ES203 Electrical Systems
Study Guide

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Unit I

PHYSICS Foundation:

- charge, current, voltage
- power, energy
- ideal sources
- resistors, capacitors, inductors
- sinusoids, RMS, phasors
- impedances
- series, parallel
- voltage, current divider
- Kirchhoff's voltage law
- Kirchhoff's current law

Lecture 1-1: Introduction and Overview

Reading: 1.1-3

Objectives: Be able to briefly and clearly explain static electricity, electric circuit

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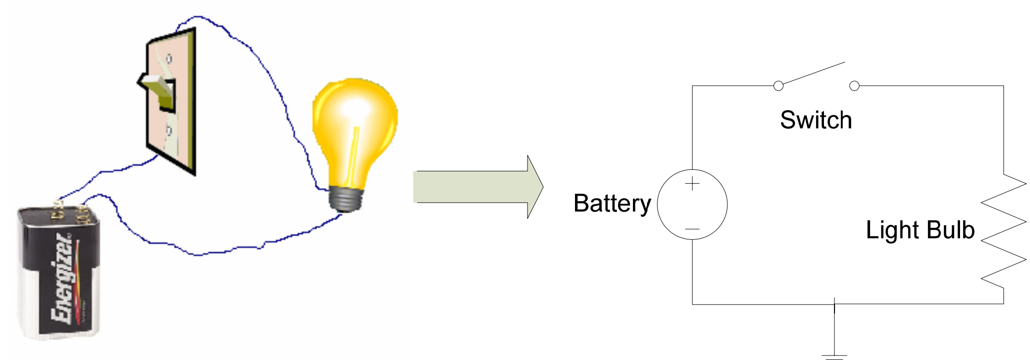
<u>In-Class Activity:</u>

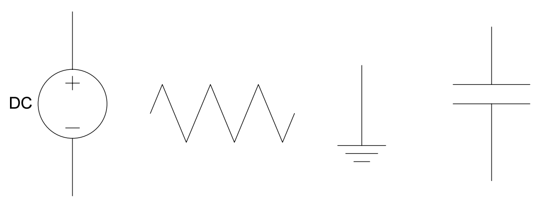
Why is it important for students who are not electrical engineers to study circuit analysis?

An **<u>electric circuit</u>** is a mathematic model that approximates the behavior of an actual electric system.



A commonly used mathematical model for electric systems is a **<u>circuit model</u>**.

The elements that comprise the circuit model are called **<u>ideal circuit components</u>**.



<u>Circuit analysis</u> is the tools applied to an electric circuit using mathematical techniques to predict the behavior of the circuit model and its ideal circuit components.

The **<u>physical prototype</u>** is an actual electric system, constructed from actual electric components.

Review the International System of Units and Standardized prefixes for powers of 10.

<u>In-Class Activity:</u>

Watch the video from Jimmy Kimmel Live. Why do you think that Jimmy had to jump in the air in order to shock the people?

Lecture 1-2: voltage, current, power, energy

Reading: 1.4-6

Objectives: Be able to briefly and clearly explain voltage, current, power, energy
Be able to write formulas for voltage, current, power
Be able to identify whether an element is delivering or absorbing power
Be able to explain the difference between power and energy
Be able to apply the law of conservation of energy to confirm that power balances for a network

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The separation of electric charge creates an electric force (**voltage**). Whenever positive and negative charges are separated, energy is expended. **Voltage** is the energy per unit charge created by this separation.

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

v is voltage in volts (V), w is energy in Joules (J), q is charge in Coulombs (C)

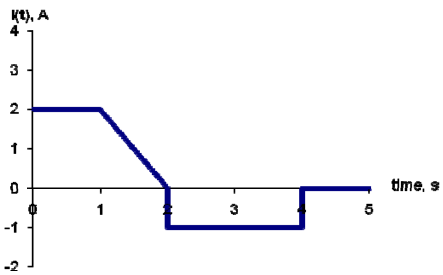
The motion of charge creates an electric fluid (**current**). The rate of charge flow is known as **electric current**.

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

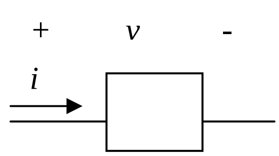
i is current in amperes (A), q is charge in Coulombs (C)

In-Class Activity

The current flowing into the positive terminal of an element is given by the following waveform. If the element is initially charged to 2 C, what is the total charge transferred to the element in 5 seconds?



An **ideal basic circuit element** has 3 attributes: (1) it has only 2 terminals, (2) it is described mathematically in terms of current and/or voltage, (3) it cannot be subdivided into other elements.

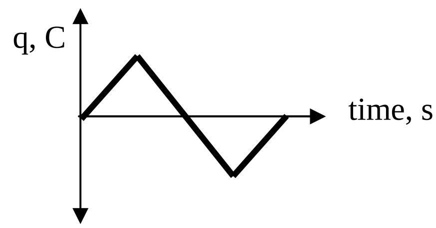


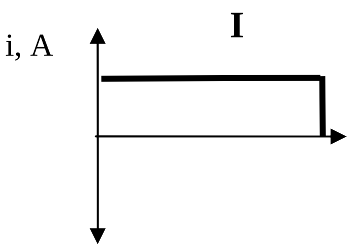
A **voltage drop** is when current flows through an element from the positive to negative terminal on an element, otherwise it is a **voltage rise**.

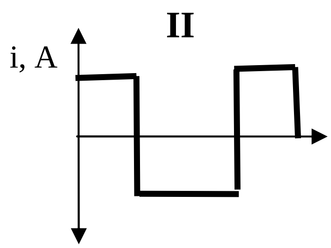
The **passive sign convention** states that when the direction of current flow through an element is in the direction of the voltage drop across the element, use a positive sign that relates the voltage to the current, otherwise use a negative sign.

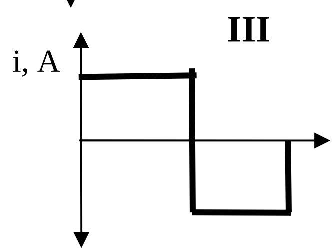
Concept Question:
The charge flowing through a light bulb is shown in the figure on the right. Which of the following figures shows the current flowing through the light bulb?

a) *I*
b) *II*
c) *III*
d) *none of the above*









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The useful output of electrically-based systems often is non-electrical. This output is expressed in terms of power or energy.

Power is the time rate of expending or absorbing energy.

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

p is the power in Watts (W), w is the energy in Joules (J), t is the time in seconds (s)

The power associated with the flow or charge follows directly from the definition of voltage and current

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

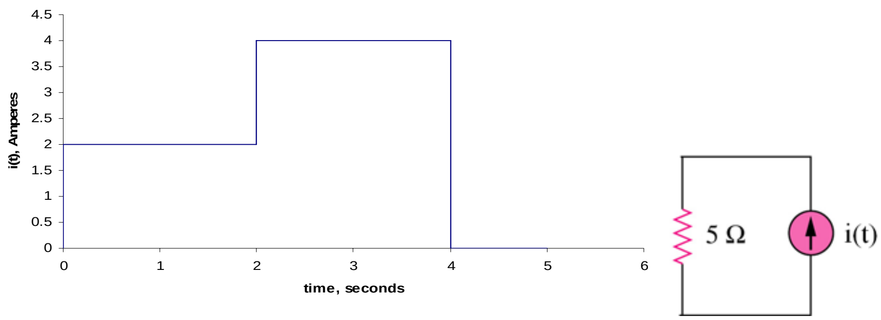
p is the power in Watts (W), v is the voltage in volts (V), i is the current in amperes (A)

If the current flowing through an element is in the direction of the voltage drop across the element, p = + vi, otherwise it is p = -vi.

If the numerical value of power is positive (p > 0), the element is **absorbing power**, otherwise the element is delivering power.

The law of conservation of energy states that energy can neither be created nor destroyed only transferred. Therefore, the total power delivered to an electric circuit must be equal to the total power absorbed.

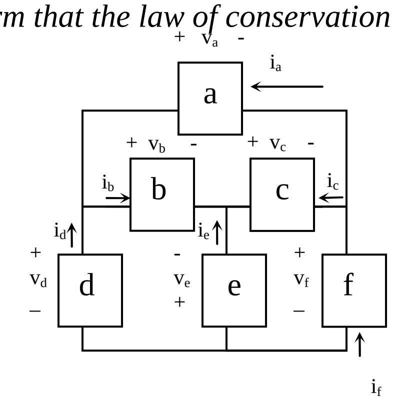
FE Preview:
A 5 Ω resistor is placed in series with a varying current. Most nearly how much energy is dissipated by the resistor over the 4 s time interval shown?



a) 80 J
b) 180 J
c) 200 J
d) 320 J

In-Class Activity:
In the following circuit, a) identify which elements are drawn to obey the passive sign convention, b) using the numerical values on the table, identify which elements are absorbing power and which are delivering power, c) confirm that the law of conservation of energy is satisfied.

element	*Voltage (V)*	*Current (A)*
a	*8*	*-4*
b	*15*	*15*
c	*-7*	*3.5*
d	*10*	*19*
e	*5*	*-18.5*
f	*2*	*-0.5*



Try Assessment problems 1.1, 1.2 on page 9, 1.3, 1.4 on page 13, 1.5, 1.6, 1.7 on page 16

Minute Paper:
Take out a sheet of paper, DO NOT PUT YOUR NAME ON IT
What concept presented today is still unclear to you?

Lecture 1-3: Circuit elements

Reading: 2.1-2

Objectives: Be able to explain Ohm's law, power across a resistor, ideal voltage and current sources, active and passive circuit elements
Be able to identify resistors in a network
Be able to solve for voltage, current and power in a resistive network
Be able to apply the law of conservation of energy to a resistive network

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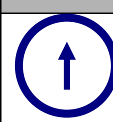
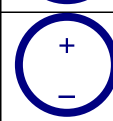
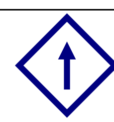
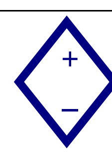
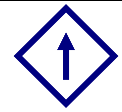
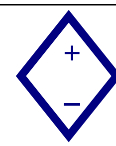
An **electric source** is a device that is capable of converting nonelectric energy to electric energy and vice versa. These sources can either absorb power or deliver power, generally by maintaining either voltage or current.

Independent sources establish a voltage or current in a circuit without relaying on voltage or currents elsewhere in the circuit.

Dependent sources or **controlled sources** establish a voltage or current in a circuit whose value depends on the value of a voltage or current elsewhere in the circuit.

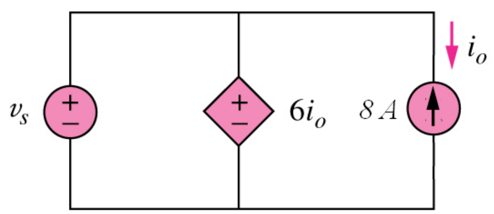
Element	Description	Graphic
Independent Sources	Establishes a voltage or current in a circuit without relying on voltages and currents elsewhere in the circuit	
ideal current source	This circuit symbol is a circle and must include an arrow for the direction of the current and a value.	 i_s
ideal voltage source	This circuit symbol is a circle and must include a polarity for the reference voltage and a value	 v_s
Dependent or Controlled Sources	Establishes a voltage or current in a circuit which depends on a voltage or current elsewhere in the circuit.	
current controlled current source (CCCS)	This circuit symbol is a diamond and it must include an arrow for the direction of the supplied current, a formula to calculate the supplied current from the controlling current, i_x. $i_s = \beta i_x$ (β is unit less)	 βi_x
voltage controlled voltage source (VCVS)	This circuit symbol is a diamond and it must include a reference polarity for the supplied voltage, a formula to calculate the supplied voltage from the controlling voltage, v_x. $v_s = \mu v_x$ (μ is unit less)	 μv_x

voltage controlled current source (VCCS)	This circuit symbol is a <u>diamond</u> and it must include an arrow for the direction of the supplied current, a formula to calculate the supplied current from the controlling voltage, v_x. $i_s = \alpha v_x$ (α's units are A/V)	 αv_x
current controlled voltage source (CCVS)	This circuit symbol is a <u>diamond</u> and it must include a reference polarity for the supplied voltage, a formula to calculate the supplied voltage from the controlling current, i_x. $v_s = \rho i_x$ (ρ's units are V/A)	 ρi_x

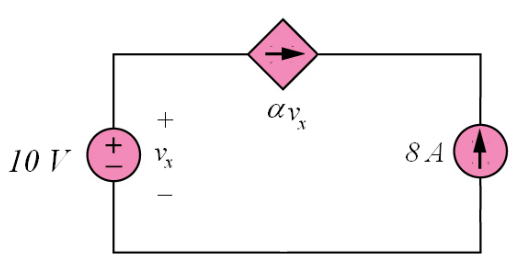
An **<u>active circuit element</u>** is one that models a device capable of generating electric energy

A **<u>passive circuit element</u>** models physical devices that cannot generate electric energy. Resistors, Inductors, and Capacitors are examples of passive circuit elements.

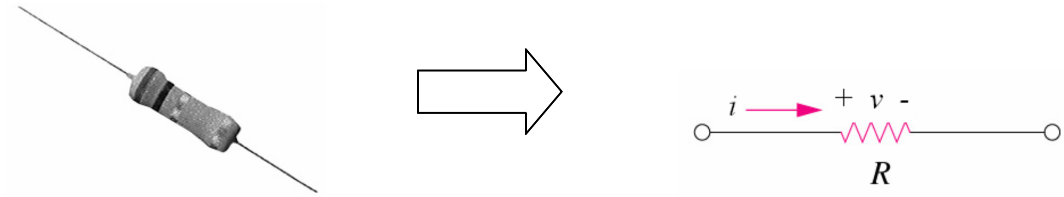
<u>In-Class Activity</u>
What value of v_s is required in order for the following interconnection to be valid?



<u>In-Class Activity</u>
What value of α is required in order for the interconnection to be valid?



Resistance, R is the capacity of materials to impede the flow of current or the flow of electric charge. The circuit element used to model this behavior is the **resistor**. Many useful devices take advantage of resistance heating including stoves, toasters, irons, and space heaters.



Ohm's law describes the voltage across a resistor, **v = iR,** where v is the voltage in volts, i is the current in amperes, and R is the resistance in ohms (Ω)

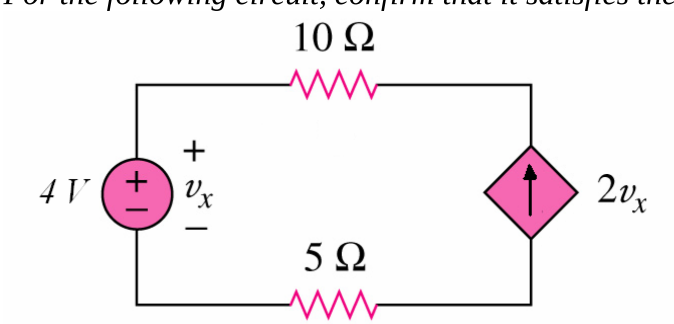
The reciprocal of resistance is **conductance, G** measured in Siemens (S) or mhos.

$$G = 1/R$$

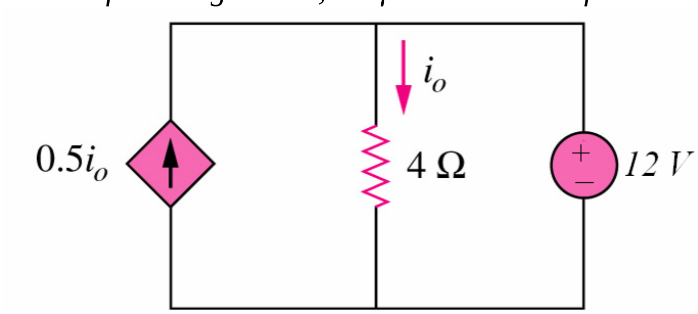
The power dissipated in a resistor is given by the following formulas

$$p = i^2R = v^2/R = v^2G = i^2/G \text{ (W)}$$

In-Class Activity
For the following circuit, confirm that it satisfies the law of conservation of energy.



In-Class Activity
For the following circuit, confirm that it satisfies the law of conservation of energy.



Try Assessment problems on 2.1 on page 28, 2.3, 2.4 on page 32

Lecture 2-1: Inductors and Capacitors

Reading: 6.1-2

Objectives: Be able to briefly and clearly explain capacitance and inductance
Be able to write formulas for voltage, current, power, energy for inductors and capacitors
Be able to identify inductors and capacitors in an electric circuit
Be able to sketch or calculate voltage, current, power, energy for an inductor and capacitor

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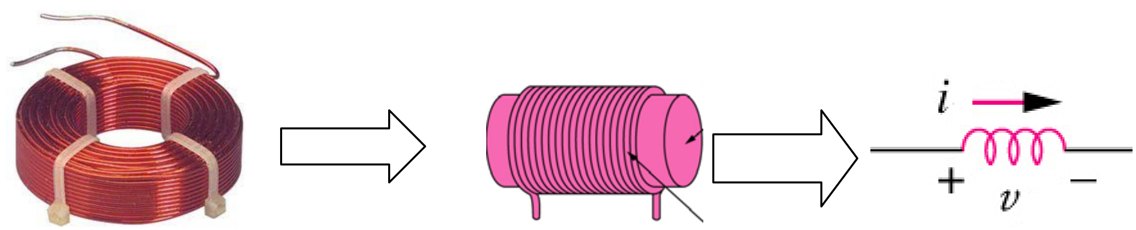
An **<u>inductor</u>** is an electrical component that opposes any change in electric current. It is composed of a coil of wire wound around a supporting core whose material may be magnetic or nonmagnetic. The source of the magnetic field is charge in motion, or current. A time-varying magnetic field induces a voltage in any conductor linked to the field. **<u>Inductance</u>** relates the induced voltage to the current. Energy can be stored in an inductor and released to fire a spark plug.



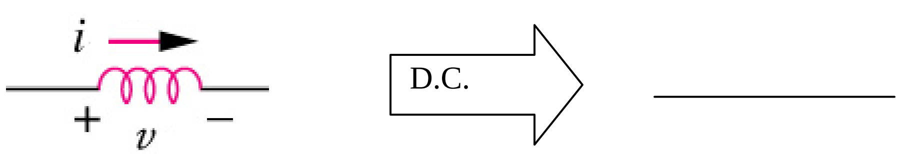
The relationship for voltage across an inductor is **<u>v = Ldi/dt</u>**, where L is the inductance in Henries (H) and i is the current in amperes. The current through the inductor is

i $= \frac{1}{L}\int_{to}^{t} v\,dt + i(t_o)$ (A)

The power in an inductor is given by **<u>p = Li di/dt</u>** (W)
The energy in an inductor is given by **<u>w = 0.5Li</u>**^{2} (J)

2 key assumptions about inductors

i. An inductor is a **<u>short circuit</u>** to a constant voltage (DC conditions)



ii. The **<u>current</u>** through an inductor cannot change abruptly.

iii. The **<u>voltage</u>** across an inductor can change instantaneously when it changes from storing to discharging energy or vice versa.

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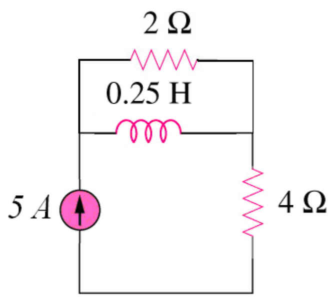
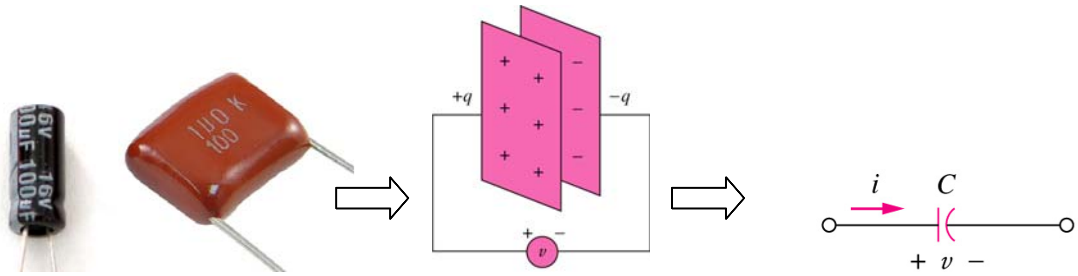
In-Class Activity:
For the following circuit, find the current through and voltage across the inductor.



A **capacitor** is an electrical component that consists of two conductors separated by an insulator or dielectric material. The capacitor is the only device other than a battery that can store electrical charge. A time-varying electric field produces a displacement in current in the space occupied by the dielectric. **Capacitance** relates the displacement current to the voltage. Energy can be stored in a capacitor and then released to fire a flashbulb.

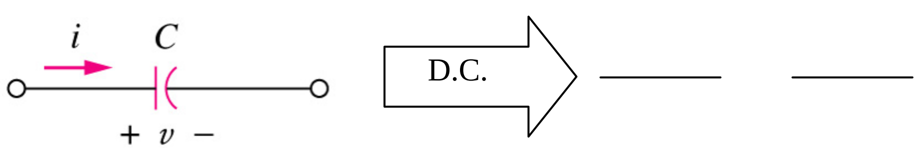


The relationship for the current through a capacitor is **i = Cdv/dt** where C is the capacitance in Farads (F) and v is the voltage in volts. The voltage across a capacitor is given by v = $\frac{1}{C}\int_{to}^{t} i\,dt + v(t_o)$ (V)

The power relationship for a capacitor is **p = Cv dv/dt** (W)
The energy relationship for a capacitor is **w = 0.5Cv^2** (J)

Properties for a capacitor:

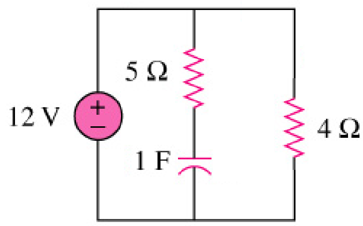
i. A capacitor is an **open circuit** to a constant voltage (DC conditions).



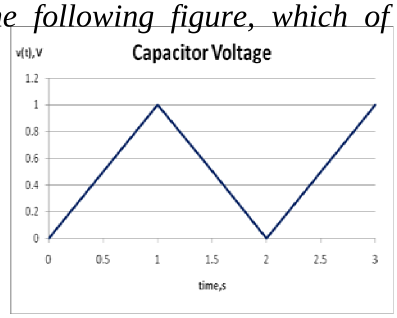
ii. The **voltage** on a capacitor cannot change abruptly.

iii. The **current** through a capacitor can change instantaneously when it changes from storing to discharging energy or vice versa.

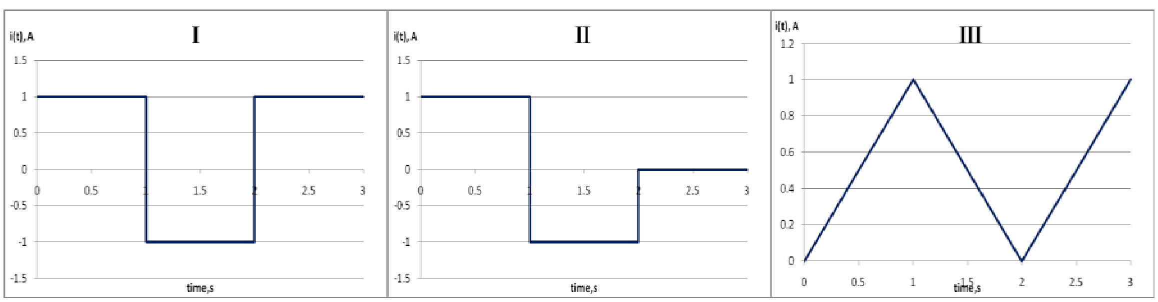
In-Class Activity:
For the following circuit, find the current through and voltage across the capacitor.



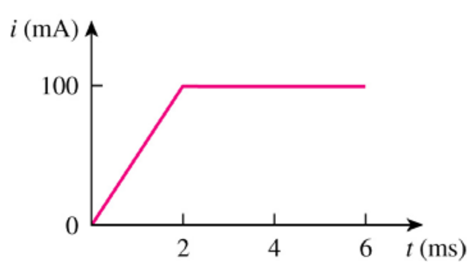
Concept Question 1:
The voltage across a 1-F capacitor is shown in the following figure, which of the following figures is a graph of the current.



a) *I*
b) *II*
c) *III*
d) *none of the above*



Concept Question 2:
An initially uncharged 1-mF capacitor has the current shown in the following figure. Calculate the voltage across the capacitor at t = 2 ms and t = 5 ms.



Try Assessment Problems 6.1 on page 195, 6.2, 6.3 on page 199

Lecture 2-2: Sinusoids, RMS, phasors

Reading: 9.1-3

Objectives: Be able to briefly and clearly explain and write formulas for RMS and average value
Be able to convert between sinusoids and phasors (angle, rectangular, polar form)
Be able to perform phasor addition, subtraction, multiplication and addition
Be able to calculate the RMS value for a function given the waveform or mathematical expression

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A **sinusoidal voltage source** produces a voltage that varies sinusoidally with time.
A **sinusoidal current source** produces a current that varies sinusoidally with time.

$$v = V_m \cos(\omega t + \phi)$$, where

V_m is the **maximum amplitude** of the sinusoidal voltage. The **period, T** of this function is measured in seconds. The reciprocal of the period is **frequency, f** measured in Hertz, **f = 1/T** (Hz)

The cyclic or angular frequency, ω is measured in radians/second, $\omega = 2\pi f$
The **phase angle, ϕ** of the sinusoidal voltage is measured in radians. If the phase angle is positive, the sinusoidal function shifts to the left whereas if it is negative, it shifts to the right.

The **RMS or effective value** of a periodic function is given by $X_{rms} = \sqrt{\frac{1}{T}\int_{t_o}^{t_o+T} x(t)^2\, dt}$

The important characteristic of a **sinusoidal function** is the **RMS value**. This value represents the square root of the mean value of the squared function.

$$V_{rms} = \sqrt{\frac{1}{T}\int_{t_o}^{t_o+T} V_m^{\,2} \cos^2(\omega t + \phi)\,dt} = \frac{V_m}{\sqrt{2}}$$

This value reduces to the following for sinusoidal functions, $V_{rms} = V_m/\sqrt{2}$
The **average or DC value** of a periodic function is given by

$$V_{avg} = V_{dc} = \frac{1}{T}\int_{t_o}^{t_o+T} v(t)\,dt$$

This value reduces to 0 for sinusoidal waveforms with no offset.
To translate between a sine expression and cosine expression, use the following diagram.

The relationship between sine and cosine can be given by the following diagram.

$\sin(\omega t + 90^\circ) = \underline{\mathbf{\cos(\omega t)}}$

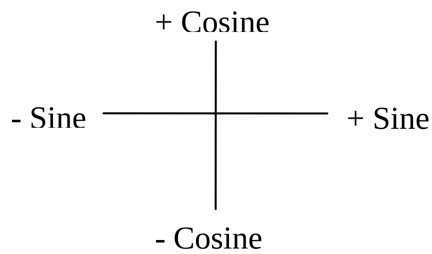
$\sin(\omega t - 90)^\circ = \underline{\mathbf{-\cos(\omega t)}}$

$\cos(\omega t + 90^\circ) = \underline{\mathbf{-\sin(\omega t)}}$

$\cos(\omega t - 90^\circ) = \underline{\mathbf{\sin(\omega t)}}$

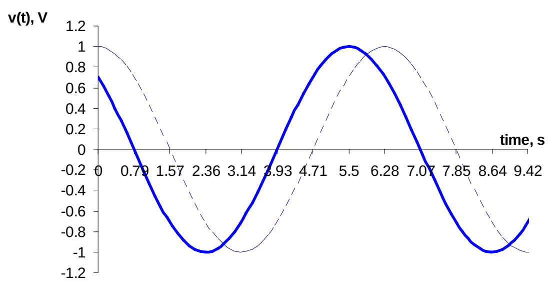
$\sin(\omega t \pm 180^\circ) = \underline{\mathbf{-\sin(\omega t)}}$

$\cos(\omega t \pm 180^\circ) = \underline{\mathbf{-\cos(\omega t)}}$



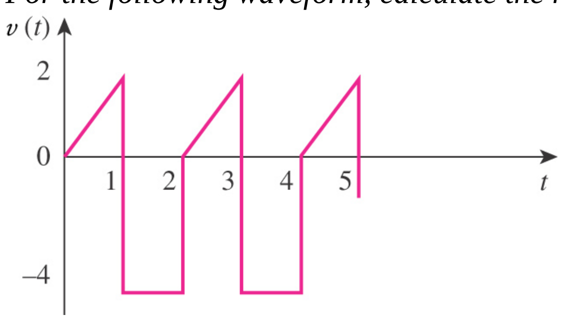
<u>In-Class Activity</u>

For the following voltage waveform, find the amplitude, phase with respect to cos ωt, frequency in Hertz and radians, RMS value and average value.



<u>In-Class Activity</u>

For the following waveform, calculate the rms and average values.



The response of an electric circuit to a sinusoidal source has two components: **transient, steady-state**. The **transient response** of a circuit is the voltage or current that becomes smaller as time elapses. The **steady – state response** is the voltage or current that exists as long as the source continues to supply the sinusoidal voltage or current.

For the steady state response,

i. the solution is a sinusoidal function
ii. the frequency of the solution is identical to the frequency of the source
iii. the maximum amplitude of the solution is different from the amplitude of the source
iv. the phase angle of the solution is different from the phase angle of the source

The **phasor** is a complex number that carries the amplitude and phase angle information of a sinusoidal function. The phasor concept is based upon Euler's identity,

$$e^{\pm j\theta} = \cos\theta \pm j\sin\theta$$

From this identity, $\cos\theta$ = **Real part of** $\{e^{j\theta}\} = \mathrm{Re}\{e^{j\theta}\}$
The sinusoidal voltage source becomes $v = V_m\cos(\omega t + \phi) = V_m\,\mathrm{Re}\{e^{j\omega t}e^{j\phi}\}$
The **phasor representation, or phasor transform** of the sinusoidal function is given by

$$\mathbf{V} = V_m e^{j\phi} \quad \text{[polar form]},$$

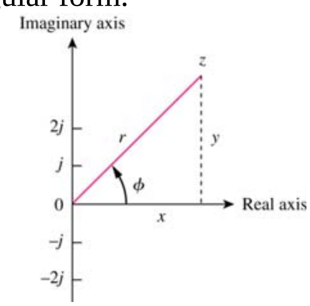
which converts the sinusoidal function from the time domain to the complex-number domain. The rectangular form of a phasor is given by

$$\mathbf{V} = V_m\cos\phi + j\,V_m\sin\phi \quad \text{[rectangular form]},$$

The angle notation of the phasor is given by

$$\mathbf{V} = V_m\angle\phi^\circ \quad \text{[angle notation]}$$

This figure is a representation of a complex number and shows the relationship between polar or exponential and rectangular form.



<u>One minute moment:</u>
Express the following sinusoid as phasors in polar, rectangular and angle notation.
$v = -7 \sin(10t + 40°) + 4 \cos(10t + 10°)$ V

<u>One minute moment:</u>
Find the sinusoid corresponding to the following phasors.
$\mathbf{I} = j(5-12j) + 10\angle 30°$ mA

<u>One minute moment:</u>
Express the following sinusoid as phasors in polar, rectangular and angle notation.
$v = -7 \sin(10t + 40°) * 4 \cos(10t + 10°)$ V

<u>One minute moment:</u>
Express the following sinusoid as phasors in polar, rectangular and angle notation.
$v = -7 \sin(10t + 40°) \div 4 \cos(10t + 10°)$ V

<u>Minute Paper:</u>
Take out a sheet o paper DO NOT PUT YOUR NAME ON IT. Answer the following question, What do you think was the most important concept presented in class today?

Lecture 2-3: Phasor Math and Impedances

Reading: 9.3, 9.4

Objectives: Be able to perform phasor addition, subtraction, multiplication and addition

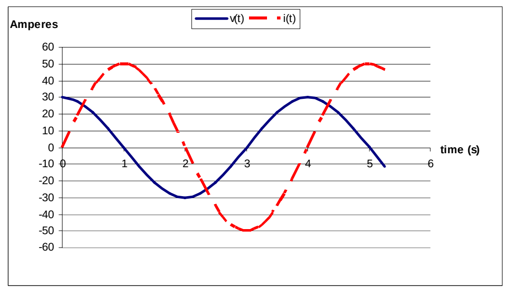
Be able to calculate the impedance of resistors, inductors, and capacitors in an AC circuit

Be able to transform a circuit with a sinusoidal source into the frequency domain using phasor representation

****

FE preview:

What is the correct phasor (polar) expression for the effective (RMS) current in the graph shown with respect to the voltage, v(t)?



a) $35\angle{-90}^\circ$ *A*

b) $35\angle 90^\circ$ *A*

c) $50\angle{-90}^\circ$ *A*

d) $50\angle 90^\circ$ *A*

FE Preview:

If $z_1 = 24.2\angle 32.3^\circ$ *and* $z_2 = 16.2\angle 45.8^\circ$*, what are* $z_1 z_2$ *and* z_1/z_2*, respectively?*

a) $40.4\angle 78.1^\circ$; $8.01\angle 13.5^\circ$

b) $392\angle 78.1^\circ$; $1.49\angle{-13.5}^\circ$

c) $392\angle 39.1^\circ$; $8.03\angle 1.4^\circ$

d) $241\angle 68.5^\circ$; $134.8\angle 38.5^\circ$

FE Preview:

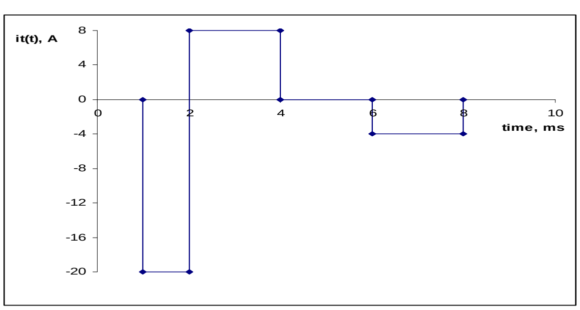
The following waveform repeats every 10 ms. What is the average value (I_{dc}) *of the waveform?*

a) *-20 A*

b) *-4.3 A*

c) *-1.2 A*

d) *8.1 A*



V = **I**R	**V** = jωL **I**	**I** = jωC **V**
the voltage and current are in phase	the voltage leads the current by 90°	the current leads the voltage by 90°

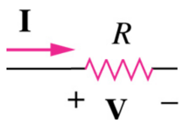
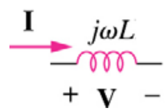
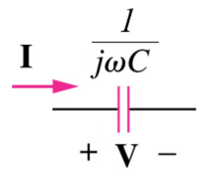
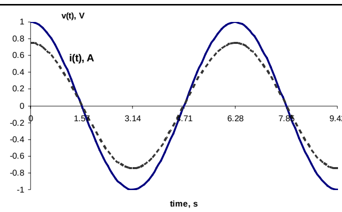
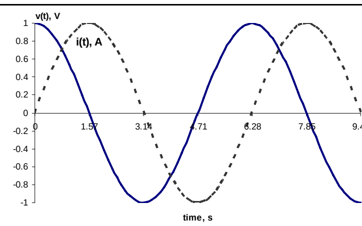
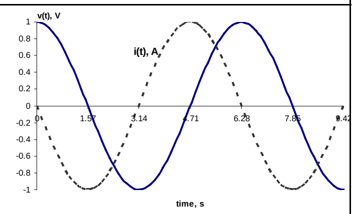

		
		

Figure 1	**Figure 2**	**Figure 3**

Ohm's Law in the frequency domain is stated as **V = IZ** where Z represents the **impedance** of the resistor, inductor and capacitor.

In all cases, impedance is measured in ohms (Ω). The real part of the impedance is **resistance** and the imaginary part of the impedance is called **reactance.**

Impedance: Z = R + jX = resistance + j(reactance) = real part + j(imaginary part) (Ω)

Element	Impedance, Z	Resistance, R	Reactance, X
Resistor	R	R	---
Inductor	jωL	---	ωL
Capacitor	-j/(ωC)	---	-1/(ωC)

<u>FE Preview:</u>
The magnitude of the reactances of a 10 mH inductor and a 0.2 μF capacitor are equal when the frequency is

a) 3.56 kHz
b) 200 MHz
c) 22.36 kHz
d) 21 kHz

Try Assessment Problems 9.1, 9.2 on page 342 and 9.3, 9.4 on page 346
<u>Minute Paper</u>
Take out a sheet of paper and create and solve one exam problem based upon the concepts presented in class today.

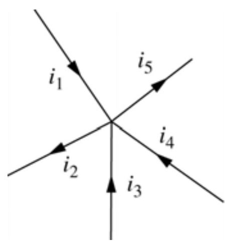
Lecture 3-1: Impedances, KVL, KCL

Reading: 9.4, 9.5, 2.4, 2.5

Objectives: Be able to transform a circuit with a sinusoidal source into the frequency domain using phasor representation
Be able to briefly and clearly explain Kirchhoff's voltage and current laws
Be able to solve circuits for voltage, current, and power using KCL and KVL

****

A **node** is a point where two or more circuit elements meet. **Kirchhoff's current law (KCL)** states that the algebraic sum of all the currents at any node in a circuit equals zero.
(i.e. current in = current out)



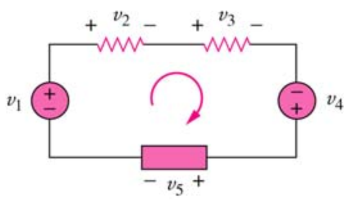
$$i_1 - i_2 + i_3 + i_4 - i_5 = 0$$

$$i_1 + i_3 + i_4 = i_2 + i_5$$

Note that Kirchhoff and Ohm's laws also apply for phasors but it is necessary to convert the circuit to the frequency domain model of a circuit and use complex numbers.

A **closed loop or path** in a circuit is any closed path in a circuit through selected basic circuit elements and return to the original node with passing any intermediate node more than once.

Kirchhoff's voltage law states that the algebraic sum of the voltages around any closed path in a circuit equals zero.

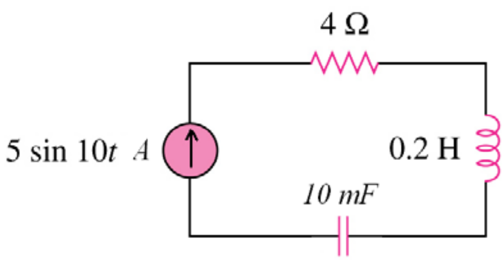


$$v_1 + v_4 = v_2 + v_3 + v_5$$

$$-v_1 + v_2 + v_3 - v_4 + v_5 = 0$$

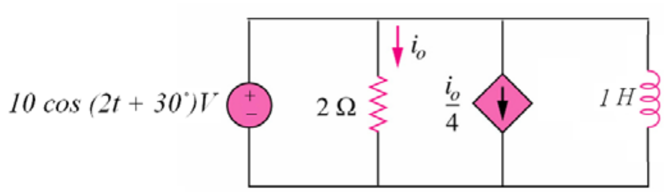
In-Class Activity

For the following circuit, redraw it in the frequency domain. Find the voltage across and current through each of the elements.



In-Class Activity

For the following circuit, redraw it in the frequency domain. Find the voltage across and current through each of the elements.



Try Assessment problems 9.3, 9.4 on page 346

Lecture 3-2: KVL, KCL

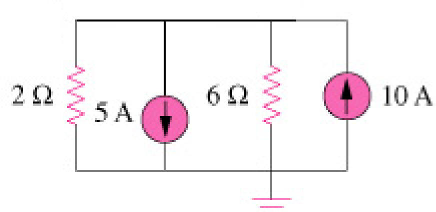
Reading: 9.4, 9.5, 2.4, 2.5

Objectives: Be able to briefly and clearly explain Kirchhoff's voltage and current laws
Be able to solve circuits for voltage, current, and power using KCL and KVL

****

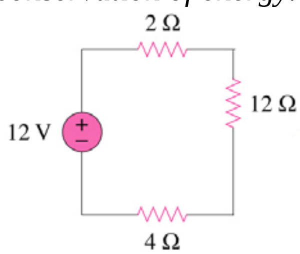
In-Class Activity

Write an outline of how you would confirm that the following circuit satisfies the law of conservation of energy.



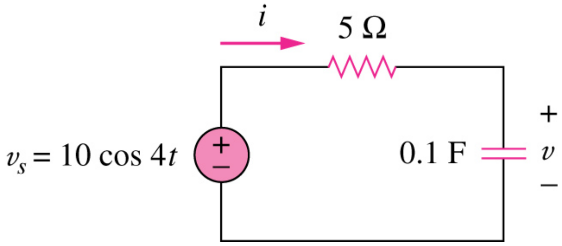
In-Class Activity

Write an outline of how you would confirm that the following circuit satisfies the law of conservation of energy.



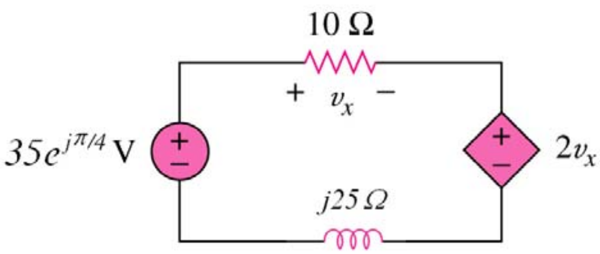
<u>In-Class Activity</u>

Find v(t) and i(t) for the following circuit.



<u>In-Class Activity</u>

For the following circuit, find v_x and the current through the element.



Try Assessment problems 2.5, 2.6, 2.7, 2.8 on page 42, 2.9, 2.10 on page 46, 9.5 on page 348

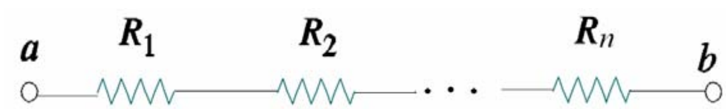
Lecture 3-3: Resistors in Parallel and Series, Voltage and Current Divider

Reading: 3.1 - 4

Objectives:
Be able to write formulas for the voltage and current divider
Be able to identify whether resistors are in series or parallel and use these concepts to simplify a resistive network
Be able to derive the voltage divider using KVL
Be able to derive the current divider using KCL
Be able to use KVL and/or KCL to find voltages and currents in an electric circuit

****

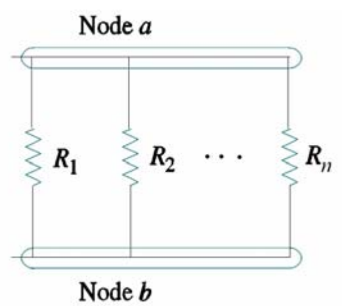
When two elements connect at a single node, they are said to be in **series**. Elements in series have the **same current**.



The equivalent resistance for resistors in series is the sum of the individual resistors. Therefore the equivalent resistance is always larger than the largest individual resistor.

$$R_{eq} = R_1 + R_2 + \ldots + R_n$$

When two elements connect at a single node pair, they are said to be in **parallel**. Elements in parallel have the same **voltage**.



The equivalent resistance is reciprocal of the sum of the individual conductances. Therefore the equivalent resistance is always smaller than the smallest individual resistor.

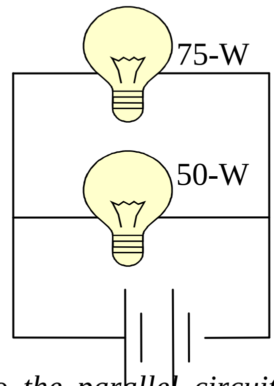
$$R_{eq} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}\right)^{-1}$$

$$G_{eq} = G_1 + G_2 + \cdots + G_n$$

The special case for 2 parallel resistors is $R_{eq} = R_1R_2/(R_1 + R_2)$

Concept Question:

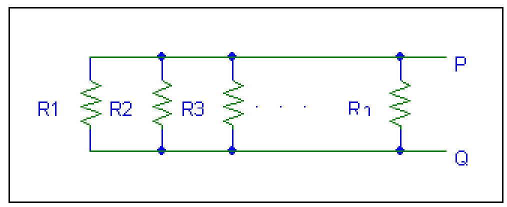
In the following circuit, a 75-W and 50-W bulb are placed in parallel across a voltage source, which of the following statements is true



a) the current through the 50-W bulb is larger
b) the current through the 75-W bulb is larger
c) the current through both bulbs is the same
d) none of the above

Concept Question:

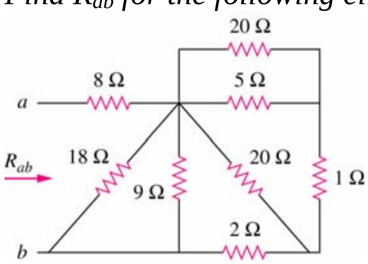
In the following figure, as more identical resistors are added to the parallel circuit between points P and Q, the total resistance between points P and Q



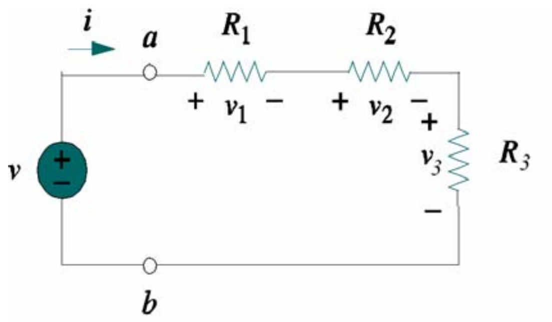
a) increases
b) decreases
c) remains the same
d) none of the above

In-Class Activity

Find R_{ab} for the following circuit.



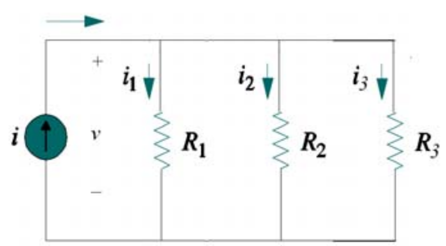
The **voltage divider** is used to calculate the voltage across several resistors when the voltage is supplied from a single source. In order to use the voltage divider, all of the elements must be in **series**.



Use KVL to find the voltage across R_3:	$-v + v_1 + v_2 + v_3 = 0$
Use Ohm's law to rewrite voltages across the resistors:	$-v + iR_1 + iR_2 + iR_3 = 0$
Solve for the current through the resistors:	$i = v/ (R_1 + R_2 + R_3)$
Use Ohm's law to find v_3:	$v_3 = iR_3 = vR_3/(R_1 + R_2 + R_3)$

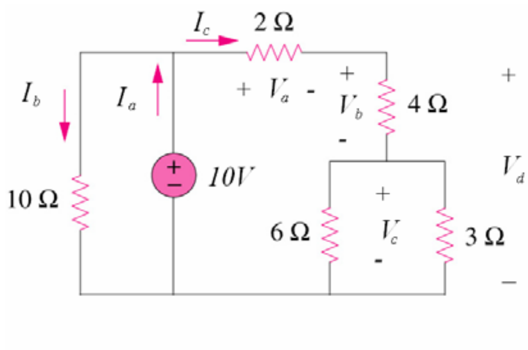
Therefore the **voltage divider rule** is $v_{\mathbf{n}} = \dfrac{R_n}{\sum_x R_x} v$

The **current divider** is used to calculate the current through several resistors when the current is supplied from a single source. In order to use the current divider rule, all of the elements must be in **parallel.**



Use KCL to find the current through R_3:	$-i + i_1 + i_2 + i_3 = 0$
Use Ohm's law to rewrite the currents across the resistors:	$-i + v/R_1 + v/R_2 + v/R_3 = 0$
Solve for the voltage across the resistors:	$v = i/(G_1 + G_2 + G_3)$
Use Ohm's law to find i_3:	$i_3 = G_3/(G_1 + G_2 + G_3)$

Therefore the **current divider rule** is $i_n = \dfrac{G_n}{G_1 + G_2 + \cdots G_n} i = \dfrac{R_{eq}}{R_n} i$



<u>*In-Class Activity*</u>
For the above circuit, if I_c is 9 mA, outline how to find the current through the 3Ω resistor. What is the current through the 3Ω and 6Ω resistors?

<u>*In-Class Activity*</u>
For the above circuit, if V_d is 3V, outline how to find the voltage across the 4Ω resistor. What is the voltage across the 4Ω, 3Ω and 6Ω resistors?

<u>*In-Class Activity*</u>
For the above circuit, use the formulas to combine series and parallel resistors, voltage divider rule and current divider rule to confirm that the law of conservation of energy is satisfied.

Try Assessment Problems 3.1 on page 62, 3.2, 3.3 on page 65, 3.4 on page 67

Lecture 4-1: Series and Parallel Impedances

Reading: 9.6, 6.3
Objectives: Be able to combine inductors, capacitors, and impedances in series and parallel
Be able to simplify circuits using parallel and series concepts to find voltages and currents in an electric circuit

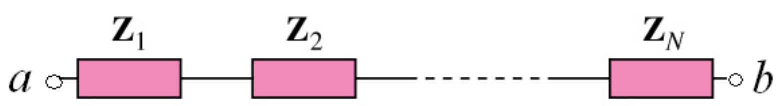
****

Recall that the impedance of a resistors is **R**, the impedance of an inductor is **jωL**, the impedance of a capacitor is **–j/(ωC)**

Recall that two elements are in **series** when they share a single node.

Recall that elements in **parallel** connect at a single node pair.

Impedances in series combine like resistors in series. Calculate the equivalent impedance by summing the individual impedances.

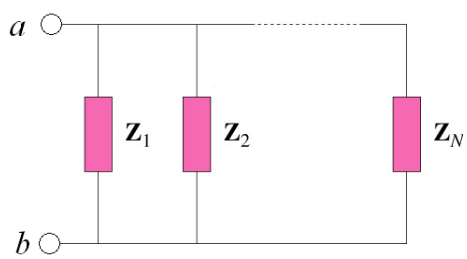


$$\mathbf{Z_{ab} = Z_1 + Z_2 + Z_3 + \cdots + Z_n}$$

Recall that the reciprocal of impedance is admittance **Y = 1/Z = G + jB** measured in Siemens. The real part of the admittance is **conductance, G** and the imaginary part is **susceptance, B** both measured in Siemens.

Impedances in parallel combine like resistors in parallel. Find the equivalent impedance by calculating the reciprocal of the sum of the admittances.

$$\mathbf{Y_{ab} = Y_1 + Y_2 + \cdots + Y_n}$$
$$\mathbf{Z_{ab} = 1/Y_{ab}}$$



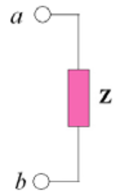
The special case for 2 parallel impedances is $\mathbf{Z_1Z_2/(Z_1 + Z_2)}$

In-Class Activity:

If the voltage across the following impedance is $10\angle 30°$ V and the current through the impedance is $5\angle 25°$ mA

a) what series-connected impedances form Z?

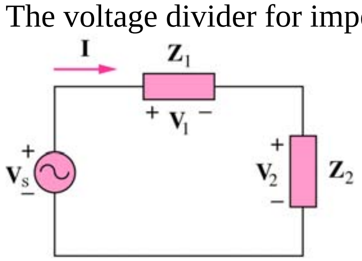
b) what parallel-connected impedances form Z?



Concept Question:

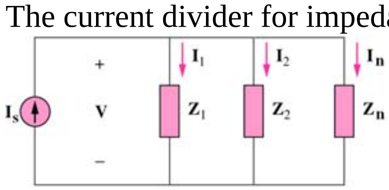
At what frequency would the following impedance be purely resistive?

The voltage divider for impedances is similar to the voltage divider for resistors



$$\mathbf{V_n} = V_n = \frac{Z_n}{\sum_x Z_x} V_s = \frac{Z_n}{Z_1 + Z_2 + \cdots Z_n} V_s$$

The current divider for impedances is similar to the current divider for resistors



$$I_n = \frac{Z_{eq}}{Z_n} I_s = \frac{Z_1 \,||\, Z_1 \,||\cdots||\, Z_b}{Z_n} I_s$$

Special Case for Two: $I_1 = \frac{Z_2}{Z_1 + Z_2} I_s$

FE Preview:

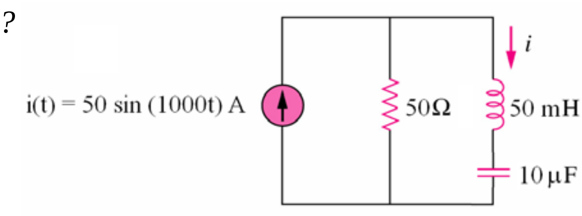
What is the current through the 50 mH inductor?

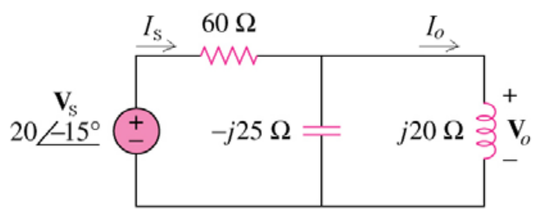
a) 35 cos(1000t + π/4) A

b) 50 sin (1000t) A

c) 35 sin (1000t + π/4) A

d) 35 sin (1000t - π/4) A





In-Class Activity 1:

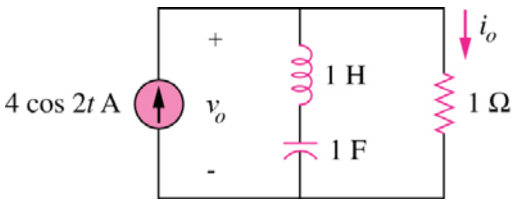
For the above circuit, use the voltage divider to find $\mathbf{V_o}$.

In-Class Activity 2:

For the circuit in the previous activity, simplify the impedances and use Ohm's law to find $\mathbf{I_s}$.

In-Class Activity 3:

For the above circuit, use the current divider to find I_o.



In-Class Activity 1:
For the above circuit, use the current divider to find i_o.

In-Class Activity 2:
For the above circuit, simplify the impedances and use Ohm's law to find v_o.

In-Class Activity 3:
Use the result of the previous activity and the voltage divider to find voltage across the capacitor.

Try Assessment Problems 9.6 on page 349, 9.7, 9.8 on page 352
Minute Paper
Take out a sheet of paper, DO NOT PUT YOUR NAME ON IT.
Write one concept from the last 4 weeks that is still unclear as you begin to prepare for Exam 1.

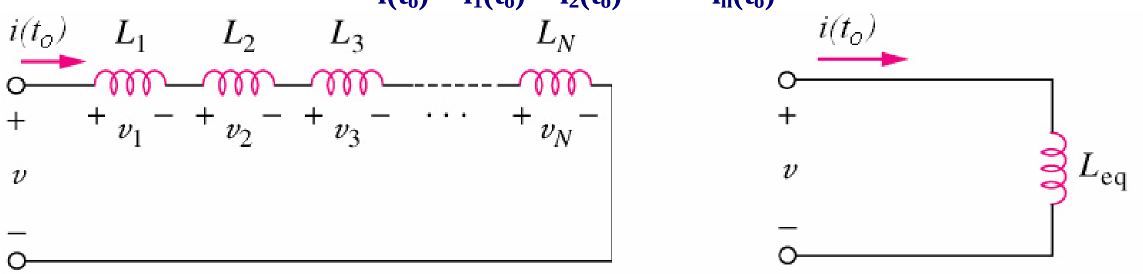
Lecture 4-2: Series and Parallel Inductors and Capacitors

Reading: 9.6, 6.3
Objectives: Be able to combine inductors, capacitors, and impedances in series and parallel
Be able to simplify circuits using parallel and series concepts to find voltages and currents in an electric circuit

****

In order to combine **inductors in series**, it is very similar to combining resistors in **series**.

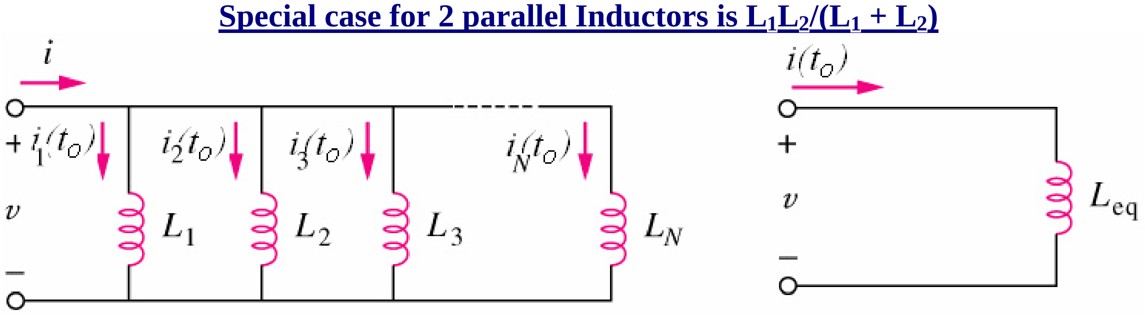
$$L_{eq} = L_1 + L_2 + \cdots + L_n$$
$$i(t_o) = i_1(t_o) = i_2(t_o) = \cdots = i_n(t_o)$$



In order to combine **inductors in parallel**, it is very similar to combining resistors in **parallel**.

$$1/L_{eq} = 1/L_1 + 1/L_2 + \cdots + 1/L_n$$
$$i(t_o) = i_1(t_o) + i_2(t_o) + \cdots + i_n(t_o)$$

Special case for 2 parallel Inductors is $L_1L_2/(L_1 + L_2)$



Assuming 0 initial conditions:

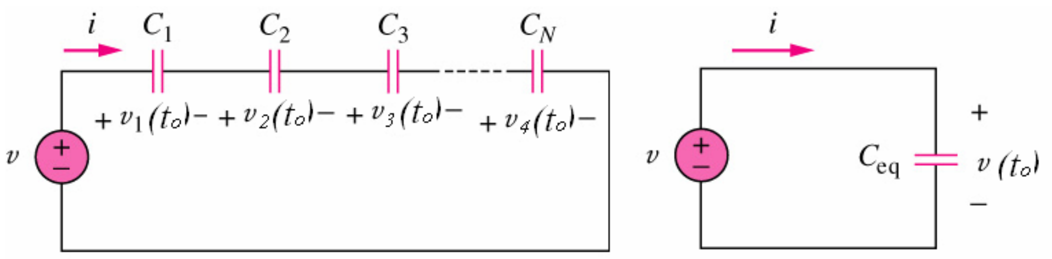
Inductor Voltage Divider: $V_n = \dfrac{L_n}{\sum_x L_x} V_s$ (similar to resistors)

Inductor Current Divider: $I_n = \dfrac{1/L_n}{\sum_x 1/L_x} I_s = \dfrac{L_{eq}}{L_1} I_s$ (similar to resistors)

In order to combine **capacitors in series**, it is very similar to combining resistors in **parallel**.

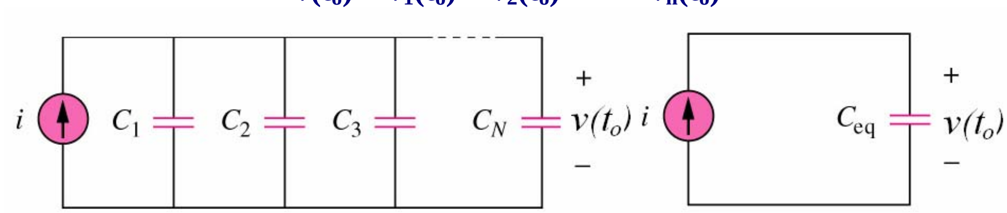
$$1/C_{eq} = 1/C_1 + 1/C_2 + \cdots + 1/C_n$$
$$v(t_o) = v_1(t_o) + v_2(t_o) + \cdots + v_n(t_o)$$

Special case for 2 series Capacitors is $C_1C_2/(C_1 + C_2)$



In order to combine **capacitors in parallel**, it is very similar to combining resistors in **series**.

$$C_{eq} = C_1 + C_2 + \cdots + C_n$$
$$v(t_o) = v_1(t_o) = v_2(t_o) = \cdots = v_n(t_o)$$



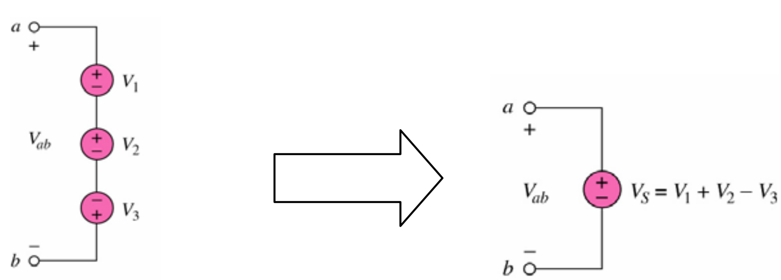
Assuming 0 initial conditions

Capacitor Voltage Divider: $V_n = \dfrac{1/C_n}{\sum_x 1/C_x} V_s = \dfrac{C_{eq}}{C_n} V_s$ (opposite of resistors)

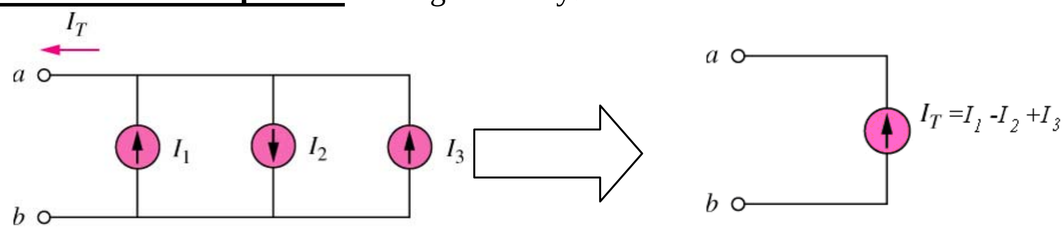
Capacitor Current Divider: $I_n = \dfrac{C_n}{\sum_x C_x} I_s$ (opposite of resistors)

*******************************Ideal Sources****************************

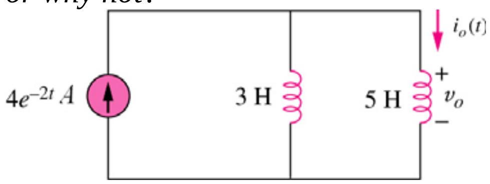
Voltage Sources in series add algebraically



Current Sources in parallel add algebraically:



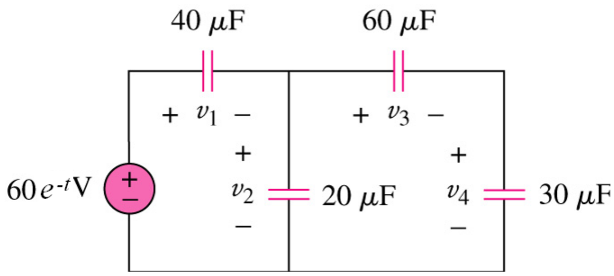
Concept Question
In the following circuit, can the initial current through each of the inductors be 0A, why or why not?



In-Class Activity
For the above circuit, calculate $v_o(t)$ and $i_o(t)$ if the initial current through the 3H inductor is 2.5 A and $i_o(0)$ = 1.5 A. Confirm that this circuit satisfies Kirchhoff's current law.

In-Class Activity

For the following figure, outline how to find the voltage across each of the capacitors in the following circuit. What is the energy trapped in the 30μF capacitor at t = 0? t = ∞?



Try Assessment Problems 6.4, 6.5 on page 203

Unit II

METHODS OF ANALYSIS

- node-voltage method
- mesh-current method
- source transformations
- Thevenin, Norton theorems
- maximum power transfer
- superposition

Lecture 5-1: The Node-Voltage Method

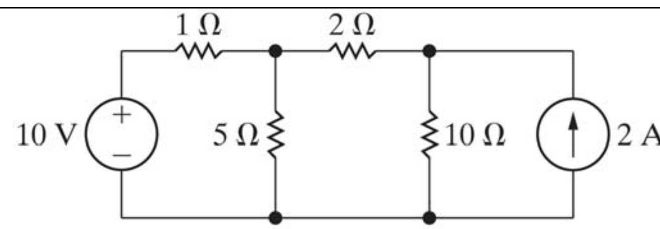
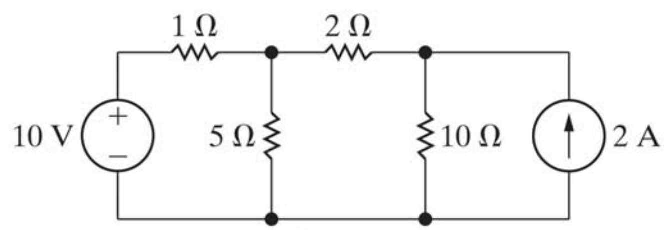
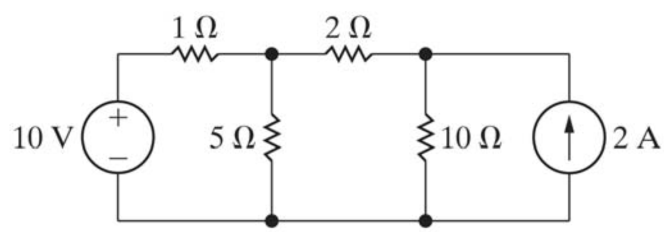
Reading: 4.1-2

Objectives: Be able to briefly and clearly explain in your own words *node, node-voltage method*
Be able to identify nodes in a circuit
Be able to apply the node-voltage method to calculate voltage, current, and power in an electric circuit

****

A **planar circuit** is a circuit that can be drawn on a plane with no crossing branches. The node-voltage method can be used on planar and non-planar circuits. However, the mesh-current method **cannot** be used on non-planar circuits (see Figures 4.1 and 4.2 on page 94 in the textbook for examples of both).

All of the terms used to describe a circuit are provided in the following table.

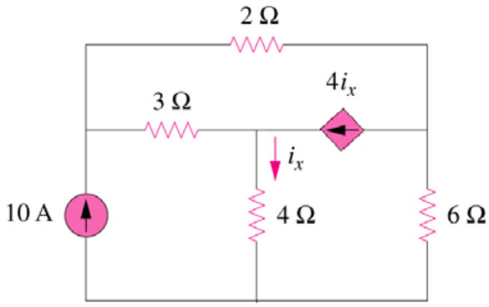
node	a point where two or more circuit elements join	 Figure: 04-05
essential node	a node where 3 or more circuit elements join	
path	a trace of adjoining basic elements with no elements included more than once	
branch	a path that connects two nodes	 Figure: 04-05
essential branch	a path which connects two essential nodes without passing through an essential node	
loop	a path whose last node is the same as the starting node	 Figure: 04-05
mesh	a loop that does not enclose any other loops	

Recall that **Kirchhoff's current law** states that the sum of the currents in and out of a node must equal zero.

The **node-voltage law** is based upon using KCL to analyze a circuit to independent simultaneous equations to solve for node voltages.

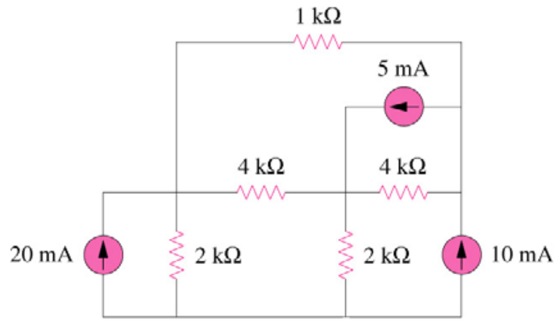
The number of equations required is based upon the branches and nodes in the circuit. If there are n nodes in a circuit, then it is possible to derive **n – 1** equations using KCL and **b-(n-1)** equations using KVL.

In-Class Activity:
How many nodes and branches are in the following circuit? How many KCL and KVL equations are required to solve for the unknown branch currents?



Steps to implement the node-voltage method

i. make a neat layout of the circuit with no branches overlapping
ii. mark one of the essential nodes the **reference node** (typically the one with the most branches near the bottom of the circuit) [*note: this is the **ground (0 V)**, all node voltages are with respect to this node*]
iii. **node voltages** are defined as the voltage rise from the ground node to a non reference node
iv. label all of the node voltages on the circuit (v1, v2, v3, etc.)
v. draw currents leaving each labeled node if it is not given
vi. use Ohm's law to write the KCL equations at each of the non-reference labeled nodes
vii. Solve the simultaneous equations by using Cramer's rule, matrix manipulation or your calculator to find the node voltages
viii. Finally complete the power table by using the derived values.

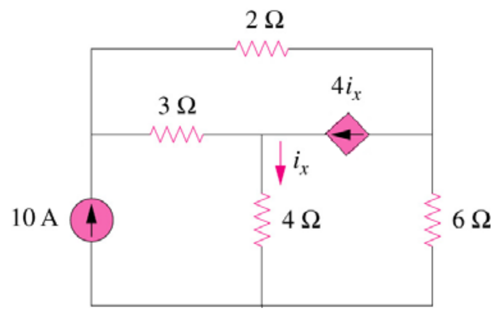


<u>*In-Class Activity:*</u>

For the above circuit, execute steps i – v of the node-voltage method. Use the node-voltage method to confirm that the circuit satisfies the law of conservation of energy.

element	**V (V)**	**I (A)**	**Power (W) delivered**	**Power (W) absorbed**
20mA				
5 mA				
10 mA				
2 kΩ				
4 kΩ				
2 kΩ				
4 kΩ				
1 kΩ				
TOTAL				

In-Class Activity:
Use the node-voltage method to find the voltage across the current sources in the following circuit.



Try Assessment Problems 4.1 and 4.2 on pages 99 and 100

Lecture 5-2: The Node-Voltage Method: Special Cases

Reading: 4.3-4

Objectives: Be able to briefly and clearly explain in your own words *node*, *node-voltage*, *node-voltage method*

Be able to apply the node-voltage method to calculate voltage, current, and power in an electric circuit for circuits with dependent sources and voltage sources.

****

As seen from the prior lecture, when circuit includes **dependent sources**, the node voltage method must be supplemented with constraint equations imposed on the dependent source.

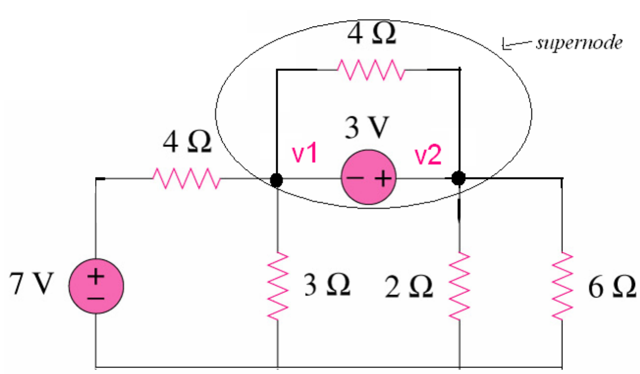
When a voltage source is between two **non-reference** nodes, the equation derivation is simplified because the voltage between the 2 essential nodes is constrained by the value of the source. This voltage source between two **non-reference** nodes and any element in parallel with it is called a **supernode**.

Properties of a supernode:

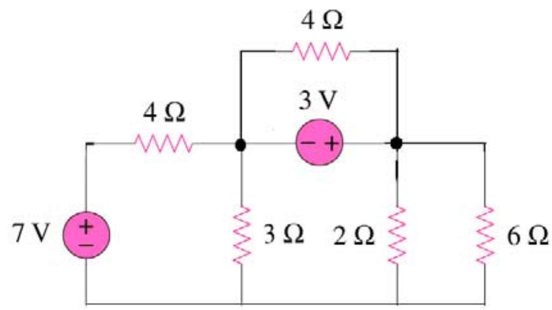
1. The voltage source inside the supernode provides a constraint equation needed to solve for the node voltages.
2. A supernode has no voltage of its own.
3. A supernode requires the application of both KCL and KVL.

To analyze the supernode:

1. perform KCL into and out of the supernode, (i.e., $i_{4\Omega} + i_{3\Omega} + i_{2\Omega} + i_{6\Omega} = 0$)
2. perform KVL at the supernode (i.e., $v_2 - v_1 = 3$ V)



Finally, since the purpose of the node-voltage method is to use KCL to find all unknown node-voltages, it is also not necessary to perform KCL at the 7V source. Instead of labeling this node as v1 or v2, refer to it at **"7V"**.



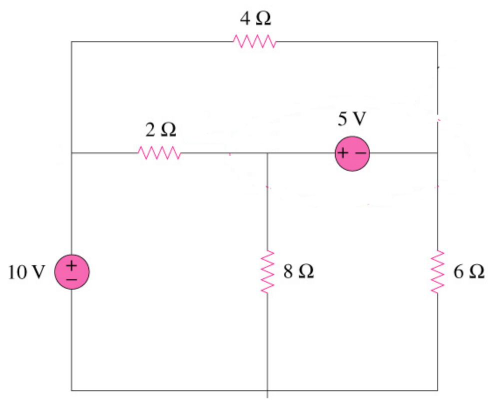
<u>In-Class Activity:</u>

For the above circuit,

a) *outline how you would use the node-voltage method to find all of the unknown voltages*

b) *confirm that the circuit satisfies the law of conservation of energy*

Element	**V (V)**	**I (A)**	**Power (W) delivered**	**Power (W) absorbed**
7V				
3V				
4 Ω				
3 Ω				
4 Ω				
6 Ω				
2 Ω				
TOTAL				



<u>In-Class Activity:</u>
For the above circuit, are there any supernodes? if so, what are they? Use the node-voltage method to analyze the circuit and confirm that the circuit satisfies the law of conservation of energy

Element	**V (V)**	**I (A)**	**Power (W) delivered**	**Power (W) absorbed**
10 V				
5 V				
2 Ω				
4 Ω				
6 Ω				
8 Ω				
TOTAL				

<u>One Minute Paper</u>
Take out a sheet of paper and DO NOT PUT YOUR NAME ON IT. State one concept related to the node-voltage method that is still unclear to you.

Try Assessment Problems 4.3 on page 101, 4.4, 4.5, and 4.6 on page 104

Lecture 5-3: The Mesh-Current Method

Reading: 4.5-6

Objectives: Be able to briefly and clearly explain in your own words *mesh*, *mesh-current*, *mesh-current method*

Be able to apply the mesh-current method to calculate voltage, current, and power in an electric circuit

****

Recall that the mesh-current method is only valid for **non planar** circuits. For the mesh-current method, use KVL to describe a circuit in terms of b – (n – 1) independent simultaneous equations.

A **mesh current** is the current that exists only in the perimeter of a mesh.

Note that Figure 4.18 illustrates mesh currents and Figure 4.4 illustrates branch currents. It should be evident that it is not always possible to identify a mesh current in terms of a branch current.

In order to implement the mesh-current method,

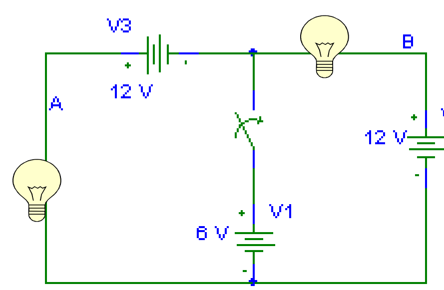
1. Assign mesh current i_1, i_2, ... i_n to the n meshes in the circuit
2. Apply KVL to each of the n meshes. Use Ohm's law to express the voltages in terms of the mesh currents
3. Solve the resulting n simultaneous equations to get the mesh currents.
4. Determine the relationship between the mesh currents and branch currents in order to find all the voltage and power in the circuit

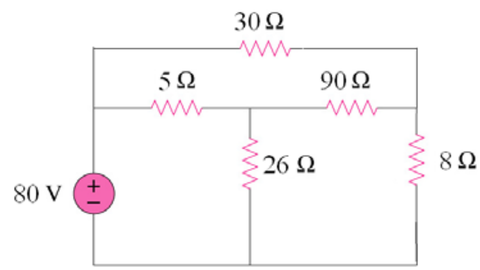
Similar to the analysis with dependent sources for the node-voltage method, the existence of a dependent source must be supplemented by an appropriate constraint equation.

Concept Question:

In the following circuit, all of the light bulbs are identical. Knowing that the intensity of a light bulb is proportional to the power dissipated across it. When the switch is closed, which of the following statements is true?

a) *Bulb B is brighter*
b) *Bulb B is dimmer*
c) *Bulb B remains the same*
d) *none of the above*

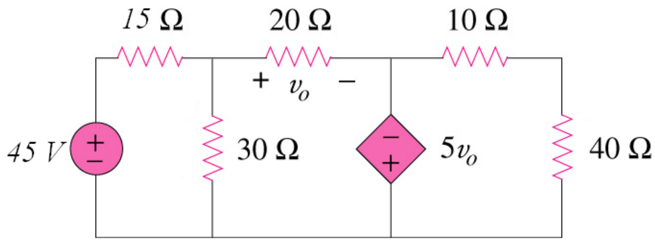




In-Class Activity:
For the above circuit, implement steps 1 – 2 of the mesh-current method

In-Class Activity
For the above circuit, confirm that it satisfies the law of conservation of energy

Element	V (V)	I (A)	P_{del} (W)	P_{abs} (W)
80 V				
5 Ω				
30 Ω				
90 Ω				
26 Ω				
8 Ω				
TOTAL				



In-Class Activity:
For the above circuit, use the mesh current method to find the mesh currents.

In-Class Activity:
Using the result of the previous activity, find the power delivered or absorbed by each of the voltage sources.

Try Assessment Problems 4.7 on page 107, 4.8 – 4.9 on page 109

Lecture 6-1: The Mesh-Current Method: Special Cases

Reading: 4.7-8

Objectives: Be able to briefly and clearly explain in your own words *mesh*, *mesh-current*, *mesh-current method*

Be able to apply the mesh-current method to calculate voltage, current, and power in an electric circuit for circuits with supermeshes

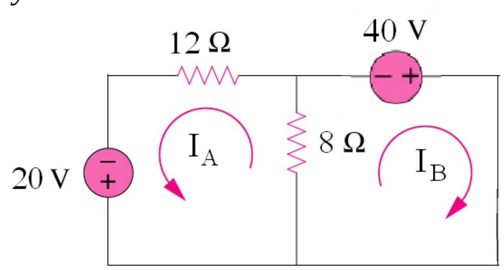
Be able to determine whether the node-voltage or mesh-current method is a better approach for analyzing a given electrical circuit

****

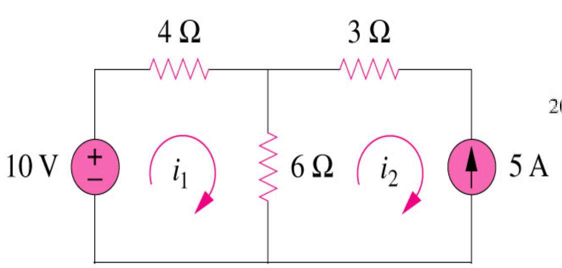
FE Preview:

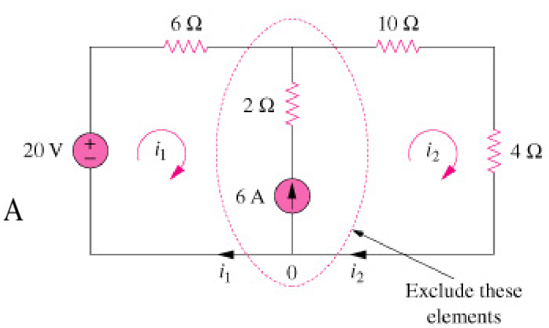
What is the current, I_B, through the 40 V battery?

a) 1.3 A
b) 2.9 A
c) 6.7 A
d) 13 A



The following 2 circuits give illustrations of how current sources affect mesh analysis.





(a) current source only in one mesh (b) two meshes have the current source in common

CASE I CURRENT SOURCE IN ONLY ONE MESH

When a current source exists only in one mesh, the mesh current is equal to the value of the source. The sign is dependent upon the direction of the source current. For the circuit in

(a) **i_2 = -5A.**

CASE II TWO MESHES HAVE THE CURRENT SOURCE IN COMMON

When the current source exists between two meshes, create a **supermesh** by excluding the current source and any elements connected in series with it. If a circuit has two or more supermeshes that intersect, they should be combined for form a larger supermesh.

A **supermesh** results when two meshes have a (dependent or independent) current source in common.

Properties of a supermesh:

1. The current source in the supermesh provides the constraint, (i.e., $\mathbf{i_2 - i_1 = 6A}$)
2. A supermesh has no current of its own
3. A supermesh requires the application of both KVL and *KCL*
   (i.e., $\mathbf{-20 + v_{6\Omega} + v_{10\Omega} + v_{4\Omega} = 0}$)

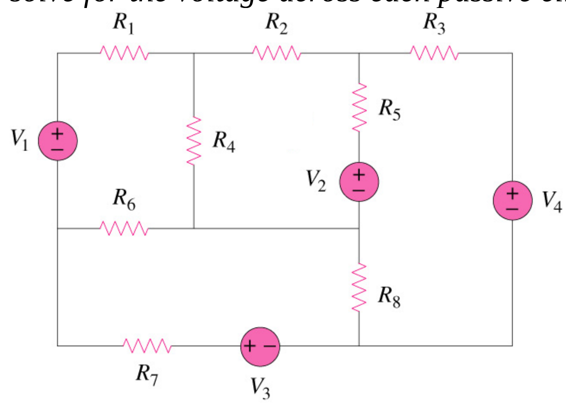
Node-Voltage Method versus Mesh-Current Method

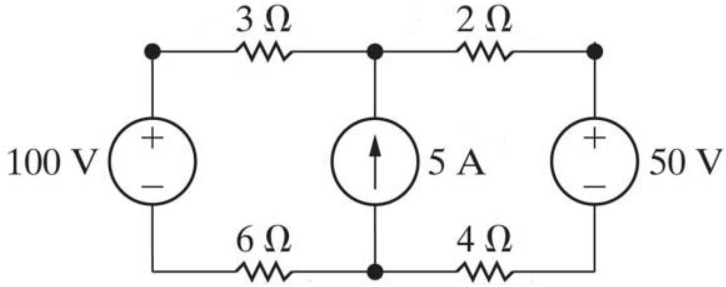
Networks that contain many series-connected elements, voltage sources, or supermeshes are more suitable for mesh analysis. Networks with parallel-connected elements, current sources, or supernodes are more suitable for nodal analysis.

- A circuit with fewer nodes than meshes is better analyzed using nodal analysis.
- A circuit with fewer meshes than nodes is better analyzed using mesh analysis.
- The key is to select the method that results in the smaller number of equations.
- Also, consider the information that is required.
- If node voltages are required, it may be expedient to apply node analysis.
- If branch or mesh currents are required, it may be more expedient to use mesh analysis.

Concept Question:

For the following circuit, would you select the node-voltage or mesh-current method to solve for the voltage across each passive circuit element? Why?





In-Class Activity:

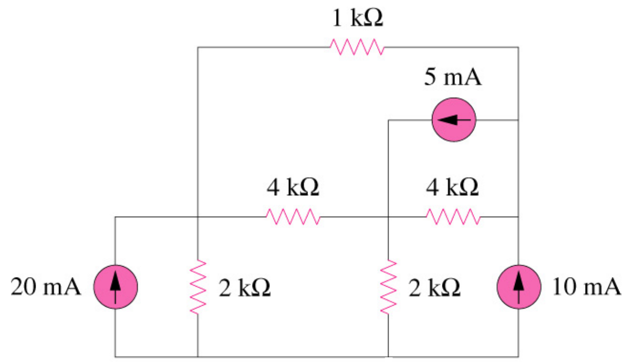
For the above circuit,

a) *are there any supermeshes in the circuit? if so, what are they?*
b) *Label all of the meshes*
c) *Write enough KVL equations to solve for each of the mesh currents*
d) *What are the values of each of the mesh currents?*

In-Class Activity:

For the above circuit, use the mesh-current method to confirm that the circuit satisfies the law of conservation of energy.

Element	**V (V)**	**I (A)**	**Power (W) delivered**	**Power (W) absorbed**
100 V				
50 V				
5 A				
2 Ω				
3 Ω				
4 Ω				
6 Ω				
TOTAL				



<u>In-Class Activity:</u>
For the above circuit, use the mesh-current method to find all of the mesh currents.

<u>In-Class Activity:</u>
Using the results of the previous activity, what is the power delivered or absorbed by the 5 mA current source?

<u>One Minute Paper</u>
Take out a sheet of paper and DO NOT PUT YOUR NAME ON IT. State one concept related to the mesh-current method that is still unclear to you.

Try Assessment Problems 4.10, 4.11, 4.12 on page 112, and 4.13 and 4.14 on page 116

Lecture 6-2: AC Node-Voltage and Mesh-Current Methods

Reading: 9.8-9

Objectives: Be able to apply the mesh-current and node-voltage methods to AC circuits

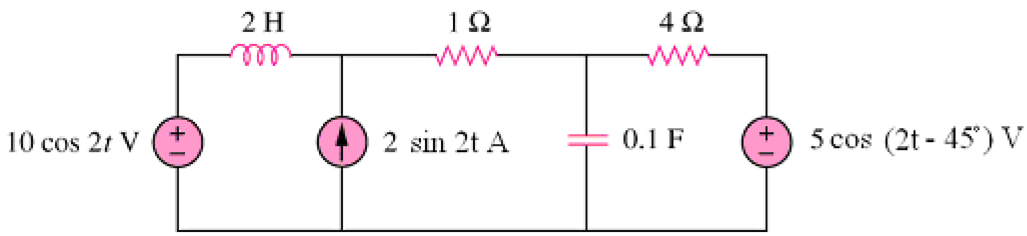
Be able to apply the mesh-current and node-voltage method to AC circuits with supernodes and supermeshes

****

The same techniques applied for DC node-voltage and mesh-current methods can also be used for AC circuits. These techniques will be demonstrated in the following activities.

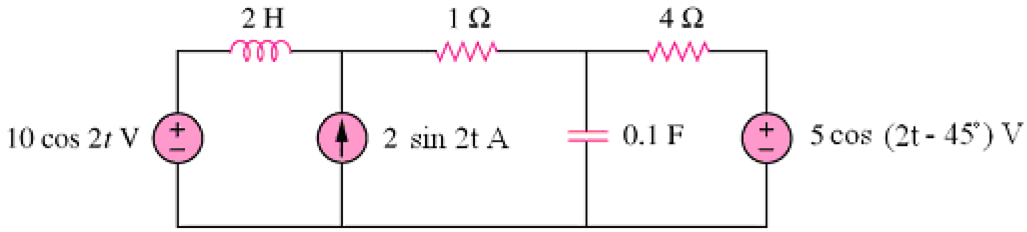
<u>In-Class Activity</u>

For the following circuit, use the node-voltage method to find the voltage across and current through the inductor and capacitor.



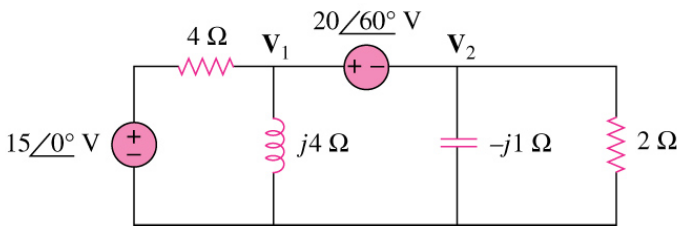
In-Class Activity

For the following circuit, use the mesh-current method to find the voltage across and current through the inductor and capacitor.



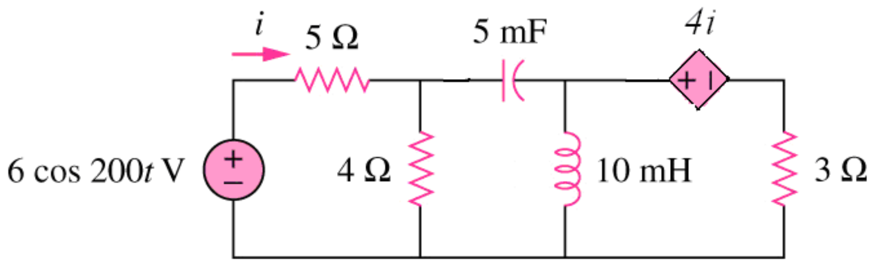
In-Class Activity

For the following circuit, use the node-voltage method to find the voltage across and current through the inductor and capacitor.



In-Class Activity

For the following circuit, use the mesh-current method to calculate the voltage across and current through the resistors.



Try Assessment Problems 9.12 and 9.13 on pages 360 and 361

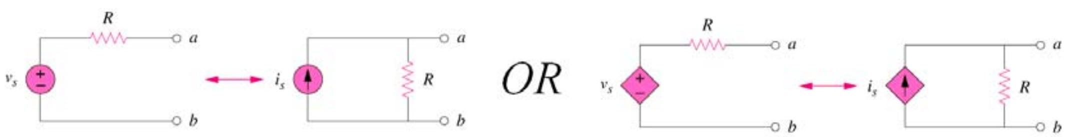
Lecture 6-3: Source Transformations

Reading: 4.9, 9.7
Objectives: Be able to briefly and clearly explain the process of applying source transformations to simplify a circuit
Be able to simplify an electric circuit by using source transformations.

****

One method to simplify passive elements in a circuit is series-parallel reductions. One technique to simplify active elements in a circuit is <u>**source transformations**</u>.

A <u>**source transformation**</u> allows a voltage source in series with a resistor to be replaced by a current course in parallel with the same resistor or vice versa.



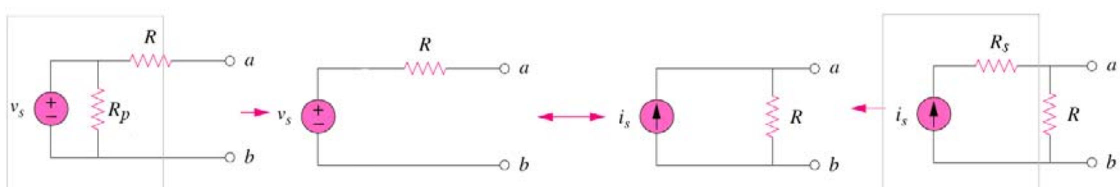
NOTE: The arrow of the current is directed toward the positive terminal of the voltage source.

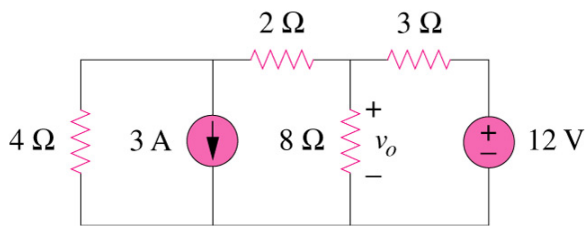
When performing the transformation from a current source to a voltage source, the value is found by using Ohm's law, $\underline{\mathbf{v_s = i_s R}}$

When performing the transformation from a voltage source to a current source, the value is found by using Ohm's law, $\underline{\mathbf{i_s = v_s/R}}$

Special Cases:

When a resistance, R_p is in parallel with the voltage source or a resistance, R_s is in series with the current source, there is no difference in the transformation circuit.



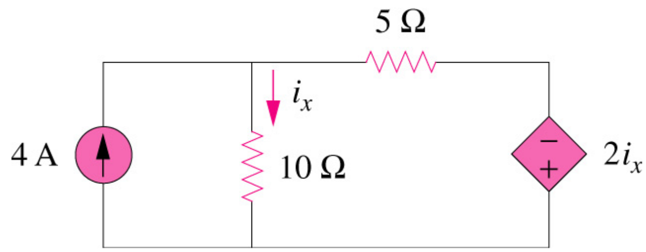


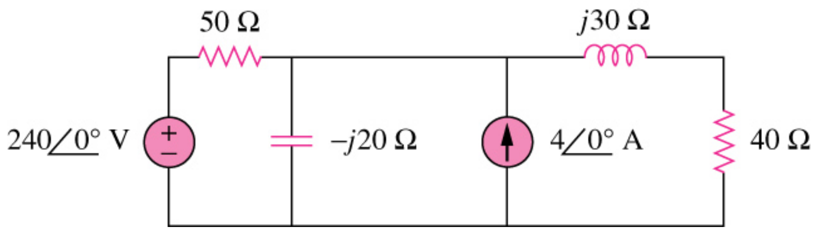
<u>In-Class Activity:</u>
For the above circuit, use source transformations to simplify the circuit to one source and 2 resistors (one must be the 8Ω resistor).

<u>In-Class Activity:</u>
For the above circuit, use source transformations to simplify the circuit and find v_o. Find the power developed by the 12 V and 3A sources.

In-Class Activity:

For the following circuit, use source transformations to find i_x.





<u>In-Class Activity:</u>
For the above circuit, simplify the circuit by performing a source transformation on the voltage source, 50 Ω and –j20Ω impedances.

<u>In-Class Activity:</u>
Using the result of the previous activity, reduce the circuit to one source and 2 impedances (one must be the 40Ω resistor).

<u>In-Class Activity:</u>
Using the result of the previous activity, find the voltage through and current across the 40Ω resistor.

Try Assessment Problems 4.15 on page 119, 9.10 and 9.11 on page 358

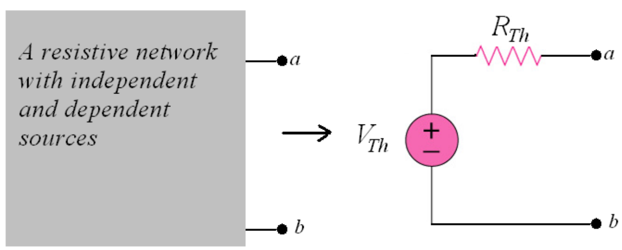
Lecture 7-1: Thevenin and Norton Equivalent Circuits

Reading: 4.10 - 11
Objectives: Be able to briefly and clearly explain Thevenin and Norton equivalence
Be able to convert a circuit to an equivalent circuit using Thevenin and Norton equivalence

****

Thevenin and Norton equivalents are circuit simplification techniques that focus on the voltage and current characteristics at the terminal of a circuit. Recall from source transformations that two circuits are said to be **equivalent** if they have the same voltage-current relationship at their terminals.

When a circuit can be simplified and described at its terminals in terms of a voltage source in series with a resistance, this is the **Thevenin equivalent circuit.**



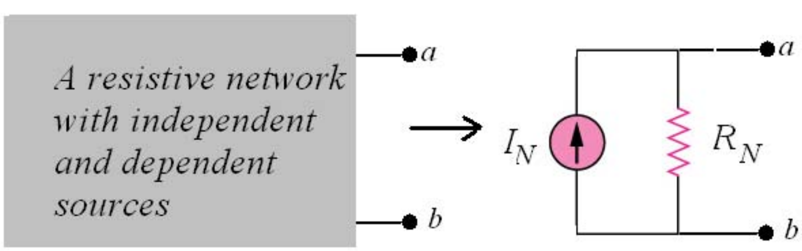
The **Thevenin Voltage, V_{th}** is the open circuit voltage across terminals a and b.

When a circuit can be simplified at its terminals and is described in terms of a current source in parallel with a resistance, this is the **Norton equivalent circuit.**

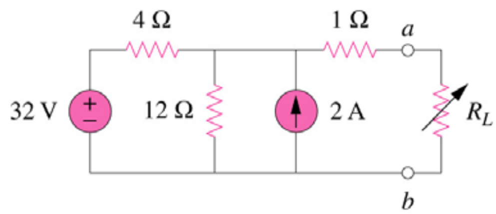
The **Norton current, I_N**, is the short circuit current between terminals a and b. The relationships between the Thevenin Voltage and Norton current are based upon Ohm's law.

$$R = V_{oc}/I_{sc} \rightarrow R_{th} = V_{th}/I_N$$

Note that $R_{Th} = R_N$



There are several techniques that can be used to find the Thevenin equivalent of a circuit. When there are only independent sources, source transformations can be used if the configuration allows.



In-Class Activity
For the above circuit, find the Thevenin equivalent to the left of terminals a and b.

In-Class Activity
For the above circuit, find the Norton equivalent to the left of terminals a and b.

In-Class Activity
For the above circuit, if there is a 5Ω load placed across the terminals of the circuit, what is the power delivered to the load?

When you cannot use source transformations to find the Thevenin or Norton equivalent of a circuit use one of the following techniques.

For independent sources only,

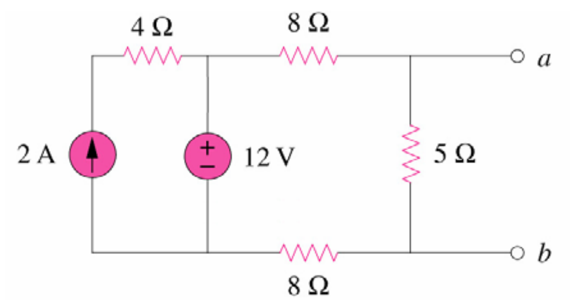
- Find the equivalent or input resistance at a-b when all independent sources are turned off, $R_{ab} = R_{Th}$

For dependent sources only,

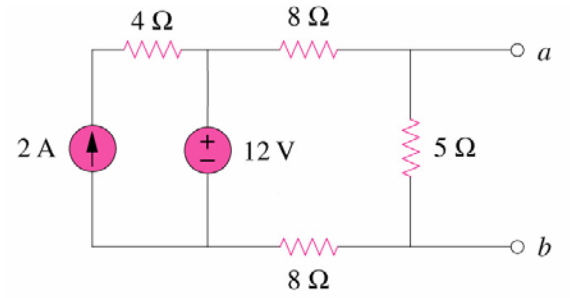
- Apply a test voltage or current across terminals a and b, the relationship between the voltage across and current through the test source is $R_{Th} = v_{test}/i_{test}$
- If R_{th} produces a negative value in your calculations, this implies that the circuit is actually absorbing power if it was assumed to be delivering power.

For a combination of independent and dependent sources,

- Find the open circuit voltage across terminals a-b, $v_{oc} = V_{Th}$
- Find the short circuit current through terminals a-b, $i_{sc} = I_N$
- Find the open circuit voltage and short circuit current between the terminals and $R_{th} = v_{oc}/i_{sc}$.



In-Class Activity
For the above circuit, find the Thevenin equivalent resistance, R_{th} by turning off all independent sources.



<u>*In-Class Activity*</u>
For the above circuit, find the Thevenin equivalent voltage, V_{th} by finding the open circuit voltage between terminals a and b (V_{ab}).

<u>*In-Class Activity*</u>
For the above circuit, find the Norton equivalent current, I_N by finding the short circuit current between terminals a and b (I_{ab}).

<u>*In-Class Activity*</u>
For the above circuit, confirm that you can also find R_{th} by using the formula V_{th}/I_N.

Try Assessment Problems 4.16-4.18 on page 123, 4.19-4.20 on page 125

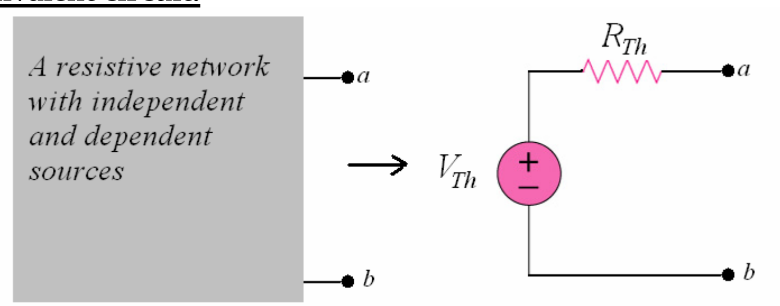
Lecture 7-2: Thevenin and Norton Equivalent Circuits, Maximum Power Transfer

Reading: 4.11 – 4.12

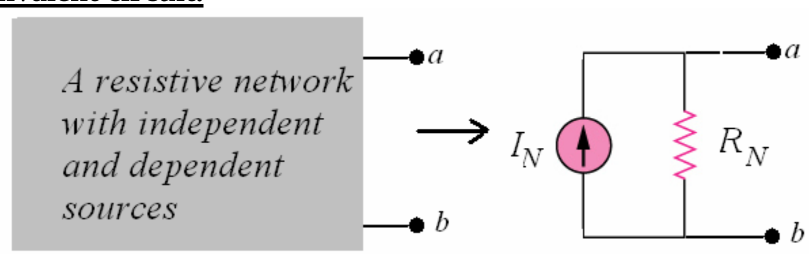
Objectives: Be able to briefly and clearly explain maximum power transfer
Be able to calculate the value of a load for maximum power transfer
Be able to derive the formula or calculate the voltage, current, and power in a load for a Thevenin or Norton equivalent circuit using KVL or KCL

****

<u>Thevenin equivalent circuit.</u>



<u>Norton equivalent circuit.</u>



When you cannot use source transformations to find the Thevenin or Norton equivalent of a circuit use one of the following techniques.

For independent and dependent sources,

- Find the open circuit voltage across a-b, $v_{oc} = V_{Th}$
- Find the short circuit current at a-b, $i_{sc} = I_N$
- Find the open circuit voltage and short circuit current between the terminals and $R_{th} = v_{oc}/i_{sc}$.

For independent sources,

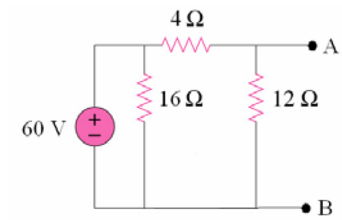
- Find the equivalent or input resistance at a-b when all independent sources are turned off, $R_{in} = R_{Th}$

For dependent sources,

- Apply a test voltage or current across terminals a and b, the relationship between the voltage across and current through the test source is $R_{Th} = v_{test}/i_{test}$
- If R_{th} produces a negative value in your calculations, this implies that the circuit is <u>actually absorbing power</u>.

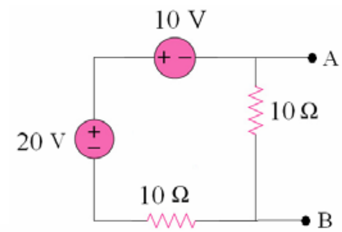
<u>FE Preview 1:</u>
What are the Thevenin equivalent resistance and voltage between terminals A and B?

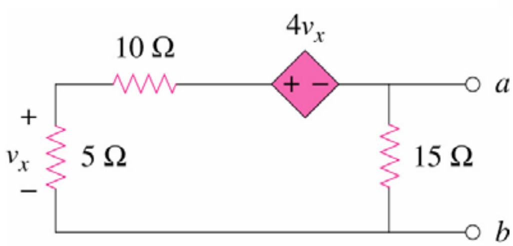
a) $R_{th} = 3\ \Omega, V_{th} = 45\ V$
b) $R_{th} = 7.5\ \Omega, V_{th} = 7.5\ V$
c) $R_{th} = 7.5\ \Omega, V_{th} = 60\ V$
d) $R_{th} = 12\ \Omega, V_{th} = 5\ V$



<u>FE Preview 2:</u>
What are the Norton equivalent source and resistance values for the circuit shown?

a) $I_N = 5\ A; R_N = 5\ \Omega$
b) $I_N = 10\ A; R_N = 20\ \Omega$
c) $I_N = 1\ A; R_N = 5\ \Omega$
d) $I_N = 1\ A; R_N = 10\ \Omega$





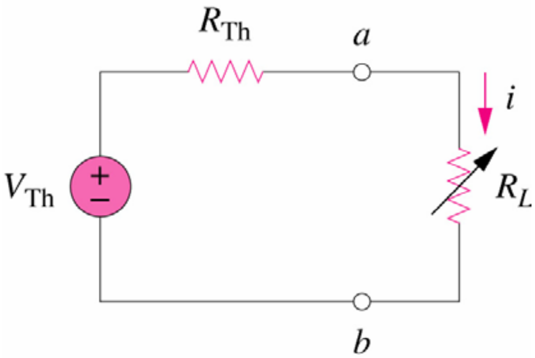
<u>In-Class Activity:</u>
For the above circuit, outline the method to find the Thevenin equivalent circuit.

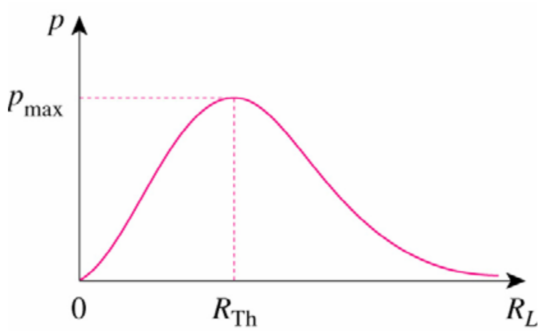
<u>In-Class Activity:</u>
For the above circuit, find the Thevenin and Norton equivalent circuits.

The primary purpose for examining the terminal characteristics of a circuit is to identify the effect that the circuit will have on a load. There are 2 types of power transfer based upon efficiency of the transfer and the amount of power transferred.

Maximum power transfer involves determining the value of a load resistor, R_L that permits maximum power delivery.

Based upon the derivation on page 127, the maximum power is transferred to the load when $\mathbf{R_L = R_{TH}}$.



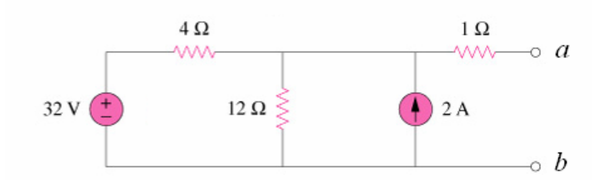


To find the power delivered to the load, use KVL, $-V_{Th} + iR_{Th} + iR_L = 0$

solving for i yields, $i = V_{Th}/(R_{Th} + R_L)$

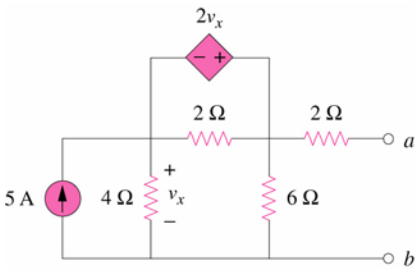
using the power formula, $p = V_{Th}^2 R_L /(R_{Th} + R_L)^2$

if $R_L = R_{Th}$, then the maximum power is $\mathbf{p_{max} = V_{Th}^2 /4R_L}$



In-Class Activity:

For the above circuit, what is the value of a load resistor placed across terminals a and b for maximum power transfer. What is the value of the power across the resistor selected? (hint: see page 2 of Lecture 7-1)



<u>In-Class Activity:</u>
For the above circuit, outline the steps to find the value of a load resistor for maximum power transfer. Be detailed as possible.

<u>ONE MINUTE PAPER</u>
Take out a sheet of paper and DO NOT put your name on it. Write one question about Thevenin and Norton equivalence that is still unclear.

Try Assessment Problems 4.21 and 4.22 on page 129

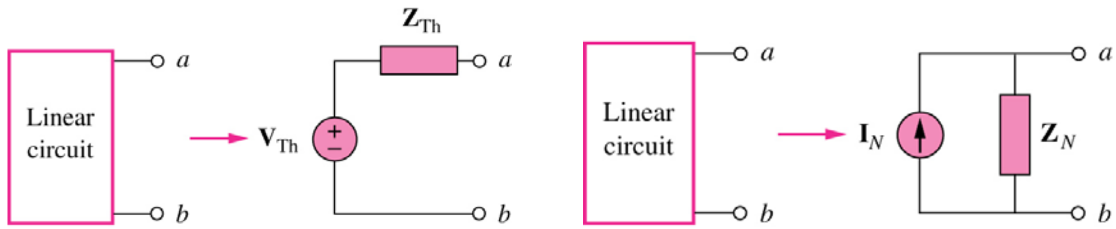
Lecture 7-3: Thevenin and Norton Equivalent for AC Circuits

Reading: 9.7

Objectives: Be able to convert an AC circuit to the Thevenin or Norton equivalent
Be able to calculate the value of a load for maximum power transfer

****

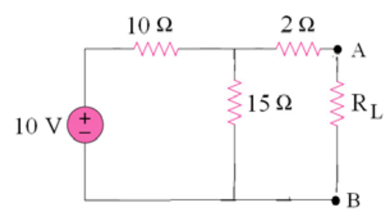
Recall that many of the techniques used to analyze DC circuits can also be used on AC circuits. This is also true for the Thevenin and Norton equivalent of a circuit. Since Thevenin and Norton equivalence for AC circuits is also used to reduce the circuit to an equivalent circuit where only the terminal characteristics on the load are relevant. One key difference between AC and DC is that for maximum power transfer $\mathbf{Z_{load} = Z^*_{Th}}$



FE Preview 1:

Size the resistor R_L to allow maximum power transfer through terminals A and B in the following circuit.

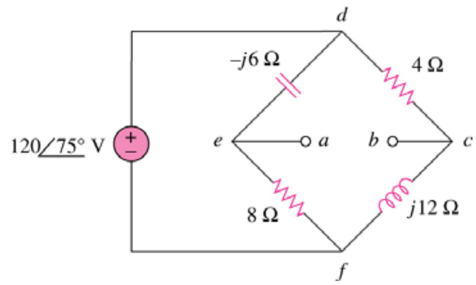
a) *2 Ω*
b) *8 Ω*
c) *15 Ω*
d) *17 Ω*



FE Preview 2:

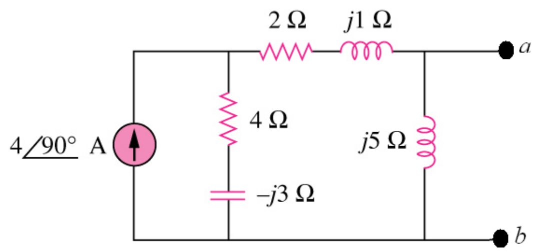
What is the internal resistance of a 9 V battery that delivers 100 A when its terminals are shorted? Assume the short circuit has negligible resistance.

a) *0.09 Ω*
b) *1.0 Ω*
c) *11 Ω*
d) *90 Ω*



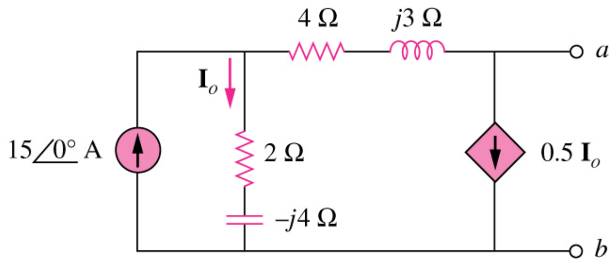
In-Class Activity
For the above circuit, what is the Thevenin equivalent impedance?

In-Class Activity
For the above circuit, what is the Thevenin equivalent voltage? Use the results of the activities to find the Norton equivalent circuit.



<u>In-Class Activity</u>

For the above circuit, find the Thevenin and Norton equivalent to the left of terminals a and b (hint: use source transformations).



<u>In-Class Activity</u>
For the above circuit, outline the steps to find the Thevenin equivalent circuit to the left of terminals a and b.

<u>In-Class Activity</u>
For the above circuit, calculate the Thevenin equivalent voltage.

<u>In-Class Activity</u>
For the above circuit, calculate the Thevenin equivalent resistance as well as the value of a load to place across terminals a and be for maximum power transfer.

Try Assessment Problems 9.10 and 9.11 on page 358

Lecture 8-1: Superposition

Reading: 4.13

Objectives:
- Be able to explain why superposition cannot be used to find power in a circuit element
- Be able to predict the effect on a load if one of the circuit elements is modified or removed
- Be able to solve for the voltage and current in an electric circuit by using superposition
- Be able to redraw ideal sources in a circuit if the element is "turned off"

****

A linear system obeys the principle of **superposition** which states that when a linear electric circuit is excited, or driven, by more than one independent source of energy, the total response is the sum of the individual response due to each source. Note that superposition can **only** be applied to find voltage and current responses in a circuit, not power. Superposition cannot be used on power because it does not have a linear relationship. For example, if, $p_1 = i_1^2R$ and $p_2 = i_2^2R$, total power in the resistor, $p \neq p_1 + p_2$

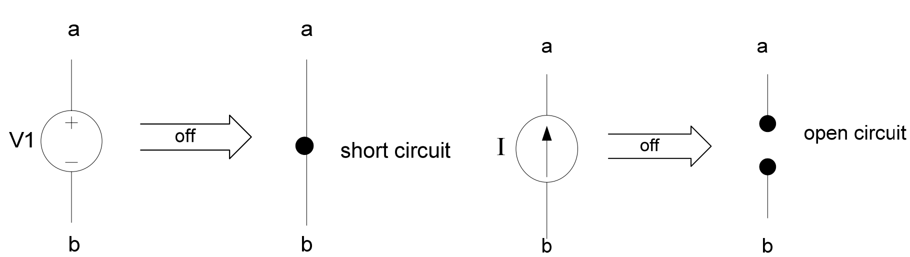
Steps to apply superposition to an electric circuit:

1. Redraw the circuit with each **independent** source turned on **one** at a time
2. For each circuit, apply a circuit analysis technique to calculate the relevant voltage or current response (v' or i')
3. Repeat step 2 for each independent source in the circuit
4. Use the principle of linearity or superposition to calculate the total response (i.e. $v = v' + v'' + \ldots$ or $v = i' + i'' + \ldots$)

The question is, "how do you turn off a voltage and/or current source in circuit analysis?"

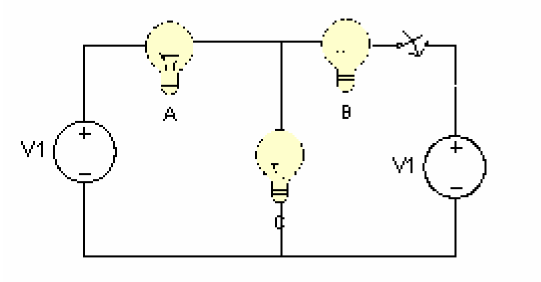
To turn off a voltage source means that it becomes **0 volts.** To turn off the voltage source, replace the voltage source with a short circuit which has a net resistance of **0Ω** and a net voltage of **0V.**

To turn of a current source means that it becomes **0 amperes.** To turn off the current source, replace the current source with an open circuit which has an infinitely large resistance and a net current of **0A**.

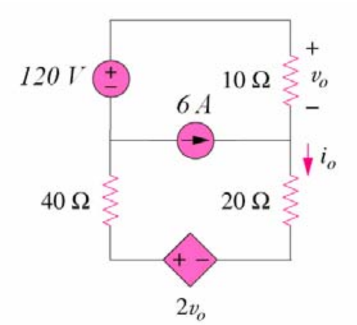


Concept Question:
In the following circuit, all of the light bulbs are identical. When the switch is closed the voltage across bulb C becomes

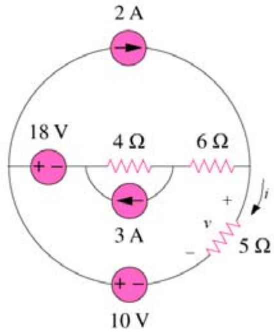
a) $V_1/2$
b) V_1
c) $1.5V_1$
d) $0.67V_1$



In-Class Activity:
For the following circuit, redraw the circuit with each of the independent sources turned on one at a time.

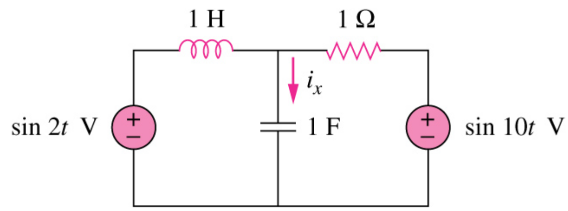


In-Class Activity:
For the above circuit, use superposition to find v_o and i_o.



<u>In-Class Activity:</u>

For the above circuit, use superposition to find the voltage and current for the 5Ω resistor. Use the total voltage and current for the 5Ω resistor to find the power delivered.



In-Class Activity:
For the above circuit, redraw the circuit with each independent source turned on one at a time.

In-Class Activity:
For the results of the prior activity, find i_x *due to each of the independent sources. What is the total response* i_x *due to both sources?*

ONE MINUTE PAPER
Take out a sheet of paper, DO NOT PUT YOUR NAME ON IT. Name one concept in this unit that is still unclear as you prepare to study for exam 2.

Unit III

OP-AMPS
inverting
non-inverting
summing
difference
POWER
- instantaneous
- average, reactive
- RMS
- complex

Lecture 8-3: Instantaneous, Average, Reactive Power

Reading: 10.1 - 2

Objectives: Be able to briefly and clearly explain: *instantaneous power, average and reactive power, leading and lagging power factor*
Be able to calculate the instantaneous, average, or reactive power for a circuit element given the waveform, voltage or current
Be able to determine whether a power factor for a load is leading or lagging by calculating the voltage and current characteristics

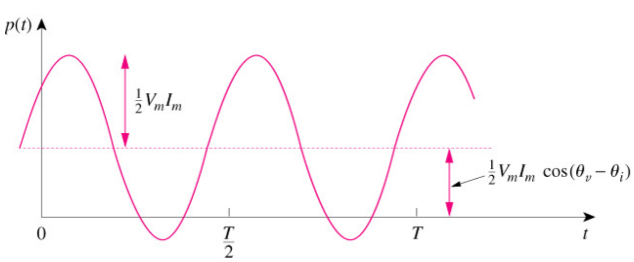
****

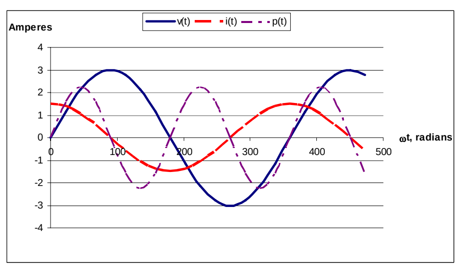
Recall from unit I that power, **p = vi** (W), this is referred to as **instantaneous power**. When the voltage and current are sinusoidal expressions, this relationship yields

$$p = vi = [V_m\cos(\omega t + \theta_v - \theta_i)][I_m \cos \omega t] = V_m I_m \cos(\omega t + \theta_v - \theta_i) \cos \omega t$$

Using trigonometric identities, the instantaneous power can also be written as

$$p = (.5V_mI_m)[\cos(\theta_v - \theta_i) + \cos(\theta_v - \theta_i) \cos 2\omega t - \sin(\theta_v - \theta_i) \sin 2\omega t]$$





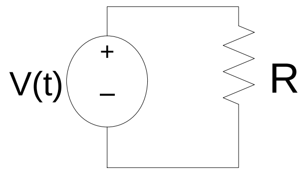
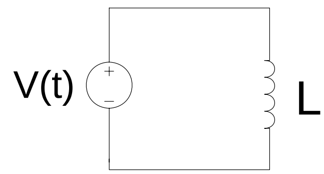
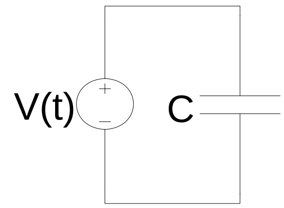
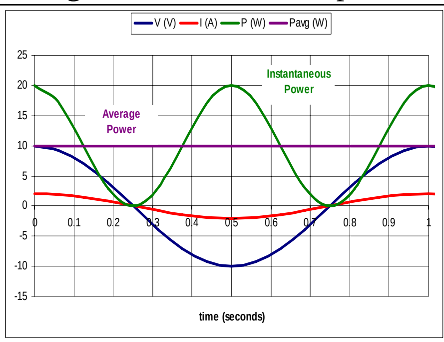
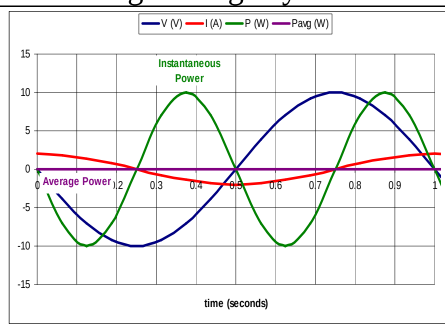
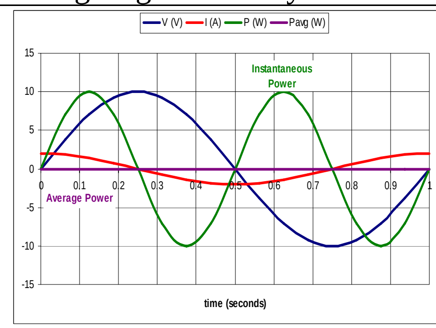
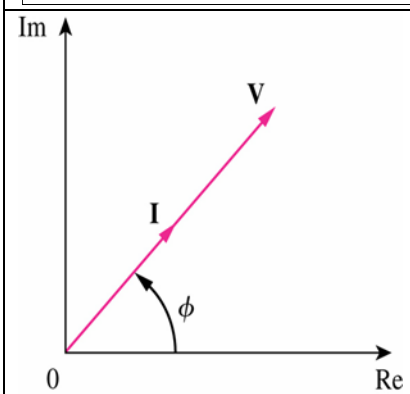
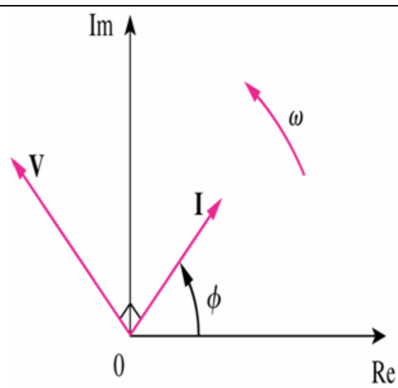
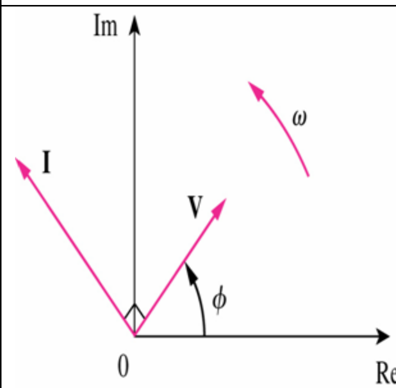
From the instantaneous power relationship,, it can be observed that the power frequency is twice the frequency of the voltage or current. Also, the power may be negative for a portion of each cycle which implies that energy stored in an inductor or capacitor is being released. When p is positive, energy is being stored and when p is negative, energy is being delivered.

Instantaneous power can be rewritten as the sum of three terms,

$$p = P + P \cos 2\omega t - Q \sin 2\omega t$$

The **average (real) power** is $P = 0.5\, V_mI_m \cos(\theta_v - \theta_i)$ **(Watts)**. Average power describes the power in a circuit that is transformed from electric to nonelectric energy. Examples of devices that convert electric energy to thermal energy are stoves, ovens, toasters, irons, water heaters, electric clothes dryers, and hair dryers.

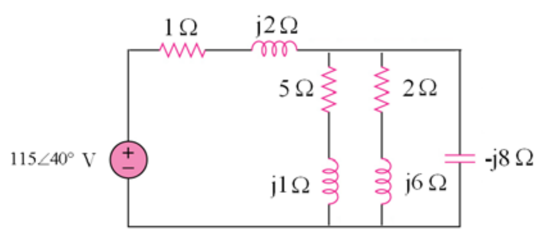
The **reactive power** is $Q = 0.5\, V_mI_m \sin(\theta_v - \theta_i)$ **(VARS).** Reactive power is associated with the energy stored in an inductor or capacitor.

Purely Resistive Circuits (Real Power)	Purely Inductive Circuits (Reactive Power)	Purely Capacitive Circuits (Reactive Power)
		
voltage and current are in phase	current lags voltage by 90°	voltage lags current by 90°
		
		
The average power is P, Q =0 p > 0 because resistors always absorb power	P = 0, Q>0 The power is measured by the reactive power, Q.	P = 0, Q < 0
Instantaneous power **p = P + P cos 2ωt**	Instantaneous power **p = -Q sin 2ωt**	Instantaneous power **p = -Q sin 2ωt**

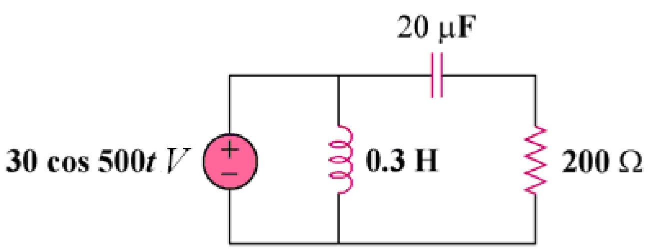
Concept Question:

What is the average power dissipated by the circuit?

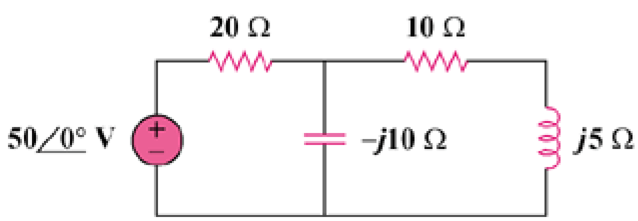
a) 24 W
b) 977 W
c) 1956 W
d) 1970 W



<u>In-Class Activity:</u>
For the following circuit, at t = 2 s, find the instantaneous power for the inductor and resistor.



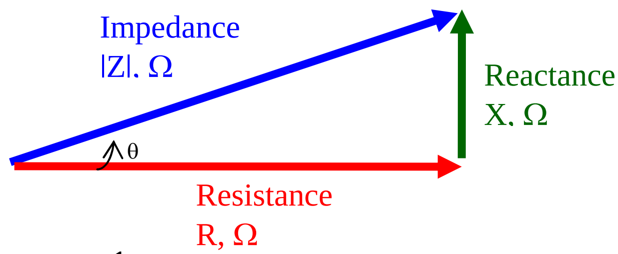
<u>In-Class Activity:</u>
For the following circuit, find the average and reactive average power absorbed by each of the elements.



The angle in the instantaneous power expression, $\underline{\theta_v - \theta_i}$ is referred to as the **<u>power factor angle.</u>**
The cosine of the power factor angle is called the **<u>power factor = pf = cos ($\theta_v - \theta_i$)</u>**
The sine of the power factor angle is called the **<u>reactive factor = rf = sin ($\theta_v - \theta_i$)</u>**
Based upon this relationship, the average power, **<u>$P = 0.5\ V_m I_m pf$</u>** (W) and **<u>$Q = 0.5 V_m I_m rf$</u>** (VAR)

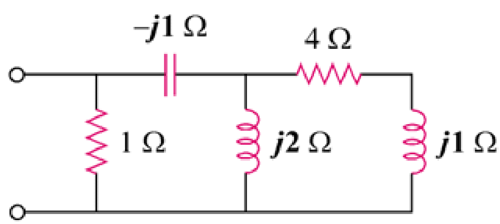
Purely Resistive Circuits (Real Power)	Inductive Circuits (Reactive Power)	Capacitive Circuits (Reactive Power)
current and voltage in phase	current lags voltage lagging power factor	current leads voltage leading power factor
pf = 1 $\theta_v - \theta_i = 0°$	pf lagging $\theta_v - \theta_i > 0$ Purely inductive: pf = 0	pf leading $\theta_v - \theta_i < 0$ Purely capacitive: pf = 0

The power factor can also be found by calculating the impedance of a load,
$\mathbf{Z} = \mathbf{V}/\mathbf{I} = |\mathbf{Z}|\angle(\theta_v - \theta_i) = R + jX$

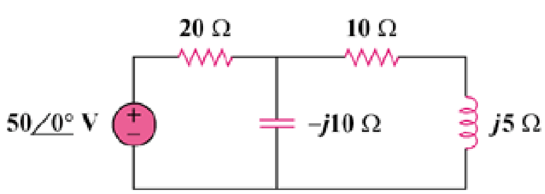


$\theta = \tan^{-1}(X/R)$ $\qquad$ $pf = \cos(\theta)$

<u>In-Class Activity:</u>
What is the power factor for the following circuit? (be sure to state leading or lagging)



<u>In-Class Activity:</u>
For the following circuit, outline the steps to find the power factor for the current source.



Try Assessment Problems 10.1 and 10.2 on page 397

Lecture 9-1: RMS Value and Power Calculations

Reading: 10.3
Objectives: Be able to write the formulas for root mean square
Be able to perform calculations that involve instantaneous, average, reactive power, power factor, and rms value

****

Recall that the formula, for the **RMS value** of a **periodic function** is given by

$$X_{rms} = \sqrt{\frac{1}{T}\int_{t_o}^{t_o+T} x(t)^2\,dt}$$

Recall that an important characteristic of the RMS value for a sinusoidal function is that

$$V_{rms} = \sqrt{\frac{1}{T}\int_{t_o}^{t_o+T} V_m^{\,2}\cos^2(\omega t+\phi)\,dt} = \frac{V_m}{\sqrt{2}}$$

If a sinusoidal voltage or current is applied to the terminals of a resistor, the average power delivered to the resistor is

$$P = \frac{1}{R}\sqrt{\frac{1}{T}\int_{t_o}^{t_o+T} V_m^{\,2}\cos^2(\omega t+\phi)\,dt}$$

$$\mathbf{P} = \frac{V^2_{rms}}{R} = I^2_{rms}R \ \ \mathbf{(W)}$$

The **rms** value is also referred to as the **effective value** of the sinusoidal voltage or current. This term is based upon the fact that given an equivalent resistive load, R, and an equivalent time period, T, the rms value of a sinusoidal source delivers the same energy to R as does a DC source of the same value. Using the effective value relationships, the average and reactive power become

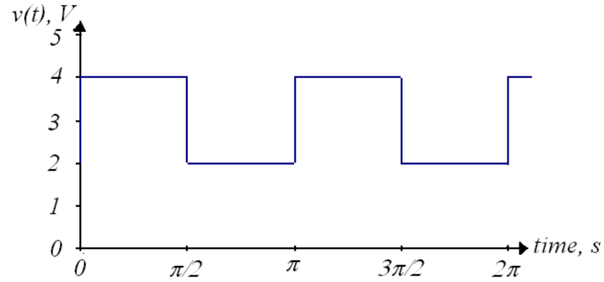
$P = (V_{rms}I_{rms})[\cos(\theta_v - \theta_i)]$ (Watts)

$Q = (V_{rms}I_{rms})[\sin(\theta_v - \theta_i)]$ (VAR)

FE Preview:

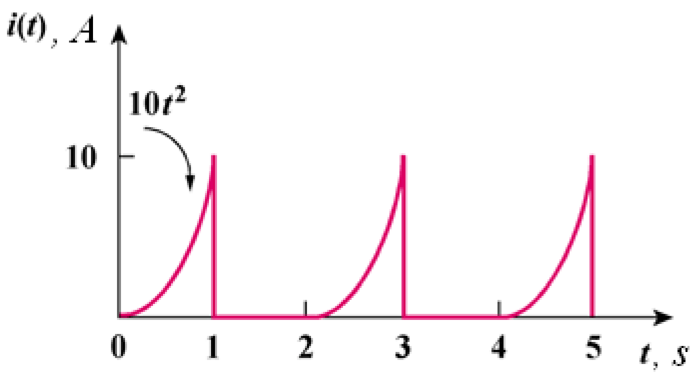
Find the effective value of the voltage for the repeating waveform.

a) *2.45 V*
b) *2.75 V*
c) *3.0 V*
d) *3.16 V*

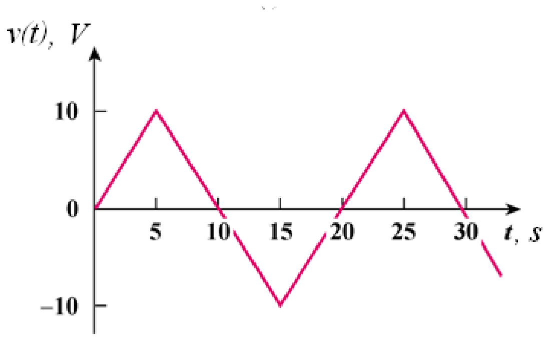


In-Class Activity:

Obtain the RMS value of the following waveform. Determine the average power dissipated in a 10Ω resistor.

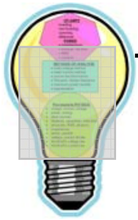


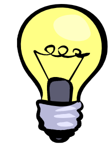
In-Class Activity:
If the following current flows through a 12 Ω resistor, determine the average power dissipated in the resistor.



Minute Paper:
Take out a sheet o paper DO NOT PUT YOUR NAME ON IT. Answer the following question, what concept concerning AC power is still unclear to you?

Try Assessment Problems 10.3 on page 400





Lecture 9-2: Complex Power and Power Calculations

Reading: 10.4
Objectives: Be able to write thee formulas for complex and apparent power
Be able to briefly and clearly explain complex and apparent power
Be able to analyze a circuit to calculate the complex and apparent power

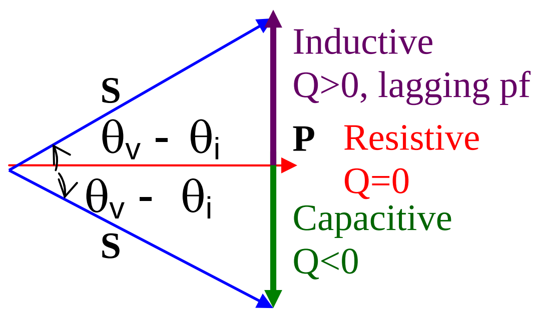
****

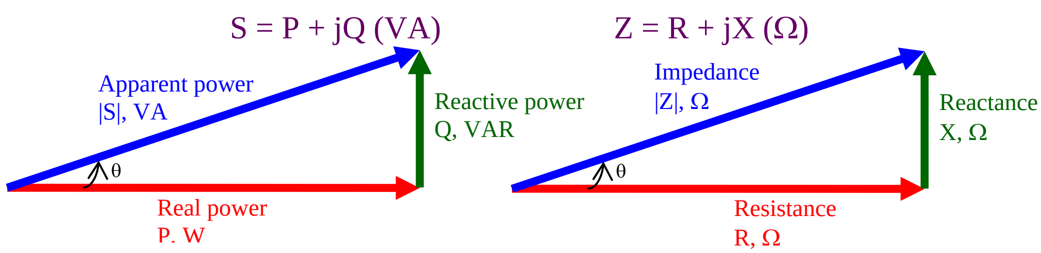
Complex power is the complex sum of the real and reactive power

$$\mathbf{S = P + jQ \ (VA)}$$

Complex power can be computed from the voltage and current phasors for a circuit. The magnitude of the complex power is the **apparent power, $|S| = \sqrt{P^2 + Q^2}$ (VA)**

The following figures show the geometric relationship between complex power, the power factor, and impedance.





$\theta = \tan^{-1}(Q/P)$ = tan-1(Q/P) = $\tan^{-1}(X/R)$ pf = $\cos(\theta)$

The apparent power requirement of a device designed to convert electric energy to nonelectric energy is more important than the average power requirement. Average power represents the useful output of the energy-converting device, but the apparent power represents the volt-amp capacity required to supply the average power.

There are several other relationships for complex power including,

$$\mathbf{S = V_{rms} I^*_{rms} = .5 V_m I^*_m = |V_{rms}|^2 / Z^* = P + jQ \ (VA)}$$

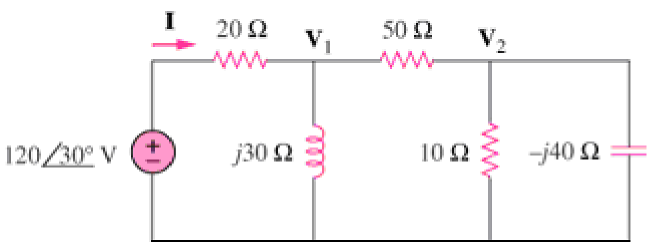
$$\mathbf{P = |I_{rms}|^2 R = 0.5 I^2_m R \ (W) \qquad Q = |I_{rms}|^2 X = 0.5 I^2_m X \ (VAR)}$$

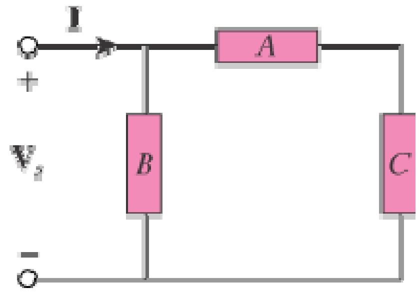
If Z is a purely resistive element, then the complex power becomes **$P = |V_{rms}|^2/R$**

If Z is a purely reactive element, then the complex power becomes **$P = |V_{rms}|^2/X$**

In-Class Activity:
A relay coil is connected to a 210-V_{rms}, 50-Hz supply. If it has a resistance of 30 Ω and an inductance of 0.5 H, calculate the apparent power supplied to the coil.

In-Class Activity:
For the following circuit, if the current, $I = 10\angle 25°$ A, what is the total apparent power supplied by the circuit? power factor of the circuit?





<u>In-Class Activity:</u>

For the above circuit, if device A receives 2 kW at 0.8 pf lagging, device B receives 3 kVA at 0.4 pf leading, while device C is inductive and consumes 1 kW and receives 500 VARs. Determine the power factor of the entire system.

<u>In-Class Activity:</u>

*For the above circuit, find **I** given that $\mathbf{V_s} = 120\angle 45^\circ V_{rms}$.*

Try Assessment Problems 10.4 – 10.6 on page 410

Lecture 9-3: Power Calculations, Maximum Power Transfer

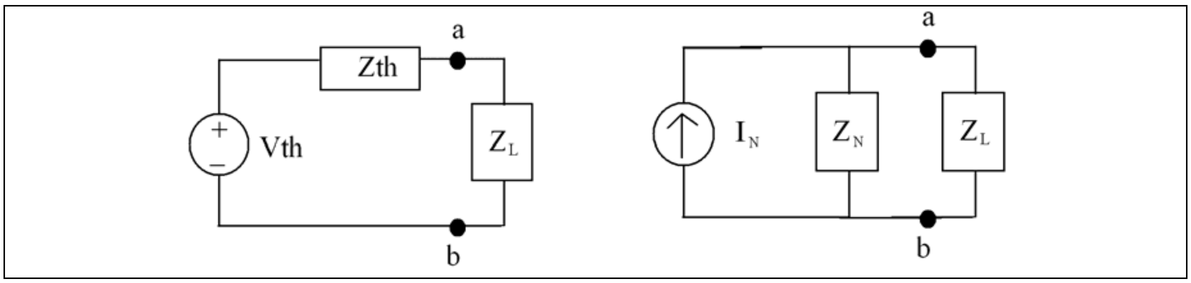
Reading: 10.5 - 6

Objectives: Be able to calculate the value of a load impedance for maximum power transfer given an electric circuit

Be able to calculate the maximum average power absorbed by a load impedance

****

Recall that in our earlier discussion of maximum power transfer some systems depend on being able to transfer the maximum amount of power from the source to the load. **Maximum power transfer** can also be applied to circuits operating in the sinusoidal steady state. For these circuits, the maximum average power is transferred to the load, Z_L when $\mathbf{Z_L = Z^*_{Th}}$.



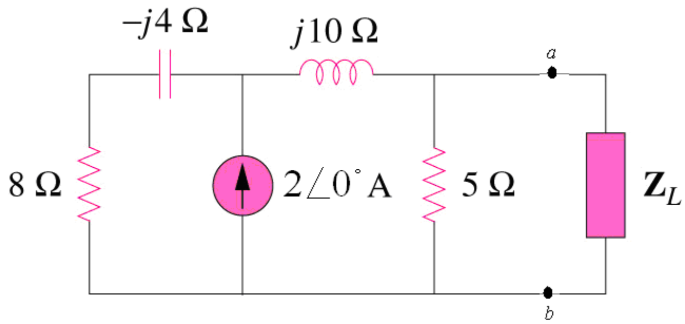
The average power delivered to the load is $\mathbf{P = |I_{rms}|^2 R_L}$

The maximum average power that can be delivered to Z_L is

$\mathbf{P_{max} = |V_{th}|^2/[4R_L]\ (rms) = |Vth|^2/[8R_L]\ (peak)}$

When there are restrictions on the load impedance, it may not be possible to set it equal to the conjugate of the Thevenin impedance.

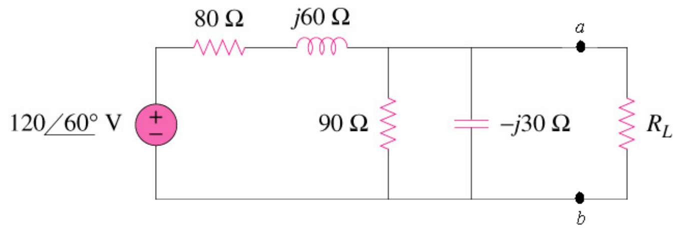
1. When the magnitude of Z_L can be adjusted but the phase angle cannot, set the magnitude of the load equal to the magnitude of the Thevenin impedance, $|Z_L| = |Z_{th}|$
2. When there are restrictions on the value of R_L and X_L, adjust X_L as close as possible to $-X_{Th}$ and then adjust R_L as close as possible to $\sqrt{R^2_{Th} + (X_L + X_{Th})^2}$



In-Class Activity
For the above circuit, what is Thevenin voltage to the left of terminals a and b?

In-Class Activity
For the above circuit, determine the impedance Z_L that results in maximum average power transferred to the load.

In-Class Activity
What is the maximum average power transferred to the load selected in the previous activity?



<u>In-Class Activity :</u>

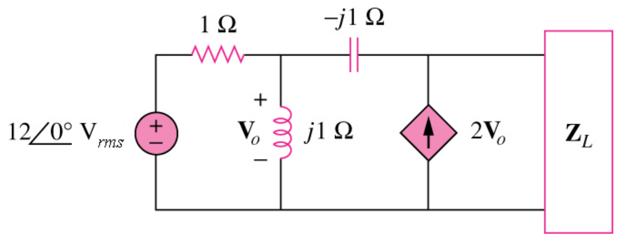
For the above circuit, what is Z_{th} to the left of terminals a and b?

<u>In-Class Activity (Special Case 1):</u>

For the above circuit, what is the value of the load ***resistance*** *that will achieve maximum power transfer? What is the power transfer for this load?*

<u>In-Class Activity:</u>

If there were no restrictions on the load ***impedance****, what would be the value of the load impedance to achieve maximum power transfer? What is the power transfer for this load?*



<u>In-Class Activity:</u>

For the above circuit, what value of Z_L results in maximum average power transfer? What is the maximum average transfer to the load selected?

<u>In-Class Activity (Special Case 2):</u>

For the above circuit, assume that R_L can be varied between 0 and 1.5 Ω and that X_L can be varied between -0.25 and 0.25Ω, what settings of R_L and X_L transfer the most average power to the load? What is the maximum average power that can be transferred under these restrictions?

Try Assessment Problem 10.7 on page 415

Lecture 10-1: Operational Amplifiers: Ideal, Inverting, Summing

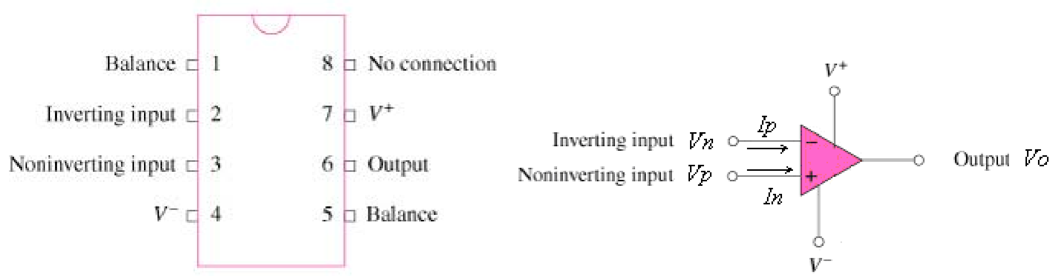
Reading: 5.1-3

Objectives:
- Be able to write the formula for an inverting and noninverting operational amplifier
- Be able to briefly and clearly explain the function of an inverting, noninverting, summing and difference amplifier
- Be able to apply KCL to an operational amplifier circuit to find voltage, current, and power
- Be able to identify whether a given circuit is an inverting noninverting, summing or difference amplifier
- Be able to state the 2 basic assumptions necessary to analyze an ideal operational amplifier

****

The **operational amplifier (opamp)** is an electronic unit that behaves like a voltage-controlled voltage source.

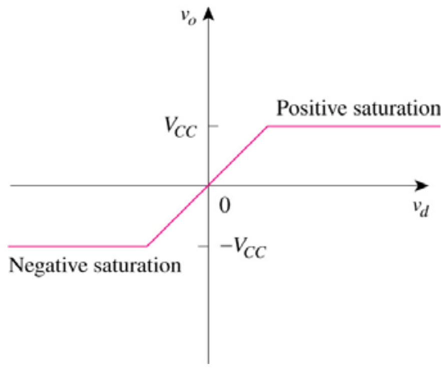
An **operational amplifier (opamp)** is an active circuit element designed to perform mathematical operations of addition, subtraction, multiplication, division, differentiation, and integration. The following figure shows an example of an operational amplifier integrated circuit as well as the symbol used to represent an op amp in circuit analysis.



The five terminals of interest on the operational amplifier are the

- Inverting input
- Non inverting input
- output
- positive power supply (V^+)
- negative power supply (V^-)

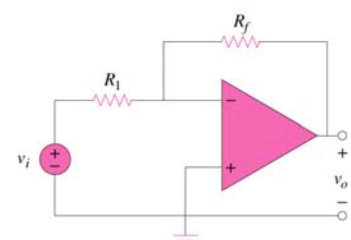
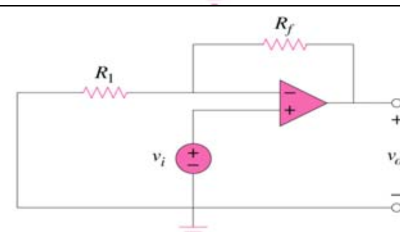
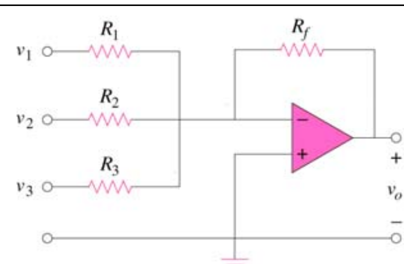
The voltage characteristic of an op amp has a linear and nonlinear region as shown by the following figure. When the op amp is operating in the linear region, the output voltage is equal to the difference in its input voltages times the multiplying constant or gain, A. When the output of the operational amplifier exceeds the positive or negative power supply it is in **saturation**. When the op amp is in saturation, the outputs are equal to the positive or negative power supply.



There are 2 constraints or assumptions to make for an ideal operational op-amp

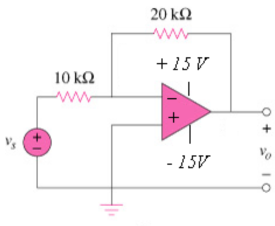
1. the **virtual short condition** states that the voltage at the positive terminal equals the voltage at the negative terminal **($v_p = v_n$)**
2. the **infinite input impedance condition** states that the current into the positive and negative terminals of the opamp is negligible **($i_p = i_n = 0A$)**

It is possible to analyze ideal operational amplifiers by applying the 2 assumptions and Kirchhoff's current laws at the input and output terminals. The following table lists some standard operational amplifier configurations. It should be noted that all of these relationships can be derived using KCL and the 2 basic assumptions for ideal operational amplifiers.

Type	Vo	Gain	Circuit
Inverting	$\frac{-R_f}{R_1} v_i$	$\frac{v_o}{v_i} = -\frac{R_f}{R_1}$	
Non inverting	$\left(1+\frac{R_f}{R_1}\right) v_i$	$\frac{v_o}{v_i} = 1+\frac{R_f}{R_1}$	
Summing	$-\frac{R_f}{R_1} v_1 - \frac{R_f}{R_2} v_2 - \frac{R_f}{R_3} v_3$	V1: $\frac{v_o}{v_1} = -\frac{R_f}{R_1}$ V2: $\frac{v_o}{v_2} = -\frac{R_f}{R_2}$ V3: $\frac{v_o}{v_3} = -\frac{R_f}{R_3}$	

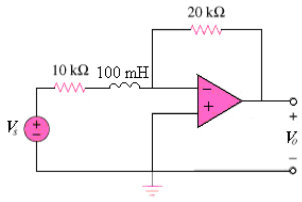
In-Class Activity:

For the following circuit, what range of input voltages will avoid op amp saturation?



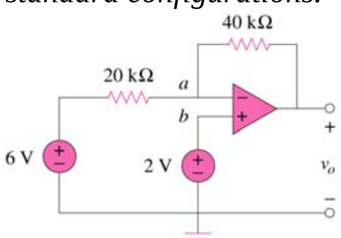
In-Class Activity:

For the following circuit, what is the absolute DC gain? What is the DC gain in dB? If the input is 2 V_{rms} at 10 kHz, what is the AC gain? What is the AC gain in dB? What is the output $\mathbf{V_o}$*?*



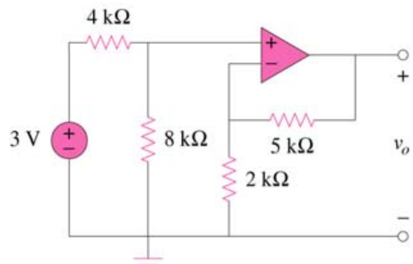
In-Class Activity:

For the following circuit, outline the steps to find v_o *since the circuit is not one of the standard configurations. What is* V_o*?*



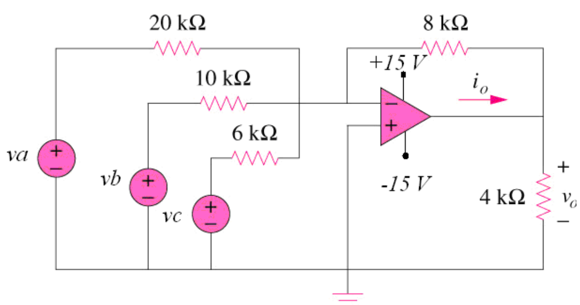
In-Class Activity:

For the following circuit, assuming the op amp is operating in its linear region, what is v_o?



In-Class Activity:

For the following circuit, what type of operational amplifier is it? If va = 1.2 V, vb = 1.5 V and vc = 2 V, what are the values for v_o and i_o?



Try Assessment Problems 5.1 on page 161, 5.2 on page 162

Lecture 10-2: Operational Amplifiers: Non inverting, Difference

Reading: 5.4 - 6

Objectives:
Be able to write the formula for an inverting and noninverting operational amplifier
Be able to briefly and clearly explain the function of an inverting, noninverting, summing and difference amplifier
Be able to apply KCL to an operational amplifier circuit to find voltage, current, and power
Be able to identify whether a given circuit is an inverting noninverting, summing or difference amplifier
Be able to state the 2 basic assumptions necessary to analyze an ideal operational amplifier

****

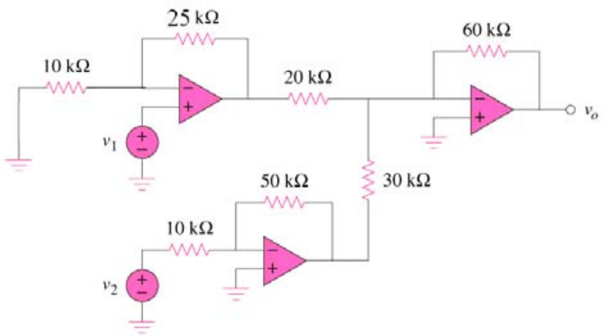
Recall that operational amplifiers are designed using transistors and diodes and are used to perform mathematical operations. There are 2 basic assumptions or conditions used to analyze ideal operational amplifiers: virtual short circuit, infinite input impedance. Using these assumptions and KCL, it is possible to find the output of any operational amplifier circuit.

In-Class Activity:
Design an operational amplifier circuit to find the average of 3 input voltages: v_a, v_b, v_c.

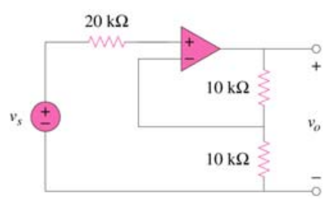
A **cascaded** operational amplifier connection is a head-to-tail arrangement of two or more op amp circuits such that the output of one is the input of the next. When op amp circuits are cascaded, each circuit is called a **stage**. The overall gain of a cascaded connection is the product of the gains of the individual op amp circuits, or

$$A = A_1A_2A_3A_4A_5\ldots A_n$$

In-Class Activity:
Assuming the following op amps are operating in a linear region, what is the output, v_o*?*
What is the numerical value of v_o *if* $v_1 = 10$ mV *and* $v_2 = 15$ mV*?*

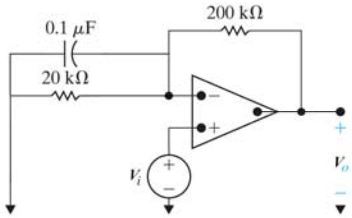


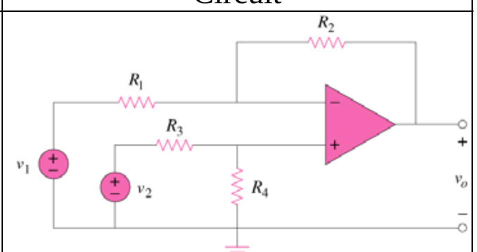
In-Class Activity:
For the following circuit, assuming the op amp operates in the linear region, if $v_o = 10V$*, what is the value of the input* v_s*?*

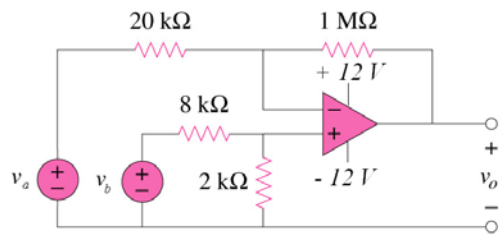


In-Class Activity:

For the following circuit, if the input is 5 V_{rms} at 100 Hz, what is the output $\mathbf{V_o}$? What is the DC gain?' What is the DC gain in dB? What is the AC gain? What is the AC gain in dB?



Type	Vo	Gains	Circuit
Difference (general)	$\frac{R_4(R_1+R_2)}{R_1(R_3+R_4)}v_2 - \frac{R_2}{R_1}v_1$	$\frac{v_o}{v_1} = -\frac{R_2}{R_1}$ $\frac{v_o}{v_2} = \frac{R_4(R_1+R_2)}{R_1(R_3+R_4)}$	
Difference (simplified) $\left(\frac{R_1}{R_2} = \frac{R_3}{R_4}\right)$	$\frac{R_2}{R_1}(v_2 - v_1)$	$\frac{v_o}{v_1} = -\frac{R_2}{R_1}$ $\frac{v_o}{v_2} = \frac{R_2}{R_1}$	



<u>In-Class Activity:</u>
For the above circuit, if v_a = 100 mV, what range of values for v_b will result in linear operation?

<u>In-Class Activity:</u>
For the above circuit, if v_a = 100 mV, what value of v_b results in an output voltage of 10V?

Try Assessment Problems 5.3 on page 164, 5.4 on page 165, 5.5 on page 166