Lecture 1: ECE110 *Introduction to Electronics*

Defining our field of study

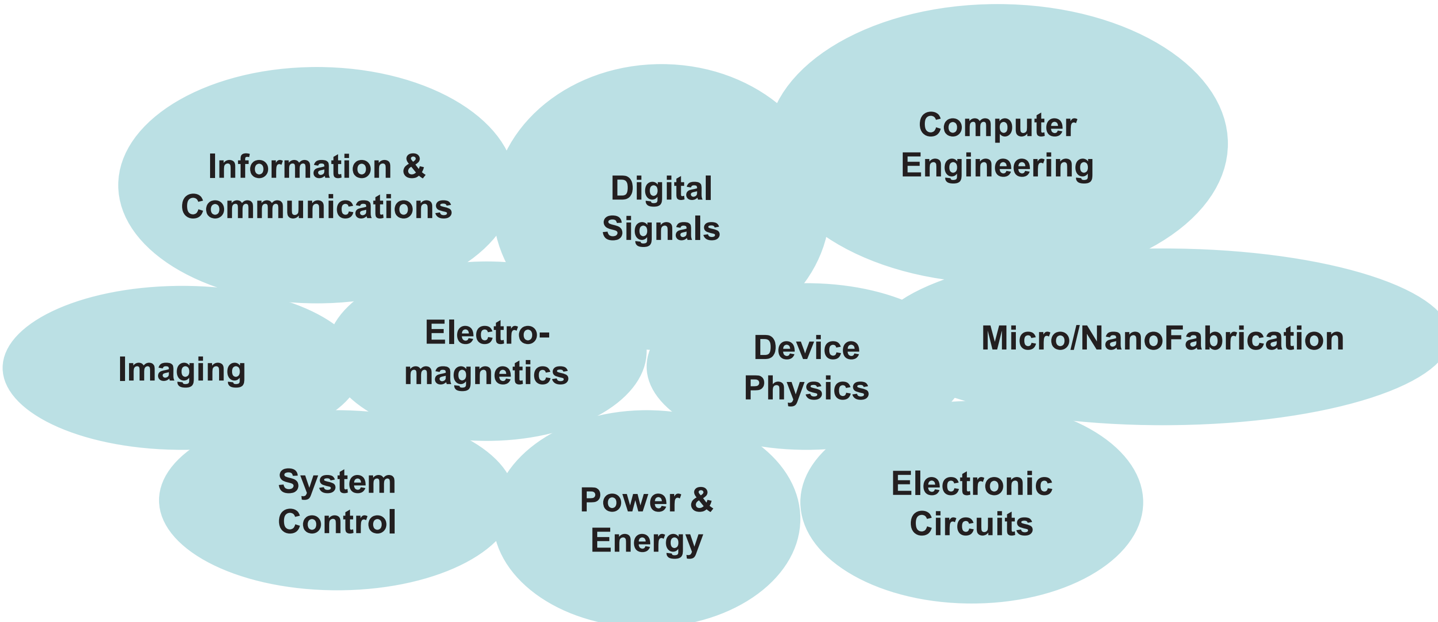
"***Engineers*** use the knowledge of mathematics and natural sciences gained by study, experience, and practice, applied with judgment, to develop ways to economically utilize the materials and forces of nature for the benefit of mankind. "

- ABET (Accreditation Board for Engineering and Technology)

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

- WikiPedia

Electrical Engineering: numerous inseparable focus areas



ECE110 introduces electrical engineering with a focus on electronics

You will:

- **measure** and **model** electrical devices
- **analyze** electrical circuits
- **construct** electrical systems
- **design** a control system for your own autonomous vehicle

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

Charge and Current

- an electron is a charged subatomic particle
- the coulomb (C) is a measure of electric charge with

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

- Electric current is the flow of electric charge in time (C/s)

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

- The ampere is the unit of electric current

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

L1Q1: What is the charge of 1 billion electrons?
L1Q2: If 1 billion electrons pass a cross section of a wire every nanosecond, what is the electric current in amps?

Voltage and Energy

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

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

L1Q3: A certain battery imparts 480 pJ to every 1 billion electrons. What is its voltage?
L1Q4: What is the charge moved through 400 V to provide 800 kJ of energy?
L1Q5: What is the average current if the energy in Q4 is provided in five seconds?

Energy and Power

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

Also, power is (rate of charge flow)·(potential difference)

And power is current·*voltage*

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

L1Q6: A flashlight bulb dissipates $6\ W$ at $2\ A$. What is the supplied voltage?

Assignments

- Homework is online via the "Lon Capa" learning management system.
  - Post your questions right inside the problem!
  - Multiple chances on most numerical questions
  - Due Fridays at 3pm
  - Absolutely no late submissions allowed (start early if you plan to be sick on Fridays)
  - To get help in office hours, bring your solution on paper! Print a pdf version of the assignment.

- Lab
  - Meets weekly **including this week** in the "lecture side", room 1005 ECEB
  - Move to 1001 ECEB when TA tells you
  - DOES NOT MEET **week of MLK/Labor Day** or **Spring/Fall Break**
  - Prelab assignments generally due at the beginning of your meeting
  - Lab submitted at the end of each lab period

Attendance policies

- Lab attendance
  - Mandatory
  - medical or personal emergency?

    Contact your lab Teaching Assistant (not me!) ASAP
  - No food/drink in 1001 ECEB (but okay in 1005 ECEB)

- Lecture attendance
  - Attend 4 out of every 5 lectures, *on average*, and you *might* get a perfect attendance score. It is collected via unannounced *i>clicker* quizzes during most lectures. You may attend ANY lecture section to gain attendance credit for that day.

Grading policies

Laboratory	**30%**
Weekly Labs	15%
Explore More! Modules	5 %
Final Project	10%
Lecture Total	**70%**
2 midterms	30%
Final Exam	25%
Lon-Capa HW	10%
Attendance	4 %
Weekly Surveys	1 %

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%

*You must score at least 50% in each of lecture and lab grades to avoid failing!

Required course materials

- IUB or TIS Bookstore
  - ECE 110 Lecture Slides (also online)
  - Lab Procedures (also online)
- ECE store
  - SparkFun ECE110 hardware kit ($110, *everyone* needs one)
  - i>clicker
- Online (courses.engr.Illinois.edu/ece110)
  - Announcements
  - Course notes, examples, videos, etc.
  - Weekly assignments

L1 Learning Objectives

a. (L1a) Compute relationships between charge, time, and current.
b. (L1b) Compute relationships between charge, voltage, and energy.
c. (L1c) Compute relationships between power, current, and voltage.

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

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

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

Lecture 2: A history… From Charge Storage to Ohm's Law

- A short video
- Capacitors
- Batteries
- Conservation of Energy
- Ohm's Law

Energy Facts

- Conservation of Energy

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

- Mechanical Energy

  Kinetic and Potential Energy; Energy vs. Power

- Electrical Energy Storage

  Capacitors and Batteries

Capacitors: store electrical energy

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

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

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

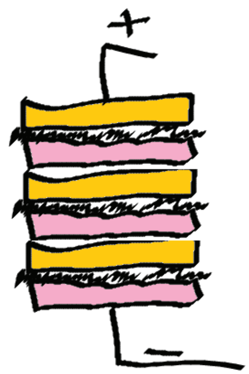
L2Q1: At what voltage would a $1\ nF$ capacitor have the energy to lift $100\ kg$ by $2\ cm$?

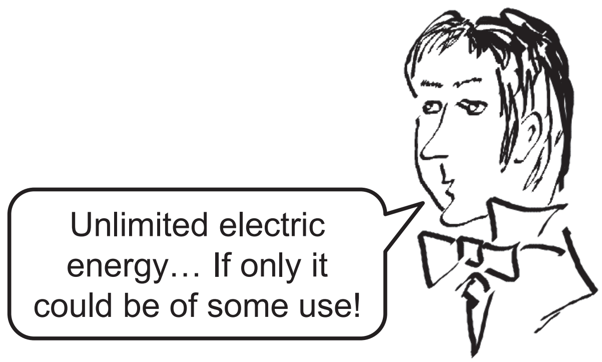
Special Capacitor: Defibrillator

L2Q2: How much energy is in the 42 μF defibrillator capacitor charged to 5 kV?

Batteries: store/generate energy

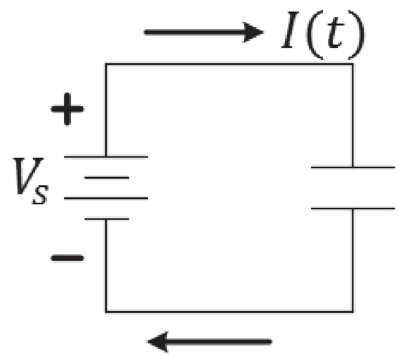
- Batteries generate electrical energy with chemical reaction
- Invention published by Volta around 1790 – huge milestone!





L2Q3: What is the charge moved through a 9-V battery to provide 3 J of energy?

Example



- $\Delta E_{battery} = \Delta E_{capacitor} + \Delta E_{waste}$
- $\Delta E_{battery} = \frac{1}{2}CV^2 + \frac{1}{2}CV^2 = CV^2$
- $\Delta E_{waste} \geq \frac{1}{2}CV^2$ is a non-obvious fact of physics (PHY212)

Batteries and capacitors notes

- The current drawn from a capacitor or battery depends on the *load.*
  - Include wires, light bulbs, LEDs, motors, etc.
  - What limits the maximum current possible?
  - We need simplified *Models* for batteries and loads
- Batteries vs. Capacitors

L2Q4: If a battery is labeled at 9 V and 500 mAh, how much energy does it store?
L2Q5: For how long can such battery power an LED if it draws 50 mA of current?

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

Motivated by long-distance telegraphy, Georg Ohm 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

L2Q6: Find the diameter of one mile of Cu ($\rho = 1.7 \times 10^{-8}\ \Omega\, m$) wire when $R\ =\ 10\ \Omega$.
L2Q7: If the resistance of one wire is $10\ \Omega$, what is the resistance of two such wires in parallel?

Resistors are devices that obey Ohm's Law

- Resistors are used to set current when voltage is given
- Resistors are used to set voltage when current is given
- Power is always dissipated in resistors, and they heat up

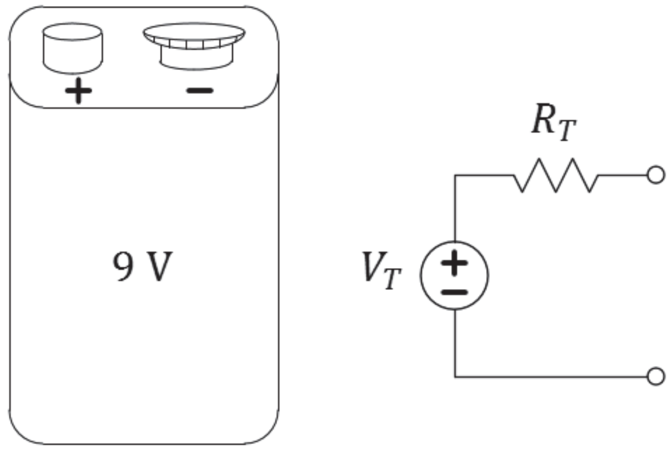
$$P = I\,V = \frac{V^2}{R} = I^2 R$$

L2Q8: If a resistor of 100 Ω is specified to 0.25 W, what is its maximum current?

L2Q9: What is the power dissipated by that resistor if there is a 6 V drop across it?

Resistances are used to model devices

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



L2Q10: If a 9 V battery has a maximum current of 2 A, what is its model contact R?

Q11: When would you want to use a capacitor over a battery?

A. When you need a burst of high current for short time
B. When you need to power something at a constant current over a long period of time
C. Always, batteries just too expensive compared to caps
D. Never, batteries are better, more expensive than caps
E. Not sure what's going on

L2 Learning Objectives

a. (L2a) Solve energy transfer problems involving mechanical potential and kinetic energy as well as efficiency (or wasted energy) considerations.
b. (L2b) Compute power, energy, and time, given two of three.
c. (L2c) For a capacitor, compute stored energy, voltage, charge, and capacitance given any of the two quantities.
d. (L2d) Compute energy stored in a battery and discharge time.
e. (L2e) Compute resistance of a cylindrical conductor given dimensions.
f. (L2f) Relate voltage and current for an "Ohmic" conductor.
g. (L2g) Perform unit conversions for energy, charge, etc.
h. (L2h) Use Ohm's Law to model the internal resistance of a physical battery.

Lecture 3 : Power and Energy

- Announcements
- Power and Energy with examples

What to do if you are Feeling Ill…

Sick? Don't come to class and risk infecting others. Instead, notify your instructor or TA as soon as possible via email of your condition.

For lecture, this will be counted towards your 20% *excused* absences.

For lab, one or two absences will typically be allowed makeup ***at the discretion of your head TA***.

More learning opportunities

- *Optional Discussion and Practice*: Fridays (10-10:50am and/or 2-2:50pm
- *Office Hours*: Room 1005 (near lab)
- Center for Academic Resources in Engineering (CARE, Grainger Library)
- *Honors section*: targeting James Scholars

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

Seeking advice and help

- Talk to Instructors and Teaching Assistants
- *Center for Academic Resources in Engineering* (CARE) for tutoring options in STEM courses.
- *ECE Department Advising Office* (2120 ECEB) for academic advice. They can also recommend others:
  - U of I *Counseling Center* for time management, study skill, test-taking skills, and confidential personal counseling
  - Disability Resources & Educational Services

Other policies

- We expect you to conduct yourselves in accordance with the University's Student Code http://admin.illinois.edu/policy/code/
- We absolutely welcome your suggestions to make this course—*your* course—better!!
- These slides contain only an overview of the syllabus. Read the syllabus handout in its entirety. It contains information useful for your first homework.

There Should Always be Alignment in a Community

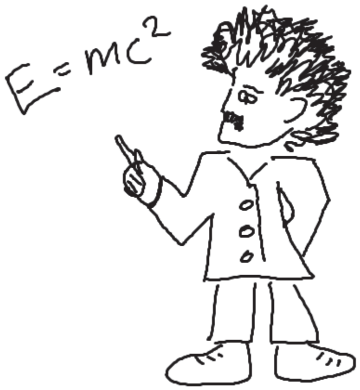
Courses Dealing with Engineering Professionalism and Ethics

- Ethics across the curriculum in electrical and computer engineering: class sessions in ECE 110, ECE 445
- Class sessions in other engineering programs: CEE 495, GE 390, MSE 201, ME 470
- CS 210, Professional and Ethical Issues in CS
- ECE/PHIL 316, Ethics and Engineering
  - Elective
  - Gen ed: advanced composition, humanities

Recall "Energy"

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

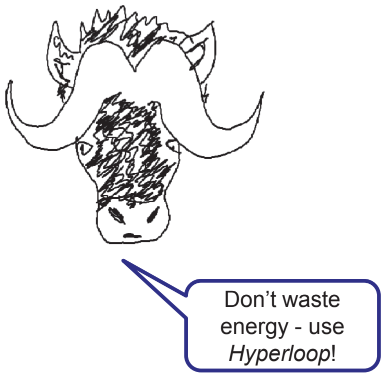
  Examples: heat, light, electrical energy, chemical, mechanical (e.g. potential, kinetic), mass, etc…



What kind of work can be done?

- 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*

Driving to Chicago - not much work!



If $\Delta E_{state} \equiv E_{useful}$, then

$$E_{input} = \Delta E_{state} + E_{waste}$$

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

L3Q1: How much energy does it take to accelerate a 2200 kg car from 0 to 60 mph?
L3Q2: What is the energy *input* needed if the engine/drive train losses are 70%?

Rate of lifting camels – power!

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

L3Q3: What is the average power needed to lift 500 kg by two meters every minute?

L3Q4: What is the power needed to expend 800 kJ in five seconds?
L3Q5: What is the charge moved through 400 V to provide 800 kJ of energy?
L3Q6: What is the average current if the energy in Q5 is provided in five seconds?

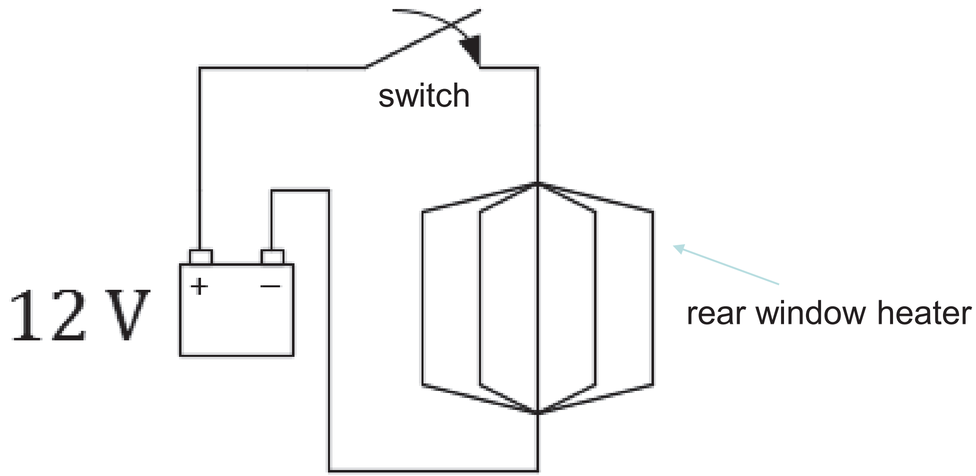
L3 Learning Objectives

a. (L3a) Solve energy transfer problems involving mechanical potential and kinetic energy as well as efficiency (or wasted energy) considerations.
b. (L3b) Compute power, energy, and time, given two of three.

Lecture 4: Circuit Modelling and Schematics

- Circuit Modeling and Schematics: A resistive heater
- Electromagnetism – Oersted's 1820 demonstration
- Measuring current and moving things that are near and far
- Long-distance telegraphy; Ohm's law
- Circuits: graphical representations and mathematical models
- Model and solve very simple (one loop) circuits
- Avoiding Ethical dilemmas

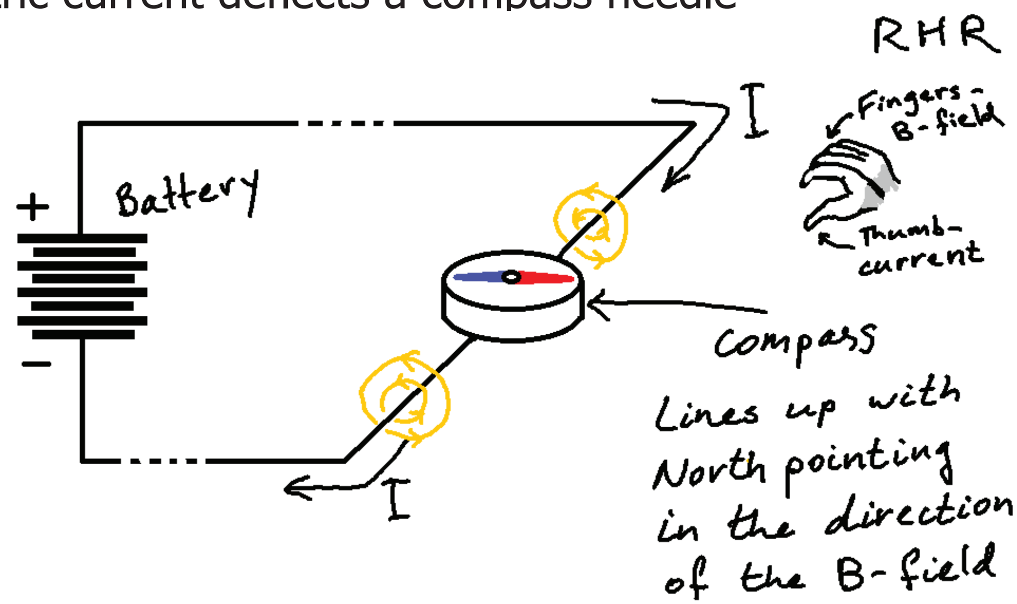
Circuit model for car window defroster



L4Q1: What is the resistance of the car window defroster if it dissipates 60 W? (Consider that the car battery has a max current of 600 A)

Oersted's discovery (1820)

An electric current deflects a compass needle



Galvanometer measures current

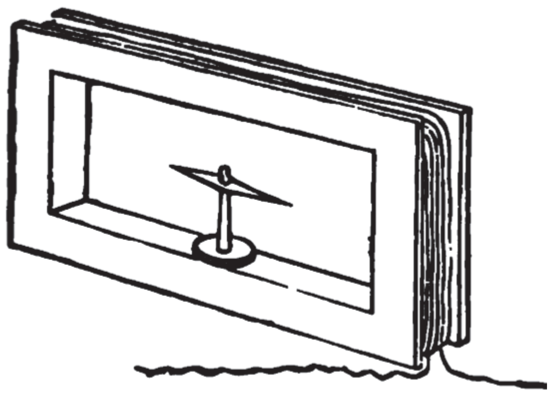
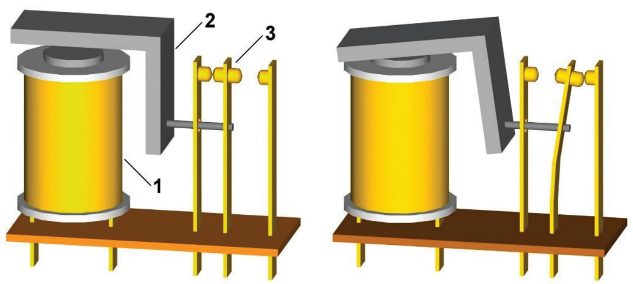


Image from PD book: Electrical Measurement and the Galvanometer: Its Construction and Uses, by T. D. Lockwood, New York: J. H. Bunnell and Co., 1890

- Each wire in a coil adds to magnetic field, B
- Wires segments on all sides add to B
- Counteracts Earth's magnetic field
- More current – bigger angle of needle

- More sophisticated galvanometers came later
- Ampere (A), becomes a fundamental unit
- I is for Intensité (Intensity in French)

A coil with current acts as a magnet



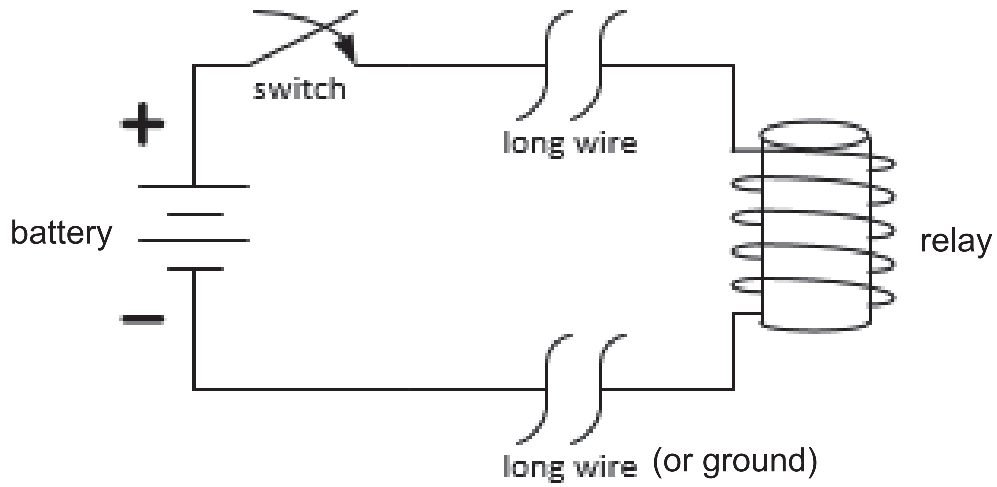
Relay principle: 1. Coil, 2. Armature, 3. Moving contact
Source: Wikimedia Commons

L4Q2: For how long can Energizer 522 (~500 mAh) 9 V battery operate a relay (JQX-15F) which draws 100 mA?

Q1 answers:

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



L4Q3: 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?

Ethical views can have multiple origins

- Value-based
- Relationship-based
- Code-based

What is professional responsibility?

Engineering professional responsibility encompasses the ethical obligations of engineers in their professional relationships with clients, employers, other engineers, and the public; these obligations include honesty and competence in technical work, confidentiality of proprietary information, collegiality in mentoring and peer review, and above all, the safety and welfare of the public, because engineers' decisions can significantly affect society and the environment. –*Prof. M. Loui*

L4Q4: What ethical viewpoint is represented above?
A. Values B. Relationships C. Code

Engineers have many ethical obligations

- Relationships with clients
  - Competence
  - Honesty
- Relationships with employers
  - Conflict of interest
  - Confidentiality, e.g., trade secrets
  - Individual and collective responsibility
  - Loyalty, whistle-blowing
- Relationships with other professionals
  - Licensing, due credit
  - Collegiality, mentoring
- Relationships with the public
  - Public understanding of technology
  - Social impacts of technology

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 (2012)

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 (2012)

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.

Case Study: Occidental Engineering

- http://www.onlineethics.org/Resources/Cases.aspx

- Break into groups or pairs and discuss.
  - Consider the issue from the viewpoint of all people involved
  - Consider the options and the consequences of each
  - Can your group come to a single conclusions?

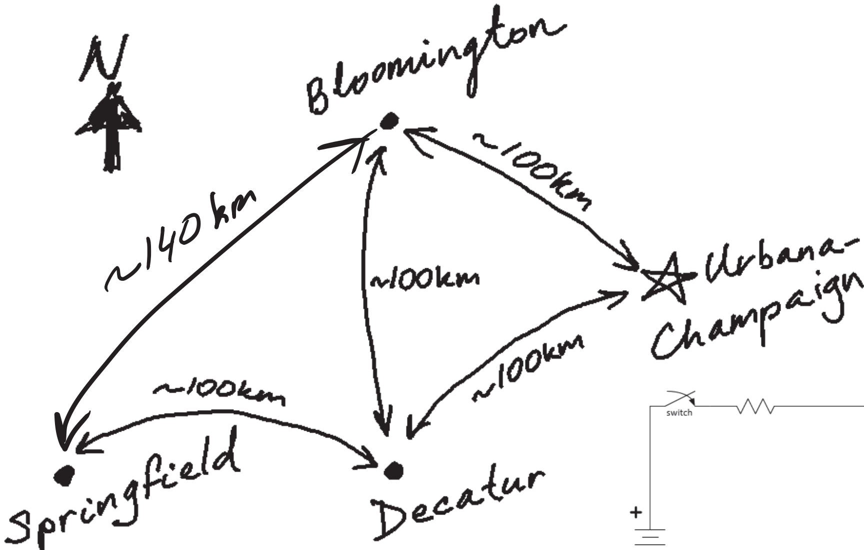
L4 Learning Objectives

a. Draw one-loop circuit schematics to model simple setups
b. Identify which items in a given code of ethics is designed to promote safe, professional behavior in various situations

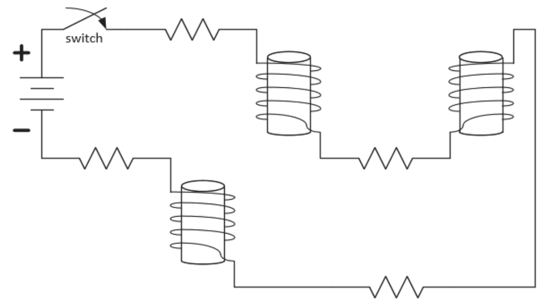
Lecture 5: Kirchhoff's Laws in Circuits

- Network Examples: Broadcast Telegraphy, Decorative Lights
- 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

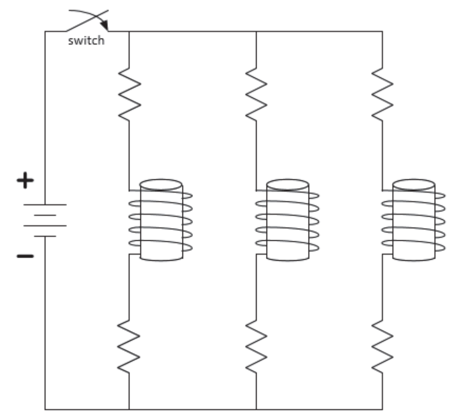
Broadcasting: multiple ways to wire relays

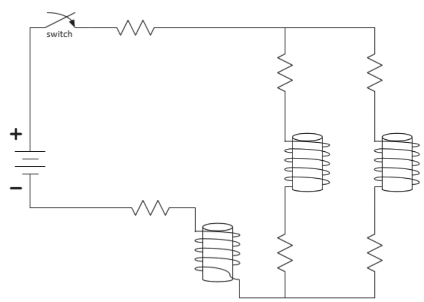


A.



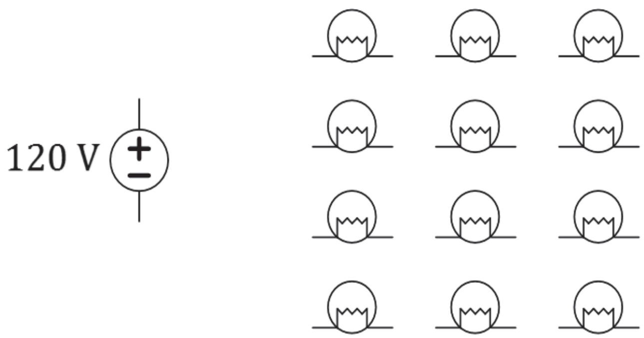
B.

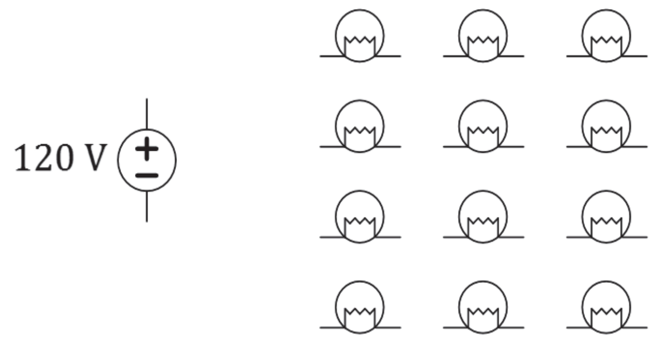




C.

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





L5Q1: Draw a circuit for 12 lightbulbs connected in *series* in one loop.
L5Q2: Draw a circuit for 12 lightbulbs connected in two *parallel* branches.

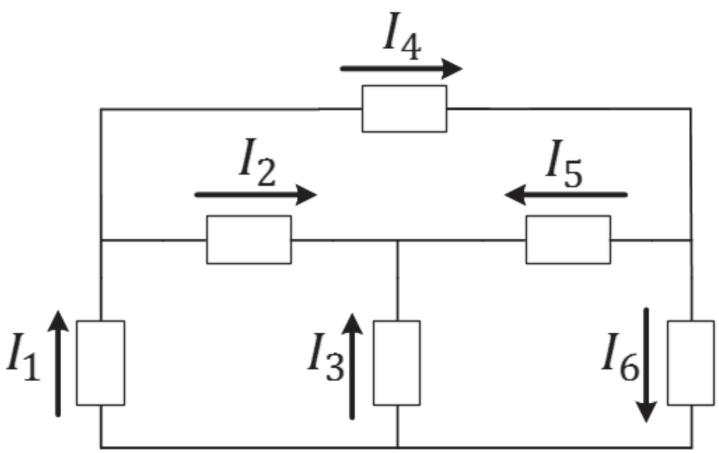
Kirchhoff's Current Law

Current in = Current out

Conservation of charge!

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

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



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. $I_6 - I_4 = I_3 + I_2$

L5Q3: Which of the equations is NOT a correct application of KCL?

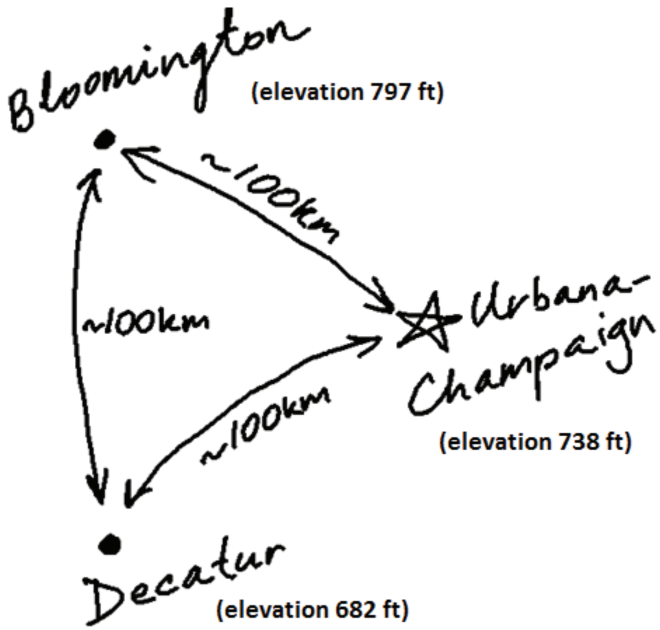
Kirchhoff's Voltage Law

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

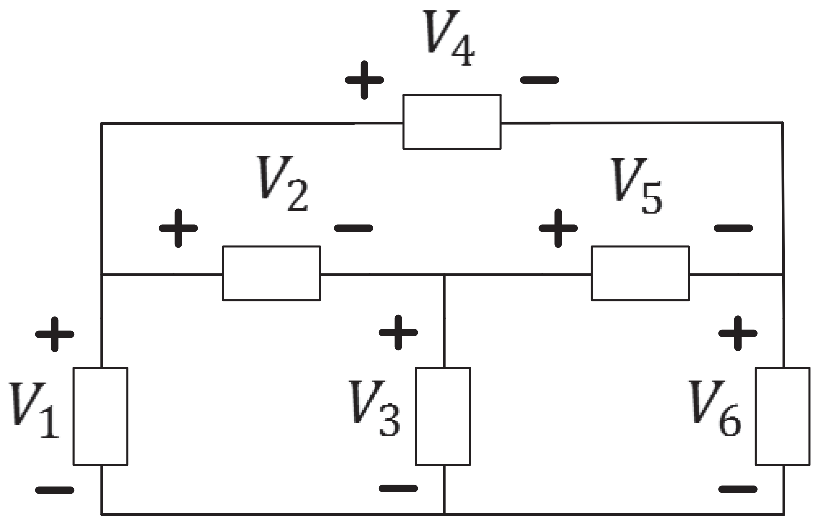
KVL and Elevation Analogy



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.

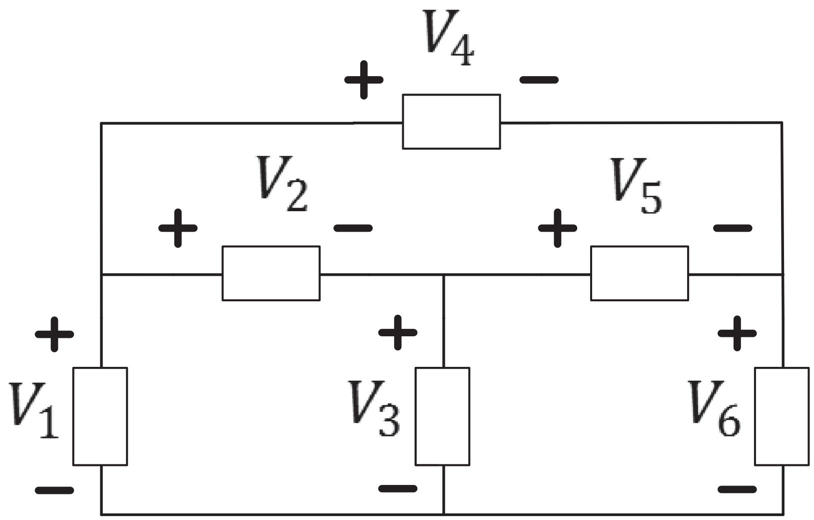
Keeping track of voltage drop *polarity* is important in writing correct KVL equations.



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. $V_3 + V_5 = V_6$

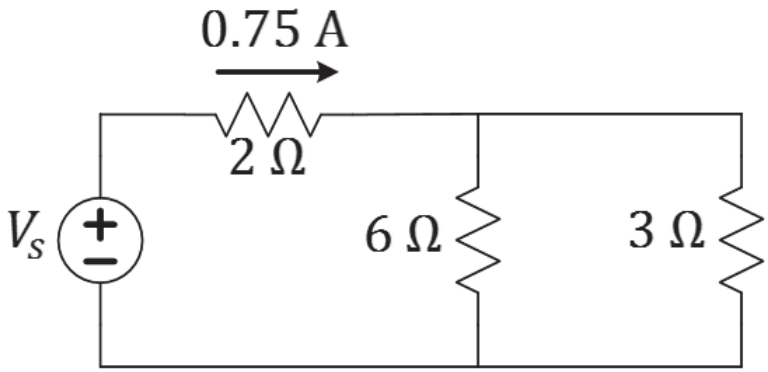
L5Q4: Which of the equations is NOT a correct application of KVL?

Missing voltages can be obtained using KVL.



L5Q5: 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?

Circuits are *solved* with Ohm's + KCL + KVL



L5Q6: What is the value of the source voltage?
L5Q7: How much power is the source supplying?
L5Q8: How much power is each resistance consuming?

Learn to avoid ethical dilemmas

Picking Up the Slack

http://www.scu.edu/r/ethics-center/ethicsblog/thebigq/15667/Picking-Up-the-Slack

Often called a "hitch-hiker" scenario…

L5Q9: What is the code which can be most readily applied in the analysis of a hitch-hiker case?

A. The ten commandments
B. The pirate code of the brethren
C. The ten precepts of Taoism
D. IEEE code of ethics
E. The student code

L5 Learning Objectives

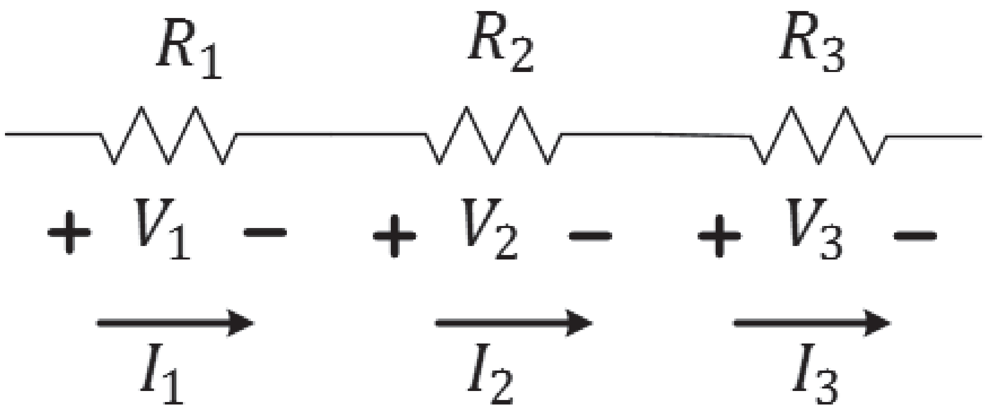
a. Draw source and resistor circuits to model real-world problems
b. Identify and label circuit nodes; identify circuit loops
c. Write node equation for currents based on KCL
d. Write loop equations for voltages based on KVL
e. Solve simple circuits with KCL, KVL, and Ohm's Law
f. Calculate power in circuit elements, verify conservation
g. Develop a plan to avoid an ethical dilemma in the laboratory

Lecture 6: Current and Voltage Dividers

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

Series Connection

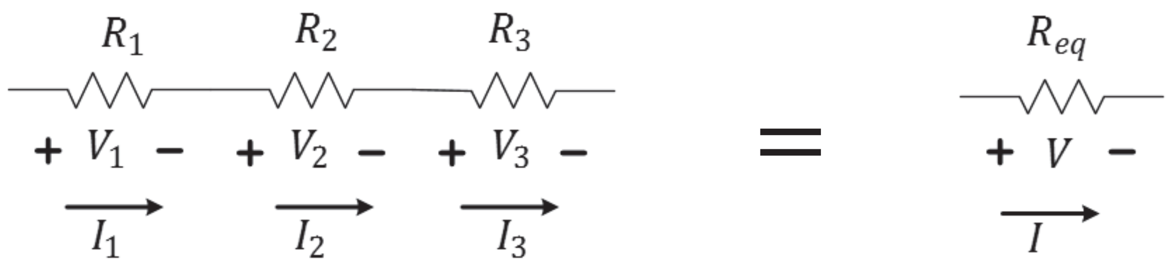
Series connections share the same current



$I_1 = I_2 = I_3$ because of KCL

Equivalent Resistance of Series Resistors

Resistances in series add up



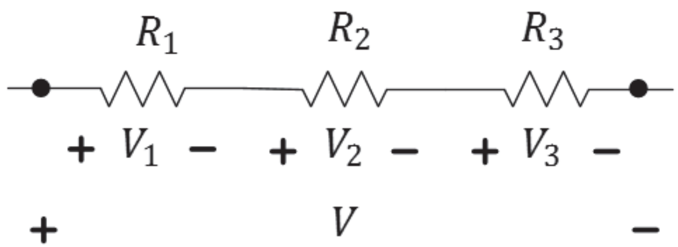
$$R_{eq} = R_1 + R_2 + \cdots + R_N$$

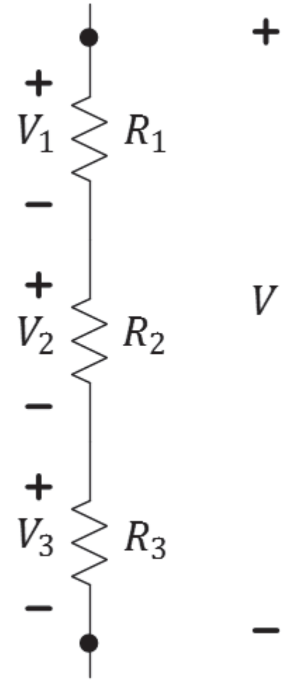
This can be intuitive: think of telegraphy wires in series.

Voltage Divider Rule (VDR)

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

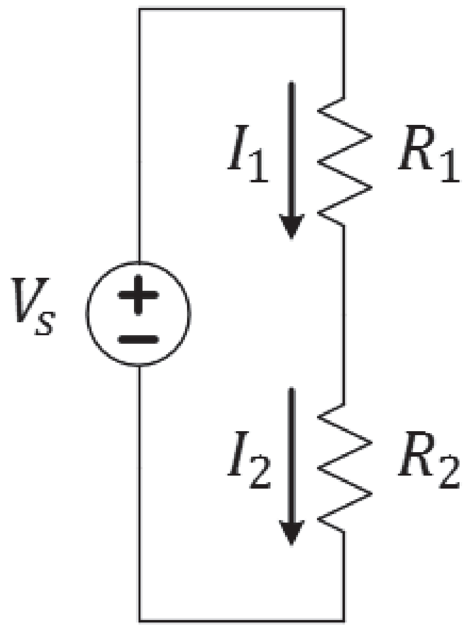
$$V_k = \frac{R_k}{R_{eq}} \cdot V$$





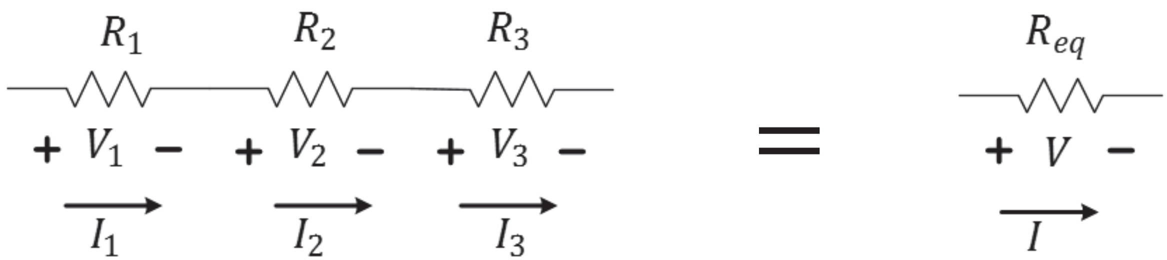
L6Q1: Can a voltage across one of the resistors be higher than the total V?

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 $I_1 > I_2$

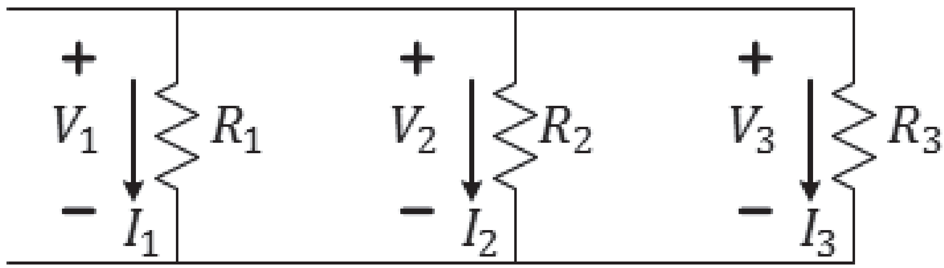
VDR Derivation



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

Parallel Connection

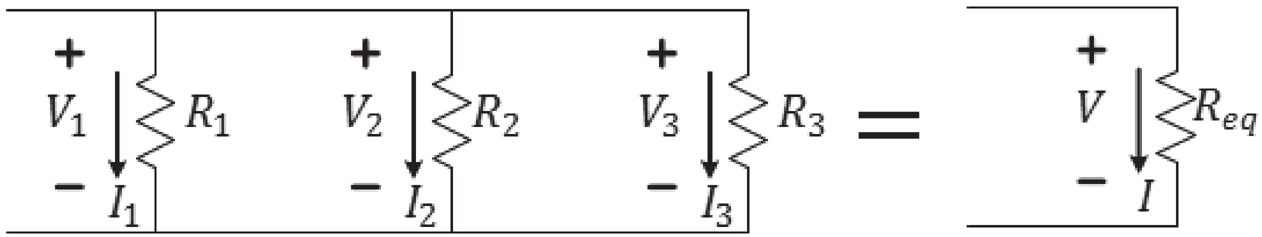
Parallel connections share the same voltage potentials at two end nodes (shared by the elements)



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

L6Q2: Are appliances in your house/apartment connected in series or in parallel?

Equivalent Resistance of Parallel Resistors



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

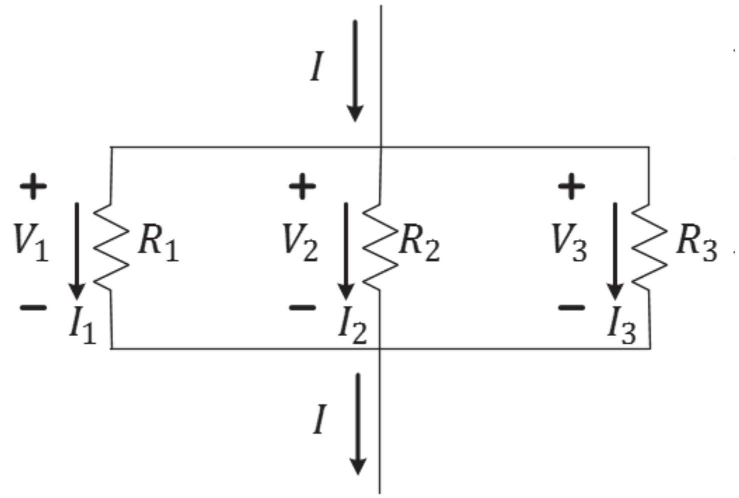
If $N = 2,\qquad R_{eq} = \frac{R_1 R_2}{R_1 + R_2}$

Adding resistance in parallel always brings resistance down!
This can be intuitive: think of combining wire strands to make a thicker wire.

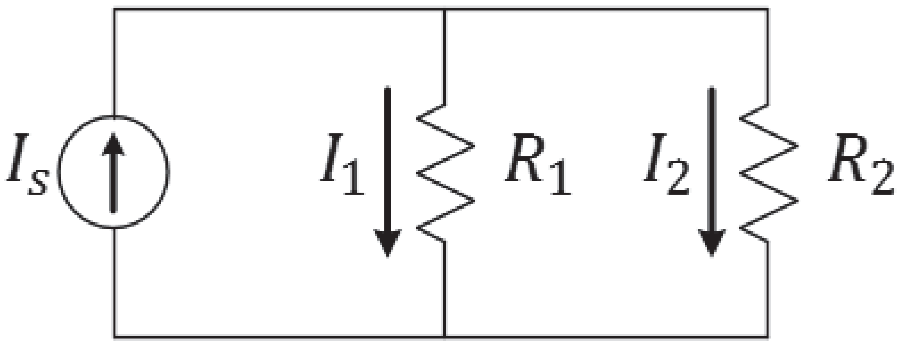
Current Divider Rule (CDR)

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

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



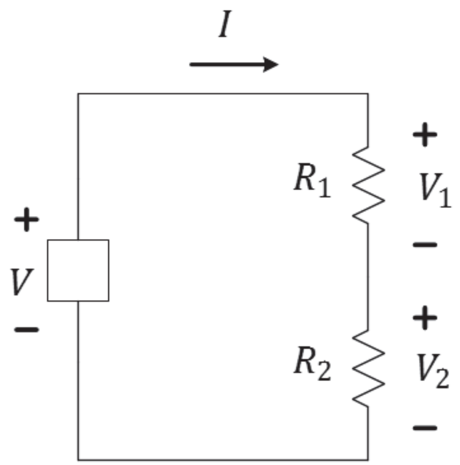
If $R_1 < R_2$, which of the following is true?



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. $I_s < I_2 < I_1$

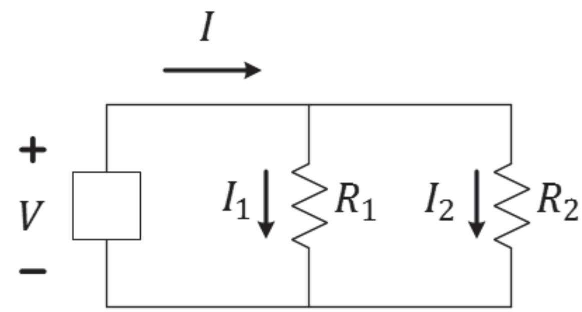
L6Q3: In a parallel connection, does a smaller or larger resistor absorb more power?

VDR and CDR for Two Resistances



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

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



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

L6Q4: If 6V falls across a series combination of 1kΩ and 2kΩ, what is V across 2kΩ?

L6Q5: If 0.15A flows through a parallel combo of 1kΩ and 2kΩ, what is I through 2kΩ?

L6Q6: If a source supplies 60W to a series combination of 10Ω and 30Ω, what is the power absorbed by the 10Ω resistor? What is absorbed by the 30Ω resistor?

L6Q7: If a source supplies 300mW to a parallel combination of 3kΩ and 2kΩ, what is the power absorbed by the 3kΩ resistor? What is absorbed by the 2kΩ resistor?

L6 Learning objectives

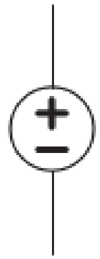
a. Identify series and parallel connections within a circuit network
b. Find equivalent resistance of circuit networks
c. Estimate resistance by considering the dominant elements
d. Apply rules for current and voltage division to these networks
e. Apply conservation of energy to components within a circuit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

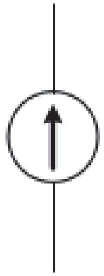
Lecture 7: More on Sources and Power

- The Meaning of Current and Voltage Sources
- Labeling of Current and Voltage and Sign of Power
- Time Varying Voltage Source – Sinusoidal, Square, Etc.
- Root-Means-Square Voltage (RMS) of a Waveform

Voltage and Current Sources Can Produce or Consume Power and Energy

- [Ideal] sources in a circuit are mathematical models
- Can be used to model real devices (or parts of circuit)
- Voltage sources have (calculable) currents through them
- Current sources have (calculable) voltages across them
- Source elements can produce <u>or</u> consume energy

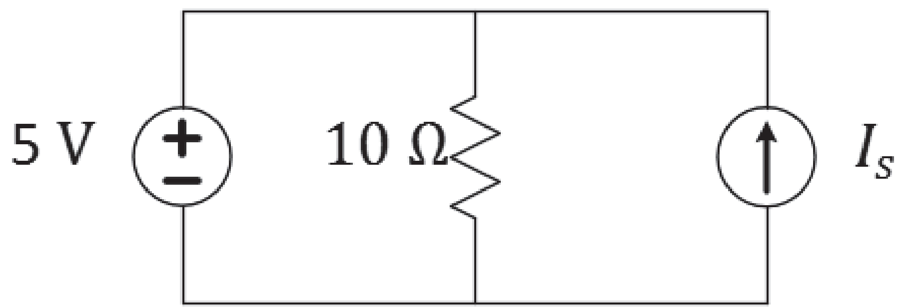




Which of the sources are delivering power?

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

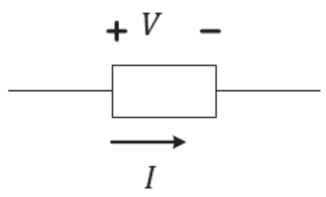
Either or Both Sources Can Supply Power



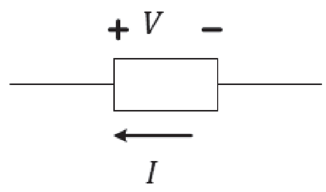
L7Q1: For what values of I_s do both sources supply power?
L7Q2: For what values of I_s does only the current source supply power?
L7Q3: For what values of I_s does only the voltage source supply power?

Taking care of labeling

- Labeling of current direction and voltage *polarity* is important!
- For any element, we label current I flowing through it from the positive side of V to the negative side of V or vice-versa



Preferable for resistors
Here, V=IR



Can be conveniently used for sources
(If it's a resistor, V = -IR)

L7Q4: In what direction does a positive current flow through a resistor?
L7Q5: In what direction does a positive current flow through a battery?

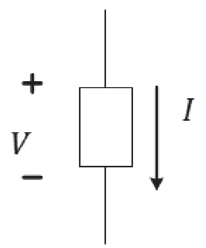
The sign of power is important

Recall: power (watts) is energy (joules) divided by time (sec)

$$P(t) = V(t)I(t)$$

$$P = VI$$

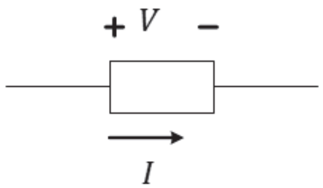
if constant (aka. DC or Direct Current). Using the standard polarity labeling: $P = \; V_{+\,-} \;\; I_{+\to-}$



$P < 0 \;\; \Rightarrow Element\; delivers\; power\; to\; the\; circuit$

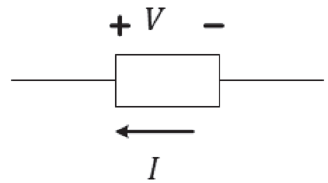
$P > 0 \;\; \Rightarrow Element\; absorbs\; power\; from\; the\; circuit$

Recap of labeling implication



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

$$P = VI$$



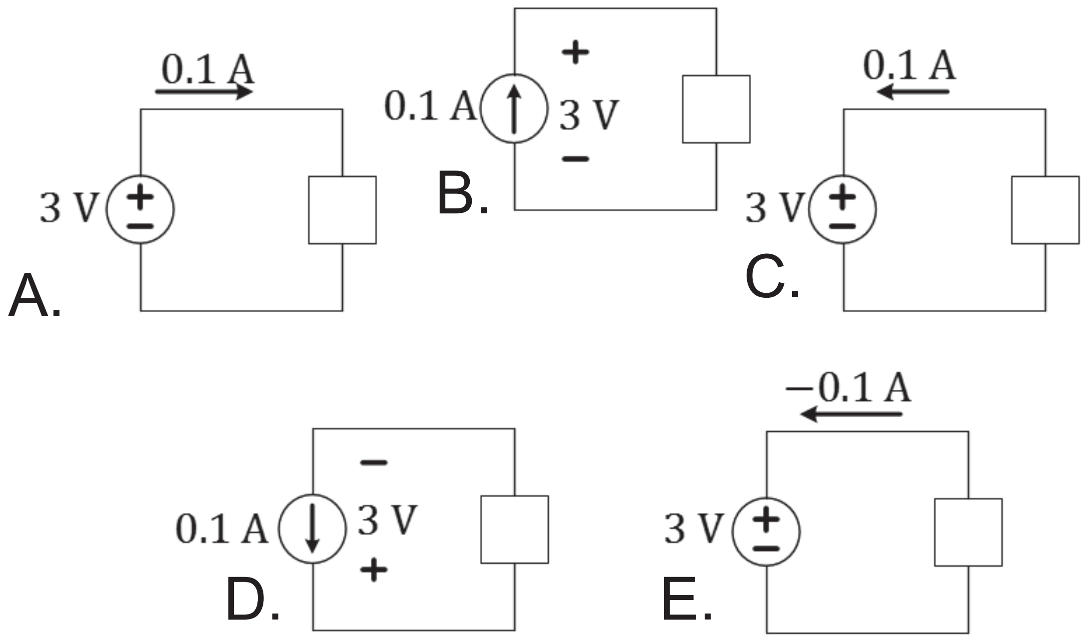
$$R = -\frac{V}{I}$$

$$P = -VI$$

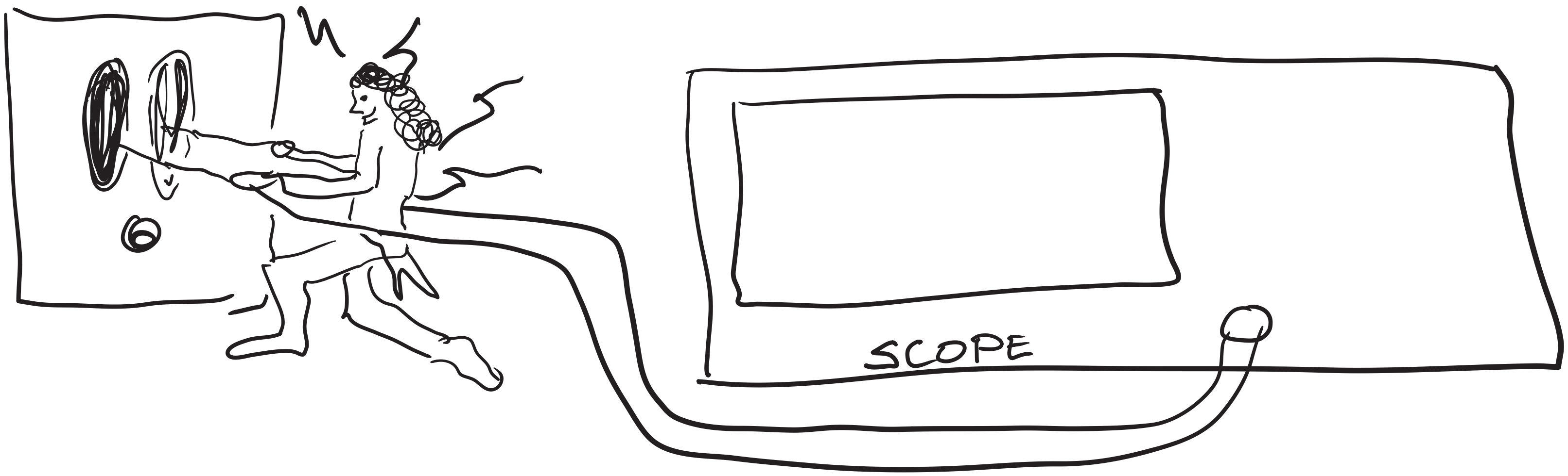
Where power is defined in such a way that it is negative when it is supplied (sourced) and positive when it is absorbed (sinked).

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

Which of the sources below absorbs power?



Voltage from the wall plug is *sinusoidal*



L7Q7: What is the peak instantaneous power absorbed by a 250Ω light bulb?

Time Average Power

(similar equation for any time-average)

$$P_{avg} = \frac{AREA_{in\,T}}{T},$$
$$T = period$$

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

$$T = sufficient\ length\ observation\ interval$$

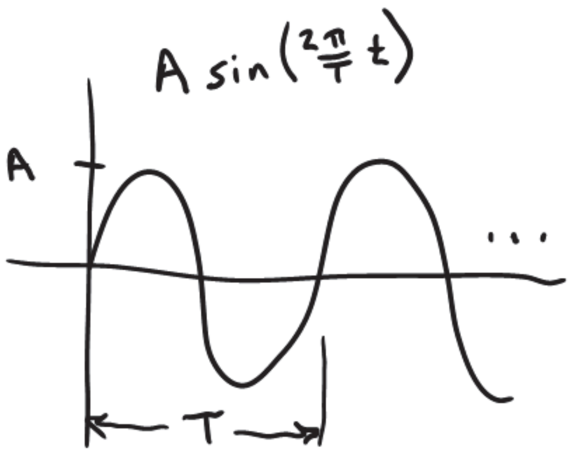
Root-Mean-Square averages

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.

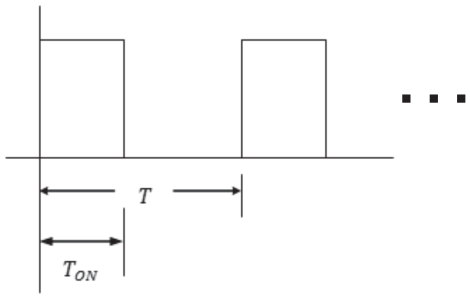
Calculating P_{avg} and V_{rms}



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

L7Q8: What is the average power absorbed by a 250Ω light bulb if A = 170V?

Calculating P_{avg} and V_{rms}



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

L7Q9: What happens to power and V_{rms} when T_{ON} is halved while T is unchanged?

L7 Learning Objectives

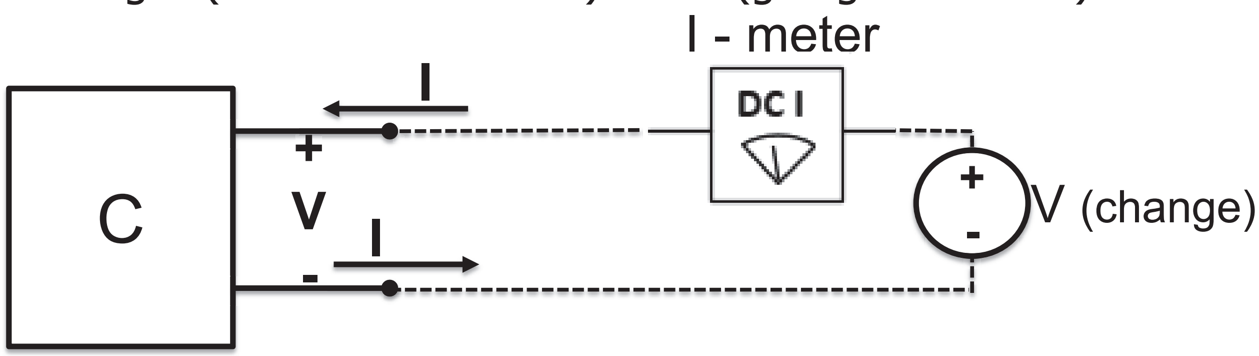
a. Correctly apply Ohm's law in a resistor (depending on labeling)
b. Determine whether power is absorbed or supplied by an element
c. Compute the time-average power from I(t), V(t) curves
d. Explain the meaning of V_{rms} and relationship to P_{avg}

Lecture 8: 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

Consider any circuit with two leads

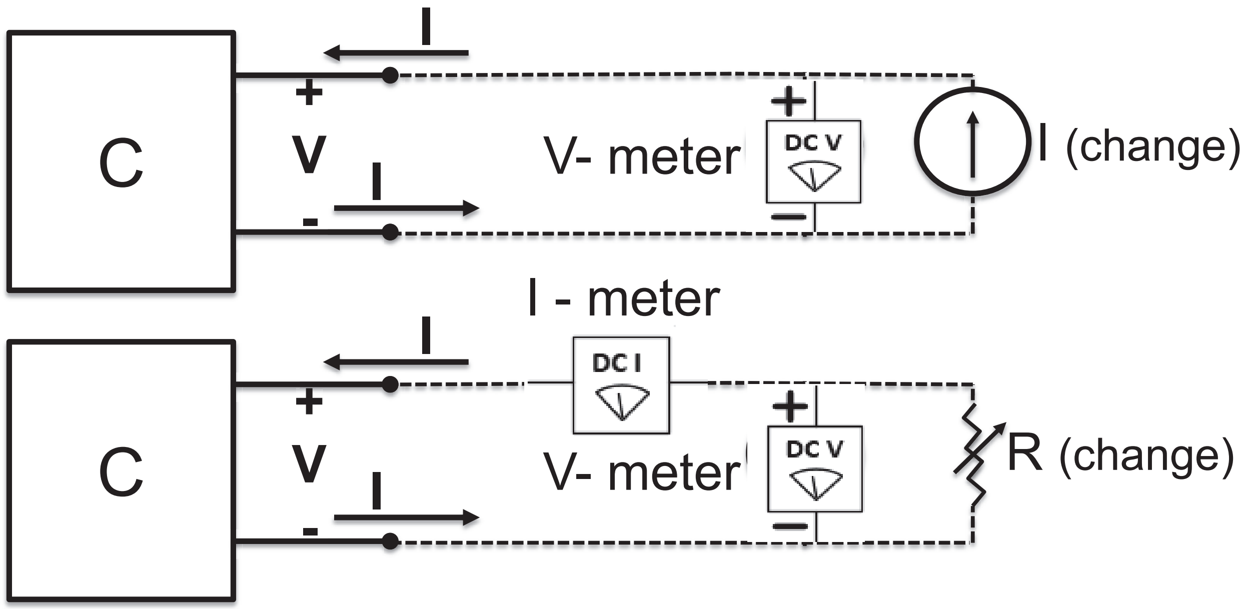
It's DC (not changing in time) behavior can be described by relating V (between terminals) and I (going in and out).



If the circuit is not too close to an ideal voltage source, the IV relationship can be measured like shown above.

L8Q1: What is the voltage drop across an ideal current-meter (ammeter)?

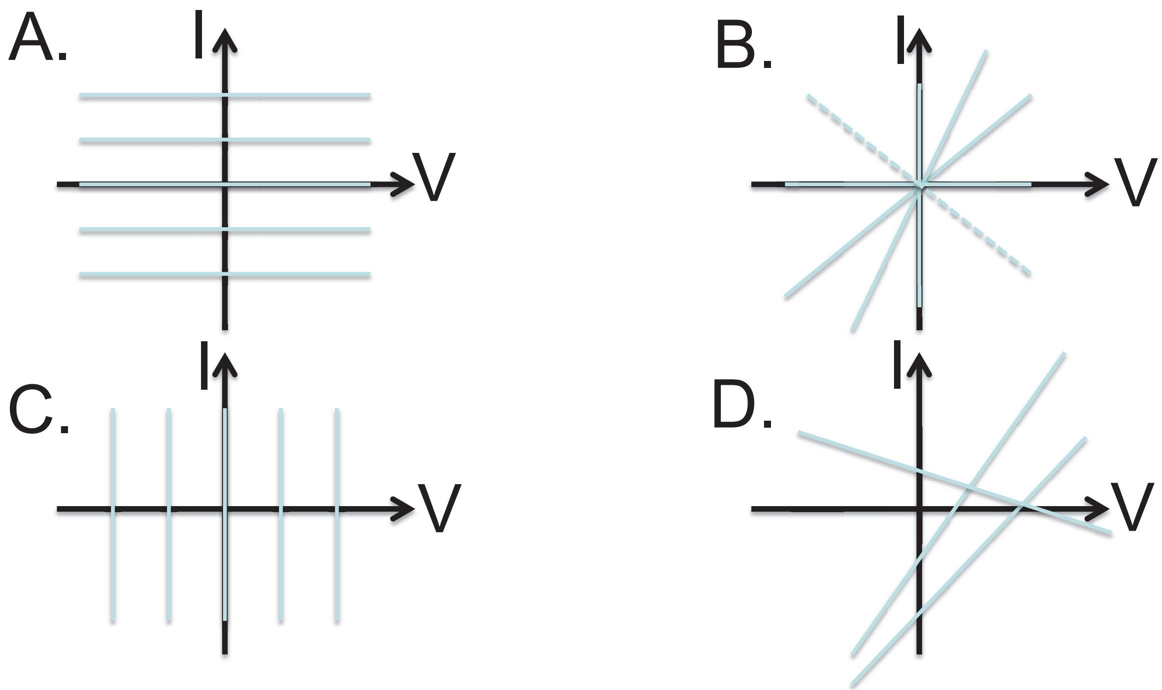
Alternative IV measurements



A variable resistor load is very practical when the circuit C provides power.

L8Q2: What is the current through an ideal voltage-meter (voltmeter)?

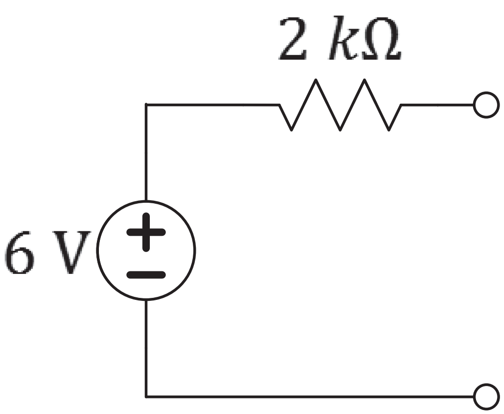
Linear I-V curves

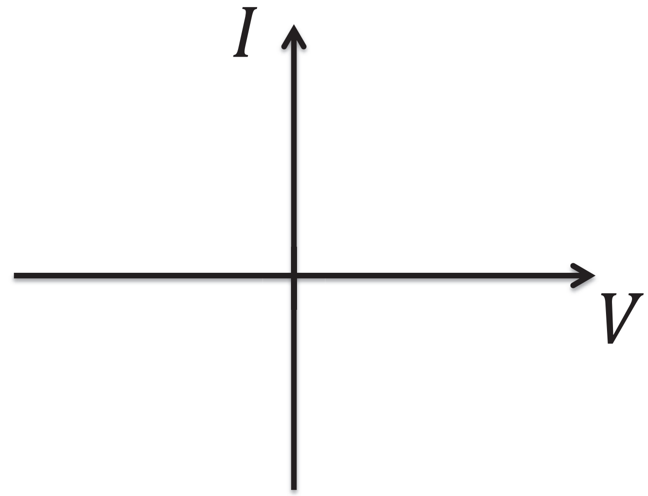


L8Q3: Which set of graphs corresponds to pure resistances?

Simple Series Circuit

Show that the circuit has a linear IV characteristic.

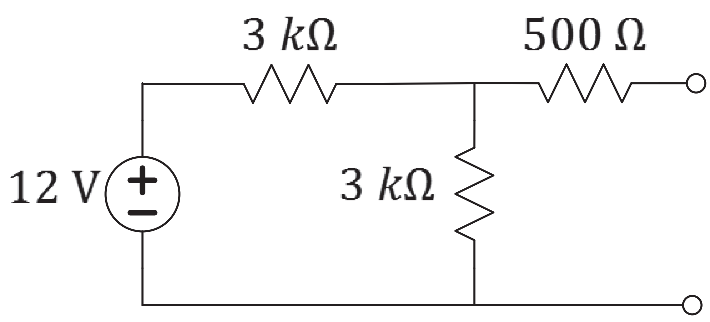


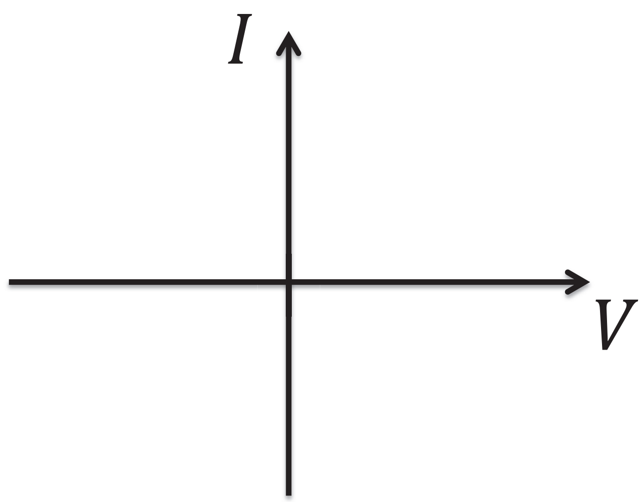


L8Q4: What are the IV characteristics of the circuit above? Include the graph.

Embedded Voltage Source

Show that this circuit also has a linear IV characteristic.





L8Q5: What are the IV characteristics of the circuit above? Include the graph.

Why we care

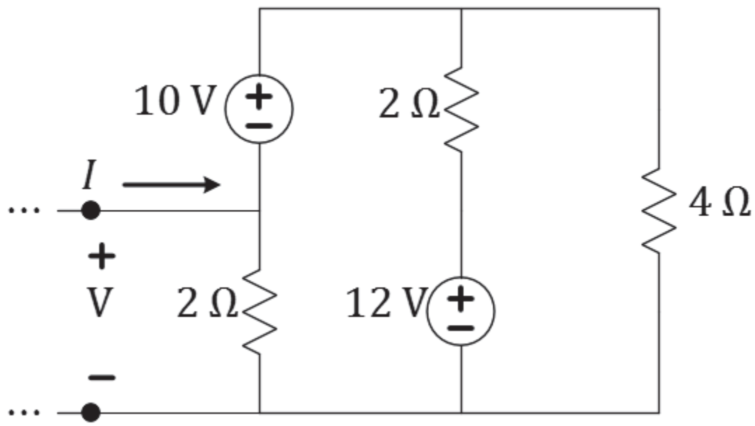
- Allows easy calculation of I and V when two sub-circuits are connected together
- Allows creating a simpler model of a given sub-circuit
- Helps understand nonlinear devices

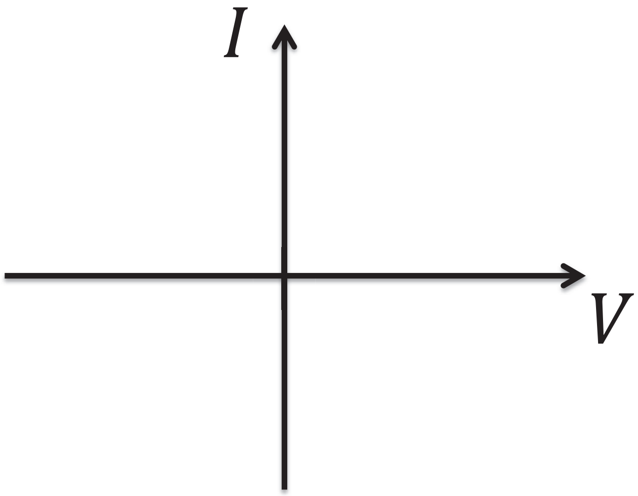
How to find IV lines

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

Linear I-Vs of source-resistor circuits

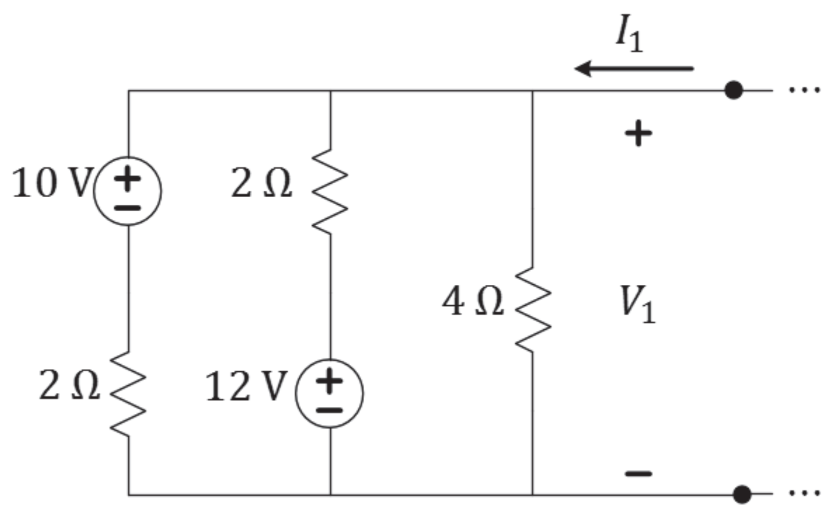
Any combination of current or voltage sources with resistor networks has a linear I-V (between any two nodes).

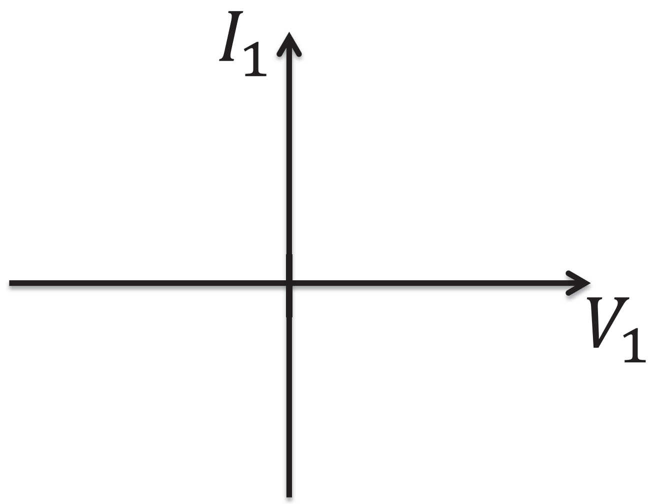




L8Q6: What are the current values I assumes when V is 0V, 2V, 4V?

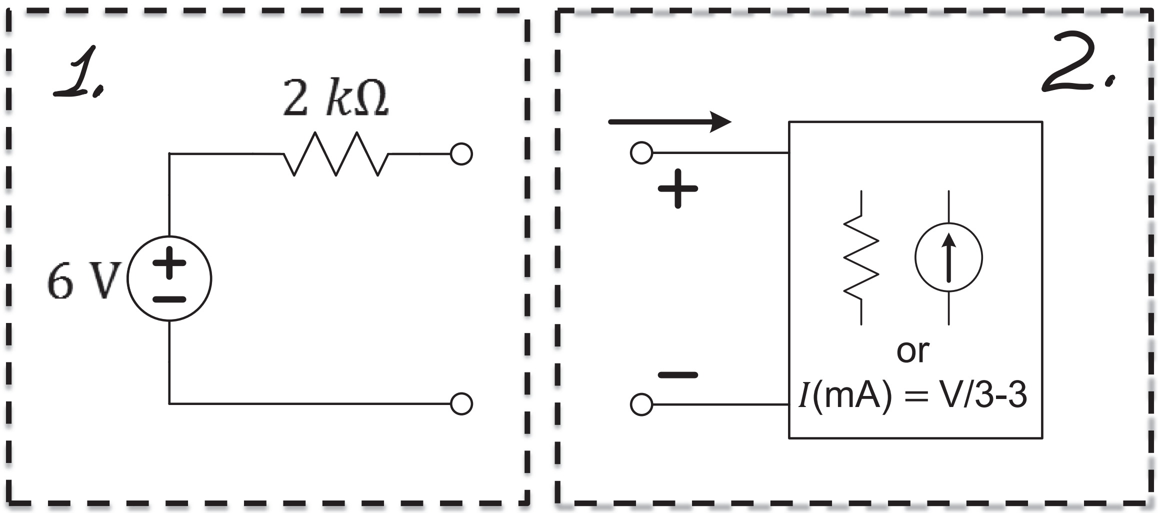
I-V line for different nodes





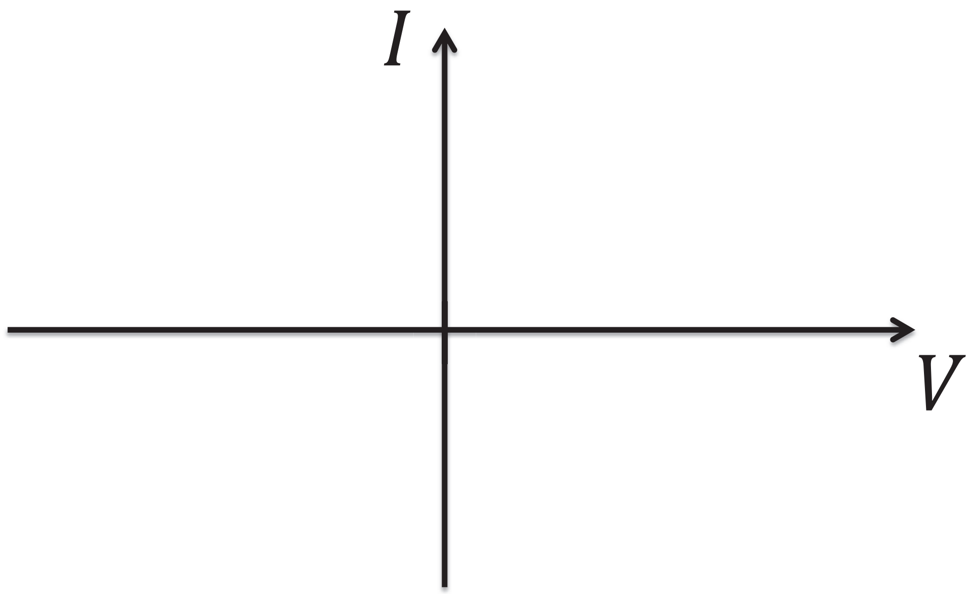
L8Q7: What are the current values taken by I_1 when V_1 is 0V, 2V, 4V?

Connecting two sub-circuits



L8Q8: What are the IV characteristics of a 3 mA current source?
L8Q9: What are the IV characteristics of a 3 kΩ resistor?

Connecting two sub-circuits (cont'd)



L8Q10: 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?

L8 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

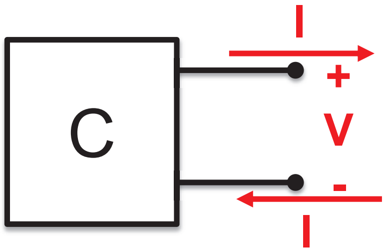
c. Find (V,I) operating points of connected sub-circuits

d. Calculate power flow between connected sub-circuits

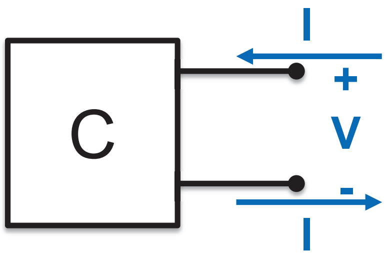
Lecture 9: Thevenin and Norton Equivalents

- Review of I-V Linear Equation
- Thevenin and Norton Equivalent Circuits
- Thevenin-Norton Transformation in Circuits
- Calculating R_{eff} by Removing Sources
- Problem Strategy and Practice

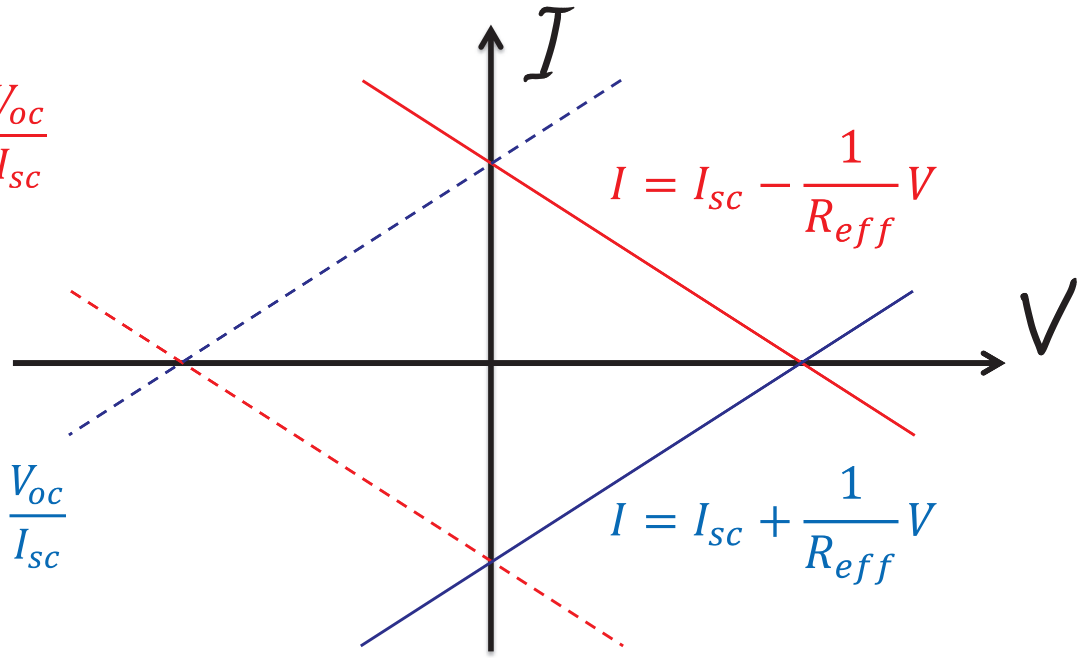
Relating I-V Line to Equation



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

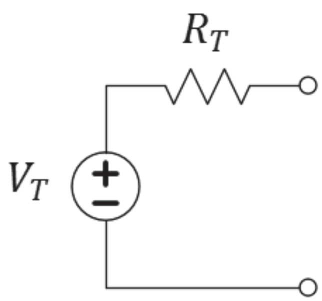


$$R_{eff} = -\frac{V_{oc}}{I_{sc}}$$

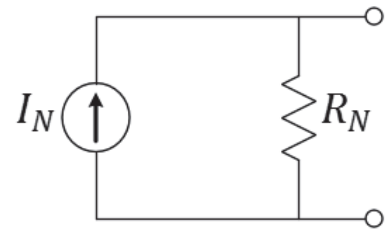


Universal: $I = I_{sc} - \frac{I_{sc}}{V_{oc}} V$

Thevenin and Norton Equivalents

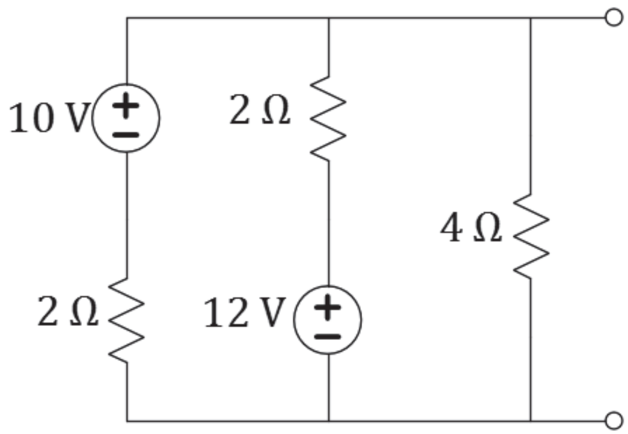


The circuit on the left and the circuit on the right can be made to behave identically by the choice of values as seen through the terminals.



- 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

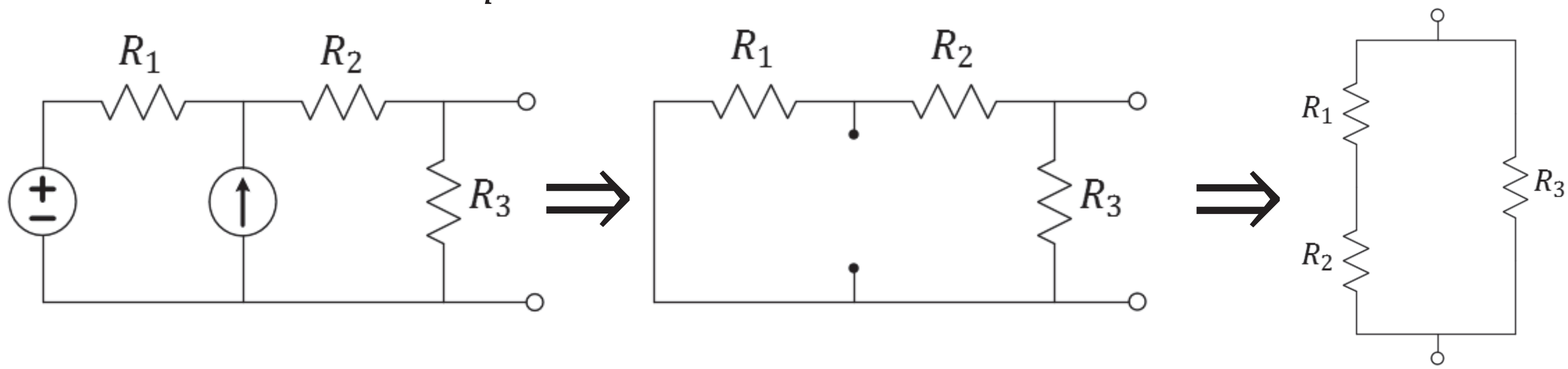
Using Transformation to Find Equivalents



L9Q1: What is the Thevenin equivalent of the circuit above?

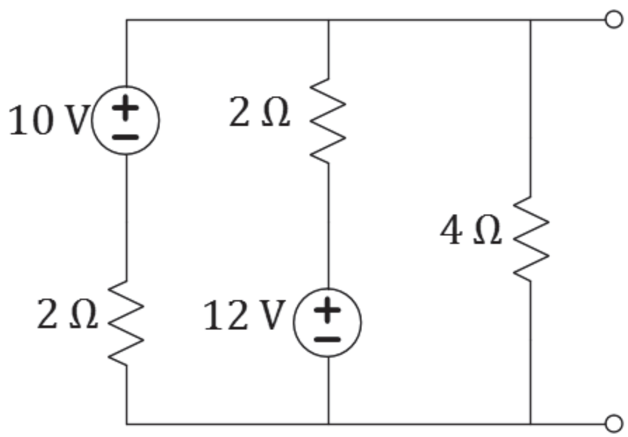
$R_{eff} = R_T = R_N$ is R_{eq} with sources removed

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



L9Q2: How is R_{eff} related to the slope of the I-V line?

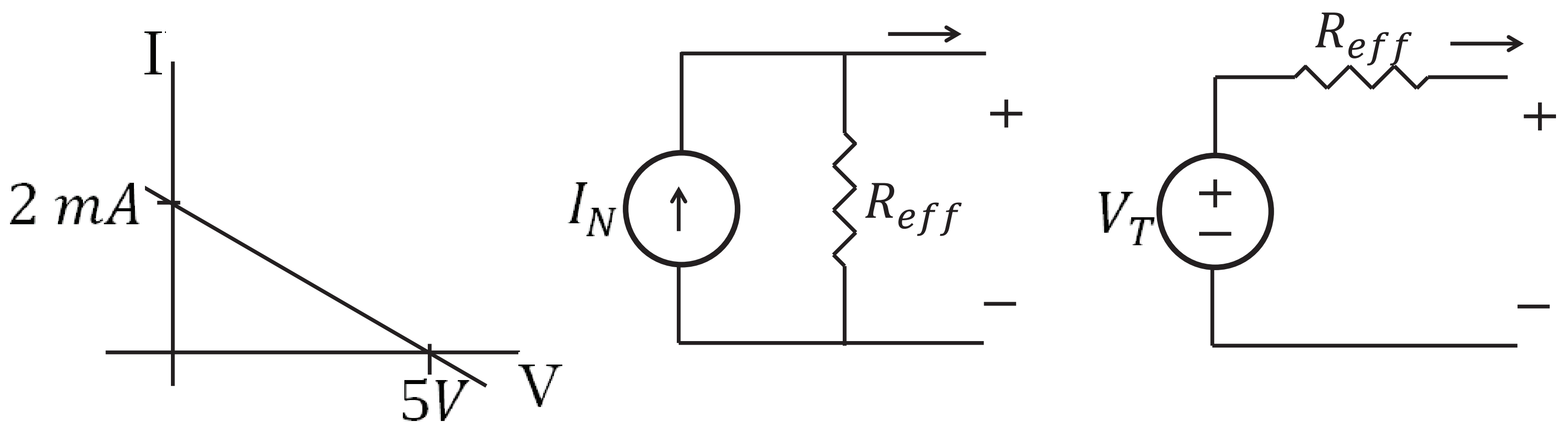
Finding R_{eff} is easy in multi-source circuits



A. 8 Ω
B. 5 Ω
C. 4 Ω
D. 2 Ω
E. 0.8 Ω

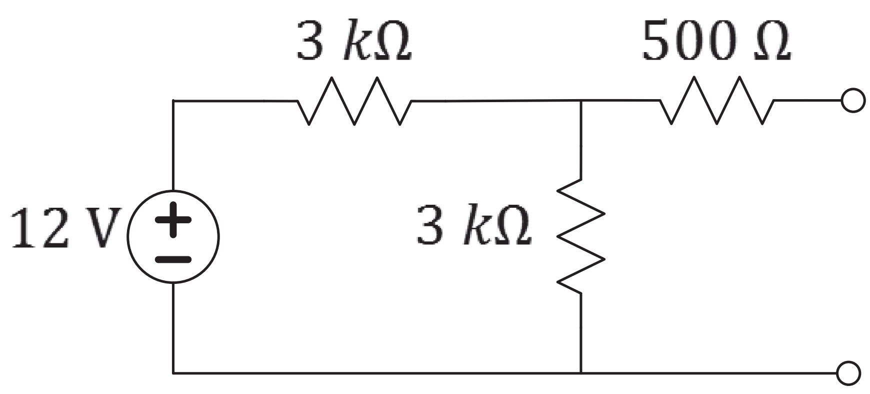
L9Q3: What is R_{eff}, for the circuit above?
L9Q4: Besides R_{eff}, is it easier to find I_{SC} or V_{OC}?

One can find a circuit given a line



L9Q5: What is R_{eff}, for the circuit with the given I-V line?

Practice makes perfect!



L9Q6: What are the Thevenin and Norton equivalents for the circuit above?

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)

L9 Learning Objectives

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

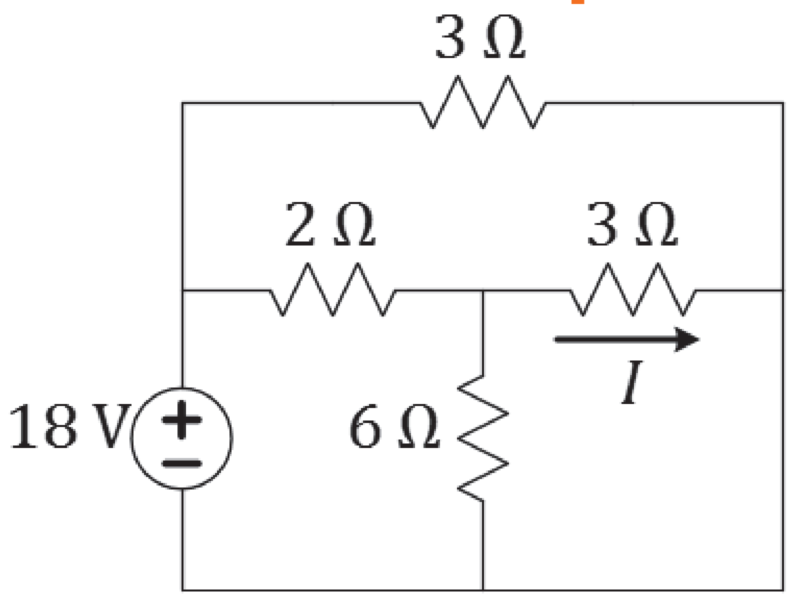
b. Represent *any* (non-vertical) linear IV characteristic by a parallel combination of a current source and a resistor (Norton equivalent circuit).

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

Lecture 10: Node Method For Circuit Analysis

- Review of circuit-solving strategies
- Node Method steps
- Practice with the Node Method

What are the possible strategies to find *I*?



L10Q1: Is one of the resistors in parallel with the voltage source? If so, which?
L10Q2: What is the value of the labeled current?

The Node Method

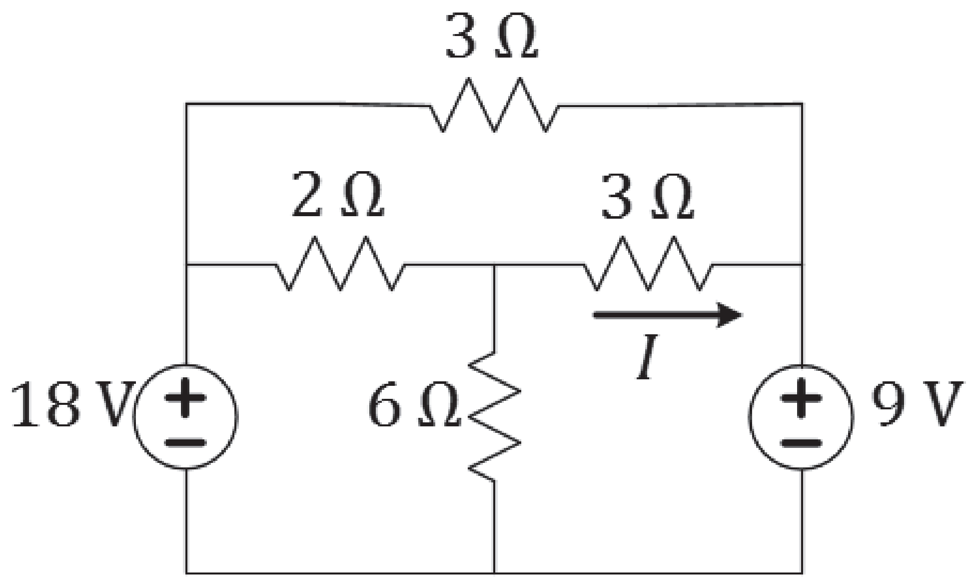
1. Identify or pick “ground” (0 V reference)

2. Label all the node voltages
   (use values when you can; variables when you must)

3. Use KCL at convenient node(s)/supernode(s)

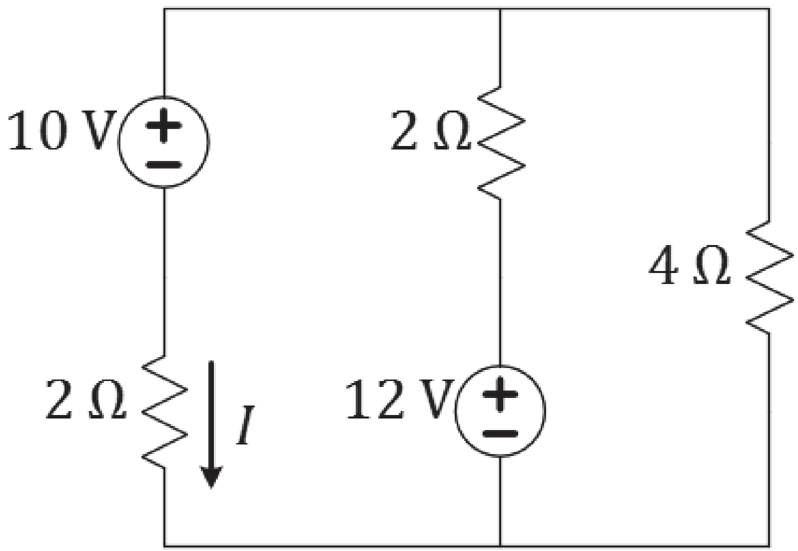
4. Use voltages to find the currents

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



L10Q3: How many nodes are in the circuit?
L10Q4: What is the value of the labeled current?

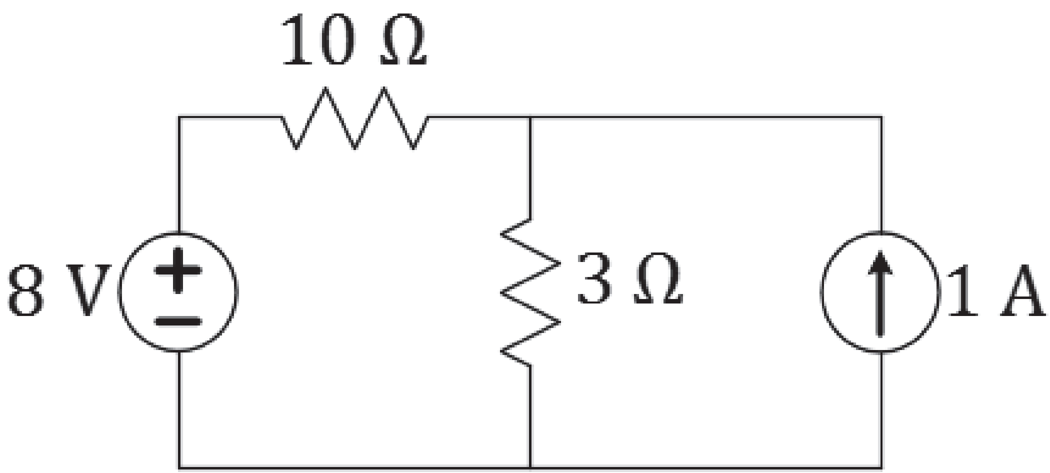
A *floating* voltage source relates two nodes



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

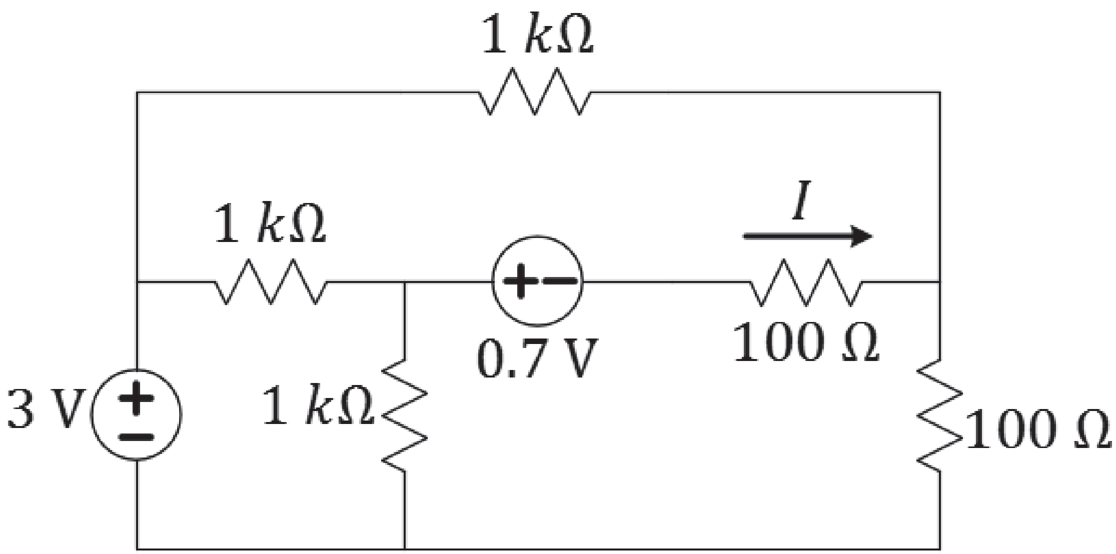
L10Q5: How many nodes are in the circuit?
L10Q6: What is the value of the labeled current?

Voltage across a current source is unknown



L10Q7: What is the power supplied or consumed by each element?

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



L10Q8: What is the value of *I* in the circuit above?

L10 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

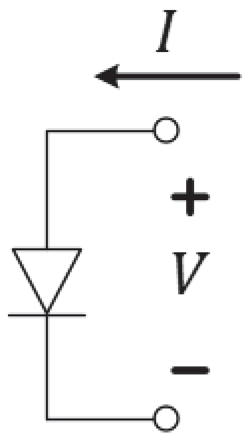
c. Identify circuit patterns in which different techniques might simplify the process of finding a solution (Practice!)

Lecture 11: Introduction to Diodes

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

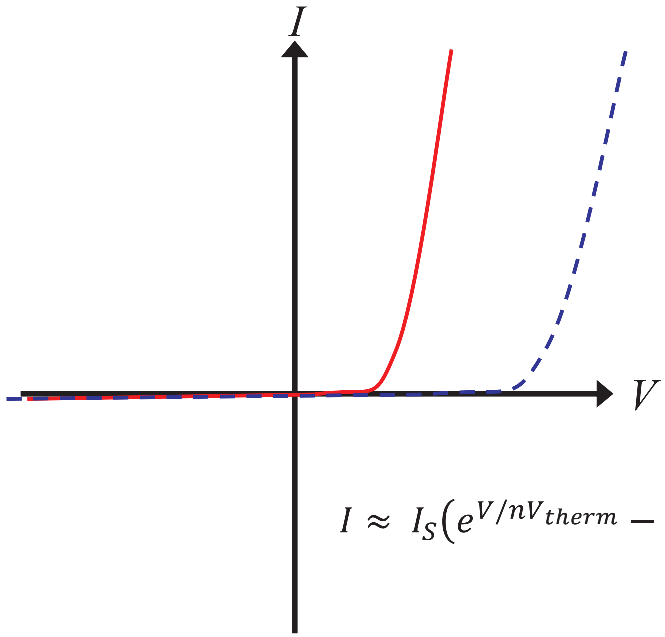
Recommended: https://learn.sparkfun.com/tutorials/diodes

Diode as a two-terminal device



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

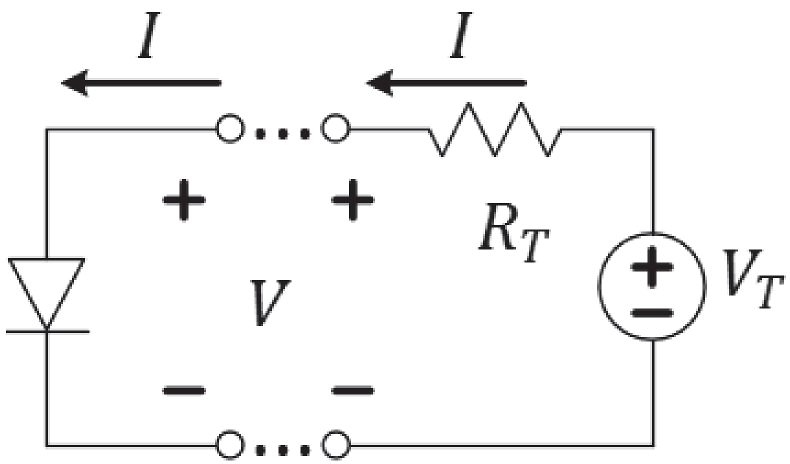
Major applications: lighting, electronics

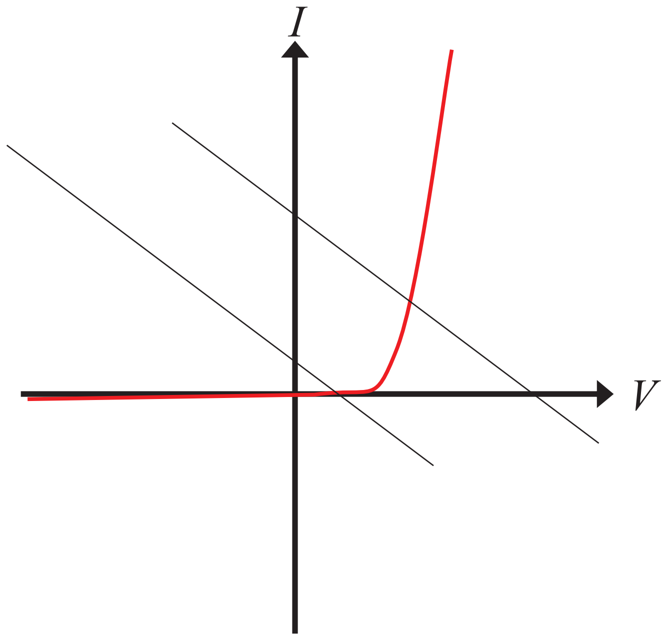


$$I \approx I_S\left(e^{V/nV_{therm}} - 1\right)$$

L11Q1: Based on the exponential equation for IV, can the diode supply power?

Connecting diode to a linear circuit



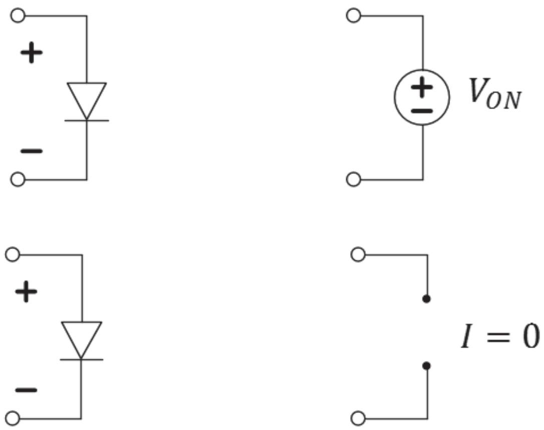


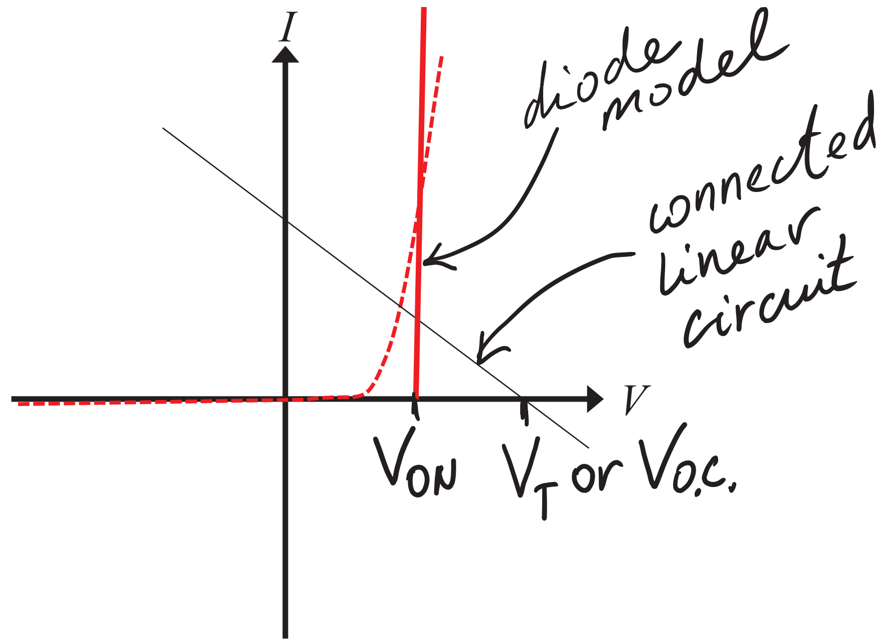
We can solve graphically for an operating point.
For an LED more current means more light.

L11Q2: What is the current flowing through the diode if $V_T < 0$?

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.





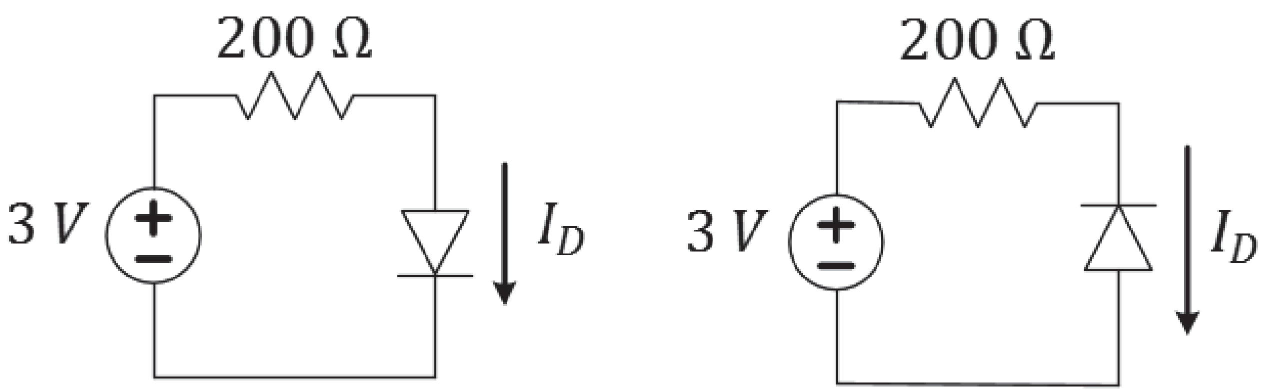
L11Q3: What is the minimum V_T of the connected linear circuit which causes current to flow through the diode if the piecewise linear model above is used?

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

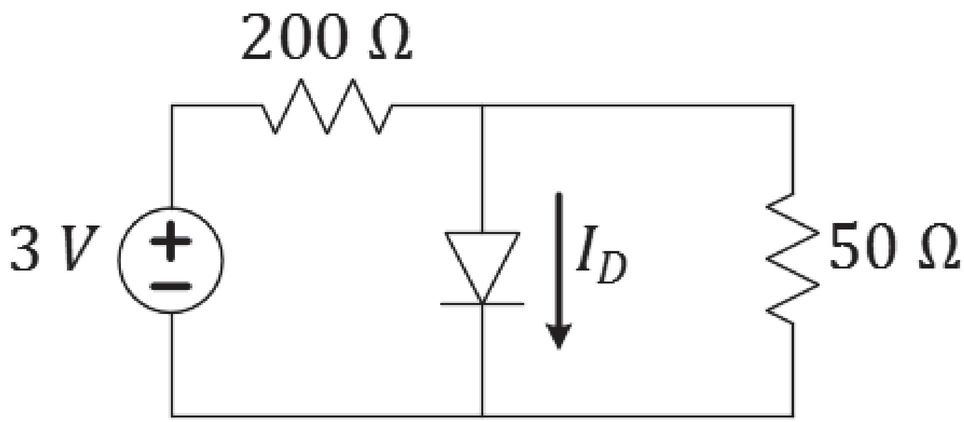
L11Q4: What is the power dissipated by a Ge diode if 30 mA is flowing through it?

Diode circuit examples (offset ideal model)



Assume offset-ideal model with V_{ON} = 0.7 (common Si diodes)
L11Q5: What is the current through the diode in the top left circuit?
L11Q6: What is the current through the diode in the top right circuit?

Diode circuit examples (offset ideal model)



L11Q7: I_D =

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

Assume offset-ideal model with V_{ON} = 0.7 (common Si diodes)
L11Q7: What is the current through the diode in the circuit?

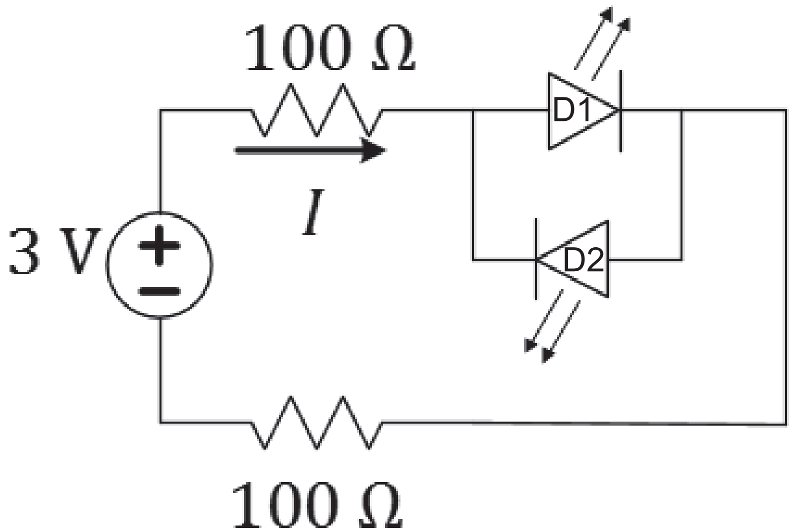
L11 Learning Objectives

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 12: Diode Circuits

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

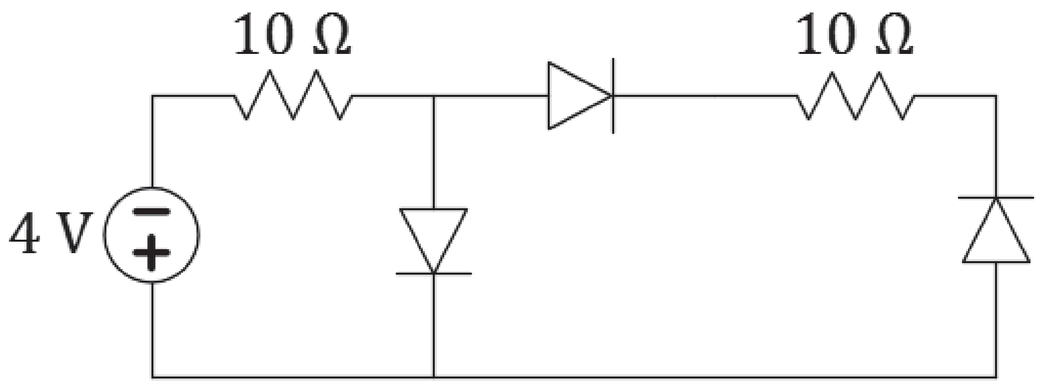
Guess-and-check example



Assume OIM with V_{ON} = 2 V (red LED)
L12Q1: What is the current supplied by the voltage source?
L12Q2: What is the power dissipated in each diode?

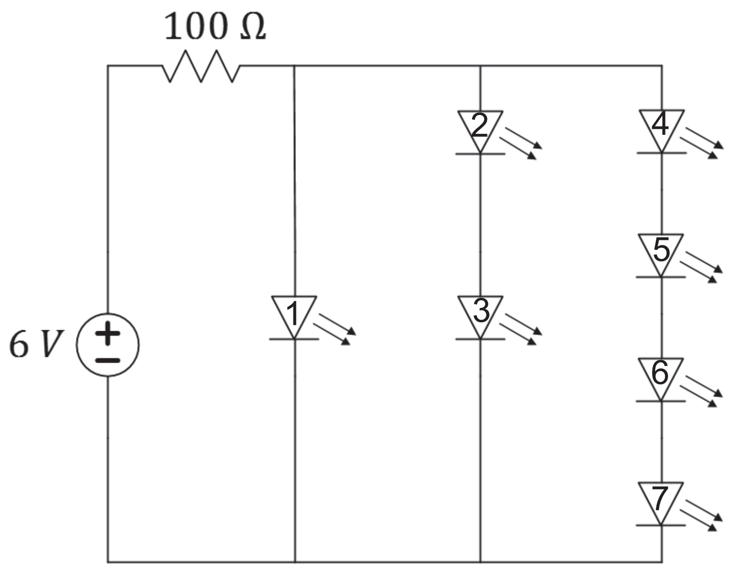
Back-to-back diodes in series are modeled by OIM as an open circuit

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



L12Q3: Assume OIM with V_{ON} = 0.7 V (Si)
What is the current through the left-most diode?

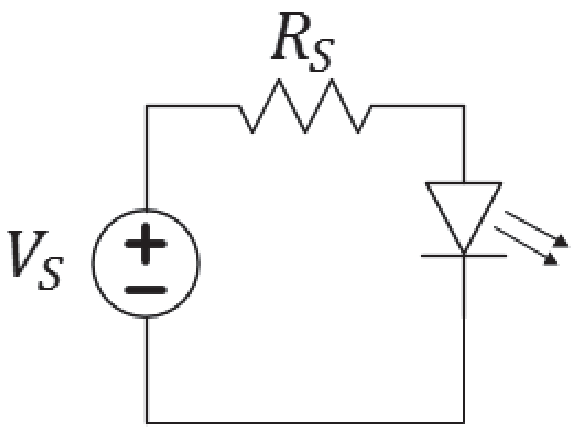
Another guess-and-check example



$$V_{on} = 2\ V$$

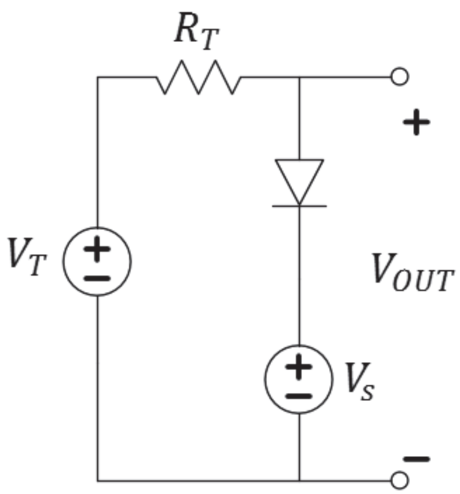
L12Q4: How many red LEDs are turned on in the circuit above? (Use OIM)

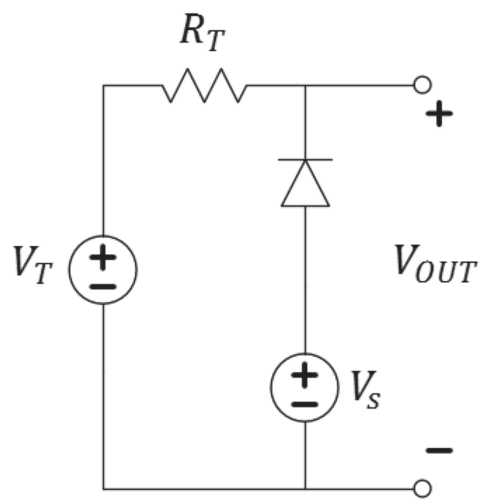
Current-limiting resistors for LEDs



Assume OIM with V_{ON} = 3.3 V (blue LED)
L12Q5: How many 1.5 V batteries are needed to turn on the LED?
L12Q6: What is the series resistance needed to get 16 mA through the LED?
L12Q7: What is the resulting power dissipation in the diode?

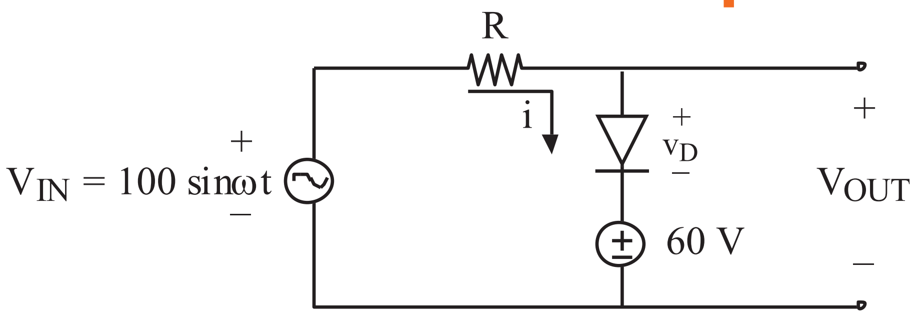
Setting voltage limits with diodes





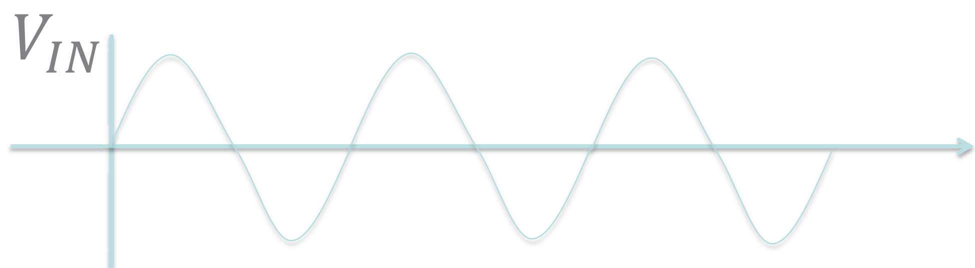
Assume linear model with V_{ON} = 0.3 V (Ge diode)
L12Q8: What is the possible range of the output voltages in the left circuit?
L12Q9: What is the possible range of the output voltages in the right circuit?

A voltage-clipping circuit sets maximum or minimum output voltage



KVL:

$V_{OUT} = 60 + v_D$



L12Q10: If the input voltage waveform is shown, what is the output waveform, assuming an ideal diode model (V_{ON} = 0 V)?

L12 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 13: Catchup and Examples

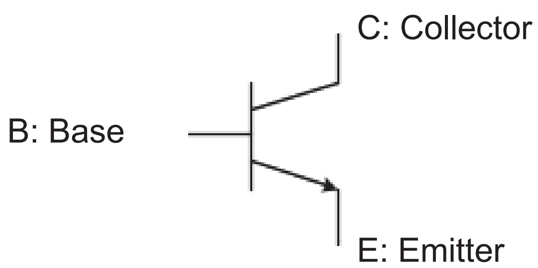
- We will use this lecture to catch up, if needed
- We will also practice solving circuits
- The slides will be distributed

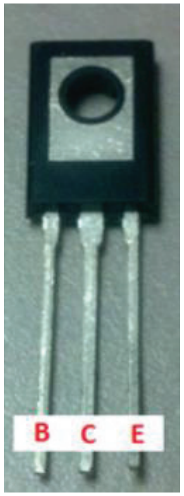
Lecture 14: Hour Exam #1 Review

- This lecture is OPTIONAL, but highly recommended!
- Attendance will not be taken
- We will use this lecture for last minute review
- We will focus on *muddy points*
- Plan to study ahead of time
- More info TBA

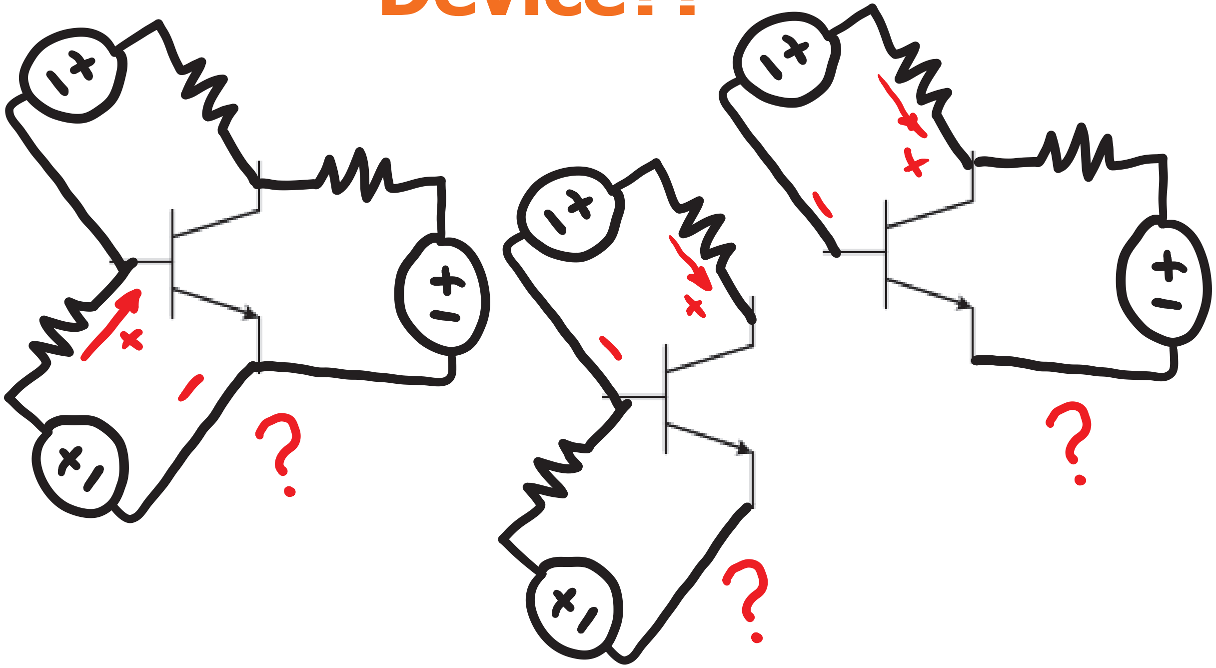
L15: The Bipolar Junction Transistor (BJT)

- 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



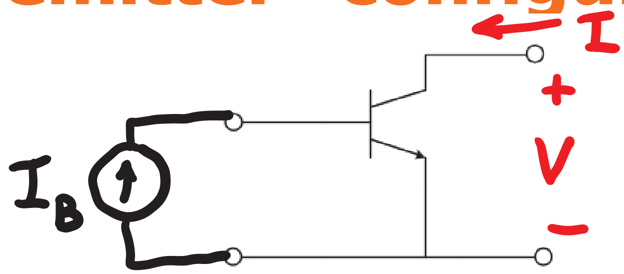


IV Characteristic of a 3-terminal Device??



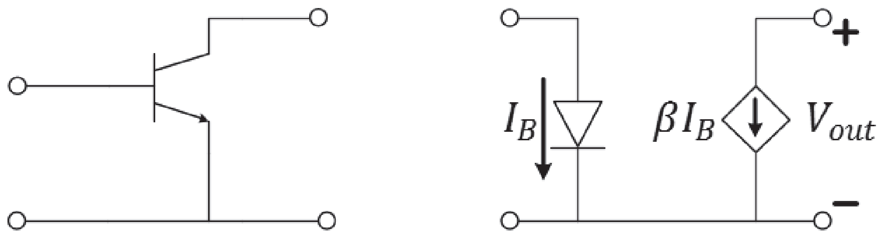
No single way to connect three-terminal device to a linear circuit.

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

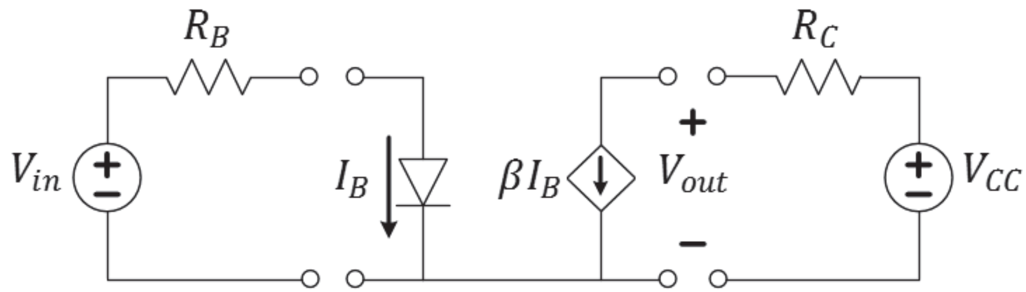


Constraints:

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

L15Q1: Given these constraints, can this "dependent" current source deliver power?

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: $V_{out} \geq V_{min} \approx 0$

L15Q2: Right-side KVL: Find an equation relating I_{max} to V_{min}.

L15Q3: Left-side KVL: Find the smallest V_{in} such that $I_B > 0$ (if $\mathrm{V_{on}} = 0.7\ V$)?

L15Q4: What is I_B if $V_{in} = 3\ V$ and $R_B = 4.6\ k\Omega$?

L15Q5: 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 Datasheet Parameters Required

Electrical Characteristics T_a = 25°C unless otherwise noted

Symbol	Parameter	Test Condition	Min.	Max.	Units
Off Characteristics					
$BV_{(BR)CEO}$	Collector-Emitter Breakdown Voltage *	I_C = 10mA, I_B = 0	40		V
$BV_{(BR)CBO}$	Collector-Base Breakdown Voltage	I_C = 10μA, I_E = 0	75		V
$BV_{(BR)EBO}$	Emitter-Base Breakdown Voltage	I_E = 10μA, I_C = 0	6.0		V
I_{CEX}	Collector Cutoff Current	V_{CE} = 60V, $V_{EB(off)}$ = 3.0V		10	nA
I_{CBO}	Collector Cutoff Current	V_{CB} = 60V, I_E = 0 V_{CB} = 60V, I_E = 0, T_a = 125°C		0.01 10	μA μA
I_{EBO}	Emitter Cutoff Current	V_{EB} = 3.0V, I_C = 0		10	nA
I_{BL}	Base Cutoff Current	V_{CE} = 60V, $V_{EB(off)}$ = 3.0V		20	nA
On Characteristics					
h_{FE}	DC Current Gain	I_C = 0.1mA, V_{CE} = 10V I_C = 1.0mA, V_{CE} = 10V I_C = 10mA, V_{CE} = 10V I_C = 10mA, V_{CE} = 10V, T_a = -55°C I_C = 150mA, V_{CE} = 10V * I_C = 150mA, V_{CE} = 1V * I_C = 500mA, V_{CE} = 10V *	35 50 75 35 100 50 40	300	
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage *	I_C = 150mA, I_B = 15mA I_C = 500mA, I_B = 50mA		0.3 1.0	V V
$V_{BE(sat)}$	Base-Emitter Saturation Voltage *	I_C = 150mA, I_B = 15mA I_C = 500mA, I_B = 50mA	0.6	1.2 2.0	V V
Small Signal Characteristics					

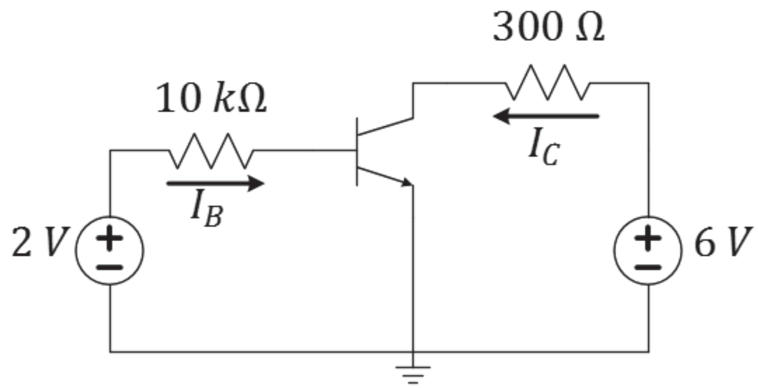
$\approx \beta$ (beside h_{FE})

$V_{CE,sat}$ (beside $V_{CE(sat)}$)

$V_{BE,on} \leq$ (beside $V_{BE(sat)}$)

L15Q6: Approximate values of $\beta, V_{BEon},$ and $V_{CE,sat}$ from the datasheet.

BJT in Active Region



BJT datasheet parameters:

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

L15Q7: Find I_B.
L15Q8: Find I_C.

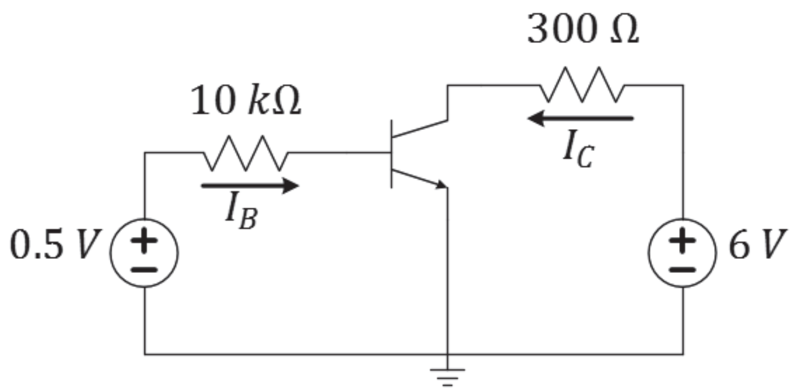
L15Q7:

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:

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

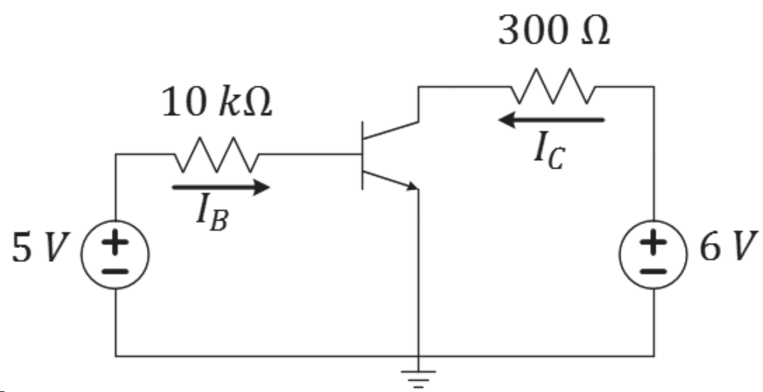


L15Q9: Find I_B.
L15Q10: Find I_C.

BJT in Saturation

BJT datasheet parameters:

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

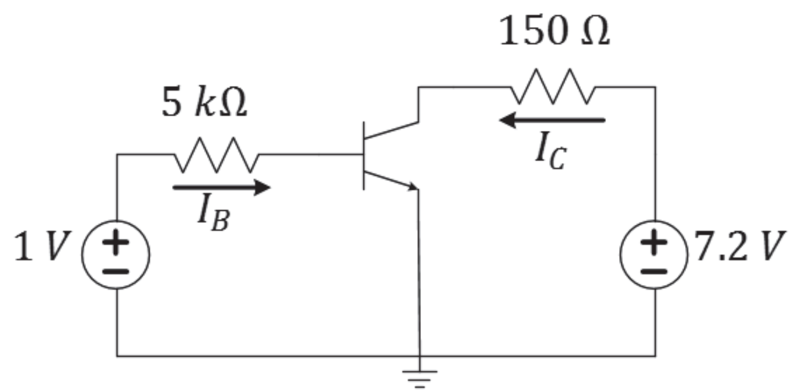


L15Q11: Find I_B.
L15Q12: Find I_C.

BJT Exercise

BJT datasheet parameters:

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

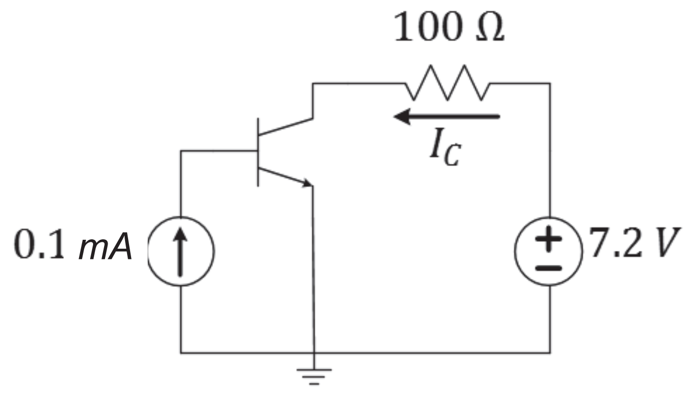


L15Q13: Find I_C and identify in which regime the transistor is operating.

BJT Exercise

BJT datasheet parameters:

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



L15Q14: Find I_C and identify in which regime the transistor is operating.
L15Q15: Determine the power consumed by the transistor.

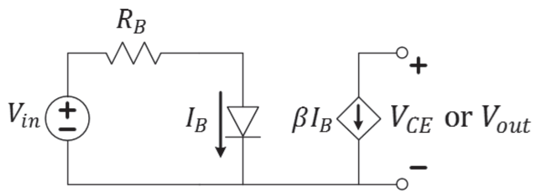
L15 Learning Objectives

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 16: BJT IV Characteristics

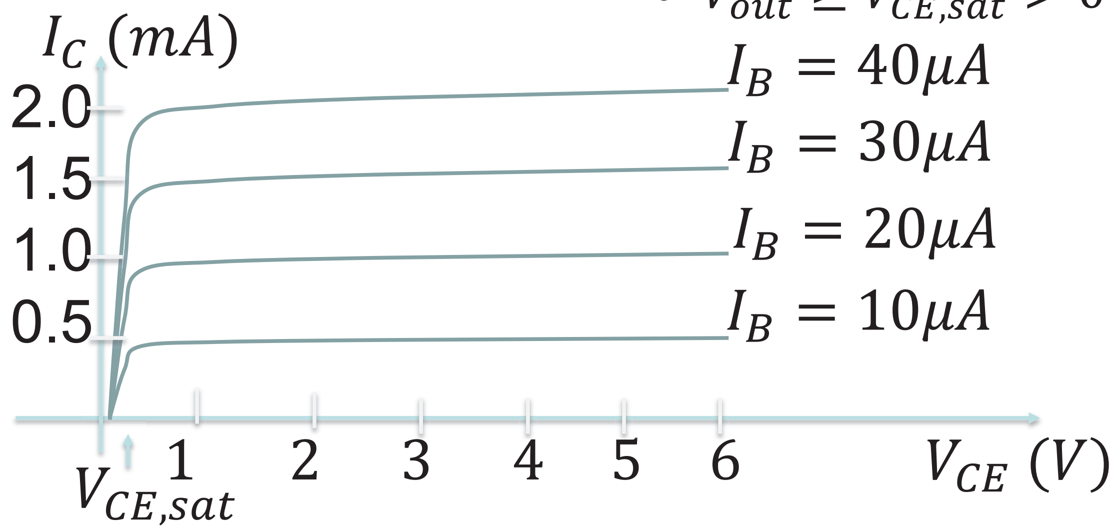
- Interpreting CE junction IV curves for transistor parameters
- Interpreting load line IV curves
- Analysis of IV curves for the (I,V) operating point
- Explore the saturation condition
- Solving transistor-regime problems

BJT IV curves of the CE junction



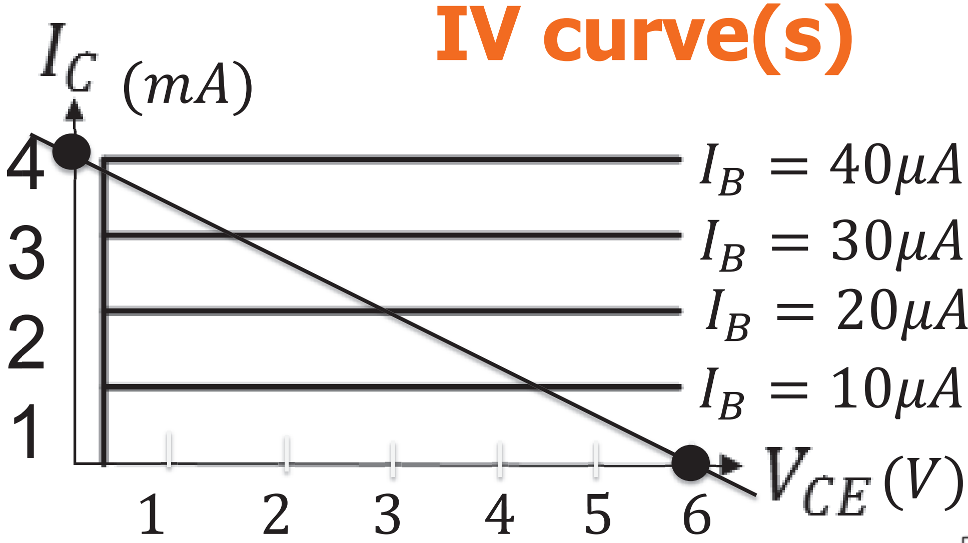
Constraints:

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



L16Q1: Use the IV plots above to estimate the value of β.

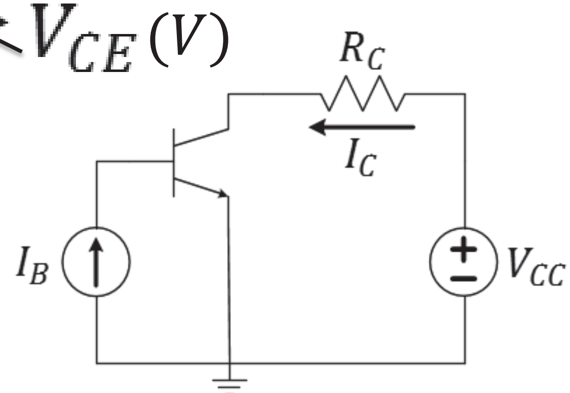
Extracting information from the IV curve(s)



L16Q6:

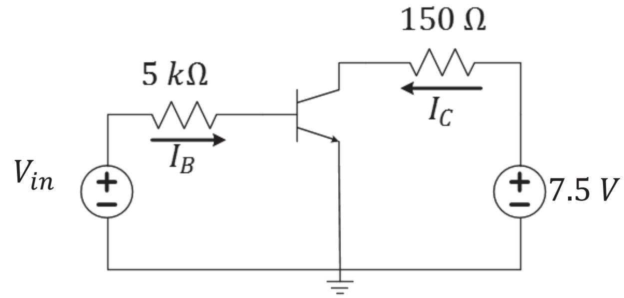
A. $I_B = 40\mu A$
B. $I_B = 30\mu A$
C. $I_B = 20\mu A$
D. $I_B = 10\mu A$
E. $I_B = 0\mu A$

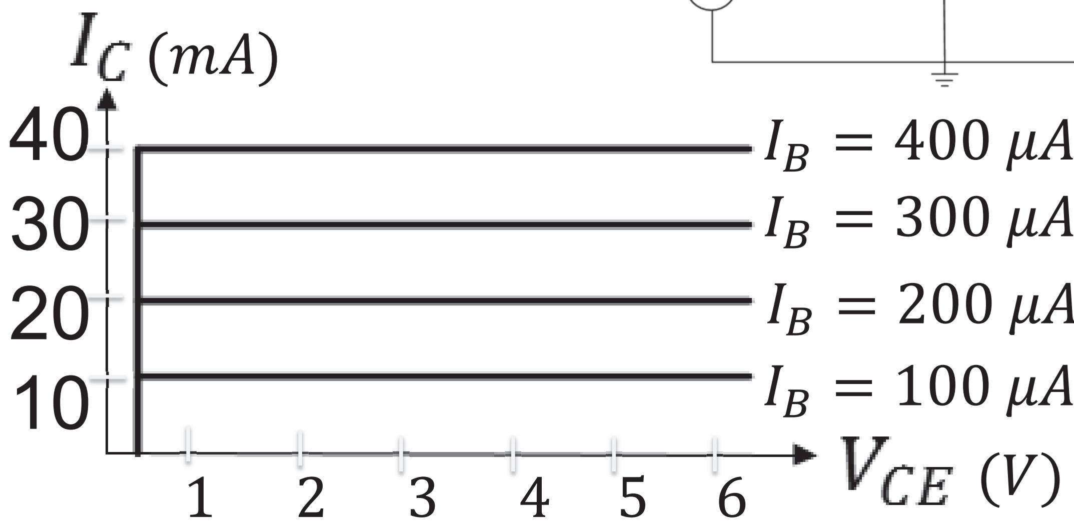
L16Q2: What is β and $V_{CE,sat}$?
L16Q3: What is V_{CC}?
L16Q4: What is R_C?
L16Q5: What is $I_{C,sat}$?
L16Q6: Which I_B results in saturation?



BJT Exercise

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

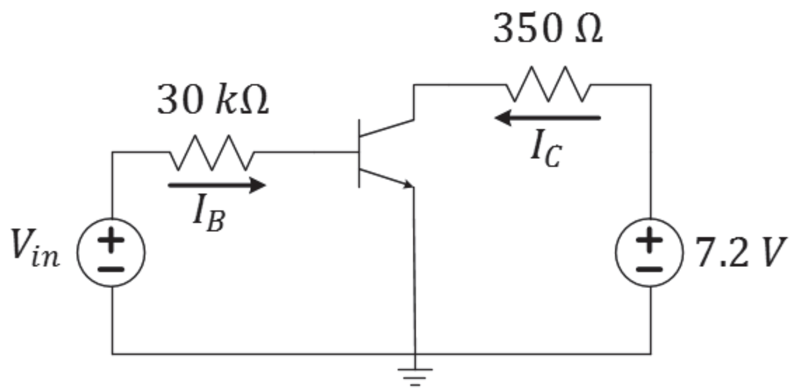




L16Q7: Estimate the operating point (I_C, V_{CE}) when $V_{in} = 1.7\ V$.

L16Q8: What value of V_{in} would drive the transistor to the edge of saturation?

BJT Exercise



BJT datasheet parameters:

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

L16Q9: What value of V_{in} would drive the transistor to the edge of saturation?

L16Q10: How does your answer change if $30\ k\Omega$ were replaced with $60\ k\Omega$?

L16Q11: How does your answer change if, instead, $350\ \Omega \rightarrow 700\ \Omega$?

L16Q10:

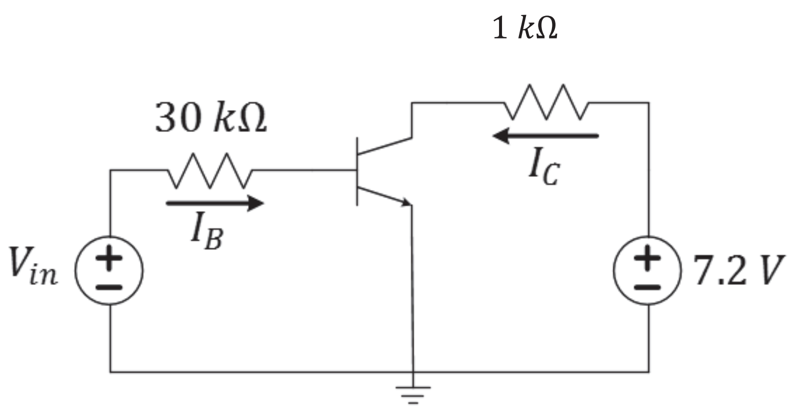
A. $V_{in@sat}$ goes up
B. $V_{in@sat}$ goes down
C. $V_{in@sat}$ stays the same

L16Q11:

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

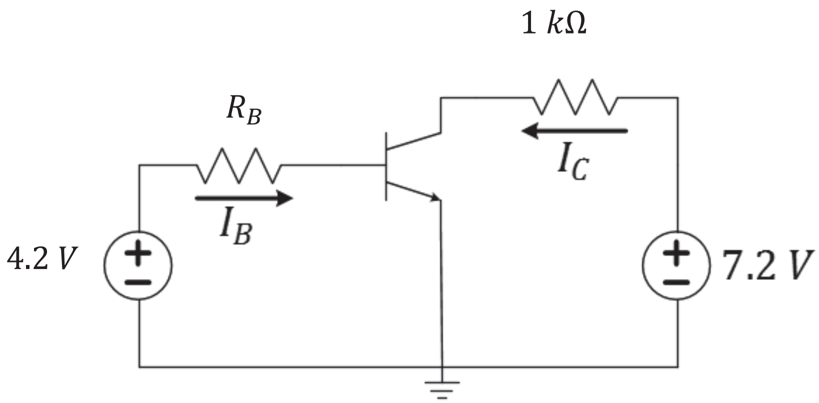
BJT circuit analysis: working back to V_{in}

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



L16Q12: Find V_{in} such that $V_{CE} = 3\ V$

BJT circuit analysis



BJT Datasheet:

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

L16Q13: Choose R_B such that the BJT is driven to the edge of saturation.

L16 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

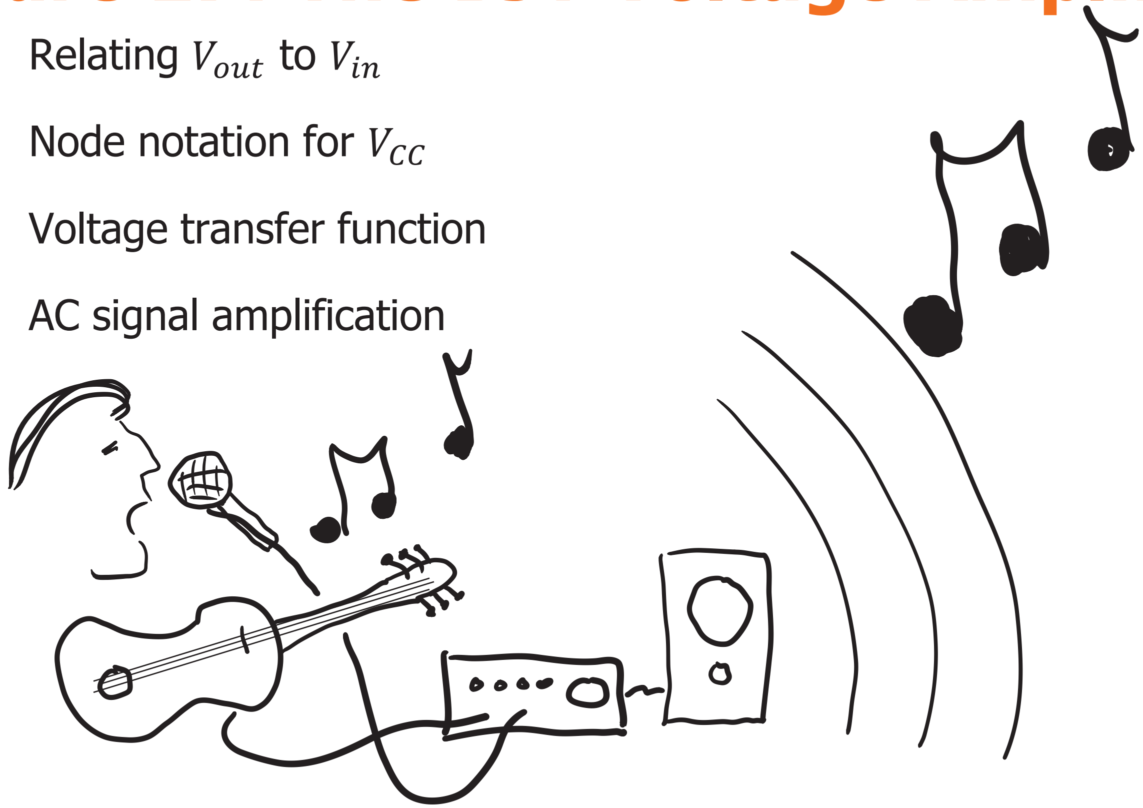
d. Identify the BJT CE operating point given IV characteristics

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 17: The BJT Voltage Amplifier

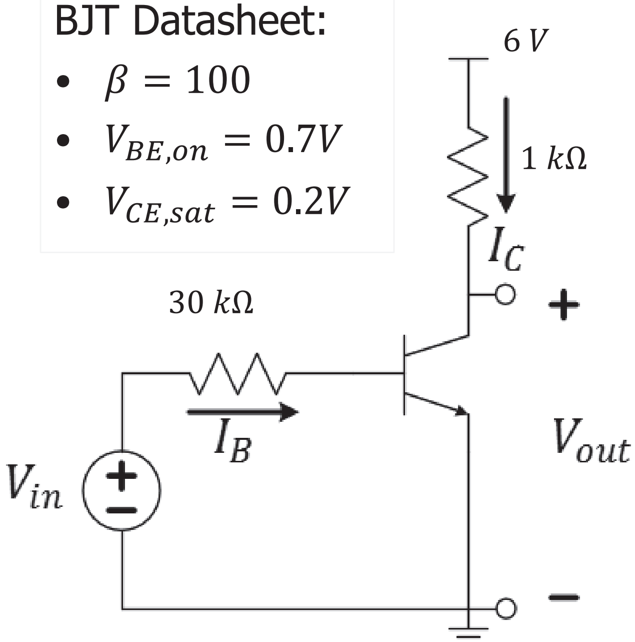
- Relating V_{out} to V_{in}
- Node notation for V_{CC}
- Voltage transfer function
- AC signal amplification



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

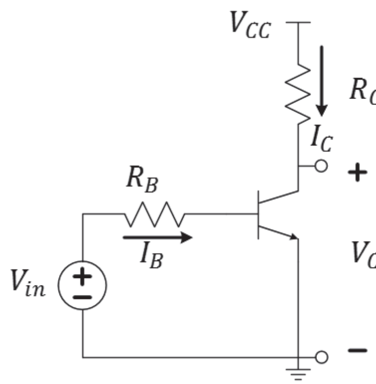
BJT Datasheet:

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



L17Q1: What is $v_{out} = V_{CE}$ for $V_{IN} = 0.3, 1, 2.5,$ and 3.5 Volts?

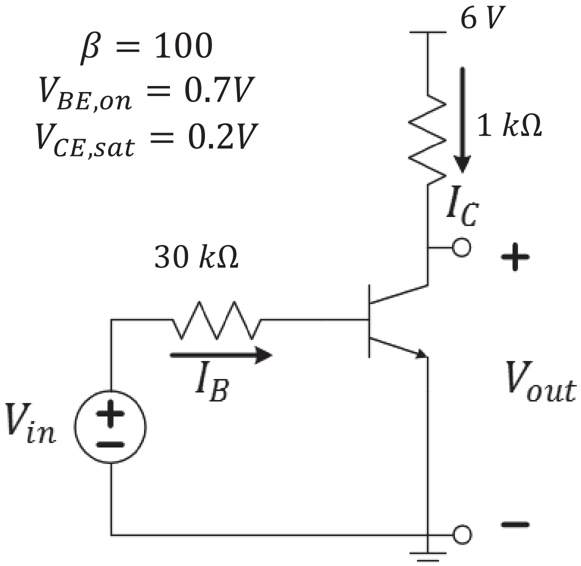
Review of BJT operating regimes

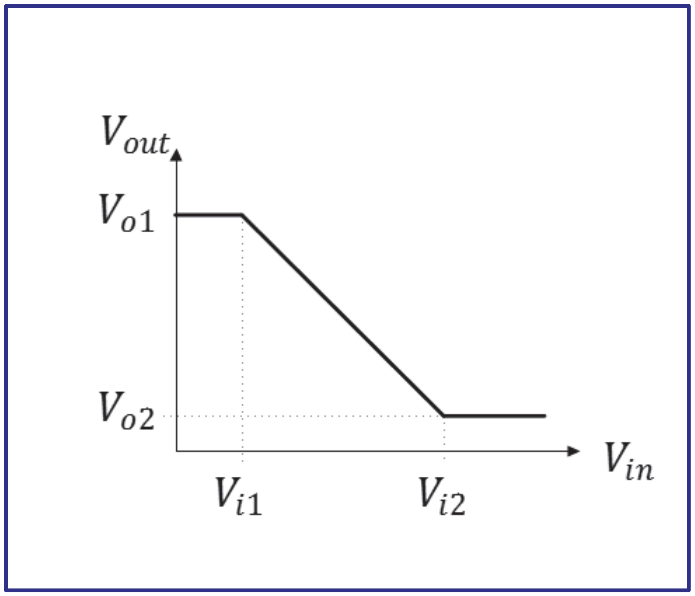


Regime	V_{in}	I_B	I_C	V_C

L17Q2: What is the formula for minimum V_{IN} which causes saturation?

Voltage transfer characteristics

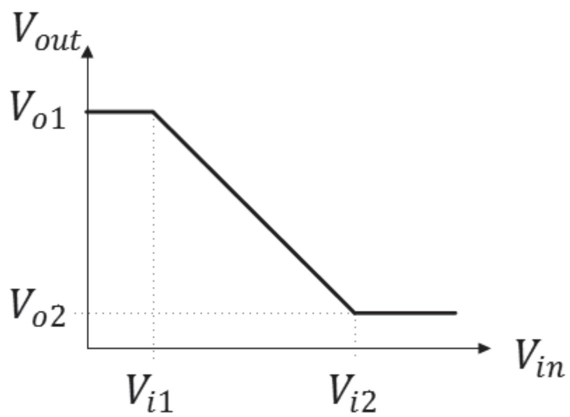




L17Q3: What are the four values $V_{o1}, V_{o2}, V_{i1}, V_{i2}$?

L17Q4: What is the $\frac{\Delta V_{out}}{\Delta V_{in}}$ slope in the active region?

Active regime for signal amplification



Consider

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

L17Q5: If $V_{IN} = 1.2 + 0.2\cos(2\pi 100t)$ what is the equation for V_{out}?

L17Q6: What is different if $V_{in} = 1.2 + 0.6\cos(2\pi 100t)$?

L17Q7: What transistor regimes are entered if $V_{in} = 1.1 + 0.3\cos(\omega t)$?

L17 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

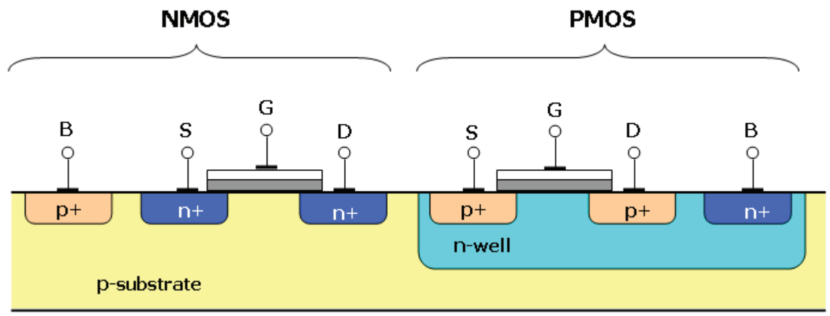
d. Determine the operating regions for an AC+DC input

e. Evaluate and AC+DC output for linear amplification

Lecture 18: Catchup and Examples or *FORGE AHEAD!*

Lecture 19: Field-Effect Transistors (FETs)

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



The Metal-Oxide-Semiconductor FET

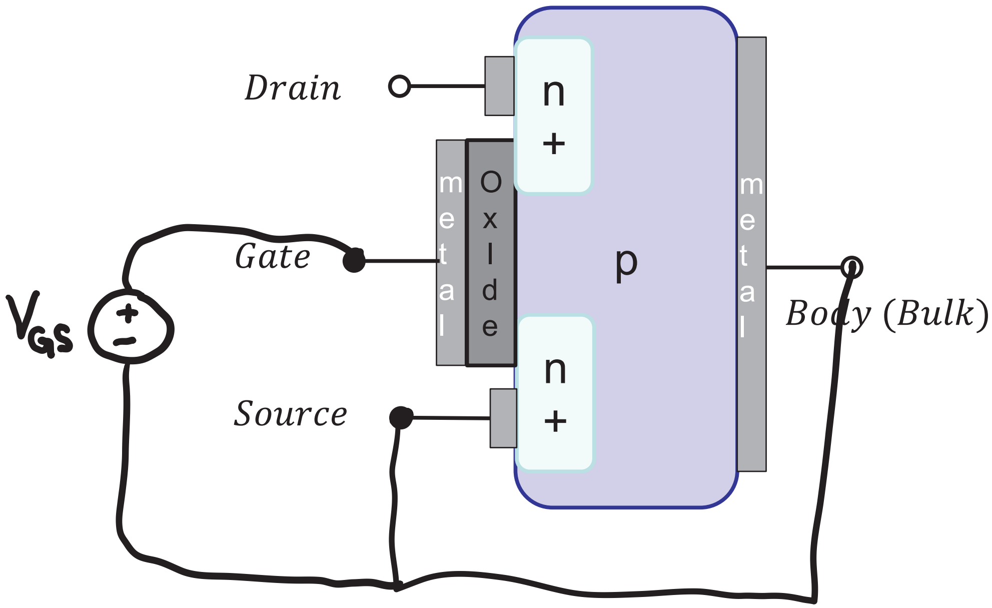
- MOSFETs are **generally** easier to fabricate; also they scale down in size better and use less power than BJTs.
- BJTs are still used in very high-speed switching integrated circuits and they are common as "discrete" devices.

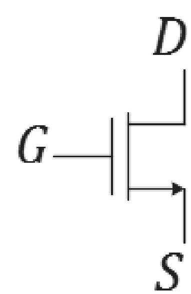
Do you know? How many transistors are in a single modern microprocessor chip?

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

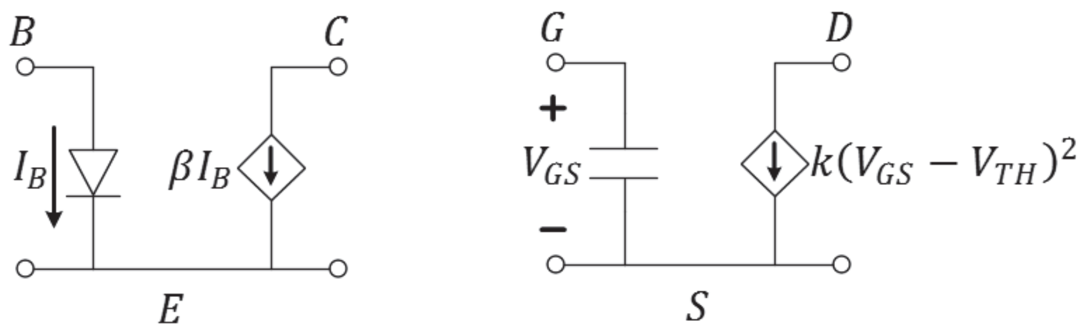
To Produce a Conductive "Channel"

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





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



Active: $I_C = \beta I_B$

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

L19Q1: What happens to drain current when $V_{GS} - V_{TH}$ doubles?

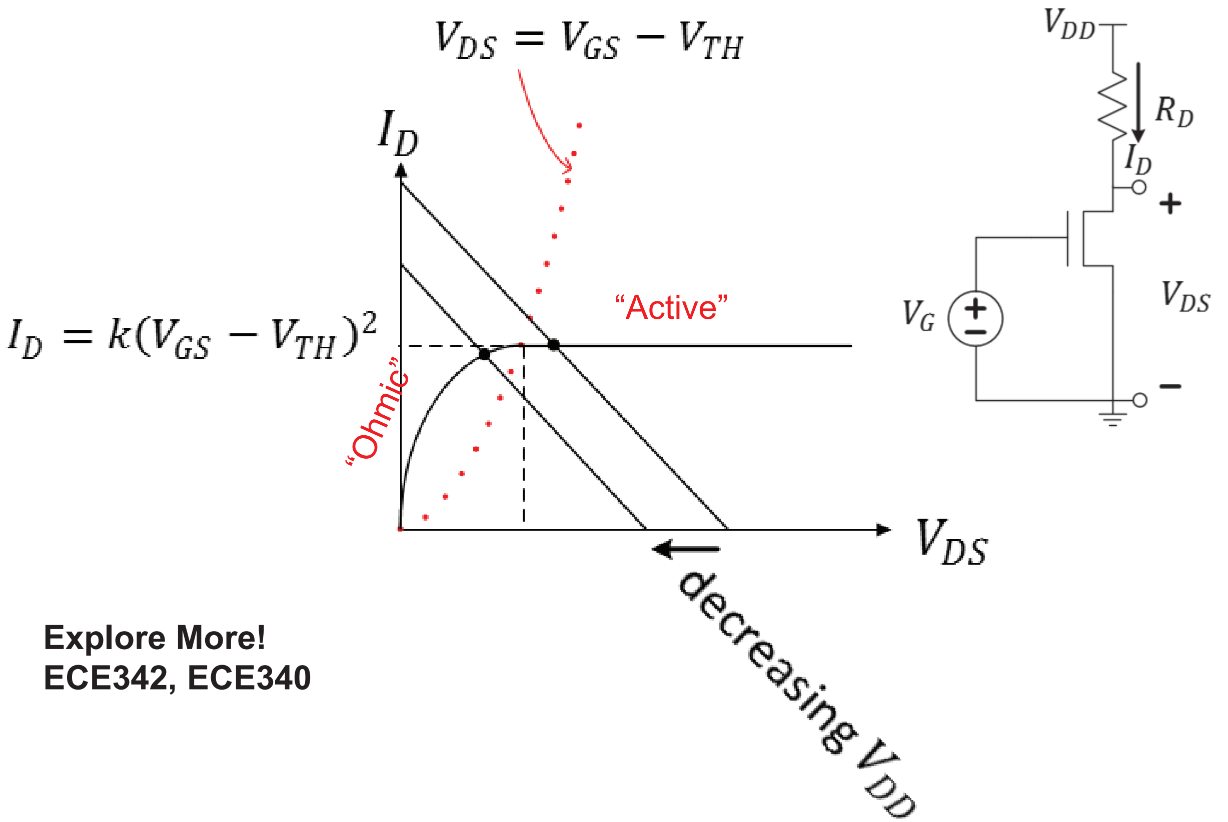
L19Q2: What is the DC current into the gate of the MOSFET model?

L19Q3: What are the units of k?

L19Q1: the drain current…

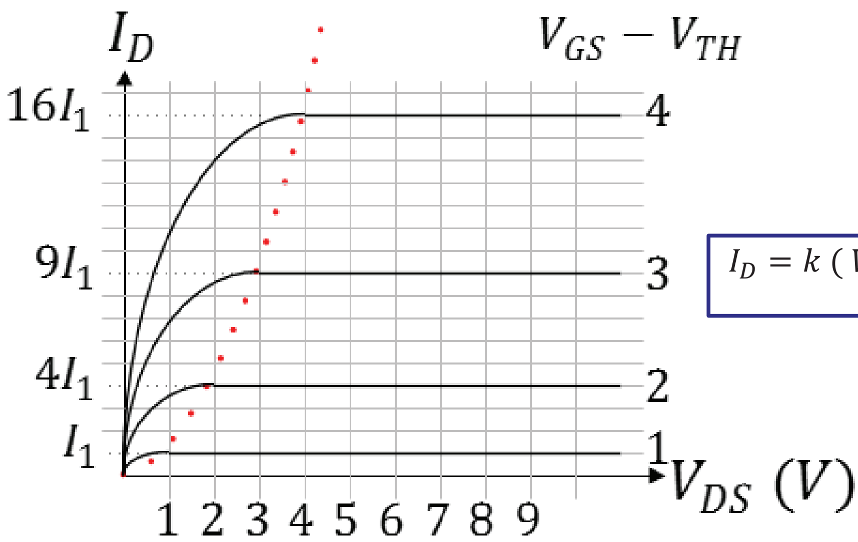
A. halves
B. stays the same
C. doubles
D. triples
E. quadruples

Measuring nMOS IV-curves



Explore More!
ECE342, ECE340

Family of nMOS IV-curves



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

L19Q6:

A. $k = 100\ mA/V^2$

B. $k = 50\ mA/V^2$

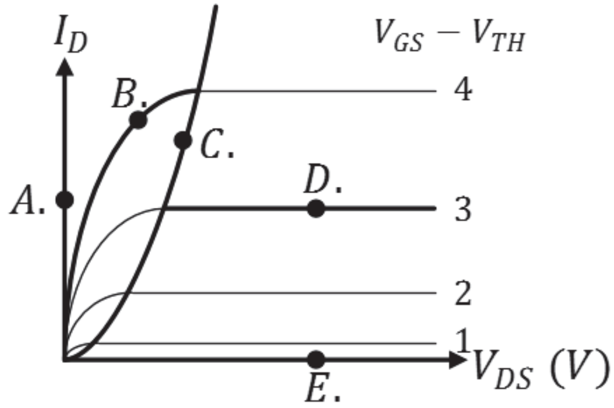
C. $k = 25\ mA/V^2$

D. $k = 12.5\ mA/V^2$

E. $k = 1\ mA/V^2$

L19Q4: If $I_1 = 100\ mA$, what is the value of k?

nMOS Exercise



L19Q5: At which operating point above would the MOSFET be in "cutoff"?

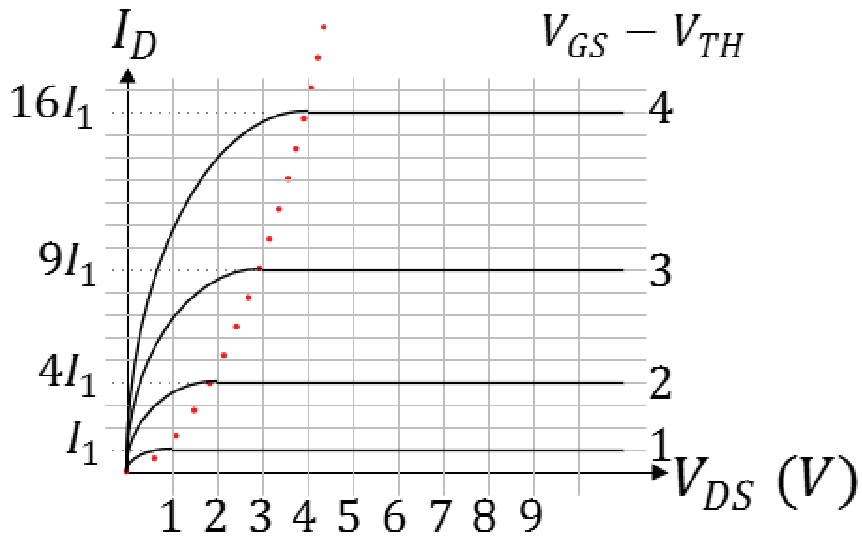
L19Q6: At which operating point above would the MOSFET be "active"?

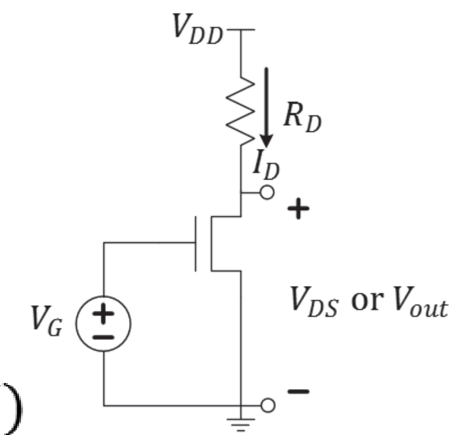
L19Q7: At which operating point above would the MOSFET be "ohmic"?

FET Exercise

FET datasheet:
$V_{TH} = 2\ V$
$I_1 = 10\ mA$

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



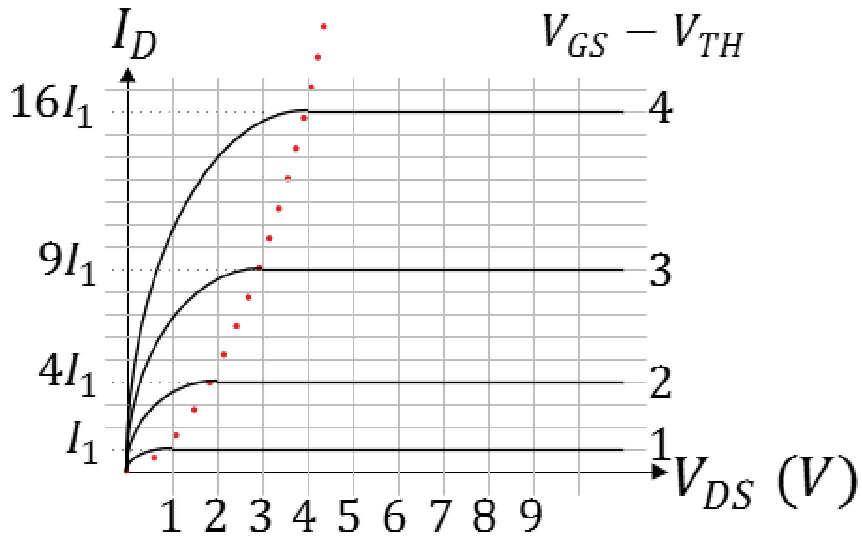


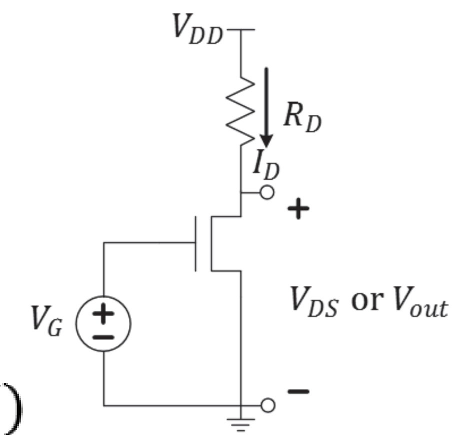
L19Q8: Use the IV plot to find the FET regime and operating point.

FET Exercise

FET datasheet:
$V_{TH} = 2\ V$
$I_1 = 10\ mA$

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





L19Q9: Find the Gate-to-Source voltage, V_{GS}.

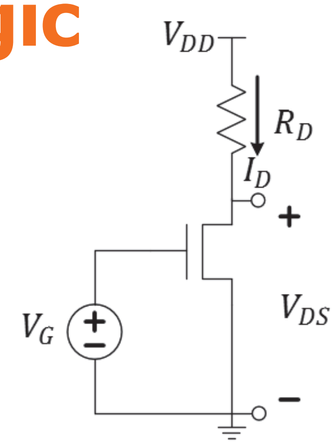
L19. Learning Objectives

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

b. To identify the regimes of nMOS with IV curves

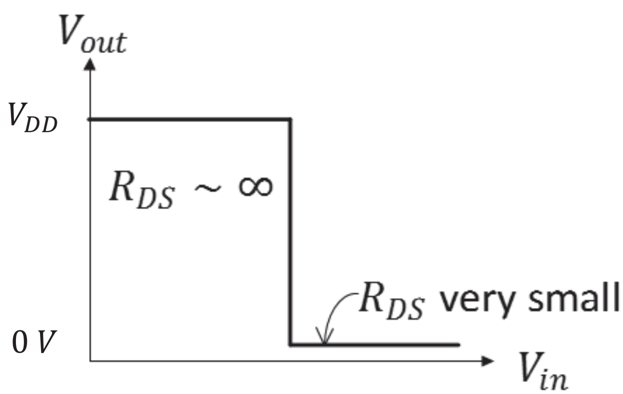
c. To solve nMOS transistor problems using IV data

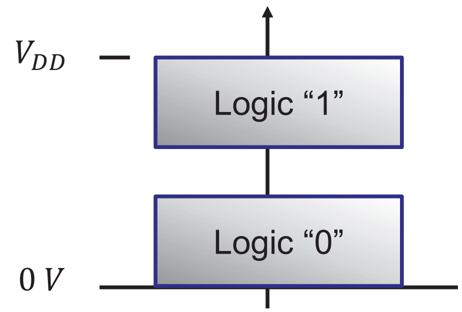
Lecture 20: cMOS Logic



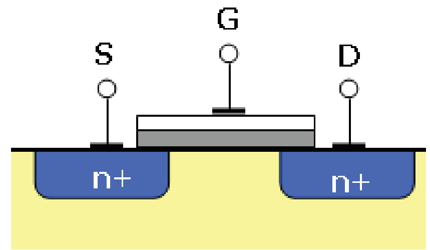
- cMOS logic and circuit models
- cMOS logic circuits and truth tables
- Switching a capacitive load

Idealized FET Model:

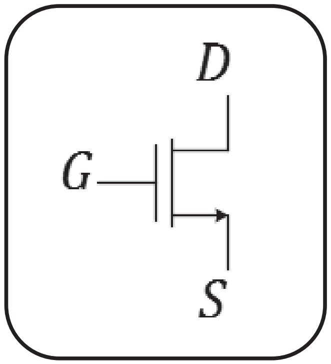




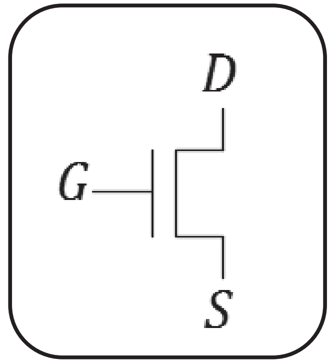
n-channel MOSFET



Circuit Symbol

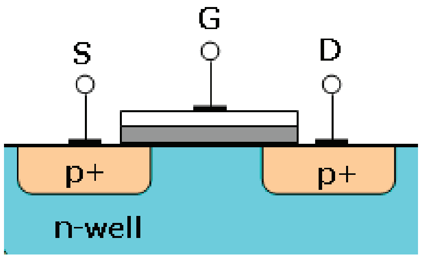


Logic Symbol

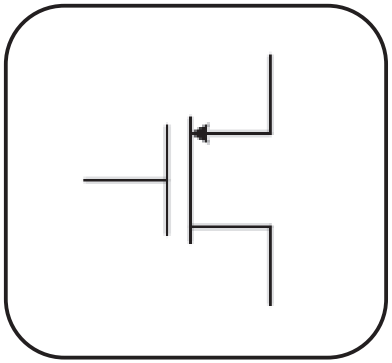


L20Q1: What happens when a logical "1" is applied to the gate?

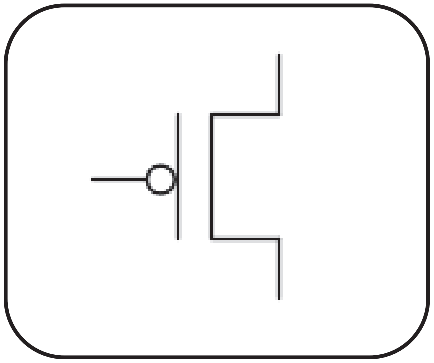
p-channel MOSFET



Circuit Symbol

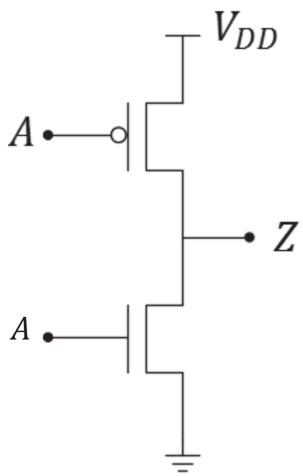


Logic Symbol



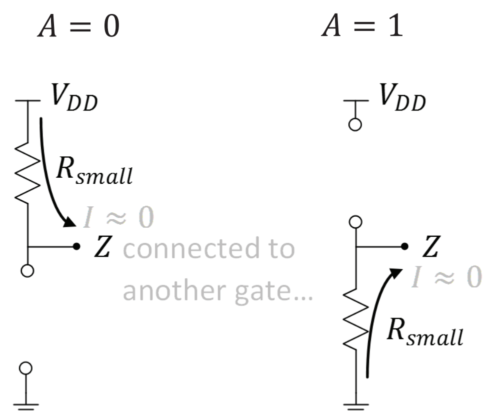
L20Q2: What happens when a logical "0" is applied to the gate?

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	

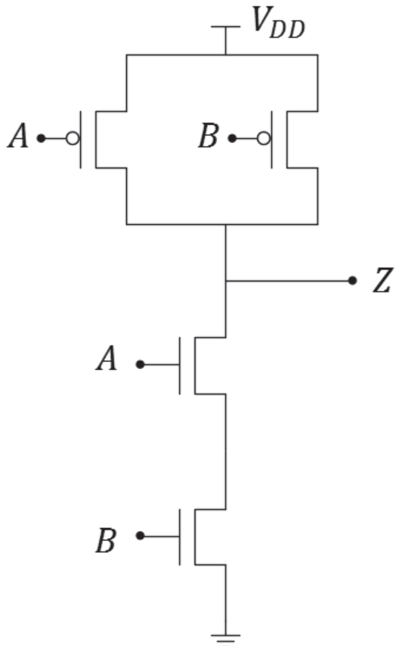


L20Q3: What is the output voltage when the input is connected to V_{DD}?

L20Q4: What is the output voltage when the input is connected to GND?

L20Q5: Complete the Logical "Truth Table".

A Two-Input cMOS Circuit

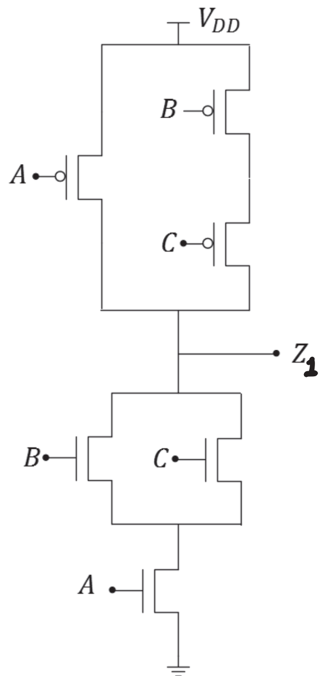


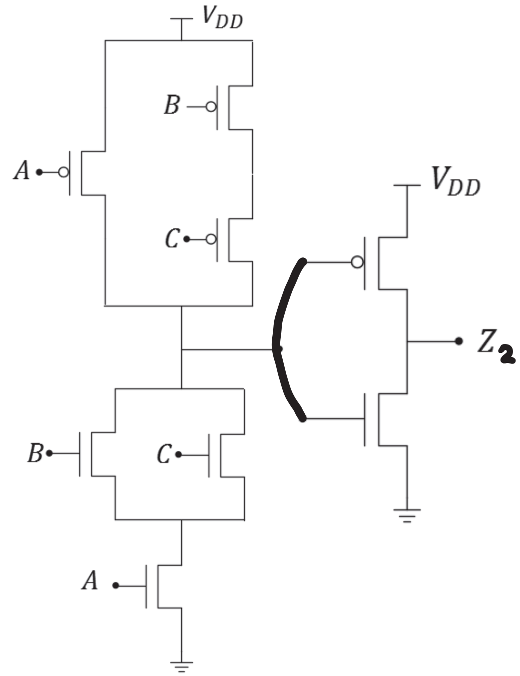
L20Q6: Complete the Truth Table.

A	B	Z
0	0	1
0	1	ρ
1	0	γ
1	1	0

L20Q6:
A. $\rho = 0, \gamma = 0$
B. $\rho = 0, \gamma = 1$
C. $\rho = 1, \gamma = 0$
D. $\rho = 1, \gamma = 1$
E. Cannot determine

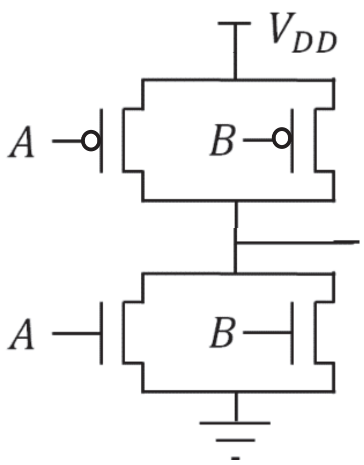
A Three-Input cMOS Circuit

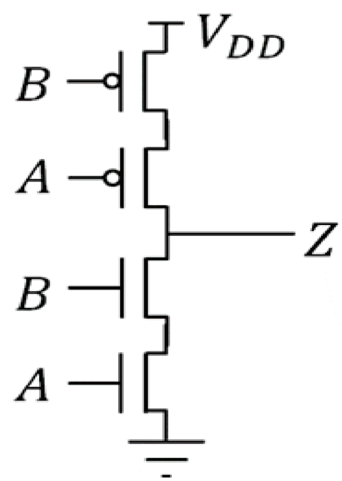




L20Q7: Complete the Truth Tables.

Improperly-Constructed cMOS Circuits





L20Q8: Attempt to complete the Truth Tables.

cMOS Energy

L20Q9: How much energy is stored in each gate ($C = 1fF$) if charged to V_{DD}?

L20Q10: 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

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

L20Q11: How many $2\ fF$ caps are switched at $1\ V$ every ns to dissipate $100\ W$?
L20Q12: If the total number of transistors on a chip is 1 billion, what is a?

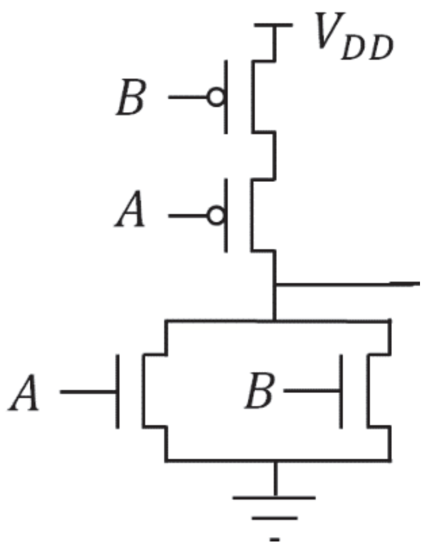
L20. Learning Objectives

a. To explain operation of a cMOS inverter

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

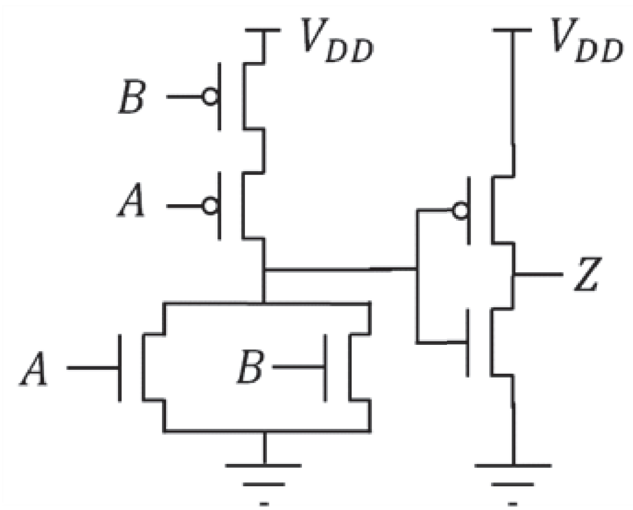
c. To calculate power consumption due to cMOS switching with capacitive loads

Two-Input cMOS Circuit



L20Q13: Complete the Truth Table.

Two-Input cMOS Circuit



L20Q14: Complete the Truth Table.

Lecture 21: Catchup and Examples or *FORGE AHEAD!*

Lecture 22: Hour Exam 2 Review

- Lecture is optional, but HIGHLY RECOMMENDED
- Will provide students a last opportunity to address outstanding questions
- Will focus on Muddy Points or problems specifically requested by students

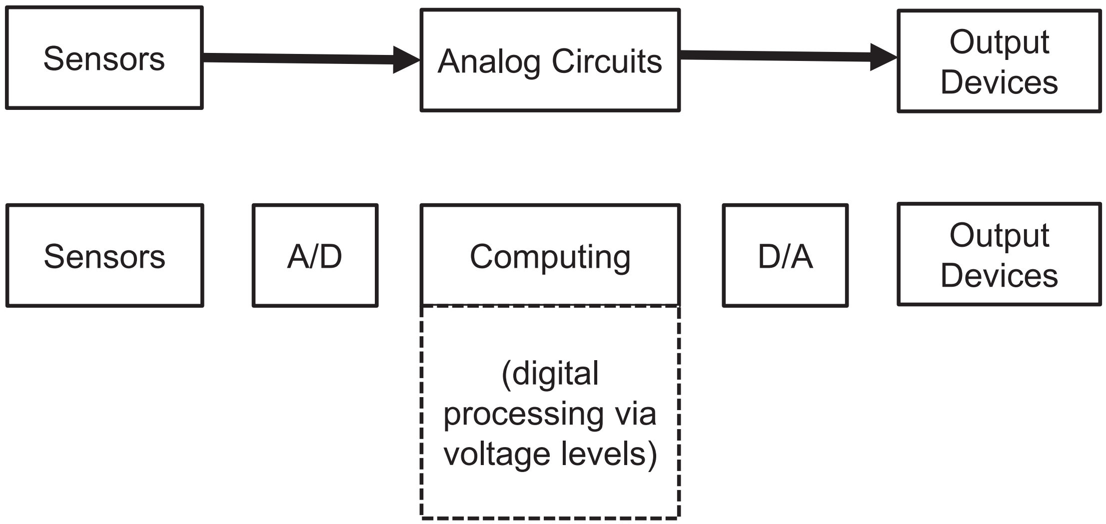
Lecture 22: HE2 Coverage (tentative)

- L01-L21 (focused on L15-L21)
- HW1-HW10 (focused on HW7-HW10)
- Includes up through cMOS Logic, but not Signals, Spectra
- No Calculators, phones, or other electronic devices
- 25 multiple choice questions in 75 minutes

Lecture 23: Signals, Spectra, and Noise

- Electronic systems and signals
- Spectral representation of signals
- Noise - random fluctuations in signals

Analog and Digital Systems

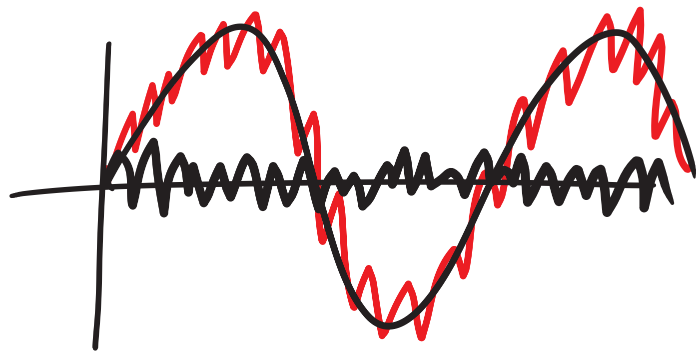


What is an analog-to-digital converter?

What is being transferred to each "subsystem"?

Additive Noise in Waveforms

signal plus noise vs. time



- Even signals that are originally "clean" become noisy
- We consider "additive" noise that "adds on" to desired signals

L23Q1: If the average power of the noise signal is 1 mW (measured across 1 Ohm), what amplitude must a sinusoidal signal have so that the signal-to-noise *power ratio* is equal to 10?

L21Q1:

A. $\approx 10\ mV$

B. $\approx 14\ mV$

C. $\approx 20\ mV$

D. $\approx 100\ mV$

E. $\approx 140\ mV$

About Noise

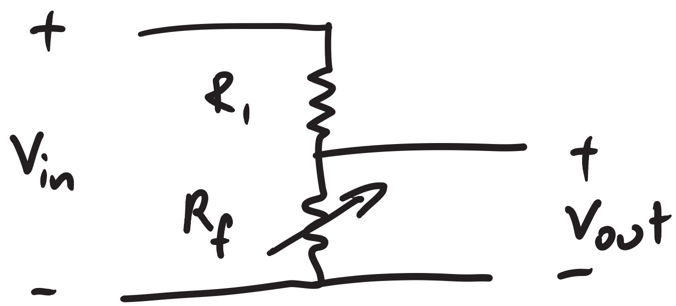
Noise is **random** voltage fluctuation

- Thermal movement of electrons is circuit noise
- Power supplies often introduce noise to circuits
- Noise limits the precision of measurements
- Noise limits ability to collect or transfer information
- It is important to limit sources of noise
- Additive noise can be reduced by averaging (filtering)
- Noise can be reduced by advanced signal processing

A Noisy DC Measurement

Thermal noise in a sensor circuit can be dominant

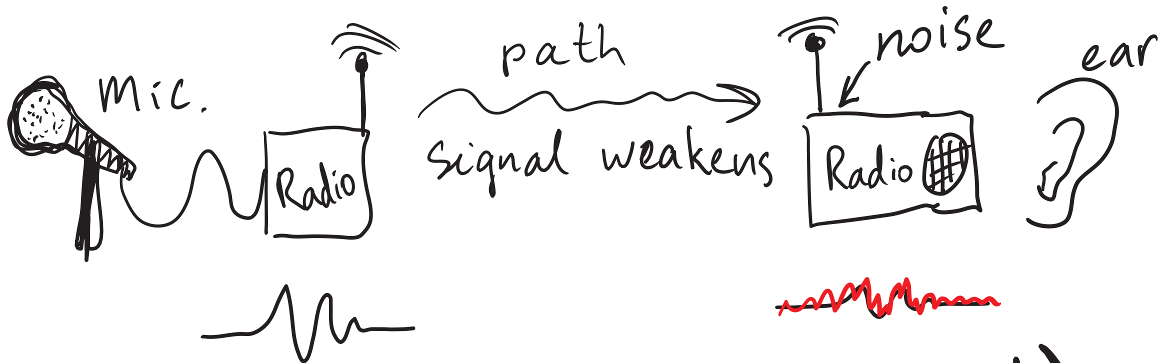
- Noise power increases with temperature and resistance
- The average value of the noise is zero



Consider a voltage divider with a flex sensor.

L23Q2: How can we improve the precision of this VDR measurement?

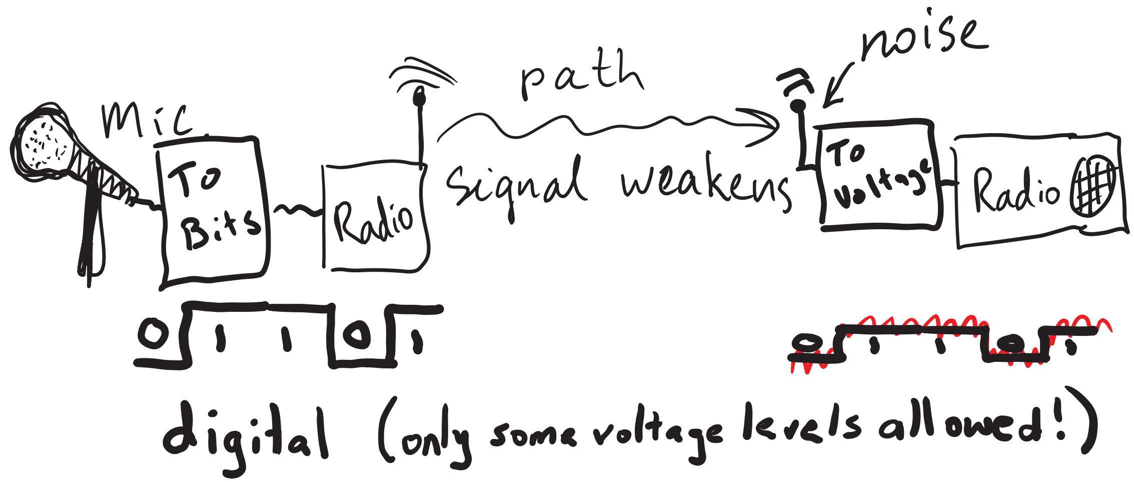
Analog systems suffer from noise



analog (no constraint on voltage levels)

Have you ever heard a noisy radio broadcast?

Noise-Free Digital Communication?



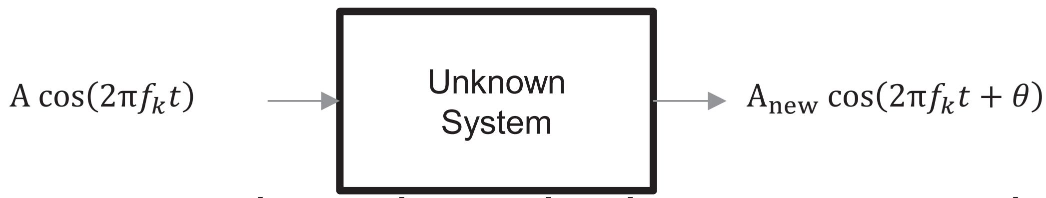
How might you distinguish the different received levels?

Sinusoids Can Represent Analog Signals

- We will represent electrical signals by waveforms $v(t)$
- Any periodic waveform can be represented by sums ($\sum$) of sinusoids (Fourier's theorem/Fourier analysis)

Explore More!
ECE210 (or ECE211)

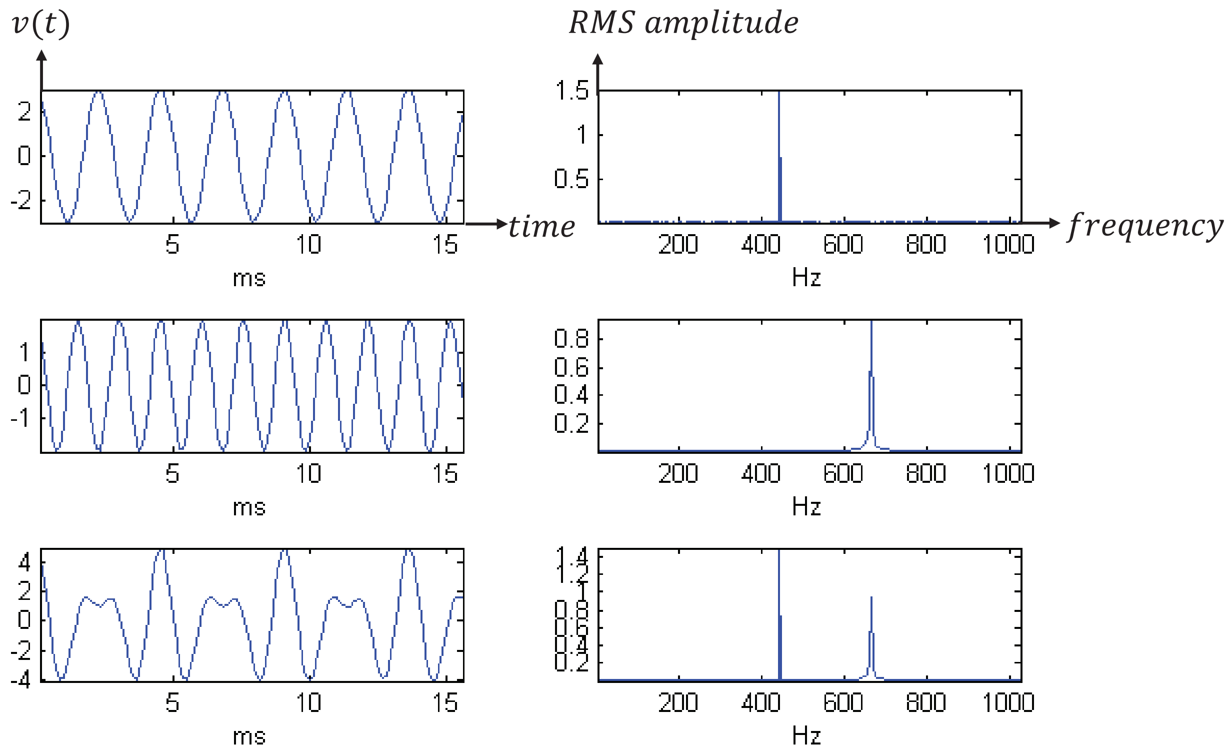
$$\boxed{v(t) = \sum_k v_k(t)} \quad v_k(t) \sim \mathrm{A}\cos(2\pi f_k t)$$



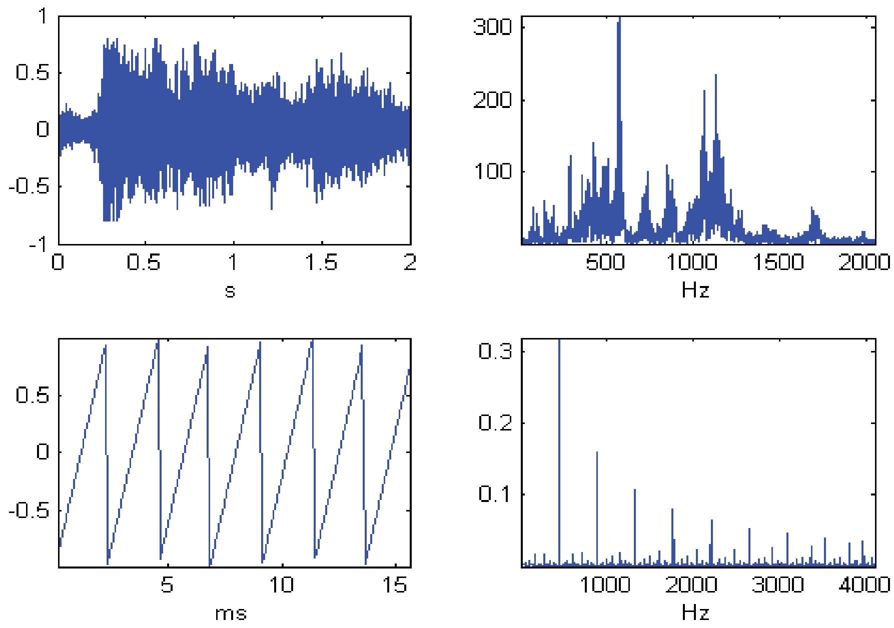
- A "filter" is a system that selectively alters A_{new} at each f_k

L23Q3: What is the frequency of $v(t) = 120\cos(2\pi 200t)$?

Spectra of Sinusoids and Sums



Spectra of Other Signals



Listing Frequencies of Periodic Signals

a. $y(t) = \cos(2\pi 50 t)$

b. $y(t) = \cos(100\pi t)$

c. $y(t) = 2\cos(100\pi t) + 5\sin(100\pi t)$

d. $y(t) = 3 + 2\cos(100\pi t) + 5\sin(300\pi t)$

e. $y(t) = 3 + 2\cos(10\pi t) + 5\sin(300\pi t)$

f. $y(t) = 3 + 2\cos(10\pi t) + 4\sin(100\pi t) + 5\sin(3000\pi t)$

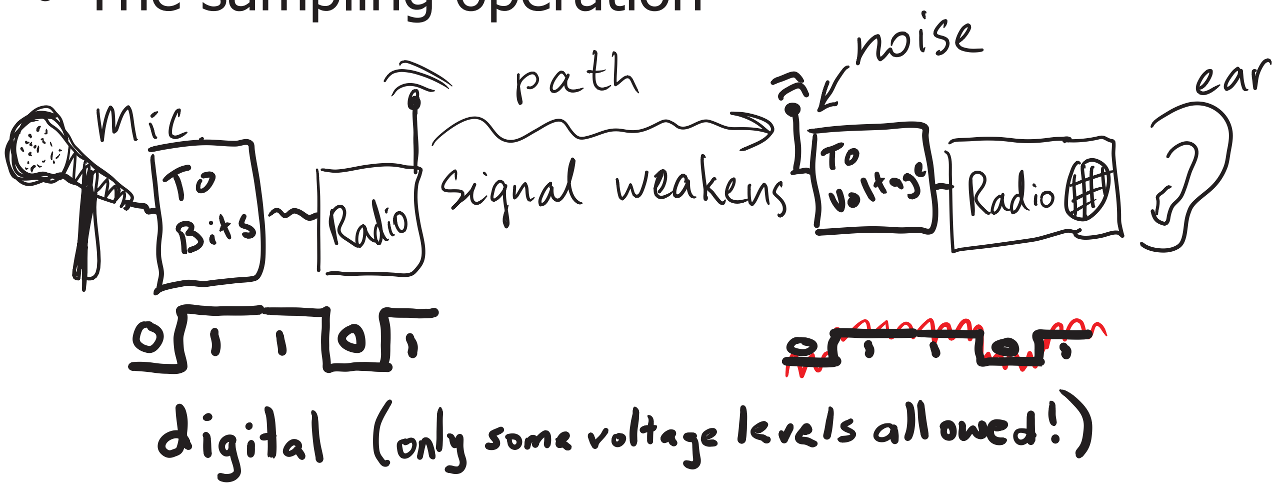
L23Q4: What is the highest frequency in each signal listed above?

Lecture 23: Learning Objectives

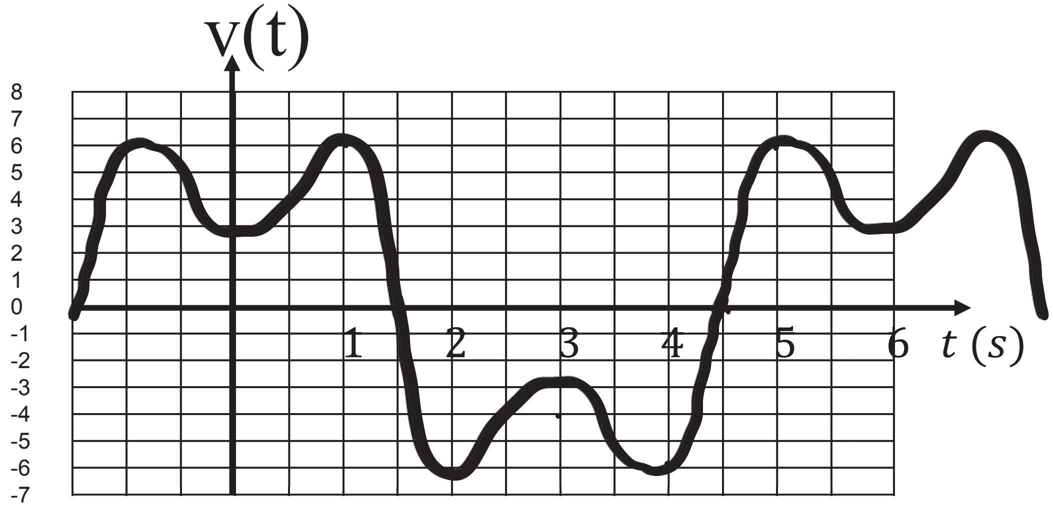
a. Compute RMS voltages from a signal-to-noise power ratio
b. Explain thermal noise and its properties
c. Provide an argument for digital immunity to noise
d. Know basic statement of Fourier's Theorem
e. Identify frequencies in sums of sinusoids
f. Recognize frequency-domain representation of signals

L24: Sampling

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



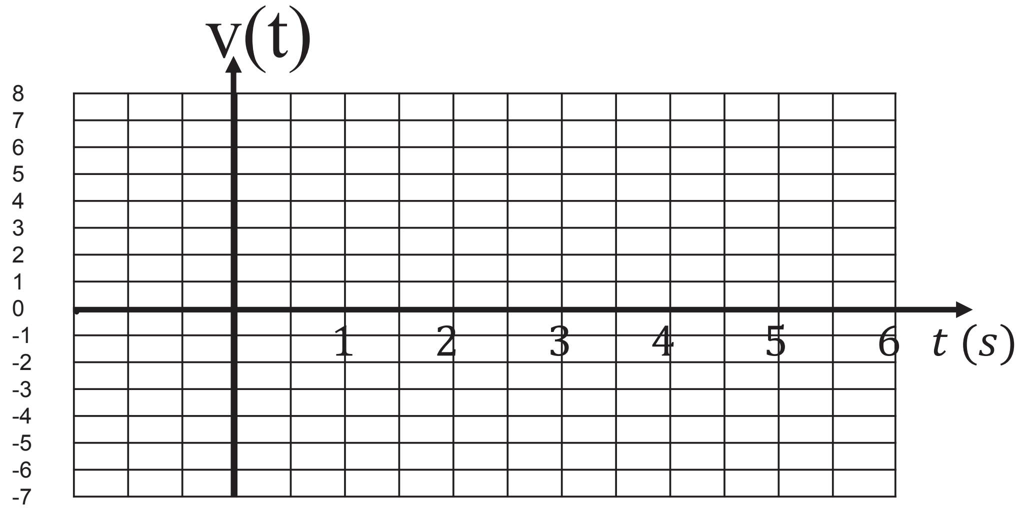
How Would you Sketch this Waveform?



L24Q1: What are the values at t=0, 2, 4, and 6 seconds?

L24Q2: Is this enough information to reproduce the waveform?

Enter Data Points of the Previous Waveform.



L24Q3: How should one connect the data points?

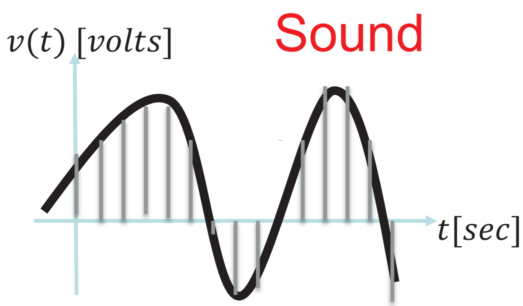
A. Point-to-point with straight lines. 

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:

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

Example: $y(t) = 5t \ sampled \ at \ T_s = 2$
Answer: $y[n] = y(nT_s) = 5\text{n}2 = 10\text{n} = \cdots, -20, -10, 0, 10, 20, \ldots$

Sampling

Sampled Sequence:

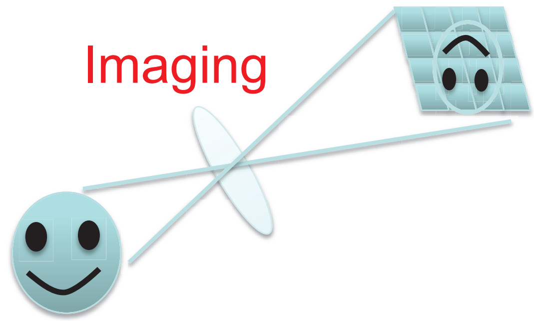
$$v[n] = v(t = nT_s), n\ integer\ (n = -2, -1, 0, 1, 2, \ldots)$$

L22Q4:Let $v_1(t) = 2cos(\pi t)$. Plot $v_1(t)$.

L24Q5:Let $v_1(t) = 2cos(\pi t)$.
If $T_s = 0.5\ s$, what is $v_1[6]$?

L24Q6: 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.

L24Q7: Speech is intelligible if frequencies up to 3.5 kHz are preserved. What should we use for T_S?

L24: 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

L25: 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.

$$f_s > 2f_{max}$$

☺No loss of information due to sampling☺

Interpolation: recreate analog with a special function!

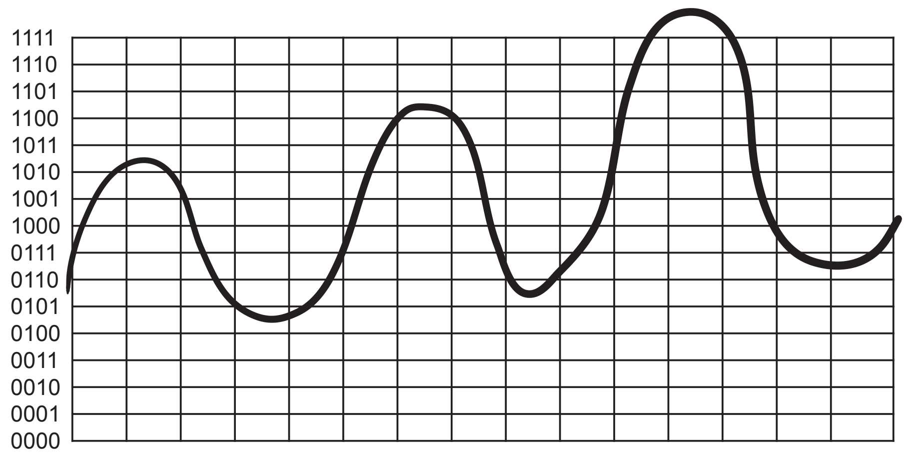
L25Q1: Speech is intelligible if frequencies up to 3.5 kHz are preserved. What is the Nyquist rate?

L25Q2: Music is often filtered to include sounds up to 20 kHz. What sampling rate should we use?

L25Q1:

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

Quantization: Round voltage values to nearest discrete level



L25Q3: 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:

0:	0	0	0
1:	0	0	1
2:	0	1	0
3:	0	1	1
4:	1	0	0
5:	1	0	1
6:	1	1	0
7:	1	1	1

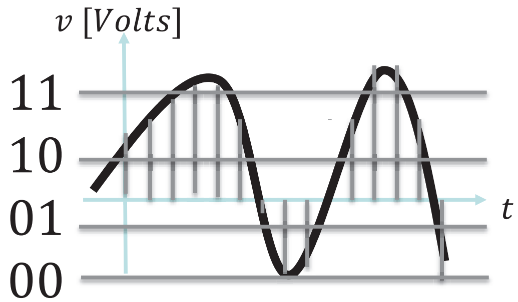
Base 10: What is the number 51?

$2-digit\ number$:	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)

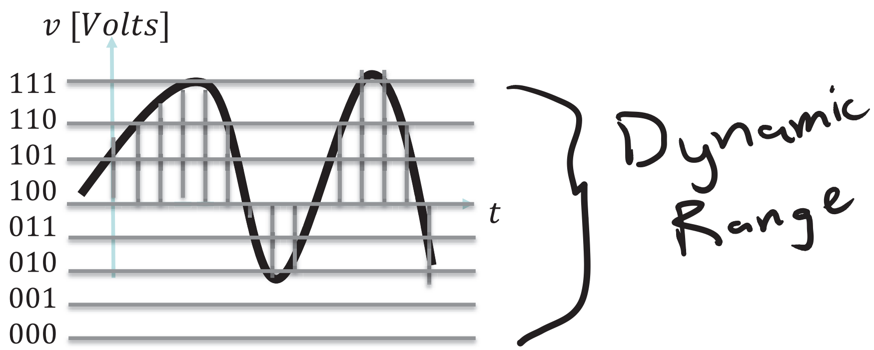


$Example: \; 2 - bit \; quantizer$

$$e[n] = v[n] - v_Q[n]$$

L25Q4: If the voltages 2.93 and 5.26 are quantized to the nearest 0.25 V, what are the quantization errors?

3-Bit Quantizer



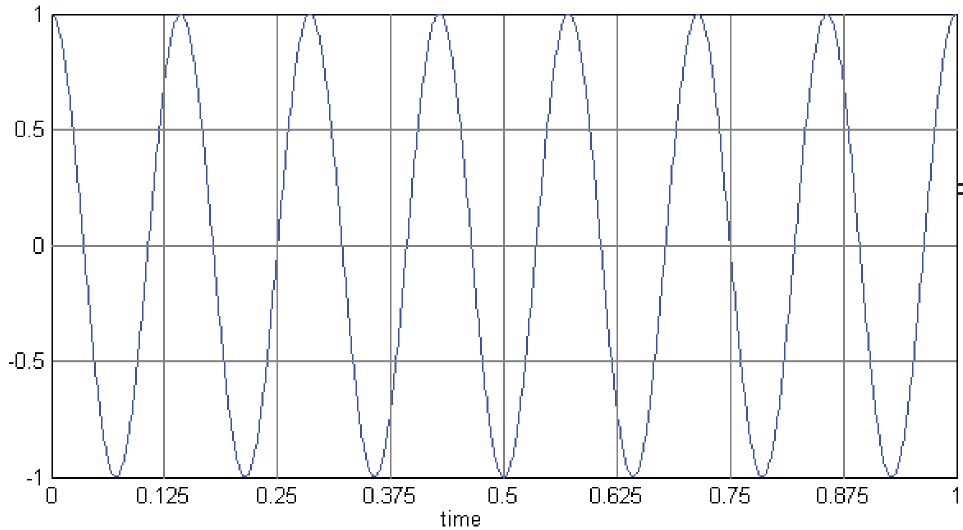
Example: 3 − *bit quantizer*

L25Q5: How many levels in a 10-bit quantizer?

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

Aliasing occurs when Sampling is sparse

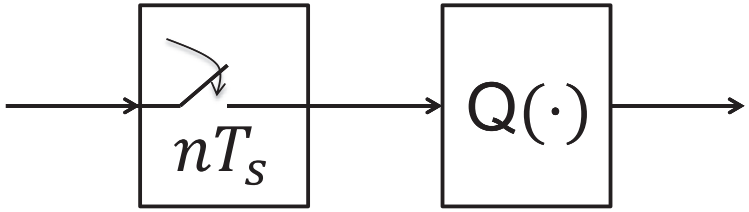
When f_s is too small (T_s is too large), high-frequency signals masquerade as lower frequency signals…



$\cos(2\pi 7t)$
$\Rightarrow f_{max} = 7\ Hz$

L25Q6: When sampling at $f_s = 8\ Hz$, what is the frequency of the signal above after reconstruction?

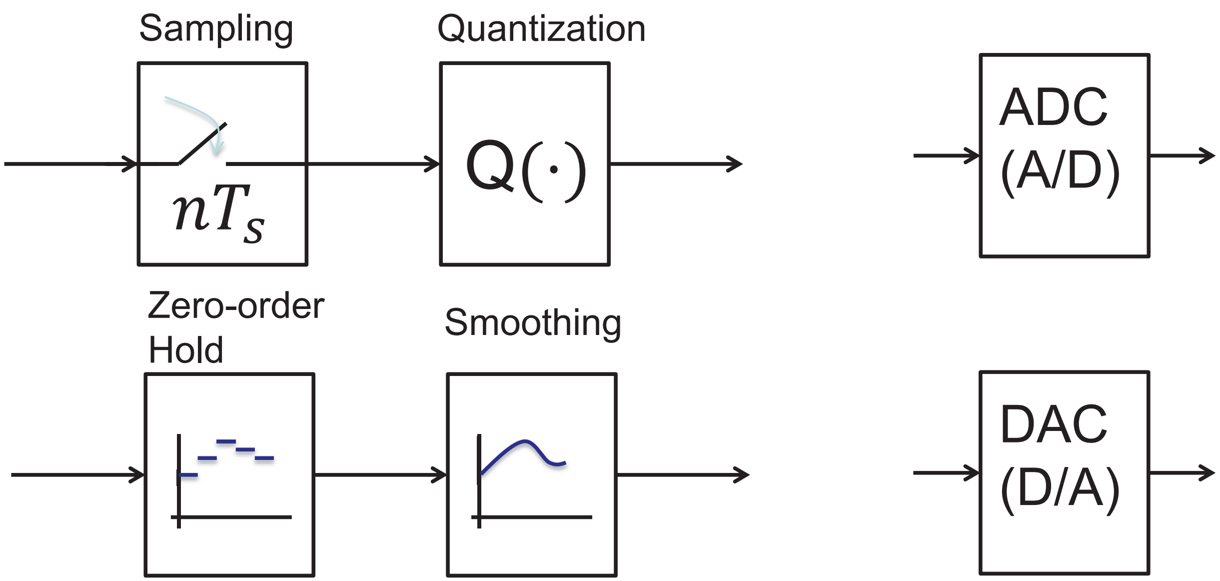
Sampling + Quantization =Digitization



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

L25Q7: Under what conditions on sampling and on quantization will you incur a loss of information?

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



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

L25Q8: 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?

L25Q9: 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?)

L25Q10: 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?

L25: 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)

L26: Quantifying Information

- Define Information
- Exploring Information-sharing games
- Quantifying Information
  - Informally via intuition
  - Formally via **Entropy**
- To use relative frequency to compute entropy, the shortest theoretical average code length.

What is Information?

Information: a)That which informs.
b) Unknown items drawn from a set.

Implies an amount of uncertainty.

Examples:

- Letters from an alphabet
- Words from a dictionary
- “voltages” entering an A/D
- Image pixel values from your camera

The Game of Twenty Questions

I have information for you.

What is it?

Guess!

Can I ask yes/no questions?

OK. You can ask 20 of them. Use them wisely.

If you have ever played this against a computer, it is amazing at how quickly the computer guesses your thought…or is it?

L26Q1

A. One
B. Two
C. Three
D. Four
E. Five

L26Q2

A. 20
B. 400
C. 2096
D. Over 1 Million
E. Over 1 Billion

L26Q1. I am thinking of a color in the set {blue, yellow, red, green}. How many Yes/No questions will it take to guess my color?

L26Q2: How many items (in a set) could be distinguished by 20 Yes/No questions?

Quantifying Information

The “amount” of data might not represent the magnitude of the information it contains. If you can **predict** data, it contains less information.

L26Q3: Which contains more information, the samurai cartoon or the samurai photo?

from Wikipedia

Consider these information sets:

- {blue, yellow, red, green}
- {blue 50%, yellow 20%, red 15%, green 15%}
- {blue 100%}

L26Q4: For which set is the unknown color most predictable?

L26Q5: For each set, how many questions will it take, on average, to guess the color?

L26Q6: For which set is more information being transferred by the question game?

Entropy measures Information

The entropy, H, of a **message** can be computed given the statistical frequencies, the p_i of each i^{th} possibility (a.k.a. the probability of each message in the set of possible messages)

$$H = \sum_{i=1}^{N} p_i \times (-\log_2(p_i)) = \sum_{i=1}^{N} p_i \times \log_2\left(\frac{1}{p_i}\right)$$

in units of “bits”!

L26Q7: What is the entropy in a result of a single flip of a fair coin?

L26Q8: What is the entropy of a number of “heads” in two coin flips?

Review of logarithms and properties

- Base-2 logarithm gives a power of 2 equivalent for a number:

$$x = \log_2 \boldsymbol{A} \quad \Rightarrow \quad \boldsymbol{A} = \boldsymbol{2^x}$$

- Logarithm of an inverse of a number is negative log of the number:

$$\log_2 \frac{\boldsymbol{1}}{\boldsymbol{A}} = -\log_2 \boldsymbol{A}$$

- Logarithm of a product is the sum of two logarithms:

$$\log_2 \boldsymbol{AB} = \log_2 \boldsymbol{A} + \log_2 \boldsymbol{B}$$

- Logarithm of a ratio is the difference of two logarithms:

$$\log_2 \frac{\boldsymbol{A}}{\boldsymbol{B}} = \log_2 \boldsymbol{A} - \log_2 \boldsymbol{B}$$

$\boldsymbol{A}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$\sim\log_2 \boldsymbol{A}$	0.0	1.0	1.6		2.3		2.8				3.5		3.7		

L26Q9: Complete the above table using logarithm properties.

L26Q10: What is $\log_2 \frac{\boldsymbol{24}}{\boldsymbol{105}}$?

Entropy of the Class by Major

S	ECE	IE	GE	DGS
p	200/400	50/400	50/400	100/400

Considering only the 4 most-represented disciplines, suppose that a selected sample of 400 ECE110 students produces the student population shown above.

L26Q11: What is the probability that a student selected from this group is an IE?

L26Q12: What is the entropy of any student's department taken from this set?

L26: Learning Objectives

a. To comparative the amount of information contained in slightly different data sets
b. To compute base-2 logarithms using log properties
c. To compute Entropy (information) in units of bits given the relative frequency of each item in a set

Entropy of the Class by Major

S	ECE	IE	GE	DGS	Other
p	200/450	50/450	50/450	100/450	50/450

Including a category of "Other", the student population by major now takes on the statistics shown above.

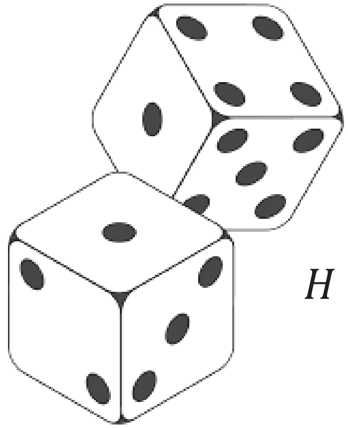
L26Q13: What is the probability that a student selected from this group is an IE?

L26Q14: What is the entropy of any student's department taken from this set?

L26Q15: What would have been the entropy if all 5 categories were equally represented by the course's student body?

Entropy of the sum of two dice

	1	2	3	4	5	6
1	2	3	4	5	6	7
2	3	4	5	6	7	8
3	4	5	6	7	8	9
4	5	6	7	8	9	10
5	6	7	8	9	10	11
6	7	8	9	10	11	12



$$H = \sum_{i=1}^{N} p_i \times \log_2\left(\frac{1}{p_i}\right)$$

S	2	3	4	5	6	7	8	9	10	11	12
p	1/36	2/36	3/36	4/36	5/36	6/36	5/36	4/36	3/36	2/36	1/36

L26Q16: What is the entropy of the sum of two dice?

L26Q17: Compare this to the entropy of one out of eleven equally-likely outcomes. Without doing any calculations, which value should be larger (carry more information)?

L27: Compression

- Lossless vs. lossy compression
- Compression ratios and savings
- Entropy as a measurement of information
- Huffman code construction and decoding

Data Compression Ratio and Savings

- Data Compression Ratio (DCR)

$$DCR = \frac{\#\ of\ bits\ in\ original\ data}{\#\ of\ bits\ in\ compressed\ data} = \frac{original\ data\ rate}{compressed\ data\ rate}$$

- Savings: $S = 1 - \frac{1}{DCR}$ $(x100\ for\ \%)$

L27Q1. Stereo audio is sampled at 44.1 kHz and quantized to 16 bits/channel and then compressed to 128 kbps mp3 playback format. What are the approximate DCR and the resulting savings?

L27Q2. A picture of a samurai was saved as a 24-bit samurai.bmp (full size, 2188 kB) and a 31 kB samurai.png. Estimate the DCR and savings from the PNG compression.

L27Q2: DCR~

A. 10
B. 30
C. 50
D. 70
E. 100

Lossy and Lossless Compression

- Lossy Compression
  - Usually leads to larger DCR and savings
  - Sometimes creates noticeable "artifacts"
  - Examples: mp3, mpeg, jpeg

from Wikipedia

- Lossless Compression (keeping all information)
  - Uses repetition or other data statistics
  - Usually leads to smaller compression ratios (~2)
  - Examples: PNG, run-length codes, Huffman codes…

L27Q3. Why was the cartoon samurai picture highly compressible?
L27Q4: Can we expect to achieve such DCR with the photograph?

Super-Fast Sandwiches, Order-By-Number Menu

Menu:	#1	#2	#3	#4	#5
Number of orders	18	8	9	10	5

The number of orders during the lunch hour for each menu item is listed above.

L27Q5: What was the relative frequency (probability) of someone ordering the menu's #1 sandwich selection (we call this p_1)?

L27Q6: What is the fewest number of bits needed to encode each of 8 possible orders with a unique (and unambiguous) bit sequence for each?

L27Q7: What is the entropy of one order given the popularity statistics above?

Huffman Codes use bits efficiently

Menu:	#1	#2	#3	#4	#5
Number of orders	18	9	8	10	5

Use fewer bits for more common **symbols**. Here's how:

1. Order the symbols from most frequent on left to least frequent on right.
2. From the two least frequent symbols, create two "branches" that connect them into a single end **nodes** of a **tree graph**.
3. Mark the least frequent branch with a "0" and the most frequent a "1"
4. Consider these two symbols be one new symbol with the combined frequency. Record this new frequency of the new node and return to step 1 (or step 2), considering nodes as new symbols.

L27Q8: Create a Huffman tree based on the order statistics given above.

Encoding and decoding Huffman

Menu:	#1	#2	#3	#4	#5
Number of orders	18	9	8	10	5
Huffman Code					

Huffman Codes are **prefix-free**! (If you know where the message starts, you can separate the symbols without confusion.)

L27Q9: Complete the table above with Huffman codes from the tree above.
L27Q10: Which menu items does not appear in the sequence 111000010100?

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

Average code length is no less than entropy

Given N symbols $S_1, S_2, \dots S_N$ and corresponding frequencies, p_i, the average length per symbol is

$$L_{avg} = \sum_{i=1}^{N} p_i \times L_i$$

$$L_{avg} \geq H$$

L27Q11: What is the average bit length per sandwich order?

L27Q12: How does the average bit length compare to entropy?

L27: Learning Objectives

a. Compute compression ratio and savings
b. To use relative frequency to compute entropy, the shortest theoretical average code length
c. To encode a symbol set with a Huffman code
d. To decode a Huffman-encoded message
e. To compute average code length for given a code

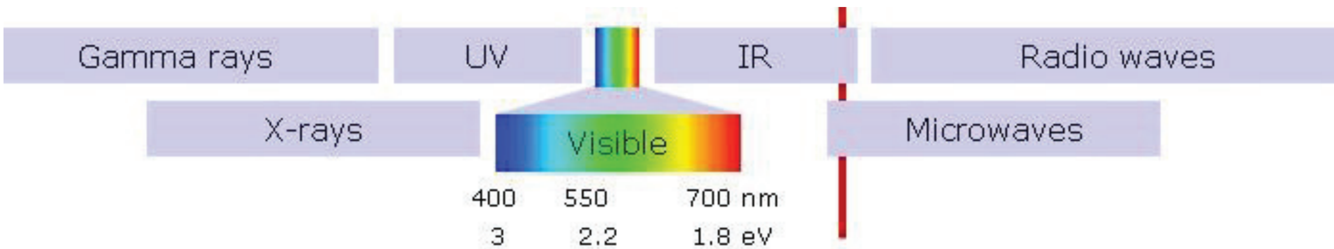
Lecture 28: Photodiodes and Solar Panels

- 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

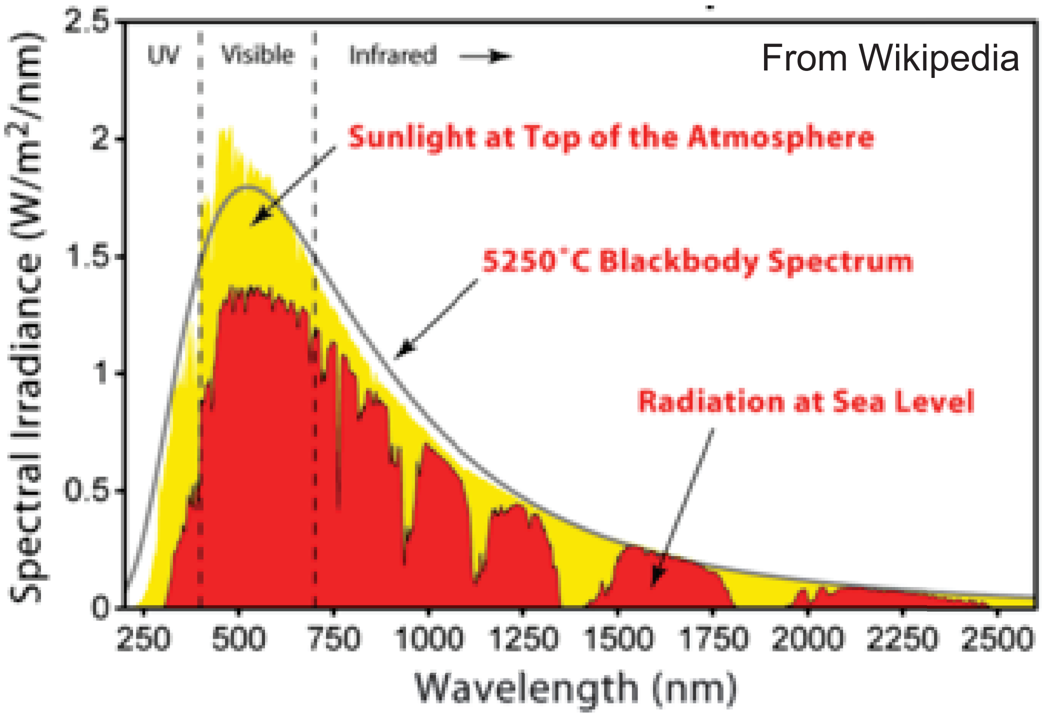
- Photons are sometimes called wave packets
- Each photon carries an amount of energy given by

  E(eV) = 1240/λ(nm) where $1\ eV = 1.6 \times 10^{-19}$ J
- The color of light depends on its wavelength, λ



L28Q1: How many photons per second are provided by a 1 mW 650 nm laser?

Available Solar Energy (Radiation Spectrum)



L28Q2: Estimate the solar irradiance (W/m^2) at sea level (hint: total red area).

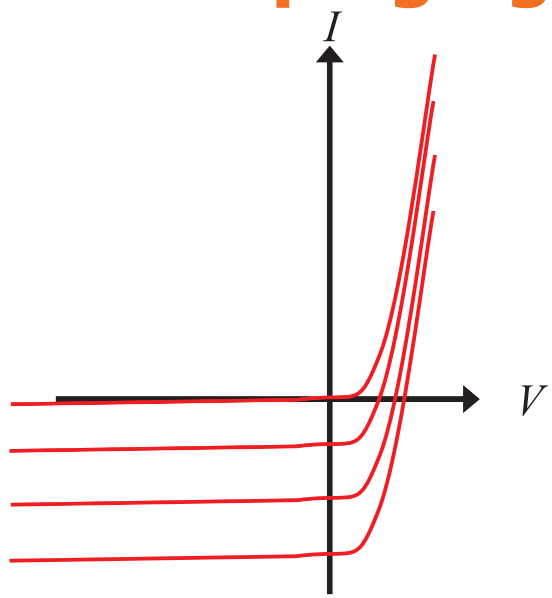
Creating electron-hole pairs in Semiconductors

- 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

L28Q3: 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

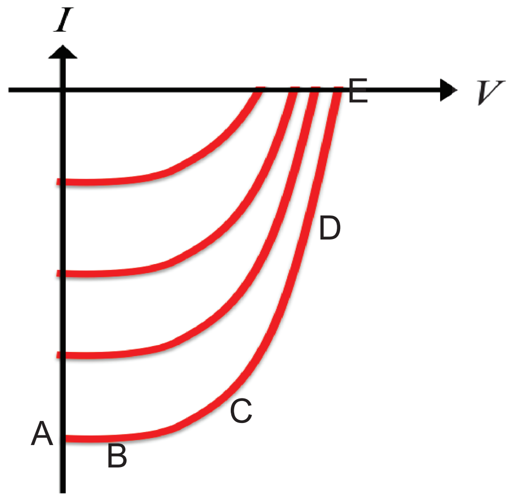
- Reverse bias mode
  - Photodetector
  - Detecting light signals
  - Energy is dissipated
- Forward bias mode
  - Photovoltaic cell
  - Energy is generated



L28Q4: Sparkfun's BPW34 photodiode generates 50 μA of current when reverse-biased and illuminated with 1 mW/cm^2 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%



L28Q5: Identify the P_{max} point above

L28Q6: If Sparkfun's BPW34 photodiode has I_{SC}=40 μA and V_{OC}=350 mV when illuminated with 1 mW/cm^2 at 950 nm, and the fill factor is 50% what is the maximum power produced?

Solar panels as energy sources

L28Q7: 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?

L28Q8: 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?

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

L29: Final Exam Review

- This lecture is mandatory.
- Attendance will be taken and counted in the usual way.
- 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.