EE Lecture 1: Circuits-1

MS 101 Makerspace

2024-25/II (Spring)

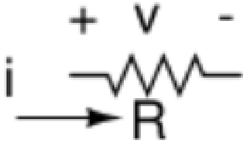
Circuits -1

- Passive electrical devices: R, L, C, Transformer and RC filters
- Independent and dependent sources
- Kirchhoff's current and voltage laws
- Superposition method

R (Resistor), L (Inductor), C(Capacitor)

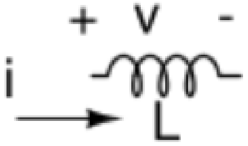
Two-terminal (single-port) devices described by their V-I characteristics

Resistor



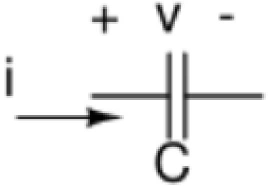
$$i = \frac{v}{R}$$

Inductor



$$i = \frac{1}{L}\int v\,dt$$

Capacitor



$$i = C\frac{dv}{dt}$$

Let $v = V_m \cos(\omega t+\theta)$, where $\omega = 2\pi f$ is the angular frequency in rad/s, f is the frequency in Hz, and θ is an arbitrary phase angle.

- **For a resistor**, $i = v/R$

  $= [V_m \cos(\omega t+\theta)]/R = (V_m/R) \cos(\omega t+\theta)$

  Hence in a resistor, i and v are in phase.
- **For an inductor**, $i = (1/L) \int v\, dt$

  $= [V_m \sin(\omega t+\theta)]/(\omega L) = [V_m/(\omega L)] \cos(\omega t+\theta-90°)$

  Hence in an inductor, i lags v by 90°.
- **For a capacitor**, $i = C\, dv/dt$

  $= -\omega C\, V_m \sin(\omega t+\theta) = \omega C\, V_m \cos(\omega t+\theta +90°)$

  Hence in a capacitor, i leads v by 90°.

- Voltage-current ratio for the above cases of R, L and C is called their **impedance.**
- Impedance of R is independent of f, but those of L and C depend on f.

A1. Resistors

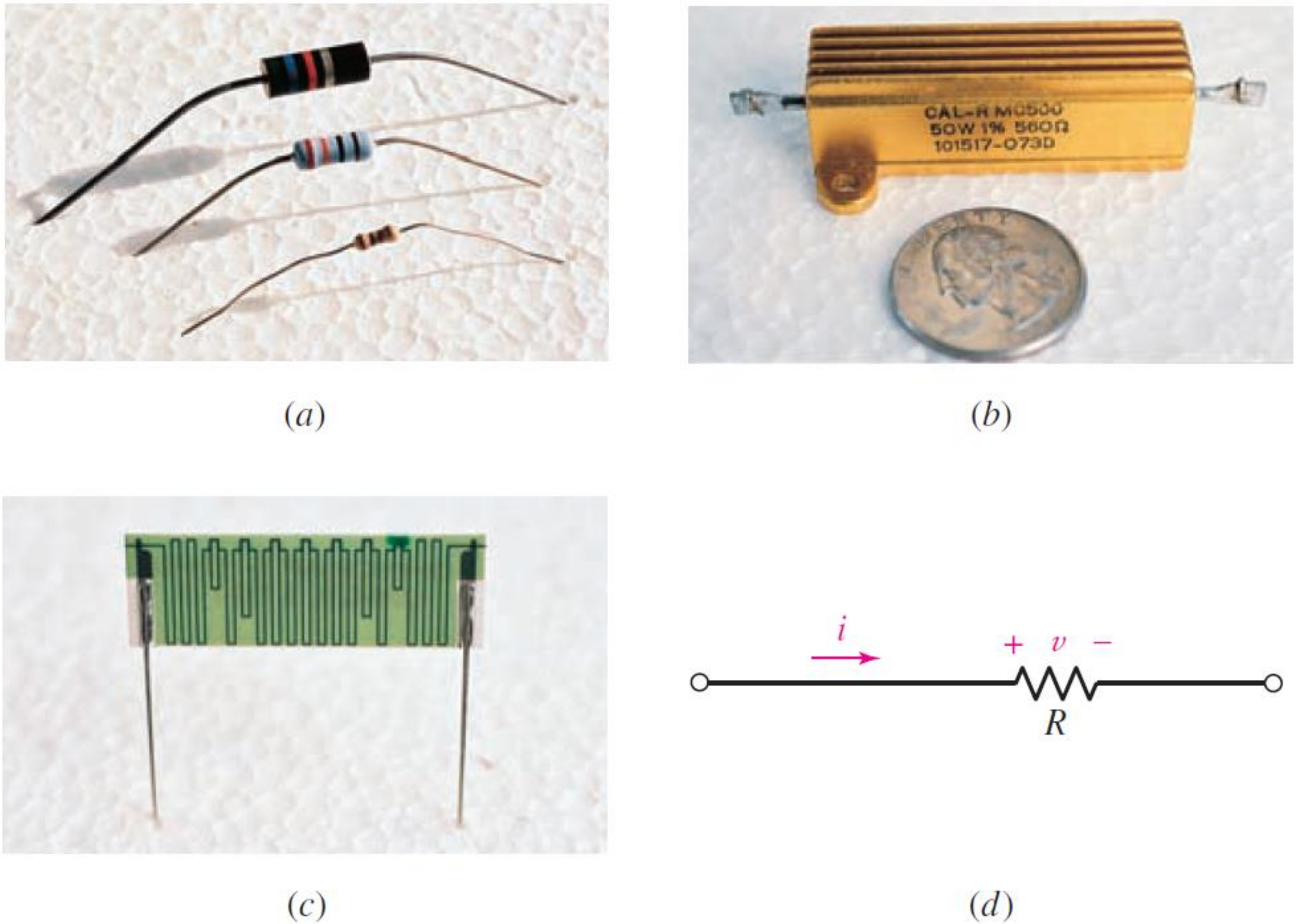


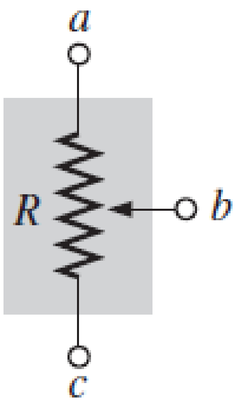
FIGURE 2.24 (*a*) Several common resistor packages. (*b*) A 560 Ω power resistor rated at up to 50 W. (*c*) A 5% tolerance 10-teraohm (10,000,000,000,000 Ω) resistor manufactured by Ohmcraft. (*d*) Circuit symbol for the resistor, applicable to all of the devices in (*a*) through (*c*).

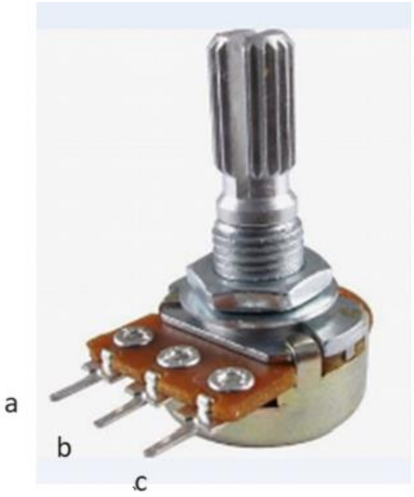
Source: Chapter 2, Sec 2.4: WH Hayt, JE Kemmerly, and SM Durbin, Engineering Circuit Analysis, 8th ed., McGraw-Hill Company, 2012

Resistors: Common Applications in Electronic Circuits

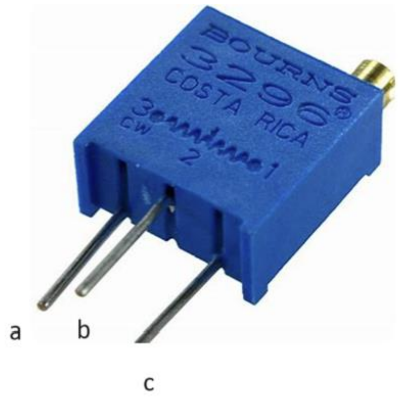
- Extensively used in all electronic circuits (different values and wattages)
- Comes in various sizes (based on the power dissipation capability)
- Most electronic circuits require only small wattage (say 1/8 watt) resistors
- Values and tolerance are generally indicated through colour codes
- **Potentiometers** (variable resistors) also used in many applications

Potentiometers

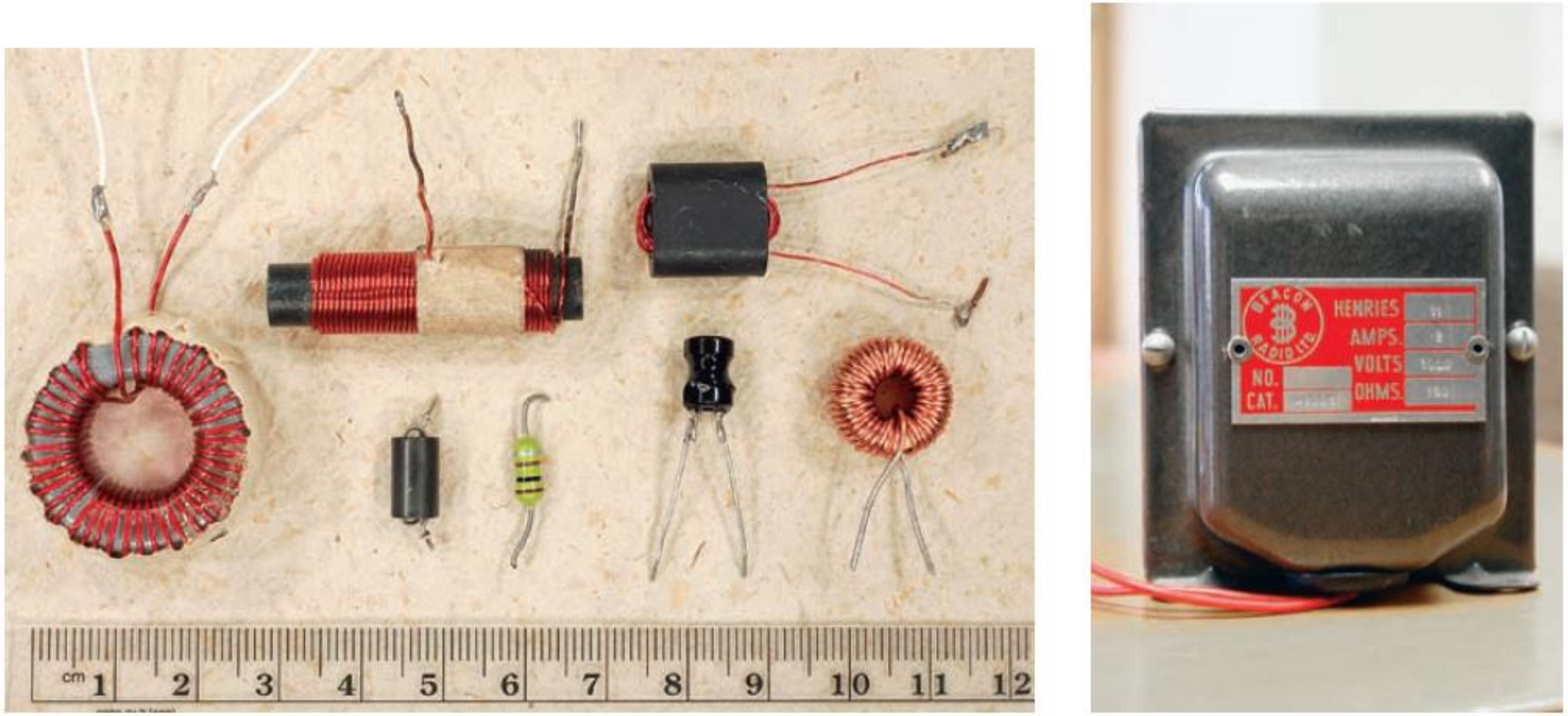




Rotating shaft (or screw) controls the sliding contact



A2. Inductors



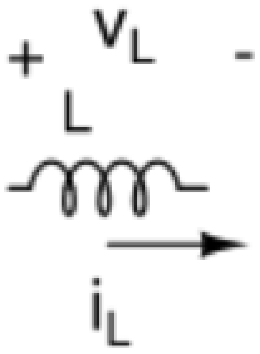
(*a*) (*b*)

FIGURE 7.11 (*a*) Several different types of commercially available inductors, sometimes also referred to as "chokes." Clockwise, starting from far left: 287 μH ferrite core toroidal inductor, 266 μH ferrite core cylindrical inductor, 215 μH ferrite core inductor designed for VHF frequencies, 85 μH iron powder core toroidal inductor, 10 μH bobbin-style inductor, 100 μH axial lead inductor, and 7 μH lossy-core inductor used for RF suppression. (*b*) An 11 H inductor, measuring 10 cm (tall) $\times$ 8 cm (wide) $\times$ 8 cm (deep).

Source: Chapter 7, Sec 7.2: WH Hayt, JE Kemmerly, and SM Durbin, Engineering Circuit Analysis, 8th ed., McGraw-Hill Company, 2012

Inductors

- **Inductor property**: current through an inductor cannot change instantaneously, but the voltage across it can change instantaneously.
- Inductors are very seldom used in general purpose electronic circuits, except for special applications



$$v_L = L\frac{di_L}{dt} \quad ; \quad i_L = \frac{1}{L}\int v_L dt$$

Applications of Inductors in Electronic Circuits

- Common Applications:
  - Switched-Mode Power Supplies (SMPS) – in the μH range
  - RF circuits: small valued inductors (in the nH to μH range)
  - Compact Fluorescent Tube (CFL) supply – μH to mH range
- Major disadvantages:
  - Large size
  - Can create disturbance (EMI) in sensitive circuits
  - Large valued inductors commonly used in electric power circuits

A3. Capacitors

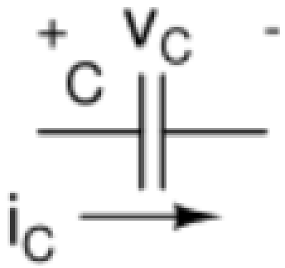
(a) (b) (c)

FIGURE 7.2 Several examples of commercially available capacitors. (*a*) Left to right: 270 pF ceramic, 20 μF tantalum, 15 nF polyester, 150 nF polyester. (*b*) Left: 2000 μF 40 VDC rated electrolytic, 25,000 μF 35 VDC rated electrolytic. (*c*) Clockwise from smallest: 100 μF 63 VDC rated electrolytic, 2200 μF 50 VDC rated electrolytic, 55 F 2.5 VDC rated electrolytic, and 4800 μF 50 VDC rated electrolytic. Note that generally speaking larger capacitance values require larger packages, with one notable exception above. What was the tradeoff in that case?

Source: Chapter 7, Sec 7.1: WH Hayt, JE Kemmerly, and SM Durbin, Engineering Circuit Analysis, 8^{th} ed., McGraw-Hill Company, 2012

Capacitors

- **Capacitor property**: voltage across a capacitor cannot change instantaneously, but the current through a capacitor can change instantaneously.

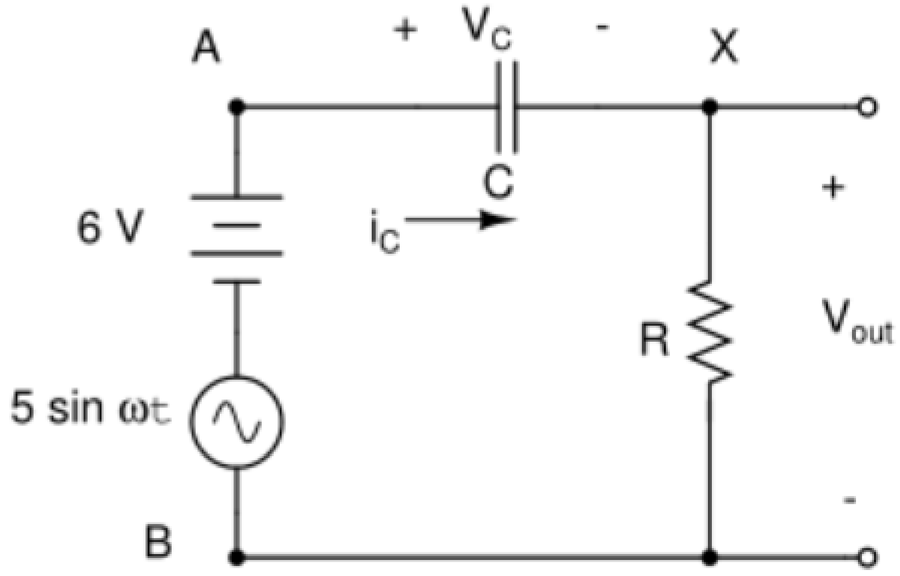


$$v_C = \frac{1}{C}\int i_C dt \quad ; \quad i_C = C\frac{dv_C}{dt}$$

Capacitors: Common Applications in Electronic Circuits…

- **C connected in series**

  "DC blocking" or "AC coupling" capacitor connected in series with a resistor to block DC voltage and couple AC voltage (e.g. amplifier circuits). C selected such that $R >> 1/\omega C$.



In the circuit shown,

let C =0.1 μF , R = 1 MΩ, f = 1 kHz

$V_{AB} = 6 + 5 \sin \omega t$ V .

Capacitive impedance = $1/\omega C$ = 1.6 kΩ

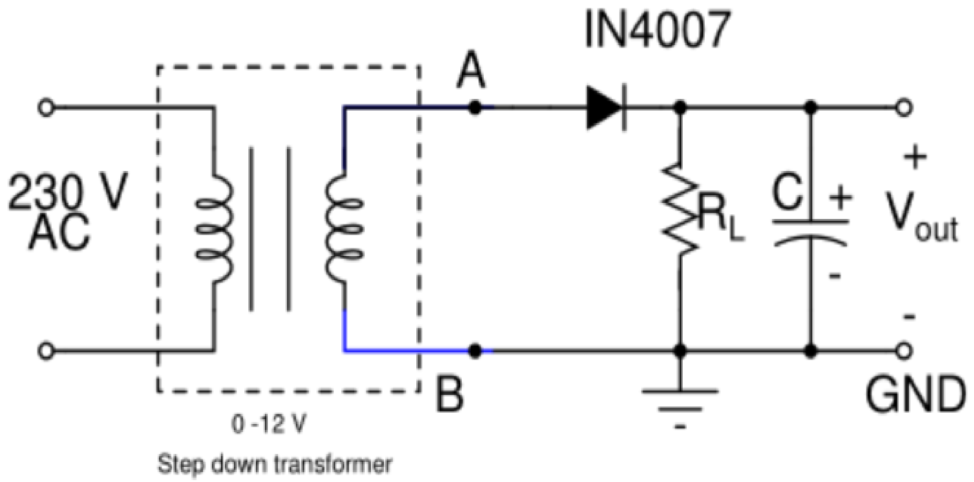
Hence, $R >> 1/\omega C$.

C will block the DC but will couple AC across R.

Hence, $V_{out} = V_{XB} = 5 \sin \omega t$ V.

…Capacitors: Common Applications in Electronic Circuits

- **C connected in parallel**
  - As a "ripple filter" capacitor at the output of a rectifier circuit (typ. 100 to 1000 μF) for reducing ripple voltages.
  - As a "bypass" capacitor (100 to 220 μF) across the emitter resistor in BJT amplifier circuits.
  - As a "de-coupling" capacitor (10 nF to 100 nF) across the power supply pins of ICs to smoothen the power supply voltage.
- **C used for timing applications**
  - In oscillator and other waveform generators (typ. small valued capacitors, say 10 nF to 200 nF).



Electrolytic Capacitor C used as a ripple filter in a half wave rectifier

A4. Transformer

- Transformer:

  Two coils of wire coupled magnetically.

- Has two ports, primary and secondary
  - Primary: the input end (left side), to which the ac voltage source V_1 is connected.
  - Secondary: the port on the right side to which the load Z_L is connected.
- Turns ratio = N_2/N_1, the ratio of the number of secondary turns to the primary turns.
  - $V_2/V_1 = N_2/N_1$
  - $V_2/V_1 < 1$: step-down transformer
  - $V_2/V_1 > 1$: step-up transformer
- DC power supplies and most other common electronic applications use step-down transformers.

  input V_1 is 230 V rms, and V_2 is typically 12 to 20 V rms.

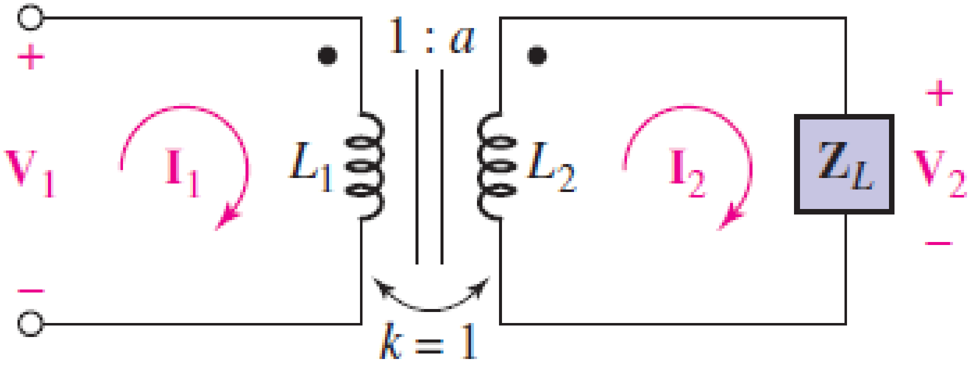


FIGURE 13.25 An ideal transformer is connected to a general load impedance.

Ref: Chapter 13, Sec 13.4: WH Hayt, JE Kemmerly, and SM Durbin, Engineering Circuit Analysis, 8th ed., McGraw-Hill Company, 2012

■ **FIGURE 13.15** A selection of small transformers for use in electronic applications; the AA battery is shown for scale only.

Source: Chapter 13, Sec 13.3: WH Hayt, JE Kemmerly, and SM Durbin, Engineering Circuit Analysis, 8th ed., McGraw-Hill Company, 2012

B1. Independent Voltage Source

- Terminal voltage is independent of the current through it.

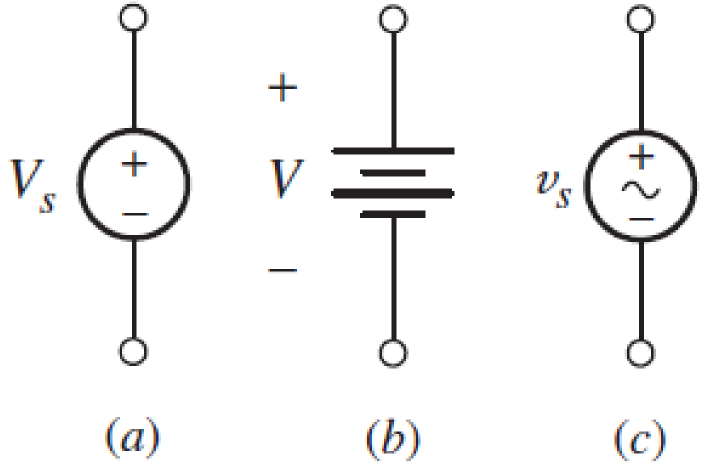


Fig.1 Independent voltage source symbols

(a) DC source symbol,

(b) Battery symbol,

(c) AC source symbol (signs indicating polarity at an arbitrary time instant)

B2. Independent Current Source

- Current supplied is independent of the voltage across its terminals.

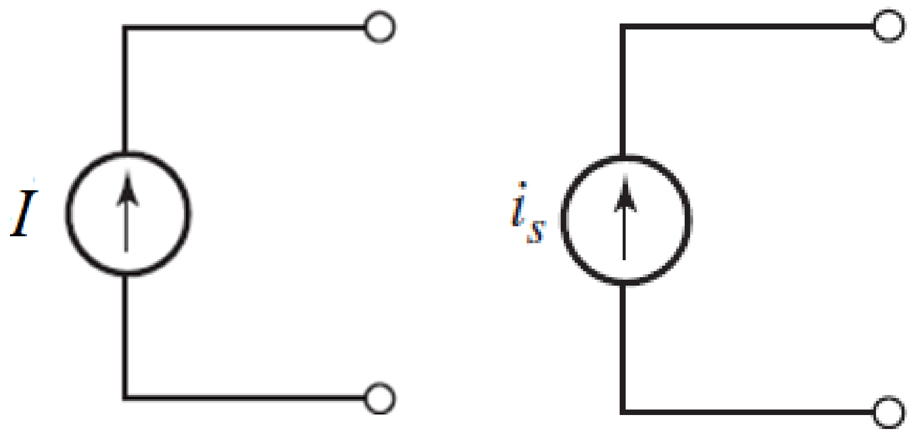


Fig. 2 Circuit symbols for independent current sources

Practical Voltage Sources

- Practical voltage sources are non-ideal.
- As the current supplied by it to a load increases, its terminal voltage progressively decreases (see Fig.3).
- This is due to a non-zero internal resistance.
- The terminal voltage of a practical voltage source equals that of an ideal one, only when current supplied is zero (or when the voltage source is open-circuited).

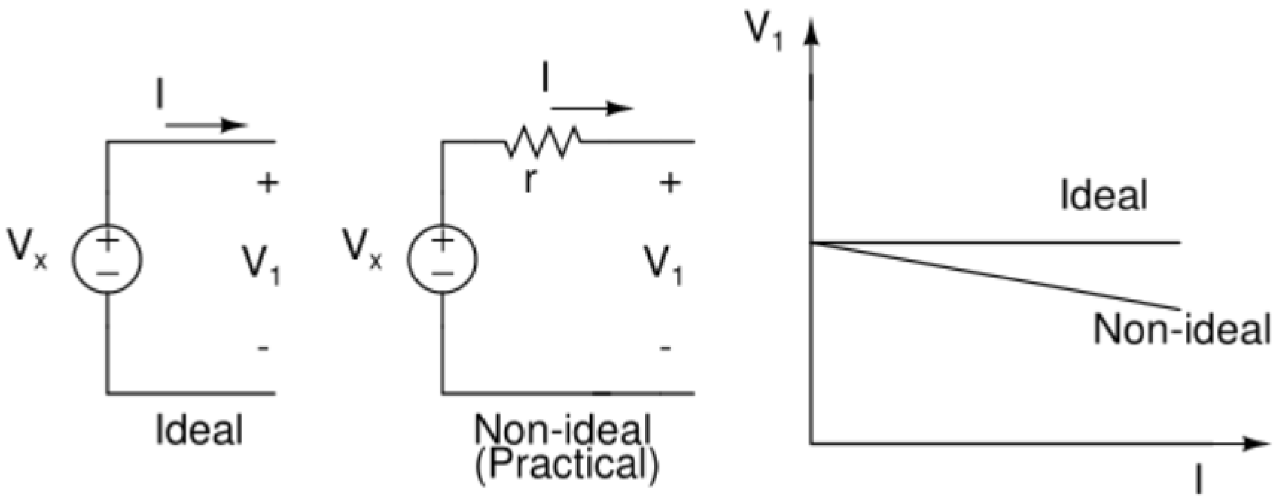


Fig. 3

Practical Current Sources

- In a practical current source, as the terminal voltage across the load increases, the current supplied by it progressively decreases (see Fig.4).
- This is due to a finite internal shunt resistance in a practical current source.
- The current supplied by a practical current source equals that of an ideal one only when the voltage across its terminals is zero (or when the current source is short-circuited).

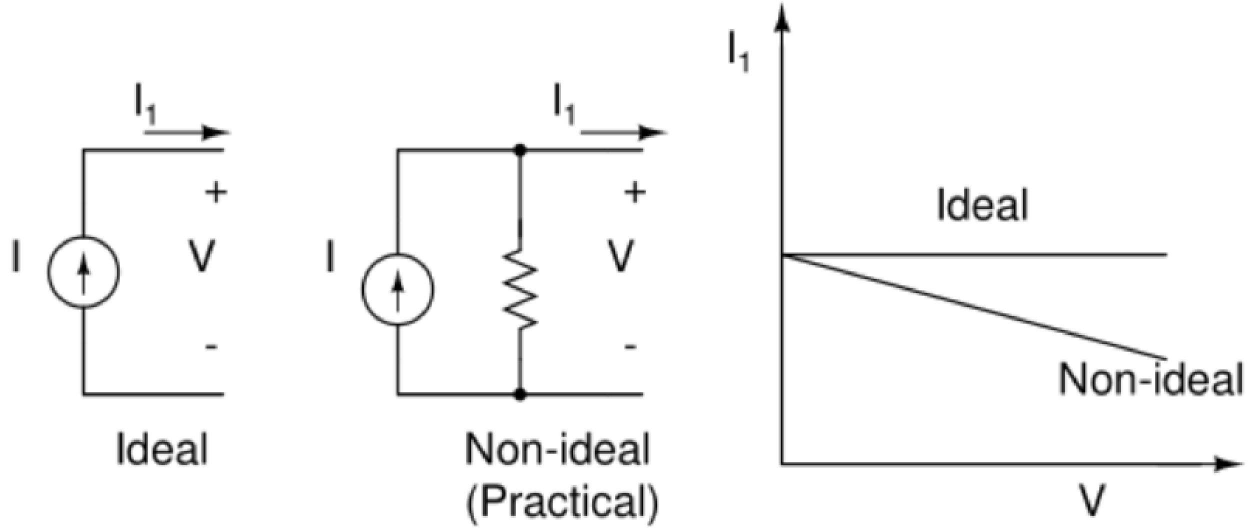


Fig. 4

B3.Dependent Sources

- **Independent sources**
  - The value of the source quantity is not affected in any way by activities in the remainder of the circuit.

- **Dependent (or controlled) sources**
  - The source quantity (voltage or current) is determined by a voltage or current existing at some other location in the system being analyzed.
  - Used in the equivalent electrical models for many electronic devices, such as transistors, operational amplifiers, and integrated circuits.
  - Shown with diamond symbols.

Dependent Sources

- Four types as shown
- In Fig 4(a) and (c), *K* is a dimensionless scaling constant.
- In Fig 4(b), *g* is a scaling factor with units of A/V.
- Fig. 4(d), *r* is a scaling factor with units of V/A.
- The controlling current i_x and the controlling voltage v_x must be defined in the circuit.

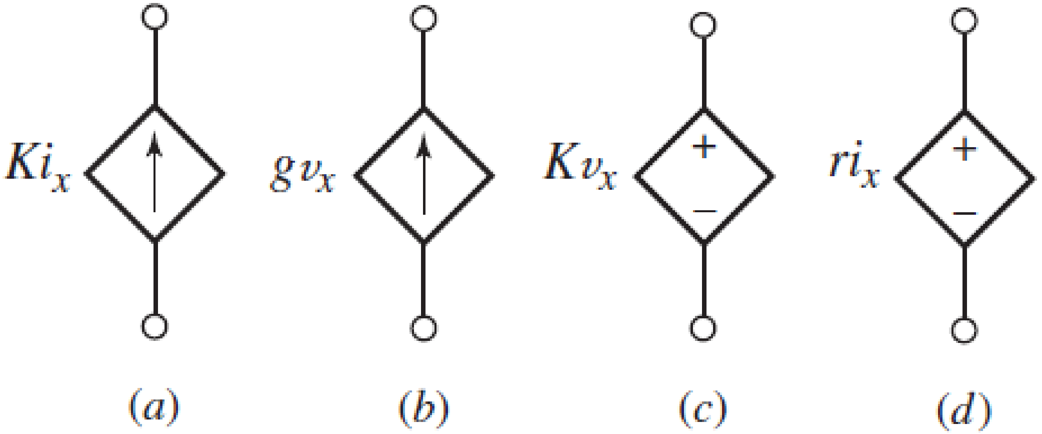


Fig. 4 Circuit symbols for the four different types of dependent sources:

(a) current-controlled current source;

(b) voltage-controlled current source;

(c) voltage-controlled voltage source;

(d) Current controlled voltage source

Node, Path, and Loop

- With reference to Fig 5,
- **Node**:
  - 1, 2 and 3 are nodes
- **Path** (moving from node to node without encountering a node more than once):
  - Node 1 to node 3 to node 2 is a path
- **Loop** (when the node at which we started is the same as the node on which we ended, the path is called a *closed path* or a *loop*):
  - Node 1 to node 3 to node 2 and then back to node 1 is a loop or a closed path

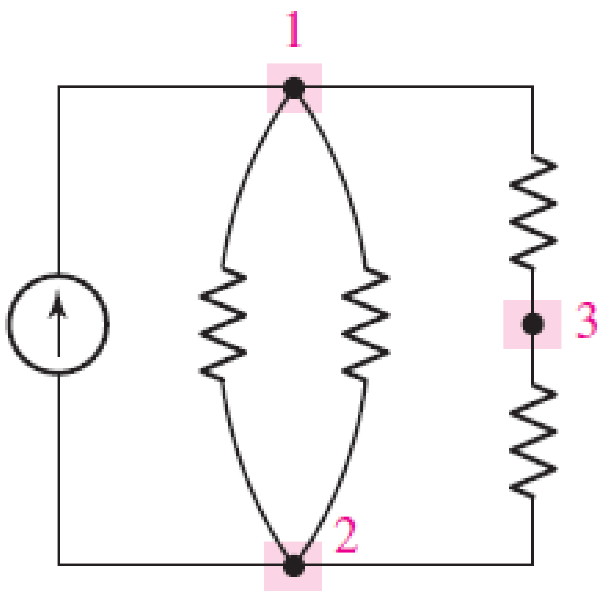


Fig. 5

Kirchhoff's Current Law (KCL)

- Statement: *The algebraic sum of the currents entering any node is zero.*

  (charge cannot accumulate at a node)

- $i_A + i_B + (-i_C) + (-i_D) = 0$

- Or, $i_A + i_B = i_C + i_D$
- i.e. the sum of the currents going in must equal the sum of the currents going out.
- A compact expression for Kirchhoff's current law is:

$$\sum_{n=1}^{N} i_n = 0$$

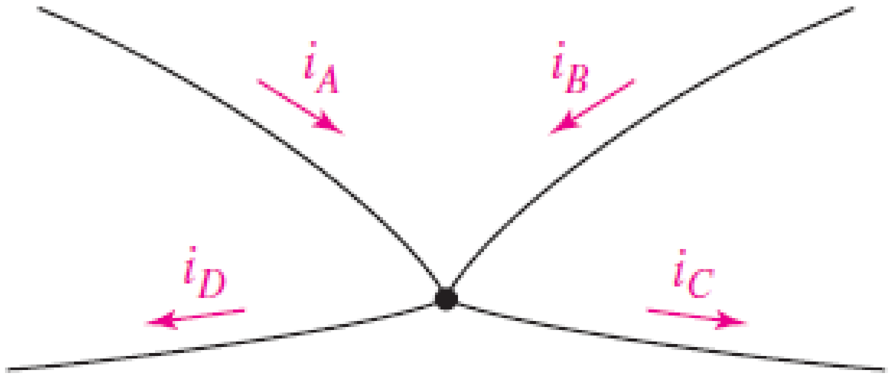


Fig. 6 Example node to illustrate the application of Kirchhoff's current law.

Kirchhoff's Voltage Law (KVL)

- Statement: *The algebraic sum of the voltages around any closed path is zero.*

  i.e. in a closed path, $$\sum_{n=1}^{N} v_n = 0$$

- Method: Move around the closed path in a clockwise direction and write down each voltage met at the +ve sign as positive and each voltage met at the –ve sign as negative.
- For the example in Fig. 7, we have

  $$-v_1 + v_2 - v_3 = 0$$

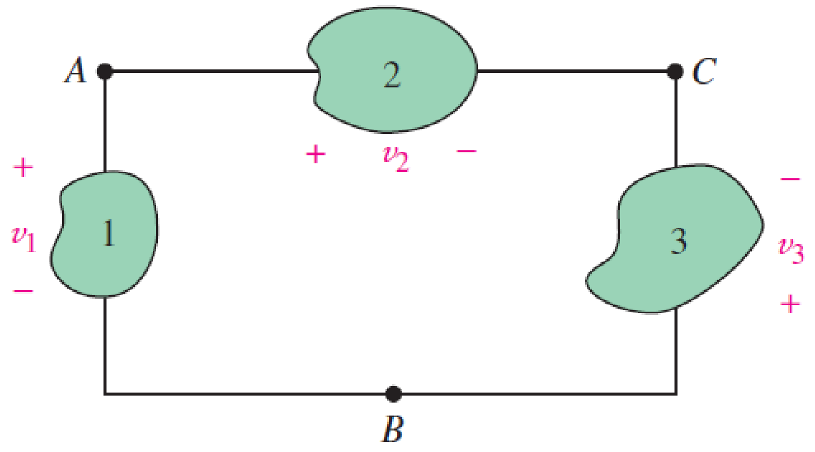


Fig. 7 The potential difference between points A and B is independent of the path selected.

Superposition Principle

- Superposition principle: The output for a weighted sum of inputs is the same weighted sum of the outputs. Let the inputs x_1 and x_2 result in outputs y_1 and y_2, respectively. The output for an input $x = ax_1 + bx_2$ is given as $y = ay_1 + by_2$. The inputs and outputs can be voltages or currents.
- Devices obeying the superposition principle are **linear**. The devices not obeying this principle are **nonlinear**.
- Circuits made of linear devices (e.g. resistors, capacitors, inductors, dependent sources) are called **linear circuits**.
- The superposition method uses the superposition principle to find a voltage or current due to multiple sources by considering one source at a time.

Superposition Method

- The Superposition method states the following:
  - The current through, or voltage across, any device is equal to the algebraic sum of the currents or voltages produced independently by each source.

- It allows us to find a solution for a current or voltage using *only one source at a time*.
- The term *algebraic* appears in the statement because the currents resulting from different sources can have different directions. Similarly, the resulting voltages can have opposite polarities.

Superposition method…

- To consider the effects of each source, the other sources must be removed.
  - When removing a voltage source, replace it with a direct connection (short circuit) of zero ohms. Any internal resistance associated with the source must remain in the network.
  - When removing a current source, replace it with an open circuit of infinite ohms. Any internal resistance associated with the source must remain in the network.
  - Since the effect of each source will be determined independently, the number of times the circuit is to be analysed is equal to the number of sources.

Numerical Example (to illustrate the Superposition Method)

Problem statement:

- **In the resistive network shown, $R_1 = R_2 = R_L = 1200\ \Omega$. $V_1 = 9$ V, $V_2 = 12$ V. Evaluate I_L in mA.**

<u>Procedure</u> (by applying Superposition Method)

- **Find I_L due to V_1 alone (say I_{L1}).**
  $V_1 = 9$ V, $V_2 = 0$ V.
  $I_{R1} = V_1 /(R_1 + R_2 \| R_L) = 9/(1200+600)$ A = 5 mA
  $I_{L1} = [R_2 /(R_2 + R_L)] \cdot I_{R1} = 0.5 * (5)$ mA = 2.5 mA.
- **Find I_L due to V_2 alone (say I_{L2}).**
  $V_1 = 0$ V, $V_2 = 12$ V.
  $I_{R2} = V_2 /(R_2 + R_1 \| R_L) = 12/(1200+600)$ A = 20/3 mA
  $I_{L2} = [R_1 /(R_1 + R_L)] \cdot I_{R2} = 0.5*(20/3)$ mA = 3.33 mA.
- **Hence, $I_L = I_{L1} + I_{L2}$**

  = 2.5 + 3.33 = 5.83 mA.