EM295

Principles of Electrical and Electronics Engineering

Basic Concepts

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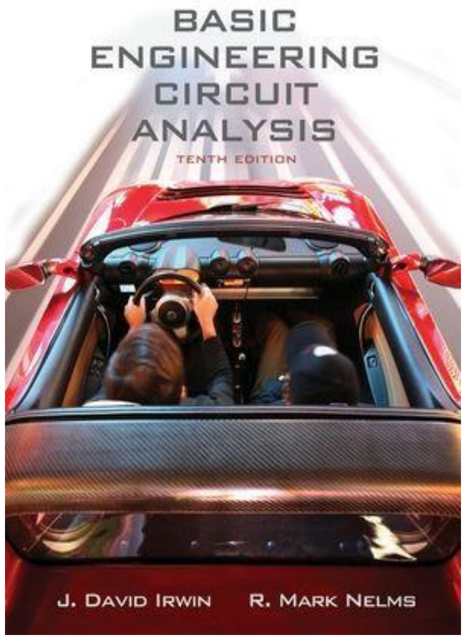
Course Textbooks



1. **Basic Engineering Circuit Analysis**, *J. David Irwin, J. Wiley.*

2. **Principles and Applications of Electrical Engineering**, *G. Rizzoni, Mc Graw Hill.*

3. **Electric Circuits**, *James W. Nilsson and Susan A. Riedel, Prentice Hall.*

4. **Fundamentals of Electric Circuits**, *Charles Alexander and Matthew Sadiku, McGraw Hill.*

Evaluation

	Quantity	Percentage (%)
Miderms	2	60
Quiz	-	-
Homework	-	-
Project	-	-
Term Paper	-	-
Laboratory Study	-	-
Other	-	-
Final Exam	1	40

Note: The semester grade point average will be determined by 60 percent of the midterm average and 40 percent of the final exam.

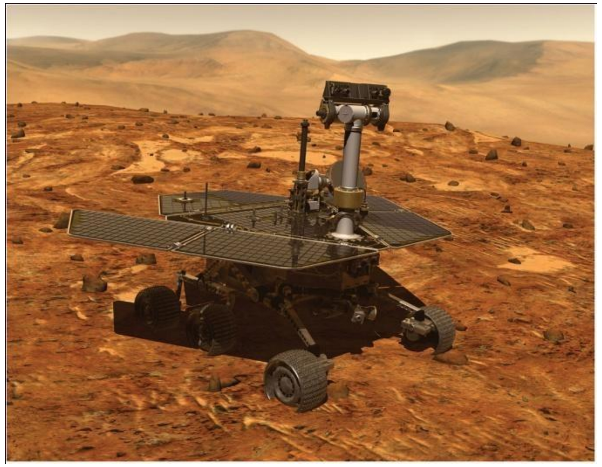
Weekly Schedule

1.	Basic concepts: Electric Charge, Electric Current, Voltage, Power, Energy. Circuit Elements: Active and Passive Circuit Elements.
2.	
3.	DC Circuits: Resistors, Series and Parallel Connections, Ohm’s Law, Loop Equations, Node Voltage Equations, Thevenin’s and Norton’s Theorems, Linearity, Superposition Principles, Source Tranformation.
4.	
5.	
7.	AC Circuits: Alternating Current Concept, Frequency, Phase, Amplitude Concepts, Complex Numbers, Condansators, Inductors, Complex Impedance, AC Circuit Analysis, Input Impedance.
8.	
9.	
10.	Electric Machines: DC and AC Current Motors.
11.	Analog Elektronics: Diods, Transistors, Opamps, Rectifiers, Mixers.
13.	
14.	Digital Elektronik: Boolean arithmetic, Logical circuit elements, Logical Circuit Design.
15.	

Note: Weeks 6 and 12 are estimated midterm weeks.

Motivation

Electrical circuits seem to be everywhere!



What is an Electric Circuit?

- The most elementary concept in electric systems is the electric circuit.

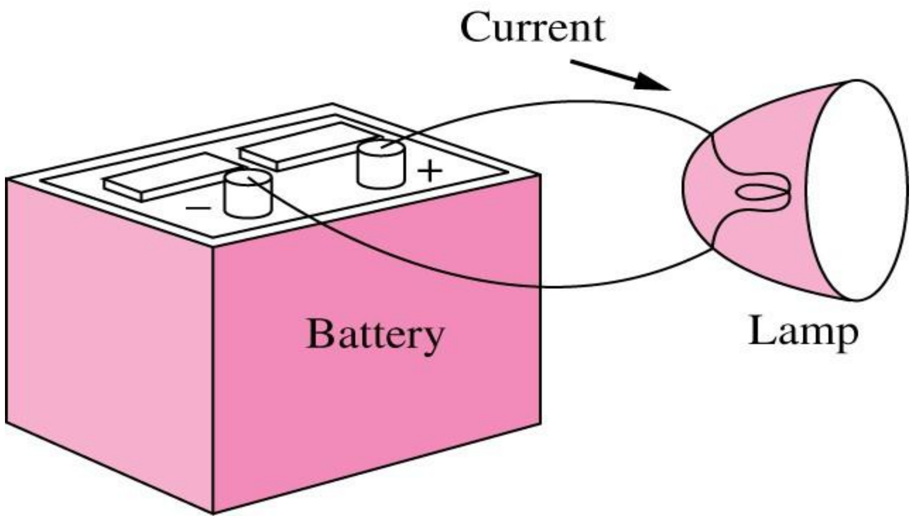
- An electric circuit is a closed current path formed by properly connecting various circuit components.

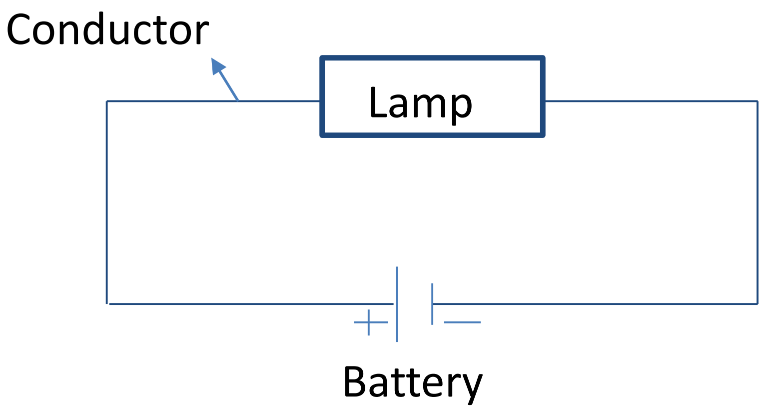
- Typical circuit or electrical components that we will see in this year:

  batteries or voltage sources, current sources, resistors, switches, capacitors, inductors, diodes, transistors, operational amplifiers (Opamps), …

- The purpose of simple or complex electrical circuits is to transfer electrical energy from one point to another.

A Simple Circuit

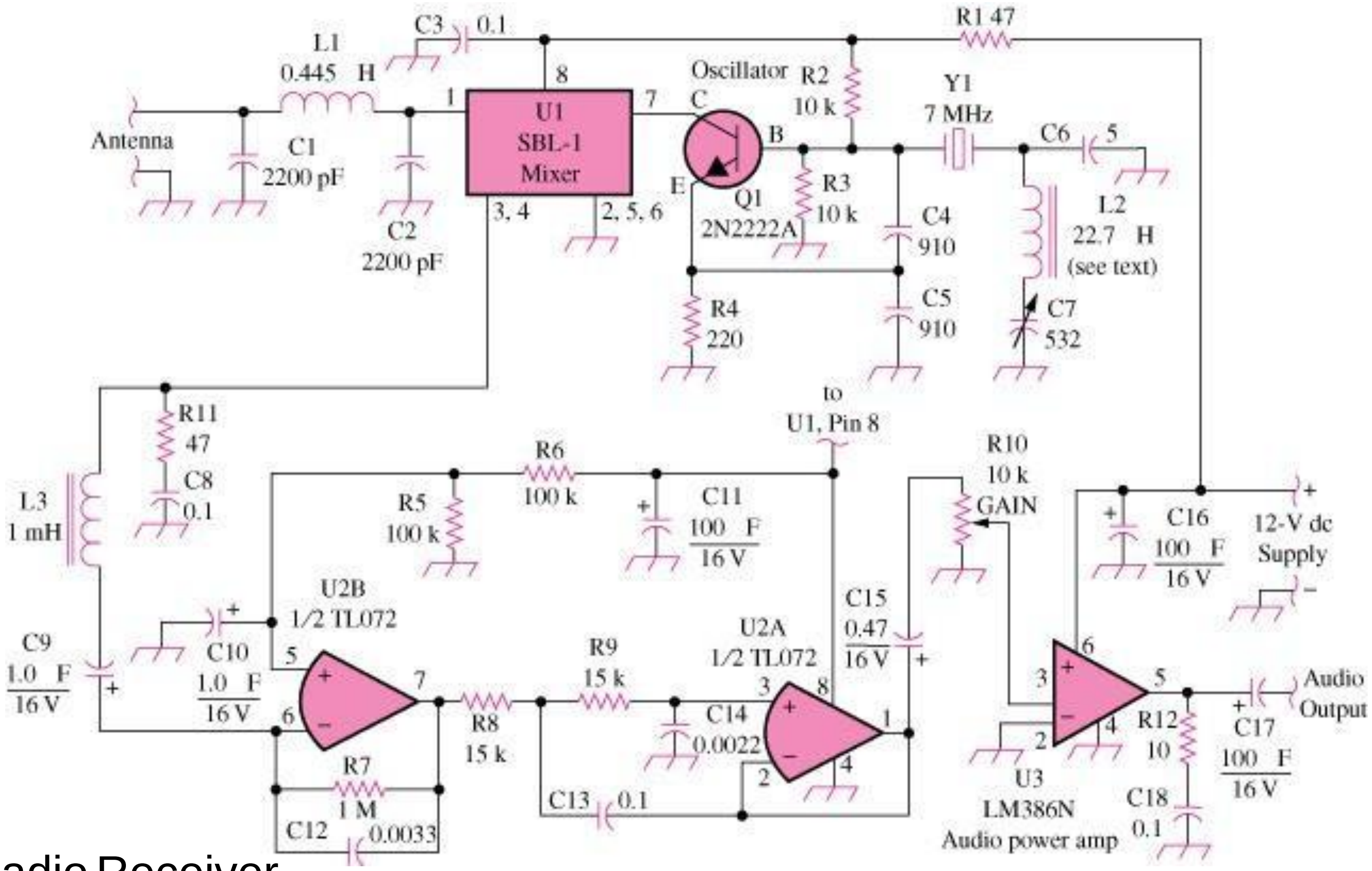




- A simple electrical circuit consists of a battery or a generator, a load and a conductor (conducting wire) as seen in the figures on the left:

1. Battery or Generator is an active circuit element that feed the circuit, that is, produces direct current.
2. Load is a circuit element that consumes the electric energy it receives from source and converts it to another type of energy. For example; a lamp converts the electrical energy it receives from the source into light energy.
3. Conductor (Conducting wire) provides connection between the source and load.
4. Switch is the element that turns the circuit on and off. It doesn't have to be active in the circuit.

A More Complicated Circuit



A Radio Receiver

System of Units

- The International System of Units or SystèmeInternational des Unités (**SI**), also known as **metric** system uses 7 mutually independent base units. All other units are *derived* units.

Base quantity	SI base unit: Name	SI base unit: Symbol
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

SI Base Units

Quantities	Symbol	Units
Electric Charge	Q, q	Coulombs (C)
Electric Current	I, i	Amperes (A)
Voltage	V, v	Volts (V)
Power	P, p	Watts (W)
Energy	W, w	Joules (J)

SI Units for some quantities in electric circuits

Note: In this course, quantities will be denoted in capital letters for DC circuits (time-invariant circuits) and small letters for Ac circuits (time-varying circuits).

SI Prefixes

Factor	Name	Symbol	Factor	Name	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	µ
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a
10^{2}	hecto	h	10^{-21}	zepto	z
10^{1}	deka	da	10^{-24}	yocto	y

SI prefixes used in electric systems are shown in blue.

For example:

I=0,01A=10mA
P=0,00005W=$50 \times 10^{-6}W = 50\mu W$

Review of Basic Circuit Concepts

- Electric Charge is the basis for describing all electrical phenomena. Thus, the most elementary quantity in electric circuits is an electric charge.

- Every matter is made up of atoms. Inside an atom, there is negative charge on electrons, positive charge on protons and no charge on neutrons. Electric charges are carried by electrons and protons. Energy transfer is provided as a result of the movement of electrical charges. Then, electric charge is the electrical property of the atomic particles that matter contains.

- Finally, electric charge definition can be made as fallows:

- **Charge** is an electrical property of the atomic particles of which matter consists and is measured in coulombs (Charles Augustin de Coulomb (1736-1806) a French Scientist)

Charge

- Electron carries - 1.602×10^{-19}
- Proton carries a positive charge of the same size.
- Thus, 1C of charge is carried by $1/ 1.602 \times 10^{-19} = 6.24 \times 10^{18}$ electrons
- Laboratory values of charges are more likely to be a fraction of a Coulumb (e.g., pC, nC, μC, or mC).
- ***Law of conservation of charge*:** charge can neither be created nor destroyed, only transferred. (This is a law in classical physics and may not be true in some odd cases!. We are not dealing with those cases anyway.)

A Material Classification

The materials are classified into 3 according to the ease of movement of the charge.

1. Conductor: a material in which charges can move to neighboring atoms with relative ease.

- One measure of this relative ease of charge movement is the electric resistance of the material
- Example conductor material: metals and carbon
- In metals the only charged particles that can move are electrons

2. Insulator: a material that opposes the charge movement (ideally infinite opposition, i.e., no charge movement)

- Example insulators: Dry air and glass

3. Semi-conductor: a material whose conductive properties are somewhat in between those of conductor and insulator

- Example semi-conductor material: Silicon with some added impurities

Electric Current (Charges in Motion!)

- Electrons that are normally stationary in conductive materials begin to move when a generator is connected to the circuit (generators electrical force to charges). Thus, the charges gain electrical energy and this is transmitted along the conductive wire. As a result, electric current forms as a result of the splashing movement of negative charges (electrons) from atom to atom.

- **Current:** net flow of charge across any cross section of a conductor, measured in Amperes (Andre-Marie Ampere (1775- 1836), a French mathematician and physicist)

- Current can be thought of as the time rate of change of charge. Mathematically, the relationship is expressed as

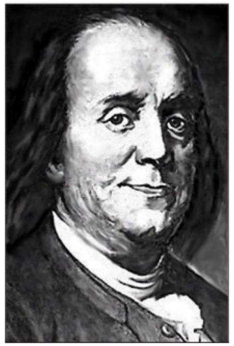
$$i(t) = \frac{dq(t)}{dt} \left(Amperes\ or\ Coulombs/second\ (A\ or\ C/s) \right)$$

- **Note:** 1A means 1C of charge change per second or a charge of 1C per second passes through any point in the circuit.

Electric Current

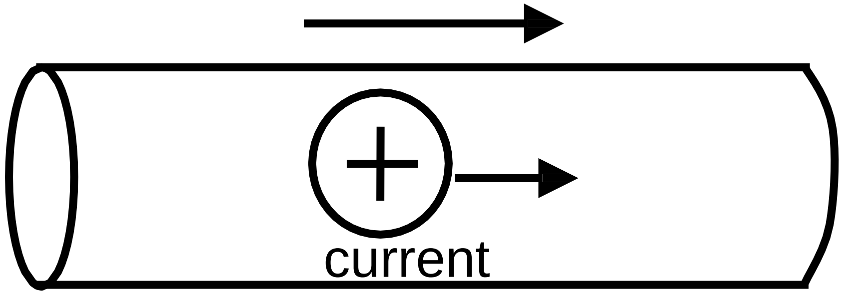
- In this case, the amount of charge passing through a certain time interval $(t_0 - t_1)$ is found as follows:

$$q(t) = \int_{t_0}^{t_1} i(x)\,\mathrm{dx}$$



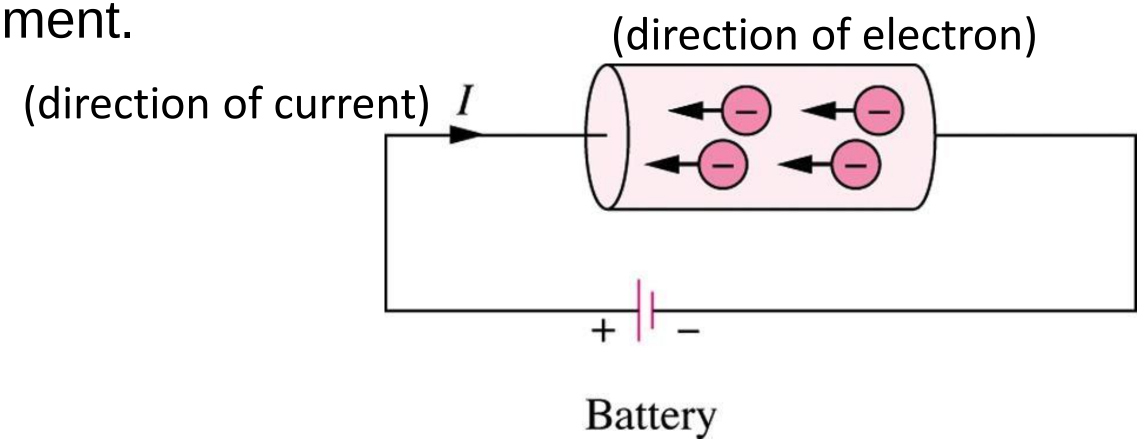
- Originally scientists (in particular Benjamin Franklin (1706-1790) an American scientist and inventor) thought that current is only due to the movement of positive charges.

- Thus the direction of the current was considered the direction of movement of positive charges.

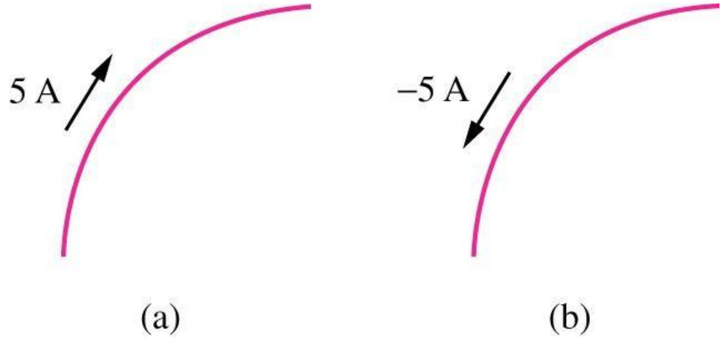


Electric Current

- In reality in metallic conductors current is due to the movement of **electrons**, however, we follow the universally accepted convention that current is in the direction of positive charge movement.



- Two ways of showing the same current:

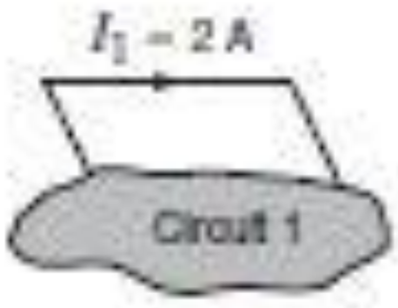


Note1: The direction of electric current is determined by the direction of motion of a positive charge.

Current Flow

Note2: Negative current in one direction is equal to positive current in the opposite direction.

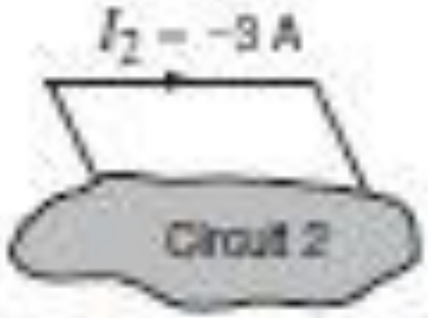
Note3: The current is displayed as positive or negative according to the selected direction.



(a)

(a) It means that a charge of 2C per second pass from left to right from any point on the conducting wire.

(b) It means that a charge of 3C per second pass from right to left from any point on the conducting wire.



(b)

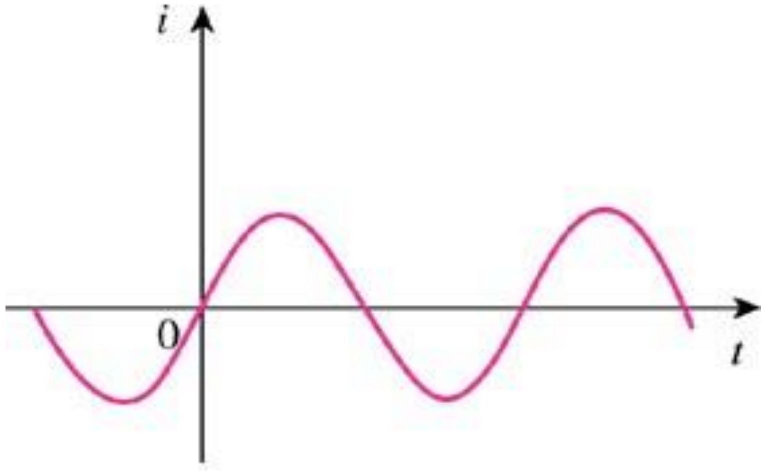
Note4: Therefore, it is not sufficient to simply give the amplitude of the variable representing the current. It is also necessary to indicate the direction of the current.

Two Important Types of Current

- Direct current (DC) is a current that remains constant with time as shown in figure (a) below. DC current sources are batteries and accumulators found in cars, flashlights, computers.

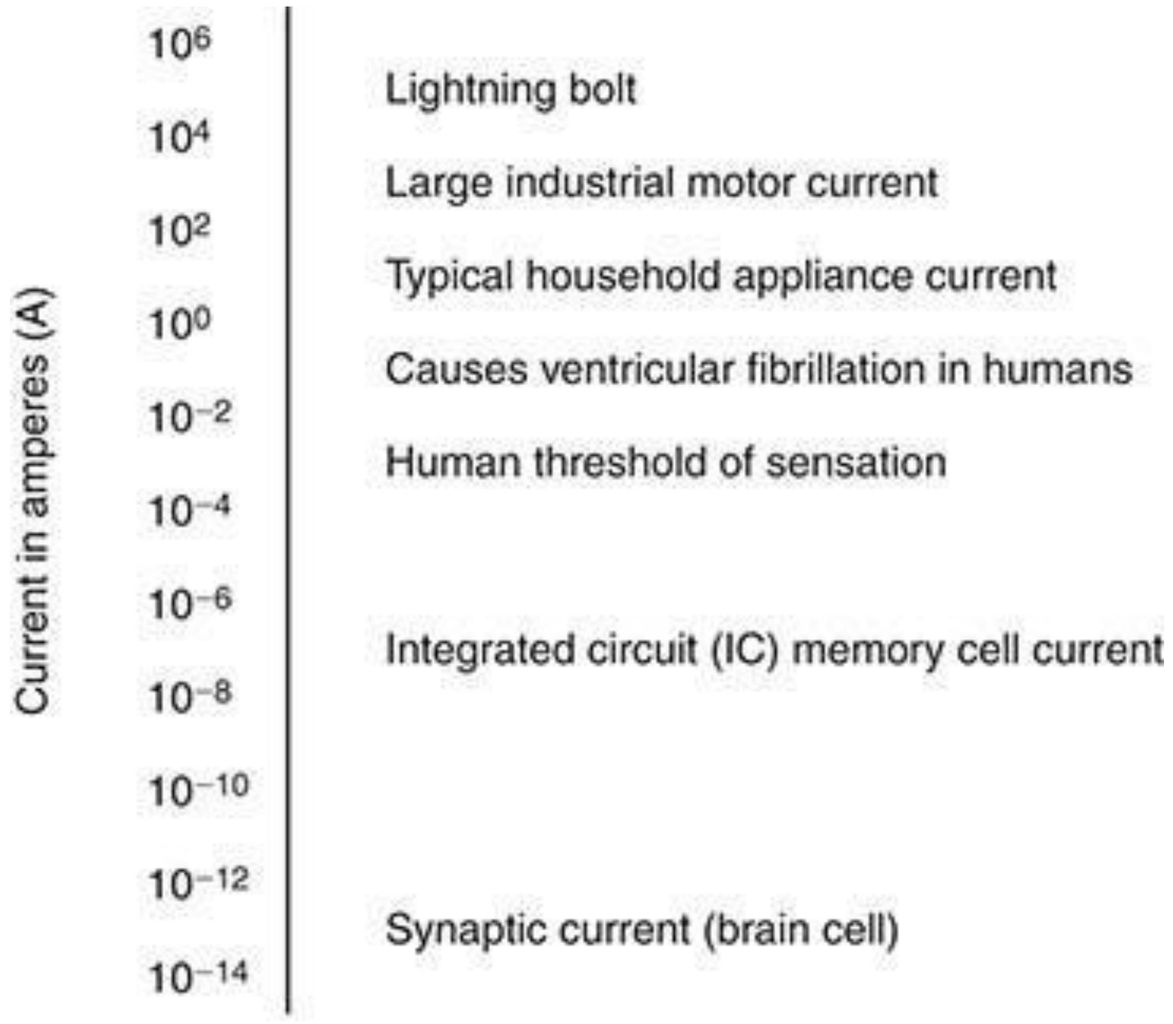
- Alternating current (AC) is a current that varies sinusoidally with time as shown in figure (b) below. It is the type of current used by household items such as refrigerators, washing machines and ovens in every house.

(a)



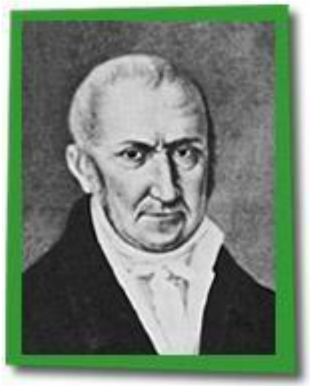
(b)

Magnitude of Some Typical Currents



Voltage (Electrical Potential)

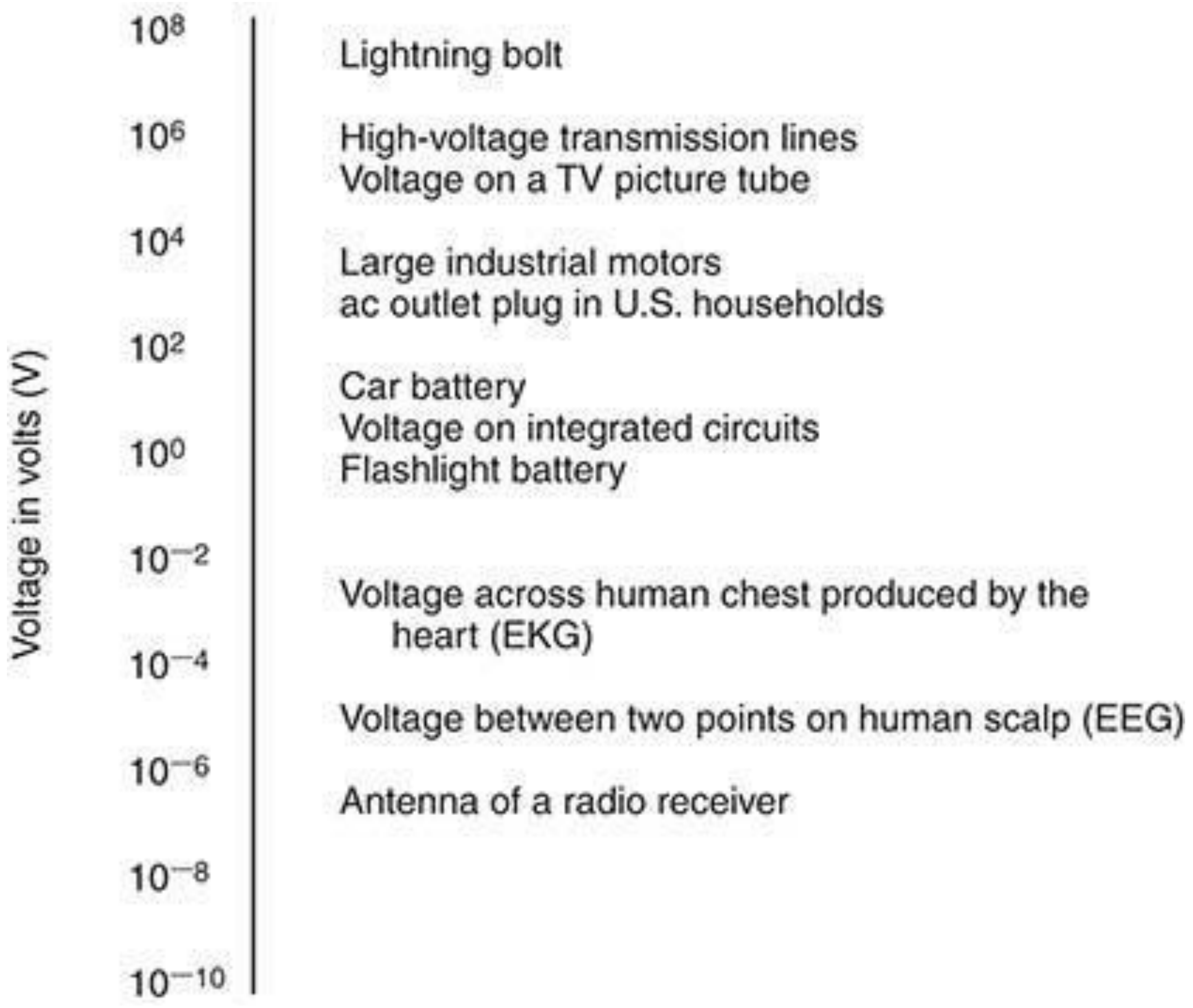
- **Voltage** (electromotive force, or electrical potential) is the energy required to move a unit positive charge through a circuit element or from one point to another of a circuit element, and is measured in Volts (Alessandro Antonio Volta (1745-1827) an Italian Physicist).



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

- Similar to electric current , there are two important voltages: DC and AC.

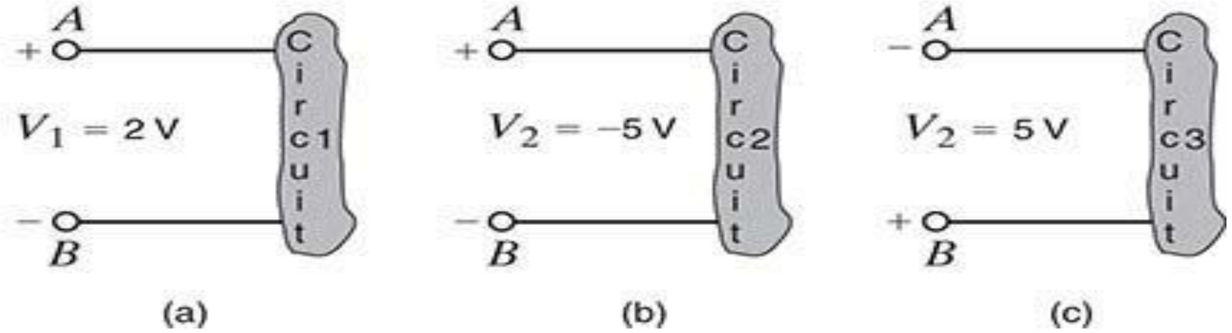
Typical Voltage Magnitudes



Voltage

- "*Voltage* between two points in a circuit is the difference in energy level of a unit charge located at each of the two points.

- Some examples:

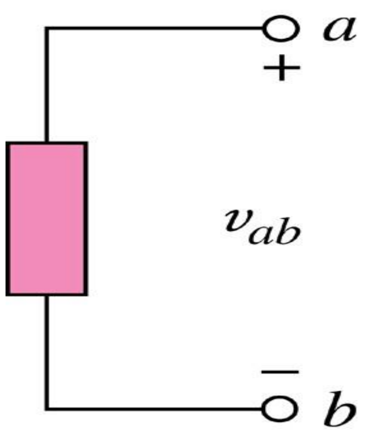


(a) The voltage between points A and B is 2V and point A is positive potential (high energy level) and point B is low potential (low energy level). Voltage drops 2V from A to B or rises 2V from B to A. ($V_1 = V_{AB} = 2V = V_A - V_B$ or $V_{BA} = -2V = V_B - V_A$)
(b) The voltage between points A and B is 5V and point B is positive potential and point A is low potential. Voltage rises 5V from A to B or drops 5V from B to A. ($V_2 = V_{AB} = -5V = V_A - V_B$ or $V_{BA} = 5V = V_B - V_A$)
(c) The voltage between points A and B is 5V and point B is positive potential and point A is low potential. The circuits in (a) and (b) are two different representations of the same voltage.

Voltage Polarity

- The plus (+) and minus (-) sign are used to define voltage polarity.

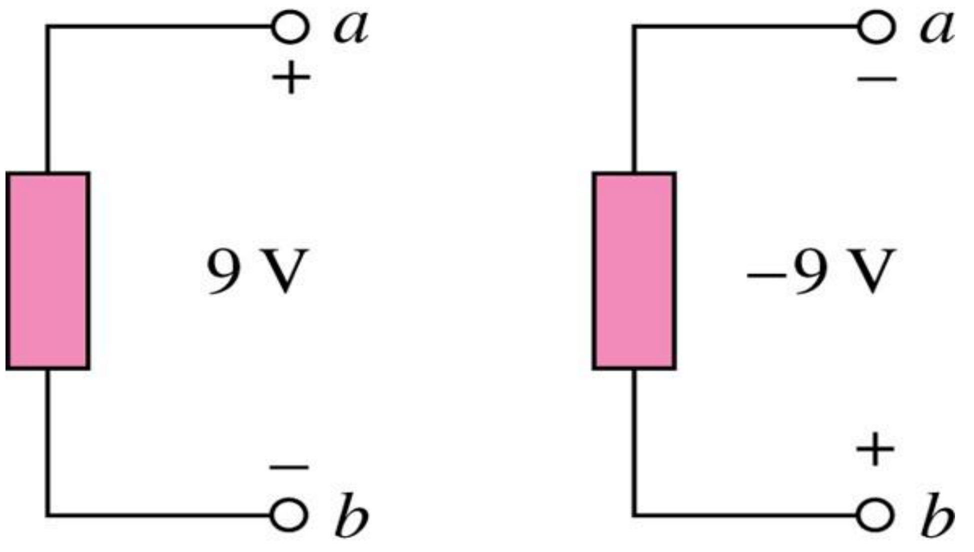
- The assumption is that the potential of the terminal with (+) polarity is higher than the potential of the terminal with (-) polarity by the amount of voltage drop.



Note: It is not possible to know at first in which direction the current or voltage will (+) result. Therefore, random reference directions are determined for current or voltage when performing circuit analysis. After the analysis, if the current or voltage of interest is (+), the chosen reference direction is correct; if the current or voltage is (-), the direction of the current or voltage is actually opposite to the selected reference direction.

Equivalent Circuits

- Figures (a) and (b) are two equivalent representation of the same voltage:

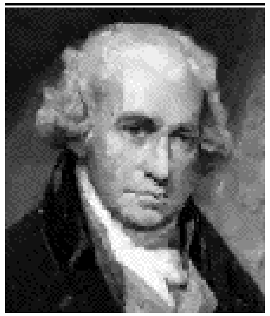


(a) (b)

- Both show that the potential of terminal a is 9V higher than the potential of terminal b.

Power

- The rate of change of (expending or absorbing) energy per unit time, measured in Watts (James Watt (1736-1819) a Scottish inventor and mechanical engineer)



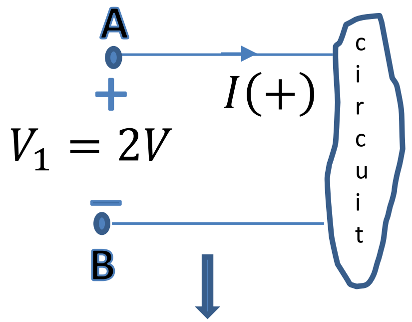
- Mathematically; $$p(t) = \frac{dw(t)}{dt}$$

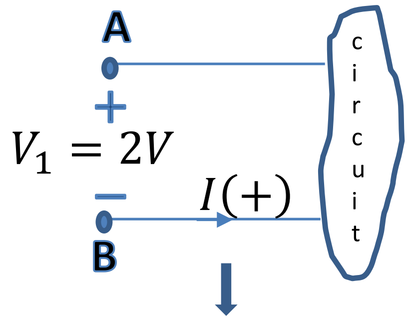
$$p(t) = v(t) \times i(t)$$

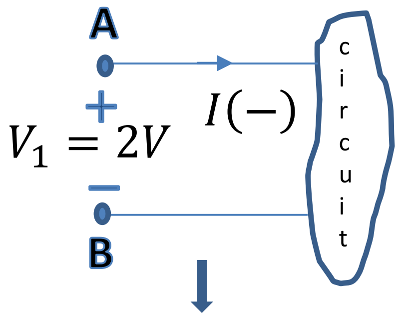
$p(t) = \frac{dw}{\cancel{dq}} . \frac{\cancel{dq}}{dt} = \frac{dw(t)}{dt}$ where $v(t) = \frac{dw}{dq}$ and $i(t) = \frac{dq}{dt}$

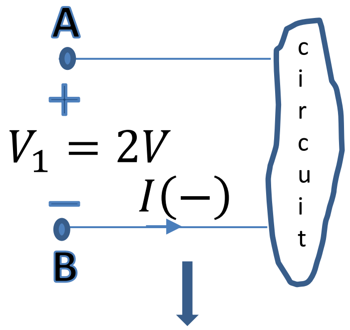
Energy

- The change in energy from time t_0 to time t_1 can be found by interprating above equations:
- $w(t) = \int_{t_0}^{t_1} p(t).dt = \int_{t_0}^{t_1} v(t).i(t).dt$









Voltage between A and B is 2V and A is higher potential point. If a unit positive charge is driven from A to B, this charge supplies energy to the circuit. And when it reaches point B, its energy is 2J less than its initial energy.

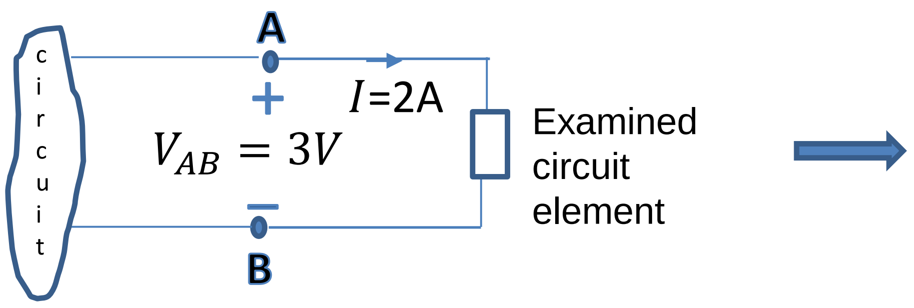
Voltage between A and B is 2V and A is higher potential point. If a unit positive charge is driven from B to A, the circuit supplies energy to this charge . And when it reaches point A, its energy is 2J more than its initial energy.

This is equivalent to driving the positive charge from point B. Because negative current in one direction is equal to positive current in the opposite direction.

This is equivalent to driving the positive charge from point A. Because negative current in one direction is equal to positive current in the opposite direction.

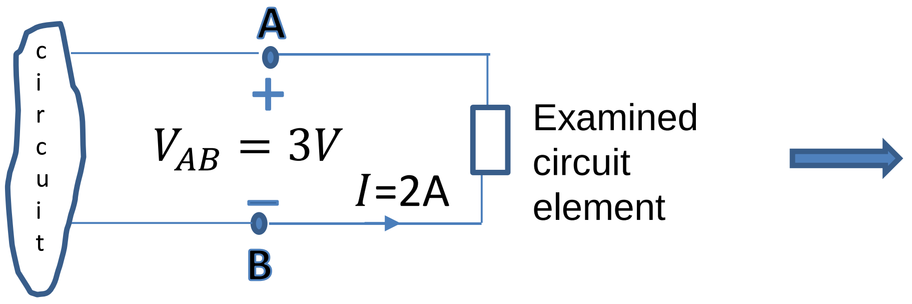
Energy

Example:



The circuit on the left side of the AB terminals supplies the examined circuit element. A charge of 2A, that is, 2C per second, flows through the examined circuit element from A to B. Therefore, the examined circuit element absorbs 6J of energy per second.

Example:



The examined circuit element supplies the circuit on the left side of the AB terminals . A charge of 2A, that is, 2C per second, flows through the examined circuit element from B to A. Therefore, supplies the circuit on the left side of the AB terminals absorbs 6J of energy per second.

Note1: Negative current in one direction is equal to positive current in the opposite direction.
Note2: Negative voltage in one direction is equal to positive voltage in the opposite direction.

A Classification of Circuit Components

- One common classification for circuit components is to group them in two major groups:

1) Passive components or passive elements

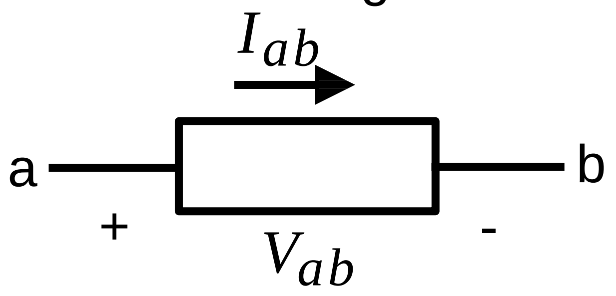
   Components or elements that absorb power.

2) Active components or active elements

   Components that are not passive! that is, components that deliver power.

Passive Sign Convention

- For calculating absorbed power: The power absorbed by any circuit element with terminals A and B is equal to the voltage drop from A to B multiplied by the current through the element from A to B, i.e., $P = V_{ab} \times I_{ab}$



- With this convention if $P \geq 0$, then the element is absorbing (consuming) power. Otherwise (i.e., $P < 0$) is absorbing negative power or actually generating (delivering, supplying) power.

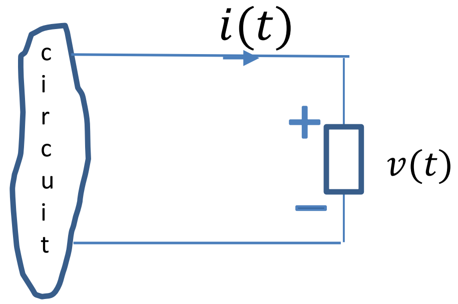
- For example;

- P=20W↔ 20W absorbing power (or -20W supplying power)

- P=-20W↔ 20W supplying power (or -20W absorbing power)

Passive Sign Convention

- According to passive sign convention; the variable for voltage $v(t)$ is defined as the voltage across the element with the positive reference at the same terminal that the current variable $i(t)$ is entering as shown in figure below.



- Next, the sign of the current entering from the positive terminal is determined.

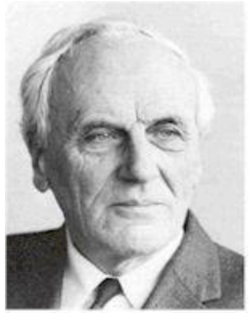
- The product of $v(t)$ and $i(t)$, with their attendent signs, will determine the magnitude and sign of the power.

- If the sign of the power is positive (that is, current is positive), power is being absorbed by the element, if the sign is negative (that is, current is negative), power ia being supplied by the element.

Tellegan's Theorem

- **Principle of Conservation of the Power:** The algebraic sum of the powers absorbed by all elements in a circuit is zero at any instance of time **(ΣP=0)**. That is, the sum of absorbed powers is equal to the sum of generated powers at each instance of time.

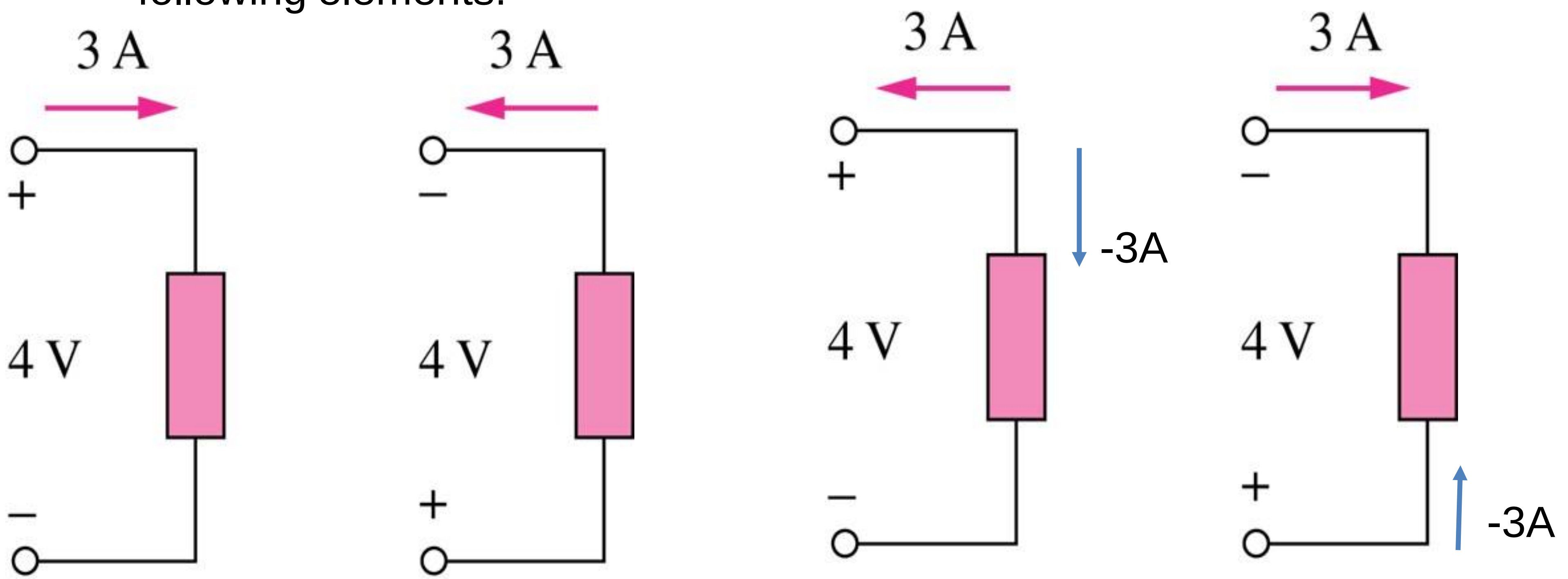
- This principle is also known as Tellegan's theorem. (Bernard D.H. Tellegan (1900-1990), a Dutch electrical engineer)



- Similarly, one can write the principle of conservation of energy.

Passive Sign Convention

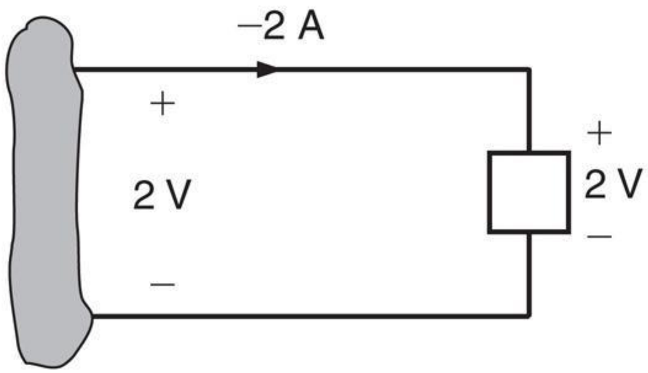
- Calculate the power absorbed or supplied by each of the following elements:

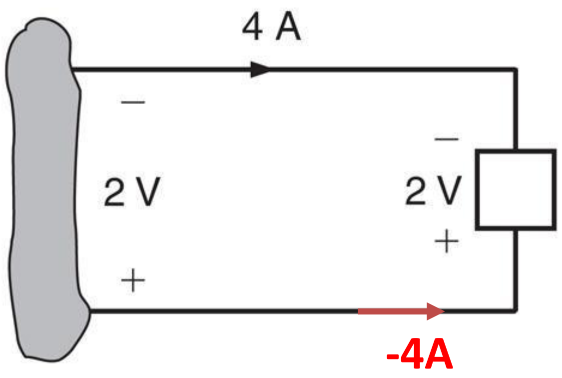


12W absorbed power or -12W supplied power	12W absorbed power or -12W supplied power	-12W supplied power or 12W absorbed power	-12W supplied power or 12W absorbed power

Example

- Given the two diagrams shown below, determine whether the element is absorbing or supplying power and how much.



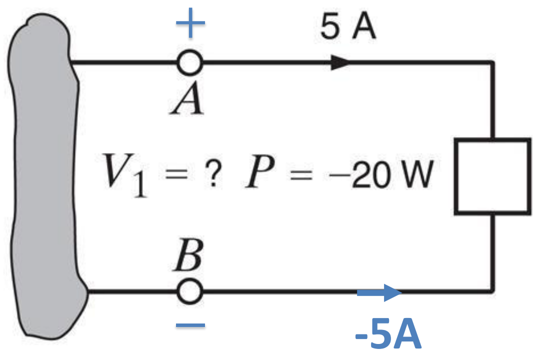


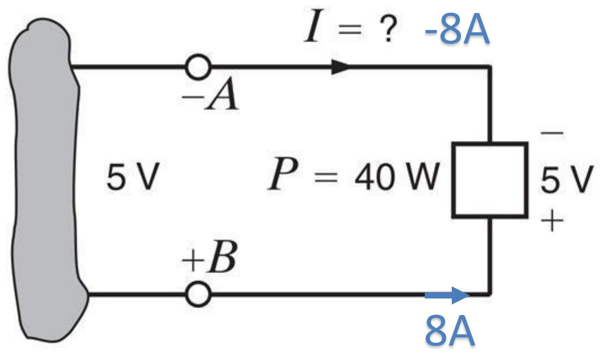
The power is P=2V.(-2A)=-4W
4W supplying power
-4W absorbing power

The power is P=2V.(-4A)=-8W
8W supplying power
-8W absorbing power

Example

- Determine the unknown voltage or current in the following figures:





P=-20W ↔ The (-) sign indicates that the power is supplied by the circuit element. Therefore, negative current flows from the (+) potential terminal. Since the current flowing through A is positive, negative current flows through B. In this case, (+) voltage point is B. From P=V.I, the voltage is 4V, B is positive terminal and A is negative terminal.

P=40W ↔ The (+) sign indicates that the power is absorbed by the circuit element. Therefore, positive current flows from the (+) potential terminal. Since the positive voltage terminal is B, the current flowing through B must be positive. From P=V.I, the current is 8A, positive current flows from B to A. Thus, the current flows from A to B is negative.

Circuit Elements

- Circuit components can be broadly classified as being either **active** or **passive**.

- An active element is capable of generating energy.
  - Example: current or voltage sources

- A passive element is an element that does not generate energy, however, they can either consume or store energy.
  - Example: resistors, capacitors, and inductors

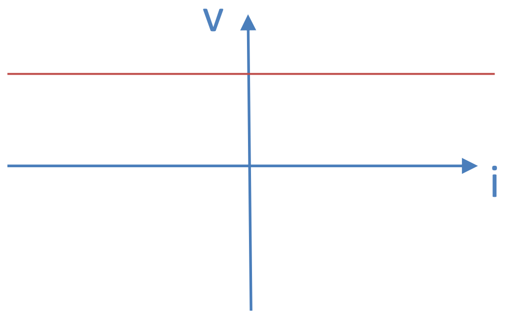
Circuit Elements

- **Some very important active elements:**

- Independent voltage source
- Independent current source
- Two dependent voltage sources
- Two dependent current sources

Note: In this course we will consider all sources as ideal.

- **Independent voltage source:** is a two terminal element that maintains a specified voltage between its terminals regardless of the current through it and other circuit elements in the circuit. This is indicated by the v-i characteristic.



v-i characteristic for independent voltage source

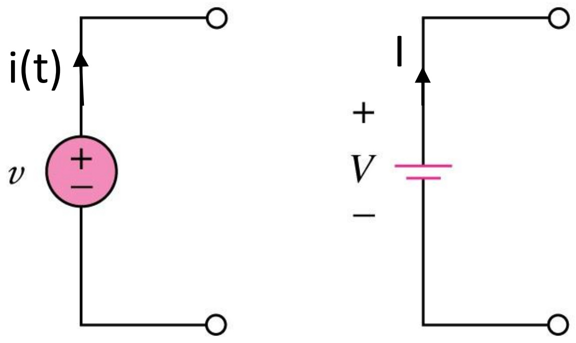
Circuit Elements

- **Note:** İdeal independent voltage sources can supply or absorb any current.

- Symbol for independent voltage source

  (a) Used for constant (dc) or time-varying voltage (ac)

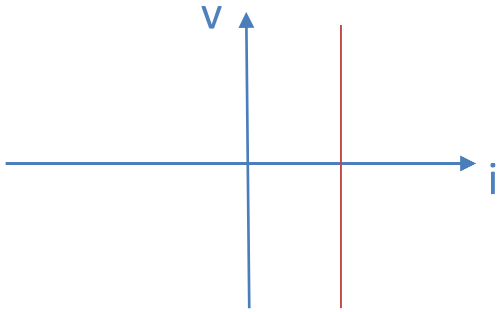
  (b) Used for constant voltage (dc)



(a) (b)

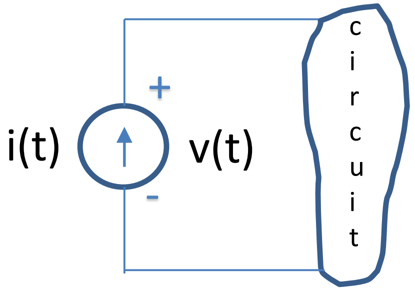
Circuit Elements

Independent current source: is a two terminal element that maintains a specified current regardless of the voltage across its terminals and other circuit elements in the circuit. This is indicated by the v-i characteristic.



v-i characteristic for independent current source

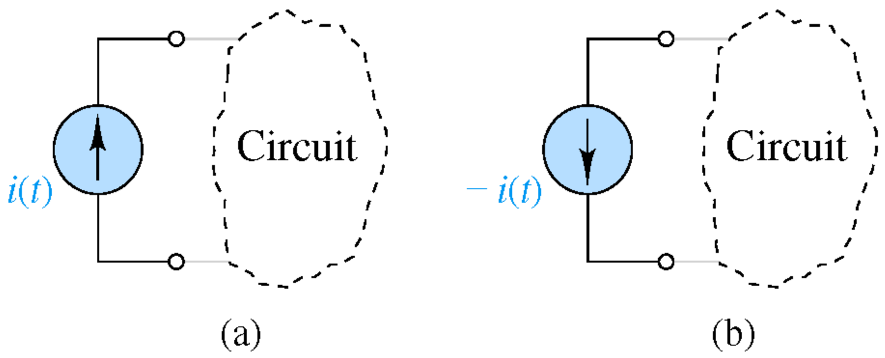
- Symbol for independent voltage source



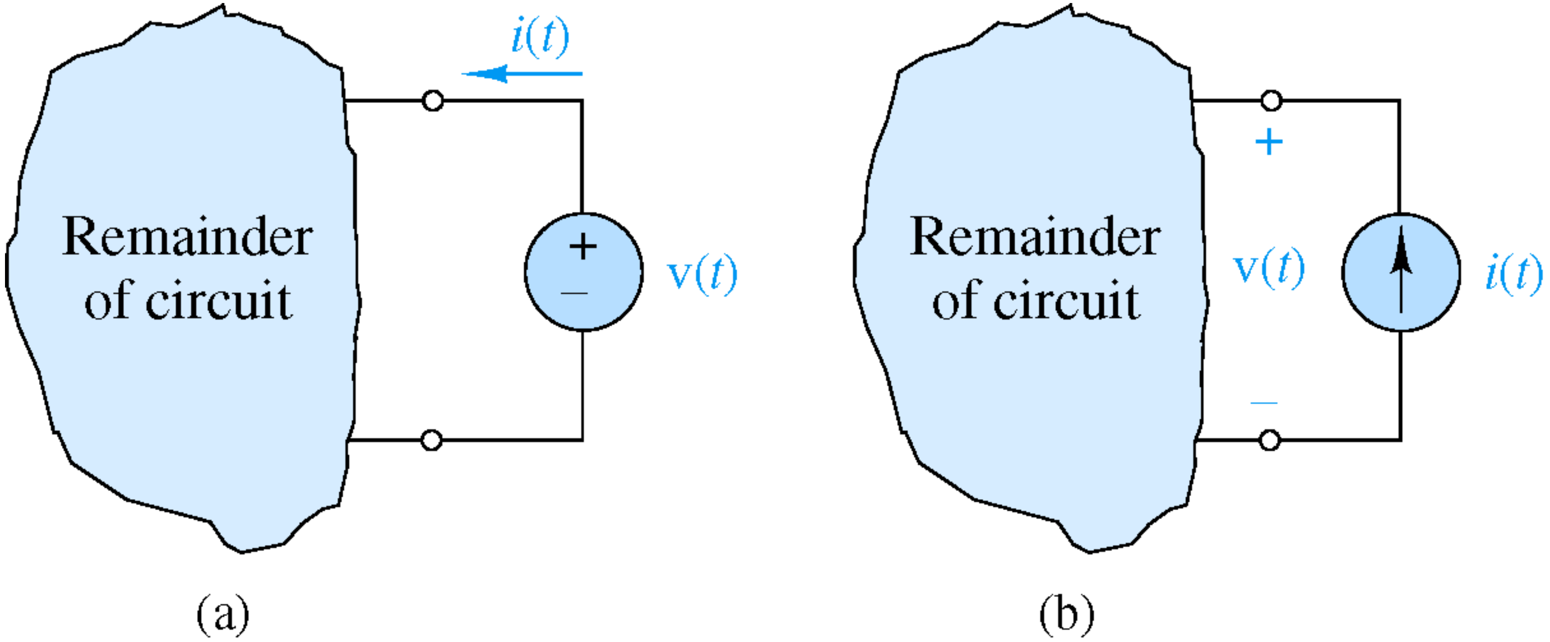
Note: All circuit elements (passive and active) are characterized by the voltage between the terminals and the current flowing through them.

Circuit Elements

- **Note:** Equivalent representation of ideal independent current sources whose current *i(t)* is maintained under all voltage requirements of the attached circuit:



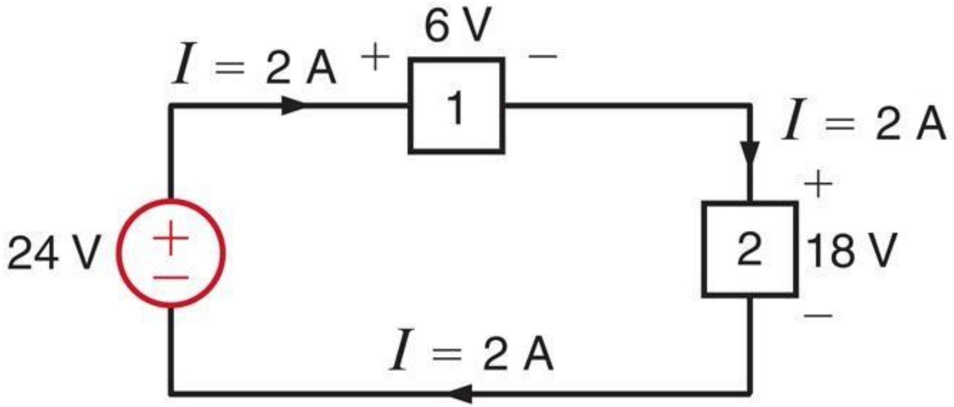
Common Voltage and Current Source Labeling



- **Note:** Passive sign convention also applies to voltage and current sources.

Example

- Determine the power absorbed or supplied by the elements of the following network:



Note: As can be seen from the result, the sum of the absorbed powers is equal to the sum of the supplied powers.

+2A current enters from the (+) terminal of the elements 1 and 2. Therefore, the elements absorb 12W and 36W respectively.

$$P_1 = 6V.(2A) = 12W$$
$$P_2 = 18V.(2A) = 36W$$

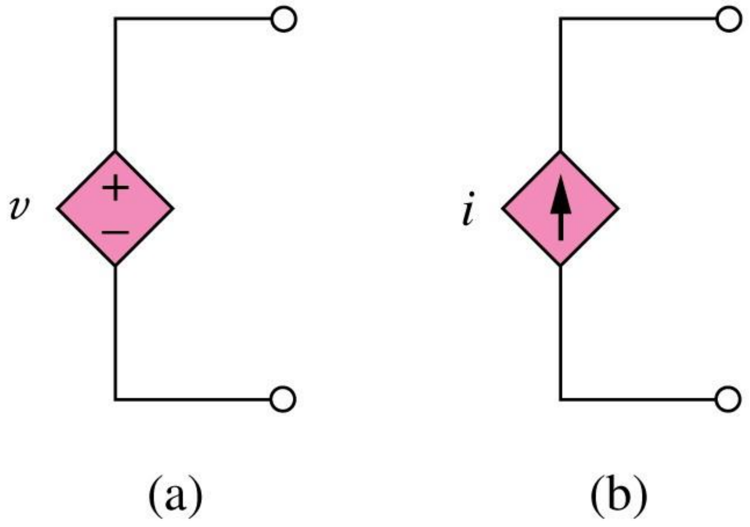
-2A current enters from the (+) terminal of independent voltage source. Therefore, this voltage source supplies 48W. (48W supplied power or -48W absorbed power)

$$P_{24V} = 24V.(-2A) = -48W$$

Dependent (Controlled) Sources

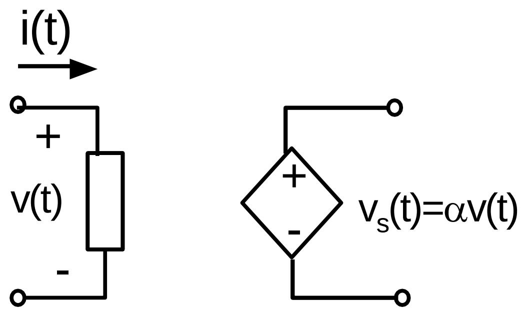
- An ideal dependent (controlled) source is an active element whose quantity is controlled by a voltage or current of another circuit element.

- Dependent sources are usually presented by diamond-shaped symbols:



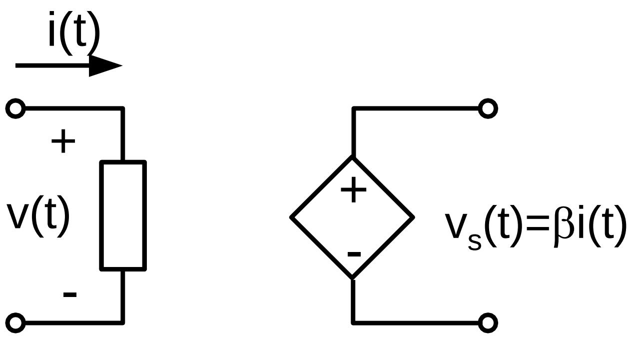
Dependent (Controlled) Source

- There are four types of dependent sources: : two dependent voltage sources and two dependent current sources
- Voltage-controlled voltage source (VCVS)



If the voltage of the dependent voltage source is controlled by the voltage of any element in the circuit, this source is a voltage controlled voltage source.

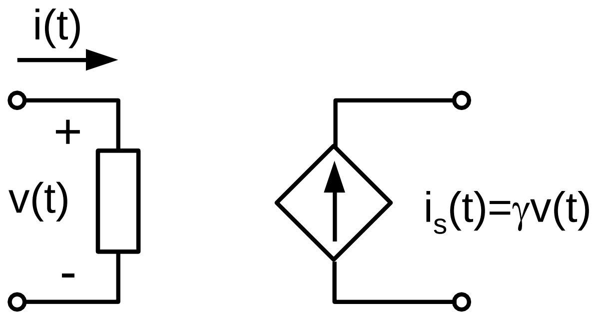
- Current-controlled voltage source (CCVS)



If the voltage of the dependent voltage source is controlled by the current flowing through any element in the circuit, this source is a current controlled voltage source.

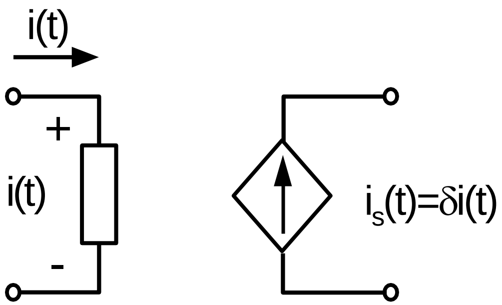
Dependent (Controlled) Sources

- Voltage-controlled current source (VCCS)



If the current of the dependent current source is controlled by the voltage of any element in the circuit, this source is a voltage controlled current source.

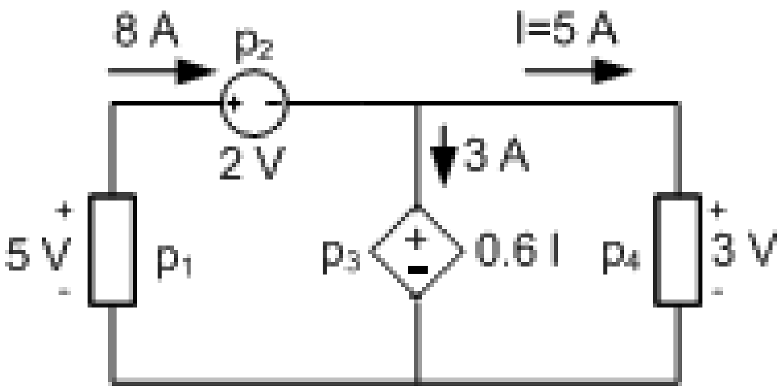
- Current-controlled current source (CCCS)



If the current of the dependent current source is controlled by the current flowing through any element in the circuit, this source is a current controlled current source.

Example: Power Calculation

- Compute the power absorbed or supplied by each component in the following circuit.



$P_1 = 5V.(-8A) = -40W \rightarrow 40W\ supplied\ power$

$P_2 = 2V.(8A) = 16W \rightarrow 16W\ absorbed\ power$

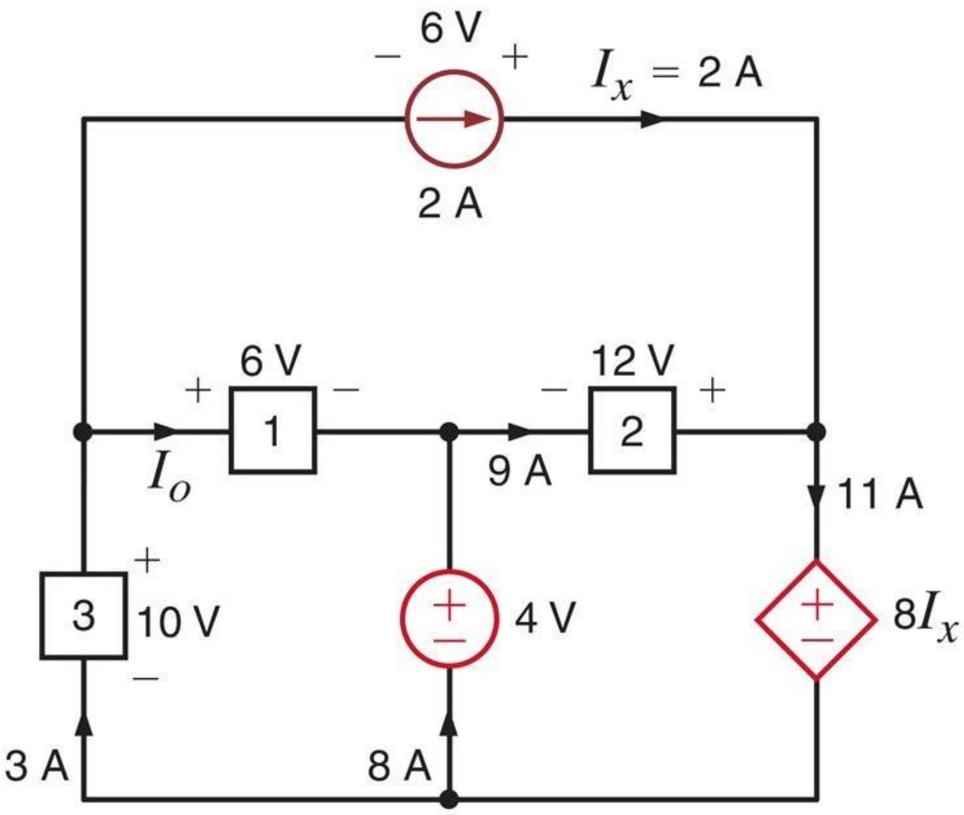
$P_3 = 3V.(3A) = 9W$ where $V_{p3} = 0.6 * I = 0.6 * 5 = 3V$ ($p_3 \rightarrow$ Current controlled voltage source) $\rightarrow$ $9W\ absorbed\ power$

$P_4 = 3V.(5A) = 15W \rightarrow 15W\ absorbed\ power$

Note: The sum of absorbed powers is equal to the sum of supplied powers.

Example

- Use Tellegan's theorem to find the current I_0 in the following circuit:



$$P_1 = 6V.(I_0) = 6I_0W$$
$$P_2 = 12V.(-9A) = -108W$$
$$P_3 = 10V.(-3A) = -30W$$

$P_{4V} = 4V.(-8A) = -32W$ *(independent voltage source)*
$P_{2A} = 6V.(-2A) = -12W$ *(independent current source)*
$P_{8I_x} = 16V.(11) = 176W$ where $V_{8I_x} = 8 * I_x = 8 * 2 = 16V$
(Current controlled voltage source)

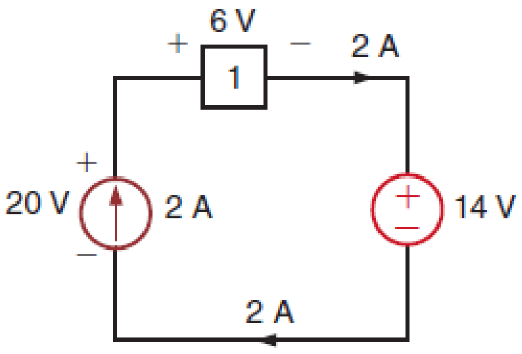
According to Tellegan's theorem: The algebraic sum of the powers absorbed by all elements in a circuit is zero:

$$6I_0 - 108 - 30 - 32 - 12 + 176 = 0 \leftrightarrow 6I_0 = 6$$

$$I_0 = 1A$$

Example

- Find the power that is absorbed or supplied by the circuit elements below.

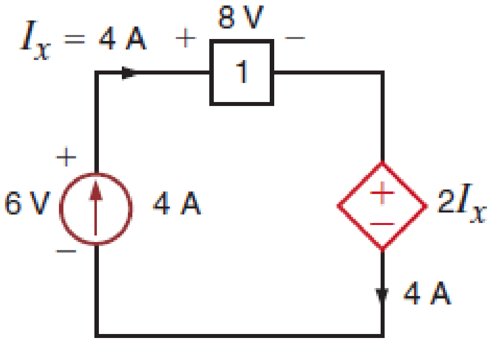


(a)

$$P_1 = 6V.(2A) = 12W$$

$P_{14V} = 14V.(2A) = 28W$ (independent voltage source with 14V)

$P_{2A} = 20V.(-2A) = -40W$ (independent current source with 2A)



(b)

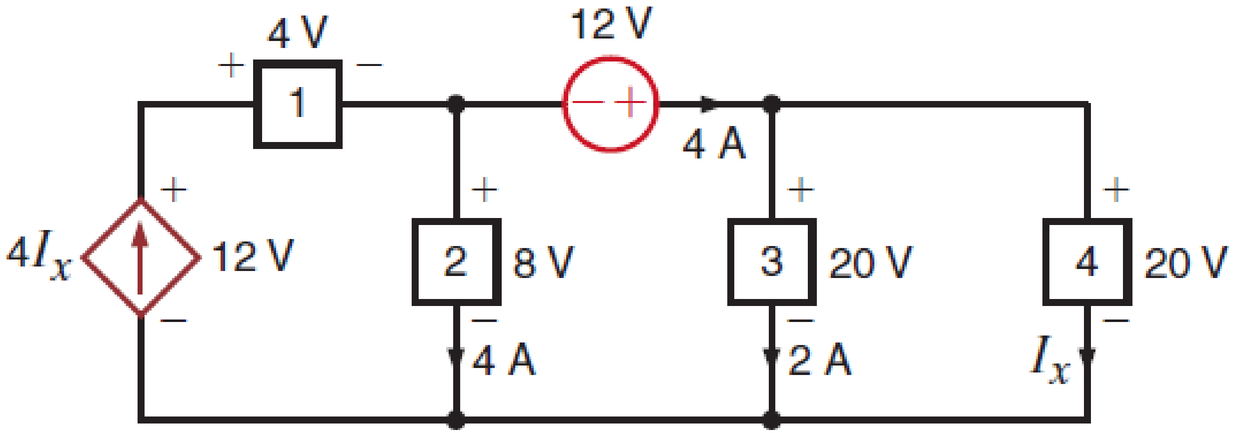
$$P_1 = 8V.(4A) = 32W$$

$P_{2I_x} = 8V.(4A) = 32W$ (Current controlled voltage source with 2 I_x V)
where $V_{I_x} = 2 * I_x = 2 * 4 = 8V$

$P_{4A} = 16V.(-4A) = -64W$ (independent current source with 4A)

Example

- Find the power absorbed or supplied by each element.



$$P_1 = 16I_x = 32W\ (absorbed\ power)$$

$$P_4 = 20I_x = 40W\ (absorbed\ power)$$

$$P_{4I_x} = -48I_x = -96W\ (96W\ supplied\ power)$$

$$P_1 = 4V.(4I_x) = 16I_xW$$
$$P_2 = 8V.(4A) = 32\ W$$
$$P_3 = 20V.(2A) = 40\ W$$
$$P_4 = 20V.(I_x) = 20I_x\ W$$

$P_{12V} = 12V.(-4A) = -48W$ *(independent voltage source)*
$P_{4I_x} = 12V.(-4I_x) = -48I_x\ W$ where $I_{4I_x} = 4 * I_x\ A$ (Current controlled current source)

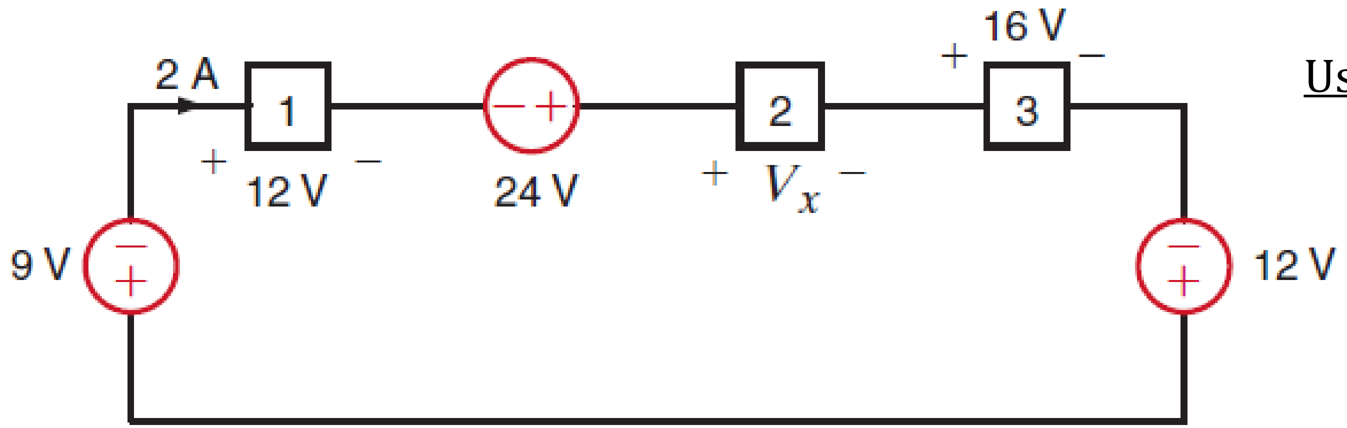
According to Tellegan's theorem: The algebraic sum of the powers absorbed by all elements in a circuit is zero:

$$16I_x + 32 + 40 + 20I_x - 48 - 48I_x = 0 \leftrightarrow -12I_x = -24$$

$$I_x = 2A$$

Example

- Use Tellegan's theorem to find the current V_x in the following circuit:



<u>Using Tellegan's Theorem;</u>

$$24 + 2V_x + 32 + 18 - 48 - 24 = 0$$

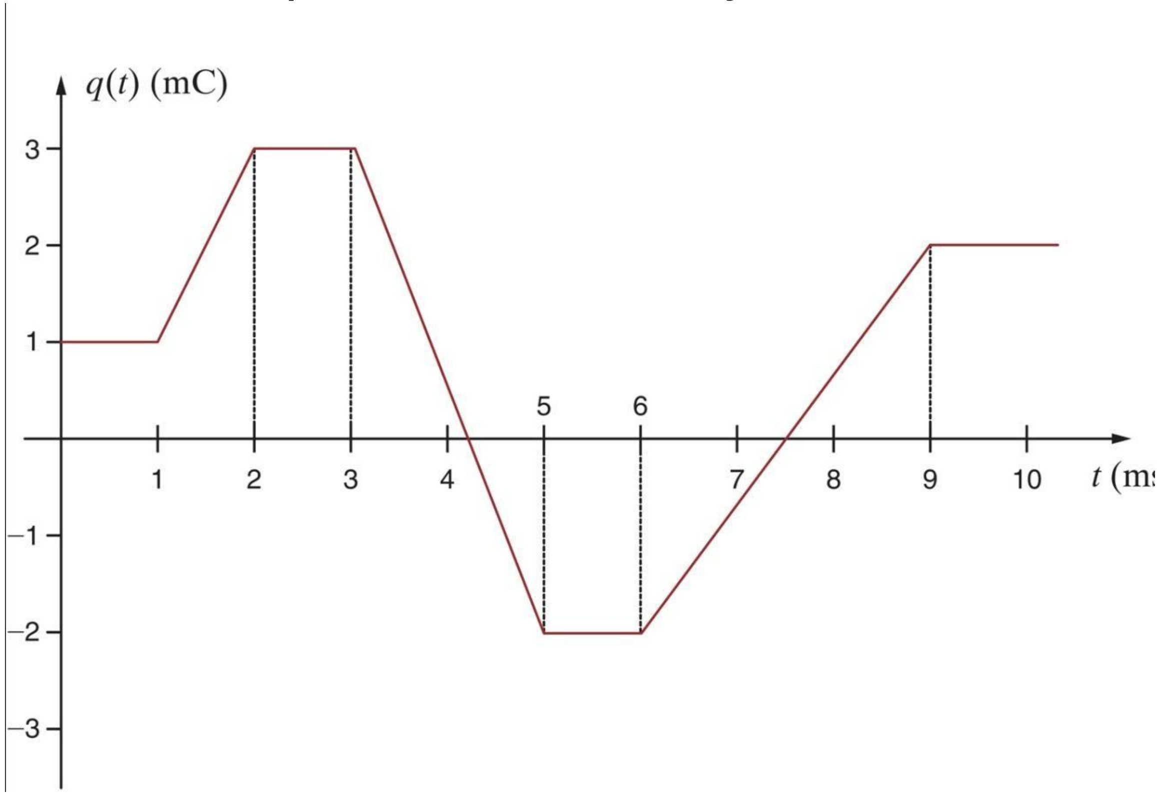
$$2V_x = -2 \leftrightarrow V_x = -1V$$

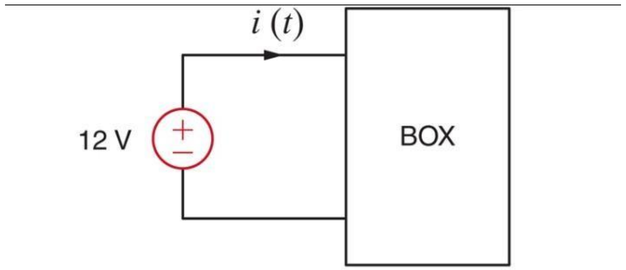
$$P_1 = 12V.(2A) = 24W$$
$$P_2 = V_x.(2A) = 2V_x\ W$$
$$P_3 = 16V.(2A) = 32W$$

$P_{9V} = 9V.(2A) = 18W$ (independent voltage source with 9 V)
$P_{24V} = 24V.(-2A) = -48W$ (independent voltage source with 24 V)
$P_{12V} = 12V.(-2A) = -24W$ (independent voltage source with 12 V)

Example

- The charge that enters the BOX is shown below. Calculate and sketch the current flowing into the BOX and the power absorbed by the BOX between 0 and 10 milliseconds.





Example

- As stated earlier, current is defined as the rate of change of charge: $i(t) = \frac{dq(t)}{dt}$
- So, the current values can be found by calculating the slopes of the load variation graph:
- When the current is constant: $I = \frac{\Delta q}{\Delta t}$
- $i(t) = 0; 0 \leq t \leq 1ms \leftrightarrow p(t) = 0W$
- $i(t) = \frac{3\times10^{-3} - 1\times10^{-3}}{2\times10^{-3} - 1\times10^{-3}} = 2A\ ; 1 \leq t \leq 2ms \leftrightarrow p(t) = v(t) * i(t) = 12V * (2A) = 24W$
- $i(t) = 0; 2 \leq t \leq 3ms \leftrightarrow p(t) = 0W$
- $i(t) = \frac{-2\times10^{-3} - 3\times10^{-3}}{5\times10^{-3} - 3\times10^{-3}} = -2.5A\ ; 3 \leq t \leq 5ms \leftrightarrow p(t) = v(t) * i(t) = 12V * (-2.5A) = -30W$
- $i(t) = 0; 5 \leq t \leq 6ms \leftrightarrow p(t) = 0$
- $i(t) = \frac{2\times10^{-3} - (-2\times10^{-3})}{9\times10^{-3} - 6\times10^{-3}} = \frac{4}{3}A\ ; 6 \leq t \leq 9ms \leftrightarrow p(t) = v(t) * i(t) = 12V * \left(\frac{4}{3}A\right) = 16W$
- $i(t) = 0; t \geq 9ms \leftrightarrow p(t) = 0W$

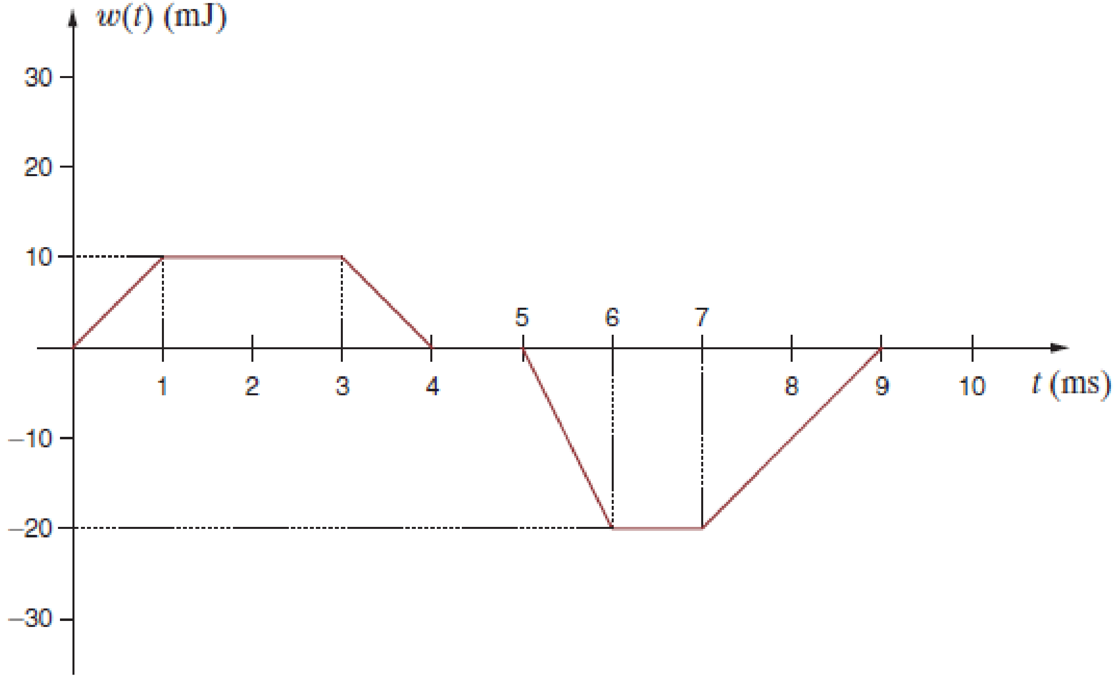
Example

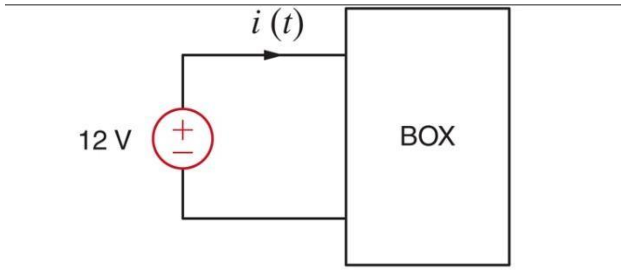
- **Note1:** As you can see; the current is zero during the time intervals when the load is constant. The current is positive when the load is increasing and negative when the load is decreasing.

- **Note2:** At $1 \leq t \leq 2ms$ and $6 \leq t \leq 9ms$ time intervals, the box absorbs power. At $3 \leq t \leq 5ms$ time interval, the box supplies power.

Example

The energy absorbed by the BOX in Fig. P1.19 is shown in the graph below. Calculate and sketch the current flowing into the BOX between 0 and 10 milliseconds.





Notes