CET 141: Day 1

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Introduction to electronic theories

Analog, digital signals

- Why do we learn Analog or Digital concepts?
  - Due to interaction between the world and computers
- The world is inherently Analog (continuous)
  - In both space (x, y, z) and time (t) 4D
- Computers are inherently Digital (discrete)
  - In both space (x, y, z) and time (t)

A computer (digital signal)

- Has to make decisions in every single time
- Uses digital “logic” as a tool for its job
- To make the decisions, answers (outputs) to each question (inputs) must be as simple as
  - Yes/No
  - Correct/Incorrect
  - Right/Wrong
  - 1/0
  - No intermediate status

The world or nature (analog signals)

- Communicates using continuous signal
- Intermediates states are allowed

- Two possibilities of the conversion:
    1. World to Computers: A to D Conversion
    2. Computers to World: D to A Conversion
- Devices
    1. A to D converters
    2. D to A converters

- A to D converters: **Sensors**
  - Temperature
  - Sound: microphones
  - Optical
  - Pressure: sound lever meters
- D to A converters: **Actuators**
  - Motors
  - Sound: speakers
  - Brakes …

INPUT
(Analog)
Hand
movement

→

MCU

→

OUTPUT
(Digital)
On/OFF

Electric current, voltage

- The world and nature
  - Inherently analog, continuous, connected, related….
  - “Continuous things” → no limits → difficult to analyze
  - People categorized the things in several discrete manners → call them modalities (or fields)
  - People found generalized parameters to represent each modality
    - Potential (generalized force)
    - Flow

Modality	Conjugate variables (vector in bold)	
	Generalized force [unit]	Flow [unit]
Electric	Voltage (Φ) [V]	Current (I) [A]
Mechanic	Force ($\mathbf{F}$) [N]	Particle velocity ($\mathbf{U}$) [m/s]
Acoustic	Pressure (P) [N/m^2]	Volume velocity ($\mathbf{V}$) [$(ms)^{-1}$]
Electro-Magnetic	Electric field ($\mathbf{E}$) [V/m]	Magnetic field ($\mathbf{H}$) [A/m]

Table A.1: Example of modalities and their conjugate variables. Upper case symbols are used for the frequency domain variables. The time domain representation of each variable can be described using the lower case of the same character, except in the EM case. But general Electro-Magnetic (EM) theories consider the time domain and its traditional notation uses capital letter for the time domain analysis. Note that in the electric field, $\mathbf{E} = -\nabla\Phi$, where Φ is scaler potential, the voltage.

Modality	Product in time domain	Ratio (Impedance Z) in frequency domain
Electric	$\phi(t)i(t)$	$Z_e = \Phi/I$
Mechanic	$\mathbf{f}(t) \cdot \mathbf{u}(t)$ (inner product)	$Z_m = F/U$
Acoustic	$p(t)\mathbf{v}(t)$ (intensity)	$Z_a = P/V$
Electro-Magnetic (EM)	$\mathcal{P} = \mathbf{E} \times \mathbf{H}$ (Poynting vector)	$\eta = \underline{\mathbf{E}}/\underline{\mathbf{H}}$

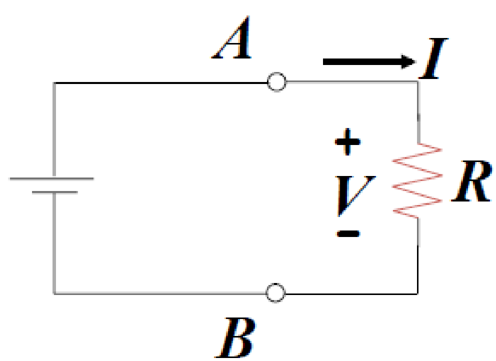
Table A.2: Power and impedance definitions for each modalities in table A.1. In general, power concept (a product of conjugate variables) can be used in time domain, however the impedance (a ratio) is thought of in the frequency domain. Assuming causality, the Laplace transformation can be applied to convert the impedance to the time domain.

- Voltage: a generalized force in electric field (potential)
- Current: a flow in electric field
- They are not intuitive to understand as they are not tasty, smelly, noisy, tangible, or visible
- However they are measurable and related to each other → VI relationship

V (voltage)
I (current)

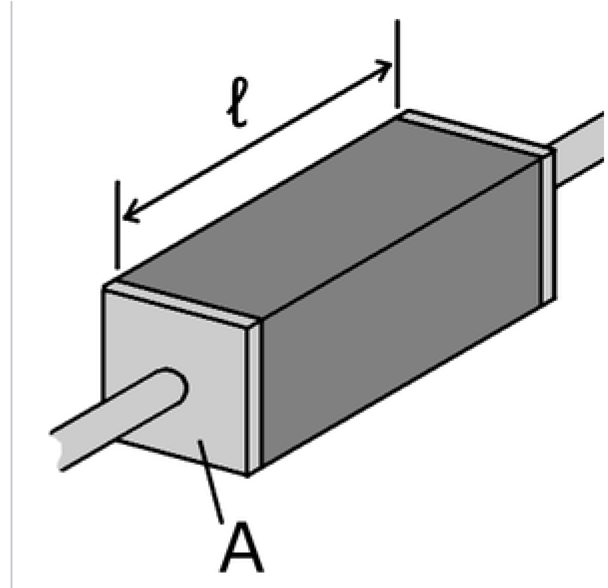
Resistance (Ohm’s law)

- A ratio V/I ➔ a constant
- Ohm’s law
  - Characterizes V and I relationship with resistance V=IR, where R has a unit of “Ohm [Ω],” called resistance
  - A resistor is a <u>passive</u>, <u>two-terminal</u>, electrical component that **implements** electrical resistance as a circuit element



and $I = \dfrac{V}{R}$

$$R = \rho \frac{\ell}{A}$$



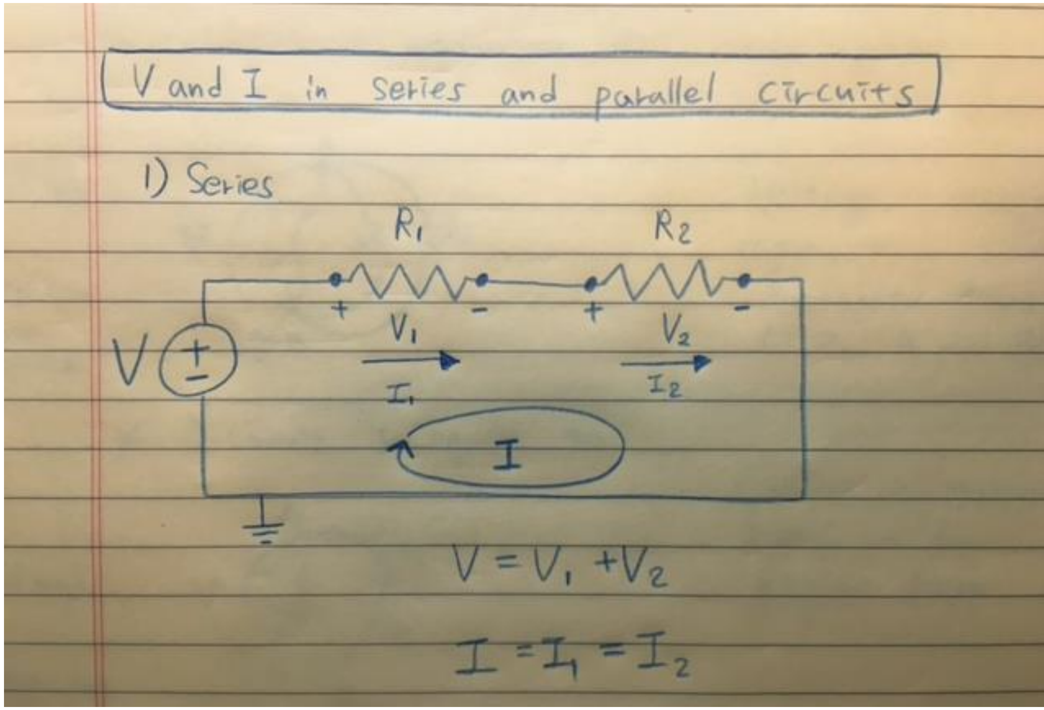
A piece of resistive material with electrical contacts on both ends.

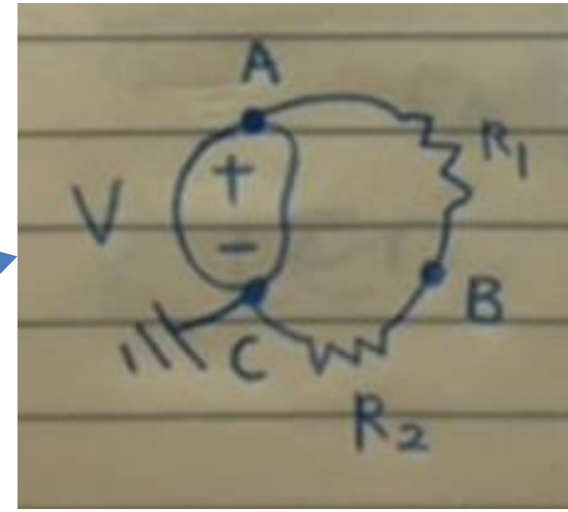
A reciprocal concept to resistivity?

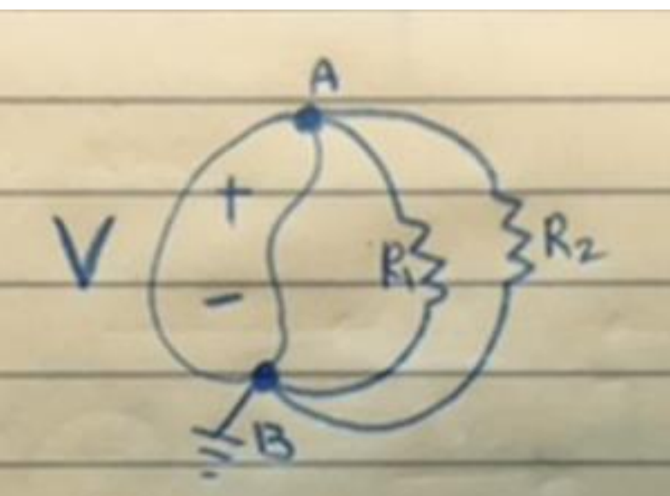
Conductivity [S]

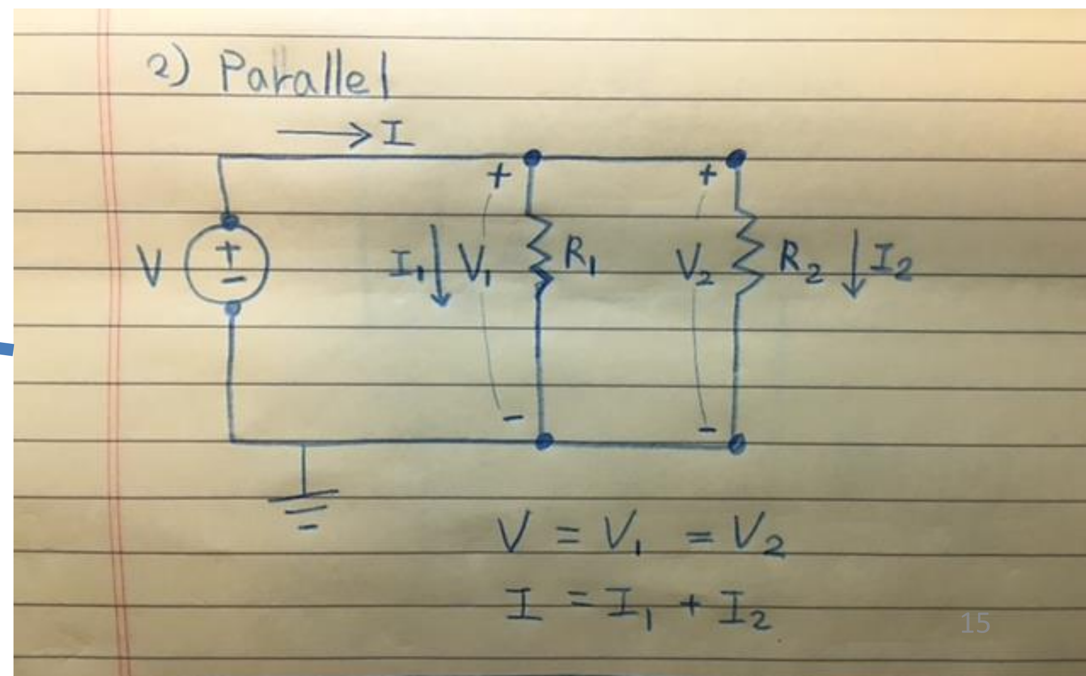
Basic resistive circuits

- Series / parallel circuits characteristics: V and I
- Series and parallel resistors

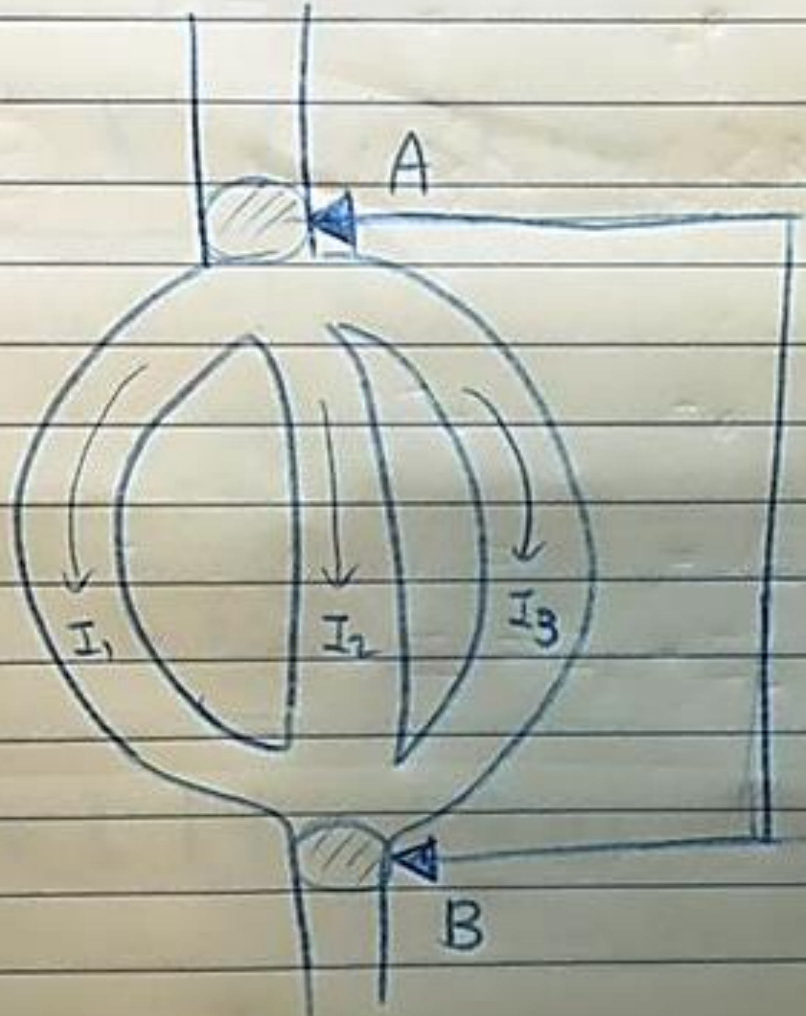

V and I in series and parallel circuits
1) Series
R_1
R_2
V_1
V_2
I_1
I_2
I
V
$V = V_1 + V_2$
$I = I_1 = I_2$


A
R_1
V
B
C
R_2


A
V
R_1
R_2
B


2) Parallel
I
V
I_1
V_1
R_1
V_2
R_2
I_2
$V = V_1 = V_2$
$I = I_1 + I_2$

A pipe with water

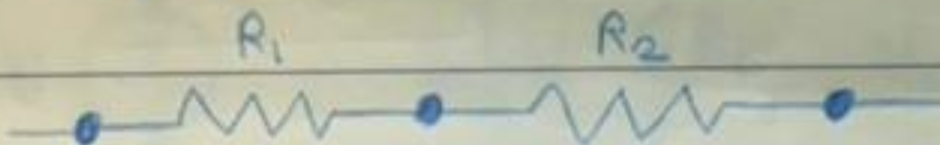


Pressure difference
at the junction
A and B
; same for all pipes

But flow I_1, I_2, I_3
can be different
in each pipe.
(based on shape differences)

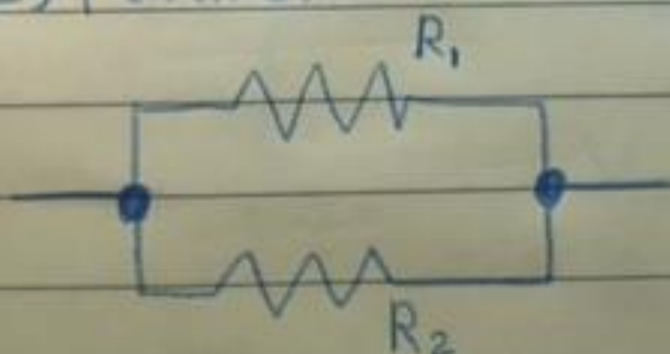
Resistors

1) Series



$$R_{total} = R_1 + R_2$$

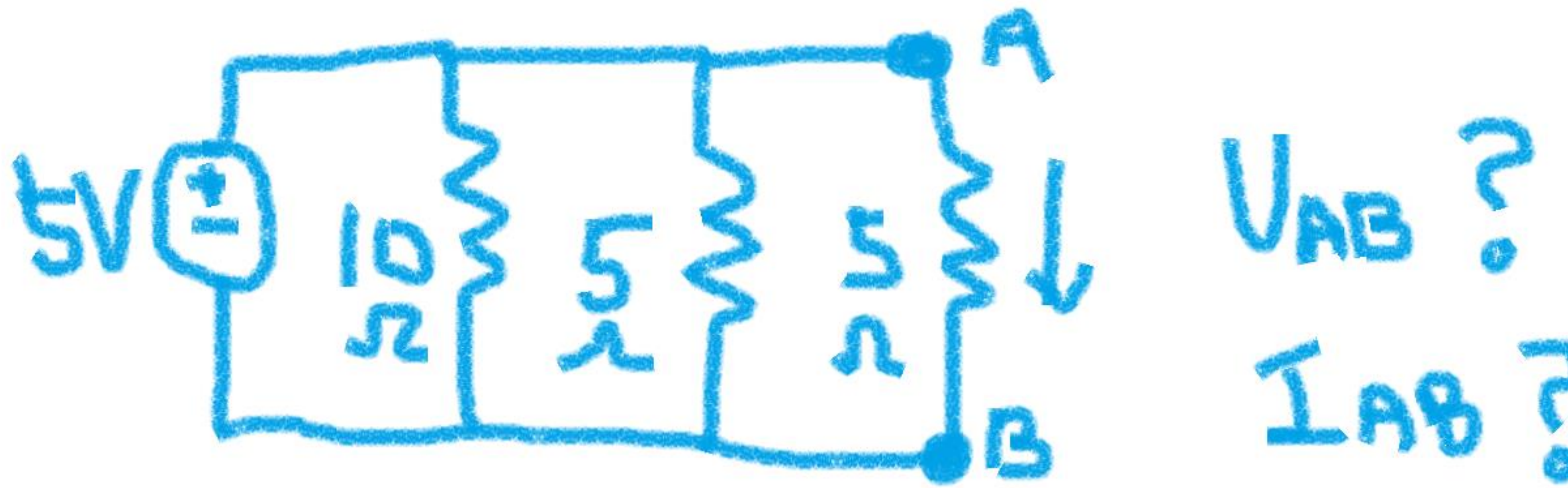
2) Parallel

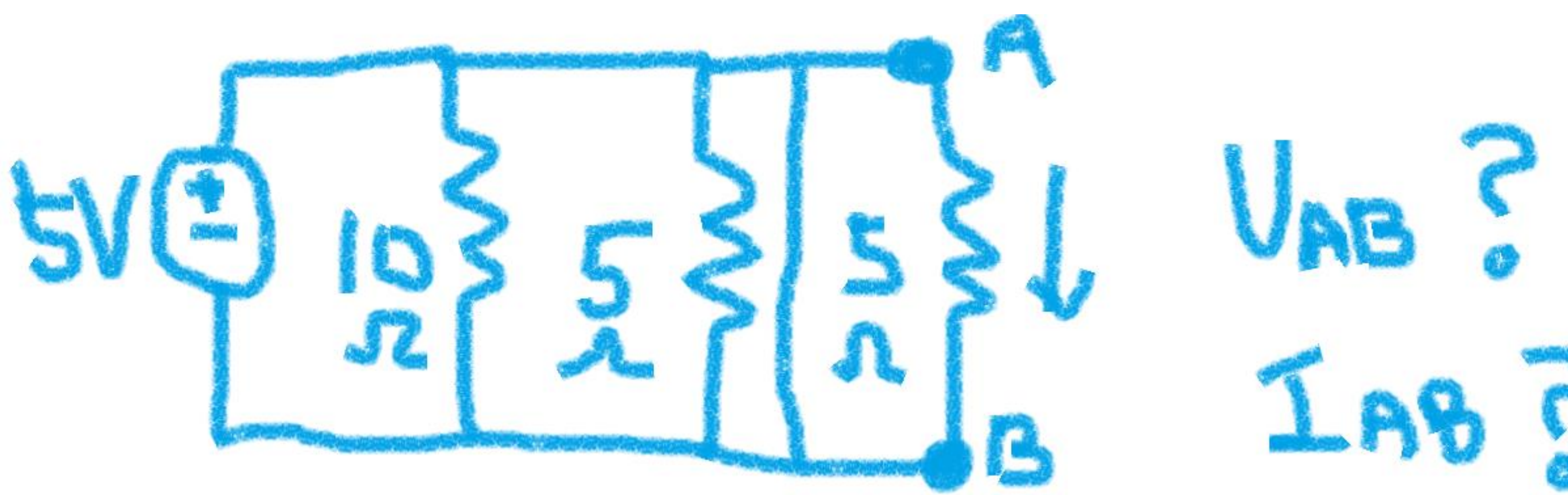


Why?

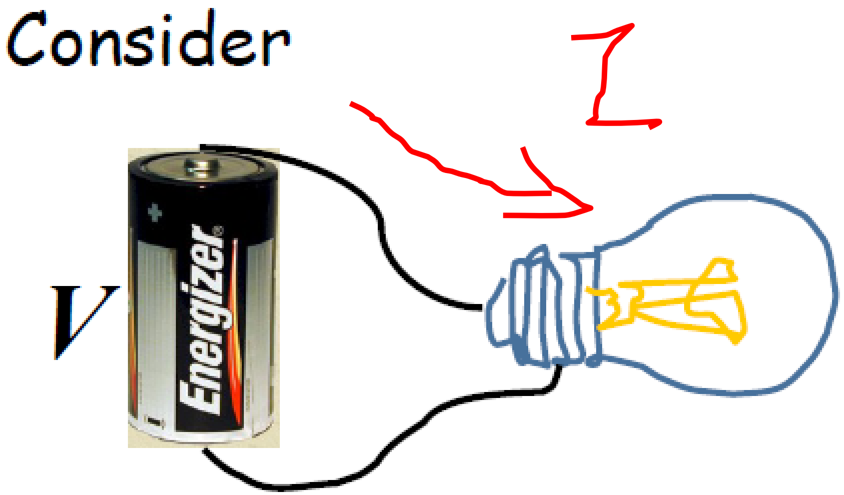
$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$R_{total} = \frac{R_1 \cdot R_2}{R_1 + R_2}$$


5V
+
−
10 Ω
5 Ω
5 Ω
A
B
VAB ?
IAB ?


5V
+
−
10 Ω
5 Ω
5 Ω
A
B
VAB ?
IAB ?

Lumped Element Abstraction



- Suppose we wish to answer this question:
  - What is the current through the bulb?

Do it a hard way by applying…

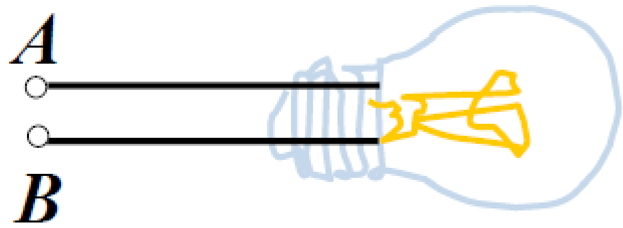
- Maxwell's equations..

DIFFERENTIAL FORM	INTEGRAL FORM	POPULAR NAME
$\nabla \cdot \mathrm{E} = \dfrac{\rho}{\epsilon_0}$	$\oint \mathrm{E} \cdot d\mathrm{S} = \dfrac{q}{\epsilon_0}$	Gauss's law for electricity
$\nabla \cdot \mathrm{B} = 0$	$\oint \mathrm{B} \cdot d\mathrm{S} = 0$	Gauss's law for magnetism
$\nabla \times \mathrm{E} = -\dfrac{\partial \mathrm{B}}{\partial t}$	$\oint \mathrm{E} \cdot d\mathrm{l} = -\dfrac{\partial \Phi_B}{\partial t}$	Faraday's law of induction
$\nabla \times \mathrm{B} = \mu_0\epsilon_0 \dfrac{\partial \mathrm{E}}{\partial t} + \mu_0 \mathrm{J}$	$\oint \mathrm{B} \cdot d\mathrm{l} = \mu_0\epsilon_0 \dfrac{\partial \Phi_E}{\partial t} + \mu_0 i$	Ampere's law (extended)

Instead, there is an easy way…

The Easy Way…

- Consider the filament of the light bulb

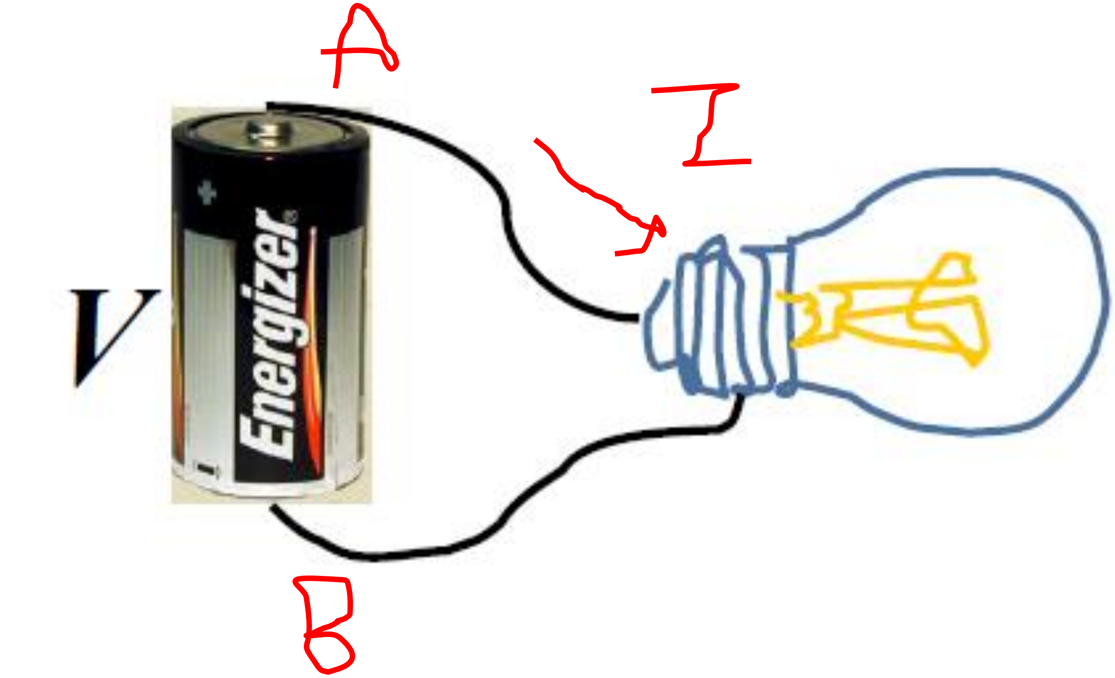


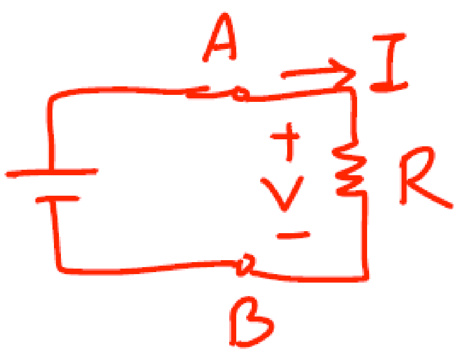
- We do not care about
  - how current flows inside the filament
  - its temperature, shape, orientation, etc.

We can replace the bulb with

a discrete resistor

for the purpose of calculating the current.



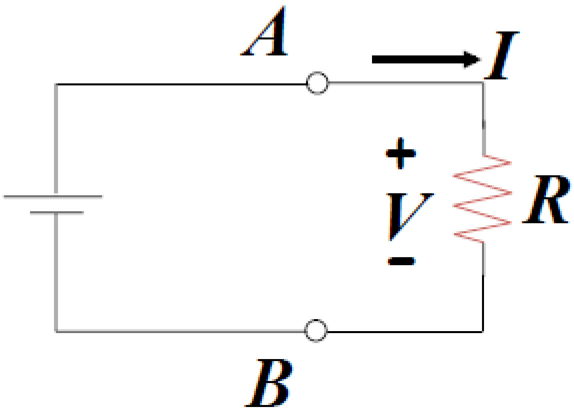


$$I = \frac{V}{R}$$

- ***R*** represents the only property of interest!
- Like with the point-mass:
  - Replace objects with their mass *m* to find: a=F/m

Lumped elements can be categorized or analyzed via their vi characteristics!!

V-I Relationship



and $I = \frac{V}{R}$

- R relates element V and I (Ohm's law)
- I=V/R called element v-i relationship

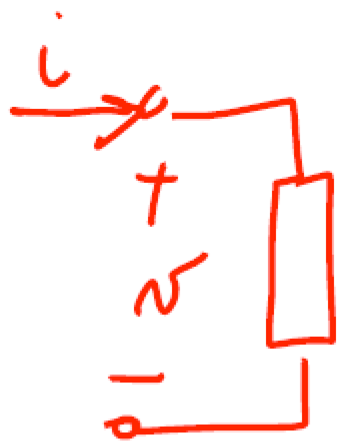
A message so far…

R

is a lumped element abstraction for the bulb.

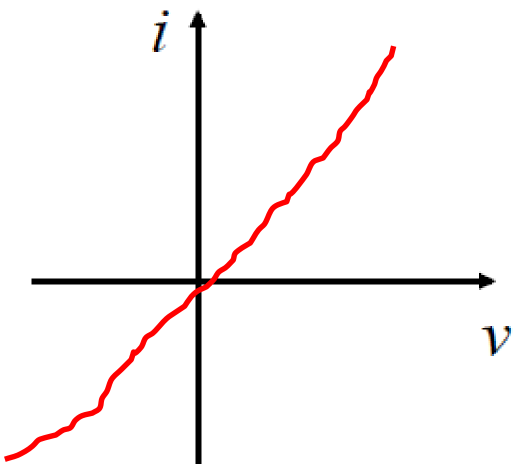
Lumped Elements

- Lumped circuit element described by its *vi* relation
- Power consumed by element = *vi*

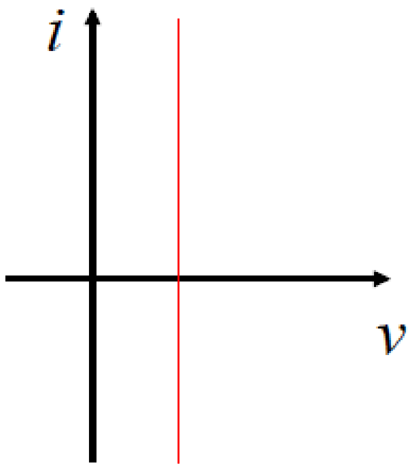


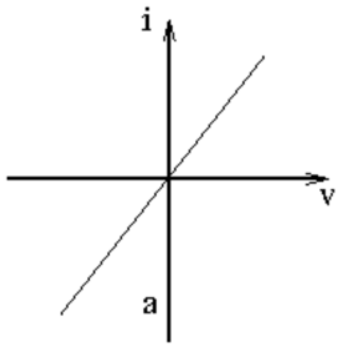
Q: **vi relationship?**

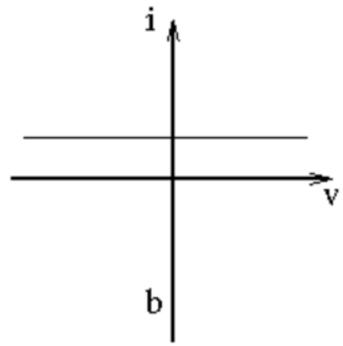
*v and I are variables changing with respect to time

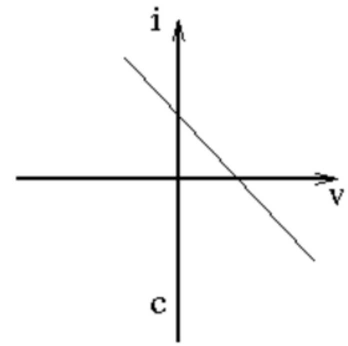


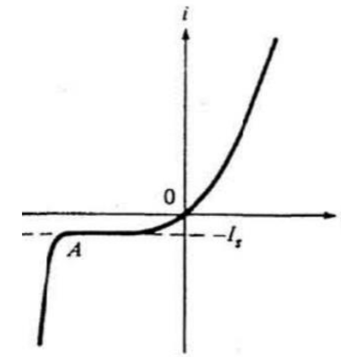
Slope: 1/R

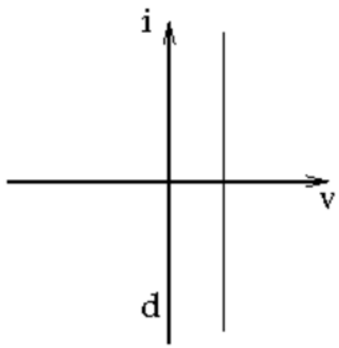


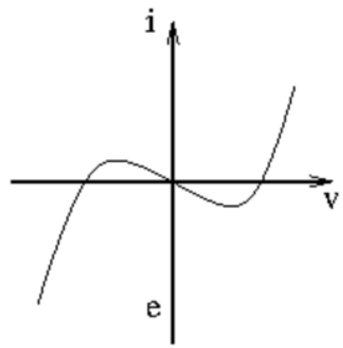


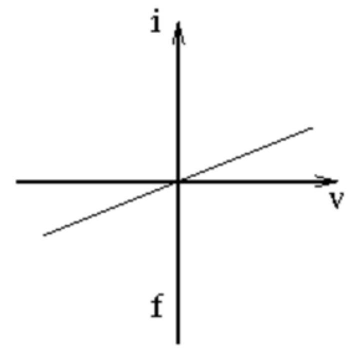


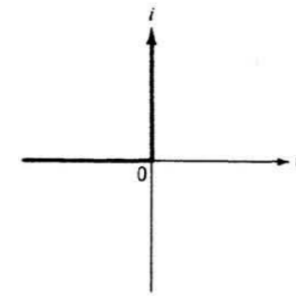


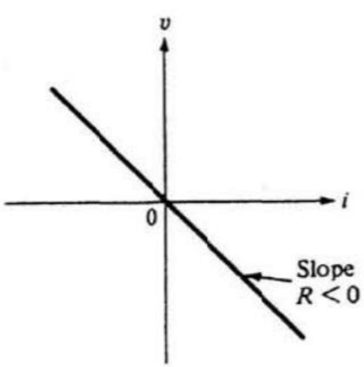




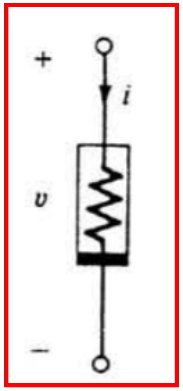




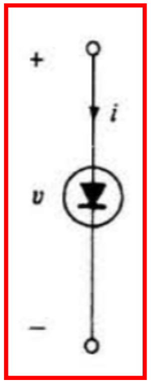




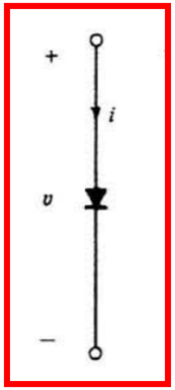
a linear active esistor with resistance R<0



A bilateral nonlinear resistor

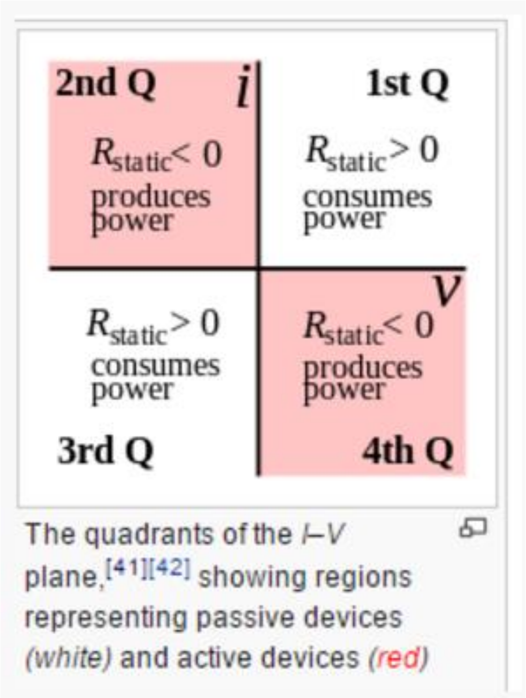


A pn-junction diode



An ideal diode

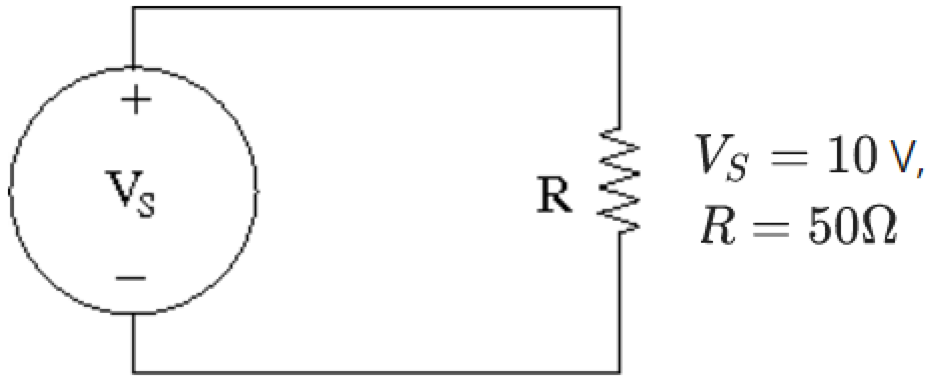
Passive or active?



Positive sign convention

- ACTIVE DEVICES (power by an element is produced): a negative R_{static} (2nd and 4th quadrants)
- PASSIVE (power by an element is consumed): a positive R_{static} (1st and 3rd quadrants)

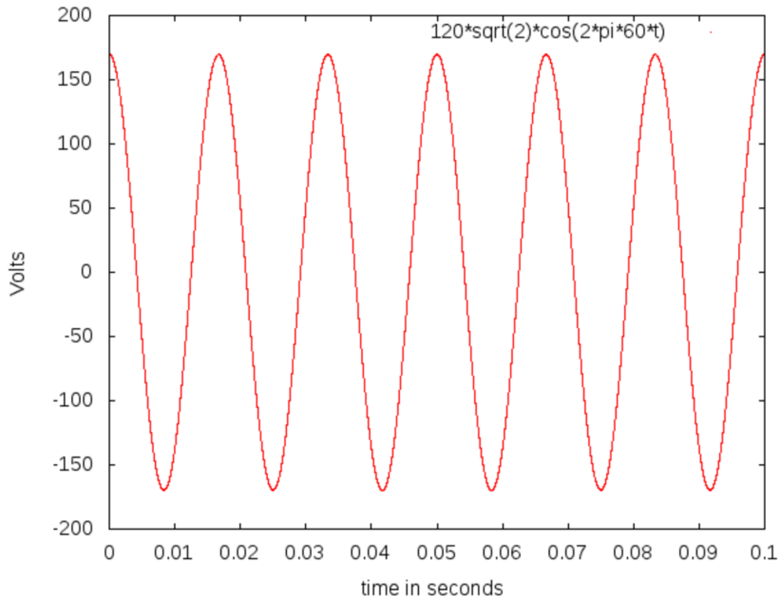
Simple DC power

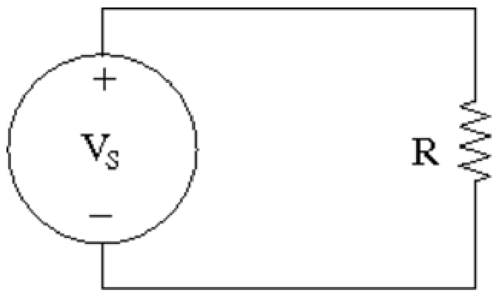


- What is the power dissipated in the resistor (in Watts)?
- What is the power entering the source (in Watts)?

Simple AC power for resistive circuit

- The plot shows 1/10 second of the voltage waveform of a 120V 60Hz AC (RMS, U.S standard)





- The actual voltage: 120·sqrt(2)·cos(2π·60·t) Volts.
- If we apply this voltage across a resistor (110.0Ω), the resistor will dissipate a time-varying power

- What is the peak power (in Watts) dissipated by the resistor?
- What is the average power (in Watts) dissipated by the resistor?

$P=I^2*R$

- Peak power = 110.[120 sqrt(2)/110]^2=261.8181
- Average Power (RMS) dissipated by resistor = 110.(120/110)^2 = 130.9090
  - average power = R . (average value of current)^2
- Energy? Power integrated over the time.

$$e(t) = \int_0^T p(t) \cdot dt$$

Back to the *vi* relationship

- Lumped elements: their behavior is completely captured by their V–I relationship
- By having lumped elements: we ignore, can't predict the real components'
  - Smell
  - Shape
  - Weight
  - Health…

Build our playground

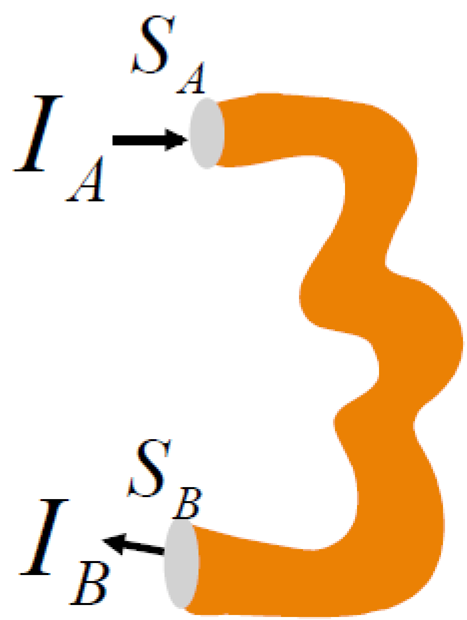
Any Assumptions?

- That seems like a huge simplification, and in general, that is not true.
- So it turns out that we have to make some pretty substantial assumptions in order to make that true.
- Therefore our abstraction is reasonable by defining I and V

I (current) definition

$\frac{\partial q}{\partial t}$: the rate of change of charge, where the charge q is the charge inside the box here

- I into S_A = I out of S_B
- True only when $\frac{\partial q}{\partial t} = 0$ **<u>in</u>** the filament



$$I_A = I_B \quad \text{only if} \quad \frac{\partial q}{\partial t} = 0$$

<u>Which does not have to be true in general</u>

The real trick

- Remember 1: we are engineers.
  - We are not required to study exactly what it is.
  - Our goal is to build interesting systems.

<u>We are allowed to make changes to the playground</u>

- And I want to say that within that playground, you come in <u>only if for the elements</u> $\frac{\partial q}{\partial t} = 0$

Remember 2: Our playground is super. For thousands of decades, our world has depended on it.

V (voltage) definition

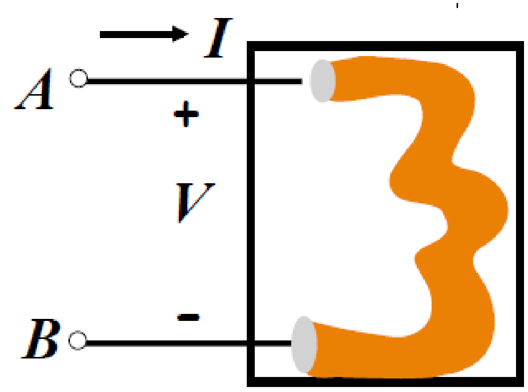
- V_{AB} defined when $\frac{\partial \varphi}{\partial t} = 0$

$$\int_0^A E \cdot dl - \int_0^B E \cdot dl$$

$$= \int_0^A E \cdot dl - \left(- \int_B^0 E \cdot dl \right)$$

$$= \int_{AB} E \cdot dl = V_{AB}$$

Where $\frac{\partial \varphi_A}{\partial t} = \frac{\partial \varphi_B}{\partial t} = 0$



$\frac{\partial \varphi}{\partial t}$=0: The rate of change of magnetic flux linked with any portion of the circuit must be 0 for all time.

V_{AB}: the line integral of E dot dl will be true when del phi B by del t is 0, **outside elements**.

Assumptions in our playground

1. $\frac{\partial q}{\partial t} = 0$, inside
2. $\frac{\partial \varphi}{\partial t} = 0$, outside
3. Signal speeds of interest should be way lower than speed of light

LMD: Lumped Matter Discipline

If these three assumptions are true: our lumped circuit model works. We can build very simple circuits.

The lumped circuit abstraction?

For example, take lumped elements

- a resistor + a voltage source + ideal wires.

Then circuits such as this that you build are called lumped circuits.

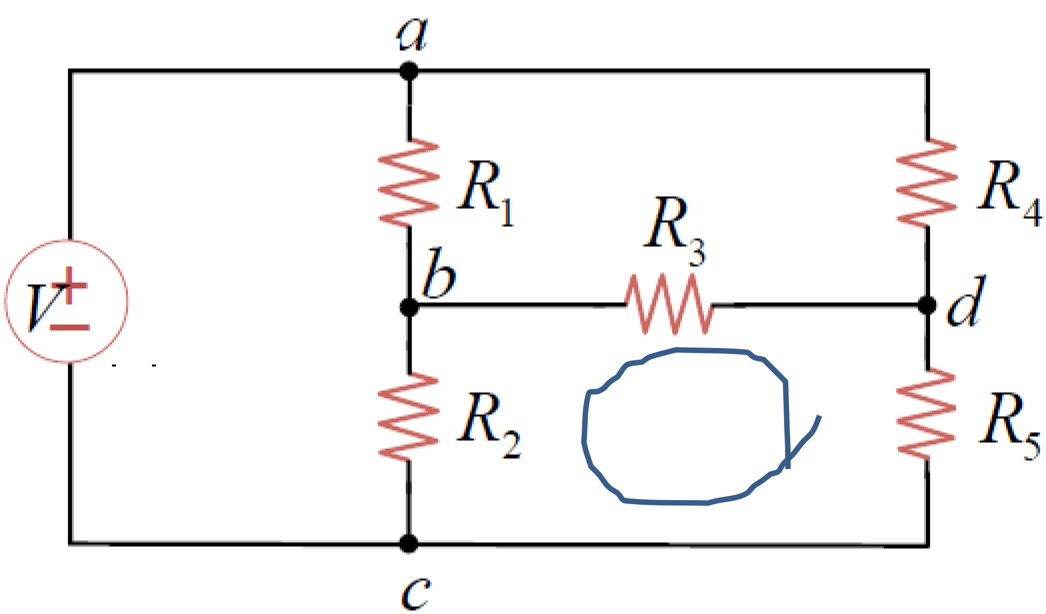
Lumped circuit abstraction:

- Very, very, simple and powerful techniques.
- Can discard the use of Maxwell's equations
- Use some very, very simple algebraic equations to be able to solve complicated circuits.

Let’s apply LMD to our circuit problem.

- **What does LMD buy us?**

- Replace the differential equations with simple algebra using lumped circuit abstraction (LCA).



A node: wires (elements) come together.

A loop: a connection of all elements that form a full circuit.

Voltages in a loop under LMD?

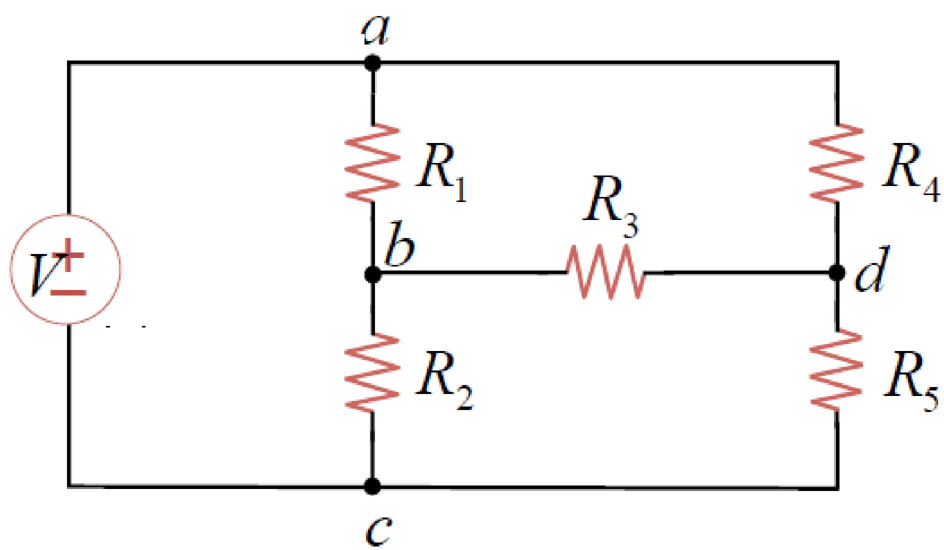
Faradays...

$$\oint E \cdot dl = \frac{-\cancel{\partial \Phi_B}}{\partial t} \xrightarrow{LMD} 0 \quad = 0$$

Therefore (take a loop) ⇒

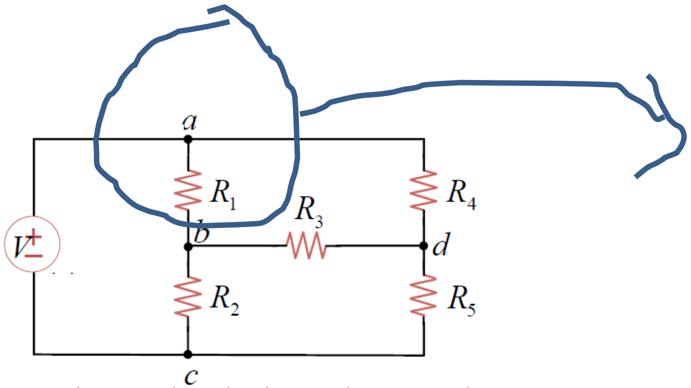
$$\Rightarrow \int_{ca} E \cdot dl + \int_{ab} E \cdot dl + \int_{bc} E \cdot dl = \underset{\text{by LMD}}{\underline{\underline{0}}}$$

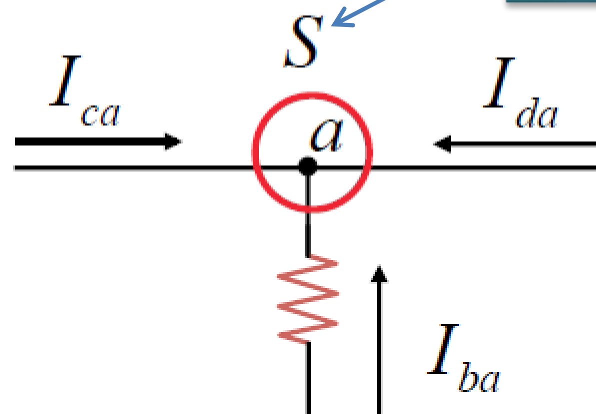
$$\Rightarrow V_{ca} + V_{ab} + V_{bc} = 0. \quad // \boxed{KVL}$$



Kirchhoff's Voltage Law (KVL):
The sum of the voltages in a closed loop is 0.

Current?





$$\oint_S \underline{J}\cdot d\underline{s} = \cancel{-\frac{dq}{dt}} \to 0 \quad \text{LMD} = 0.$$

the surface S ⇒ 3 currents are going int it.

→ $I_{ca} + I_{da} + I_{ba} = 0$.

<u>simply conservation of a charge</u>

Kirchhoff's Current Law (KCL):
The sum of the currents into a node is 0.

KVL and KCL Summary

- KVL in a loop: $\sum V_{drop} = \sum V_{gain}$

Remember our playground assumptions

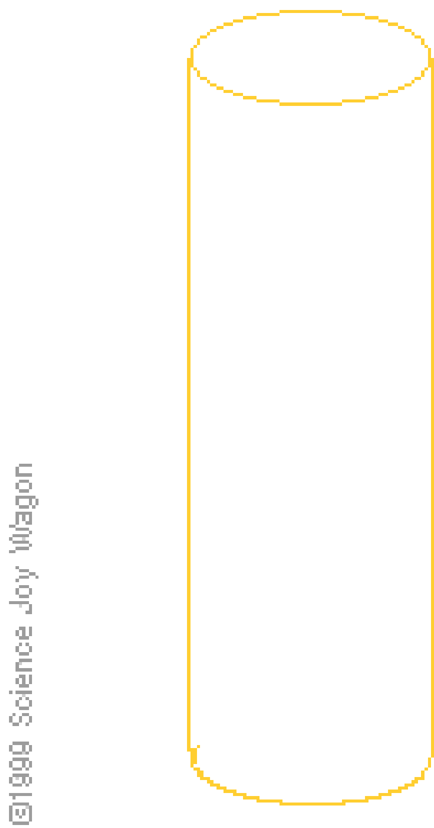
- KCL at a node: $\sum I_{in} = \sum I_{out}$

What will happen outside of our play ground?

For example:

1. $\frac{\partial q}{\partial t} \neq 0$, inside and
2. $\frac{\partial \varphi}{\partial t} \neq 0$, outside

Quasi-static assumptions in classic circuit theories: Eddy currents and diffusion waves



- If a magnetic field near a conductor is changing in time, the traveling magnetic field can be described by the diffusion equation

- A magnet traveling inside of a copper pipe
  - The primary magnetic field, "eddy current", the eddy current which cancels the force of gravity.
  - The magnet falling outside of a conductor: a free fall
  - Falling inside of the conducting pipe: experiencing a significant delay, due to the opposing force caused by the eddy current (against gravity)

Tools

1. Resistors in series/parallel
2. Voltage/current divider

v-i relationships (from lumped circuit abstraction)

- For a R

- For a voltage source

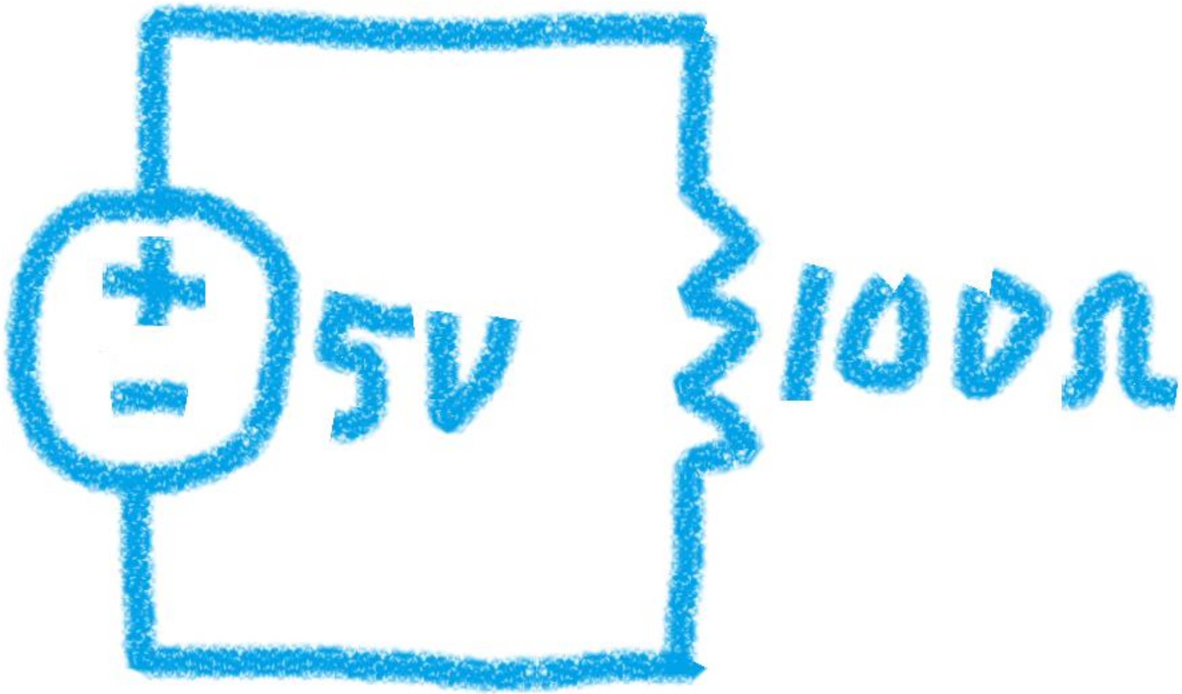
- For a current source

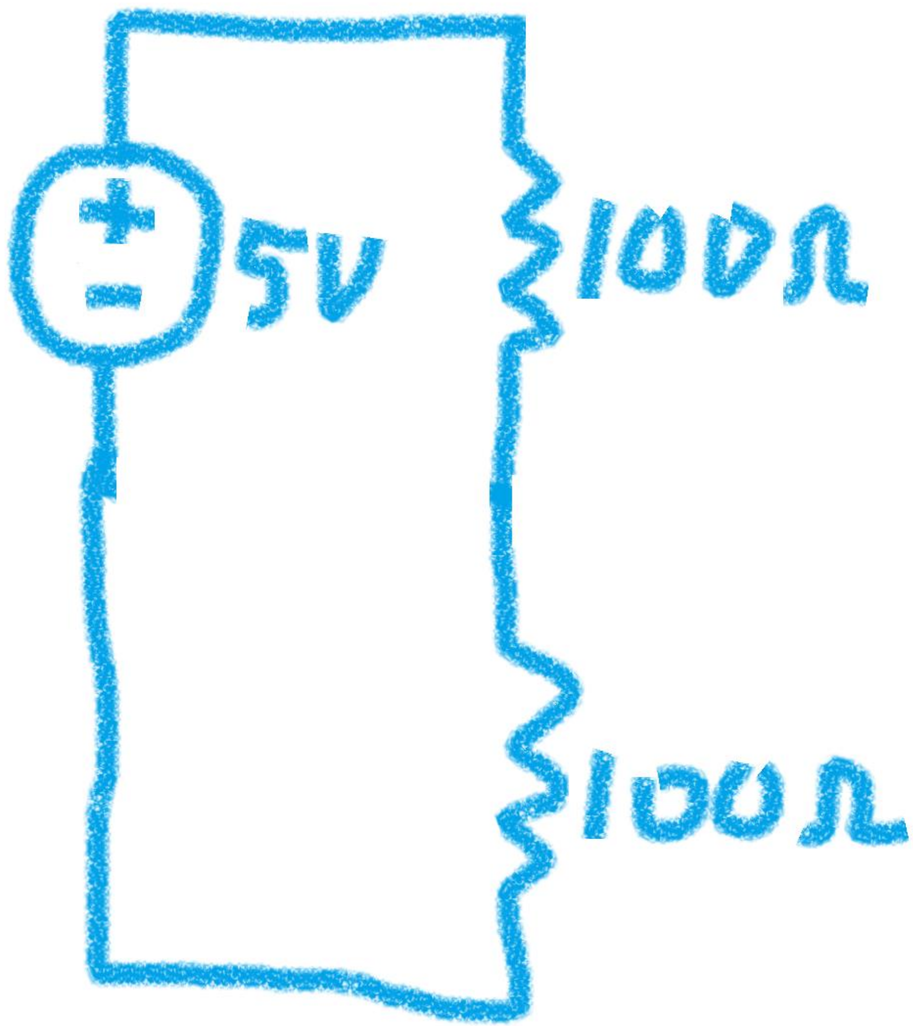
How to solve a circuit question

1. Set a GND
2. Set a polarity for every single component
3. Apply Ohm's las, KCL, KVL

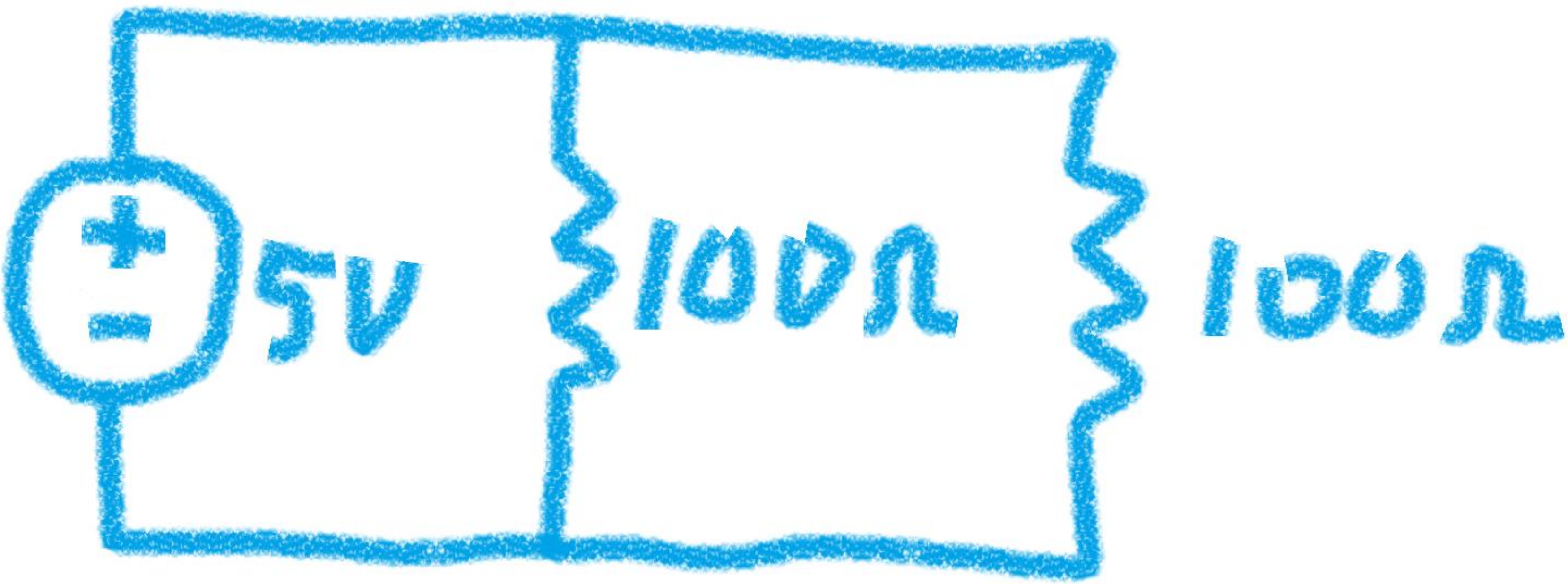
Always remember,

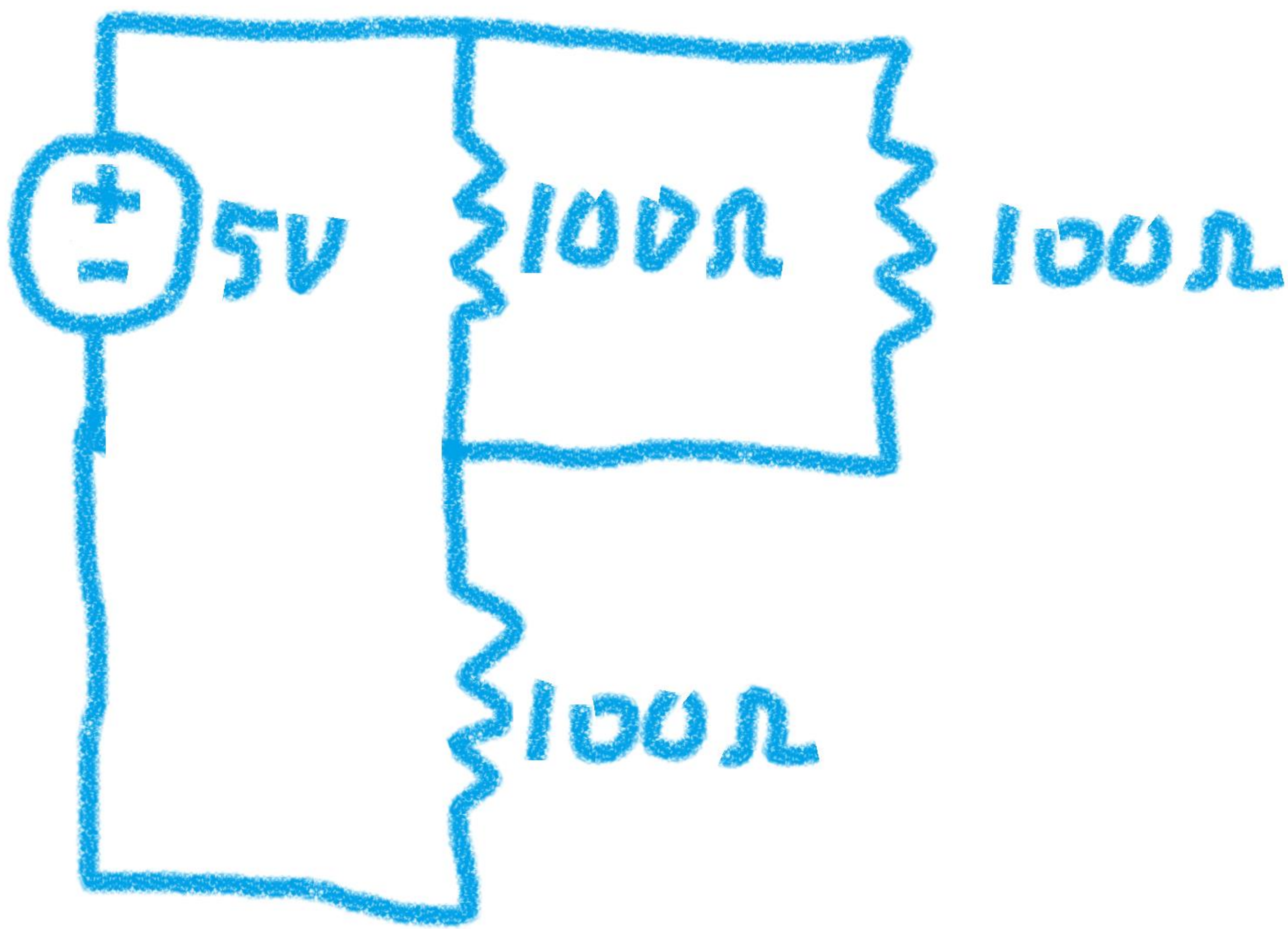
- Currents flow from + to –
- A voltage is calculated across two nodes as a difference.


+
−
5V
100Ω



+
-
5V
100Ω
100Ω


+
-
5V
100Ω
100Ω

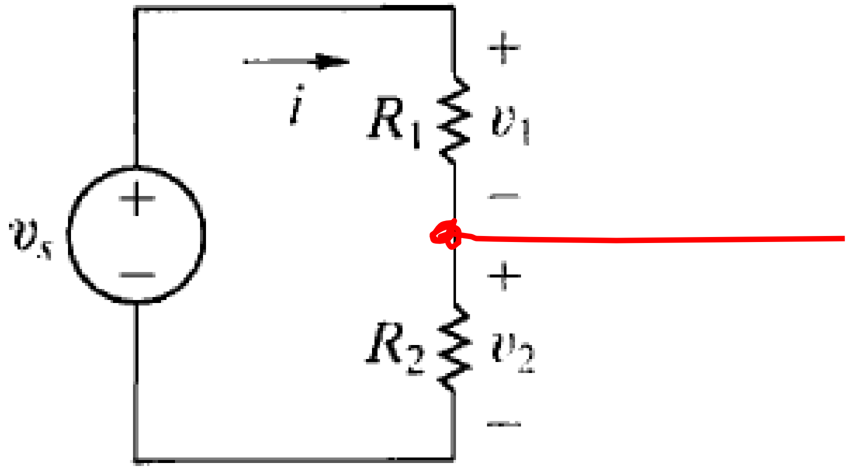


+
-
5V
100Ω
100Ω
100Ω

The Voltage-Divider Circuits

$$v_s = iR_1 + iR_2,$$

$$i = \frac{v_s}{R_1 + R_2}.$$

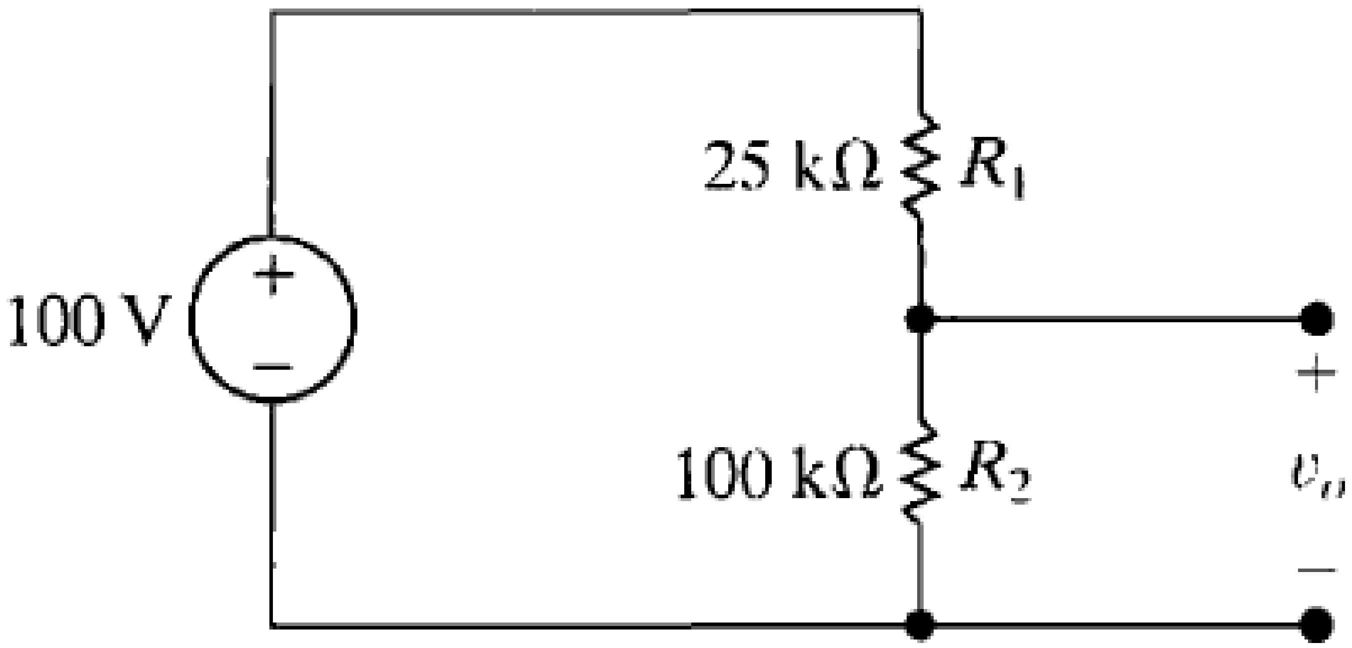


Via Ohm's law

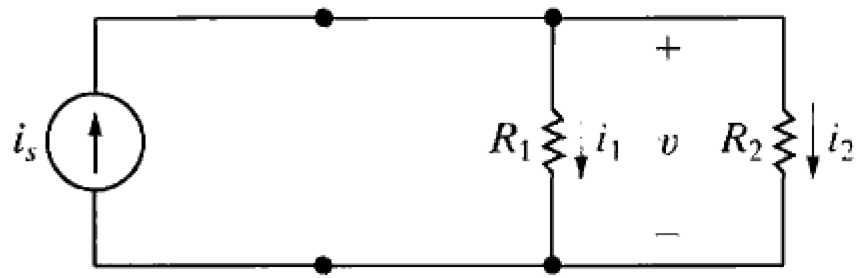
$$v_1 = iR_1 = v_s \frac{R_1}{R_1 + R_2},$$

$$v_2 = iR_2 = v_s \frac{R_2}{R_1 + R_2}.$$

- Find the maximum and minimum value of v_o



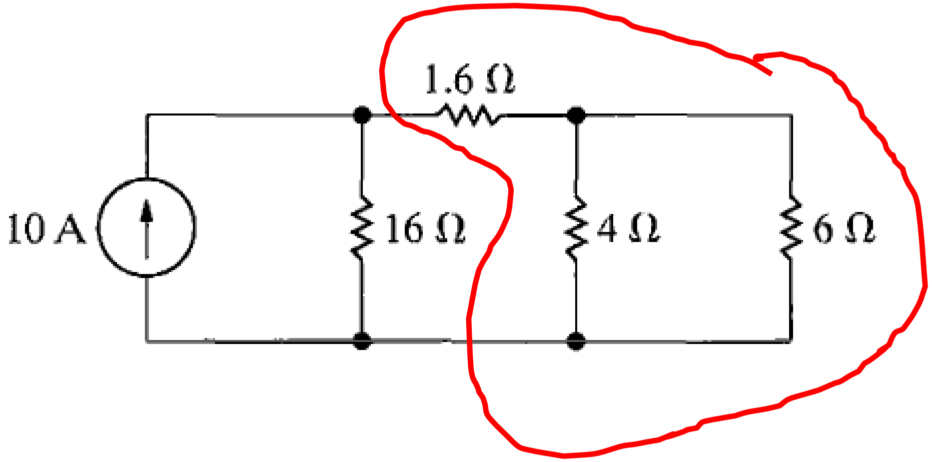
The Current-Divider Circuits

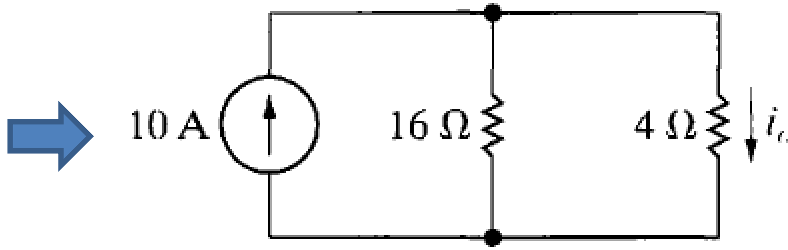


$$v = i_1 R_1 = i_2 R_2 = \frac{R_1 R_2}{R_1 + R_2} i_s$$

$$i_1 = \frac{R_2}{R_1 + R_2} i_s \qquad i_2 = \frac{R_1}{R_1 + R_2} i_s$$

- Find the power dissipated in the 6Ω resistor





i_0: the current in the 1.6Ω resistor

- Find R_{eq}, and Use current division to find the current i_0 and use voltage division to find the voltage v_0