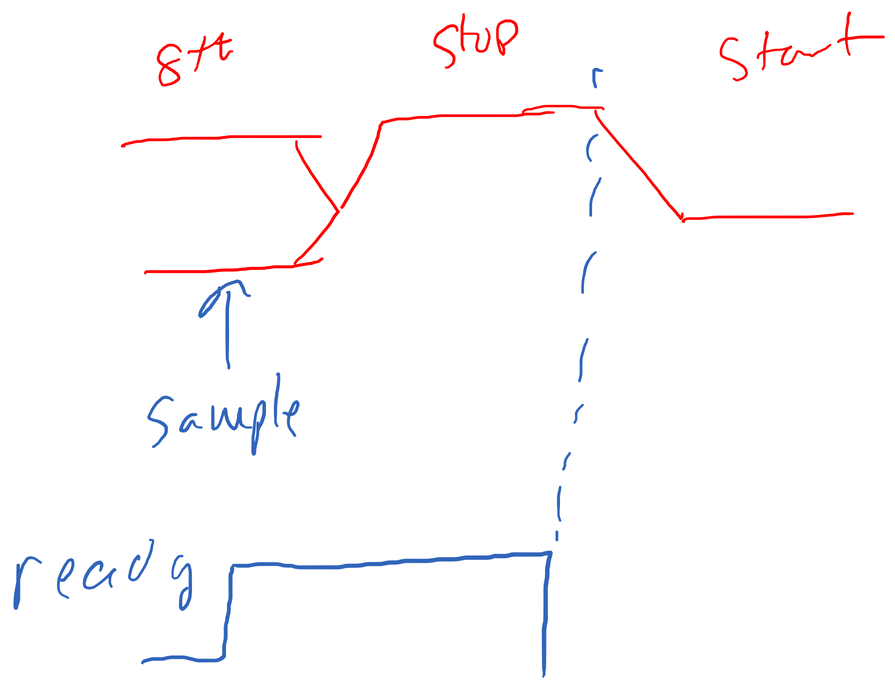
Circuits + CMOS



Andrew Lukefahr
Indiana University - Bloomington

The Compute Stack

python

C/C++

assembly

CPU

Seq. Logic / State machines

Digital Logic

Transistors / Circuits

Physics / Chemistry

dive

dive

The Complexity Stack

python

C — ↑ software

Assembly ISA — ↓ hardware

State machines — FF's + clks

Boolean Logic — AND / OR / NOT

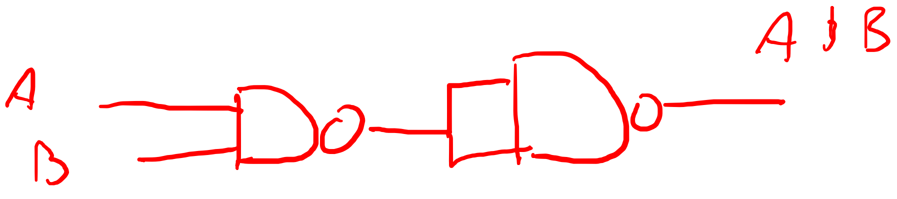
Transistors — MOSFETS!

All Digital Logic is NAND

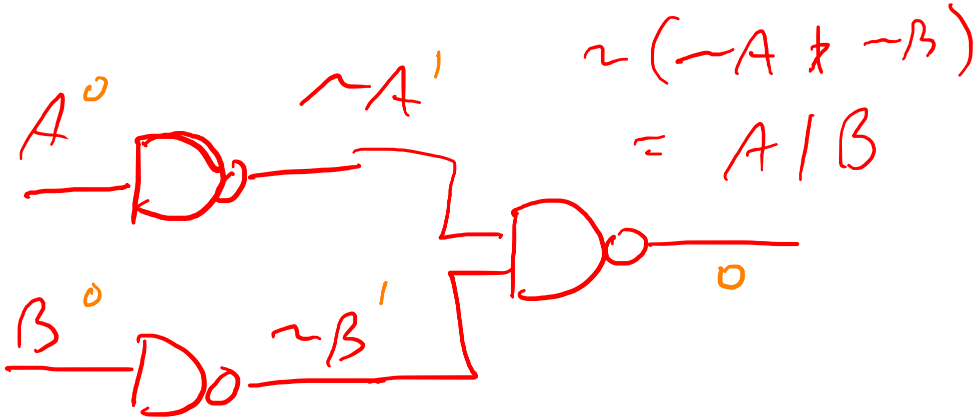
- Given: NAND
- Build: AND, OR, NOT

A	B	A | B
0	0	0
0	1	1
1	0	1
1	1	1

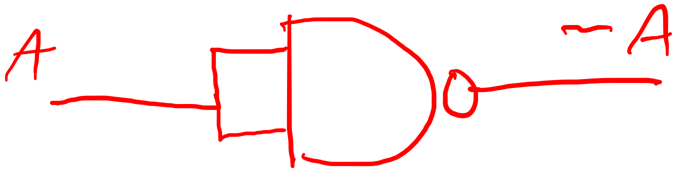
AND



OR



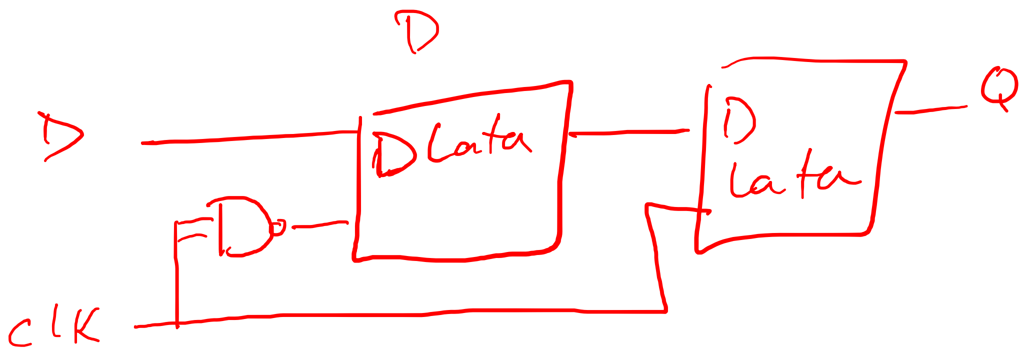
NOT



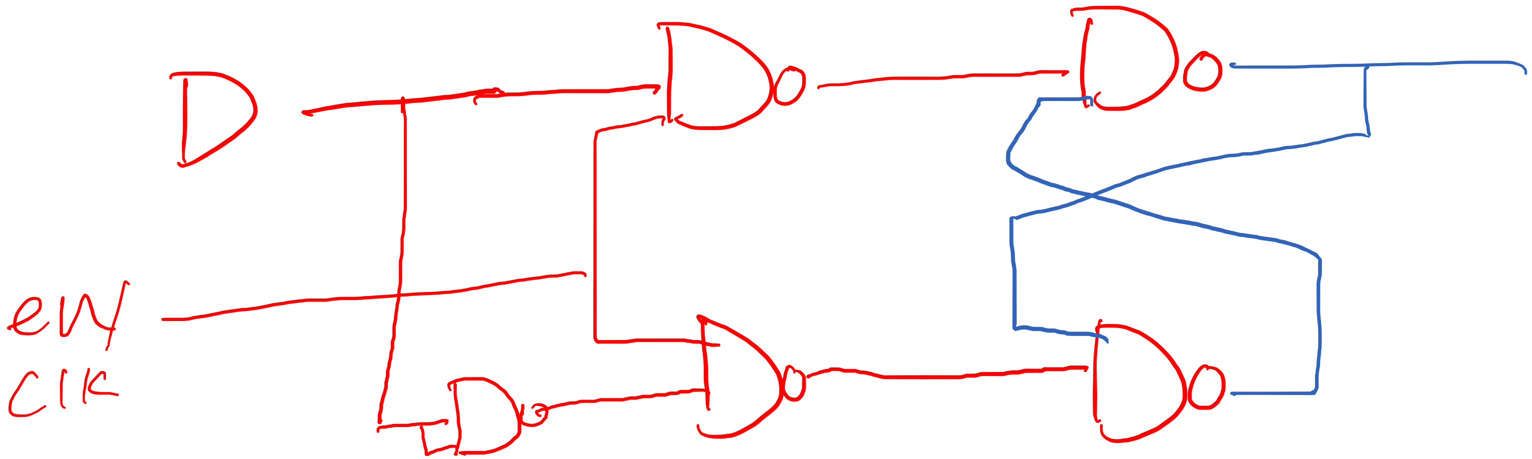
All Digital Logic is NAND

- Given: NAND
- Build: D Flip Flop

D FF

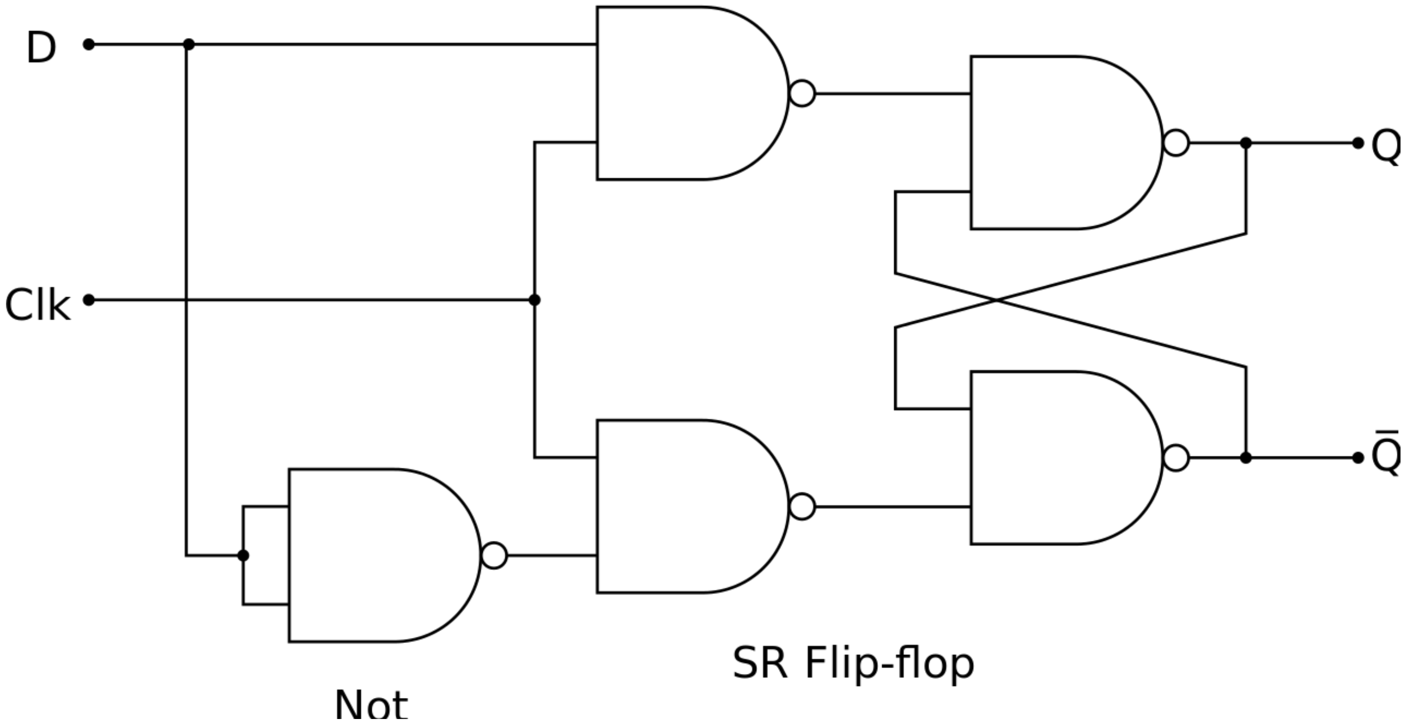


D Latch



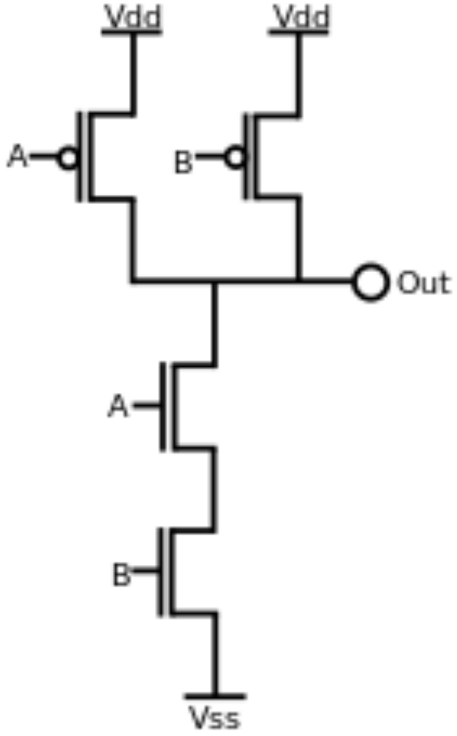
All Digital Logic is NAND

- Given: NAND
- Build: D Flip Flop



How do we build NAND?

- It’s not magic, it’s an electronic circuit



Review: Voltage

lots of electrons

e^- e^- e^-

e^- e^-

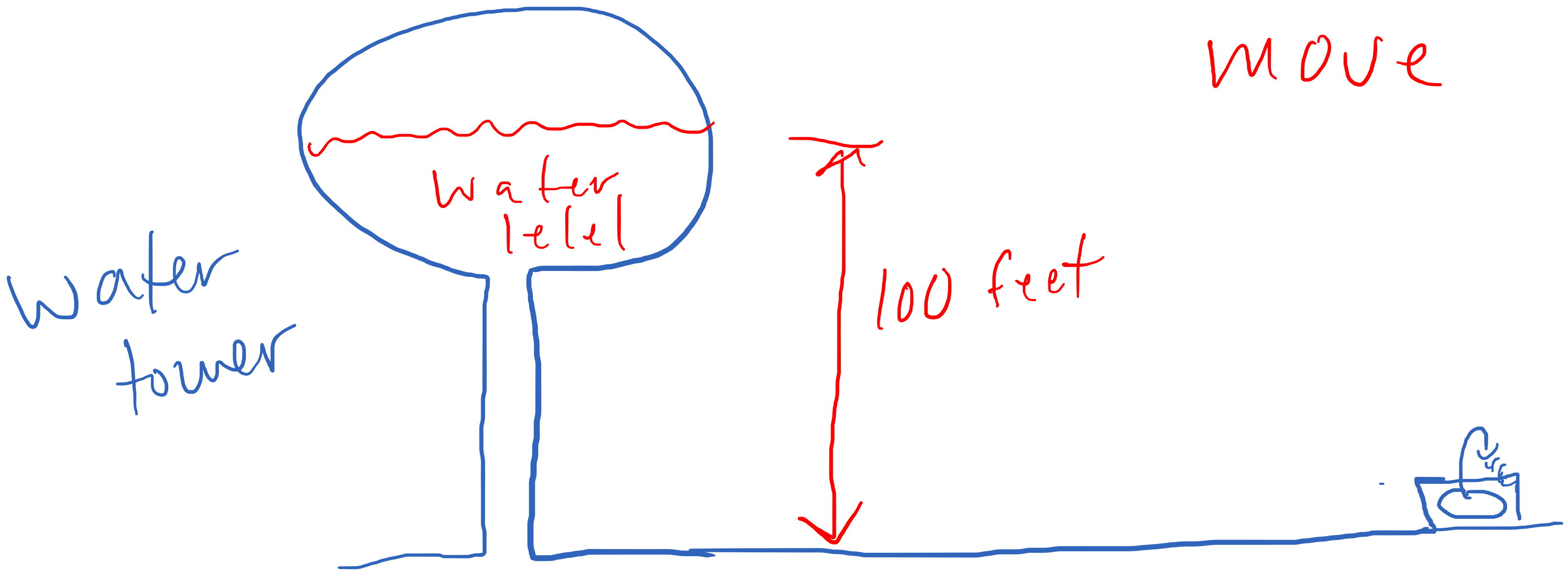
e^- e^-

force of wanting to move

not many over here

e^-

e^-



A positive electric field surrounding a group of one or more protons will exert:

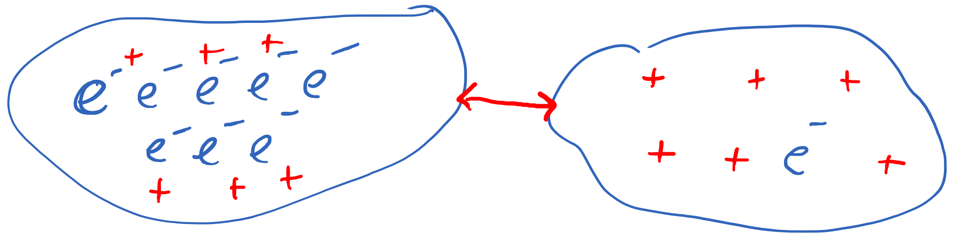
- a repelling force on other groups of protons,
- an attracting force on groups of electrons.

Since an electric field can cause charged particles to move, it can do some amount of work, and so it is said to have potential energy.

The amount of energy an electric field can impart to unit charge is measured in *joules per coulomb*, more commonly known as *voltage*.

Voltage may be thought of as the "electro-motive force" that can cause charged particles to move.

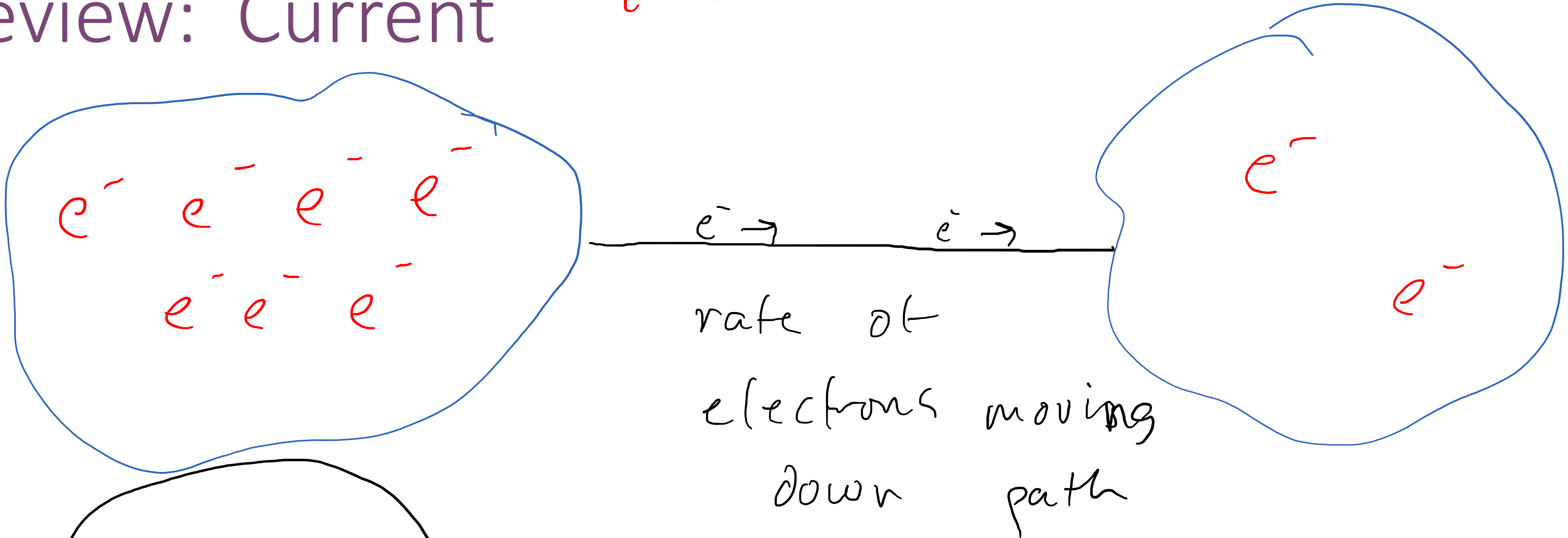
A power supply contains imbalance of electrons, with material on one side (the negative side) containing an abundance of electrons, and material on the other (positive) side containing a relative absence of electrons.

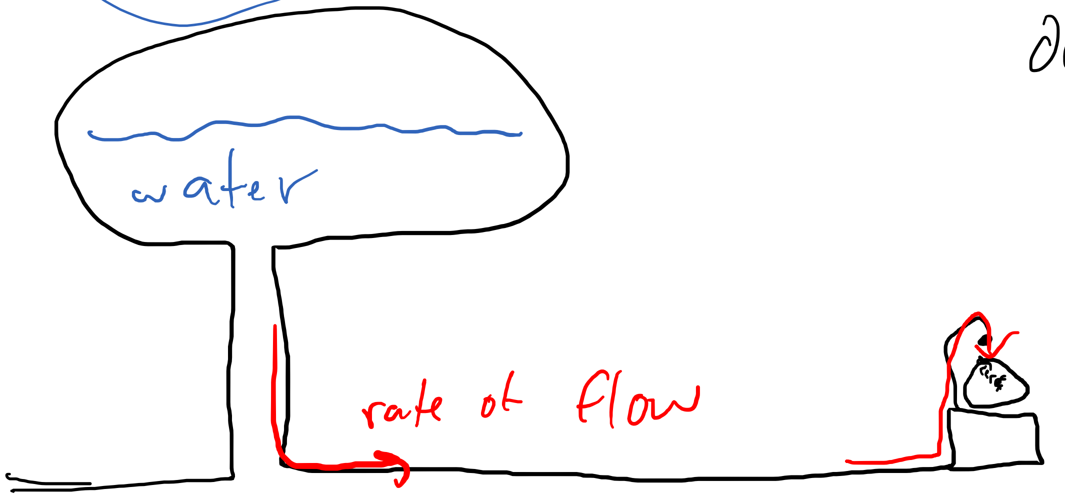


Review: Current

i = current

$\sqrt{-1} = \cancel{i}\ j$





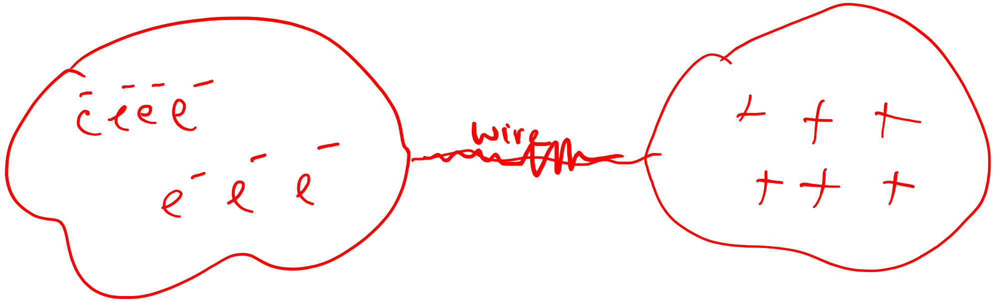
Electrons carry the smallest possible amount of negative charge, and billions of them are present in even the tiniest piece of matter.

In most materials, electrons are held firmly in place by heavier protons, these materials are called *insulators*.

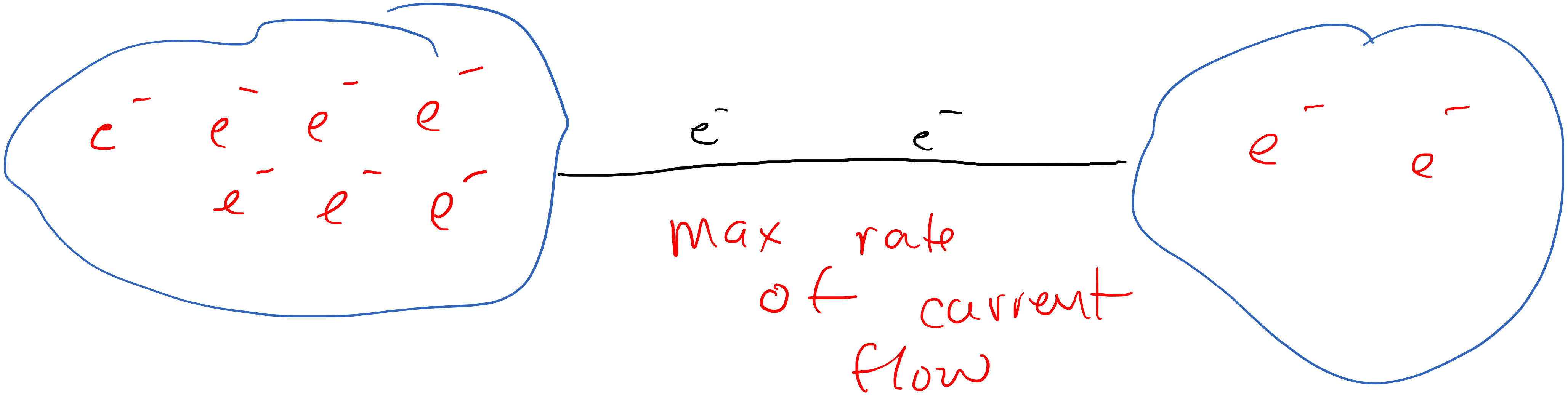
By contrast, in other materials (like metals) electrons can move more easily from atom to atom, these materials are called *conductors*.

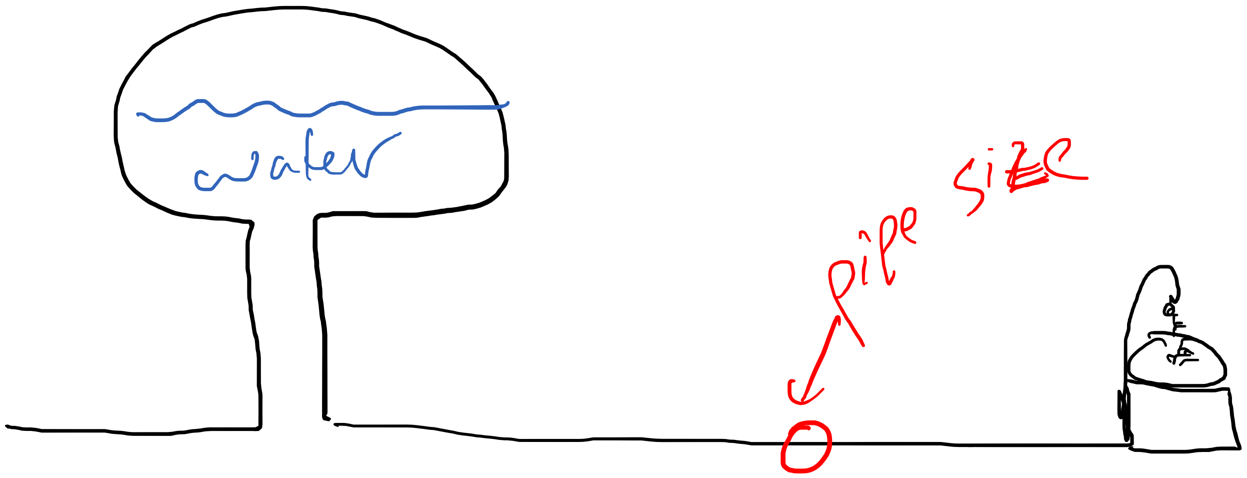
The movement of electrons in a conductor is called *electric current*, measured in amperes or *amps*.

If a power supply is used to impress a voltage across a conductor, electrons will move from the negative side of the supply through the conductor towards the positive side.



Review: Resistors





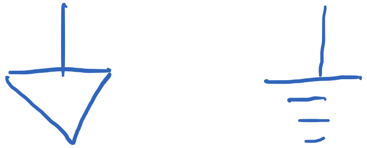
Resistance

All materials, even conductors, exhibit some amount of resistance to the flow of electric current.

The amount of resistance determines how much current can flow—the higher the resistance, the less current can flow.

By definition, a conductor has very low resistance, so a conductor by itself would never be placed across a power supply because far too much current would flow, damaging either the supply or the conductor itself.

An electronic component called a resistor would be used in series with the conductor to limit current flow.

ground = GND = 

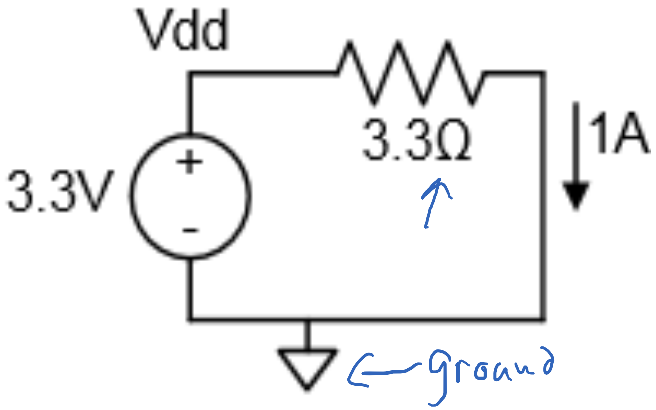
Review: Ohmn's Law

- $V = I \cdot R$

voltage = current · Resistance

$3.3 = i? \cdot 3.3$

voltage



$$i = \frac{3.3V}{3.3\Omega} = 1 \text{ Amp}$$

* actually electrons flow from ⊖ to ⊕ ... but we draw it backwards

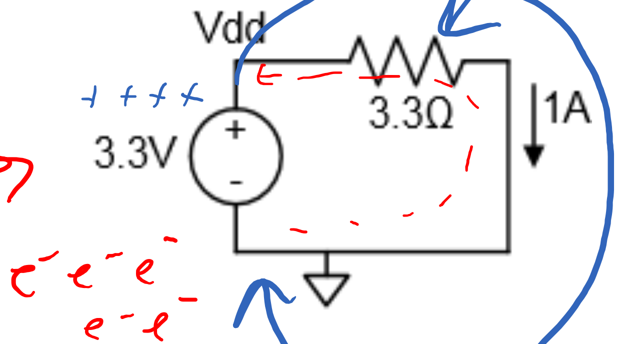
In 1827, George Ohm demonstrated through a series of experiments that voltage (V), current (I), and resistance (R) are related through a fundamental relationship:

$$V = I \cdot R$$

This most basic equation in electronics shows that when any two of the three quantities are known, the third can be derived.

resistor

Example:



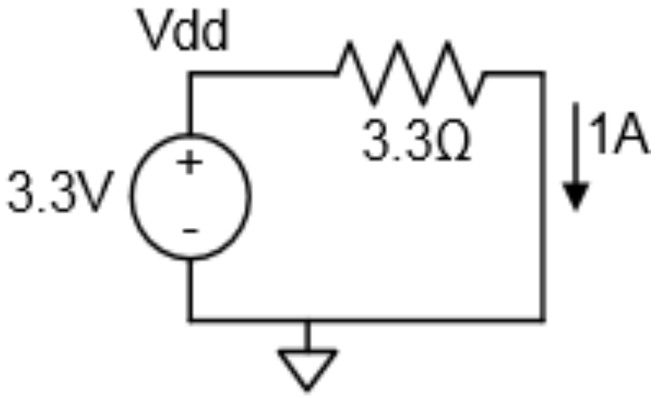
Voltage V_{dd} impressed across the resistance (represented by the symbol Omega, Ω) 3.3Ω, will cause 1A current to flow.

Review: Power

- $P = V \cdot I$

Power = Voltage · Current

$\underline{3.3}$ = 3.3V · 1A



3.3 Watts

$P = VI$, $V = IR \Rightarrow P = (IR)I = P = I^2R$

In electric circuits, power (measured in Watts) is defined as voltage times current:

$$P = V \cdot I$$

The power transferred to the resistor at any given time results in resistor heating. The more power transferred to the resistor, the hotter it gets.

For a given voltage, a smaller-valued resistor would allow more current to flow (see Ohm's law), and therefore more energy would be dissipated as heat.

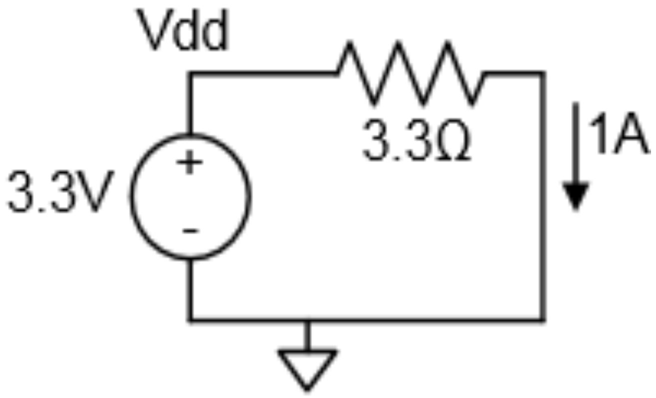
Review: Energy

- $E = P \cdot t$

Energy = Power · time

= 3.3 watts · 3 seconds

= 9.9 Joules



P = 3.3 watts

The total energy consumed in an electric circuit is simply the time integral of power, measured in Watts per second, or Joules. If the power P is constant, than the energy delivered in time t is:

$$E = P \cdot t$$

Thus, in the previous circuit, the electric power delivered to the resistor is:

$$P = 3.3V \cdot 1A = 3.3\ Watts$$

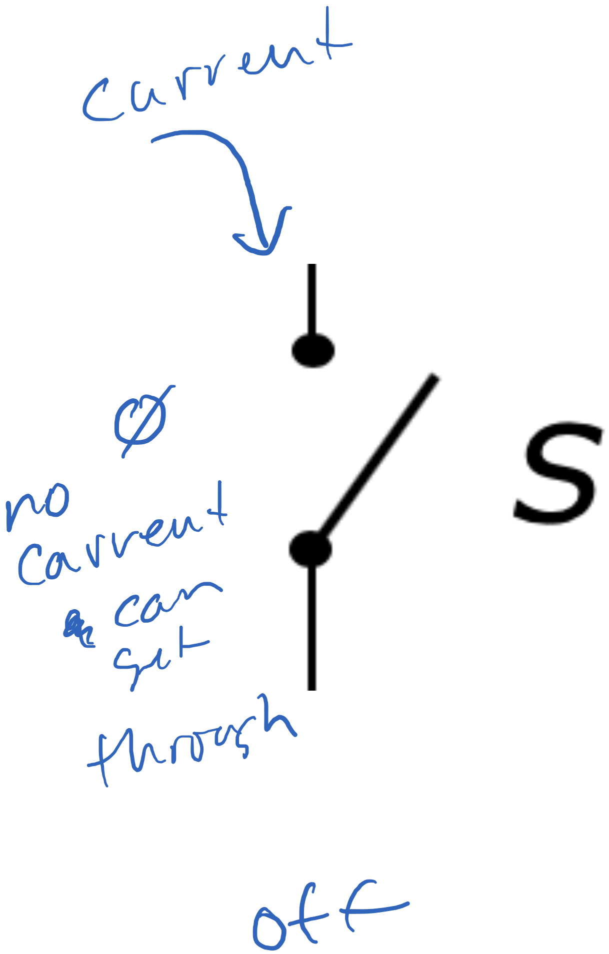
Energy dissipated in 1 second:

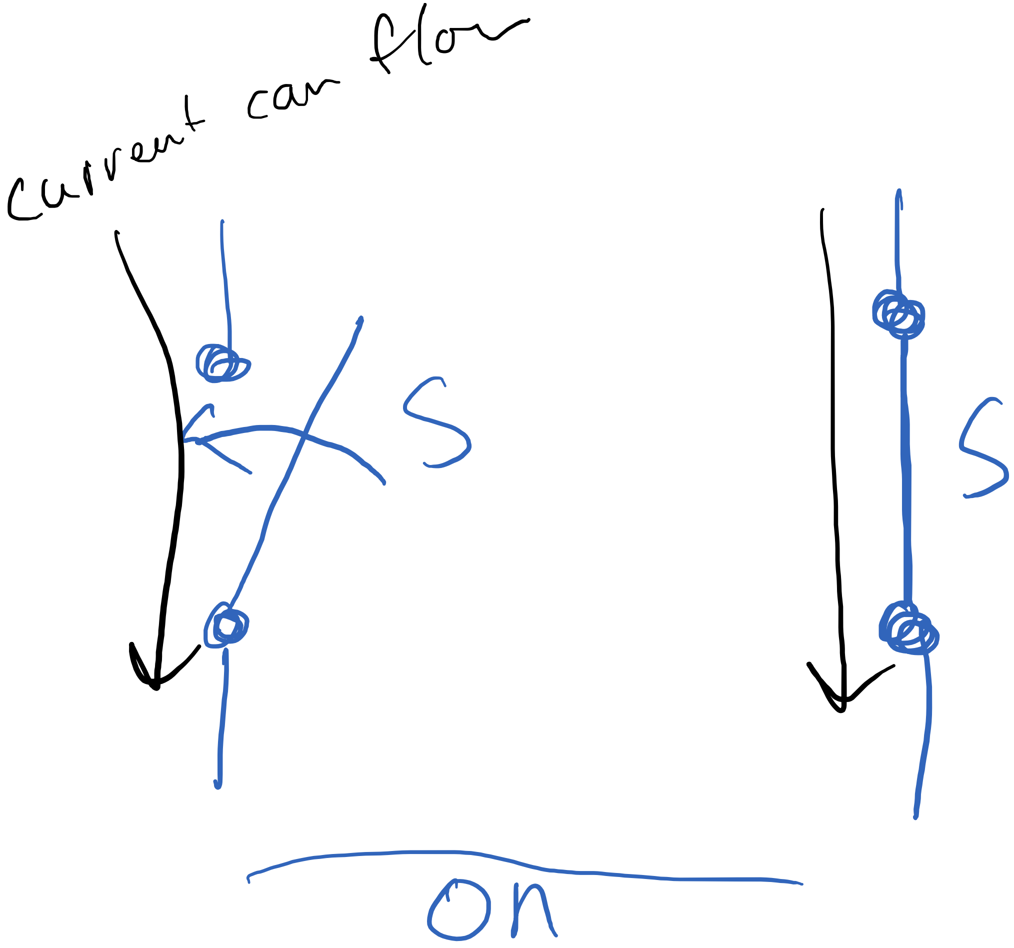
$$E = 3.3W \cdot 1second = 3.3\ J$$

Many devices can provide only limited current; if your circuit draws too much current from the device, it can malfunction.

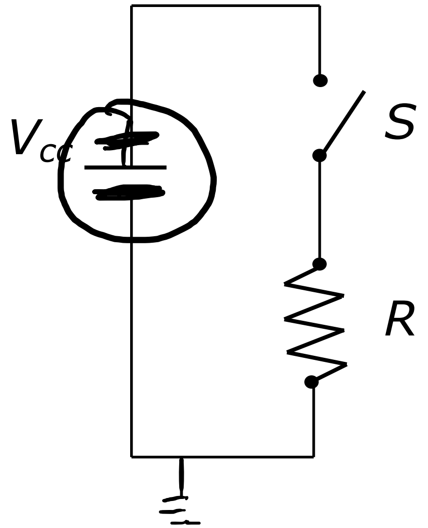
Increasing the resistance in your circuit may solve this problem.

Review: Switch

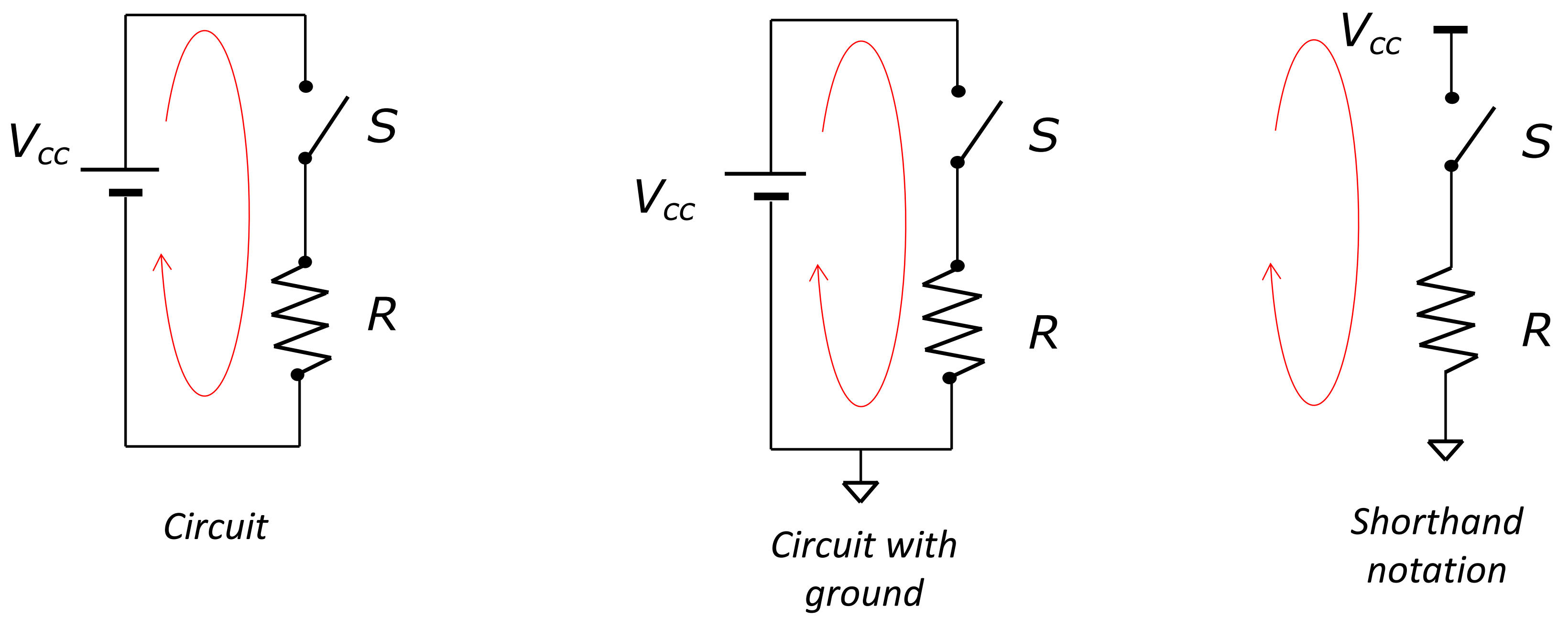




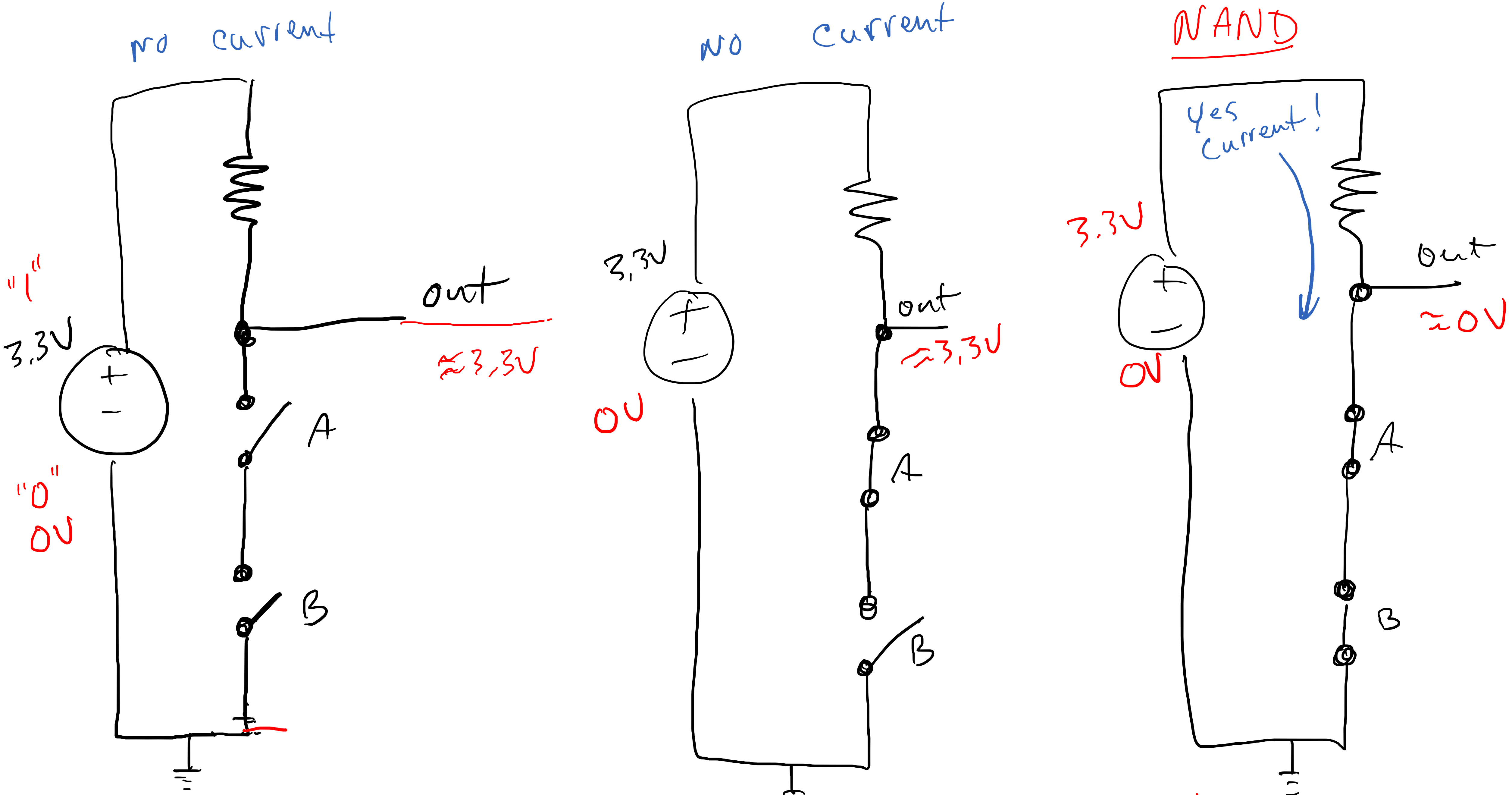
Basic Circuits



An electronic circuit is formed by connecting a set of components with wires. We consider wires to be ideal, meaning that their resistance is 0, and the voltages across a wire is 0V.

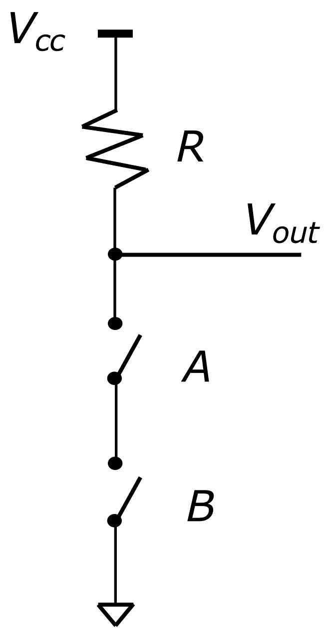


Most electronic circuits use signals that are within 5 to 10 volts of ground; in recent years, circuit signals are within 1 to 5 volts of ground.



Stopped here

Drop the LED from AND circuit and take the voltage from the resistor as the output:



A	B	V_{out}
open	open	high
open	closed	high
closed	open	high
closed	closed	low

A	B	V_{out}
0	0	1
0	1	1
1	0	1
1	1	0

Convention:

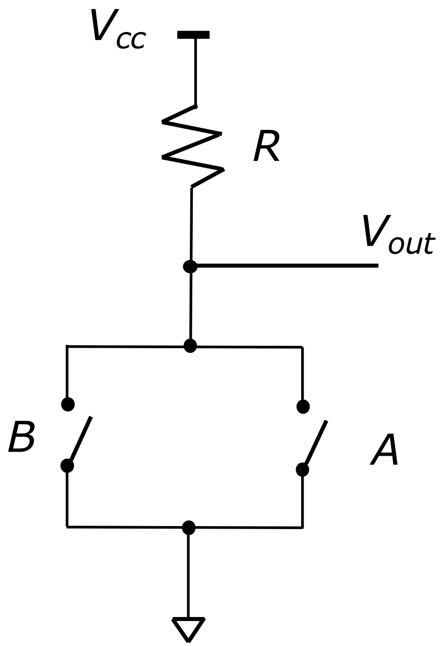
Open: 0
Closed: 1

Low voltage: 0
High voltage: 1

This circuit does not implement *AND*, rather it implements inverted *AND*, *NOT-AND*, or *NAND* logic operation!

NOR

Drop the LED from the OR circuit and take the voltage from the resistor as the output:



A	B	V_{out}
open	open	HV
open	closed	LV
closed	open	LV
closed	closed	LV

A	B	V_{out}
0	0	1
0	1	0
1	0	0
1	1	0

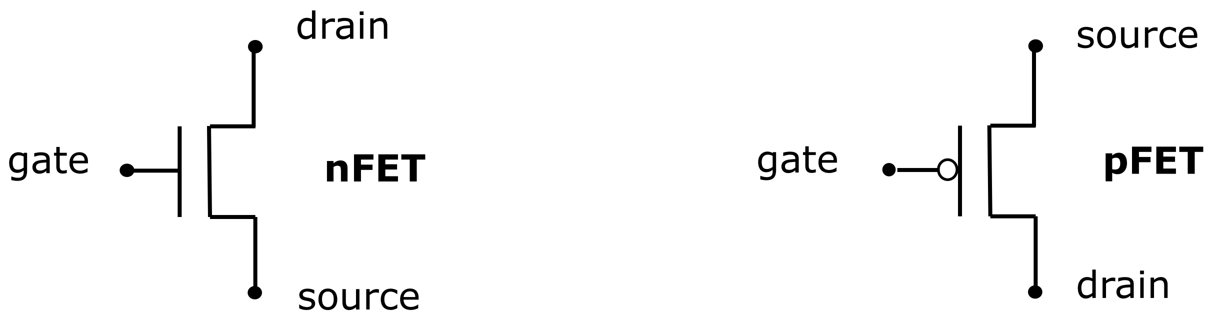
This circuit does not implement *OR*, rather it implements inverted *OR*, *NOT-OR,* or *NOR* logic operation!

Digital electronic circuits are built from electronic switches that are called transistors instead of the mechanical switches and resistors.

The basic concept is the same—the switches (*transistors*) are arranged so that they can be turned on or off by signals carrying either LV or HV.

The transistor switches used in modern digital circuits are called "Metal Oxide Semiconductor Field Effect Transistors", or *MOSFETs*(or just *FETs*).

FETs are three terminal devices that can conduct current between two terminals (the source and the drain) when a third terminal (the gate) is driven by an appropriate logic signal.



In the simplest *nFET* model (which is appropriate for our use here), the electrical resistance between the source and the drain is a function of the gate voltage—the higher the gate voltage, the lower the resistance (and therefore, the more current that can flow).

In analog circuits (like audio amplifiers), the gate voltage is allowed to assume any voltage between *GND* and V_{dd} .

In digital circuits, the gate voltage is constrained to be either *HV* (close to V_{dd}) or low voltage (close to *GND*).

Of course, when the gate voltage changes from *HL* to *LV* or vice-versa, it must necessary assume voltages between *HL* and *LV* —we assume that this happens infinitely fast, so that we can ignore *FET* characteristics during the time the gate voltage is switching.

All matter is made up of atoms that contain both positively and negatively *charged particles* (protons and electrons).

A *coulomb* is a measure of charge derived (in a somewhat circular fashion) from a measurement of electric current.

> One coulomb of charge is transferred by one ampere of current in one second
>
> To get a matter of scale, one coulomb of charge flows through a 120W light bulb in one second.

If one coulomb of protons could be isolated and held one meter apart from one coulomb of electrons, an attractive force (given by *Coulombs law*) of 8.988×10^9 Newton, equivalent to almost one million tons at the earth's surface, would exist between them.

It is this large intra-particle force that is harnessed to do work in electric circuits.

Voltage

The potential electrical energy available in the power supply, measured in volts, is determined by the number of electrons it can store, the separation distance between negative and positive materials, the properties of the barrier between the materials, and other factors.

Some power supplies (like small batteries) output less than a volt, while others (like power generation stations) can output tens of thousands of volts.

In general, power supplies of up to 9V – 12V are considered “safe” for humans to interact with, but some people can have adverse (and potentially fatal) interactions with even low-voltage supplies.

In our work, we will not encounter any supplies above 5V.

The lines leaving the positive and negative sides of the power supply represent conductors with an insignificant amount of resistance.

Thus, the voltage delivered by the power supply is present at both sides of the resistor (3.3V) at the left side of the resistor, and 0V (GND) and the right side of the resistor.

As current flows through the resistor, collisions occur between the electrons flowing from the power supply and the materials in the resistor.

These collisions cause electrons to give up their potential energy, and that energy is dissipated as heat.

Skip

Power

In electric circuits, power (measured in Watts) is defined as voltage times current:

$$P = V \cdot I$$

The power transferred to the resistor at any given time results in resistor heating. The more power transferred to the resistor, the hotter it gets.

For a given voltage, a smaller-valued resistor would allow more current to flow (see Ohm's law), and therefore more energy would be dissipated as heat.

~~Sp~~ skip

Energy

The total energy consumed in an electric circuit is simply the time integral of power, measured in Watts per second, or Joules. If the power *P* is constant, than the energy delivered in time *t* is:

$$E = P \cdot t$$

Thus, in the previous circuit, the electric power delivered to the resistor is:

$$P = 3.3V \cdot 1A = 3.3\ Watts$$

Energy dissipated in 1 second:

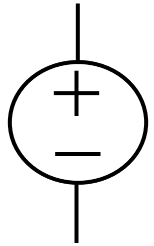
$$E = 3.3W \cdot 1second = 3.3\ J$$

Many devices can provide only limited current; if your circuit draws too much current from the device, it can malfunction.

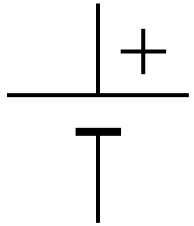
Increasing the resistance in your circuit may solve this problem.

Voltage sources provide operating power to digital circuits, in the form of batteries or power supply units connected to the mains supply.

Constant voltage source:



Battery:

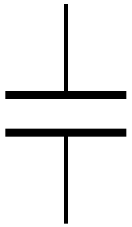


An ideal voltage source maintains the constant voltage difference between its terminals regardless of the current flowing through them.

Real voltage sources used as power supplies can only do that for a limited range of current flow. Within that range, the voltage is approximately constant within specified bounds.

However, once the current exceeds a specified limit, the power supply may either reduce the voltage or fail.

Capacitor is a component that stores the electric charges and thus stores energy.



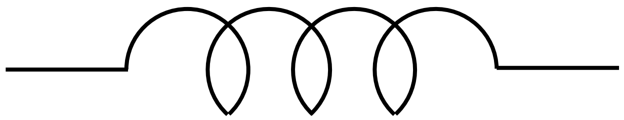
Capacitor conceptually consists of two plates, separated by an insulator. One plate contains positive charge, the other one negative. This results in a voltage across the plates.

The relationship between the stored charge (Q), voltage (V) and capacitance (C):

$$Q = C \cdot V$$

Capacitance C is measured in Farads (F). One F is a very large capacitance, in digital circuits we usually use capacitors from a few *pico Farads* ($1pF = 10^{-12} F$) to *mili Farads* ($1mF = 10^{-3} F$).

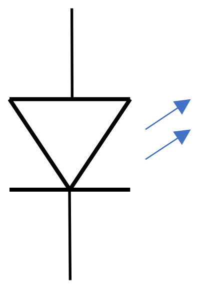
Inductor is a component that stores the electric energy in a form or a magnetic field.



An inductor could be implemented as a helical coil of wire.

Winding the coil around a toroidal core with magnetic permeability confines the field to the core and increases inductivity.

LED is a semiconductor component which passes the current in one direction. If there is enough current, LED will emit light.



A typical current which will activate an LED is about 5 to 10 mA.

The voltage of an LED which is ON, is about 1.5V.

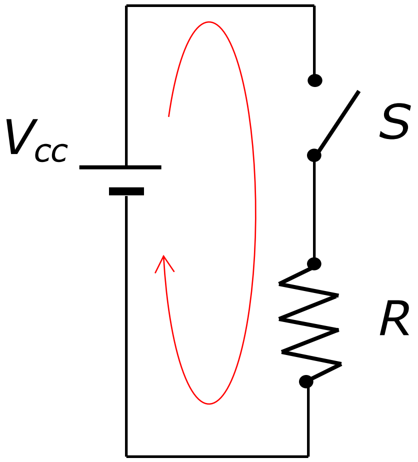
Electronic Circuit

A collection of electronic components that have been assembled and interconnected to perform a given function is commonly referred to as a circuit.

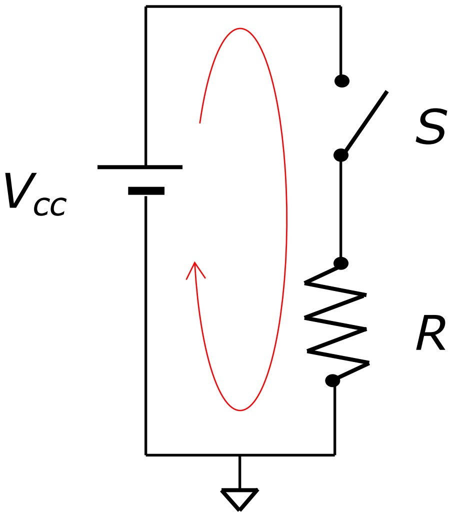
The word circuit derives from the fact that electric power must flow from the positive terminal of a power source through one or more electronic devices and back to the negative terminal of a power source, thereby forming a circuit.

If the connections between an electronic device and either the positive or negative terminals of a power supply are interrupted, the circuit will be broken and the device will not function.

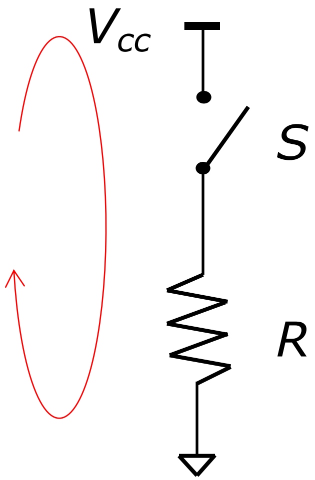
An electronic circuit is formed by connecting a set of components with wires. We consider wires to be ideal, meaning that their resistance is 0, and the voltages across a wire is 0V.



Circuit



Circuit with ground

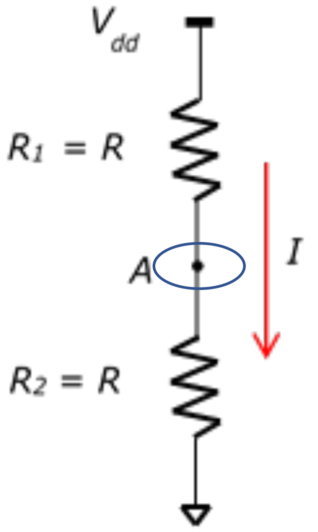


Shorthand notation

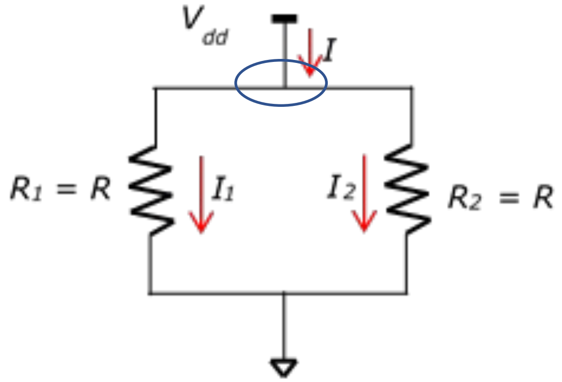
Most electronic circuits use signals that are within 5 to 10 volts of ground; in recent years, circuit signals are within 1 to 5 volts of ground.

At any node (junction) in an electrical circuit, the sum of currents flowing into that node is equal to the sum of currents flowing out of that node.

Examples:



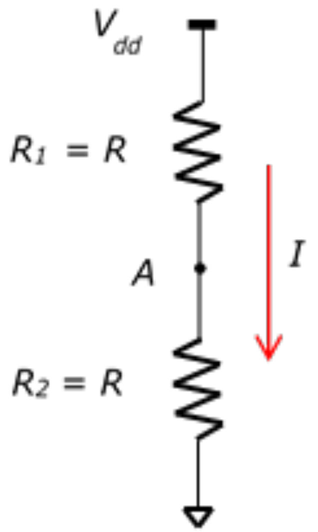
The current flowing into the node A (the current through R1) is the same as the current flowing out (the current through R2)



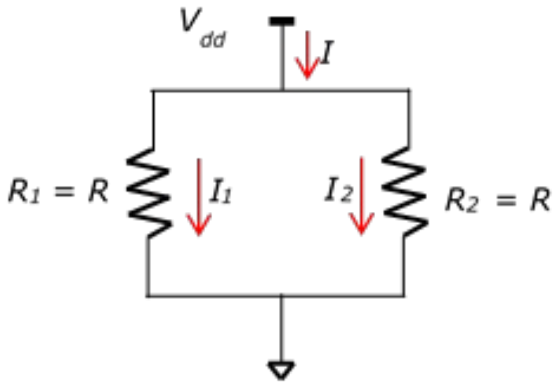
$I = I_1 + I_2$

The algebraic sum of the voltages across resistances in a closed loop is equal to the total voltages of power supplies available in that loop.

Examples:



$V_{dd} = V_{R1} + V_{R2}$



$V_{dd} = V_{R1} = V_{R2}$

Mechanical switch:

Closed: represents logic 1

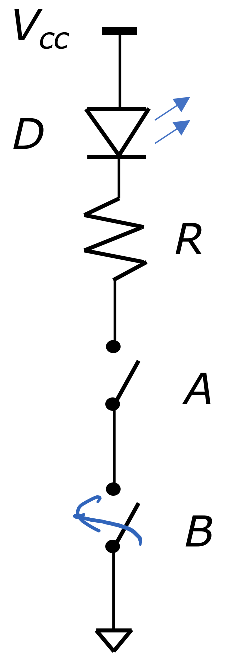
Open: represent logic 0

LED:

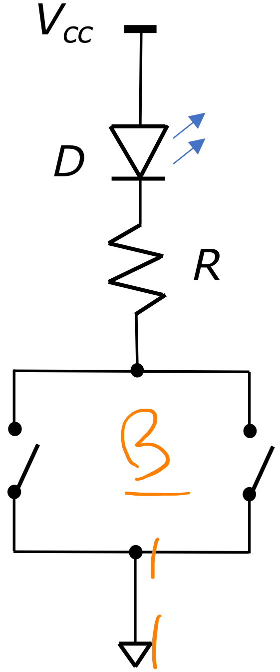
There is current: LED lights (ON)

No current: LED does not light (OFF)

A	B	D
C	C	ON
O	C	OFF
C	O	OFF
O	O	OFF



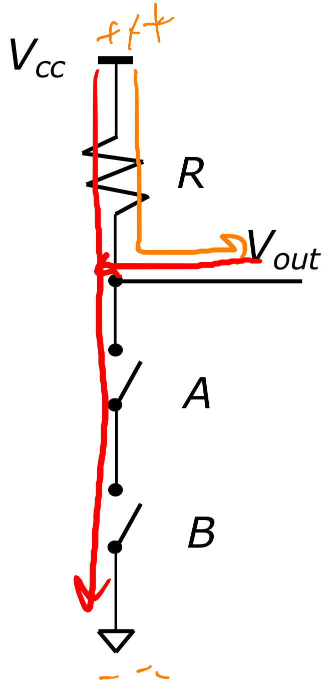
A circuit which implements *AND* operation.



A	B	D
1	1	1
0	1	0
1	0	0
0	0	0

A circuit which implements *OR* operation.

Drop the LED from AND circuit and take the voltage from the resistor as the output:



A B Vout

open open Vcc

A	B	V_{out}
open	open	high
open	closed	high
closed	open	high
closed	closed	low

closed closed GND

A	B	V_{out}
0	0	1
0	1	1
1	0	1
1	1	0

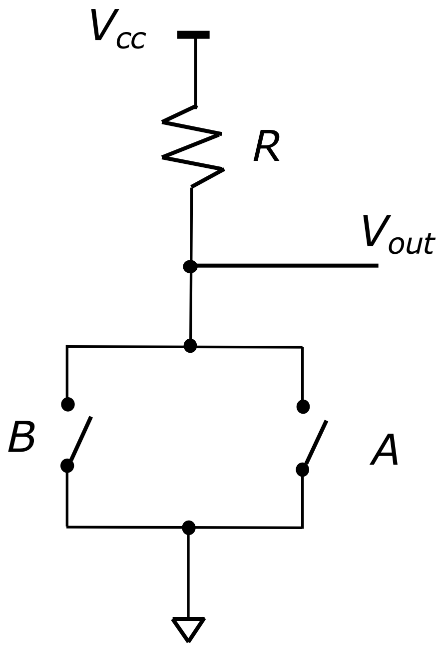
Convention:

Open: 0
Closed: 1

Low voltage: 0
High voltage: 1

This circuit does not implement *AND*, rather it implements inverted *AND*, *NOT-AND*, or *NAND* logic operation!

Drop the LED from the OR circuit and take the voltage from the resistor as the output:



A	B	V_{out}
open	open	HV
open	closed	LV
closed	open	LV
closed	closed	LV

A	B	V_{out}
0	0	1
0	1	0
1	0	0
1	1	0

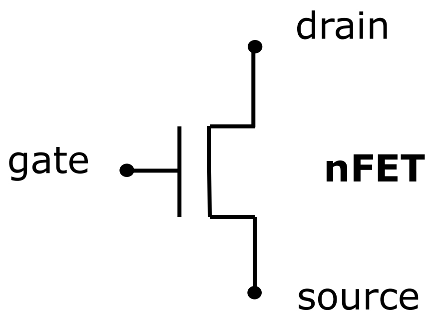
This circuit does not implement *OR*, rather it implements inverted *OR*, *NOT-OR,* or *NOR* logic operation!

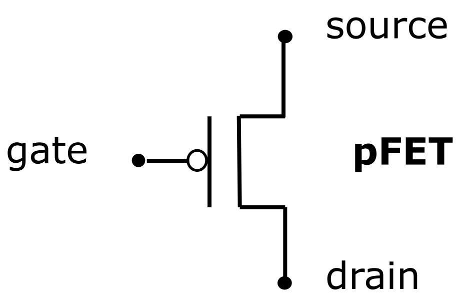
Digital electronic circuits are built from electronic switches that are called transistors instead of the mechanical switches and resistors.

The basic concept is the same—the switches (*transistors*) are arranged so that they can be turned on or off by signals carrying either LV or HV.

The transistor switches used in modern digital circuits are called “Metal Oxide Semiconductor Field Effect Transistors”, or *MOSFETs*(or just *FETs*).

FETs are three terminal devices that can conduct current between two terminals (the source and the drain) when a third terminal (the gate) is driven by an appropriate logic signal.





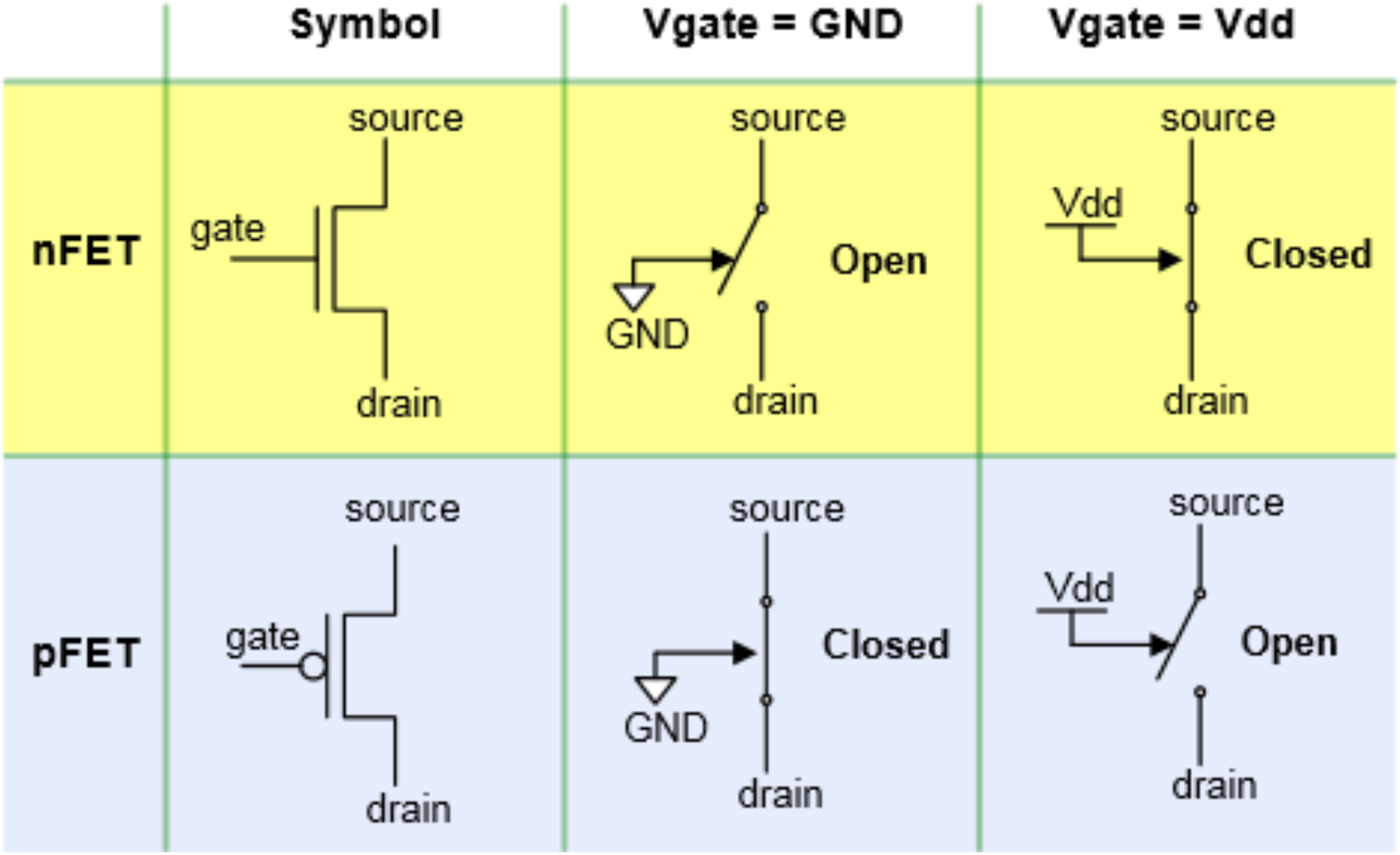
In the simplest *nFET* model (which is appropriate for our use here), the electrical resistance between the source and the drain is a function of the gate voltage—the higher the gate voltage, the lower the resistance (and therefore, the more current that can flow).

In analog circuits (like audio amplifiers), the gate voltage is allowed to assume any voltage between *GND* and V_{dd} .

In digital circuits, the gate voltage is constrained to be either *HV* (close to V_{dd}) or low voltage (close to *GND*).

Of course, when the gate voltage changes from *HL* to *LV* or vice-versa, it must necessary assume voltages between *HL* and *LV* —we assume that this happens infinitely fast, so that we can ignore *FET* characteristics during the time the gate voltage is switching.

FET as a switch



Switching Mode of MOS FET Operation

We use MOS FETs in the switching mode of operation, meaning they are either in the state *ON* of state *OFF*.

ON:

The resistance between drain and source is very low, several *100 ohms*. If we look at the MOS FET as switch, we say that the switch is closed, and we approximate MOS FET with a short circuit between drain and source.

OFF:

The resistance between drain and source is very high, *100 Mohms*. If we look at the MOS FET as switch, we say that the switch is open, and we approximate MOS FET with an open circuit between drain and source.

In both of the states, the gate current is very low (pA) and we approximate that the gate current is 0.

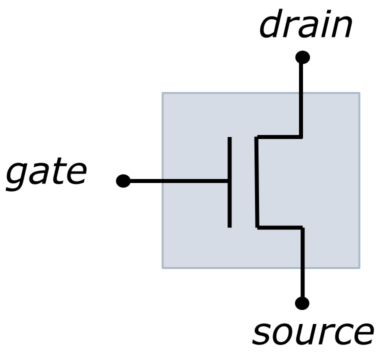
nFET is turned ON by high gate voltage.

pFET is turned ON by low gate voltage.

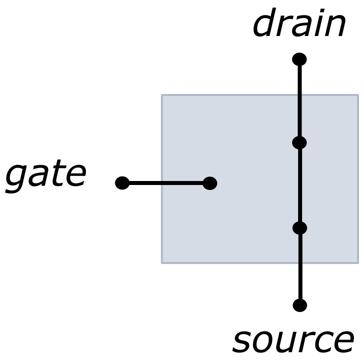
Gate	nFET	pFET
HV	ON	OFF
LV	OFF	ON

Equivalent circuits:

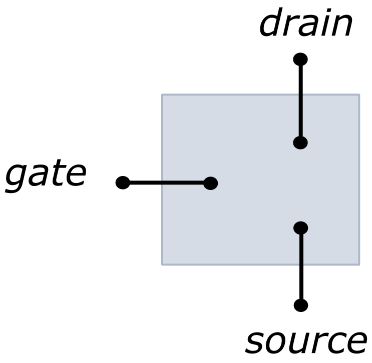
MOS FET:



MOS FET is ON:



MOS FET is OFF:



FETs can be arranged into circuits that perform useful logic functions such as AND, OR, NOT, etc.

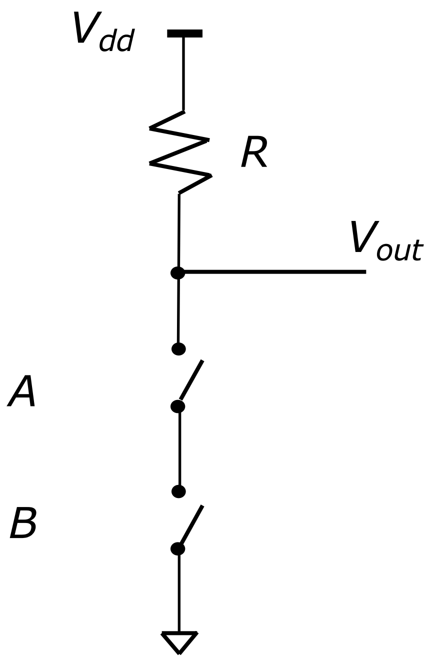
In this application, several very small FETs are constructed on a single small piece of silicon (or chip of silicon) and then interconnected with equally small metal wires.

These microscopic FETs typically occupy an area of less than $1x10^{-7}\ m^2$. Since a silicon chip might measure several millimeters on a side, several millions of FETs can be constructed on a single chip.

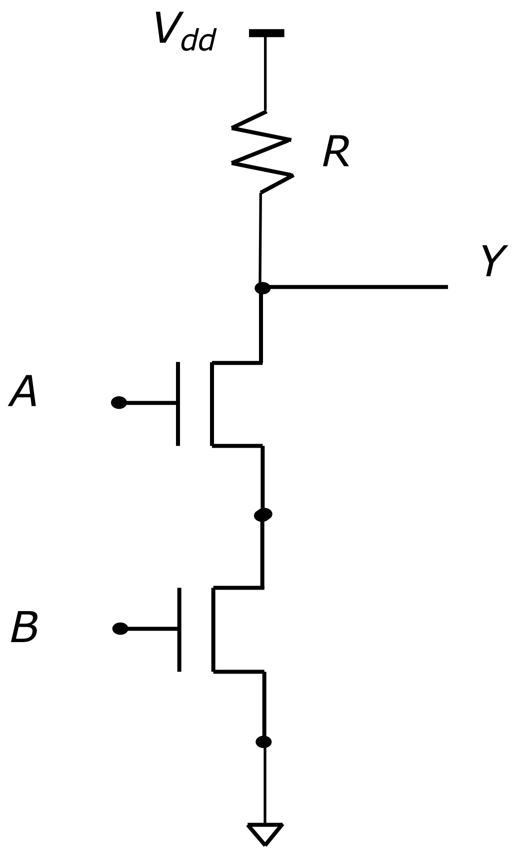
Circuits assembled in this fashion are said to form “integrated circuits” (or IC's), because all circuit components are constructed and integrated on the same piece of silicon.

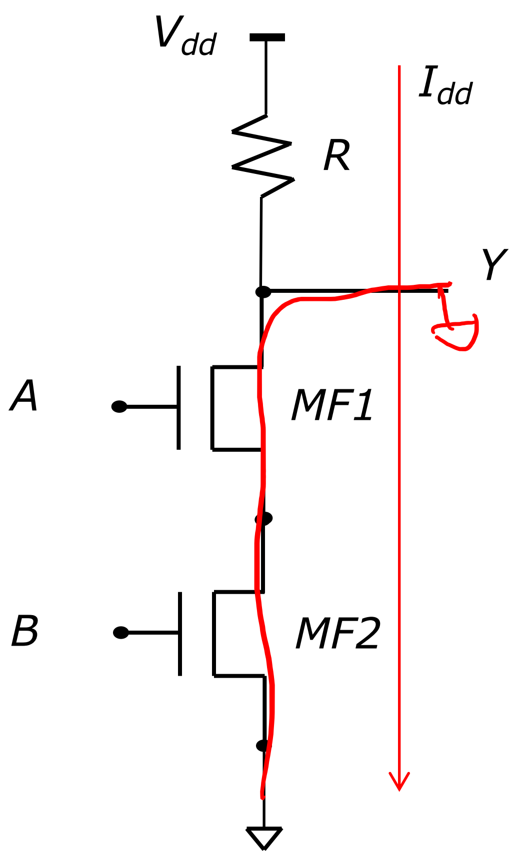
nFET Based NAND Gate

Mechanical switches:



Switches implemented by *nFETs*:





A	B	MF1	MF2	I	Y
LV	LV	off	off	0	HV
LV	HV	off	on	0	HV
HV	LV	on	off	0	HV
HV	HV	on	on	V_{dd}/R	LV

If we interpret HV as logic 1, and LV as logic 0, then we have the truth table:

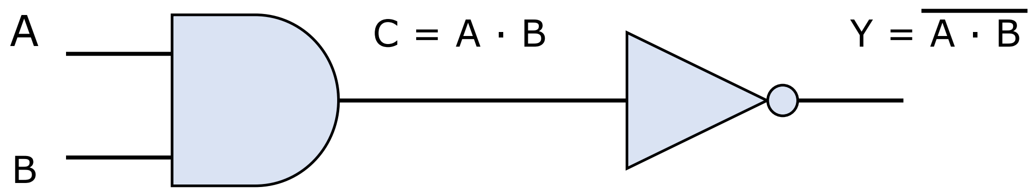
A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

This is inverted AND gate, or NAND gate!

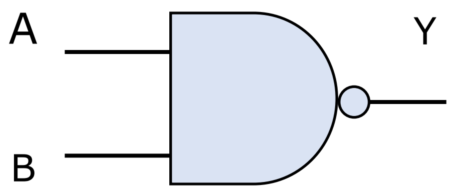
Truth table of a NAND gate:

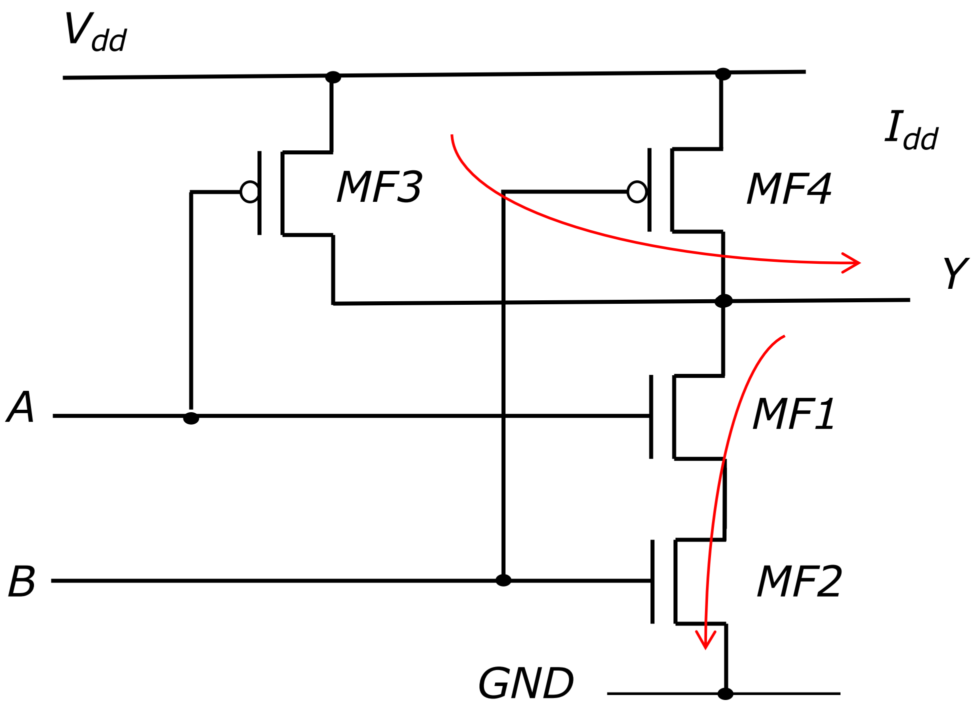
A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

NAND gate is AND followed by NOT gate:



Graphical symbol of NAND gate:





Both nFET and pFET transistors are used to implement the gate.

Advantage: no current from V_{dd} to GND in either state, thus extremely low power dissipation.

A	B	MF1	MF2	MF3	MF4	I	Y
LV	LV	off	off	on	on	0	HV
LV	HV	off	on	on	off	0	HV
HV	LV	on	off	off	on	0	HV
HV	HV	on	on	off	off	0	LV

CMOS Power Dissipation

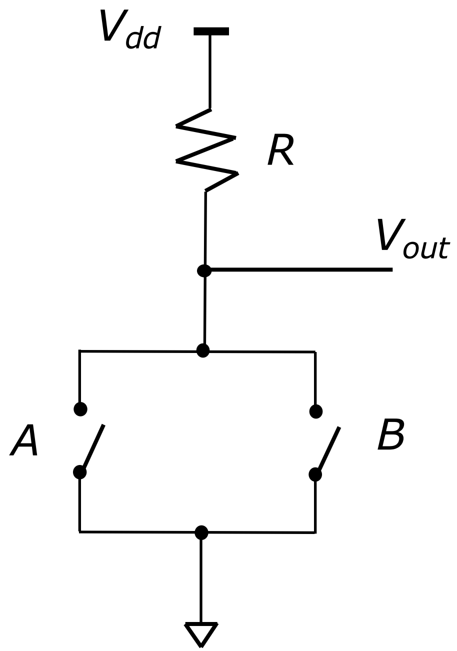
Because there is no current in either state, the CMOS gates have extremely low power dissipation.

Dissipation is due to following effects:

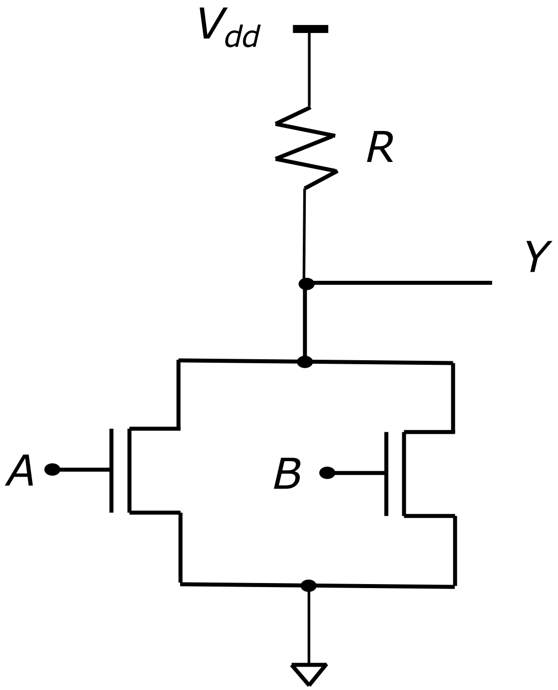
- When the output switches from one logic level to another, there is a short period of time when all output transistors are ON, and the current flows from V_{dd} to GND.
- Gates have some parasitic capacitance, and during the switching of output from one voltage level to another, the output has to charge and discharge gates that are connected to the output.

As the working frequency of CMOS gates increase, so will the power dissipation.

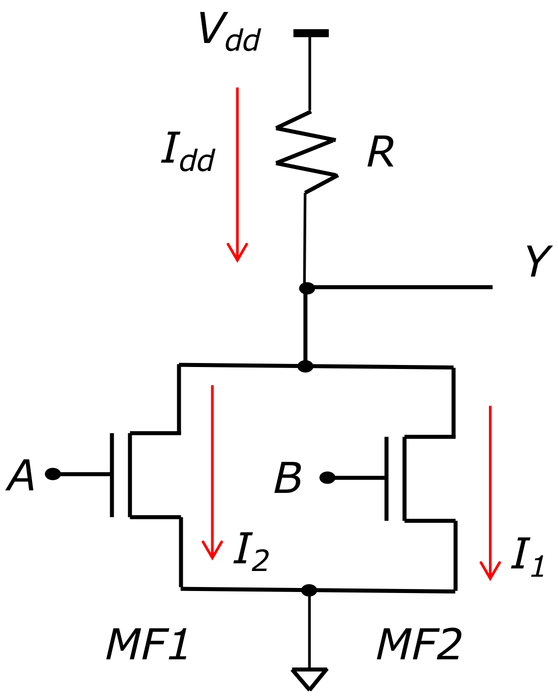
Mechanical:



Switches implemented by nFETs:



Analysis of nFET Based NOR Gate



A	B	MF1	MF2	I	Y
LV	LV	off	off	0	HV
LV	HV	off	on	0	LV
HV	LV	on	off	0	LV
HV	HV	on	on	V_{dd}/R	LV

If we interpret HV as logic 1, and LV as logic 0, then we have the truth table:

A	B	Y
0	0	1
0	1	0
1	0	0
1	1	0

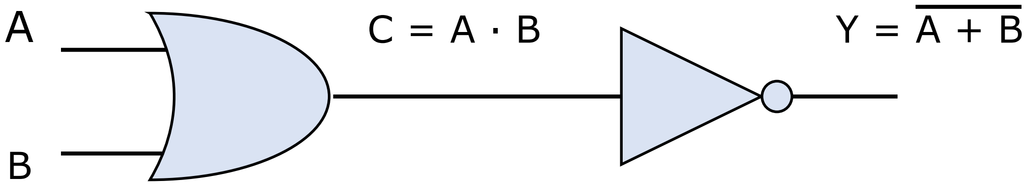
This is inverted OR gate, or NOR gate.

FET Based NOR Gate

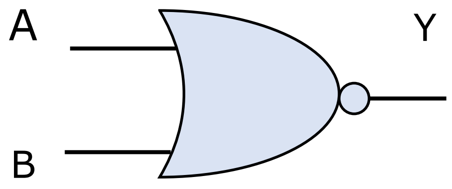
Truth table of a NOR gate:

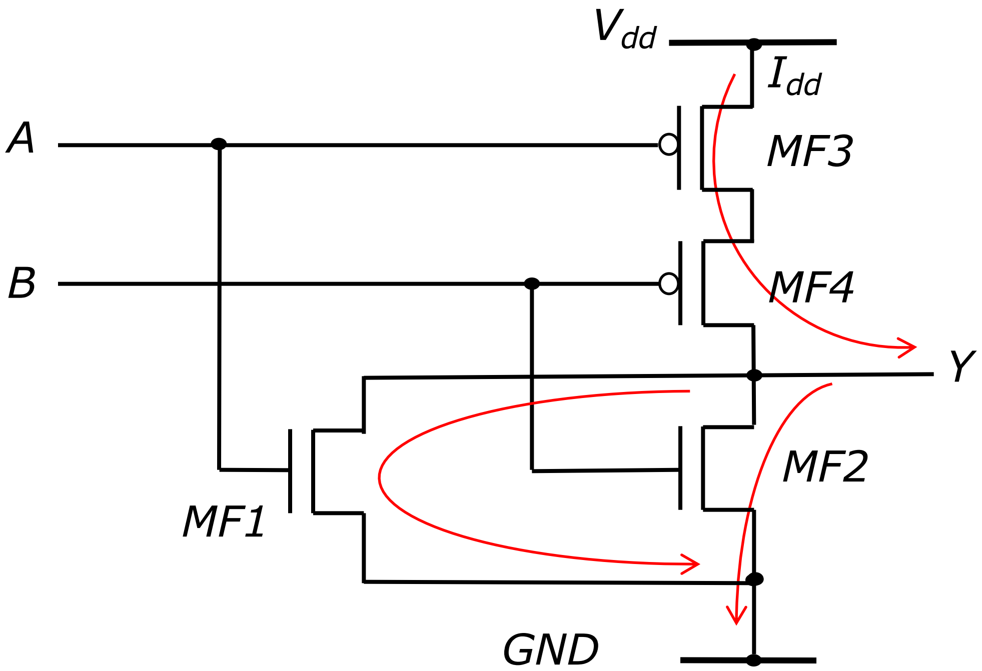
A	B	Y
0	0	1
0	1	0
1	0	0
1	1	0

NOR gate is OR followed by NOT gate:



Graphical symbol of NOR gate:



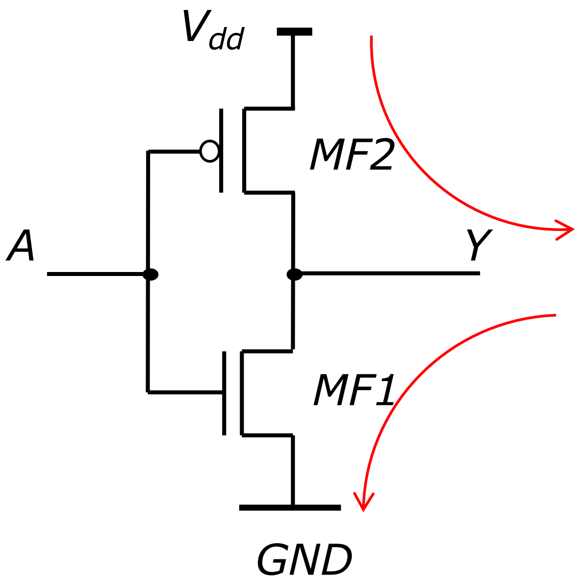


Both *nFET* and *pFET* transistors are used to implement the gate.

Advantage: no current from V_{dd} to *GND* in either state, thus extremely low power dissipation.

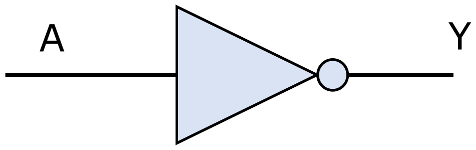
A	B	MF1	MF2	MF3	MF4	I	Y
LV	LV	off	off	on	on	0	HV
LV	HV	off	on	on	off	0	LV
HV	LV	on	off	off	on	0	LV
HV	HV	on	on	off	off	0	LV

CMOS inverter:



A	MF1	MF2	I_{dd}	Y
LV	off	on	0	HV
HV	on	off	0	LV

A	Y
0	1
1	0



$Y = \overline{A} = \sim A = A'$