Recommended learning opportunities

- **Workshops** (as announced each week)
- **Office Hours** Room 1005 (near lab), Monday-Friday
- **CARE** Grainger Library
- **Honors projects** targeting James Scholars, ECE110+ECE120

Encountering various difficulties? Contact your Instructor, lab TA, or the advising office on the second floor (2120 ECEB)!

Lecture 1: ECE110 *Introduction to Electronics: Key Intro Concepts*

Electrical

Charge

Engineering

Current

Voltage

Power

Energy

The Field of Study Defined

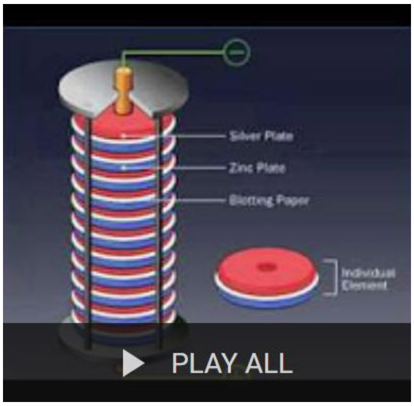
"***Engineers*** use the knowledge of mathematics and natural sciences gained by study, experience, and practice, applied with judgment, to develop ways to economically utilize the materials and forces of nature for the benefit of mankind. "

- ABET (Accreditation Board for Engineering and Technology)

Electrical engineering (EE) is a field of **engineering** that generally deals with the study and application of electricity, electronics, and electromagnetism

- WikiPedia

A short history of Electrical Engineering



Charge

- Charge is measured in coulombs (C)
- Capital or lowercase "Q" is the variable typically used to represent charge
- an electron is a charged subatomic particle
- the coulomb is extremely large compared to the charge of a single electron

$$\frac{-1.6\times 10^{-19}C}{electron} \quad \underset{=}{(notation\ change)} \quad \frac{-1.6\,\mathrm{e}-19\ \ C}{electron}$$

- Electronics is much more than just movement of electrons

Current: the rate at which Charge moves


Image is public domain.

- Current is measured in units of amps (A)
- Capital or lowercase "I" is the variable typically used to represent current…it means *intensity*.
- Electric current is the flow of electric charge in time (C/s)

$$i(t) = \frac{dq(t)}{dt}$$

- The ampere is the unit of electric current

$$1\ A = 1\ C/s$$

- Current is measured by an *ammeter*

"DC" Current

For *constant* rates called "Direct Current" or "DC", we typically use capitalized variables and can replace the differential with observations in some time, Δt.

$$I = \Delta Q/\Delta t$$

$$\text{the } \Delta \text{ means "the change in"}$$

Charge and Current

Help Sheet:

$$\frac{-1.6\,\mathrm{e}-19\ \ C}{electron}$$

$$I = \frac{\Delta Q}{\Delta t}$$

$$1\ A = \frac{1\ C}{1\ s}$$

Question: What is the charge of 1 billion electrons?

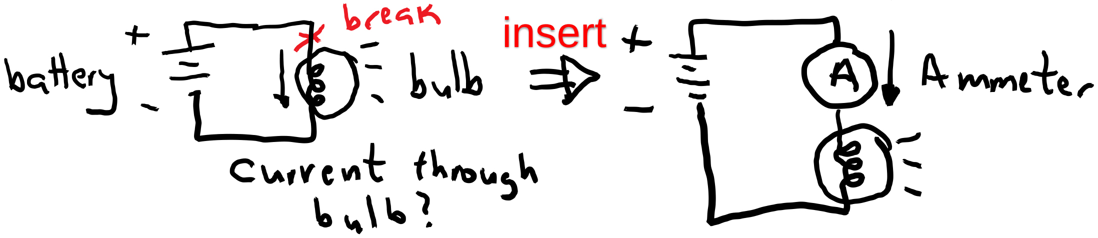
A. 160 e-12 C
B. 16 e-12 C
C. 1.6 e-12 C
D. 1.6 C
E. 160 C

Q: A "typical" electronics circuit might have 1 billion electrons pass a cross section of a wire every nanosecond, what is the electric current in amps?

A. 0.00000016 A
B. 0.160 A
C. 1 A
D. 1e-9 A
E. 160e-12 A

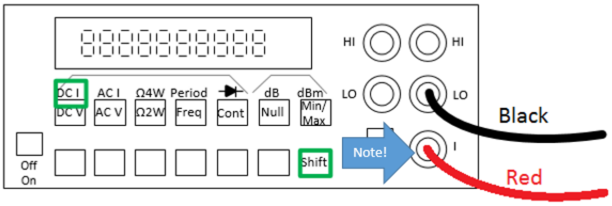
The Ammeter

To use an ammeter to measure current, the circuit must first be "broken" and the ammeter inserted between the detached wires. The ammeter repairs the circuit and the current being measured is forced to flow through the ammeter.

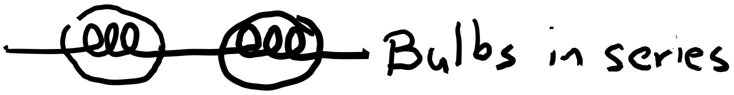


The Ammeter

We say the ammeter is connected in <u>series</u>. Any devices connected in a way to force them to share the same current are said to be connected in series.



Use Shift-DCI to measure DC current. Plug the red cable in the I port.



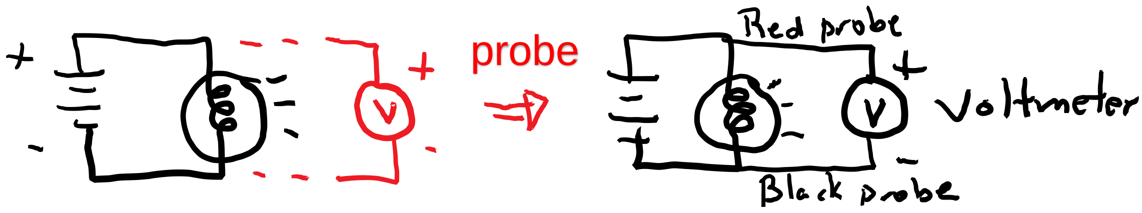
Voltage

- Voltage across two points in space is the energy it requires to move each “unit” of charge between those two points. Alternately, it is the energy released when one unit of charge is allowed to move between two points in space (moving from a higher potential to a lower potential).
- As an example, it should take no energy (0 volts) to move charge through an ideal (zero-resistance) conductor connected in a loop. As a second example, a 9-volt battery delivers 9 Joules of energy to each Coulomb of charge it moves.
- Voltage, as seen by the description above, is *differential* (measured between two points) and not absolute (cannot be measured at a single point without a reference).
- In many circuits, voltage potential is provided by a battery. Think of a battery that pushes electrons through a circuit (perhaps a light bulb).
- Voltage is measured with a voltmeter in units of volts $[V]$.

$$V = \frac{\Delta \mathrm{E}}{\Delta Q}$$

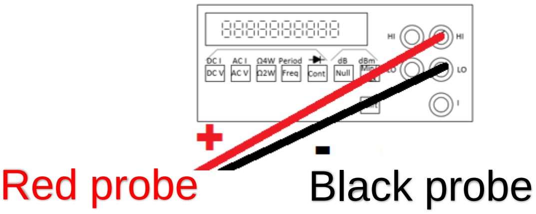
The Voltmeter

To use voltmeter, the meter’s probes are placed across the device whose voltage value is desired. The circuit is ***not*** broken-and-repaired when using the voltmeter. The meter is merely placed between two circuit locations.



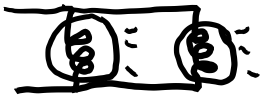
The Voltmeter

We say the voltmeter is connected in parallel. Any devices connected in a way to force them to share the same voltage are said to be connected in parallel.



Red probe

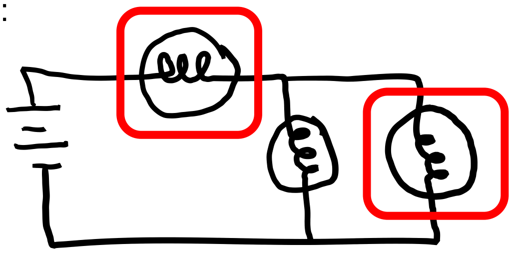
Black probe



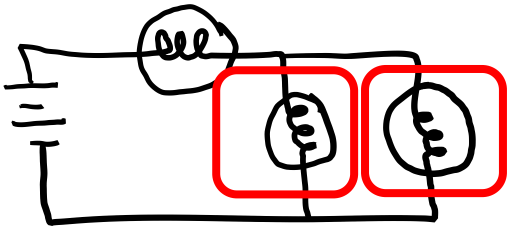
Two Bulbs in parallel.

(A) Series, (B) Parallel, (C) Neither, or (D) Both?

Q:

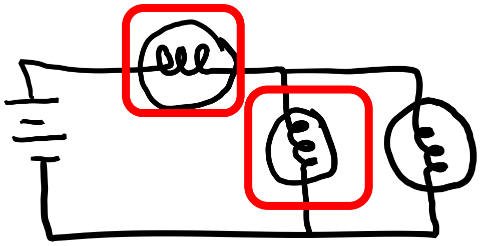


Q:

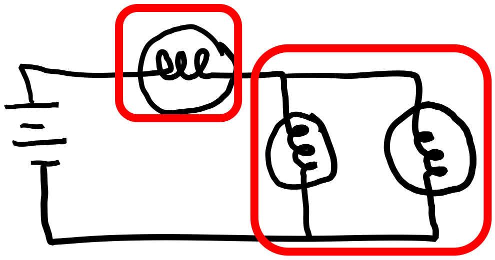


(A) Series, (B) Parallel, (C) Neither, or (D) Both?

Q:



Q:



ECE110 Laboratory

- **Measure** device data
- **Model** behavior
- **Make** interesting circuits
- **Master** design of your own circuits

The laboratory provides a hands-on opportunity to both learn and to showcase your skills!

Required

- ECE Supply Center
  - ECE110 Electronics Kit
  - i>clicker/app
- Online (courses.engr.Illinois.edu/ece110)
  - ECE110 Lecture Slides (IUB bookstore)
  - ECE110 Lab Procedures (IUB bookstore)

Recommended

- ECE Supply Center
  - Voltmeter
  - Multipurpose wire stripper
  - Arduino (or RedBoard) + cable

Schedule

- Homework
  - First assignment due on Wednesday, September 4
  - Online via **PrairieLearn**
  - Discussion of problems and course announcements on **Piazza**
  - Due **Wednesdays at 11:59 pm**. Get it done early!
  - Office Hours…To be posted soon

Schedule

- Lab
  - Labs start on Monday, September 9
  - Purchase Lab kit in ECE Supply Center
  - Purchase Lab Procedures at IUB
  - Prelab assignments due at the beginning of each meeting

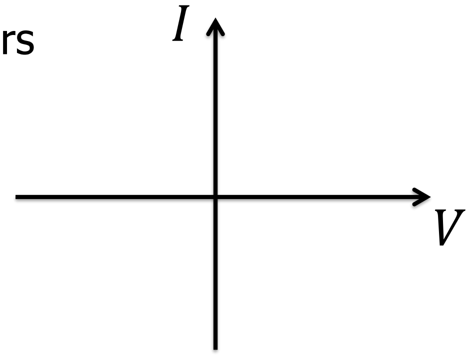
L1 Learning Objectives

a. (L1a) Compute relationships between charge, time, and current.
b. (L1b) Define voltage.
c. (L1c) Identify series and parallel elements in a circuit.
d. (L1d) Describe how to insert an ammeter and a voltmeter into a circuit.

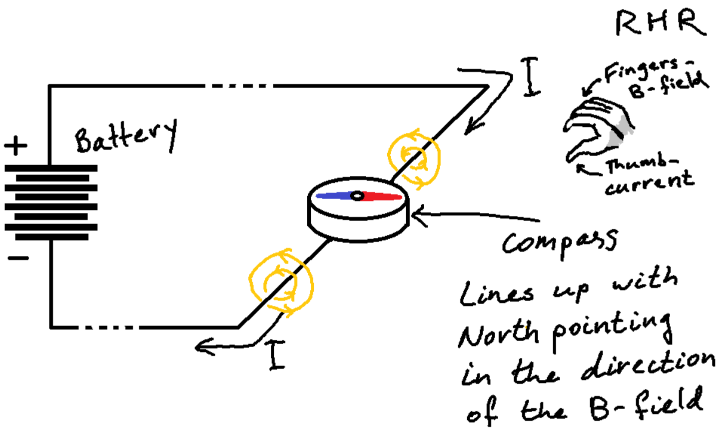
$$I = \frac{\Delta Q}{\Delta t} \qquad V = \frac{\Delta \mathrm{E}}{\Delta Q}$$

Lecture 2: Current and Voltage Measurements

- Measuring current: galvanometer
- Measuring voltage: Comparators
- Current-vs-Voltage plots
- IV characteristics
- Ohm’s Law
- Cylindrical Conductors
- IV-based modeling



Electric current deflects a compass needle



In History…

Hans Christian Oersted’s observation of this effect in 1820 may have surprised him during his lecture demonstration to advanced students. Detailed experiments followed later.

Image in Public Domain

Galvanometer measures current

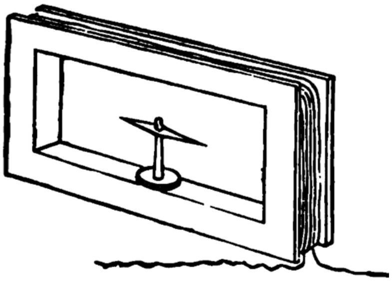
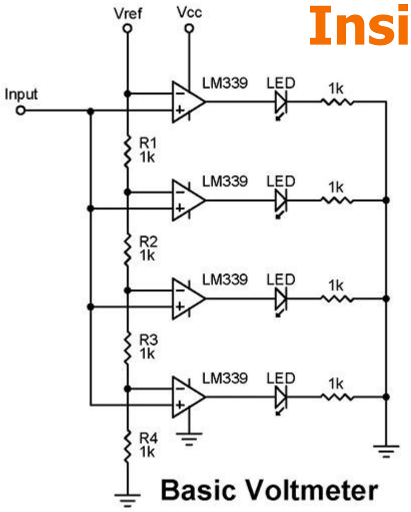


Image from book: Electrical Measurement
and the Galvanometer: Its Construction and Uses,
by T. D. Lockwood, New York: J. H. Bunnell and Co., 1890
Image in Public Domain.

- Each winding in coil adds to magnetic field, B
- B counteracts Earth’s magnetic field
- More current – bigger angle of needle
- More sophisticated galvanometers came later

Inside a Voltmeter

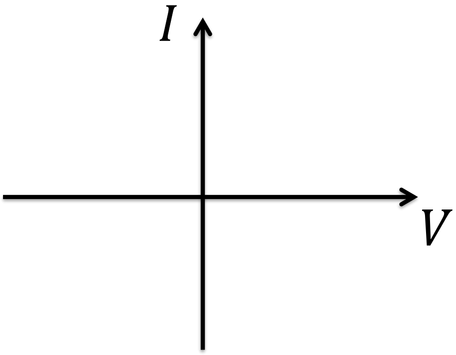


- Compares the input voltage to known voltages.
- Uses “voltage dividers” and “comparators”
- This is stuff we will understand through ECE110!

Image from https://www.nutsvolts.com/questions-and-answers/led-voltmeter

Current vs Voltage Measurements

- Current-vs-Voltage plots
- IV characteristics
- Ohm's Law



Ohm's law models the current and voltage relationship in conductors

Motivated by applications of long-distance telegraphy, Georg Ohm (~1825) conducted careful experimentation to find this widely-used approximate mathematical model:

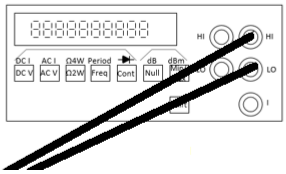
$$I = \frac{V}{R}$$

where $R = \rho \frac{l}{A}$ is resistance of a *conductor* (e.g. wire)

with length, l, and area A, and where ρ is *resistivity* - a material parameter

Resistors also known as Conductors

$$I = \frac{V}{R} \qquad R = \rho \frac{l}{A}$$



Our ohmmeter uses the same connections but different settings than the voltmeter! Polarity doesn't matter for Ohms. Why?

Question: Find the diameter of one mile of Cu ($\rho = 1.7 \times 10^{-8}\ \Omega\, m$) wire when $R = 10\ \Omega$.

A. $1.7\ \mu m$
B. $1.9\ mm$
C. $1\ cm$
D. $19\ cm$
E. $1.7\ m$

Q: If the resistance of one wire is $10\ \Omega$, what is the resistance of two such wires in parallel?

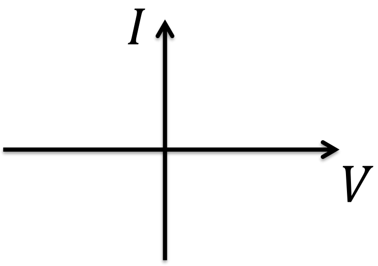
A. $2.5\ \Omega$
B. $5\ \Omega$
C. $10\ \Omega$
D. $20\ \Omega$
E. $40\ \Omega$

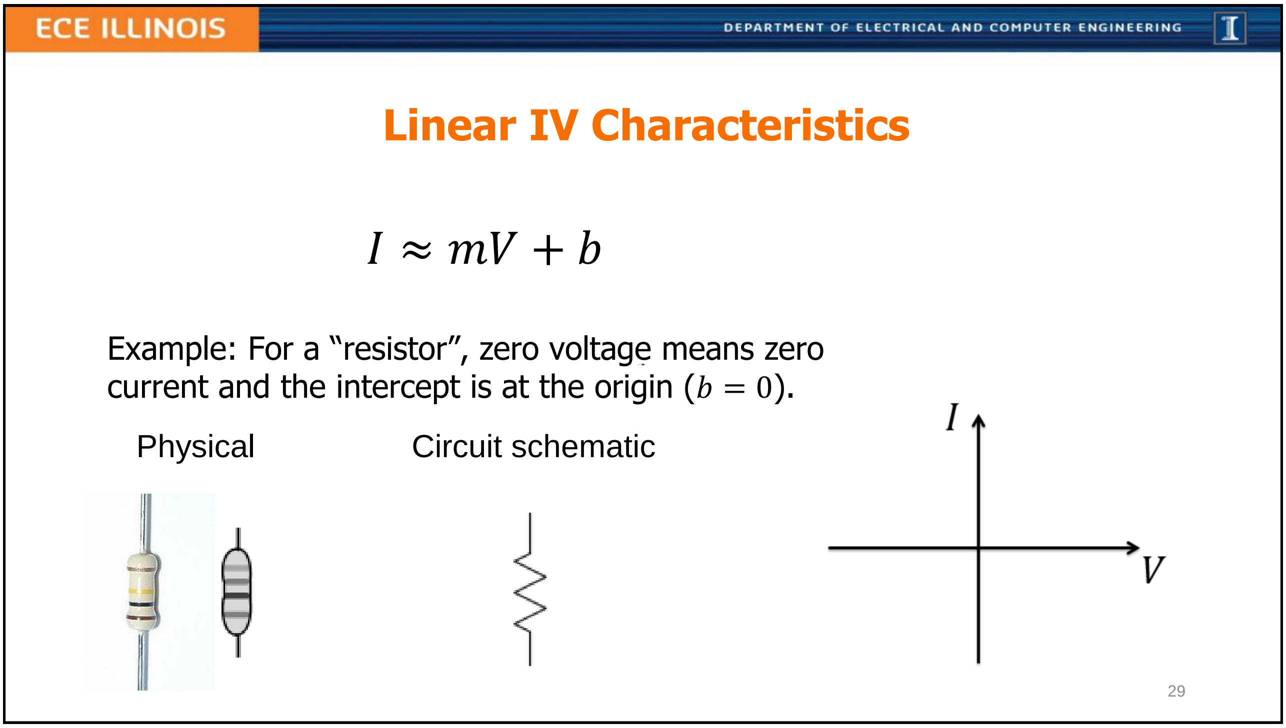
The Relationship between Current and Voltage is very revealing for many devices

Devices composed of voltage sources, current sources, and resistors have "IV" relationships described by a simple line:

$$I \approx mV + b$$

where m is the slope and b is the intercept of this line on the I (current) axis.





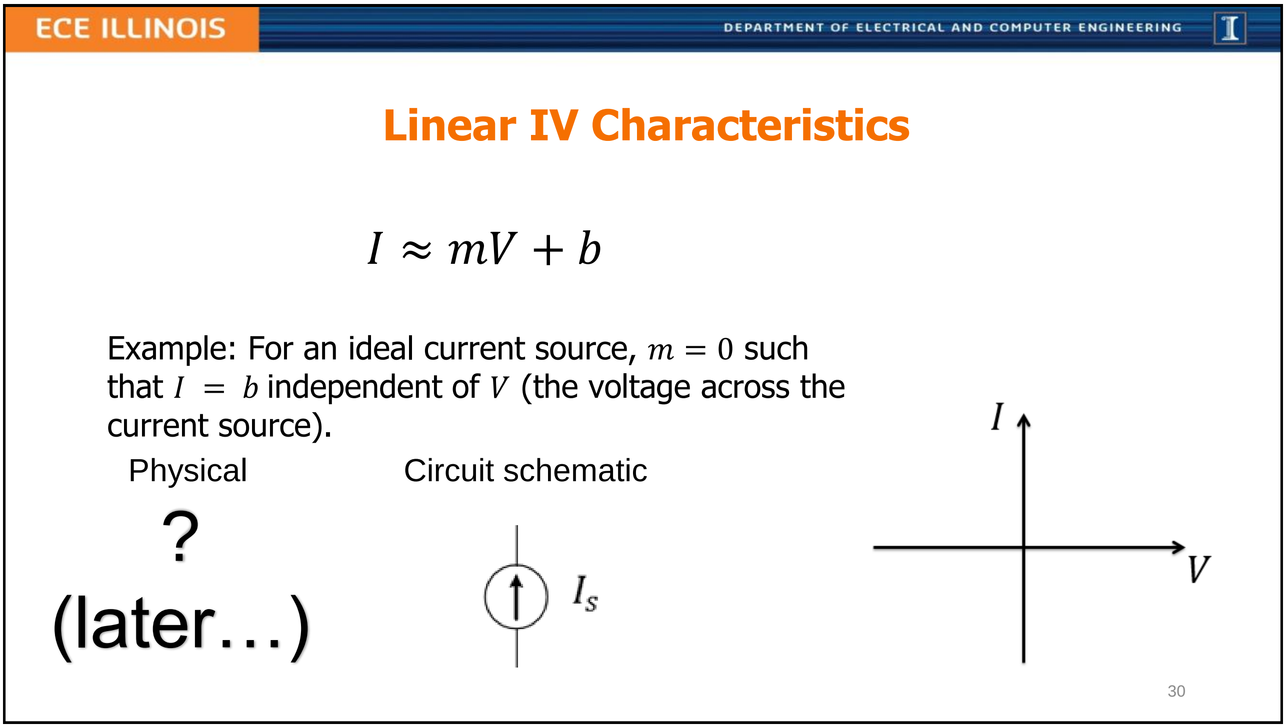
Linear IV Characteristics

$$I \approx mV + b$$

Example: For a "resistor", zero voltage means zero current and the intercept is at the origin ($b = 0$).

Physical

Circuit schematic



Linear IV Characteristics

$$I \approx mV + b$$

Example: For an ideal current source, $m = 0$ such that $I = b$ independent of V (the voltage across the current source).

Physical

?

(later…)

Circuit schematic

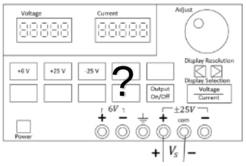
Linear IV Characteristics

$$I \approx mV + b$$

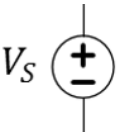
"Banana" cables and "alligator" clips are used to make connections to the sources and meters in the lab.

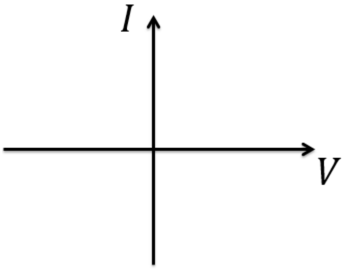
Example: For an ideal voltage source, $V = V_S$ and the current through the source is unconstrained (the limit as $m \to \infty, b \to -\infty$).

Physical



Circuit schematic





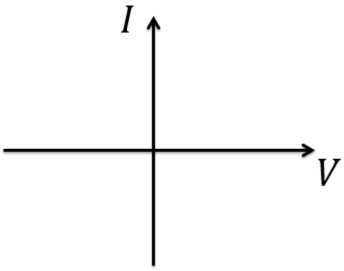
Linear IV Characteristics

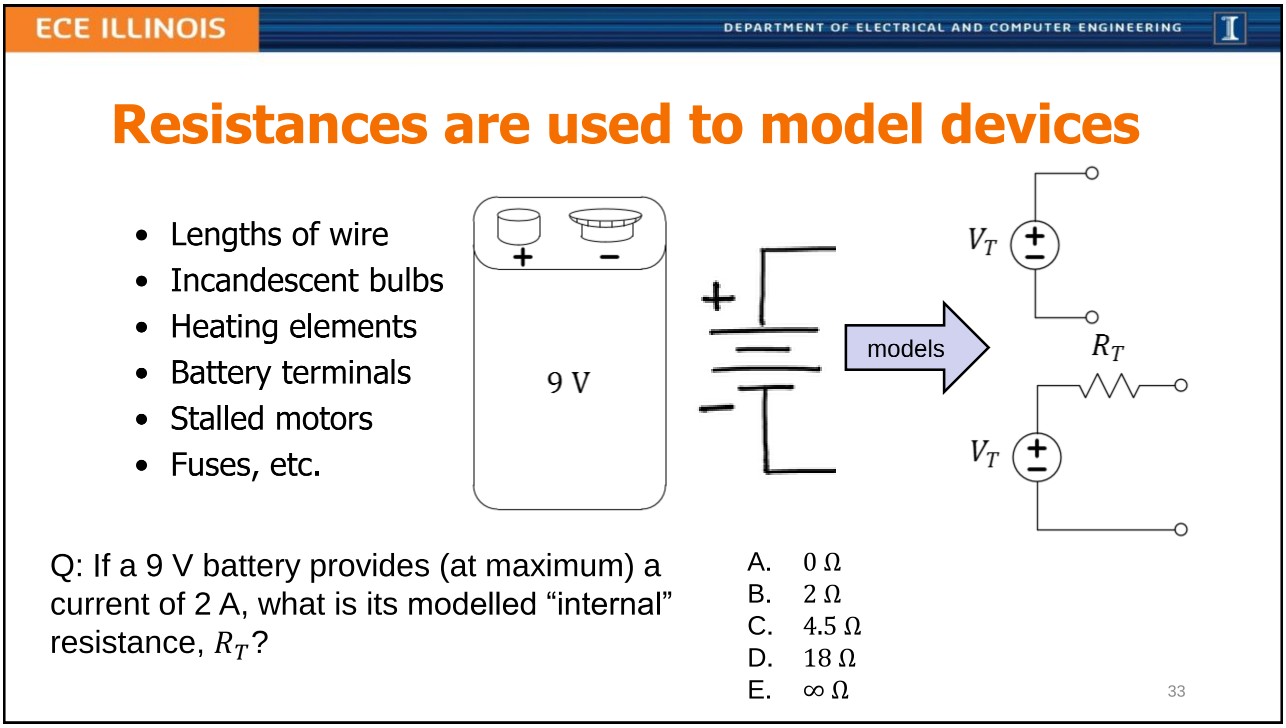
$$I \approx mV + b$$

Example: What happens with a non-ideal voltage source, for example, a battery?

Physical

Circuit schematic



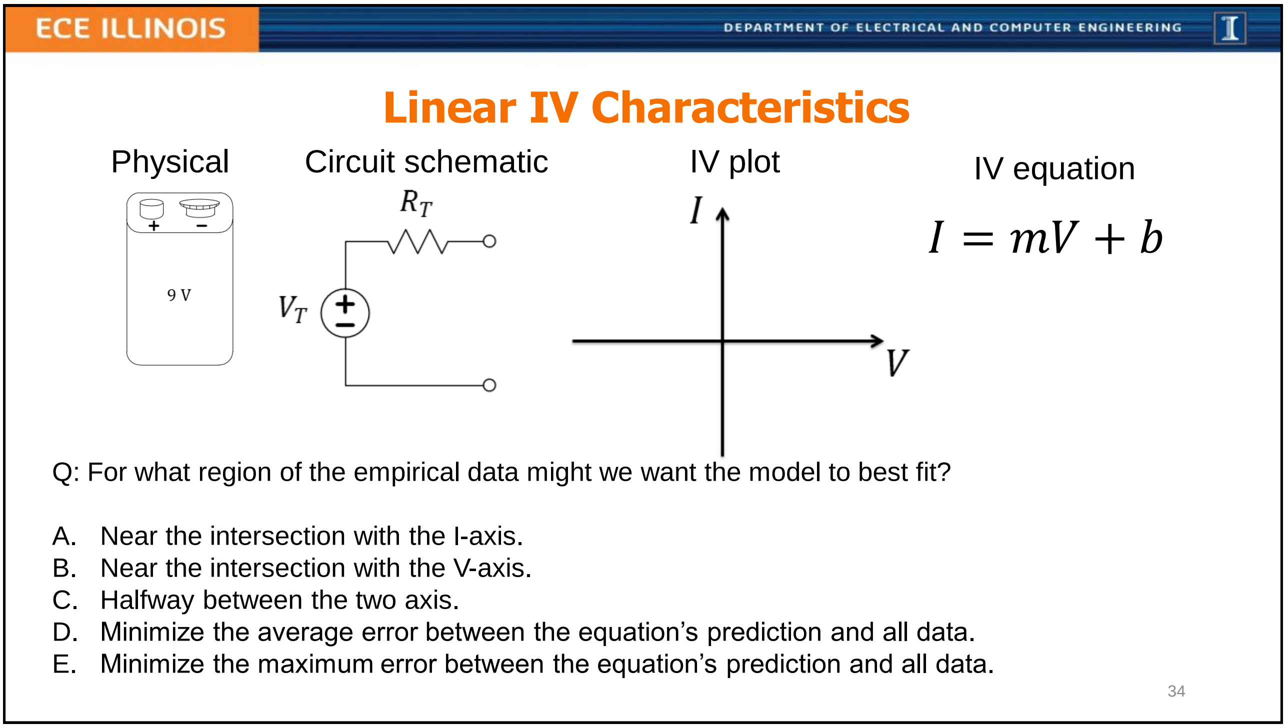


Resistances are used to model devices

- Lengths of wire
- Incandescent bulbs
- Heating elements
- Battery terminals
- Stalled motors
- Fuses, etc.

Q: If a 9 V battery provides (at maximum) a current of 2 A, what is its modelled “internal” resistance, R_T?

A. $0\ \Omega$
B. $2\ \Omega$
C. $4.5\ \Omega$
D. $18\ \Omega$
E. $\infty\ \Omega$



Linear IV Characteristics

Physical

Circuit schematic

IV plot

IV equation

$$I = mV + b$$

Q: For what region of the empirical data might we want the model to best fit?

A. Near the intersection with the I-axis.
B. Near the intersection with the V-axis.
C. Halfway between the two axis.
D. Minimize the average error between the equation’s prediction and all data.
E. Minimize the maximum error between the equation’s prediction and all data.

Feeling Sick? Can’t make class?

Please, don’t risk infecting others.

Lab: Notify your lab TA (not me!) before lab to request an excused absence. Up to two may be granted.

Lecture: Do nothing. Missed lectures will be counted towards your 20% *excused* absences.

Forgot your i>clicker? Do nothing; will be counted towards your 20% excused absences.

L2 Learning Objectives

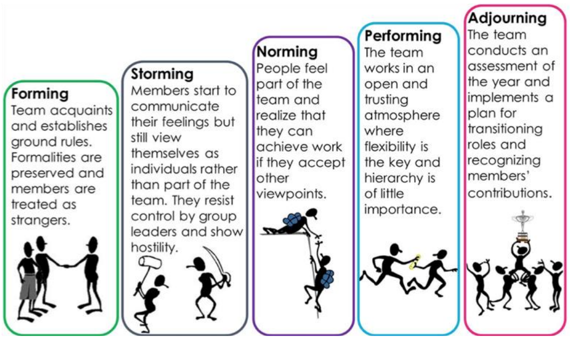
a. Compute resistance of a cylindrical conductor given dimensions.
b. Relate voltage and current for an “Ohmic” conductor.
c. Use Ohm’s Law to model the internal resistance of a physical battery.

Lecture 3: Professional Development; Circuit Models and Schematics

- Professional Development: Teamwork and Growth
- Circuit Modeling and Schematics
- Model and solve very simple (one loop) circuits
- Examples: Broadcast Telegraphy, Decorative Lights

Teamwork

- Contrary to the movies, most engineers do not work in isolation!
- Design teams must be functional to be effective



Forming Team acquaints and establishes ground rules. Formalities are preserved and members are treated as strangers.

Storming Members start to communicate their feelings but still view themselves as individuals rather than part of the team. They resist control by group leaders and show hostility.

Norming People feel part of the team and realize that they can achieve work if they accept other viewpoints.

Performing The team works in an open and trusting atmosphere where flexibility is the key and hierarchy is of little importance.

Adjourning The team conducts an assessment of the year and implements a plan for transitioning roles and recognizing members' contributions.

Tuckman's Theory. (Forming, Storming, Norming, and Performing: The Stages of Team Building, 2015)

image credit: https://culclzha.wordpress.com/2017/10/09/the-challenges-of-managing-a-diverse-team/

CATME is a tool we will use in lab to assist in team formation and feedback to help students learn how to move more quickly to the "performing" stage of the team activities!

IEEE Code of Ethics (2012)

IEEE – Institute of Electrical and Electronics Engineers

We, the members of the IEEE, in recognition of the importance of our technologies in affecting the quality of life throughout the world, and in accepting a personal obligation to our profession, its members and the communities we serve, do hereby commit ourselves to the highest ethical and professional conduct and agree:

IEEE Code of Ethics

1. to accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment;
2. to avoid real or perceived conflicts of interest whenever possible, and to disclose them to affected parties when they do exist;
3. to be honest and realistic in stating claims or estimates based on available data;
4. to reject bribery in all its forms;
5. to improve the understanding of technology, its appropriate application, and potential consequences;

IEEE Code of Ethics

6. to maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations;
7. to seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others;
8. to treat fairly all persons regardless of such factors as race, religion, gender, disability, age, or national origin;
9. to avoid injuring others, their property, reputation, or employment by false or malicious action;
10. to assist colleagues and co-workers in their professional development and to support them in following this code of ethics.

Avoid Dilemmas and Grow Professionally!

Picking Up the Slack…search at Santa Clara University:

http://www.scu.edu/

❖ Often called a "hitch-hiker" scenario…

Q: What do you feel Greg should do?

A. Value the relationship, grade Natalie the same as the group.
B. Greg is not a babysitter…give Natalie the grade she earned.
C. Give Natalie a worse grade than the group, but better than she deserved.
D. Talk to Natalie before deciding which grade to give.
E. Talk to the Instructor before deciding which grade to give.

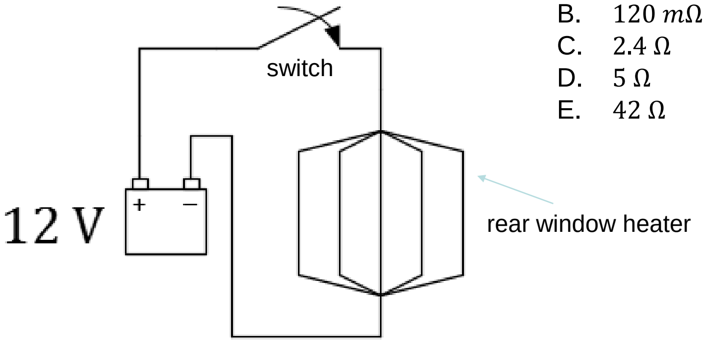
Q: What would you have done differently?

Good Course:
ECE 316
Ethics and Engineering
(also Adv. Composition)

Circuit model for car window defroster

Q: What is the resistance of the car window defroster if it dissipates 60 W? (Consider that the car battery has a max available current of 500 A)

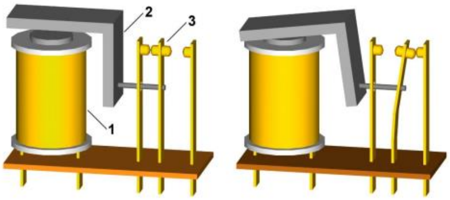
A. $24\ m\Omega$
B. $120\ m\Omega$
C. $2.4\ \Omega$
D. $5\ \Omega$
E. $42\ \Omega$



Q: What percentage of the available battery current is sent to the rear window heater?

A. 1%
B. 10%
C. 50%
D. 75%
E. 95%

A coil with current acts as a magnet

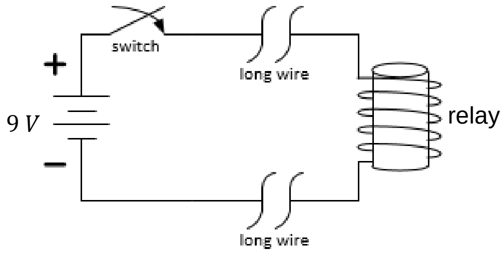


Relay principle: 1. Coil, 2. Armature, 3. Moving contact
Source: Wikimedia Commons

Q: For how long can Energizer 522 (~500 mAh) 9 V battery operate a relay (JQX-15F) which draws 100 mA?

A. About 1.5 hours
B. About 3 hours
C. About 5 hours
D. About 9 hours
E. About 45 hours

Circuit Model For a Telegraph Loop

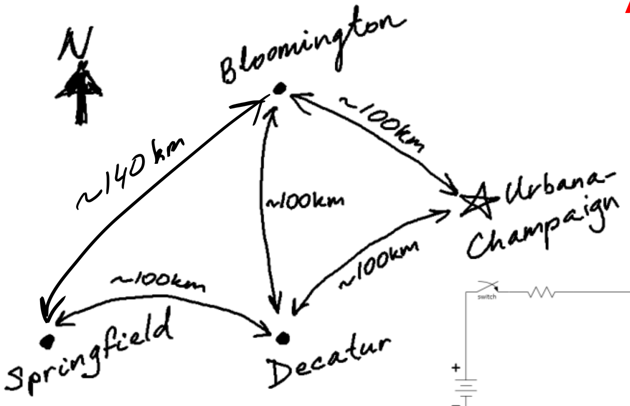


(This wire is sometimes replaced by earth)

Q: If a 9 V battery with 4 Ω contact resistance is used and the relay has 80 Ω and the wire has 10 Ω/mile, what is the maximum telegraph distance which will result in a 50 mA current through the relay circuit loop?

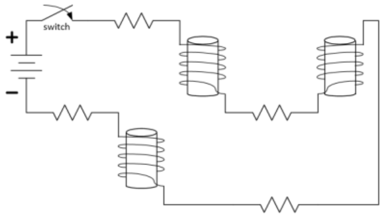
A. 0.5 miles
B. 5 miles
C. 10 miles
D. 100 miles
E. 500 miles

Broadcasting: multiple ways to wire relays

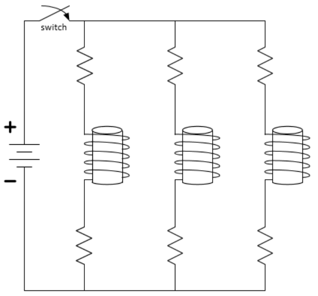


i>clicker Q:
Which method (A, B, or C) is a parallel combination of towns?

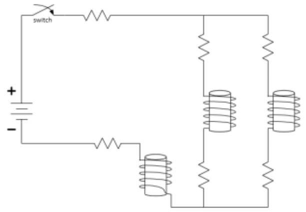
A.



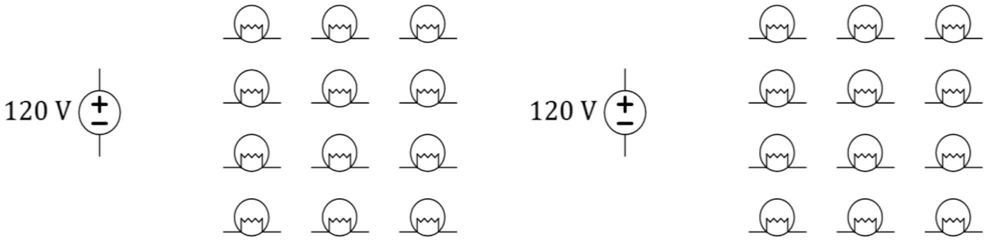
B.



C.



Decorative lights: multiple ways to connect bulbs to the wall power plug

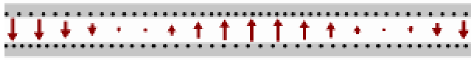


Q: Draw a circuit for 12 lightbulbs connected in *series* in one loop.
Q: Draw a circuit for 12 lightbulbs connected in two *parallel* branches.

L3 Learning Objectives

a. Identify five stages of team building
b. Explain how a code of ethics can aide in professional growth
c. Develop a plan to avoid an ethical dilemma in the laboratory
d. Draw source and resistor circuits to model real-world problems

Explore More!



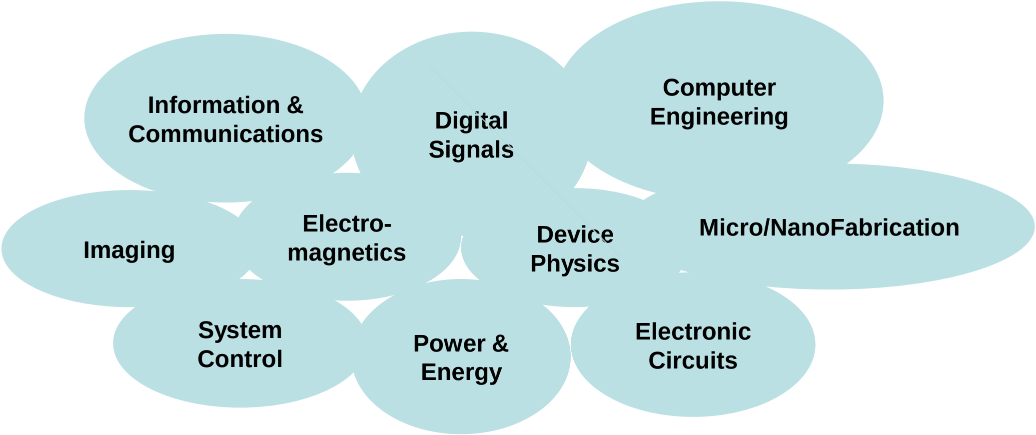
ECE 329 Fields and Waves I
ECE 350 Fields and Waves II

A wave traveling rightward along a lossless transmission line.
Black dots represent electrons, and arrows show the electric field.
Image in Public Domain under CC0
Source: https://en.wikipedia.org/wiki/Transmission_line

Policies

- Lab attendance is **mandatory**, each and every week
- **No food/drink in 1001 ECEB**
- Food and drink **allowed in 1005 ECEB**, only. Since this room is used for office hours, take your book bag with you into the lab.
- Lecture attendance is semi-mandatory…see next slide

Electrical Engineering inseparable focus areas



Lecture 4 : Power and Energy

- Relationship between Voltage and Energy
- Relationship between Power and Energy
- Energy Efficiency

Voltage and Energy

- **Energy** is **the ability to do work**, measured in joules (J), BTUs, calories, kWh, etc.
- **Voltage** is **the work done per unit charge** (eg. J/C) against a static electric field to move charge between two points

$$\boxed{V = \frac{\Delta \mathrm{E}}{\Delta Q}}$$

- Also, 1 volt ($1\ V$) is the electric potential difference between two points that will impart $1\ J$ of energy per coulomb ($1\ C$) of charge that passes through it.

$$\Delta E = \Delta Q\ V$$

Q: A certain battery imparts 480 pJ to every 1 billion electrons. What is its voltage?

A. 1.5 V
B. 3 V
C. 6 V
D. 9 V
E. 12 V

Voltage and Energy

$$E = Q\,V$$

Tesla Model S

Q: What is the charge moved through 400 V (EV battery) to provide 800 kJ of energy?

A. $1\ mC$
B. $1\ C$
C. $1\ kC$
D. $1\ MC$
E. $1\ GC$

Q: What is the average current if the energy in Q4 is provided in five seconds?

A. $1\ \mu A$
B. $4\ mA$
C. $4\ A$
D. $10\ A$
E. $400\ A$

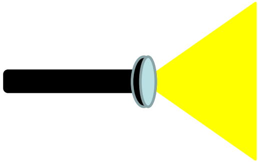
Energy and Power

Power is **the rate at which energy is transferred**.

Power is $(rate\ of\ charge\ flow) \times (potential\ difference)$

Power is $current \times voltage$

$$P = \frac{\Delta E}{\Delta t} = \frac{\Delta Q}{\Delta t}\,V = I\,V$$



Q: A flashlight bulb dissipates $6\ W$ at $2\ A$. What is the supplied voltage?

A. 1.5 V
B. 3 V
C. 6 V
D. 9 V
E. 12 V

Energy in General

- Energy is **ability to do work**
- Energy comes in many forms
- Energy is conserved (can change forms)

Examples: heat, light, electrical energy, chemical, mechanical (e.g. potential, kinetic), mass, etc…

What is “work” ?

- drive to Chicago
- move a couch
- cook an egg
- lift a camel
- launch a satellite
- stay awake in lecture (try!)
- electrocute somebody (don’t!)
- send an email (to Brazil or Urbana?)
- *write down some of your own ideas*

Energy Storage

- Mechanical Energy

  Kinetic Energy Potential Energy

- Electrical Energy Storage

  Capacitors Batteries

- Conservation of Energy

$$E_{input} = E_{useful} + E_{waste}$$

Efficiency

- Distance: 200 km
- Elevation Drop: 44 m
- Where is the waste?

$$E_{input} = Eusef_{ul} + E_{waste} = \eta E_{input} + (1-\eta)E_{input}$$

η is called “efficiency”

$(1-\eta)$ is called “losses”

Explore More!

Elon Musk is in the news much these days as Hyperloop One comes on line. What are some benefits of Hyperloop technology? What are some cons?

Driving to Chicago…accounting

Q: What minimum energy does it take to accelerate a 2200 kg mass (car) from 0 to 60 mph?

A. $8\ mJ$
B. $1\ J$
C. $80\ J$
D. $1\ kJ$
E. $800\ kJ$

Q: What is the energy *input* needed if the engine/drive train losses are 70%?

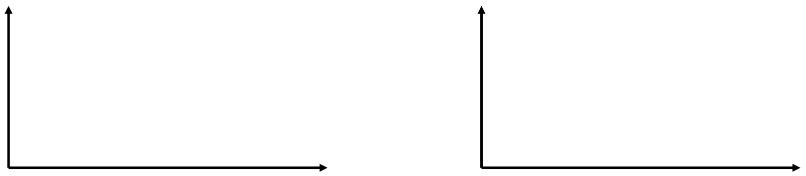
A. $2.6\ mJ$
B. $2.6\ J$
C. $26\ J$
D. $2.6\ kJ$
E. $2.6\ MJ$

Q: A certain gas car gets 50 km/gal (avg). How much energy does it take to get to Chicago?

A. $500\ mJ$
B. $500\ J$
C. $500\ kJ$
D. $500\ MJ$
E. $500\ GJ$

Loading camels: different power; same E!

Definition of power: $P = \frac{\Delta E}{\Delta t}$ is rate of energy…



Loading Camels: What is the average power needed to lift 500 kg by two meters every minute?
Acceleration of Tesla car: What is the power needed to expend 800 kJ in five seconds?

A. $160\ mW$
B. $160\ W$
C. $160\ kW$
D. $160\ MW$
E. $160\ GW$

L4 Learning Objectives

a. Compute power, energy, and time, given two of three
b. Solve energy transfer problems involving mechanical potential and kinetic energy as well as efficiency (or wasted energy) considerations
c. Perform unit conversions for energy, charge, etc
d. Use a power vs. time plot to describe the difference between power and energy

Lecture 5: Circuit Devices in the Lab

- Describe resistors and discuss power limitations of physical resistors
- Describe capacitors and the amount of energy they can store
- Describe batteries and how to compute usage based on their energy rating
- Describe the Transistor and why it is important to us
- Describe the MOSFET and a simple model for it
- Describe an Invertor and a simple model for it

Uses of Resistors

- Current limiting
  - Example: Preventing LED burnout
- Prevent a node from “floating” by either “tying it high” or “tying it low”
  - Example: Using a button for binary input
- Divide a voltage by a known fraction
  - Example: Voltage comparison in a digital voltmeter
- Divide a current by a known fraction
  - Example: Scaling current to the range of a galvanometer in an ammeter
- Tune a circuit’s “time constant”
  - Example: RC filter design

Resistors are devices that obey Ohm's Law

- Resistors always dissipate power; they heat up
- Resistors do not store or deliver (DC) energy
- Using Ohm's Law…

$$P = I\,V = \frac{V^2}{R} = I^2 R$$

In History…

Henry **Cavendish** conducted similar experiments over 40 years earlier than Georg **Ohm** using Leyden jars for voltage sources and the shock felt by his body as an *ad hoc* ammeter!

Image in Public Domain

Resistors

$$P = I\,V = \frac{V^2}{R} = I^2 R$$

Q: What power is dissipated by a 100 Ω resistor when a 6 V drop is measured across it?

A. $360\ mW$
B. $160\ W$
C. $360\ kW$
D. $160\ MW$
E. $360\ GW$

Q: A 100 Ω resistor is rated at 0.25 W. What is its maximum rated current?

A. $50\ mA$
B. $400\ mA$
C. $50\ A$
D. $400\ A$
E. $50\ kA$

Capacitors: store electrical energy

$C = Q/V$ – capacitance is the charge-to-voltage ratio of a capacitor

$$E_{capacitor} = \frac{1}{2}CV^2$$

In History…

The first device for storing electrical energy became known as Leyden Jar after the city in which it was built (1745). It had a capacitance of about $1\ nF$.

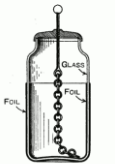


Image in Public Domain

In History…

Yes, **Benjamin Franklin** collected electrostatic charge from a storm using a kite in 1752, but also formulated the *principle of conservation of electric charge* and coined the terms “positive” and “negative” with respect to the charge carriers (current).

Capacitors

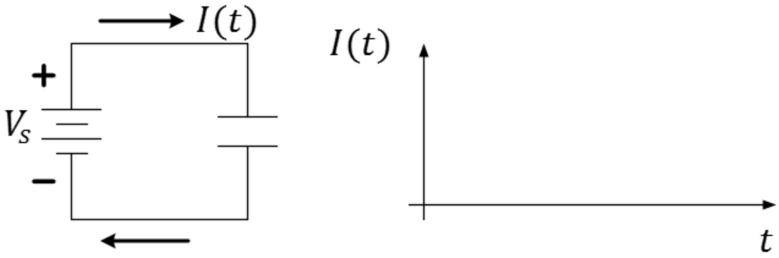
Q: At what voltage would a $1\ nF$ capacitor have the energy to lift $100\ kg$ (a camel, perhaps?) by $2\ cm$?

A. $200\ mV$
B. $250\ mV$
C. $200\ V$
D. $250\ V$
E. $200\ kV$

Example Uses of Capacitors

- Smoothing out voltages
- Separating or combining AC and DC

Efficiency of Charging a Capacitor



- $\Delta E_{battery} = \Delta E_{capacitor} + \Delta E_{waste}$
- $\Delta E_{waste} \geq \frac{1}{2} C V^2$

Physics 212

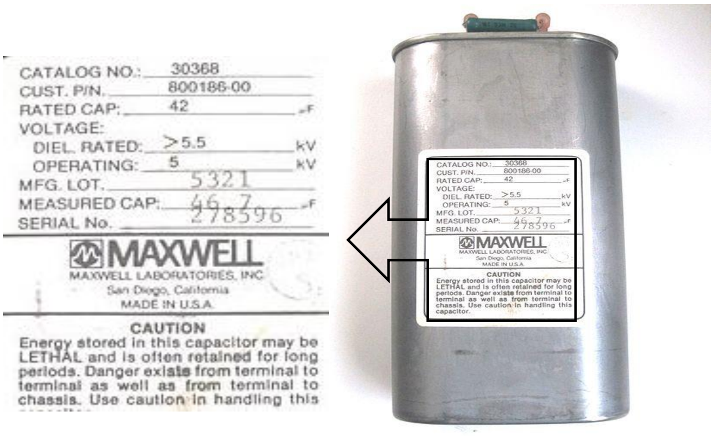
- $\Delta E_{battery} \approx \frac{1}{2} C V^2 + \frac{1}{2} C V^2 = C V^2$

Special Capacitor: Defibrillator

Q: How much energy, E_{cap}, is in the 42 µF defibrillator capacitor charged to 5 kV?

$E_{cap} =$

A. $5.25\ mJ$
B. $5.25\ J$
C. $525\ J$
D. $525\ MJ$
E. $525\ GJ$



CATALOG NO.: 30368
CUST. P/N. 800186-00
RATED CAP: 42 µF
VOLTAGE:
DIEL. RATED: >5.5 kV
OPERATING: 5 kV
MFG. LOT. 5321
MEASURED CAP: 46.7 µF
SERIAL No. 278596

MAXWELL
MAXWELL LABORATORIES, INC
San Diego, California
MADE IN U.S.A.

CAUTION
Energy stored in this capacitor may be LETHAL and is often retained for long periods. Danger exists from terminal to terminal as well as from terminal to chassis. Use caution in handling this

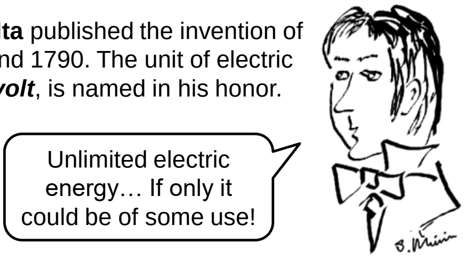
Q: Half of the capacitor's charge, Q, is then drained off. How much energy does it hold now?

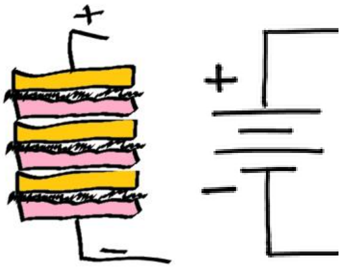
A. $\frac{E_{cap}}{8}$
B. $\frac{E_{cap}}{4}$
C. $\frac{E_{cap}}{2}$
D. E_{cap}
E. $2E_{cap}$

Batteries store and generate electrical energy with a chemical reaction

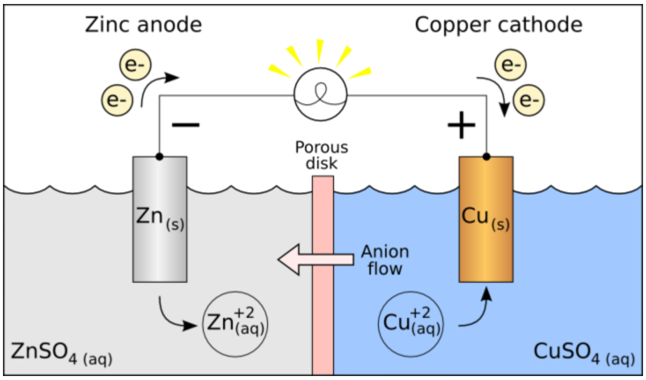
In History…

Alessandro Volta published the invention of the battery around 1790. The unit of electric "pressure", the ***volt***, is named in his honor.





Explore More! on Batteries



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Read more: https://en.wikipedia.org/wiki/Galvanic_cell

Chemistry 102 and 103!

Batteries

Q: How much charge moves through a 9-V battery to provide 3 J of energy?

A. $0.33\ C$
B. $3\ C$
C. $27\ C$
D. $330\ MJ$
E. $27\ kC$

Q: If a battery is labeled at 9 V and 500 mAh, how much energy does it store in joules?

A. $18\ mJ$
B. $56\ mJ$
C. $4.5\ J$
D. $18\ J$
E. $16\ kJ$

Q: For how long can such battery power an LED if that draws 50 mA of current?

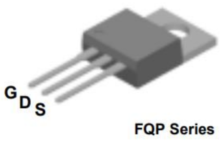
A. $0.1\ hr$
B. $1\ hr$
C. $5\ hr$
D. $10\ hr$
E. $50\ hr$

The Transistor

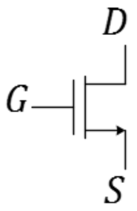
- The transistor changed the world!
- Prior to the transistor, we had the vacuum tube:
  - Large
  - Hot
  - Low efficiency
  - High failure rate
  - Could not be integrated into an IC

The MOSFET (a transistor)

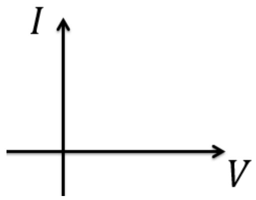
Physical



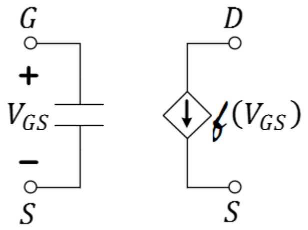
Circuit schematic



IV Plot (for fixed V_{GS})



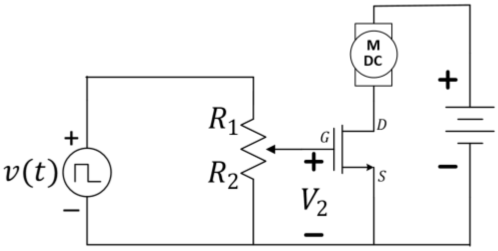
Linear Model



Interpretation: Terminals D and S may be considered to contain a current source whose current is controlled by V_{GS}. The controlling side is generally much lower power than the current source side making the controller easier to design and lower cost.

The MOSFET In Practice

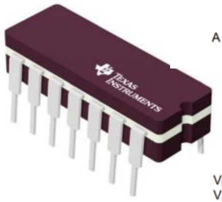
In lab, we will use the MOSFET as an efficient method of motor control…

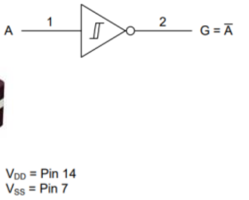


The (Logical) Inverter

The invertor is a *powered* IC, meaning that it will need something like a battery to make it work. In the circuit schematic, it is assumed that the voltage at input A and the output G are measured relative to the negative side of the battery, referenced as “ground” in the Linear Model.

Physical Circuit schematic IV Plot (for output G) Linear Model (for G)





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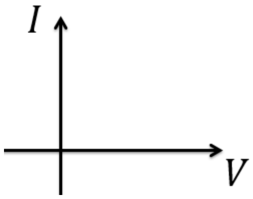
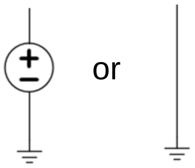
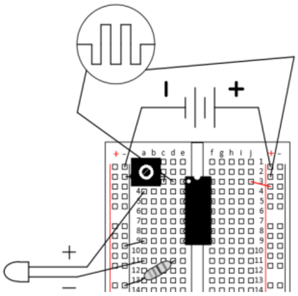


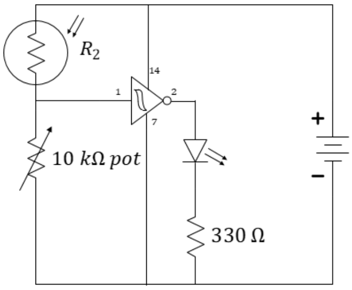


Interpretation: The output, G, of the invertor will look like either a voltage source (when the input voltage at A is low or a wire (short to ground) when the input voltage is close to the supplied battery voltage.

The Invertor in Practice

In lab, we use an inverter as the power source to drive an LED as ambient light is blocked from a photoresistor (by a hand or a cloud). The invertor, itself, gets power from a battery attached between pins 7 and 14. The inverter *buffers* the control circuit from the LED which the light-detection circuit is unable to power directly.





L5 Learning Objectives

a. Compute current/voltage rating for a resistor based on its power rating
b. For a capacitor, compute stored energy, voltage, charge, and capacitance given any of the two quantities.
c. Compute energy stored in a battery and discharge time.
d. Identify features of the Transistor that make it an improvement over vacuum tubes
e. Describe the MOSFET and a simple model for it
f. Describe an Invertor and a simple model for it

Lecture 6: Kirchhoff's Laws in Circuits

- Kirchhoff’s Current Law (KCL) – Conservation of Charge
- Kirchhoff’s Voltage Law (KVL) – Conservation of Energy
- Solving Circuits with KCL, KVL, and Ohm’s Law
- Power Conservation in Circuits

Kirchhoff’s Current Law

Current in = Current out

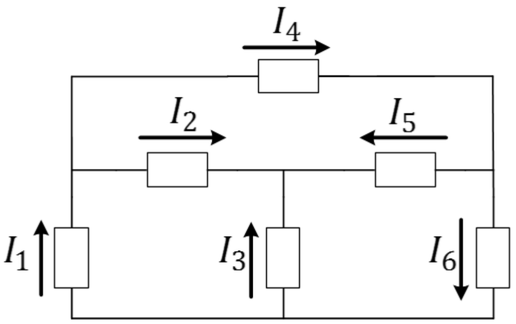
Conservation of charge!

(What goes in must come out, or…
…the total coming in is zero)

Image source: MONGABAY.COM

$$Through\ a\ closed\ surface\ (balloon),\ \sum_{k=1}^{N} I_k = 0\ where\ I_k\ are\ the\ currents\ flowing\ in\ (alt. out)\ of\ the\ balloon.$$

KCL equations are often used at *nodes*, but can also be used for a *sub-circuit*



Q: Which of the equations is NOT a correct application of KCL?

A. $I_1 = I_2 + I_4$
B. $I_4 = I_5 + I_6$
C. $I_1 + I_3 = I_6$
D. $I_3 + I_5 = I_2$
E. $I_6 - I_4 = I_3 + I_2$

Kirchhoff's Voltage Law

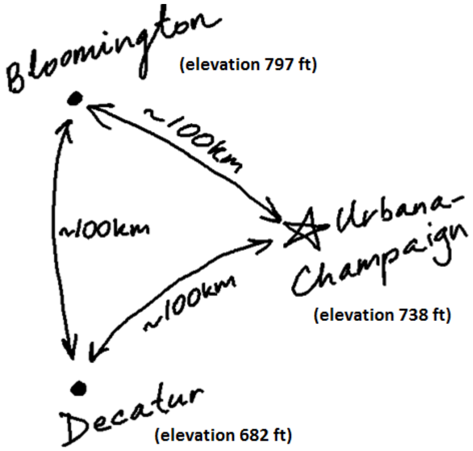
The sum of all voltages around any closed path (loop) in a circuit equals zero

Conservation of Energy!

With voltage, what goes up, must come down

$$\mathit{Around\ a\ closed\ loop\ (path)} \sum_{k=1}^{M} V_k = 0 \ \ \mathit{where}\ V_k\ \mathit{are\ the\ voltages\ measured}\ CW (alt. CCW)\ \mathit{in\ the\ loop.}$$

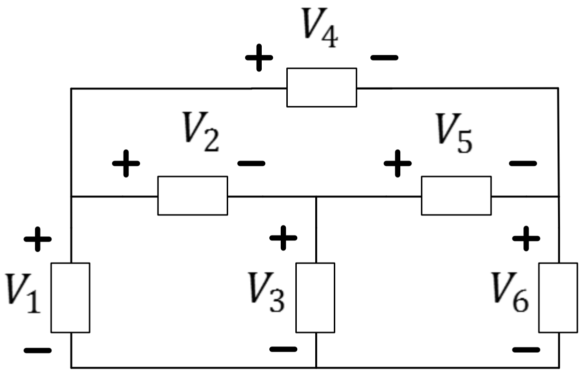
KVL and Elevation Analogy



Free Picture: Stairs To The Sky ID: 191634
© Jennifer Harvey | Dreamstime Stock Photos

One can add up elevation changes as we go in a loop from city to city.
The result should be zero, independent of the path taken.

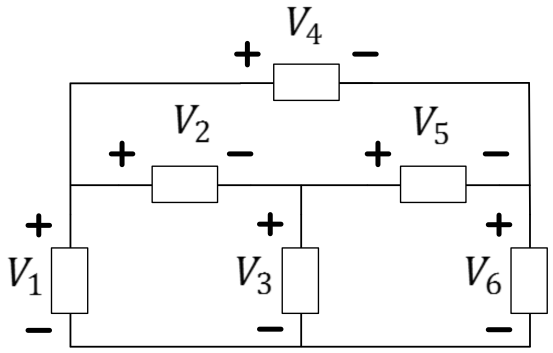
Keeping track of voltage drop *polarity* is important in writing correct KVL equations.



Q: Which of the equations is NOT a correct application of KVL?

A. $V_1 - V_2 - V_3 = 0$
B. $V_1 = V_2 + V_5 + V_6$
C. $V_1 - V_4 = V_6$
D. $V_3 + V_2 = V_1$
E. $V_3 + V_5 = V_6$

Missing voltages can be obtained using KVL.



In History…

The conceptual theories of electricity held by **Georg Ohm** were generalized in **Gustav Kirchhoff**'s laws (1845). Later, **James Clerk Maxwell**'s equations (1861) generalized the work done by Kirchhoff, Ampere, Faraday, and others.

ECE 329 Fields and Waves I

Explore More!

$$\oiint_{\partial\Omega} \mathbf{E}\cdot d\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_\Omega \rho\, dV$$

$$\oiint_{\partial\Omega} \mathbf{B}\cdot d\mathbf{S} = 0$$

$$\oint_{\partial\Sigma} \mathbf{E}\cdot d\boldsymbol{\ell} = -\frac{d}{dt}\iint_\Sigma \mathbf{B}\cdot d\mathbf{S}$$

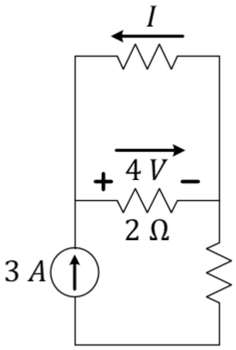
$$\oint_{\partial\Sigma} \mathbf{B}\cdot d\boldsymbol{\ell} = \mu_0\iint_\Sigma \mathbf{J}\cdot d\mathbf{S} + \mu_0\varepsilon_0\frac{d}{dt}\iint_\Sigma \mathbf{E}\cdot d\mathbf{S}$$

Maxwell's equations in Integral Form
Image Credit: Wikipedia.org

Q: What are the values of the voltages V_1, V_2 and V_6 if $V_3 = 2\ V, V_4 = 6\ V, V_5 = 1\ V$?

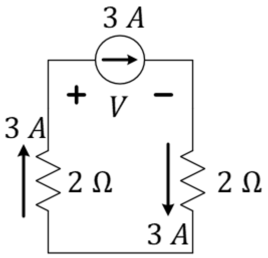
Examples

Q: Find the value of I.



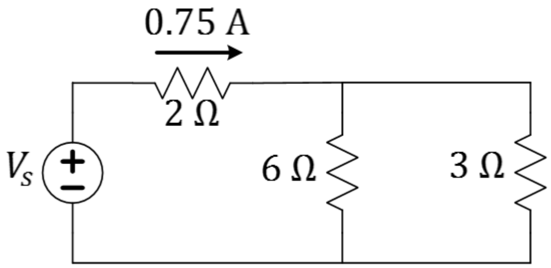
A. $-3\ A$
B. $-2\ A$
C. $-1\ A$
D. $1\ A$
E. $2\ A$

Q: Find the value of V.



A. $-12\ V$
B. $-6\ V$
C. $-3\ V$
D. $6\ V$
E. $12\ V$

Circuits solved with Ohm’s + KCL + KVL



Q: What is the value of the source voltage?

Q: How much power is the source supplying?

Q: How much power is each resistance consuming?

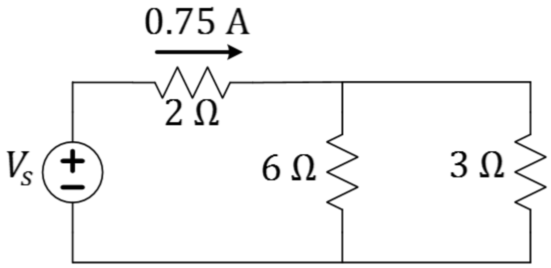
L6 Learning Objectives

a. Identify and label circuit nodes; identify circuit loops
b. Write node equation for currents based on KCL
c. Write loop equations for voltages based on KVL
d. Solve simple circuits with KCL, KVL, and Ohm’s Law
e. Calculate power in circuit elements, verify conservation

Lecture 7: Application of KVL, KCL, Ohm’s

- Example Problems and Practice

Circuits solved with Ohm’s + KCL + KVL



Q: What is the value of the source voltage?

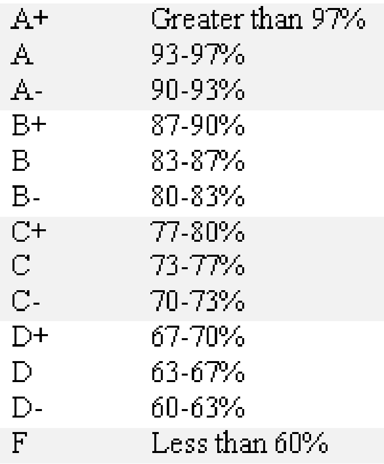
Q: How much power is the source supplying?

Q: How much power is each resistance consuming?

Circuits solved with Ohm's + KCL + KVL

- Instructor's Choice!

Grading policies



A+	Greater than 97%
A	93-97%
A-	90-93%
B+	87-90%
B	83-87%
B-	80-83%
C+	77-80%
C	73-77%
C-	70-73%
D+	67-70%
D	63-67%
D-	60-63%
F	Less than 60%

Laboratory	**30%** [1]
Lecture Total	**70%** [1]
3 midterms	30%
Final Exam	25% [2]
Homework	10%
Attendance	5 %

[1] You must obtain 50% of the lecture score and 50% of the lab score to avoid failing the course!

[2] The Final Exam can have an effective weight of 35% by replacing the lowest midterm grade.

Seeking advice and help?

- **Talk to us!** Instructors, graduate TAs, undergrad course aides want to know you!
- **CARE:** the *Center for Academic Resources in Engineering* provides study periods and tutoring options in many STEM courses.
- ***ECE Advising Office*** (2120 ECEB) provides all kinds of advice. They can also recommend others:
  - **U of I *Counseling Center*** for time management, study skill, test-taking skills, and confidential personal counseling. Plus, Dr. Ken at Engineering Hall!
  - **DRES**: the Disability Resources & Educational Services center for aid in overcoming unique challenges that you may encounter through your education

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Learning Objectives

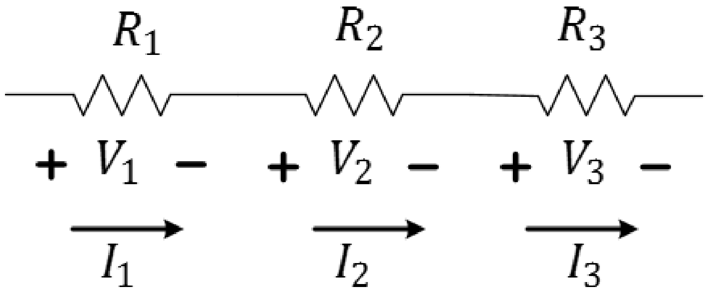
- Example Problems and Practice
- Series and Parallel resistance
- Equivalent Resistance
- More Problems and Practice

Lecture 8: Circuit Tools

- Equivalent Resistance Defined
- Voltage Divider
- Current Divider
- Power Dissipation in Series and Parallel Resistive Loads
- Example Problems and Practice

Series Connection

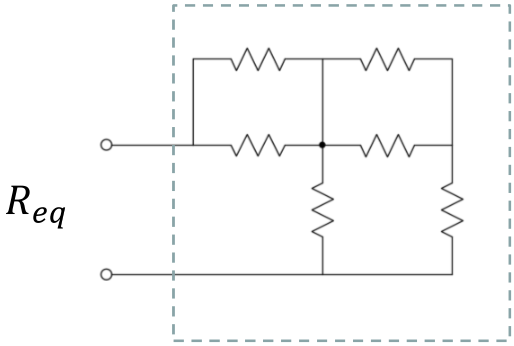
Series connections share the same current



$I_1 = I_2 = I_3$ because of KCL

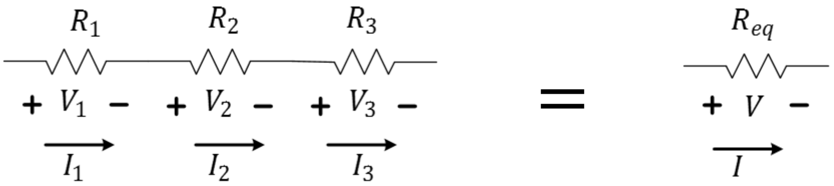
Equivalent Resistance

Equivalent Resistance is the resistance value you get when you place an entire resistive network into a (virtual) box and characterize it as an Ohmic device (a new resistor).



Equivalent Resistance of Series Resistors

Resistances in series add up



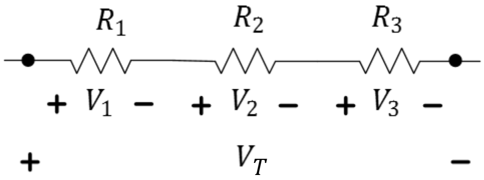
$$R_{eq} = R_1 + R_2 + \cdots + R_N$$

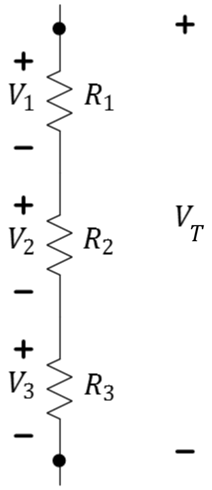
This can be intuitive: think of telegraphy wires in series.

Voltage Divider Rule (VDR)

When a voltage divides across resistors in series, more voltage drop appears across the largest resistor.

$$V_k = \frac{R_k}{R_{eq}} \cdot V_T$$

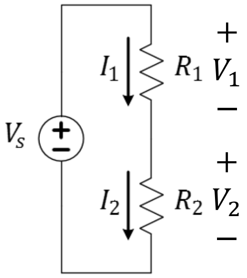




Q: Can V_1 be a larger value than V_T?

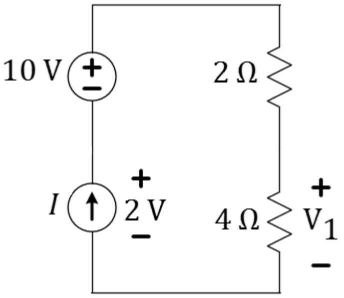
A. Yes
B. No
C. Not sure

Q: If $R_1 < R_2$, which of the following is true?



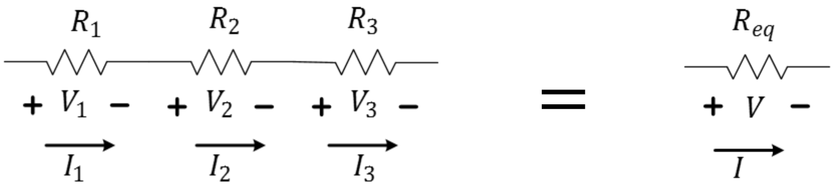
A. $V_1 < V_2$ and $I_1 < I_2$
B. $V_1 < V_2$ and $I_1 = I_2$
C. $V_1 = V_2$ and $I_1 = I_2$
D. $V_1 > V_2$ and $I_1 = I_2$
E. $V_1 > V_2$ and $I_1 > I_2$

Q: Use VDR to find V_1.



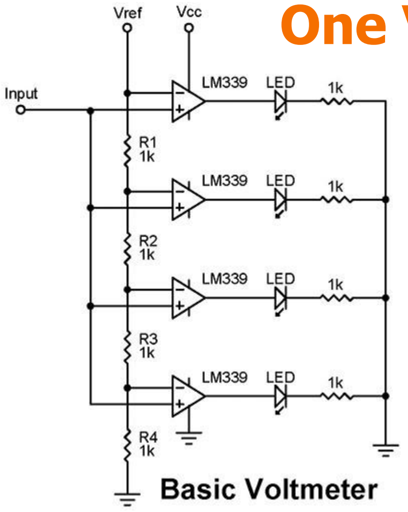
A. $V_1 \leq -6\,V$
B. $-6 < V_1 \leq -2\,V$
C. $-2 < V_1 \leq 2\,V$
D. $2 < V_1 \leq 6\,V$
E. $6\,V < V_1$

VDR Derivation



Since $I = I_k$, $\frac{V}{R_{eq}} = \frac{V_k}{R_k}$ by Ohm's Law. So, $V_k = \frac{R_k}{R_{eq}} \cdot V$

One VDR Application

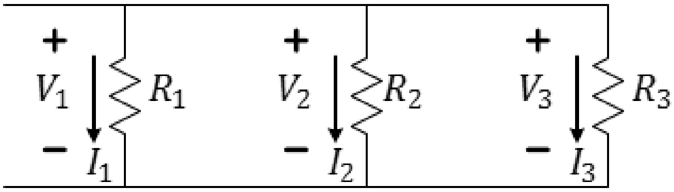


Basic Voltmeter

Image from https://www.nutsvolts.com/questions-and-answers/led-voltmeter

Parallel Connection

Parallel connections share the same voltage potentials at two end nodes (shared by the elements)

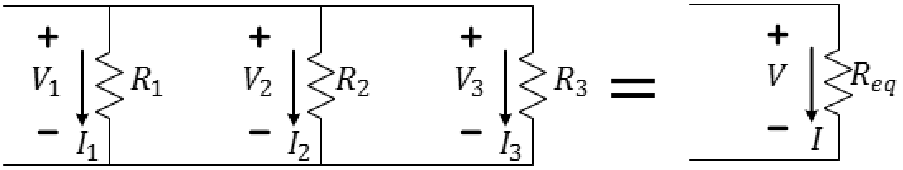


$$V_1 = V_2 = V_3 \text{ because of KVL}$$

A. B.

Q: Are appliances in your house/apartment connected in series or in parallel?

Equivalent Resistance of Parallel Resistors



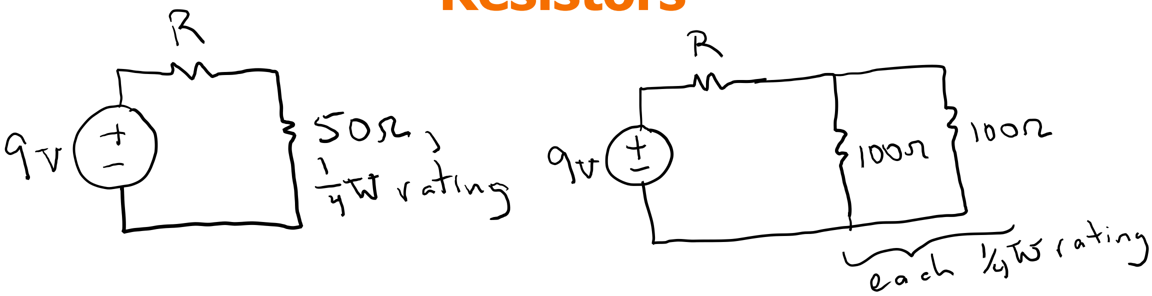
$$\boxed{\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_N}}$$

If $N = 2$, $R_{eq} = \frac{R_1 R_2}{R_1 + R_2}$

Q: Which statement is true in general?

A. $R_{eq} \approx R_1$
B. $R_{eq} < R_1$
C. $R_{eq} > R_1$
D. None of these is true

Resistors



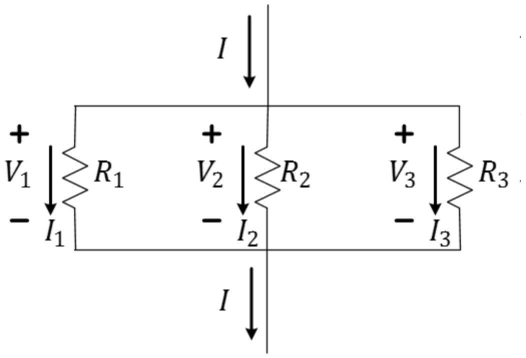
Q: Which statement is true regarding a single 50-Ohm resistor and two 100-Ohm resistors used as shown above in the same circuit?

A. The 100-Ohm parallel combination has twice the power rating.
B. The 100-Ohm parallel combination has a resistance of 200 Ohms.
C. The 100-Ohm parallel combination has twice the probability of failure.
D. None of these are true.
E. All of these are true.

Current Divider Rule (CDR)

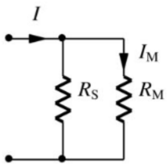
When a current divides into two or more paths, a greater amount of current will go down the path of lower resistance.

$$I_k = \frac{R_{eq}}{R_k} \cdot I$$



One CDR Application

- High-current Ammeter
- Use a high-power shunt resistance R_S to carry most of the current
- Measure the current through R_M (the meter resistor) using a galvanometer.

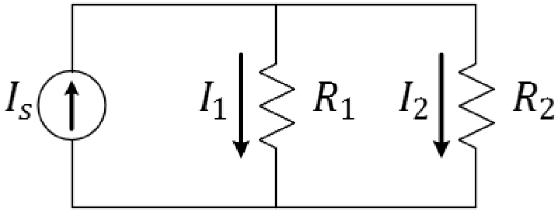


Q: Which is true in this application?

A. $R_S \ll R_M$
B. $R_S \gg R_M$
C. $R_S \approx R_M$

Q: Give the formula for I (the current we want measured) in terms of I_M (the current we did measure).

Q: If $R_1 < R_2$, which of the following is true?

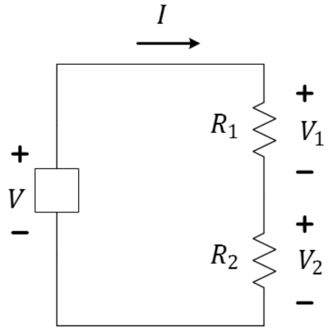


A. $I_1 < I_2 < I_s$
B. $I_1 < I_s < I_2$
C. $I_2 < I_1 < I_s$
D. $I_2 < I_s < I_1$
E. $I_s < I_2 < I_1$

A. B.

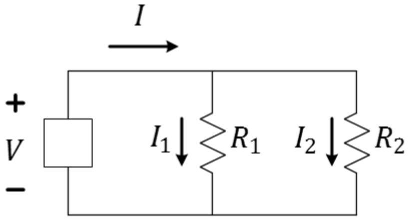
Q: In a parallel connection, does a smaller or larger resistor absorb more power?

VDR and CDR for Two Resistances



$$V_1 = \frac{R_1}{R_1 + R_2} V$$

$$V_2 = \frac{R_2}{R_1 + R_2} V$$



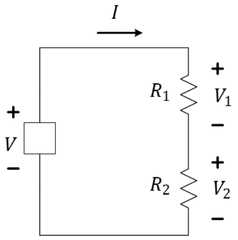
$$I_1 = \frac{R_2}{R_1 + R_2} I \qquad I_2 = \frac{R_1}{R_1 + R_2} I$$

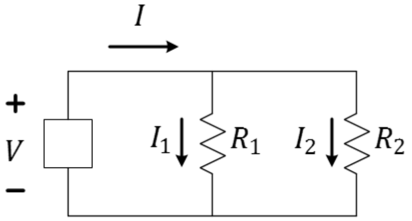
Bad Idea: try to memorize these formulae.
Good Idea: try to note trends and understand concepts !

Example, if $R_1 = 1\ \Omega$ and $R_2 = 2\Omega$, then $V_2 : V_1$ will be in a $2:1$ ratio for the series circuit.
If $R_1 = 1\ \Omega$ and $R_2 = 2\Omega$, then $I_2 : I_1$ will be in a $1:2$ ratio for the series circuit.

Why?

VDR and CDR for Two Resistances

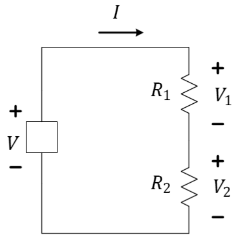


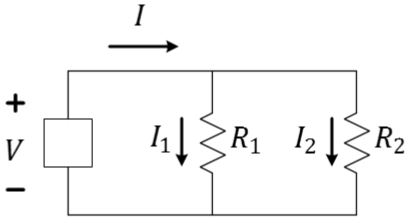


Q: If 6V falls across a series combination of 1kΩ and 2kΩ, what is V across 2kΩ?

Q: If 0.15A flows through a parallel combo of 1kΩ and 2kΩ, what is I through 2kΩ?

VDR and CDR for Two Resistances





Q: If a source supplies 60W to a series combination of 10Ω and 30Ω, what is the power absorbed by the 10Ω resistor? What power is absorbed by the 30Ω resistor?

Q: If a source supplies 300mW to a parallel combination of 3kΩ and 2kΩ, what is the power absorbed by the 3kΩ resistor? What power is absorbed by the 2kΩ resistor?

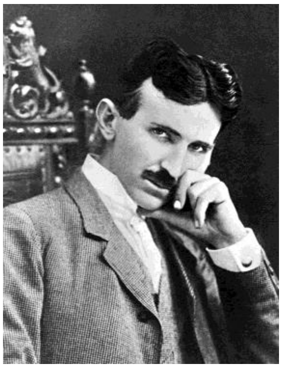
L8 Learning objectives

a. Identify series and parallel connections within a circuit network
b. Compute power ratings of resistor networks
c. Find equivalent resistance of circuit networks
d. Estimate resistance by considering the dominant elements
e. Apply rules for current and voltage division to these networks
f. Apply conservation of energy to components within a circuit network

Lecture 9: AC and Time-average Power

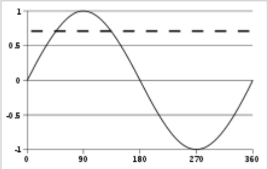
- AC and DC
- Time-average Powre
- Root-Means-Square (RMS) Voltage
- The Meaning of Current and Voltage Sources
- Labeling of Current and Voltage and Sign of Power

Alternating vs. Direct Current

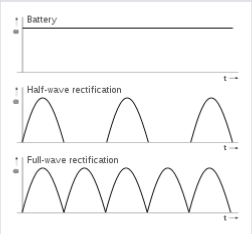


Nikola Tesla

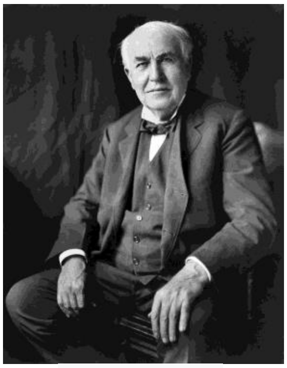
AC/DC



A sine wave, over one cycle (360°). The dashed line represents the root mean square (RMS) value at about 0.707



Types of direct current



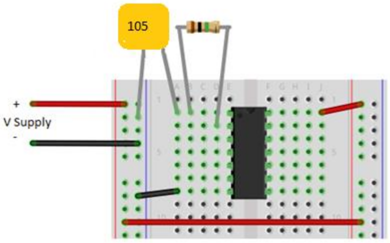
Thomas A Edison

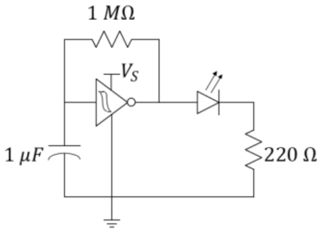
Have you ever heard of the “Current Wars”?

A. Yes
B. No

In Practice: Time-varying signals

In lab, we use the output of the invertor to change the input in a feedback loop. A "high" output drives the input high and a low input drives the input low. The invertor's function causes "oscillation" to occur and the LED to flash. Note how the capacitor allows for changing input voltage.





Power

For time-varying signals, power is a time-varying signal.

$$p(t) = i(t)v(t)$$

The time-average power is often of interest. Time average is computed by the equation

$$P_{avg} = \frac{\int_{-\infty}^{\infty} p(t)dt}{\int_{-\infty}^{\infty} dt}$$

Power

$$P_{avg} = \frac{\int_{-\infty}^{\infty} p(t)dt}{\int_{-\infty}^{\infty} dt}$$

- If v(t) and i(t) are periodic, then $p(t)$ is periodic with period T

$$P_{avg} = \frac{\int_T p(t)dt}{T} = area\ under\ p(t)\ divided\ by\ T = Energy\ in\ one\ period\ divided\ by\ T$$

- If v(t) and i(t) are constant (DC), then $p(t)$ is constant

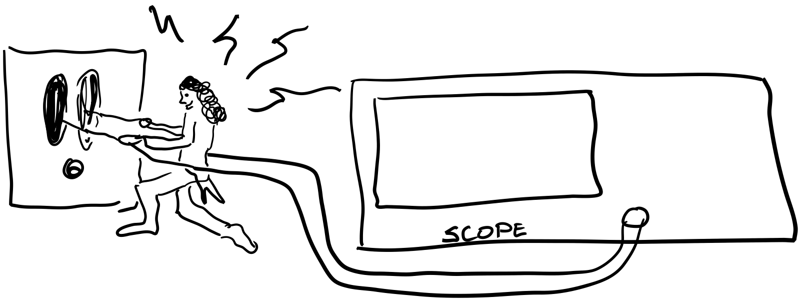
$$P_{avg} \equiv P = IV$$

For non-periodic signals (e.g. constant white noise)

$$P_{avg} \approx \frac{\int_T p(t)dt}{T}$$

Where T is a sufficiently-long observation time

Voltage from the wall plug is *sinusoidal*



Q: What is the peak instantaneous power absorbed by a 250Ω light bulb?

A. 1 W
B. 10 W
C. 100 W
D. 1 kW
E. 10 kW

In History…

In the 1880's and 1890's, **Nikola Tesla** played a large role in improving DC motors, developing AC motors and generators, and developing many high-frequency/high-voltage experiments including many in the area of remote control and wireless telephony. **Marconi**'s 1901 cross-Atlantic wireless transmission likely infringed upon a few of Tesla's nearly 300 patents.

Time Average Power: What's RMS??

$$\begin{aligned} P_{avg} &= \frac{\int_{-\infty}^{\infty} p(t)dt}{\int_{-\infty}^{\infty} dt} \\ &= \frac{\int_{-\infty}^{\infty} v(t)i(t)dt}{\int_{-\infty}^{\infty} dt} \\ &= \frac{\int_{-\infty}^{\infty} \frac{v^2(t)}{R} dt}{\int_{-\infty}^{\infty} dt} \quad \text{(for a resistor)} \\ &= \frac{1}{R}\frac{\int_{-\infty}^{\infty} v^2(t)dt}{\int_{-\infty}^{\infty} dt} \\ &= \frac{1}{R}\, avg\{v^2(t)\} \end{aligned}$$

Define $V_{rms} \overset{\text{def}}{=} \sqrt{\frac{\int_{-\infty}^{\infty} v^2(t)dt}{\int_{-\infty}^{\infty} dt}}$ so that $P_{avg} = \frac{V_{rms}^2}{R}$ (for a resistor)

Important Comment: RMS voltage helps us find time-averaged power. We don't want RMS power…what does that even mean??

Important Comment #2: for things that are not resistors, we may need to look at $p(t)$ directly as V_{rms} doesn't tell the whole story.

Important Comment #3: You can use both V_{rms}, I_{rms}, and something called a power factor in more-advanced circuit courses.

Root-Mean-Square averages

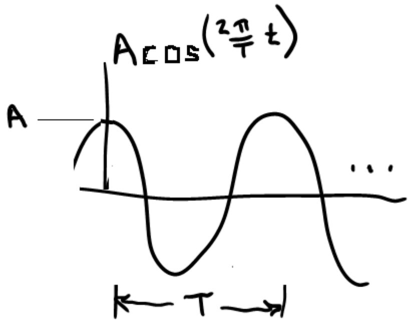
RMS is meaningful when interested in power production/dissipation in AC.

$$V_{RMS} = \sqrt{Average[v^2(t)]}$$

1. Sketch $v^2(t)$
2. Compute $Average[v^2(t)]$
3. Take $\sqrt{}$ of the value found in part 2.

Calculating P_{avg} and V_{rms}

$Trig\ identity: \cos(A)\cos(B) = \frac{1}{2}[\cos(A-B) + \cos(A+B)]$

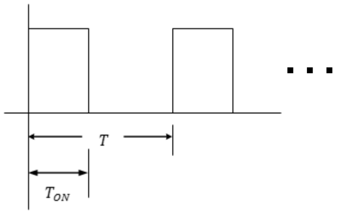


USA “Mains voltage”

Q: What is the average power absorbed by a 250Ω light bulb if A = 170V?

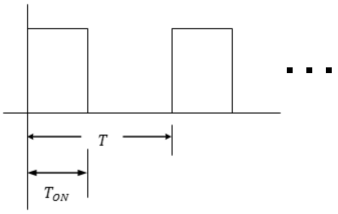
Calculating P_{avg} and V_{rms}

$Duty\ Cycle\ Definition: \quad \frac{T_{ON}}{T}$



Q: What happens to power and V_{rms} when T_{ON} is halved while T is unchanged?

Calculating P_{avg} and V_{rms}



Q: Why isn't the RMS voltage of the signal above generally equal to $V_{rms}/\sqrt{2}$?

L9 Learning Objectives

a. Compute the time-average power from $p(t)$ plots
b. Compute the rms voltage from $v(t)$ plots
c. Explain the meaning of V_{rms} and relationship to P_{avg}

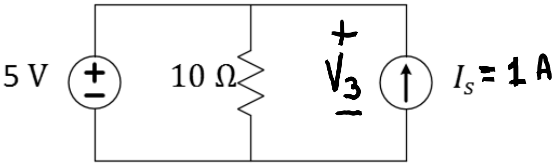
Lecture 10: Signed Power and Design

- Exercises under constraints on components

Which of the sources are delivering power?

A. The voltage source only
B. The current source only
C. Both
D. Neither
E. Not enough information to tell

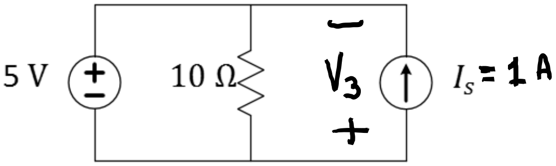
Polarity labels for Kirchhoff are Arbitrary



Q: Find the value of V_3.

Q: Find the power, P_3.

Polarity labels for Kirchhoff are Arbitrary

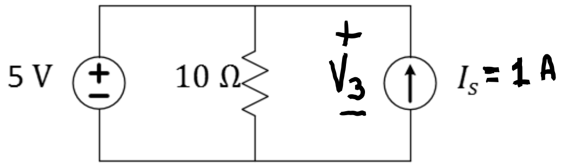


Q: Find the value of V_3.

Q: Find the power, P_3.

Q: Does the sign of P_3 have any meaning?

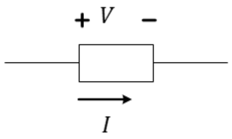
Polarity Labels for Power MATTERS!



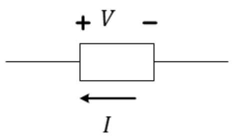
Standard convention means to assign current arrow as flowing from voltage's + to – labels. Alternately, you assign voltages + and – labels at the tail and point of the current arrow, respectively.

Although you can use ANY polarity labels to apply KVL and KCL…
- Use Standard (also called "passive") convention if computing power
- Use Standard convention if applying Ohm's Law

Ohm's Law: V=IR Assumes Standard Convention



"Current downhill" is preferable for resistors



"Current uphill" can be convenient for sources.

Universal Ohm's Law:

If a resistor, then…

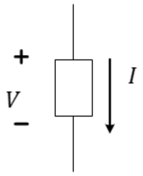
$$V = IR$$

$$V = -IR$$

$$I_{+\to-} = \frac{V}{R}$$

Power Equation: P=IV Assumes Standard

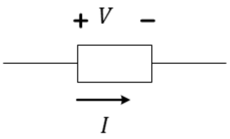
Using the standard polarity labeling: $P = V\ I_{+\rightarrow-}$



$$\boxed{P < 0} \Rightarrow \mathit{Element}\ \boxed{\mathit{delivers}}\ \mathit{power\ to\ the\ circuit}$$

$$\boxed{P > 0} \Rightarrow \mathit{Element}\ \boxed{\mathit{absorbs}}\ \mathit{power\ from\ the\ circuit}$$

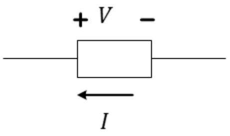
Recap of labeling implication



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

$$P = VI$$

"Standard Reference"



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

$$P = -VI$$

"Non-Standard Reference"

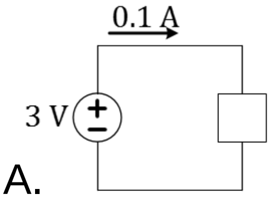
This way, power is defined such that it is negative when it is supplied (sourced) and positive when it is absorbed (sinked).

Universal:

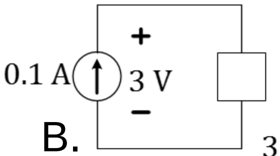
Ohm's Law: $I_{+\rightarrow-} = \frac{V}{R}$
Power Eqn: $P = VI_{+\rightarrow-}$

L7Q6: With power defined as above,
what is the sum of powers for all circuit elements?

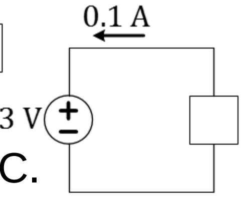
Which of the sources below absorbs power?



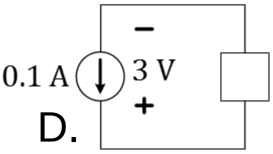
A.



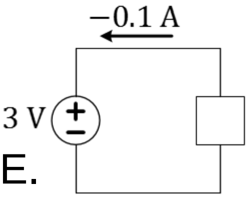
B.



C.

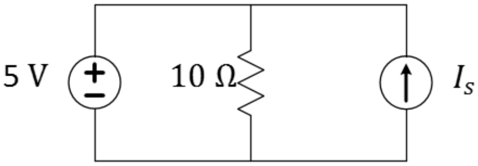


D.



E.

Either or Both Sources Can Supply Power



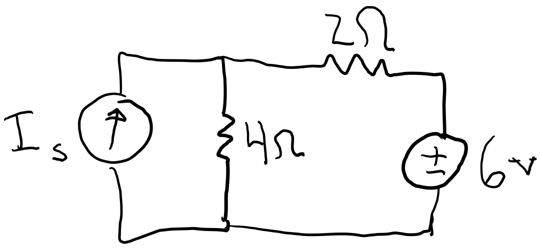
Q: For what values of I_s do both sources supply power?

Q: For what values of I_s does only the current source supply power?

Q: For what values of I_s does only the voltage source supply power?

Exercise

Q: What is the maximum value of I_S for which the voltage source supplies power?



A. -3 A
B. -1.5 A
C. 0 A
D. 1.5 A
E. 3 A

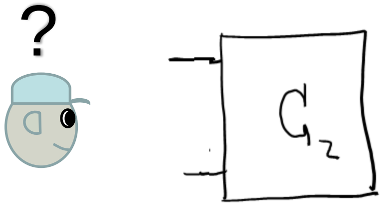
L10 Learning Objectives

a. Assign polarity of current and voltage
b. Properly apply Ohm’s Law to conditions of standard and non-standard polarities
c. Properly apply the signed-Power formula to to conditions of standard and non-standard polarities
d. Derive solutions of circuits under specific power constraints.

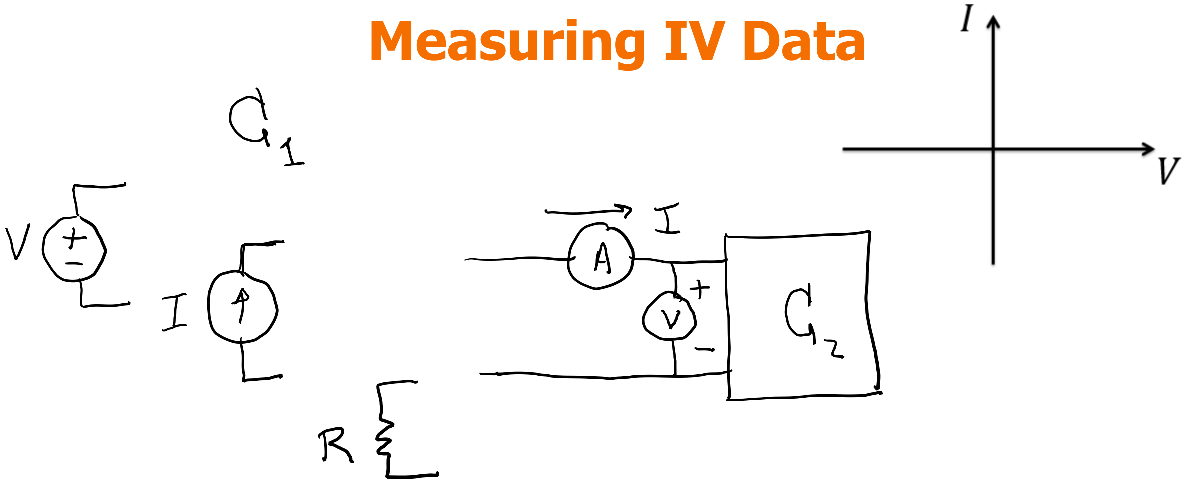
Lecture 11: IV Characteristics

- Measuring I-V Characteristics of Circuits
- Calculating I-V Characteristics of Linear Circuits
- Operating (I,V) point when Sub-circuits are Connected
- Power and the I-V Characteristics

What’s in the Box?

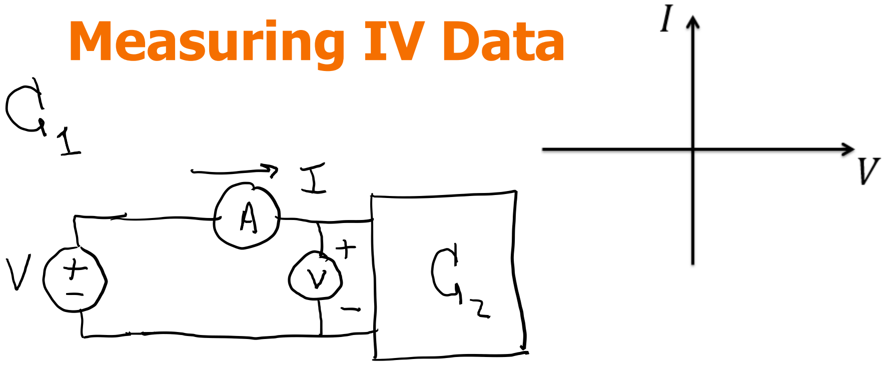


Measuring IV Data



Q: What is the voltage drop across an ideal current-meter (ammeter)?

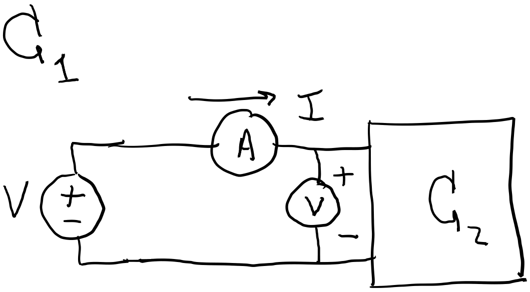
Measuring IV Data

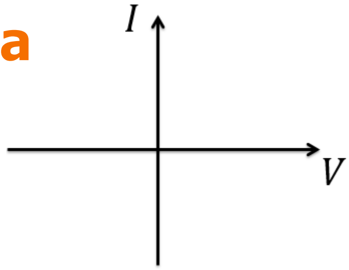


Q: What is the voltage drop across an ideal current-meter (ammeter)?

A. 0 V
B. 1 V
C. Depends on the ammeter's internal resistance

Measuring IV Data

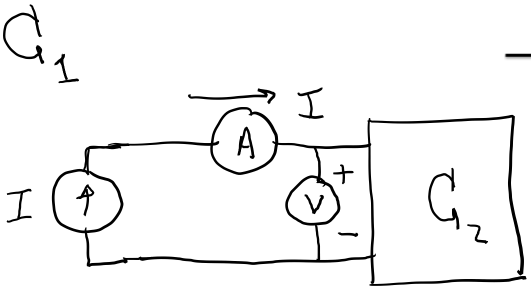


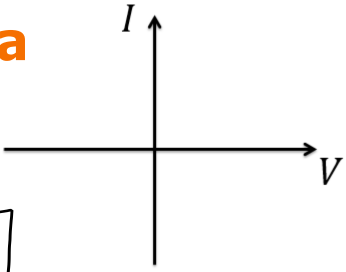


Q: When would this technique be a bad idea?

A. When C_2 is another voltage source
B. When C_2 is a current source
C. When C_2 is a resistor

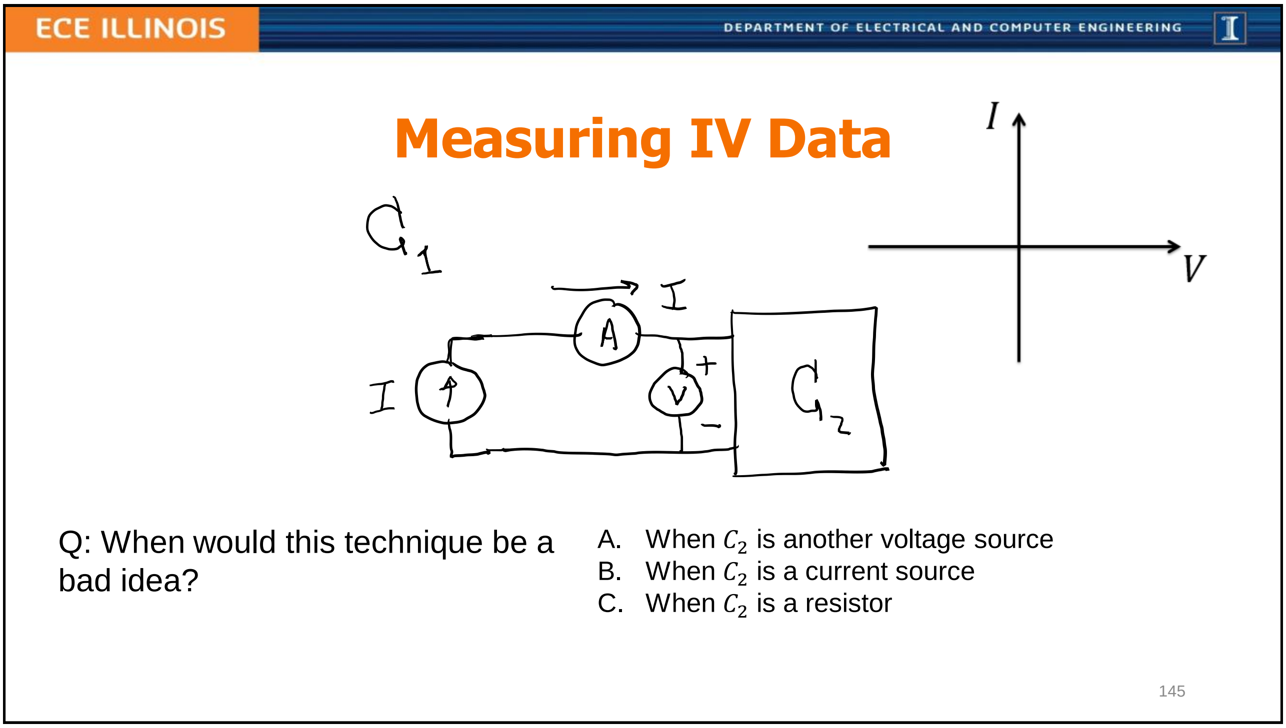
Measuring IV Data





Q: What is the current flow through an ideal voltmeter?

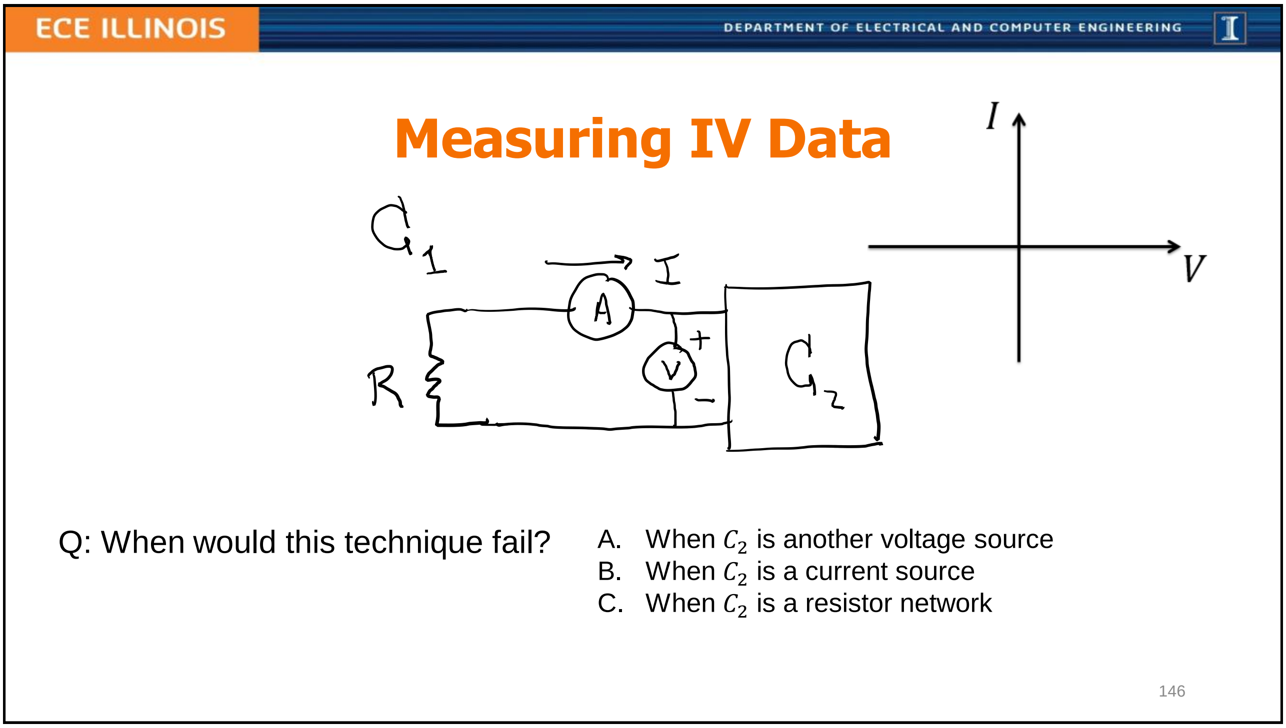
A. 0 A
B. 1 A
C. Depends on the voltmeter's internal resistance



Measuring IV Data

Q: When would this technique be a bad idea?

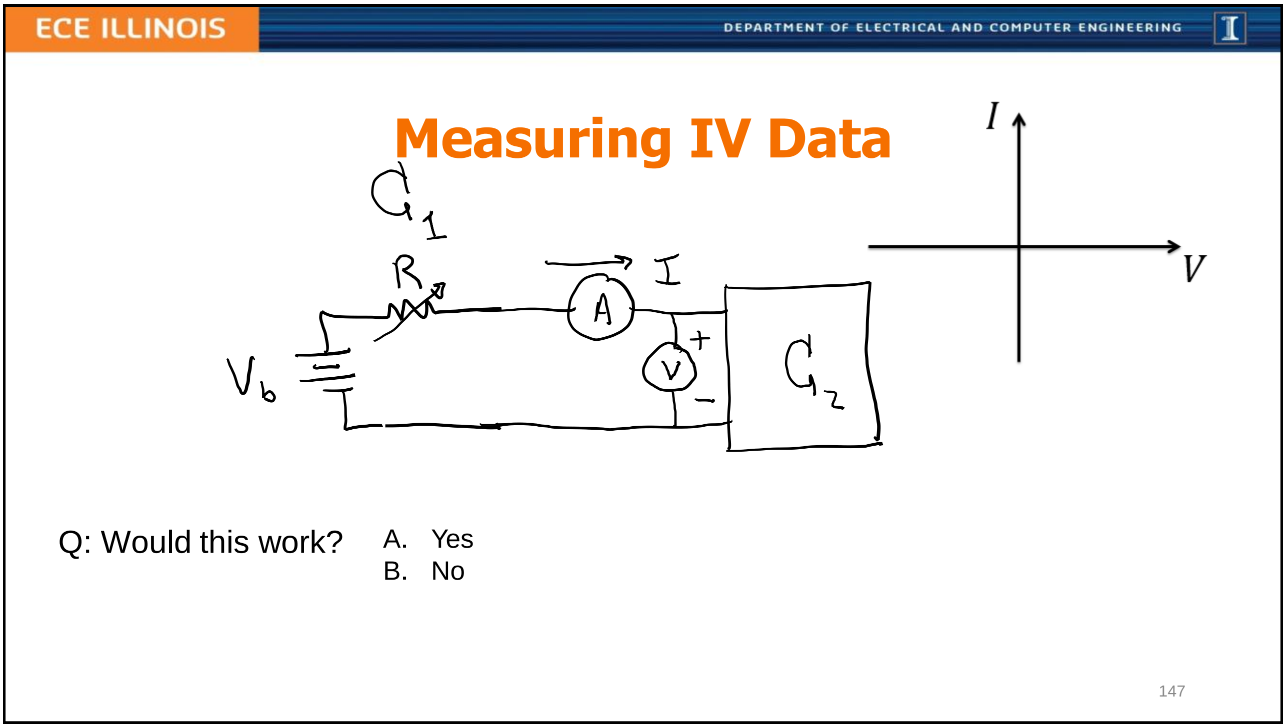
A. When C_2 is another voltage source
B. When C_2 is a current source
C. When C_2 is a resistor



Measuring IV Data

Q: When would this technique fail?

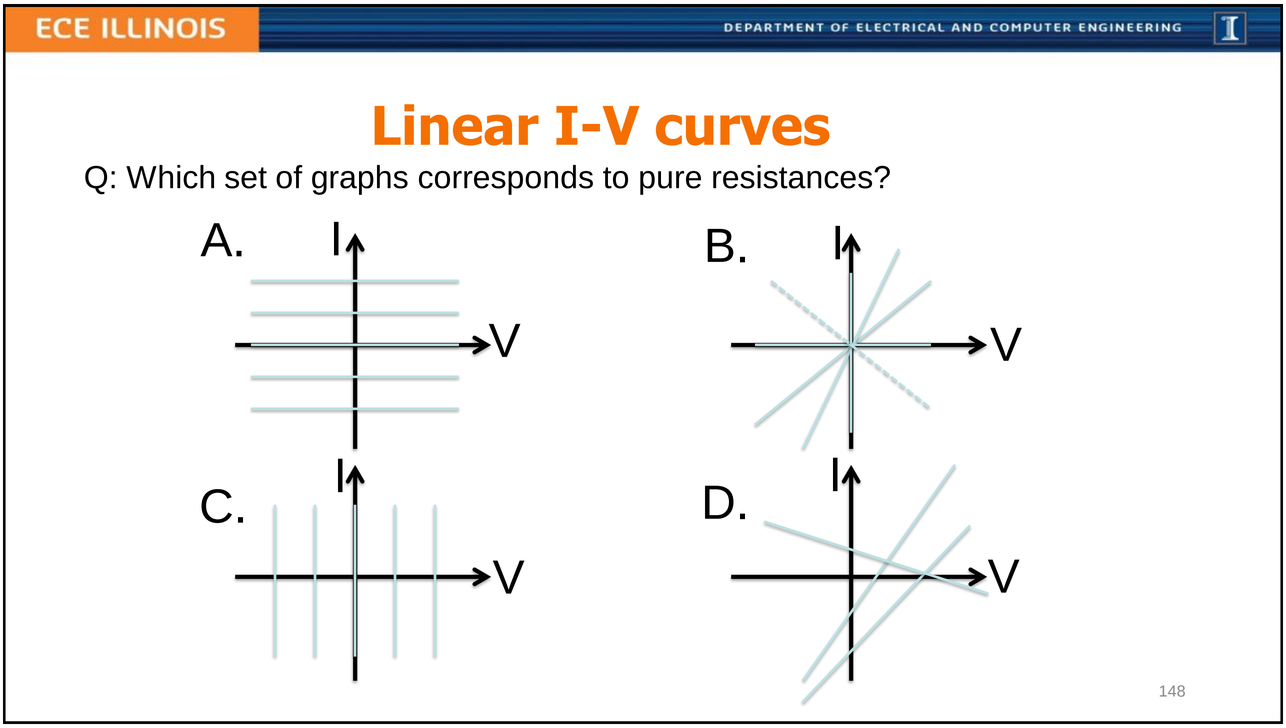
A. When C_2 is another voltage source
B. When C_2 is a current source
C. When C_2 is a resistor network



Measuring IV Data

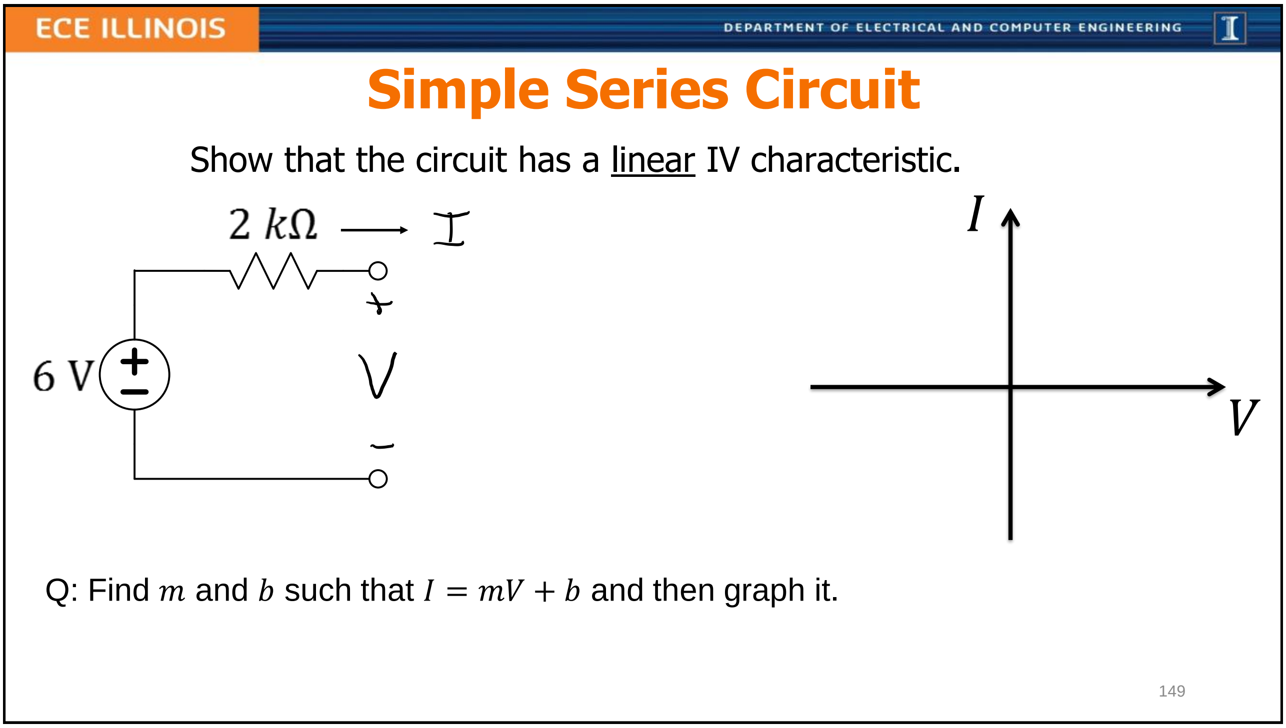
Q: Would this work?

A. Yes
B. No



Linear I-V curves

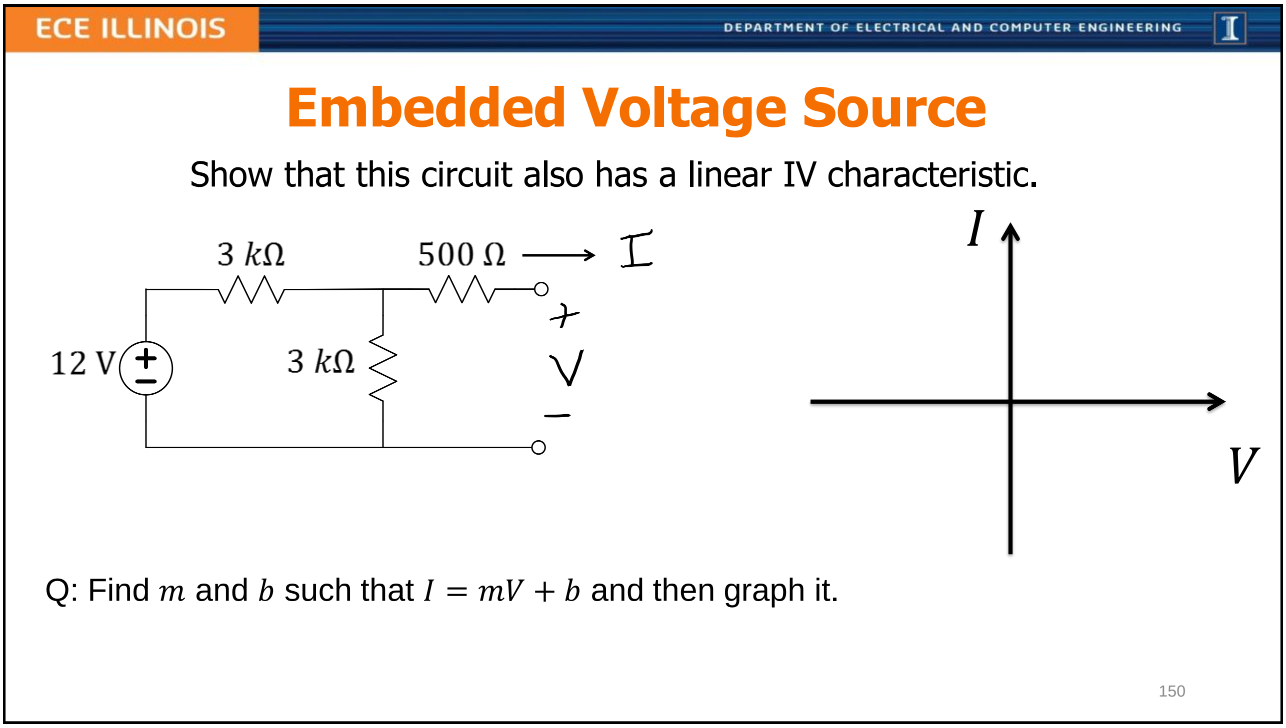
Q: Which set of graphs corresponds to pure resistances?



Simple Series Circuit

Show that the circuit has a linear IV characteristic.

Q: Find m and b such that $I = mV + b$ and then graph it.



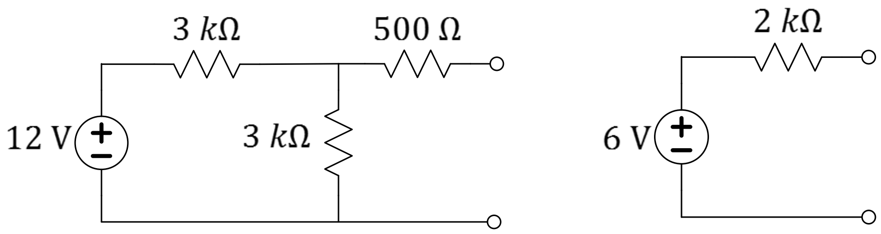
Embedded Voltage Source

Show that this circuit also has a linear IV characteristic.

Q: Find m and b such that $I = mV + b$ and then graph it.

Embedded Voltage Source

Show that this circuit also has a linear IV characteristic.



Q: If both circuits produce the same $I = mV + b$ plot, can the IV data be used to tell which of the two circuits is “in the box”?

A. Yes
B. No
C. Other

Why we care

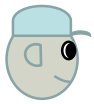
- Allows easy calculation of I and V when two sub-circuits are connected together
- Allows creating a simpler model of a given sub-circuit
- Helps understand nonlinear devices

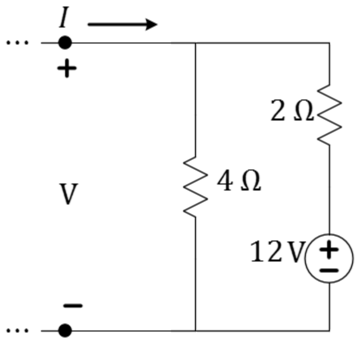
Many Common Methods to find IV lines

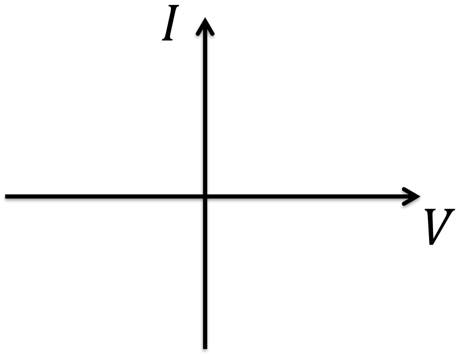
- Use ***circuit analysis*** for *variable* V (like before)
- Find two points (usually ***open*** and ***short***)
- Use $\boldsymbol{R_{eff}}$ and either ***open*** or ***short*** (Wednesday)

Linear I-Vs of source-resistor circuits

Any combination of current or voltage sources with resistor networks has a linear I-V (between any two nodes).

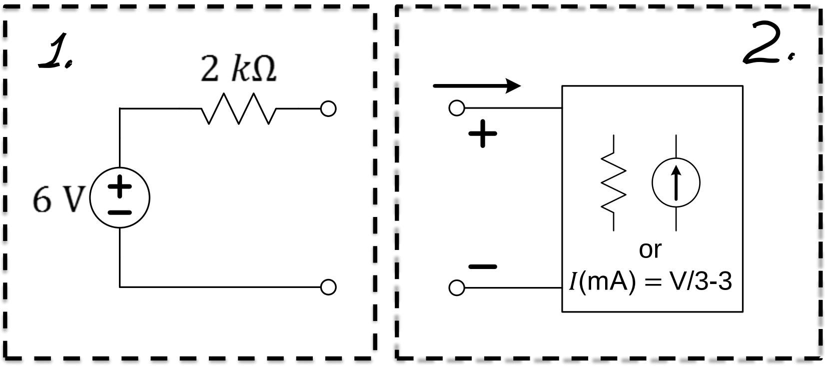


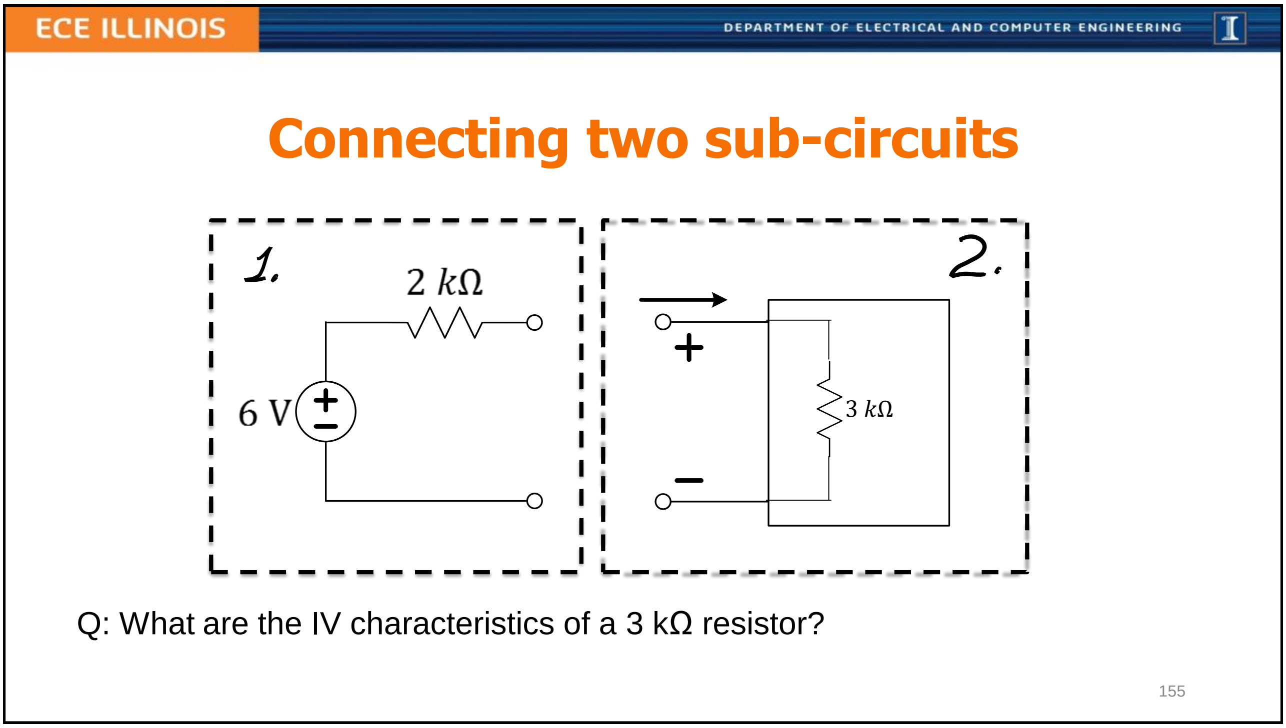




Q: What are the current values of I when V is equal to 0V, 2V, and 4V?

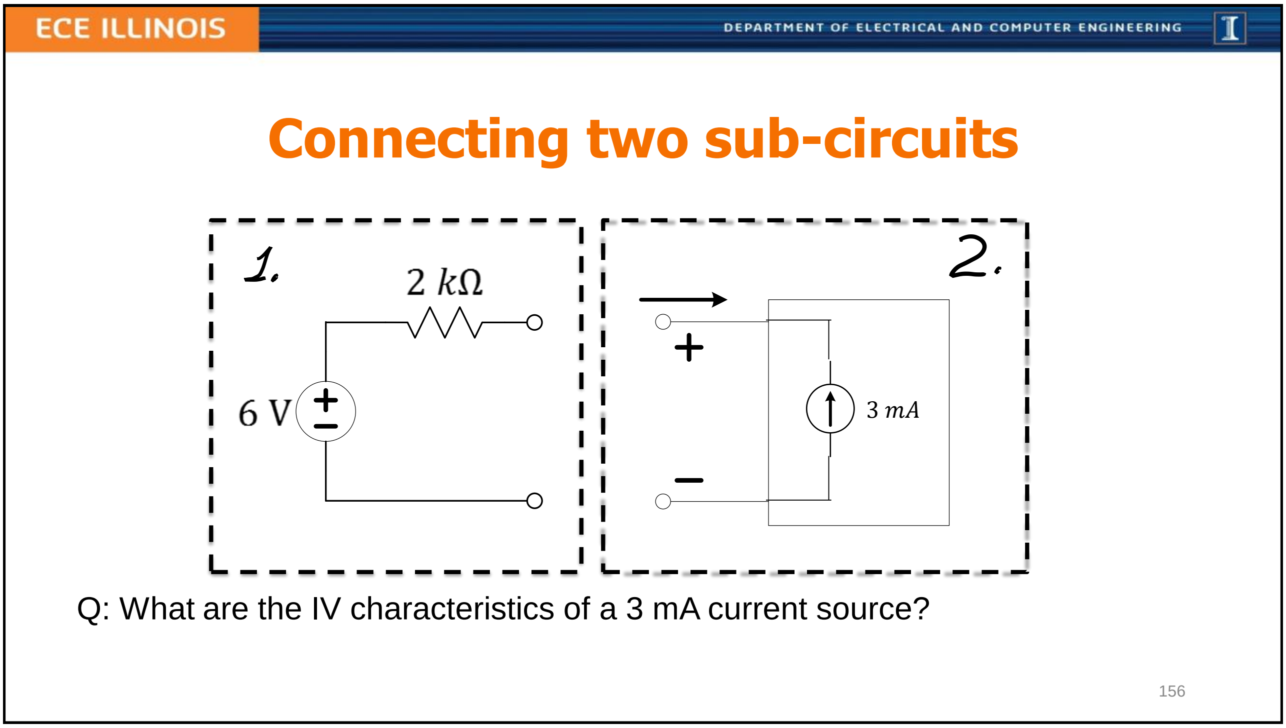
Connecting two sub-circuits





Connecting two sub-circuits

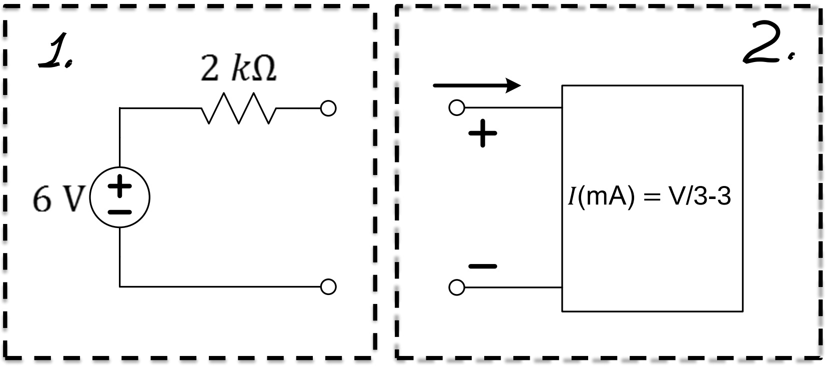
Q: What are the IV characteristics of a 3 kΩ resistor?



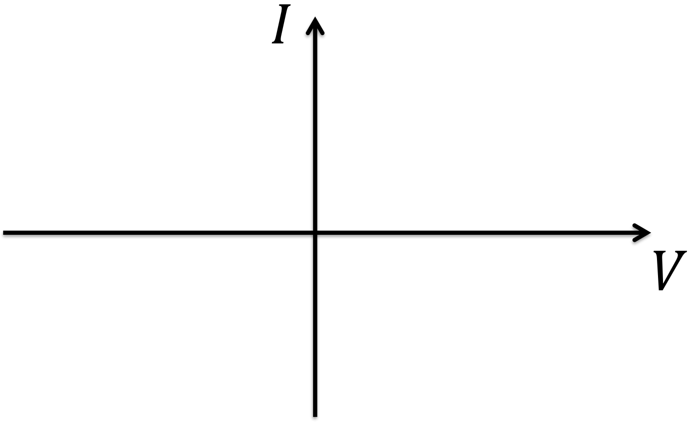
Connecting two sub-circuits

Q: What are the IV characteristics of a 3 mA current source?

Connecting two sub-circuits



Connecting two sub-circuits (cont’d)



Q: Considering the three choices for circuit #2, what is the operating point when the two sub-circuits are connected? Which sub-circuit supplies the power?

L11 Learning Objectives

a. Given one of the three sub-circuit descriptions (IV equation, IV line, diagram), find the other two

Note that more than one circuit diagram fits an IV description

b. Quickly identify the IV representations of voltage and current sources, resistors, and combinations

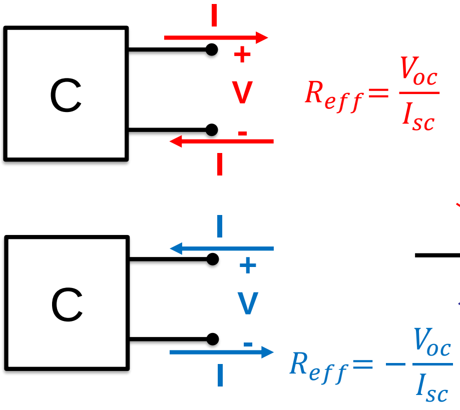
c. Find (V,I) operating points of connected sub-circuits

d. Calculate power flow between connected sub-circuits

Lecture 12: Thevenin Equivalents

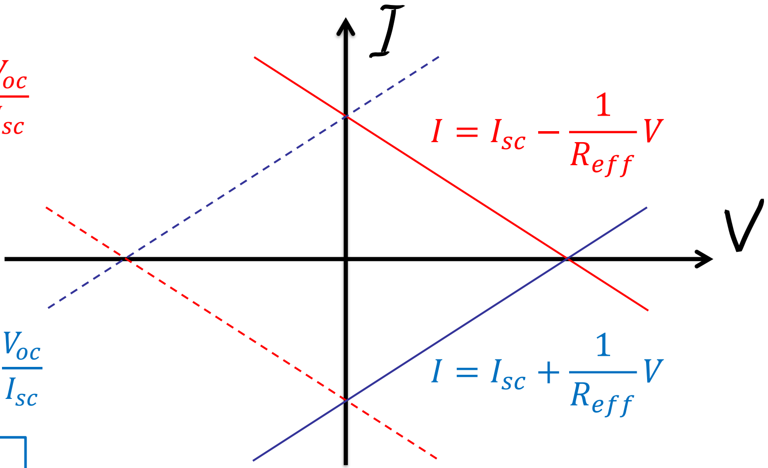
- Review of I-V Linear Equation
- Thevenin Equivalent Circuit
- Effective Resistance in Linear network
- Calculating R_{eff} by Removing Sources
- Problem Strategy and Practice

Relating I-V Line to Equation



$R_{eff} = \frac{V_{oc}}{I_{sc}}$

$R_{eff} = -\frac{V_{oc}}{I_{sc}}$

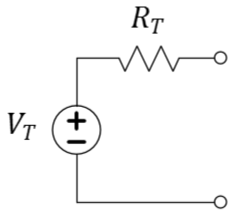


$I = I_{sc} - \frac{1}{R_{eff}} V$

$I = I_{sc} + \frac{1}{R_{eff}} V$

Universal: $I = I_{sc} - \frac{I_{sc}}{V_{oc}} V$

Thevenin Equivalent



Any linear IV $I = mV + b$ can be matched by the circuit on the left with proper selection of V_T and R_T.

- The Thevenin will have the same universal formula $I = I_{sc} - \frac{I_{sc}}{V_{oc}} V$
- It will contain all information on how original circuit interact with others
- However, it loses information on power dissipation WITHIN the circuit

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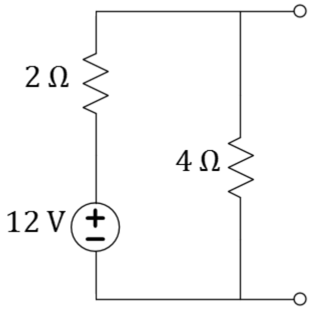
Example

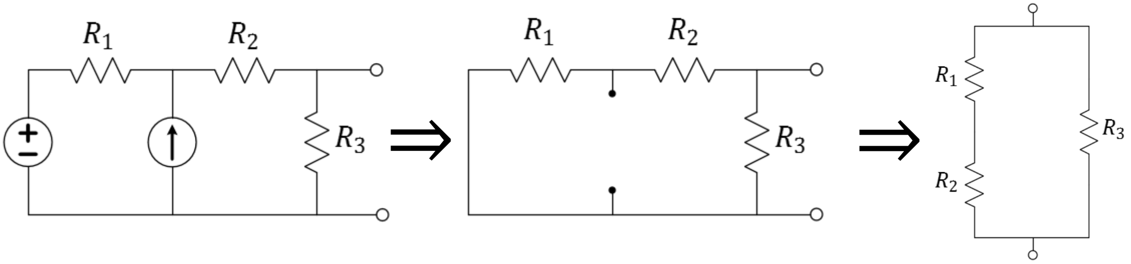


Q: Discuss different ways can you find $I = mV + b$ for this circuit.

Q: What is the Thevenin equivalent of the circuit?

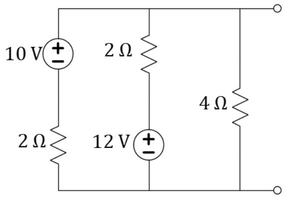
Effective Resistance: $R_{eff} = R_T = R_N$ is R_{eq} with sources "zeroed"

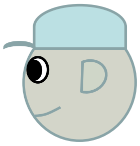
1. Short-circuit all voltage sources (i.e. set them to zero)
2. Open-circuit all current sources (i.e. set them to zero)
3. Find resulting R_{eq} using parallel and series relationships



Q: How is R_{eff} related to the slope of the I-V line?

Finding R_{eff} is easy in multi-source circuits





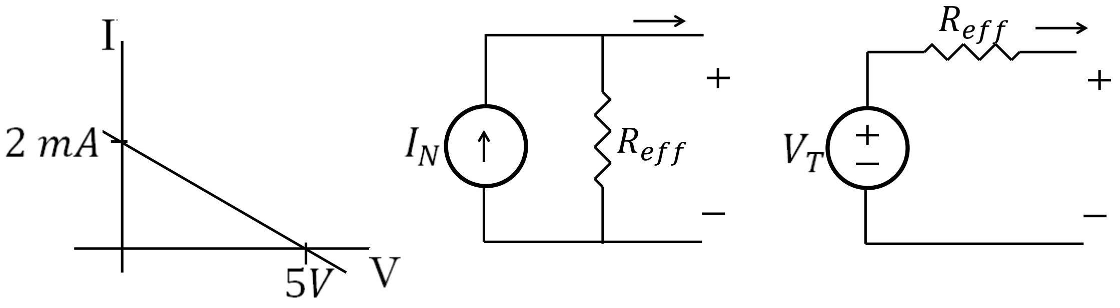
Q: What is R_{eff}, for the circuit?

A. 8 Ω
B. 5 Ω
C. 4 Ω
D. 2 Ω
E. 0.8 Ω

Q: Besides R_{eff}, is it easier to find I_{SC} or V_{OC}?

A. I_{sc}
B. V_oc

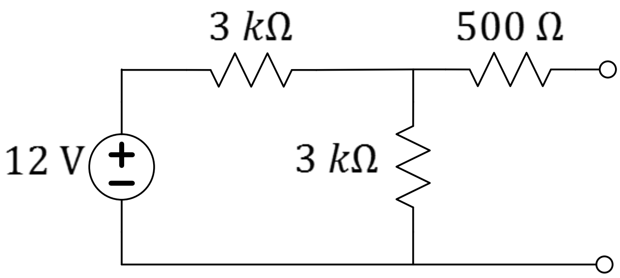
One can find a circuit given a line



Q: What is R_{eff}, for the circuit with the given I-V line?

- $A.$ 2.5 mΩ
- $B.$ 4 $m\Omega$
- $C.$ 4 Ω
- $D.$ 2.5 $k\Omega$
- $E.$ 4 $k\Omega$

Practice makes perfect!



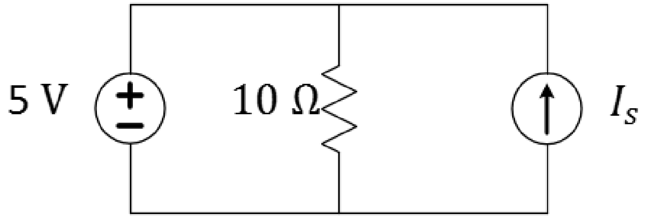
Q: What is the Thevenin equivalent for the circuit above?

In History…

Leon Charles Thevenin was a telegraph engineer. In 1883, his theorem expanded modelling of circuits and simplified circuit analysis based on Ohm's Law and Kirchhoff's Laws.

The dual "Norton's theorem" didn't arrive until 1926 with the efforts of Bell Labs engineer, **Edward Lawry Norton**.

Flashback! Use Thevenin to solve.



Q: For what values of I_s does only the voltage source supply power?

Summary

- Any linear network can be represented by a simple series Thévenin circuit [or, equivalently, by a simple parallel Norton circuit]
- There are several methods for determining the quantities and depending on what is given about the original circuit
- It is the same resistance, R_{eff}, value for both the Thévenin and the Norton circuits, found as R_{eq} with the sources removed (SC for V-sources, OC for I-sources)

L12 Learning Objectives

a. Represent *any* (non-horizontal) linear IV characteristic by a series combination of a voltage source and a resistor (Thévenin equivalent circuit).

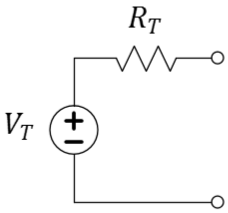
b. Represent *any* (non-vertical) linear IV characteristic by a parallel combination of a current source and a resistor (Norton equivalent circuit).

c. Find the parameters of Thévenin and Norton equivalent circuits, $R_{eff}, V_T,$ and I_N when given a circuit.

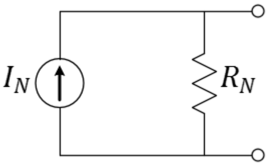
Lecture 13: Norton and IV tools

- Norton
- Source Transformations
- Superposition

Thevenin and Norton Equivalents

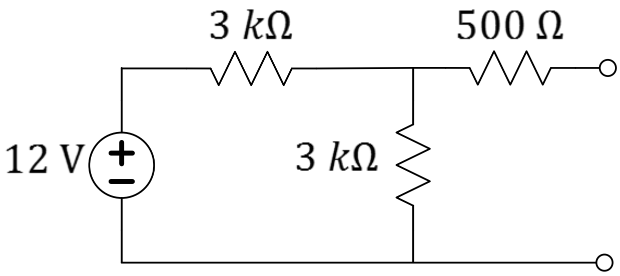


The circuit on the left and the circuit on the right can be made to behave identically by the choice of values as seen through the terminals.



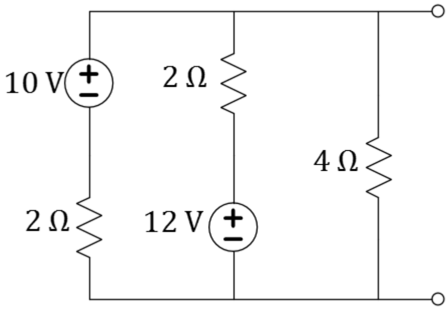
- Either can be used to represent universal: $I = I_{sc} - \frac{I_{sc}}{V_{oc}} V$
- Contain all information on how circuits interact with other circuits
- Loses information on power dissipation WITHIN the circuit

Norton



Q: What is the Norton equivalent for the circuit above?

Source Transformations

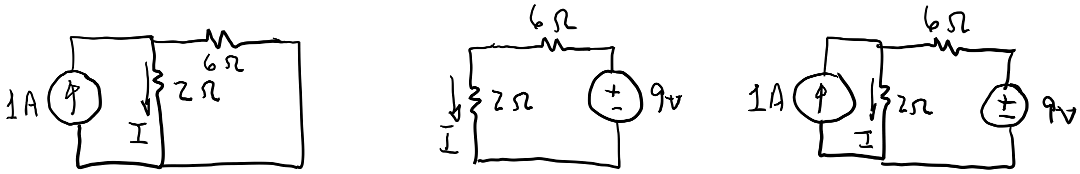


“Source transformations” involve changing Thevenin subcircuits into Norton and Norton subcircuits into Thevenin to gain an advantage in absorbing another part of the circuit. Continue until the entire circuit has been reduced to either a Thevenin or Norton equivalent.

Q: Use “source transformations” to find the Thevenin equivalent of the circuit above.

Superposition

Q: Find I for all three circuits and discuss.



***<u>Superposition</u>** <u>Theorem</u>. The total current in any part of a linear **circuit** equals the algebraic sum of the currents produced by each source separately. To evaluate the separate currents to be combined, replace all other voltage sources by short **circuits** and all other current sources by open **circuits**.*

From: http://hyperphysics.phy-astr.gsu.edu/hbase/electric/suppos.html

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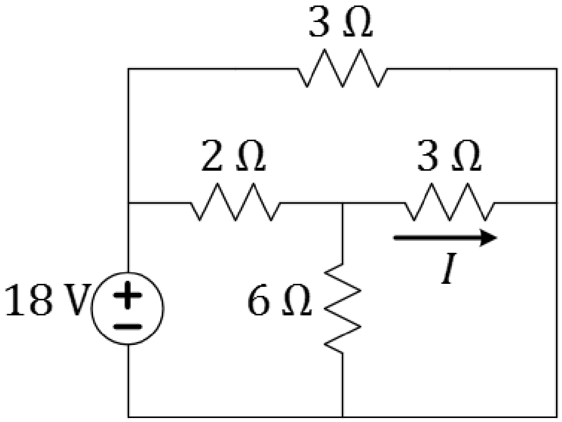
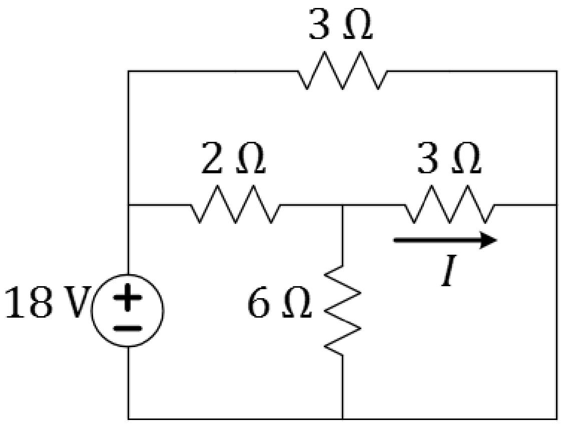
What are the possible strategies to find I?



Q: Is one of the resistors in parallel with the voltage source? If so, which?

Q: What is the value of the labeled current?

More…



L13 Learning Objectives

a. Explain equivalency of Thevenin and Norton by matching points on the IV.
b. Solve circuits for the Norton Equivalent
c. Use Source Transformations to reduce a circuit to Thevenin and/or Norton
d. Use Superposition to reduce a tougher circuit analysis to analysis of two or more single-supply circuits.

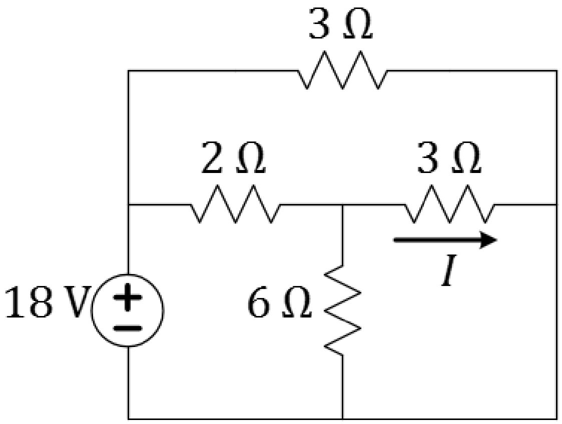
Lecture 14: Node Method For Circuit Analysis

- Review of circuit-solving strategies
- Node Method steps
- Node Method with a “floating” source
- Practice with the Node Method

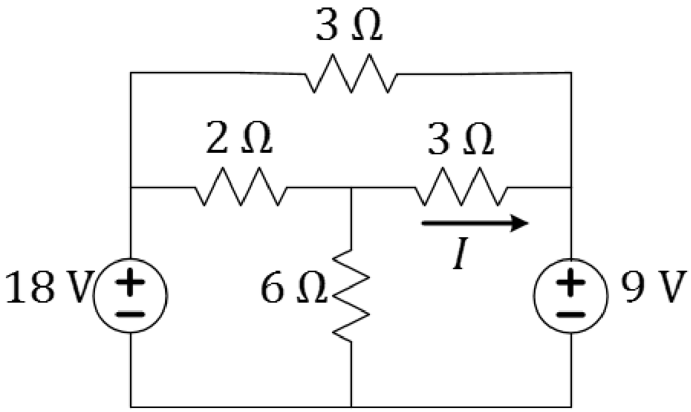
The Node Method

1. Identify or pick “ground” (0 V reference)
2. Label all the node voltages
   (use values when you can; variables when you must)
3. Use KCL at convenient node(s)/supernode(s)
4. Use voltages to find the currents

Try Node Method



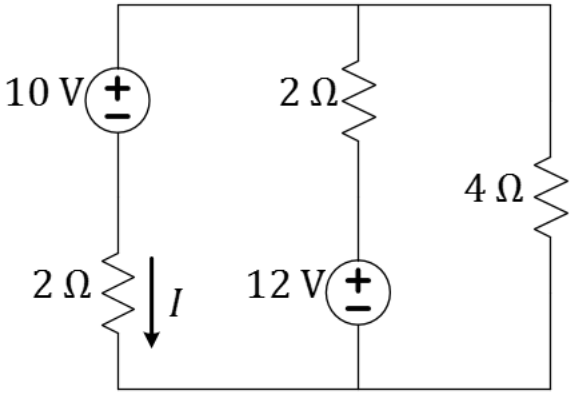
Node method is a good strategy for this problem because it contains two sources



A. 1
B. 2
C. 3
D. 4
E. 5

Q: How many nodes are in the circuit?
Q: What is the value of the labeled current?

A *floating* voltage source: relates two nodes but has no known relationship to ground

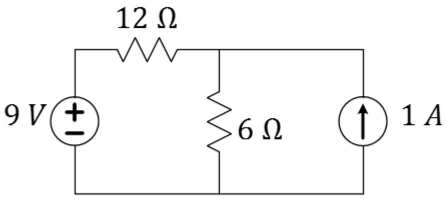


Q: How many nodes are in the circuit?

A. 1
B. 2
C. 3
D. 4
E. 5

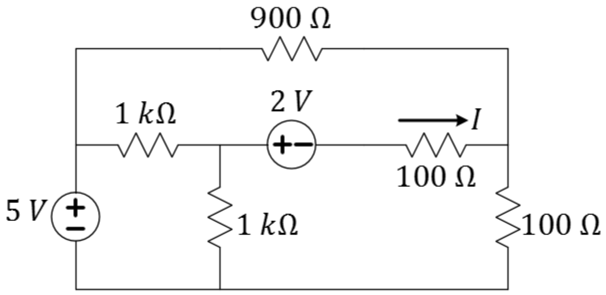
Q: What is the value of the labeled current?

Voltage across a current source is unknown



Q: What is the power supplied or consumed by each element?

Sometimes two or more node voltages are unknown (more challenging!)



Q: What is the value of *I* in the circuit above?

L14 Learning Objectives

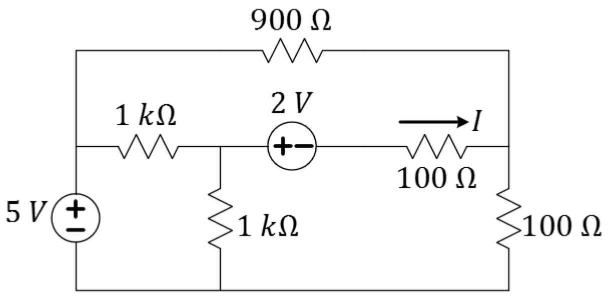
a. Outline (list, describe) steps of the Node Method

b. Use these steps to speed the process of performing circuit analysis via KCL/KVL/Ohm's

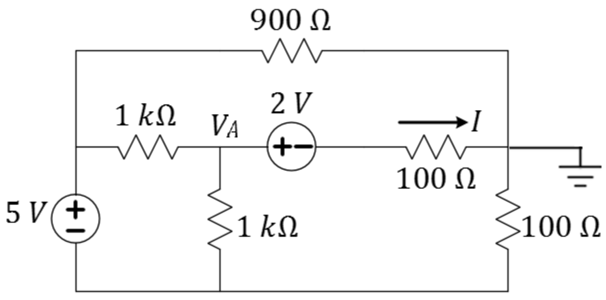
c. Identify circuit patterns in which different techniques might simplify the process of finding a solution (Practice!)

L15: Exercises; Characterizing Sensors

- More exercises on Node Method
- Keys to characterizing sensors for your Final Project!



Q: What is the value of *I* in the circuit above?



Q: What is the value of V_A in the circuit above?

Characterizing Resistive Sensors

- A resistive sensor changes resistance as its environment changes around it. Examples:
  - Photoresistor: resistance decreases as light intensity increases
  - Thermistor: resistance decreases as it warms
  - Flex sensor: resistance increases as it bends
- The obvious part of the characterization is to measure the resistance under various conditions.
- The less obvious task is to use your data to PREDICT how it will behave in the final circuit and to VERIFY your prediction!

Example: Resistive Sensors

Consider a photoresistive sensor used in a voltage divider. Sketch below the steps to characterizing it…

L15 Learning Objectives

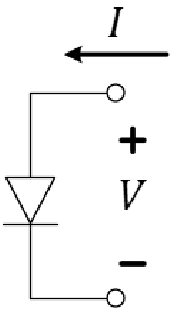
a. Understand sensor types
b. Provide a complete measure-model-and-predict analysis of sensors

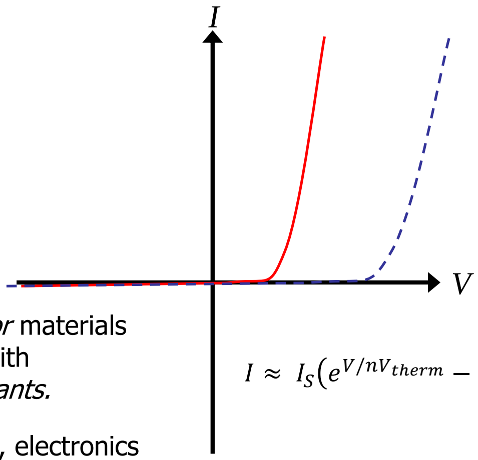
Lecture 16: Introduction to Diodes

- Diode IV characteristics
- Connecting diode to a linear circuit
- Piecewise linear models of diodes

Recommended: https://learn.sparkfun.com/tutorials/diodes

Diode as a two-terminal device





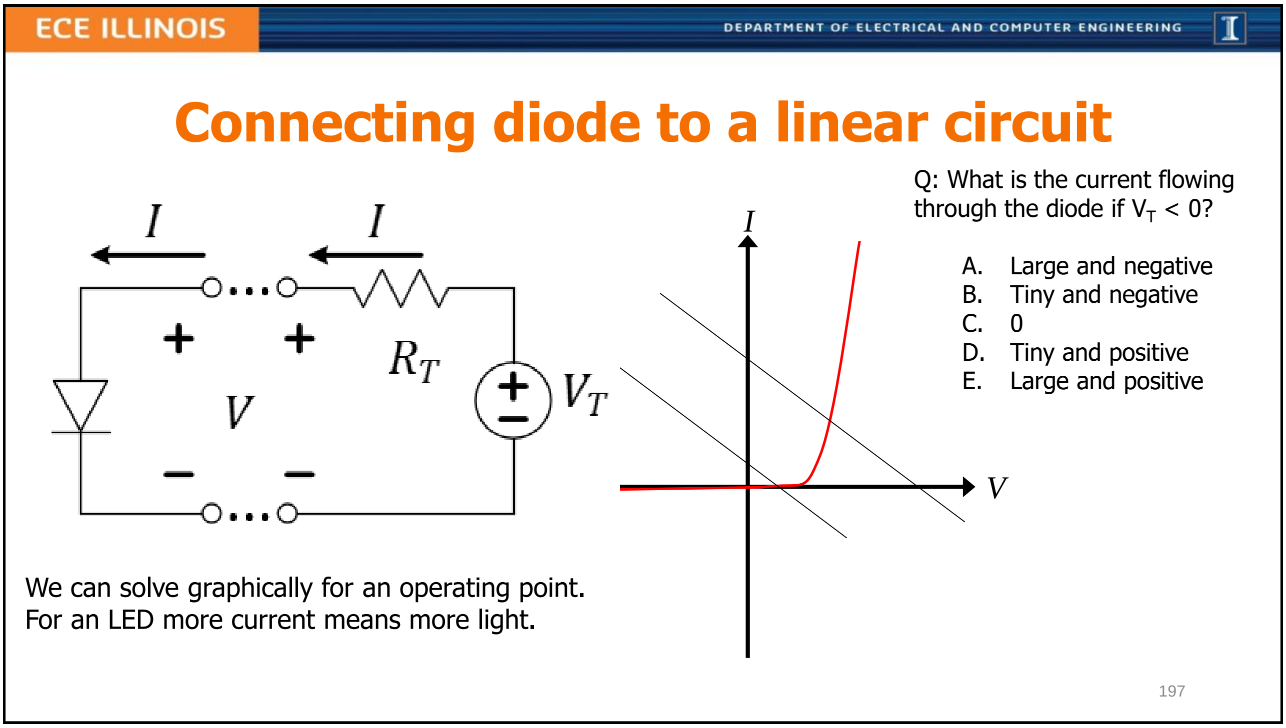
$$I \approx I_S\left(e^{V/nV_{therm}} - 1\right)$$

Q: Based on the exponential equation for IV, can the diode supply power?

A. Yes
B. No

Made out of *semiconductor* materials like Si, Ge, AlGaAs, GaN with some additives called *dopants.*

Major applications: lighting, electronics

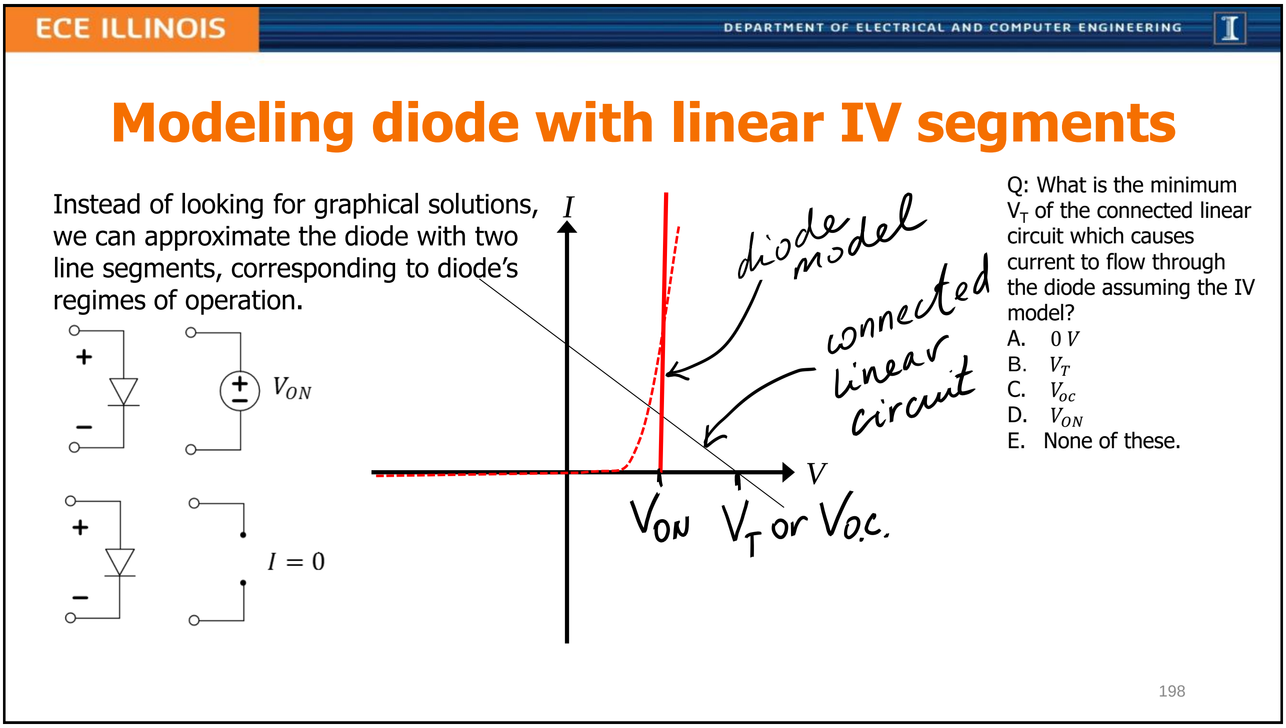


Connecting diode to a linear circuit

Q: What is the current flowing through the diode if $V_T < 0$?

A. Large and negative
B. Tiny and negative
C. 0
D. Tiny and positive
E. Large and positive

We can solve graphically for an operating point.
For an LED more current means more light.



Modeling diode with linear IV segments

Instead of looking for graphical solutions, we can approximate the diode with two line segments, corresponding to diode's regimes of operation.

Q: What is the minimum V_T of the connected linear circuit which causes current to flow through the diode assuming the IV model?

A. $0\ V$
B. V_T
C. V_{oc}
D. V_{ON}
E. None of these.

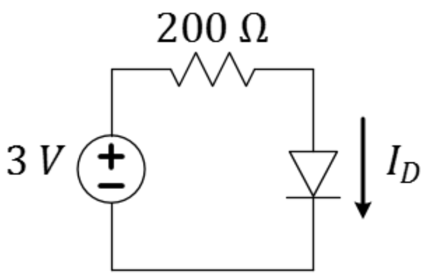
Different diode types have different V_{ON}

Diode Type	V_{ON}(V)	Applications
Silicon	0.6-0.7	General; integrated circuits; switching, circuit protection, logic, rectification, etc.
Germanium	~0.3	Low-power, RF signal detectors
Schottky	0.15-0.4	Power-sensitive, high-speed switching, RF
Red LED (GaAs)	~2	Indicators, signs, color-changing lighting
Blue LED (GaN)	~3	Lighting, flashlights, indicators
"Ideal"	0	Can neglect V_{ON} for high voltage applications

Q: What is the power dissipated by a Ge diode if 30 mA is flowing through it?

A. $3\ mW$
B. $9\ mW$
C. $30\ mW$
D. $90\ mW$
E. $900\ mW$

Diode circuit examples (offset ideal model)

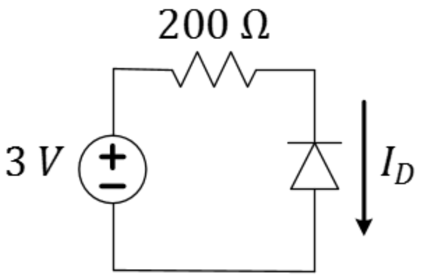


Assume offset-ideal model with V_{ON} = 0.7 (common Si diodes)

Q: What is the current through the diode?

A. 15 mA
B. 11.5 mA
C. 5 mA
D. 1.15 mA
E. 0 mA

Diode circuit examples (offset ideal model)



Assume offset-ideal model with V_{ON} = 0.7 (common Si diodes)

Q: What is the current through the diode?

- A. 15 mA
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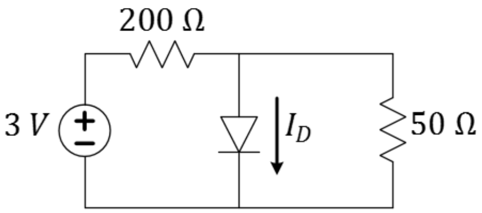
- D. 1.15 mA
- E. 0 mA

Diode circuit examples (offset ideal model)



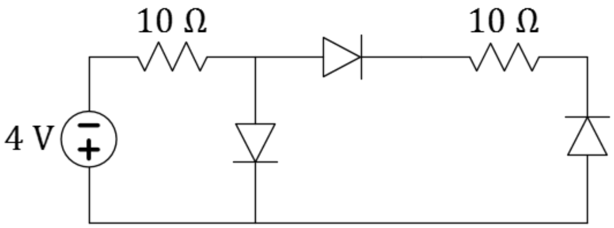
Assume offset-ideal model with V_{ON} = 0.7 (common Si diodes)

Q: What is the current through the diode in the circuit?

$I_D =$

- $A.$ $-11.5\ mA$
- $B.$ $-2.5\ mA$
- $C.$ $0\ mA$
- $D.$ $+2.5\ mA$
- $E.$ $+11.5\ mA$

Back-to-back diodes in series are modeled by OIM as an open circuit



Q: Assume OIM with V_{ON} = 0.7 V (Si)
What is the current through the left-most diode?

A. $0\ Amps$
B. $0.2\ Amps$
C. $0.33\ Amps$
D. $0.4\ Amps$
E. $3.3\ Amps$

L16 Learning Objectives

a. Draw a “typical” diode IV curve and describe its shape

b. Explain how to use graphical analysis to find the operating point of a diode connected to a linear circuit

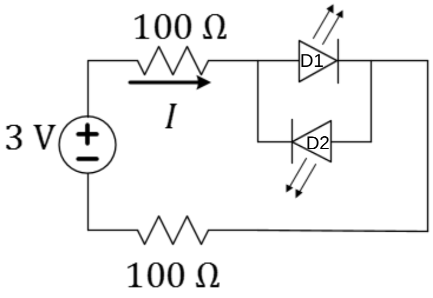
c. Describe the offset ideal diode model (open, V-source)

d. Solve simple circuit problems with one diode, given V_{ON}

Lecture 17: Diode Circuits

- Guess-and-check for diode circuits
- Current-limiting resistors and power dissipation
- Voltage-limiting (clipping) diode circuits

Guess-and-check example



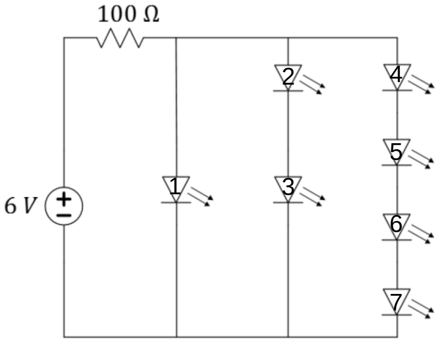
Assume OIM with V_{ON} = 2 V (red LED)

Q: What is the current supplied by the voltage source?

Q: What is the power dissipated in each diode?

D1:		D2:	
A.	$-20\ mW$	A.	$-20\ mW$
B.	$-10\ mW$	B.	$-10\ mW$
C.	$0\ mW$	C.	$0\ mW$
D.	$10\ mW$	D.	$10\ mW$
E.	$20\ mW$	E.	$20\ mW$

Another guess-and-check example



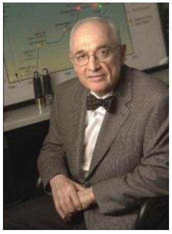
$V_{on} = 2\,V$, all diodes OIM

Q: How many red LEDs are turned on in the circuit?

A. 1
B. 2
C. 3
D. 4
E. 7

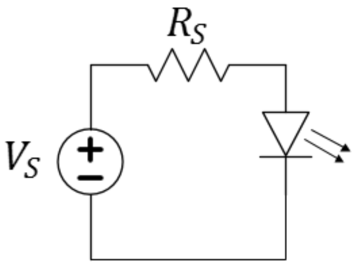
ECE Spotlight…

The first visible-light LED was developed by University of Illinois alumnus (and, later, professor) Nick Holonyak, Jr., while working at General Electric in 1962 with unconventional semiconductor materials.
He immediately predicted the widespread application of LED lighting in use today.



Current-limiting resistors for LEDs

Assume OIM with V_{ON} = 3.3 V (blue LED)



Q: How many 1.5 V batteries are needed to turn on the LED?

A. 1
B. 2
C. 3
D. 4
E. 5

Q: What is the series resistance, R_S, needed to get 16 mA through the LED?

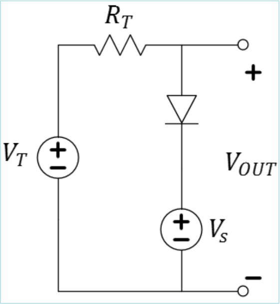
A. 5 Ω
B. 10 Ω
C. 25 Ω
D. 50 Ω
E. 75 Ω

Q: What is the resulting power dissipation in the diode?

A. $19\,mW$
B. 32 mW
C. $53\,mW$
D. $100\,mW$
E. $320\,mW$

Setting voltage limits with diodes

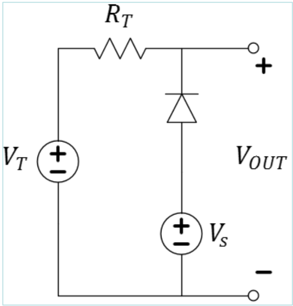
Assume OIM model with V_{ON} = 0.3 V (Ge diode)



Q: What is the possible range of the output voltages?

$V_{out} \in$

A. $(-\infty, V_S + 0.3]$
B. $[V_S + 0.3, 0]$
C. $[V_S - 0.3, V_S + 0.3]$
D. $[V_S - 0.3, \infty)$
E. $[V_S + 0.3, \infty)$



Q: What is the possible range of the output voltages?

$V_{out} \in$

A. $(-\infty, V_S + 0.3]$
B. $[V_S + 0.3, 0]$
C. $[V_S - 0.3, V_S + 0.3]$
D. $[V_S - 0.3, \infty)$
E. $[V_S + 0.3, \infty)$

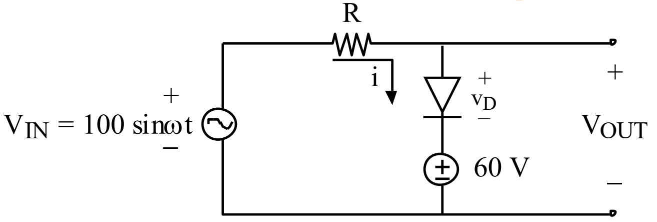
L17 Learning Objectives

a. Solve circuit analysis problems involving sources, resistances, and diodes
b. Estimate power dissipation in diode circuits
c. Select appropriate current-limiting resistors
d. Determine voltage limits and waveforms at outputs of diode voltage-clipping circuits

Lecture 18: Diode Applications

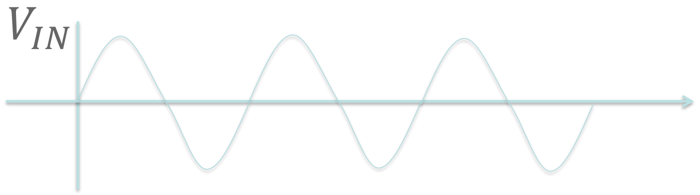
- Voltage clipping
- Rectifiers
- Flyback diode (lab)
- Instructor option…

A voltage-clipping circuit sets maximum or minimum output voltage

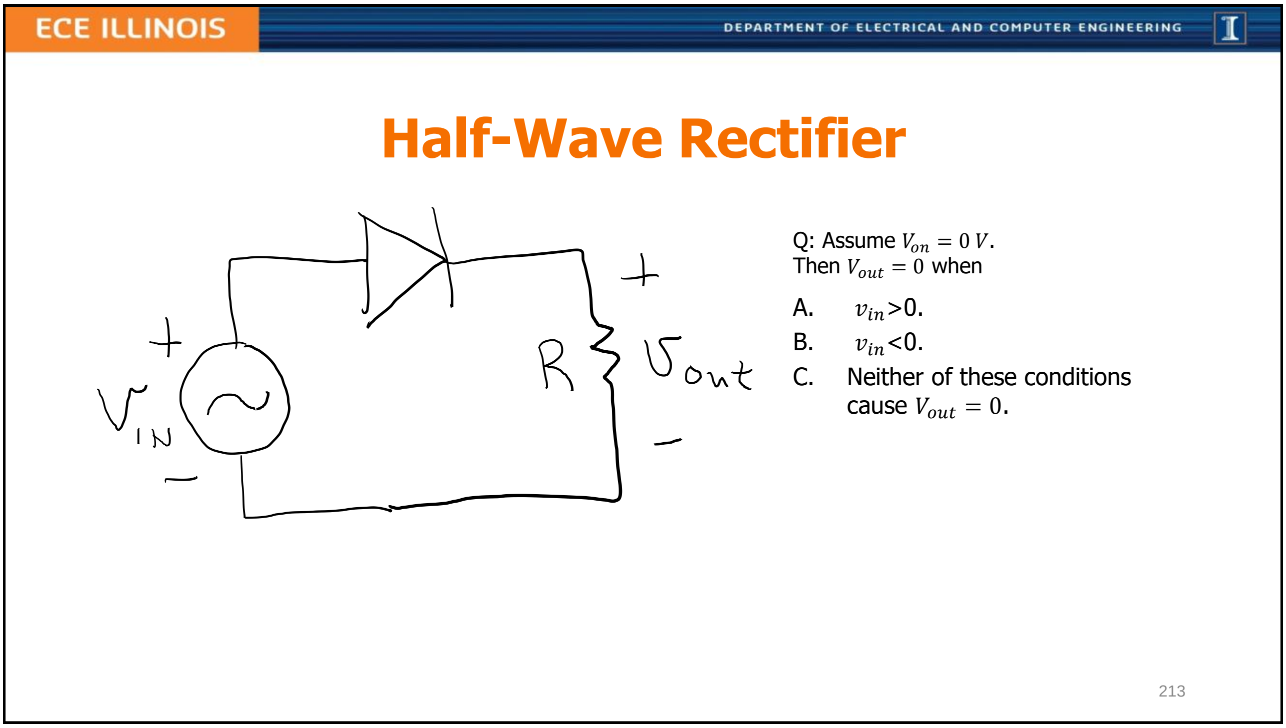


KVL:

$V_{OUT} = 60 + v_D$



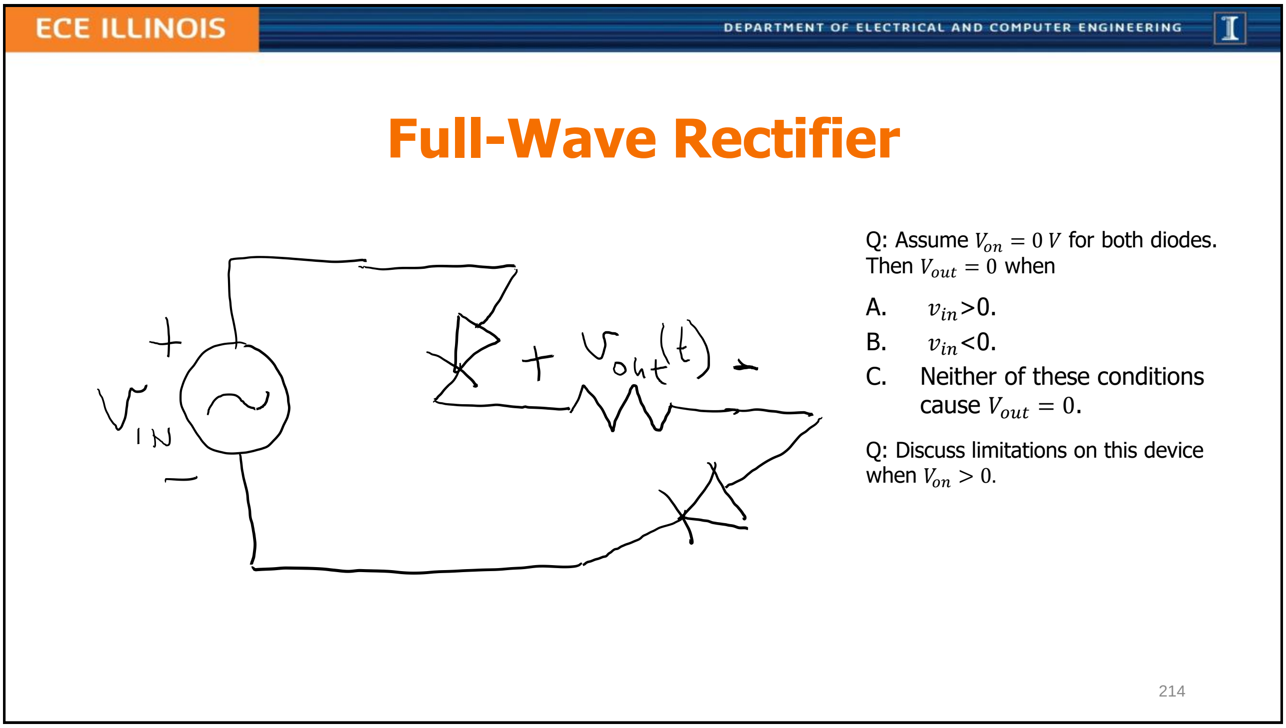
Q: If the input voltage waveform is shown, what is the output waveform, assuming an ideal diode model (V_{ON} = 0 V)?



Half-Wave Rectifier

Q: Assume $V_{on} = 0\,V$.
Then $V_{out} = 0$ when

A. v_{in}>0.
B. v_{in}<0.
C. Neither of these conditions cause $V_{out} = 0$.



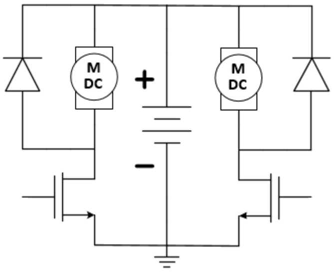
Full-Wave Rectifier

Q: Assume $V_{on} = 0\,V$ for both diodes.
Then $V_{out} = 0$ when

A. v_{in}>0.
B. v_{in}<0.
C. Neither of these conditions cause $V_{out} = 0$.

Q: Discuss limitations on this device when $V_{on} > 0$.

Flyback Diode: Motor protection



Q: Assume $V_{on} = 0\,V$ for both diodes. Then $V_{out} = 0$ when

A. $v_{in}>0$.
B. $v_{in}<0$.
C. Neither of these conditions cause $V_{out} = 0$.

Q: Discuss limitations on this device when $V_{on} > 0$.

This diode is known by many other names, such as kickback diode, snubber diode, commutating diode, freewheeling diode, suppression diode, clamp diode, or catch diode. -Wikipedia on Flyback Diode

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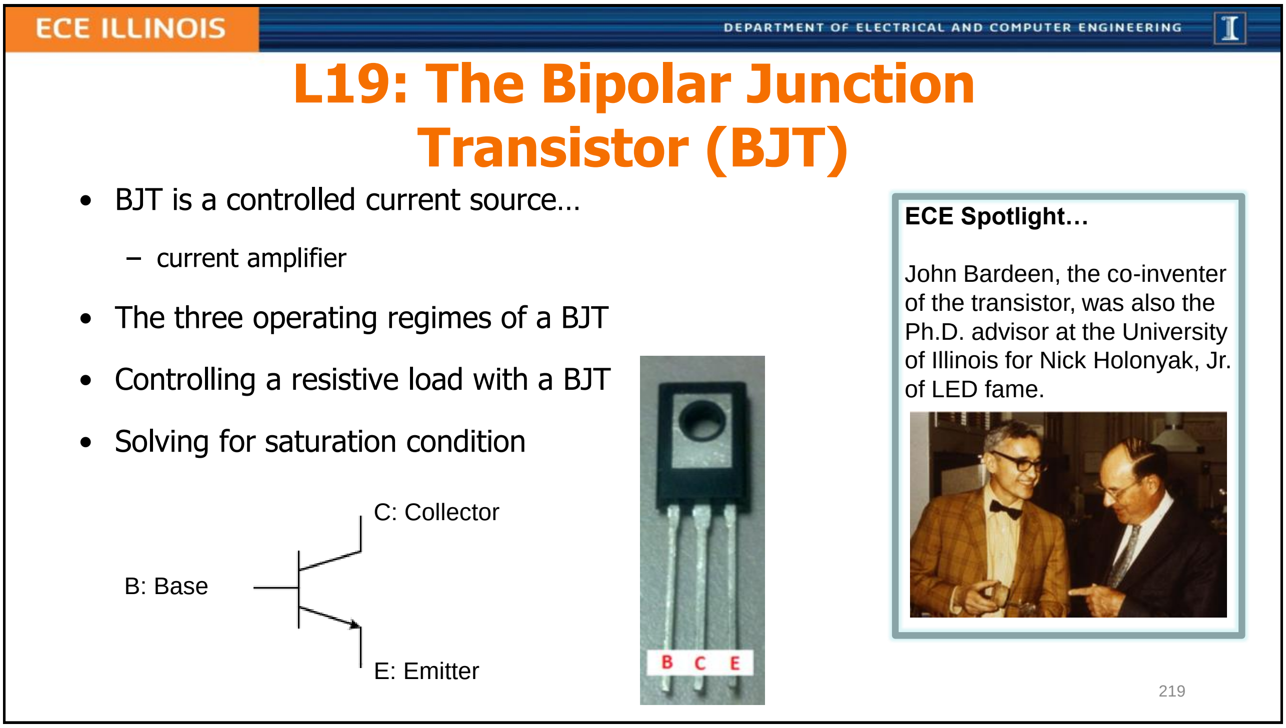
Instructor Option

Instructor Option

L18 Learning Objectives

a. Determine voltage limits and waveforms at outputs of diode voltage-clipping circuits

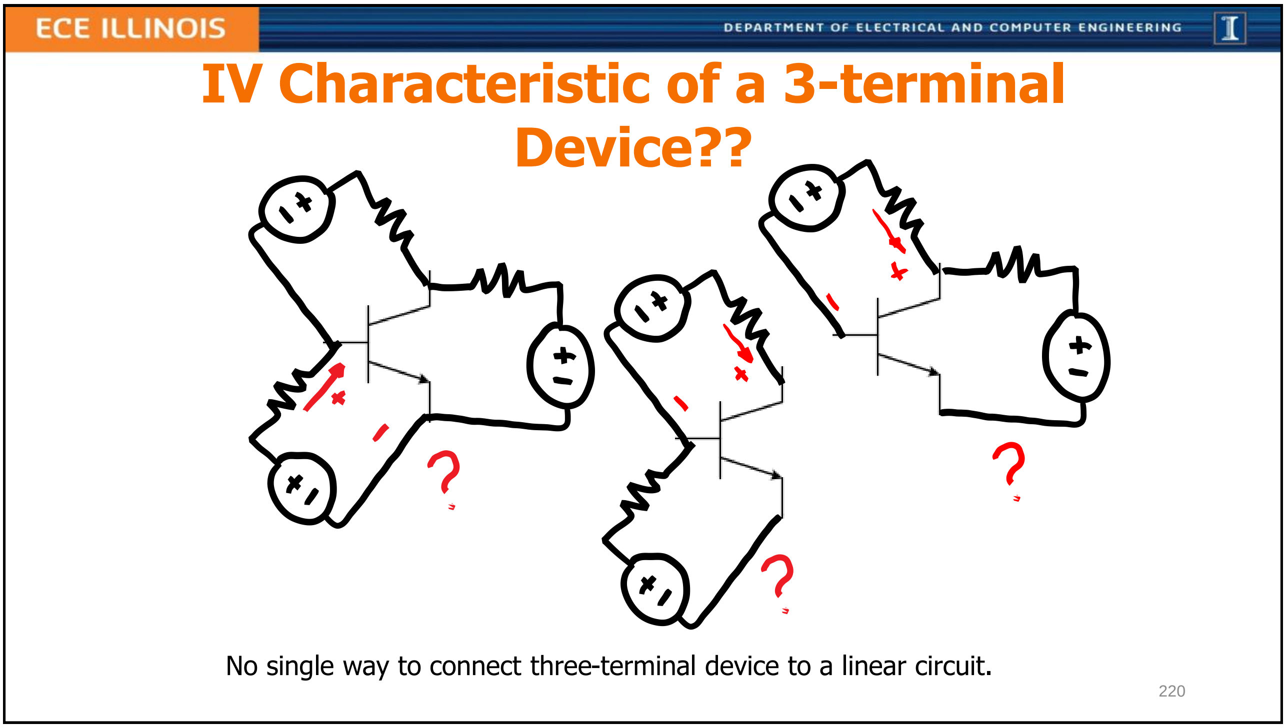


L19: The Bipolar Junction Transistor (BJT)

- BJT is a controlled current source…
  - current amplifier
- The three operating regimes of a BJT
- Controlling a resistive load with a BJT
- Solving for saturation condition

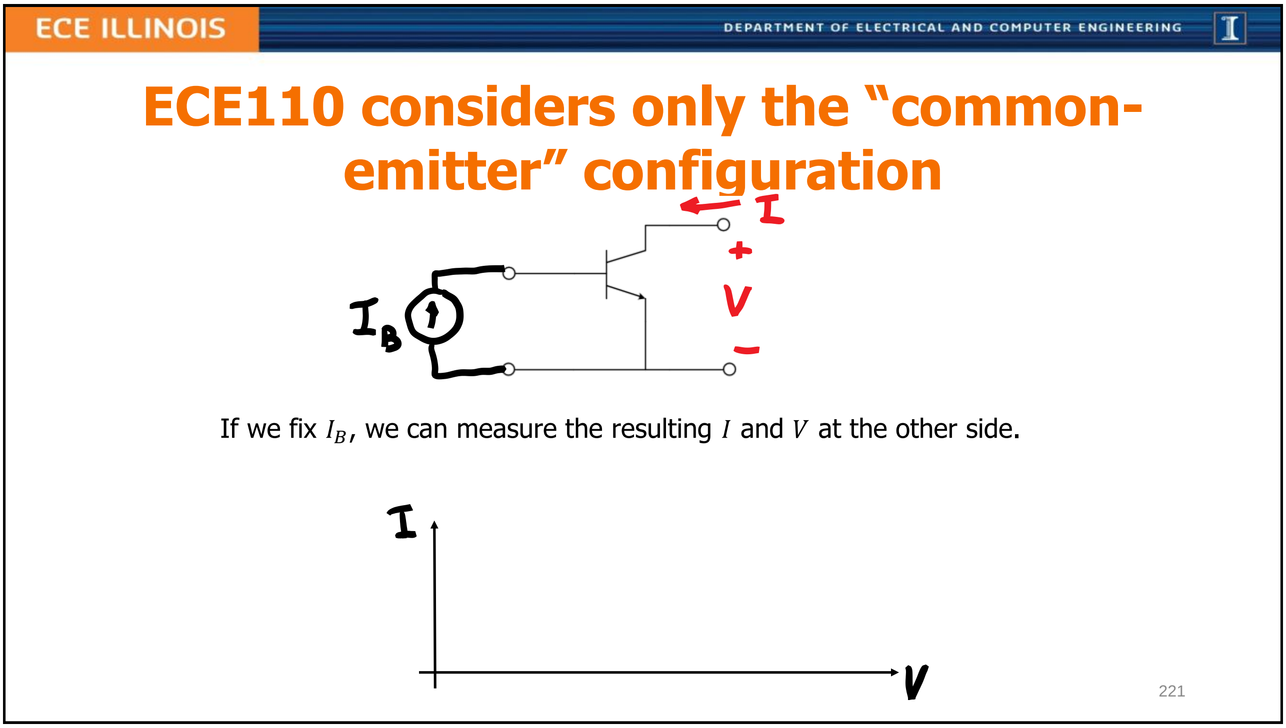
ECE Spotlight…

John Bardeen, the co-inventer of the transistor, was also the Ph.D. advisor at the University of Illinois for Nick Holonyak, Jr. of LED fame.



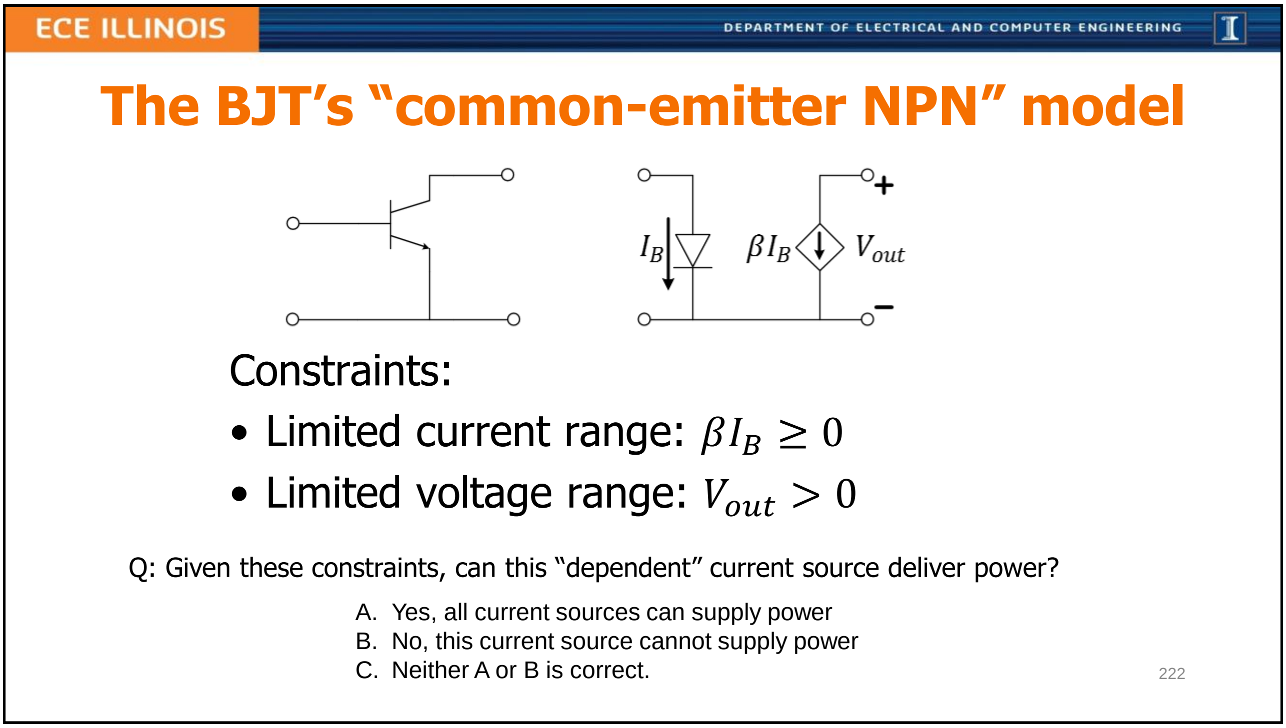
IV Characteristic of a 3-terminal Device??

No single way to connect three-terminal device to a linear circuit.



ECE110 considers only the "common-emitter" configuration

If we fix I_B, we can measure the resulting I and V at the other side.



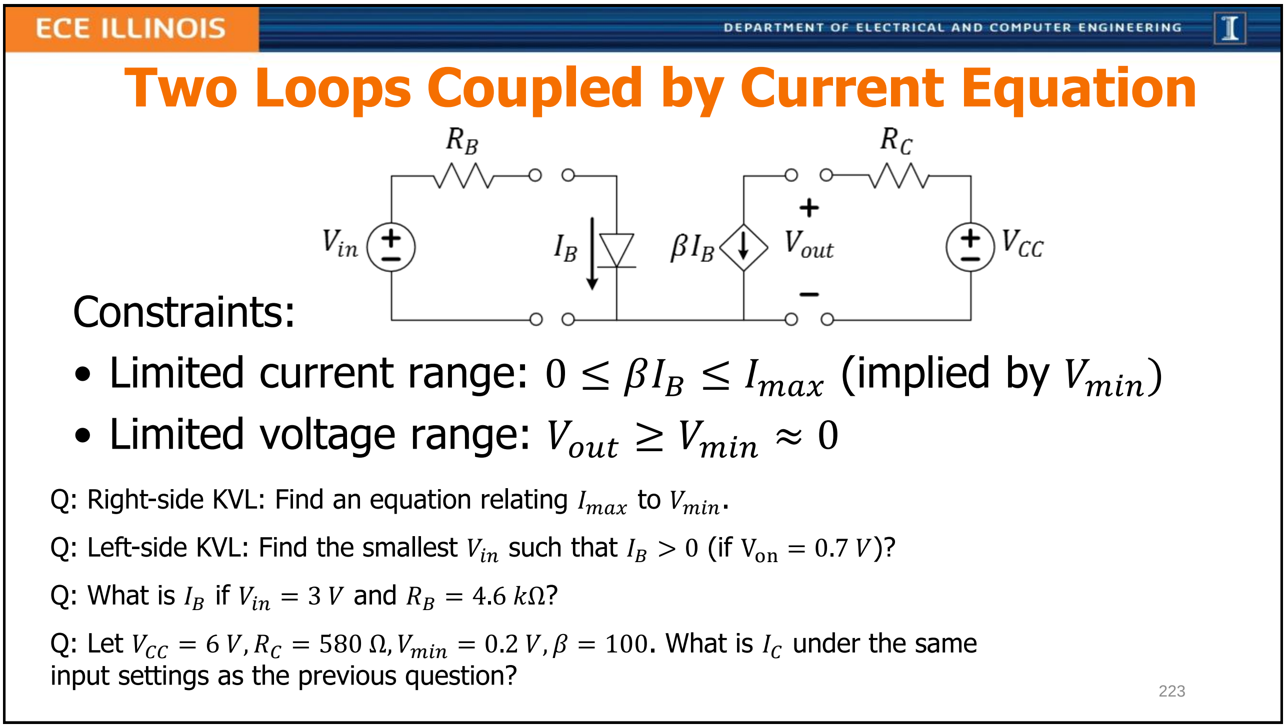
The BJT's "common-emitter NPN" model

Constraints:

- Limited current range: $\beta I_B \geq 0$
- Limited voltage range: $V_{out} > 0$

Q: Given these constraints, can this "dependent" current source deliver power?

A. Yes, all current sources can supply power
B. No, this current source cannot supply power
C. Neither A or B is correct.



Two Loops Coupled by Current Equation

Constraints:

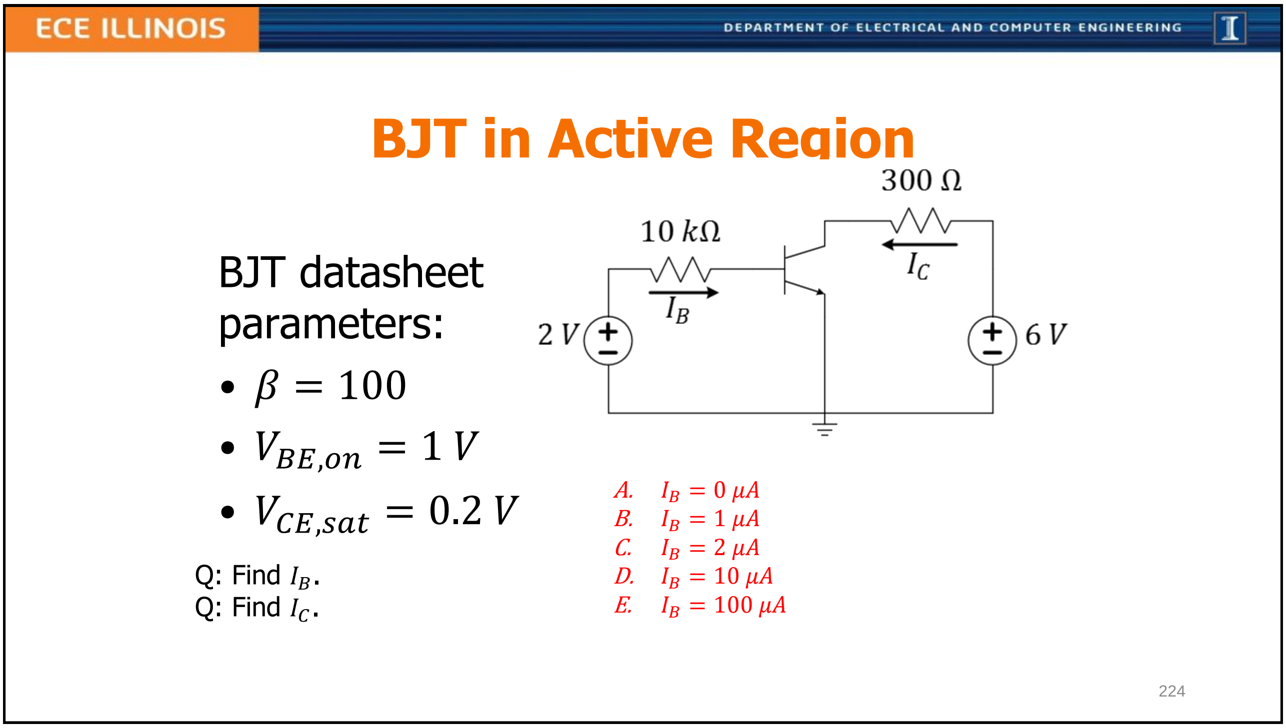
- Limited current range: $0 \leq \beta I_B \leq I_{max}$ (implied by V_{min})
- Limited voltage range: $V_{out} \geq V_{min} \approx 0$

Q: Right-side KVL: Find an equation relating I_{max} to V_{min}.

Q: Left-side KVL: Find the smallest V_{in} such that $I_B > 0$ (if $\mathrm{V_{on}} = 0.7\,V$)?

Q: What is I_B if $V_{in} = 3\,V$ and $R_B = 4.6\,k\Omega$?

Q: Let $V_{CC} = 6\,V, R_C = 580\,\Omega, V_{min} = 0.2\,V, \beta = 100$. What is I_C under the same input settings as the previous question?



BJT in Active Region

BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 1\,V$
- $V_{CE,sat} = 0.2\,V$

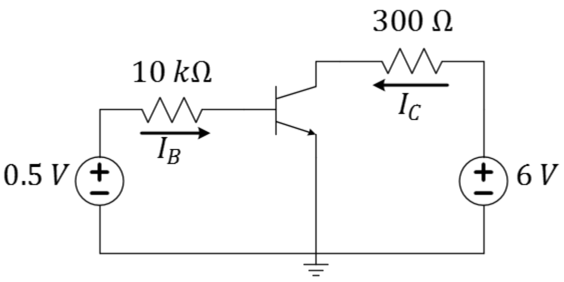
Q: Find I_B.
Q: Find I_C.

A. $I_B = 0\,\mu A$
B. $I_B = 1\,\mu A$
C. $I_B = 2\,\mu A$
D. $I_B = 10\,\mu A$
E. $I_B = 100\,\mu A$

BJT in Cutoff

BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 1\ V$
- $V_{CE,sat} = 0.2\ V$

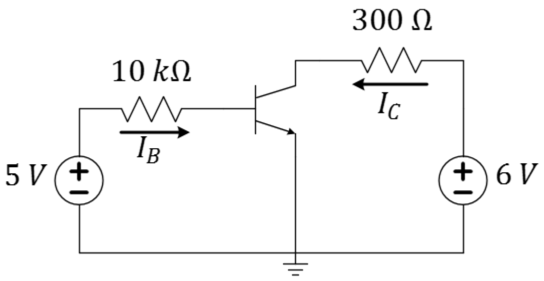


Q: Find I_B.
Q: Find I_C.

BJT in Saturation

BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 1\ V$
- $V_{CE,sat} = 0.2\ V$

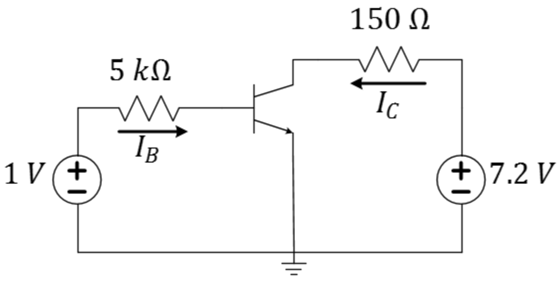


Q: Find I_B.
Q: Find I_C.

BJT Exercise

BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 1\ V$
- $V_{CE,sat} = 0.2\ v$

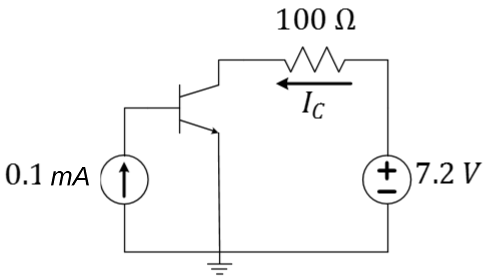


Q: Find I_C and identify in which regime the transistor is operating.

BJT Exercise

BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 1\ V$
- $V_{CE,sat} = 0.2\ V$



Q: Find I_C and identify in which regime the transistor is operating.
Q: Determine the power consumed by the transistor.

L19 Learning Objectives

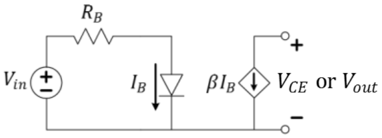
a. Identify B, E, C terminals on an npn-BJT symbol
b. Explain BJT's three regimes of operation
c. Calculate active-regime I_C using V_{BEon} in the BE loop
d. Calculate maximum I_C based on $V_{CE,sat}$ and CE loop
e. Calculate I_C given complete biasing conditions and transistor parameters, no matter which regime
f. Calculate the power dissipated by a transistor

Lecture 20: BJT IV Characteristics

> "**Transistor**. This is an abbreviated combination of the words "transconductance" or "transfer", and "varistor". The device logically belongs to the varistor family, and has the transcondutance or transfer impedance of a device having gain, so that this combination is descriptive." Bell Labs memo

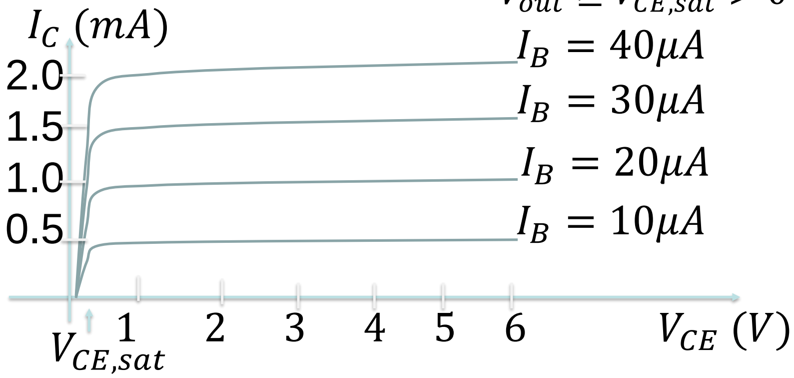
- Interpreting CE junction IV curves for transistor parameters
- Interpreting load line IV curves
- Analysis of IV curves for the (I,V) operating point
- Explore the saturation condition
- Solving transistor-regime problems

BJT IV curves of the CE junction



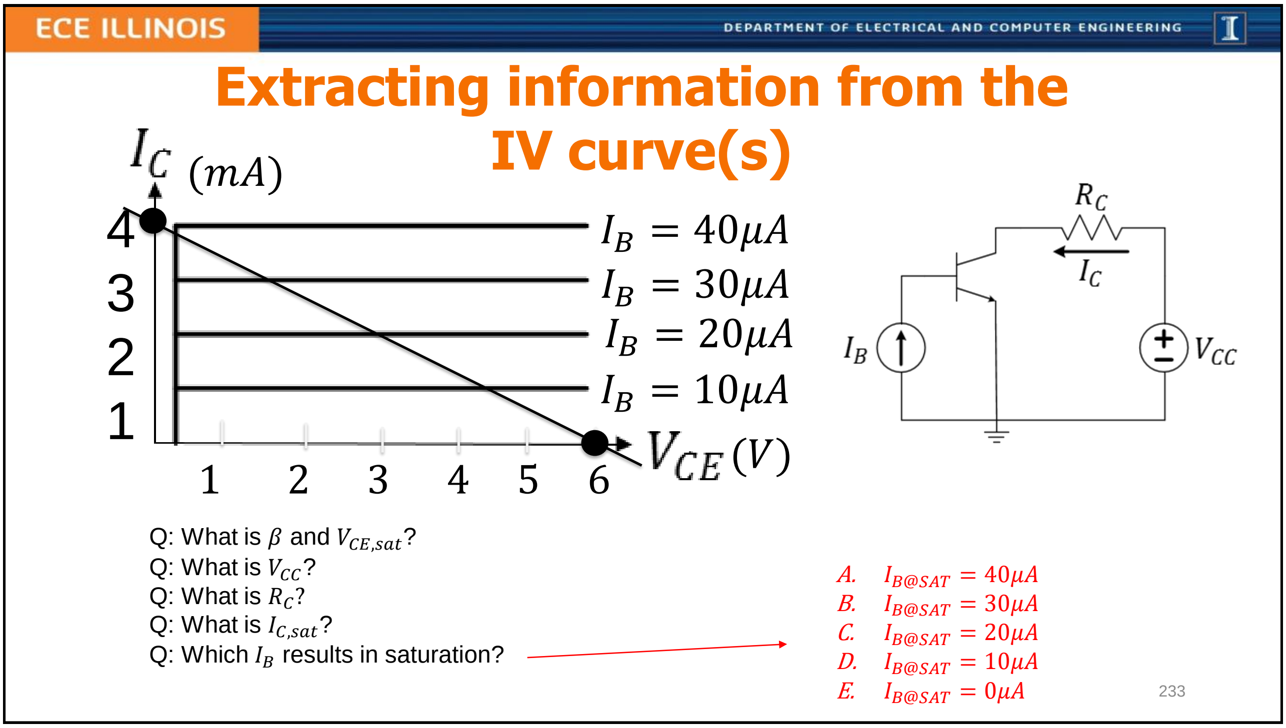
Constraints:

- $0 \leq \beta I_B \leq I_{C,sat}$
- $V_{out} \geq V_{CE,sat} > 0$



Q: Use the IV plots to estimate the value of β.

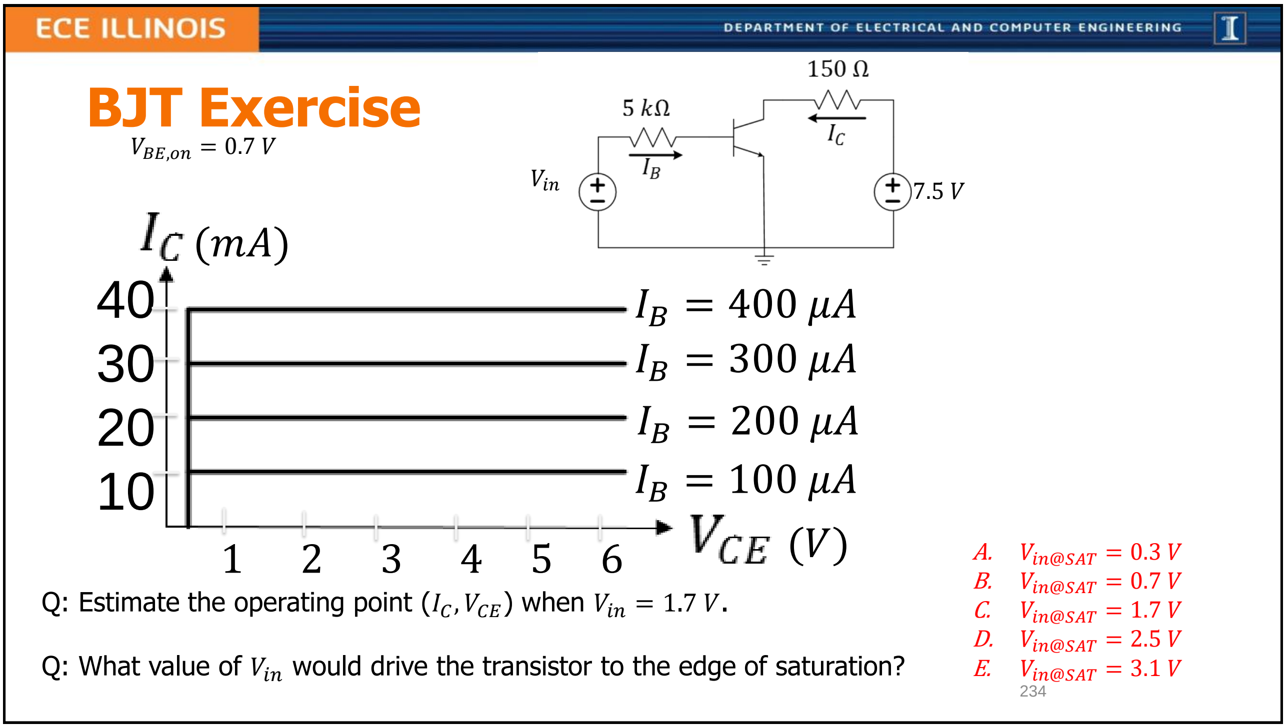
A. 10
B. 20
C. 50
D. 100
E. 200



Extracting information from the IV curve(s)

Q: What is β and $V_{CE,sat}$?
Q: What is V_{CC}?
Q: What is R_C?
Q: What is $I_{C,sat}$?
Q: Which I_B results in saturation?

- A. $I_{B@SAT} = 40\mu A$
- B. $I_{B@SAT} = 30\mu A$
- C. $I_{B@SAT} = 20\mu A$
- D. $I_{B@SAT} = 10\mu A$
- E. $I_{B@SAT} = 0\mu A$



BJT Exercise

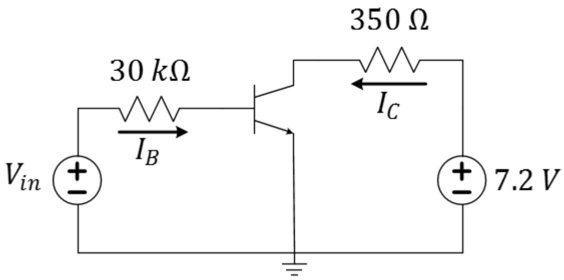
$V_{BE,on} = 0.7\ V$

Q: Estimate the operating point (I_C, V_{CE}) when $V_{in} = 1.7\ V$.

Q: What value of V_{in} would drive the transistor to the edge of saturation?

- A. $V_{in@SAT} = 0.3\ V$
- B. $V_{in@SAT} = 0.7\ V$
- C. $V_{in@SAT} = 1.7\ V$
- D. $V_{in@SAT} = 2.5\ V$
- E. $V_{in@SAT} = 3.1\ V$

BJT Exercise



BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 0.7\ V$
- $V_{CE,sat} = 0.2\ V$

Q: What value of V_{in} would drive the transistor to the edge of saturation?

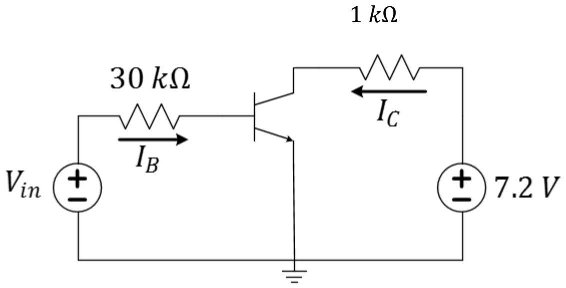
Q: How does your answer change if $30\ k\Omega$ were replaced with $60\ k\Omega$?

Q: How does your answer change if, instead, $350\ \Omega \rightarrow 700\ \Omega$?

Q10:	Q11:
A. $V_{in@sat}$ goes up	*A.* $V_{in@sat}$ goes up
B. $V_{in@sat}$ goes down	*B.* $V_{in@sat}$ goes down
C. $V_{in@sat}$ stays the same	*C.* $V_{in@sat}$ stays the same

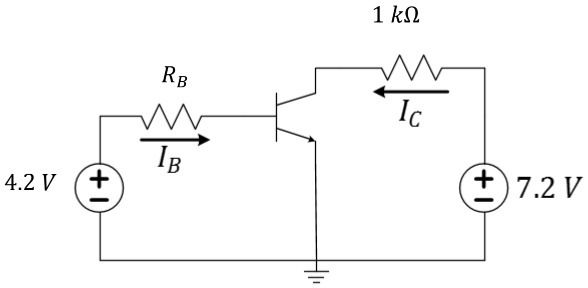
BJT circuit analysis: working back to V_{in}

BJT Datasheet: $\beta = 100, V_{BEon} = 0.7V, V_{CE,sat} = 0.2V$



Q: Find V_{in} such that $V_{CE} = 3\ V$

BJT circuit analysis



BJT Datasheet:

- $\beta = 100,$
- $V_{BEon} = 0.7\ V$
- $V_{CE,sat} = 0.2\ V$

Q: Choose R_B such that the BJT is driven to the edge of saturation.

L20 Learning Objectives

a. Find β and $V_{CE,sat}$ for a given BJT IV characteristic

b. Find V_{CC} and R_C from the IV characteristic of the load line

c. Compute $I_{C,sat}$ from $V_{CC}, V_{CE,sat}$, and R_C

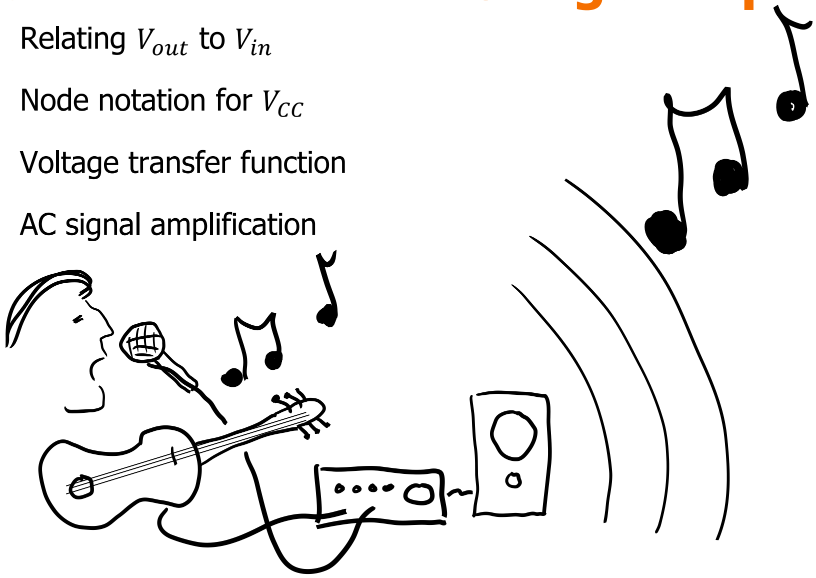
d. Identify the BJT CE operating point given IV characteristics

e. Solve numerically for unknown parameters among $\{V_{in}, R_B, I_B, \beta, V_{BE,on}, V_{CE,sat}, I_C, R_C, V_{CC}, I_{C,sat}\}$ when given some or all of the other values

f. Determine settings to drive transistor into a desired regime

Lecture 21: The BJT Voltage Amplifier

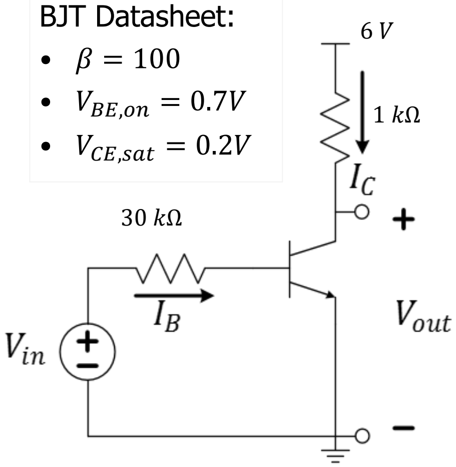
- Relating V_{out} to V_{in}
- Node notation for V_{CC}
- Voltage transfer function
- AC signal amplification



Calculating V_{out} from V_{in} (revisited)

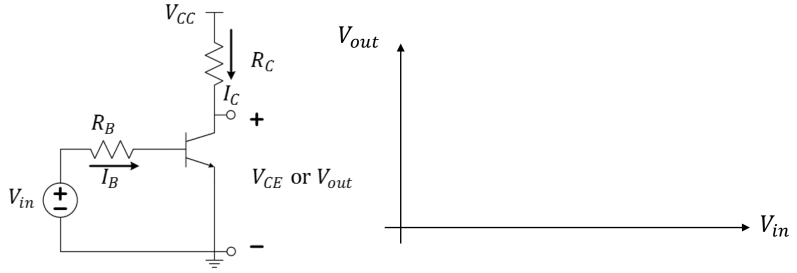
BJT Datasheet:

- $\beta = 100$
- $V_{BE,on} = 0.7V$
- $V_{CE,sat} = 0.2V$



Q: What is $v_{out} = V_{CE}$ for $V_{IN} = 0.3, 1, 2.5, \text{and } 3.5$ Volts?

Review of BJT operating regimes



Regime	Vin	IB	IC	VC

Q: What is the formula for minimum V_{IN} which causes saturation?

A. $V_{in} = \frac{V_{CC}-V_{CE,sat}}{R_C}$

B. $V_{in} = V_{CC} + V_{BEon}$

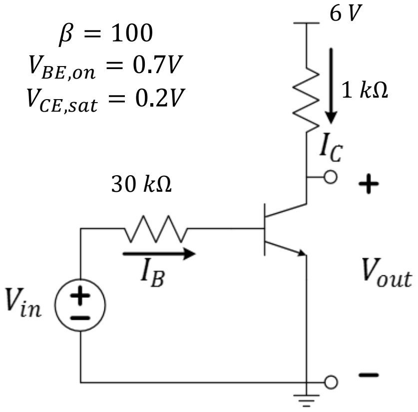
C. $V_{in} = V_{CE,sat} + I_B R_B$

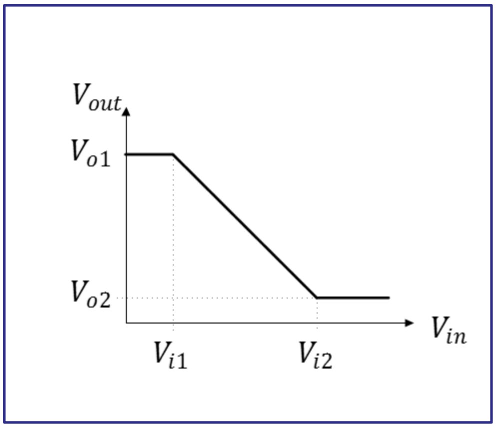
D. $V_{in} = V_{CC} - I_C R_C + I_B R_B$

E. $V_{in} = V_{BEon} + \frac{R_B}{\beta R_C}(V_{CC} - V_{CE,sat})$

Voltage transfer characteristics

$\beta = 100$
$V_{BE,on} = 0.7V$
$V_{CE,sat} = 0.2V$

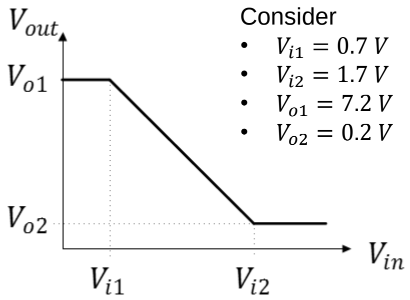




Q: What are the four values $V_{o1}, V_{o2}, V_{i1}, V_{i2}$?

Q: What is the $\frac{\Delta V_{out}}{\Delta V_{in}}$ slope in the active region?

Active regime for signal amplification



Consider

- $V_{i1} = 0.7\ V$
- $V_{i2} = 1.7\ V$
- $V_{o1} = 7.2\ V$
- $V_{o2} = 0.2\ V$

Q: If $V_{IN} = 1.2 + 0.2\cos(2\pi 100t)$, what is the equation for V_{out}?

Q: What is different if $V_{in} = 1.2 + 0.6\cos(2\pi 100t)$?

Q: What transistor regimes are entered if $V_{in} = 1.1 + 0.3\cos(\omega t)$?

A. Active only
B. Cutoff and active
C. Active and saturation
D. Saturation only
E. Cutoff, active, and saturation

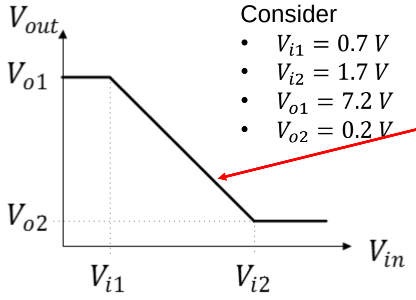
L21 Learning Objectives

a. Explain the voltage transfer curve (V_{out} vs. V_{in})
b. Find the transition points on the voltage transfer curve
c. Find the slope of the active region in the transfer curve
d. Determine the operating regions for an AC+DC input
e. Evaluate and AC+DC output for linear amplification

Lecture 22: More on Transistors

- Exercises in BJTs
- Revisit MOSFET

Active regime for signal amplification

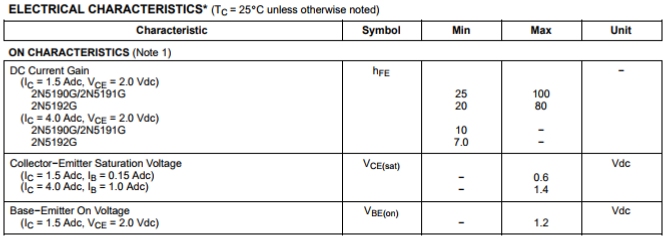


Consider
- $V_{i1} = 0.7\ V$
- $V_{i2} = 1.7\ V$
- $V_{o1} = 7.2\ V$
- $V_{o2} = 0.2\ V$

Q: Derive an equation that gives V_{out} as a function of V_{in}. Hint, find the equation of this line!

[This equation will be accurate only accurate in the linear portion of the active region.]

BJT Datasheet Parameters
2N5192G



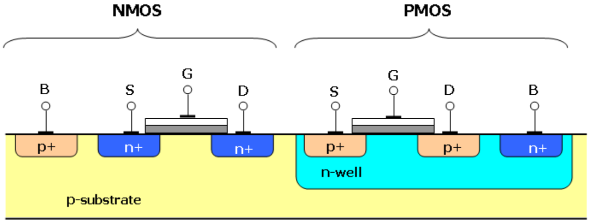
ELECTRICAL CHARACTERISTICS* (T_C = 25°C unless otherwise noted)

	Characteristic	Symbol	Min	Max	Unit
	ON CHARACTERISTICS (Note 1)				
$\approx \beta$	DC Current Gain (I_C = 1.5 Adc, V_{CE} = 2.0 Vdc) 2N5190G/2N5191G 2N5192G (I_C = 4.0 Adc, V_{CE} = 2.0 Vdc) 2N5190G/2N5191G 2N5192G	h_{FE}	 25 20 10 7.0	 100 80 – –	–
$V_{CE,sat}$	Collector–Emitter Saturation Voltage (I_C = 1.5 Adc, I_B = 0.15 Adc) (I_C = 4.0 Adc, I_B = 1.0 Adc)	$V_{CE(sat)}$	 – –	 0.6 1.4	Vdc
$V_{BE,on} \leq$	Base–Emitter On Voltage (I_C = 1.5 Adc, V_{CE} = 2.0 Vdc)	$V_{BE(on)}$	 –	 1.2	Vdc

Q: Approximate the values of $\beta, V_{BEon},$ and $V_{CE,sat}$ from the datasheet.

Field-Effect Transistors (FETs)

- Advantages of MOSFETs for IC manufacturing
- A little physics of MOSFET operation



The Metal-Oxide-Semiconductor FET

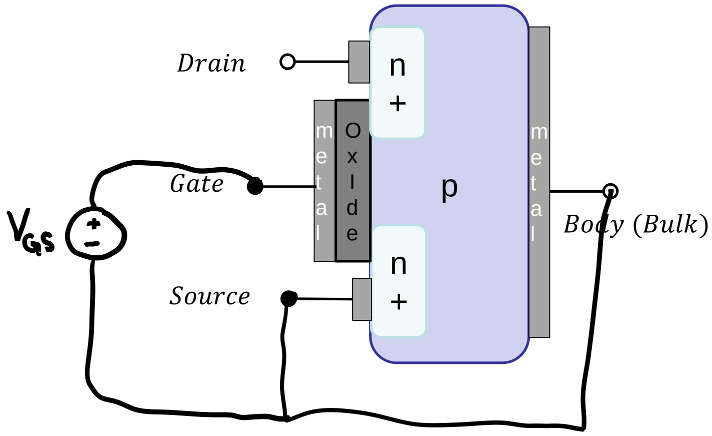
- MOSFETs are **generally** easier to fabricate; also they scale down in size better and use less power than BJTs.
- BJTs are still used in very high-speed switching integrated circuits and they are common as "discrete" devices.

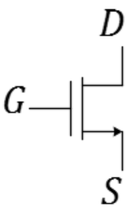
Do you know? How many transistors are in a single modern microprocessor chip?

A. ~100,000
B. ~1,000,000
C. ~10,000,000
D. ~100,000,000
E. ~1,000,000,000

To Produce a Conductive "Channel"

Source and Body are tied together and $V_{GS} > V_{TH} > 0$





L22 Learning Objectives

a. Derive an equation for $V_{out}\ vs. V_{in}$ accurate in the linear region of the transistor.

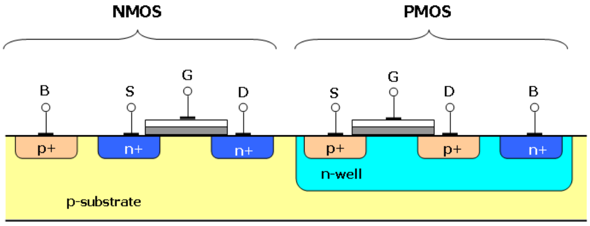
b. Be able to extract information from a transistor datasheet

c. Name advantages/disadvantages of MOSFET vs BJT

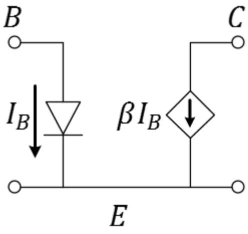
d. Describe a diagram of MOSFET physics

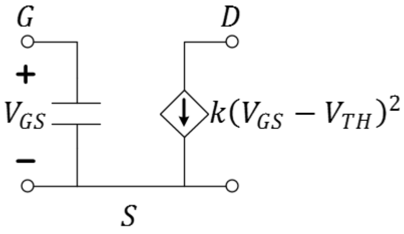
Lecture 23: Field-Effect Transistors (FETs)

- Advantages of MOSFETs for IC manufacturing
- A little physics of MOSFET operation
- MOSFET transistor regimes: operating voltages and current



BJT (NPN) vs. MOSFET (n-channel) active region models





Active: $I_C = \beta I_B$

Active: $I_D = k\ (V_{GS} - V_{TH})^2$

ECE Spotlight…

Prof. **Rosenbaum** emphasized in one 2016 paper, the need for physically-accurate circuit models to predict and protect against electrostatic discharge.

Elyse Rosenbaum
University of Illinois

Q: What happens to drain current when $V_{GS} - V_{TH}$ doubles?

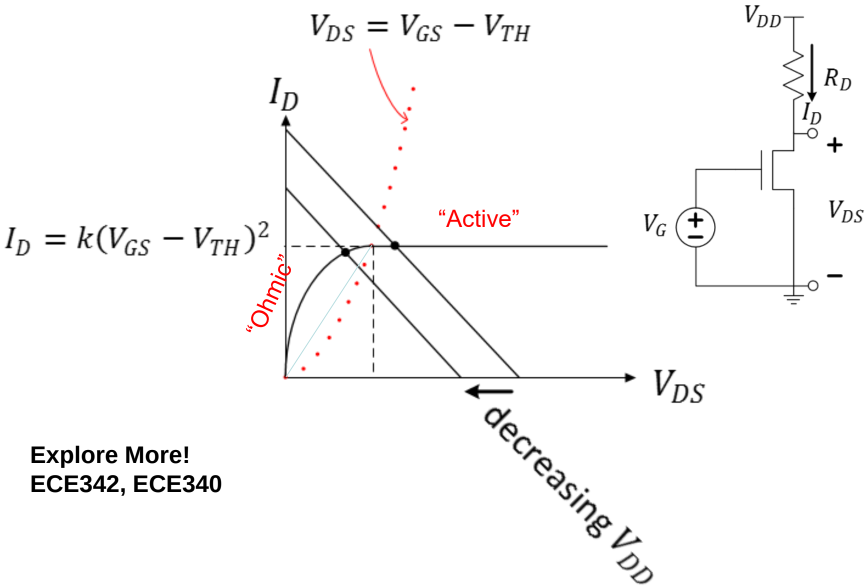
Q: What is the DC current into the gate of the MOSFET model?

Q: What are the units of k?

Q1: the drain current…

A. halves
B. stays the same
C. doubles
D. triples
E. quadruples

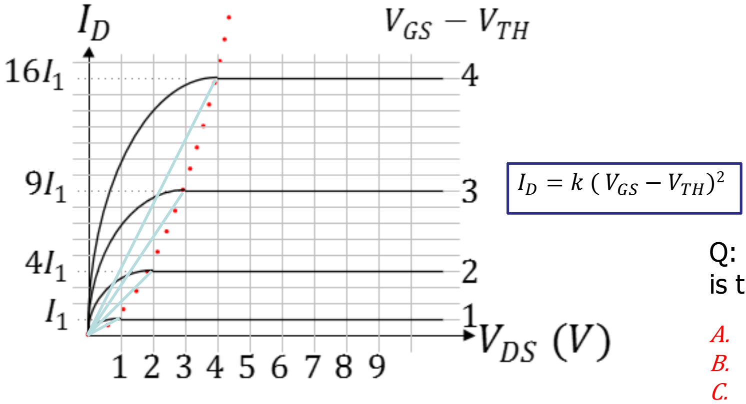
Measuring nMOS IV-curves



Explore More!
ECE342, ECE340

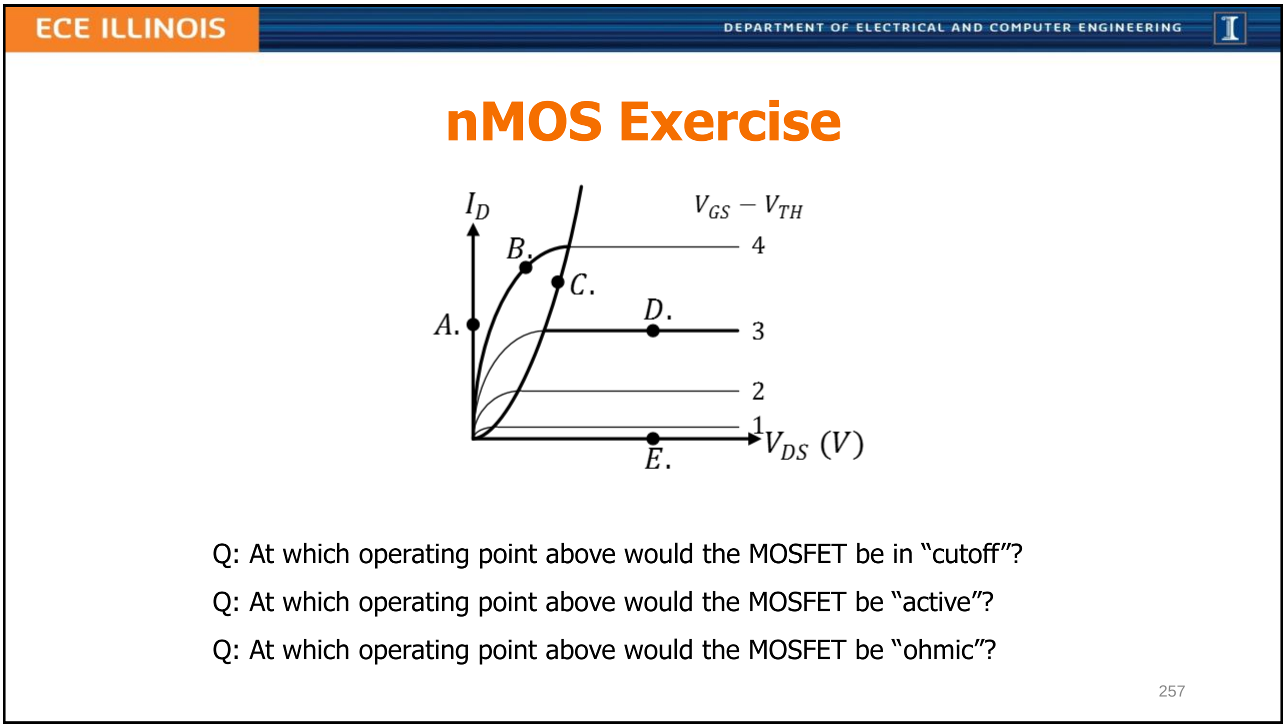
Family of nMOS IV-curves

$I_D = k\ (V_{GS} - V_{TH})V_{DS}$



Q: If $I_1 = 100\ mA$, what is the value of k?

- *A.* $k = 100\ mA/V^2$
- *B.* $k = 50\ mA/V^2$
- *C.* $k = 25\ mA/V^2$
- *D.* $k = 12.5\ mA/V^2$
- *E.* $k = 1\ mA/V^2$

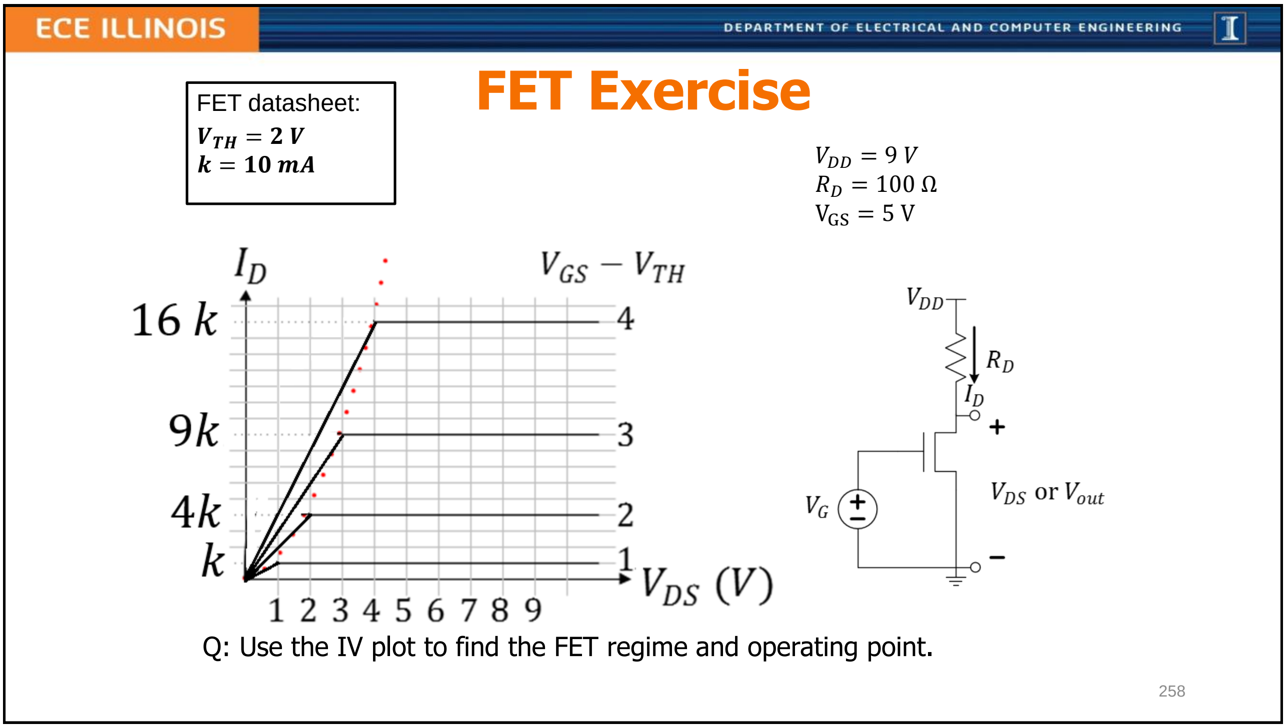


nMOS Exercise

Q: At which operating point above would the MOSFET be in “cutoff”?

Q: At which operating point above would the MOSFET be “active”?

Q: At which operating point above would the MOSFET be “ohmic”?



FET Exercise

FET datasheet:
$\boldsymbol{V_{TH} = 2\ V}$
$\boldsymbol{k = 10\ mA}$

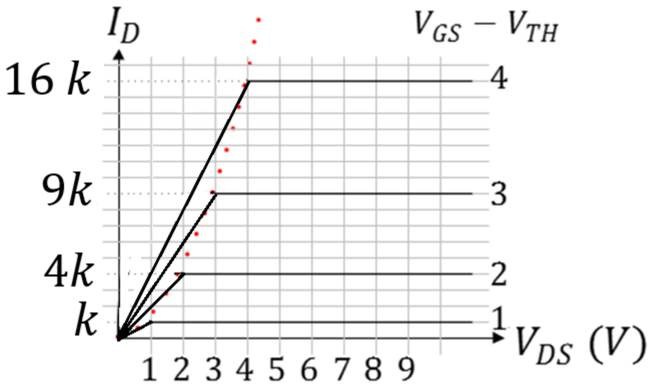
$V_{DD} = 9\ V$
$R_D = 100\ \Omega$
$\mathrm{V_{GS}} = 5\ \mathrm{V}$

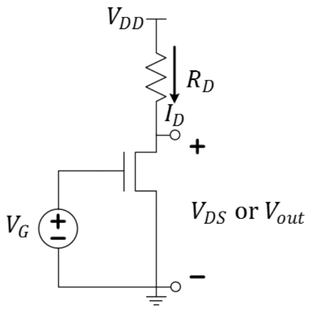
Q: Use the IV plot to find the FET regime and operating point.

FET Exercise

FET datasheet:
$\boldsymbol{V_{TH} = 2\ V}$
$\boldsymbol{k = 10\ mA}$

$V_{DD} = 9\ V$
$R_D = 100\ \Omega$
$\mathrm{V_{DS}} = 5\ \mathrm{V}$





Q: Find the Gate-to-Source voltage, V_{GS}.

L23. Learning Objectives

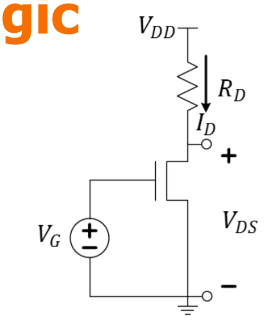
a. To recognize the physics of enhancing/creating a channel in a MOS Transistor

b. To identify the regimes of nMOS with IV curves

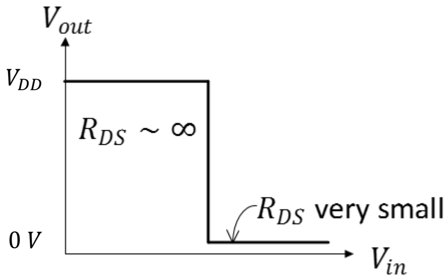
c. To solve nMOS transistor problems using IV data

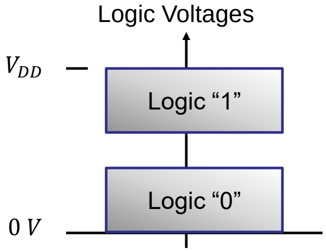
Lecture 24: cMOS Logic

- cMOS logic and circuit models
- cMOS logic circuits and truth tables
- Switching a capacitive load

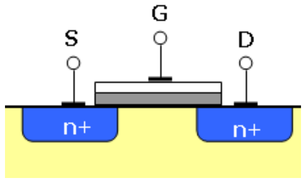


Idealized FET Model:

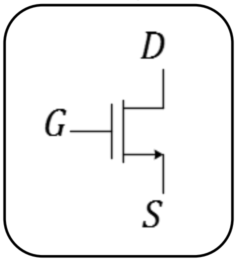




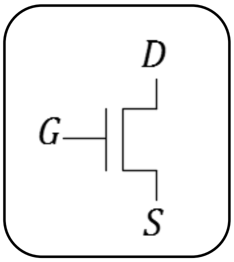
n-channel MOSFET



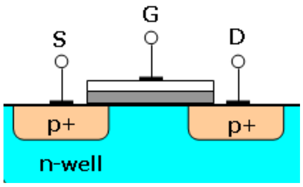
Circuit Symbol



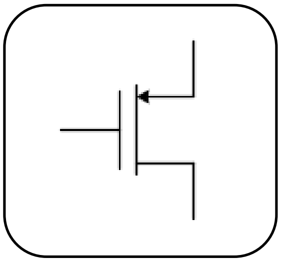
Logic Symbol



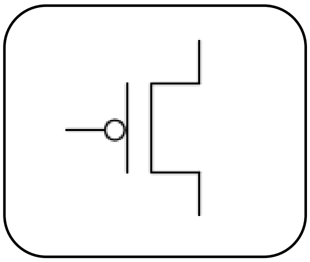
p-channel MOSFET



Circuit Symbol



Logic Symbol

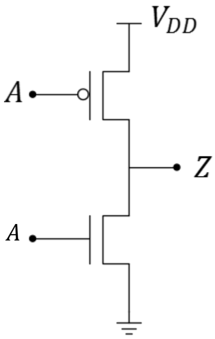


Q: What happens when a logical "0" is applied to the gate?

A. Electrons are attracted to the gate and a channel forms.
B. Electrons are chased from the gate and a channel is formed.
C. The voltage is too low to effect the channel at all.

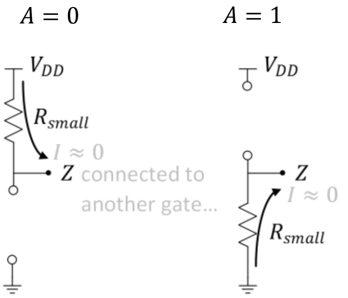
---

cMOS implementation of Inverter



***Truth Table*:**
For *each and every* logical combination of inputs, list the resulting logical output

input	output
A	**Z**
0	
1	

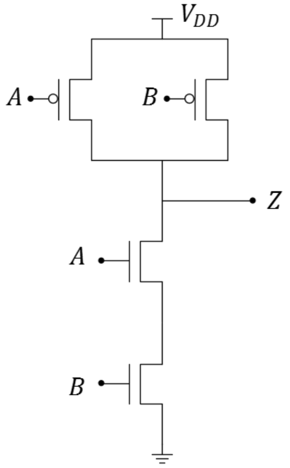


Q: What is the output voltage when the input is connected to V_{DD}?

Q: What is the output voltage when the input is connected to GND?

Q: Complete the Logical "Truth Table".

A Two-Input cMOS Circuit

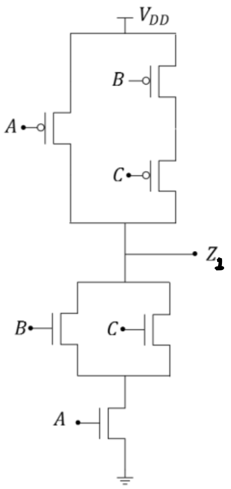


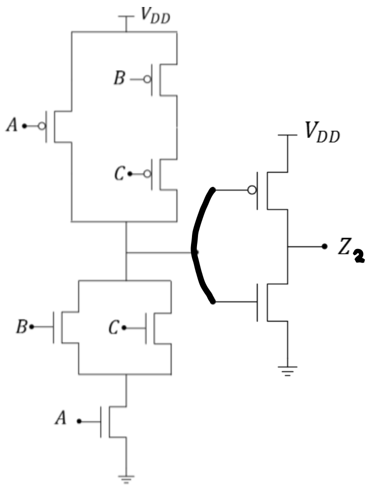
A	B	Z
0	0	1
0	1	ρ
1	0	γ
1	1	0

Q: Complete the Truth Table.

A. $\rho = 0, \gamma = 0$
B. $\rho = 0, \gamma = 1$
C. $\rho = 1, \gamma = 0$
D. $\rho = 1, \gamma = 1$
E. Cannot determine

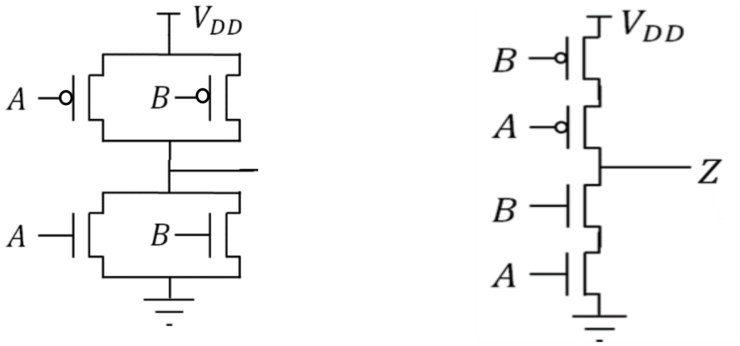
A Three-Input cMOS Circuit





Q: Complete the Truth Tables.

Improperly-Constructed cMOS Circuits



Q: Attempt to complete the Truth Tables.

---

cMOS Energy

Q: How much energy is stored in each gate ($C = 1fF$) if charged to V_{DD}?

Q: How much energy is consumed from the voltage source to charge it?

Power consumed by a single switching FET

$$P = a\, f\, C\, V^2 n$$

a – activity factor
f – switching frequency
C – load capacitance
V – switching voltages
n – number of transistors switching

ECE Spotlight…

Prof. **Hanumolu** works to produce useful circuits with small dimensions that "can be implemented in small area and with minimal power consumption while operating at high [frequency]."

- Largest source of power consumption in computer chips
- Reduction of contributing factors is a technological goal

Q: How many $2\ fF$ caps are switched at $1\ V$ every ns to dissipate $100\ W$?
Q: If the total number of transistors on a chip is 1 billion, what is a?

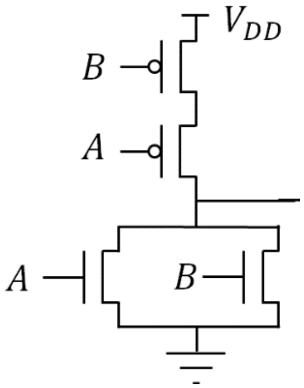
L24. Learning Objectives

a. To explain operation of a cMOS inverter

b. To interpret cMOS logic and express in Truth Table form

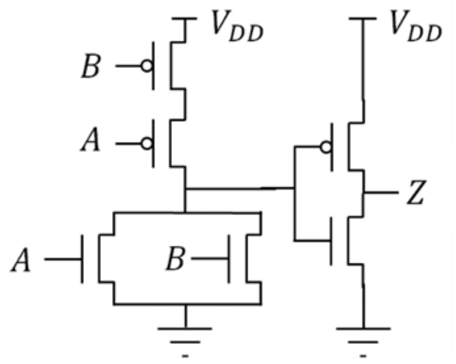
c. To calculate power consumption due to cMOS switching with capacitive loads

Two-Input cMOS Circuit



Q: Complete the Truth Table.

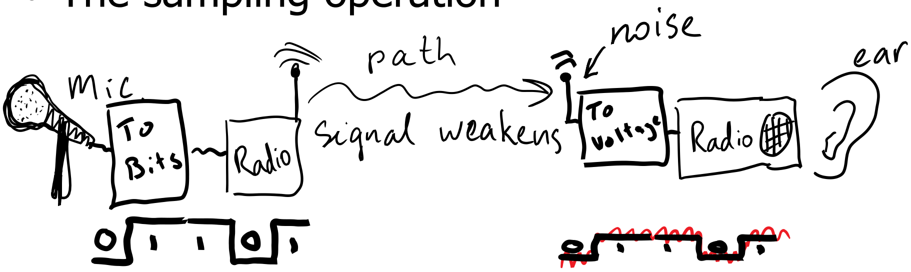
Two-Input cMOS Circuit



Q: Complete the Truth Table.

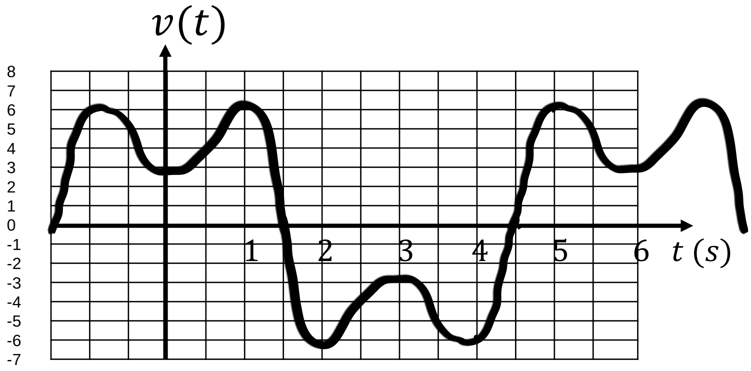
L25: Analog-to-Digital

- Noise-immunity motivation
- Describing waveforms by samples
- The sampling operation



digital (only some voltage levels allowed!)

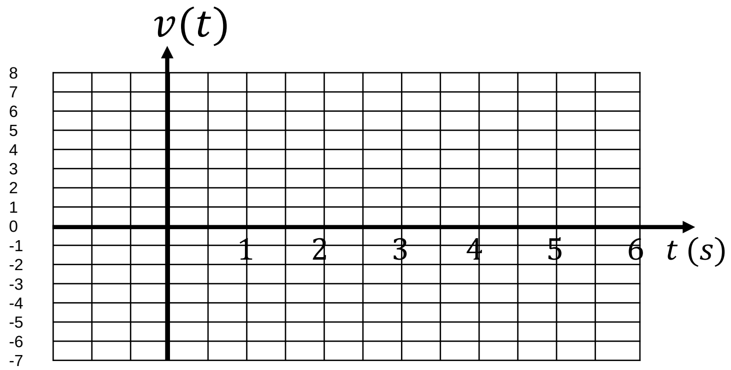
How Would you Sketch this Waveform?



Q: What are the values at $t = 0, 2, 4, and\ 6$ seconds?

Q: Is this enough information to reproduce the waveform?

Enter Data Points of the Previous Waveform.



Q: How should one connect the data points?

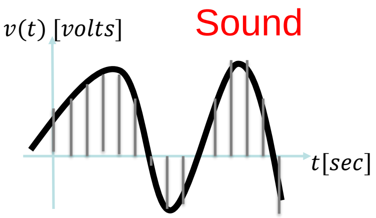
A. Point-to-point with straight lines. 

B. Point-to-point with curvy lines. 

C. Point-to-point, but only with horizontal and vertical lines. 

When storing these values using bits, how many should we use? (NEXT LECTURE!)

Sampling: Sensing real-world data at uniform intervals



T_s: Sampling period

$$f_s = \frac{1}{T_s} : Sampling\ Frequency$$

Sampled Sequence:

$$v[n] = v(t = nT_s), n\ integer\ (n = -2, -1, 0, 1, 2, \dots)$$

Example: $y(t) = 5t\ sampled\ at\ T_S = 2$

Answer: $y[n] = y(nT_s) = 5\text{n}2 = 10\text{n} = \cdots, -20, -10, 0, 10, 20, \dots$

Sampling

Sampled Sequence:

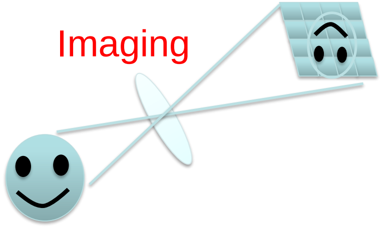
$$v[n] = v(t = nT_s), n\ integer\ (n = -2, -1, 0, 1, 2, \dots)$$

Q: Let $v_1(t) = 2cos(\pi t)$. Plot $v_1(t)$.

Q: Let $v_1(t) = 2cos(\pi t)$.
If $T_s = 0.5\ s$, what is $v_1[6]$?

Q: Let $v(t) = 5\cos\left(\frac{\pi}{3}t\right) - 2cos(\pi t)$.
If $T_s = 0.5\ s$, what is $v[6]$?

Sampling: Sensing real-world data at uniform intervals



Think About It! How does sampling work in digital photography?

Largest Sampling Period, T_S

If you sample fast enough to catch the highs/lows on a wiggly waveform, **then** you can smoothly reconnect the data points to recreate it.

Q: Speech is intelligible if frequencies up to 3.5 kHz are preserved. What should we use for T_S?

A. $< \frac{1}{7}\ ms$
B. $< \frac{1}{3.5}\ ms$
C. $< \ 3.5\ ms$
D. $> 3.5\ ms$
E. $> \ 7\ ms$

L25: Learning Objectives

a. Explain the motivation for digital signals

b. Determine reasonable sampling interval for plotted waveforms

c. Sample an algebraic signal given a sampling interval

L26: Preserving Information in A/D

- Nyquist Rate
- Quantization
- Memory Registers
- Binary Numbers
- Aliasing
- A/D block diagram
- D/A block diagram

Nyquist Rate: lower bound on f_s

A sampled signal can be converted back into its original analog signal without any error if the sampling rate is more than twice as large as the highest frequency in the signal.

$$\boxed{f_s > 2f_{max}}$$

☺No loss of information due to sampling☺

Interpolation: recreate analog with a special function!

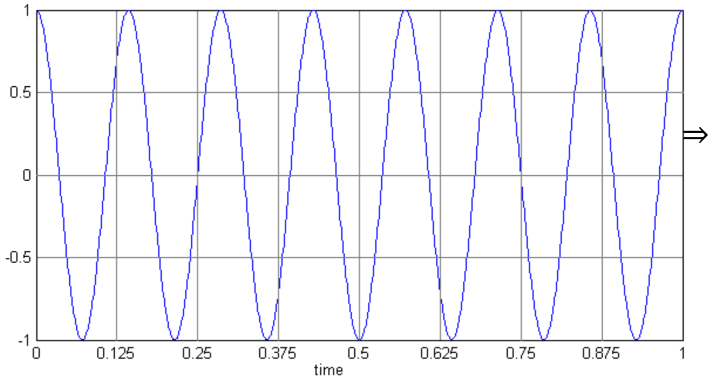
Q: Speech is intelligible if frequencies up to 3.5 kHz are preserved. What is the Nyquist rate?

Q: Music is often filtered to include sounds up to 20 kHz. What sampling rate should we use?

A. 1.75 kHz
B. 3.5 kHz
C. 5.25 kHz
D. 7 kHz
E. 8 kHz

Aliasing occurs when Sampling is sparse

When f_s is too small (T_s is too large), high-frequency signals masquerade as lower frequency signals…

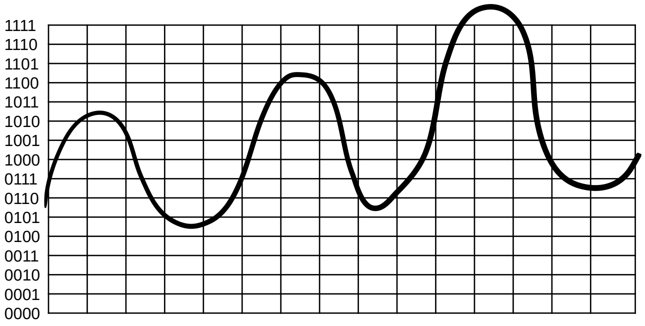


$\cos(2\pi 7t)$

$\Rightarrow f_{max} = 7\ Hz$

Q: When sampling at $f_s = 8\ Hz$, what is the frequency of the signal above after reconstruction?

Quantization:
Round voltage values to nearest discrete level



Q: Assume we sample at the vertical lines. Digitize the waveform using four-bit samples.

Computers are made of cMOS Circuits

- **Registers** are combinations of logic circuits that utilize electrical **feedback** to serve as computer's working memory.
- Each register element is a bit which can be 0 (low) or 1 (high)
- Example: An 8-bit register holds 8 binary values.

Choose the largest 8-bit binary value.

A. 00001011
B. 00010110
C. 00010000
D. 00001111
E. 00000101

Binary Numbers

Any number system has a base, N, with N digits $\{0, \ldots, N-1\}$, and n-digit number representations with the distance from the decimal point indication what base power each digit represents.

3-digit Binary integers:

$\mathbf{0}$: 0 0 0
$\mathbf{1}$: 0 0 1
$\mathbf{2}$: 0 1 0
$\mathbf{3}$: 0 1 1
$\mathbf{4}$: 1 0 0
$\mathbf{5}$: 1 0 1
$\mathbf{6}$: 1 1 0
$\mathbf{7}$: 1 1 1

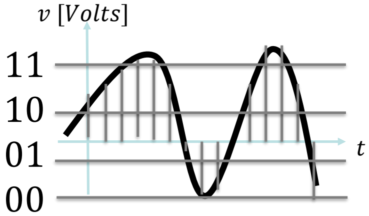
Base 10: What is the number 51?

$2-digit\ number$:	5	1
$position\ (in\ decimal)$:	$10s\ place$	$1s\ place$
$meaning\ (in\ decimal)$:	$5 \times 10 +$	1×1

Base 2: What is the number 101_2?

$3-digit\ number$:	1	0	1
$position\ (in\ decimal)$:	4	2	1
$meaning\ (in\ decimal)$:	$1 \times 4 +$	$0 \times 2 +$	1×1

More bits=More levels= Less Quantization Error (Noise)

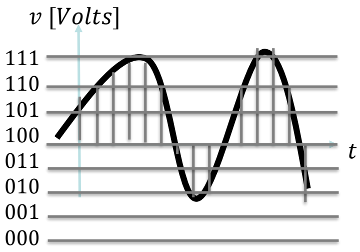


Example: 2 − *bit quantizer*

$$\boxed{e[n] = v[n] - v_Q[n]}$$

Q: If the voltages 2.93 and 5.26 are quantized to the nearest 0.25 V, what are the quantization errors?

3-Bit Quantizer



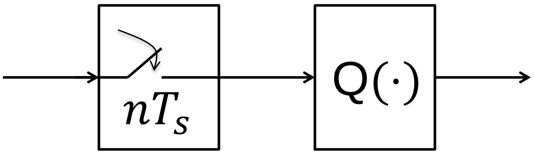
Dynamic Range

Example: 3 − *bit quantizer*

Q: How many levels in a 10-bit quantizer?

A. 4
B. 8
C. 10
D. 100
E. 1024

Sampling + Quantization =Digitization



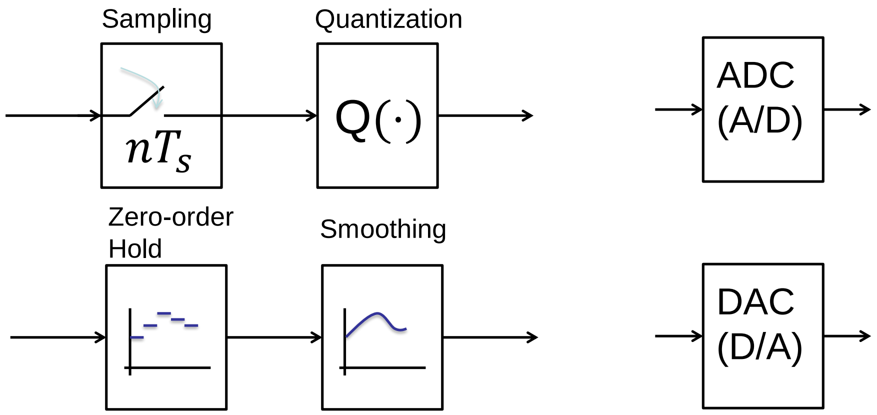
nT_s

$Q(\cdot)$

- $Sampling\ Rate\ =\ 1/(Sampling\ Period)$ $\quad f_s = \frac{1}{T_s}$
- $\uparrow Sampling\ Rate \Rightarrow \uparrow Memory\ usage$
- $\downarrow Sampling\ Rate \Rightarrow Loss\ of\ Information?$

Q: Under what conditions on sampling and on quantization will you incur a loss of information?

Analog-to-Digital Converter
Digital-to-Analog Converter



Sampling

Quantization

nT_s

$Q(\cdot)$

ADC (A/D)

Zero-order Hold

Smoothing

DAC (D/A)

The zero-order hold results in an analog voltage. What circuit parts might a smoothing filter contain?

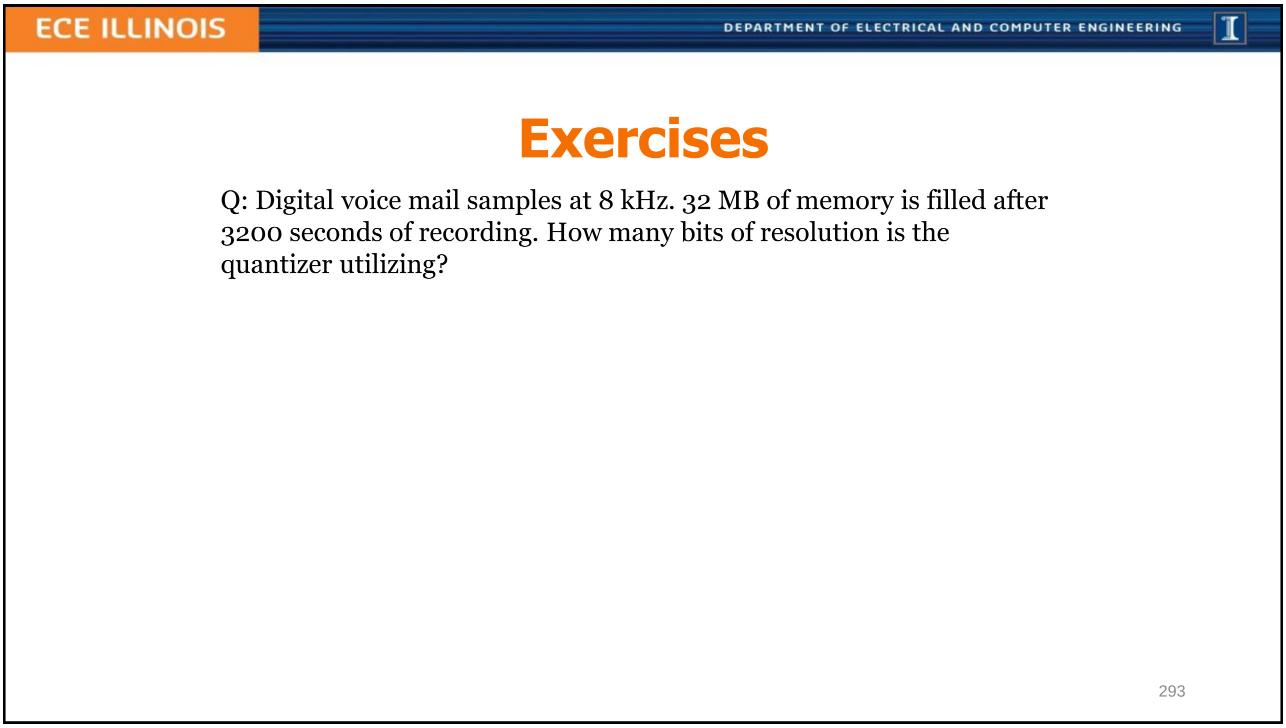
A. Resistors B. Capacitors C. Diodes D. BJTs E. MOSFETs

Exercises

Q: CD-quality music is sampled at 44.1 kHz with a 16-bit quantizer. How much memory (in Bytes) is used to store 10 seconds of sampled-and-quantized data?

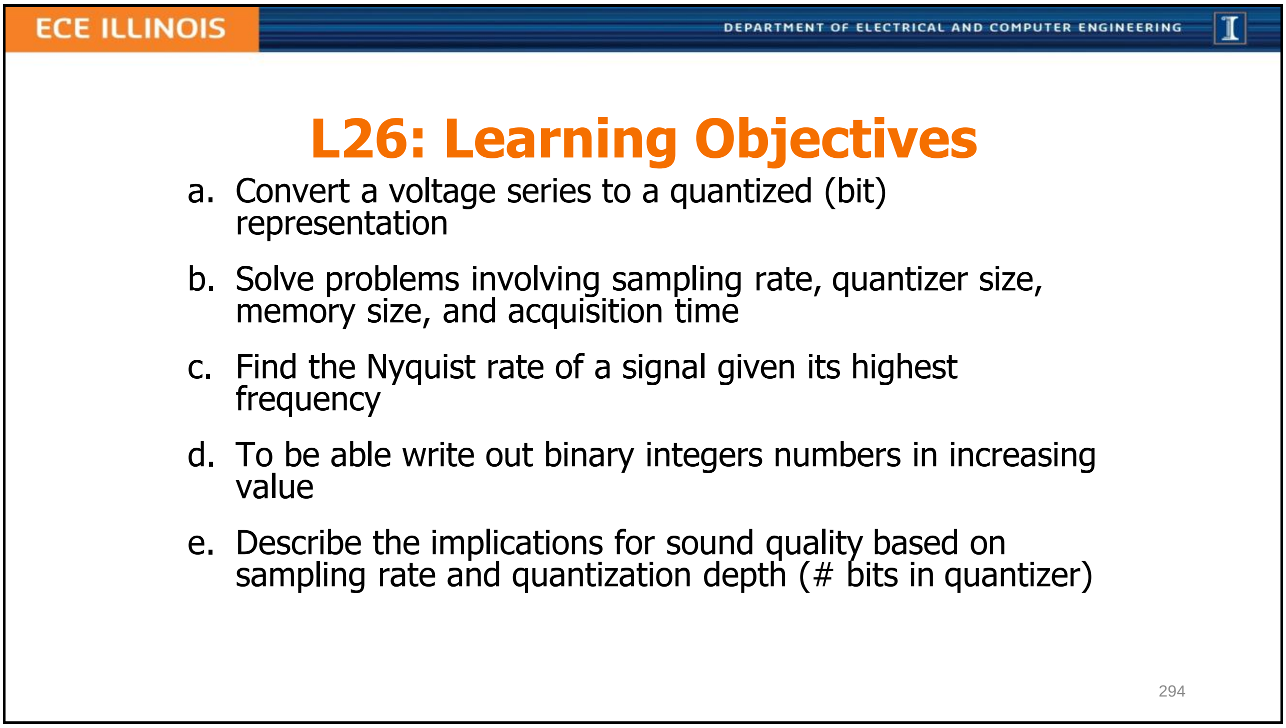
Exercises

Q: CD-quality music is sampled at 44.1 kHz with a 16-bit quantizer. It is stored on a 700 MB CD. How many minutes of music do you predict a single CD can hold? (Does your answer account for stereo?)



Exercises

Q: Digital voice mail samples at 8 kHz. 32 MB of memory is filled after 3200 seconds of recording. How many bits of resolution is the quantizer utilizing?



L26: Learning Objectives

a. Convert a voltage series to a quantized (bit) representation

b. Solve problems involving sampling rate, quantizer size, memory size, and acquisition time

c. Find the Nyquist rate of a signal given its highest frequency

d. To be able write out binary integers numbers in increasing value

e. Describe the implications for sound quality based on sampling rate and quantization depth (# bits in quantizer)

Lecture 27: Content Personalization

More of what you want to know! Instructor will choose the content and learning objectives based largely on student surveys from early in the semester!

L27: Learning Objectives

a. Both the content and learning objectives of this lecture will be determined by the instructors during the semester. They will use feedback provided by the students to tailor their choices.

Lecture 28: Photodiodes and Solar Panels

- The nature of light
- Photon absorption in semiconductors
- Photocurrent in diodes and its use
  - Detecting light and signals
  - Generating electrical energy
- Energy from solar panels

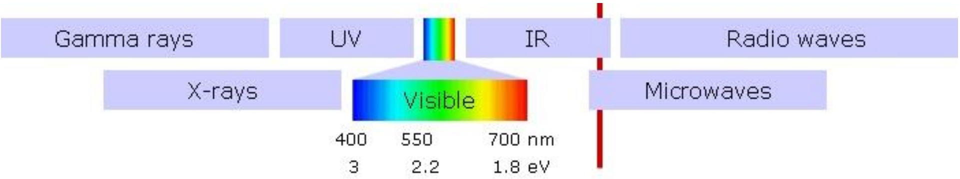
Light consists of (Energetic) Photons

- Photons are sometimes called wave packets
- Each photon (of wavelength λ in *nm*) carries an amount of energy

$$E = \frac{1240}{\lambda}\left[\frac{eV}{photon}\right]$$

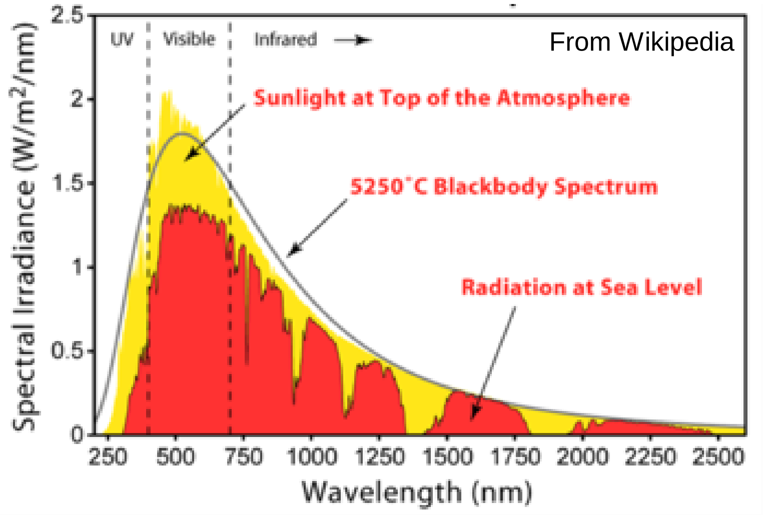
$1\ eV$ is equivalent to $1.6 \times 10^{-19}\ J$

- The color of light depends on its wavelength, λ



Q: How many photons per second are provided by a 1 mW 650 nm laser?

Available Solar Energy (Radiation Spectrum)



From Wikipedia

Pick the closest answer:

A. $1\ W/m^2$
B. $10\ W/m^2$
C. $100\ W/m^2$
D. $1000\ W/m^2$
E. $10\ kW/m^2$

Q: Estimate the solar irradiance (W/m^2) at sea level (hint: total red area).

Creating electron-hole pairs in Semiconductors

- An electron in a material can absorb a photon’s energy
- An electron can sometimes lose energy to emit a photon
- Semiconductor electrons have a gap in allowed energy, E_g
- Photons with energy bigger than the gap are absorbed
- Absorbed photons can create usable electrical energy

Exercises

Q: What is the maximum wavelength absorbed by:

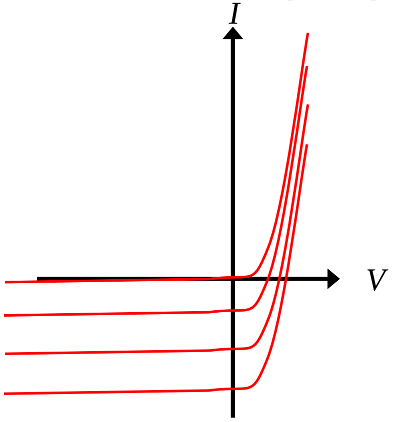
Si ($E_g = 1.1\ eV$),

by GaN ($E_g = 3.4\ eV$),

and by diamond carbon ($E_g = 5.5\ eV$)?

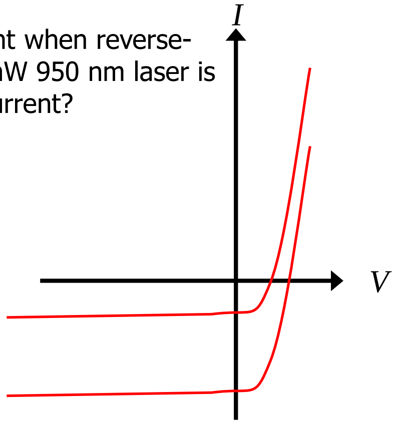
Photodiode IV depends on impinging Light

- Reverse bias mode
  - Photodetector
  - Detecting light signals
  - Energy is dissipated
- Forward bias mode
  - Photovoltaic cell
  - Energy is generated



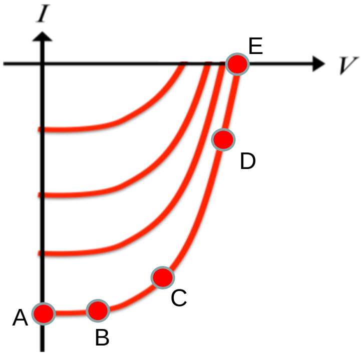
Exercise

Q: Sparkfun's BPW34 photodiode generates 50 μA of current when reverse-biased and illuminated with 1 mW/cm² at 950 nm. If a 1 mW 950 nm laser is focused on the photodetector, what is the resulting photocurrent?



Photovoltaic operation collects Energy

- Forward-bias mode
- $P = IV$ is supplied
- Maximum power point
- $P_{max} = I_m V_m = FF\ I_{sc} V_{oc}$
- Typical FF = 70%



Q: Identify the P_{max} point above

Q: If Sparkfun's BPW34 photodiode has $I_{SC} = 40\ \mu A$ and $V_{OC} = 350\ mV$ when illuminated with 1 mW/cm² at 950 nm, and the fill factor is 50% what is the maximum power produced?

Solar panels as energy sources

Q: Assuming 500 W/m^2 solar irradiance and a 25% efficient solar panel, how much roof area should be covered to supply 50A at 120V?

Q: Given an average of 5 hours of sunshine per day and a utility cost of $0.11/kWh how much of the utility cost can such a solar panel save?

ECE Spotlight…

ECEB is aspiring to a Net Zero Energy rating and targeting LEED Platinum certification from the U.S. Green Building Council. You should look into the project to learn how it is being achieved. Do some of your own number crunching!

Lecture 28 Learning Objectives

a. Relate photon flux (photons/sec) to power and wavelength
b. Calculate maximum absorbed wavelength for a band gap
c. Sketch photodiode IV curve and explain operating regimes
d. Calculate reverse bias current for incident light power
e. Calculate maximum power from IV intercepts and fill factor
f. Estimate power (and its $ value) produced by a solar panel

Lecture 29: Course Review

- If you have a request that a specific question or topic be covered on this day, please email your instructor.
- Other questions will focus on *muddy points*.
- More info TBA.
