ECE/ENGRD 2100

Introduction to Circuits for ECE

Lecture 1

Electrical Quantities and Constitutive Relationships

Course Information

Course:	Introduction to Circuits for ECE (ECE/ENGRD 2100)
Lecture:	MWF 10:10-11:00 am in Thurston Hall 205
Labs:	TWF 12:20-2:15 pm in Phillips Hall 237 (during 6 weeks)
Discussions:	WF 1:25-2:15 pm in Phillips Hall 233 (during non-lab weeks)
Instructors:	Khurram Afridi, afridi@cornell.edu, Phillips Hall 420
	Clifford Pollock, crp10@cornell.edu, Phillips Hall 418
Head TA:	Aobo Chen, ac2299@cornell.edu
Office Hours:	Wed 2:15-3:15 pm (Afridi in Phillips 420)
	Thur 1-2:30 pm (Pollock in Phillips 418)
	Thur 4-5 pm (Chen in Phillips 429)
	Use "ECE 2100" in subject line of course related emails

Resources

Textbook

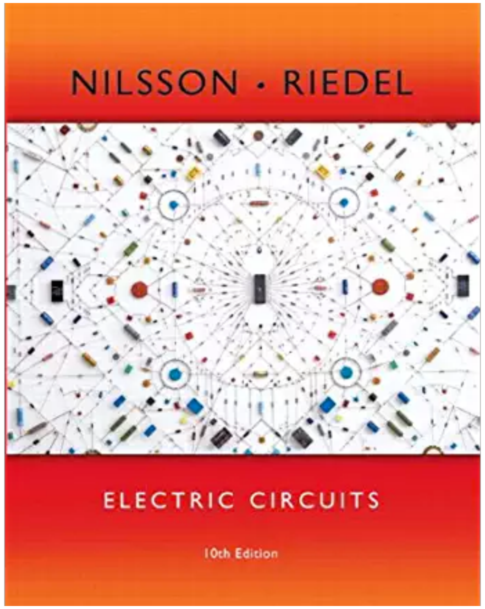
- Nilsson and Riedel, *Electric Circuits*, 10th edition

Lecture Slides

- Slides with annotations posted on course website on Blackboard (blackboard.cornell.edu) after lecture

TAs

- Karthik Krishna-Jayaram, kk969@cornell.edu
- Shashank Pathak, sp2534@cornell.edu
- Oleksandr Kuzura, odk8@cornell.edu
- Logan Horowitz, lhh48@cornell.edu
- Maria Bobbett, mb2567@cornell.edu
- Sanush Kehelella, snk32@cornell.edu
- Jessica Tawade, jt658@cornell.edu



Assessment

Homework, Prelabs, Lab Reports

- 6 homework assignments, 6 prelab assignments, 6 lab reports
- Collaboration on homework, prelabs and lab reports is allowed; however, all work you turn in must be your own (except lab reports which are by team)

Exams

- Two prelims and one final exam

Grading

- Homework: 15%
- Prelabs: 6%
- Lab reports: 24%
- Prelims: 25%
- Final: 25%
- Class participation: 5% (0.33% per week – ask/answer question per week)

Due dates enforced by Blackboard

see **Course Syllabus** and **Course Calendar** posted on Blackboard for details on policies and procedures

Important Policies and Procedures

Homework, Prelab, Lab Report Submission Procedure/Policies

- Write your name and email address on the front page
- Scan b&w at 150-300 dpi into a single easily readable pdf file
- Submit online via Blackboard by uploading single pdf
- Keep a copy of your work
- No late work will be accepted (except with prior approval)

Exam Policies

- Exams will be closed-book and closed-notes
- One double-sided page formula sheet will be allowed

Teaching Philosophy

- Develop intuitive understanding
- To help me understand your interests and teach you better, please attend at least one of my office hours in next four weeks

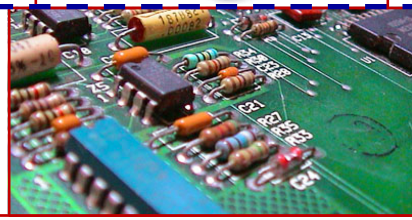
Announcements

- Recommended Reading:
  - Textbook Chapter 1 and Chapter 2
- Homework 1, Prelab 1 and Lab 1 are out
  - Prelab 1 due by 12:20 pm on Tuesday January 29, 2019
  - Homework 1 due by 11:59 pm on Friday February 1, 2019
  - Lab report 1 due by 11:59 pm on Friday February 8, 2019
- Lab 1 is next week (starting Tuesday January 29, 2019)

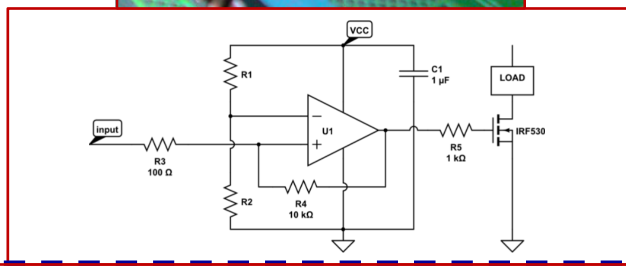
What is ECE/ENGRD 2100 About?

Electronic systems

ECE/ENGRD 2100

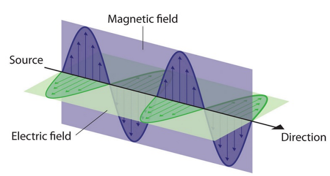


Electronic circuits



Circuit Theory

- Kirchhoff's Laws
- Device Laws



$$\nabla \cdot \mathbf{D} = \rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

Electromagnetic Theory

- Maxwell's Equations
- Material Physics

Nature

Electromagnetic Theory

Maxwell's Equations

$\nabla \cdot \vec{D} = \rho \quad \Longleftrightarrow \quad \oiint \vec{D} \cdot \overrightarrow{ds} = \iiint \rho \, dv$ — Gauss' Law

$\nabla \times \vec{E} = -\dfrac{\partial \vec{B}}{\partial t} \quad \Longleftrightarrow \quad \oint \vec{E} \cdot \overrightarrow{dl} = -\dfrac{\partial}{\partial t} \iint \vec{B} \cdot \overrightarrow{ds} = -\dfrac{\partial \Phi}{\partial t}$ — Faraday's Law

$\nabla \cdot \vec{B} = 0 \quad \Longleftrightarrow \quad \oiint \vec{B} \cdot \overrightarrow{ds} = 0$ — Magnetic Flux Continuity

$\nabla \times \vec{H} = \vec{J} + \dfrac{\partial \vec{D}}{\partial t} \quad \Longleftrightarrow \quad \oint \vec{H} \cdot \overrightarrow{dl} = \iint \vec{J} \cdot ds + \dfrac{\partial}{\partial t} \iint \vec{D} \cdot \overrightarrow{ds}$ — Ampere's Law

where
$$\left.\begin{aligned} \vec{D} &= \epsilon \vec{E} \\ \vec{B} &= \mu \vec{H} \\ \vec{J} &= \sigma \vec{E} \end{aligned}\right\} \text{Material Physics}$$

$\vec{E}$ - Electric Field Intensity [V/m]

$\vec{D}$ - Electric Flux Density [C/m^2]

$\vec{H}$ - Magnetic Field Intensity [A/m]

$\vec{B}$ - Magnetic Flux Density [T]

$\vec{J}$ - Current Density [A/m^2]

Circuit Theory

- Goal of circuit theory: Predict electrical behavior of physical circuits
- Simplification of electromagnetic theory
- Applies under restricted set of conditions: (which apply for all time):

(1) $\frac{\partial \Phi}{\partial t} = 0$ outside side devices & through loops → $\oint \vec{E} \cdot \overrightarrow{dl} = 0$

for all time

(2) $\frac{\partial q}{\partial t} = 0$ inside devices & at nodes → $\oiint \vec{J} \cdot ds = 0$

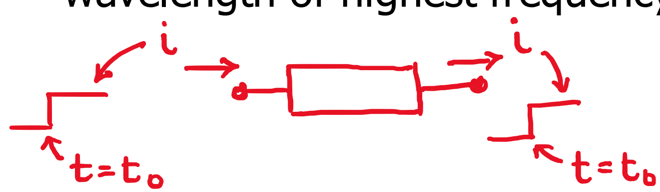
for all time

} Terminal voltages and currents of device are unique

(3) Largest circuit dimension $\ll c\Delta t = \frac{c}{f} = \lambda$

wavelength of highest frequency

} Propagation effects can be neglected

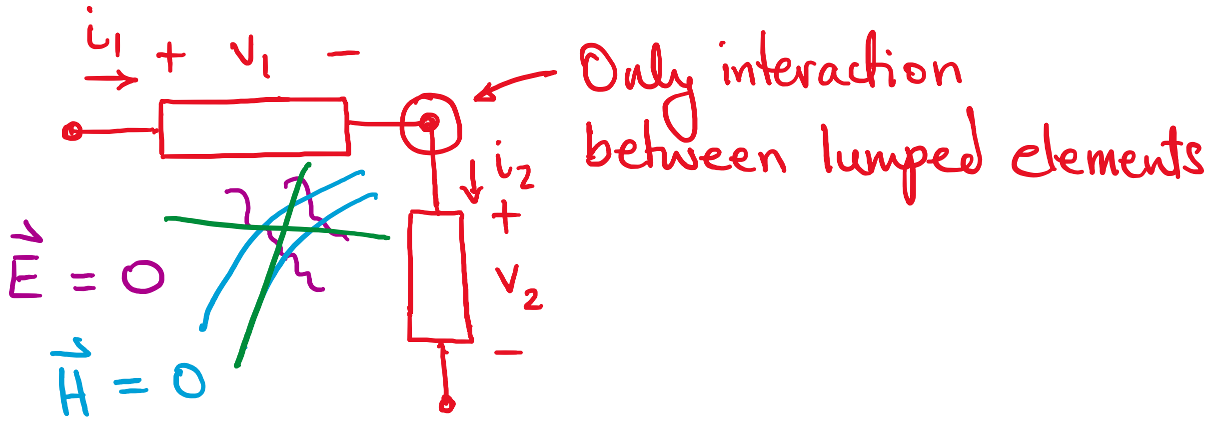


Since (1) and (2) are true for all time, they imply that magnetic and electric fields are zero outside the devices

Circuit Theory (Cont.)

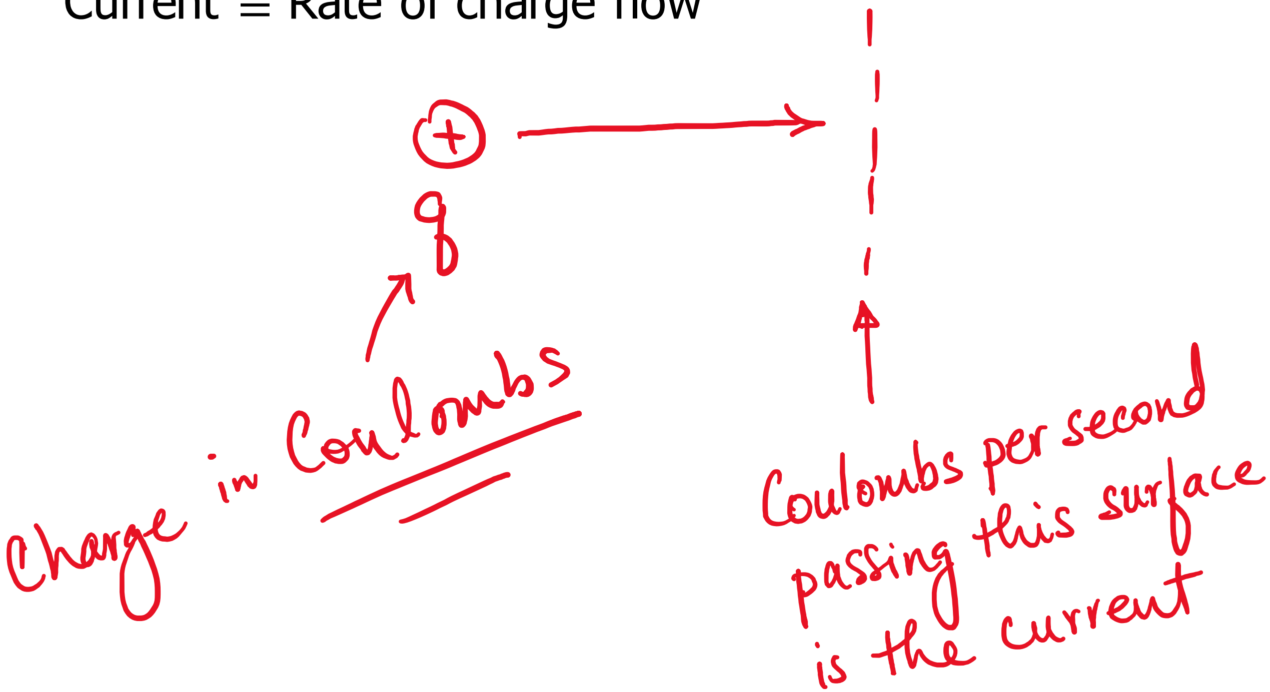
- Allows modeling of individual devices in a circuit as Lumped Elements that interact with each other only through their terminal voltage and current (since magnetic and electric fields outside the devices are zero)

- Makes circuit analysis much easier than solving Maxwell's equations



Current (and Charge)

Current ≡ Rate of charge flow



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

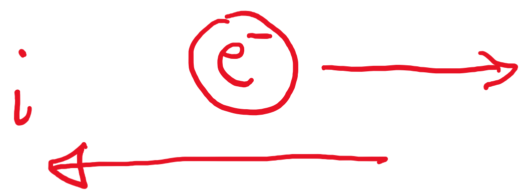
Current is uniquely defined when $\frac{\partial q}{\partial t} = 0$ inside devices

Current is measured in Amps [A]

1 A = 1 C/s

Current (Cont.)

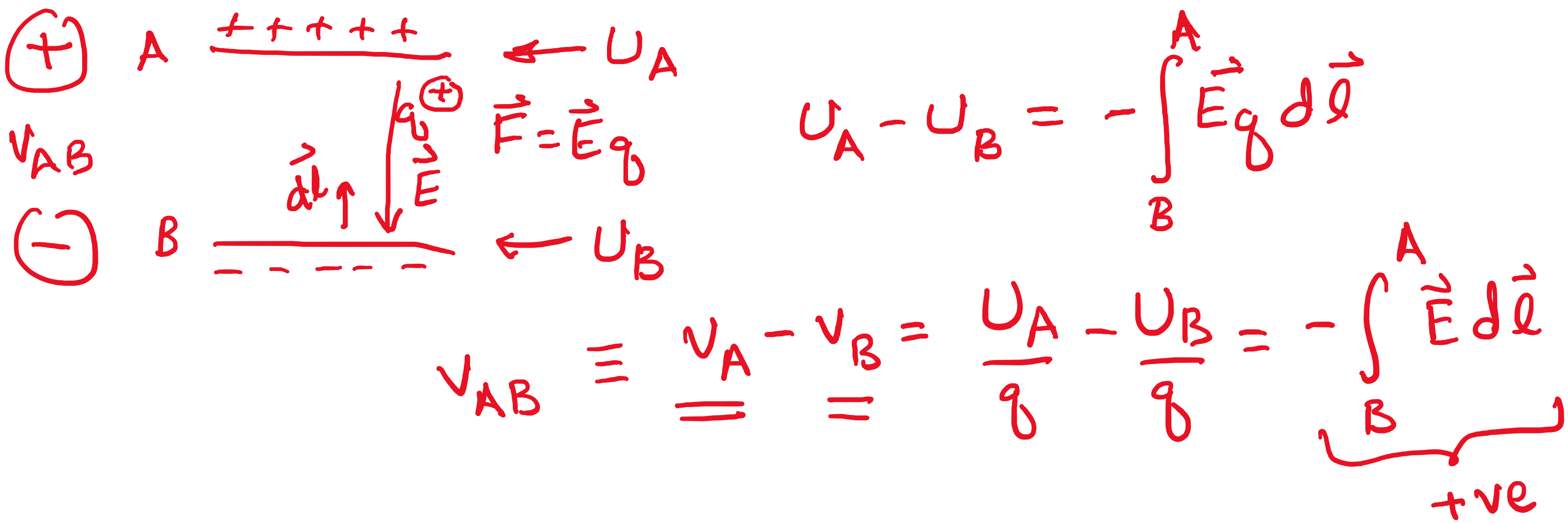
- Current is the “through” variable
- Current through an element is analogous to the flow of an incompressible fluid flowing through a fluid processing device
- In metallic conductors moving charge carriers are electrons, but direction of current is defined as the direction of flow of positive charges
  - So in metallic conductors positive direction of current is opposite to direction of electron flow



- Charge is quantized (charge of one electron = -1.6×10^{-19} C) and therefore so is current, but will neglect this as typical currents never get this small

Voltage (and Energy)

Voltage ≡ Energy per unit charge $\quad v = \frac{dw}{dq}$



$$v_{AB} = v_A - v_B = -\int_B^A \vec{E} \cdot \vec{dl}$$

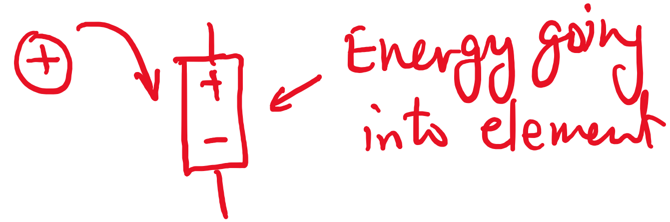
Voltage is uniquely defined when $\frac{\partial \Phi}{\partial t} = 0$ outside devices

There is no absolute value of voltage – voltage is always defined at a location relative to the voltage at another location

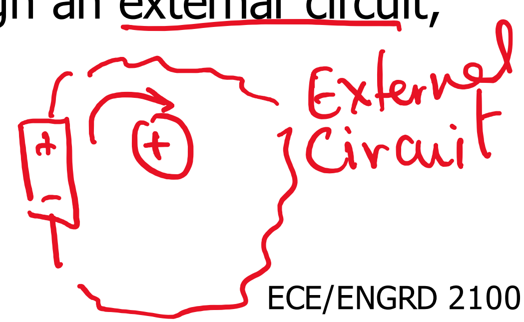
Voltage is measured in Volts [V] $\qquad$ 1 V = 1 J/C = 1 N-m/C

Voltage (Cont.)

- Voltage is the "across" variable
- Voltage across an element is analogous to pressure difference at two ends of a fluid processing device
- Voltage across an element is the amount of work per unit charge that the charge can do when it moves from the +ve terminal to the –ve terminal
  - If charge moves from +ve to –ve terminal through the element, energy is delivered to the element

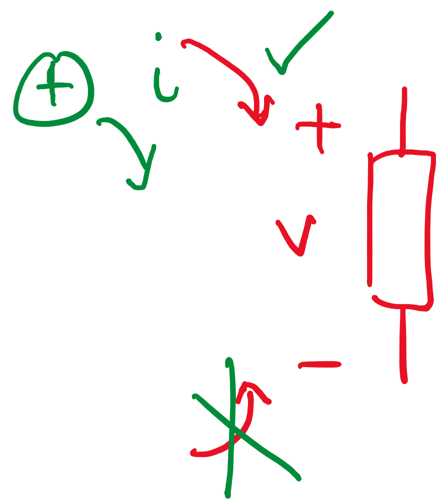


  - If charge moves from +ve to –ve terminal through an external circuit, energy is delivered to the external circuit



Associated Variables Convention

- In circuit theory it is very helpful to follow conventions when describing voltage across and current through an element



Reference the current direction into the positive voltage terminal

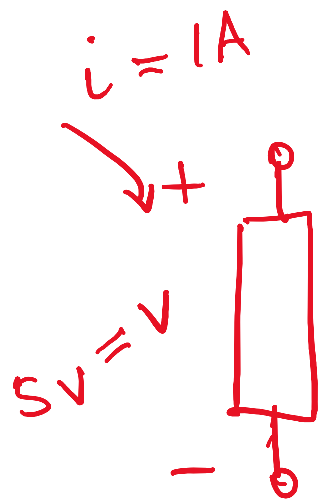
"Associated Variables Convention" is also know as the "Passive Sign Convention"

Power

Power ≡ Time Rate of Change of Energy = Rate at which Work is done

$$P = \frac{dw}{dt} = \frac{dw}{dq} \cdot \frac{dq}{dt} = v \cdot i$$

$\frac{dw}{dq} \equiv v$, $\frac{dq}{dt} \equiv i$



$v = 5\,V$

$i = 1\,A$

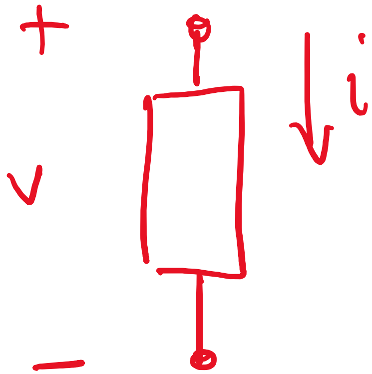
$P = 5\,W$

Power is measured in Watts [W]

1 W = 1 J/s

Constitutive Relationship

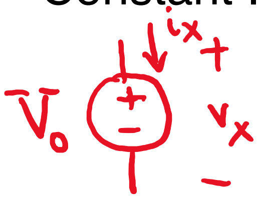
Relation between voltage across and current through an element is called the constitutive relationship of the element (also called element law or I-V curve)



Constitutive relationship only depends on the element and not on how it is connected in the circuit

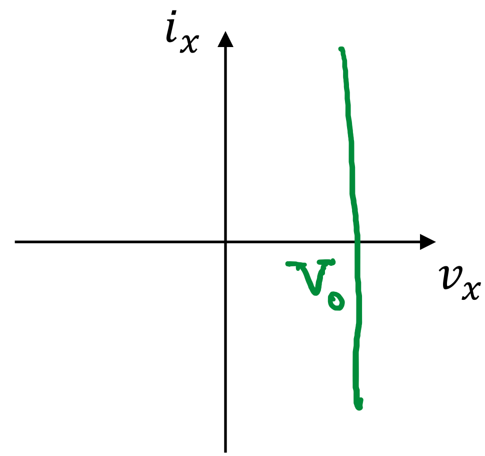
Constitutive (v-i) Relations for Ideal Sources

Constant Independent Voltage Source

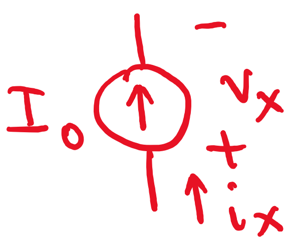


$v_x = V_0$

- Power can go in or out

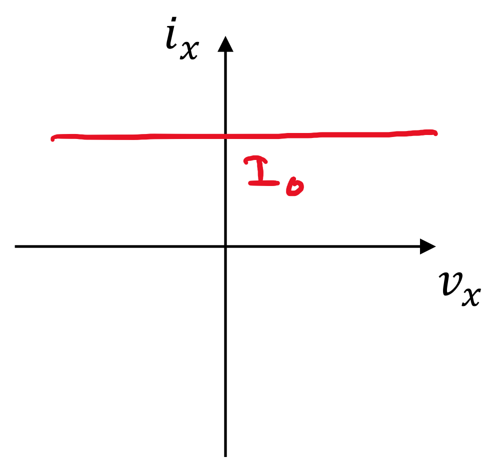


Constant Independent Current Source



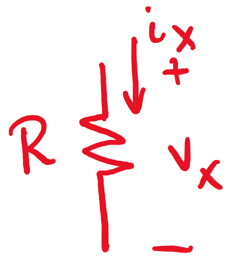
$i_x = I_0$

- Power can go in or out

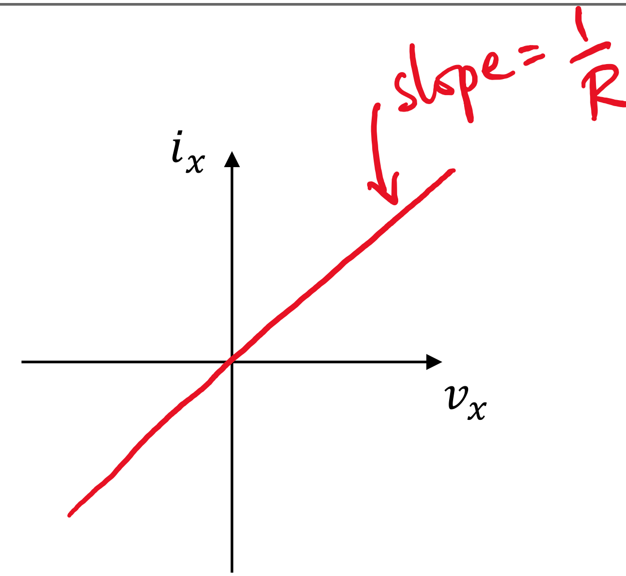


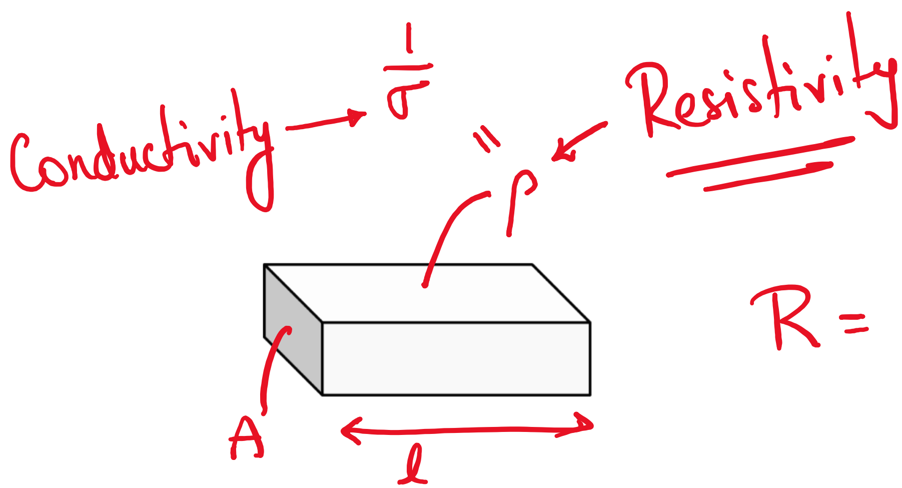
Constitutive (v-i) Relation for Resistor

Linear Resistor



$$v_x = R i_x$$





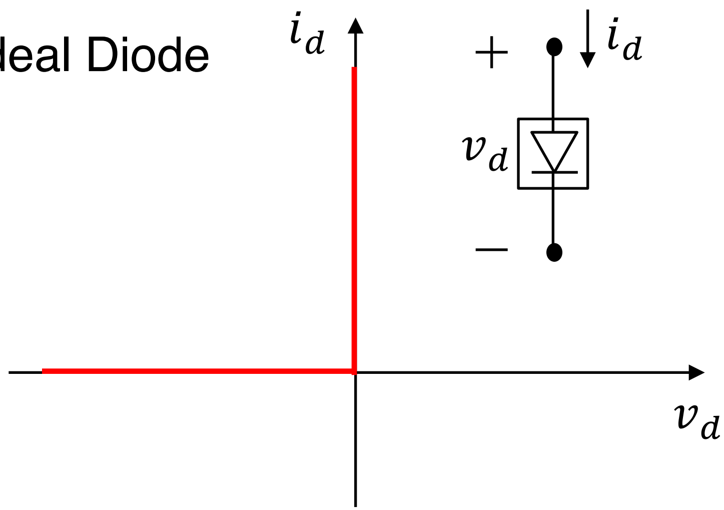
$$R = \rho \frac{l}{A}$$

Resistance is measured in Ohms [Ω]

1 Ω = 1 V/A

Constitutive (v-i) Relations of Nonlinear Resistors

Ideal Diode



Real Diode