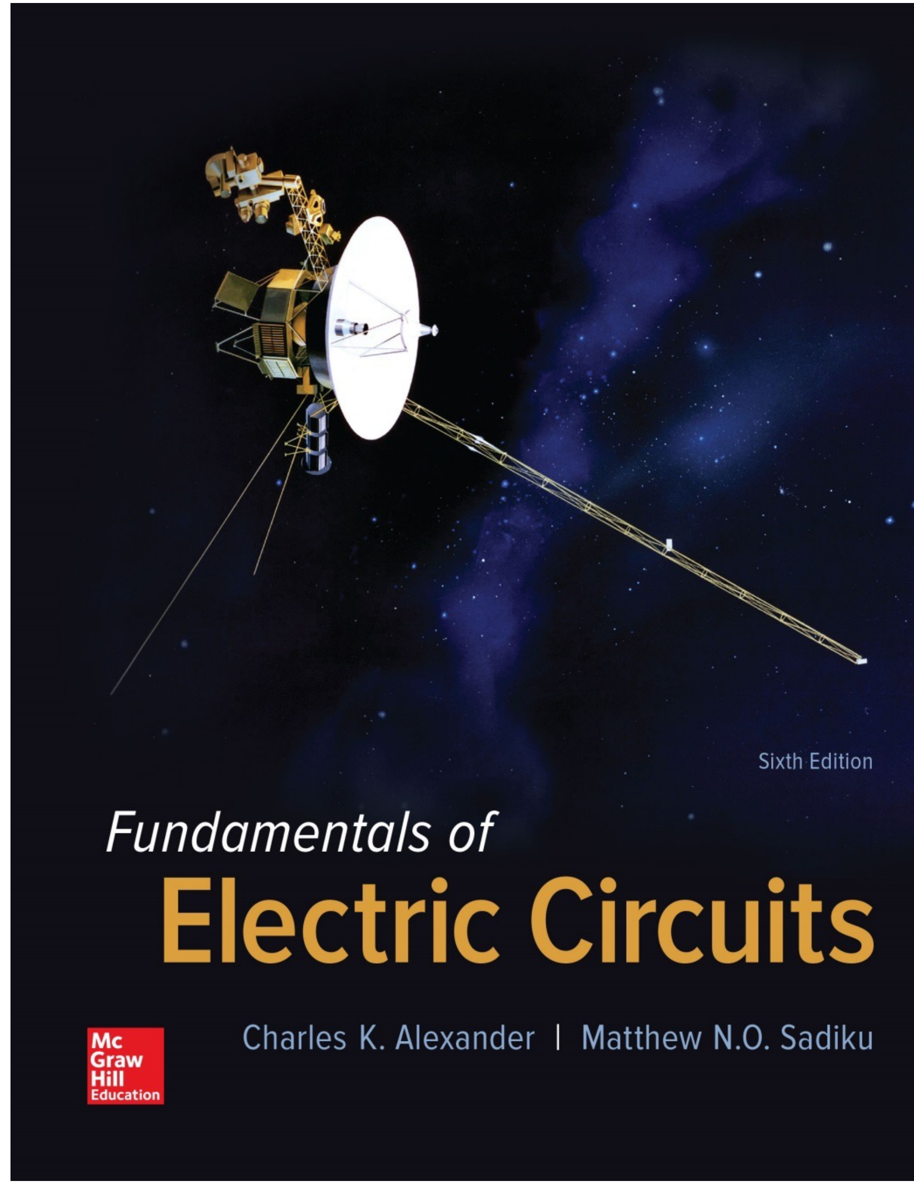
Fundamentals of
Electric Circuits
Chapter 6

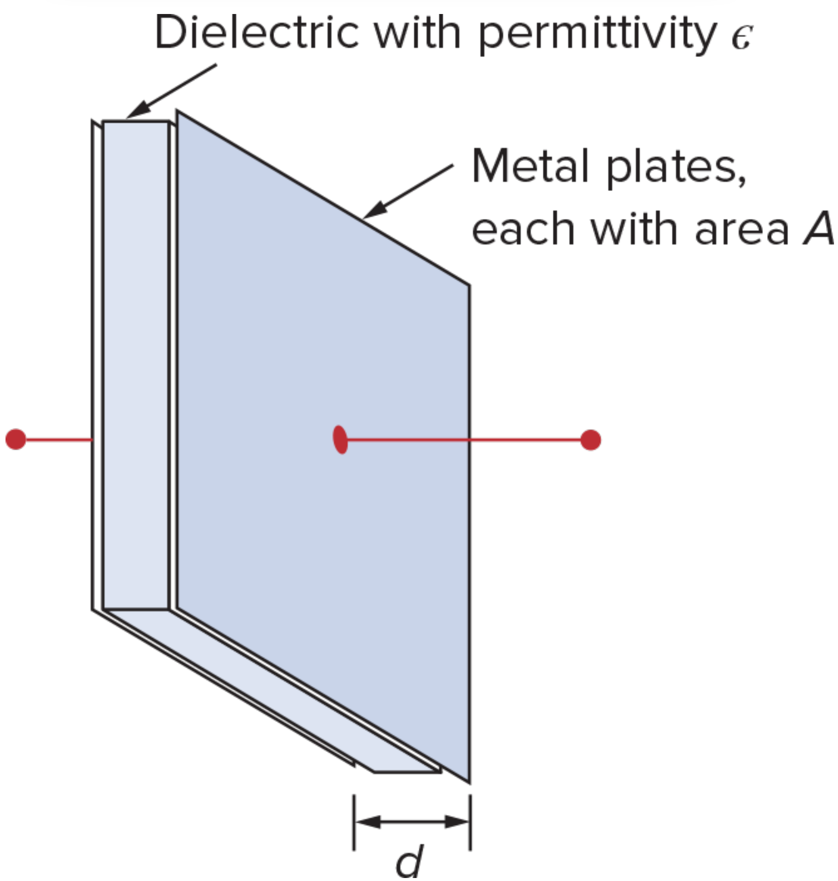
Capacitors and Inductors



6.1 Introduction

- This chapter will introduce two new linear circuit elements:
  - ✓The capacitor
  - ✓The inductor
- Unlike resistors, these elements do not dissipate energy
- They instead store energy
- We will also look at how to analyze them in a circuit

6.2 Capacitors



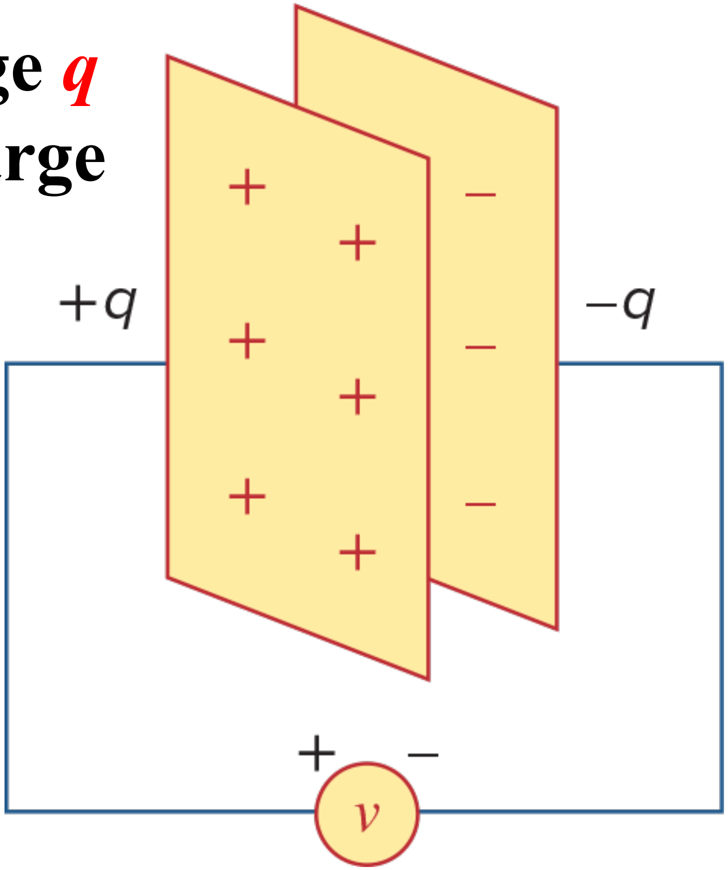
- A capacitor is a passive element that stores energy in its electric field
- It consists of two conducting plates separated by an insulator (or dielectric)
- The plates are typically aluminum foil
- The dielectric is often air, ceramic, paper, plastic, or mica

Capacitors

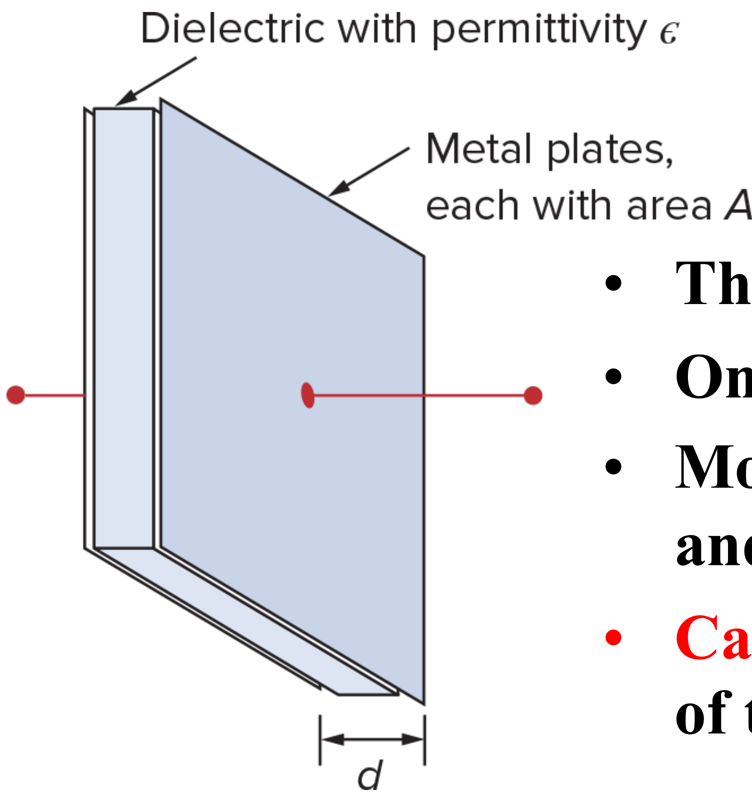
- When a voltage source v is connected to the capacitor, the source deposits a positive charge q on one plate and a negative charge $-q$ on the other.
- The charges will be equal in magnitude
- The amount of charge is proportional to the voltage:

$$q = Cv$$

where C is the capacitance



Capacitance



- **The unit of capacitance is the *Farad* (F)**
- **One Farad is 1 Coulomb/Volt**
- **Most capacitors are rated in picofarad (pF) and microfarad (μF)**
- **Capacitance is determined by the geometry of the capacitor:**
  - **Proportional to the area of the plates (A)**
  - **Inversely proportional to the space between them (d)**

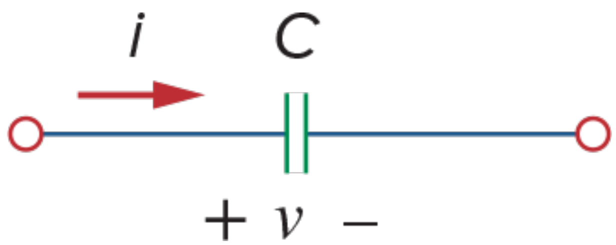
$$C = \frac{\varepsilon A}{d}$$

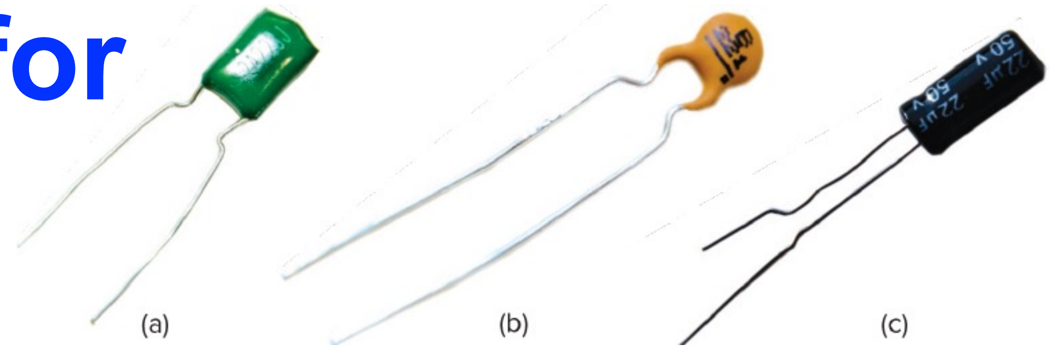
- **ε is the permittivity of the dielectric**

$$q = Cv$$

$$C = \frac{q}{v}$$

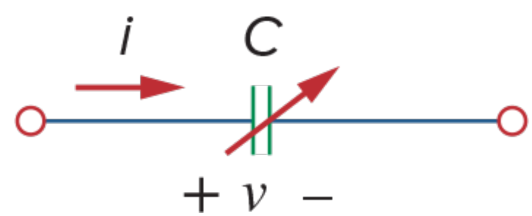
Applications for Capacitors





Fixed capacitors: (a) polyester capacitor, (b) ceramic capacitor, (c) electrolytic capacitor.

- **Capacitors have a wide range of applications, some of which are:**
  - **Blocking DC**
  - **Passing AC**
  - **Shift phase**
  - **Store energy**
  - **Suppress noise**
  - **Start motors**

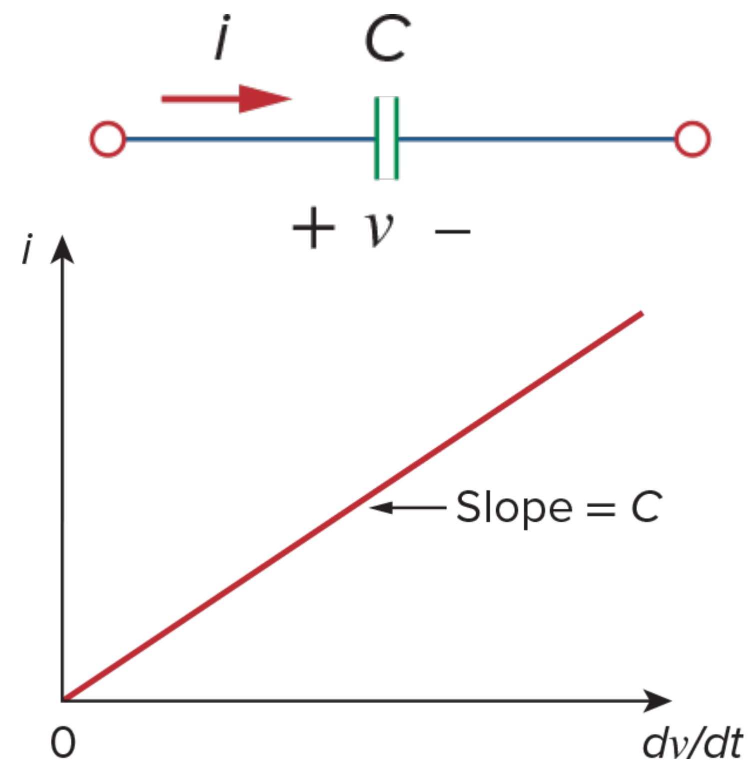


Variable capacitors

Current Voltage Relationship

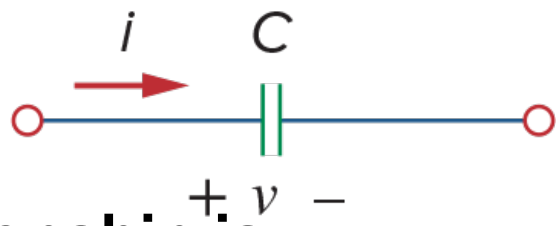
- Using the formula for the charge stored in a **capacitor**, we can find the **current voltage relationship**
- Take the first derivative with respect to time gives:

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



- This assumes the passive sign convention

Stored Charge



- Similarly, the voltage-current relationship is:

$$i = C\frac{dv}{dt} \qquad v(t) = \frac{1}{C}\int_{t_0}^{t} i(\tau)\,d\tau + v(t_0)$$

- This shows the capacitor has a memory, which is often exploited in circuits
- The instantaneous power delivered to the capacitor is

$$p = vi = Cv\frac{dv}{dt}$$

- The energy stored in a capacitor is:

$$w = \int_{-\infty}^{t} p(\tau)\,d\tau = C\int_{-\infty}^{t} v\frac{dv}{d\tau}\,d\tau = C\int_{v(-\infty)}^{v(t)} v\,dv = \frac{1}{2}Cv^2\Big|_{v(-\infty)}^{v(t)}$$

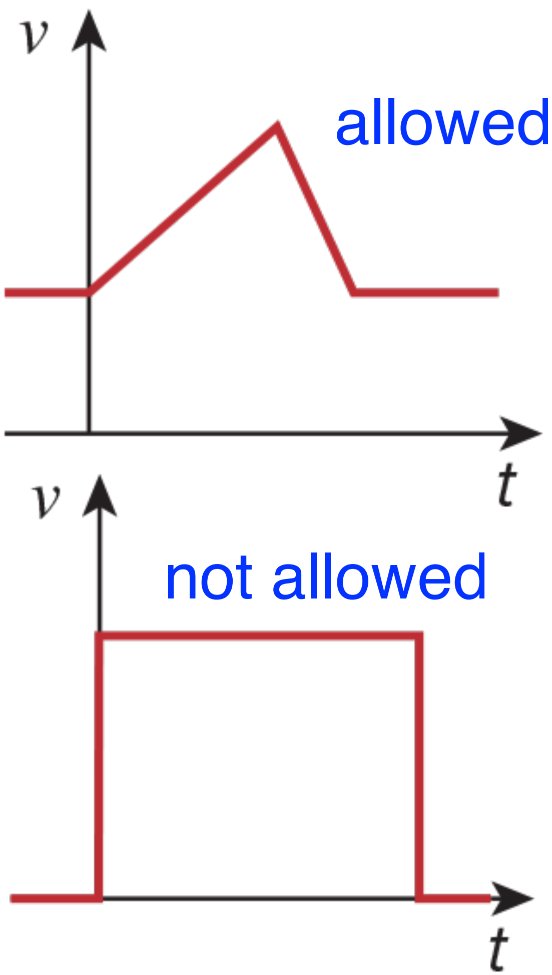
$$w = \frac{1}{2}Cv^2 \qquad w = \frac{q^2}{2C}$$

Properties of Capacitors

- **Ideal capacitors all have these characteristics:**

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

Voltage across a capacitor:



✓ When the voltage is not changing, the current through the cap is zero.

✓ This means that with DC applied to the terminals no current will flow.

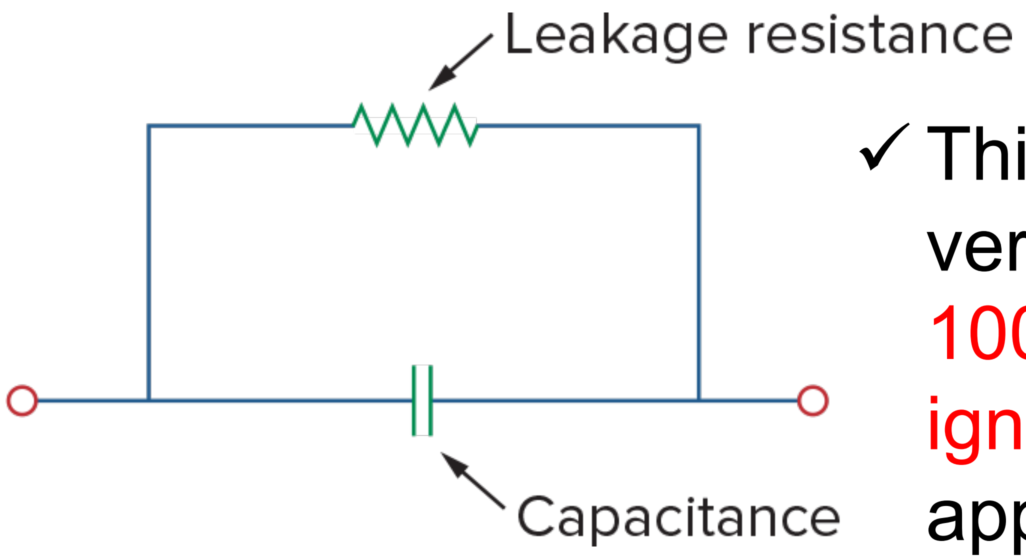
✓ <u>Except</u>, the voltage on the capacitor's plates can't change instantaneously.

✓ An abrupt change in voltage would require an infinite current!

✓ This means if the voltage on the cap does not equal the applied voltage, charge will flow and the voltage will finally reach the applied voltage.

Properties of capacitors

- ✓ An ideal capacitor does not dissipate energy, meaning stored energy may be retrieved later
- ✓ A real capacitor has a parallel-model leakage resistance, leading to a slow loss of the stored energy internally



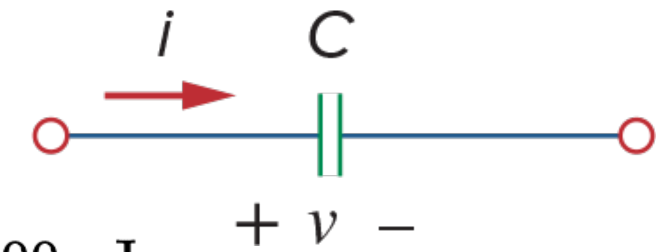
- ✓ This resistance is typically very high, on the order of 100 MΩ and thus can be ignored for many circuit applications.

Example 6.1

(a) Calculate the charge stored on a 3-pF capacitor with 20 V across it.

$$q = Cv = 3 \times 10^{-12} \times 20 = 60 \text{ pC}$$

(b) Find the energy stored in the capacitor.



$$w = \frac{1}{2} Cv^2 = \frac{1}{2} \times 3 \times 10^{-12} \times 400 = 600 \text{ pJ}$$

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

Example 6.2

The voltage across a $5-\mu$F capacitor is

$$v(t) = 10 \cos 6000t \text{ V}$$

$$v(t) = \frac{1}{C}\int_{t_0}^{t} i(\tau)\,d\tau + v(t_0)$$

Calculate the current through it.

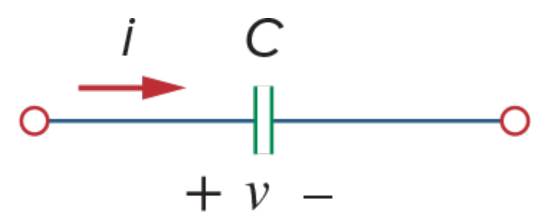
$$i(t) = C\frac{dv}{dt} = 5 \times 10^{-6} \frac{d}{dt}(10 \cos 6000t)$$

$$= -5 \times 10^{-6} \times 6000 \times 10 \sin 6000t$$

$$= -0.3 \sin 6000t \text{ A}$$

Example 6.3

Determine the voltage across a $2-\mu\text{F}$ capacitor if the current through it is



$$i(t) = 6e^{-3000t}\ \text{mA}$$

Assume that the initial capacitor voltage is zero.

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

$$v(t) = \frac{1}{C}\int_0^t i\,d\tau + v(0)$$

$$= \frac{1}{2\times10^{-6}}\int_0^t 6e^{-3000t}\,d\tau$$

$$= \frac{6\times10^{6}}{2\times(-3000)}\,e^{-3000\tau}\Big|_0^t$$

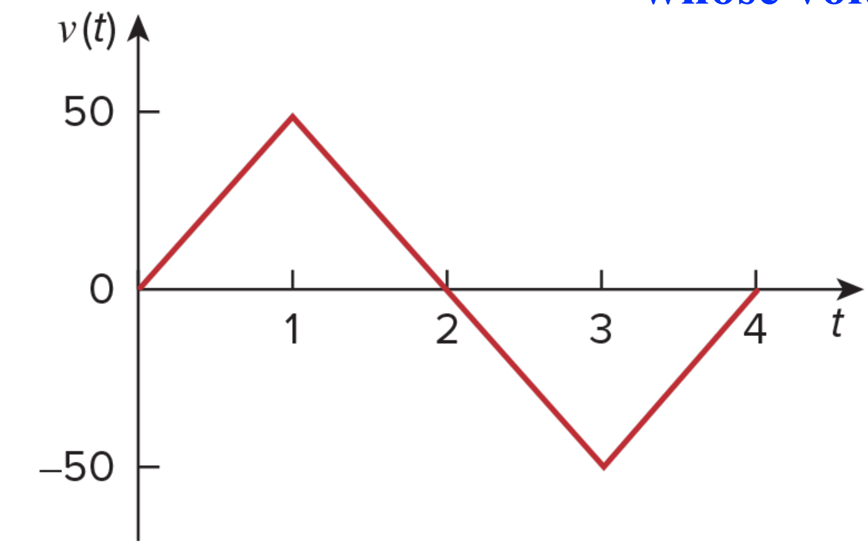
$$= -10^3(e^{-3000t} - 1)$$

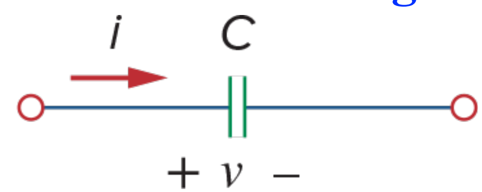
$$= (1 - e^{-3000t})\times10^3(mV)$$

$$= (1 - e^{-3000t})\ (V)$$

Example 6.4

Determine the current through a 200−μF capacitor whose voltage is shown in the figure.





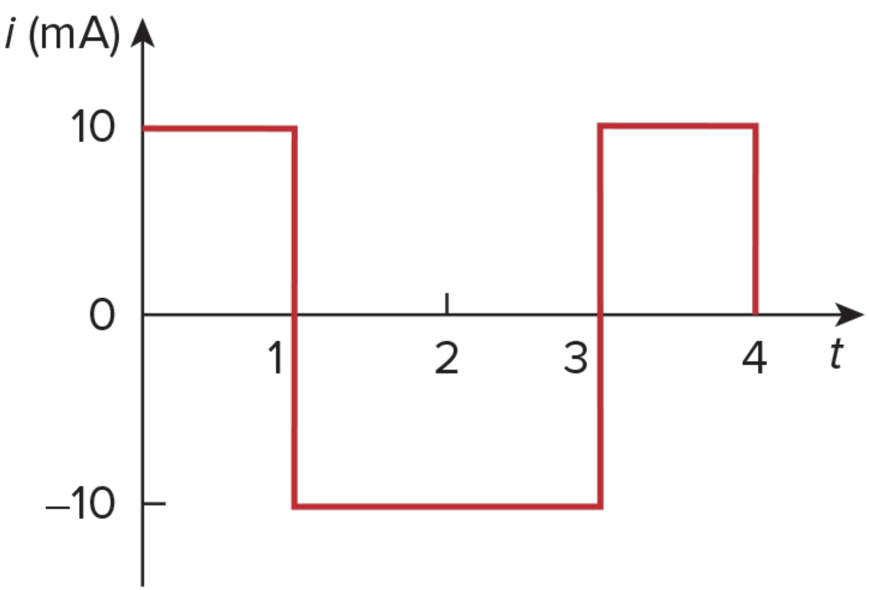
$$i = C\frac{dv}{dt}$$

$$v(t) = \begin{cases} 50t \text{ (V)} & 0 < t < 1 \\ 100 - 50t \text{ (V)} & 1 < t < 3 \\ -200 + 50t \text{ (V)} & 3 < t < 4 \\ 0 & \text{otherwise} \end{cases}$$

$$i(t) = C\frac{dv(t)}{dt}$$

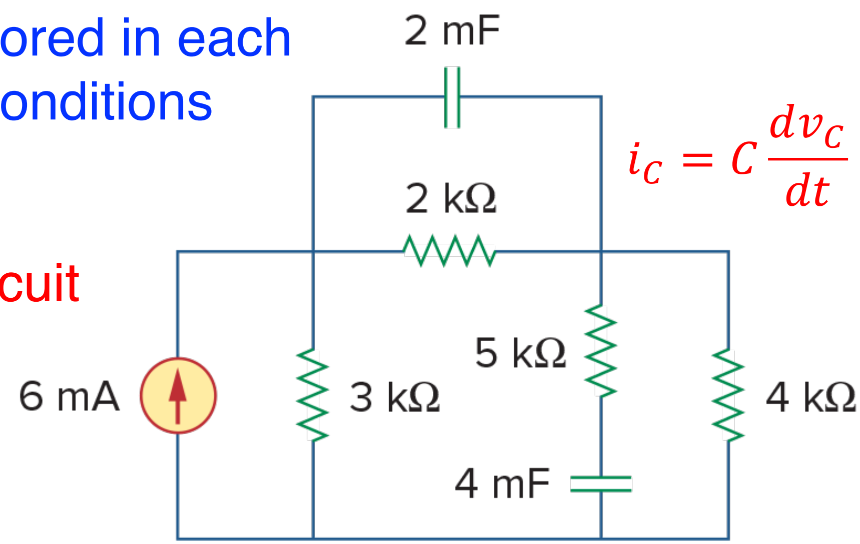
$$= 200\times10^{-6} \begin{cases} 50 \text{ (A)} & 0 < t < 1 \\ -50 \text{ (A)} & 1 < t < 3 \\ 50 \text{ (A)} & 3 < t < 4 \\ 0 & \text{otherwise} \end{cases}$$

$$= \begin{cases} 10 \text{ (mA)} & 0 < t < 1 \\ -10 \text{ (mA)} & 1 < t < 3 \\ 10 \text{ (mA)} & 3 < t < 4 \\ 0 & \text{otherwise} \end{cases}$$



Example 6.5

Obtain the energy stored in each capacitor under dc conditions



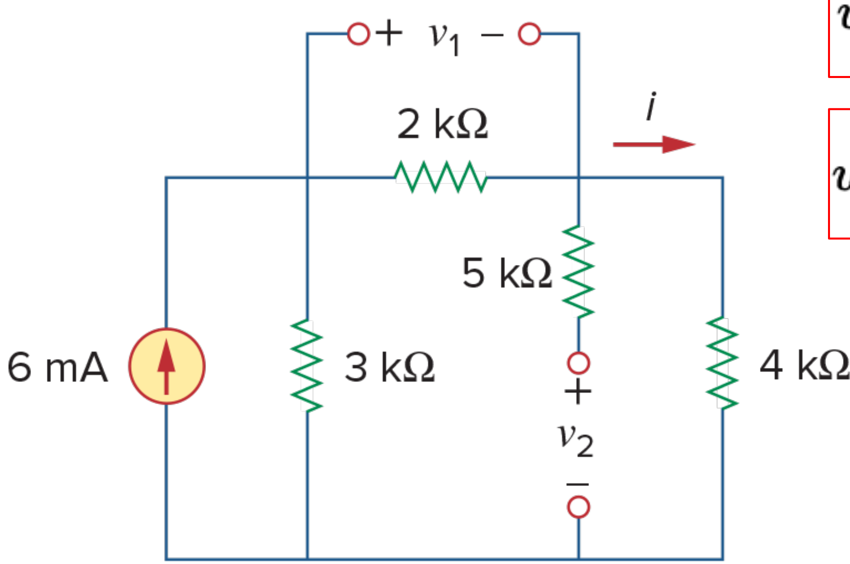
$i_C = C\dfrac{dv_C}{dt}$

dc $\rightarrow$ $i_C = C\dfrac{dv_C}{dt}$ $\rightarrow$ capacitor $\rightarrow$ open circuit

$$i = \frac{3}{3+2+4}(6\text{ mA}) = 2\text{ mA}$$

$$v_1 = 2000i = 4\text{ V}$$

$$v_2 = 4000i = 8\text{ V}$$

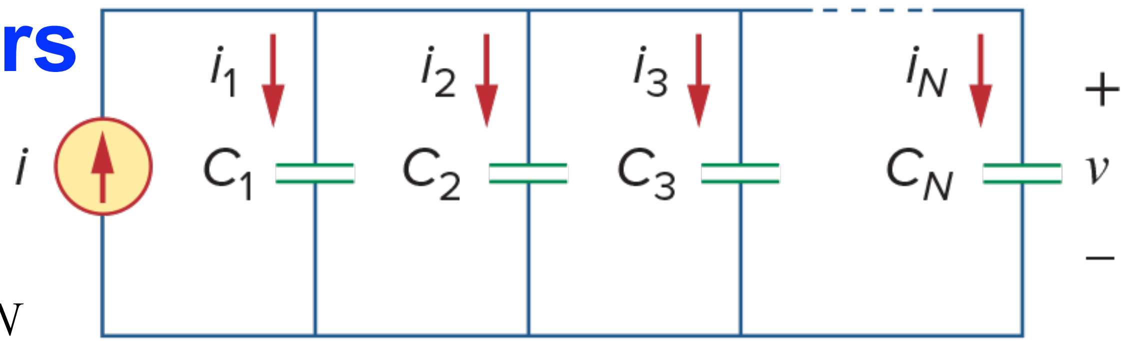


$$\boxed{w_1 = \frac{1}{2}C_1 v_1^2 = \frac{1}{2}\left(2\times 10^{-3}\right)(4)^2 = 16\text{ mJ}}$$

$$\boxed{w_2 = \frac{1}{2}C_2 v_2^2 = \frac{1}{2}\left(4\times 10^{-3}\right)(8)^2 = 128\text{ mJ}}$$

6.3 Series and Parallel Capacitors

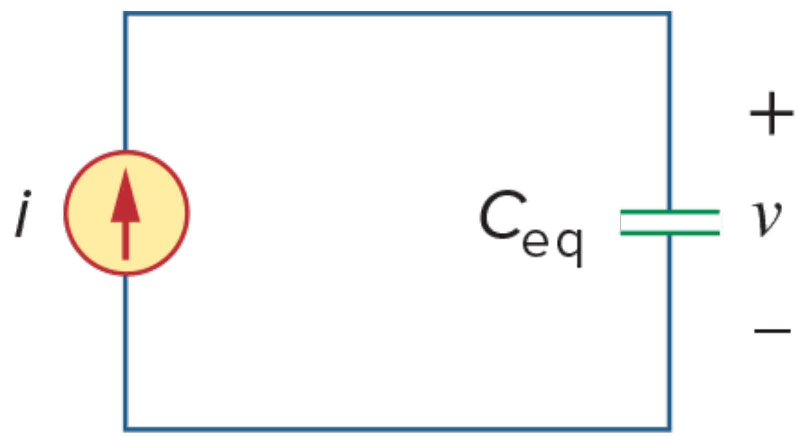
Parallel Capacitors



$$i = i_1 + i_2 + i_3 + \cdots + i_N$$

$$i = C_1 \frac{dv}{dt} + C_2 \frac{dv}{dt} + C_3 \frac{dv}{dt} + \cdots + C_N \frac{dv}{dt}$$

$$= \left(\sum_{k=1}^{N} C_k \right) \frac{dv}{dt} = C_{eq} \frac{dv}{dt}$$

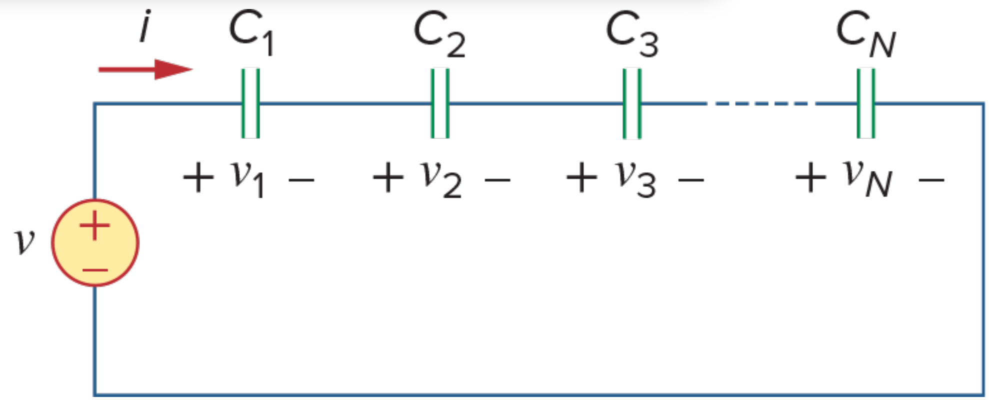


$$C_{eq} = C_1 + C_2 + C_3 + \cdots + C_N$$

parallel capacitors combine as the sum of all capacitance

6.3 Series and Parallel Capacitors

Series Capacitors



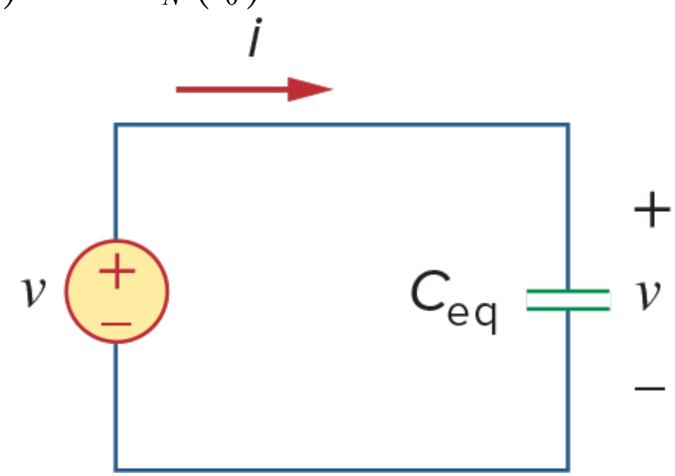
$$v = v_1 + v_2 + v_3 + \cdots + v_N$$

$$v = \frac{1}{C_1}\int_{t_0}^{t} i(\tau)\,d\tau + v_1(t_0) + \frac{1}{C_2}\int_{t_0}^{t} i(\tau)\,d\tau + v_2(t_0) + \frac{1}{C_3}\int_{t_0}^{t} i(\tau)\,d\tau + v_3(t_0) + \cdots + \frac{1}{C_N}\int_{t_0}^{t} i(\tau)\,d\tau + v_N(t_0)$$

$$= \left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots + \frac{1}{C_N}\right)\int_{t_0}^{t} i(\tau)\,d\tau + v_1(t_0) + v_2(t_0) + v_3(t_0) + \cdots + v_N(t_0)$$

$$= \frac{1}{C_{eq}}\int_{t_0}^{t} i(\tau)\,d\tau + v(t_0)$$

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots + \frac{1}{C_N}$$



series combination of capacitors
resembles the parallel combination of resistors.

Series and Parallel Caps

$$C = \frac{\varepsilon A}{d}$$

- Another way to think about the combinations of capacitors is this:
  - A parallel combining is equivalent to
    - increasing the surface area of the capacitors:
    - This would lead to an increased overall capacitance

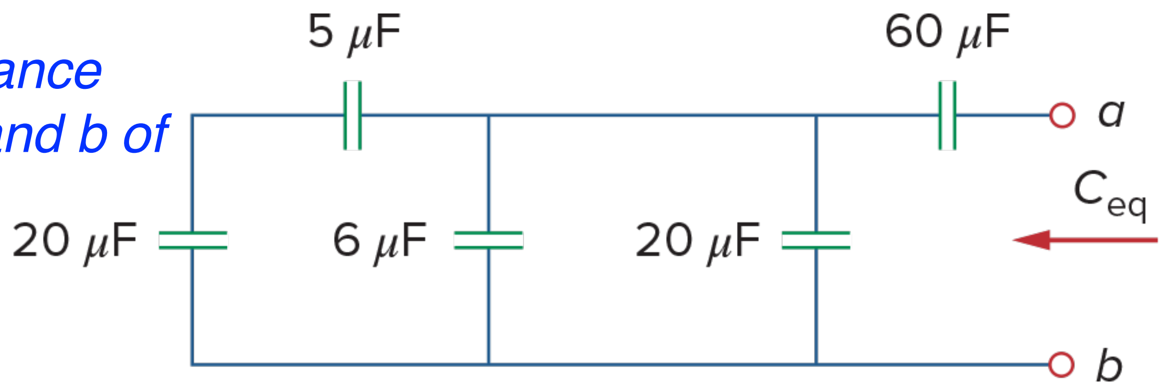
$$C_{eq} = C_1 + C_2 + C_3 + \cdots + C_N$$

  - A series combination can be seen as
    - increasing the total plate separation
    - This would result in a decrease in capacitance

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots + \frac{1}{C_N}$$

Example 6.6

Find the equivalent capacitance seen between terminals a and b of the circuit



The $20-\mu$F and $5-\mu$F capacitors are in series:

$$\frac{20 \times 5}{20 + 5} = 4\ \mu\text{F}$$

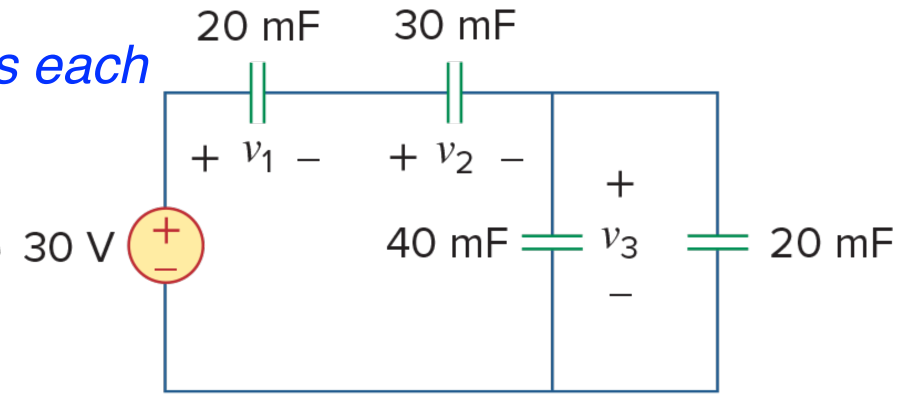
This 4-μF capacitor is in parallel with the 6-μF and 20-μF capacitors:

$$4 + 6 + 20 = 30\ \mu\text{F}$$

This 30-μF capacitor is in series with the 60-μF capacitor.

$$\boxed{C_{\text{eq}} = \frac{30 \times 60}{30 + 60} = 20\ \mu\text{F}}$$

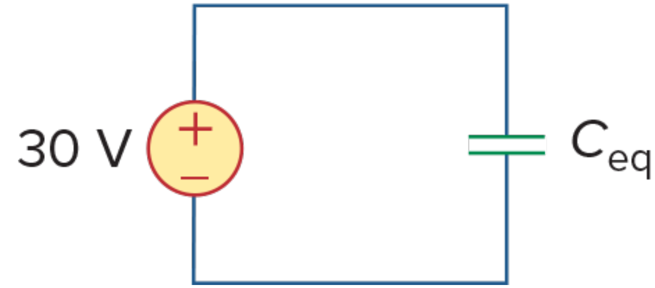
Example 6.7 *find the voltage across each capacitor*



$$C_{eq} = \frac{1}{\frac{1}{60} + \frac{1}{30} + \frac{1}{20}} \text{ mF} = 10 \text{ mF}$$

total charge $q = C_{eq} v = 10 \times 10^{-3} \times 30 = 0.3 \text{ C}$

Charge acts like current, since i = dq/dt



$$v_1 = \frac{q}{C_1} = \frac{0.3}{20 \times 10^{-3}} = 15 \text{ V}$$

$$v_2 = \frac{q}{C_2} = \frac{0.3}{30 \times 10^{-3}} = 10 \text{ V}$$

$$v_3 = 30 - v_1 - v_2 = 5 \text{ V}$$

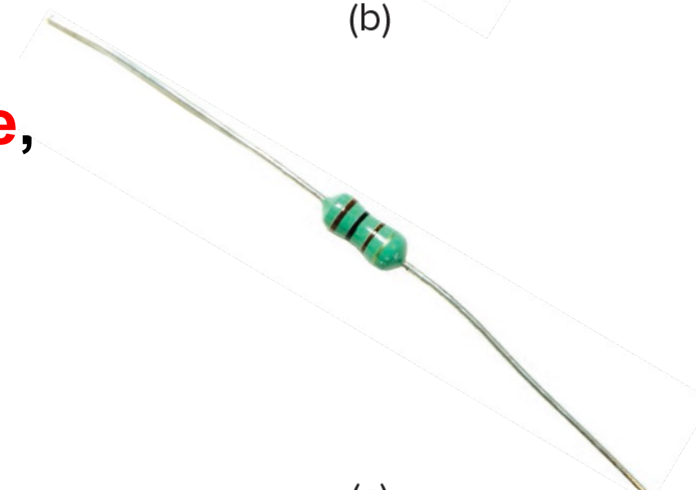
or $v_3 = \dfrac{q}{60 \text{ mF}} = \dfrac{0.3}{60 \times 10^{-3}} = 5 \text{ V}$

6.4 Inductors

- An **inductor** is a passive element that **stores energy** in its **magnetic field**
- They have applications in power supplies, transformers, radios, TVs, radars, and electric motors.
- Any **conductor** has **inductance**, but the effect is typically enhanced by coiling the wire up.

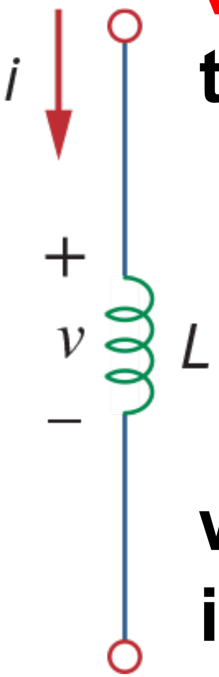

(a)


(b)

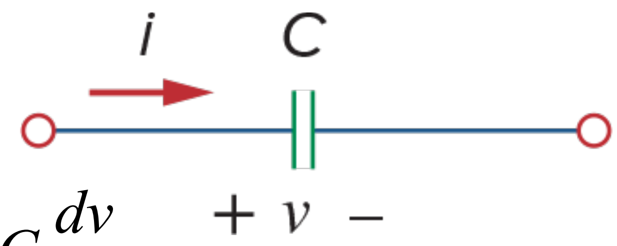

(c)

Inductors

- If a current is passed through an inductor, the voltage across it is directly proportional to the time rate of change in current



$$v = L\frac{di}{dt}$$



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

where, *L*, is the unit of inductance, measured in Henries, H.

- On Henry is 1 volt-second per ampere (V-s/A).
- The voltage developed tends to oppose a changing flow of current.

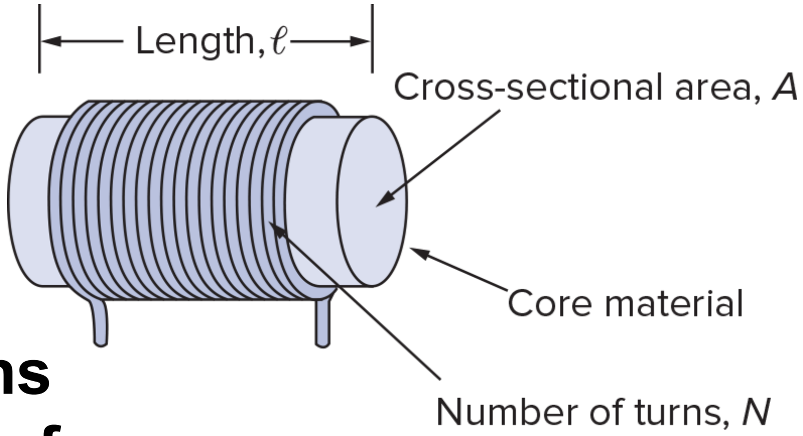
Inductors

- **Calculating the inductance depends on the geometry:**
- **For example, for a solenoid the inductance is:**

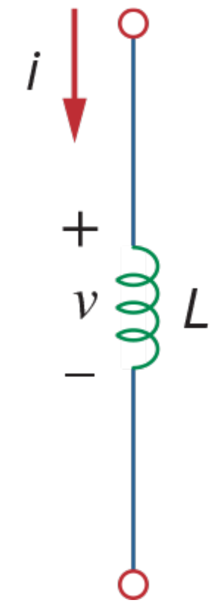
$$L = \frac{N^2 \mu A}{l}$$

here *N* is the number of turns of the wire around the core of cross sectional area *A* and length *l*.

- **The material used for the core has a magnetic property called the permeability, *μ*.**



Current in an Inductor

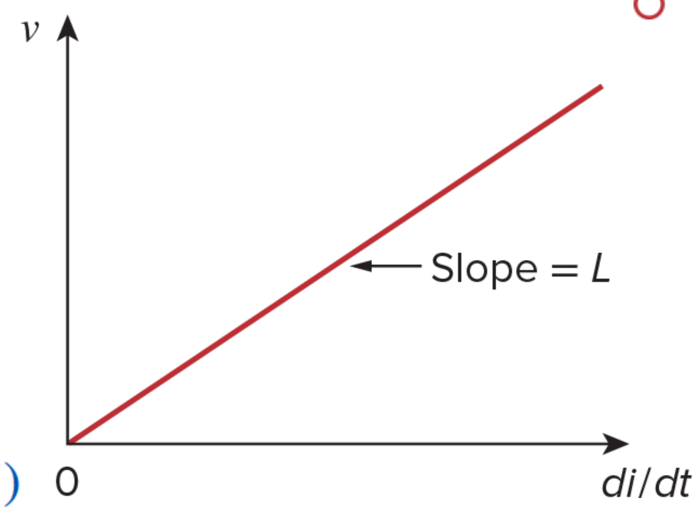


- **The current voltage relationship for an inductor is:**

$$I = \frac{1}{L}\int_{t_0}^{t} v(\tau)\,d\tau + i(t_0) \qquad v = L\frac{di}{dt}$$

- **The power delivered to the inductor is:**

$$p = vi = \left(L\frac{di}{dt}\right)i$$



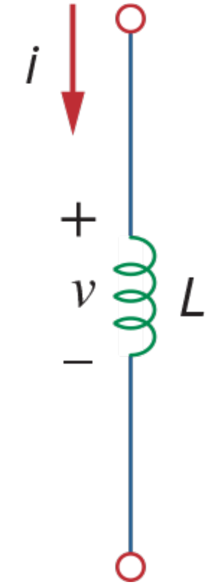
- **The energy stored is:**

$$w = \int_{-\infty}^{t} p(\tau)\,d\tau = L\int_{-\infty}^{t} \frac{di}{d\tau}\,i\,d\tau$$

$$= L\int_{-\infty}^{t} i\,di = \frac{1}{2}Li^2(t) - \frac{1}{2}Li^2(-\infty)$$

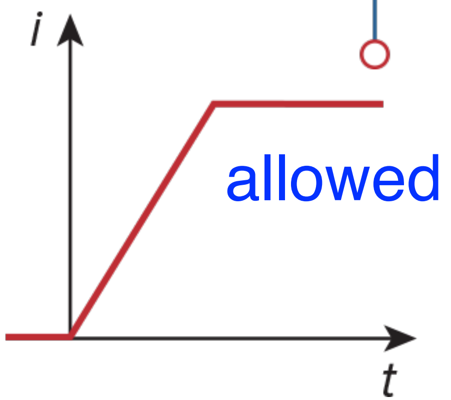
$$w = \frac{1}{2}Li^2$$

Properties of Inductors

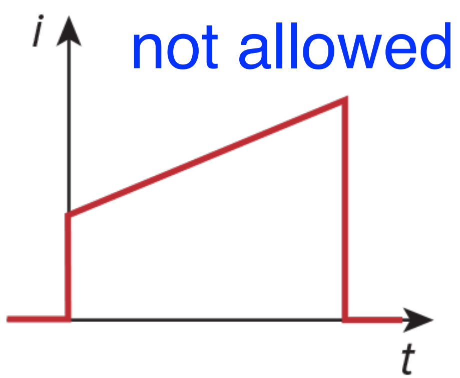


- If the current through an inductor is constant, the voltage across it is zero
- Thus an inductor acts like a short for DC

$$v = L\frac{di}{dt} \qquad I = \frac{1}{L}\int_{t_0}^{t} v(\tau)\,d\tau + i(t_0)$$

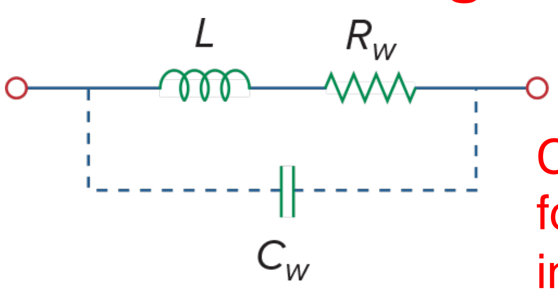


- The current through an inductor cannot change instantaneously
- If this did happen, the voltage across the inductor would be infinity!
- This is an important consideration if an inductor is to be turned off abruptly; it will produce a high voltage



Properties of Inductors

- Like the ideal capacitor, the **ideal inductor does not dissipate energy** stored in it.
- **Energy stored** will be returned to the circuit later
- In reality, **inductors** do have **internal resistance** due to the wiring used to make them.
- A **real inductor** thus has a **winding resistance** in **series** with it.



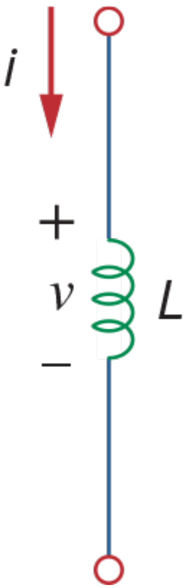
Circuit model for a practical inductor

- There is also a small **winding capacitance** due to the closeness of the windings
- These two characteristics are typically small, though at **high frequencies**, the **capacitance** may matter.

Example 6.8

Find the voltage across the inductor and the energy stored in it.

The current through a 0.1-H inductor is $i(t) = 10te^{-5t}$ A.



$$v = L\frac{di}{dt}$$

$$v = 0.1\frac{d}{dt}(10te^{-5t})$$

$$= e^{-5t} + t(-5)e^{-5t} = e^{-5t}(1 - 5t) \text{ V}$$

$$w = \frac{1}{2}Li^2$$

$$= \frac{1}{2}(0.1)100t^2e^{-10t} = 5t^2e^{-10t} \text{ J}$$

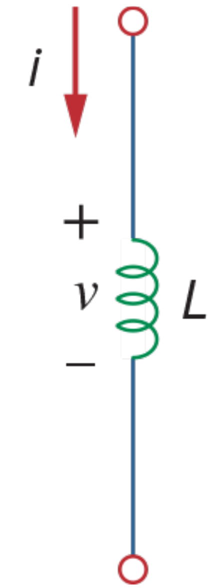
$$v = L\frac{di}{dt}$$

$$I = \frac{1}{L}\int_{t_0}^{t} v(\tau)d\tau + i(t_0)$$

$$p = vi = \left(L\frac{di}{dt}\right)i$$

$$w = \frac{1}{2}Li^2$$

Example 6.9



Find the current through a 5-H inductor

if the voltage across it is $v(t) = \begin{cases} 30t^2 \text{ (V)} & t > 0 \\ 0 & t < 0 \end{cases}$

Find the energy stored at t = 5 s. Assume i(v) > 0.

$$\begin{aligned} i(t) &= \frac{1}{L}\int_{t_0}^{t} v(\tau)\, d\tau + i(t_0) \\ &= \frac{1}{5}\int_{0}^{t} 30\tau^2\, d\tau + i(0) \\ &= \frac{30}{5}\left(\frac{t^3}{3}\right) + 0 \\ &= 2t^3 \text{ (A)} \end{aligned}$$

$$\begin{aligned} p &= v \times i \\ &= 30t^2 \times 2t^3 \\ &= 60t^5 \end{aligned}$$

$$\begin{aligned} w &= \int_0^t p\, dt \\ &= \int_0^5 60t^5 dt \\ &= 60\left(\frac{t^6}{6}\right)\Big|_0^{t=5} \\ &= 156{,}250 \text{ (J)} \\ &= 156.25 \text{ (kJ)} \end{aligned}$$

$$v = L\frac{di}{dt}$$

$$I = \frac{1}{L}\int_{t_0}^{t} v(\tau) d\tau + i(t_0)$$

$$p = vi = \left(L\frac{di}{dt}\right) i$$

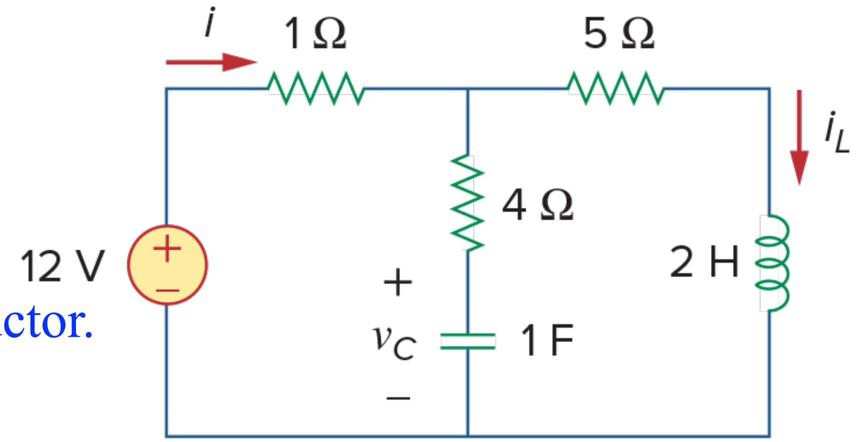
$$w = \frac{1}{2}Li^2$$

Example 6.10

Consider the circuit under dc conditions, find:

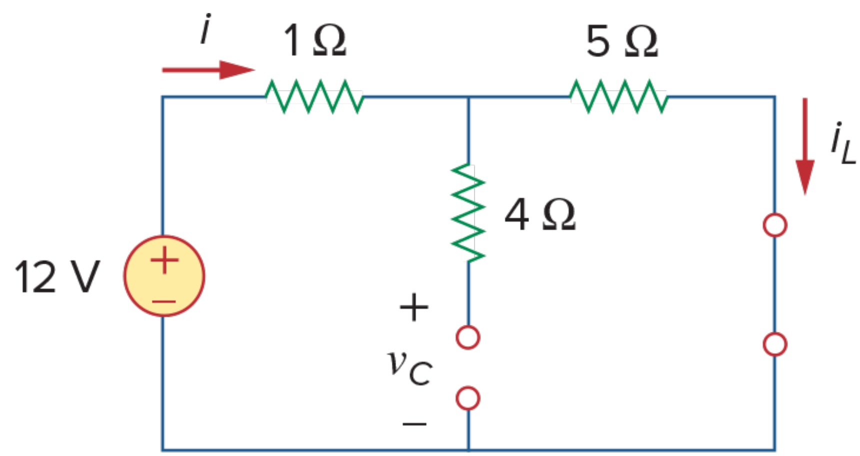
(a) $\boldsymbol{i}$, $\boldsymbol{v}_C$, and $\boldsymbol{i}_L$,

(b) the energy stored in the capacitor and inductor.



$$i = C\frac{dv}{dt}$$ DC ⇒ $\boldsymbol{i}\rightarrow 0$ ⇒ C open circuit

$$v = L\frac{di}{dt}$$ DC ⇒ $\boldsymbol{v}\rightarrow 0$ ⇒ L short circuit



$$i = i_L = \frac{12}{1+5} = 2\text{ A}$$

$$v_C = 5i = 10\text{ V}$$

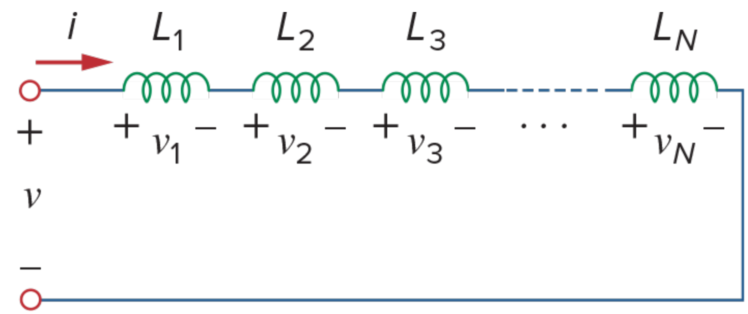
$$w_C = \frac{1}{2}Cv_C^2 = \frac{1}{2}(1)(10^2) = 50\text{ J}$$

$$w_L = \frac{1}{2}Li_L^2 = \frac{1}{2}(2)(2^2) = 4\text{ J}$$

6.5 Series and Parallel Inductors

Series Inductors

- **Applying KVL to the loop:**

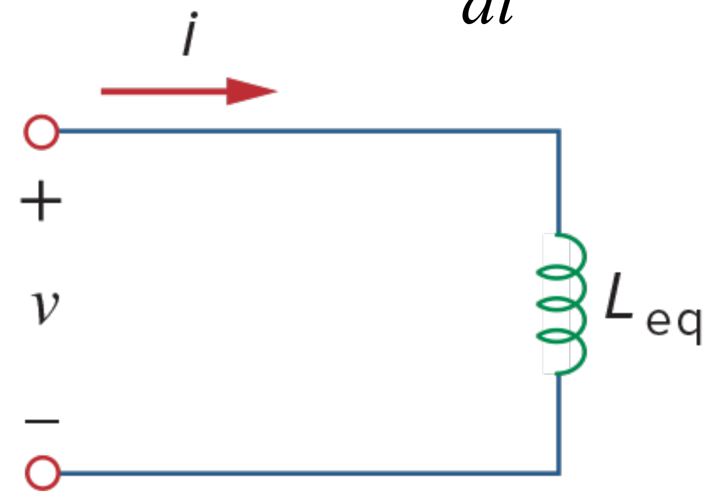


$$v = v_1 + v_2 + v_3 + \cdots + v_N$$

$$v = L\frac{di}{dt}$$

$$v = L_1\frac{di}{dt} + L_2\frac{di}{dt} + L_3\frac{di}{dt} + \cdots + L_N\frac{di}{dt}$$

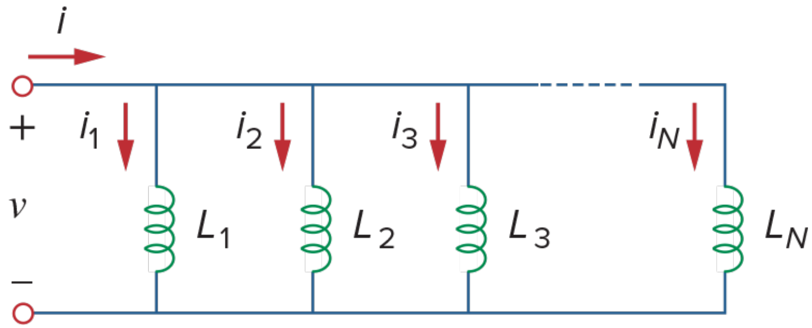
$$= \left(\sum_{k=1}^{N} L_k\right)\frac{di}{dt} = L_{eq}\frac{di}{dt}$$



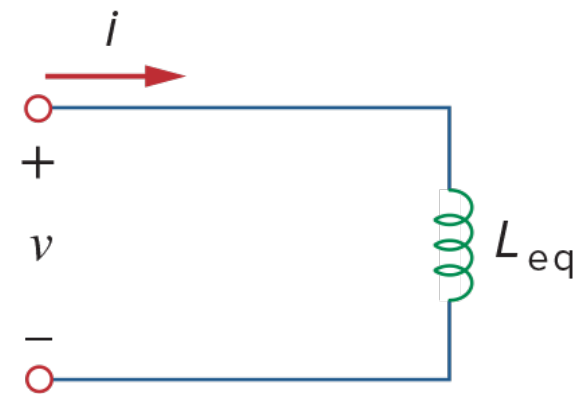
$$L_{eq} = L_1 + L_2 + L_3 + \cdots + L_N$$

Here we can see that the inductors have the same behavior as resistors

Parallel Inductors



$$v = L\frac{di}{dt}$$



- **Applying KCL to the circuit:**

$$i = i_1 + i_2 + i_3 + \cdots + i_N$$

$$i = \left(\sum_{k=1}^{N}\frac{1}{L_k}\right)\int_{t_0}^{t} v\,dt + \sum_{k=1}^{N} i_k(t_0) = \frac{1}{L_{eq}}\int_{t_0}^{t} v\,dt + i(t_0)$$

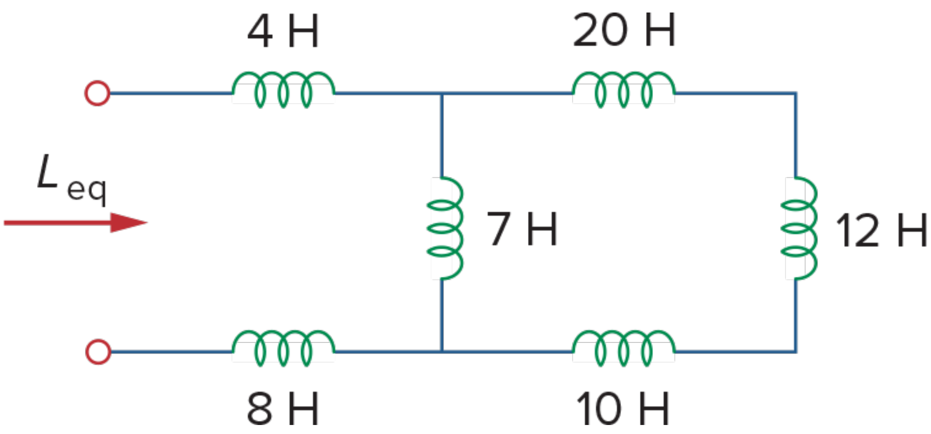
$$i(t_0) = i_1(t_0) + i_2(t_0) + \cdots + i_N(t_0)$$

$$\frac{1}{L_{eq}} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \cdots + \frac{1}{L_N}$$

- **Once again, the parallel combination resembles that of resistors**
- **On a related note, the Δ-Y transformation can also be applied to inductors and capacitors in a similar manner, as long as all elements are the same type.**

Example 6.11

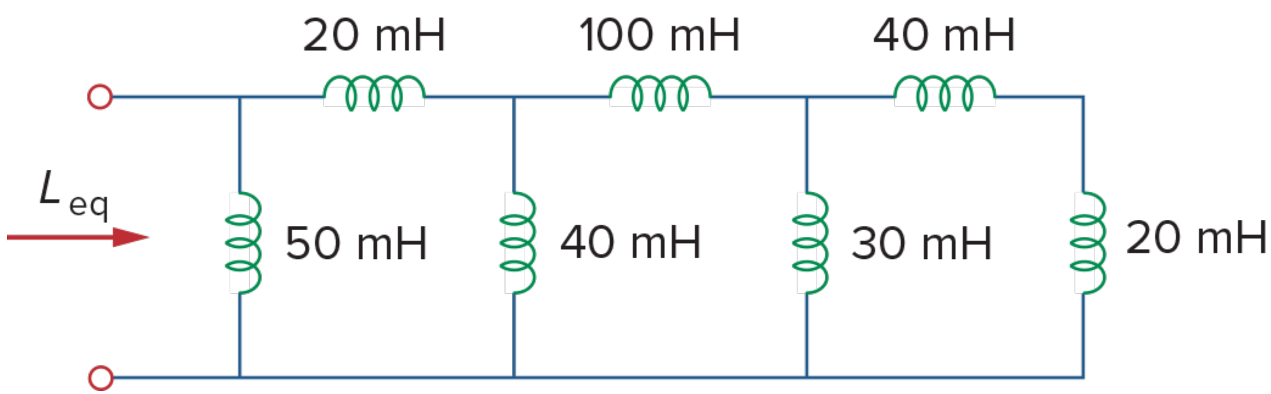
Find the equivalent inductance



$$\frac{7 \times 42}{7 + 42} = 6 \text{ H}$$

$$L_{eq} = 4 + 6 + 8 = 18 \text{ H}$$

Practice Problem 6.11



$$\begin{aligned} L_{eq} &= 50 \mathbin{/\!/} \{20 + [40 \mathbin{/\!/} (100 + 30 \mathbin{/\!/} 60)]\} \\ &= 50 \mathbin{/\!/} \{20 + [40 \mathbin{/\!/} 120]\} \\ &= 50 \mathbin{/\!/} \{20 + 30\} \\ &= 50 \mathbin{/\!/} 50 \\ &= 25 \text{ (mH)} \end{aligned}$$

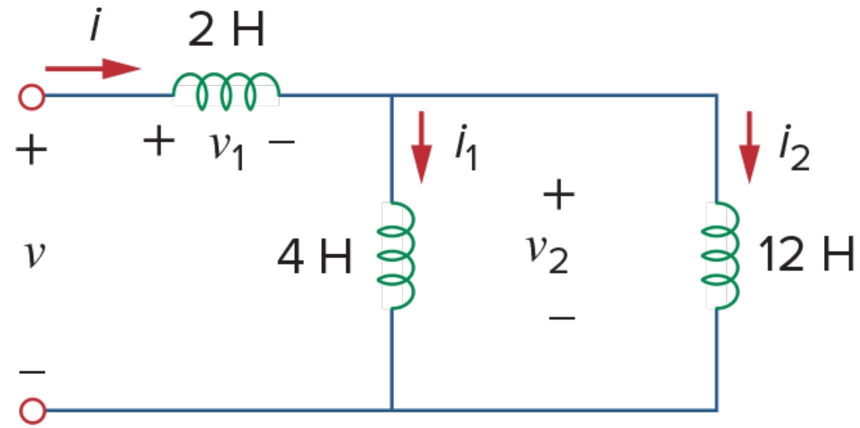
Example 6.12

For the, $i(t) = 4\cdot(2 - e^{-10t})$ mA. If $i_2(0) = -1$ mA, find:

(a) $i_1(0)$

(b) $v(t)$, $v_1(t)$, and $v_2(t)$;

(c) $i_1(t)$ and $i_2(t)$.



(a) From $i(t) = 4(2 - e^{-10t})$ mA,

$$i(0) = 4(2 - 1) = 4 \text{ mA}$$

$$i = i_1 + i_2$$

$$\Rightarrow \boxed{i_1(0) = i(0) - i_2(0) = 4 - (-1) = 5 \text{ mA}}$$

(b) The equivalent inductance

$$L_{eq} = 2 + 4 \parallel 12 = 2 + 3 = 5 \text{ H}$$

$$\begin{aligned} v(t) &= L_{eq}\frac{d\,i(t)}{dt} \\ &= 5\times\frac{d[4\cdot(2 - e^{-10t})]}{dt} \\ &= 5\times[4\times10e^{-10t}] \\ &= 200e^{-10t} \text{ (mV)} \end{aligned}$$

$$\begin{aligned} v_1(t) &= 2\frac{d\,i(t)}{dt} = 2\times[4\times10e^{-10t}] \\ &= 80e^{-10t} \text{ (mV)} \end{aligned}$$

$$\begin{aligned} v_2(t) &= v(t) - v_2(t) \\ &= (200 - 80)e^{-10t} \\ &= 120e^{-10t} \text{ (mV)} \end{aligned}$$

(c) The current i_1

$$\begin{aligned} i_1(t) &= \frac{1}{4}\int_0^t v_2(t)\,dt + i_1(0) \\ &= \frac{1}{4}\int_0^t 120e^{-10t}dt + 5 \\ &= \frac{120}{4}\left(\frac{e^{-10t}}{-10}\right)\Bigg|_0^t + 5 \\ &= -3(e^{-10t} - e^0) + 5 \\ &= -3e^{-10t} + 8 \text{ (mA)} \end{aligned}$$

$$\begin{aligned} i_2(t) &= \frac{1}{12}\int_0^t v_2(t)\,dt + i_2(0) \\ &= \frac{1}{12}\int_0^t 120e^{-10t}dt - 1 \\ &= \frac{120}{12}\left(\frac{e^{-10t}}{-10}\right)\Bigg|_0^t - 1 \\ &= -(e^{-10t} - e^0) - 1 \\ &= -e^{-10t} \text{ (mA)} \end{aligned}$$

Check if

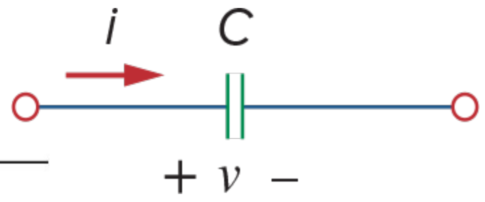
$i(t) = 4\cdot(2 - e^{-10t})$?

Summary of Capacitors & Inductors

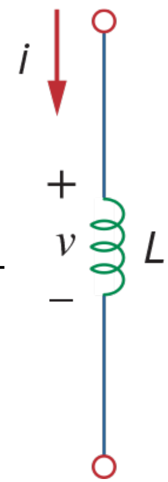
TABLE 6.1

Important characteristics of the basic elements.†

Relation	Resistor (R)	Capacitor (C)	Inductor (L)
v-i:	$v = iR$	$v = \frac{1}{C}\int_{t_0}^{t} i(\tau)d\tau + v(t_0)$	$v = L\frac{di}{dt}$
i-v:	$i = v/R$	$i = C\frac{dv}{dt}$	$i = \frac{1}{L}\int_{t_0}^{t} v(\tau)d\tau + i(t_0)$
p or w:	$p = i^2R = \frac{v^2}{R}$	$w = \frac{1}{2}Cv^2$	$w = \frac{1}{2}Li^2$
Series:	$R_{eq} = R_1 + R_2$	$C_{eq} = \frac{C_1C_2}{C_1 + C_2}$	$L_{eq} = L_1 + L_2$
Parallel:	$R_{eq} = \frac{R_1R_2}{R_1 + R_2}$	$C_{eq} = C_1 + C_2$	$L_{eq} = \frac{L_1L_2}{L_1 + L_2}$
At dc:	Same	Open circuit	Short circuit
Circuit variable that cannot change abruptly:	Not applicable	v	i



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

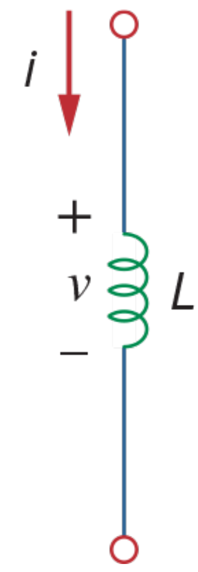


$$v = L\frac{di}{dt}$$

Applications

Inductors

$$v = L\frac{di}{dt}$$



- Due to their bulky size, inductors are less frequently used as compared to capacitors, however they have some applications where they are best suited.

- They can be used to create a large amount of current or voltage for a short period of time.
- Their resistance to sudden changes in current can be used for spark suppression.
- Along with capacitors, they can be used for frequency discrimination.