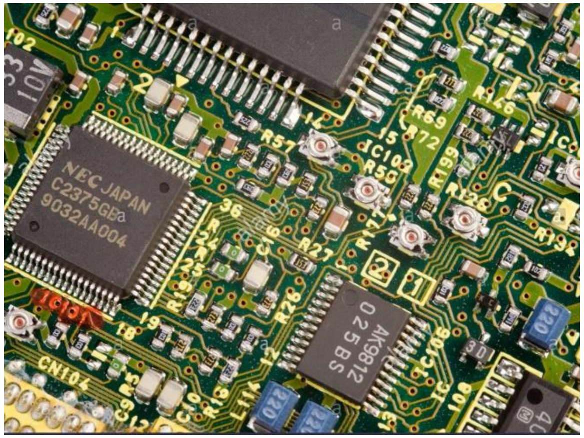
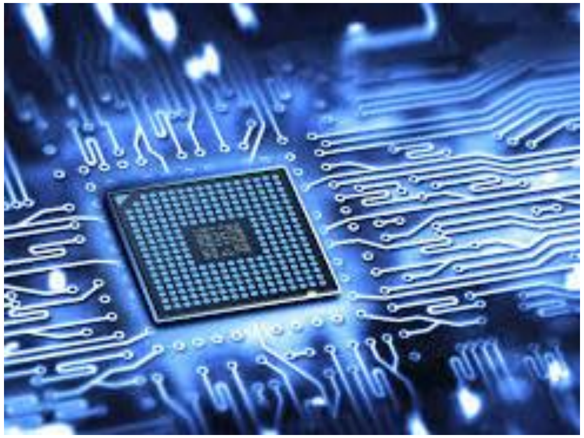
ELEC 2400 Electronic Circuits

Chapter 1: Fundamentals





Course Website: http://canvas.ust.hk

HKUST, 2021-22 Fall

Chapter 1: Fundamentals

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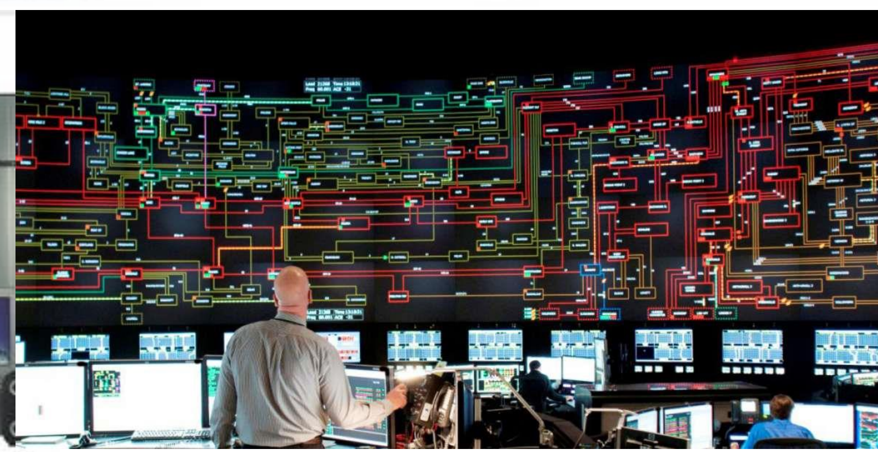
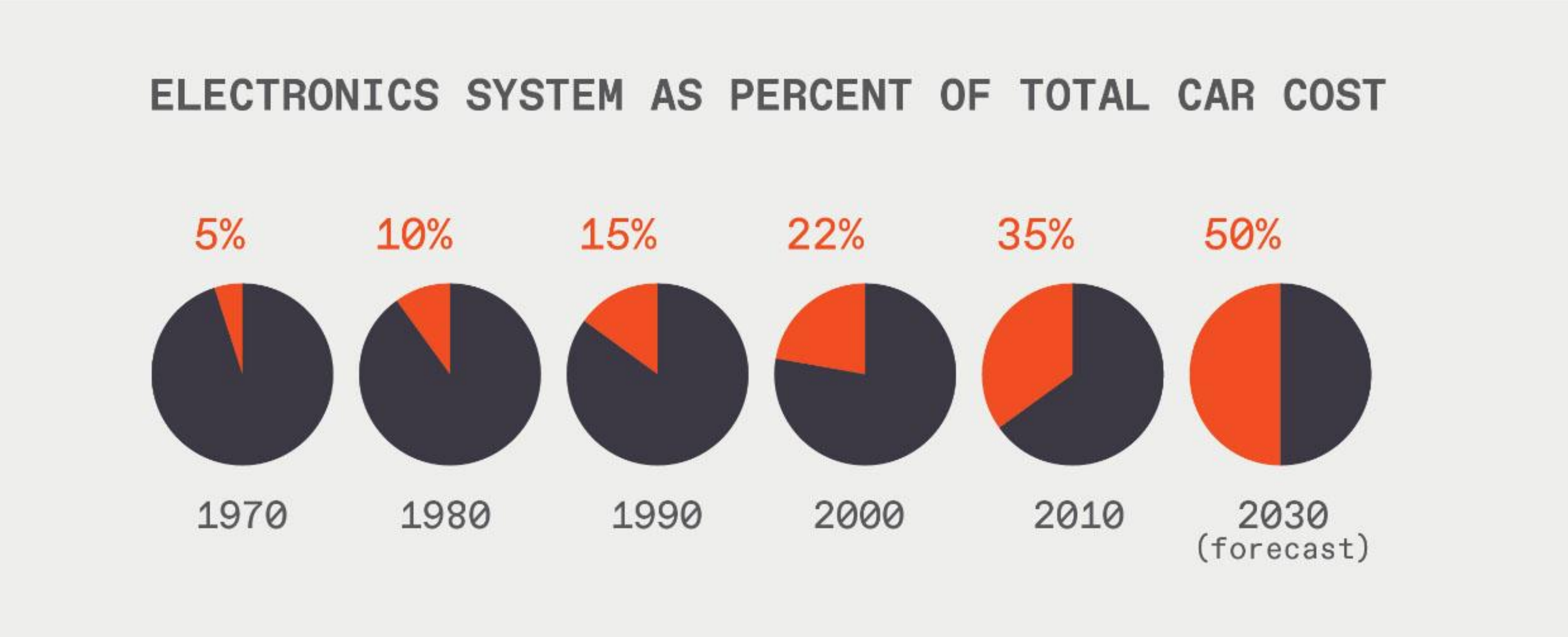
1.1 Introduction



Electronics are everywhere. So are circuits!

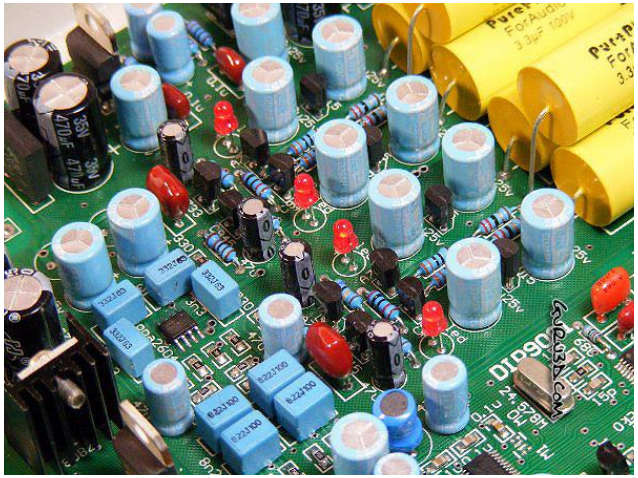
Car Electronics



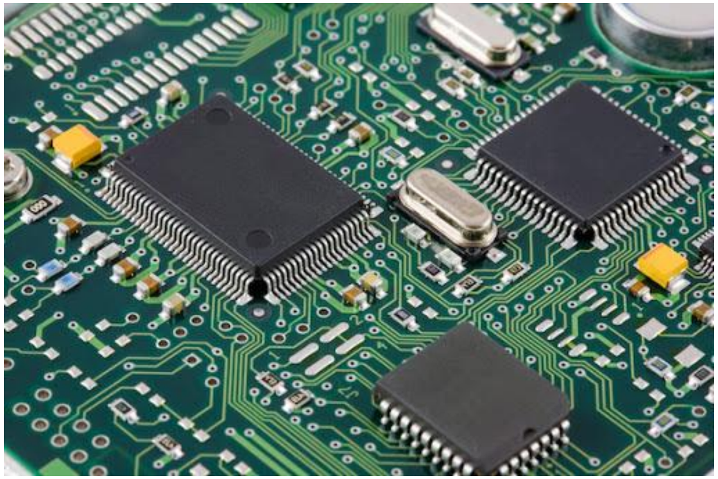
Today, high-end cars like the BMW 7-series may contain 150 microprocessor-based electronic control units (ECUs) or more, while pick-up trucks like Ford's F-150 top 150 million lines of code. Even low-end vehicles are quickly approaching 100 ECUs and 100 million of lines of code as more features that were once considered luxury options, such as adaptive cruise control and automatic emergency braking, are becoming standard.

https://spectrum.ieee.org/cars-that-think/transportation/advanced-cars/software-eating-car

Circuit Evolution

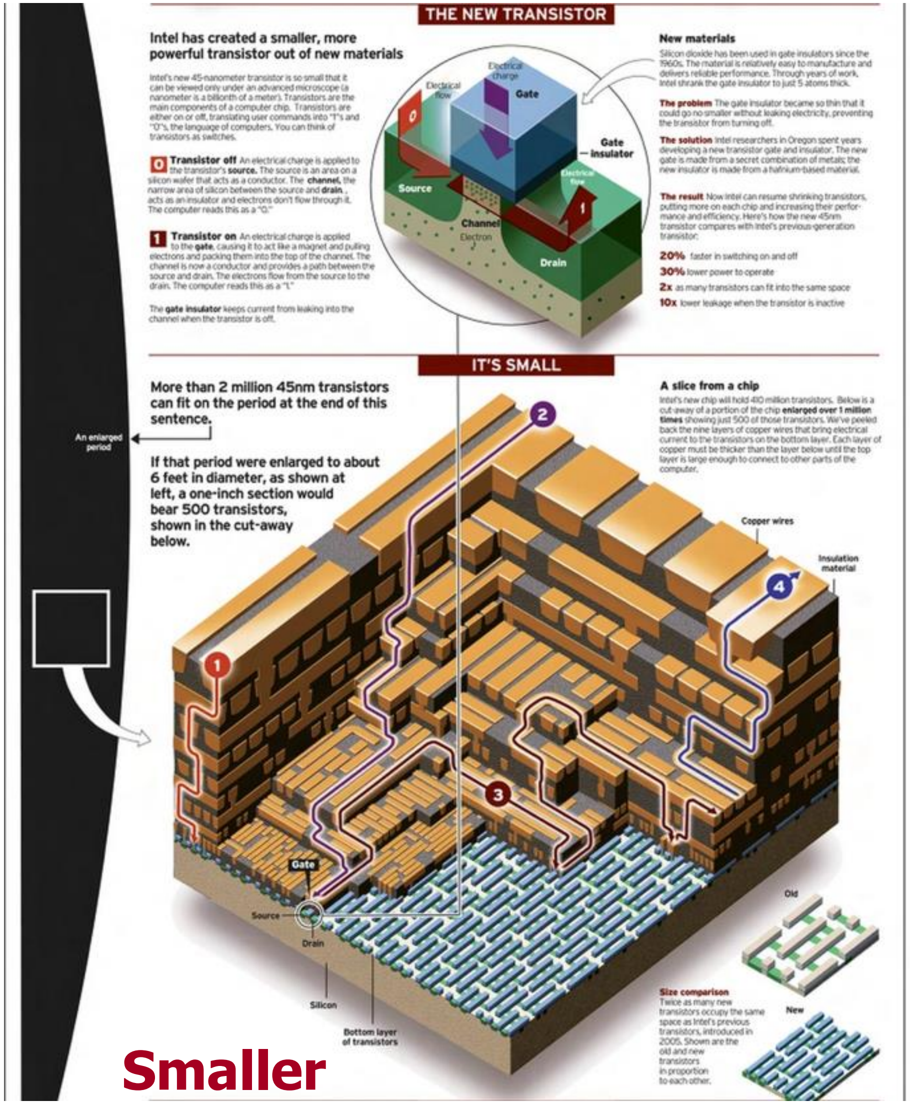


Discrete Components



Mainly ICs

Intel 45 nm Technology
Steve Cowden, The Oregonian, 2009



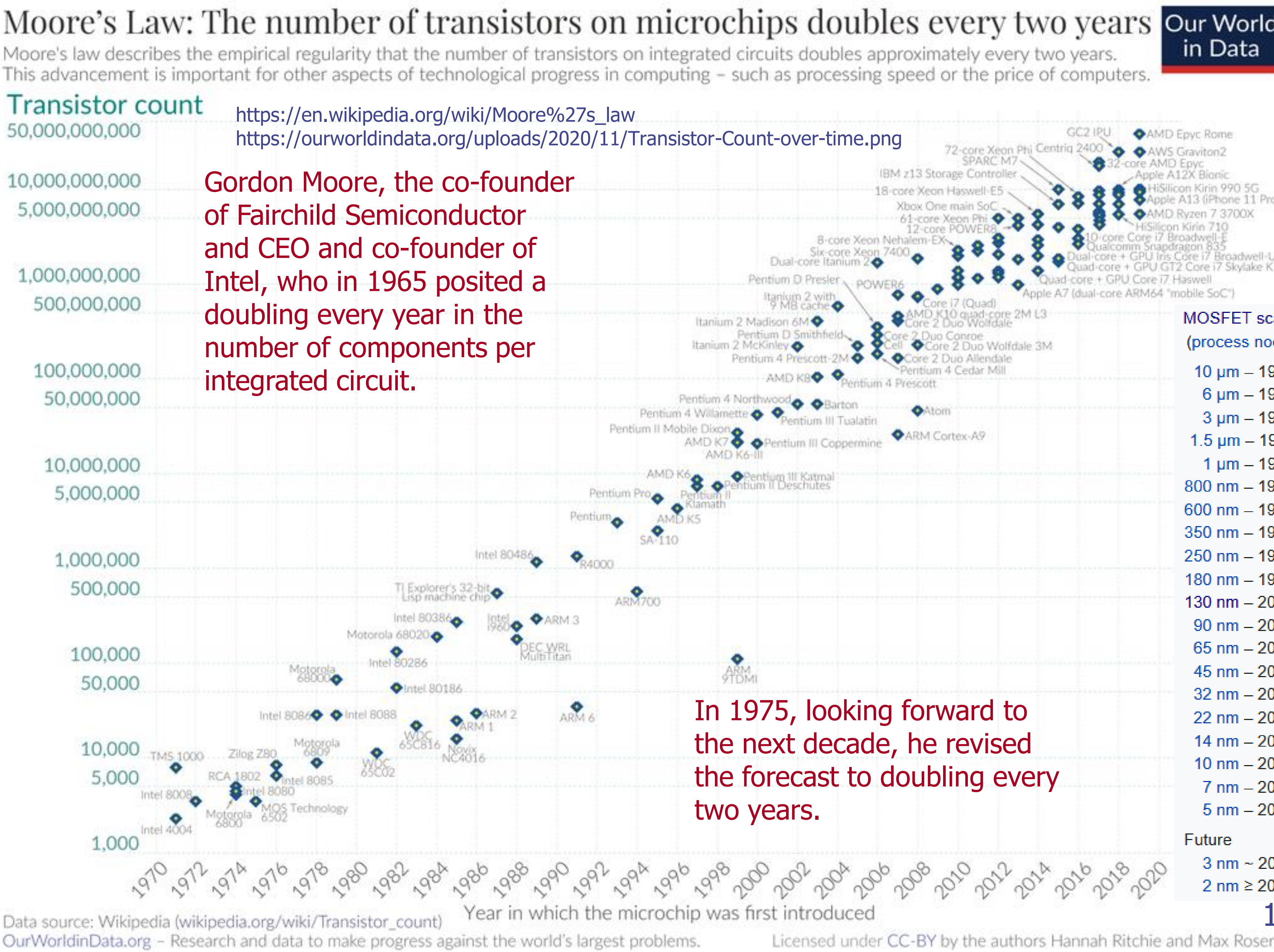
Smaller Transistors

Moore's Law

https://en.wikipedia.org/wiki/Moore%27s_law
https://ourworldindata.org/uploads/2020/11/Transistor-Count-over-time.png

Gordon Moore, the co-founder of Fairchild Semiconductor and CEO and co-founder of Intel, who in 1965 posited a doubling every year in the number of components per integrated circuit.

In 1975, looking forward to the next decade, he revised the forecast to doubling every two years.



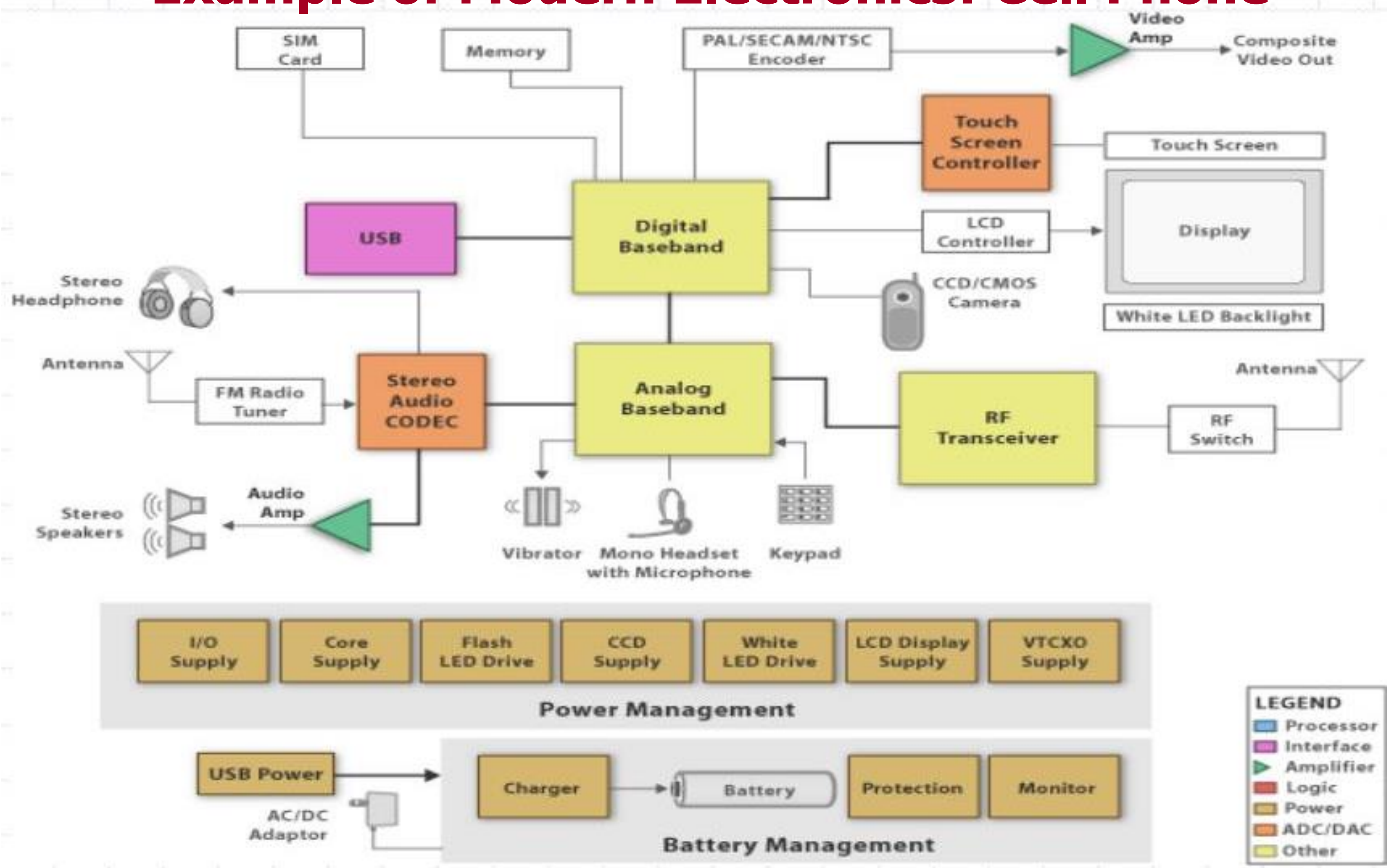
MOSFET scaling (process nodes)

10 µm – 1971
6 µm – 1974
3 µm – 1977
1.5 µm – 1981
1 µm – 1984
800 nm – 1987
600 nm – 1990
350 nm – 1993
250 nm – 1996
180 nm – 1999
130 nm – 2001
90 nm – 2003
65 nm – 2005
45 nm – 2007
32 nm – 2009
22 nm – 2012
14 nm – 2014
10 nm – 2016
7 nm – 2018
5 nm – 2020

Future

3 nm ~ 2022
2 nm ≥ 2023

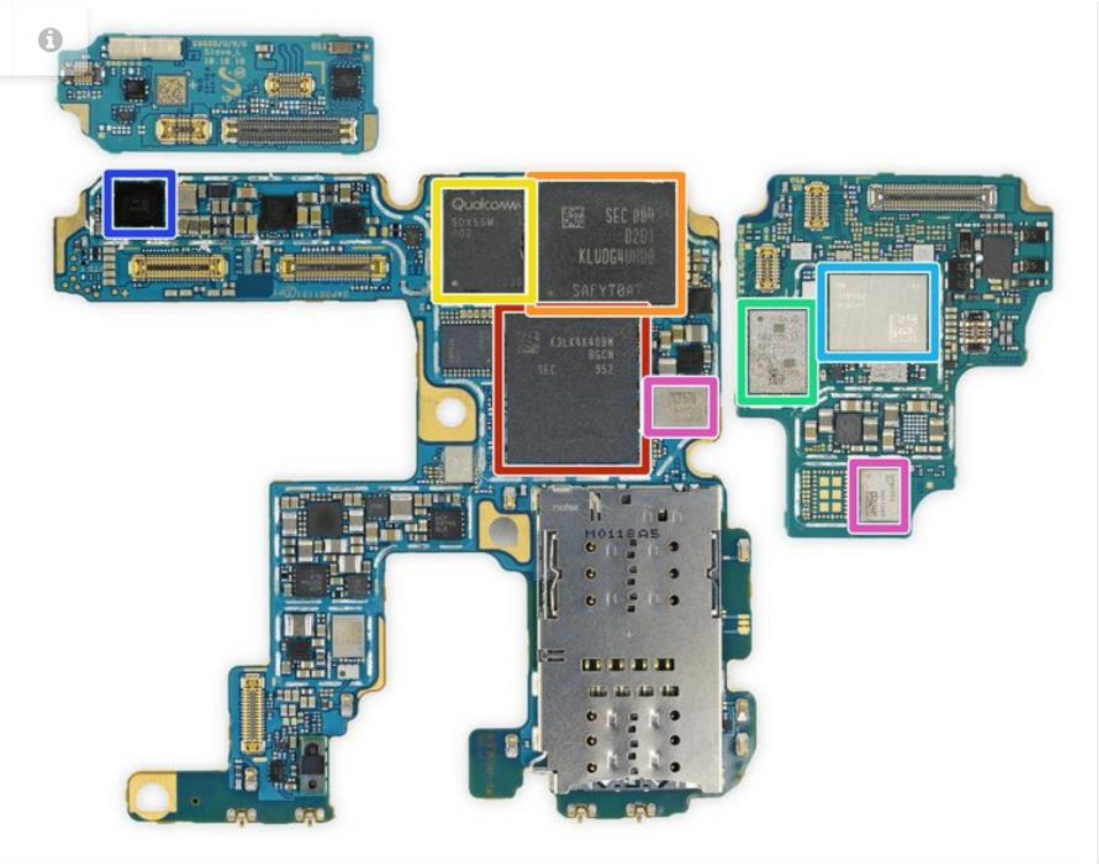
Example of Modern Electronics: Cell Phone



https://www.slideserve.com/odin/technopreneurship-course-on-mobile-repairing

Transducers: accelerometer, gyroscope, barometer, magnetometer, Hall effect, thermometer, humidity, proximity, touch screen, fingerprint, ambient light, display, camera (visible and infrared), LED, infrared laser, microphone, speaker, vibrator, antenna, …

Samsung Galaxy S20 Cell Phone Teardown

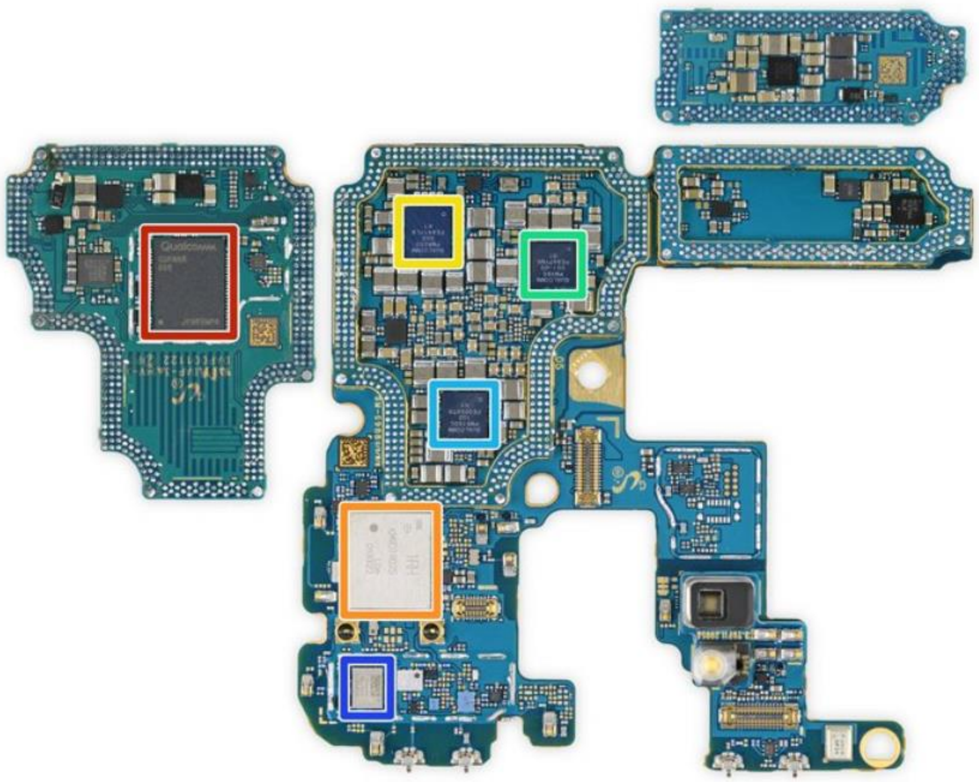


Mother Board Front Side

- With all shields down, we can get a better look at the silicon hiding beneath:
  - Samsung K3LK4K40BM-BGCN 12 GB LPDDR5 RAM layered over Qualcomm 865 SoC
  - Samsung KLUDG4UHDB-B2D1 128 GB UFS 3.0 flash storage
  - Qualcomm SDX55M 2nd-gen 5G modem
  - Skyworks SKY58210-11 RF Front-End Module
  - Qorvo QM78092 Front-End Module
  - Maxim MAX77705C power management IC
  - Qualcomm QPM5677 and QPM6585 5G power amplification modules

https://www.ifixit.com/Teardown/Samsung+Galaxy+S20+Ultra+Teardown/131607
https://www.youtube.com/watch?v=k-OZVWcyN5w

Samsung Galaxy S20 Cell Phone Teardown

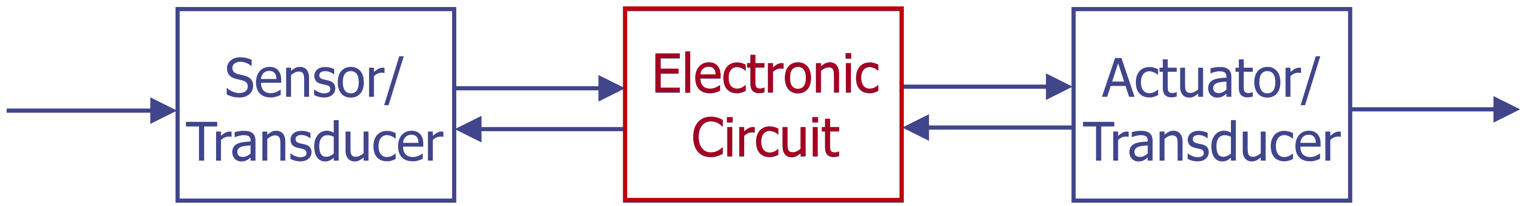


- But wait! Flippin' the boards over reveals even more flippin' chips:
  - Qualcomm SDR865 RF Tranceiver
  - Murata KM9D19075 Wi-Fi & Bluetooth Module
  - Qualcomm PM8250 power management IC
  - Qualcomm PMX55 power management IC
  - Qualcomm PM8150C power management IC
  - Qualcomm QDM4870 front-end module

Mother Board Back Side

https://www.ifixit.com/Teardown/Samsung+Galaxy+S20+Ultra+Teardown/131607
https://www.youtube.com/watch?v=k-OZVWcyN5w

General Electronics Model



Input Signals
- Mechanical
- Thermal
- Pressure
- Humidity
- Weight
- Sound
- Flow
- Electrical
- Magnetic
- Electromagnetic
- Chemical
- Optical
- …

Electrical Signals and Controls

Electrical Signals and Controls

Outputs
- Motion
- Pneumatic
- Hydraulic
- Valve
- Heater
- Cooler
- Speaker
- Electrical
- Magnetic
- Electromagnetic
- Display
- LED
- Scanner
- …

Electronic circuits interact with the physical world via sensors and actuators, collectively known as transducers.

ELEC 2400 mainly deals with Electronic Circuits

Types of Electronic Circuits

By signal type: analog (continuous), digital (0's and 1's), mixed-signal.

By levels of integration: system-on-chip (SOC), chipset, integrated circuit (IC), discrete, hybrid.

By frequency: low frequency (LF), radio frequency (RF).

By current, voltage or power: microelectronics, high voltage, high power.

By operating temperature: high temperature.

ELEC 2400 mainly deals with discrete analog circuits.

It provides the foundation for other types of electronic circuits

1.2.1 Electric Charge

Charge (q, Q, or $q(t)$) is the basic quantity in electrical circuits.

There are positive and negative charges. Like charges repel, unlike charges attract.

The unit of charge is the coulomb (C).

The smallest indivisible charge is the

elementary charge, which is defined as

$e = \text{exactly } 1.602176634 \times 10^{-19}$ C.

In other words, the coulomb is defined as

$1\text{ C} = \text{charge of } 1/(1.602176634 \times 10^{-19})$

$= 6.24 \times 10^{18}\ e.$

A proton has a charge of e.

An electron has a charge of $-e$.

Charles Coulomb
1736 - 1806

Conservation of Charge

Charge cannot be created or destroyed.

The total positive charge and the total negative charge of an isolated system are each constant.

A system is neutral if the net total charge is zero, i.e., total positive charge = |total negative charge|.

Circuit operations, such as energy transfer and information processing, are movements of charge.

1.2.2 Current

Current is the rate of change (flow) of charge. The unit of current is the ampere (A), defined as: 1 A = 1 C/s.

$$I = \frac{\Delta Q}{\Delta t}$$

IMPORTANT The direction of a current:

- Is defined as the direction that POSITIVE charges (+) flow.
- Direction of current must be shown in the
- circuit diagram.

+ + + + + + → $I = 1\ A$ →

positive (+) ions

– – – – – – → $I_1 = -1\ A$ →

← $I_2 = 1\ A$

electrons (–)
negative ions (–)

André-Marie Ampère
1775 - 1836

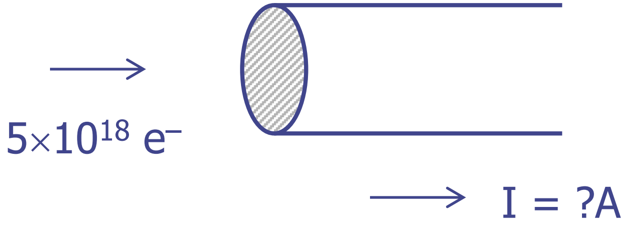
Note: The direction of current flow is opposite to the direction of electron flow.

Example 1-1

Example 1-1:

Qn. 5×10^{18} electrons flow uniformly through the cross-section of a wire in 2 s. Find the (average) current I.

Soln.



$$I = \frac{\Delta Q}{\Delta t} = \frac{5\times10^{18}\times(-1.6\times10^{-19})}{2} = -0.4A$$

Qn. Given q(t) = 5t C (coulomb), find i(t).

$$i(t) = \frac{dq(t)}{dt} = \frac{d}{dt}(5t) = 5A$$

Example 1-2

Sometimes a hybrid unit is used because it is easier to use and to understand. Examples: eV, Ah, kWh, …

Example 1-2:

1 Ah is a unit of charge
= 1 A current for 1 hour
= 1 C/s $\times$ 3600 s = 3600 C

An Li-ion rechargeable battery may have a capacity of 2000 mAh (= 2 Ah) , that is, the battery can supply 2000 mA (= 2 A) for 1 hour. (Manufacturers prefer to use mAh instead of Ah.)

Example 1-3

Example 1-3:

Recall 1 Ah = 1000 mAh = 3600 coulombs

1450 mAh

= 5220 C

= 1.45 A for 1 hour of battery operation

or 145 mA for 10 hours

or 2.9 A for 0.5 hour

etc.

Constant, Instantaneous, and Average Value

If the current is constant over time:

$$I = \frac{\Delta Q}{\Delta t}$$

If the current is time varying, the instantaneous current i(t) is the value of current i at time t:

$$i(t) = \frac{dq(t)}{dt}$$

The average current I is the time average of i(t) from 0 to T:

$$I = \frac{1}{T}\int_0^T i(t)dt$$

Direct Current and Alternating Current

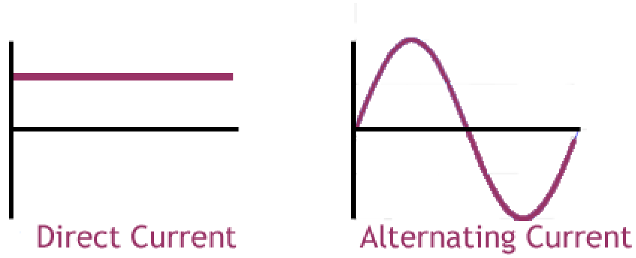
DC and AC: If the flow of charge is steady such that the current is a constant, it is called a direct current (DC). If the charge flow fluctuates such that it is sometimes stronger and sometimes weaker, and may even reverse the direction, then the current changes with time, and it is called an alternating current (AC).

In the past, an alternating current was always a sinusoidal current:

$$i(t) = I_o \sin(\omega t + \theta)$$

A sinusoidal waveform is characterized by its amplitude (I_o), angular frequency ($\omega = 2\pi f$, f is frequency), and phase (θ).

In general, DC and AC are used as adjectives that can refer to voltages as well as currents.



Time Dependence

Nowadays, we use the term DC to specify a quantity that is independent of time (constant value), and the term AC to specify a time-dependent quantity.

Convention: for easy reading, we often use upper case for a DC quantity, and lower case for time-dependent variables.

Time-independent: V_1, I_2, V_{dd}
Time-dependent: $v_3(t)$, $i_4(t)$

Time-dependent quantities may not be simple sinusoids, and special techniques are used for their analysis.

Transient Analysis: Time dependence will decay to constant values eventually.

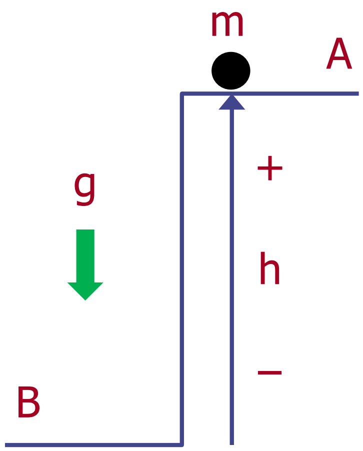
Harmonic Analysis: Any periodic time series in the steady state can be decomposed as a sum (superposition) of many sinusoids with harmonic (multiple) frequencies and amplitudes and phases (Fourier series analysis).

1.2.3 Potential Energy and Potential

In mechanical engineering, gravitational potential energy is a stored mechanical energy set up by a gravitational field. A mass m acquires potential energy by virtue of its location in the field. For example, if the elevation at A is h above that at B on earth, the potential energy difference between A and B is mgh.

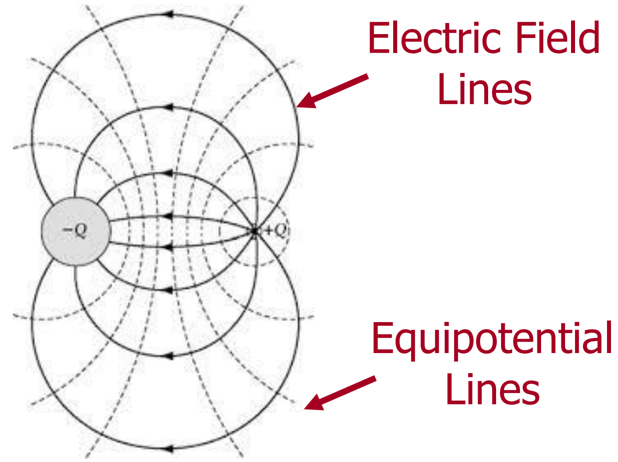
Implications:

- It would take an amount of energy equal to mgh to move the mass from B to A.
- The same amount of energy will be released if the mass moves from A to B.
- If we take B as the ground level, we can say the potential energy is 0 at B and mgh at A.
- Alternatively, we can define potential as the potential energy per unit mass. The potential at A will simply be gh then.



Electric Potential / Voltage

Likewise, electric potential energy is a stored electrical energy. It is set up by an electric field. A charge acquires electric potential energy by virtue of its location in the field.

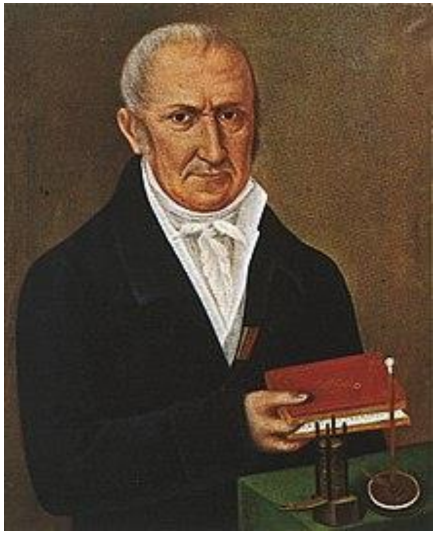


Electric potential is defined as the electric potential energy per unit charge.

Another name for electric potential is voltage.

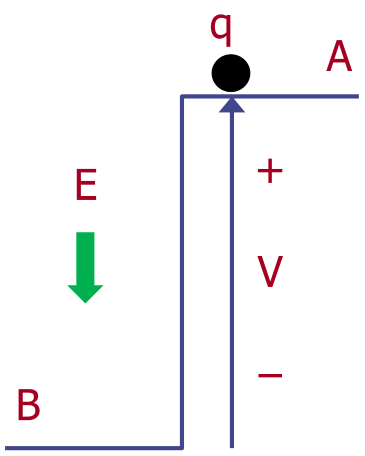
The unit of voltage is the volt (V), which is defined as

1 volt = 1 joule / 1 coulomb



Alessandro Volta
1745 - 1827

Electric Potential / Voltage



Let the voltage at A and B be V_A and V_B , respectively.

For a charge q, the electric potential energy at A and B are qV_A and qV_B , respectively.

Let V be the potential difference between V_A and V_B , i.e., $V = V_A - V_B$:

- It would take an amount of energy equal to qV to move the charge from B to A.
- The same amount of energy will be released if the charge moves from A to B.
- The above statements work for both positive and negative charges and voltages.
- If we take B as the ground potential, we can say the voltage is 0 volt at B and V volt at A.

Voltage / Potential Summary

Voltage is a relative quantity, and it is convenient to define

$$V_{AB} = V_A - V_B = -(V_B - V_A) = -V_{BA}$$

Voltage is also known as potential. The ground potential is usually assigned to be 0 V. For example, if V_B is the ground potential, then

$$V_{AB} = V_A - V_B = V_A - 0 = V_A$$

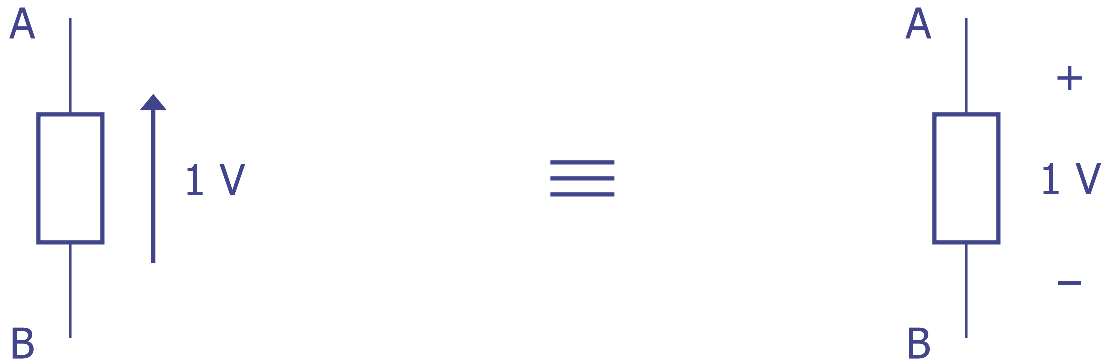
The voltage/potential at A (V_A) is implicitly referenced to the ground potential.

As voltage is a relative quantity, it is also known as voltage difference or potential difference.

The movement of charge is controlled by the potential difference (voltage difference) between two points, and potential difference could be related to electric field strength set up by a charge configuration (there are other ways).

Two Ways of Labeling Voltage

MUST BE SHOWN IN THE CIRCUIT DIAGRAM

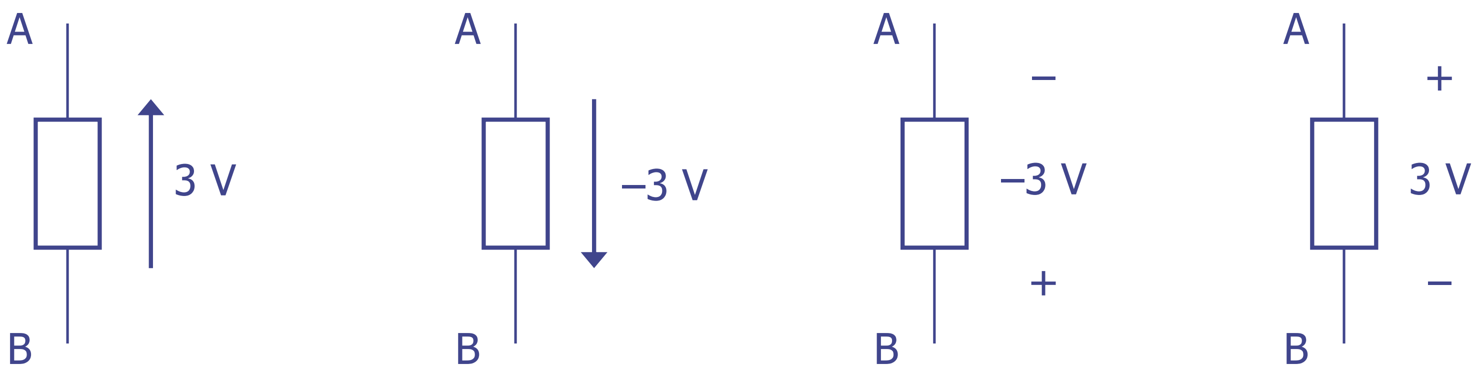


PREFERRED

Example 1-4:

Qn. Are the following 4 cases the same?

Ans. Yes, they are the same.

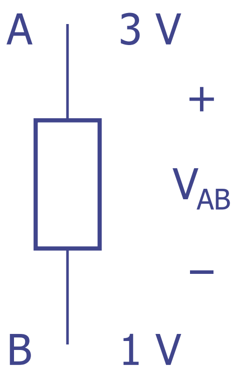


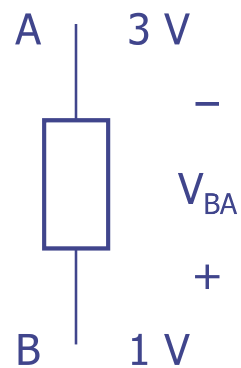
Example 1-5

Example 1-5:

Qn. Is $V_{AB} = -V_{BA}$?

Ans. Yes.





$$\begin{aligned} V_{AB} &= V_A - V_B \\ &= 3\ \text{V} - 1\ \text{V} \\ &= 2\ \text{V} \end{aligned}$$

$$\begin{aligned} V_{BA} &= V_B - V_A \\ &= 1\ \text{V} - 3\ \text{V} \\ &= -2\ \text{V} \end{aligned}$$

Example 1-6

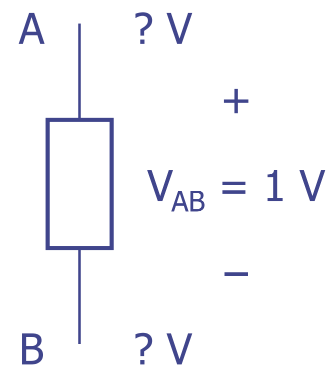
Example 1-6:

Given $V_{AB} = 1$ V, find V_A and V_B.

Soln. As voltage is a relative quantity, given only V_{AB}, both V_A and V_B cannot be uniquely determined.

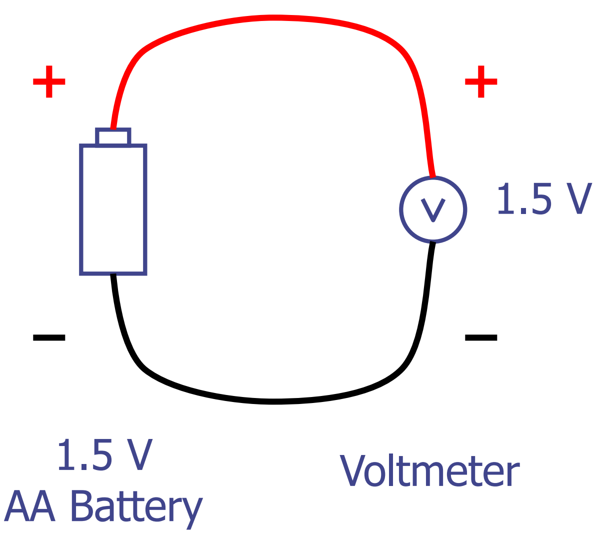
For example,

$$
\begin{aligned}
V_{AB} &= V_A - V_B \\
&= 1\text{ V} - 0\text{ V} \\
&= 2\text{ V} - 1\text{ V} \\
&= 3.5\text{ V} - 2.5\text{ V} \\
&\text{etc.}
\end{aligned}
$$



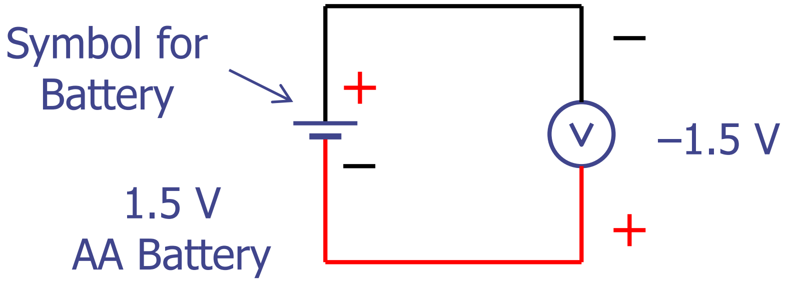
Measure Voltage with Voltmeter

To measure the voltage across an element (for example, battery) using an analog or a digital voltmeter, connect the **red** probe to the **positive** terminal and the **black** probe to the **negative** terminal.

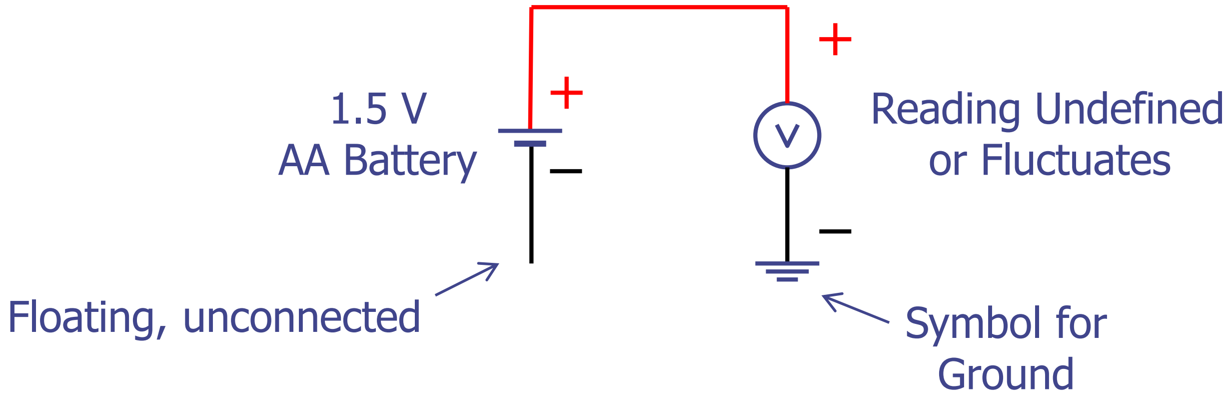


Measurement Needs a Complete Circuit

Reversing the connection of the voltmeter gives a negative reading.



An incomplete circuit gives no reading.



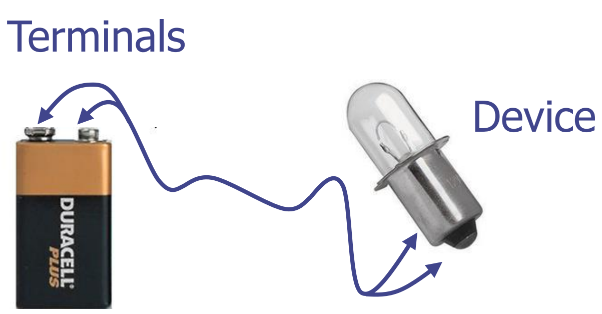
1.3.1 Circuit Modeling

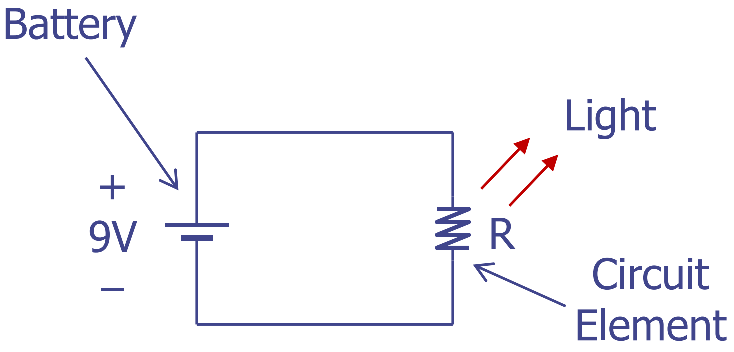
So how do we analyze electronic circuits?

Electronic devices and circuits such as batteries, lamps, transistors, amplifiers, computer chips, etc., can be modeled as comprising of circuit elements such as voltage sources, switches, resistors, capacitors, inductors, diodes, transistors, etc.

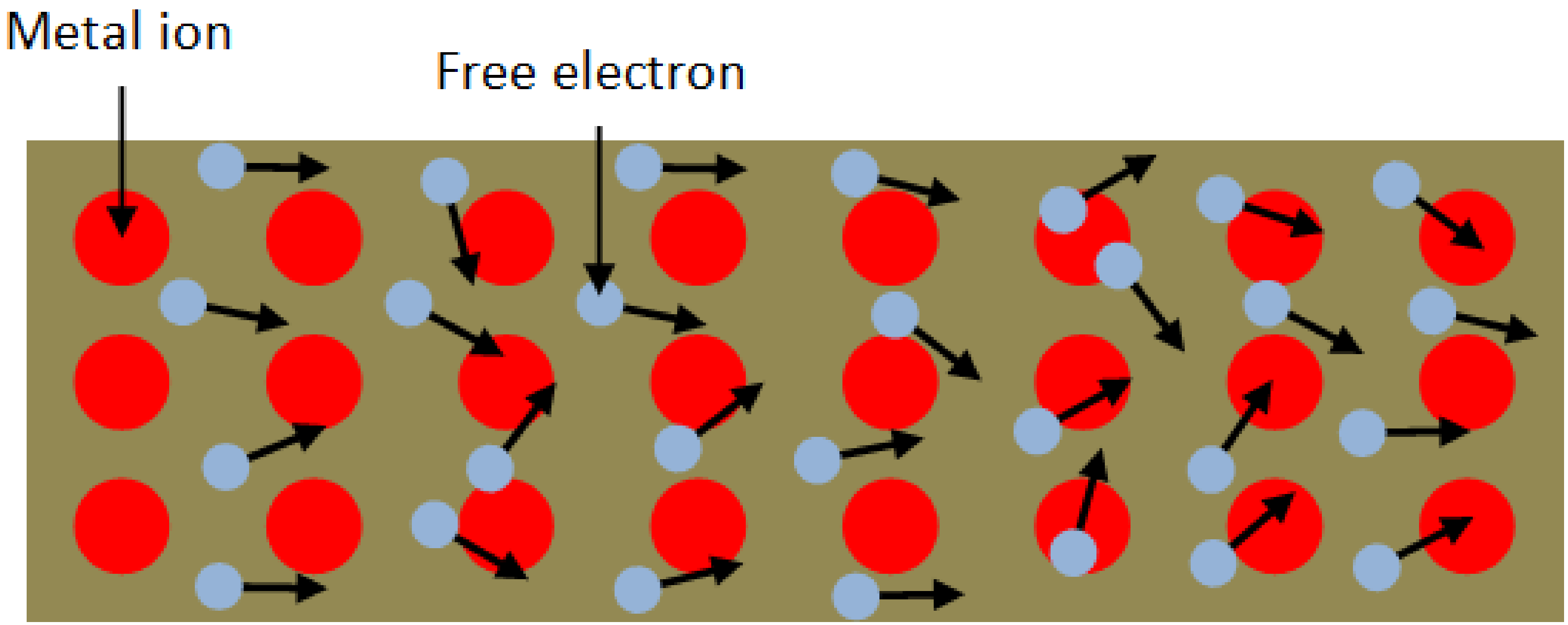
A circuit is an interconnection of these circuit elements (forming a closed circuit), for example, a battery driving a light bulb.

Next we would need to develop the models for these circuit elements.





Resistor



The microscopic model of electrical conduction can be very complicated.

https://en.wikipedia.org/wiki/Drude_model

Capacitor and Inductor

Capacitor

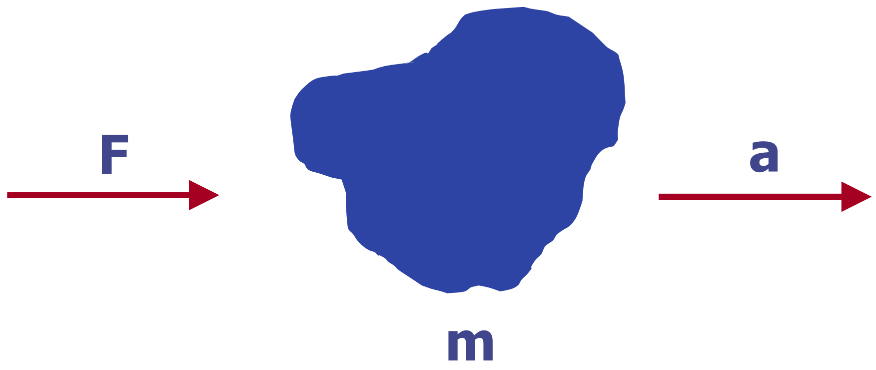
Inductor

Maxwell's Equations

Name	Equation	
	Integral form	Differential form
Faraday's law of induction	$\oint_c \vec{E} \cdot d\vec{l} = -\iint_S \frac{\partial \vec{B}}{\partial t} \cdot d\vec{S}$	$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$
Ampère-Maxwell law	$\oint_c \vec{H} \cdot d\vec{l} = \iint_S \vec{J} \cdot d\vec{S} + \iint_S \frac{\partial \vec{D}}{\partial t} \cdot d\vec{S}$	$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$
Gauss' electric law	$\oiint_S \vec{D} \cdot d\vec{S} = \iiint_V \rho \, dV$	$\nabla \cdot \vec{D} = \rho$
Gauss' magnetic law	$\oiint_S \vec{B} \cdot d\vec{S} = 0$	$\nabla \cdot \vec{B} = 0$

The general solution can be obtained by solving Maxwell's equations, but this is the hard way!

Lumped Parameter Model



Recall F = ma in mechanical engineering. If all we wanted is the linear acceleration under the applied force, we can use a lumped parameter model that greatly simplifies the analysis. The entire object is modeled as a point mass having only a single parameter of interest, its mass.

It is important to understand what we missed in the lumped parameter model. We can't tell:

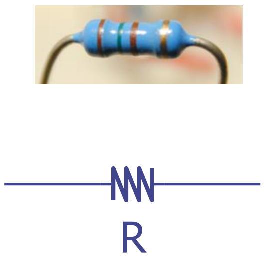
- The effect due to the object size or shape, or the point of action of the force.
- The rotation of the object.
- The deformation within the object.

1.3.2 Lumped Circuit Model

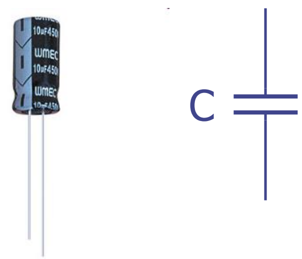
A lumped circuit element is physically small compared to the wavelength (λ = c/f, c is speed of light) of the signals concerned.

In this course, we assume all circuit components are lumped elements. This may not be true for radio frequency (RF) circuits.

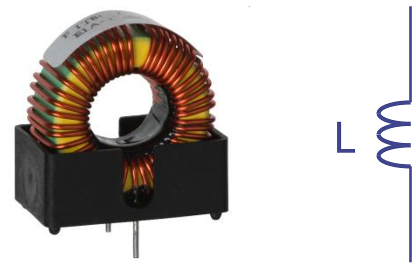
Resistor



Capacitor



Inductor



Assumption: the circuit is modeled as an interconnection of concentrated elements (resistors, capacitors, and inductors, etc.) joined by a network of perfectly conducting wires. The circuit elements have idealized lumped parameters (resistance, capacitance, inductance, etc.).

1.3.3 Ohm's Law and Resistors

When voltage is applied across a piece of material, for example, by a battery, current will flow. For many materials, the amount of current is proportional to the voltage, and the relation is described by Ohm's law:

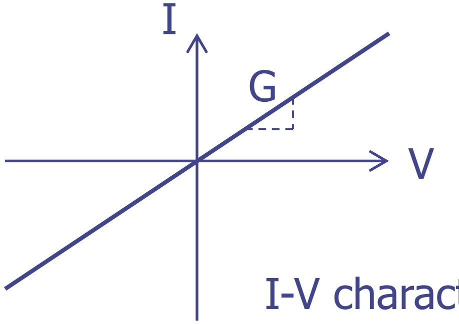
$$V = I \times R \qquad (I = V/R)$$

and R is the resistance of the material, with the unit ohm (Ω). In a circuit, we use resistors (devices made to have precise resistance) to control current flow.

Ohm's law can be written as

$$I = G \times V$$

with $G = 1/R$



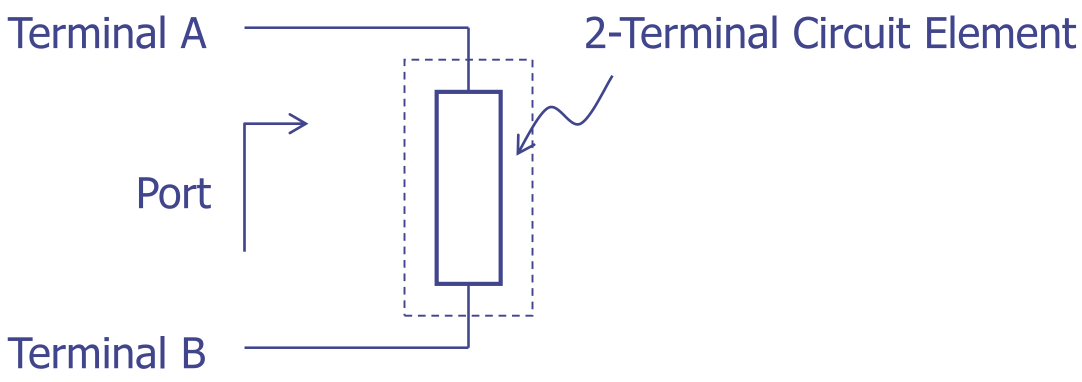
G is the reciprocal of R and is known as the conductance. The unit is the siemens (S), where $S = \Omega^{-1}$.

1.3.4 Terminals and Ports

A circuit element has at least two external connections called terminals. For example, a 1.5 V AA battery has a positive and a negative terminal.

Two terminals of a circuit constitutes a port, for example, input port or output port.

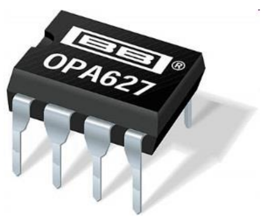
A 1-port element has the same port as the input port and the output port (the input may be current, and the output is then the voltage).

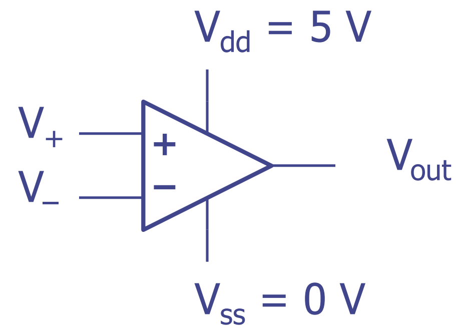


Example 1-7

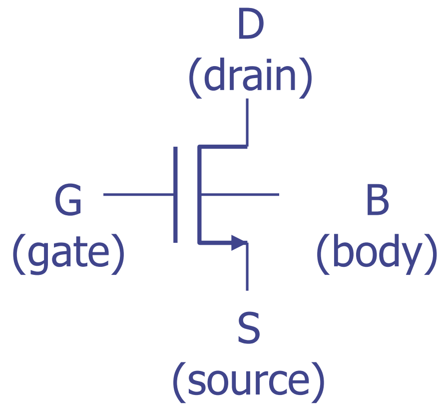
Example 1-7:

An operational amplifier (op amp) is a 5-terminal element if V_{dd} and V_{ss} are counted. Otherwise, it is a 3-terminal element.





A MOS transistor is a 4-terminal element.



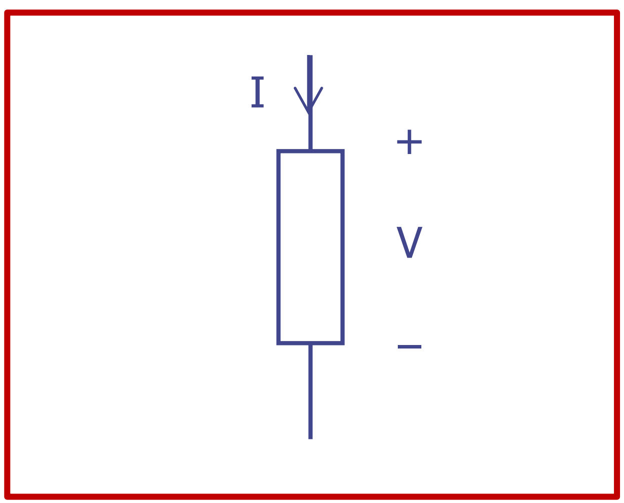
1.3.5 I-V Characteristic & Reference Direction

A 2-terminal (1-port) circuit element can be characterized (described) by a current and a voltage using the reference direction, such that

(1) the current enters from the (arbitrarily defined) positive terminal and exits from the negative terminal; and

(2) the voltage measures across the positive and negative terminals.

The I-V relation is called the I-V characteristic of the element.



IMPORTANT
Reference Direction

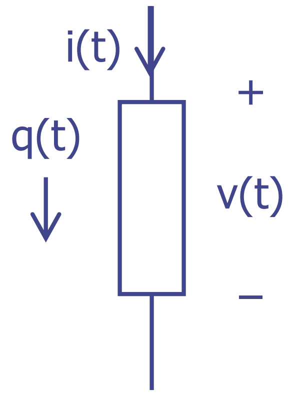
1.4.1 Electric Power

Power is the rate of doing work, or equivalently,

$$P = \text{rate of change of energy}$$

Power is measured in watt (W) or in joule/s (J/s).

Reference Direction



The reference direction must be used for power calculations:

During the time Δt, a quantity of charge Δq flows from the high voltage terminal to the low voltage terminal, thus giving up (or consuming) an amount of electric potential energy equal to $\Delta E = v(t)\Delta q$.

Hence, instantaneous power $p(t) = \Delta E/\Delta t = v(t)\Delta q/\Delta t = v(t) \times i(t)$.

If both voltage and current are constant, i.e., DC conditions, then

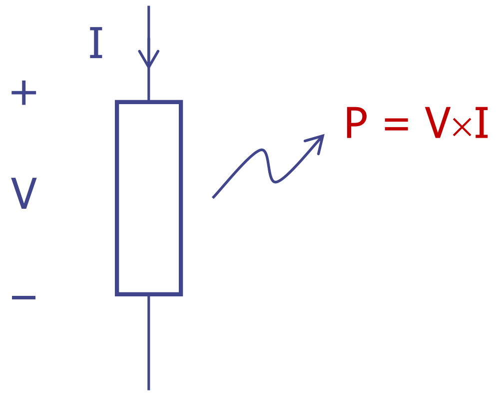
$$P = V \times I$$

Alternatively, 1 watt = 1 W = (1 volt) × (1 ampere) = 1 VA

Power of 2-Terminal Elements

Using the reference direction for current and voltage, if V×I is positive, electric power is consumed or dissipated by that element.

The electric power that is consumed can be converted to another form of energy, e.g., heat in a resistor or chemical energy in charging a battery.



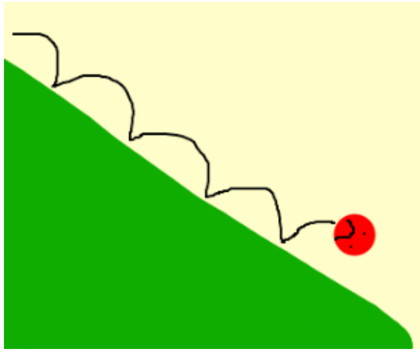
On the other hand, if V×I is negative, electric power is generated, e.g., by a battery from its stored chemical energy.

If the voltage and/or current is time-dependent, and if p(t) = v(t)·i(t) is periodic with a period T, then the average power P_{ave} is given by

$$P_{ave} = \frac{1}{T}\int_0^T p(t)\,dt = \frac{1}{T}\int_0^T \left(v(t)\cdot i(t)\right)dt$$

Summary on Electric Power

Positive Power, $V \times I > 0$
Positive charge moving from higher to lower potential, giving up electrical energy.



Battery: charging, electrical energy is converted to chemical energy.

Resistor: electrical energy is dissipated as heat.

Negative Power, $V \times I < 0$
Positive charge moving from lower to higher potential, gaining or generating electrical energy.

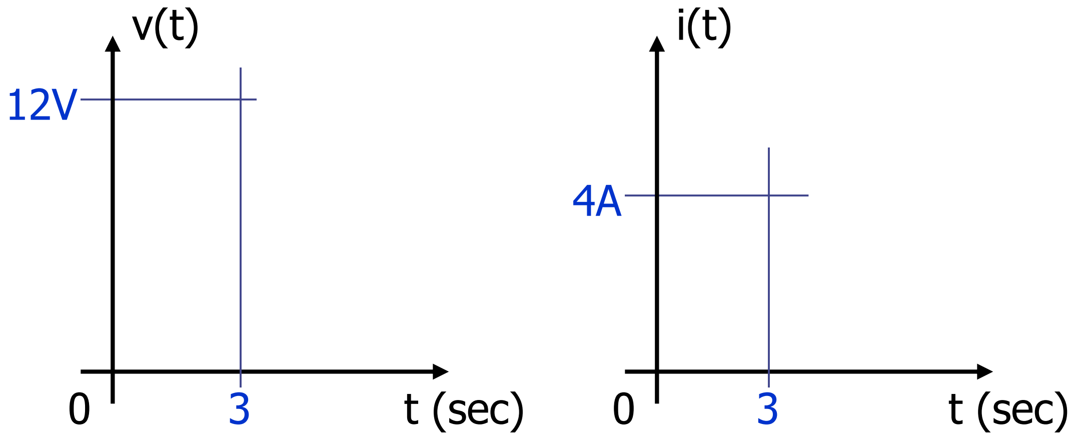
Battery: discharging, chemical energy is converted to electrical energy.

Resistor: impossible under normal circumstances.

Example 1-8

Example 1-8:

Qn. Find the instantaneous power p(t) at t = 3 sec.



Ans: p(3) $= v(3) \times i(3)$

$= 12\ V \times 4\ A$

$= 48\ W$

Example 1-9

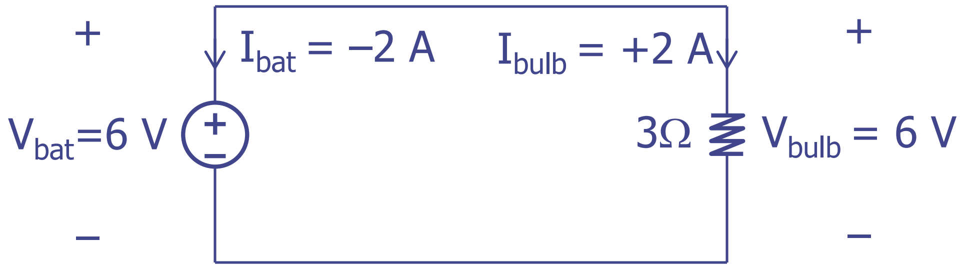
Example 1-9:

A flashlight bulb is modeled as a resistor, and the power dissipated is

$$P_{bulb} = V_{bulb} \times I_{bulb} = 6\text{ V} \times 2\text{ A} = +12\text{ W}$$

The battery is an active element, as the power is negative:

$$P_{bat} = V_{bat} \times I_{bat} = 6\text{ V} \times -2\text{ A} = -12\text{ W}$$

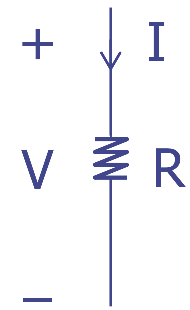


Power and Energy Dissipation of Resistors

The power dissipated by a resistor is

$$P = V \times I = I \times R \times I = I^2 R$$

$$= V \times \frac{V}{R} = \frac{V^2}{R}$$



The energy consumed (work done) by a resistor in a duration of t is

$$W = P \times t = V \times I \times t$$

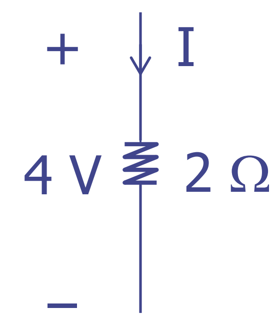
Example 1-10:

1. The power dissipated by the 2 Ω resistor is

   $P = 4 \times 2 = 8$ W

2. The energy consumed by the resistor in 2 s is

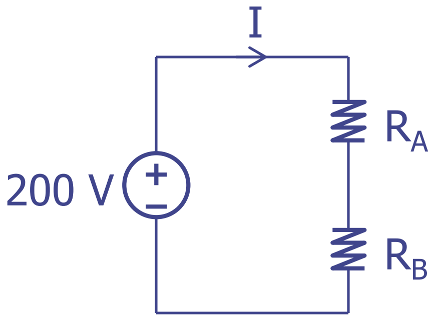
   $W = 8 \times 2 = 16$ J



Example 1-10 (1)

Example 1-10:

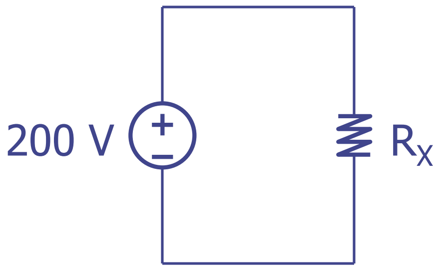
Qn. Which of Bulb A and Bulb B is brighter, assume that brightness is proportional to the power dissipated?



Bulb A consumes 100 W at 200 V

Bulb B consumes 400 W at 200 V

Example 1-10 (2)



Soln. Connect R_A and R_B in turns to 200 V, and

$$P_{A(200V)} = 100W = \frac{V^2}{R_A} = \frac{200^2}{R_A} \Rightarrow R_A = 400\Omega$$

$$P_{B(200V)} = 400W = \frac{V^2}{R_B} = \frac{200^2}{R_B} \Rightarrow R_B = 100\Omega$$

Return to the original case, with $R_T = R_A + R_B = 500\ \Omega$, and

$$I = \frac{V}{R_A + R_B} = \frac{200}{500} = 0.4A$$

$$P_A = I^2 R_A = 0.4^2 \times 400 = 64W$$

$$P_B = I^2 R_B = 0.4^2 \times 100 = 16W$$

Therefore, Bulb A is brighter than Bulb B.

Example 1-11

Example 1-11:

Some light bulbs have resistances that change with temperature. Now, a light bulb draws 4 A from a 120 V DC source at start up when cold, and dissipates 60 W in the steady state when driven by the same source. Compute the resistances when the light bulb is cold and when it is hot. Compute the power dissipated when it is cold. Can you draw any inference on the results?

Soln: R(cold) = 120 V/4 A = 30 Ω

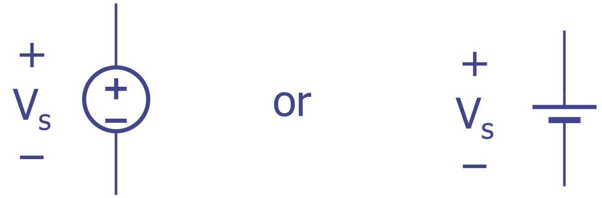
R(hot) = $(120\ V)^2$/60 W = 240 Ω

P(cold) = 120 V$\times$4 A = 480 W

When the light bulb is cold, it consumes 8 times the power when it is hot, and is much easier to be blown out when you turn it on cold.

1.4.2 Ideal Voltage and Current Sources

Independent (Ideal) Voltage Source: maintains a constant voltage V_s across its terminals, independent of the load (current).



A good example of voltage source is the battery.

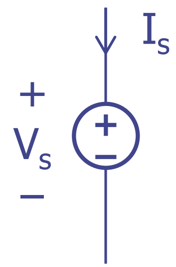
Example 1-27: For the circuit below, what is the output voltage V_o for R = 1 Ω, 1 GΩ, 0.1 Ω, 0 Ω?

Soln. V_o = 30 V for R = 1 Ω, 1 GΩ, 0.1 Ω, but is undefined for R = 0 Ω

⇒ An ideal voltage source cannot drive a short circuit.

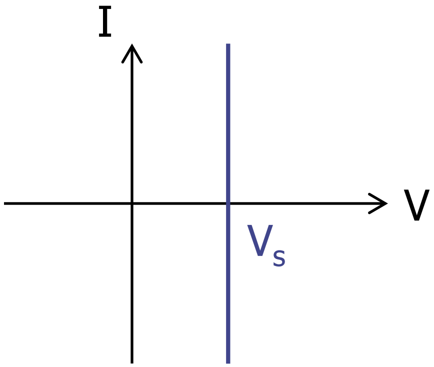
Voltage Source Sinks or Sources Current

Using the reference direction, a voltage source may sink or source current:



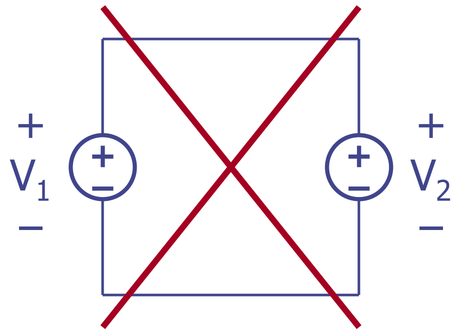
If $I_s > 0$, V_s is sinking current ($P > 0$, dissipating power)
If $I_s < 0$, V_s is sourcing current ($P < 0$, generating power). This is the normal operation of a voltage source.

I-V Characteristic of Ideal Voltage Source



Voltage Sources Cannot Be Connected in Parallel

Voltage sources of different potentials ($V_1 \neq V_2$) should never be connected in parallel:

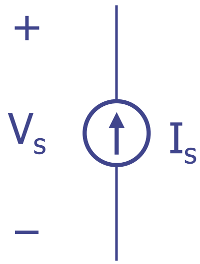


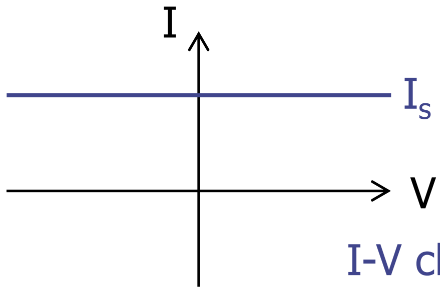
A voltage source sinks or sources current to force the external circuit in parallel with itself to have the same potential difference. If $V_1 > V_2$, then V_1 will source a large current to force V_2 to be equal to V_1, while V_2 does the same thing by sinking a large current. Hence, the two voltage sources fight with each other.

For physical devices, large current may destroy both.

Ideal Current Source

Independent (Ideal) current Source: maintains a constant current I_s across its terminals, independent of the voltage V_s across its terminals.





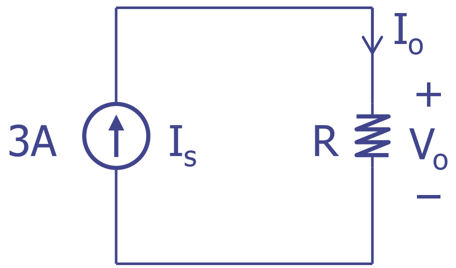
I-V characteristic

A current source is usually constructed using complicated electronic circuits.

Example 1-28: For the circuit below, what is the current I_o for $R = 0\ \Omega$, $1\ G\Omega$, $\infty\ \Omega$?

Soln. $I_o = 3$ A for $R = 0\ \Omega$ and $1\ G\Omega$, but is undefined for $R = \infty\ \Omega$

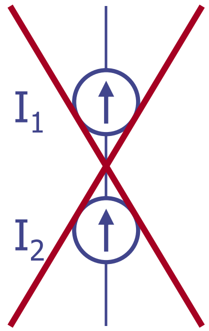
$\Rightarrow$ an ideal current source cannot drive an open circuit.



For protection, a current source usually comes with a compliance voltage above which it will not source the requested current.

Current Sources Cannot Be Connected in Series

Current sources of different potentials ($I_1 \neq I_2$) should never be connected in series:

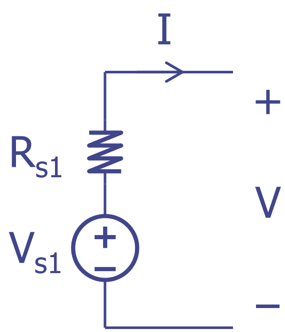


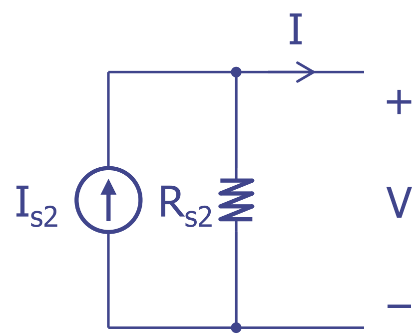
The current source I_1 forces the branch to have a current of I_1, but the current source I_2 also forces the same branch to have a current of I_2. One branch cannot have two different currents, and the connection is not allowed.

Practical Voltage and Current Sources

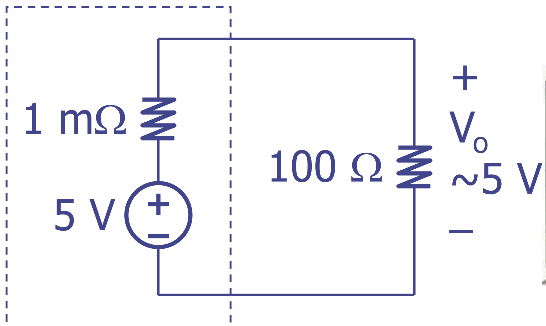
A practical voltage source is modeled as an ideal voltage source V_s having a small (but non-zero) internal resistance R_s in series.

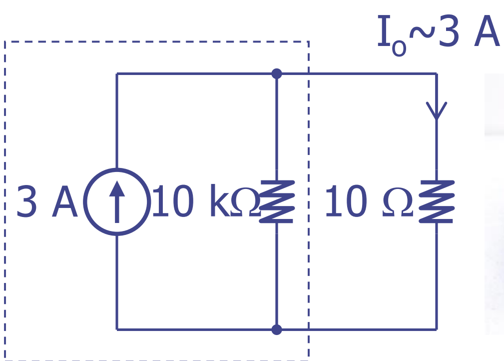
A practical current source is modeled as an ideal current source I_s having a large internal resistance R_s in parallel.





Examples:

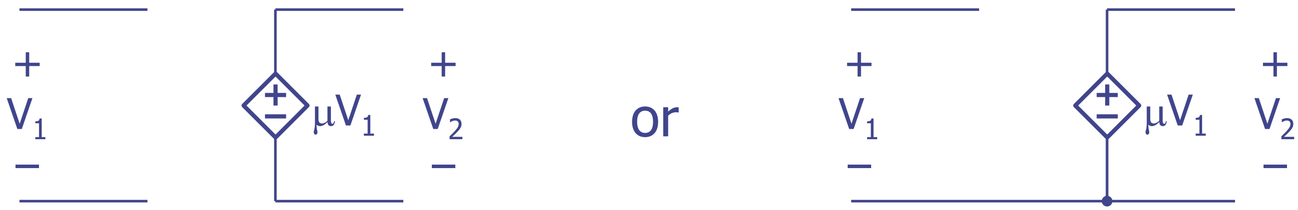




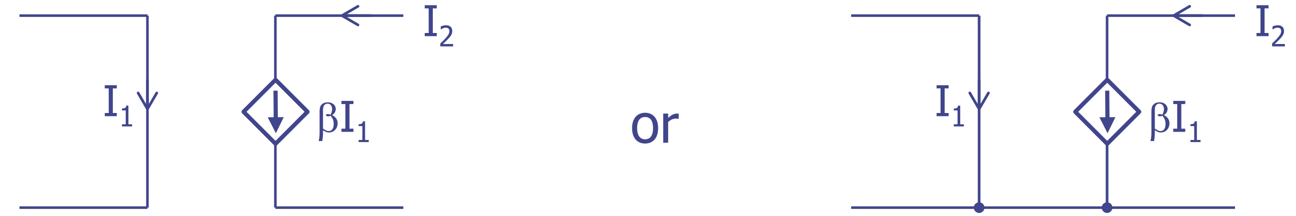
1.4.3 Dependent Sources (1)

Besides independent sources, there are sources that depend on (or controlled by) a voltage or current at another location of the circuit, and they are known as dependent sources. Four types of dependent sources can be identified, and we use a rhombus as the circuit symbol as shown.

Voltage-controlled voltage source (VCVS), or voltage amplifier:

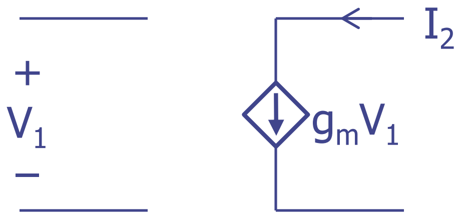


Current-controlled current source (CCCS), or current amplifier:

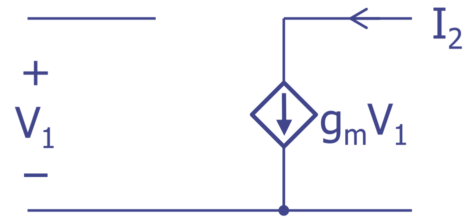


Dependent Sources (2)

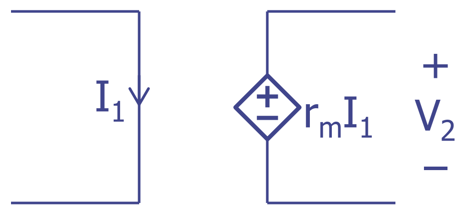
Voltage-controlled current source (VCCS), or transconductance amplifier:



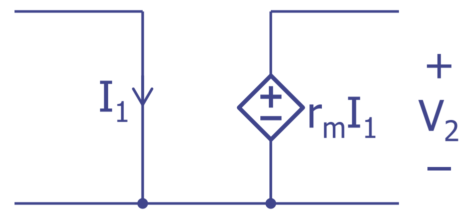
or



Current-controlled voltage source (CCVS), or transresistance amplifier:



or



The current $I_2=g_mV_1$ is generated by V_1 located in another part of the circuit, and the prefix "trans" is added. The same applies to r_m.

Passive and Active Components

Loosely speaking, passive components are circuit elements that only consume or store electrical energy, while active components have the ability to generate electrical energy.

Using the reference direction, passive components have a positive average power (consumes or stores power): $P_{ave} = (V \times I)_{ave} > 0$; while active components have a negative average power (generates power): $P_{ave} < 0$.

Passive components: resistors, capacitors, inductors, transformers, diodes.

Active components: batteries, voltage and current sources, transistors and op amps (output signal power > input signal power, with the help of DC power supplies).