哈爾濱工業大學(深圳)
HARBIN INSTITUTE OF TECHNOLOGY, SHENZHEN

Fundamentals of Electric Circuits

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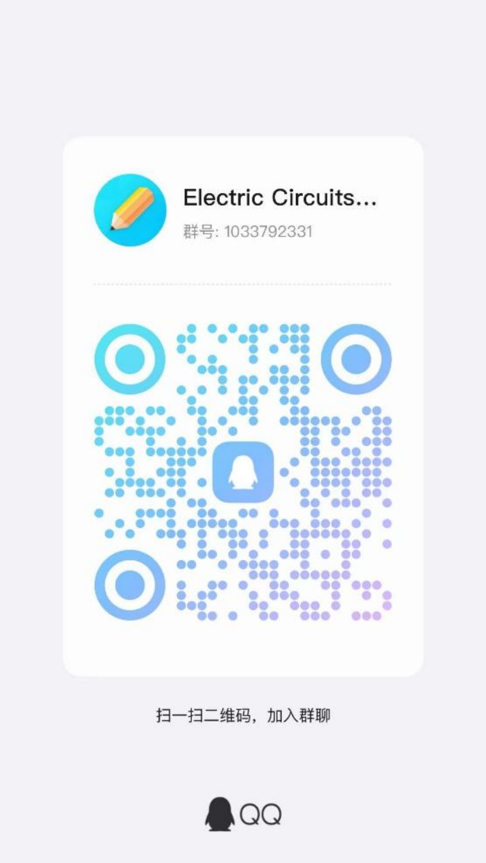
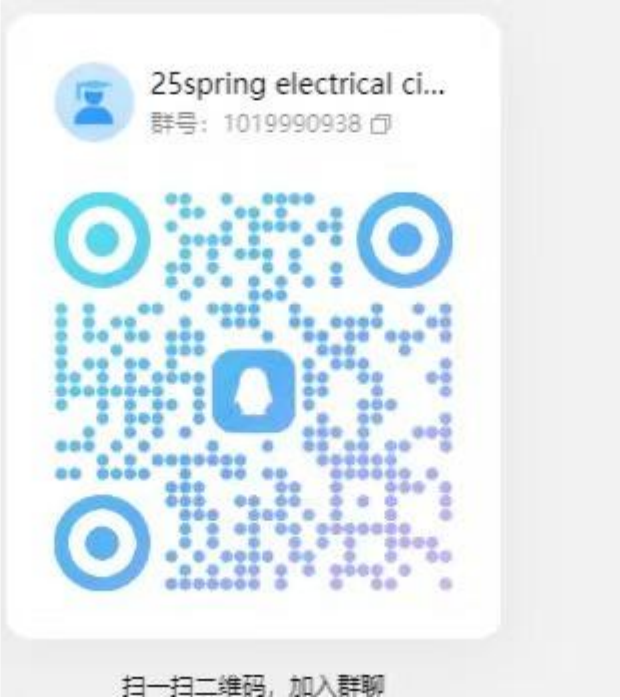
About the course

Theory

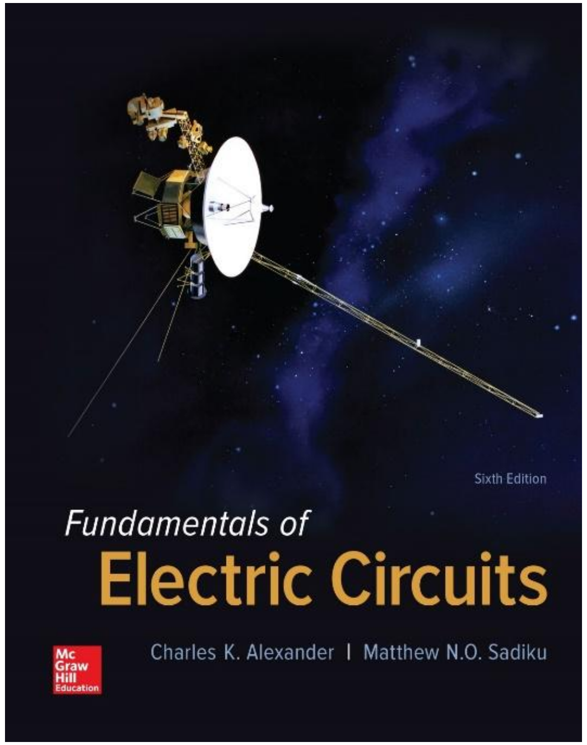


QQ group: 1033792331

Experiment



Textbook



More about the course

Assessment

Assignments & Attendance	40%
Final Examination	60%
Total	100%

Make up exam

Final Examination	100%
Total	100%

More about the course

CHAPTER 1 Basic Concepts

CHAPTER 2 Basic Laws

CHAPTER 3 Methods of Analysis

CHAPTER 4 Circuit Theorems

CHAPTER 5 Operational Amplifiers

CHAPTER 6 Capacitors and Inductors

CHAPTER 7 Sinusoids and Phasors

CHAPTER 8 AC Power Analysis

More about the course

Don't ask me what contents/what questions will be in the examinations.

I will highlight the most important contents in each chapter. All questions in the examinations are similar to those in the exercises!!!

Let's try to finish as much as possible in class!!!

CHAPTER 1 Basic concepts

Objective

- This chapter introduces the concept of voltage and current.
- The concept of a circuit will be introduced.
- Sources will be introduced.
- These can provide either a specified voltage or current.
- Dependent and independent sources will be discussed.
- Also a strategy for solving problems will be introduced.

1.1 What is a circuit?

Smartphones

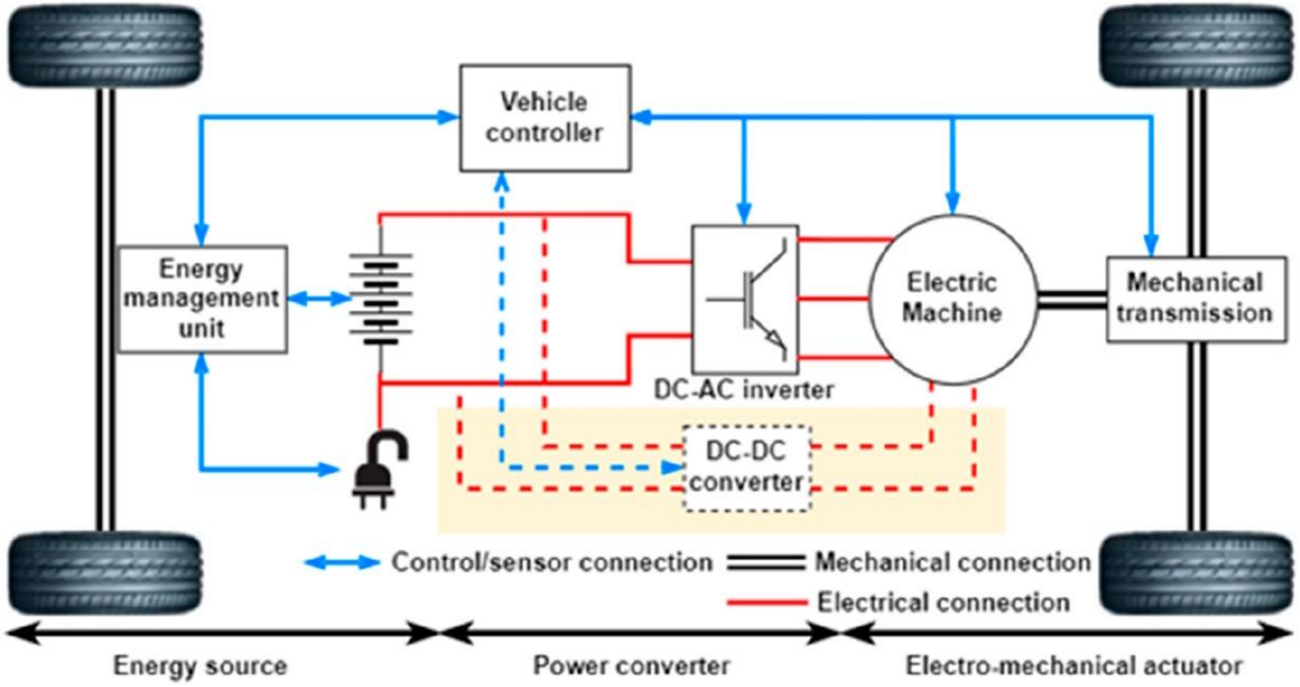
Laptop Computers

Drones

AI / Robots

Smart Electric Vehicles

EV powertrain

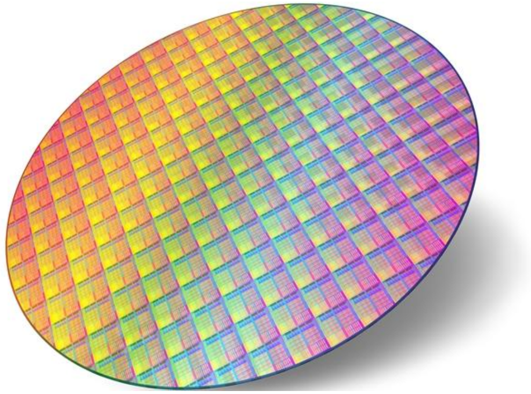


The energy source: battery pack, battery management system, onboard charger, thermal management system

Power conversion: the main traction drive inverter, bidirectional dc/dc converter

Drive system: traction motor

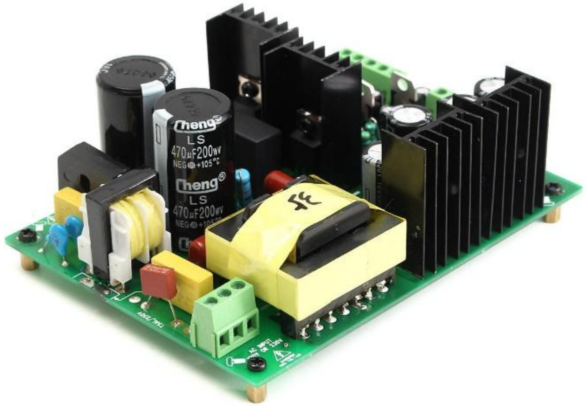
1.1 What is a circuit?



Semiconductors

Integrated Circuits

Printed Circuit Boards



Power Supplies

Signal Processing

Control Systems

1.1 What is a circuit?

- **An electric circuit is an interconnection of electrical elements.**

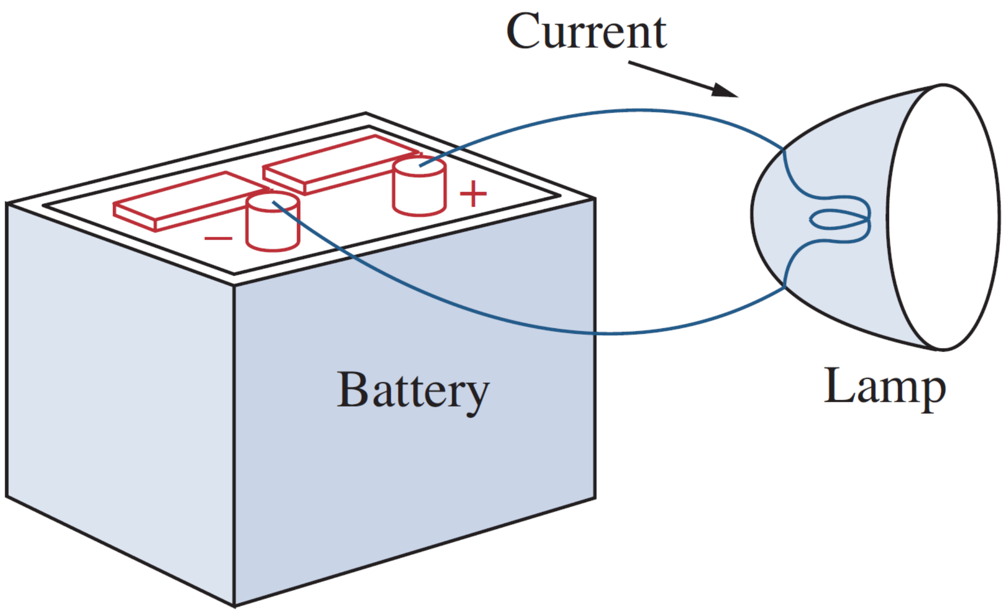


Figure 1.1
A simple electric circuit.

1.1 What is a circuit?

- **An electric circuit is an interconnection of electrical elements.**

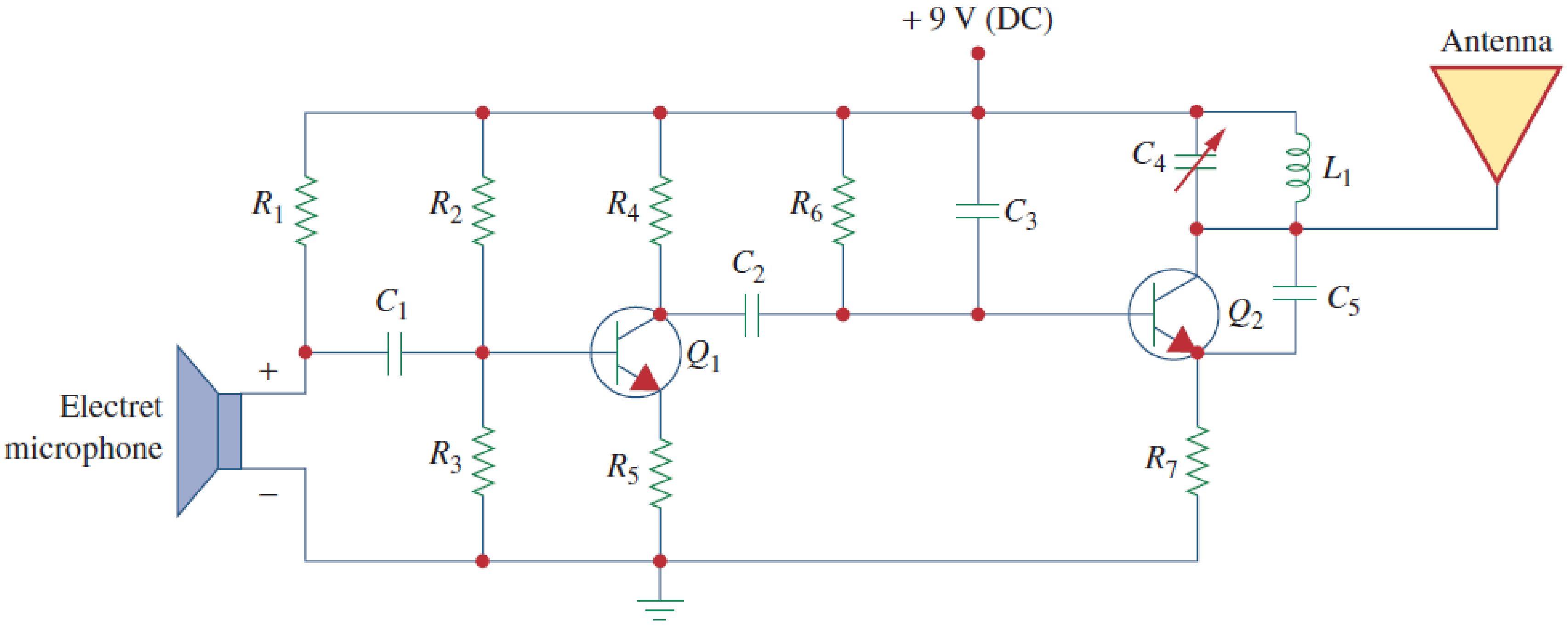
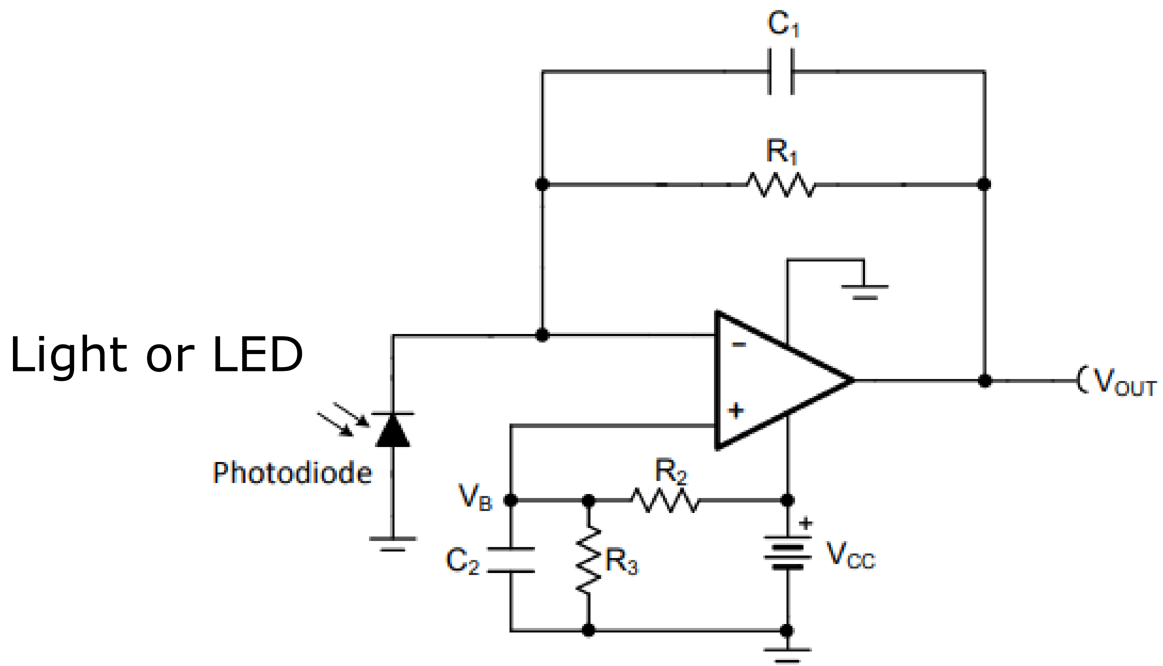


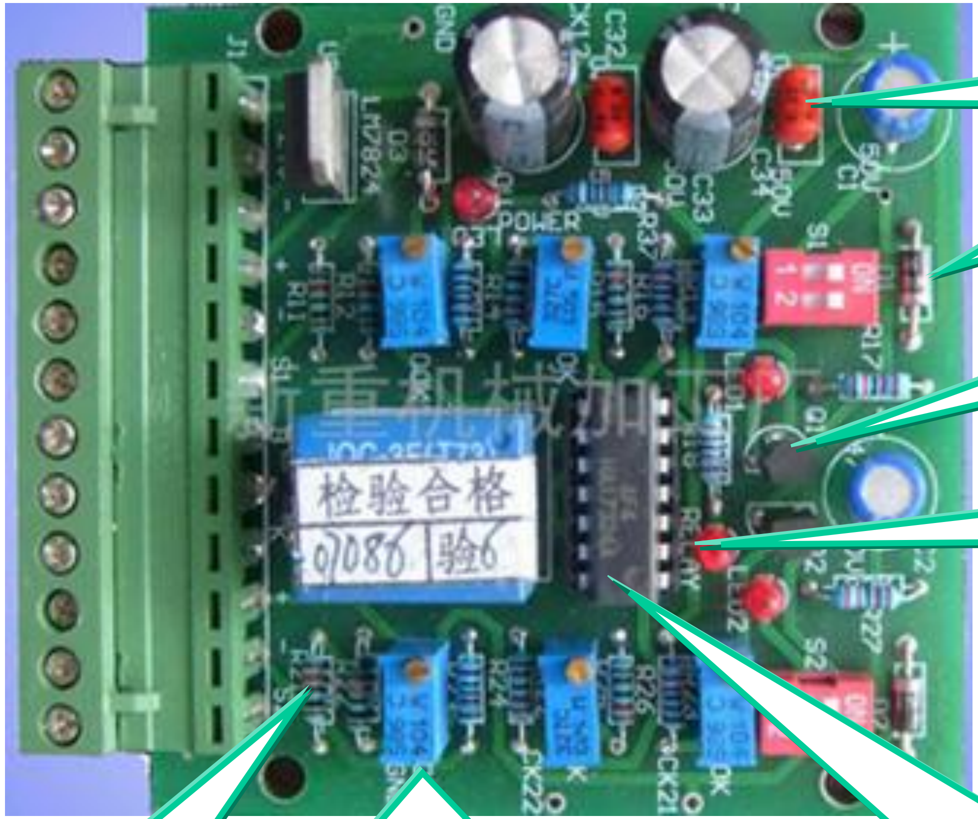
Figure 1.2
Electric circuit of a radio transmitter.

1.1 What is a circuit?

A photoelectric circuit to transfer light to electricity, i.e., voltage



1.1 What is a circuit?



capacitor

diode

transistor

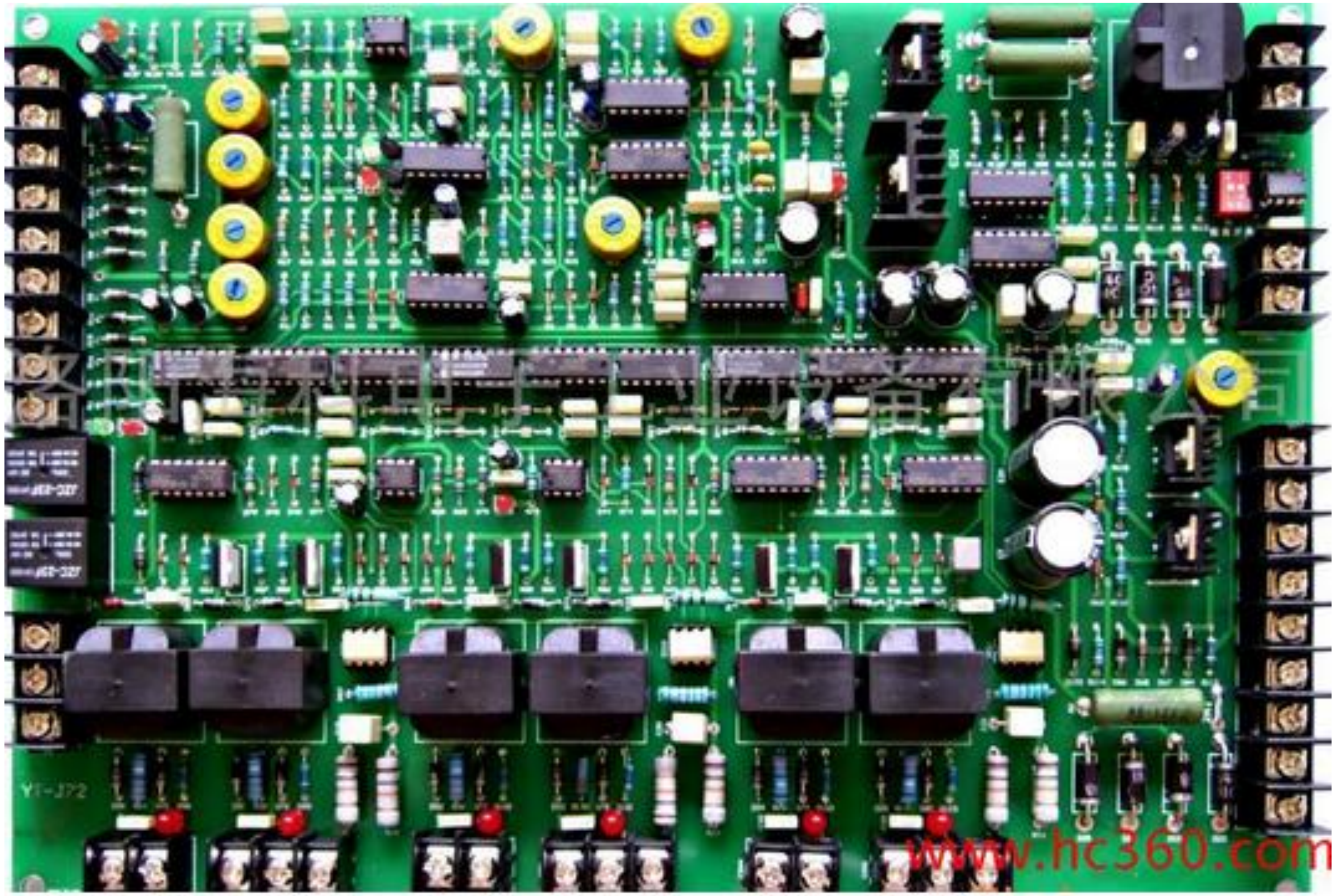
light-emitting diode

resistor

potentiometer

integrated chip

1.1 What is a circuit?



1.1 What is a circuit?

Our goal in this text is to learn various analytical techniques and computer software applications for describing the behavior of a circuit.

1.2 Units

- When taking measurements, we must use units to quantify values
- We use the International Systems of Units (SI for short)
- Prefixes on SI units allow for easy relationships between large and small values

- TABLE 1.2
- The SI prefixes.

Multiplier	Prefix	Symbol
10^{18}	exa	E
10^{15}	Peta	P
10^{12}	Tera	T
10^{9}	Giga	G
10^{6}	Mega	M
10^{3}	Kilo	k
10^{2}	Hecto	h
10	Deka	da
10^{-1}	Deci	d
10^{-2}	Centi	c
10^{-3}	Milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	P
10^{-15}	femto	f
10^{-18}	atto	a

1.3 Charge and Current

Charge is an electrical property of the atomic particles of which matter consists, measured in coulombs (C).

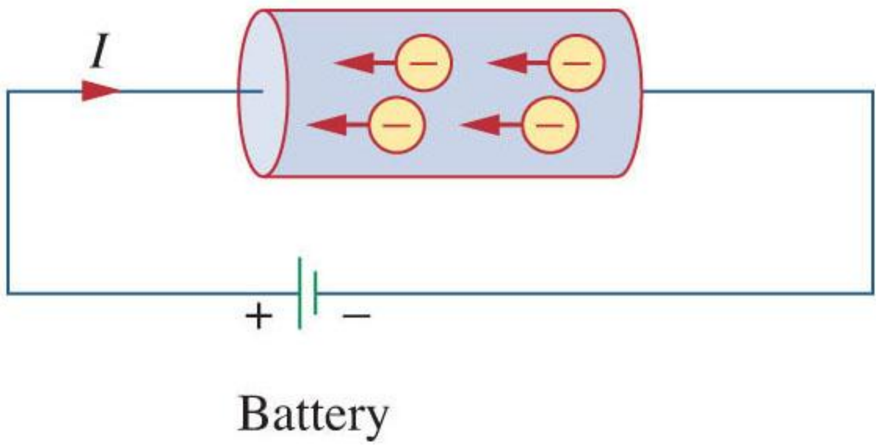
- **Charge is a basic quantity in an electric circuit**
- **The presence of equal numbers of protons and electrons leaves an atom neutrally charged.**
- **Charge of single electron is -**$1.602 * 10^{-19}$C
- **Charge of single proton is** $1.602 * 10^{-19}$C
- **One Coulomb is quite large,** $6.24 * 10^{18}$ **electrons.**

Charge

10^{-6}	**micro**	μ
10^{-9}	nano	n
10^{-12}	pico	P

- **In the lab, one typically sees (pC, nC, or μC)**
- **Charge is always integral multiples of electron charge**
- ***Law of conservation of charge*: Charge cannot be created or destroyed, only transferred. Thus, the algebraic sum of the electric charges in a system does not change.**

Current



- The movement of electric charge is called a current
- Historically the current flow is taken as the movement of positive charges
- Current in metallic conductors is due to negatively charged electrons

Current

Electric current is the time rate of change of charge, measured in amperes (A).

- **Current, *i*, is measured as charge moved per unit time through an element.**

$$i = \frac{dq}{dt}$$

$$1\text{mA} = 10^{-3}\text{A}$$

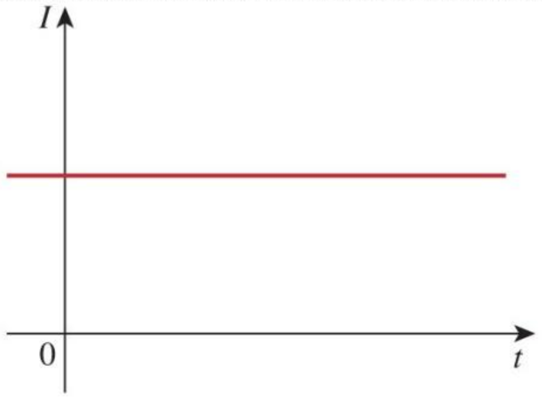
$$1\mu\text{A} = 10^{-6}\text{A}$$

- **Unit is Ampere (A), 1ampere=1Coulomb/second**
- **The charge transferred from time t_o and t is**

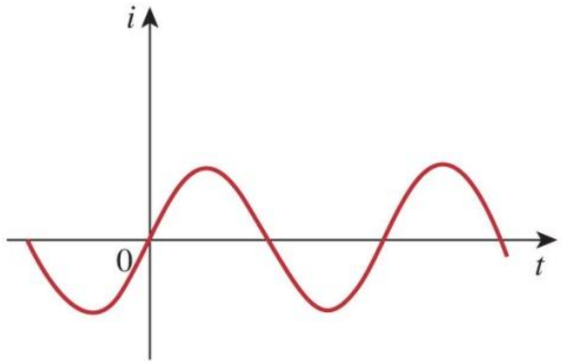
$$\boxed{Q \triangleq \int_{t_0}^{t} i\, dt}$$

Two types of current: DC vs. AC

- A Direct Current (DC) flows only in one direction and can be constant or time varying.
- A common source of DC is a battery.
- An alternating current (AC) is a current that changes direction with respect to time.
- Mains power is an typical AC source
- By convention, constant current is represented by capital *I*, time varying current (either dc or ac) uses the lowercase *i*



(a)



(b)

DC vs. AC

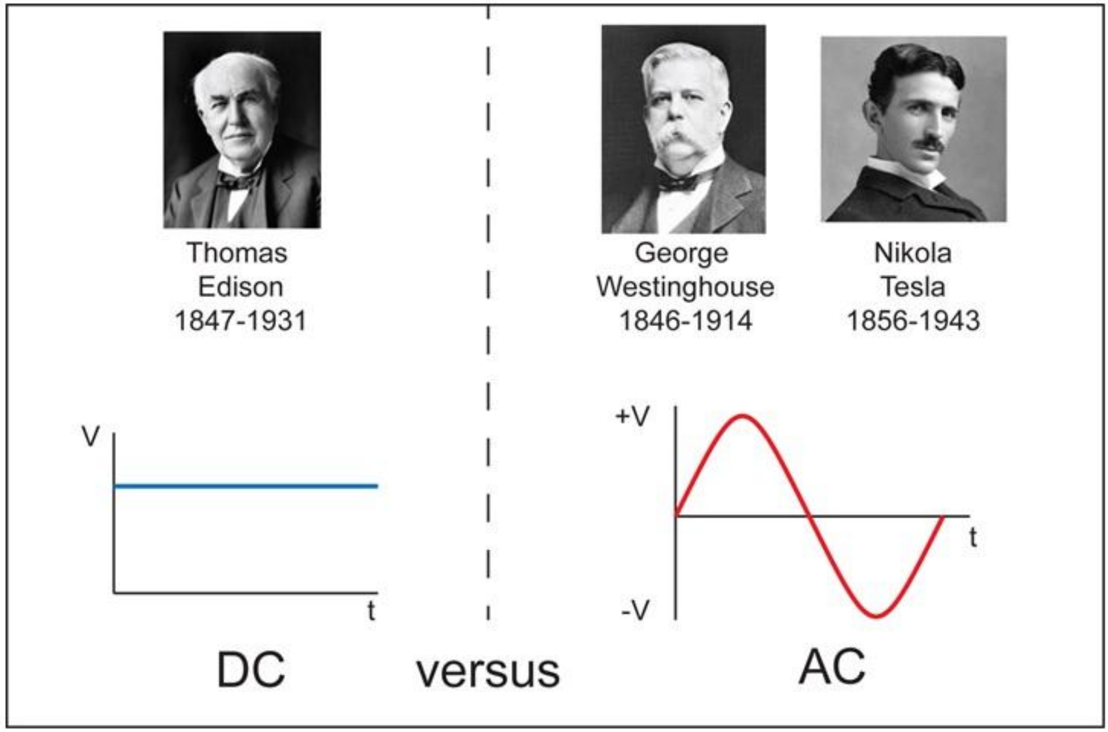
Why is AC better for power transmission than DC?

DC

- DC cannot be stepped up or down in voltage easily (especially in the 1880s) hence it had to be distributed at the voltages used by the consumer
- Since the resistance of the wire is pretty much constant low voltages meant high currents. High currents resulted in large power losses over relatively short distances (less than 2 km)
- This meant that a lot of power or boost stations were needed to supply large cities and from locations where hydroelectric power could be generated.
- Today, through the use of solid state electronics it has become easy to switch from DC to AC and if high temperature superconductors are developed, transmission of power as DC may prove to be more economical.

AC

- AC can easily be stepped up and down in voltage using transformers
- AC could be generated at a low voltage, stepped up to very high voltages for transmission and then stepped down again for consumer use.
- Higher voltages-low currents are better for power transmission because the power lost in transmission due to the wire resistance is proportional to the square of the current ($P=I^2R$) but only directly proportional to the voltage ($P = VI$)
- With AC the power loss per kilometer was a lot lower hence power or boost stations could be spaced far apart, resulting in a much cheaper and more attractive grid system
- AC had the disadvantages that it caused power loses through electromagnetic radiation and induction and the frequencies used were apt to be more deadly.



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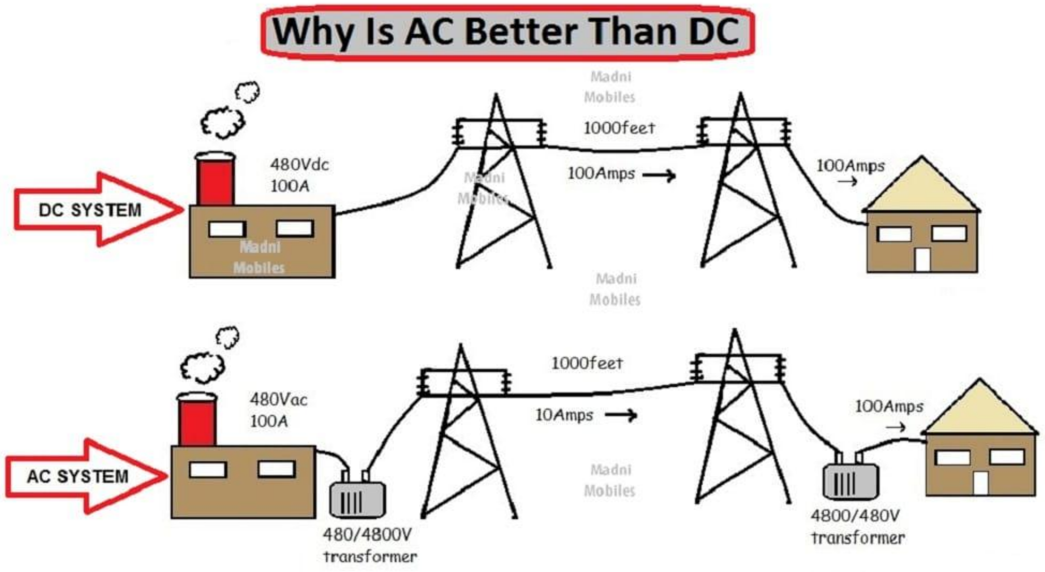
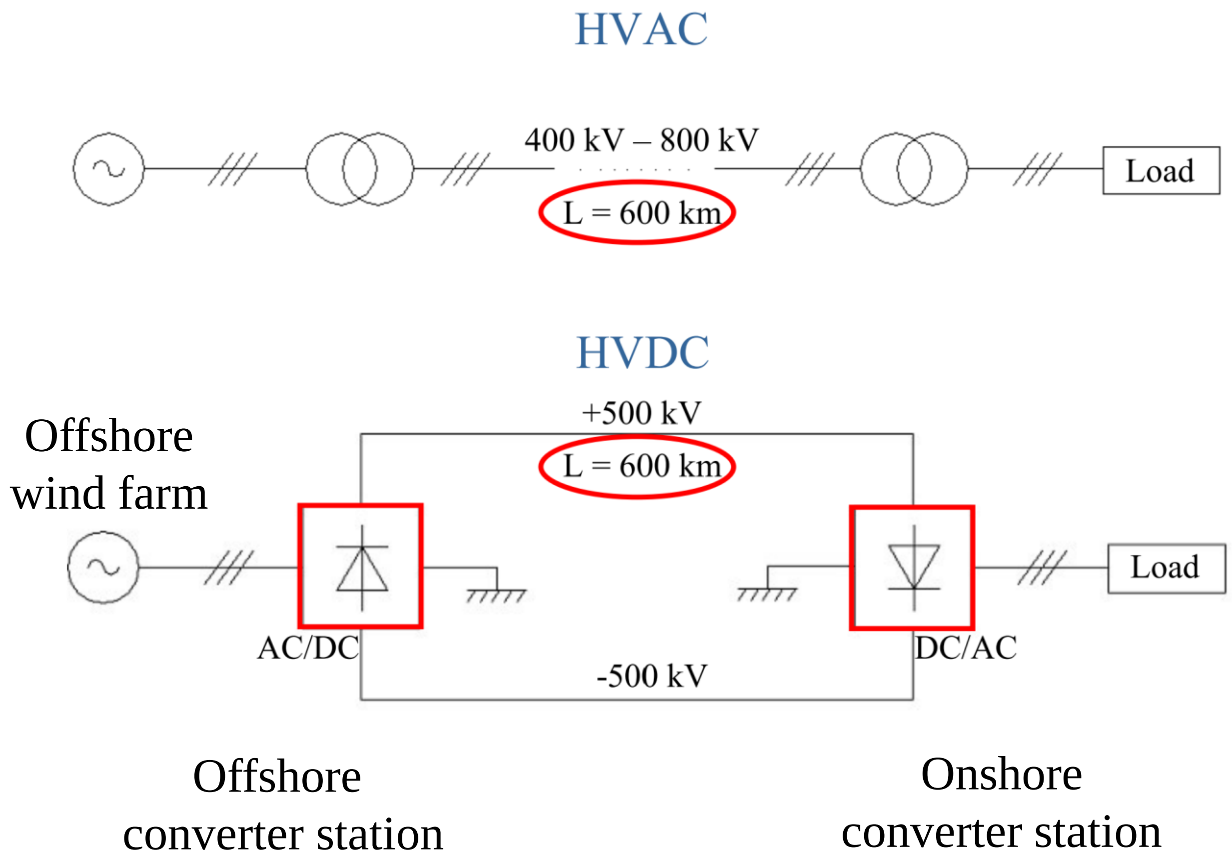


HVAC vs. HVDC Transmission (offshore wind application)



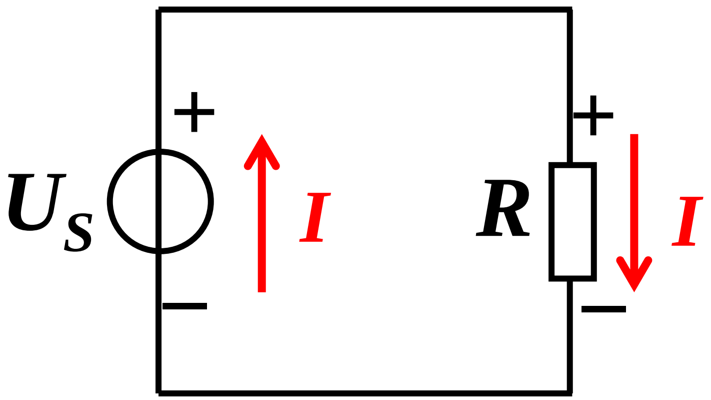
HVDC transmission schemes have some distinct advantages:

- lower costs for long-distance bulk power transmission;
- lower costs for cable transmission (subsea, offshore);
- ability to exchange power between two asynchronous power systems, even two systems with different frequencies;
- AC system support capabilities, including power flow control, frequency and voltage support, oscillation damping, and fault current limiting;

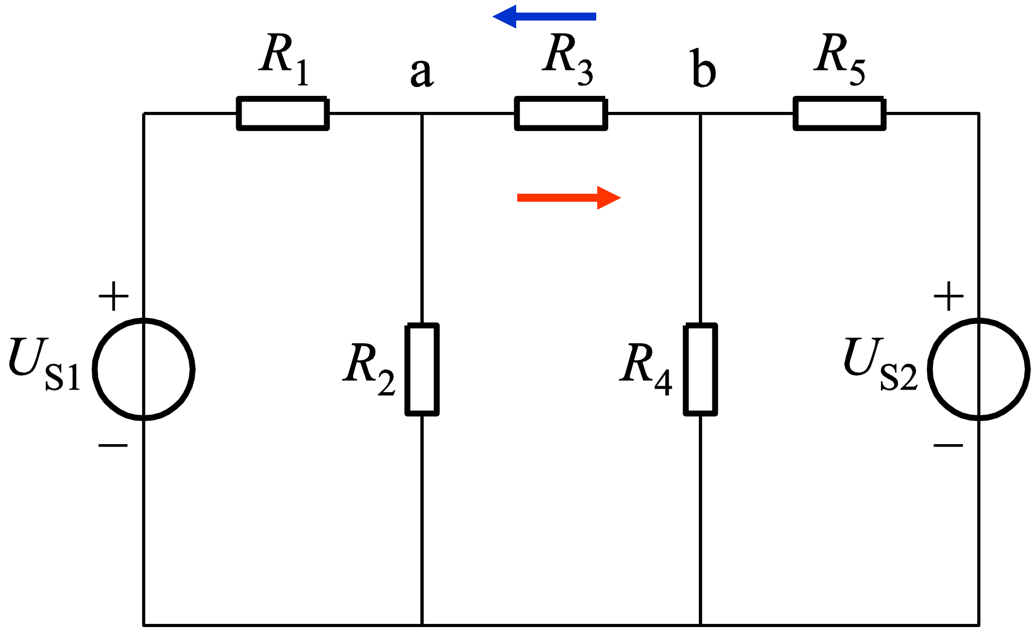
Ultra High Voltage (UHV) DC Transmission

Direction of Current

- **The direction of current flow is conventionally taken as the direction of positive charge movement.**

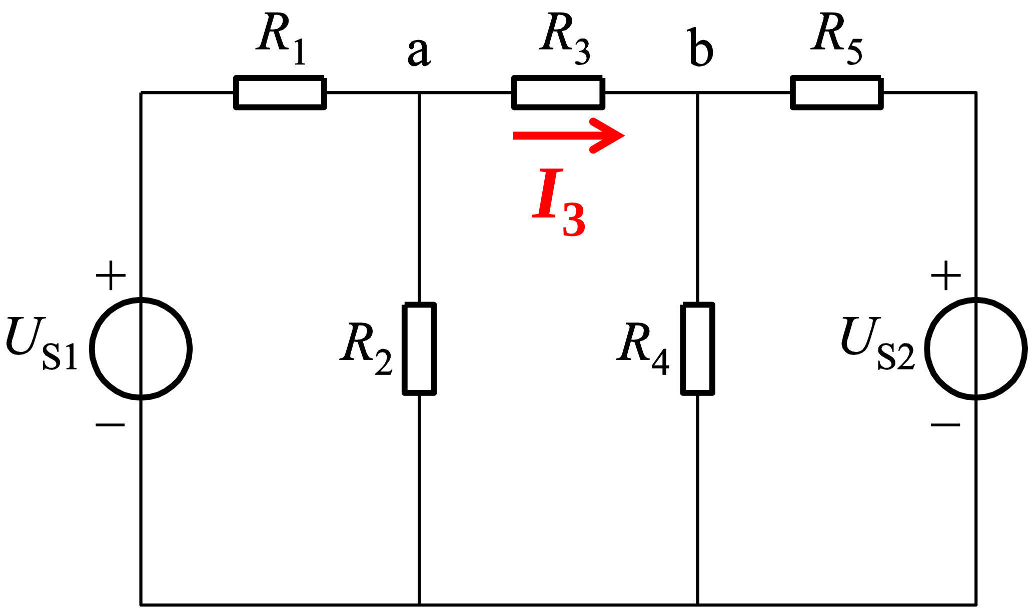


Direction of Current



Reference Direction of current

- **Define the reference direction of interest**
- **We don't need to use the actual current direction as our reference, and often have no choice in the matter.**
- **Calculate the current according to circuit laws**
- **The sign of the current indicates the actual current direction**

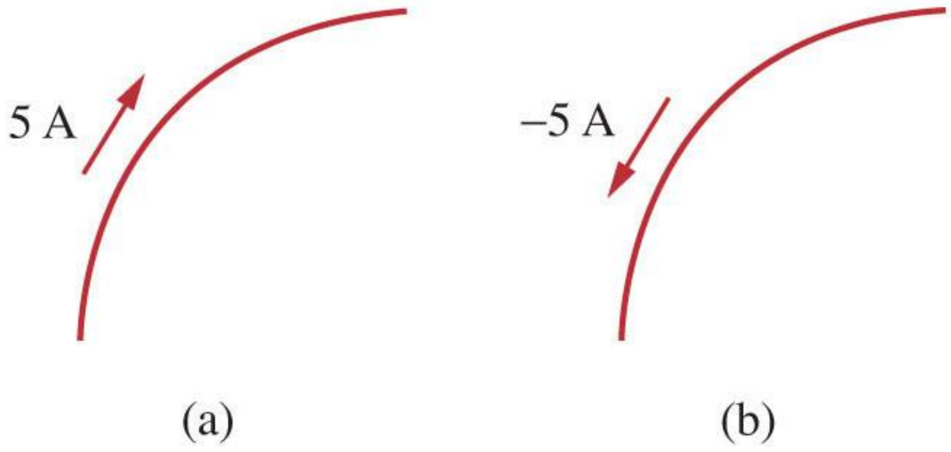


if I_3 is positive, **the actual current direction is consistent with the reference direction.**

if I_3 is negative, **the actual current direction is opposite to the reference direction.**

Direction of Current

- **An arrow indicates the reference direction of current**
- **A positive current through a component is the same as a negative current flowing in the opposite direction.**



Example 1.1

How much charge is represented by 4,600 electrons?

Solution:

Each electron has -1.602×10^{-19} C. Hence 4,600 electrons will have

$$-1.602 \times 10^{-19}\ \text{C/electron} \times 4{,}600\ \text{electrons} = -7.369 \times 10^{-16}\ \text{C}$$

Example 1.2

The total charge entering a terminal is given by $q = 5t \sin 4\pi t$ mC. Calculate the current at $t = 0.5$ s.

Solution:

$$i = \frac{dq}{dt} = \frac{d}{dt}(5t \sin 4\pi t) \text{ mC/s} = (5 \sin 4\pi t + 20\pi t \cos 4\pi t) \text{ mA}$$

At $t = 0.5$,

$$i = 5 \sin 2\pi + 10\pi \cos 2\pi = 0 + 10\pi = 31.42 \text{ mA}$$

Example 1.3

Determine the total charge entering a terminal between $t = 1$ s and $t = 2$ s if the current passing the terminal is $i = (3t^2 - t)$ A.

Solution:

$$Q = \int_{t=1}^{2} i\,dt = \int_{1}^{2} (3t^2 - t)\,dt$$

$$= \left(t^3 - \frac{t^2}{2}\right)\Bigg|_1^2 = (8 - 2) - \left(1 - \frac{1}{2}\right) = 5.5 \text{ C}$$

Practice Problem 1.3

The current flowing through an element is

$$i = \begin{cases} 4 \text{ A}, & 0 < t < 1 \\ 4t^2 \text{ A}, & t > 1 \end{cases}$$

Calculate the charge entering the element from $t = 0$ to $t = 2$ s.

Answer: 13.333 C.

1.4 Voltage

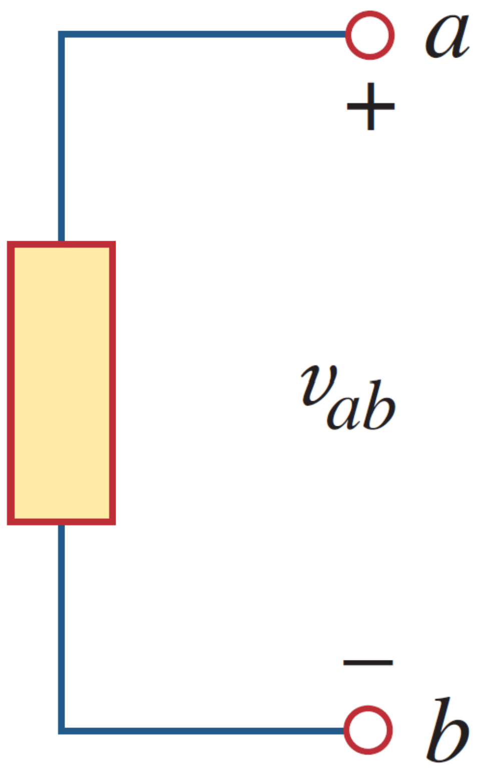
- **Electrons move when there is external electromotive force (emf)/ a potential difference between two locations.**
- **This potential difference is expressed by voltage (volts, V).**
- **The voltage v_{ab} between two points *a* and *b* in an electric circuit is the energy needed to move a unit charge from *b* to *a***

$$v_{ab} \triangleq \frac{dw}{dq}$$

where w is energy in joules (J) and q is charge in coulombs (C)

Reference Direction of Voltage

- **The voltage direction is conventionally taken from the high potential to low potential.**
- **The plus (+) and minus (-) signs are used to define reference direction (voltage polarity);**
- **The V_{ab} can be interpreted: the potential at point *a* is V_{ab} volts higher than that of point *b*;**
- **V_{ab} = - V_{ba}**



Reference Direction of Voltage

- **In Figure(a), there is a 9V voltage drop from a to b or equivalently a 9V voltage rise from b to a**

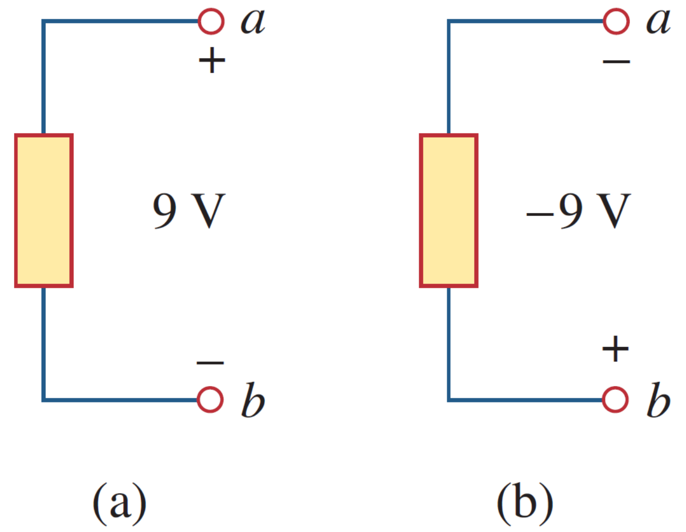


Figure 1.7
Two equivalent representations of the same voltage v_{ab}: (a) Point a is 9 V above point b; (b) point b is -9 V above point a.

1.5 Power and Energy

Power is the time rate of expending or absorbing energy, measured in watts (W).

$$p = \frac{dw}{dt} = \frac{dw}{dq} \cdot \frac{dq}{dt} = vi$$

- **It is equal to the rate of energy provided or consumed per unit time.**
- **The power is the product of voltage and current**
- **It is measured in Watts (W)**

Conservation of Energy

$$p = \frac{dw}{dt} = \frac{dw}{dq} \cdot \frac{dq}{dt} = vi$$

- **In a circuit, energy cannot be created or destroyed.**
- **Thus power also must be conserved.**
- **All power supplied must be absorbed by the other elements, i.e, the algebraic sum of power is zero.**

$$\boxed{\sum p = 0}$$

Power and Energy

$$p = \frac{dw}{dt} = \frac{dw}{dq} \cdot \frac{dq}{dt} = vi$$

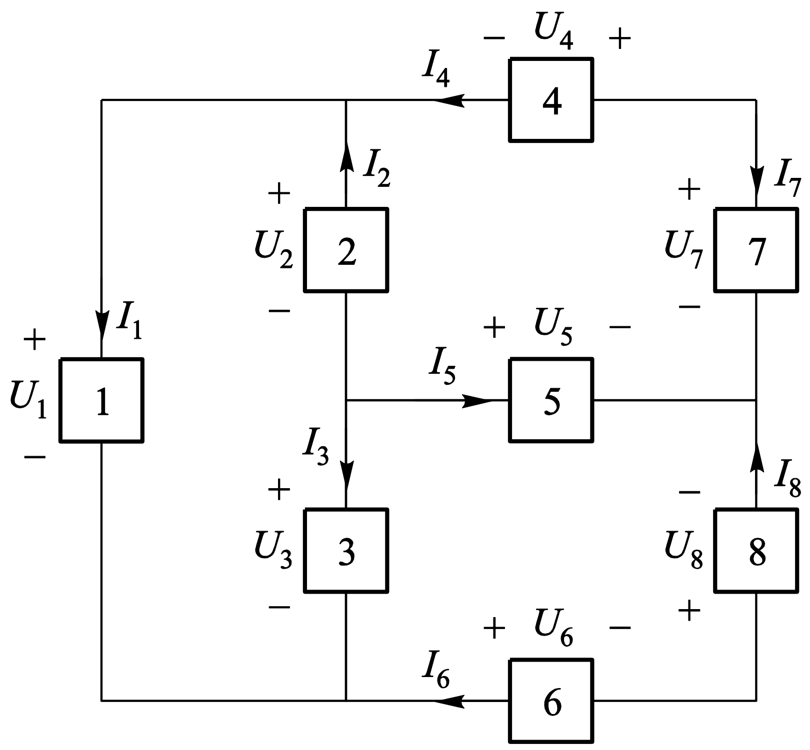
- **Energy (J) absorbed or supplied from time t_o to time t is**

$$w = \int_{t_0}^{t} p\, dt = \int_{t_0}^{t} vi\, dt$$

- **Power companies usually measure energy in watt-hours (Wh)**

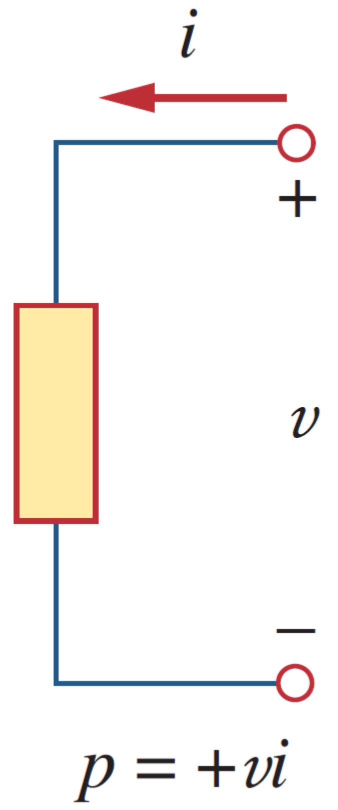
$$1\ \text{Wh} = 3{,}600\ \text{J}$$

Power ?



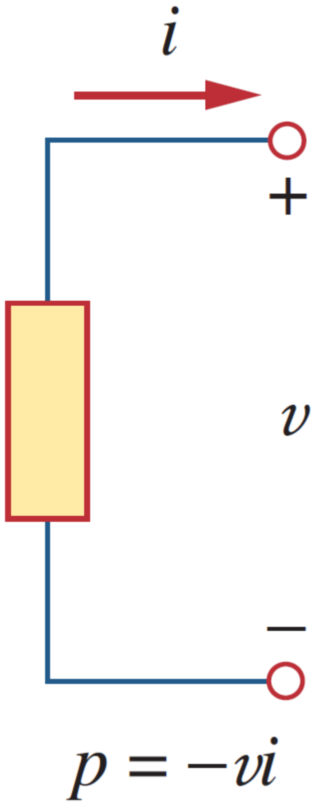
Passive Sign Convention: the relationship between current *i* and voltage *v*

- **Passive sign convention** is satisfied when the current enters through the positive terminal of an element, and ***p=+vi***
- **If the power has a + sign, power is being absorbed by the element.**
- **If the power has a – sign, power is being supplied by the element.**



Passive Sign Convention: the relationship between current *i* and voltage *v*

- **If the current enters through the negative terminal of an element, and $p=-vi$**
- **If the power has a + sign, power is being absorbed by the element.**
- **If the power has a – sign, power is being supplied by the element.**



Example

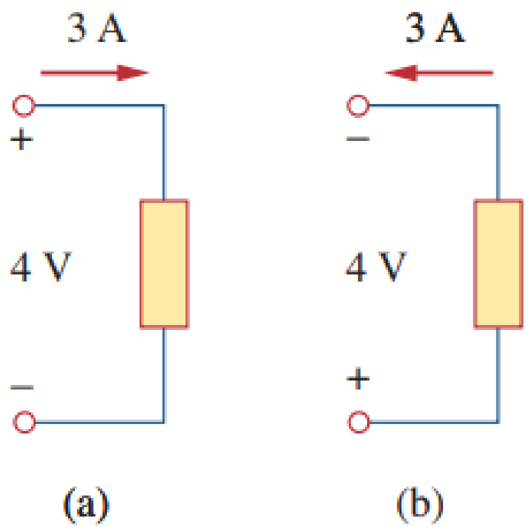


Figure 1.9
Two cases of an element with an absorbing power of 12 W: (a) $p = 4 \times 3 = 12$ W, (b) $p = 4 \times 3 = 12$ W.

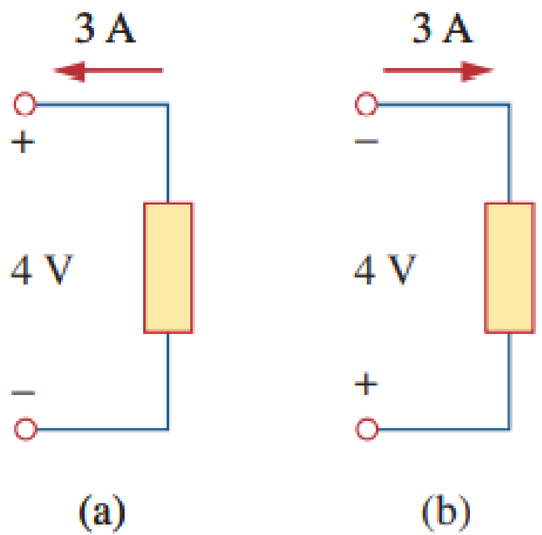


Figure 1.10
Two cases of an element with a supplying power of 12 W: (a) $p = -4 \times 3 = -12$W, (b) $p = -4 \times 3 = -12$ W.

Supplying or absorbing?

Example

Find the power delivered to an element at $t = 3$ ms if the current entering its positive terminal is

$$i = 5 \cos 60\pi t \text{ A}$$

and the voltage is: (a) $v = 3i$, (b) $v = 3\, di/dt$.

Find the power delivered to an element at $t = 3$ ms if the current entering its positive terminal is

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and the voltage is: (a) $v = 3i$, (b) $v = 3\, di/dt$.

Solution:

(a) The voltage is $v = 3i = 15 \cos 60\pi t$; hence, the power is

$$p = vi = 75 \cos^2 60\pi t \text{ W}$$

At $t = 3$ ms,

$$p = 75 \cos^2 (60\pi \times 3 \times 10^{-3}) = 75 \cos^2 0.18\pi = 53.48 \text{ W}$$

(b) We find the voltage and the power as

$$v = 3\frac{di}{dt} = 3(-60\pi)5 \sin 60\pi t = -900\pi \sin 60\pi t \text{ V}$$

$$p = vi = -4500\pi \sin 60\pi t \cos 60\pi t \text{ W}$$

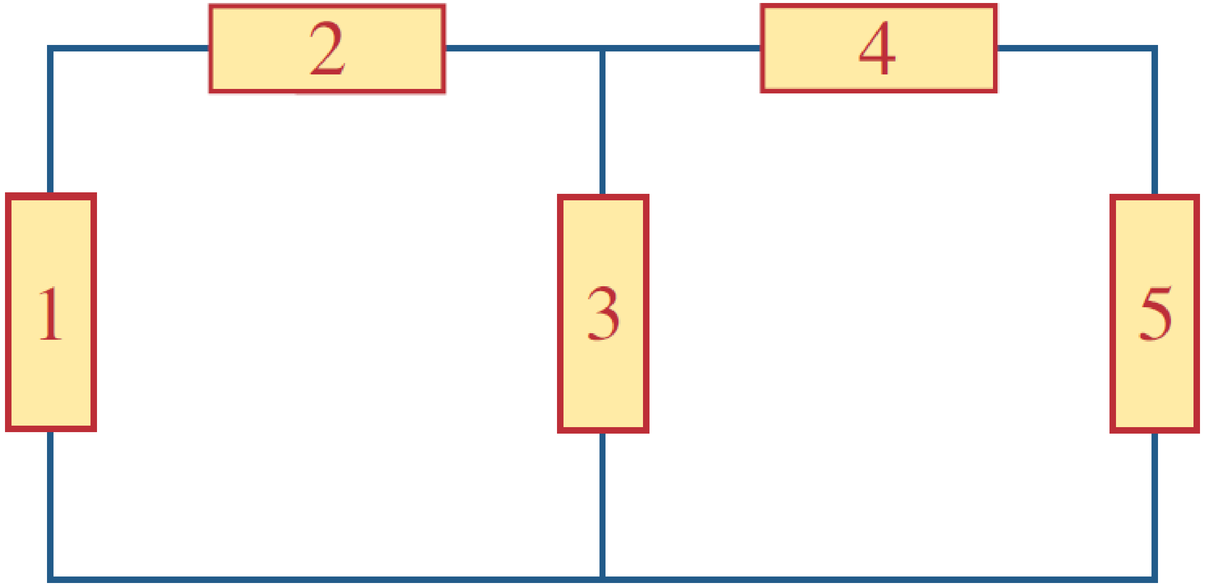
At $t = 3$ ms,

$$\begin{aligned} p &= -4500\pi \sin 0.18\pi \cos 0.18\pi \text{ W} \\ &= -14137.167 \sin 32.4^\circ \cos 32.4^\circ = -6.396 \text{ kW} \end{aligned}$$

Example

In the circuit, there are five elements. If $p_1 = -205$ W, $p_2 = 60$ W, $p_4 = 45$ W, $p_5 = 30$ W.

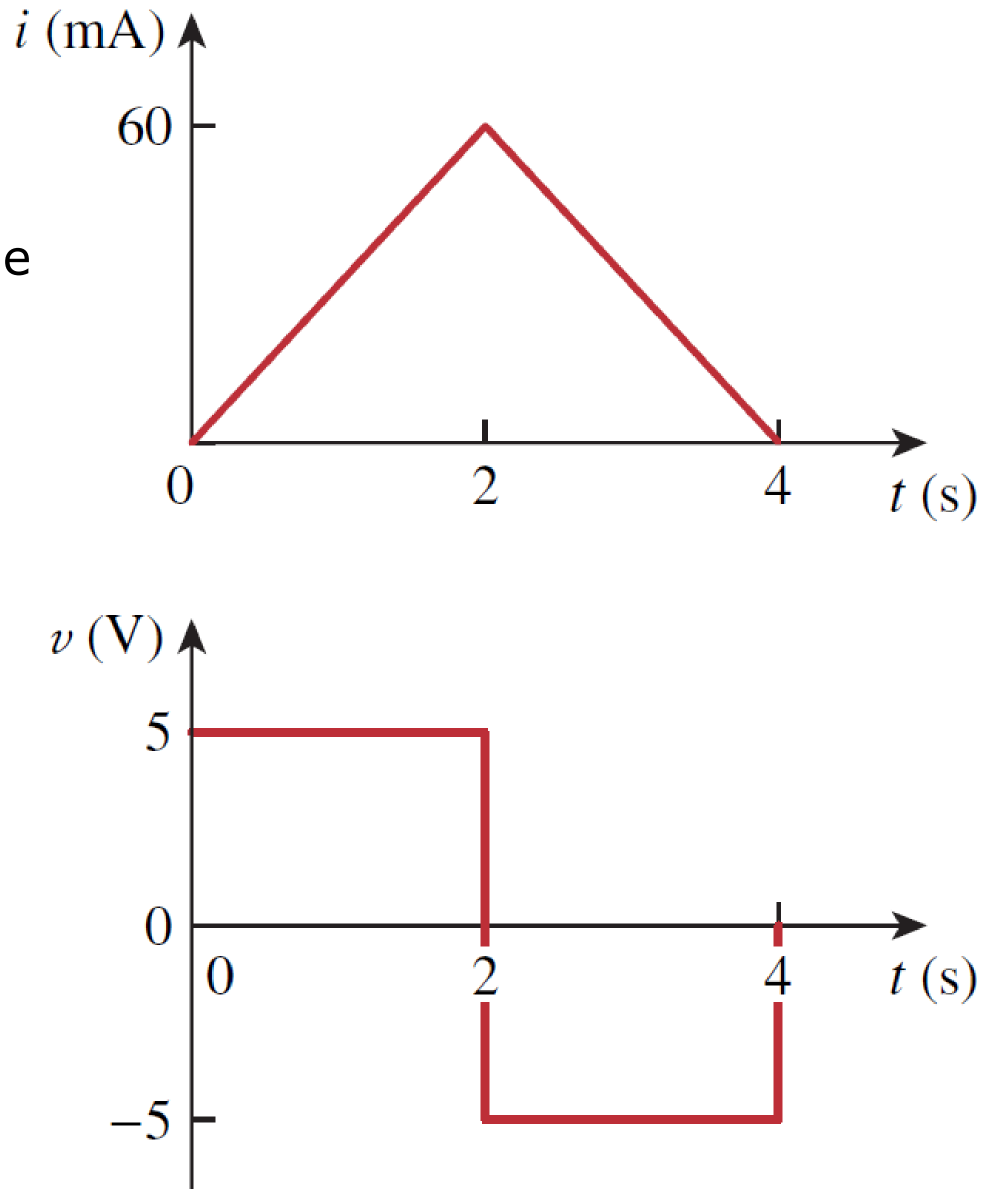
Calculate the power p_3 received or delivered by element 3.



Example

The Figure shows the current through and the voltage across an element:

(a) Sketch the power delivered to the element for $t > 0$.



1.6 Circuit Elements

Active vs Passive

- Active elements can generate energy
  - Generators
  - Batteries
  - Operational Amplifiers
- Passive elements do not generate energy
  - Resistors
  - Capacitors
  - Inductors

Question

- Passive elements do not generate energy
  - Resistors
  - Capacitors
  - Inductors

Question: Do passive elements absorb energy?

1.6 Circuit Elements:

- Active elements
  - voltage source
    - Independent voltage source
    - Dependent voltage source
  - current source
    - Independent current source
    - Dependent current source

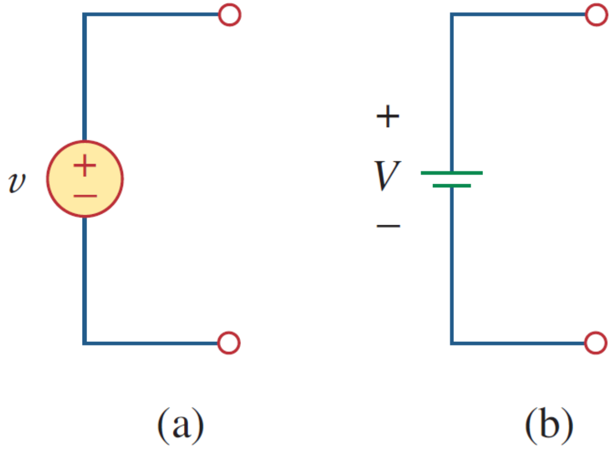
1.6 Circuit Elements:

Ideal independent source

An ideal independent source is an active element that provides a specified voltage or current that is completely independent of other circuit elements.

Ideal Voltage Source

- Provide a specified voltage completely independent of the current through the source.
- An ideal independent voltage source has no internal resistance.
- It also is capable of producing any amount of current needed to establish the desired voltage at its terminals.
- Thus we can know the voltage at its terminals, but we don't know the current.



1.6 Circuit Elements:

What are non-ideal sources?

Tips: all sources are non-ideal.

Ideal Current Source

- Provide a specified current completely independent of the voltage across the source.
- They have infinite resistance.
- They will generate any voltage to establish the desired current through them.
- We can know the current through them in advance, but not the voltage.

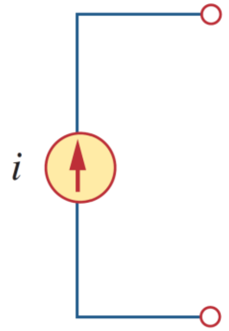


Figure 1.12
Symbol for independent current source.

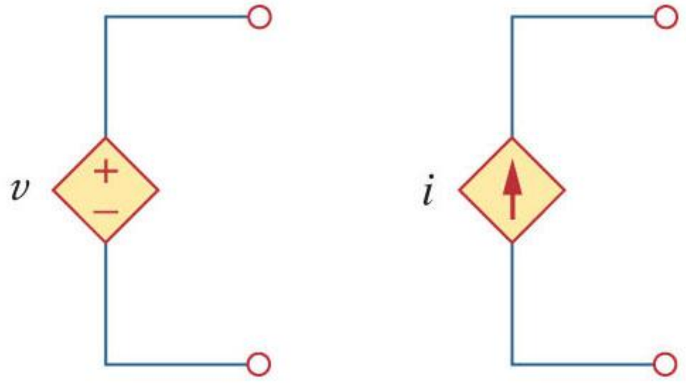
Ideal sources

- Both the voltage and current source ideally can generate infinite power.
- They are also capable of absorbing power from the circuit.
- It is important to remember that these sources do have limits in reality:
- Voltage sources have an upper current limit.
- Current sources have an upper voltage limit.

Dependent Sources

An **ideal dependent** (or **controlled**) **source** is an active element in which the source quantity is controlled by another voltage or current.

- **Symbolically represented as a diamond**
- **Four types:**
  - **A voltage-controlled voltage source (VCVS).**
  - **A current-controlled voltage source (CCVS).**
  - **A voltage-controlled current source (VCCS).**
  - **A current-controlled current source (CCCS).**



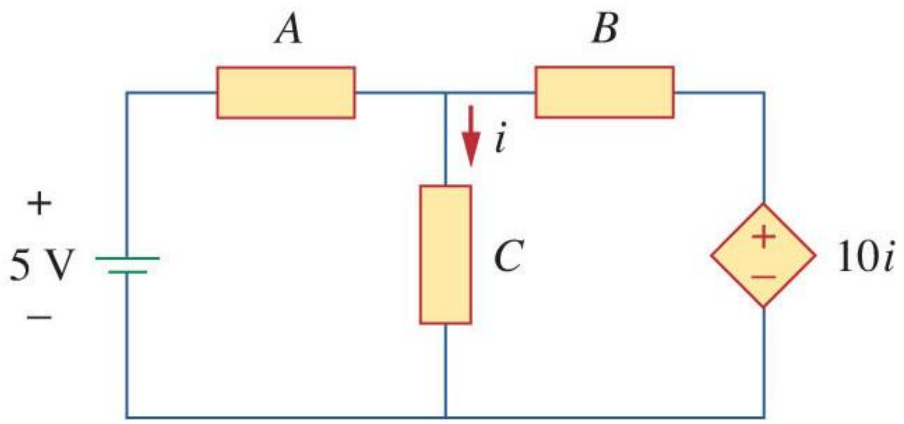
(a) (b)

Circuit Applications of Dependent Sources

- **Dependent sources are good models for some common circuit elements:**
  - **Transistors: In certain modes of operation, transistors take either a voltage or current input to one terminal and cause a current that is somehow proportional to the input to appear at two other terminals.**
  - **Operational Amplifiers: The basic concept is they take an input voltage and generate an output voltage that is proportional to that.**

Dependent Source example

- The circuit shown below is an example of using a dependent source.
- The source on the right is controlled by the current passing through element C.



Example

Calculate the power supplied or absorbed by each element in Fig. 1.15.

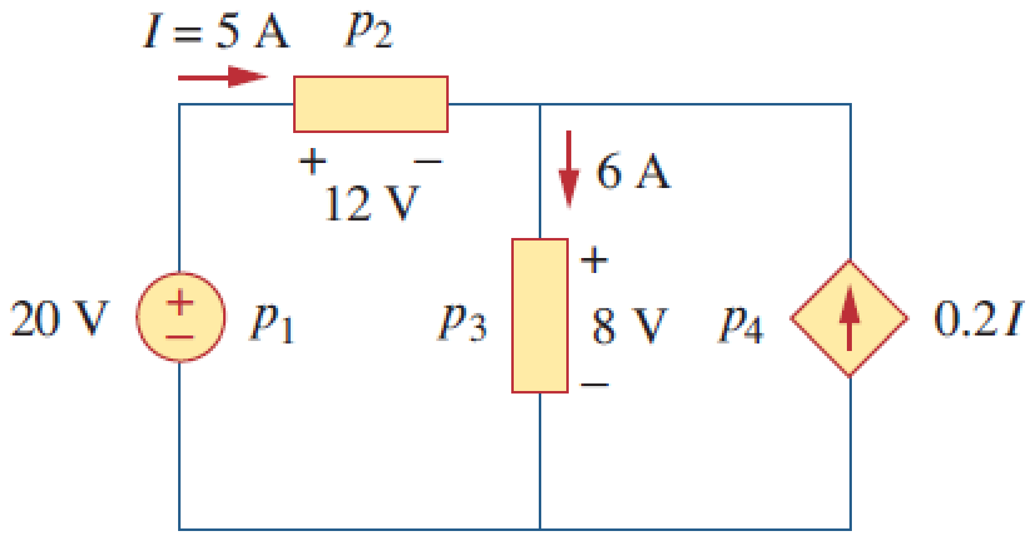


Figure 1.15
For Example 1.7.

Calculate the power supplied or absorbed by each element in Fig. 1.15.

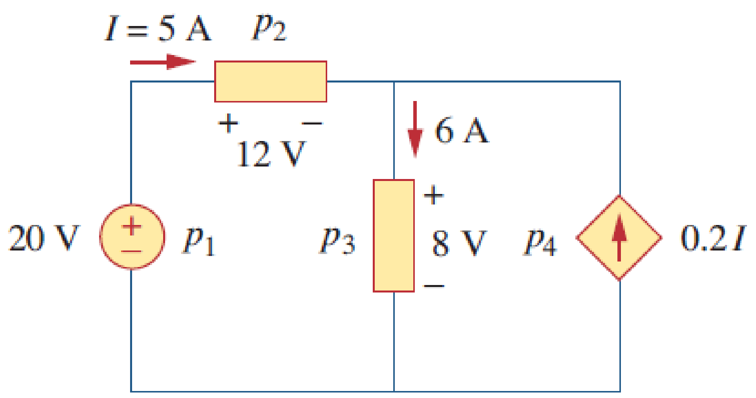


Figure 1.15
For Example 1.7.

Solution:

We apply the sign convention for power shown in Figs. 1.8 and 1.9. For p_1, the 5-A current is out of the positive terminal (or into the negative terminal); hence,

$$p_1 = 20(-5) = -100 \text{ W} \qquad \text{Supplied power}$$

For p_2 and p_3, the current flows into the positive terminal of the element in each case.

$$p_2 = 12(5) = 60 \text{ W} \qquad \text{Absorbed power}$$
$$p_3 = 8(6) = 48 \text{ W} \qquad \text{Absorbed power}$$

For p_4, we should note that the voltage is 8 V (positive at the top), the same as the voltage for p_3, since both the passive element and the dependent source are connected to the same terminals. (Remember that voltage is always measured across an element in a circuit.) Since the current flows out of the positive terminal,

$$p_4 = 8(-0.2I) = 8(-0.2 \times 5) = -8 \text{ W} \qquad \text{Supplied power}$$

We should observe that the 20-V independent voltage source and $0.2I$ dependent current source are supplying power to the rest of the network, while the two passive elements are absorbing power. Also,

$$p_1 + p_2 + p_3 + p_4 = -100 + 60 + 48 - 8 = 0$$

In agreement with Eq. (1.8), the total power supplied equals the total power absorbed.

Example

Practice Problem 1.7

Compute the power absorbed or supplied by each component of the circuit in Fig. 1.16.

Answer: $p_1 = -45$ W, $p_2 = 18$ W, $p_3 = 12$ W, $p_4 = 15$ W.

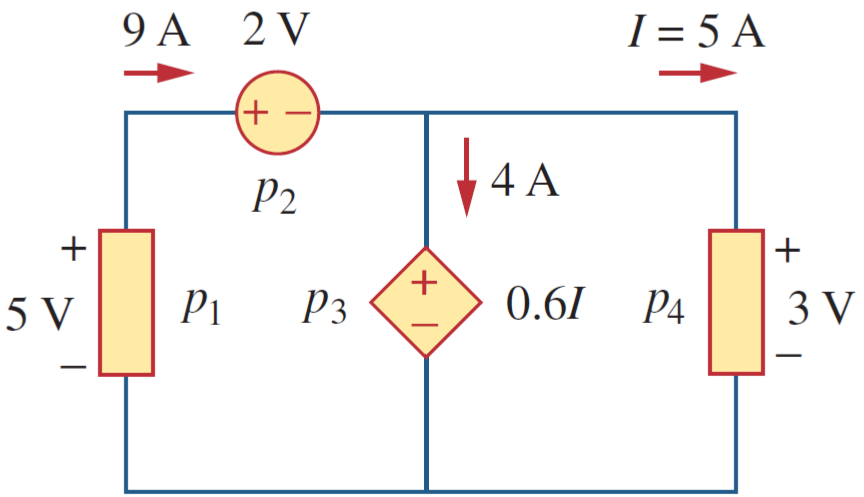


Figure 1.16
For Practice Prob. 1.7.

1.7 Problem Solving

An effective method for determining the solution of any engineering problem is given:

1. Carefully define the problem.
2. Present everything you know about the problem.
3. Establish a set of alternative solutions and determine the one that promises the greatest likelihood of success.
4. Attempt a problem solution.
5. Evaluate the solution and check for accuracy.
6. Has the problem been solved satisfactorily? If so, present the solution; if not, then return to step 3 and continue through the process again.

1.7 Problem Solving

- **1. Carefully <u>define</u> the problem**
  - This is the most important step
  - What needs to be solved?
  - What questions need to be addressed before solving? Find the sources to answer them.
- **2. <u>Present</u> everything you know about the problem**
  - What do you know?
  - What don’t you?

1.7 Problem Solving

- **3. Establish a set of <u>alternative</u> solutions and determine the one that promises the greatest likelihood of success.**
  - **Most problems have more than one way to be solved**
  - **But not all solutions are simple**
  - **Are the required tools available?**

1.7 Problem Solving

- 4. <u>Attempt</u> to solve the problem
  - Documenting this process is very important
- 5. <u>Evaluate</u> the solution and check for accuracy
  - Does it makes sense?
  - Is it consistent with any assumptions made?
- 6. Is the solution <u>satisfactory</u>? If not, try an alternate solution.

Application

A flashlight battery has a rating of 0.8 ampere-hours (Ah) and a lifetime of 10 hours.

(a) How much current can it deliver?

(b) How much power can it give if its terminal voltage is 6 V?

(c) How much energy is stored in the battery in Wh?

Battery capacity (ampere-hour)= Discharge Time (hour) * Discharge Current (ampere)

Application

The electron beam in a TV picture tube carries 10^{15} electrons per second. As a design engineer, determine the voltage V_o needed to accelerate the electron beam to achieve 4 W.

Solution:

The charge on an electron is

$$e = -1.6 \times 10^{-19}\text{ C}$$

If the number of electrons is n, then $q = ne$ and

$$i = \frac{dq}{dt} = e\frac{dn}{dt} = (-1.6 \times 10^{-19})(10^{15}) = -1.6 \times 10^{-4}\text{ A}$$

The negative sign indicates that the current flows in a direction opposite to electron flow as shown in Fig. 1.18, which is a simplified diagram of the CRT for the case when the vertical deflection plates carry no charge. The beam power is

$$p = V_o i \qquad \text{or} \qquad V_o = \frac{p}{i} = \frac{4}{1.6 \times 10^{-4}} = 25{,}000\text{ V}$$

Thus, the required voltage is 25 kV.

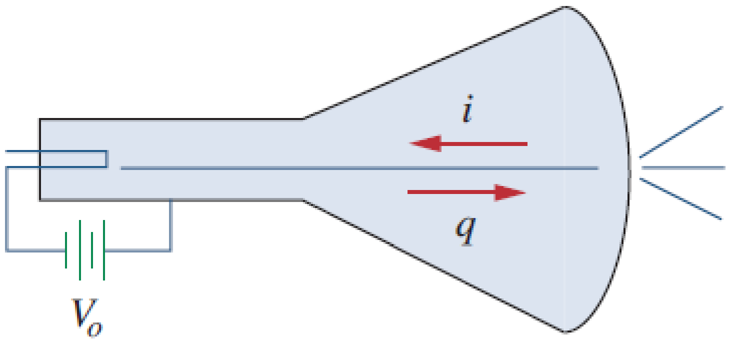


Figure 1.18
A simplified diagram of the cathode-ray tube; for Example 1.8.

Summary

1. An electric circuit consists of electrical elements connected together.
2. The International System of Units (SI) is the international measurement language, which enables engineers to communicate their results. From the seven principal units, the units of other physical quantities can be derived.
3. Current is the rate of charge flow past a given point in a given direction.

$$i = \frac{dq}{dt}$$

4. Voltage is the energy required to move 1 C of charge through an element.

$$v = \frac{dw}{dq}$$

5. Power is the energy supplied or absorbed per unit time. It is also the product of voltage and current.

$$p = \frac{dw}{dt} = vi$$

6. According to the passive sign convention, power assumes a positive sign when the current enters the positive polarity of the voltage across an element.

Summary

7. An ideal voltage source produces a specific potential difference across its terminals regardless of what is connected to it. An ideal current source produces a specific current through its terminals regardless of what is connected to it.
8. Voltage and current sources can be dependent or independent. A dependent source is one whose value depends on some other circuit variable.

Assignment

1.2 Determine the current flowing through an element if the charge flow is given by

(a) $q(t) = (3t + 8)$ mC

(b) $q(t) = (8t^2 + 4t - 2)$ C

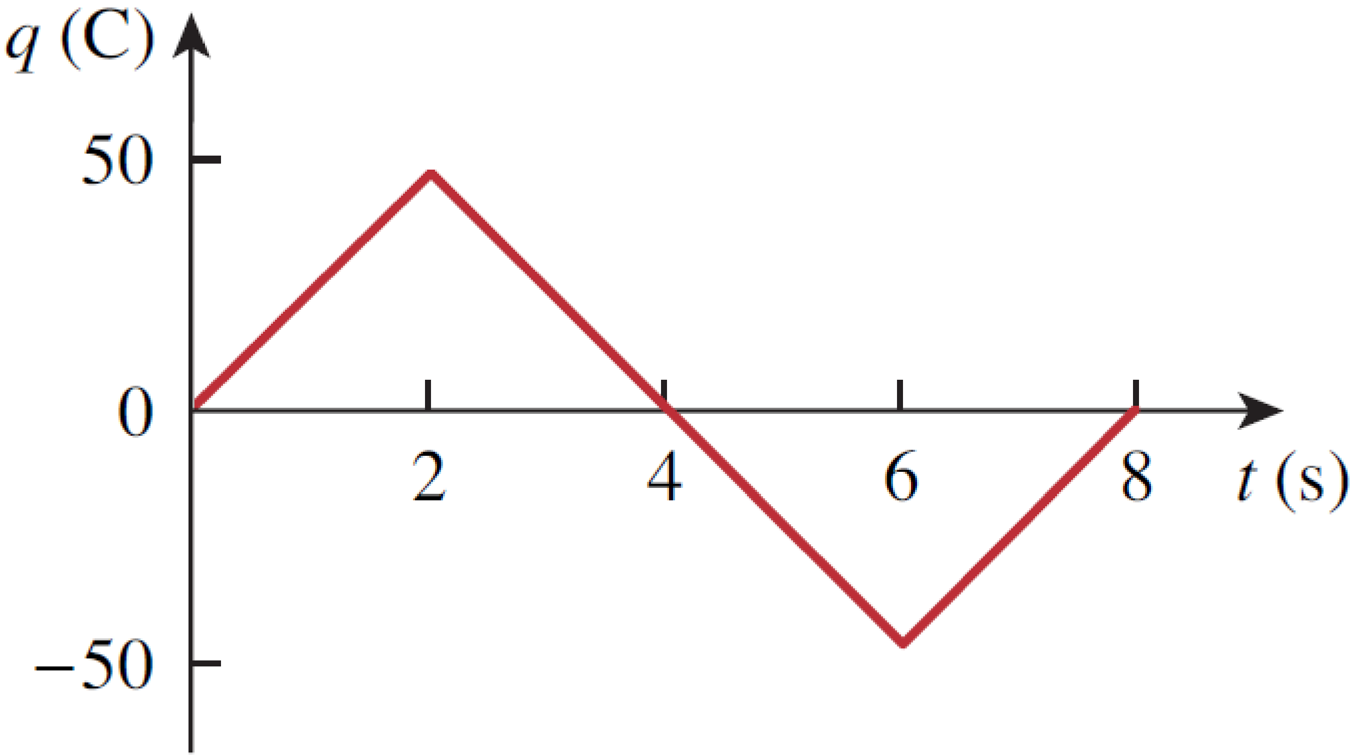
(c) $q(t) = (3e^{-t} - 5e^{-2t})$ nC

(d) $q(t) = 10 \sin 120\pi t$ pC

(e) $q(t) = 20e^{-4t} \cos 50t\,\mu$C

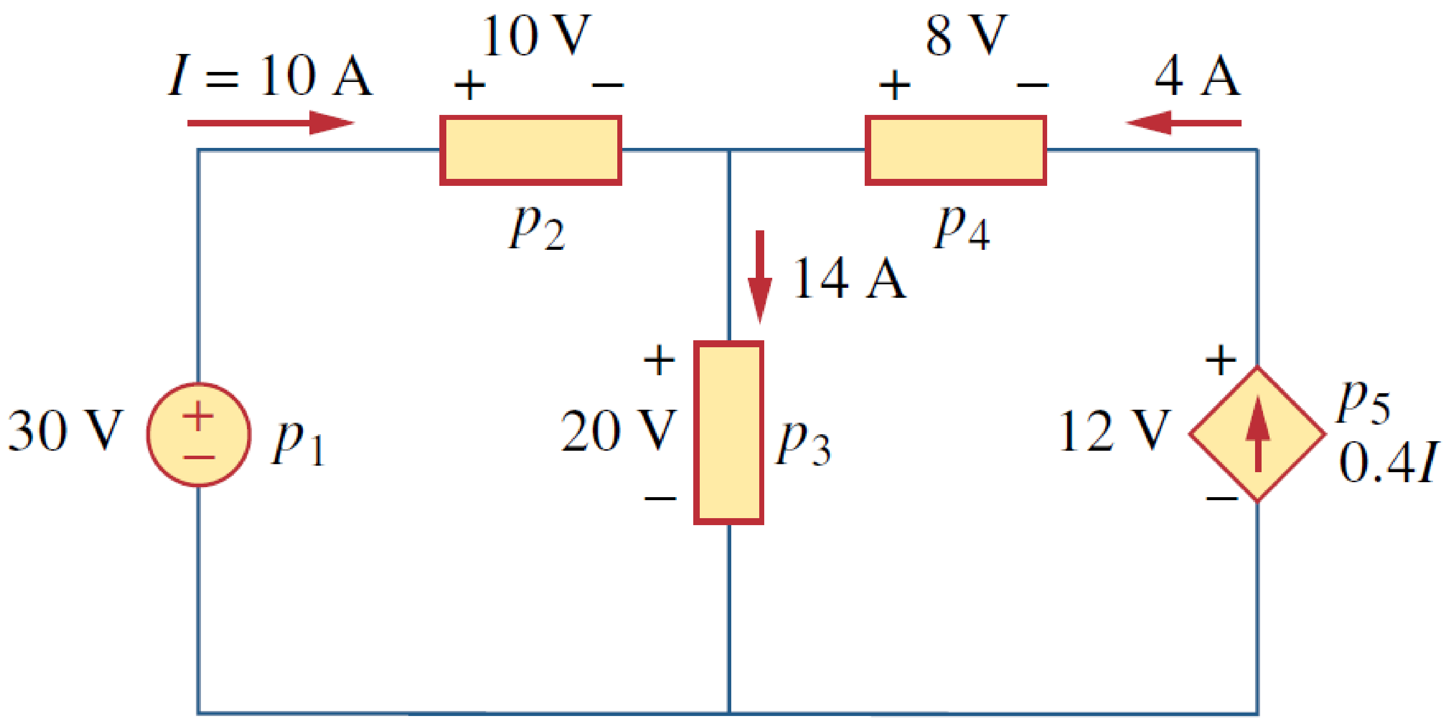
Assignment

1.7 The charge flowing in a wire is plotted in Fig. 1.24. Sketch the corresponding current.



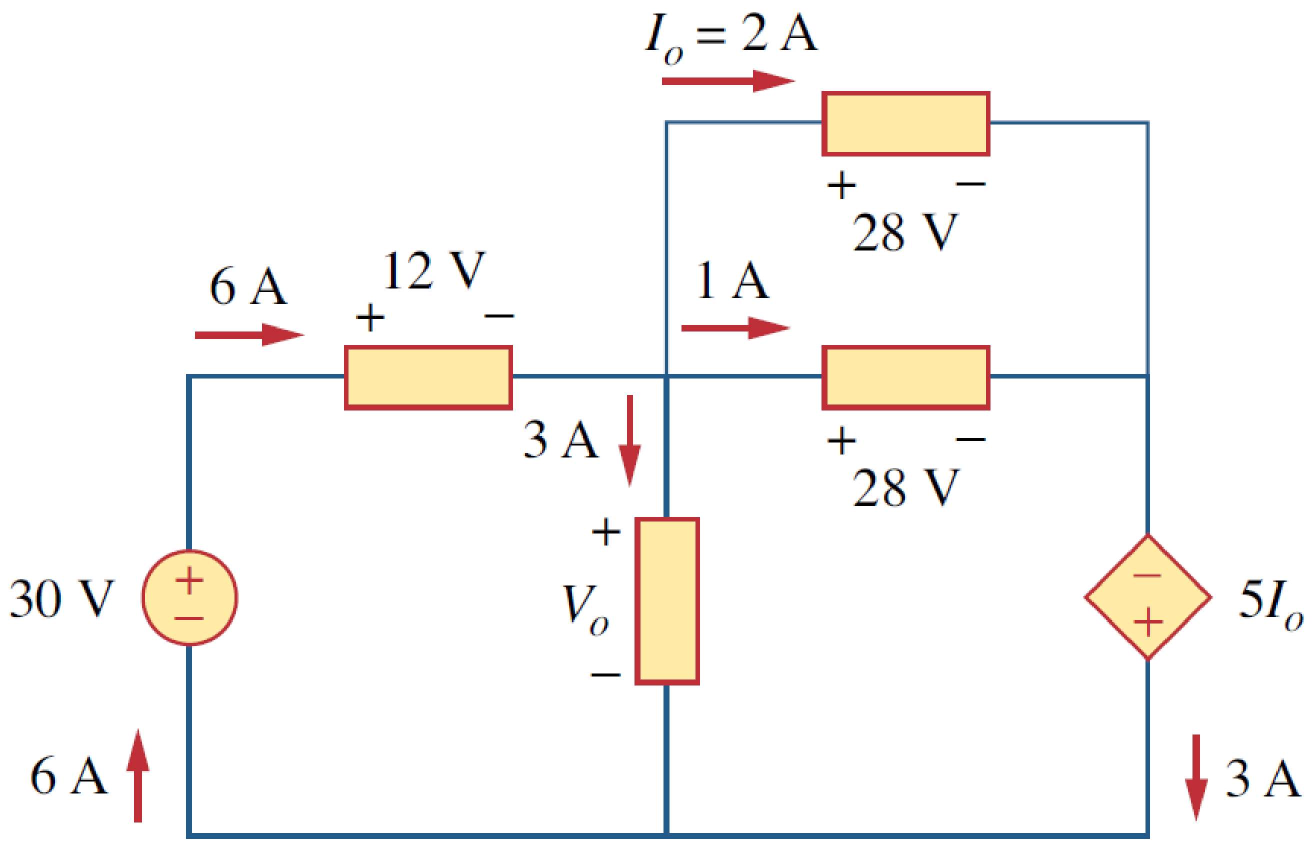
Assignment

1.18 Find the power absorbed by each of the elements in Fig. 1.29.



Assignment

1.20 Find V_o and the power absorbed by each element in the circuit of Fig. 1.31.



Thank You!