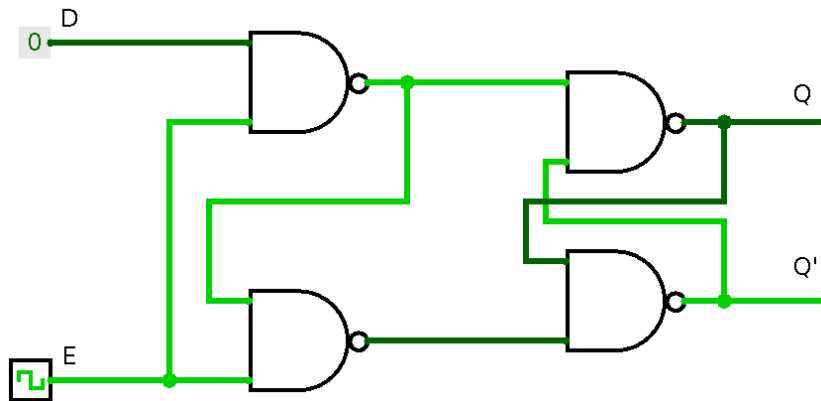
D	E	\bar{S}	\bar{R}	Q	\bar{Q}
0	0	1	1	hold	
0	1	1	0	0	1
1	0	1	1	hold	
1	1	0	1	1	0

🔥 D-latch truth table - III

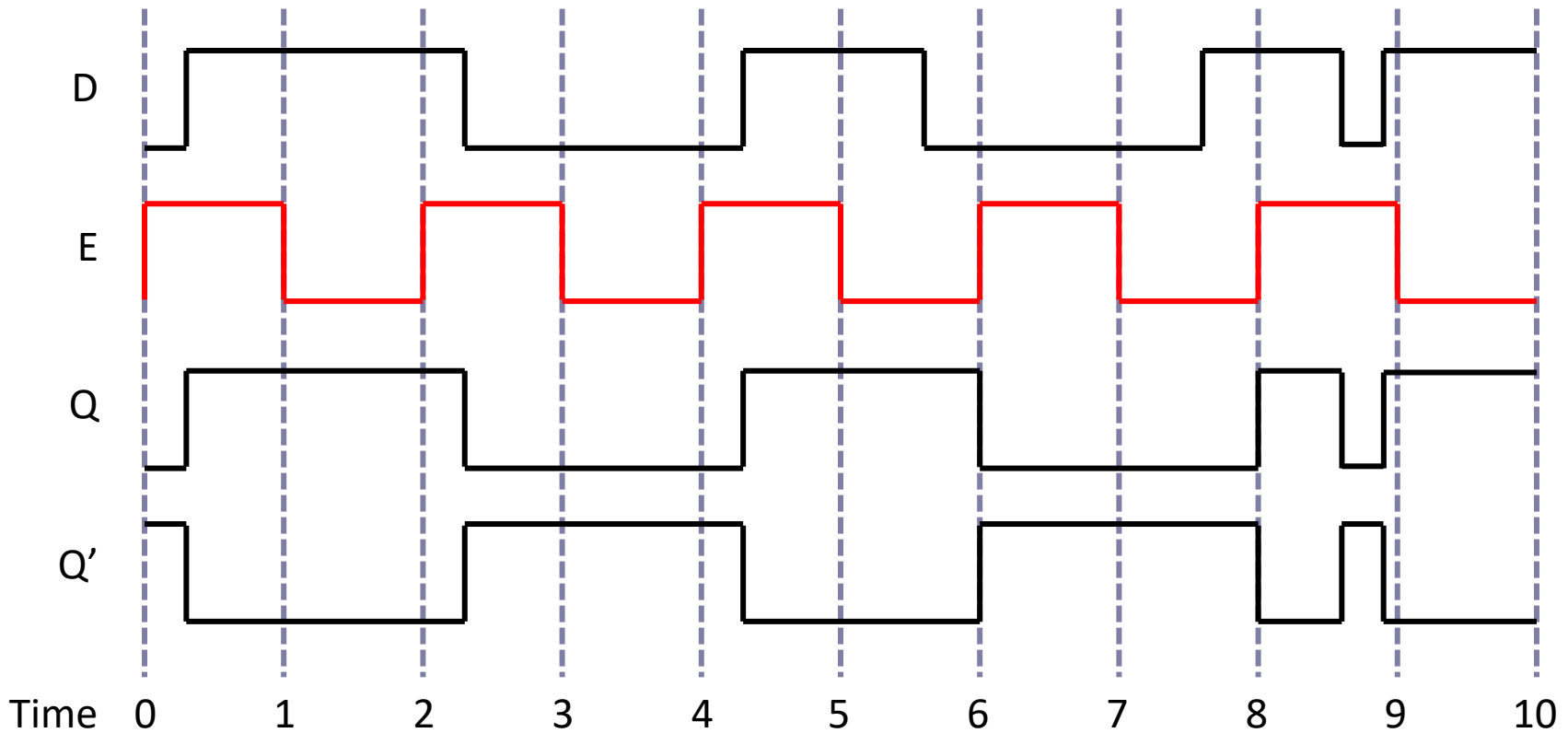
S'	R'	Q	Q'
1	1	hold	
1	0	0	1
0	1	1	0
0	0	Not allowed	

D	E	\bar{S}	\bar{R}	Q	\bar{Q}
0	0	1	1	hold	
0	1	1	0	0	1
1	0	1	1	hold	
1	1	0	1	1	0

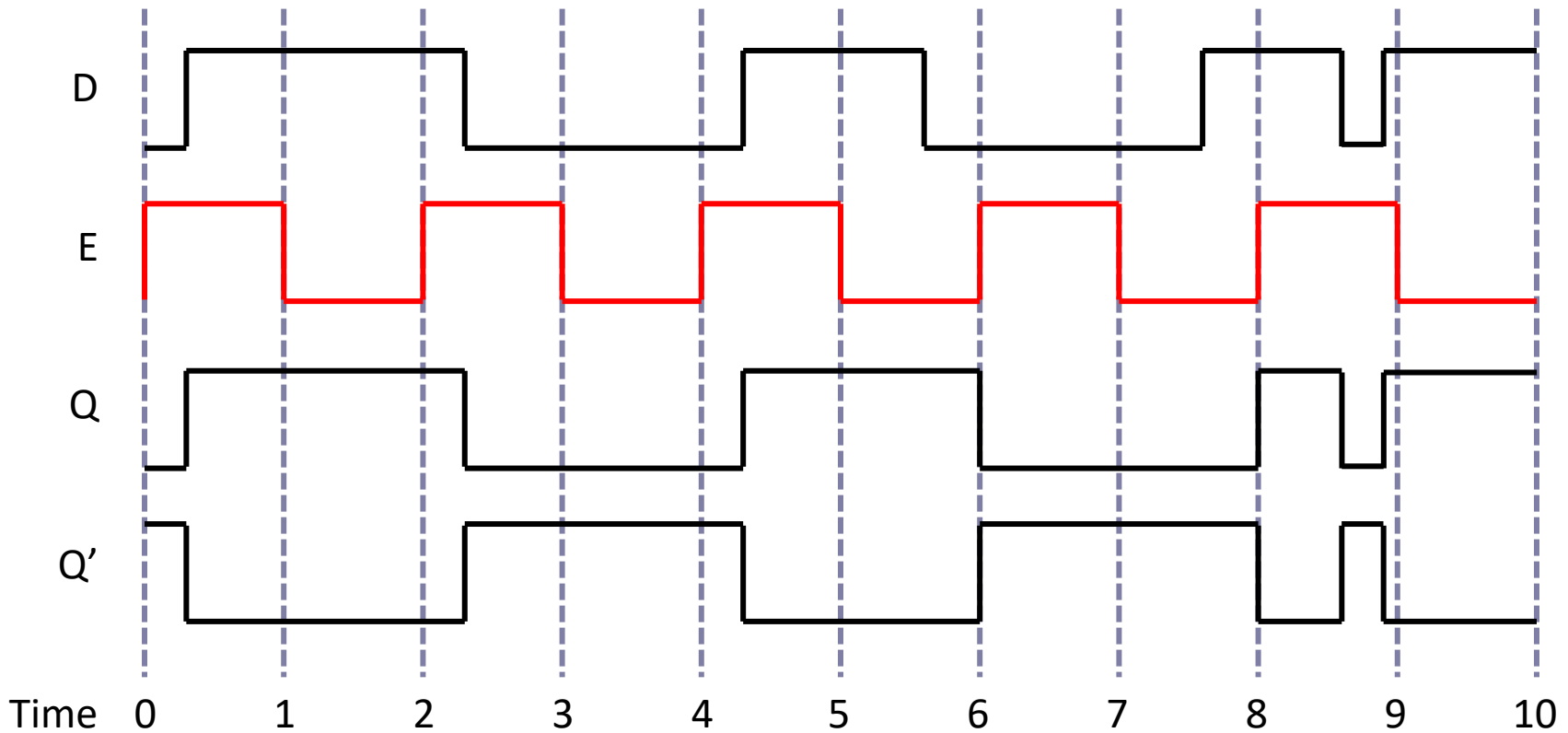
🔥 D-latch simulation



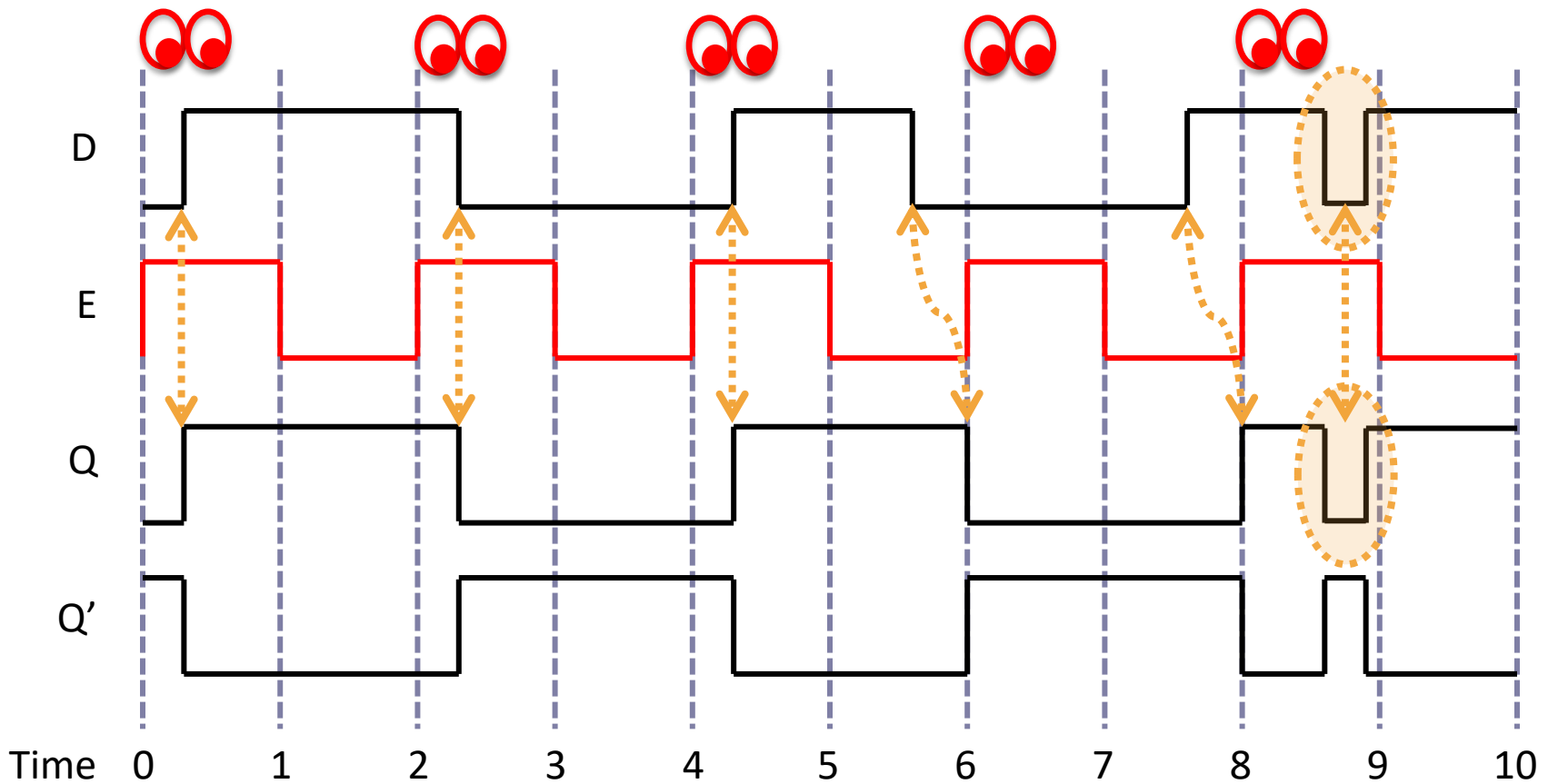
Waveform



Waveform

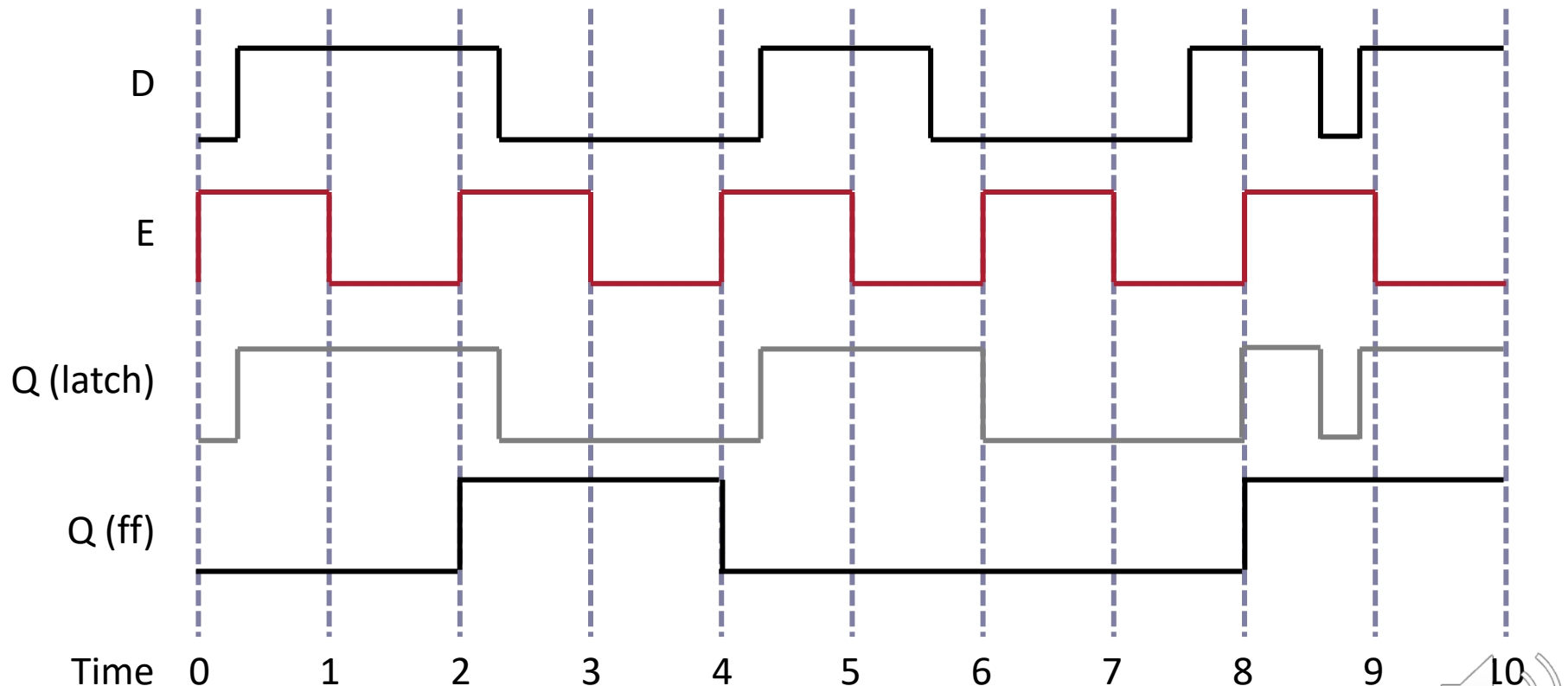


Waveform



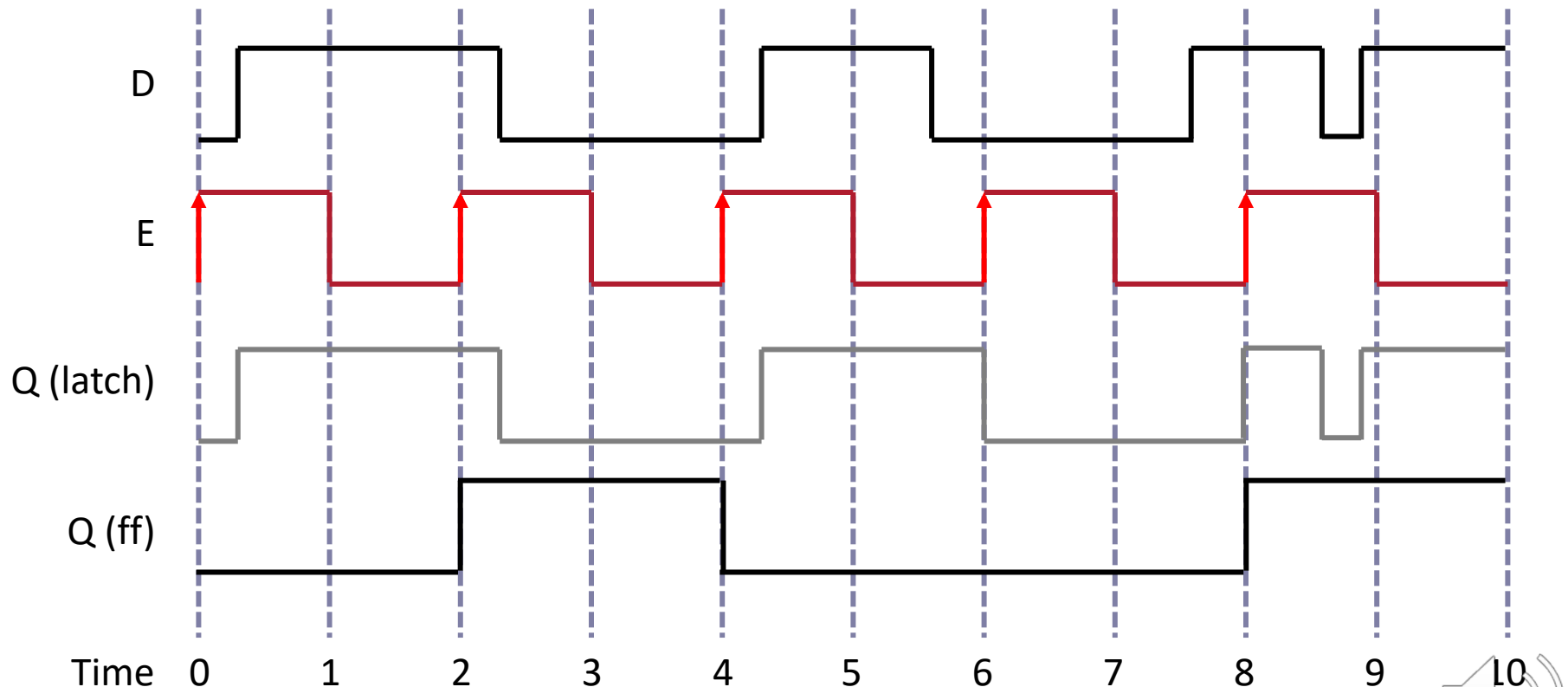
🔥 Level vs. edge triggering

- Latches are *level* sensitive.
- We can also build *edge* sensitive devices - Flip-flops



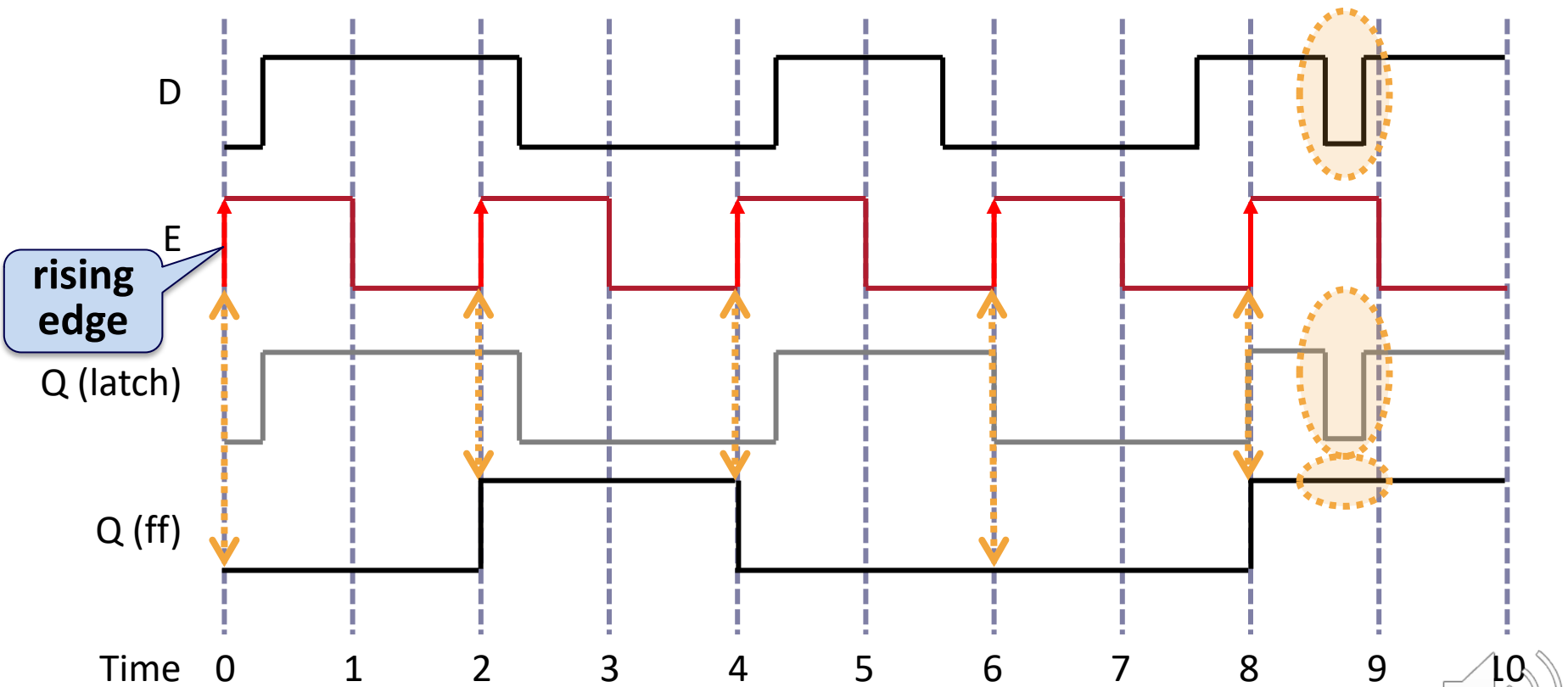
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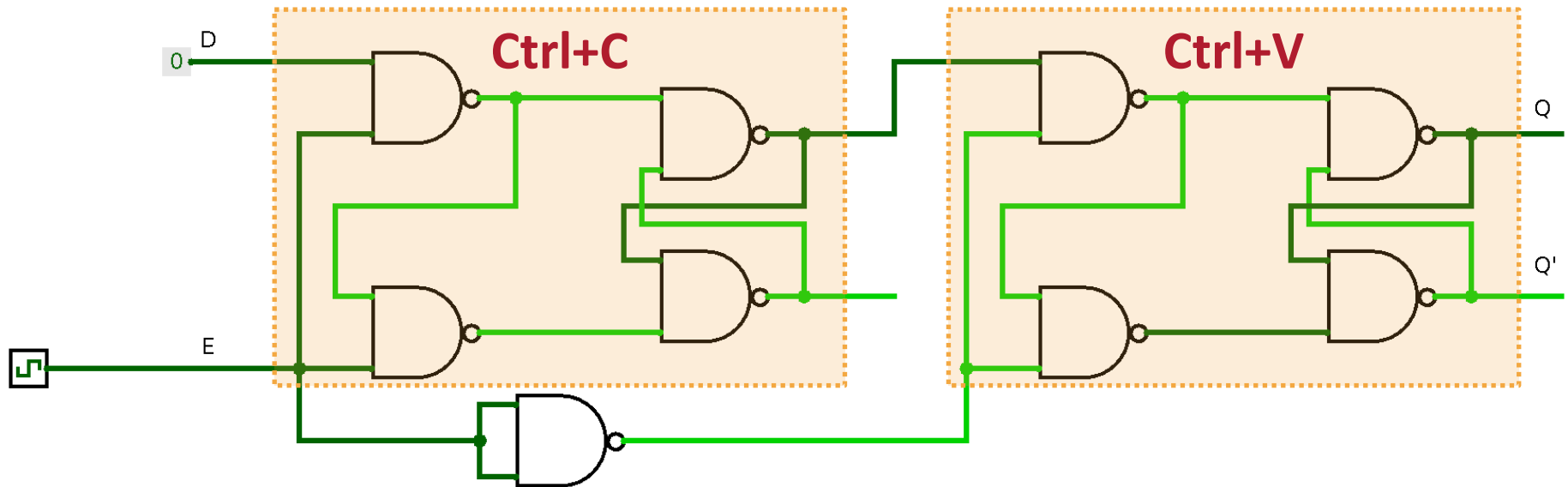


🔥 Level vs. edge triggering

- Latches are *level* sensitive.
- We can also build *edge* sensitive devices - Flip-flops



🔥 Building a D-type flip-flop



- Two D-type latches.
- Inverted enable signal to the second latch.

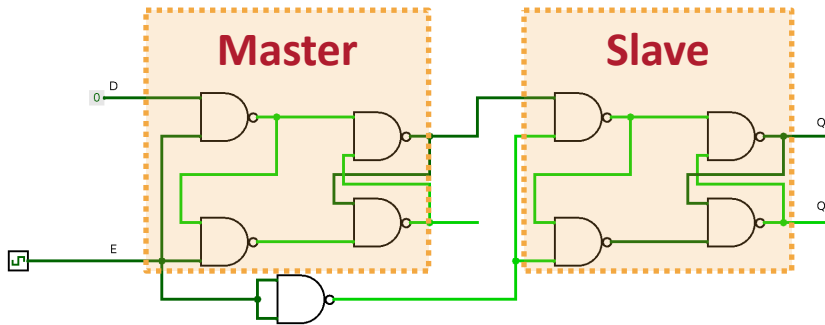
- 



🔥 D-type flip-flop transition



What have we built?

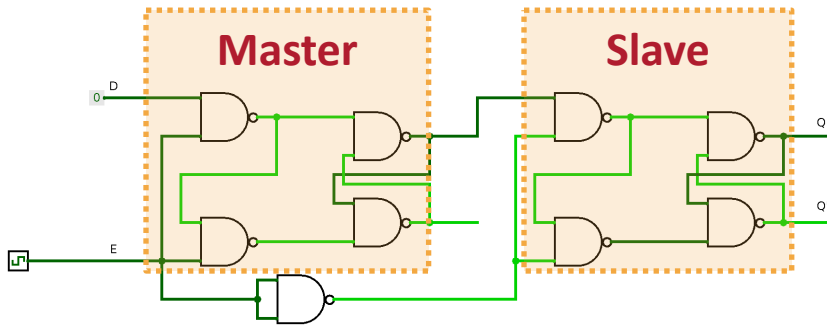


D	E >	Q
0	Rising	Q_prev
0	Falling	0
1	Rising	Q_prev
1	Falling	1



🔥 D-type flip-flop transition

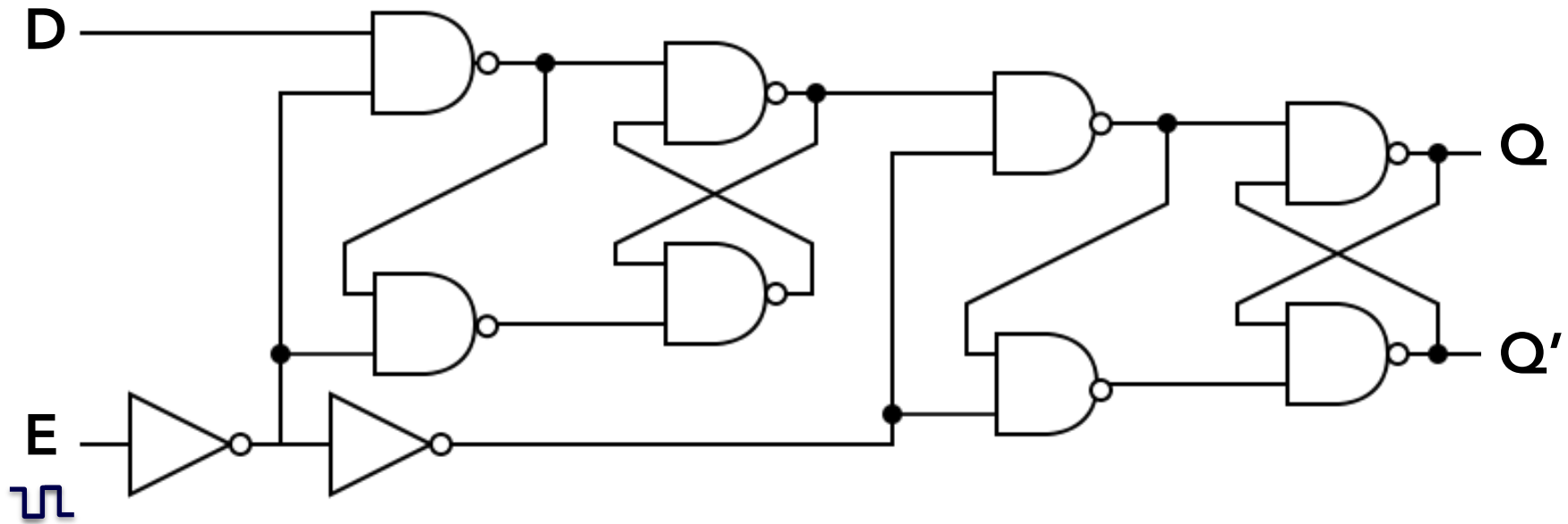
What have we built?



D	E >	Q
0	Rising	Q_prev
0	Falling	0
1	Rising	Q_prev
1	Falling	1

- We have built a **falling-edge** or **negative-edge triggered** flip-flop.
 - Note, the timing diagram earlier demonstrated *positive edge* behaviour.
- There is **more than one way** to make a D-type FF.
 - Explore different designs in the next NAND lab.
- How would we make it **positive-edge**?

🔥 How can we make it **positive-edge**?

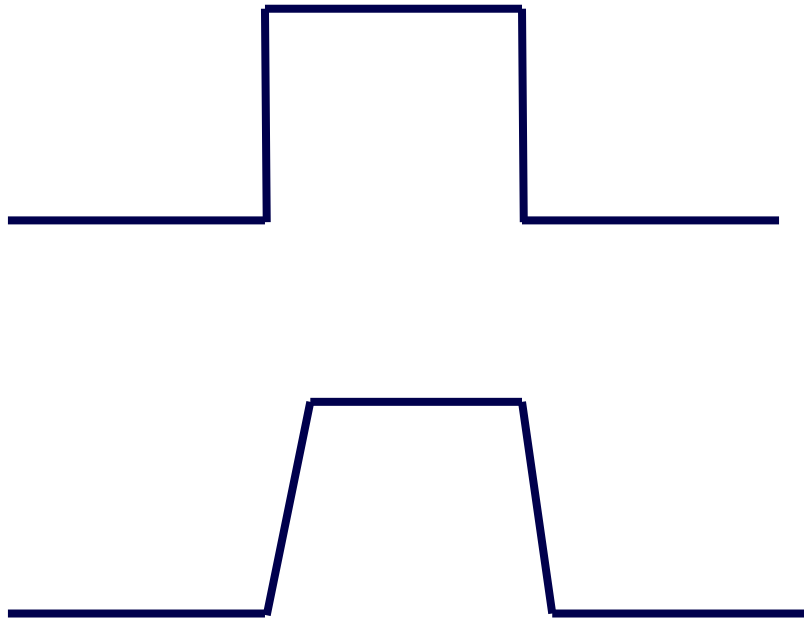


... by adding an inverter that negates the enable signal, E.

e?



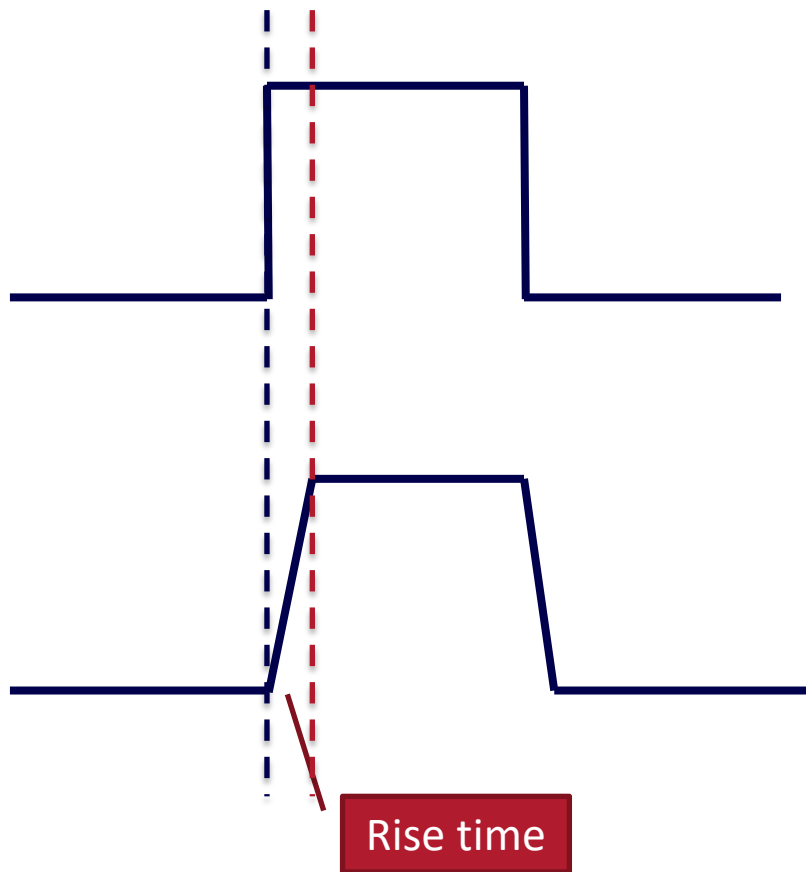
Timing



- We imagine signal transitions as instant.
- But they're not!
 - Wires and transistors have capacitances.
 - They have a charge/discharge time.
 - Remember the Ring Oscillator!

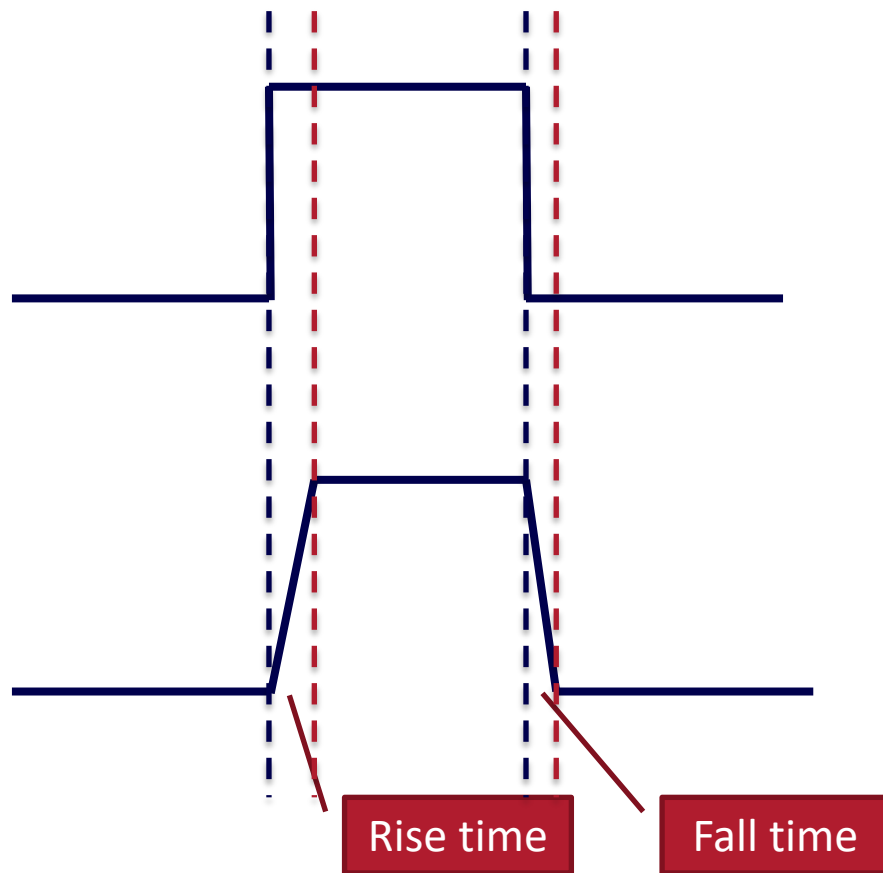


🔥 Timing: rise times



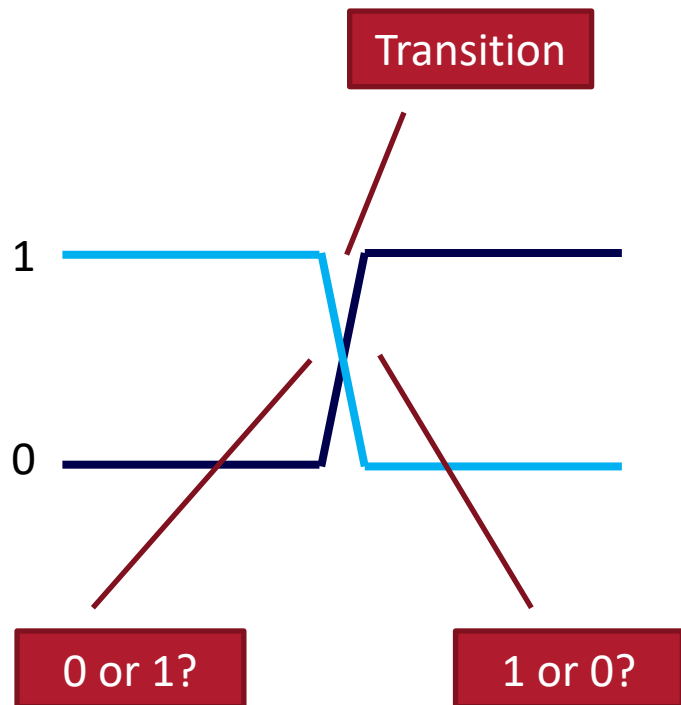
- We imagine signal transitions as instant.
- But they're not!
 - Wires and transistors have capacitances.
 - They have a charge/discharge time.
 - Remember the Ring Oscillator!
- This results in rise & fall times.

Timing: rise times and fall times



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- But they're not!
 - Wires and transistors have capacitances.
 - They have a charge/discharge time.
 - Remember the Ring Oscillator!
- This results in rise & fall times.

🔥 Timing: rise times and fall times



- When a signal changes there is a period of time where **we don't know its value**.
- So, if events (i.e. clock edges) happen at the wrong time, then **unexpected behaviour can occur**.

🔥 Timing constraints



*the
event*

Clock

t_{setup}

t_{hold}

D

Q

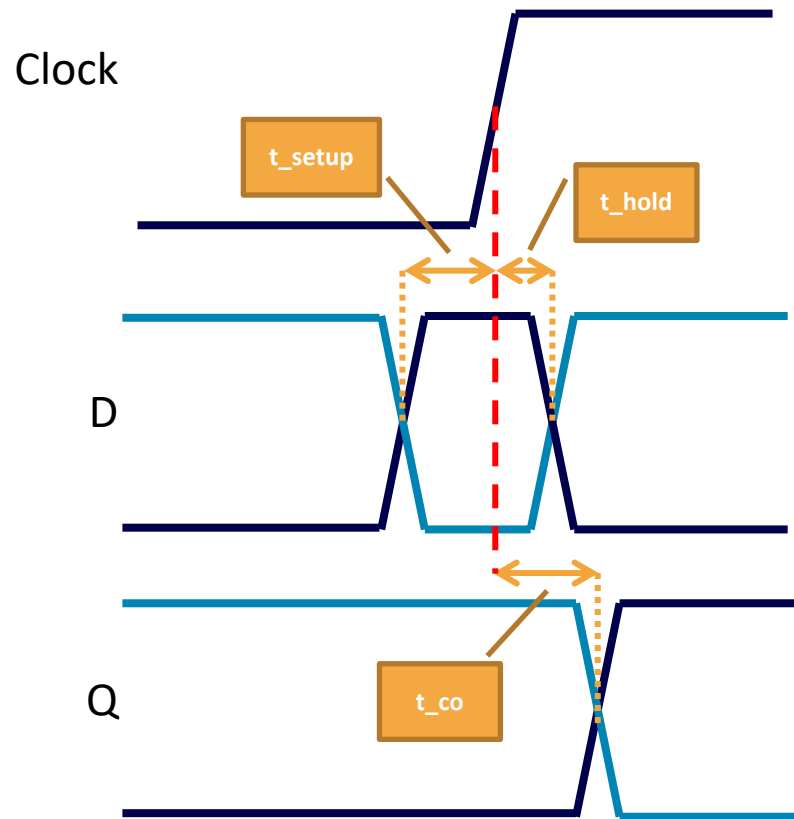
t_{co}

We specify **timing constraints** to try to avoid these problems.

- Setup time (t_{setup})
 - How long the signal should be settled **before** the **event**, e.g. rising clock edge.
- Hold time (t_{hold})
 - How long the signal should remain settled **after** the **event**.
- Clock-to-output (t_{co})
 - The time between the **event** and the **output changing**.



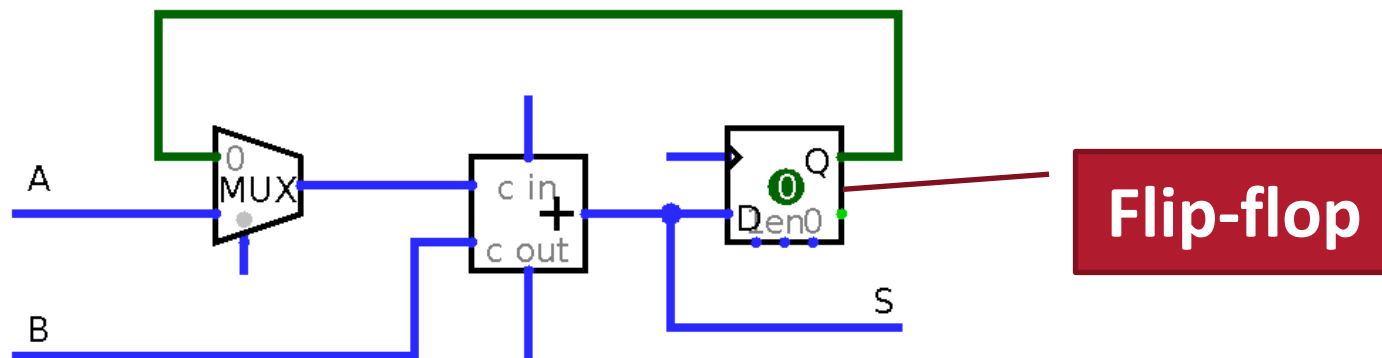
🔥 Timing constraints



- We specify **timing constraints** to try to avoid these problems.
- Setup time (t_{setup})
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- Hold time (t_{hold})
 - How long the signal should remain settled **after** the **event**.
- Clock-to-output (t_{co})
 - The time between the **event** and the **output changing**.

🔥 Combinatorial vs. sequential logic

- To enforce a sequence reliably, we can:
 - Store result values
 - Control when values are stored
- This allows us to build a sequential system, combining **storage** and **combinatorial logic**.



What have we got now?

- We have enough devices to perform **sequences of operations**.
 - Results can be **stored and reused** in the next operation.
 - We have to set or reset our inputs **by hand** at each stage in the sequence.
 - We have a **clock** that we have to operate **by hand**.
- We have flip-flops – single units of **memory**.
 - Soon we will have more complex memories.
 - And ways of controlling the system **without** manual (by hand) intervention.



In this lecture

Foundations

- Data representation, logic, Boolean algebra.

Building blocks

- Transistors, transistor based logic, simple devices, **storage**.

Modules

- Memory, simple controllers, FSMs, processors and execution.

Programming

- Machine code, assembly, high-level languages, compilers.

Wrap-up

- Operating systems, energy aware computing.



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