CS140 Lecture 02a:
The Machinery of Computation:
Circuits and Gates

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Thanks to Charles Petzold for some diagrams and Aaron Stevens for some slides.

Overview/Questions

In your previous CS courses, you've probably learned about abstraction and digital representation of information/data.

Now we're ready to ask some tough questions:

- What is the machinery of computation?
- How does digital computation happen?
- Why did we learn about binary numbers?

The Machinery of Computation

The Central Processing Unit (CPU) is where computation happens.

- The CPU is a microprocessor chip made up of billions (10^9) of circuits.
- What is a circuit?
- What does a circuit do?
- How are circuits arranged to do computation?

A Plumbing Primer

How faucets work

A faucet is like an gate, which controls the flow of water.

ON: the water flows from the source into the sink.

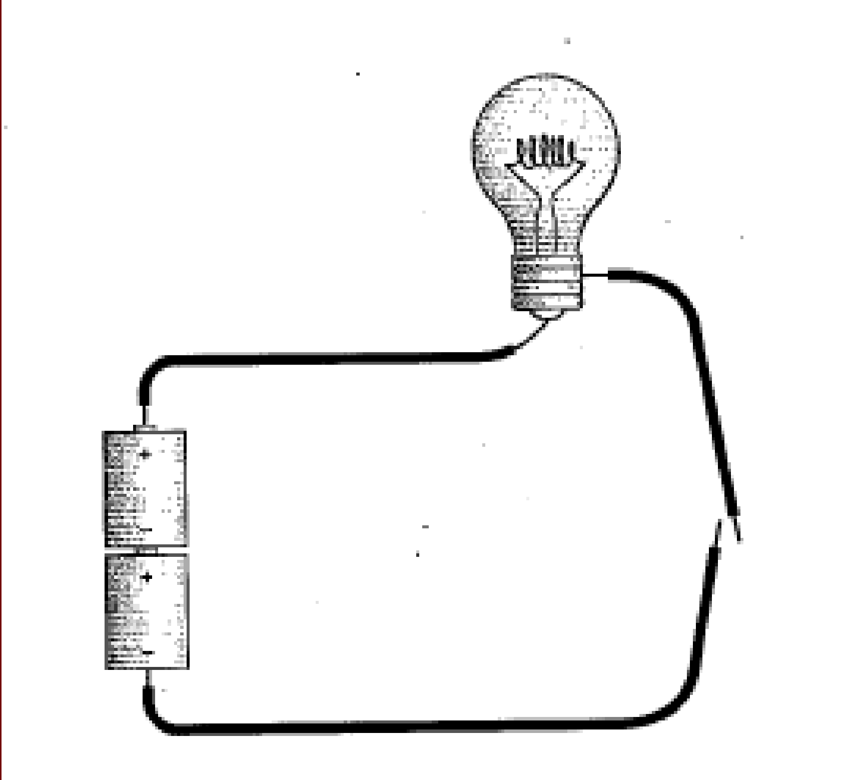
OFF: the water gets stopped at the gate, and never makes it into the sink.

Wikimedia Commons – User: Chabacano

Anatomy of a Flashlight

A flashlight has 3 main components:

- A battery
- A bulb
- A conductor (e.g. wire)

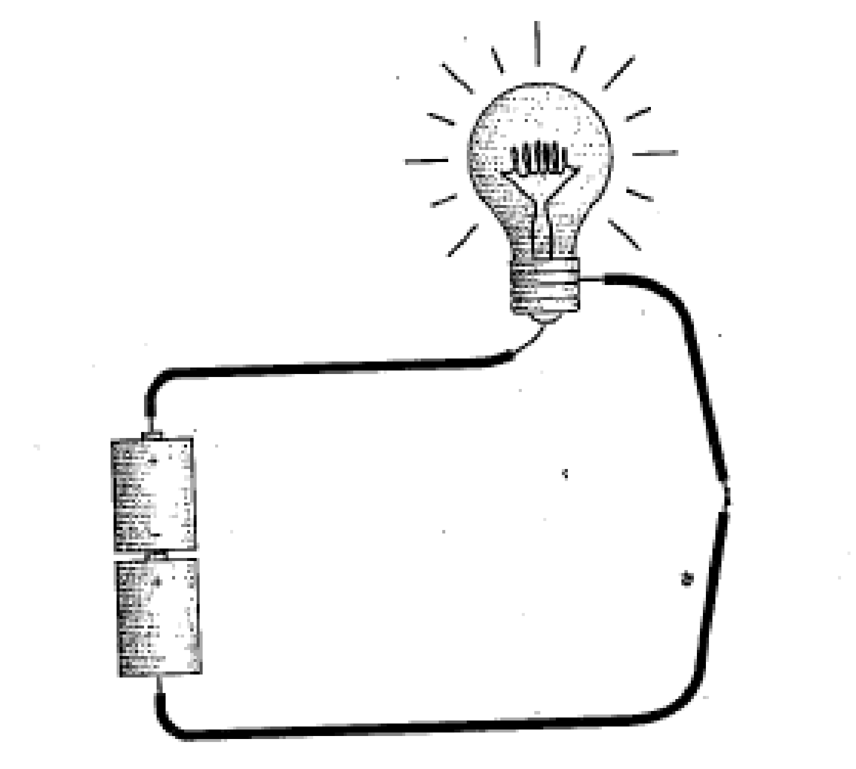


Anatomy of a Flashlight

Here the wires are connected, which forms a sort of circle, called a circuit.

The circuit allows electrons to move from a source to a sink.

Along the way, the bulb is lit.



Edison’s First Rule of Electricity

You cannot make electricity flow without a plug.

or, more precisely:

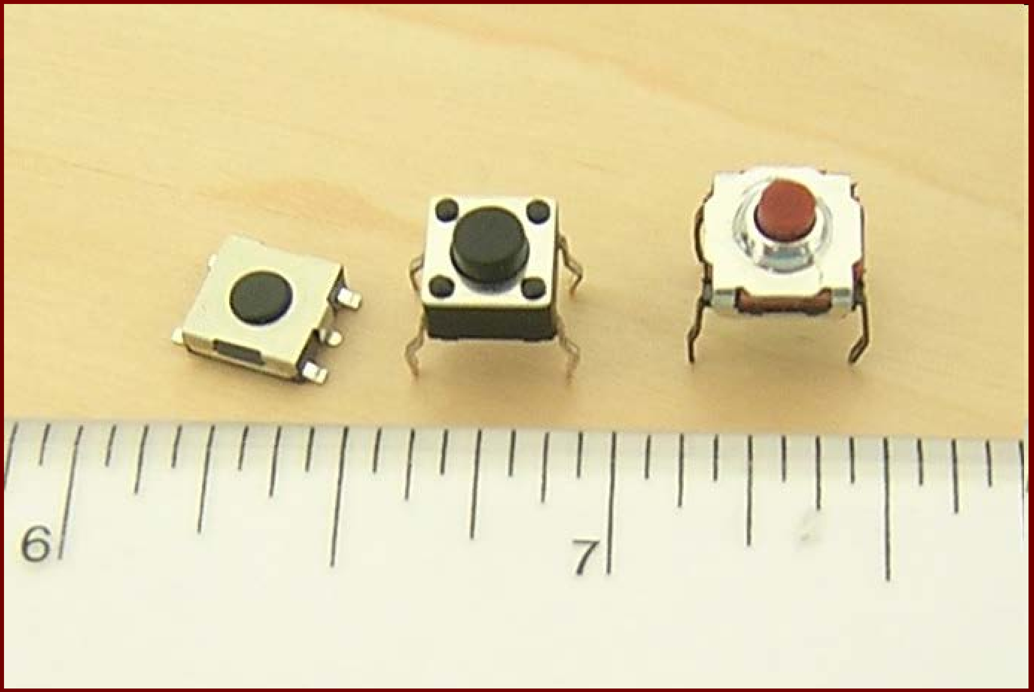
Electric current flows through a closed circuit.

If the wire is not connected, the circuit is said to be “open”, and the electrons don’t flow.

of course, electrons can flow through the air (e.g. lightning, arcs, etc.) but let’s keep it simple for now

We need a switch...

Wikimedia Commons: Author Funpika



Wikimedia Commons: Author Scwerllguy

ON: the electrons flows from the source into the sink.

OFF: the electrons gets stopped at the gate, and never makes it into the sink.

... an electronically controlled switch...

Wikimedia Commons: Dave Fischer

Vacuum Tubes

"a device used to amplify, switch, otherwise modify, or create an electrical signal by controlling the movement of electrons in a low-pressure space"

...a small switch!

Wikimedia Commons – User: Transisto

Transistors!

a semiconductor device commonly used to amplify or switch electronic signals.

AT&T Bell Labs – 1947

The greatest invention of the 20th century?

Light Switch Circuits

We will now consider several examples to demonstrate some techniques for wiring circuits with light switches.

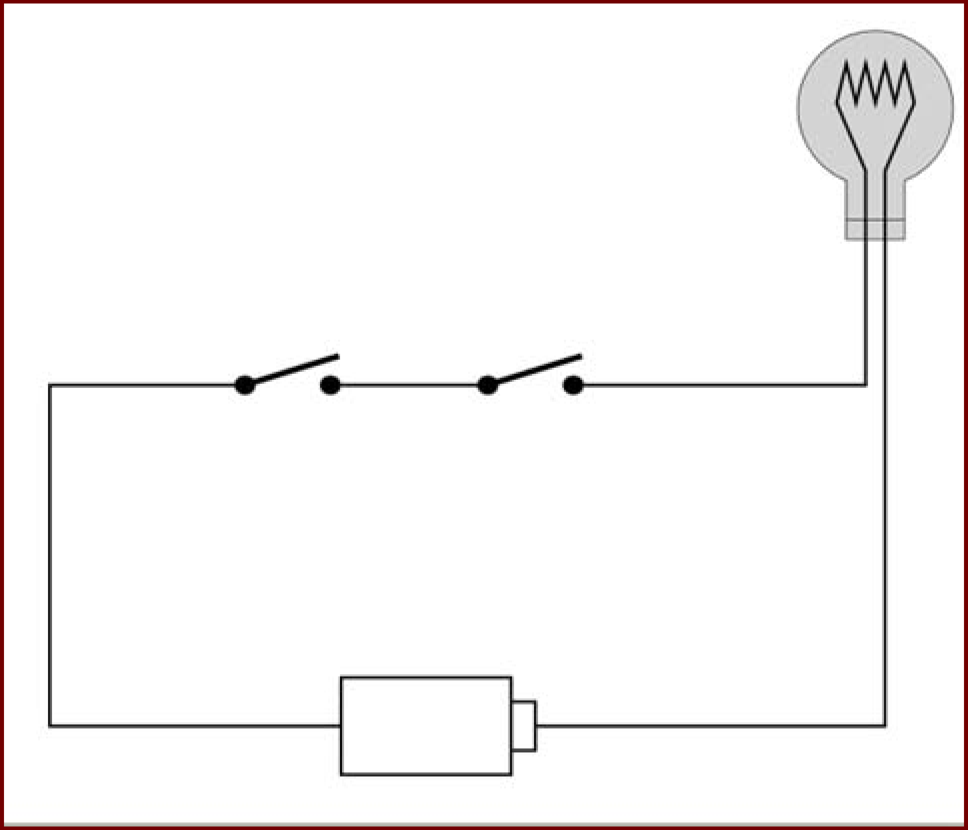
This link brings up a great animated/interactive version, but I've reproduced "still" pictures on the following slides.

http://www.charlespetzold.com/blog/2007/09/LogicalSwitches.xaml

http://www.charlespetzold.com/blog/2007/09/ThreeWaySwitch.xaml

Switches in Series

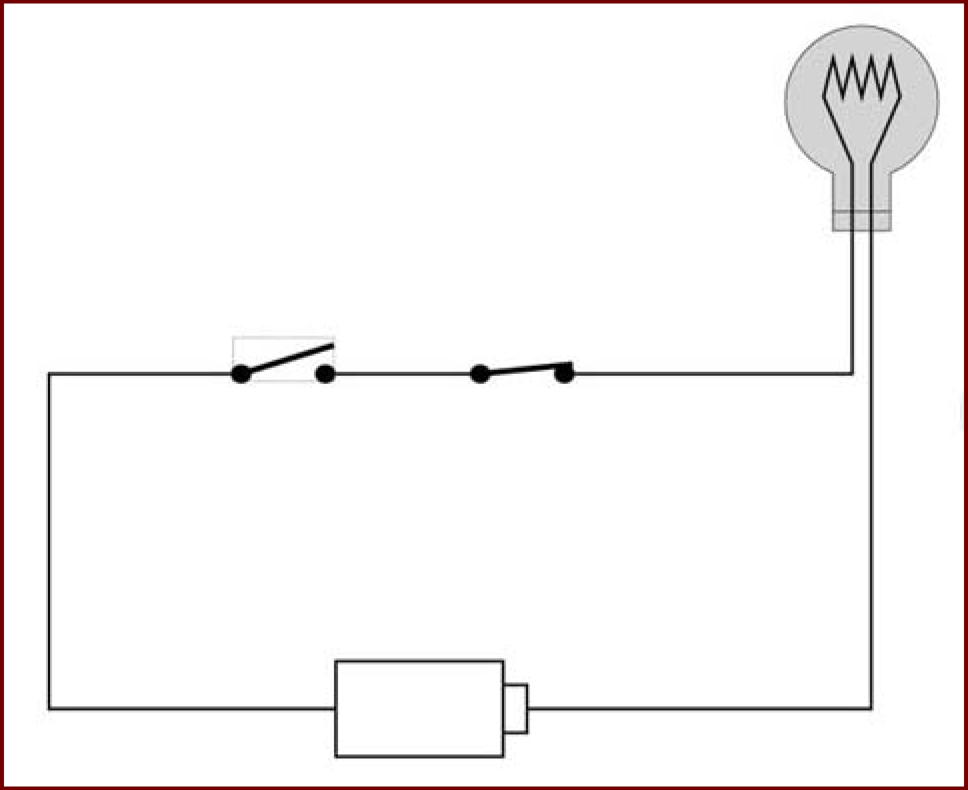
Consider this arrangement, called wiring in *series*.
(the light is off)



Switches in Series

Now we close one switch (e.g. connect the wire)

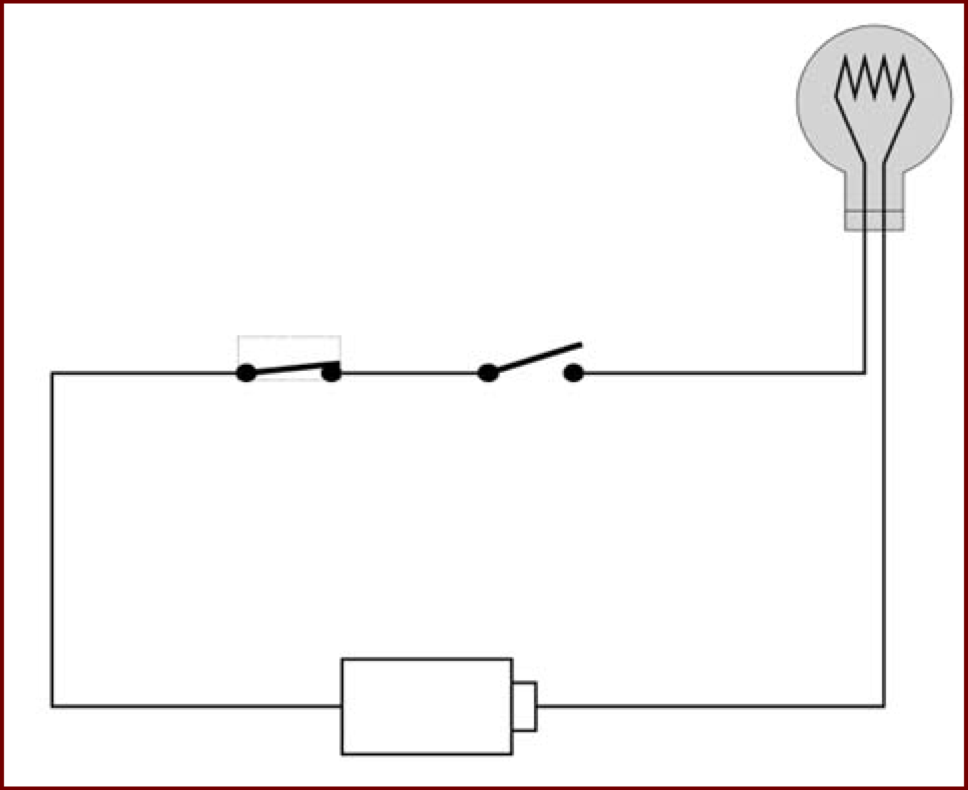
(the light is still off)



Switches in Series

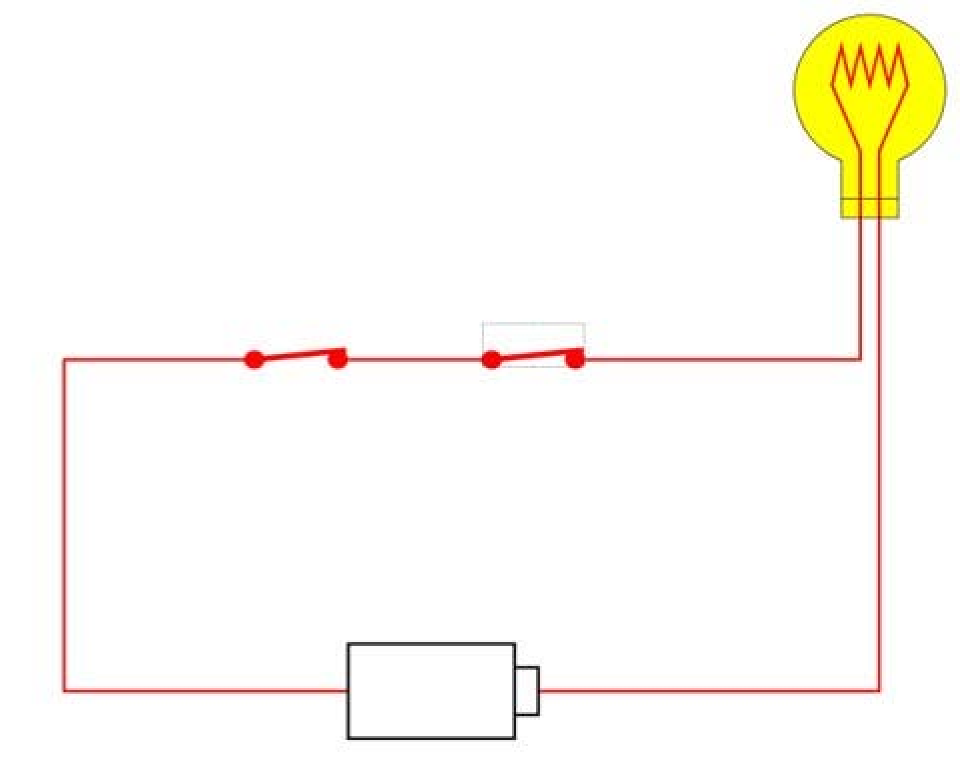
Now we close the other switch (e.g. connect the wire)

(the light is still off)



Switches in Series

Now we close both switches (e.g. connect the wire)
(now the light is on)



Switches in Series: Summary

Left Switch	Right Switch	Light Bulb
OFF	OFF	OFF
OFF	ON	OFF
ON	OFF	OFF
ON	ON	ON

Light is on if and only if *both* switches were closed (on).

Building Blocks

These wiring arrangements are the fundamental building blocks of computer circuitry.

- Each switch has 2 states (on or off)
- Each light bulb has 2 states (on or off)

We can abstractly describe switches and bulbs as each having a 1 bit state.

Building Blocks

Gates (not Bill)

Simple electric circuits which perform like our light switch examples.

The input values explicitly determine the output values.

We assume the “switch” is controlled by a electronic input rather than a physical switch.

Describing Gates and Circuits

We describe gates and circuits using:

Boolean expressions

Uses Boolean algebra, a mathematical notation for expressing two-valued (T/F) logic.

Logic diagrams

A graphical representation of a circuit; each gate has its own symbol.

Truth tables

A table showing all possible input value and the associated output values.

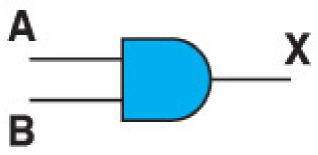
AND Gate

The AND gate accepts two input signals.
The output is 1 if and only if both inputs are 1.
Otherwise the output is 0.

Boolean Expression

$$X = A \cdot B$$

Logic Diagram Symbol



Truth Table

A	B	X
0	0	0
0	1	0
1	0	0
1	1	1

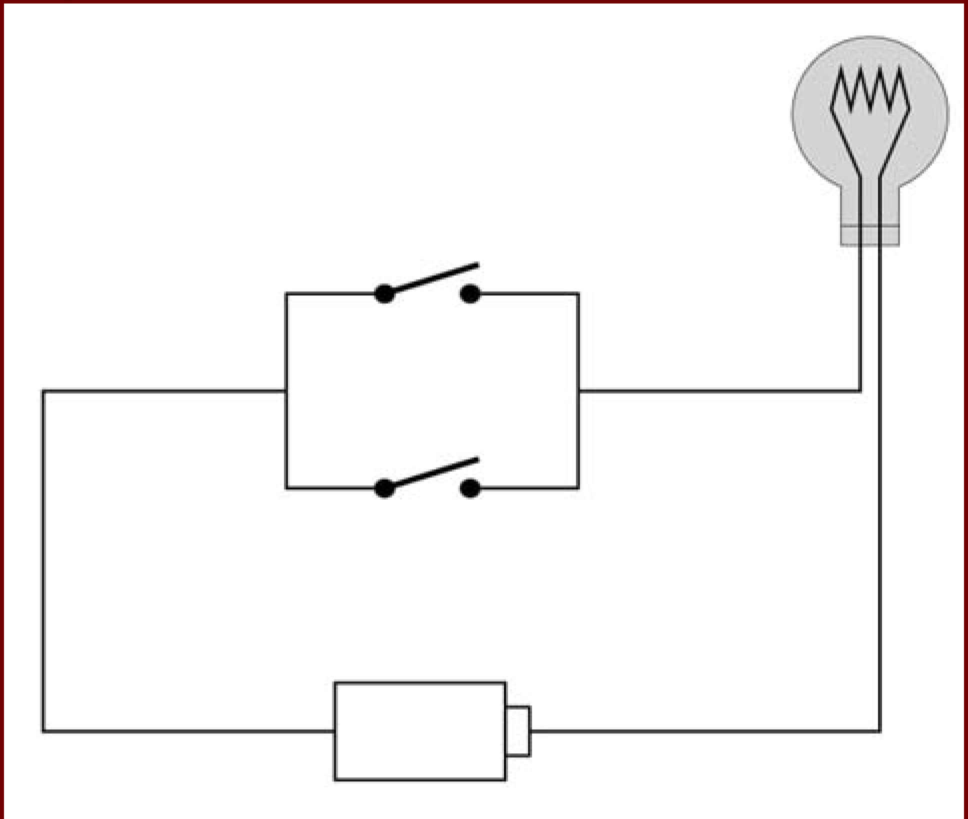
Figure 4.2 **Various representations of an AND gate**

Just like wiring in series.

Switches in Parallel

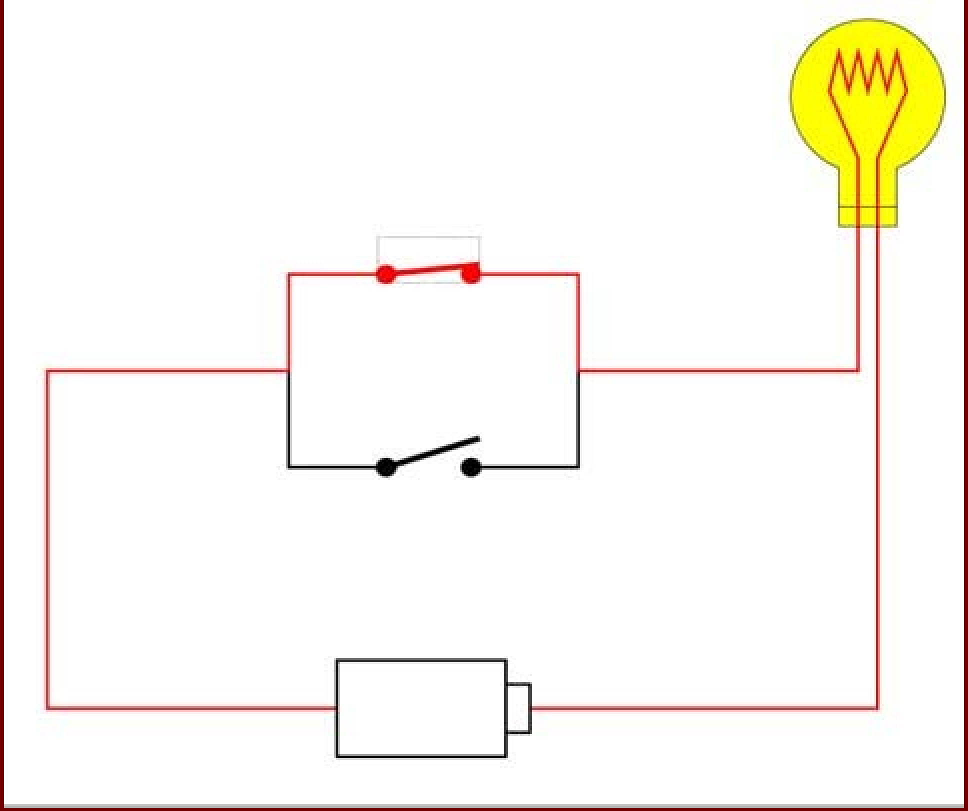
Now let's try connecting the switches a little differently. Consider this arrangement, called wiring in *parallel*.

(the light is off)



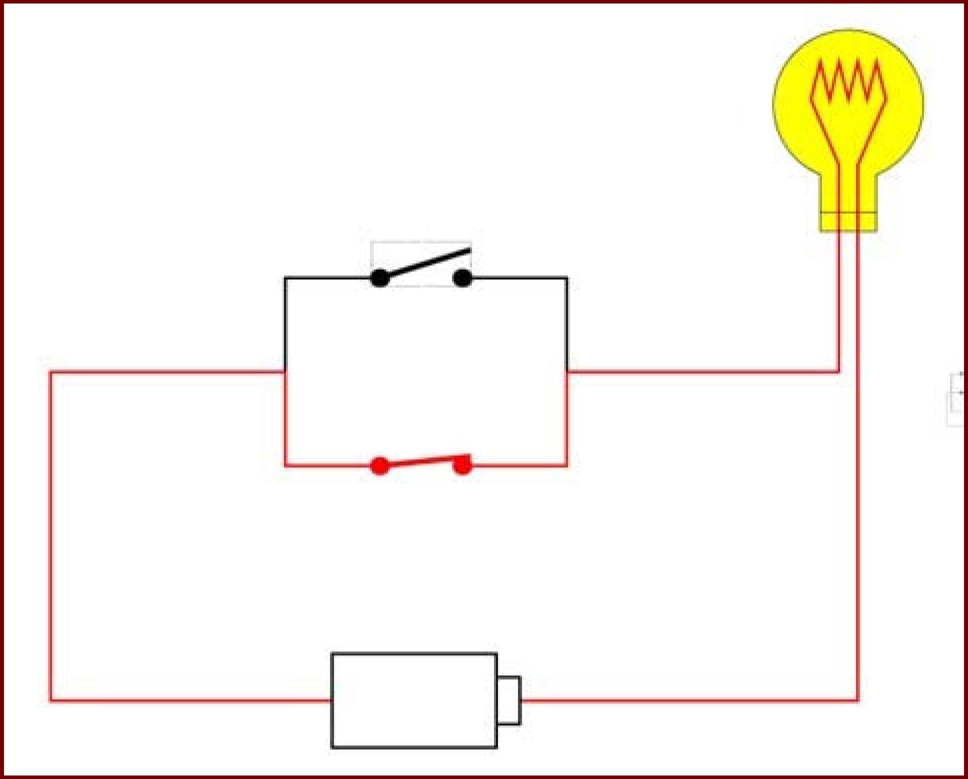
Switches in Parallel

Now we close just the top switch.
(the light came on!)



Switches in Parallel

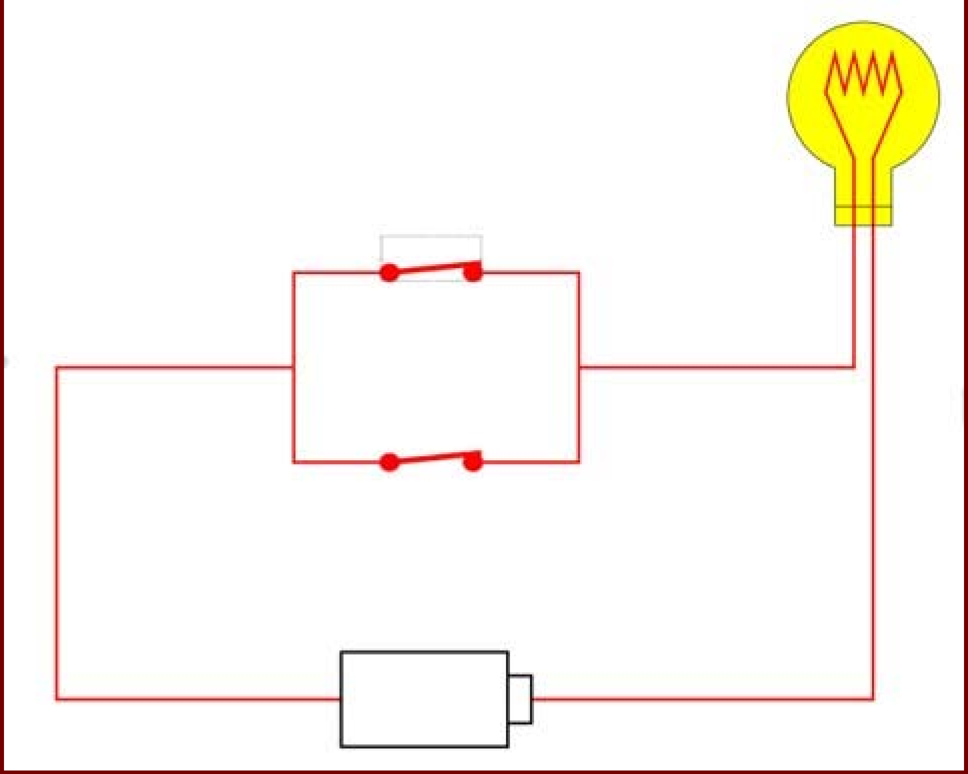
Or we just the bottom switch.
(the light is still on!)



Switches in Parallel

Or we close both switches!

(the light is still on!)



Switches in Parallel: Summary

Top Switch	Bottom Switch	Light Bulb
OFF	OFF	OFF
OFF	ON	ON
ON	OFF	ON
ON	ON	ON

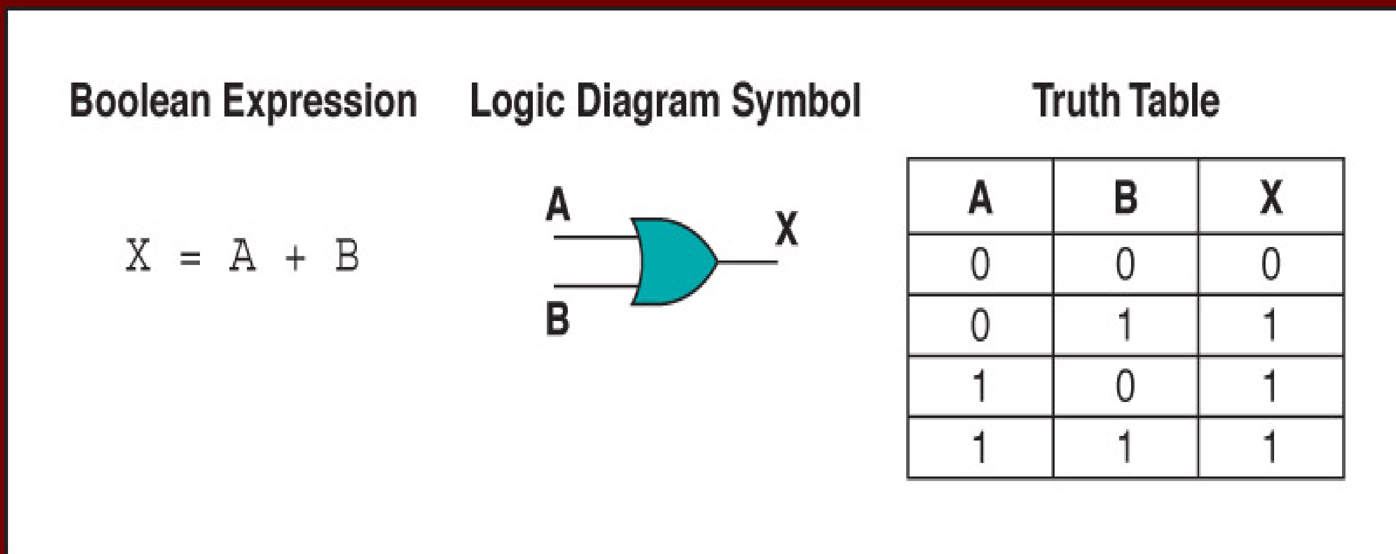
Light is on if either switch alone, or both switches together are closed (on).

OR Gate

The OR gate accepts two input signals.

The output is 1 if either input is 1.

The output is 0 if both inputs are 0.



A	B	X
0	0	0
0	1	1
1	0	1
1	1	1

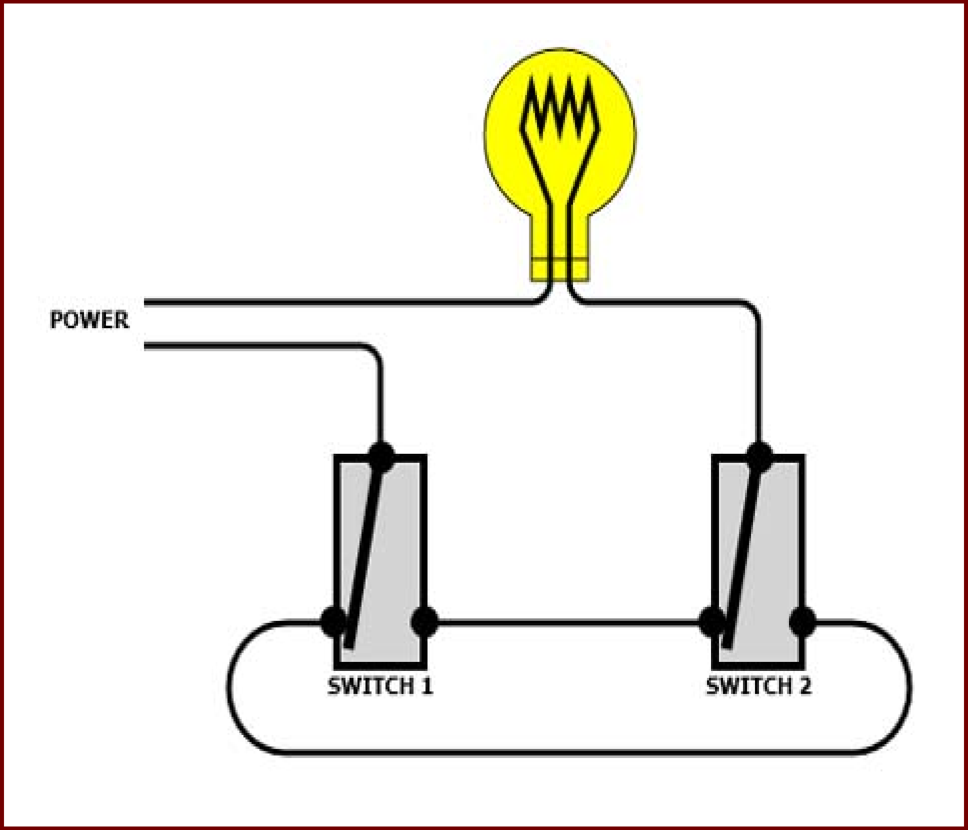
Figure 4.3 Various representations of a OR gate

Just like wiring in parallel.

A 3-Way Switch

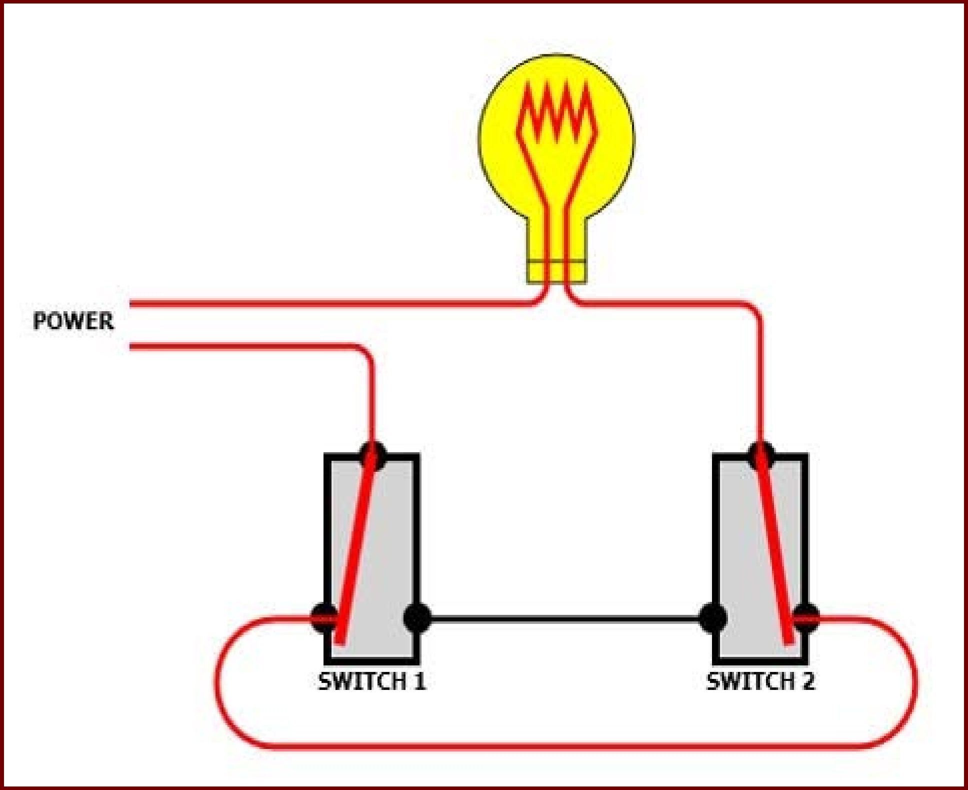
Consider this arrangement, called wiring a 3-way switch.

Both switches are to the left (the light is off).



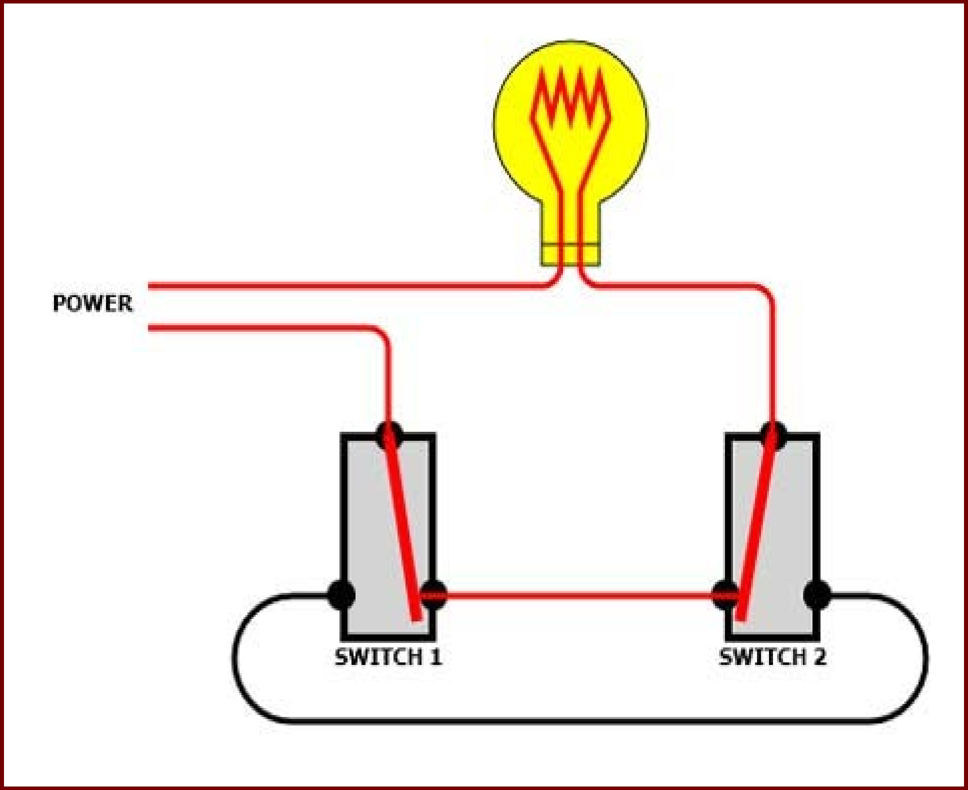
A 3-Way Switch

Now we have one switch left, one switch right.
(the light is on).



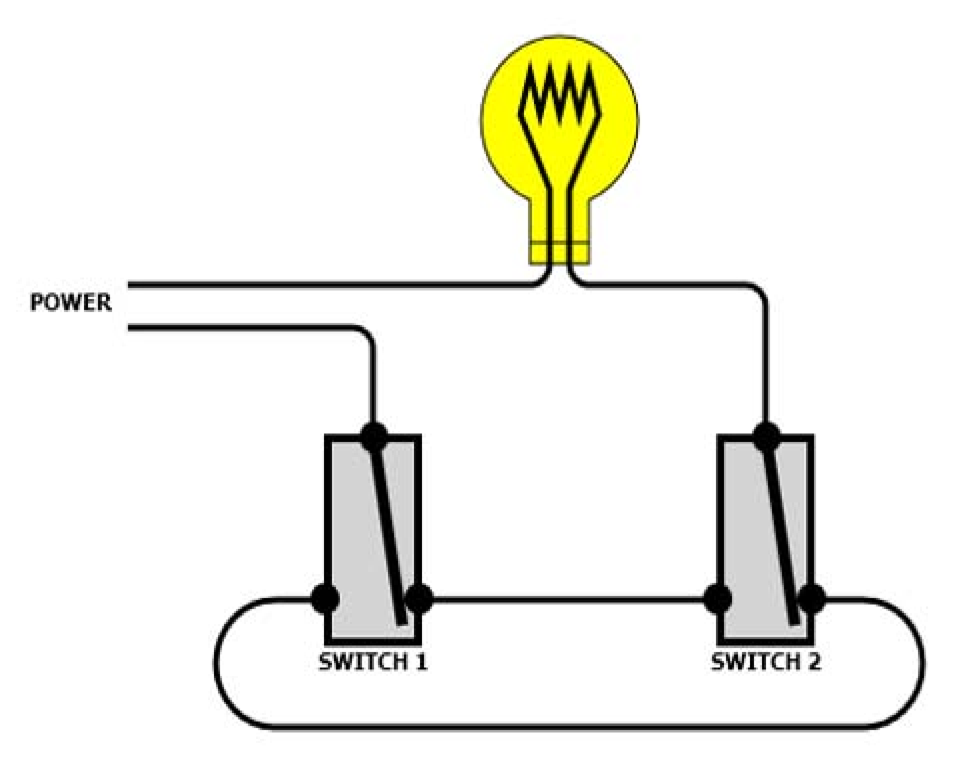
A 3-Way Switch

Now we have one switch right, one switch left.
(the light came one)



A 3-Way Switch

Now we have both switches to the right.
(now the light is off again)



3 Way Switch: Summary

Left Switch	Right Switch	Light Bulb
LEFT	LEFT	OFF
LEFT	RIGHT	ON
RIGHT	LEFT	ON
RIGHT	RIGHT	OFF

Light is on if and only if

one switch is left and the other switch is right

XOR Gate

An XOR (eXclusive OR) gate accepts two input signals

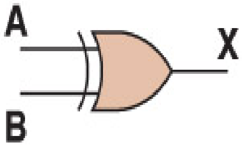
When the 2 inputs differ, the output is 1

When both inputs are the same, the output is 0

Boolean Expression

$$X = A \oplus B$$

Logic Diagram Symbol



Truth Table

A	B	X
0	0	0
0	1	1
1	0	1
1	1	0

Figure 4.4 **Various representations of an XOR gate**

Just like wiring with a 3-way switch.

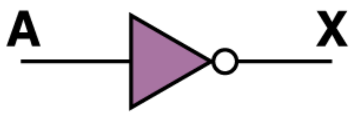
NOT Gate

The NOT gate accepts one input signal (0 or 1). The output is the opposite.

Boolean Expression

$X = A'$

Logic Diagram Symbol



Truth Table

A	X
0	1
1	0

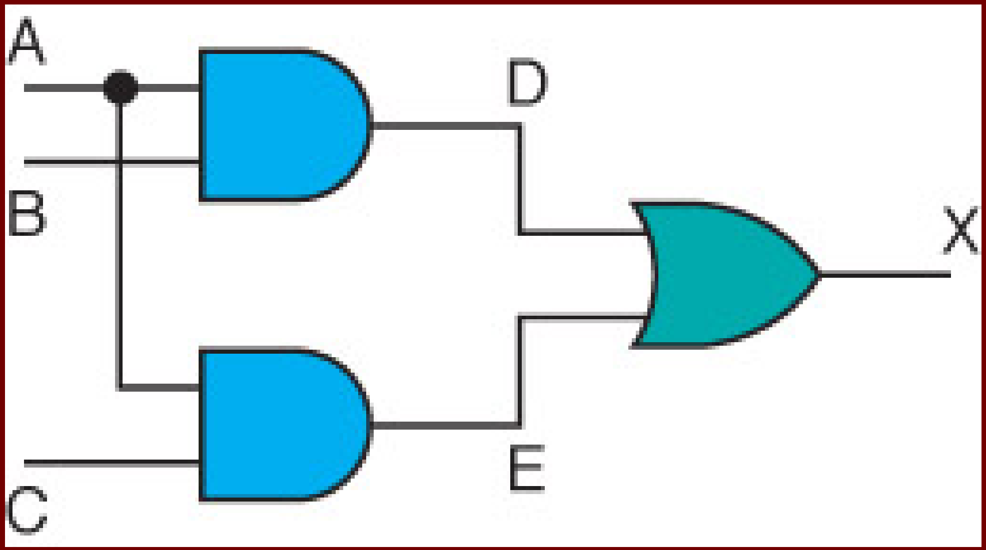
Figure 4.1 **Various representations of a NOT gate**

A NOT Gate is also called an inverter.

Combinational Circuits

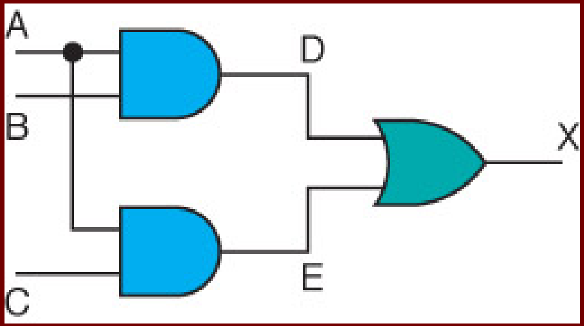
Combines some basic gates (AND, OR, XOR, NOT) into a more complex circuit.

- Outputs from one circuit flow into the inputs of another circuit.
- The **input values** explicitly determine the output values.



Combinational Circuits

Three inputs require eight rows to describe all possible input combinations ($2^3 = 8$):



A	B	C	D	E	X
0	0	0	0	0	0
0	0	1	0	0	0
0	1	0	0	0	0
0	1	1	0	0	0
1	0	0	0	0	0
1	0	1	0	1	1
1	1	0	1	0	1
1	1	1	1	1	1

This same circuit using a Boolean expression is (AB + AC)

Canonical Representation: AB'C + ABC' + ABC

Take-Away Points

- Gates control the flow of electric current.
- Basic logic gates (AND, OR, XOR, NOT)
- Combination gates