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A PURDUE UNIVERSITY SCHOOL
Indianapolis

ECE 202 – Spring 2015

(Butler Campus)

Purdue School of Engineering and Technology, IUPUI

Scott Weigand

January 12, 2015

Course Information

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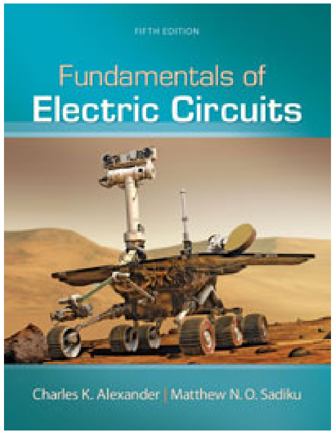
- Course ECE 202 Spring 2014 (Butler Campus)
  - Monday & Wednesday 6:00 – 7:15 pm
  - Room: JH 336B
  - No Class: 19 Jan (MLK Day)
  - No Class: 10 - 12 March (Spring Break)
- Oncourse https://oncourse.iu.edu/portal :
  - Lecture Notes, Homework, links to tools
- Text:
  - *5th Edition: "Fundamentals of Electric Circuits" by* Alexander and Sadiku
- Syllabus / Course Description:
  - http://et.engr.iupui.edu/departments/ece/courses/ece/20200.php
- Instructor: Scott Weigand
  - Phone: 317-509-1686 (cell / text)
  - E-mail: saweigan@iupui.edu
  - Office Hours: After class Monday & Wednesday



Grading

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- 10% for 10 Homework Assignments
- 60% for 4 Quizzes (15% each)
- 30% for Final Exam

Expectations of Students

- Responsibility to learn:
  - Attend lectures, read text and review lecture material, do homework assignments, check email and On Course for up to date course info
  - Emergencies may Excuse student from missing due dates for Homework or missing Exam time – and student must request makeup time BEFORE the event (by email, phone)
- Integrity:
  - IUPUI policy: http://www.iupui.edu/code/#page
  - Cheating on Exams will result in an "F" grade for the course
  - Any grading mistakes or disputes must be submitted in writing within 2 weeks after paper or exam is returned.
- Professionalism: Get Ready for the Working World
  - Treat Professor and other students with respect
  - Take opportunities for continuous improvement

Expectations of the Instructor

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- Teaching Responsibility
  - Prepared for Lectures
  - Available for help – set office hours & email
  - Prompt feedback on HW, Exams
- Integrity
  - Professional behavior, following IUPUI policy
  - Open and honest feedback
- Prepare Students for the Working World
  - Teaching Best Practices for Circuit Design

Outline of ECE 202

Spring 2015 Butler Campus (May be adjusted during semester)

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Date	Lecture Topic	Chapter	Homework
1/12	Review Circuit Analysis (ECE 201)	Ch. 1 - 7	
1/14	Review Circuit Analysis (ECE 201)	Ch. 8 - 11	
1/19	**No Class - Martin Luther King Day**		
1/21	Magnetic Coupling, Mutual Inductance	Ch. 13.1 - 13.3	HMWK 1 Due
1/26	Linear Transformers	Ch. 13.4	HMWK 2 Due
1/28	Ideal Transformers	Ch. 13.5	
2/2	Autotransformers, Applications, & Exam Review	Ch. 13.6, 13.8, 13.9	HMWK 3 Due
2/4	**Quiz 1**		
2/9	Frequency Response, Transfer function, Bode Plots	Ch. 14.1 - 14.4	
2/11	Bode Plots, Series Resonance	Ch. 14.4 - 14.5	
2/16	Series Resonance & Parallel Resonance	Ch. 14.5 - 14.6	HMWK 4 Due
2/18	Parallel Resonance, Passive Filters	Ch. 14.6 - 14.7	
2/23	Passive Filters, Active Filters, Pspice	Ch. 14.7, 14.8, 14.10	HWMK 5 Due
2/25	Magnitude and Frequency Scaling, Applications	Ch. 14.9, 14.12	
3/2	Exam Review		HWMK 6 Due
3/4	**Quiz 2**		
3/9	**No Class - Spring Break - Butler**		
3/11	**No Class - Spring Break - Butler**		
3/16	Introduction to Laplace Transform	Ch. 15.1 - 15.3	
3/18	Inverse Laplace Transform, Convolution Integral	Ch. 15.4 - 15.5	
3/23	Laplace Circuit Element Models	Ch. 16.1 - 16.2	HWMK 7 Due
3/25	Laplace Circuit Analysis	Ch. 16.3	
3/30	Transfer Functions	Ch. 16.4	HWMK 8 Due
4/1	Aplications & Exam Review	Ch. 16.6	
4/6	**Quiz 3**		
4/8	Two Port Network - Impedance "Z" Parameters	Ch. 19.1 - 19.2	
4/13	Admittance "Y" Parameters, Hybrid "H" Parameters	Ch. 19.3 - 19.4	HMWk 9 Due
4/15	Transmission "ABCD" Parameters, Relationships	Ch. 19.5 - 19.6	
4/20	Applications & Exam Review	Ch. 19.9	HMWk 10 Due
4/22	**Quiz 4**	Ch. 19	
4/27	Final Exam Review		
4/29 or 5/4	**Final Exam (Butler)**		

IUPUI Spring Break → 3/16

Franklin Spring Break → 3/30

Where this course fits in

Prerequisites

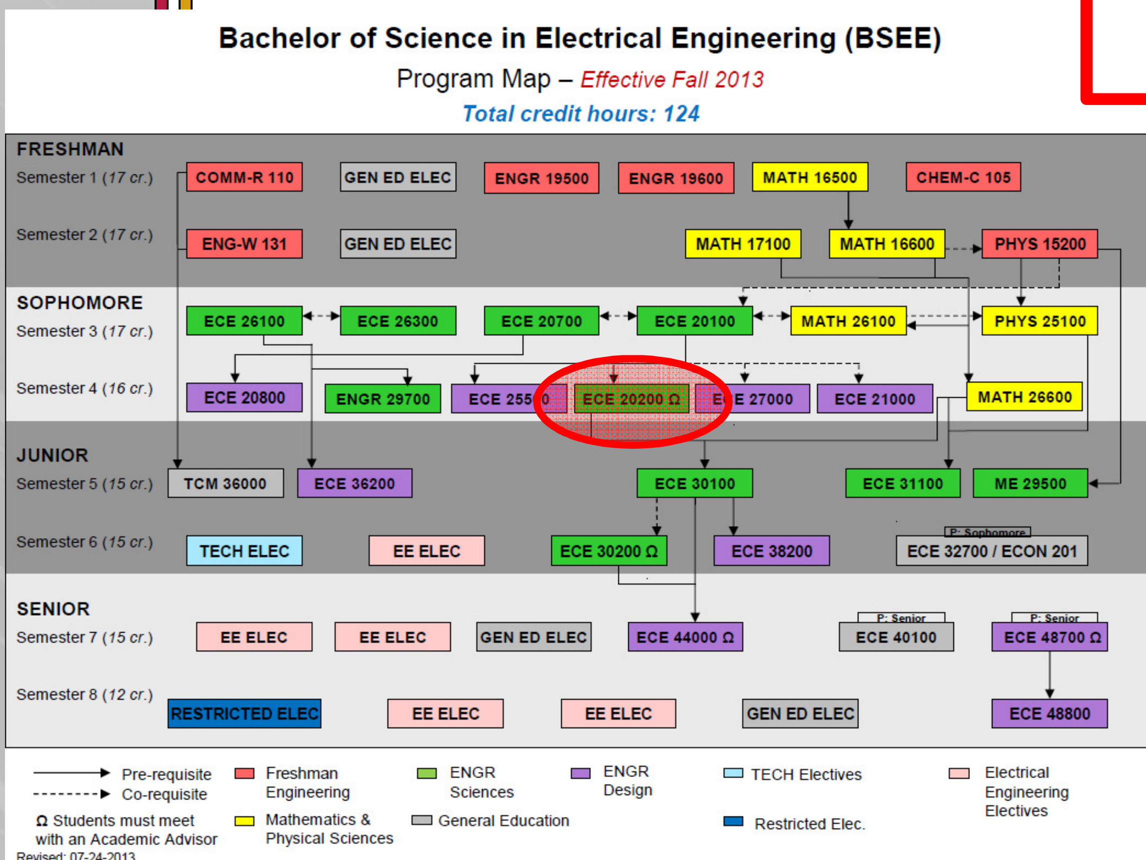
ECE 201 "Linear Circuit Analysis I"
MATH 261 "Multivariate Calculus"

This Course

ECE 202 "Linear Circuit Analysis II"

What's Next

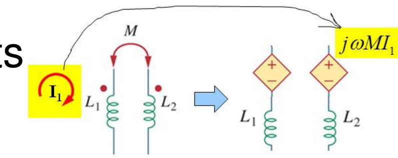
ECE 301 "Signals and Systems"
ECE 302 "Probabilistic Methods"

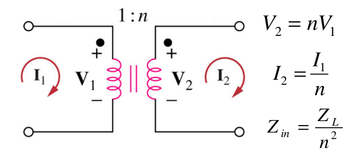


ECE 202 Overview

EXAM 1

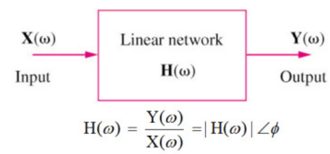
- Chapter 13: Magnetically coupled circuits
  - Mutual Inductance
  - Linear Transformers
  - Ideal Transformers

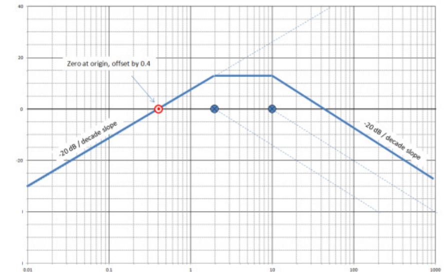


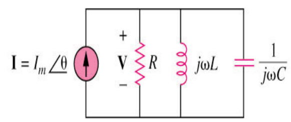


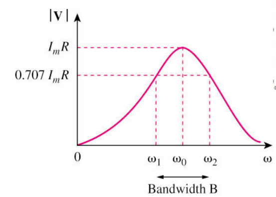
EXAM 2

- Chapter 14: Frequency Response
  - Introduction to the Transfer Function
  - Bode Plots (Magnitude / Phase)
  - Series / Parallel resonant circuits
  - Passive / Active Filters





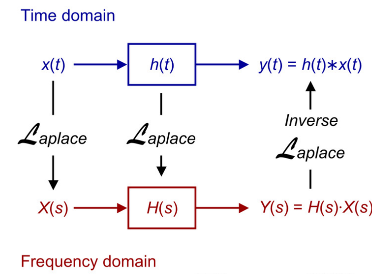




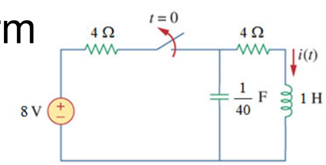
EXAM 3

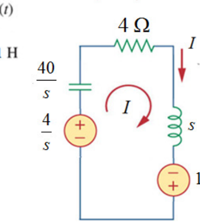
- Chapter 15: Laplace Transform (Theory)
  - Transformation from “t – domain” to the “s – domain”
  - Properties of Laplace Transform
  - Convolution Integral (“Flip and shift”)

$$y(t) = x(t) * h(t) = \int_{-\infty}^{\infty} x(\lambda) h(t-\lambda) d\lambda$$



- Chapter 16: Application of Laplace Transform
  - Circuit analysis in the “s – domain”
  - Transfer Function in “s – domain”

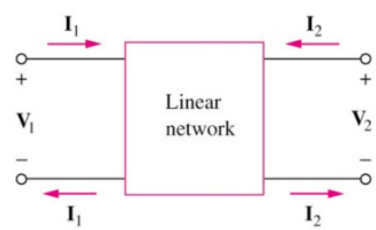




$f(t)$	$F(s)$
$\delta(t)$	1
$u(t)$	$\frac{1}{s}$
e^{-at}	$\frac{1}{s+a}$

EXAM 4

- Chapter 19: Two-Port Networks (“black box”)
  - Z – parameters, Y – parameters
  - H – parameters
  - Transmission “ABCD” parameters



$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = [z] \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

- Part I DC Circuits
  - 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: First-Order Circuits

Basic Concepts - Chapter 1 Review

1.2 Systems of Units (X)

1.3 Charge and Current

1.4 Voltage

1.5 Power and Energy

1.6 Circuit Elements

1.3 Charge and Current

- The relationship between current i (A), charge q (C), and time t (s) is $i = dq/dt$, and 1 A = 1C/s.
- The charge transferred between t_0 time and t is

$$Q = \int_{t_0}^{t} i dt$$

- A direct current (dc) is a current that remains constant with time.
- An alternating current (ac) is a current that varies sinusoidally with time.

1.4 Voltage

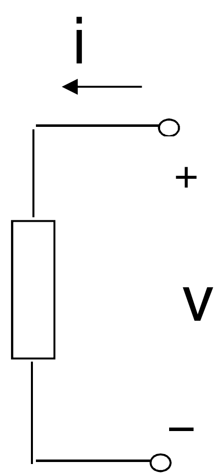
- Voltage (or potential difference) is the energy required to move a unit charge through an element, measured in volts (V).
- Mathematically, $v_{ab} = dw / dq$
  - w is energy in joules (J) and q is charge in coulomb (C).
  - V_{ab} is the voltage measured in volts between (a) and (b).
  - 1 volt = 1 joule/coulomb
- Voltage (potential difference) is always measured with respect to a reference (i.e. ground).

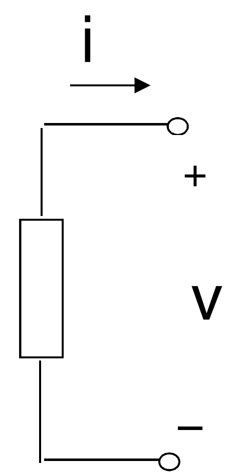
1.5 Power and Energy (1)

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

- Mathematical expression:

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





Passive sign convention

P = +vi
absorbing power

p = –vi
supplying power

1.5 Power and Energy (2)

- The law of conservation of energy requires that the algebraic sum of power in a circuit, at any instant of time, must be zero:

$$\sum p = 0$$

- Energy is the capacity to do work, measured in joules (J).

- The energy absorbed or supplied by an element from time t_0 to t_1 is expressed as:

$$w = \int_{t_0}^{t_1} p\,dt = \int_{t_0}^{t_1} vi\,dt$$

1.6 Circuit Elements (1)

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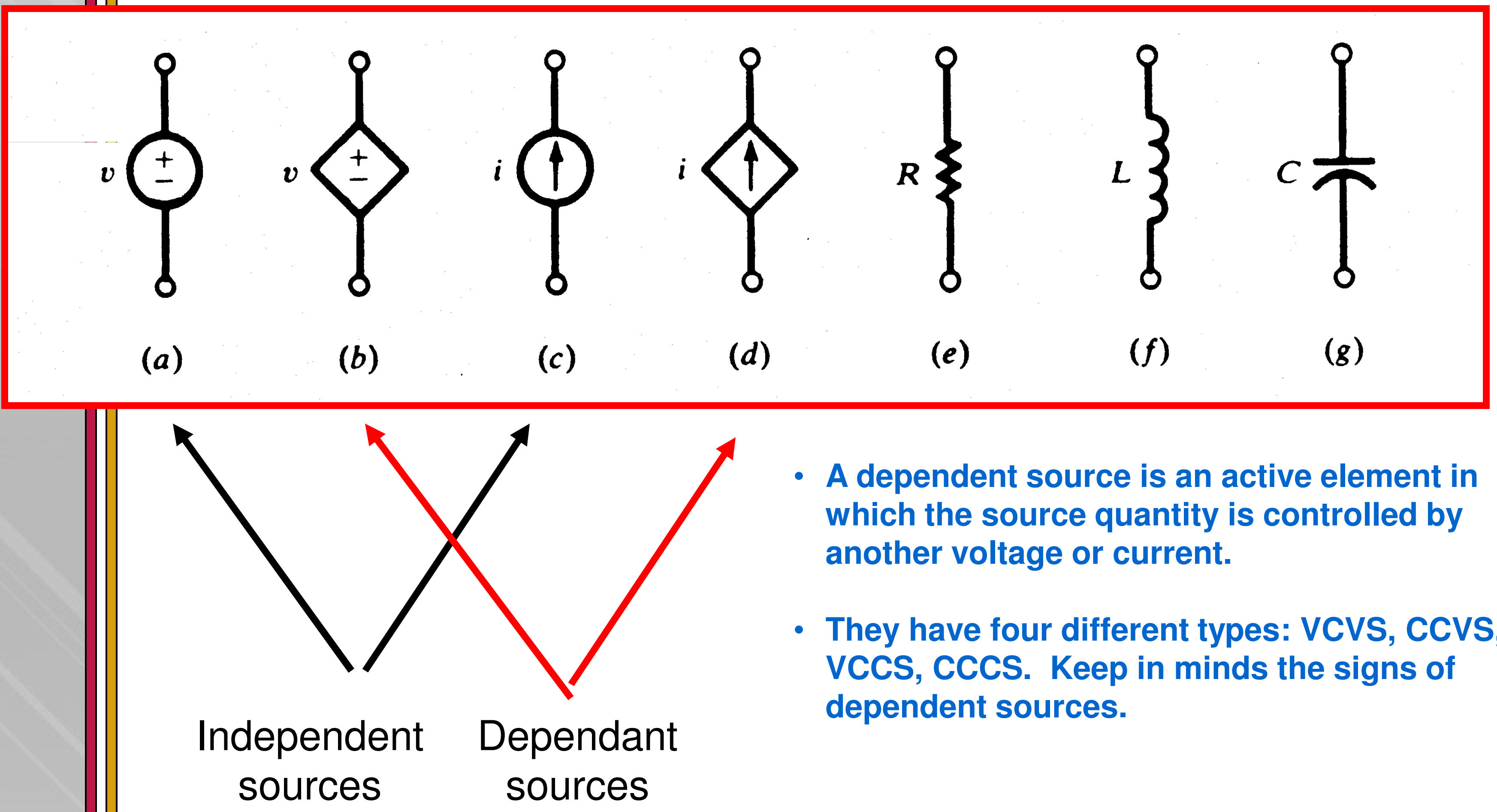
Active Elements **Passive Elements**



- **A dependent source is an active element in which the source quantity is controlled by another voltage or current.**
- **They have four different types: VCVS, CCVS, VCCS, CCCS. Keep in minds the signs of dependent sources.**

Basic Laws - Chapter 2 Review

- 2.2 Ohm's Law
- 2.3 Nodes, Branches, and Loops (X)
- 2.4 Kirchhoff's Laws
- 2.5 Series Resistors and Voltage Division
- 2.6 Parallel Resistors and Current Division
- 2.7 Wye-Delta Transformations

2.2 Ohms Law (1)

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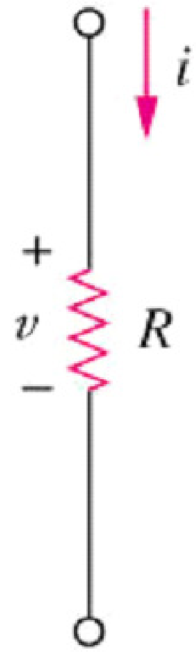
- Ohm's law states that the voltage across a resistor is directly proportional to the current *i* flowing through the resistor.

$$v = iR$$

- A short circuit is a circuit element with resistance approaching **zero (0)**.

- An open circuit is a circuit element with resistance approaching **infinity (∞)**.



2.2 Ohms Law (2)

- *Conductance* *G* is the ability of an element to conduct electric current; it is the reciprocal of resistance R and is measured in mhos or siemens.

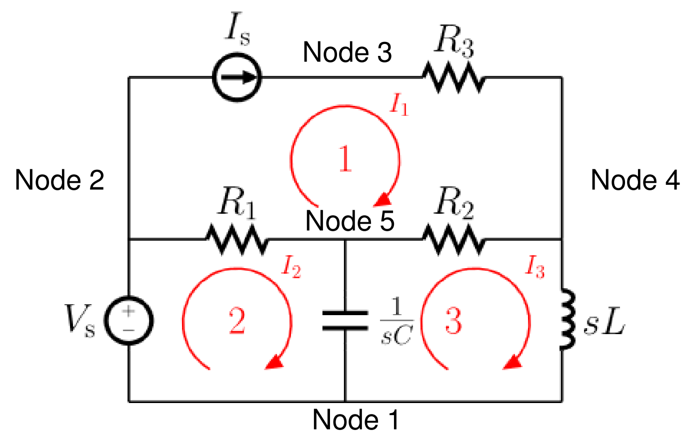
$$G = \frac{1}{R} = \frac{i}{v}$$

- The power dissipated by a resistor:

$$p = vi = i^2 R = \frac{v^2}{R}$$

2.3 Nodes, Branches and Loops

- A branch represents a single element (component) such as a voltage source or a resistor.
- A node is the point of connection between two or more branches.
- A loop is any closed path in a circuit.



3 Loops
5 Nodes
7 Branches (elements)

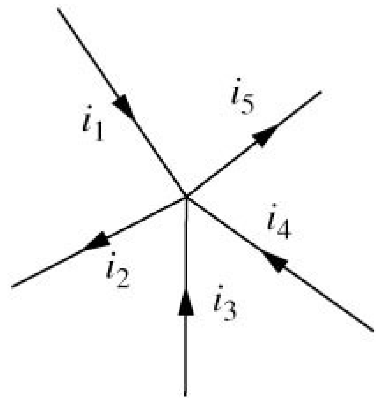
7 = 3 + 5 - 1

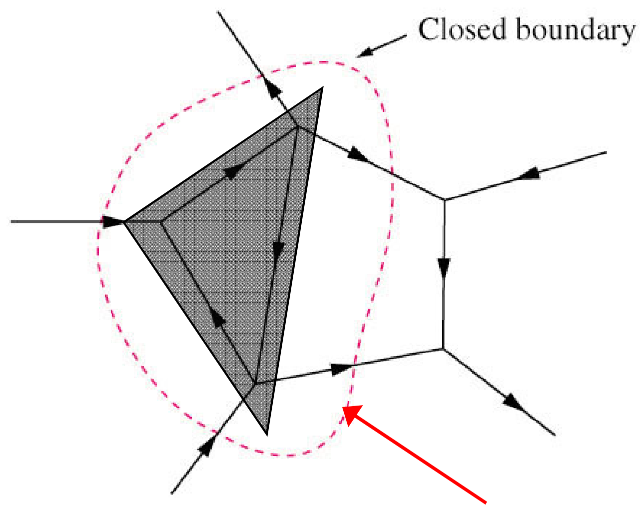
- A network with b branches, n nodes, and l independent loops will satisfy the fundamental theorem of network topology:

$$b = l + n - 1$$

2.4 Kirchhoff's Current Law (KCL)

- The algebraic sum of currents entering a node (or a closed boundary) is zero.



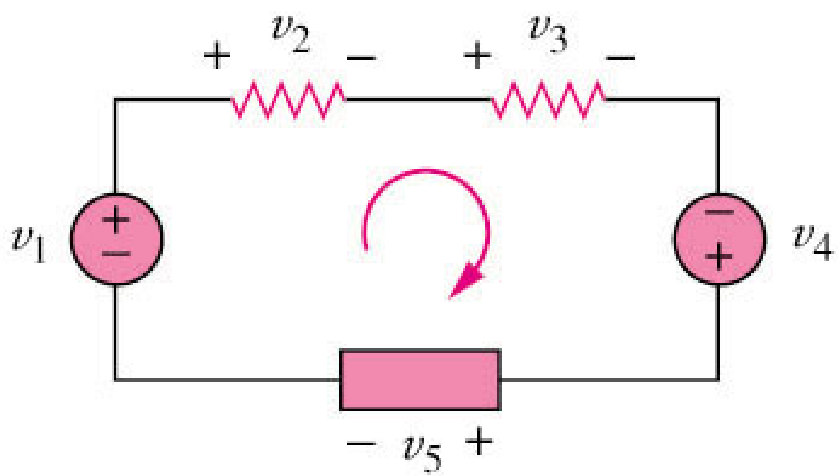


"Super-Node!"
Chapter 3.2

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

2.4 Kirchhoff's Voltage Law (KVL)

- The algebraic sum of all voltages around a closed path (or loop) is zero.



Mathematically, $$\sum_{m=1}^{M} v_m = 0$$

2.5 Series Resistors and Voltage Division

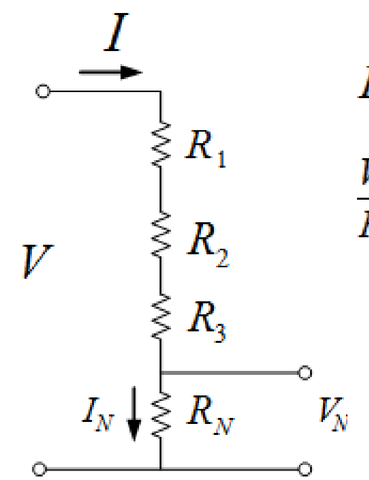
- Series: Two or more elements are in series if they are cascaded or connected sequentially and consequently carry the same current.

- The equivalent resistance of any number of resistors connected in a series is the sum of the individual resistances.

$$R_{eq} = R_1 + R_2 + \cdots + R_N = \sum_{n=1}^{N} R_n$$

- The voltage divider can be expressed as

$$v_n = \frac{R_n}{R_1 + R_2 + \cdots + R_N} v$$



$$I_N = I$$

$$\frac{V_N}{R_N} = \frac{V}{R_{eq}} = \frac{V}{\sum_{i=1}^{N} R_i}$$

2.6 Parallel Resistors and Current Division

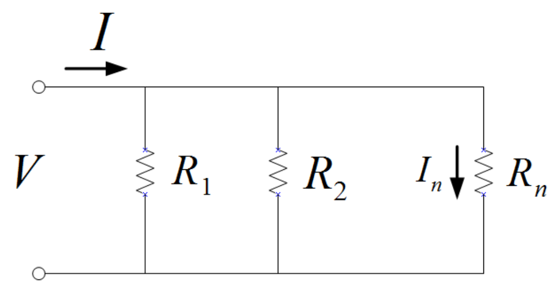
- Parallel: Two or more elements are in parallel if they are connected to the same two nodes and consequently have the same voltage across them.

- The equivalent resistance of a circuit with N resistors in parallel is:

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_N}$$

- The total current i is shared by the resistors in inverse proportion to their resistances. The current divider can be expressed as:

$$i_n = \frac{v}{R_n} = \frac{iR_{eq}}{R_n}$$

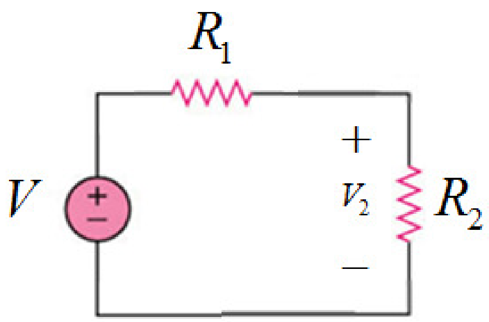


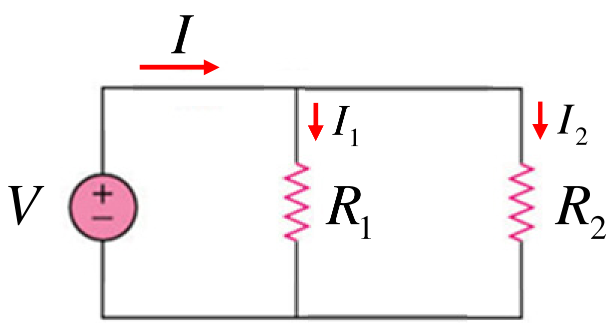
$$V_n = V$$

$$I_n R_n = I R_{eq}$$

2.5 & 2.6 Voltage Divider / Current Divider

- You should be expected to know the equations for a voltage divider & current divider for simple circuits.





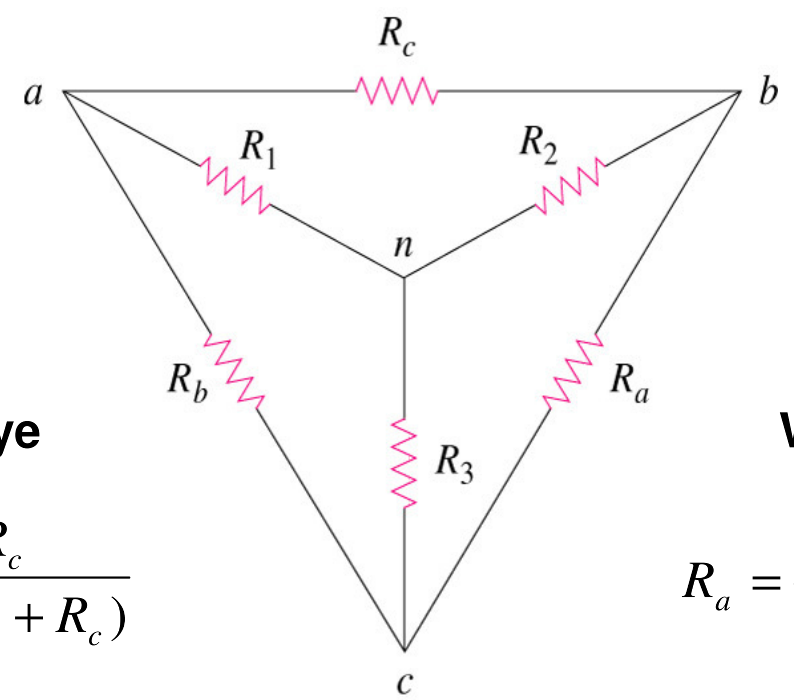
Simple Voltage Divider

$$V_2 = \left(\frac{R_2}{R_1 + R_2}\right)V$$

Simple Current Divider

$$I_2 = \left(\frac{R_1}{R_1 + R_2}\right)I$$

2.7 Wye-Delta Transformations



Delta -> Wye

$$R_1 = \frac{R_b R_c}{(R_a + R_b + R_c)}$$

$$R_2 = \frac{R_c R_a}{(R_a + R_b + R_c)}$$

$$R_3 = \frac{R_a R_b}{(R_a + R_b + R_c)}$$

Wye -> Delta

$$R_a = \frac{R_1 R_2 + R_2 R_3 + R_3 R_1}{R_1}$$

$$R_b = \frac{R_1 R_2 + R_2 R_3 + R_3 R_1}{R_2}$$

$$R_c = \frac{R_1 R_2 + R_2 R_3 + R_3 R_1}{R_3}$$

Methods of Analysis - Chapter 3 Review

- 3.2 Nodal Analysis
- 3.3 Nodal Analysis with Voltage Sources
- 3.4 Mesh Analysis
- 3.5 Mesh Analysis with Current Sources

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3.2 Nodal Analysis

- Procedure for analyzing circuits using node voltages
- Uses KCL to sum currents at each node → $\boxed{i_{in} = i_{out}}$

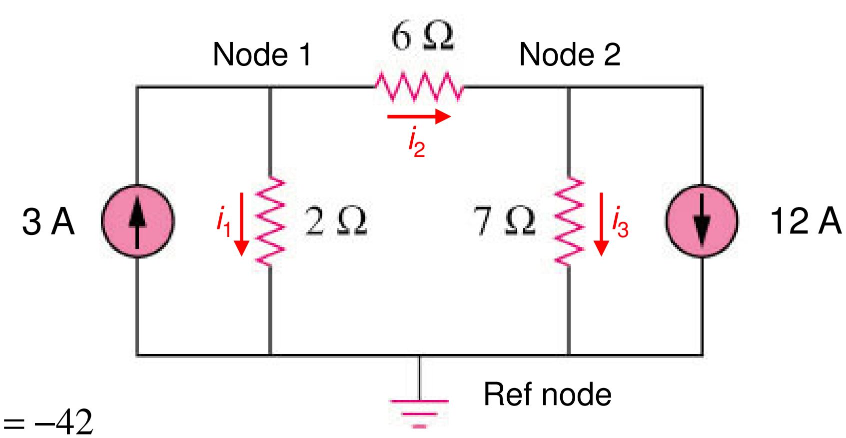
Steps to determine the node voltages:

1. Select a node as the reference node (i.e. ground).
2. Assign voltages v1,v2,…,vn-1 to the remaining n-1 nodes. The voltages are referenced with respect to the reference node.
3. Apply KCL to each of the n-1 non-reference nodes. Use Ohm's law to express the branch currents in terms of node voltages.
4. Solve the resulting simultaneous equations to obtain the unknown node voltages.

Node 1	Node 2
$3 = i_1 + i_2 \Rightarrow i_1 + i_2 = 3$	$i_2 = i_3 + 12 \Rightarrow i_2 - i_3 = 12$
$\frac{v_1}{2} + \frac{v_1 - v_2}{6} = 3$	$\frac{v_1 - v_2}{6} - \frac{v_2}{7} = 12$
$3v_1 + v_1 - v_2 = 3 \times 6$	$7(v_1 - v_2) - 6v_2 = 12 \times 42$
$4v_1 - v_2 = 18$	$7v_1 - 13v_2 = 504$

Solve $\begin{bmatrix} 4 & -1 \\ 7 & -13 \end{bmatrix}\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} 18 \\ 504 \end{bmatrix} \Rightarrow v_1 = -6 \;;\; v_2 = -42$

Practice Problem 3.1



3.3 Nodal Analysis with Voltage Source

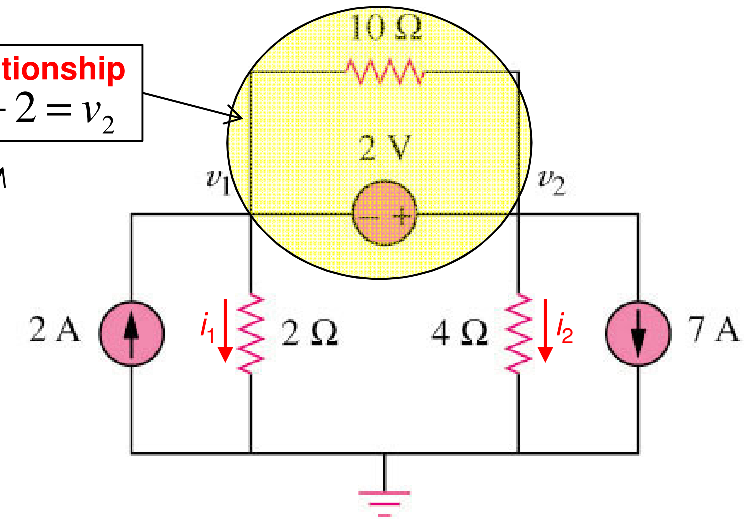
If circuit contains a voltage source (dependent or independent), use a "Super Node"

Steps to determine the node voltages:

1. Create a super-node by enclosing a (dependent or independent) voltage source connected between two non-reference nodes and any elements connected in parallel with it.
2. Observe that enclosed source gives a relational equation between the nodes combined by the "super-node" (you get one for free!)
3. Apply KCL to the "Super-Node" and follow same steps as before for Nodal Analysis to create equations.
4. Solve the resulting simultaneous equations to obtain the unknown node voltages.

Example 3.3 –circuit with independent voltage source

Relationship
$v_1 + 2 = v_2$



Super node

$$i_{in} = i_{out}$$
$$2 = i_1 + i_2 + 7$$
$$i_1 + i_2 = -5$$
$$\frac{v_1}{2} + \frac{v_2}{4} = -5$$
$$2v_1 + v_2 = -20$$

Apply $i_{in} = i_{out}$ to super-node

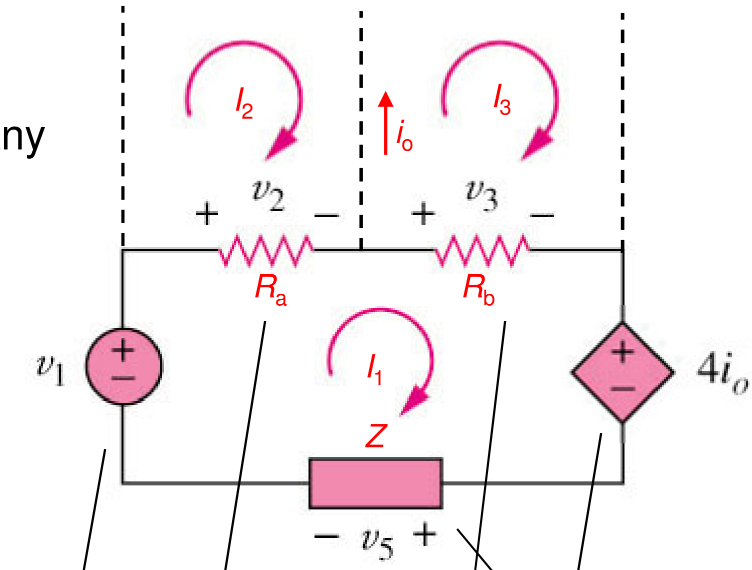
$$\begin{bmatrix} 1 & -1 \\ 2 & 1 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} -2 \\ -20 \end{bmatrix} \Rightarrow \quad v_1 = -7.333 \quad ; \quad v_2 = -5.333$$

3.4 Mesh Analysis (1)

- Procedure for analyzing circuits using mesh currents
- Applies KVL to find unknown currents.
- A mesh is a loop which does not contain any other loops within it.

Steps to determine the mesh currents:

1. Assign mesh currents i_1, i_2, …, in to the n meshes.
2. Apply KCL to each of the n meshes. Use Ohm's law to express the voltages in terms of the mesh currents.
3. Solve the resulting n simultaneous equations to get the mesh currents.

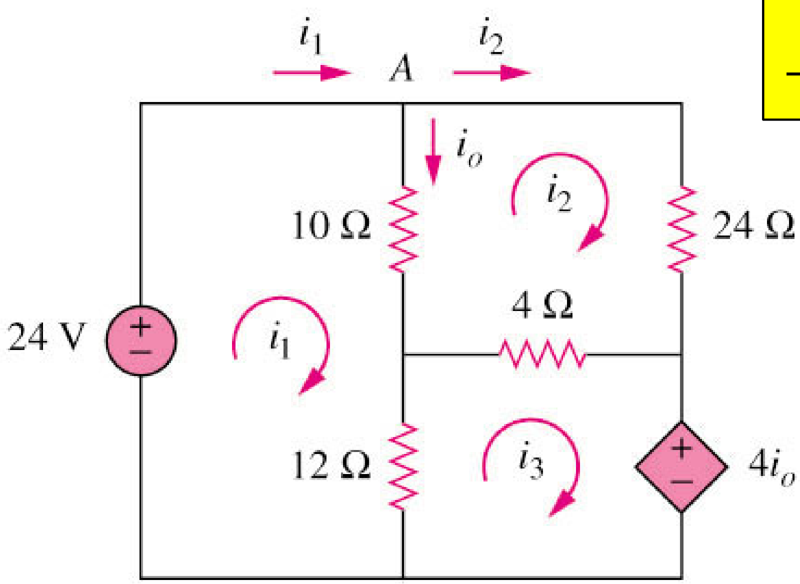


$$\sum_{i=1}^{N} v_i = 0$$

$$-v_1 + R_a(i_1 - i_2) + R_b(i_1 - i_3) + 4i_0 + Zi_1 = 0$$

Current enters negative terminal so v_1 is negative

3.4 Mesh Analysis (Example)



i_2 Mesh

$$-10i_1 + 38i_2 - 4i_3 = 0$$

i_1 Mesh

$$-24 + 10(i_1 - i_2) + 12(i_1 - i_3) = 0$$
$$11i_1 - 5i_2 - 6i_3 = 12$$

i_3 Mesh

$$-12i_1 - 4i_2 + 16i_3 + 4(i_1 - i_2) = 0$$
$$-8i_1 - 8i_2 + 16i_3 = 0$$

Solve

$$\begin{bmatrix} 11 & -5 & -6 \\ -10 & 38 & -4 \\ -8 & -8 & 16 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} = \begin{bmatrix} 12 \\ 0 \\ 0 \end{bmatrix} \Rightarrow \begin{matrix} i_1 = 2.25 \\ i_2 = 0.75 \\ i_3 = 1.5 \end{matrix}$$

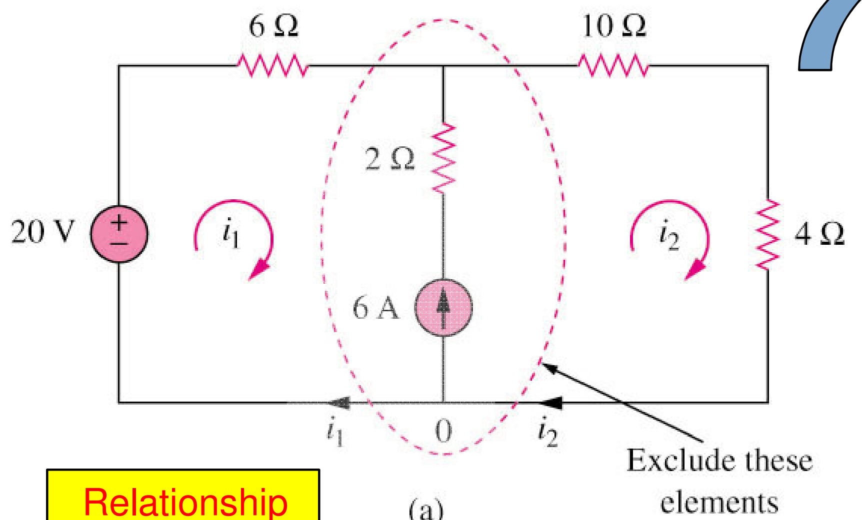
3.5 Mesh Analysis with Current Source (1)

Circuit with current source "Use a Super-Mesh"

Super Mesh

$$-20 + 6i_1 + 10i_2 + 4i_2 = 0$$

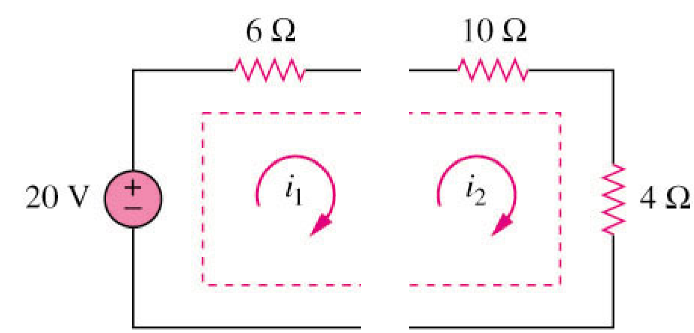
$$6i_1 + 14i_2 = 20$$



Relationship

$$i_1 - i_2 = -6$$

(a)



(b)

A **super-mesh** results when two meshes have a (dependent or independent) current source in common as shown in (a).

We create a super-mesh by excluding the current source and any elements connected in series with it as shown in (b).

3.5 Mesh Analysis with Current Source (2)

The properties of a super-mesh:

- The current source in the super-mesh is not completely ignored; it provides the constraint equation necessary to solve for the mesh currents.
- A super-mesh has no current of its own.
- A super-mesh requires the application of both KVL and KCL.

Nodal versus Mesh Analysis

- Select the method that results in the smaller number of equations.

- Choose nodal analysis for
  - Circuits with fewer nodes than meshes.
  - Networks with parallel-connected elements, current sources, or supernodes are more suitable for nodal analysis.
  - If node voltages are required, may be expedient to apply nodal analysis

- Choose mesh analysis
  - Circuits with fewer meshes than nodes.
  - Networks that contain many series connected elements, voltage sources, or supermeshes are more suitable for mesh analysis.
  - If branch or mesh currents are required, may be better to use mesh analysis.

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4.2 Linearity Property
4.3 Superposition
4.4 Source Transformation
4.5 Thevenin's Theorem
4.6 Norton's Theorem
4.7 Derivations of Theorems (X)
4.8 Maximum Power Transfer

4.2 Linearity Property

It is the property of an element describing a linear relationship between cause and effect.

A linear circuit is one whose output is linearly related (or directly proportional) to its input.

Homogeneity (scaling) property

$$v = i\,R \quad \rightarrow \quad k\,v = k\,i\,R$$

Additive property

$$v_1 = i_1 R \text{ and } v_2 = i_2 R$$
$$\rightarrow \; v = (i_1 + i_2) R = v_1 + v_2$$

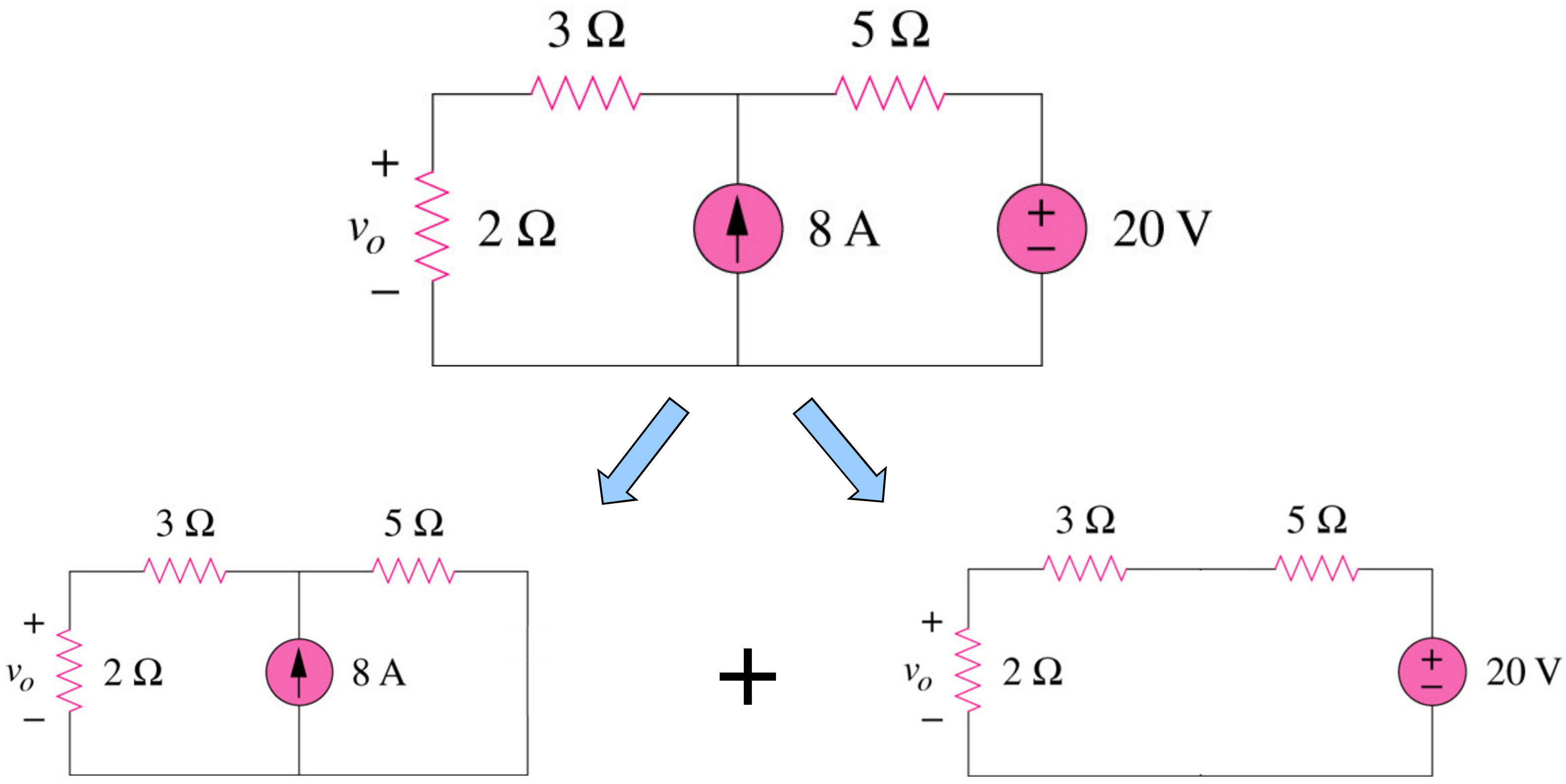
4.3 Superposition Theorem (1)

It states that the voltage across (or current through) an element in a linear circuit is the algebraic sum of the voltages across (or currents through) that element due to EACH independent source acting alone.

The principle of superposition helps us to analyze a linear circuit with more than one independent source by calculating the contribution of each independent source separately.

4.3 Superposition Theorem (2)

We consider the effects of 8A and 20V one by one, then add the two effects together for final v_o.



Short circuit the voltage sources
V = 0 = short circuit

Open circuit the current sources
I = 0 = open circuit

4.3 Superposition Theorem (3)

Steps to apply superposition principle

1. Turn off all independent sources except one source. Find the output (voltage or current) due to that active source using nodal or mesh analysis.

2. Repeat step 1 for each of the other independent sources.

3. Find the total contribution by adding algebraically all the contributions due to the independent sources.

4.3 Superposition Theorem (4)

Two things have to be keep in mind:

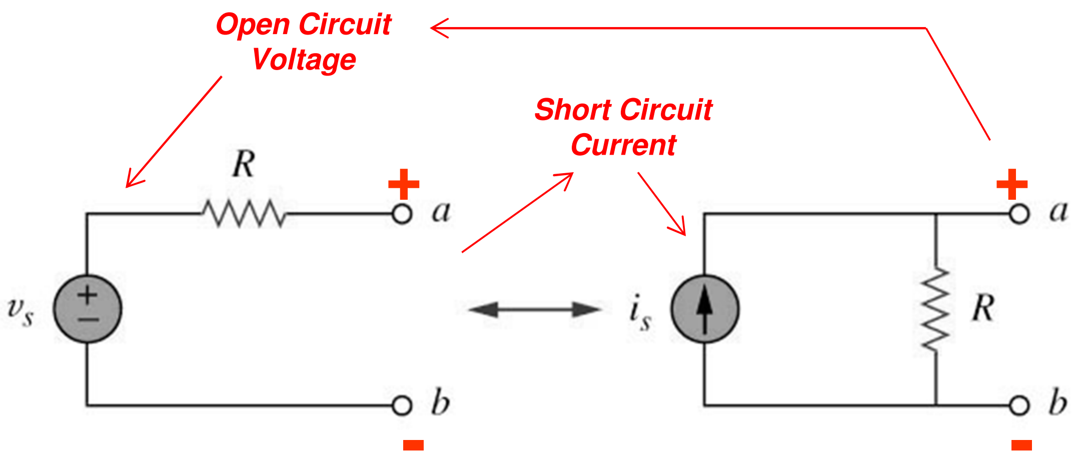
1. When we say turn off all other independent sources:
   - Independent voltage sources are replaced by 0 V (short circuit) and
   - Independent current sources are replaced by 0 A (open circuit).

2. Dependent sources are left intact because they are controlled by circuit variables.

4.4 Source Transformation (1)

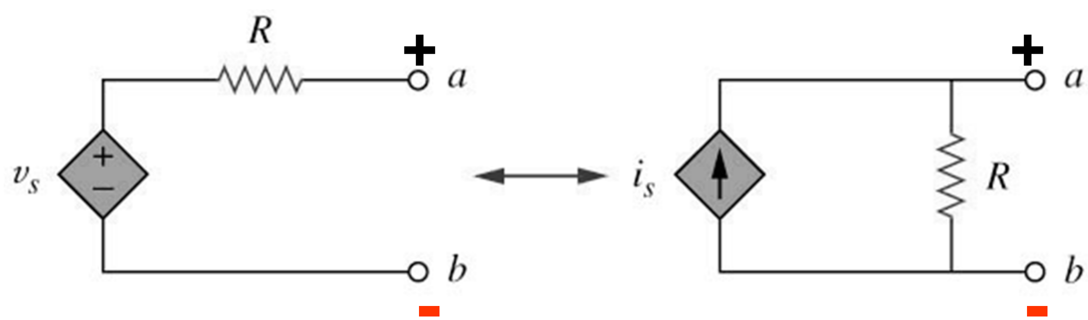
- An equivalent circuit is one whose *v-i* characteristics are identical with the original circuit.
- It is the process of replacing <u>a voltage source v_S in series with a resistor R</u> by a <u>current source i_S in parallel with a resistor R</u>, or vice versa.

4.4 Source Transformation (2)



(a) Independent source transform

- The arrow of the current source is directed toward the positive terminal of the voltage source.



(b) Dependent source transform

Note: Pay attention to dependent variable

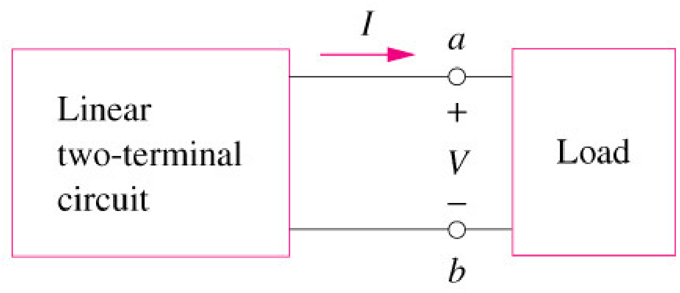
- The source transformation is not possible when R = 0 for voltage source and R = ∞ for current source.

4.5 Thevenin’s Theorem

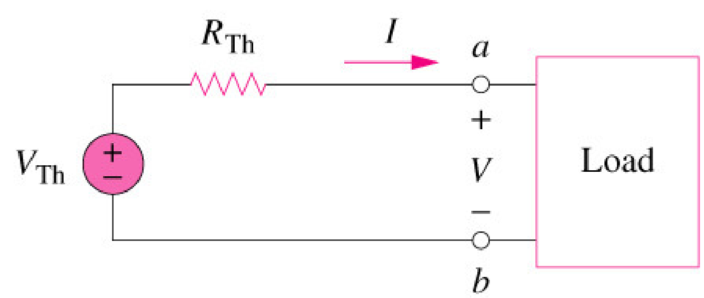
It states that a linear two-terminal circuit (Fig. a) can be replaced by an equivalent circuit (Fig. b) consisting of a voltage source V_{TH} in series with a resistor R_{TH},

- V_{TH} is the open-circuit voltage at the terminals.

- R_{TH} is the input or equivalent resistance at the terminals when the independent sources are turned off.



(a)



(b)

V_{TH} = Open-Circuit voltage at the terminals

R_{TH} = Open-Circuit voltage / Short Circuit Current (V_{oc} / I_{sc})

4.6 Norton's Theorem

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It states that a linear two-terminal circuit can be replaced by an equivalent circuit of a current source I_N in parallel with a resistor R_N,

Where:

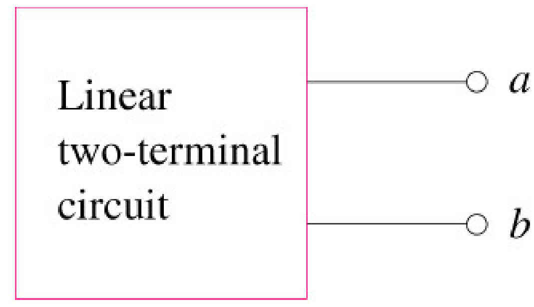
- I_N is the short circuit current through the terminals.
- R_N is the input or equivalent resistance at the terminals when the independent sources are turned off.

The Thevenin's and Norton equivalent circuits are related by a source transformation.

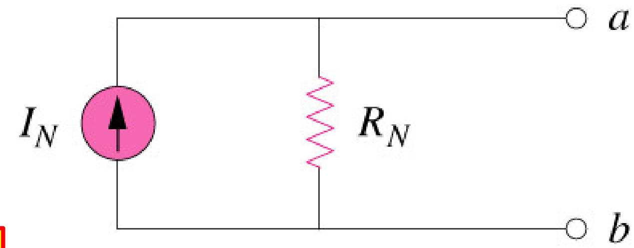
$I_N = i_{sc}$ (short circuit current)

$V_{TH} = v_{oc}$ (open circuit voltage)

$$R_{Th} = R_N = \frac{V_{Th}}{I_N}$$



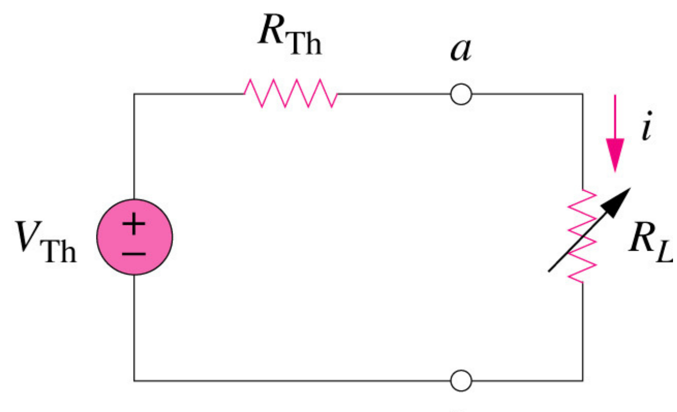
(a)



(b)

4.7 Maximum Power Transfer

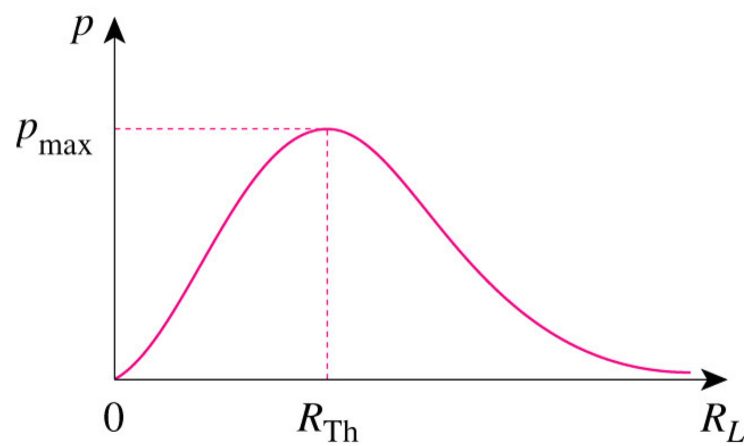
If the entire circuit is replaced by its Thevenin equivalent except for the load, the power delivered to the load is:



$$P = i^2 R_L = \left(\frac{V_{Th}}{R_{Th} + R_L} \right)^2 R_L$$

For maximum power dissipated in R_L, P_{max}, for a given R_{TH} and V_{TH},

$$R_L = R_{TH} \quad \Rightarrow \quad P_{max} = \frac{V_{Th}^2}{4R_L}$$

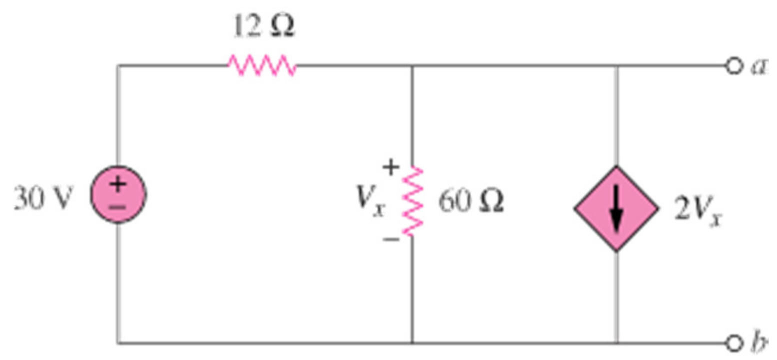


The power transfer profile with different R_L

Maximum power transfer takes place when $R_L = R_{Th}$

Chapter 4 Example

Problem 4.47 – Obtain the Thevenin and Norton equivalent circuits of the circuit with respect to terminals a and b. Find the maximum power.



Open Circuit Voltage

$$\frac{v_{oc}-30}{12}+\frac{v_{oc}}{60}+2v_{oc}=0$$
$$5v_{oc}-150+v_{oc}+120v_{oc}=0$$
$$126v_{oc}=150$$
$$v_{oc}=1.1905$$

Short Circuit Current

$$i_{sc}=\frac{30}{12}=2.5$$

$$V_{Th}=v_{oc}=1.1905$$
$$I_N=i_{sc}=2.5$$
$$R_{Th}=R_N=\frac{v_{oc}}{i_{sc}}=0.4762$$
$$P_{\max}=\frac{V_{Th}{}^2}{4R_{Th}}=\frac{1.1905^2}{4\times 0.4762}=0.744$$

Operational Amplifier Chapter 5 Review

5.2 What is an Op Amp?

5.3 Ideal Op Amp

5.4 Inverting Amplifier

5.5 Non-inverting Amplifier

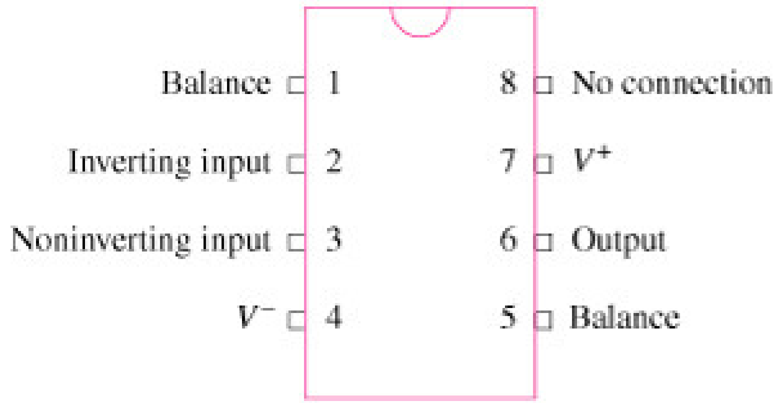
5.6 Summing Amplifier

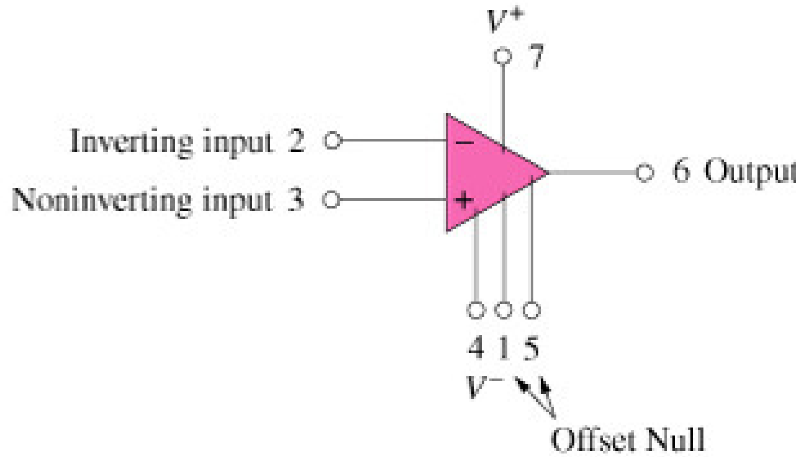
5.7 Difference Amplifier

5.2 What is an Op Amp (1)

- It is an electronic component that behaves like a voltage-controlled voltage source.
- It is an active circuit element designed to perform mathematical operations of ***addition***, ***subtraction***, ***multiplication***, ***division***, ***differentiation*** and ***integration***.

5.2 What is an Op Amp (2)





A typical op amp: (a) pin configuration, (b) circuit symbol

5.2 What is an Op Amp (3)

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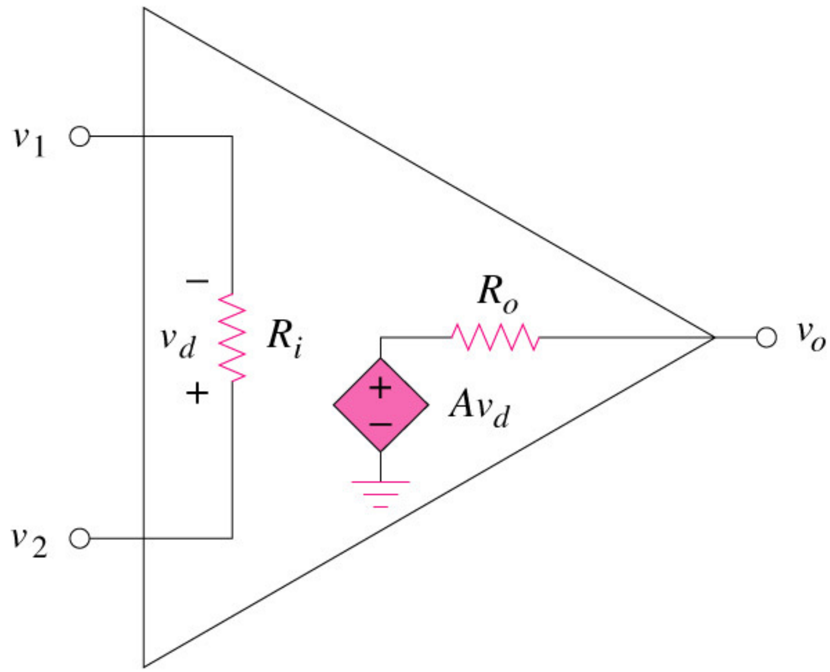
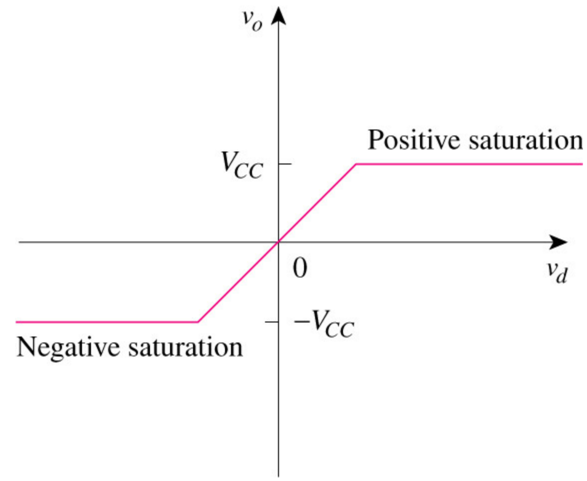
The equivalent circuit
Of the non-ideal op amp



Op Amp output:
v_o as a function of V_d



$$v_d = v_2 - v_1; \quad v_o = Av_d = A(v_2 - v_1)$$

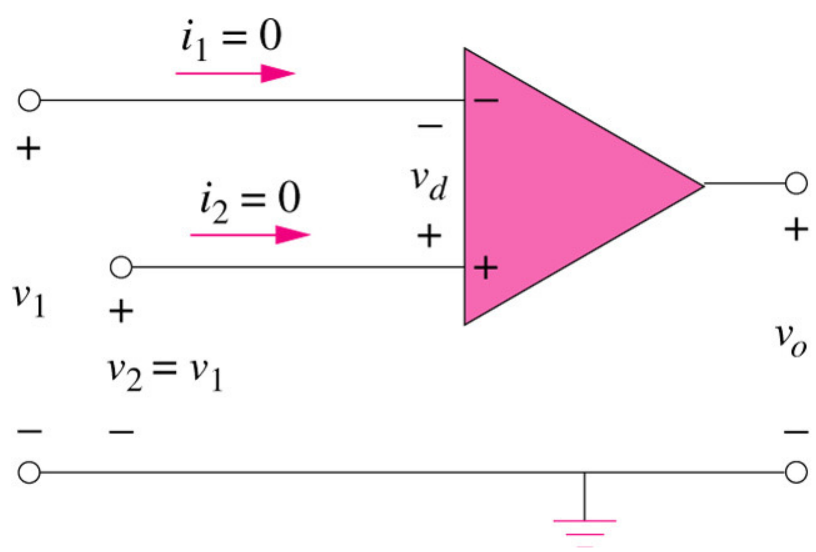
5.3 Ideal Op Amp

An ideal op amp has the following characteristics:

1. Infinite open-loop gain, A ≈ ∞
2. Infinite input resistance, $R_i \approx \infty$
3. Zero output resistance, $R_o \approx 0$

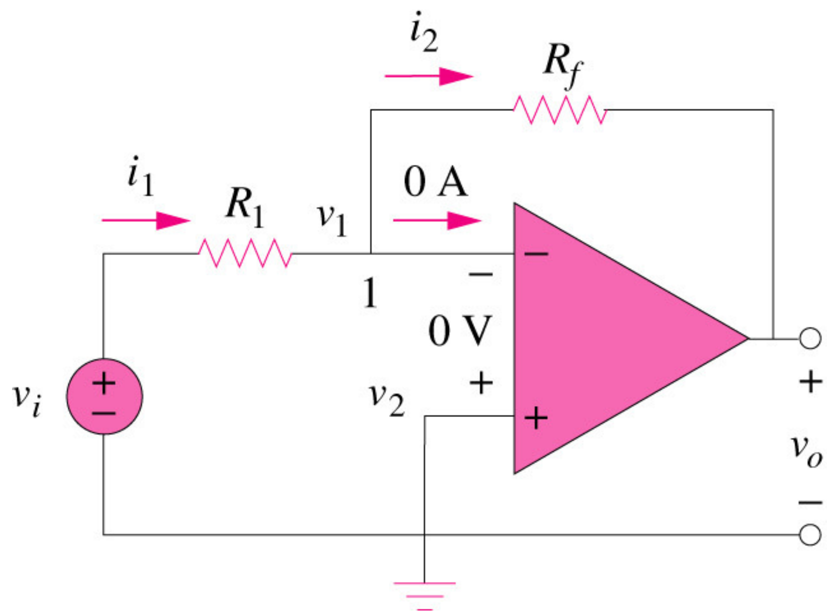
Properties used in circuit analysis

$$\boxed{\begin{aligned} i_1 &= 0 \\ i_2 &= 0 \\ v_1 &= v_2 \end{aligned}}$$



5.4 Inverting Amplifier

- Inverting amplifier reverses the polarity of the input signal while amplifying it



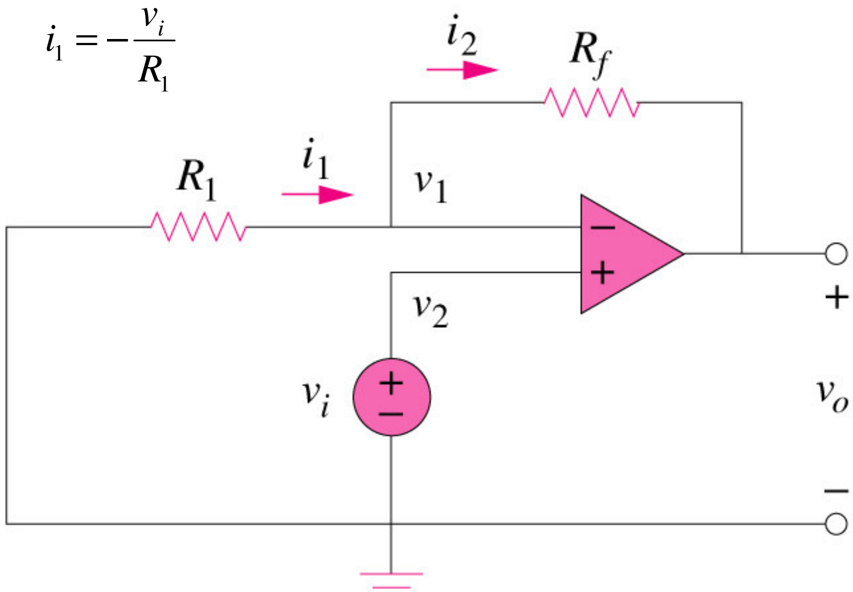
$$v_o = -\frac{R_f}{R_1} v_i$$

5.5 Non-inverting Amplifier

- Non-inverting amplifier is designed to produce positive voltage gain

$$i_1 = i_2$$

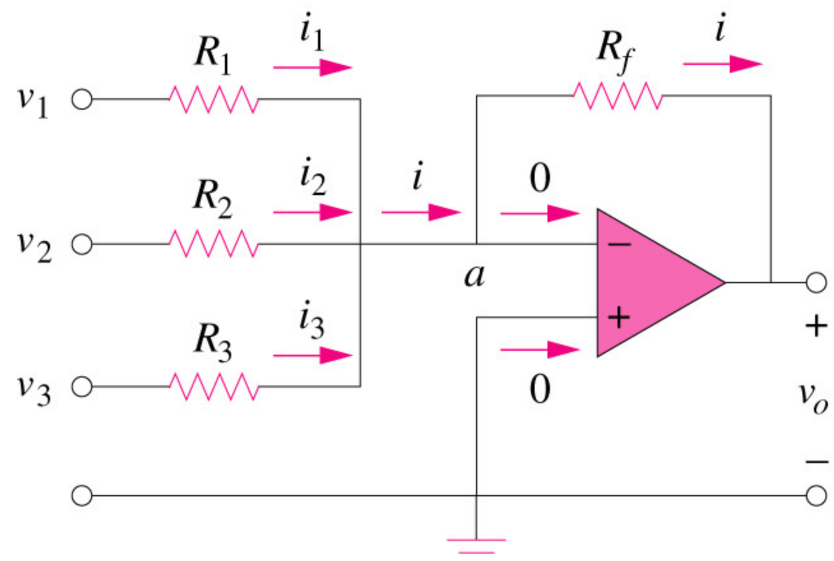
$$i_1 = -\frac{v_i}{R_1}$$



$$v_o = \left(1 + \frac{R_f}{R_1}\right) v_i$$

5.6 Summing Amplifier

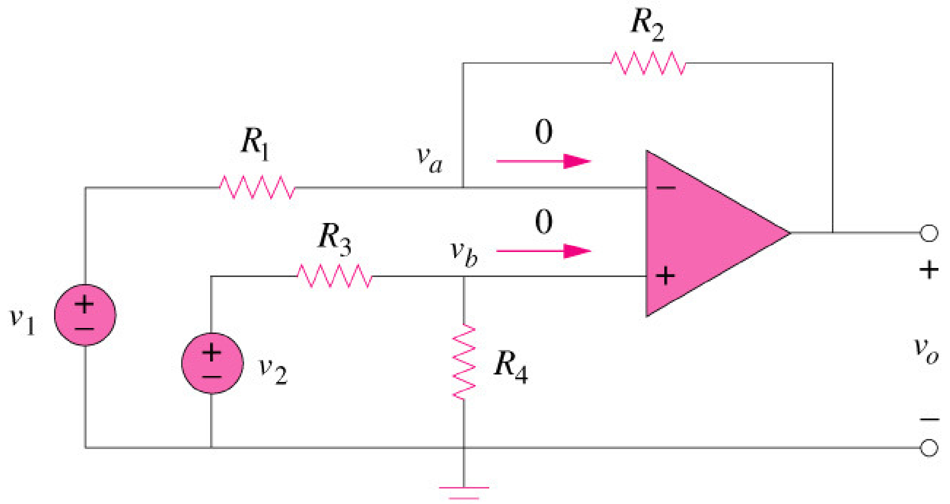
- Summing Amplifier is an op amp circuit that combines several inputs and produces an output that is the weighted sum of the inputs.



$$v_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right)$$

5.7 Difference Amplifier

- Difference amplifier is a device that amplifies the difference between two inputs but rejects any signals common to the two inputs.



$$v_o = \frac{R_2(1+R_1/R_2)}{R_1(1+R_3/R_4)}v_2 - \frac{R_2}{R_1}v_1 \Rightarrow v_o = v_2 - v_1 \text{, if } \frac{R_2}{R_1} = \frac{R_3}{R_4} = 1$$

6.2 Capacitors

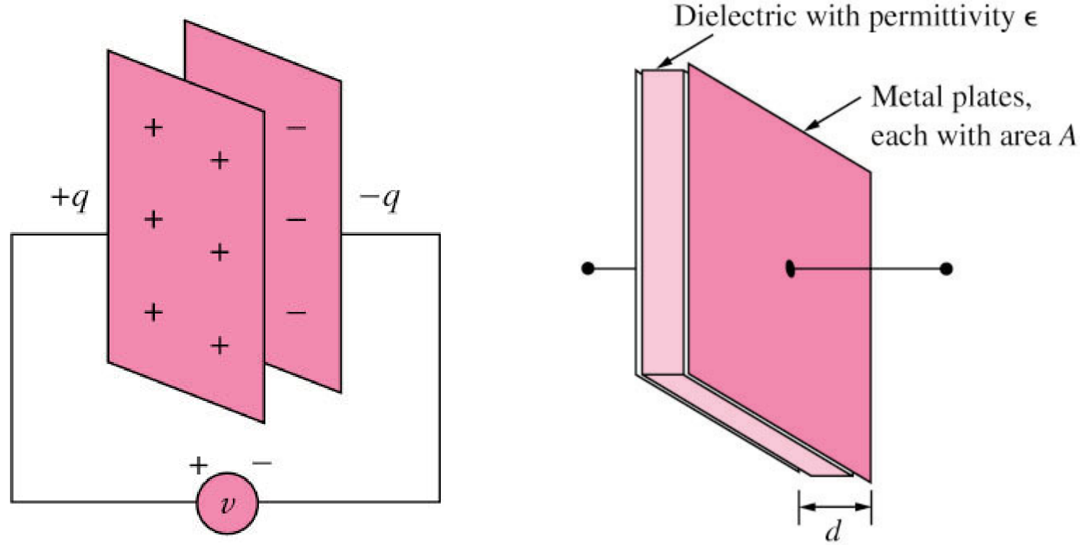
6.3 Series and Parallel Capacitors

6.4 Inductors

6.5 Series and Parallel Inductors

6.2 Capacitors (1)

- A capacitor is a passive element designed to **store energy** in its **electric field.**

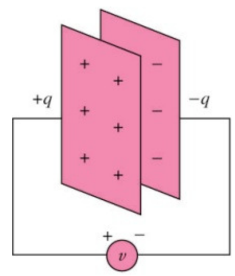


- A **capacitor** consists of two conducting plates separated by an insulator (or dielectric).

6.2 Capacitors (2)

- **Capacitance** *C* is the ratio of the charge *q* on one plate of a capacitor to the voltage difference *v* between the two plates, measured in farads (F).

$$q = C\,v \qquad \text{and} \qquad C = \frac{\varepsilon\, A}{d}$$



- Where ε is the permittivity of the dielectric material between the plates, A is the surface area of each plate, d is the distance between the plates.
- Unit: F, pF (10^{-12}), nF (10^{-9}), and μF (10^{-6})

6.2 Capacitors (3)

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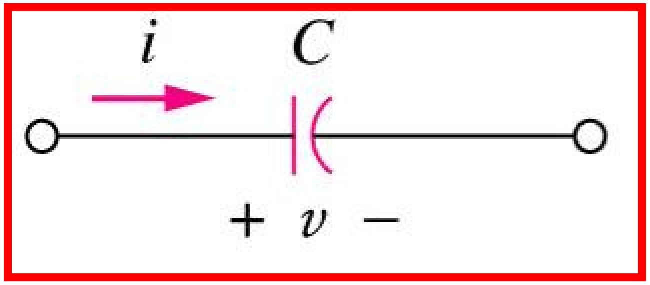
- If ***i*** is flowing into the +ve terminal of C
  - Charging => ***i*** is +ve
  - Discharging => ***i*** is –ve



- The current-voltage relationship of capacitor according to above convention is

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

and

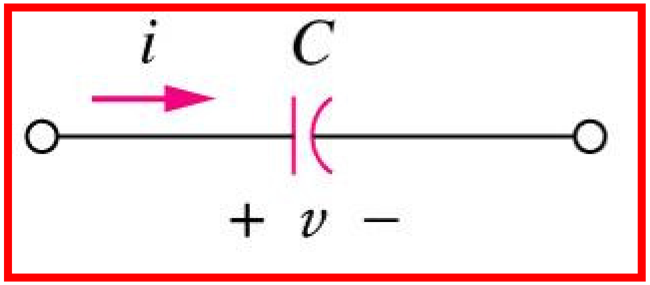
$$\boxed{v = \frac{1}{C}\int_{t_0}^{t} i\,dt + v(t_0)}$$

Note that if voltage is DC the current will go to zero (Open Circuit to DC !)

6.2 Capacitors (4)

- The energy, ***w***, stored in the capacitor is

$$\boxed{w = \frac{1}{2} C v^2}$$

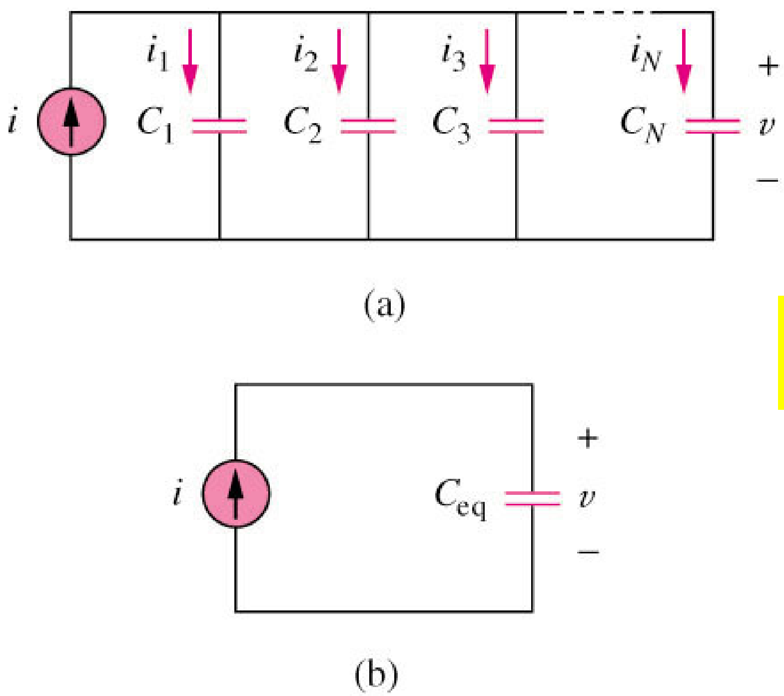


Important Concept!

- A capacitor is
  - an **open circuit** to dc (dv/dt = 0).
  - its voltage **cannot change abruptly.**

6.3 Series and Parallel Capacitors (1)

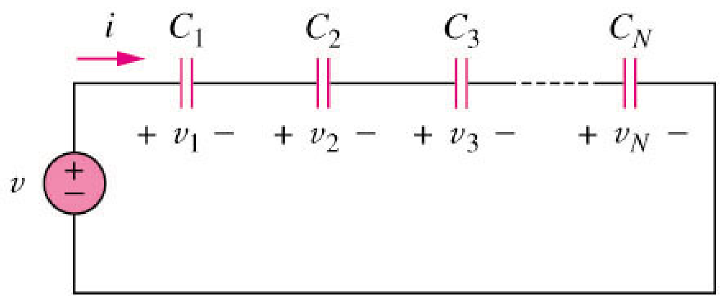
- The equivalent capacitance of *N* **parallel-connected** capacitors is the sum of the individual capacitances.



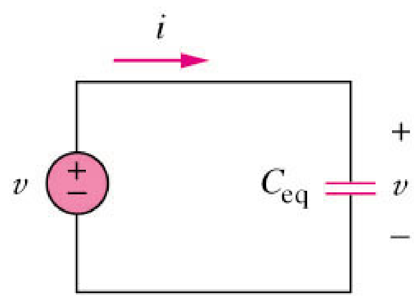
$$C_{eq} = C_1 + C_2 + ... + C_N$$

6.3 Series and Parallel Capacitors (2)

- The equivalent capacitance of *N* **series-connected** capacitors is the reciprocal of the sum of the reciprocals of the individual capacitances.



(a)

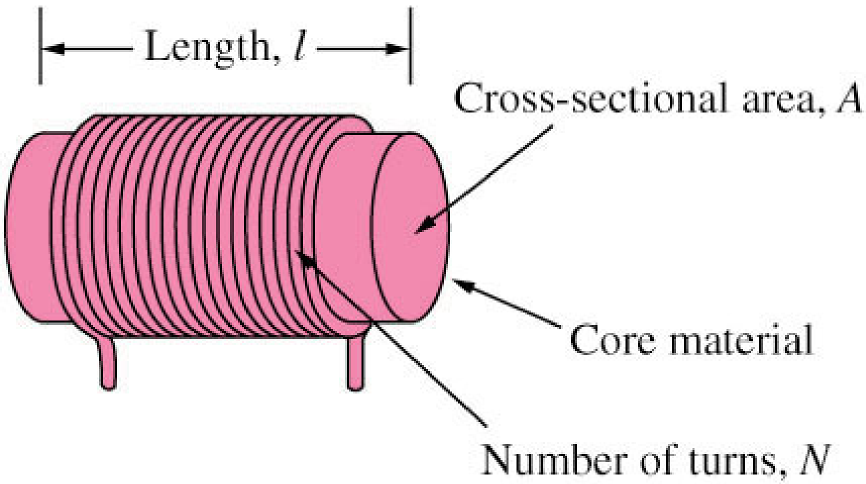


(b)

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

6.4 Inductors (1)

- An inductor is a passive element designed to store energy in its magnetic field.



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

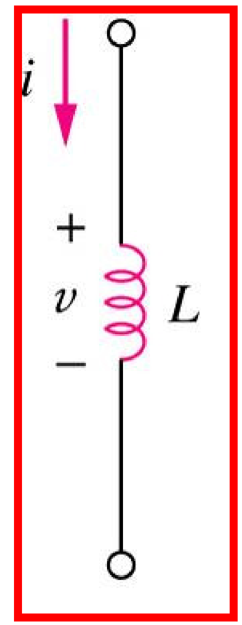
- An inductor consists of a coil of conducting wire.
- The unit of inductors is Henry (H), mH (10^{-3}) and μH (10^{-6}).

6.4 Inductors (2)

- Inductance is the property whereby an inductor exhibits opposition to the change of current flowing through it, measured in henrys (H).
- The current-voltage relationship of an inductor:

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

$$\boxed{i = \frac{1}{L}\int_{t_0}^{t} v(t)\,dt + i(t_0)}$$



*Note that if currentis DC the voltage will go to zero (**Short Circuit to DC** !)*

6.4 Inductors (3)

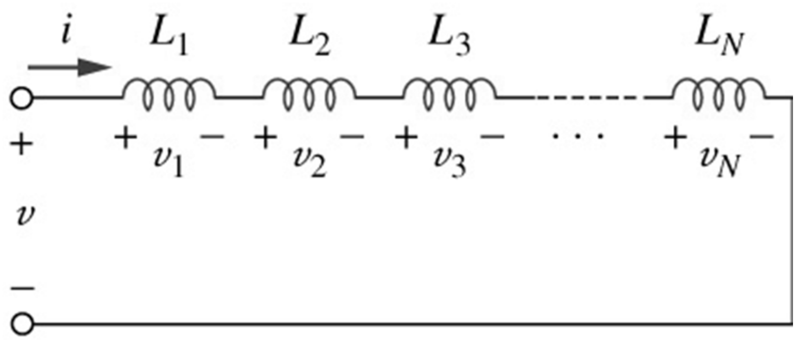
- The energy stored in an inductor:

$$w = \frac{1}{2} L i^2$$

- An inductor acts like a short circuit to dc (di/dt = 0).
- The current through an inductor cannot change abruptly.

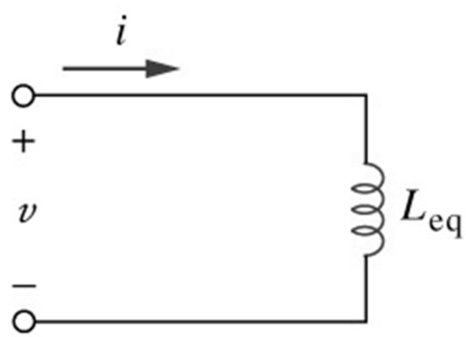
6.5 Series and Parallel Inductors (1)

- The equivalent inductance of **series-connected** inductors is the sum of the individual inductances.



(a)

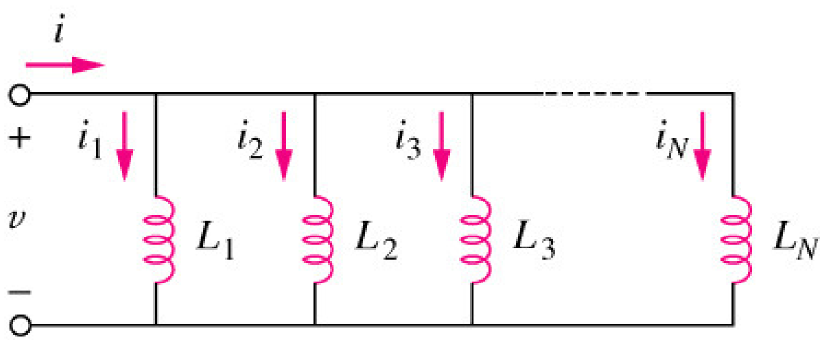
$$L_{eq} = L_1 + L_2 + \ldots + L_N$$



(b)

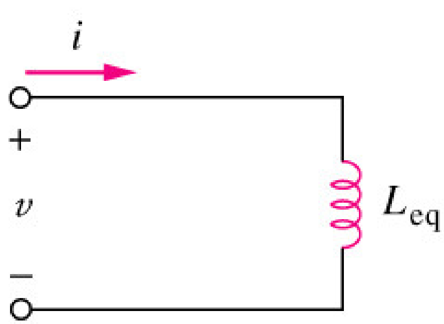
6.5 Series and Parallel Inductors (2)

- The equivalent inductance of **parallel-connected** inductors is the reciprocal of the sum of the reciprocals of the individual inductances.



(a)

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



(b)

7.2 The Source-Free RC Circuit

7.3 The Source-Free RL Circuit

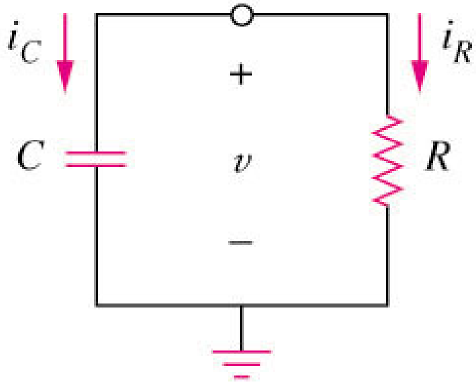
7.4 Unit-step Function

7.5 Step Response of an RC Circuit

7.6 Step Response of an RL Circuit

7.2 The Source-Free RC Circuit (1)

- A **first-order circuit** is characterized by a first-order differential equation.



By KCL

$$i_R + i_C = 0 \rightarrow \frac{v}{R} + C\frac{dv}{dt} = 0$$

Ohms law

Capacitor law

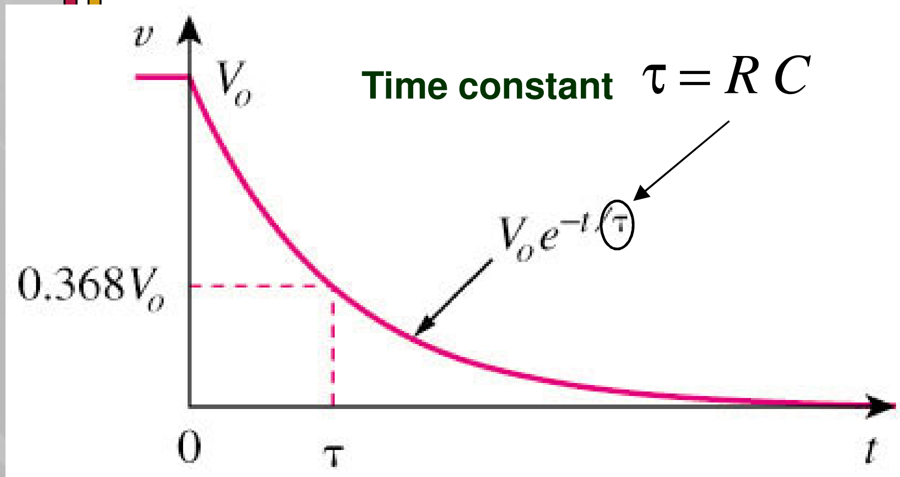
- Apply Kirchhoff's laws to purely resistive circuit results in algebraic equations.
- Apply the laws to RC and RL circuits produces differential equations.

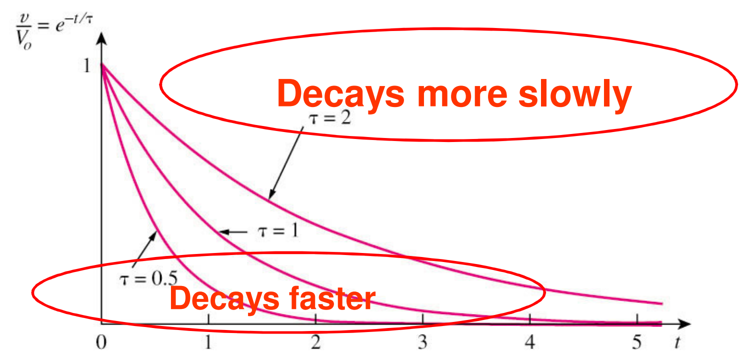
7.2 The Source-Free RC Circuit (2)

- The **source-free** RC circuit occurs when its dc source is suddenly disconnected. The energy stored in the capacitor is released to the resistor.
- Solving the differential equation gives:

$$\frac{dv}{dt} + \frac{v}{RC} = 0$$

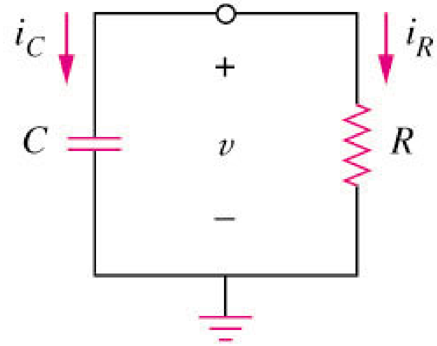
$$v(t) = V_0 e^{-t/RC}$$





- The **time constant** τ of a circuit is the time required for the response to decay by a factor of 1/*e* or 36.8% of its initial value.
- v decays faster for small τ and slower for large τ.

7.2 The Source-Free RC Circuit (3)



Natural Response of RC circuit

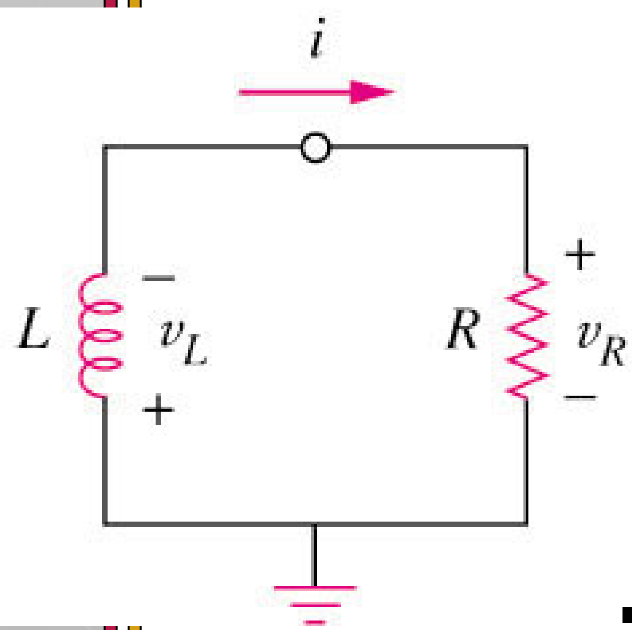
$$v(t) = V_0 \, e^{-t/\tau} \quad \text{where} \quad \tau = R\,C$$

The key to working with a source-free RC circuit is finding:

1. The initial voltage $v(0) = V_0$ across the capacitor.
2. The time constant $\tau = RC$.

7.3 The Source-Free RL Circuit (1)

- A **first-order RL circuit** consists of a inductor L (or its equivalent) and a resistor (or its equivalent)



By KVL

$$v_L + v_R = 0$$

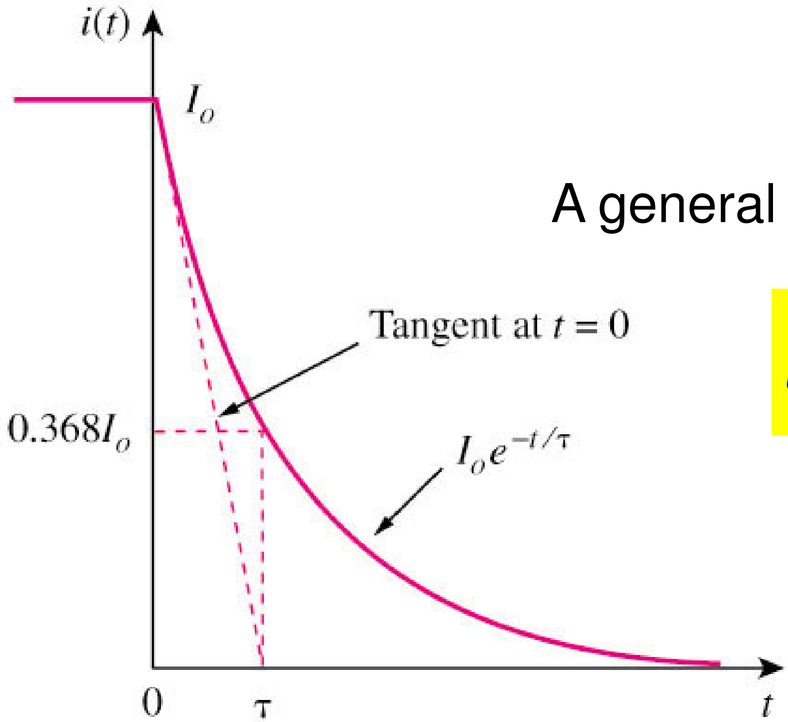
$$\rightarrow \quad L\frac{di}{dt} + iR = 0$$

Inductors law

Ohms law

$$\rightarrow \quad \frac{di}{i} = -\frac{R}{L}dt \quad \rightarrow \quad i(t) = I_0 e^{-Rt/L}$$

7.3 The Source-Free RL Circuit (2)



A general form representing a RL

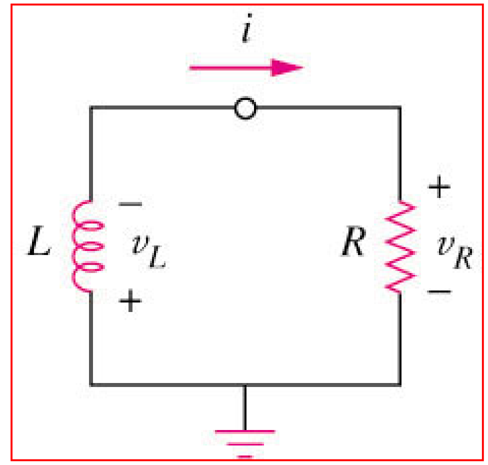
$$i(t) = I_0\, e^{-t/\tau}$$

where $$\tau = \frac{L}{R}$$

- The **time constant** τ of a circuit is the time required for the response to decay by a factor of 1/*e* or 36.8% of its initial value.
- $i(t)$ decays faster for small τ and slower for large τ.
- The general form is very similar to a RC source-free circuit.

7.3 The Source-Free RL Circuit (3)

$$i(t) = I_0 \, e^{-t/\tau}$$ where $$\tau = \frac{L}{R}$$



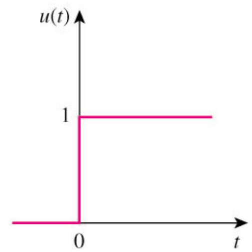
The key to working with a source-free RL circuit is finding:

1. The initial current $i(0) = I_0$ through the inductor.
2. The time constant $\tau = L/R$.

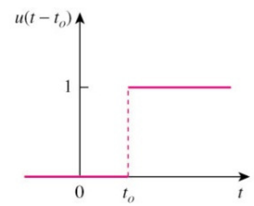
7.4 Unit-Step Function (1)

- The **unit step function** $u(t)$ is 0 for negative values of t and 1 for positive values of t.

$$u(t) = \begin{cases} 0, & t < 0 \\ 1, & t > 0 \end{cases}$$



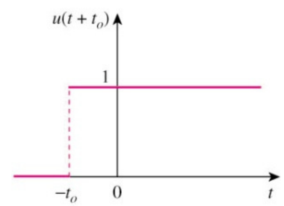
$$u(t - t_o) = \begin{cases} 0, & t < t_o \\ 1, & t > t_o \end{cases}$$



(a)

$$\text{"delay" of } t_o$$

$$u(t + t_o) = \begin{cases} 0, & t < -t_o \\ 1, & t > -t_o \end{cases}$$

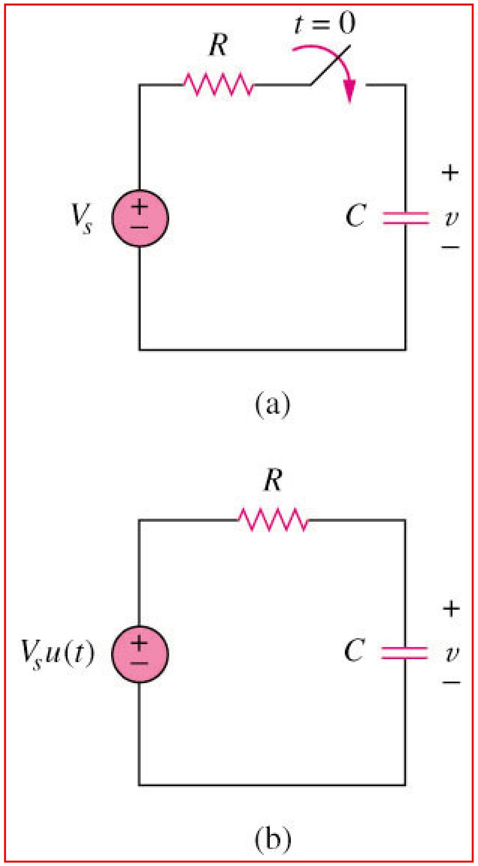


(b)

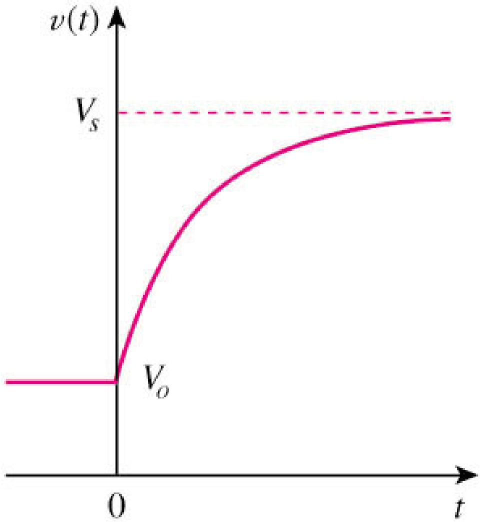
$$\text{"advance" of } t_o$$

7.5 The Step-Response of a RC Circuit (1)

- The **step response** is the response of the circuit due to a sudden application of a dc voltage or current source.



7.5 The Step-Response of a RC Circuit (2)



$$v(t) = \begin{cases} V_0 & t < 0 \\ V_s + (V_0 - V_s)e^{-t/\tau} & t > 0 \end{cases}$$

Final value at t -> ∞

Initial value at t = 0

Source-free Response

Another way of looking at the response is as follows:

Complete Response	=	Steady-State Response (Permanent Part)	+	Transient Response (Temporary Part)
		V_s	+	$(V_0 - V_s)e^{-t/\tau}$

Complete Response	=	Natural Response (Stored Energy)	+	Forced Response (Independent Source)
		$V_0 e^{-t/\tau}$	+	$V_s(1 - e^{-t/\tau})$

7.5 The Step-Response of a RC Circuit (3)

Three steps to find out the step response of an RC circuit:

$$\tau = \frac{1}{RC}$$

1. The initial capacitor voltage v(0).
2. The final capacitor voltage v(∞) — DC voltage across C.
3. The time constant τ.

$$v(t) = v(\infty) + [v(0+) - v(\infty)]e^{-t/\tau}$$

Note: The above method is a short-cut method. You may also determine the solution by setting up the circuit formula directly using KCL, KVL , ohms law, capacitor and inductor VI laws.

7.6 The Step-Response of a RL Circuit (1)

Three steps to find out the step response of an RL circuit:

1. The initial inductor current i(0) at t = 0+.
2. The final inductor current i(∞).
3. The time constant τ.

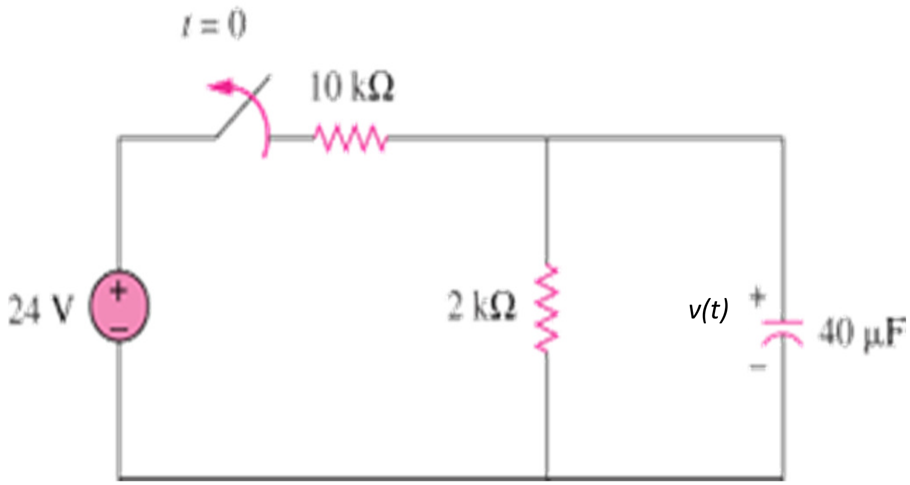
$$\tau = \frac{L}{R}$$

$$i(t) = i(\infty) + [i(0+) - i(\infty)]\, e^{-t/\tau}$$

Note: The above method is a short-cut method. You may also determine the solution by setting up the circuit formula directly using KCL, KVL , ohms law, capacitor and inductor VI laws.

Chapter 7 Example (1)

Problem 7.6 – The switch has been closed for a long time, and it opens at t = 0. Find v(t) for t $\geq$ 0.



$$v_0(t<0) = 24\frac{2}{2+10} = 4$$

$$v_f(\infty) = 0$$

$$\tau = \frac{1}{RC} = \frac{1}{2k \times 40\mu} = 12.5$$

$$v(t) = 4e^{(-t/12.5)}$$

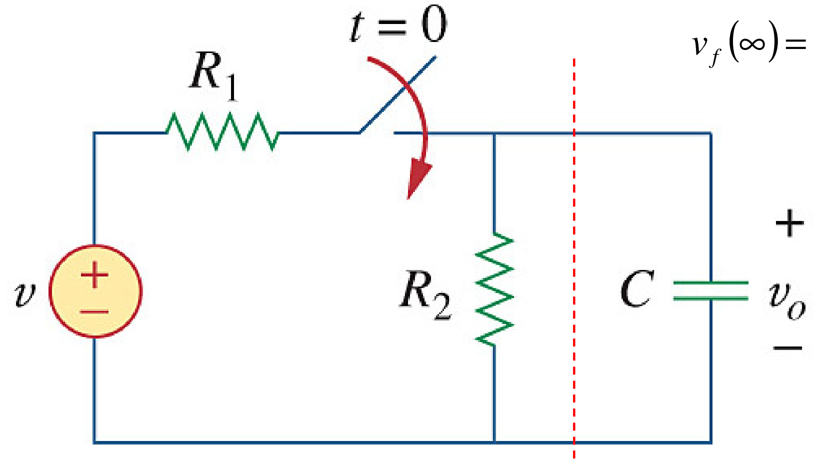
$$v(t) = v(\infty) + [v(0+) - v(\infty)]e^{-t/\tau}$$

$$v(t) = \quad 0 \quad + [\ 4 \quad - \quad 0\ ]e^{-t/125}$$

Chapter 7 Example (2)

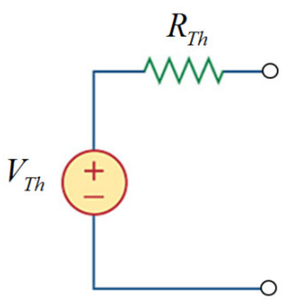
Problem 7.41 – The switch has been open for a long time, and it closes at t = 0. Find $v_o(t)$ for $t \geq 0$.

v =12V, R_1=6Ω, R_2=30Ω, C=1F, $v_o(0)$ =0V



$$v_f(\infty) = v\frac{R_2}{R_1+R_2} = 12\frac{30}{36} = 10$$

Find Thevenin Equivalent circuit



$$V_{Th} = v_{oc} = v\frac{R_2}{R_1+R_2} = 10$$

$$R_{Th} = \frac{v_{oc}}{i_{sc}} = \frac{v\frac{R_2}{R_1+R_2}}{\frac{v}{R_1}} = \frac{R_1R_2}{R_1+R_2} = 5$$

$$\tau = \frac{1}{R_{Th}C} = \frac{1}{5}$$

$$v_o(t) = v(\infty) + [v(0+) - v(\infty)]\,e^{-t/\tau}$$

$$v_o(t) = 10 + [0 - 10]\,e^{-t/5}$$

$$v_o(t) = 10\left(1 - e^{-t/5}\right)$$