

SI100B
Introduction to Information
Science and Technology
(Electrical Engineering)

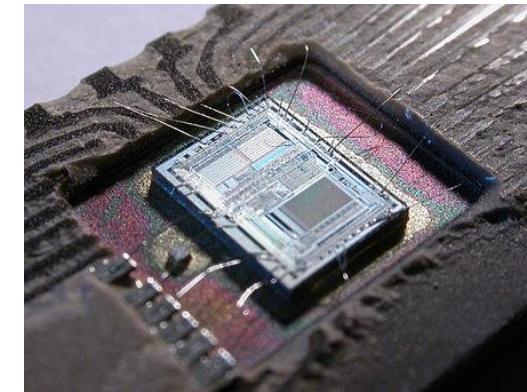
Lecture #2 Semiconductor &
Electronic Devices

Instructor: Junrui Liang (梁俊睿)
Sept. 15th, 2022

The Theme Story



Devices (1)



Circuits (4)

Systems (1)



(Pictures are from the Internet)

Study Purpose of Lecture #2

- 哲学 (bao'an) 三问
 - Who are you?
 - Where are you from?
 - Where are you going?

To answer those questions
throughout your life



- In this lecture, we ask
 - Why semiconductor 半导体 can be used to process information?
 - What are the fundamental semiconductor devices 器件?
 - How an integrated circuit (IC) 集成电路 is built?



Lecture Outline

1. The historical ways of information processing
 2. Fundamental circuit components and their dynamics *
 3. Semiconductor
 4. PN junction
 5. Diode
- (break) -----
6. Transistor
 7. Switch and logic gate (digital application)
 8. Linear amplification (analog application)
 9. Integrated circuit manufacturing and the Moore's Law

The history of information processing (calculation)



Digits 手指



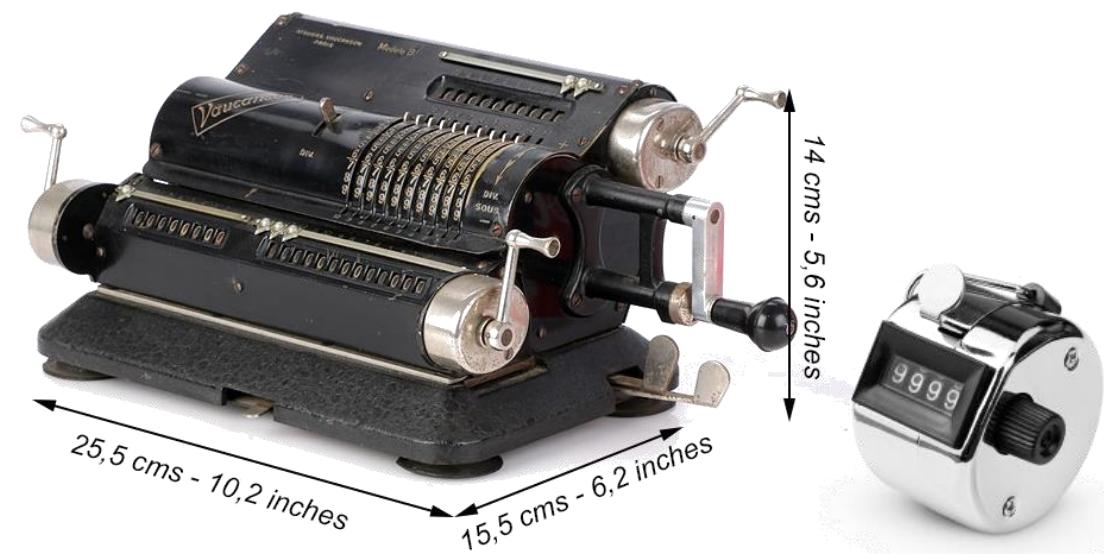
Counting rods 算筹



Abacus 算盘



Slide rule 计算尺
(可计算加、减、乘、除、指数、对数等)

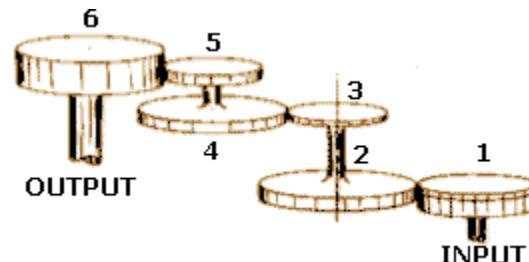
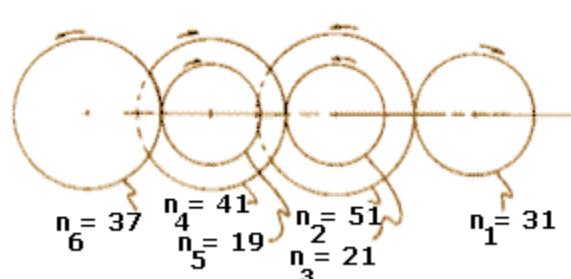


Mechanical calculator (computer?) 机械计算器

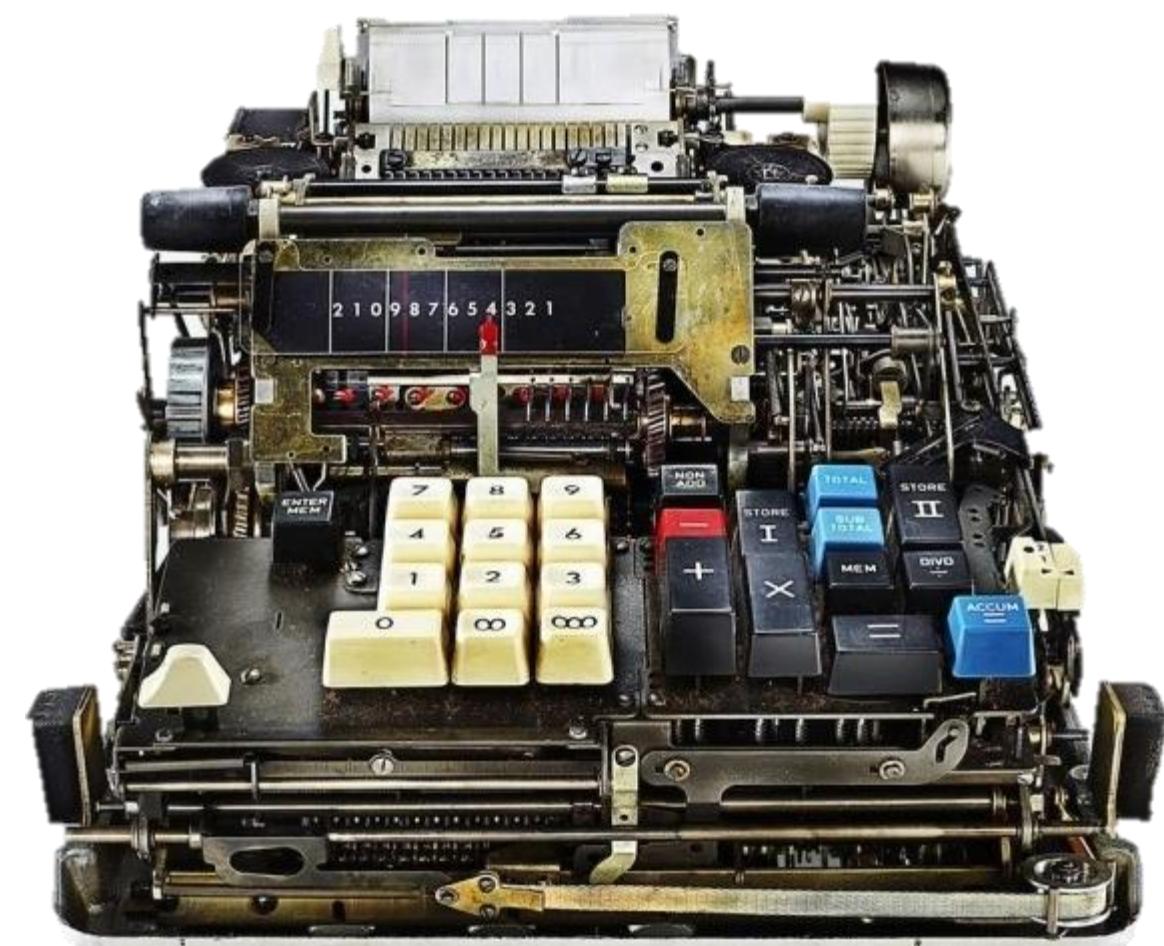
(Pictures are from the Internet)

Why no longer mechanical calculator?

- Gears 齿轮 are the kernel of many mechanical calculator



- Difficulty in scaling down



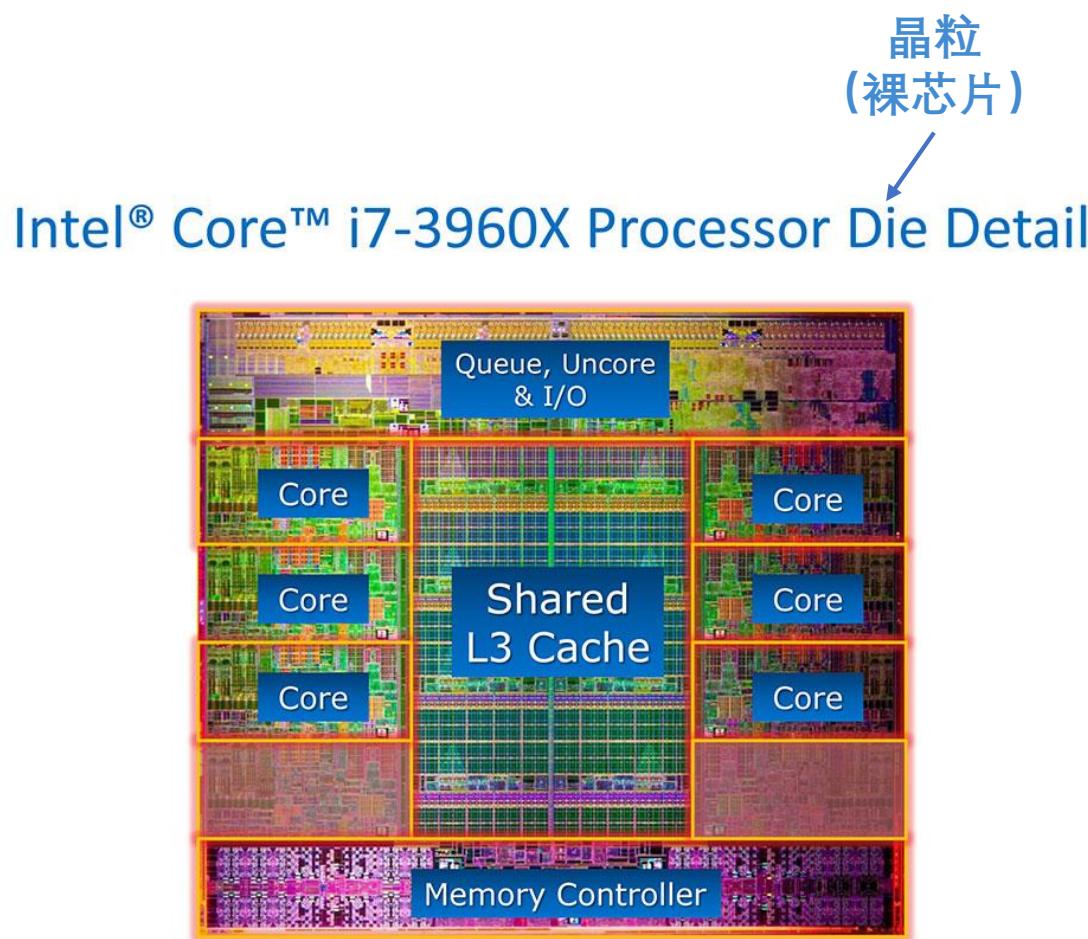
ENIAC - the first electronic computer

- The first programmable, electronic, general purpose **digital computer**
- Able to solve "a large class of numerical problems" through **reprogramming**
- It was **Turing-complete** 图灵完备性
- By the end of its operation in 1956, ENIAC contained
 - 18,000 **vacuum tubes** 真空管
 - 7,200 **crystal diodes** 二极管
 - 1,500 **relays** 继电器
 - 70,000 **resistors** 电阻
 - 10,000 **capacitors** 电容
 - about 5,000,000 hand-soldered joints
 - weighed 27 tons
 - roughly $2.4\text{ m} \times 0.9\text{ m} \times 30\text{ m}$ in size
 - occupied 167 m^2
 - consumed 150 kW of electricity
 - one ENIAC hour $\approx 2,400$ human hours



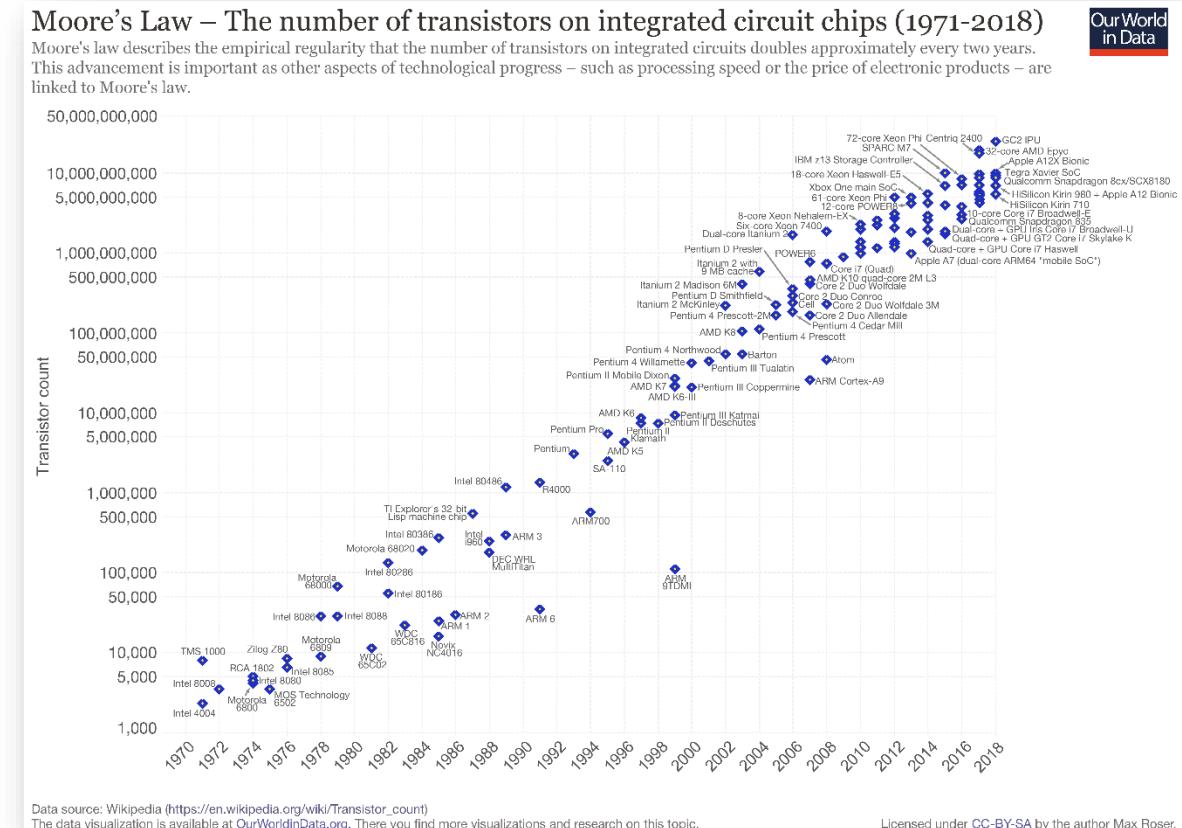
(Pictures are from the Internet)

The magic of integrated circuit (IC)



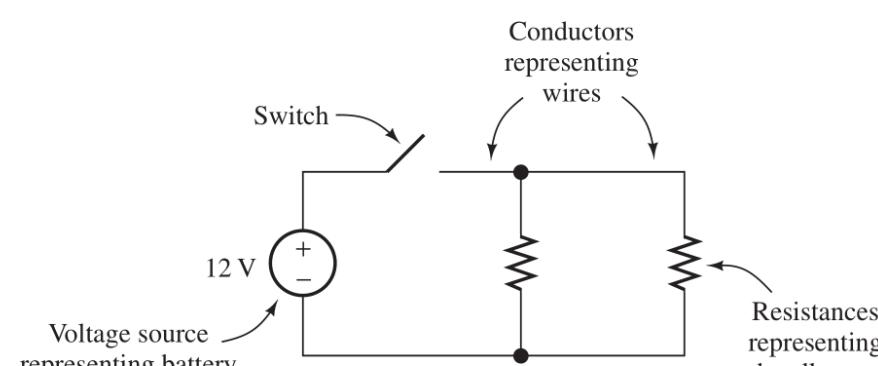
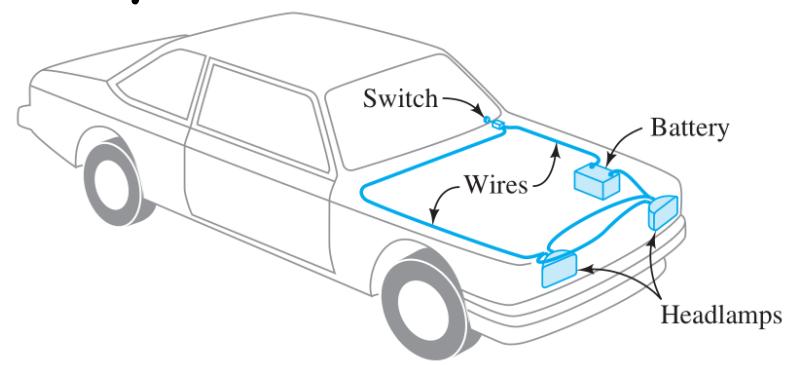
(Pictures are from the Internet)

- Core i7 3rd Generation (Nov. 2011)
 - 32 nm process 制程工艺 technology
 - 2.27 billion (2,270,000,000) transistors 晶体管

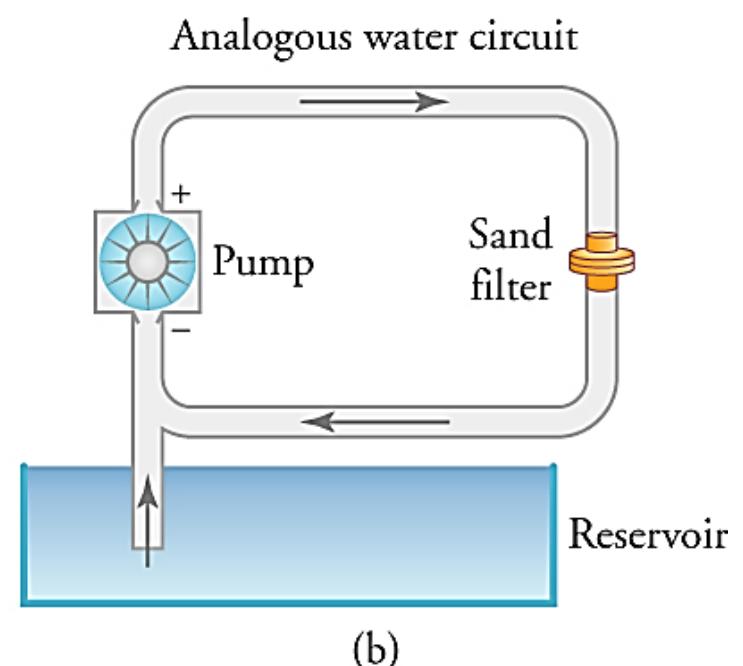
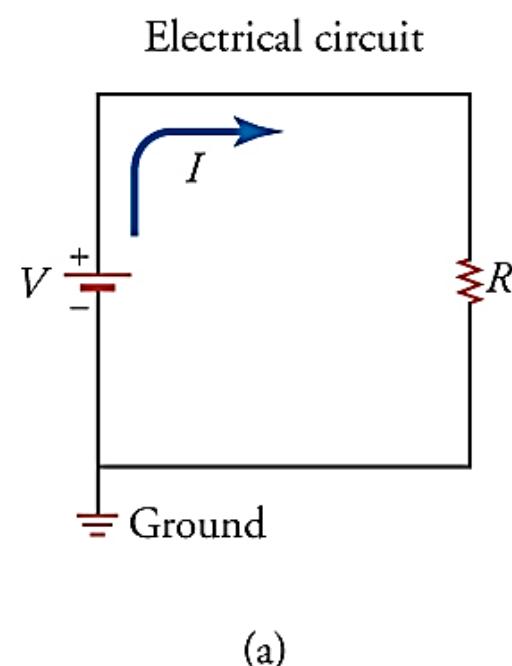


Electrical circuit

- An electrical circuit consists of various types of **circuit elements** connected in **closed paths** by conductors.
- The **fluid-flow analogy** can be very helpful initially in understanding electrical circuits.



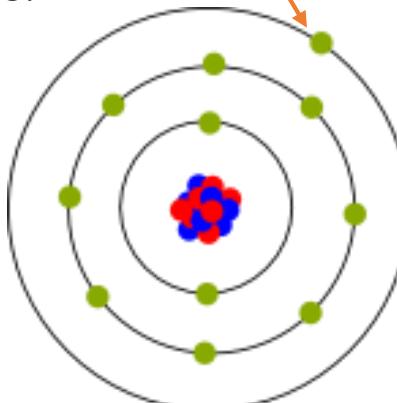
(EE Section 1.2)



Conductor and insulator

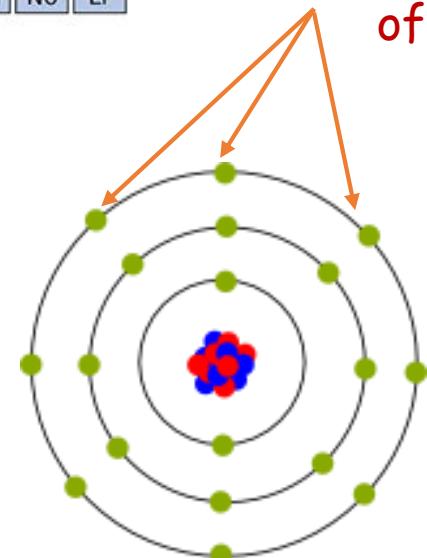
Conductor 导体

- The atoms have single (or few) electrons in the outer orbit called **valence electrons** (价电子)
- They might become **free electrodes** (自由电子) and can be moved from one atom to another easily and enhance the movement of electrons.



Insulator 绝缘体

- has many (7-8) electrons in the outer orbit.
- these electrons are very difficult to move from one atom to the other and **resist the movement of electrons**.



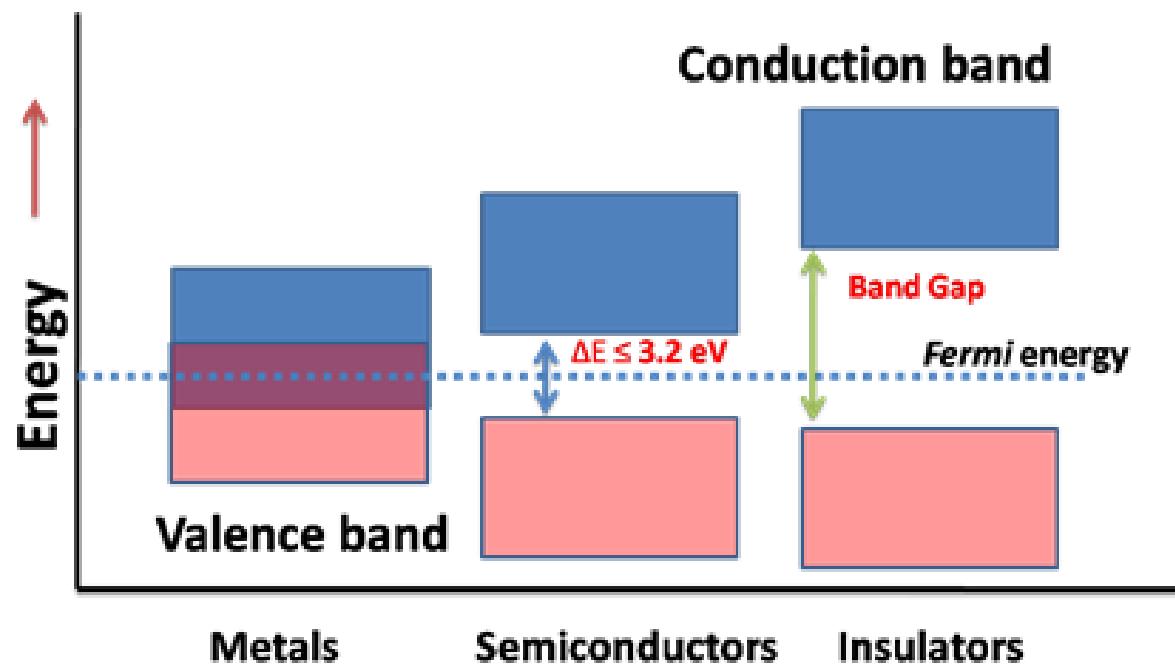
Group → 1 ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H															He		
2	Li	Be																Ne
3	Na	Mg																Ar
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Fl	Uup	Lv	Uus	Uuo
				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Key Metals Nonmetals Metalloids

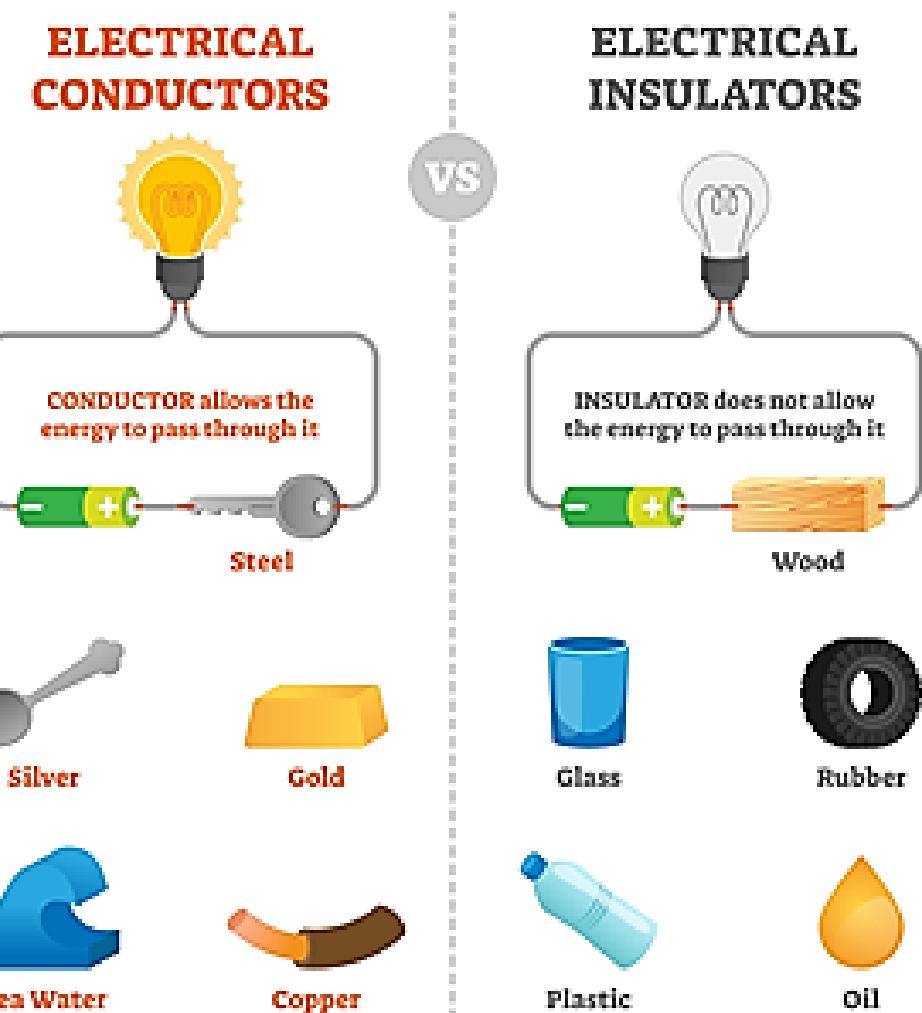
(Pictures are from the Internet)

Conductor and insulator

- Physical insight



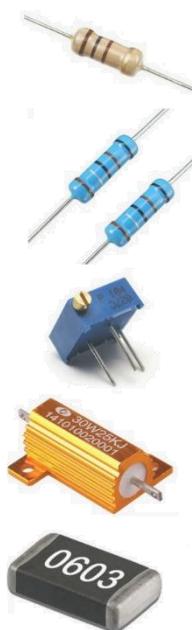
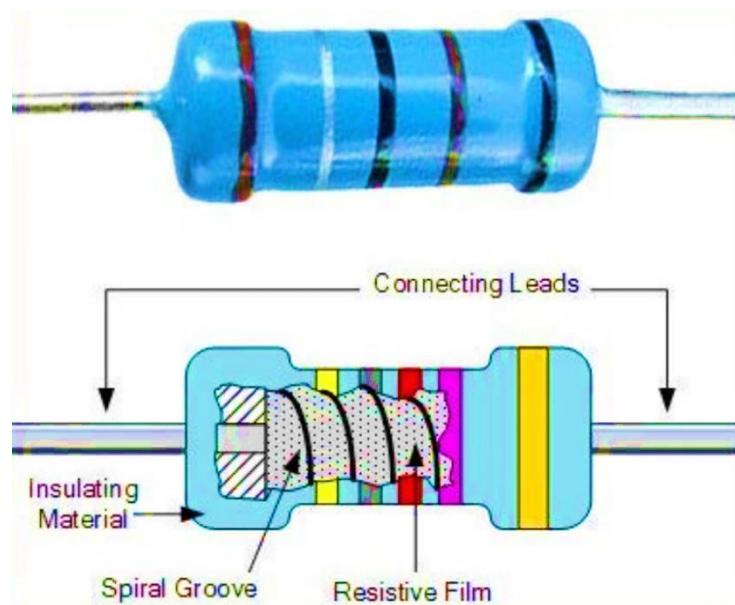
- Everyday life experience



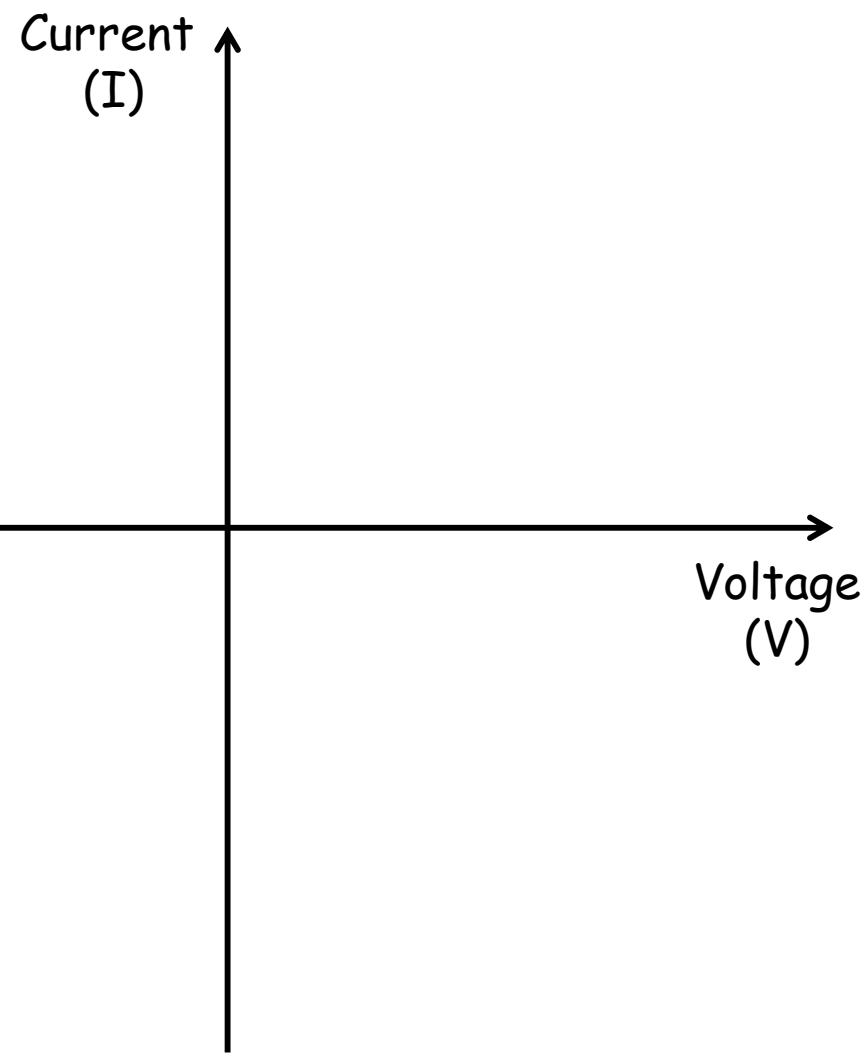
(Pictures are from the Internet)

The electrical characteristic of a resistor

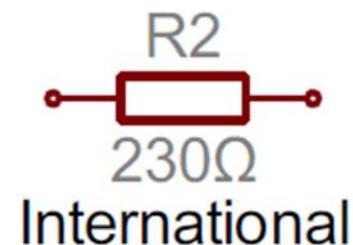
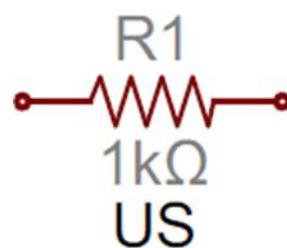
- Practical resistors



- The I-V characteristics?



- Symbol



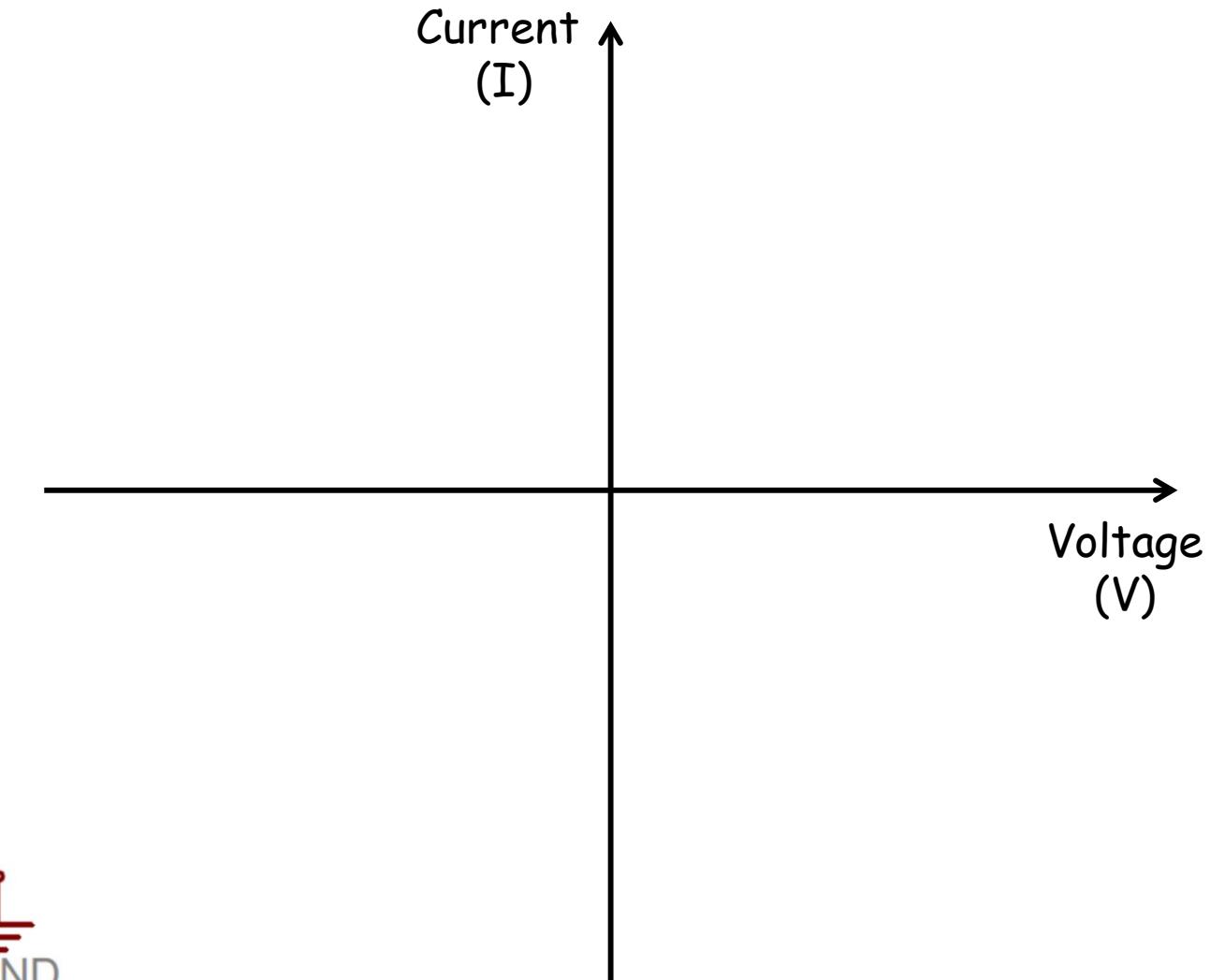
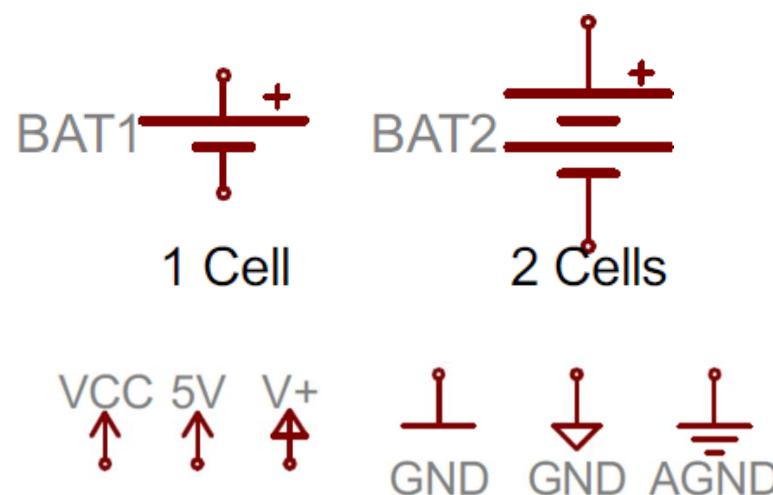
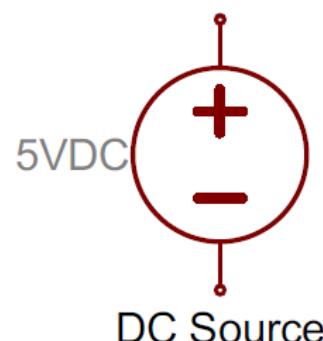
(Pictures are from the Internet)

The electrical characteristic of a dc voltage source

- Practical voltage (power) supply
- The I-V characteristics?



- Symbol



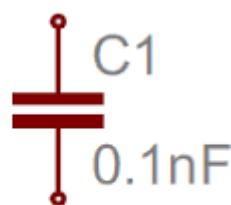
(Pictures are from the Internet)

The electrical characteristic of a capacitor

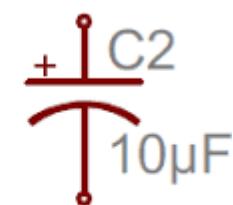
- Practical capacitors



- Symbol

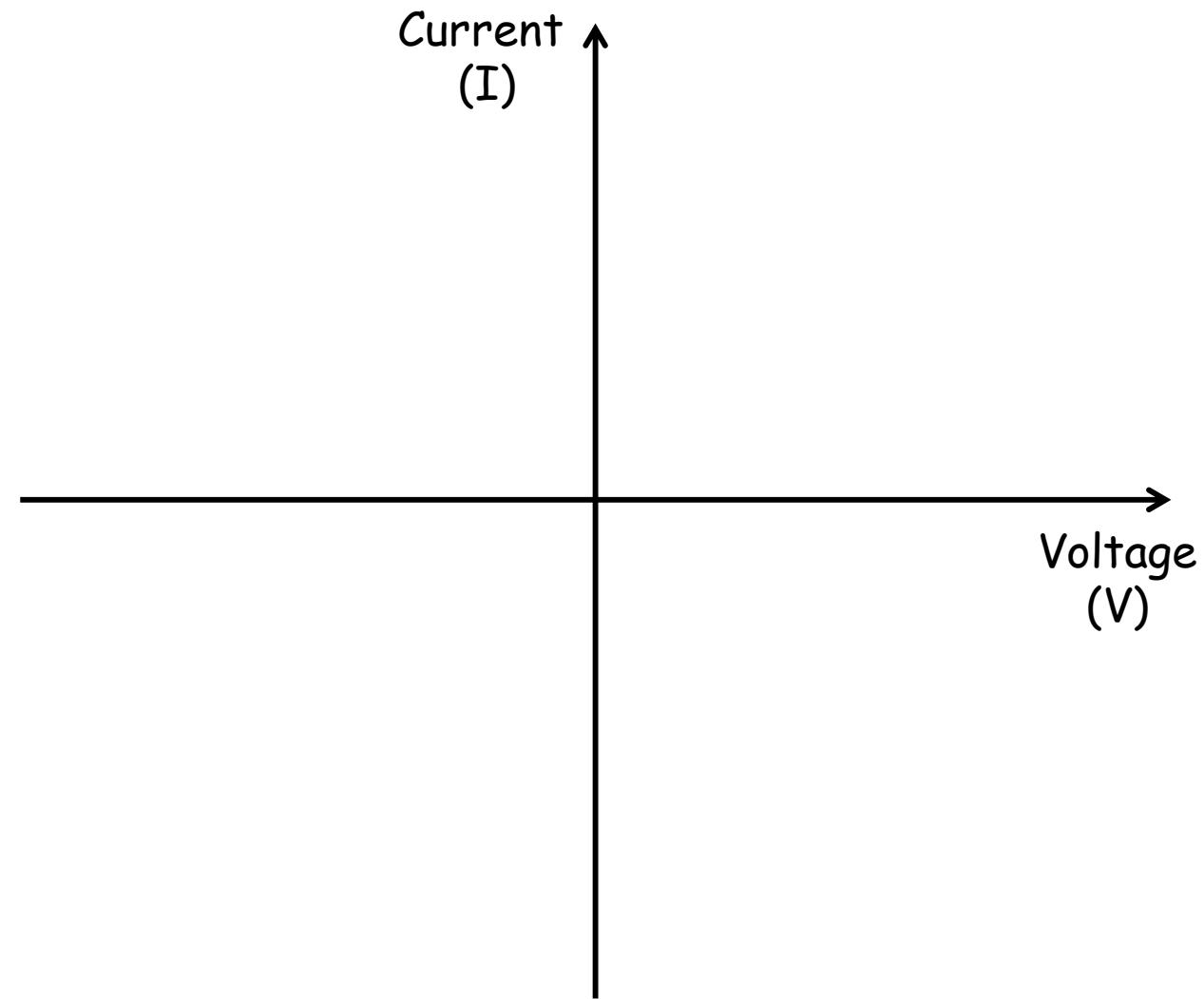


Non-polarized



Polarized

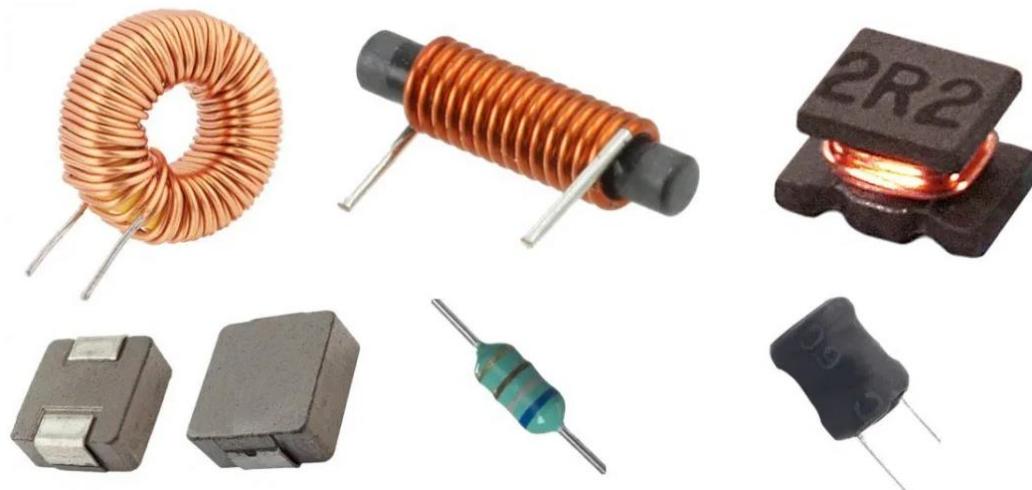
- The I-V characteristics?



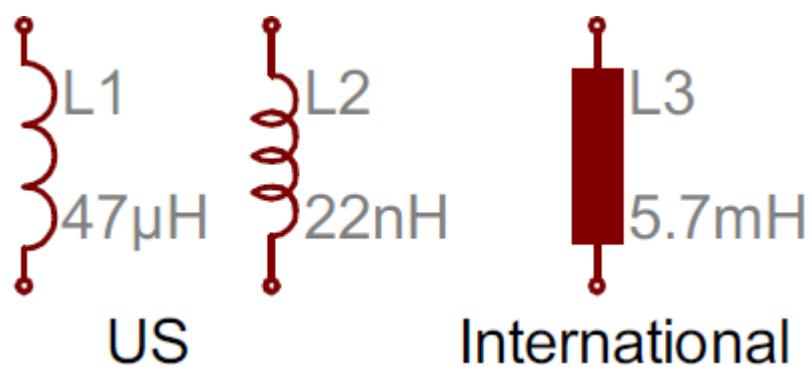
(Pictures are from the Internet)

The electrical characteristic of a capacitor

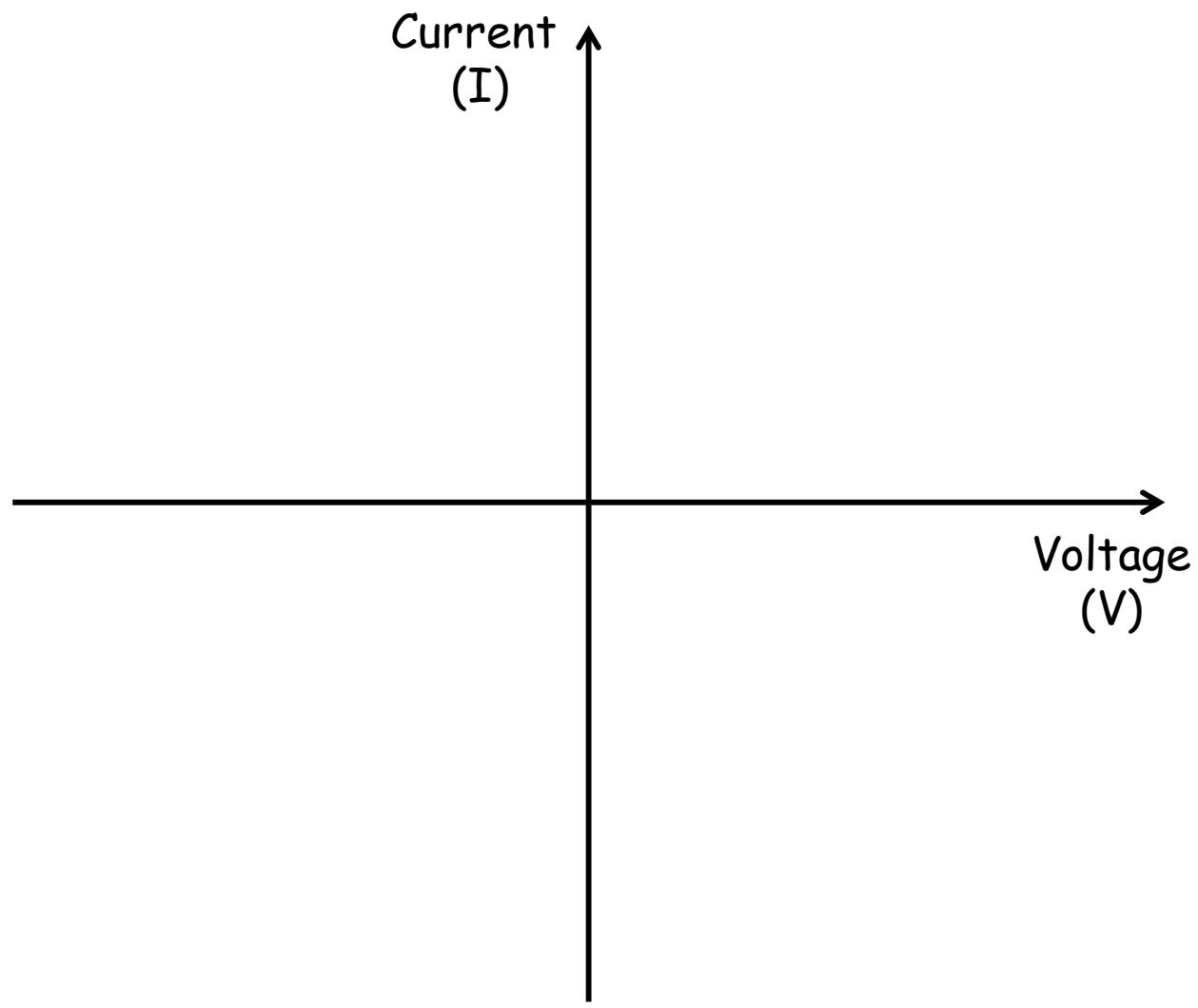
- Practical inductors



- Symbol



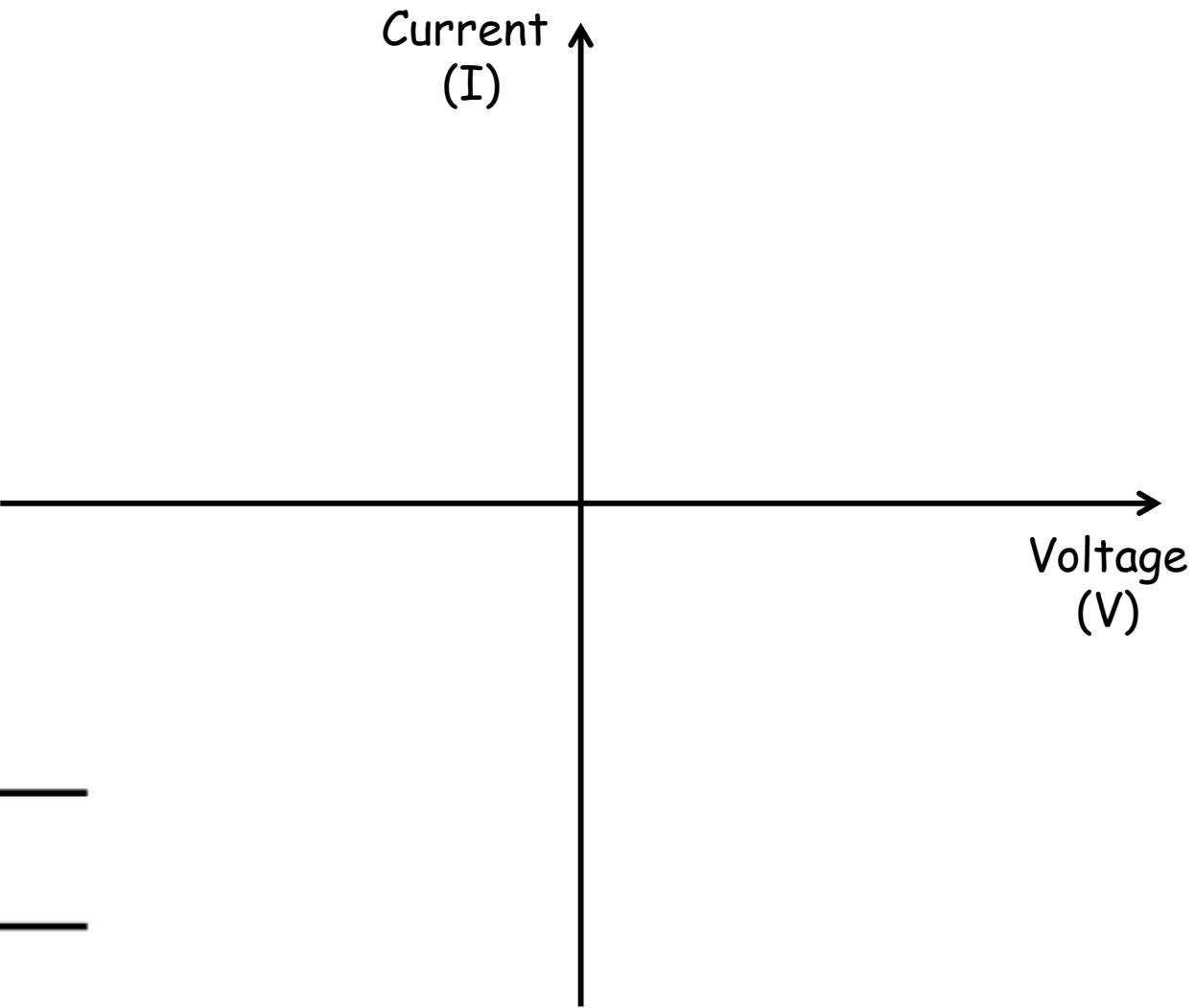
- The I-V characteristics?



(Pictures are from the Internet)

The electrical characteristic of a switch

- The I-V characteristics?



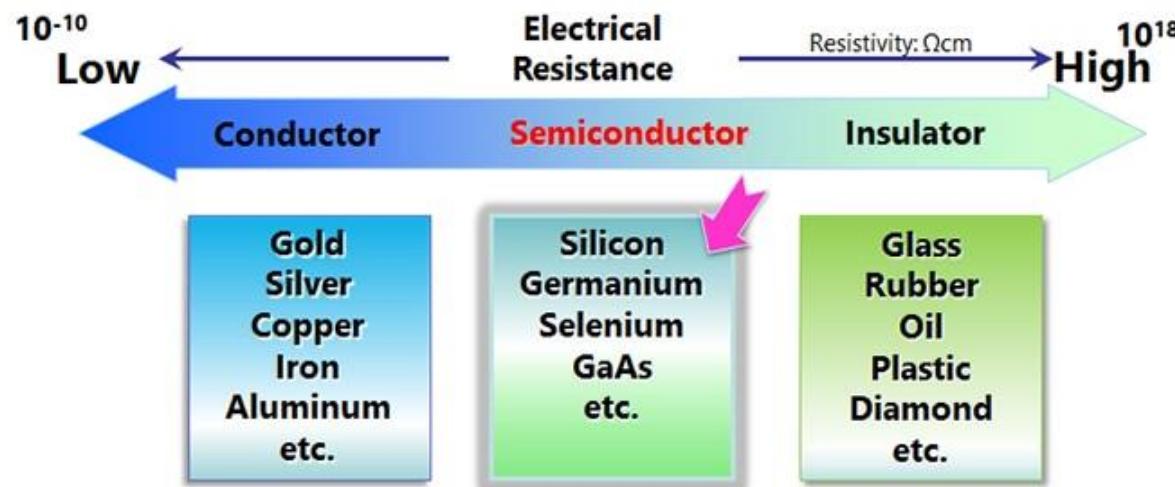
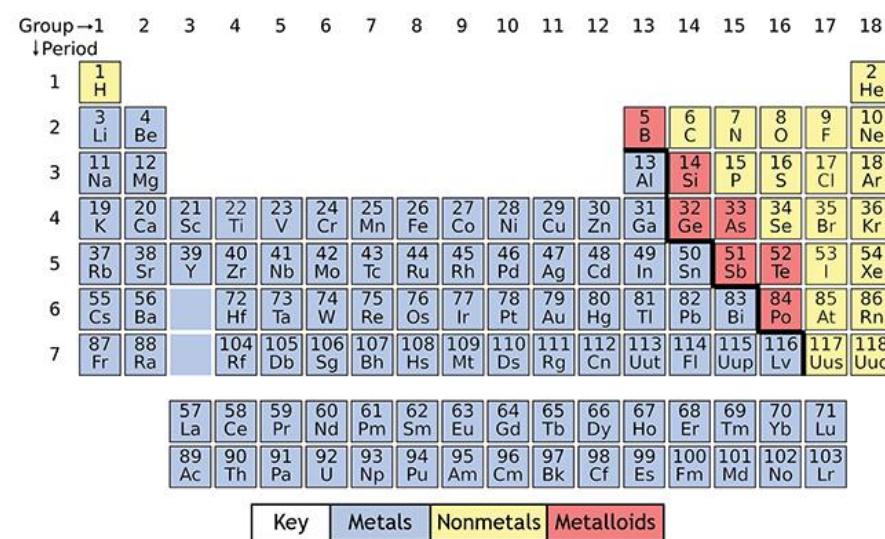
- OFF (an insulator)

An electrical circuit diagram showing a horizontal line with two open terminal circles. A diagonal line labeled "Open" extends from the top terminal circle towards the top-left.
- ON (a conductor)

An electrical circuit diagram showing a horizontal line with two closed terminal circles (represented by small dots). A diagonal line labeled "Closed" extends from the top terminal circle towards the top-left.

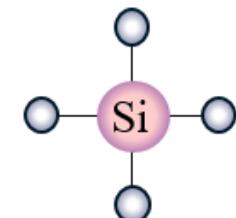
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Semiconductor

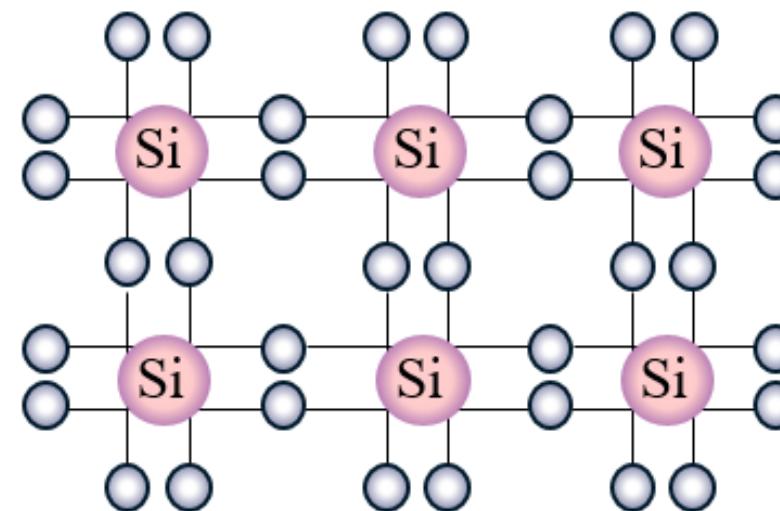
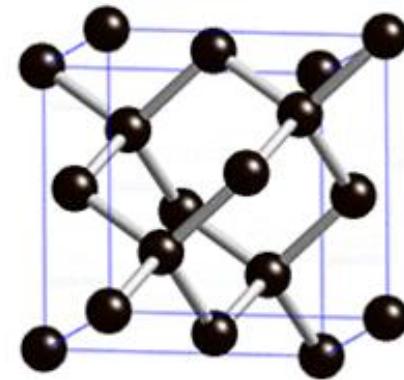


• Silicon crystal 硅晶体

Si: Atomic number 14



Crystallization

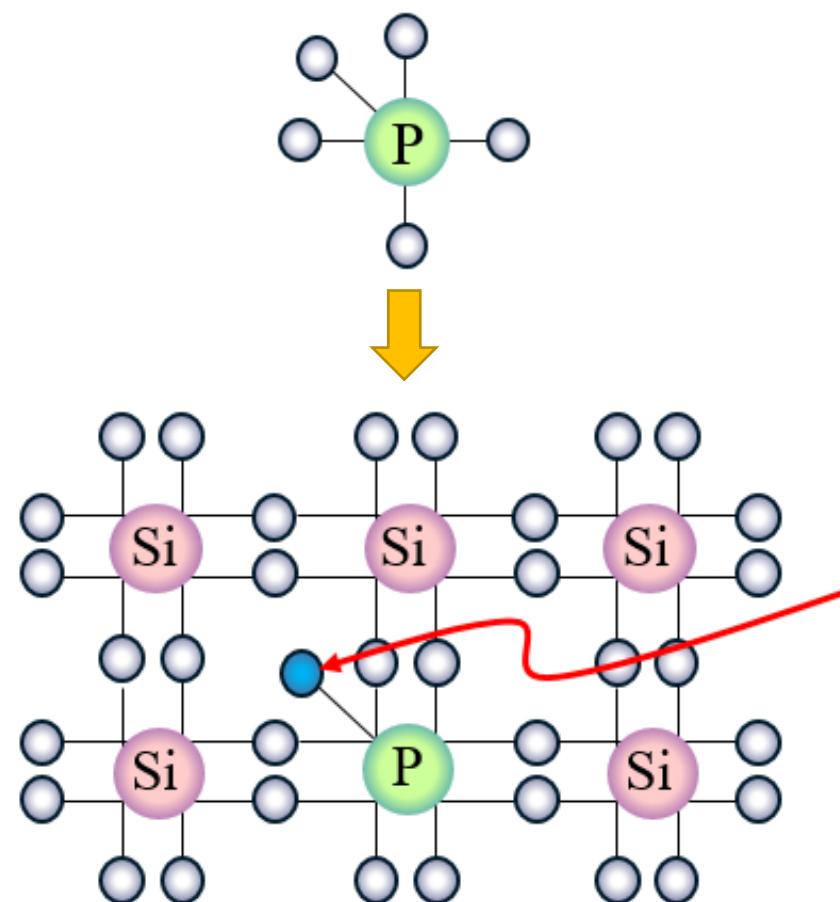


(Pictures are from the Internet)

After doping

- N-type semiconductor

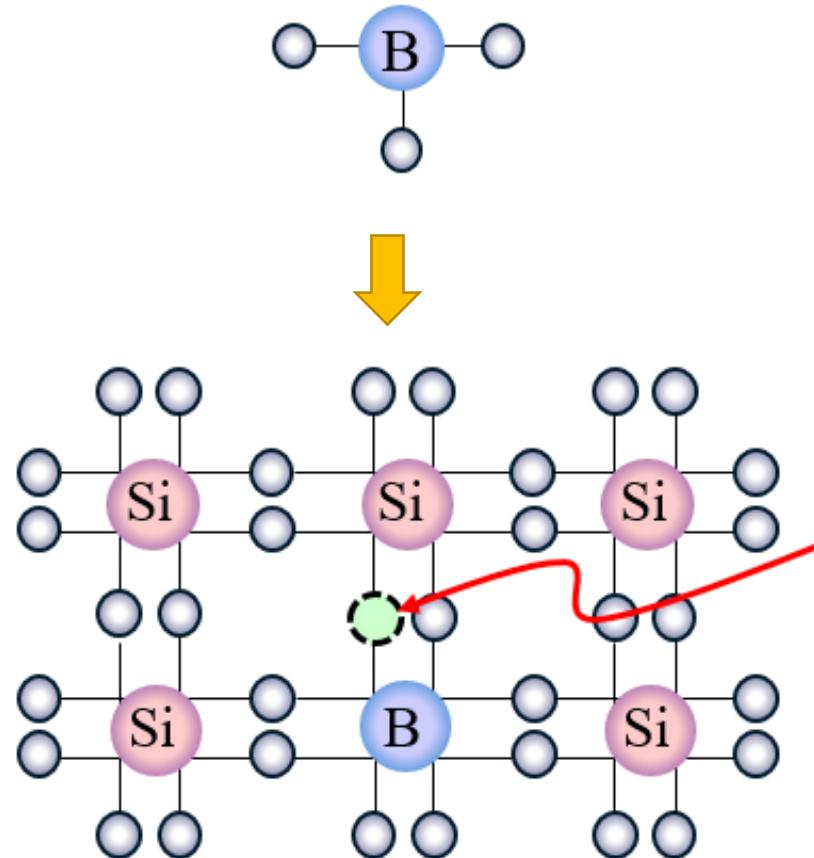
- Some of the silicon atoms are replaced with P (phosphorus) 磷



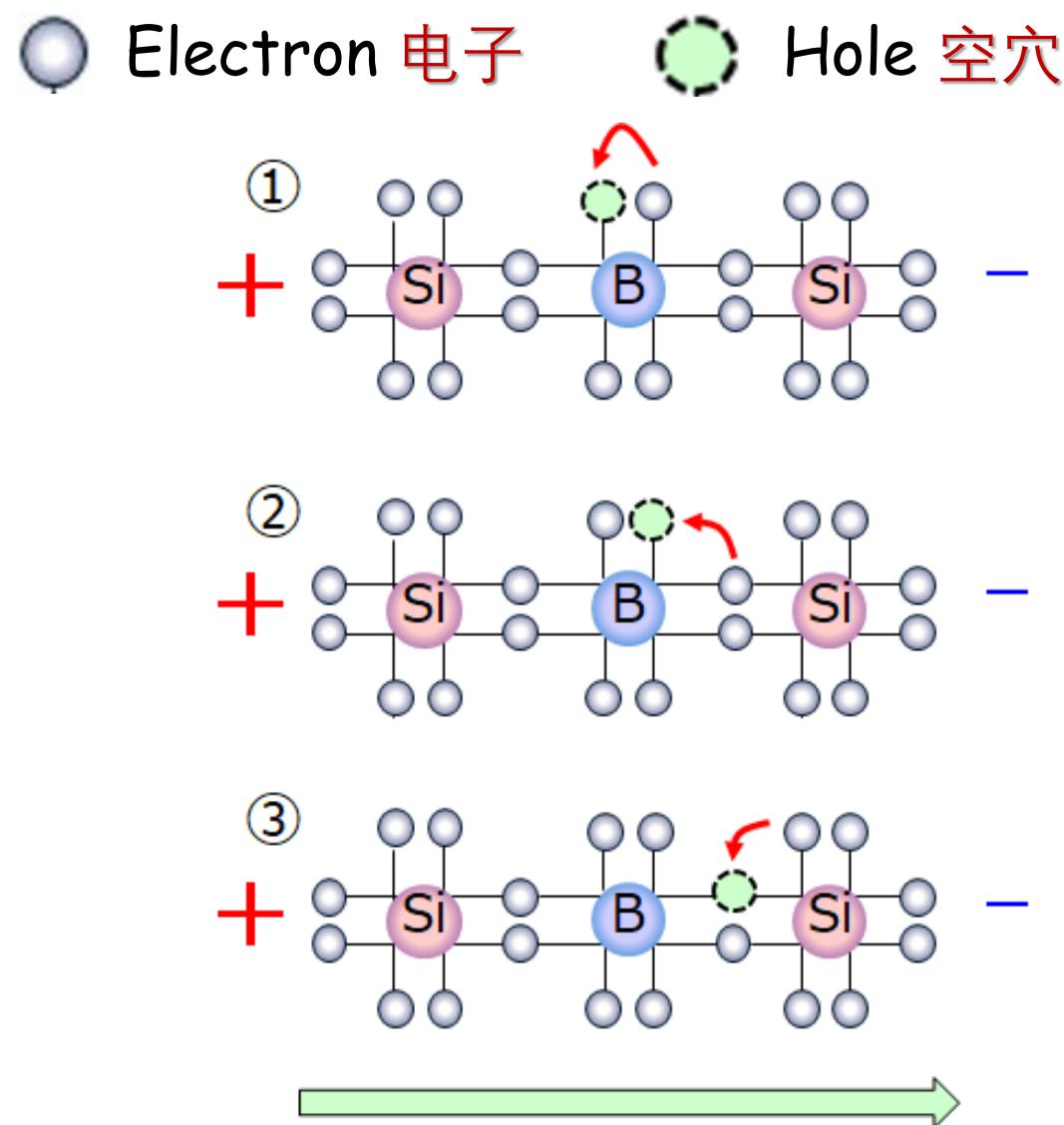
(Pictures are from the Internet)

- P-type semiconductor

- Some of the silicon atoms are replaced with B (boron) 硼

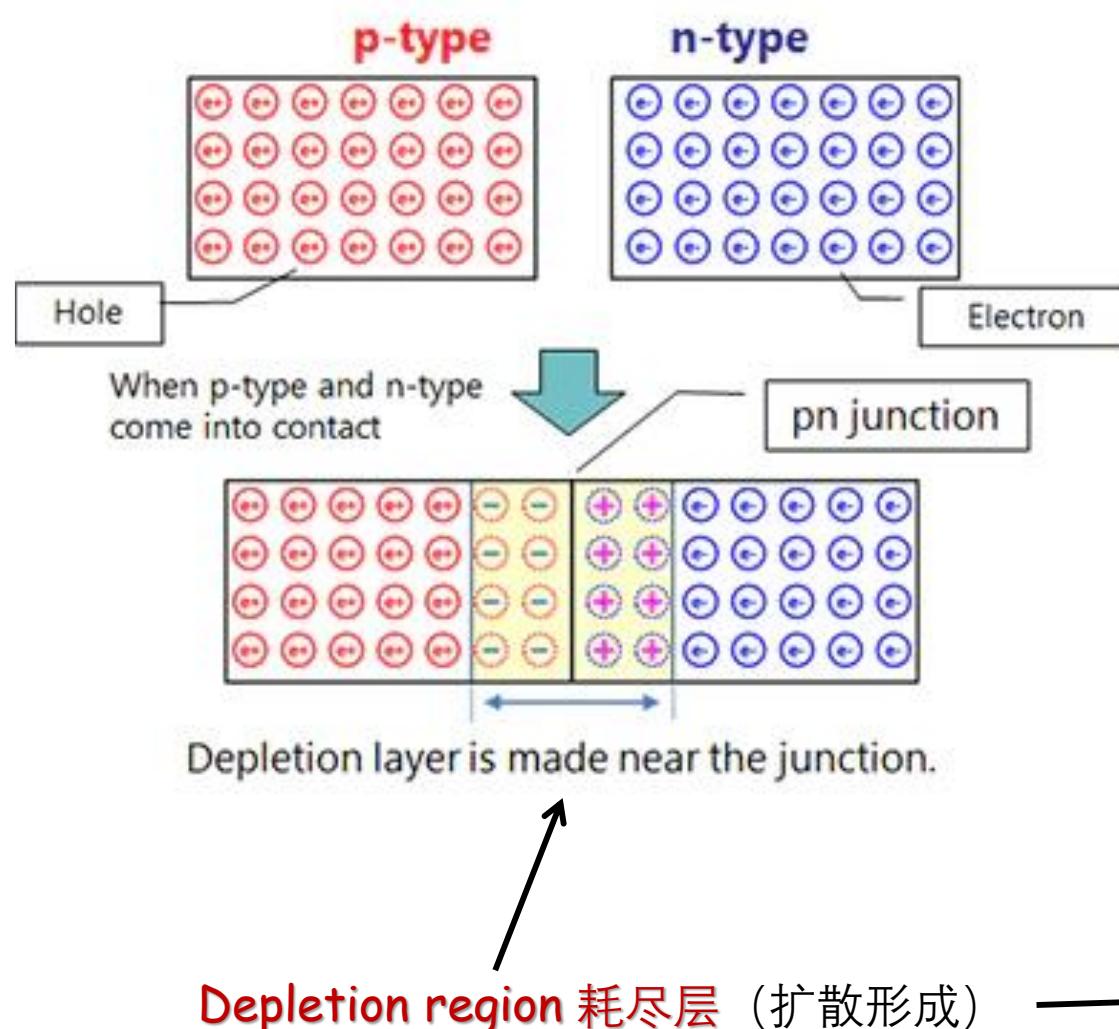


How current flows in p-type semiconductors



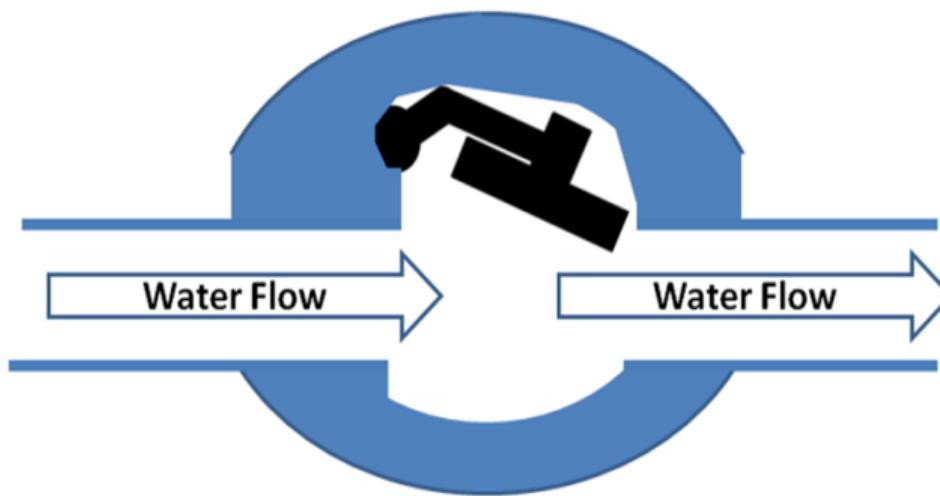
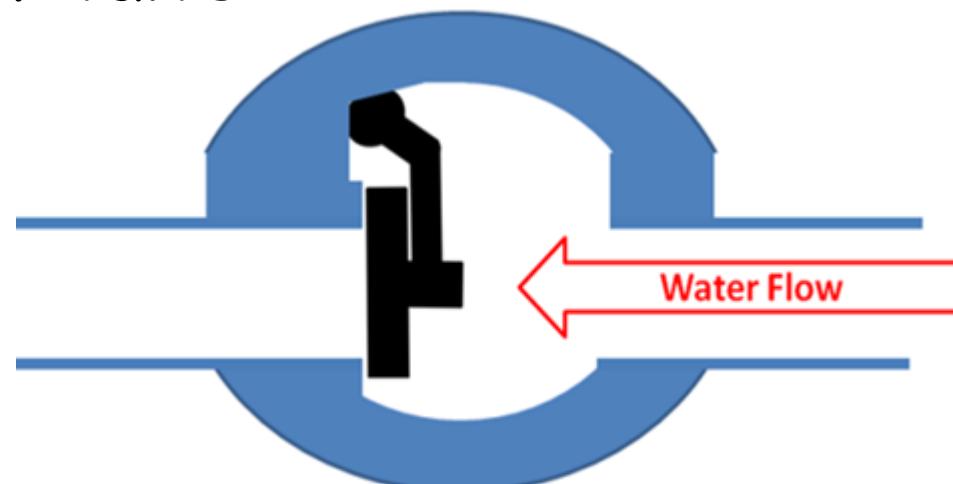
1. Electrons are drawn to the positive (+) pole 正极 and move to close holes.
2. Then, as the electrons move to vacant holes, new holes are created and then the adjacent electrons move to the new vacant holes again.
3. As this process is repeated, electrons move toward the positive (+) pole, and at the same time, the holes appear to move toward the negative (-) pole 负极.
4. Only electrons are actually moving, but the holes can be considered as having positively charged particles.

When p-type meets n-type

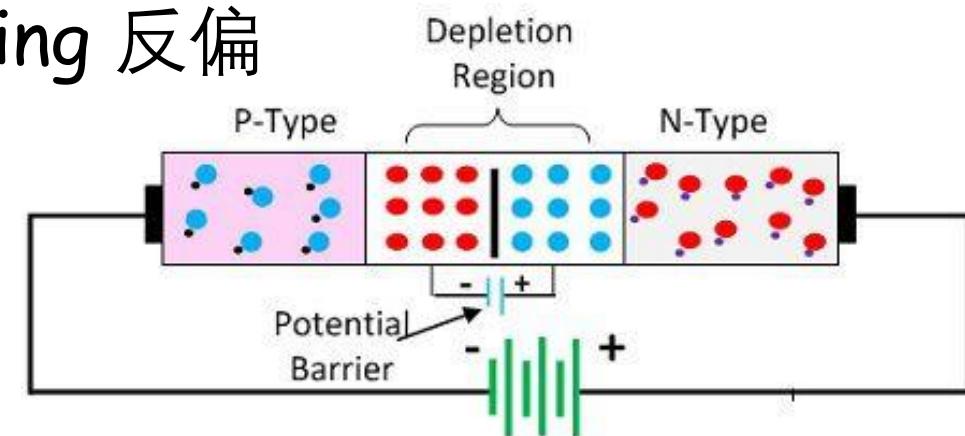


Uni-directional flow

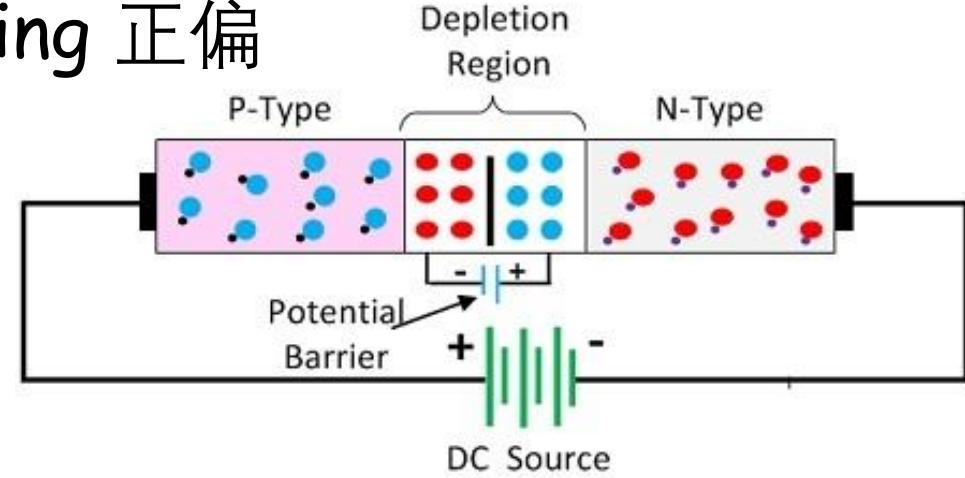
- Flapper valve



- Reversed biasing 反偏



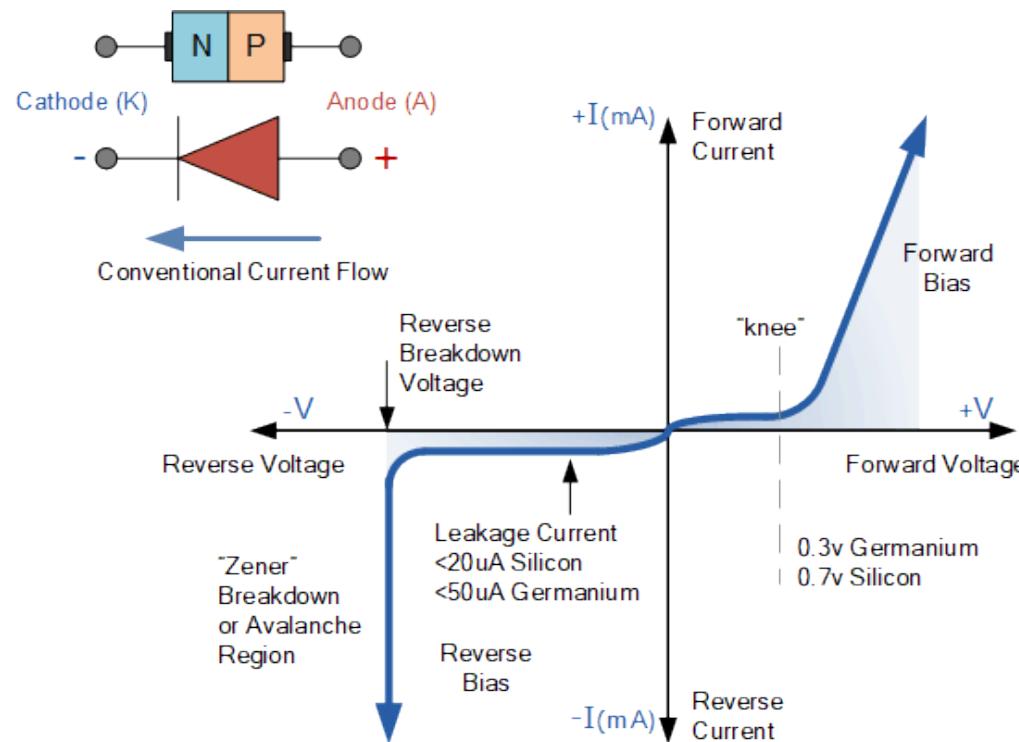
- Forwarded biasing 正偏



Holes ● Electrons ●
Free Electrons • Free Holes •

Diode characteristic

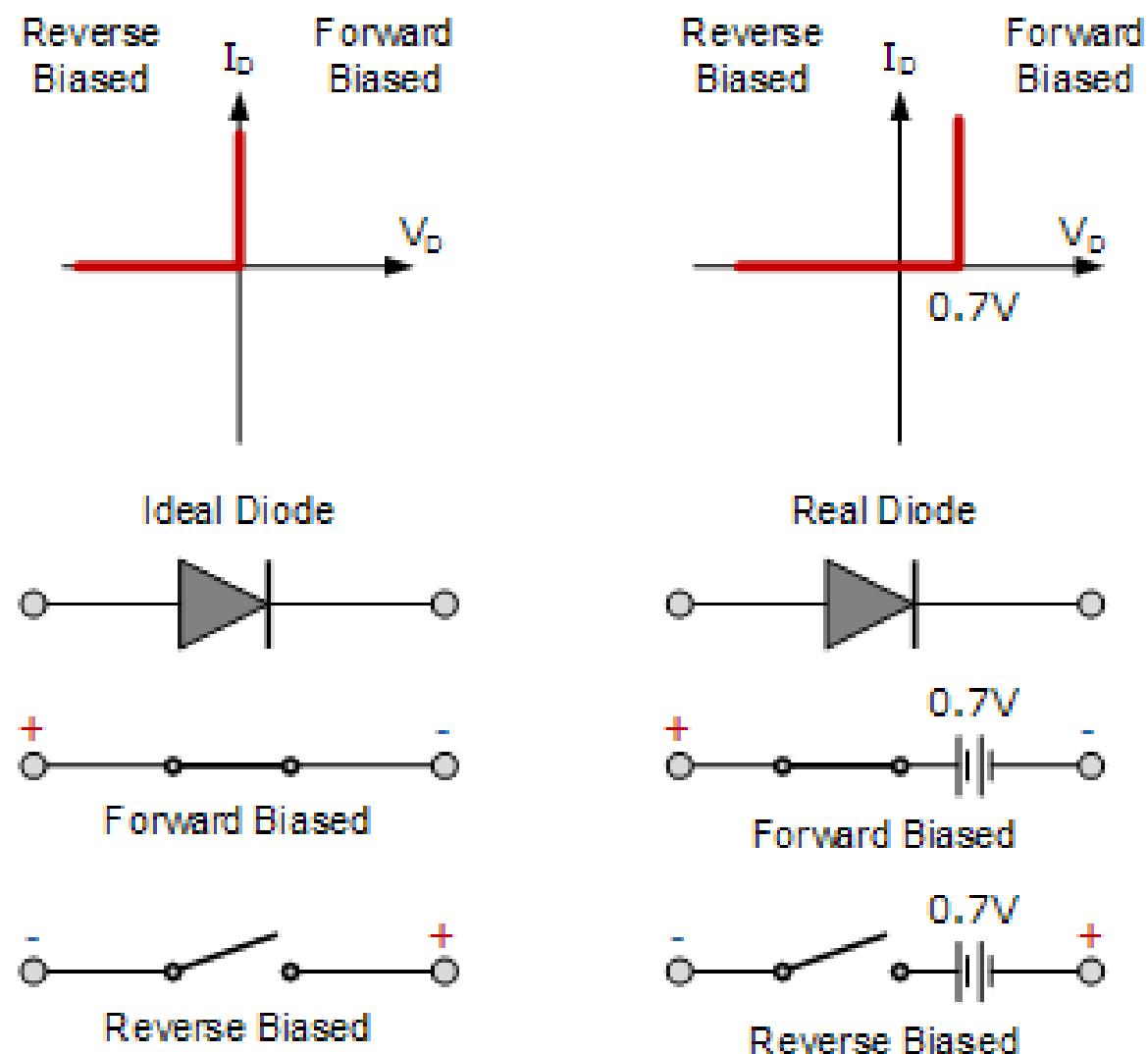
- Solid-state devices 固态器件



- Shockley diode equation

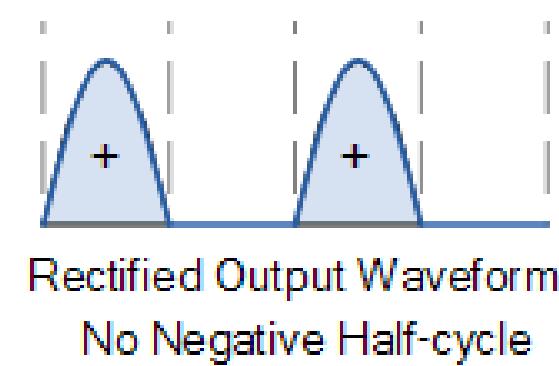
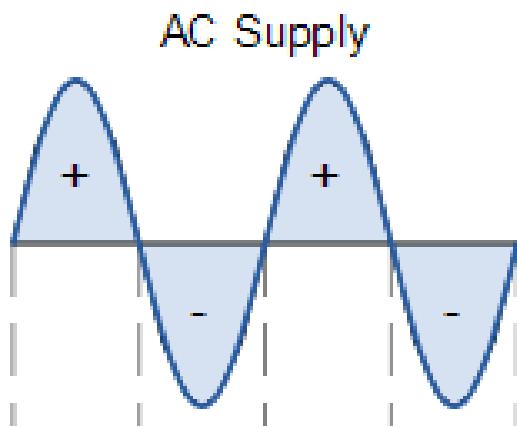
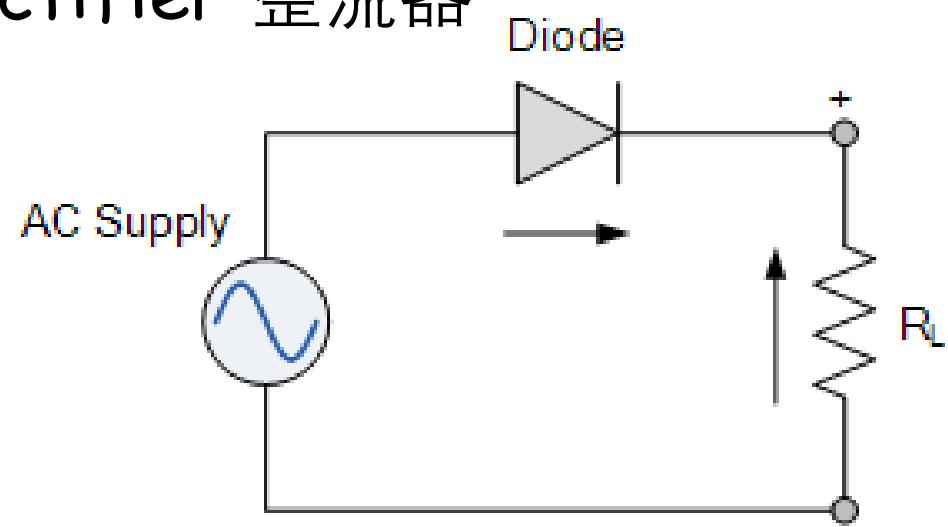
$$I = I_S \left[e^{\left(\frac{V_d}{nV_T} \right)} - 1 \right]$$

- Simplified models

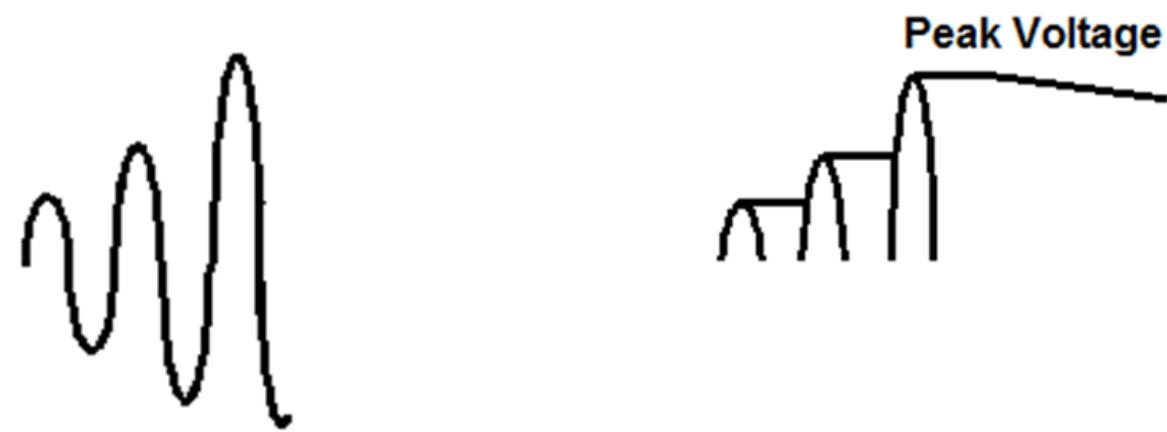
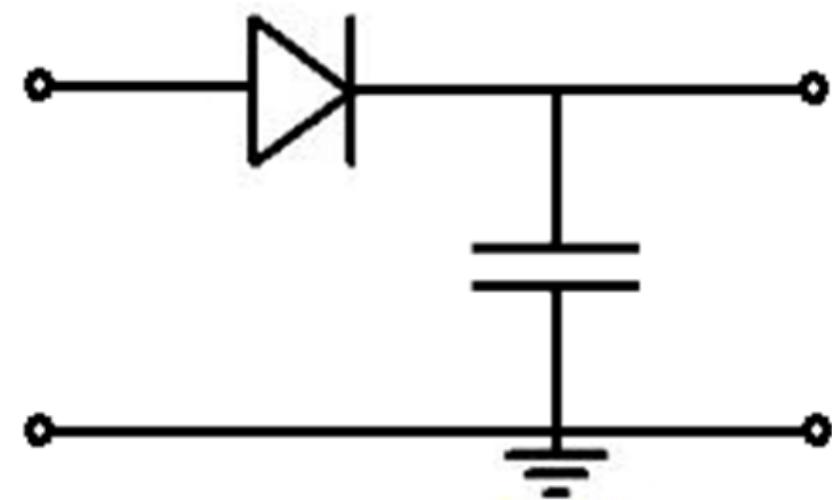


Diode circuits

- Rectifier 整流器

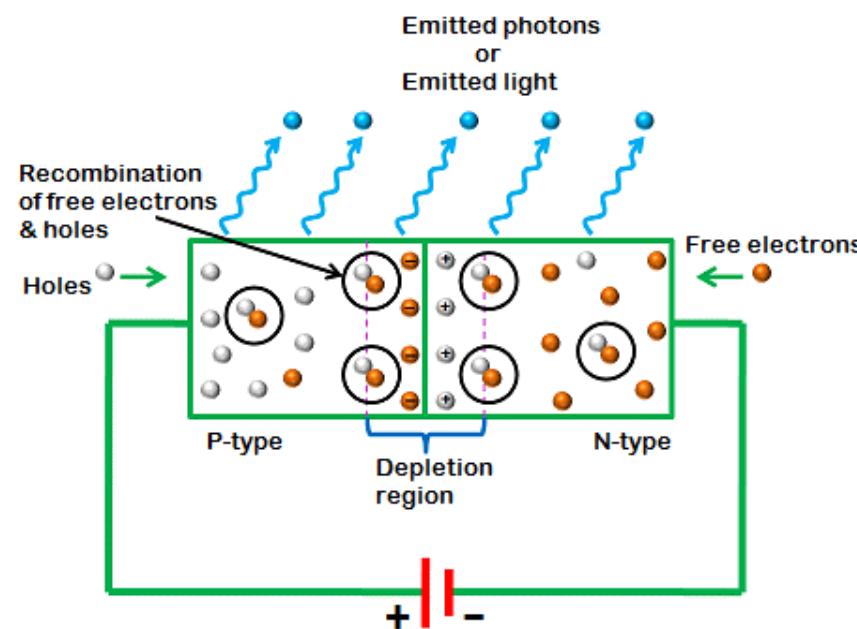
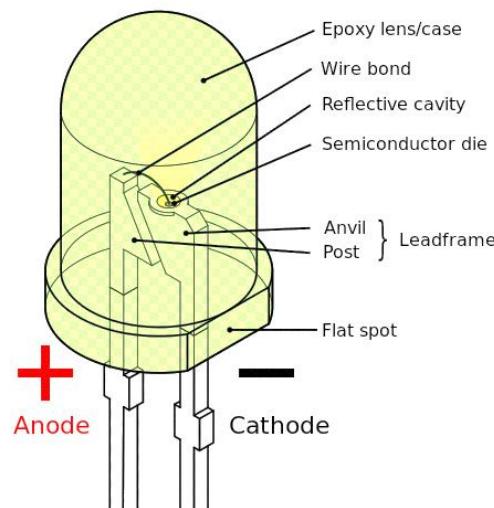


- Peak detector 峰值检测

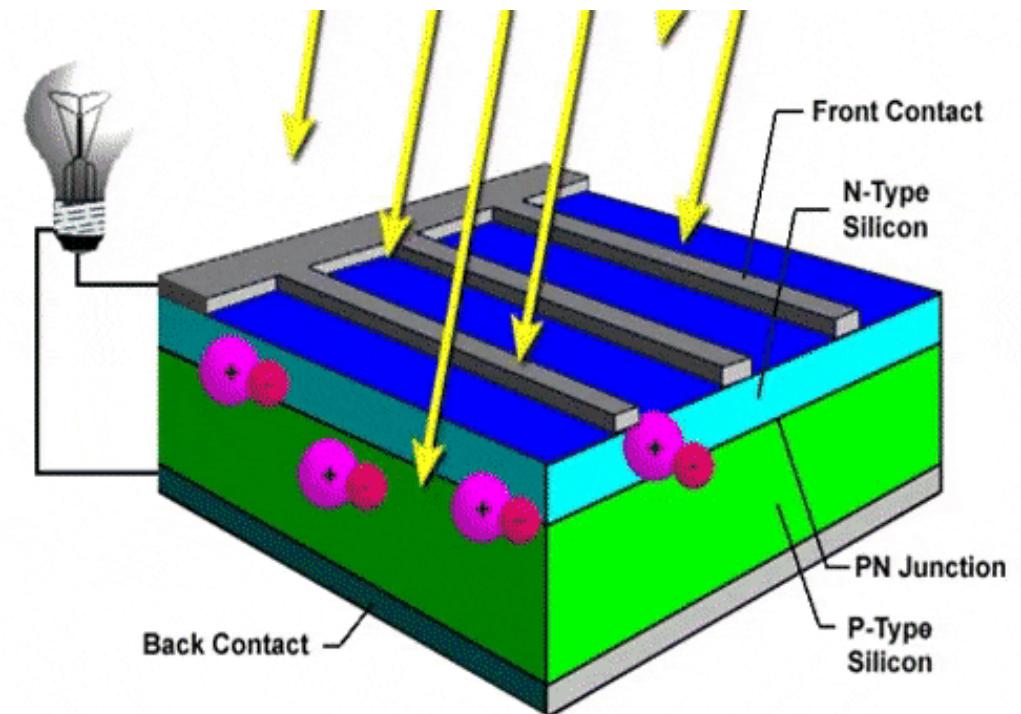


Other applications of PN junction

- LED (light emitting diode)

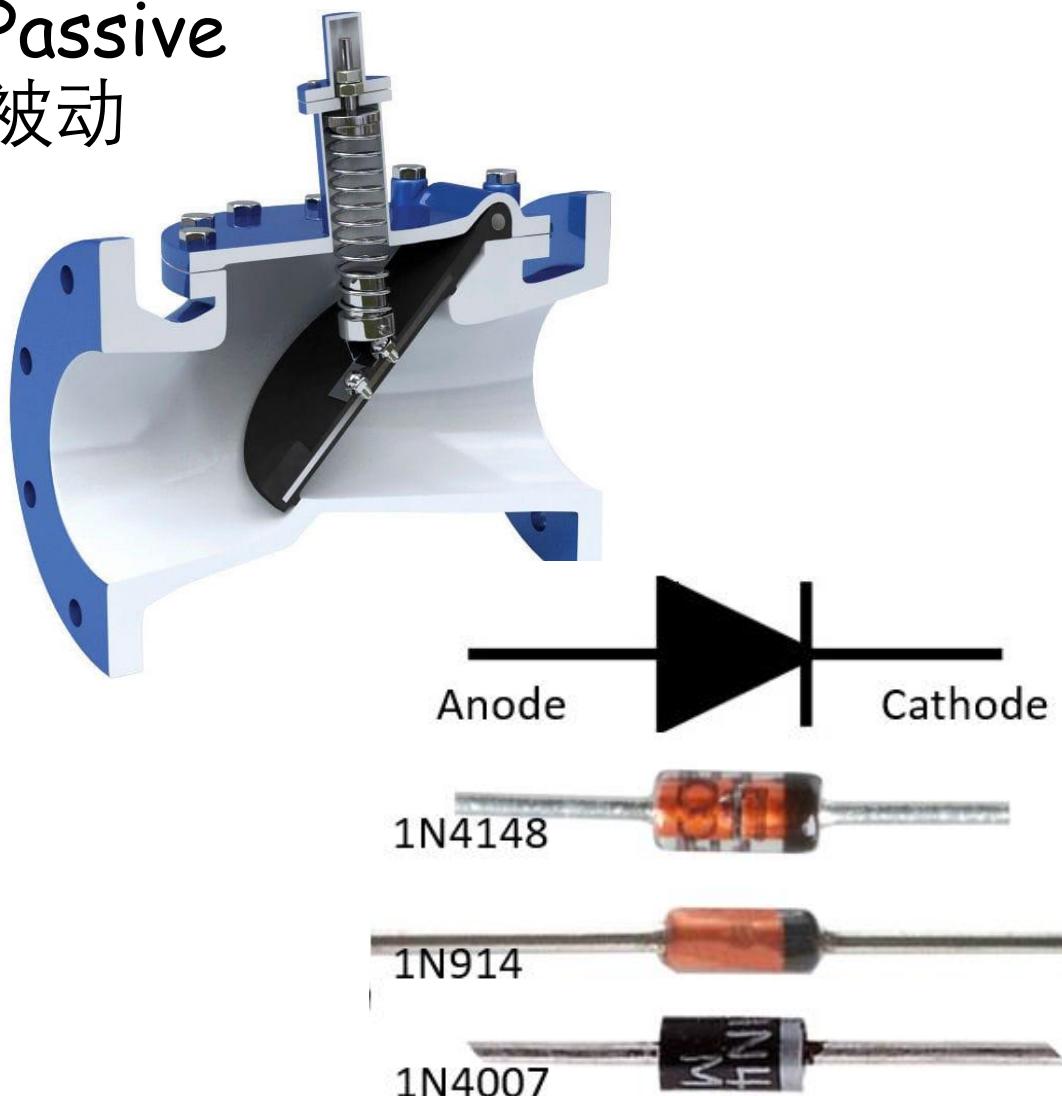


- Solar PV (photovoltaics)



Passive and active switches

- Passive
被动



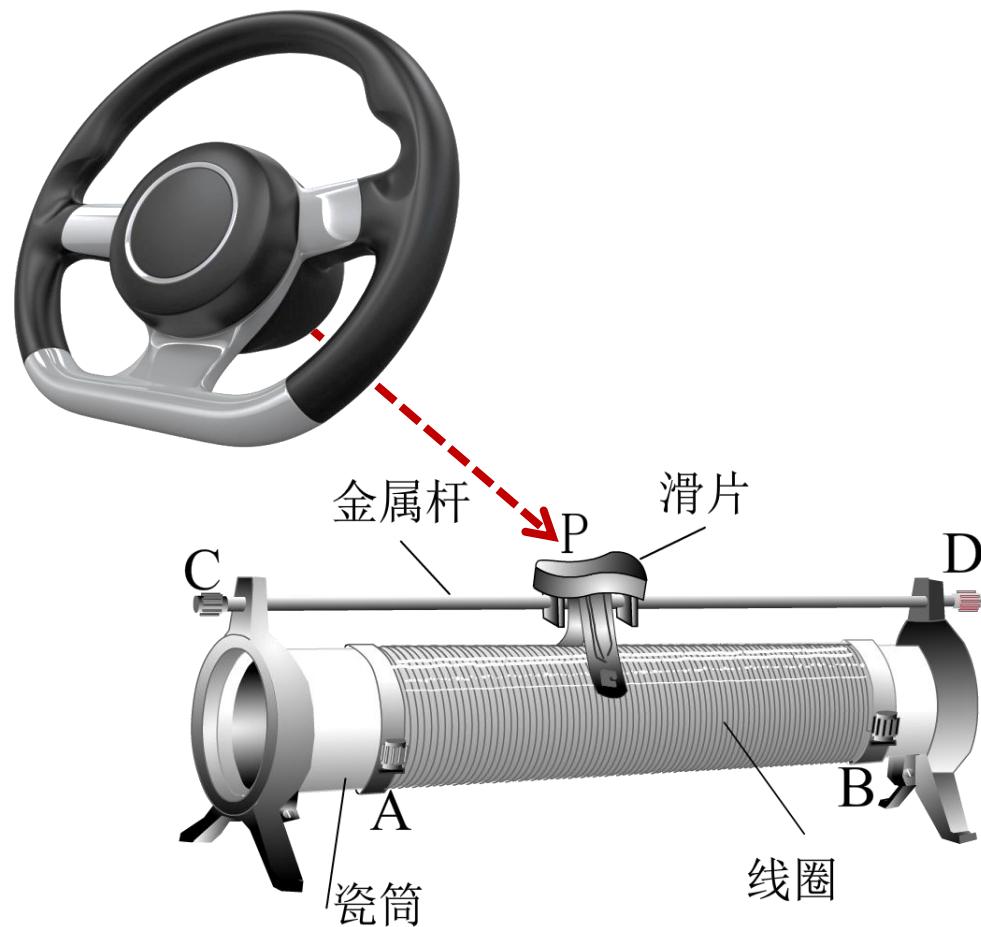
- Active
主动



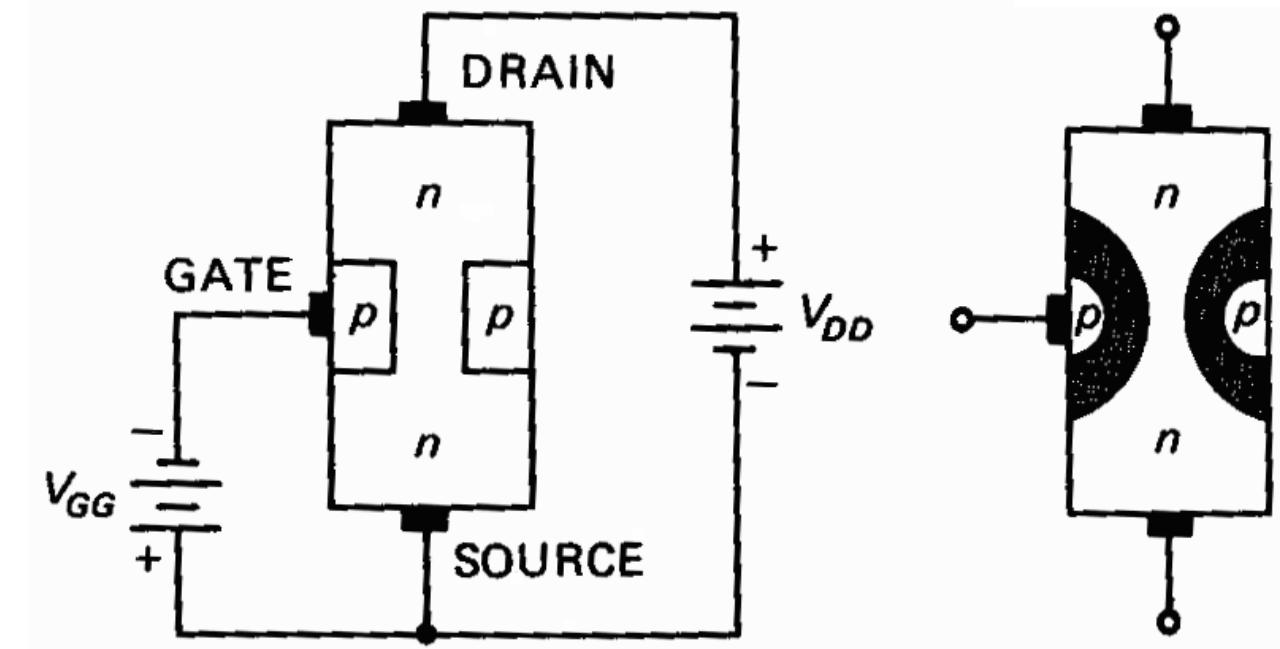
Electronic
counterpart?

History of transistors

- Transistor (晶体管)
“transfer” 转换 + “resistor” 电阻

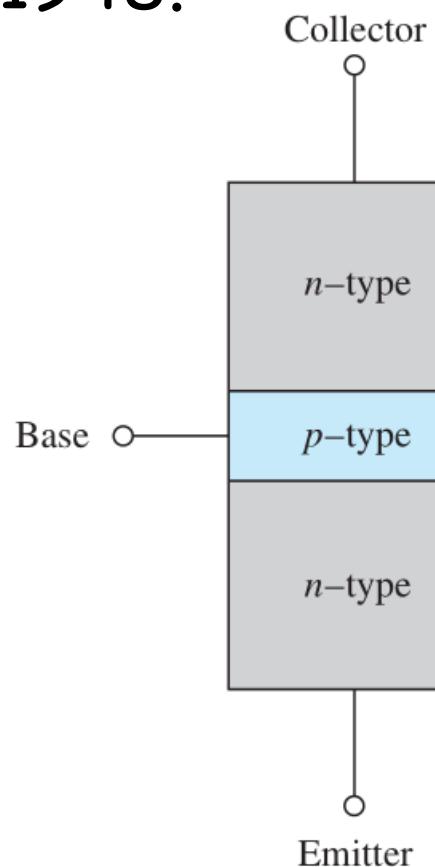


- Junction field-effect transistor (JFET) 结型场效应晶体管, was first patented by Heinrich Welker in 1945

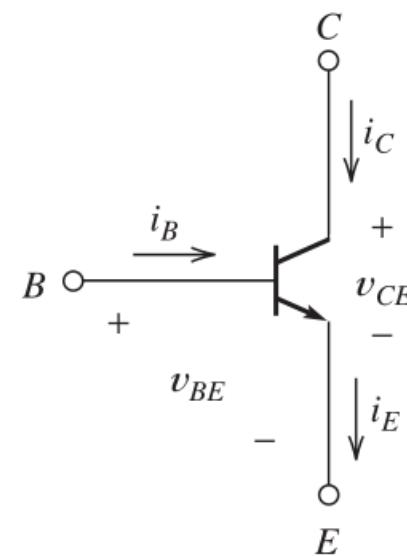


History of transistors

- Shockley's **bipolar junction transistor (BJT)** 双极型晶体管 in 1948.

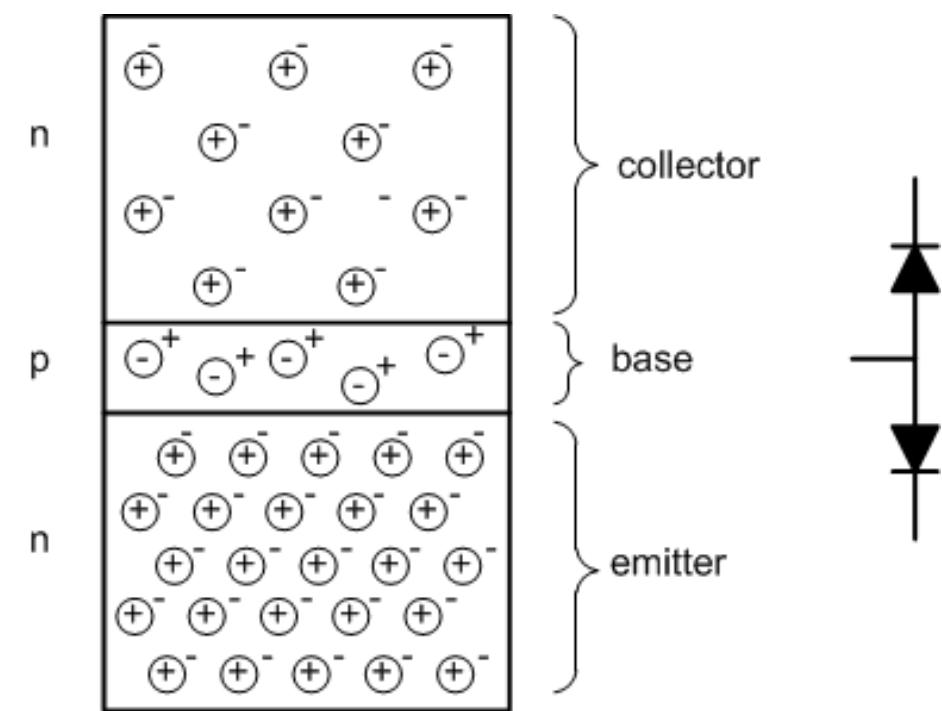


(a) Physical structure



(b) Circuit symbol

- By the mid-1950s, researchers had largely given up on the FET concept, and instead focused on bipolar junction transistor (BJT) technology

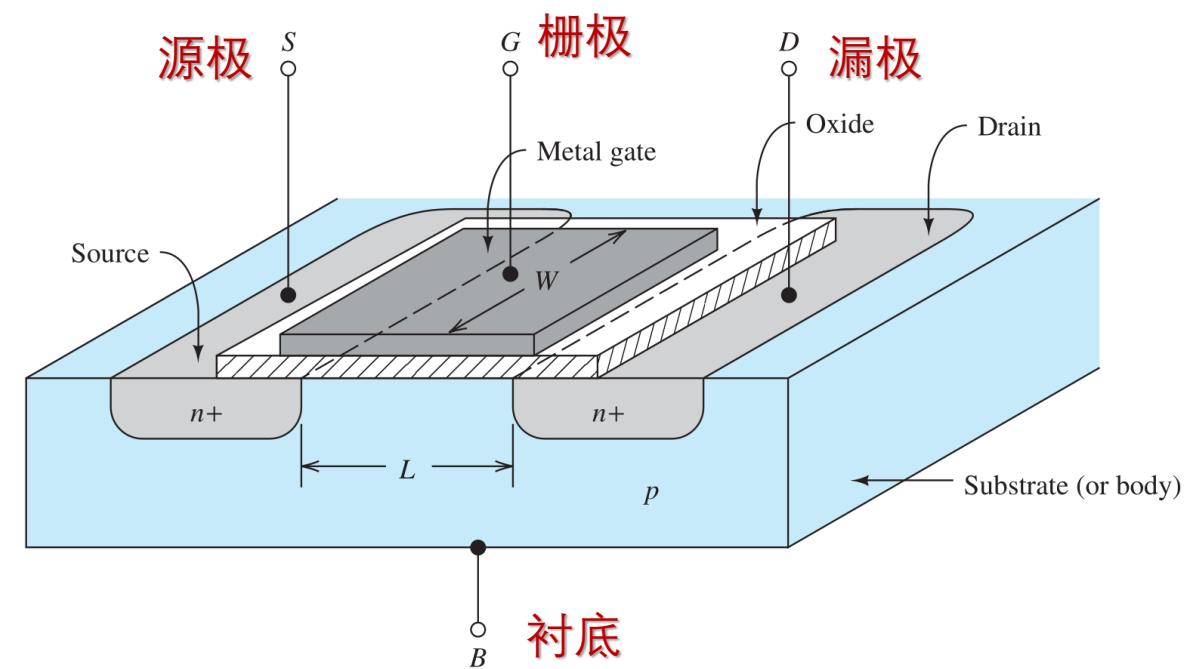


History of transistors

- The **metal-oxide-semiconductor field-effect transistor (MOSFET)** 金属氧化物半导体场效应晶体管 was invented by Mohamed Atalla and Dawon Kahng at Bell Lab in 1959.



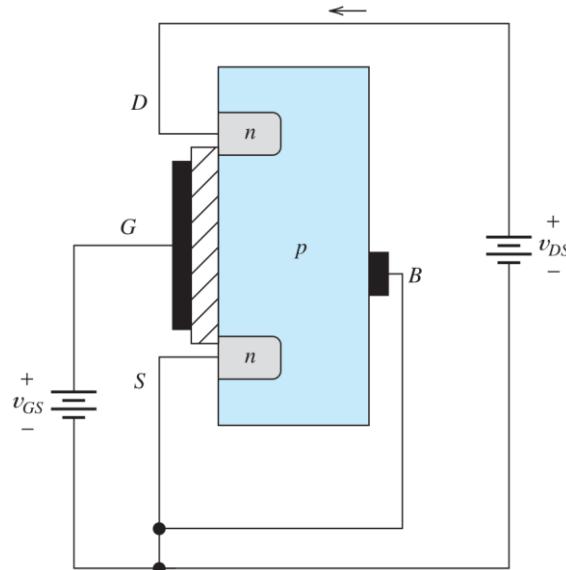
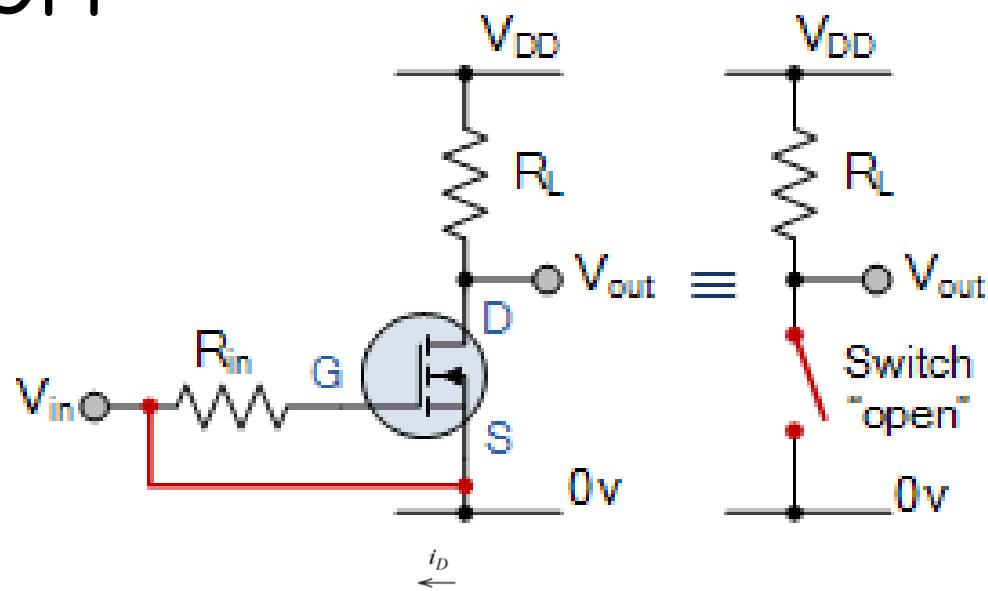
- high **scalability**
- much lower **power consumption**
- higher density** than BJT
- possible to build high-density integrated circuits (ICs)



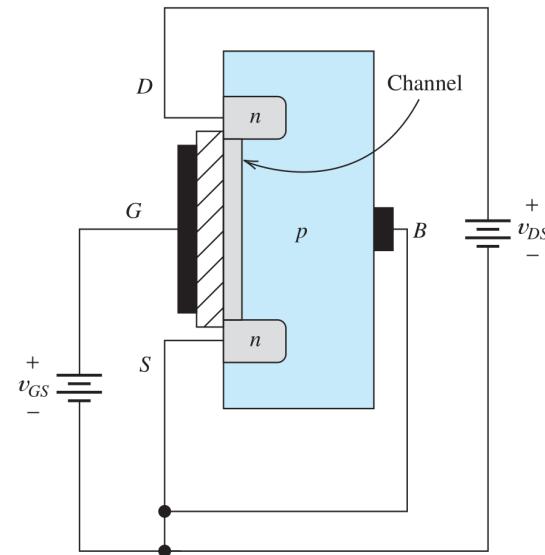
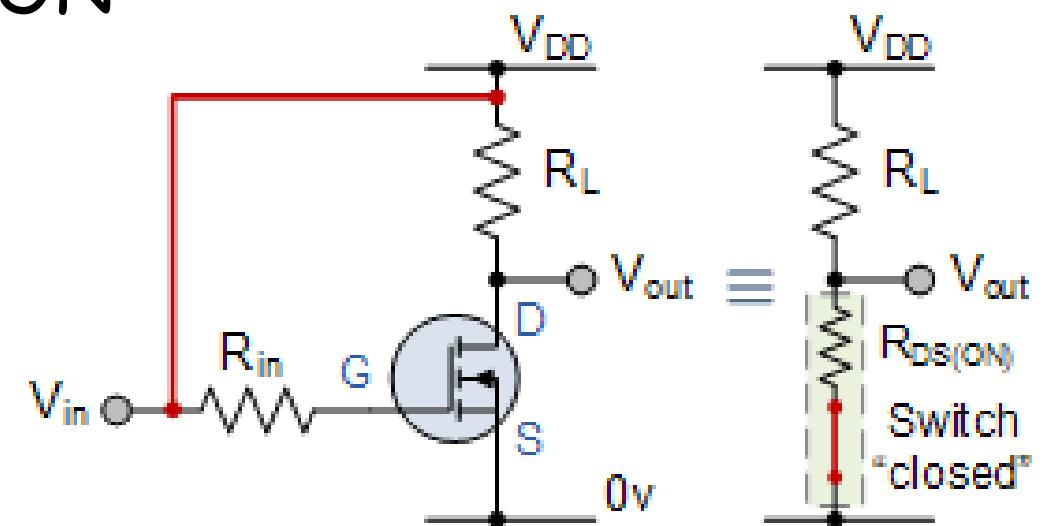
(https://en.wikipedia.org/wiki/History_of_the_transistor)

MOSFET operation

- OFF

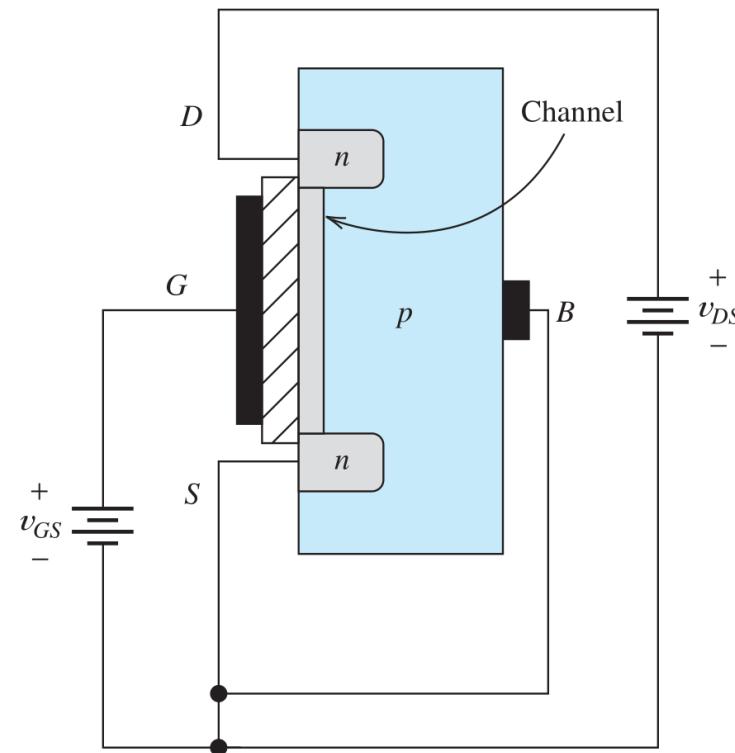


- ON

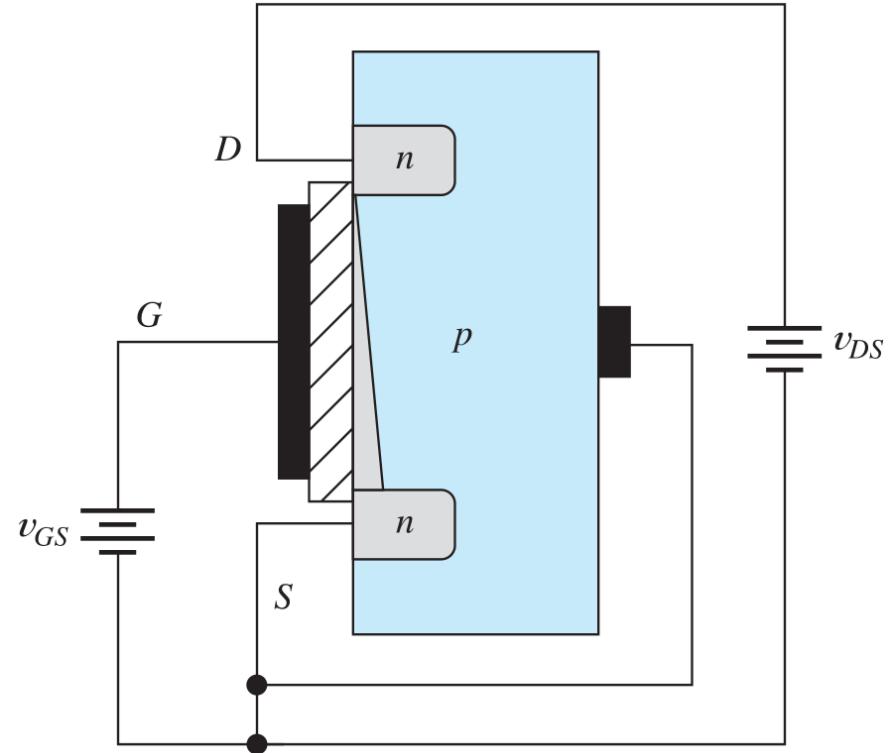


MOSFET operation

- Ideal channel

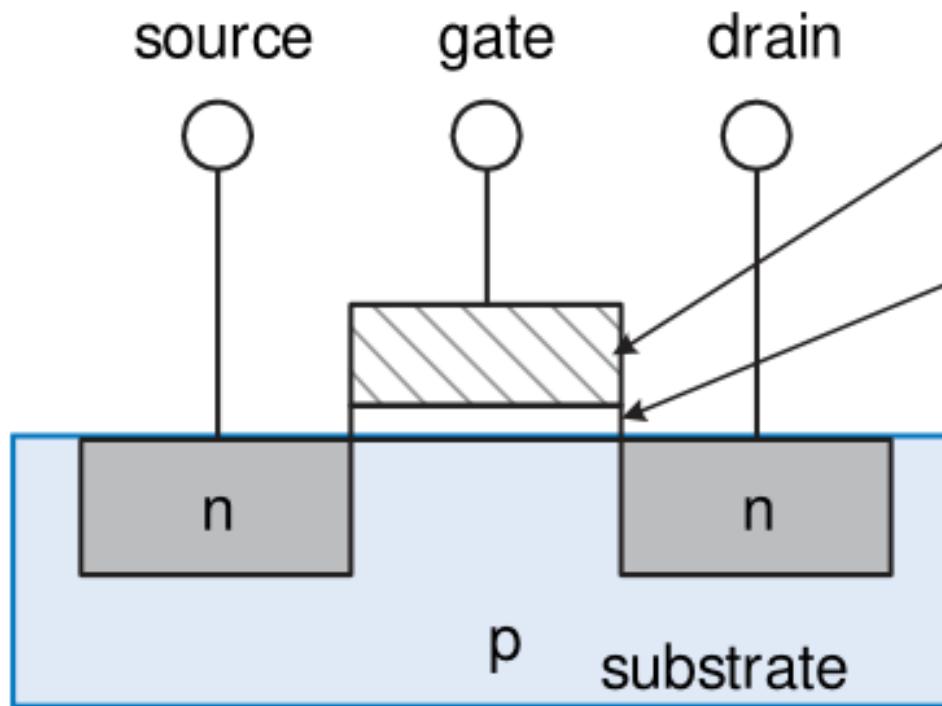


- Actual channel

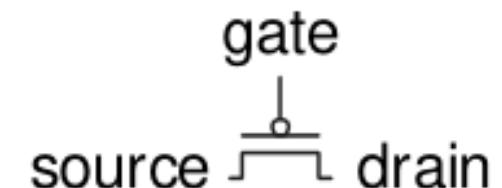
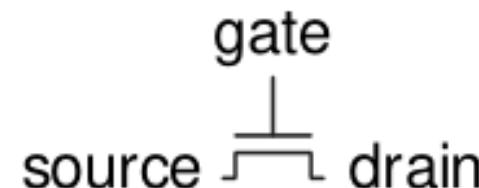
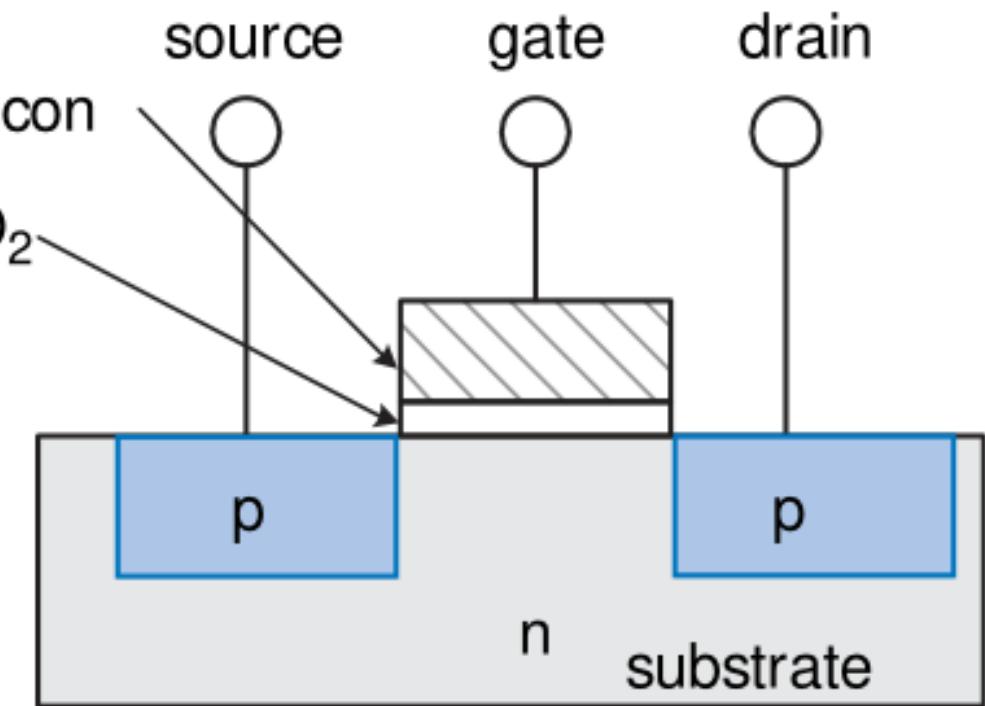


NMOS & PMOS

NMOS

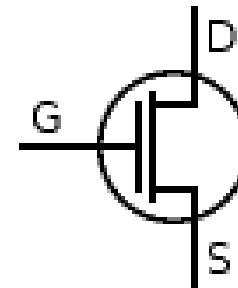
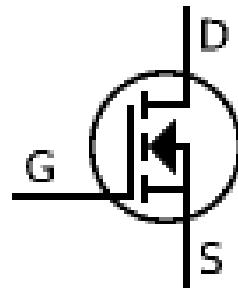


PMOS

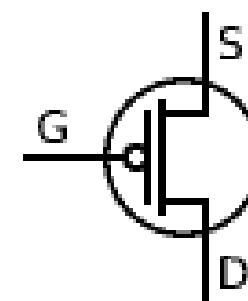
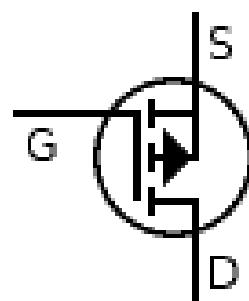


Symbols

- Symbol
- NMOS

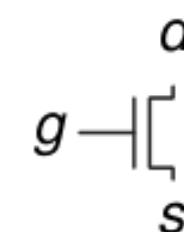


- PMOS

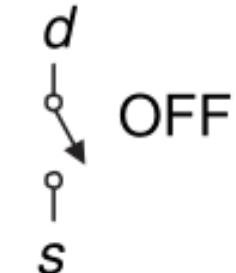


- ON / OFF

nMOS

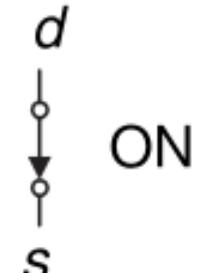


$$g = 0$$



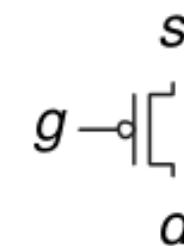
OFF

$$g = 1$$



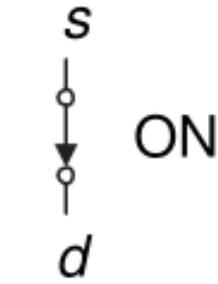
ON

pMOS

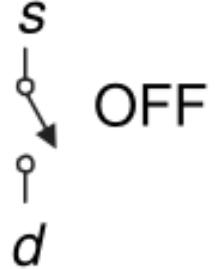


s

d

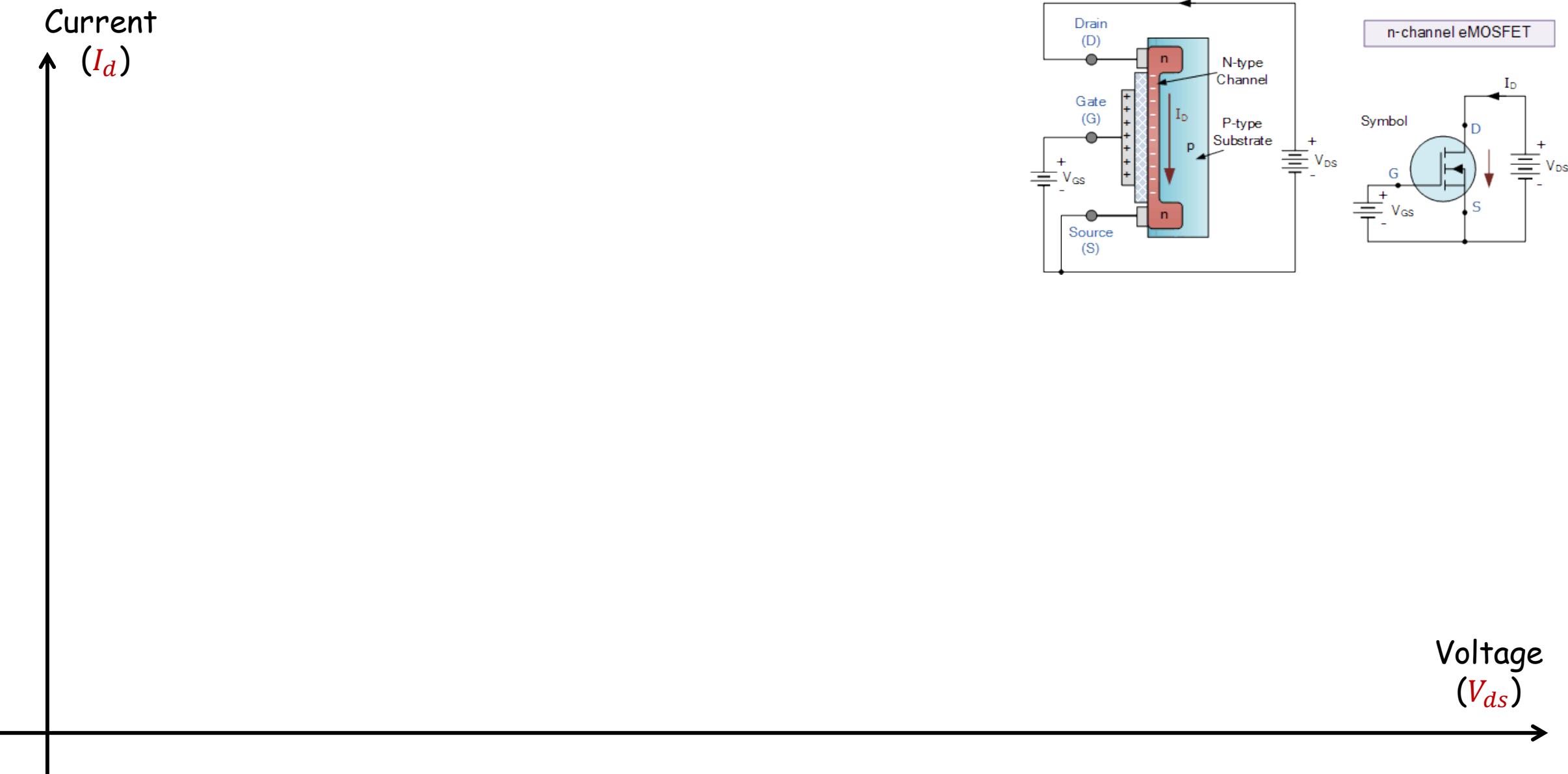


ON



OFF

The I-V characteristic of a MOSFET



Computation

- Arithmetic

$$5.5 - 3.4 = 2.1$$

$$15 / 3 = 5$$

$$2 + 15 = 17$$

$$3 \times (4+2) = 18$$

25% of 12 is 3

$$\sqrt{9} = 3$$

$$\frac{3}{4} \times 16 = 12$$

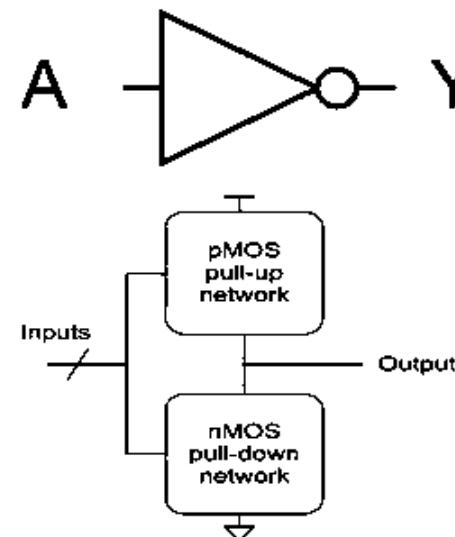
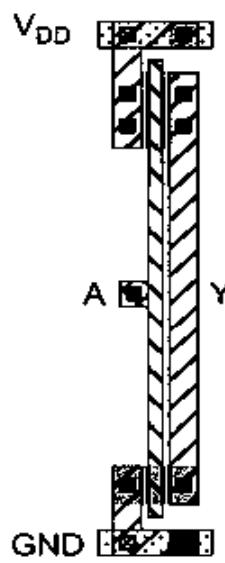
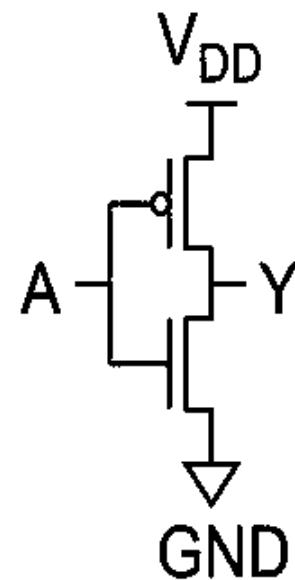
- Boolean logic



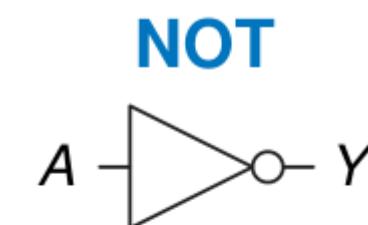
CMOS & not gate

- CMOS technology
(**Complementary** Metal-Oxide-Semiconductor Transistor,
互补金属氧化物半导体)

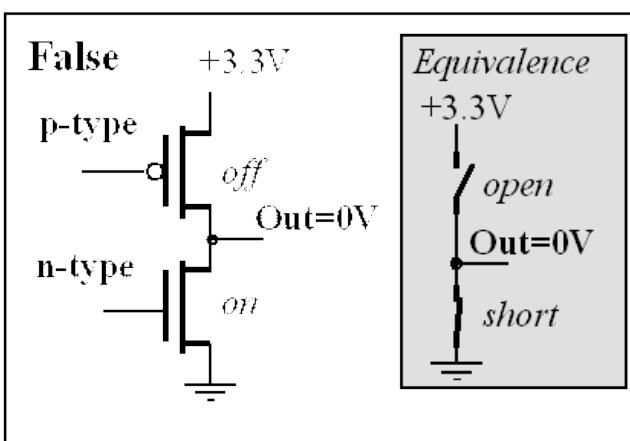
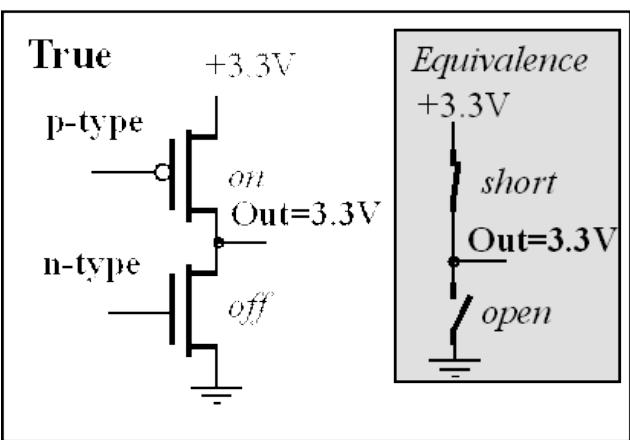
BASICS OF CMOS TECHNOLOGY



- Not gate 非门

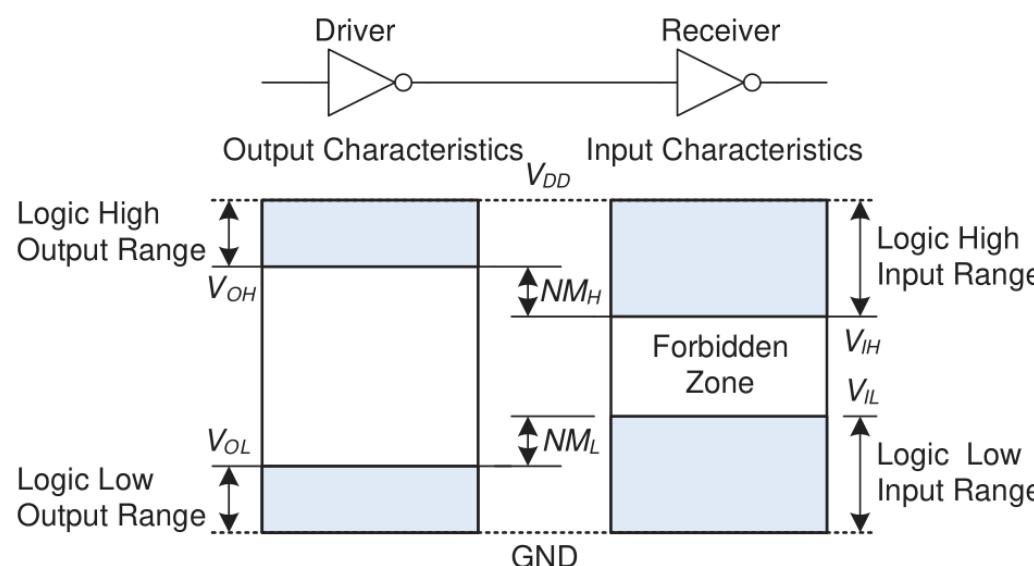


A	Y
0	1
1	0

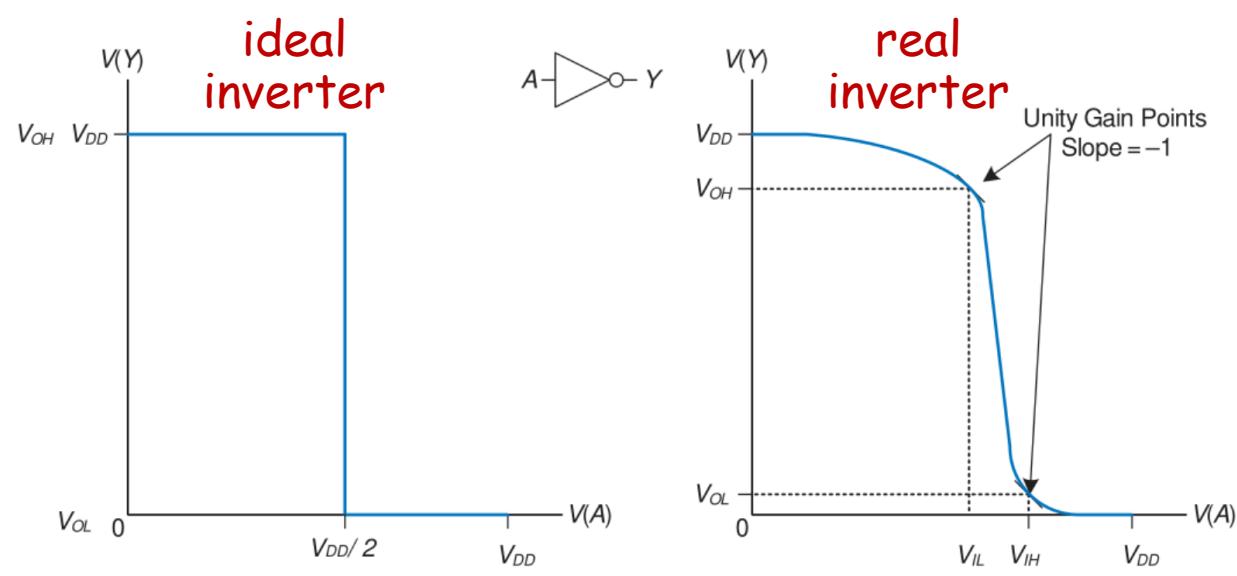


Logic voltage levels

- How to **physically** express the virtual concept of logic?



- DC transfer characteristics

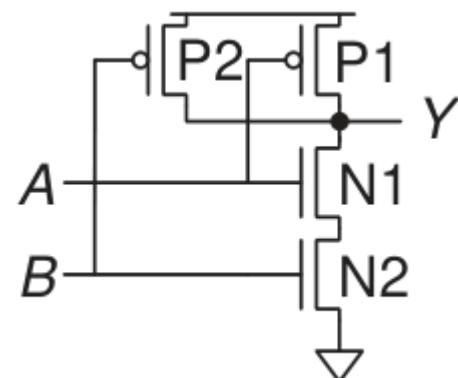
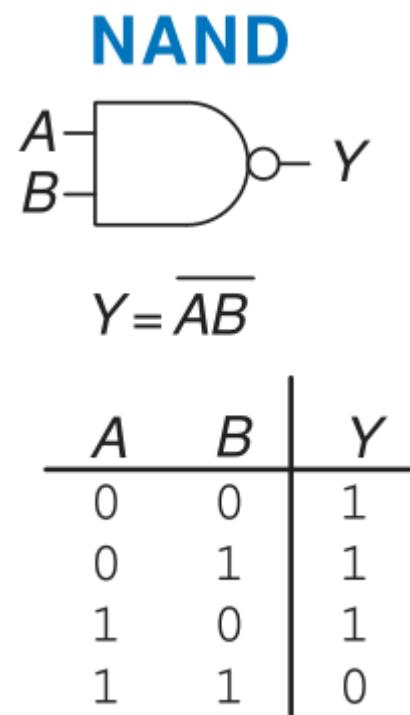


- Logic families

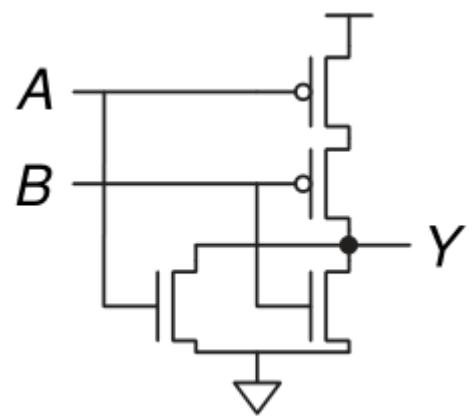
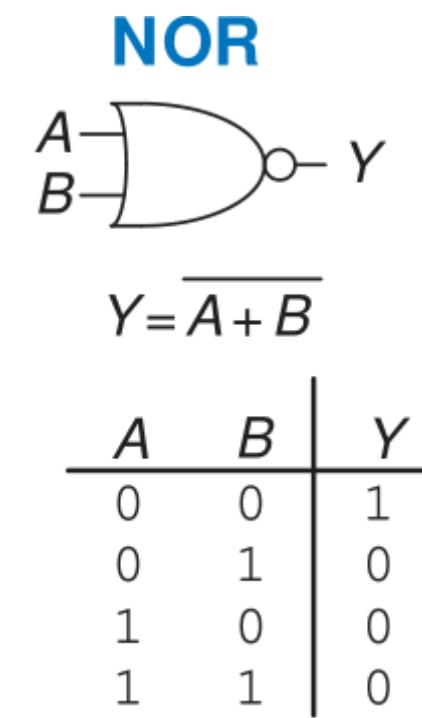
Logic Family	V_{DD}	V_{IL}	V_{IH}	V_{OL}	V_{OH}
TTL	5 (4.75–5.25)	0.8	2.0	0.4	2.4
CMOS	5 (4.5–6)	1.35	3.15	0.33	3.84
LVTTL	3.3 (3–3.6)	0.8	2.0	0.4	2.4
LVCMOS	3.3 (3–3.6)	0.9	1.8	0.36	2.7

Other logic gates

- NAND gate 与非门

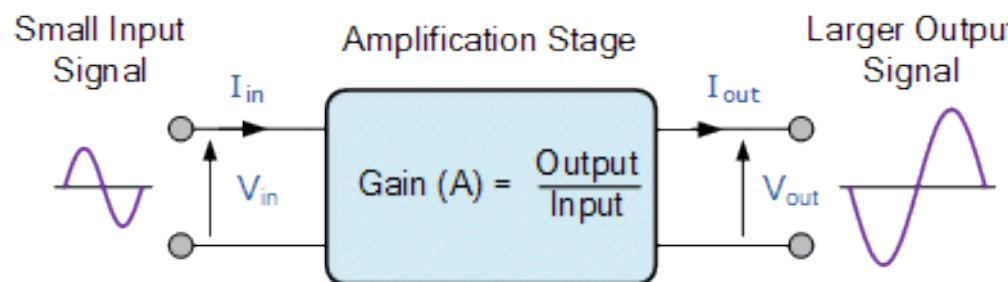


- NOR gate 或非门

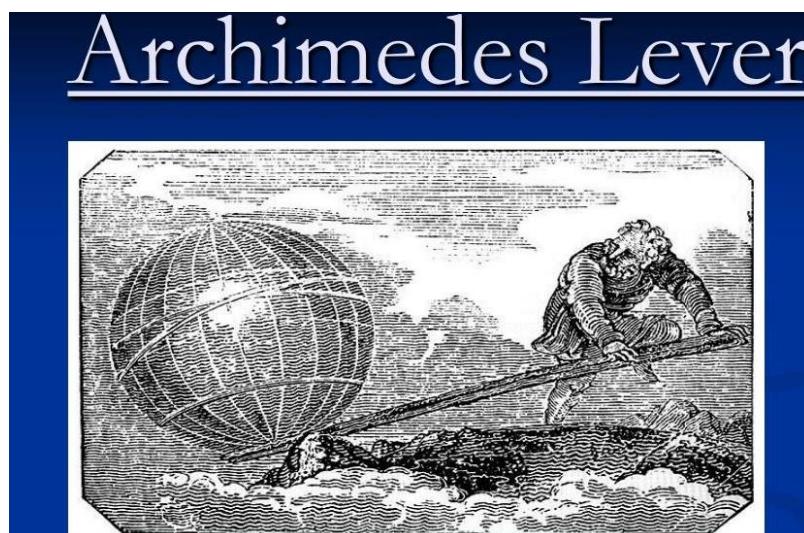


Amplification and CMOS amplifier

- What is an amplifier

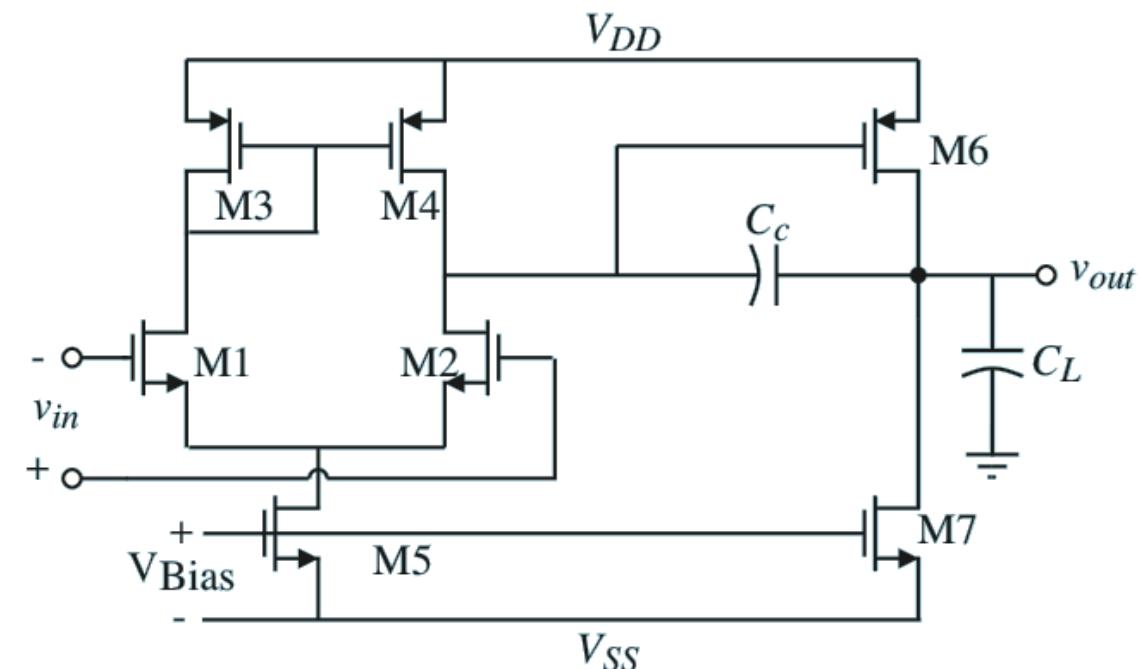


- Why we need amplifier



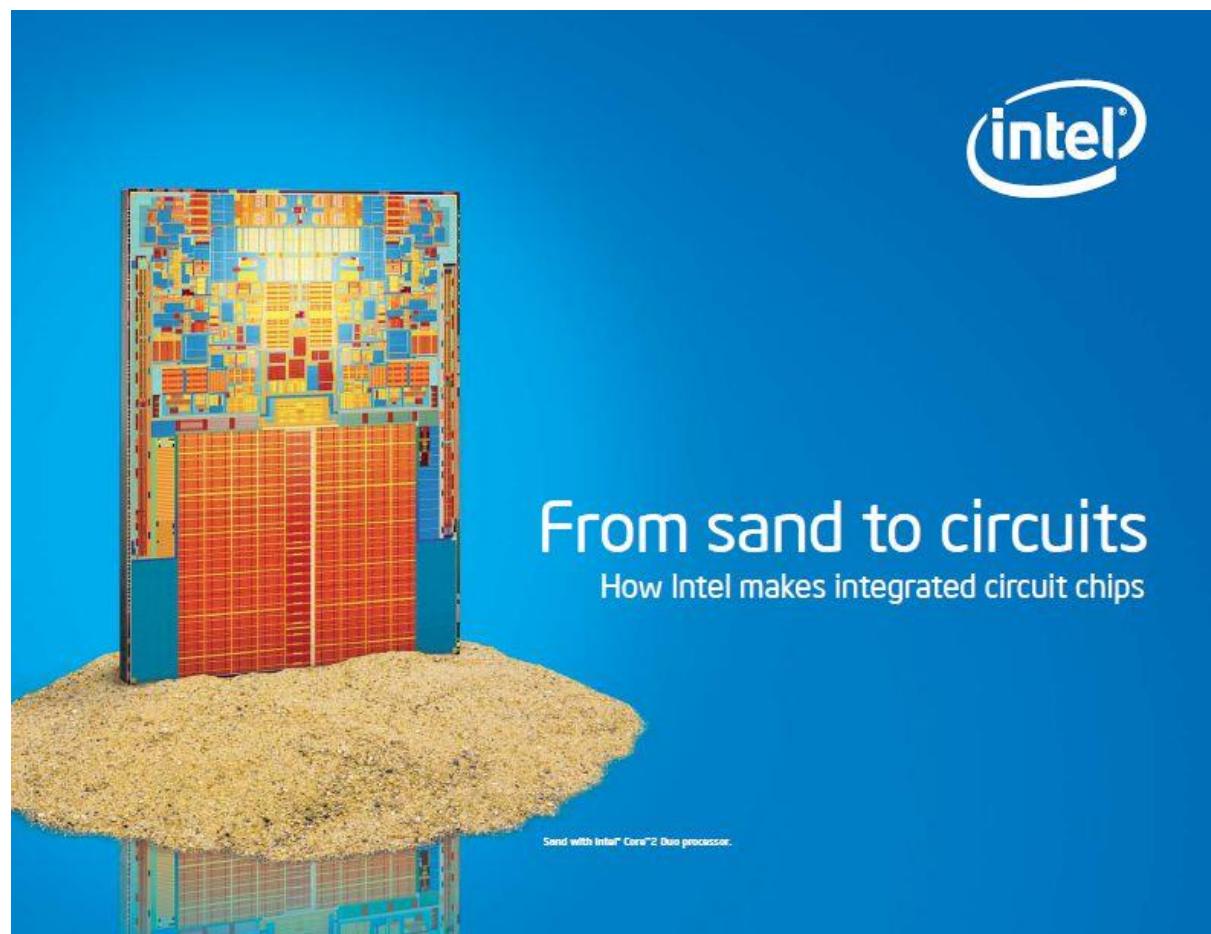
"Give Me a Place To Stand on, and I'll Move the Earth."

- CMOS amplifier



(will be further elaborated in the 6th lecture)

From sand to valuable integrated circuits (ICs)

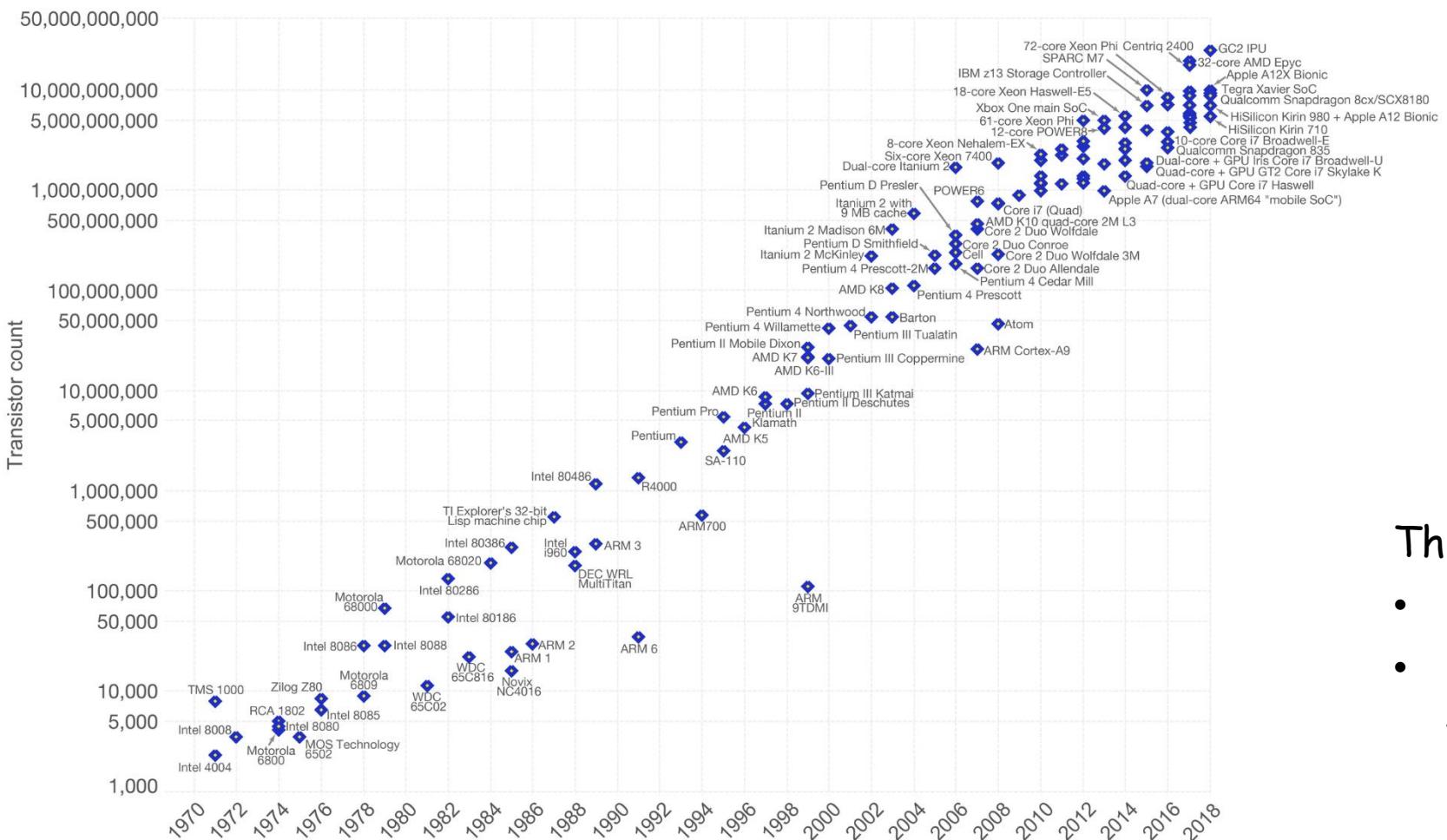


- Three recommended video for self-study
 - 从沙子到芯片的完整流程 (Intel)
<https://www.bilibili.com/video/BV1Rt411A7bV>
 - CPU制造过程 (格罗方德 GlobalFoundries, 前身AMD半导体)
<https://www.bilibili.com/video/BV1TW411q7Eq>
 - 芯片制造介绍和光刻技术 (英飞凌Infineon)
<https://www.bilibili.com/video/BV1Jt4y1X783>

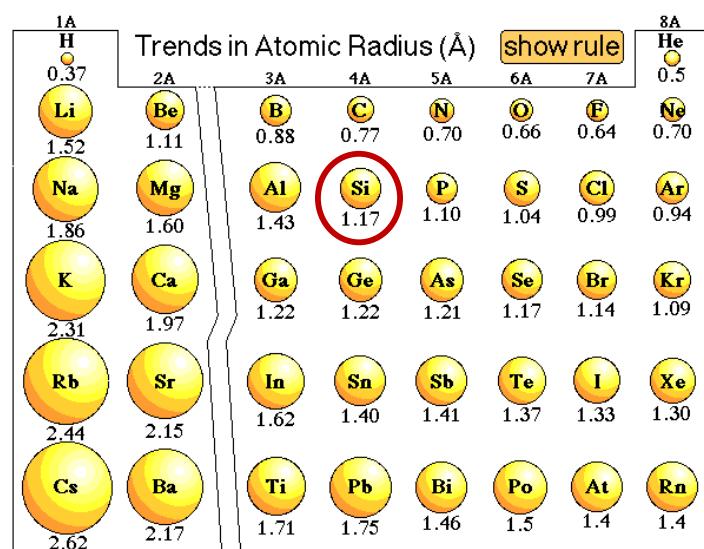
The Moore's Law

Moore's Law – The number of transistors on integrated circuit chips (1971-2018)

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are linked to Moore's law.



Our World
in Data



The physical limit:

- Silicon atom diameter $\approx 0.23 \text{ nm}$
- The most advanced smallest transistor feature is **7 nm**
(less than 35 silicon atoms wide)

Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)

The data visualization is available at OurWorldInData.org. There you find more visualizations and research on this topic.

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