CSC258 Winter 2016
Computer Organization

Lecture 1

Thanks to Andrew Petersen, Myrto Papadopouplou and Steve Engels for previous course materials.

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Today's outline

- **Why** CSC258
- **What** is in CSC258
- **How** to do well in CSC258

- Start learning

Why take CSC258?

As a computer science student, it is **embarrassing** to not know how a computer works.

You have to take CSC258, then CSC369 to know how computers work.

More specifically…

- Why are computers built with 1's and 0's and boolean logics?
- How does the computer do everything with just 1's and 0's?
- What is stored in that "minecraft.exe" file, what exactly happens when I double-click on it?
- How does the CPU run an if-statement, or for loop, or recursion?

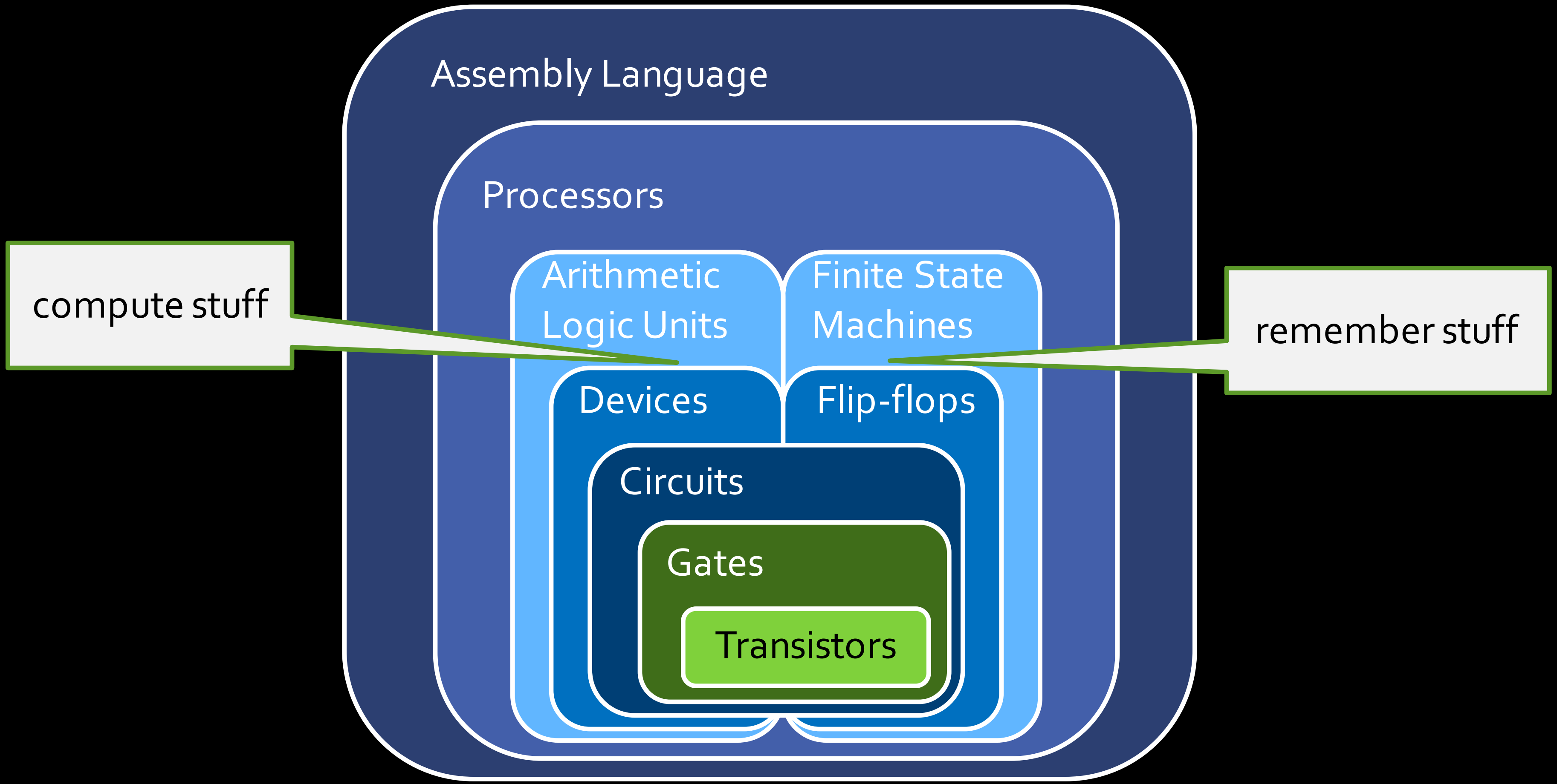
CSC258 has all the answers!

CSC258 Course Goals

- You'll know exactly how a computer is physically built, and you can build one if you want.
- Base on your hardware knowledge, you will be able to engineer the performance of your software like never before.
- Basically, after taking this course, the computer will never look the same to you again.

What's in CSC258?

The architecture of a computer hardware, level by level, bottom-up



We learn the whole real deal

- From atom level to assembly level
- Above the assemblylevel is the Operating System, whose main job is **virtualization**, i.e., create convenient illusions.

- Everything you learn from every CS course are all **illusions** except for **CSC258**

How to do well in CSC258

First of all …

Be interested

Course website

http://www.cs.toronto.edu/~ylzhang/csc258w16/

All course materials are here.

Lectures (Monday 3-5pm, IB-345)

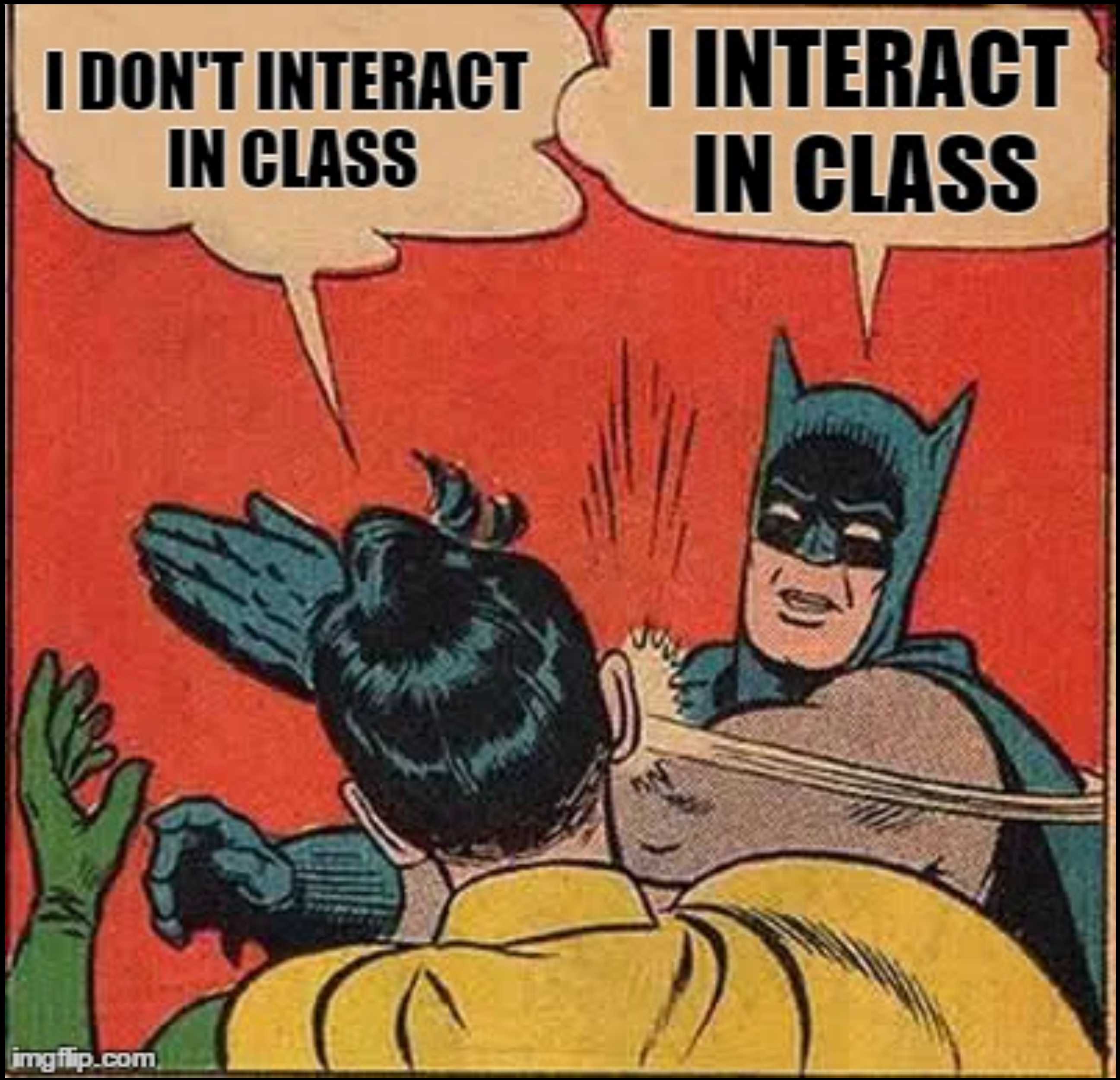
- Learn the concepts and theories.

A tip for lectures

Get involved in classroom interaction

- Answering a question
- Making a guess / bet / vote
- Back-of-envelope calculations

Emotional involvement makes the brain remember better!


I DON'T INTERACT IN CLASS
I INTERACT IN CLASS
imgflip.com

Labs ! (start from Week 2)

- Hands-on exercises in which you will build real pieces of hardware.
- Work in **pairs**.
- ONLY go to the tutorial section that you are registered to on ROSI/ACORN. If you want to switch lab section, find someone who is willing to change (use Piazza) and let me know.
- Most of the labs involve work **before** the lab.
- **Lab marks are NOT easy free giveaways!**

If you are on the waiting list right now, and still hope to get in, send me an email this week to inform me, so I can make arrangement about labs.

Exams !

- Midterm
  - In class 50 minutes, Feb 22
- Final exam
  - Some time in April

Marking scheme

▪ Labs:	4% x 10 = 40%
▪ Midterm:	20%
▪ Final exam:	40%
	100%

Must get 40% of final exam to pass

Bonus Mark!

There is a **quiz** at the end of each week's lecture. About what's learned in this week and/or last week. (start from Week 2)

Each quiz earns you some **points**.

At the end of the terms, bonus marks will be awarded according to the **ranking** of quiz points earned.

Top 20% students gets 3% bonus in final grade; top 50% gets 2% bonus in final grade.

The purpose of this is to give you some incentive to keep up with the lecture material, so that you can succeed in exams.

Discussion board (Piazza)

https://piazza.com/utoronto.ca/winter2016/csc258h5

- All course announcements will be posted on Piazza.
- **Daily** reading is required.

Office hours

Monday 5-6:30pm, priority for CSC258 students
Tuesday 5-6:30pm, priority for CSC309 students
Friday 5-6:30pm, priority for CSC263 students

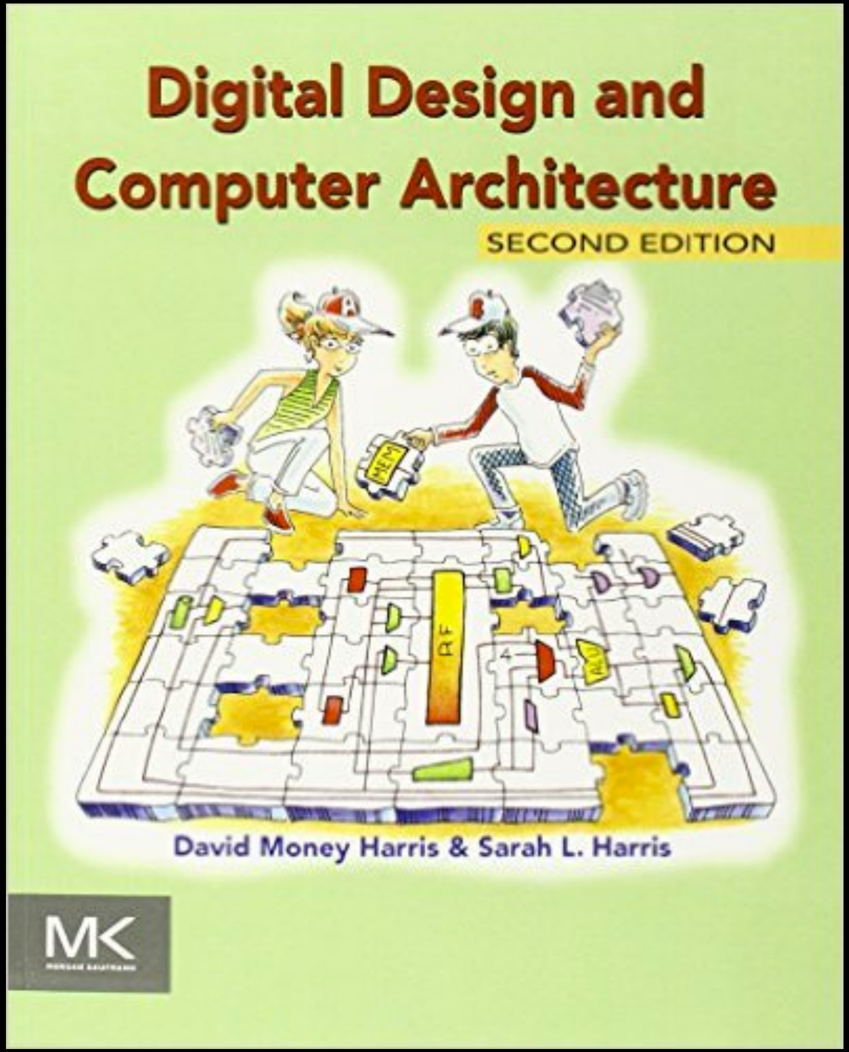
Going to office hours is very helpful, also it is a good habit to foster in college.


Algorithms
GODIVA

Textbook: DDCA

Digital Design and Computer Architecture, 2nd edition, 2012by David Harris, Sarah Harris

Available online at UofT library (link in course info sheet)



Weekly feedback form

http://goo.gl/forms/o248ETWgnS

Good feedbacks directly improves your learning experience.
Have your issues addressed weekly rather than termly.

Checklist: How to do well

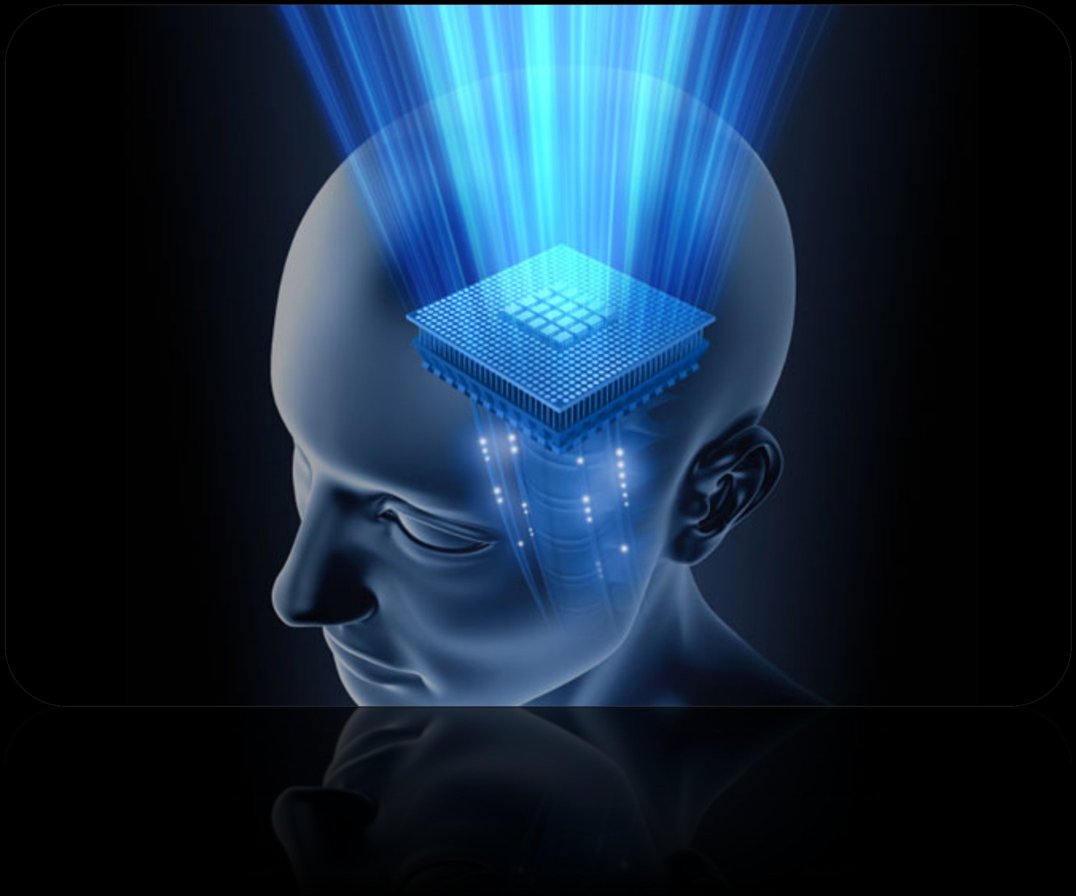
- Be interested
- Check course website and Piazza regularly
- Go to lectures, interact in class
- Be prepared for the quiz
- Read the slides, read the book
- Work hard on the labs
- Go to office hours
- Discuss on Piazza
- Give weekly feedback
- Do well in midterm and final

It will be a lot of work, and a lot of fun!

Let the learning begin

Basic Logic Gates

You already know something…

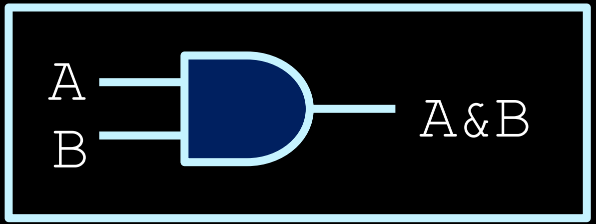


Logic from math course

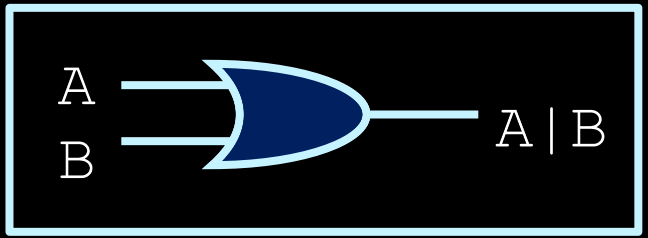
- Create an expression that is true iff the variables `A` and `B` are true, or `C` and `D` are true.

```
G = (A & B) | (C & D)
```

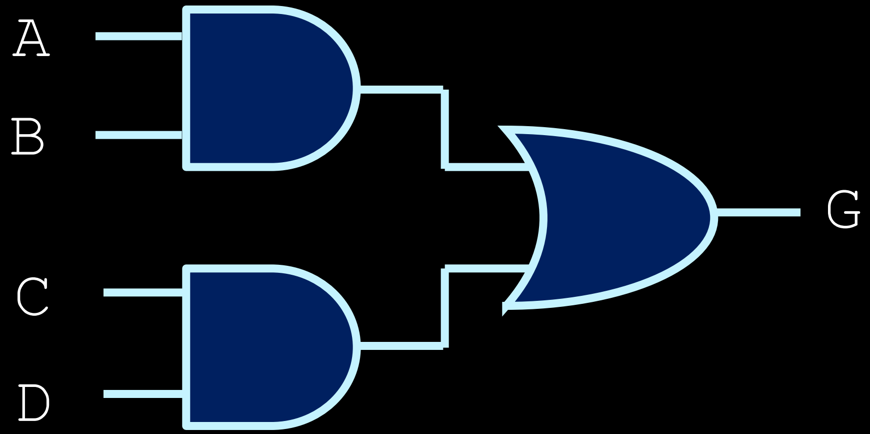
```
G = (A & B) | (C & D)
```



AND Gate



OR Gate



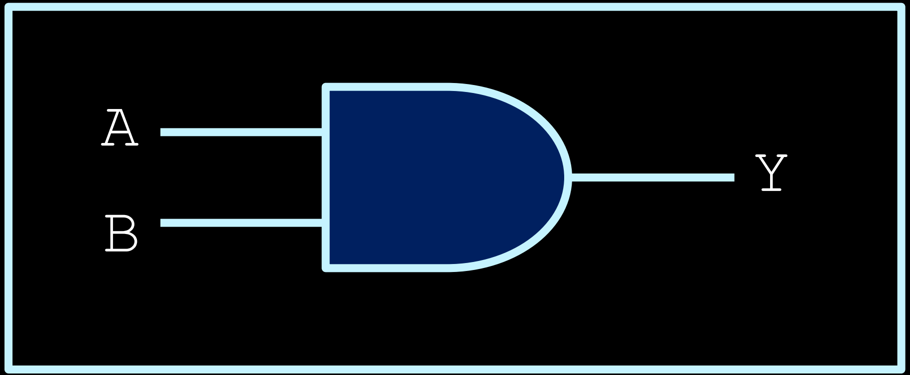
You just designed your first circuit in CSC258!

Gates = Boolean logic

- If we know the logical expression, we already know how to put logic gates together to form a circuit.
- Just need to know which logic operations are represented by which gate!

Let's meet all the gates.

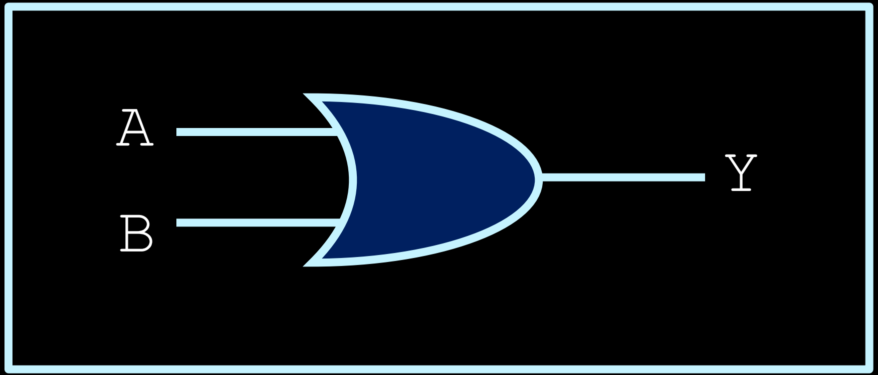
AND Gates



Truth table

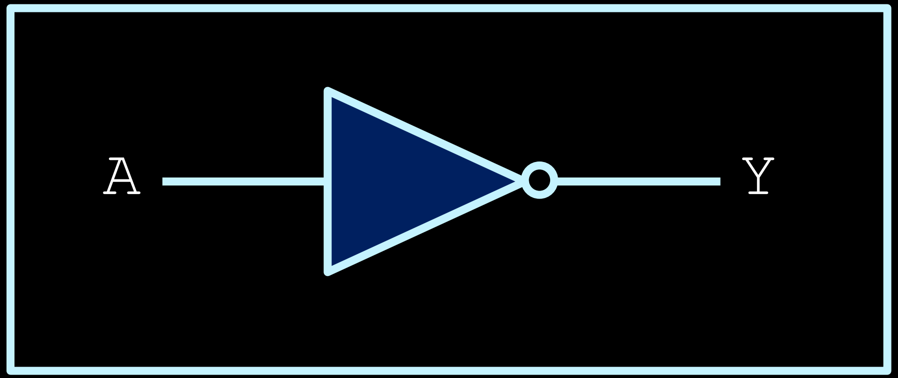
A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

OR Gates



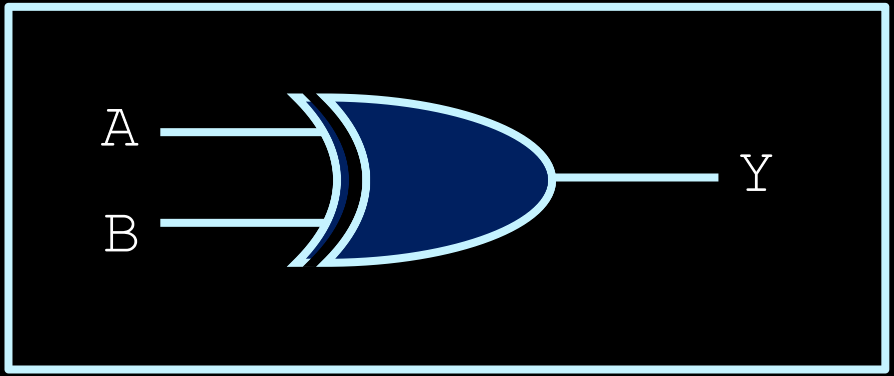
A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

NOT Gates



A	Y
0	1
1	0

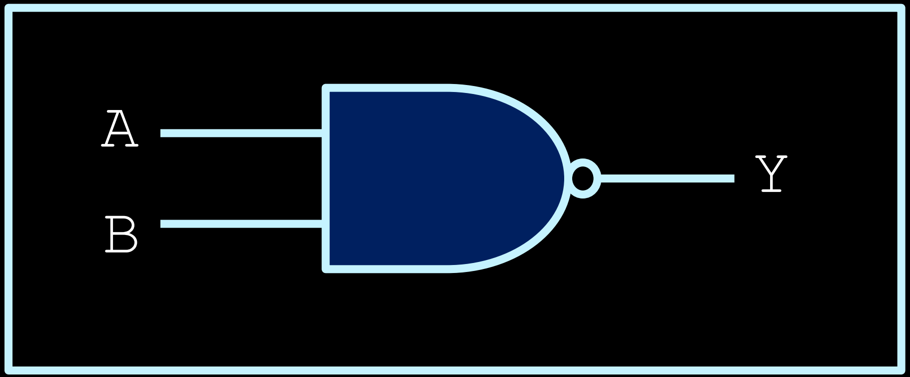
XOR Gates



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

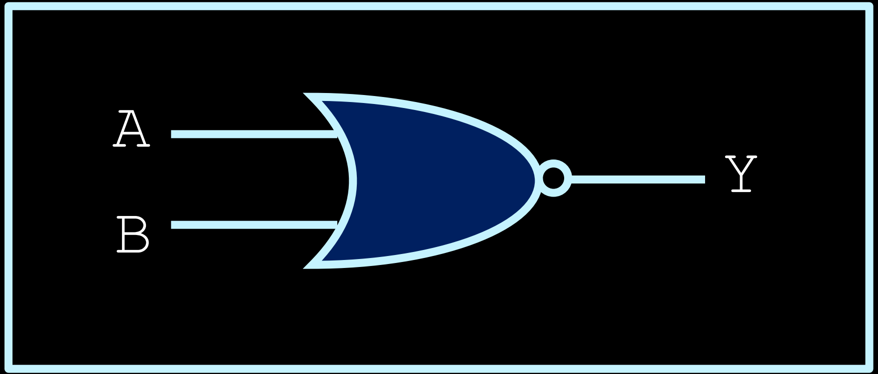
Bill Gates

NAND Gates



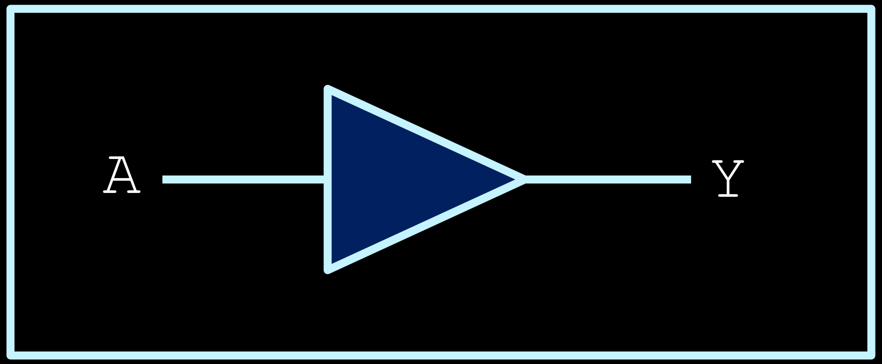
A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

NOR Gates



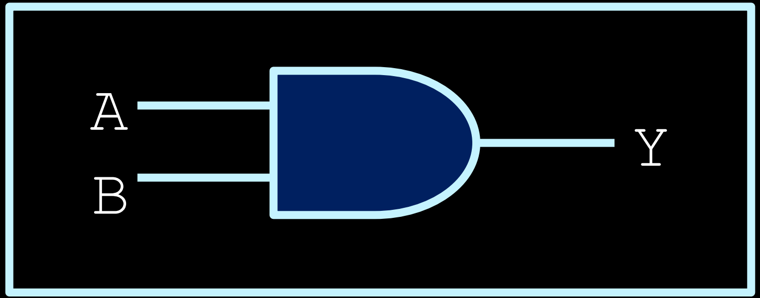
A	B	Y
0	0	1
0	1	0
1	0	0
1	1	0

Buffer

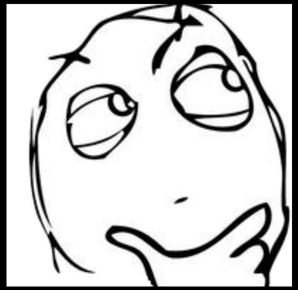


This is not as silly as you might think now, as we'll see later…

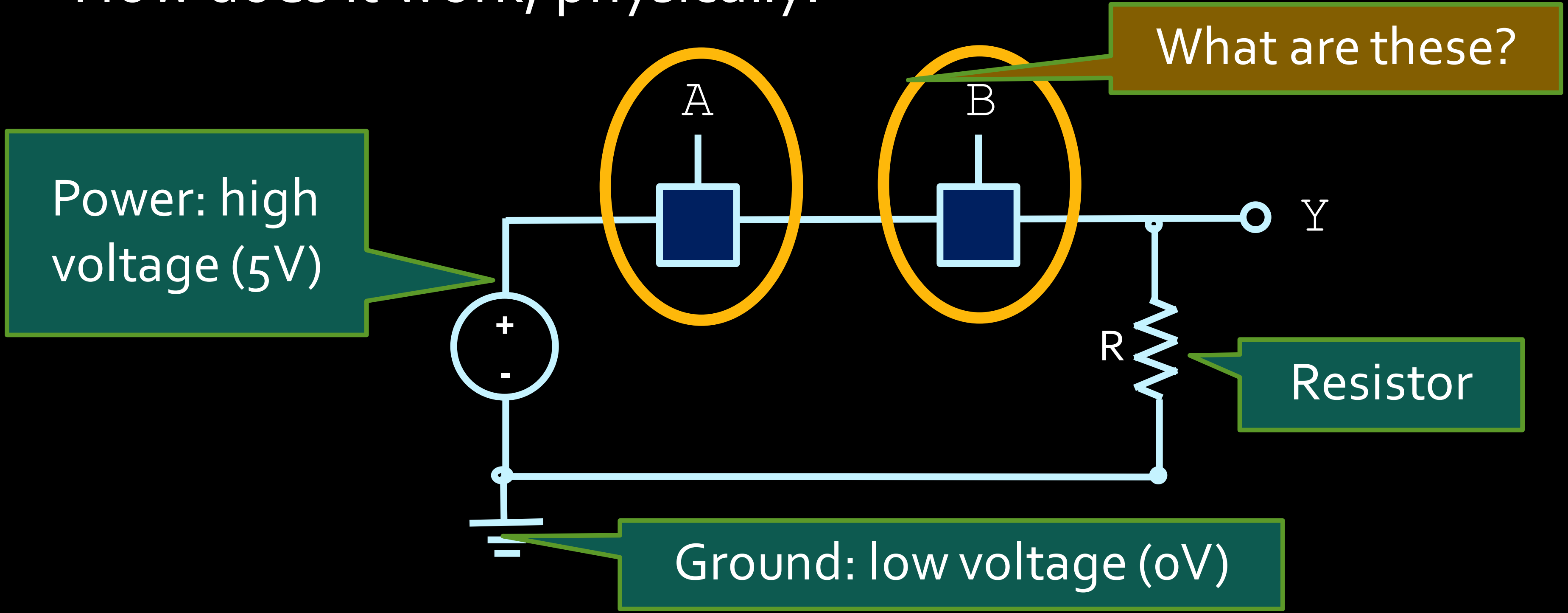
A	Y
0	0
1	1

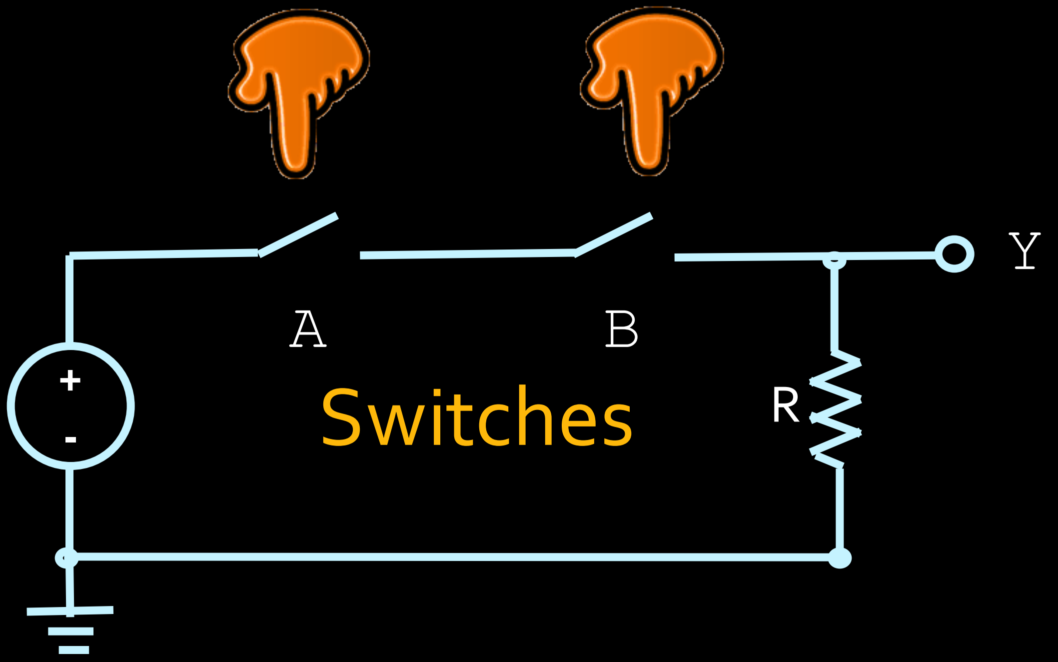


AND Gate



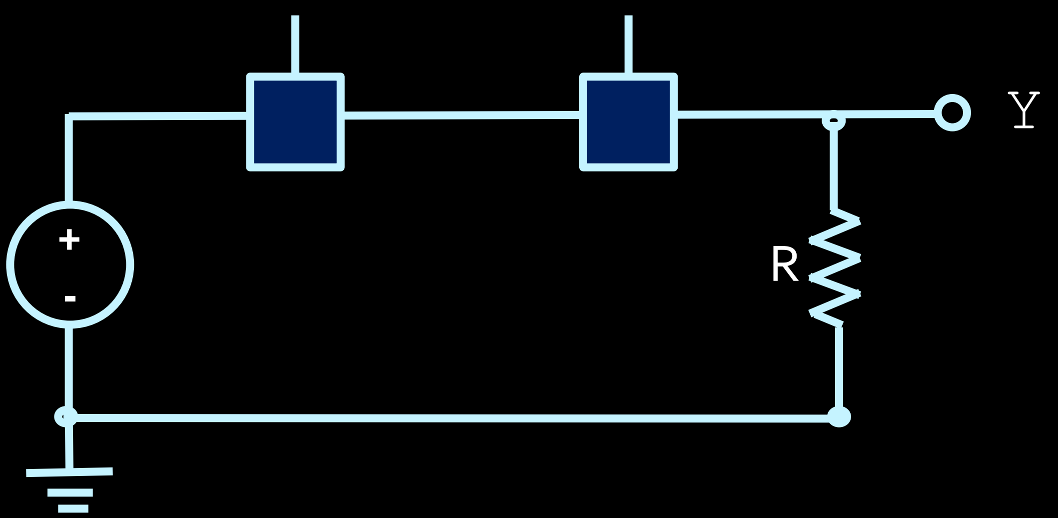
This is just a symbol…
What does it really look like, inside?
How does it work, physically?

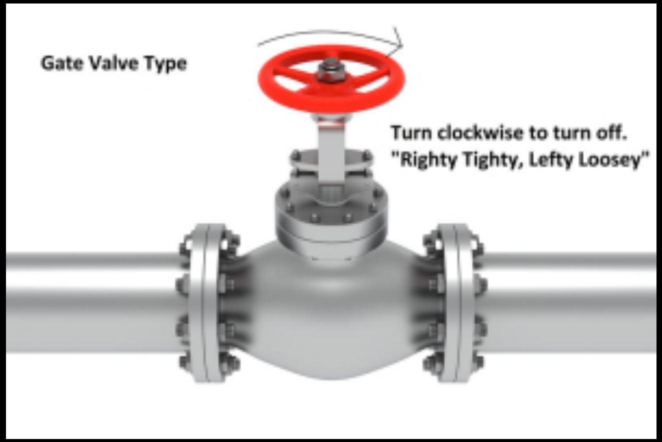




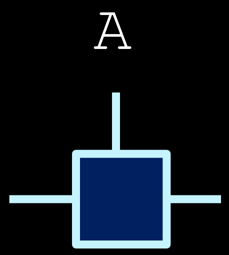
When and only when both A are B are switched **ON**, Y has high voltage.

Gates

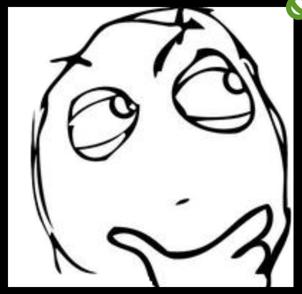




- Gate is like a switch, but controlled by the voltage of the input signal, instead of by a finger.
- Gate A is switched ON when signal A is of high voltage.
- When and only when both A and B have high voltage, Y has high voltage.
- High voltage is 1 (True), low voltage is 0 (False).
- **Y is True iff both A and B are True (Y = A & B).**



Gate is switched ON when signal A is of high voltage …



Why?

How?

What does the inside of a gate look like?

Answer: There are **transistors**.

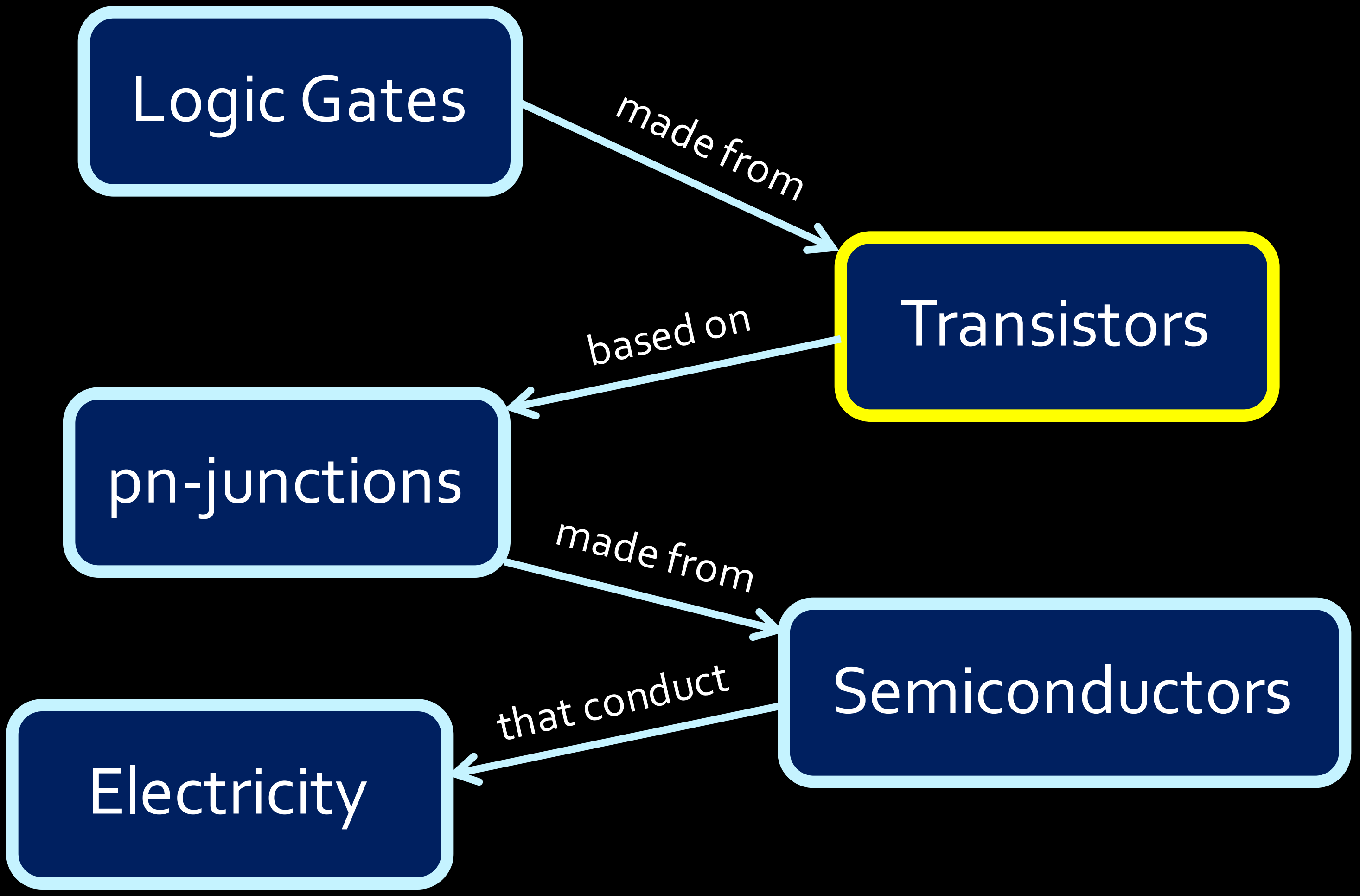
Transistors

One of the greatest inventions of the 20th century

- Invented by William Shockley, John Bardeen and Walter Brattain in 1947, replacing previous vacuum-tube technology.
  - Nobel Prize for Physics in 1956.

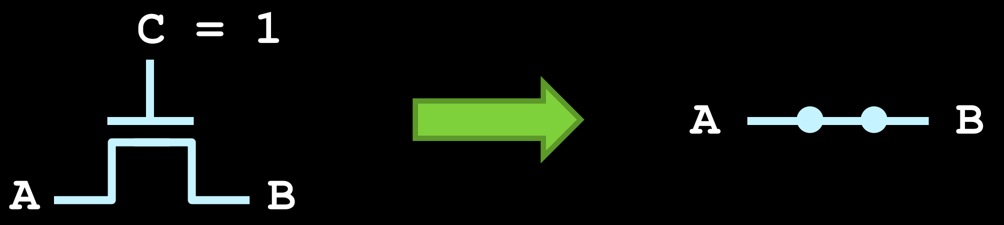
Building block for the hardware of all your computers and electronic devices.

Where do transistors fit?

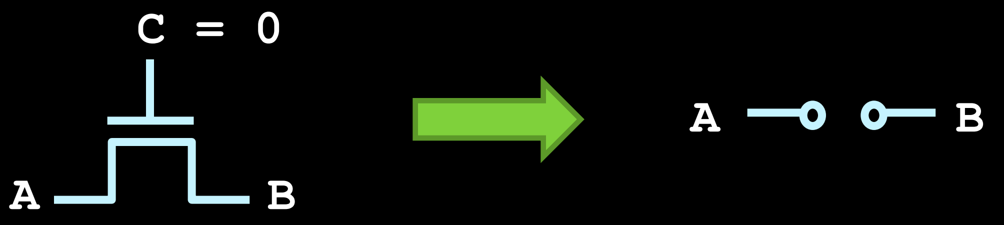


What do transistors do?

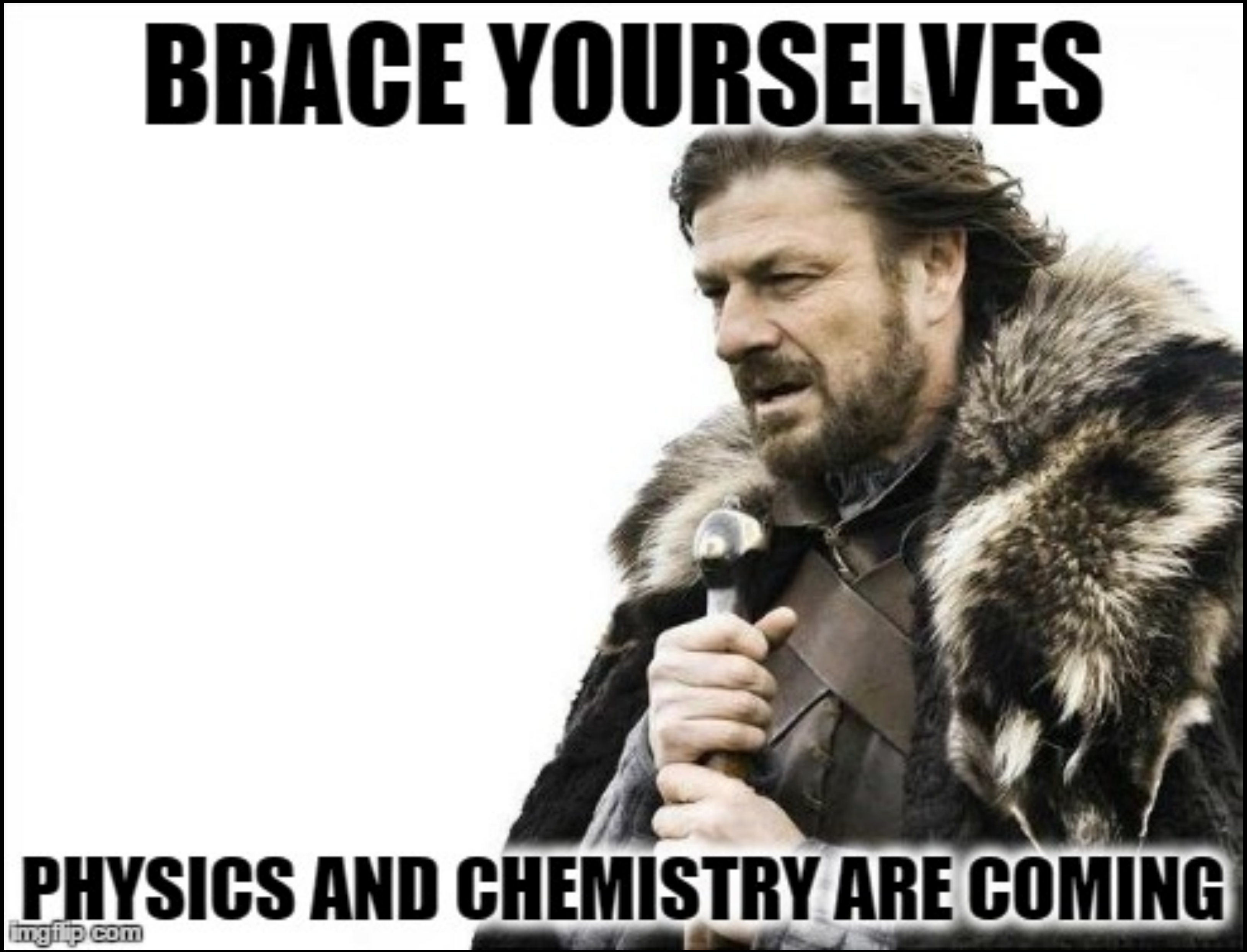
- Transistors connect Point A to Point B, based on the value at Point C.
  - If the value at Point C is high, A and B are connected.



  - And if the value at Point C is low, A and B are not.



  - Need to know a little about electricity now….


BRACE YOURSELVES
PHYSICS AND CHEMISTRY ARE COMING
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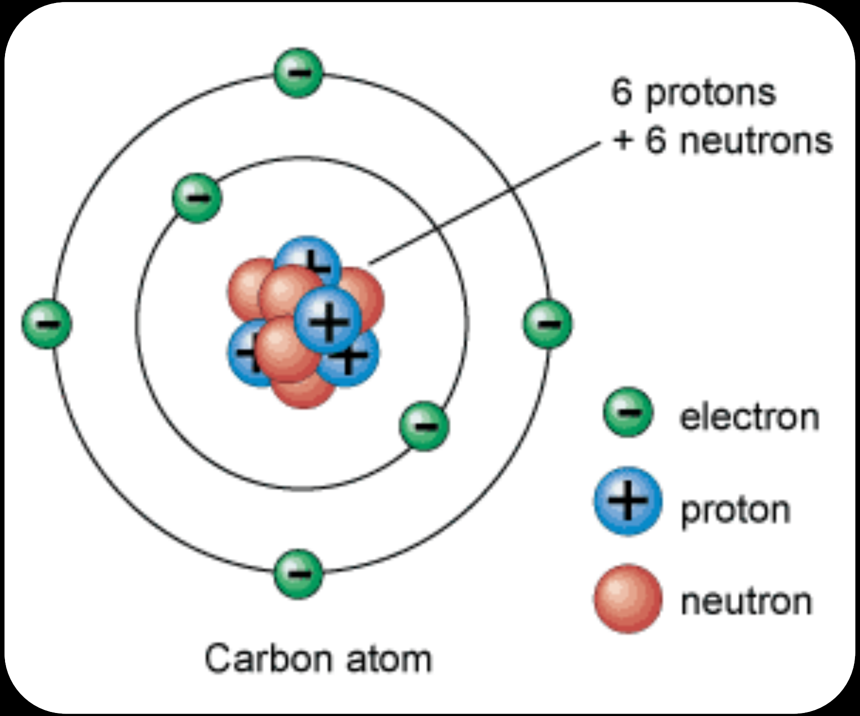
Outline of the story

- Electricity, basic concepts
- Insulators, conductors, in between …, Semiconductors
- Impure semiconductors, p-type / n-type
- Put p-type and n-type together -- pn-junction
- Apply voltage to a pn-junction – principle of transistors
- A real-world manufacturing of transistor -- MOSFET

Electricity Basics

Everything is made out of atoms …

- Protons are big (hardly move) and positively charged.
- Electrons are small (easily move) and negatively changed.
- Neutrons are big and of course, neutral.
- Overall, an atom is neutral.



What is Electricity?

- Electricity is the flow of charged particles (usually electrons) through a material.
  - Electricity could be caused by the flow of protons as well, but since they're so much bigger than electrons, we usually assume that it's the electrons flowing.

How do electrons flow?

They flow …

Keep this analogy in mind…

How do electrons flow?

- Electrons want to flow from regions of high electrical potential (many electrons) to regions of low electrical potential (fewer electrons).
  - Like water flows from high to low.

- This potential is referred to as voltage (V).
- The rate of this flow is called the current (I).
- Resistance (I = V / R) is like how narrow the pipe is.
  - Narrower water pipe has higher resistance.

Note

The direction of the current is opposite to the direction of the electron movement, because electrons are negatively charged.

More on Resistance

- Electrical resistance indicates how well a material allows electricity to flow through it:
  - High resistance (aka insulators) don't conduct electricity at all.
  - Low resistance (aka conductors) conduct electricity well, and are generally used for wires.

- Semiconductors are somewhere in between conductors and insulators, which makes it interesting…

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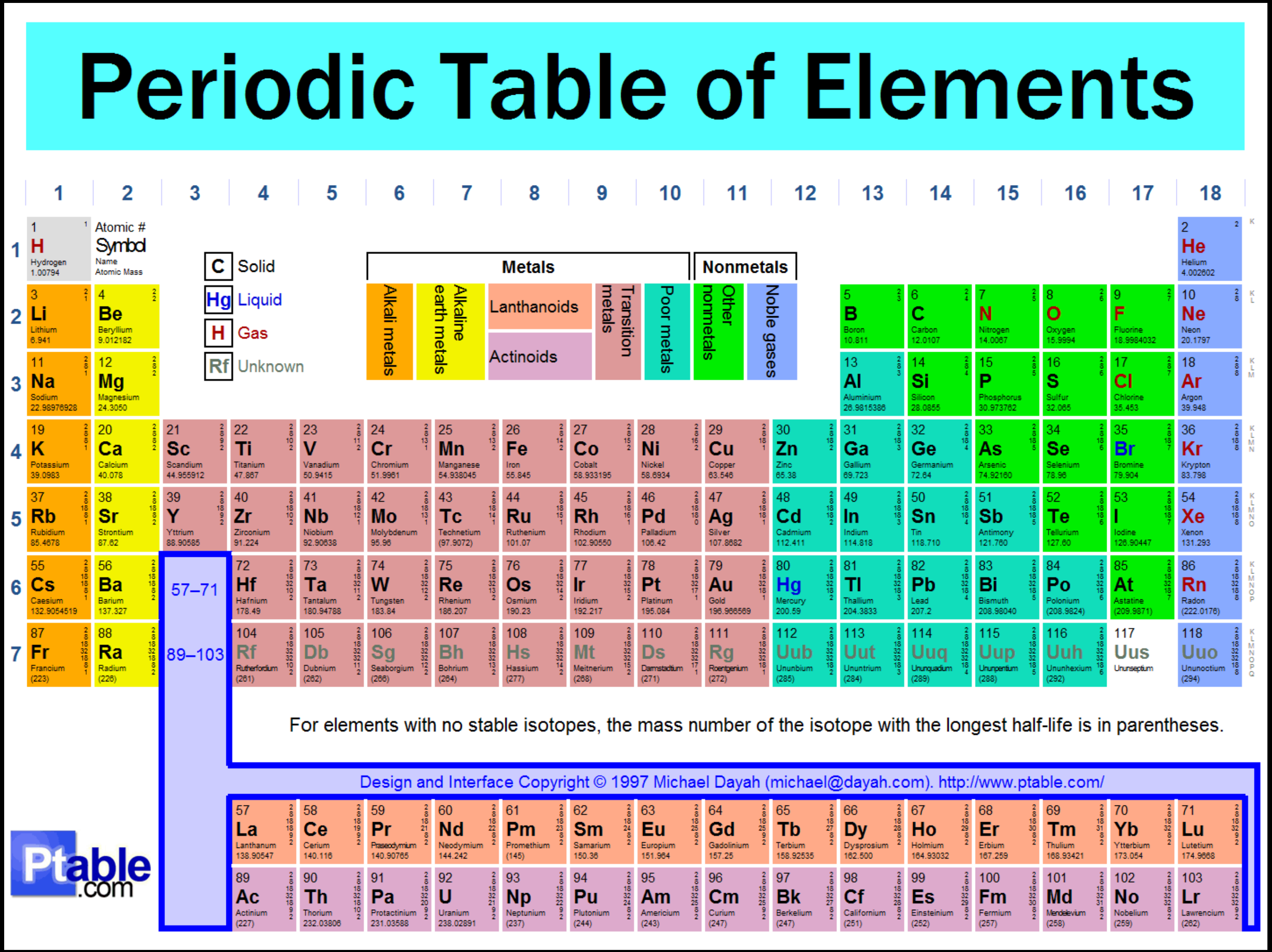
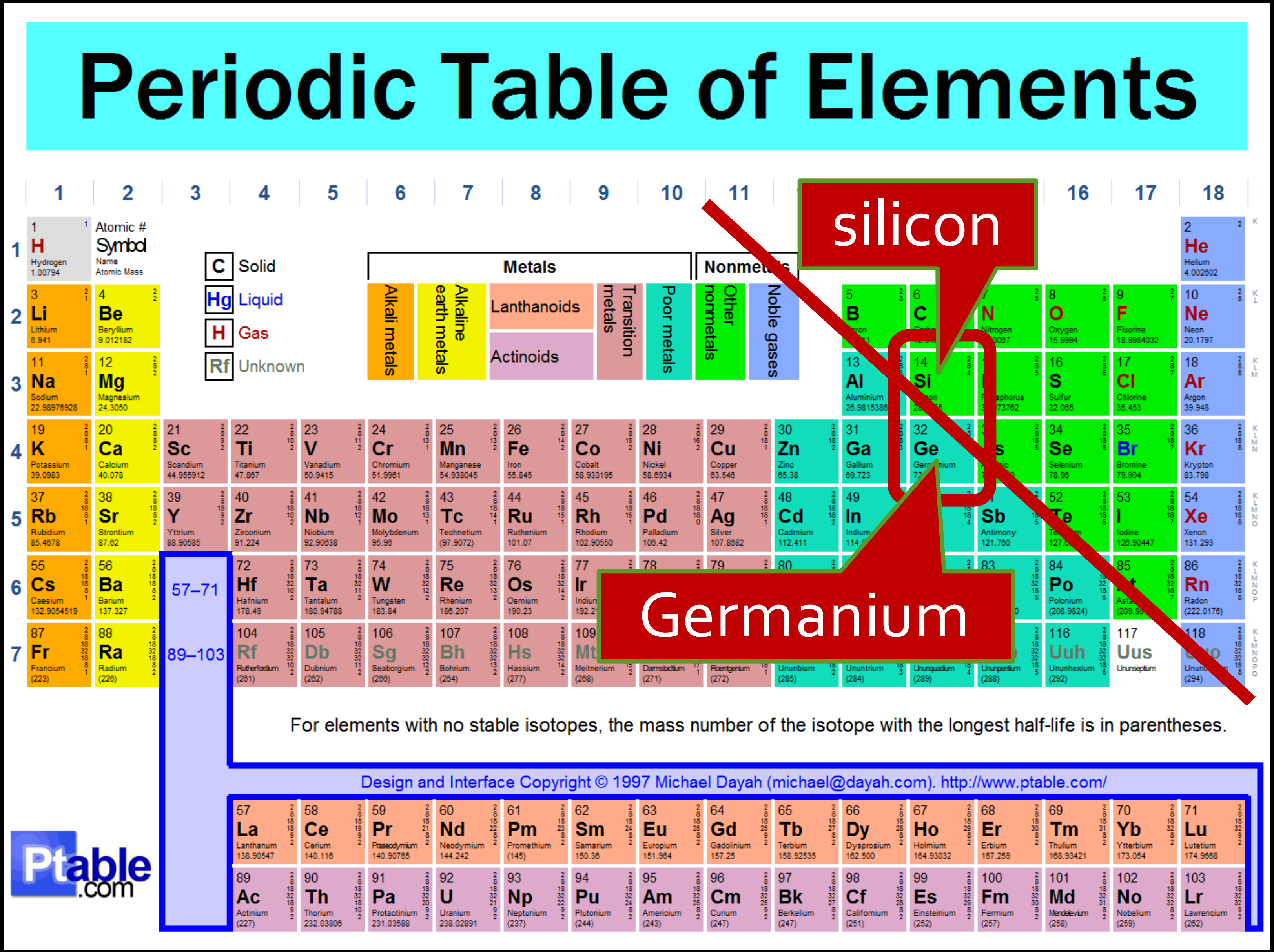
Semiconductors

Here comes the chemistry




Periodic Table of Elements
silicon
Germanium
Atomic #
Symbol
Name
Atomic Mass
C Solid
Hg Liquid
H Gas
Rf Unknown
Metals
Nonmetals
Alkali metals
Alkaline earth metals
Lanthanoids
Actinoids
Transition metals
Poor metals
Other nonmetals
Noble gases
57–71
89–103
For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.
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Conductivity of Semiconductors

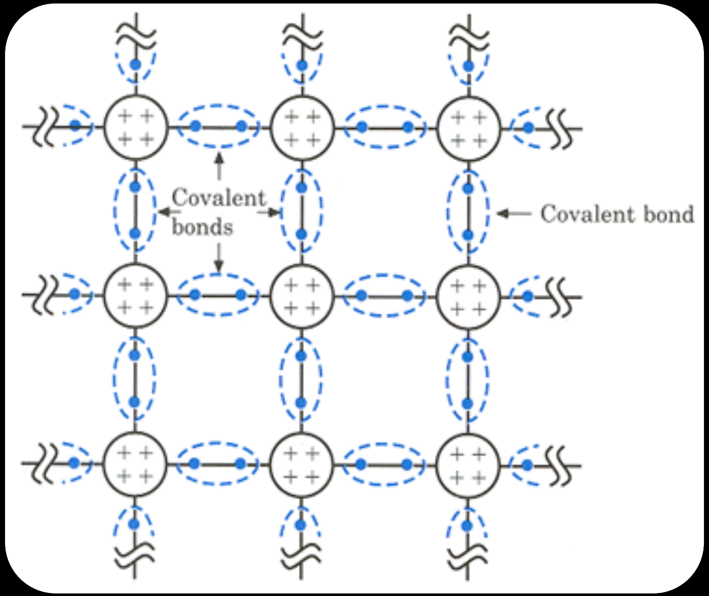
- Semiconductor materials (e.g., silicon and germanium) straddle the boundary between conductors and insulators, behaving like one or the other, depending on factors like temperature and impurities in the material.

Impurity

Pure semiconductor is pretty stable

- Each atom has 4 electrons, forming bonds with other atoms, and the structure is pretty stable.

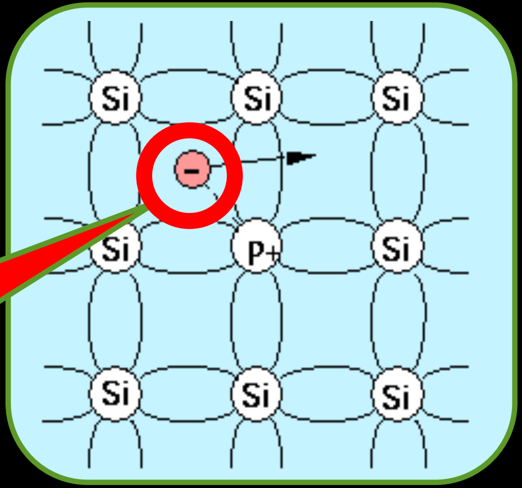
- At room temperature, a weak current will flow through the material, much less than that of a conductor.



Encourage semiconductor's conductivity

N-type:

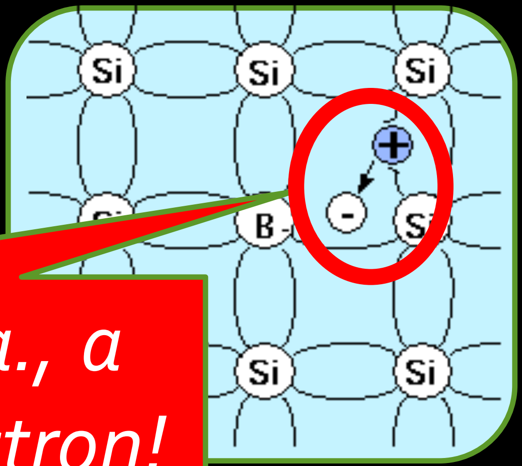
Add some atoms with **5** valence electrons, such as Phosphorus.



An extra electron!

P-type:

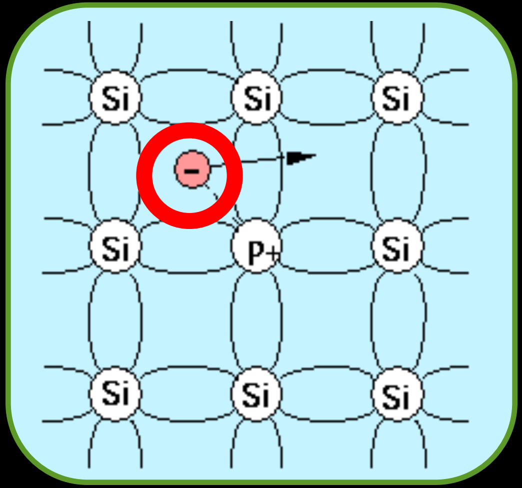
Add some atoms with **3** valence electrons, such as Boron.



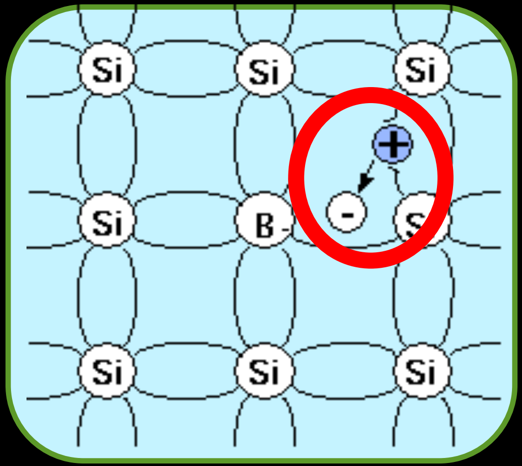
A missing electron, a.k.a., a "hole", like a positive electron!

Encourage semiconductor's conductivity

The extra electrons and the holes are charge carriers, which can move freely through the materials.



Thus the conductivity is encouraged.



This process of adding stuff is called **doping**, (n or p type).

Free electrons move like

Free holes move like

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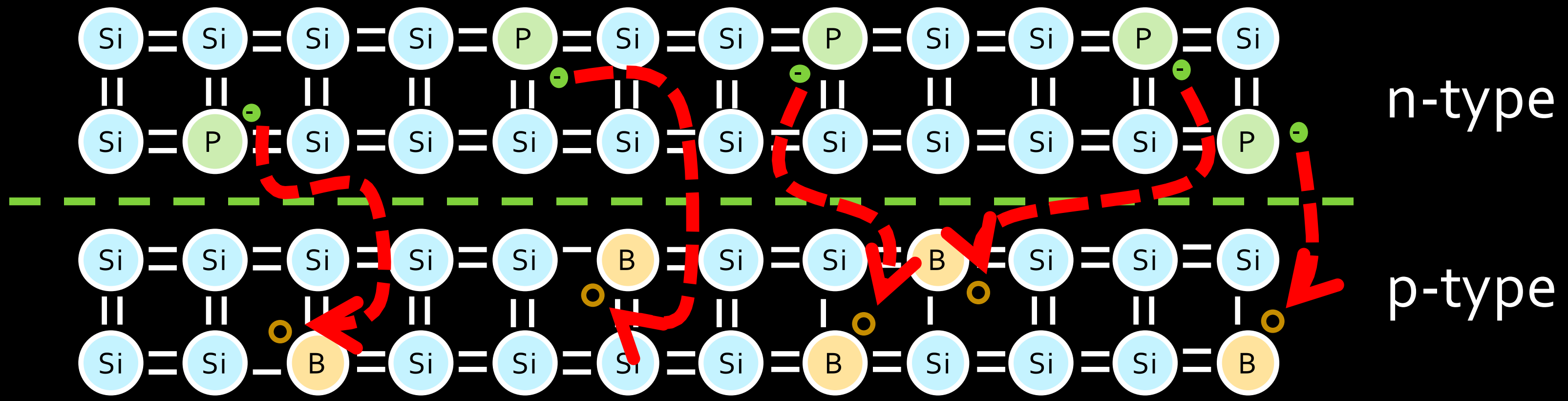
PN-junctions

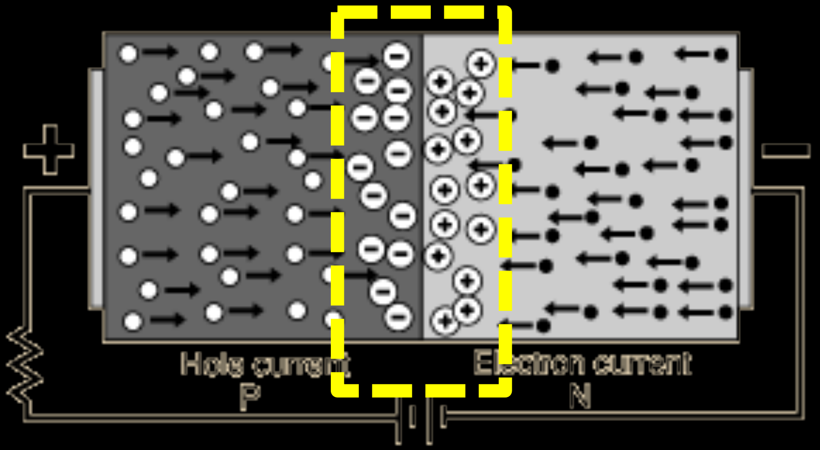
Bringing p and n together

- What happens if you brought some p-type material into contact with some n-type material?



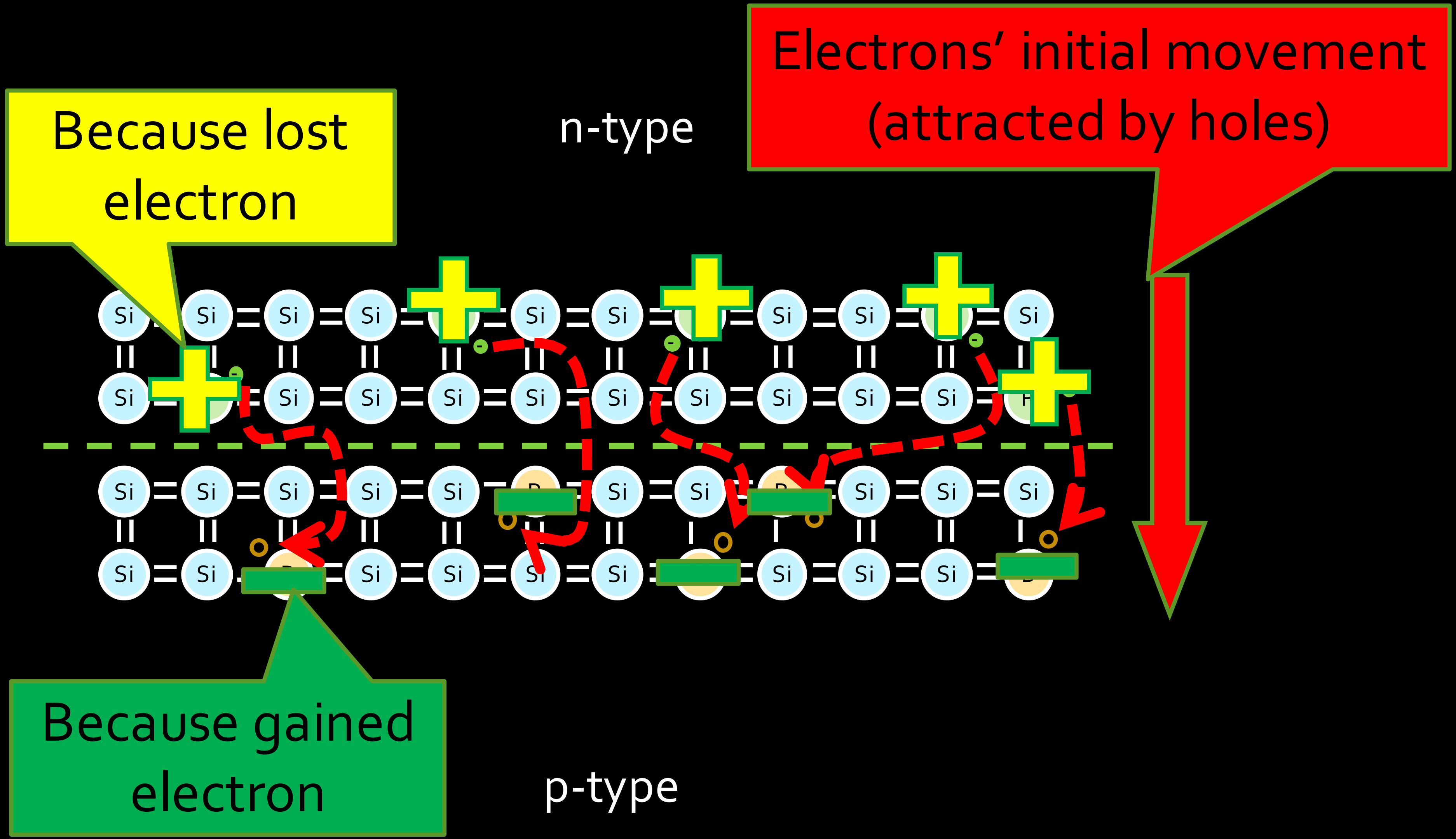
- The electrons at the surface of the n-type material are drawn to the holes in the p-type.

p-n Junctions



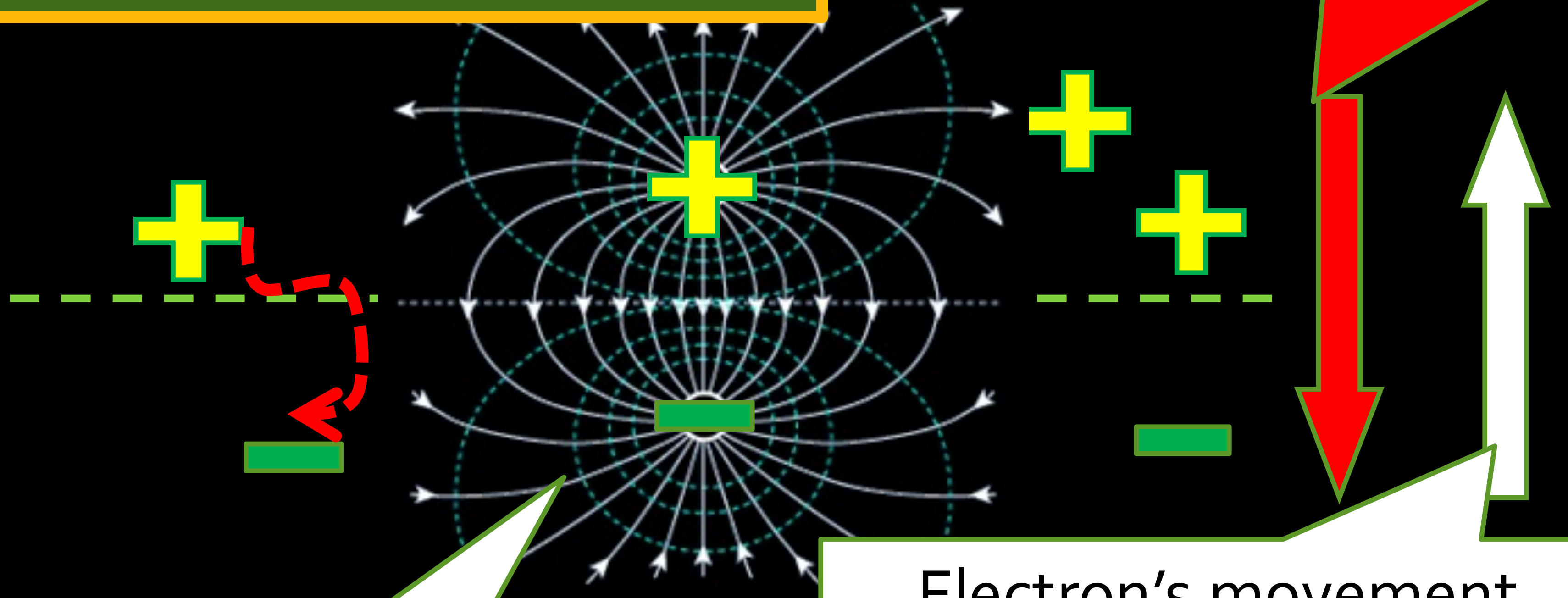
- When left alone, the electrons from the n section of the junction will fill the holes of the p section, cancelling each other and create a section with no free carriers called the depletion layer.

- Once this depletion layer is wide enough, the doping atoms that remain will create an electric field in that region.



Because lost electron
n-type
Electrons' initial movement (attracted by holes)
Si
Because gained electron
p-type

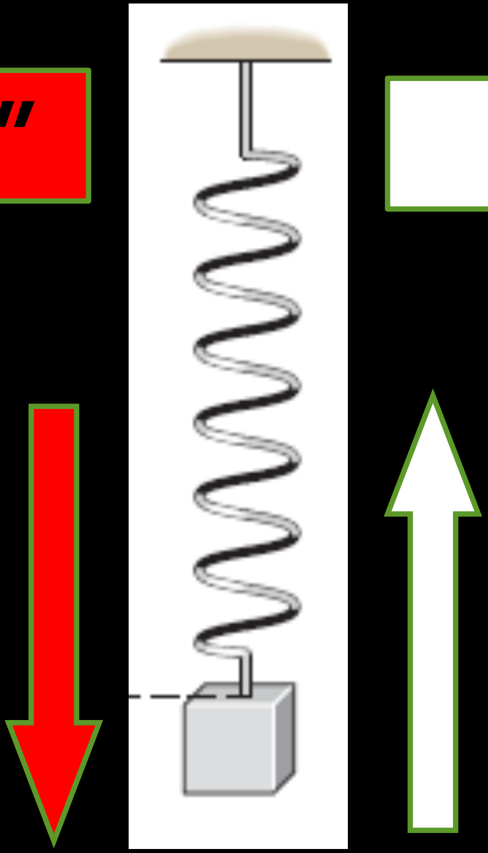
Diffusion increases the width of depletion layer, and drift draws it back. An **equilibrium** is reached, when the depletion layer is of a certain width.



Analogy: Spring with weight

"Diffusion"

Attracted by gravity (hole)



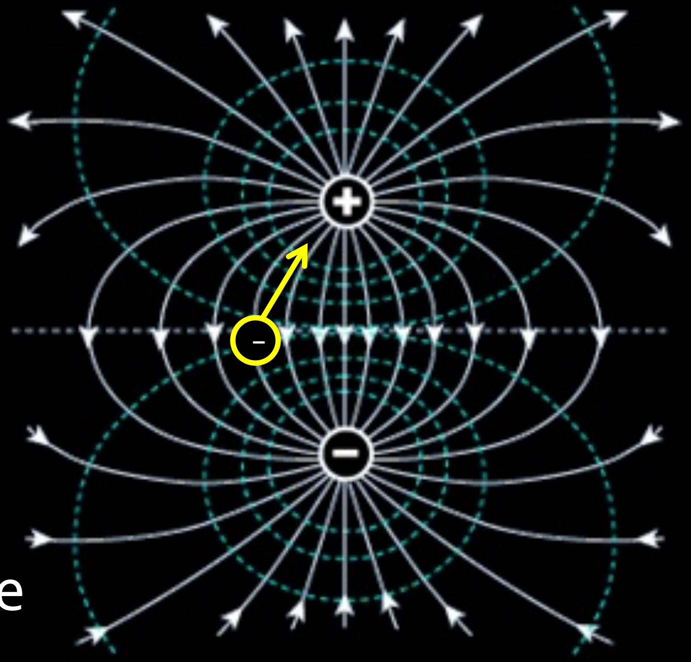
"Drift"

Drawn by spring force field

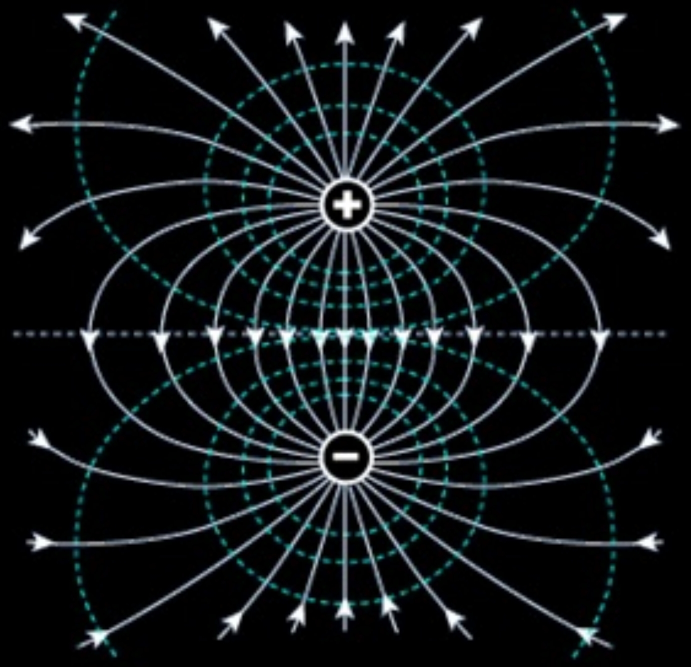
An equilibrium is reached when the spring is stretched by a certain length.

Electric fields (after class reading)

- What is an electric field?
  - When a phosphorus atom loses its electron, the atom develops an overall positive charge.
  - Similarly, when a boron atom takes on an extra electron, that atom develops an overall negative charge.
  - If an electron was dropped between the two, it would be attracted to the phosphorus atom, and repelled by the boron atom.
  - This effect is called an electric field.



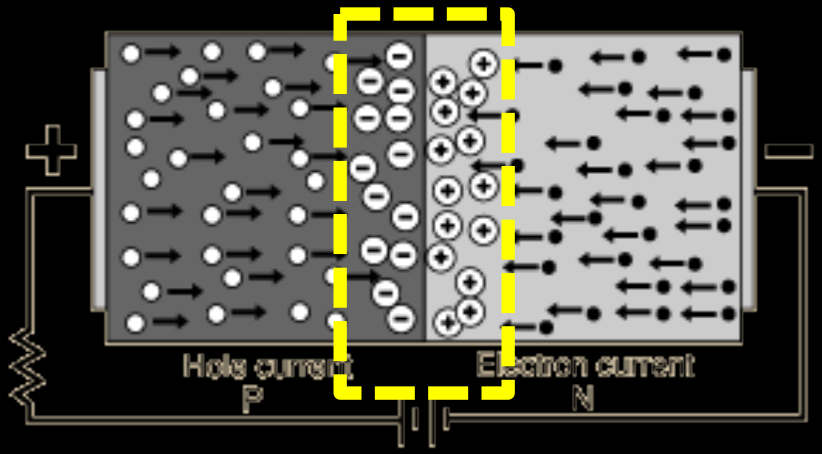
Electric fields (after class reading)



- A depletion layer is made up of many of these electrically imbalanced phosphorus and boron atoms.
- The electric field caused by these atoms will cause holes to flow back to the p section, and electrons to flow back to the n section.
  - The current caused by this electric field is called drift.
  - The current caused by the initial electron/hole recombination is called diffusion.
- At rest, these two currents reach equilibrium.

Summary of pn-junction

P



N

When we put **p** and **n** together, they will form a depletion layer with electric field in it.

The depletion layer grows up to a certain **width**, until equilibrium is reached.

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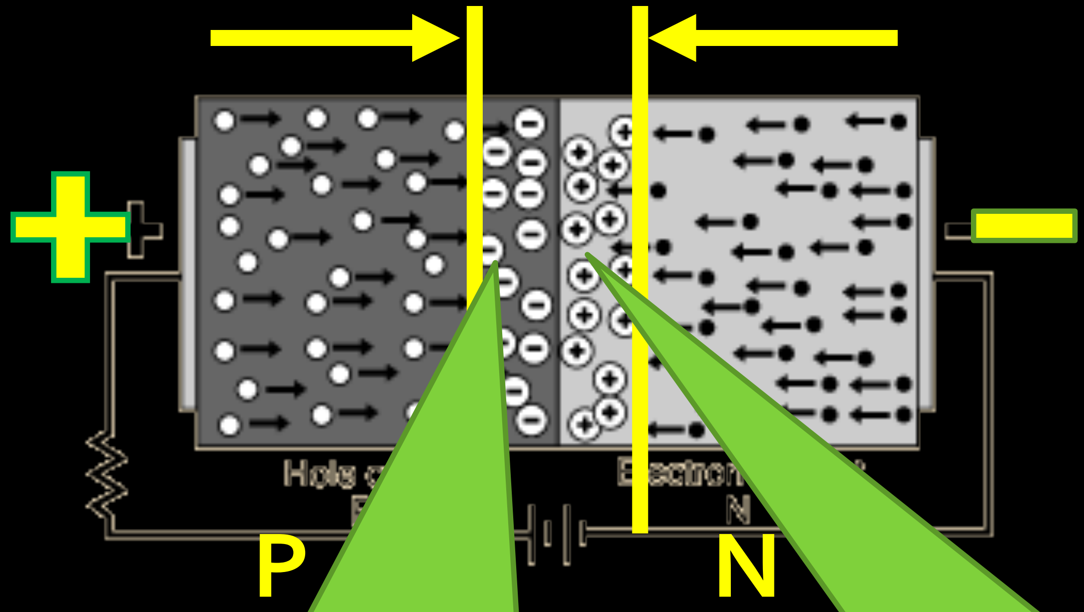
- Put p-type and n-type together -- pn-junction
- Apply voltage to a pn-junction – principle of transistors
- A real-world manufacturing of transistor -- MOSFET

Apply voltage to a PN-junction

It could be applied in two possible directions

- **P**ositive voltage to the **P** side
- **P**ositive voltage to the **N** side

Forward Bias (Positive voltage to P)

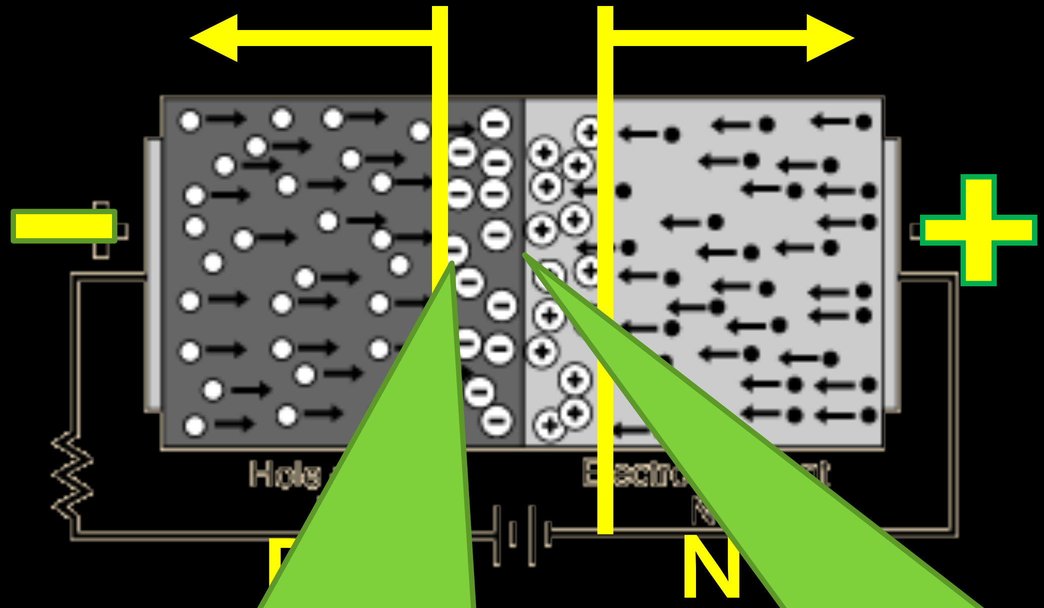


Negative charges sucked out of depletion layer

Positive charges sucked out of depletion layer

Depletion layer becomes **narrower.**

Reverse Bias (Positive voltage to N)



Negative charges **injected** into depletion layer

Positive charges **injected** into depletion layer

Depletion layer becomes **wider.**

Apply forward bias

- Depletion layer narrower
- Easier to travel through
- Better conductivity
- Like switch **connected**

Apply reverse bias

- Depletion layer wider
- Harder to travel through
- Worse conductivity
- Like switch **disconnected**

That's how transistors work!

Outline of the story

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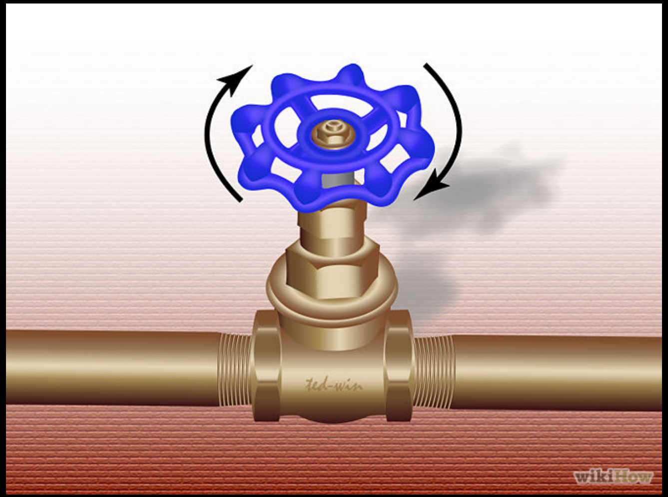
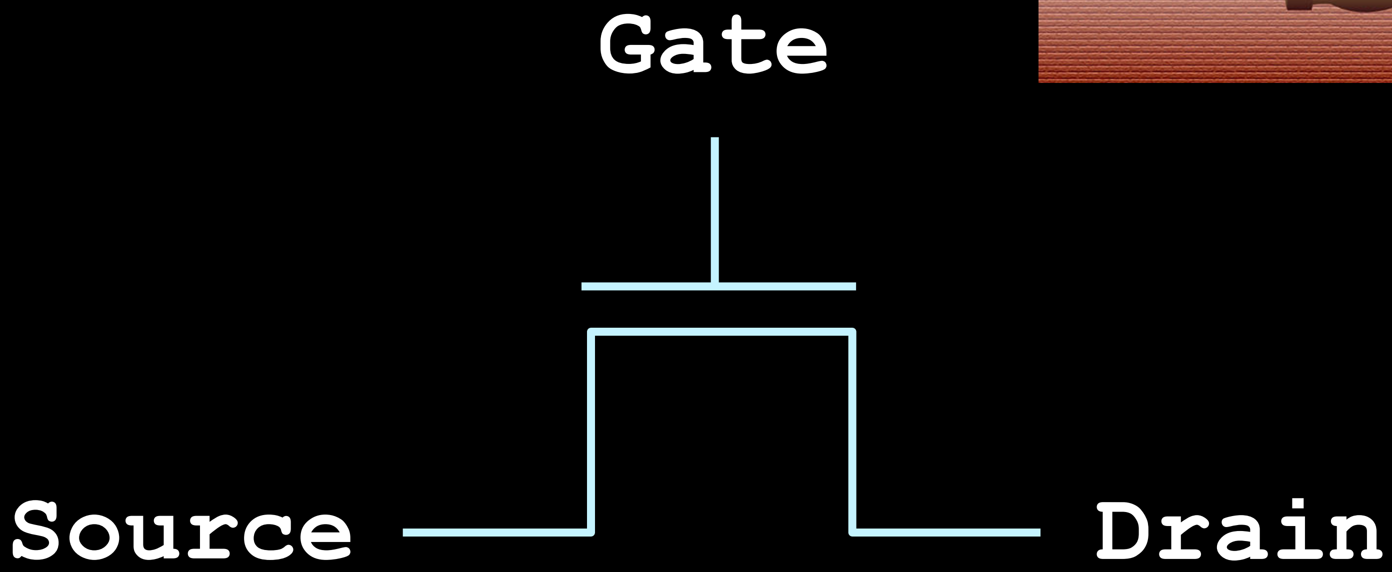
Creating transistors

- Transistors use the characteristics of p-n junctions to create more interesting behaviour.
- Three main types:
  - Bipolar Junction Transistors (BJTs)
  - Metal Oxide Semiconductor Field Effect Transistor (MOSFET)
  - Junction Field Effect Transistor (JFET)
- The last two are part of the same family, but we'll only look at the MOSFET for now.

Metal Oxide Semiconductor
Field Effect Transistor




Gate
Source
Drain

Metal

Oxide

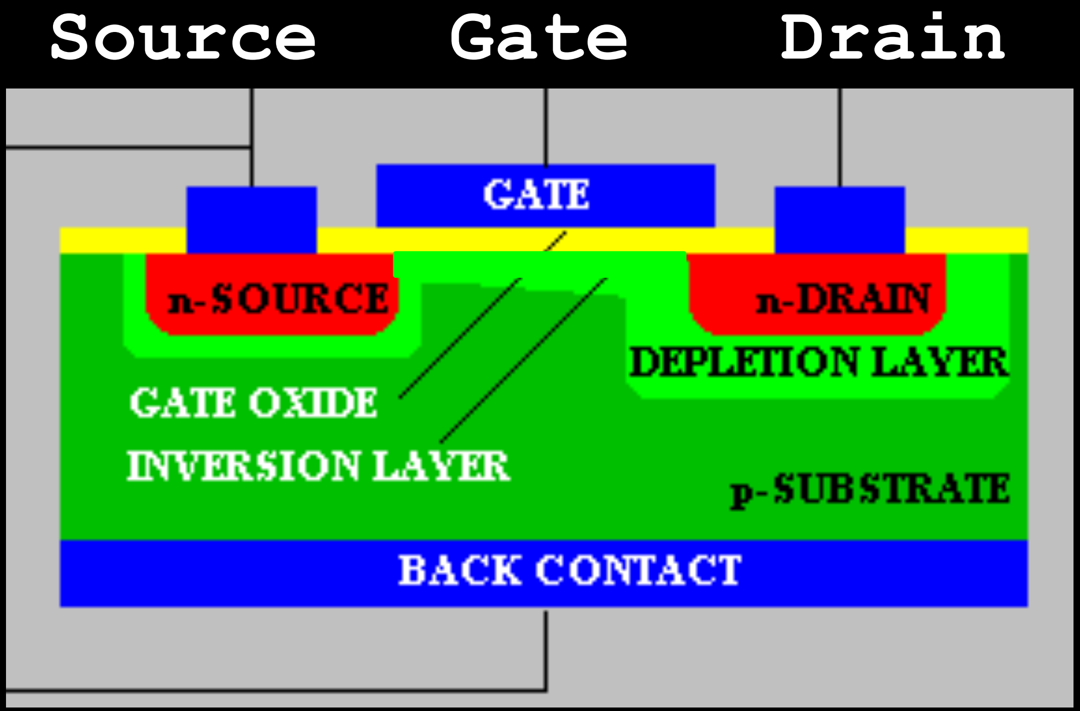
Insulator

Conductor, can apply electric charge to it

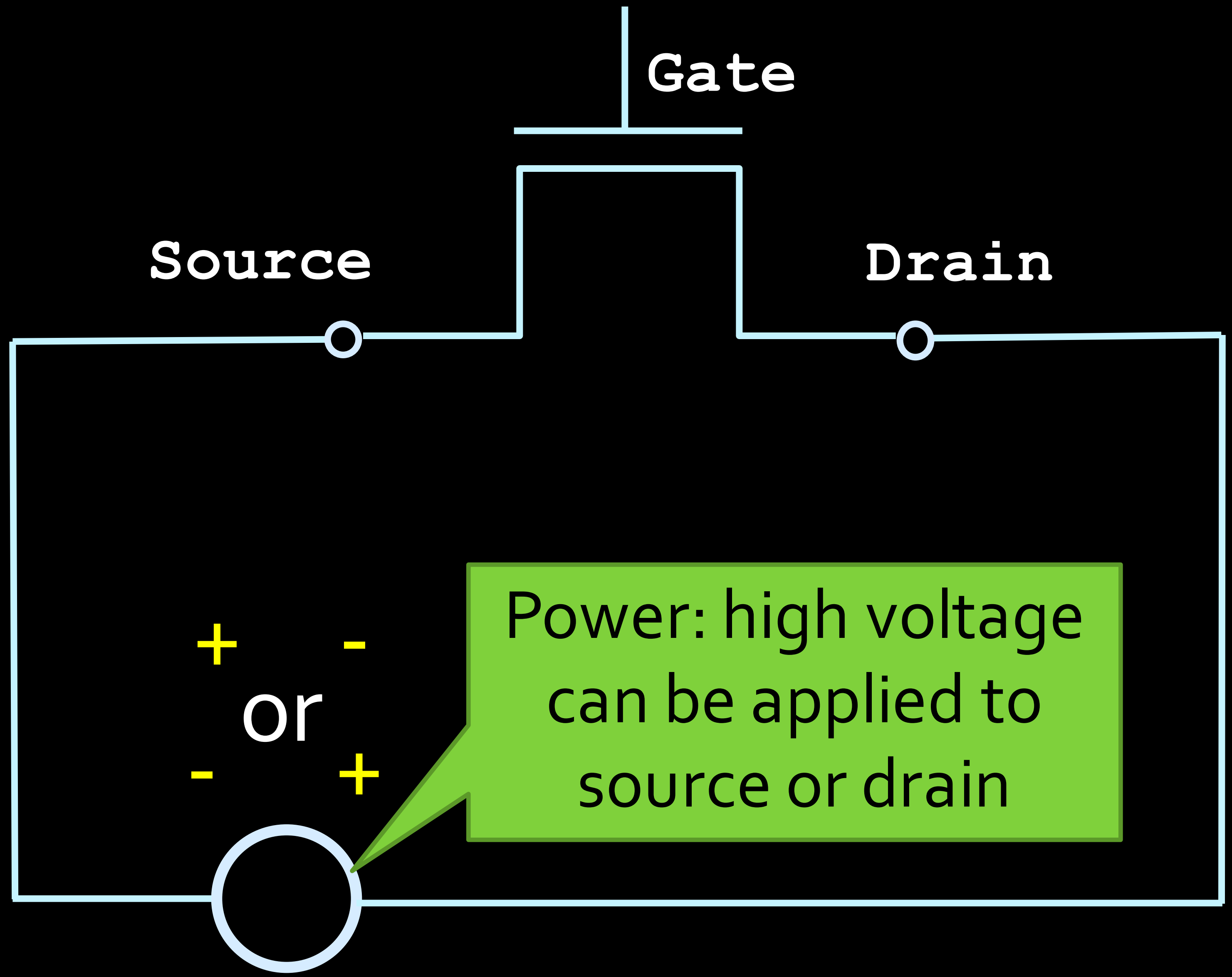
N-type

P-type

Semiconductors, doped



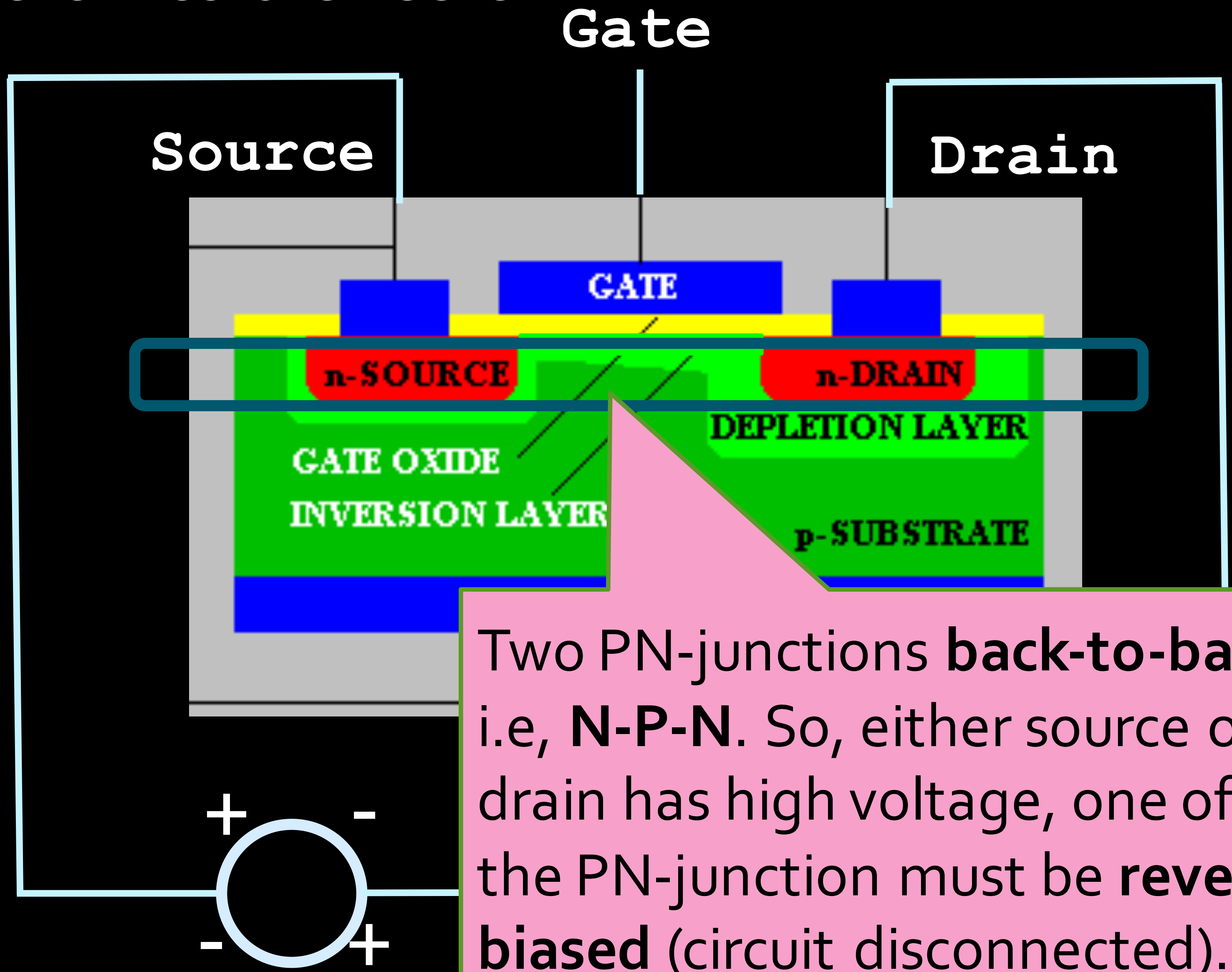
Put a MOSFET into a circuit



Power: high voltage can be applied to source or drain

Metal | Oxide | N-type | P-type

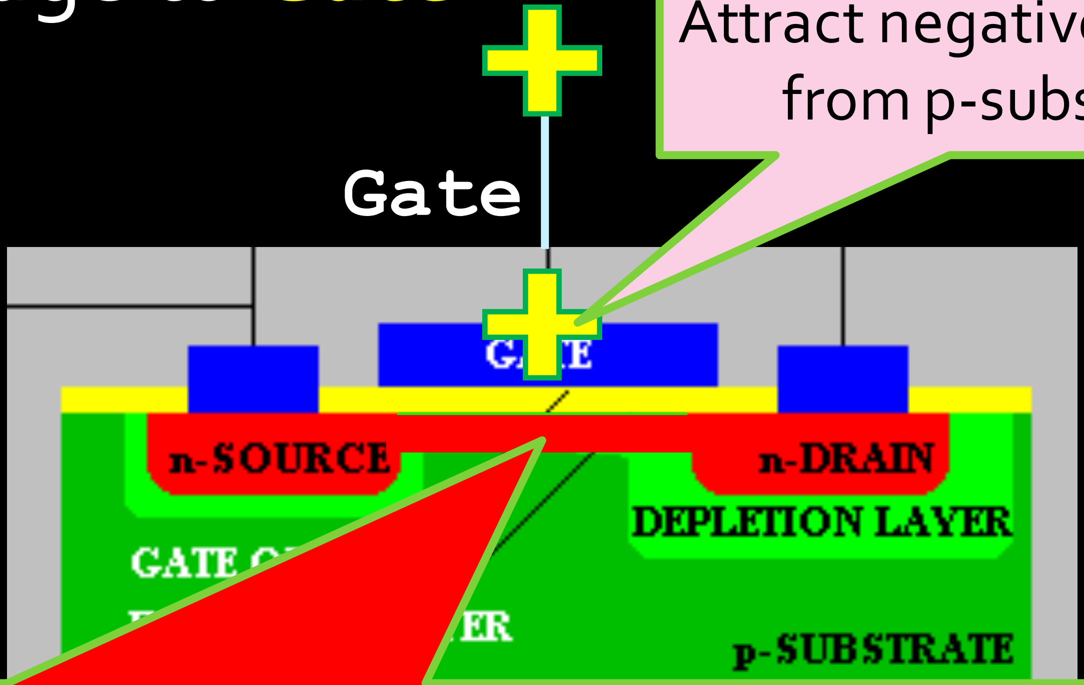
Put it into a circuit



Two PN-junctions **back-to-back**, i.e, **N-P-N**. So, either source or drain has high voltage, one of the PN-junction must be **reverse biased** (circuit disconnected).

Metal | Oxide | N-type | P-type

But things change if we apply high voltage to **Gate**



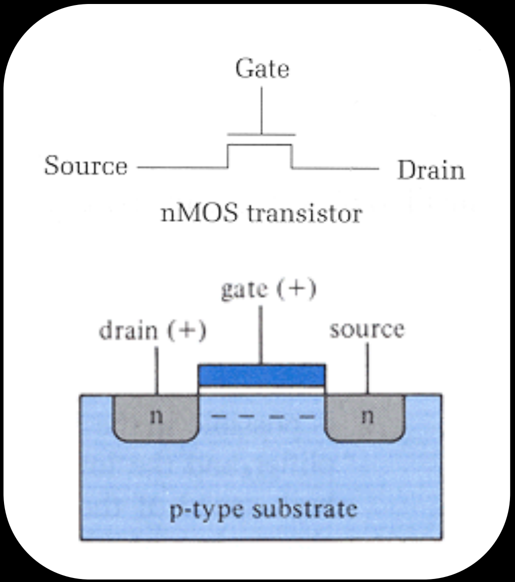
Attract negative charges from p-substrate

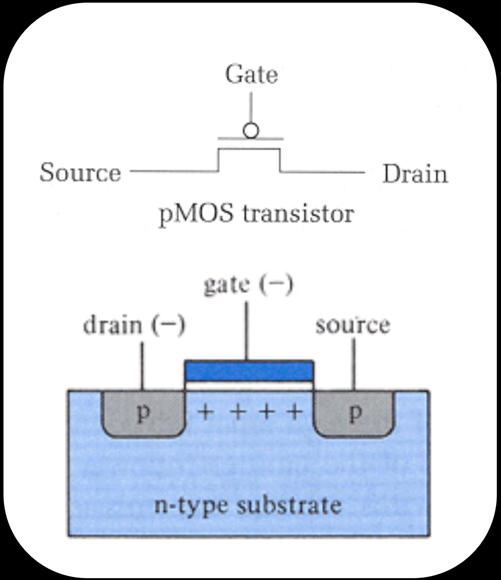
Create n-type channel between source and drain, **CIRCUIT CONNECTED**

The wider the channel, the higher the current

Two types of MOSFET

- **nMOS** (what we just describe)
  - N-P-N
  - Gate high, connected
  - Gate low, disconnected
- pMOS (opposite to nMOS)
  - P-N-P
  - Gate low, connected
  - Gate high, disconnected





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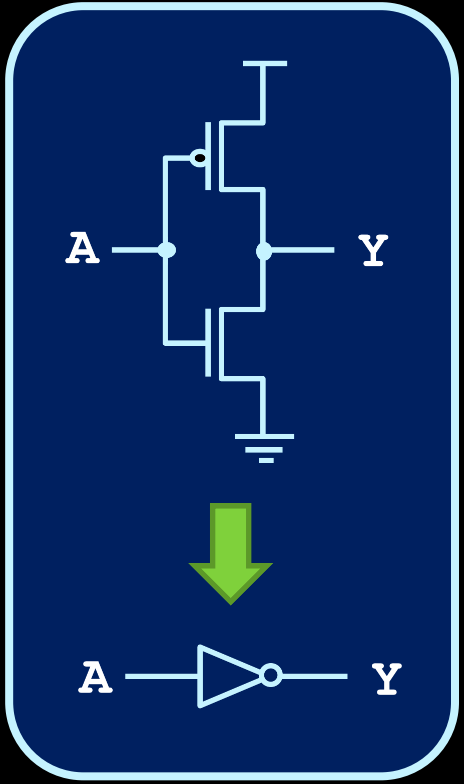
Use transistors build Logic Gates

Transistors to Logic Gates

Create gates using a combination of transistors

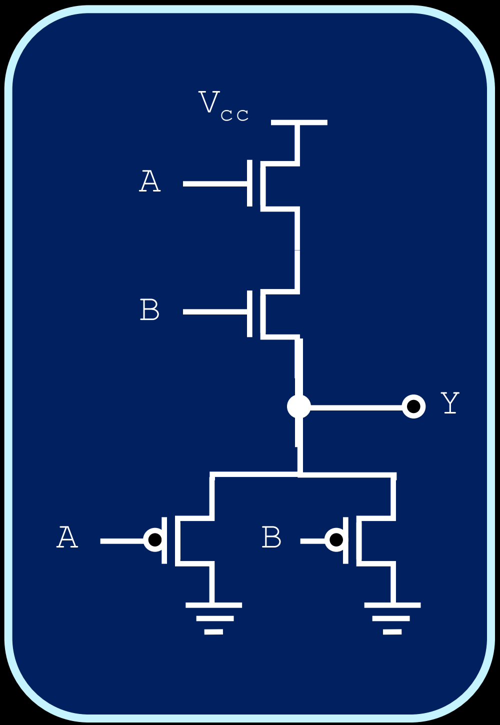
Physical data:

- "High" input = 5V
- "Low" input = 0V
- Switching time ≈ 120 picoseconds
- Switching interval ≈ 10 ns

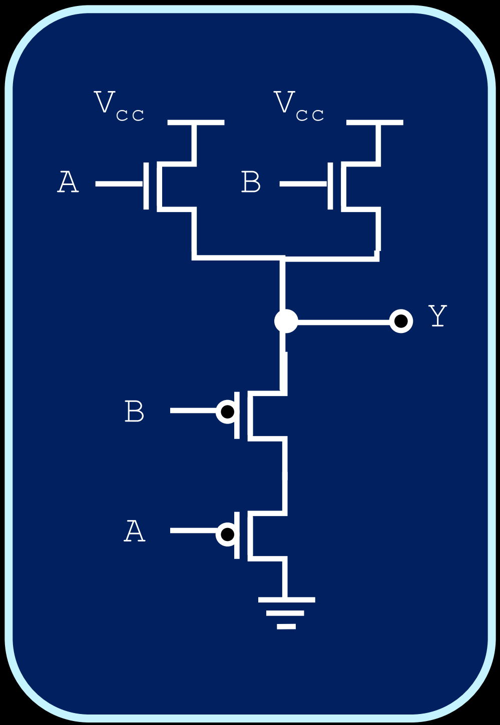


NOT Gate

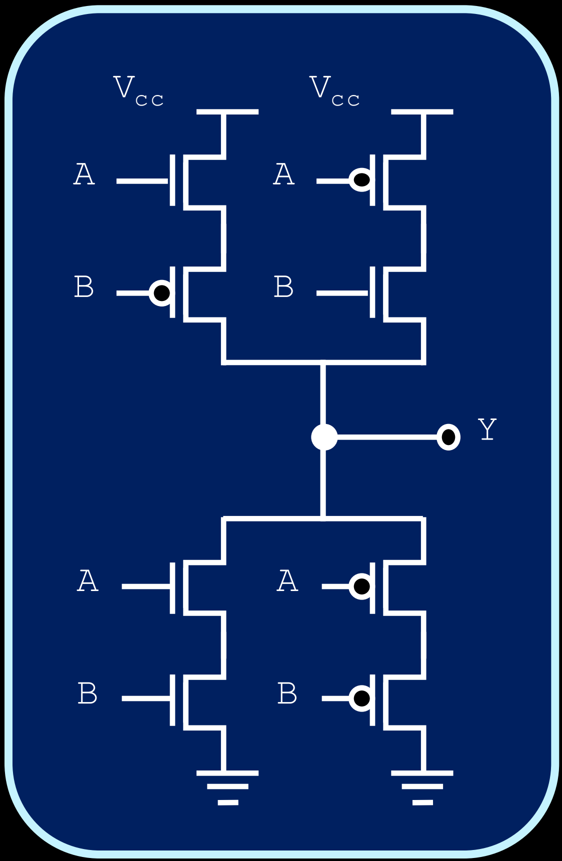
Transistors into gates



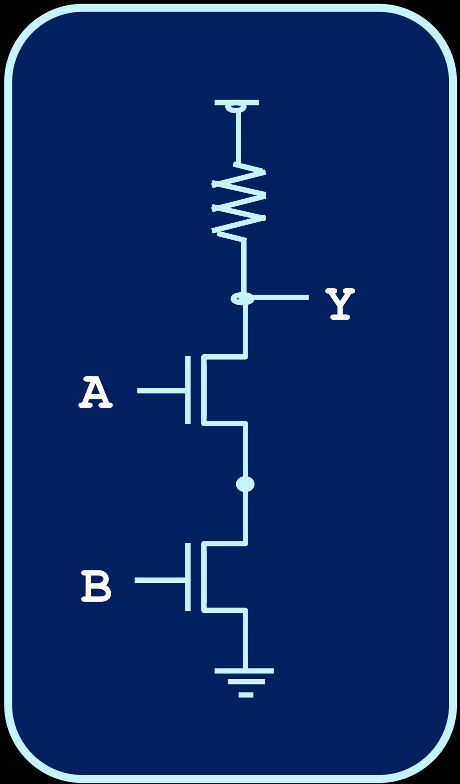
AND



OR



XOR



NAND is the most awesome (and common) logic gate

- It uses fewer transistors than other gates
- All other logic functions (AND, OR, ...) can be implemented using only NAND.

Challenge for home: implement AND, OR, NOT, XOR using only NAND.

Next week:

- Circuit creation