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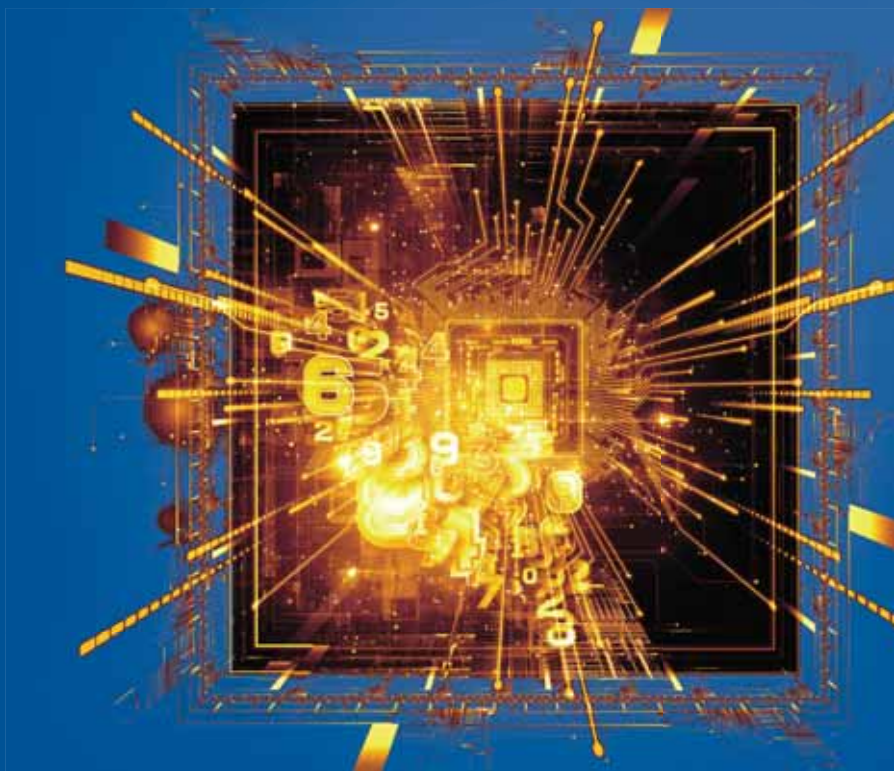
Topic
Science
& Mathematics

Subtopic
Physics

Understanding Modern Electronics

Course Guidebook

Professor Richard Wolfson
Middlebury College



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Richard Wolfson is the Benjamin F. Wissler Professor of Physics at Middlebury College, and he teaches in Middlebury's Environmental Studies Program. He did undergraduate work at the Massachusetts Institute of Technology and Swarthmore College, graduating from Swarthmore with a bachelor's degree in

Physics and Philosophy. He holds a master's degree in Environmental Studies from the University of Michigan and a doctorate in Physics from Dartmouth.

Professor Wolfson's books include *Nuclear Choices: A Citizen's Guide to Nuclear Technology* and *Simply Einstein: Relativity Demystified*, both of which exemplify his interest in making science accessible to non-scientists. His textbooks include three editions of *Physics for Scientists and Engineers*, coauthored with Jay M. Pasachoff; three editions of *Essential University Physics*; two editions of *Energy, Environment, and Climate*; and *Essential College Physics*, coauthored with Andrew Rex. Professor Wolfson also has published in *Scientific American* and writes for *The World Book Encyclopedia*.

Professor Wolfson's current research involves the eruptive behavior of the Sun's corona, as well as terrestrial climate change. His other published work encompasses such diverse fields as medical physics, plasma physics, solar energy engineering, electronic circuit design, nuclear issues, observational astronomy, and theoretical astrophysics. His knowledge of electronics stems not only from his professional activities as a physicist but also from a lifelong interest in electronics as a hobbyist.

In addition to *Understanding Modern Electronics*, Professor Wolfson has produced four other lecture series for The Great Courses: *Einstein's Relativity and the Quantum Revolution: Modern Physics for Non-Scientists*; *Physics in*

Your Life; Earth's Changing Climate; and Physics and Our Universe: How It All Works. He also has lectured for One Day University and *Scientific American's* Bright Horizons cruises.

Professor Wolfson has spent sabbaticals at the National Center for Atmospheric Research, the University of St. Andrews, and Stanford University. In 2009, he was elected a Fellow of the American Physical Society. ■

Disclaimer

This series of lectures is intended to increase your understanding of the principles of modern electronics. These lectures include experiments in the field of modern electronics performed by an experienced professional.

These experiments may include dangerous materials and are conducted for informational purposes only, to enhance understanding of the material.

Warning: The experiments performed in these lectures can be dangerous. Any attempt to perform these experiments on your own is undertaken at your own risk.

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Understanding Modern Electronics

Scope:

Electronic devices are woven into the fabric of 21st-century life. Some—your smartphone, your laptop computer, your flat screen TV—are obvious. Others—the myriad electronic sensors, computers, and controls that keep your car running at top efficiency; the microcontrollers that increasingly find their way into the most humble of kitchen appliances; the smart electric meters that help manage your household energy consumption—ply their electronic magic largely hidden from view. And devices that were once purely mechanical—thermometers, bathroom scales, clocks and watches—are now largely electronic.

In the context of this electronic world, *Understanding Modern Electronics* has two purposes, either one of which provides ample reason to view and participate actively in this course. First, the understanding this course provides can enhance your appreciation and effective use of electronic devices. Second, for those who might want to go on to build their own electronic circuits, the course lays the groundwork of basic electronic concepts, introduces the building blocks of electronic circuits, and develops many important circuits used in modern electronics.

The course begins by distinguishing electronics from electricity, introduces basic electrical and electronic concepts, and quickly moves into electronic circuitry. You will learn the language of electronic circuit diagrams and meet new and useful electronic components. After a look at AC versus DC, power supply circuits, and electronic filters (for, among other things, bass/treble controls and noise reduction), the course introduces the semiconductors that are at the heart of modern electronics. Focusing on transistors—among the most important inventions of the 20th century—the course then describes how these devices are used as amplifiers. By the end of this section, you will have a strong grasp of the workings of the audio amplifiers that are in everything from phones to televisions to stereo systems.

The course then turns to operational amplifiers—versatile, inexpensive, integrated-circuit devices that function not only as amplifiers for audio and for electronic instruments but can also add, subtract, accumulate, and serve as oscillators to generate useful electronic signals and sounds. Op-amps achieve their versatility through the magic of negative feedback; thus, this section of the course begins with a look at the feedback concept and the many systems—electronic and otherwise—that make use of negative feedback. Practical applications discussed here include an electronic thermometer, a light meter, and servomechanisms that allow us to control, with exquisite precision, the movement of massive machinery.

To this point, the course has emphasized analog electronics—circuits in which electrical quantities are analogs of continuously varying physical quantities, such as sound, temperature, and brightness. But today's electronic circuits are increasingly digital, encoding information as quantities that can take on only two values—the binary digits 0 and 1. The penultimate section of the course begins with digital basics, introducing the logical operations that are at the heart of all digital processing, including computers, then explores contemporary electronic realizations of these digital logic operations. The course goes on to build more sophisticated digital circuits, including computer memory circuits, electronic counters, frequency dividers (used in digital watches), and circuits that let computers exchange information with peripheral devices or help cell phones stream your voice over the airwaves as a sequence of digital 1s and 0s.

The final section of the course shows how electronic circuits convert information from the analog world of everyday life to the world of digital processing—and back again. Important examples include cell phone communications and contemporary music recording, distribution, and playback; these examples bring together material from throughout the entire arc of the course.

The course ends with a lecture on electronics in your future, showing how continued miniaturization and the associated increase in the power of electronic circuits will bring sophisticated electronics into virtually every aspect of 21st-century life.

You can learn about electronics as a purely intellectual exercise, and this course will help you do so. But electronics is also an active pursuit, whether at the hobbyist's workbench or in the engineer's laboratory. Throughout *Understanding Modern Electronics*, you'll get many practical tips about building electronic circuits and working with electronic instruments. Although the course doesn't provide you with actual hands-on experience, it comes close—through the use of electronic circuit simulation software that's web-based, independent of what type of computer or even tablet you use, and free or at low cost. If you choose to do the projects at the end of each lecture, you'll use this software to build, explore, troubleshoot, and even design electronic circuits that are almost like the real thing. ■

Abbreviations and Symbols

AC	alternating current
A	ampere
β	beta (transistor current gain)
DC	direct current
F	farad
Hz	hertz
kHz	kilohertz (k means 1000)
μF	microfarad (μ means one-millionth)
mA	milliamp (m means one-thousandth)
Ω	ohm
V	volt
W	watt

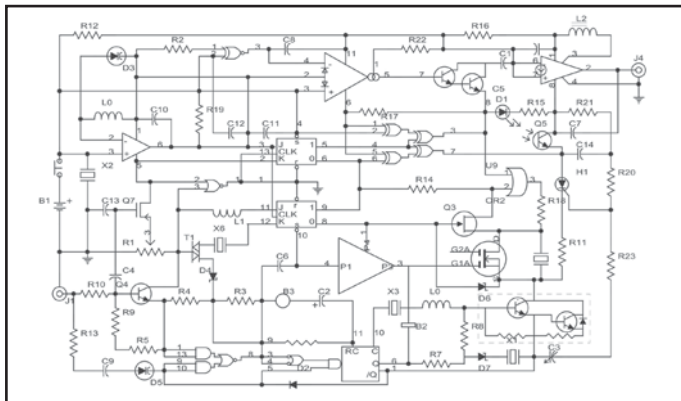
Electricity and Electronics

Lecture 1

The most obvious reason for learning about modern electronics is that electronic devices are ubiquitous in our world. Consider some of the things you use that are electronic: an iPad, a smartphone, a laptop, a TV, the instrument panel of your car, a GPS system, a camera, the loudspeaker in your audio system, and so on. We'll start in this lecture by distinguishing electricity—the more mundane topic—from electronics—the more sophisticated. Then, we'll cover a bit of background on basic electricity. Key topics in this lecture include the following:

- Electricity and electronics
- A brief history of electronics
- Moore's law
- Volts, amps, and watts
- Resistance and Ohm's law.

Electricity and Electronics



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Electronics involves the control of one electrical circuit by another, and it involves using devices that allow that kind of control, often with weaker electrical quantities controlling stronger ones. An *electrical circuit* is an interconnection of components intended to do something useful, such as

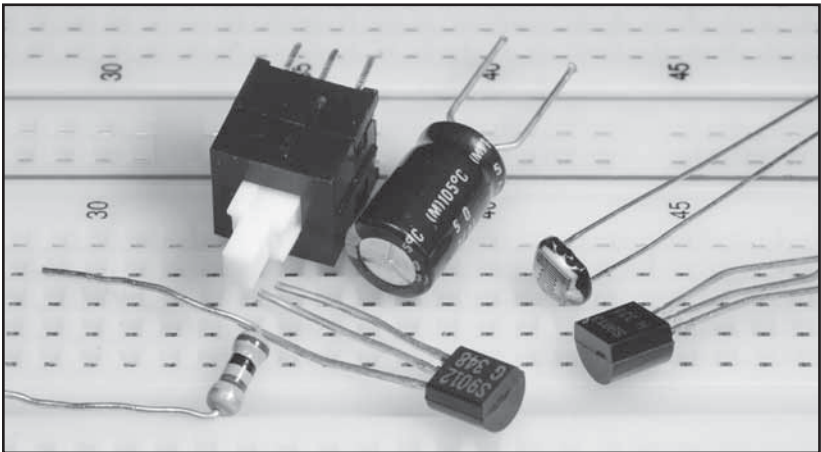
display video or amplify sound. Usually—but not always—a circuit includes a source of energy.

A Brief History of Electronics

For the first half of the 20th century, the device used to control electric current was the vacuum tube. These were evacuated glass tubes containing metal electrodes, between which electrons flowed. The tubes were designed in different ways for different functions. By applying different electrical signals to the *grid* (the *control* electrode in the tube), the amount of current that flowed through the tube could be controlled.



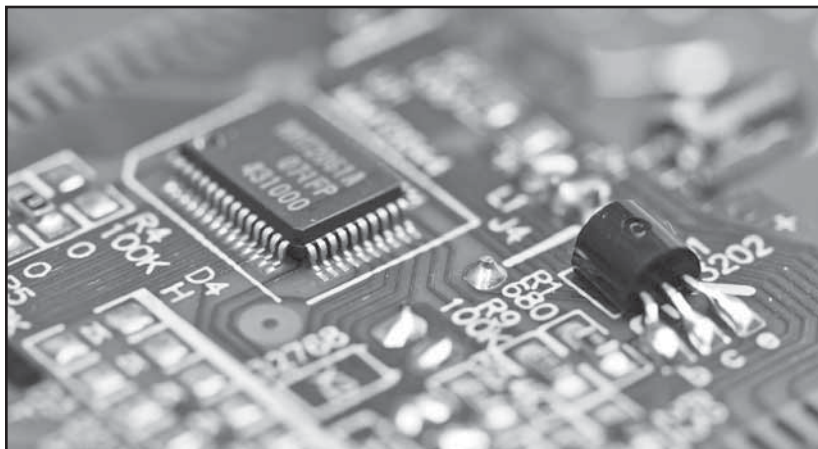
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In the 1950s, a revolution occurred in electronics with the invention of the transistor. The transistor did exactly what the vacuum tube did—that is, it

allowed one circuit to control another—but it was much smaller, and it was a solid-state device.



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In the late 1960s and early 1970s came yet another development: the technological ability to interconnect many transistors and other electronic components on a single tiny wafer of the element silicon. That was the integrated circuit. Today, integrated circuits contain anywhere from a handful to billions of individual transistors.

Moore's Law

In 1965, Gordon Moore, a cofounder of Intel Corporation, made the following prediction: As we learn to make integrated circuits increasingly compact, the number of transistors on a single chip will double every 18 months. Actually, the number of transistors has doubled about every 2 years. Moore's prediction is known as *Moore's law*, and it will probably hold for at least another 10 years.

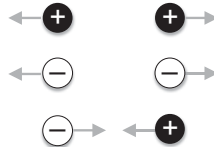


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Volts, Amps, and Watts

Electric Charge

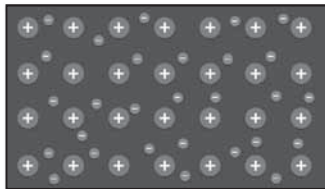
- Likes repel; opposites attract
- Protons carry positive charge
 - So do holes in semiconductors
- Electrons carry negative charge
 - Metals contain vast numbers of free electrons



Electric charge is a fundamental property of matter. It comes in two varieties: positive and negative. The protons that are in atomic nuclei are the main carriers of positive charge, and electrons are carriers of negative charge. There are vast numbers of free electrons in metals.

Conductors and Insulators

Conductor



Insulator



We can talk about free charges as a way of distinguishing two kinds of materials: conductors and insulators. An electrical conductor is a material

containing charges that are free to move. In metals, the most common conductors, those free charges, are electrons. Typically, one or two electrons at the outermost periphery of the metal atoms become free, not bound to individual atoms. They're free to move throughout the metal, and that's what makes the material a conductor. An insulator is a material lacking free charges. In an insulator, all the individual electrons are bound tightly to the atoms and can't be moved.

Current and Voltage

- **Current: a flow of charge**
 - Amount of charge per time crossing a given area
 - Unit: ampere (amp, A)
 - 1 A is about 6×10^{18} electrons per second
 - 1 A is about the current in a 100-watt (W) incandescent light bulb
 - Common in electronics: milliamp, mA (0.001 A)
 - Direction of current is that of positive charge flow
 - Even though most current is carried by electrons
- **Voltage: the “push” that drives current**
 - A measure of energy per charge
 - Unit: volt (V)
 - AAA, AA, C, D batteries: 1.5 V; car battery: 12 V; wall outlet: 120 V
 - Typical in electronic circuits: 5–15 V

Electric current is a flow of charge, which is measured in amperes (A). Voltage is the push that drives current through a wire or an electrical or electronic device. It's a measure of the energy per charge, and its unit is volts (V).

Electric Power

Electric current: charge per time

Voltage: energy per charge

Multiply them together:

$$\text{current} \times \text{voltage} = \left(\frac{\text{charge}}{\text{time}} \right) \left(\frac{\text{energy}}{\text{charge}} \right) = \frac{\text{energy}}{\text{time}}$$

= POWER (watts)

$$\text{Power (watts)} = \text{amps} \times \text{volts}$$

Multiplying current (flow of charge) by voltage (push) gives us a third important quantity, energy per time, or electric power. Power is the rate at which a system delivers, consumes, loses, produces, or transfers energy from one form to another. Power is measured in watts (W).

Resistance and Ohm's Law

Electrical Resistance

- Measures resistance to the flow of *current*
 - Property of a material and its geometrical size and shape
 - Ohm's law:

$$\text{current} = \frac{\text{voltage}}{\text{resistance}} \quad I = \frac{V}{R}$$
 - Via algebra:

$$V = IR, \quad R = V/I$$
 - Unit of resistance: ohm (Ω)
 - $1 \Omega = 1 \text{ volt/amp}$

Typically, conductors have resistance; they don't let current flow easily. The resistance of a particular component is a function of both the material it's made of and its geometrical size and shape. There's a simple relationship, known as *Ohm's law*, between current and voltage: current = voltage/resistance, or $I = V/R$. The unit of resistance is the ohm (Ω). Ohm's law can be written in three different forms, but they're all equivalent: $I = V/R$, $V = IR$, or $R = V/I$.

Suggested Reading

Introductory

Brindley, *Starting Electronics*, 4th ed., chapter 1 through p. 28

Lowe, *Electronics All-in-One for Dummies*, book I, chapters 1–2.

Platt, *Make: Electronics*, chapter 1.

Shamieh and McComb, *Electronics for Dummies*, 2nd ed., chapters 1–2.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 1, sections 1.1–1.2.1.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 1; chapter 2 through section 2.5.

Projects

Stimulate the circuits for the projects in these lectures online at CircuitLab (www.circuitlab.com) or DoCircuits (www.docircuits.com).

Hard Starting

The connection between a car's battery and the wire supplying the starter motor has corroded to the point where its resistance is $0.05\ \Omega$. When you try to start the car, the starter motor draws 100 A. What's the voltage across the bad connection?

LED Lamps

An LED lamp operates at 120 V and puts out the same amount of light as a standard 100-W incandescent lamp. It draws 150 mA of current. Compare the power consumption of the two lamps.

Questions to Consider

Answers to starred questions may be found in the back of this guidebook.

1. What is Moore's law, and how is it responsible for the proliferation of increasingly powerful and less expensive electronic devices?
- *2. An electric stove burner has a resistance (when it's on) of about $40\ \Omega$. It operates at 240 V (as do some large household appliances, such as stoves, water heaters, and electric clothes dryers). Find (a) the current through the burner and (b) its power consumption.

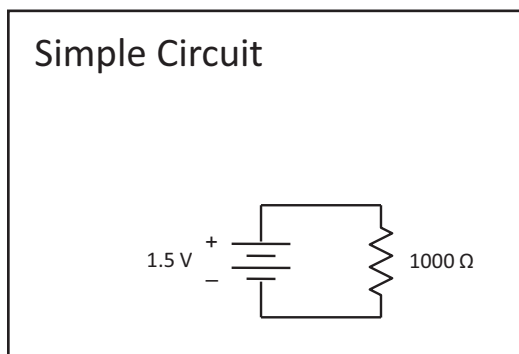
Circuits and Symbols

Lecture 2

In this lecture, we'll look at electronic circuits, that is, interconnections of electronic components. As you recall, in the last lecture, we looked at a particular electronic component, the resistor. We'll look at resistors in more detail in this lecture, but we'll also learn how to represent many other kinds of electronic devices in circuits and how to read circuit diagrams. In addition, we'll begin to see how to interconnect electrical systems. Key topics we'll cover are:

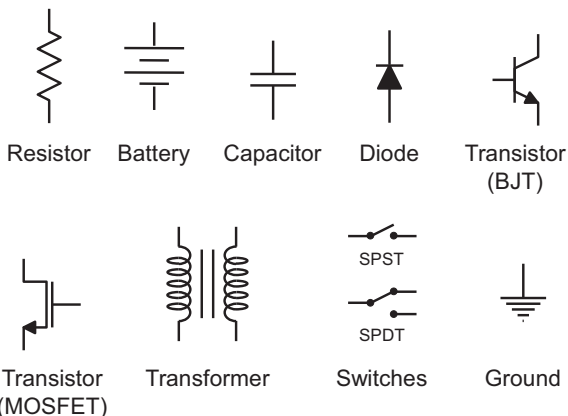
- Components and their symbols
- The ideal battery
- Voltage-current characteristics
- Series components: resistors
- A simple circuit: the voltage divider
- Real batteries
- Parallel components: resistors.

Components and Their Symbols



A simple electrical circuit might consist of a 1.5-V battery connected with a 1000-Ω resistor. This circuit has a source of electrical energy, a battery, and a *load*, something to which that energy is supplied. That load might be a loudspeaker, a motor, or as here, simply a resistor.

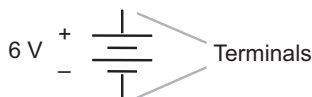
Some Electronic Symbols



The symbols that represent circuits constitute a language to learn.

The Ideal Battery

Meet the Battery

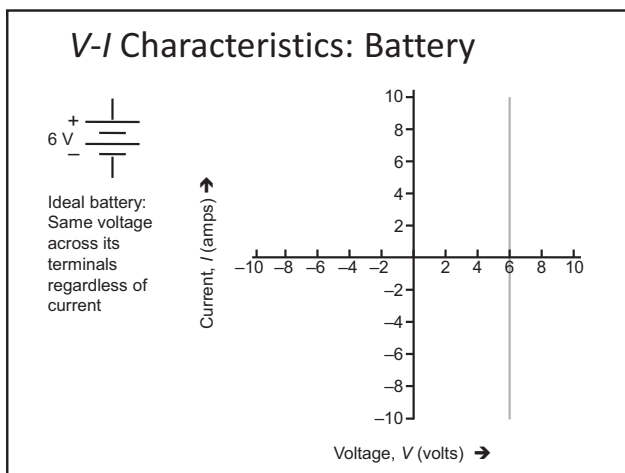


Battery: An example of a voltage source

Ideal battery: Maintains the same voltage across its terminals
—regardless of how much current it's supplying

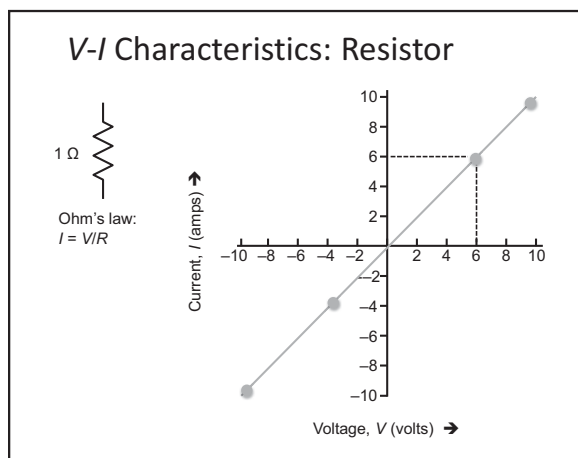
A battery is a simple example of a *voltage source*. It converts chemical energy into electrical energy, and it produces, in principle—if it's ideal—exactly the same voltage across its terminals, regardless of how much current it supplies.

Voltage-Current Characteristics



To describe the voltage-current (V - I) characteristics of an ideal 6-V battery, we can draw a graph with voltage (V) on the horizontal axis and current (A) on the vertical axis. The resulting V - I characteristic curve is a straight vertical line—6 V, regardless of current.

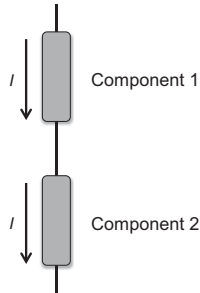
We can draw a similar graph for a 1- Ω resistor. The resulting curve for the resistor is a straight diagonal line with a slope of 1 A for every volt.



Series Components: Resistors

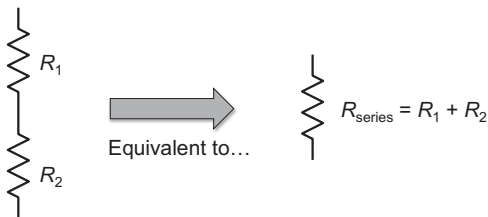
Series Components

- Two components are in series if current flowing through one of them has nowhere to go but into the second component
- Same current (I) through both components



Two electronic components are in series if the current flowing through one of them has nowhere to go but into the next one. Because the current that's flowing through one device goes into the other, the same current flows through both components.

Series Resistors



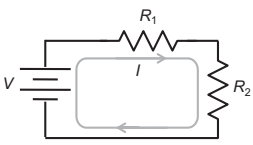
Example: $R_1 = R_2 = R$

$$R_{\text{series}} = R + R = 2R$$

Imagine we have two resistors, R_1 and R_2 . Because current through R_1 can flow only through R_2 , the two are in series. Resistors in series simply add; thus, the series resistance is the sum of the two resistances.

A Simple Circuit: The Voltage Divider

The Voltage Divider



Battery voltage V ; what's the voltage across R_2 ?

R_1, R_2 in series; equivalent resistance is $R_1 + R_2$

Current in series circuit is:

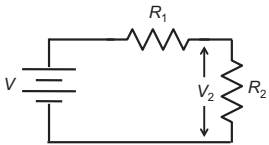
$$I = \frac{V}{R_1 + R_2}$$

Apply Ohm's law to R_2 :

$$V_2 = IR_2 = \left(\frac{V}{R_1 + R_2} \right) R_2 = \left(\frac{R_2}{R_1 + R_2} \right) V$$

A *voltage divider* is basically two series resistors, R_1 and R_2 , across some source of voltage, V . This device divides the voltage in proportion to the resistances.

The Voltage Divider



$$V_2 = \left(\frac{R_2}{R_1 + R_2} \right) V$$

Special cases:

$R_1 = R_2 \quad V_2 = \frac{1}{2}V$

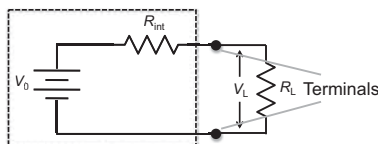
$R_2 = 0 \quad V_2 = 0$
(No voltage across zero resistance)

$R_1 \gg R_2 \quad V_2 \approx V$
(R_1 is approximating a perfect wire)

One special case of a voltage divider is when R_1 and R_2 are equal. In that case, the output voltage, or the voltage across R_2 , is $\frac{1}{2}V$. If R_2 is 0, we get no voltage across it; it's a perfect wire. If R_2 is much greater than R_1 , then V_2 is almost equal to the battery voltage; R_1 becomes almost a perfect wire if R_2 is much greater than R_1 .

Real Batteries

Modeling a Real Battery



V_0 The battery's rated voltage (1.5 V, 6 V, etc.)

R_{int} The battery's internal resistance

R_L The load resistance

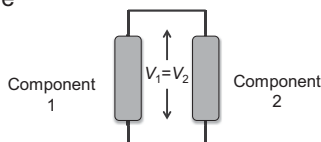
$$V_L = \left(\frac{R_L}{R_{int} + R_L} \right) V_0$$

To model a real battery, imagine an ideal battery in series with a resistor, representing the battery's *internal resistance*. Real batteries or any real sources of voltage have internal resistance, which must be taken into account to use them correctly. The loads put across them can't be too low so we don't drop a voltage across that internal resistance, which would make the voltage across the battery terminals much lower than the battery's rated voltage.

Parallel Components: Resistors

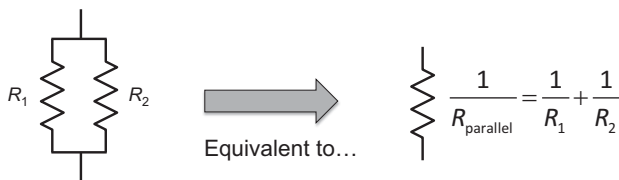
Parallel Components

- Two components are in parallel if the two ends of each component are connected together
- Same voltage (V) across both components



Two components are in parallel if the two ends of each component are connected, and therefore, they have exactly the same voltage across either of them.

Parallel Resistors



Example: $R_1 = R_2 = R$

$$\frac{1}{R_{\text{parallel}}} = \frac{1}{R} + \frac{1}{R} = \frac{2}{R} \quad \Rightarrow \quad R_{\text{parallel}} = \frac{R}{2}$$

Parallel combination is sometimes called a *current divider* because current coming into the combination splits between R_1 and R_2 , with more current going through the lower resistance.

Suggested Reading

Introductory

Brindley, *Starting Electronics*, 4th ed., chapter 1, p. 28 to end.

Lowe, *Electronics All-in-One for Dummies*, book I, chapter 5.

Platt, *Make: Electronics*, chapter 1.

Shamieh and McComb, *Electronics for Dummies*, 2nd ed., chapter 3.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 1, sections 1.2.2–1.2.3; appendix B.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 2, sections 2.11–2.13.

Project

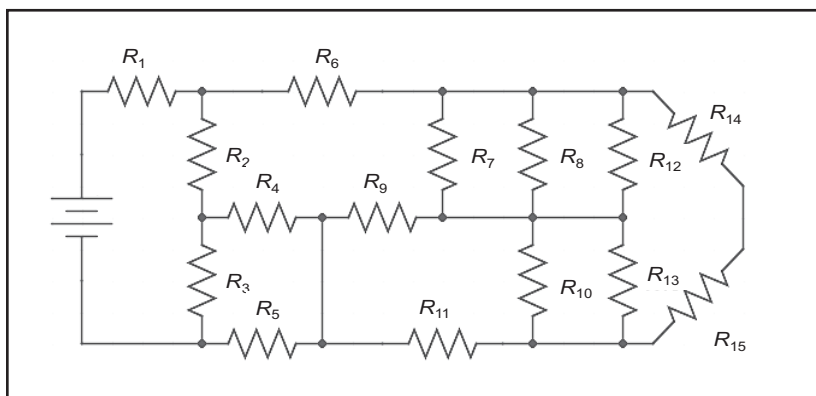
Resistors

Using only $1000\text{-}\Omega$ resistors (as many as you want), design a voltage divider that produces 4 V when connected across a 6-V battery.

Suppose you connect a $10,000\text{-}\Omega$ resistor ($10\text{ k}\Omega$) across your voltage divider between the points where you're supposed to have 4 V . Will the voltage across this resistor be exactly 4 V ? If not, explain why not and determine what the actual voltage will be.

Questions to Consider

- *1. Identify pairs of series and parallel components in the circuit below.



- *2. A 6-V battery has an internal resistance of $0.25\text{ }\Omega$. If you connect a $5\text{-}\Omega$ resistor across the battery, what will be the voltage across the battery's terminals?

Instruments and Measurement

Lecture 3

In this lecture, we will look at a practical matter, namely, how we measure electrical quantities, especially voltage and current. We need to understand measurement for a number of reasons—to verify that components and circuits are working correctly and to read the output of electronic instrumentation. In addition to describing procedures for measuring electrical quantities, we will also look at the instruments used to measure them. Key topics we'll explore include the following:

- Voltmeters: characteristics and use
- Ammeters: characteristics and use
- Ohmmeters: characteristics and use
- The oscilloscope.

Clarifying Vocabulary

Clarifying Vocabulary

voltage \longleftrightarrow across

current \longleftrightarrow through

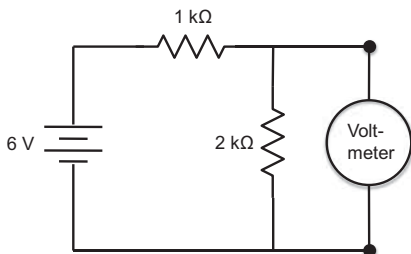
In working with electrical meters, it's important to understand two ideas: (1) Current is a flow *through* electrical components, and (2) voltage is a difference in energy per charge and appears *across* two points in a circuit.

Voltmeters: Characteristics and Use

Measuring Voltage

Voltage divider: should be 4 V across 2 k Ω

Voltmeter measures voltage across itself



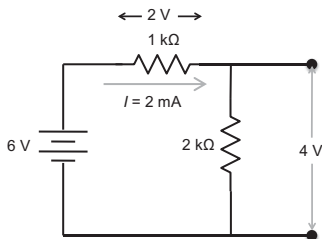
So: connect voltmeter across component whose voltage you're measuring

A voltmeter measures the voltage between its two terminals—the voltage across itself. To exploit that fact, a voltmeter is connected in a circuit in such a way that the voltage across the voltmeter is the same as the voltage across the circuit component whose voltage is being measured.

The previous lecture ended with the following project: Using only 1000- Ω resistors, design a voltage divider that produces 4 V when connected across a 6-V battery. For this project, we needed to connect the voltmeter to measure the voltage across the 2-k Ω resistor in the circuit, not the battery or the 1-k Ω resistor.

Lecture 2 Project Problem

Voltage divider: should be 4 V across 2 k Ω

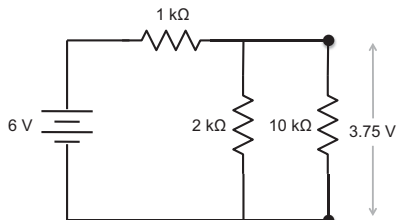


With 6 V across a combined resistance of 1 k Ω and 2 k Ω , we have 6 V across 3 k Ω , or 2 mA. We have 2 mA flowing through the 1-k Ω resistor—therefore, 2 V across the 1-k Ω resistor—and the remaining 4 V from the 6-V battery across the 2-k Ω resistor. If we put a 10-k Ω resistor in parallel with the 2-k Ω resistor, we get 3.75 V—less than the 4 V we had at first.

Lecture 2 Project Problem

Voltage divider: should be 4 V across 2 k Ω

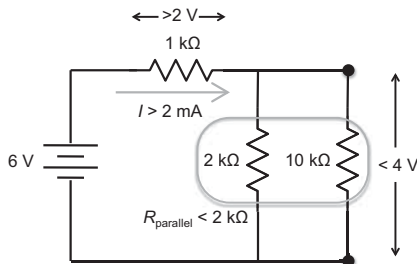
Put another resistor in parallel with 2 k Ω :
voltage decreases



Lecture 2 Project Problem

Voltage divider: should be 4 V across 2 k Ω

Put another resistor in parallel with 2 k Ω :
voltage decreases



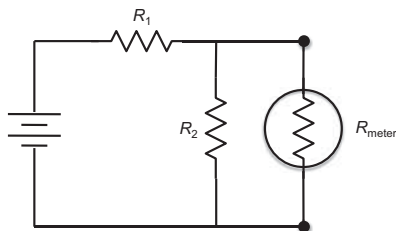
Current flows through the 1-k Ω resistor, then splits and flows through the parallel combination, but it adds up to a current that's greater than 2 mA. With a current greater than 2 mA flowing through the 1-k Ω resistor, the voltage across the 1-k Ω resistor is greater than 2 V. That leaves a voltage across the parallel combination—remember, parallel resistors have the same voltage—that is less than 4 V. If we work out the math, it's 3.75 V.

Implication for Voltmeters

If voltmeter draws current, it will lower the voltage it's measuring!

Ideal voltmeter should have infinite resistance!

In practice, much greater than circuit resistances.



If a voltmeter draws current from the circuit, it will lower the voltage it's trying to measure. The implication here is that an ideal voltmeter should have infinite resistance. In practice, it should have a resistance much greater than the resistances of the circuits being measured.

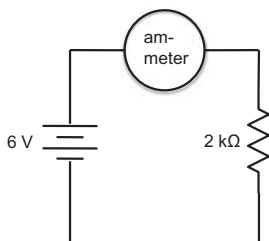
Ammeters: Characteristics and Use

Measuring Current

6-V battery, 2-k Ω resistor; current should be $I = V/R = 3 \text{ mA}$

Ammeter: measures current through itself

Series components: current through first component has nowhere to go but through second component



So: Break circuit; put ammeter in series with component whose current you're measuring

An ammeter measures current through itself. Current comes in one lead, goes through the ammeter, and goes out the other lead. We must put the ammeter in a circuit in such a way that the current we're measuring is through the component we're interested in.

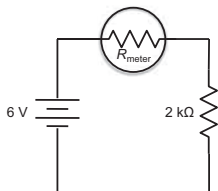
If an ammeter has any resistance whatsoever, it will reduce the total circuit current. The implication is that the ideal ammeter should have zero resistance; in practice, it should have a much lower resistance than any resistance in the circuit.

Implication for Ammeters

If ammeter has resistance, it will lower the current it's measuring!

Ideal ammeter should have zero resistance!

In practice, much lower than circuit resistances.

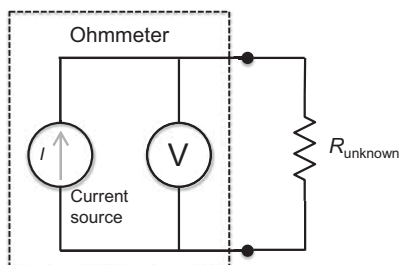


Ohmmeters: Characteristics and Use

Measuring Resistance

Pass a known current, I , through resistor and measure voltage, V

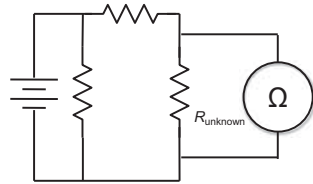
Ohm's law gives $R_{\text{unknown}} = V/I$



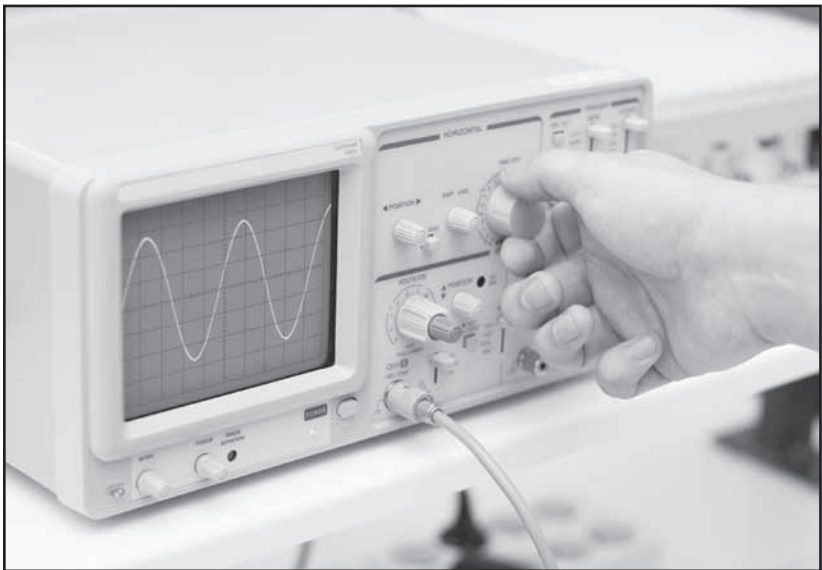
Measuring resistance requires an active circuit. We pass a known current through a resistor and measure the voltage, then use Ohm's law to determine the resistance ($I = V/R$ or $R = V/I$).

Don't try to measure the resistance in a circuit by putting an ohmmeter across it because the ohmmeter will try to pass current through the entire circuit—through other resistors and through the battery—and will not properly measure the resistance of the one resistor you're interested in. Instead, disconnect the resistance, then put the ohmmeter across it.

How to Measure Resistance

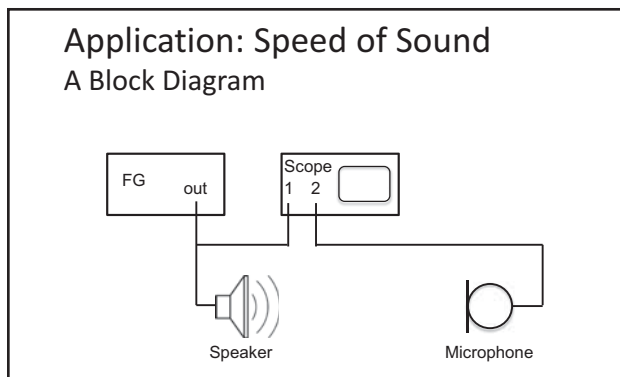


The Oscilloscope



© tomasnikulase/Stock/Thinkstock

An oscilloscope is a wonderfully versatile instrument that measures voltage as a function of time.



To measure the speed of sound with an oscilloscope, we hook up a function generator to a loudspeaker and also to one input channel of the oscilloscope. We then pick up the sound with a microphone and send that signal into the second channel of the oscilloscope. The oscilloscope shows the time difference between when the signal is sent and when it's picked up, and that gives us the speed of sound: a little over 300 meters per second (m/s), or about 700 miles per hour.

Suggested Reading

Introductory

Brindley, *Starting Electronics*, 4th ed., chapter 3.

Lowe, *Electronics All-in-One for Dummies*, book I, chapters 8–9.

Platt, *Make: Electronics*, chapter 1, emphasizing the sections on instruments and measurement. See also p. 231 for a possible inexpensive way to turn your computer into an oscilloscope, although Platt isn't enthusiastic about this approach.

Shamieh and McComb, *Electronics for Dummies*, 2nd ed., chapters 10, 12–13.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., appendix L.

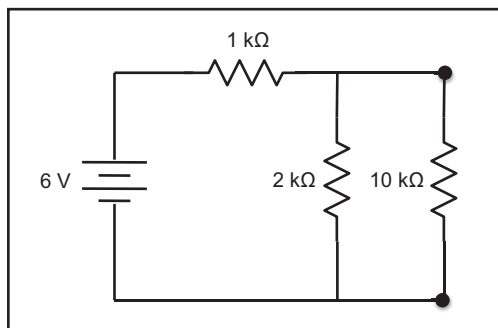
Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 7, sections 7.3–7.5.

Project

Lecture 2 Project Circuit Simulation

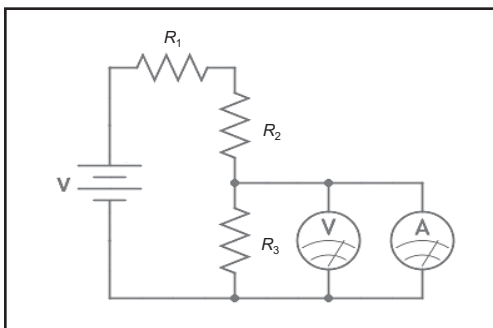
Simulate the circuit from Lecture 2's project. Verify that the voltage across the 2-k Ω resistor is what you expect.

Add the 10-k Ω resistor in parallel and verify that the voltage across the combination decreases as expected.



Questions to Consider

- *1. An electronics neophyte attempts to measure the voltage across and current through the resistor R_3 in the circuit shown below, simultaneously connecting a voltmeter and an ammeter across the resistor, as shown. Is either measurement successful? Is either meter at risk?



- *2. An oscilloscope displays voltage as a function of what other physical quantity?

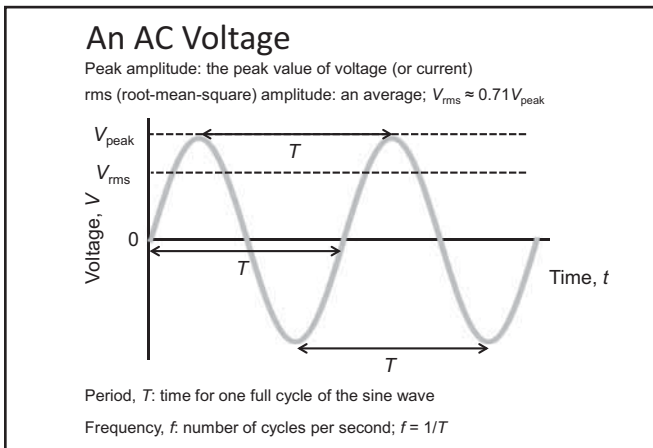
AC versus DC

Lecture 4

So far in this course, we've dealt with batteries as power sources; batteries involve chemical reactions that maintain, basically, a fixed, steady voltage across the battery's terminals. But when you plug something into a wall outlet, you get a time-varying voltage. There are good reasons for using such alternating current (AC) in power systems: Rotating generators naturally make AC power, and it's easy to change voltage levels in AC systems. In this lecture, we'll look at AC with regard to AC power, audio, and other signals that vary with time. Key topics include the following:

- Characterizing alternating current
- Transformers
- Diodes
- Capacitors and regulators.

Characterizing Alternating Current



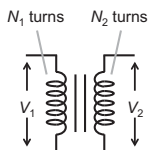
The waveform of basic alternating current is called a sine wave. An AC voltage can be plotted as a function of time, with time on the horizontal axis and voltage on the vertical axis; 0 V is the horizontal line through the

middle. From an arbitrary start time (designated $t = 0$), the AC voltage rises to a peak, comes back down through 0, and goes to a negative peak.

Transformers

Meet the Transformer

Uses electromagnetic induction to transform voltage levels in AC circuits



$$V_2 = \frac{N_2}{N_1} V_1$$

Transformers use electromagnetic induction to transform voltage levels in AC circuits. Here, V_1 and V_2 represent the voltages that appear across the primary and the secondary. We have N_1 turns on the primary and N_2 turns on the secondary; V_2 is $(N_2/N_1)V_1$. If $N_2 > N_1$, we have a *step-up transformer*; if $N_2 < N_1$, it's a *step-down transformer*.

Diodes

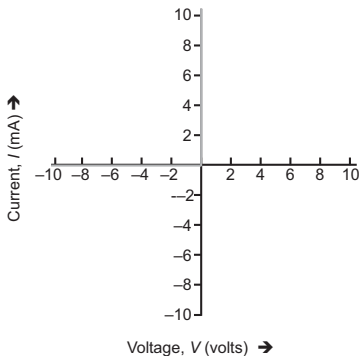
Meet the Diode

V-I characteristics, ideal diode

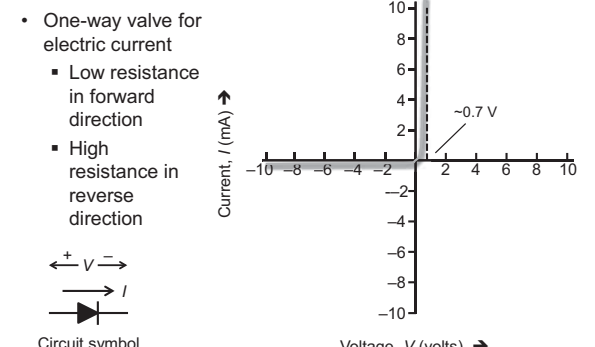
- One-way valve for electric current
 - Low resistance in forward direction
 - High resistance in reverse direction



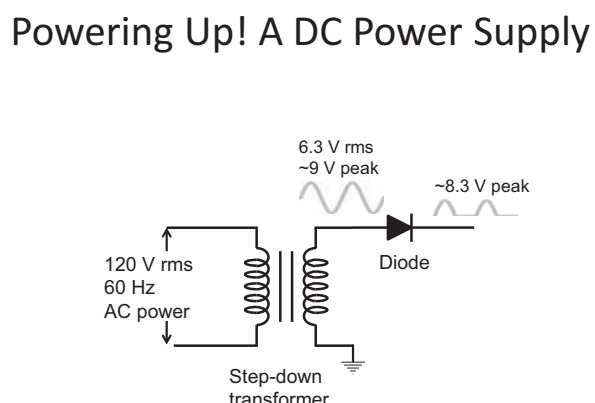
Circuit symbol



Manuscript Draft



Powering Up! A DC Power Supply

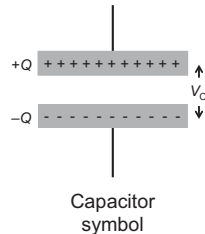


A diode and a step-down transformer are key components in a *power supply*, such as those that supply DC power to electronic devices. Notice that the output of the diode follows that of the transformer while the latter is positive, but as soon as the transformer output goes negative, the diode shuts off; the diode becomes an open circuit and no longer passes current. In a sense, we've made DC, because we've made a voltage that goes in only one direction, but it's far from steady.

Capacitors and Regulators

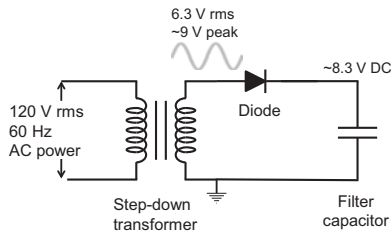
Meet the Capacitor

- A pair of conductors separated by an insulator
- Stores charge and energy
- Charge proportional to voltage: $Q = CV$
- Capacitance C : ratio of charge to voltage
 - 1 coulomb/volt = 1 farad
- Takes time to charge
 - Introduces delays in circuits
 - Voltage across capacitor can't change instantaneously

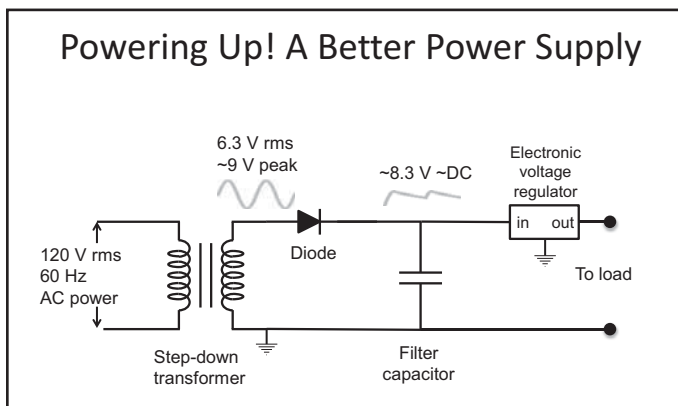


A *capacitor* is a pair of conductors separated by an insulator; it stores charge and energy. The charge and voltage are proportional; thus, if we put a certain voltage across the capacitor, we get a proportional amount of charge on the plates. The capacitance, C , is the ratio of how much charge we get for a given voltage.

Powering Up! A DC Power Supply



We can use the capacitor as a filter in our power supply to smooth out the variations we see after the diode. After we insert the capacitor into the circuit, we get a nearly steady DC voltage.



The job of an integrated-circuit voltage *regulator* is to take an unregulated input voltage (that may even be varying somewhat) and produce an output voltage that is fixed by the specifications of the regulator. The regulator we'll use is designed to produce an output voltage of 5 V. Once again, we can measure the output with the oscilloscope, and we see a steady, smooth DC voltage.

Suggested Reading

Introductory

Brindley, *Starting Electronics*, 4th ed., chapters 4; 6; and 7, p. 117 to end.

Lowe, *Electronics All-in-One for Dummies*, book II, chapter 3; book IV, chapters 1–3.

Platt, *Make: Electronics*, chapter 2, pp. 62–63; chapter 3, p. 134.

Shamieh and McComb, *Electronics for Dummies*, 2nd ed., chapter 4 through p. 80.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 1, sections 1.3–1.6.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 2, sections 2.20–2.23.2; chapter 3, section 3.6.11; chapter 4, pp. 415–420; chapter 11.

Project

A Power Supply

Simulate a simple 5-V DC power supply with 100- Ω load resistance. Use a 120-V AC rms voltage source. Choose an appropriate turns ratio for your transformer:

- Ignore other transformer parameters.
- Don't forget the 0.7-V drop across the diode.

Try capacitors of 1 mF, 10 mF, and 50 mF to see which makes the ripple nearly imperceptible. You'll need to run a time-domain simulation:

- CircuitLab: start/stop times 2, 2.1 s, time step 0.5 ms, “include zero” in advanced graphing.
- DoCircuits: analysis time 0.1 s; use an oscilloscope at the output.

Tweak your transformer to achieve ~5 V DC. For extra learning, add an integrated-circuit voltage regulator.

Questions to Consider

1. A step-up transformer increases voltage. Why, with a step-up transformer, aren't we getting something for nothing?
2. In what way is a diode like a simple on-off switch?
3. Of the components in a power supply, which is most directly responsible for smoothing the varying voltage that the diode would otherwise yield?
4. If you lower the load resistance connected across a simple power supply, such as the one developed in this lecture, will the ripple get worse or better? Explain.

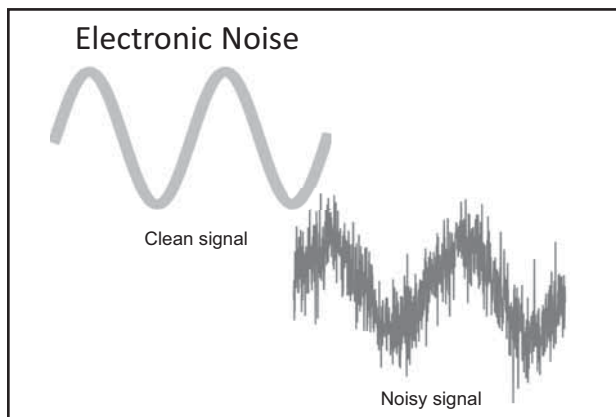
Up the Treble, Down the Bass!

Lecture 5

In the preceding lecture, we looked at AC signals, voltages and currents that varied sinusoidally with time. The emphasis was largely on a single frequency. But life would be pretty dull if we had only one frequency. In fact, we're usually confronted with a mixture of frequencies, as in the audible spectrum—the sounds we hear. We need circuits that can process signals consisting of multiple frequencies—filter circuits. In this lecture, we'll learn how filters can process the different frequencies that appear in electronic signals and, consequently, in other signals, such as sound, that we might then convert to electronic signals. Topics to be covered include these:

- Filters and their uses
- Capacitors up close
- A simple low-pass filter
- A simple high-pass filter
- Filter characteristics
- Band-pass filters
- Application: a loudspeaker network.

Filters and Their Uses



In the real world, there are sources of electromagnetic noise in our electrical signals. We can remove that noise with an electronic filter.

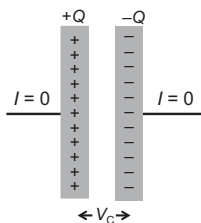
Capacitor Up Close

A conceptual picture of a filter shows an input, consisting of a mix of frequencies, and an output, consisting of an altered mix of frequencies.

Filter Operation: Conceptual



Capacitor



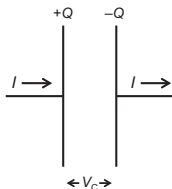
Constant voltage: no charge moving on or off capacitor plates

Therefore: no current through wires leading to capacitor

One component that allows the filtering of frequencies is the *capacitor*. A capacitor is a pair of conductors separated by an insulator.

Capacitors Up Close

- Capacitor: a pair of conductors separated by an insulator
 - Capacitor charge and voltage are proportional: $Q = CV$



Increasing voltage: charge moves onto capacitor plates

Therefore: current flows through wires leading to capacitor

Current is the rate of charge flow: $I = \Delta Q / \Delta t$

Charge Q is proportional to voltage V

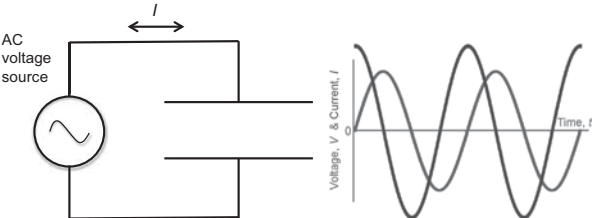
Therefore current depends on the *rate of change of voltage*:

$$I = C \frac{\Delta V}{\Delta t}$$

Charge goes onto the capacitor plates when a voltage is put across the capacitor. The voltage and the charge are proportional, and that proportionality defines the *capacitance* of the capacitor.

Capacitors Up Close

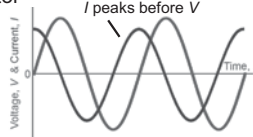
- Capacitor: a pair of conductors separated by an insulator
 - Current is proportional to rate of change of voltage: $I = C \frac{\Delta V}{\Delta t}$
 - Higher frequency \rightarrow higher current



With a sinusoidally varying voltage, charges pile up on the capacitor plates. As the voltage swings negative, charge flows off the plates, and then reverses, with negative charge ending up on the upper plate and positive charge on the lower. This process keeps repeating, so there's always current flowing through the wires leading to the capacitor.

"Ohm's Law" for Capacitors

- Capacitor acts "sort of" like frequency-dependent resistor
 - "Resistance" proportional to $1/\text{frequency}$
 - High frequency \rightarrow low "resistance" and vice versa
 - $f \rightarrow \infty$ (very high frequency): capacitor acts like short circuit
 - $f \rightarrow 0$ (very low frequency): capacitor acts like open circuit
- Why "sort of"?
 - Because capacitor changes phase
 - Current leads voltage in capacitor
 - Better name than "resistance": *capacitive reactance*, X_C
 - X_C proportional to $1/fC$



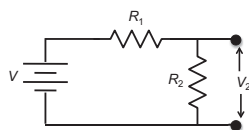
Ohm's law doesn't apply to capacitors because the voltage and current are not proportional in a capacitor. But when there is an AC signal coming to a capacitor, there is a sense in which we can talk about the proportionality between voltage and current—in particular, between the maximum value of the voltage and the maximum value of the current. We can say, then, that a capacitor acts *sort of* like a frequency-dependent resistor.

A Simple Low-Pass Filter

A circuit consisting of an AC voltage source and resistor in series with a capacitor also acts *sort of* like a voltage divider. The capacitive reactance goes down as the frequency goes up; therefore, at high frequencies, the capacitor acts more like a short circuit, or a low resistance.

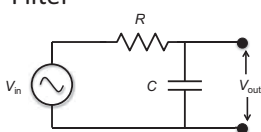
At high frequencies, the circuit is like a voltage divider, with less voltage across the capacitor—and therefore the output—than would be the case with low frequencies. Therefore, this is a low-pass filter.

Lecture 2 Voltage Divider



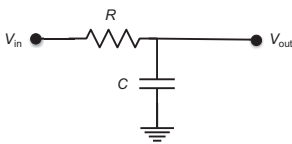
$$V_2 = \left(\frac{R_2}{R_1 + R_2} \right) V$$

Filter



$$V_{\text{out peak}} = \left(\frac{X_C}{\sqrt{R^2 + X_C^2}} \right) V_{\text{in peak}}$$

Simplifying the Diagram



Low-pass filter

$$V_{\text{out peak}} = \left(\frac{X_C}{\sqrt{R^2 + X_C^2}} \right) V_{\text{in peak}}$$

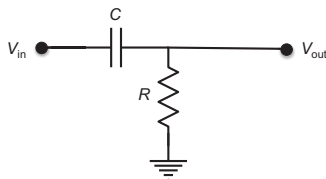
$$X_C \propto \frac{1}{f}$$

Circuits are frequently drawn with the capacitor going to ground, and it's understood that the input voltage is applied relative to ground and the output voltage is measured relative to ground.

A Simple High-Pass Filter

A high-pass filter is the opposite of a low-pass filter. Again, thinking of this as a sort of voltage divider, the capacitor's "resistance" is small for high frequencies but large for low frequencies. As a result, the output voltage is reduced for low frequencies.

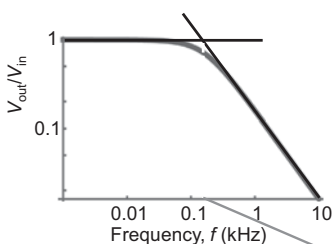
High-Pass Filter



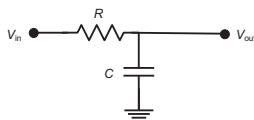
$$V_{\text{out peak}} = \left(\frac{R}{\sqrt{R^2 + X_c^2}} \right) V_{\text{in peak}} \quad X_c \propto \frac{1}{f}$$

Filter Characteristics

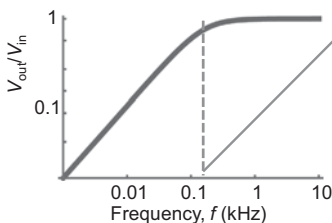
Filter Characteristics



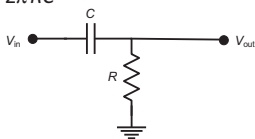
$$R = 1 \text{ k}\Omega, C = 1 \text{ }\mu\text{F}$$



Low-pass filter



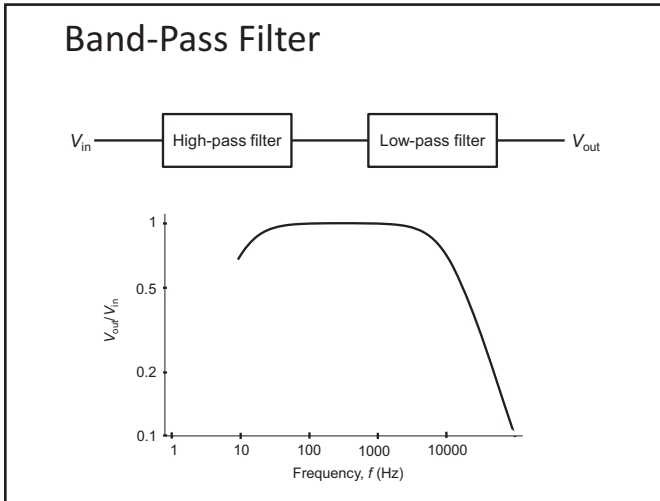
$$f = \frac{1}{2\pi RC} = 159 \text{ Hz}$$



High-pass filter

We can analyze high- and low-pass filters a little more carefully and essentially display what they do by looking at curves that describe their frequency response, that is, how much signal they let through as a function of frequency.

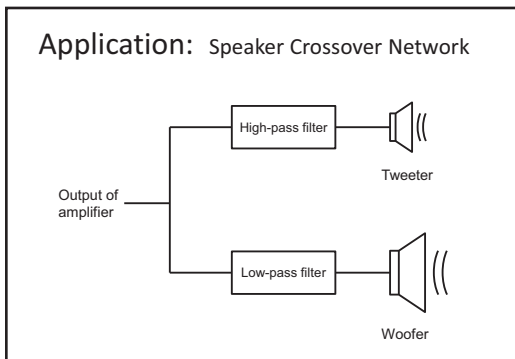
Band-Pass Filters



If we combine a high-pass filter and a low-pass filter, it seems as if no frequencies would get through. But if we pick the break points differently (*knee frequencies*), we can build a band-pass filter for a particular band of frequencies. This might be useful in a communication system to allow limited bandwidth to carry information with a limited range of frequencies.

Application: A Loudspeaker Network

In loudspeaker systems, a high-pass filter passes only the high frequencies to the tweeter, and a low-pass filter passes only the low frequencies to the woofer.



Suggested Reading

Introductory

Brindley, *Starting Electronics*, 4th ed., chapter 5, pp. 85–91.

Platt, *Make: Electronics*, chapter 2, experiment 9; chapter 5, experiment 29.

Shamieh and McComb, *Electronics for Dummies*, 2nd ed., chapter 4, p. 80 to end.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 1, section 1.7.13.2.

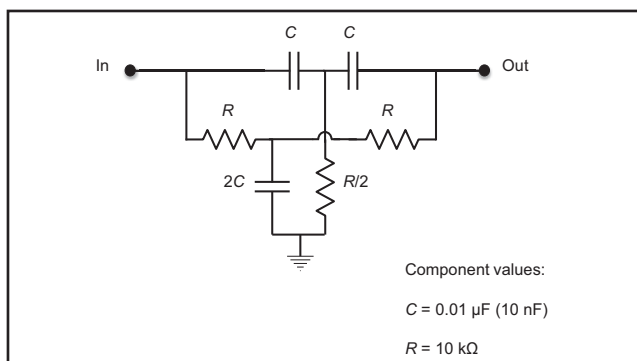
Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 2, section 2.33; chapter 9.

Project

Twin-T Filter

Simulate the circuit shown and explore its filter characteristics. Make a log-log plot of the ratio of output voltage to input voltage over the frequency range $10\text{ Hz} \leq f \leq 100\text{ kHz}$.

- Straightforward: Use a voltage function generator (under *Signal Sources*) as the input. Use a fixed voltage but different frequencies. Run a time-domain simulation for each f and plot V_{out} .
- Extra learning: Explore CircuitLab's frequency domain simulation.



Questions to Consider

- *1. What is an approximate way to characterize a capacitor (a) at low frequencies and (b) at high frequencies?
2. Even though we talk of a capacitor as approximating a frequency-dependent “resistance,” that characterization isn’t quite accurate. How is the AC voltage-current relation for a capacitor different than that for a resistor?
3. What’s the purpose of the crossover network in a loudspeaker system?

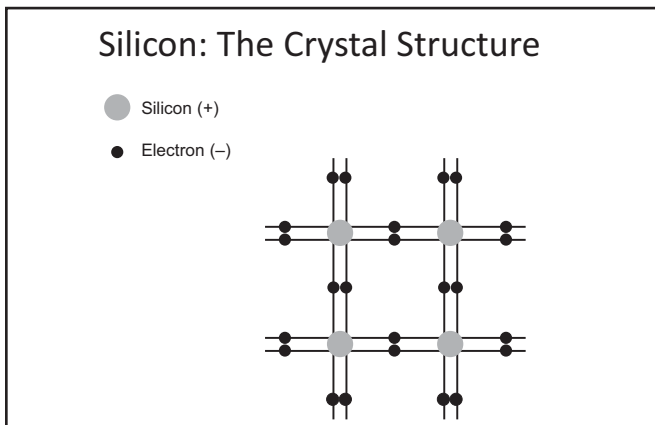
Semiconductors—The Miracle Material

Lecture 6

In this lecture, we will look at semiconductors, the miracle materials that are at the heart of most modern electronic devices, including transistors, diodes, and a host of others. Semiconductors replaced the vacuum tubes from the first half of the 20th century with tiny solid-state devices that consume very little power; billions of them can fit on a single silicon integrated-circuit chip. In this lecture, we'll discuss diodes, important components in their own right and also important to understanding the transistors that we'll cover in Lecture 7. Main topics in this lecture are as follows:

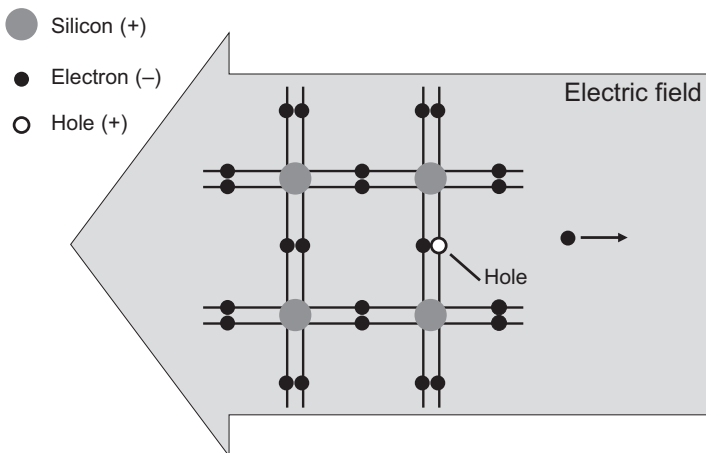
- Silicon atoms, silicon crystals, and intrinsic semiconductors
- Doping semiconductors: N- and P-type semiconductors
- The PN junction
- Diodes.

Silicon Atoms, Silicon Crystals, and Intrinsic Semiconductors



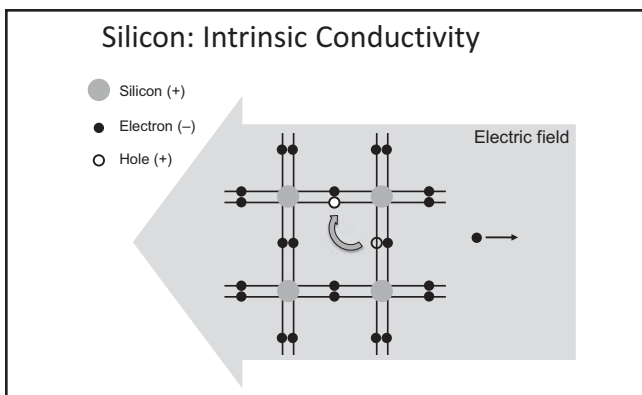
Silicon is the element at the heart of semiconductor electronics. It has a crystal structure, in which every atom is bonded to its nearest neighbors by the sharing of two electrons.

Silicon: Intrinsic Conductivity



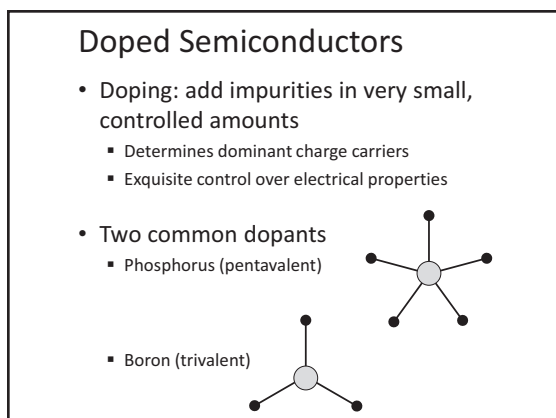
Silicon and other semiconductors conduct electricity by an unusual mechanism: At normal temperatures, random thermal motions might free one of the electrons in a silicon crystal from its bond. Freeing the electron leaves behind a “hole” in the crystal structure where the electron was.

Imagine that we apply an electric field, perhaps by introducing a sheet of positive charge beyond the right edge of the diagram and a sheet of negative charge beyond the left. The positive charge attracts electrons, and a free electron moves in response to this field (opposite the field, since it’s negative) and, thus, carries electric current, just as it would in a metal. But something else happens: The field can cause an electron bound in the crystal structure to “jump” into the nearby hole left when the original electron was freed. As a result, the hole effectively moves to the left and acts just like a *positive* charge carrier.



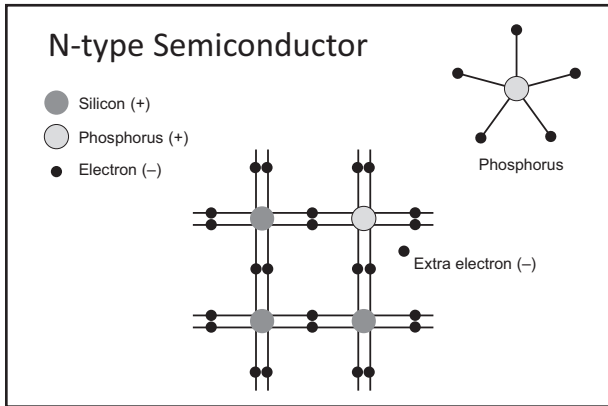
So the intrinsic conductivity of a semiconductor material, such as silicon, is caused not only by the presence of electrons, as in a metal, but also by the *absence* of electrons—that is, by holes. The holes act like positive charge carriers, and we will think of them as particles carrying positive charge. The holes, too, can move through the crystal structure, carrying electric current.

Doping Semiconductors: N- and P-Type Semiconductors

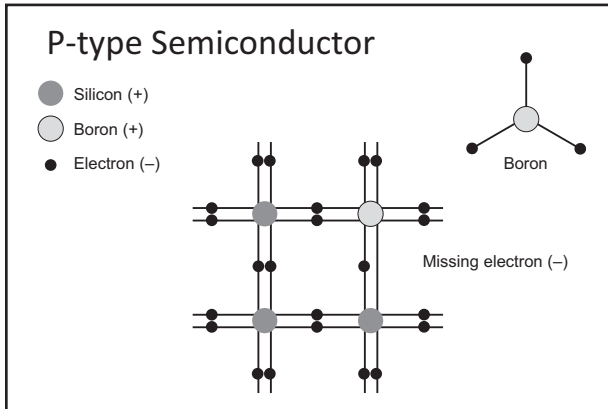


The process of doping determines the dominant charge carrier in silicon and other semiconductors. By doping appropriately, we can make semiconductors that have almost all of their current carried by electrons or by holes. Doping also provides exquisite control over the details of electrical properties, in

particular, how good a conductor the material is. Two common dopants are phosphorus and boron.



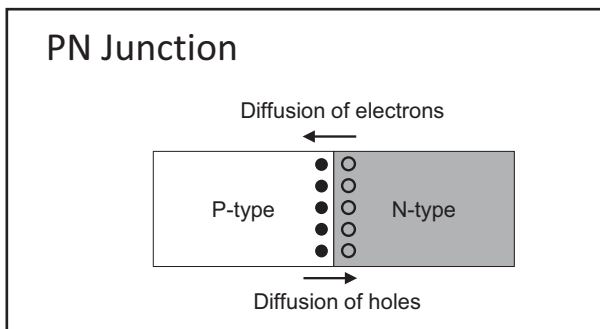
Phosphorus has five outermost electrons, but only four of them can participate in the silicon structure. Once it's introduced through doping, the phosphorus will fit itself into the crystal structure, but that one electron will be free and able to carry electric current. As a result, the dominant charge carriers in this *N-type semiconductor* are electrons.



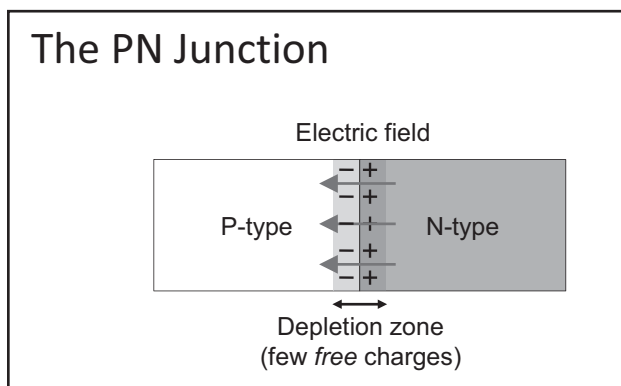
An analogous process occurs with boron. Boron has only three valence electrons, but the silicon structure needs four electrons. Thus, there is a missing

electron (a hole) in the bond structure. In a boron-doped material, the majority charge carriers are positive holes. This is called a *P-type semiconductor*.

The PN Junction

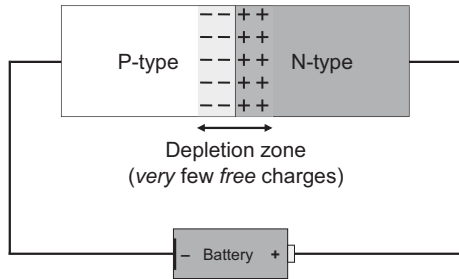


A *PN junction* is the interface between a piece of P-type material and a piece of N-type material. In the N-type material, there are many electrons, and in the P-type material, there are very few free electrons. At the junction, *diffusion* occurs—the process whereby some of the electrons move into the P-type material to ease out the abrupt gradient at the junction. Those electrons then recombine with holes. A similar process goes the other way, with holes diffusing into the N-type material. They, too, recombine with electrons.



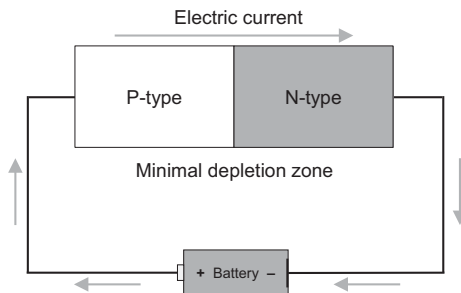
As a result, there are very few free charge carriers in the junction region (here, called the *depletion zone*), making the junction a poor conductor.

The PN Junction: Reverse Bias



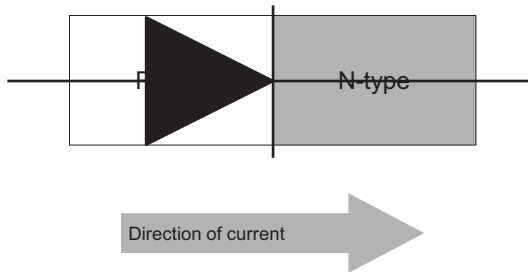
If we connect the positive terminal of a battery to the N-type material and the negative terminal to the P-type material, the electric field at the PN junction is reinforced, causing the depletion zone to grow. Now there is a larger region where there are very few free charges, which means that the device can hardly conduct electricity at all. The PN junction is basically an open circuit. This is called *reverse bias*.

The PN Junction: Forward Bias



If we connect the battery the other way, it can eliminate the electric field and allow current to flow across the junction from the P-type into the N-type material. That's called *forward bias*; under this condition, the junction becomes a fairly good conductor, and electric current can flow around the circuit.

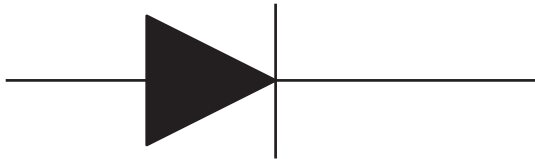
The PN Junction: A One-Way “Valve”



We're left with something that conducts electricity with a battery connected in one direction but not in the other direction. The PN junction becomes a one-way valve for electricity. Current can flow from P to N, but it can't flow from N to P.

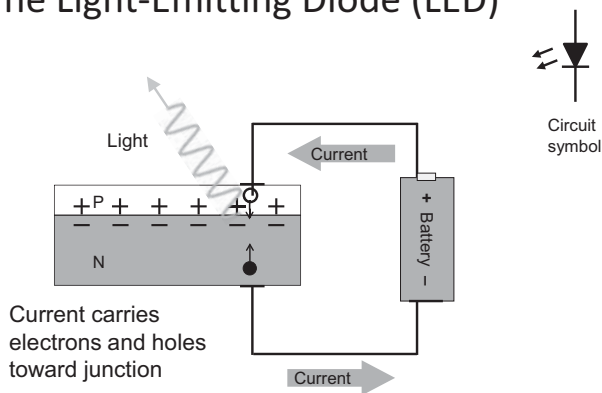
Diodes

The Diode: A PN Junction



As you recall, we used a diode that passed current in one direction and not the other in our power supply to change AC into DC (the process of *rectification*). That was the step that cut off the negative-going portion of the AC. The PN junction does exactly the same thing; in fact, a diode *is* a PN junction.

The Light-Emitting Diode (LED)



The obvious use of the diode is in converting AC to DC, but there are many other uses of diodes in electronic circuits. One specialized type of diode is the light-emitting diode (LED), which converts electrical energy to light.

Another specialized type of diode is the photovoltaic cell, which takes in sunlight and produces electricity. It, too, is a PN junction diode.



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Suggested Reading

Introductory

Brindley, *Starting Electronics*, 4th ed., chapter 6.

Lowe, *Electronics All-in-One for Dummies*, book II, chapter 5.

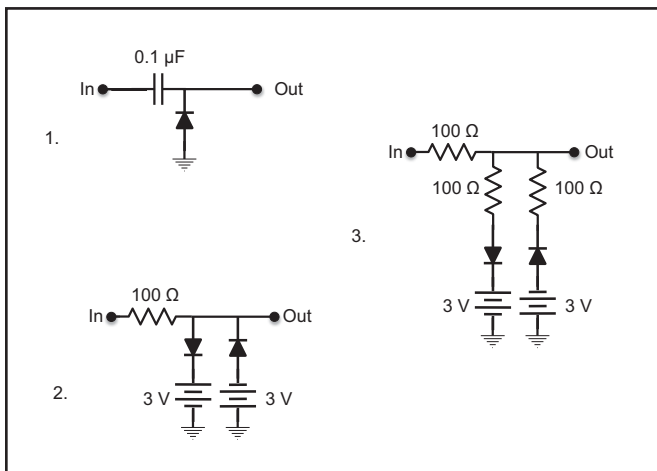
Shamieh and McComb, *Electronics for Dummies*, 2nd ed., chapter 6 through p. 125.

Advanced

Scherz and Monk, *Practical Electronics for Inventors*, chapter 2, section 6; chapter 4, sections 4.1–4.2.

Project

Diode Applications



Simulate each circuit below. At the input, use a voltage function generator producing a 10-V p-p, 1-kHz triangle wave. Look at both the input and output with time domain simulation. Describe in words what each circuit does.

Questions to Consider

1. The N in *N-type semiconductor* stands for “negative.” Does that mean an N-type semiconductor is negatively charged? Explain and answer the analogous question for a P-type semiconductor.
2. Explain the terms *forward biased* and *reverse biased* as applied to diodes.
3. What is the purpose of doping silicon?

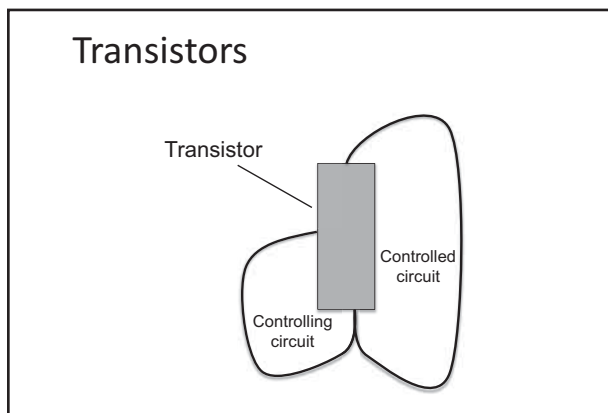
Transistors and How They Work

Lecture 7

Transistors are among the most important inventions of the 20th century. They came into full-scale use in electronic circuits in the 1960s, quickly replacing vacuum tubes. Transistors are at the heart of all modern electronics because they allow one circuit to control another. In this lecture, an introduction to how ideal transistors work will enable us to understand simple transistor-based circuits. By the end of the lecture, we'll build a circuit that uses a transistor as a switch. Key topics in this lecture include the following:

- Electronic control: the concept
- Field-effect transistors: MOSFETs and JFETs
- Bipolar junction transistors (BJTs)
- V - I characteristics for the BJT
- Application: BJT switch.

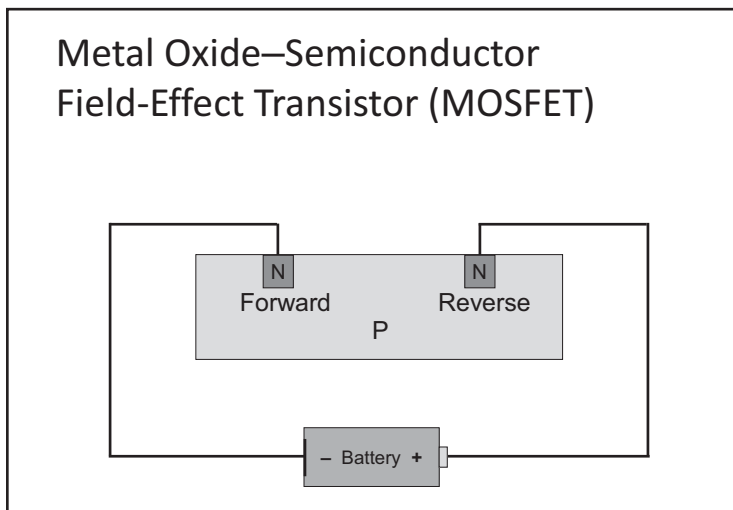
Electronic Control: The Concept



The minimum number of connections to a device that lets one circuit control another is three, and that's the number of connections to a transistor. Because there are only three connections, the two circuits must have one point in common.

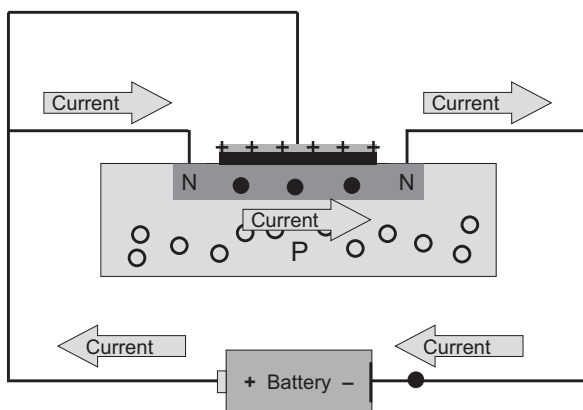
There are two main kinds of transistors: field-effect transistors (FETs) and bipolar junction transistors (BJTs). FETs are voltage-controlled devices, while BJTs are current controlled.

Field-Effect Transistors: Metal Oxide–Semiconductor FETs (MOSFETs)



There are two kinds of FETs: metal oxide–semiconductor FETs (MOSFETs) and junction FETs (JFETs). A basic MOSFET consists of a block of P-type semiconductor material embedded with two inserts of N-type material. As we saw in the last lecture, the PN junction is at the heart of almost all semiconductor electronic devices. Here, we see two PN junctions. There is also a battery connected with its positive terminal to the N-type region of the right-hand PN junction. In this configuration, that junction is reverse biased, and no current can flow. Reversing the battery would give a similar picture, now with the left-hand junction reverse biased, so again, no current can flow.

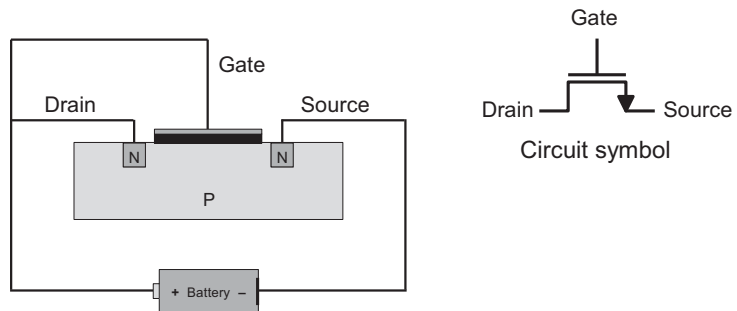
MOSFET



A transistor is a three-terminal device, and for the MOSFET, the third terminal is the *gate*. The gate is a metal electrode separated from the rest of the transistor by a thin insulating layer. This gate structure gives the MOSFET one of its virtues, namely, very high resistance between the metal gate and the rest of the circuit. As a result, the MOSFET gate draws very little current from the circuit it's connected to.

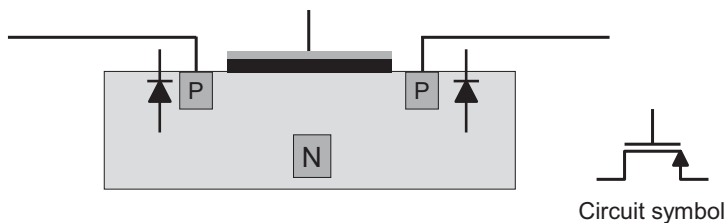
If we then apply a positive voltage to the insulated gate, it acquires a positive charge; that charge can't flow anywhere because of the insulating material, but it attracts negative electrons into the region below the gate. Effectively, the whole *channel* (the region between the two intrusions of N-type material) becomes N-type. Now there are no junctions—just a continuous piece of N-type semiconductor—and the transistor can conduct.

N-Channel MOSFET



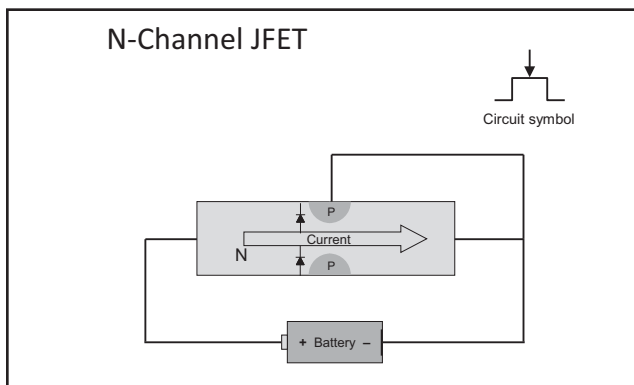
This MOSFET is an N-channel MOSFET because the channel becomes *negative* when the transistor is in the conducting state.

P-Channel MOSFET



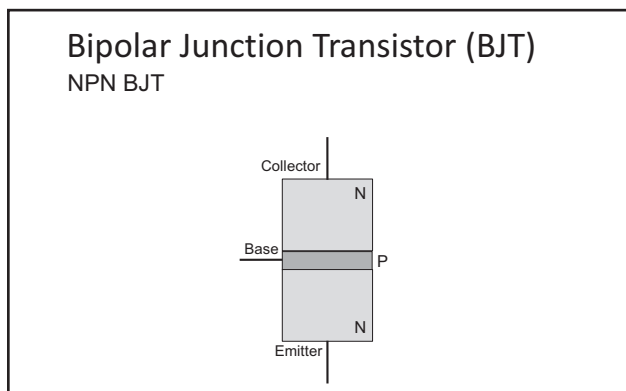
We can also make P-channel MOSFETs, in which we reverse the N- and P-type material.

Field-Effect Transistors: Junction FETs (JFETs)



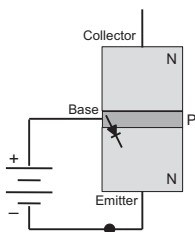
Like a MOSFET, the JFET is a device in which a voltage applied to the gate controls the flow of current through the transistor. Again, the transistor becomes a device that allows one circuit to control another.

Bipolar Junction Transistors (BJTs)



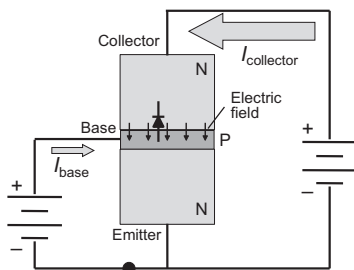
An NPN BJT consists of three regions: an upper N region (collector), a P region (base), and a lower N region (emitter). Notice that the P-type base region, separating the collector and the emitter, is very narrow; that's the key to transistor operation. Wires are connected to the three regions, so again, we have a three-terminal device.

NPN BJT

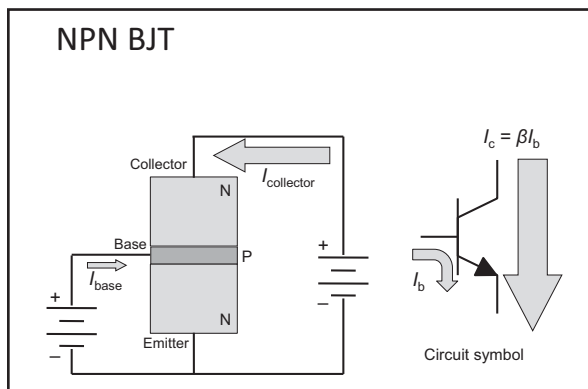


If we connect a battery between the emitter and base, with its positive terminal at the base, we have a forward-biased PN junction between the base and the emitter; in that configuration, current will flow. The current consists of electrons flowing opposite from the direction of the current because electrons are negative.

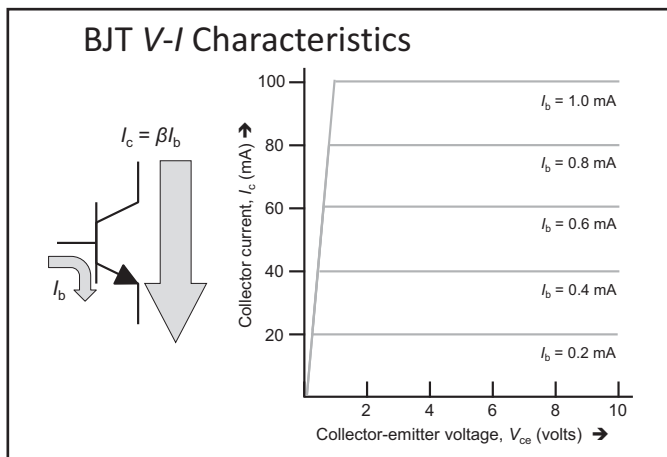
NPN BJT



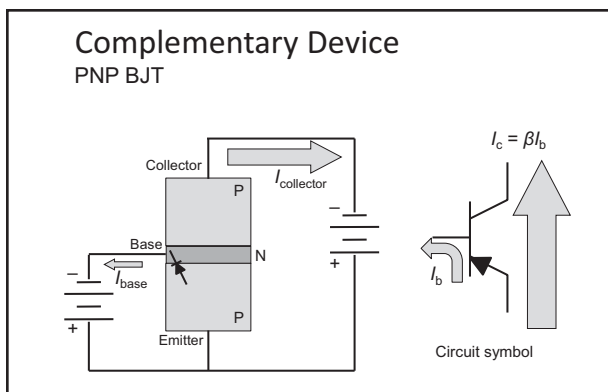
If we connect another battery with its positive terminal to the collector and negative to the emitter, we reverse bias the collector-base junction. Remember that a reverse-biased junction has a strong electric field; here, that field points downward. Remember, too, that electrons, being negative, move opposite the direction of the field. Now, the current in the base-emitter circuit is continually injecting electrons into the base, where they would normally continue out the base wire and into the positive terminal of the battery. But the base is thin, so it's possible for electrons entering the base to “feel” the strong electric field at the collector-base junction, in which case they'll be whisked into the collector and can flow around the collector-emitter circuit. If the base is very thin, most of the electrons entering the base will end up in the collector circuit, and as a result, the collector current will be much greater than the base current—typically, on the order of 100 times larger.



In this way, the BJT multiplies currents. It takes a small base current, which we can control through the base circuit, and produces a much larger but proportional collector current. The ratio of collector to base current is the transistor's *current gain*, and it's given the symbol β (lowercase Greek *beta*). For typical BJTs, β is generally in the range from about 50 to about 200 or so.



We can characterize a BJT in the same way we characterized other electronic devices, namely, by drawing V - I curves. But the transistor has a third terminal, and the collector current depends on the base current. So the BJT has not one but infinitely many characteristic curves, one for each possible level of base current.



Just as with the FETs, there is a complementary device to the NPN BJT, namely, a PNP BJT transistor. Its base is N-type material, while its collector and emitter are P-type. It works in the same way as the NPN, but with all voltages and currents reversed.

Application: BJT Switch

Application: A Transistor Switch

A delicate switch is capable of handling at most 5 mA of current, yet you need it to switch on a light bulb that draws 100 mA at 12 V. How can a BJT help?

Finding R :

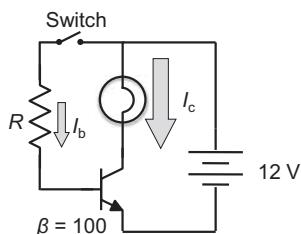
Need $I_c = 100 \text{ mA}$

$\beta = 100$, so need $I_b = 1 \text{ mA}$

Voltage across R : $12 \text{ V} - 0.7 \text{ V}$
(base-emitter diode) $= 11.3 \text{ V}$

Ohm's law: $R = V/I$

$= 11.3 \text{ V} / 1 \text{ mA} = 11.3 \text{ k}\Omega$



Let's assume that we have a manual switch that is very delicate, capable of handling, at most, 5 mA of current before it burns out. But we need it to switch on a 12-V light bulb that draws 100 mA—20 times as much as the switch

can handle. In this case, we can use a BJT as a simple switch. We have to choose a base-circuit resistance that will ensure the transistor turns fully on and passes the needed 100 mA with no more than 5 mA of base current. The diagram above shows the appropriate calculation.

Suggested Reading

Introductory

Brindley, *Starting Electronics*, 4th ed., chapter 8.

Lowe, *Electronics All-in-One for Dummies*, book II, chapter 6 through p. 302; pp. 306–311.

Platt, *Make: Electronics*, chapter 2, experiment 10.

Shamieh and McComb, *Electronics for Dummies*, 2nd ed., chapter 6, p. 126 through end.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 2 through section 2.2.1.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 4, section 4.3 through p. 437.

Project

Automatic Nightlight

A photosensor outputs 0 V until the ambient light decreases below a certain level, after which it outputs 5 V. You want to use this signal to turn on a light bulb that draws 250 mA at 24 V. Design a transistor switch to accomplish this and simulate it. Assign your light bulb the appropriate resistance. Verify that your circuit works.

Questions to Consider

1. What makes the transistor one of the most important inventions of the 20th century?
2. What does it mean that an FET is *voltage controlled*, while a BJT is *current controlled*?
- *3. Determine the maximum permissible of the resistance (R) in the transistor switch described in this lecture when the following changes are made: (a) transistor β increases to 150; (b) battery voltage increases to 24 V; (c) the light bulb draws 500 mA when fully on.

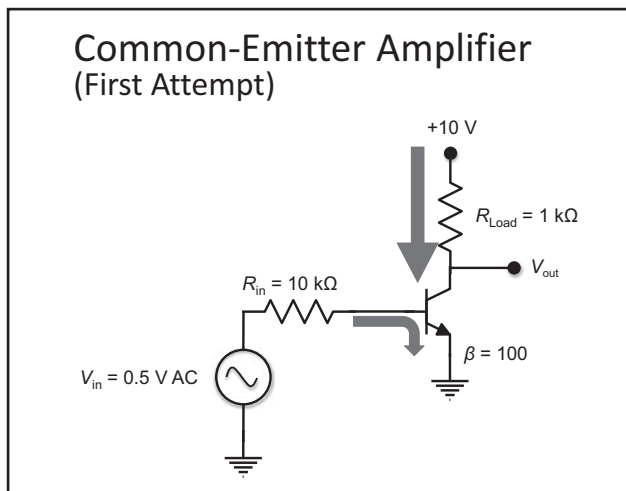
Transistors as Amplifiers

Lecture 8

In the preceding lecture, we learned about several kinds of transistors, including MOSFETs, JFETs, and BJTs. One of the earliest applications for transistors was as amplifiers, devices that make weak signals stronger. We're all familiar with amplifiers in the audio realm; a radio has an audio amplifier, as does a stereo system and a cell phone. In this lecture, we'll develop a simple circuit for an audio amplifier. Then, in the next lecture, we'll combine that with some other circuits to make a complete audio amplifier system. Key topics in this lecture are as follows:

- The common-emitter BJT amplifier
- Biasing
- Load line analysis
- Distortion
- Better biasing.

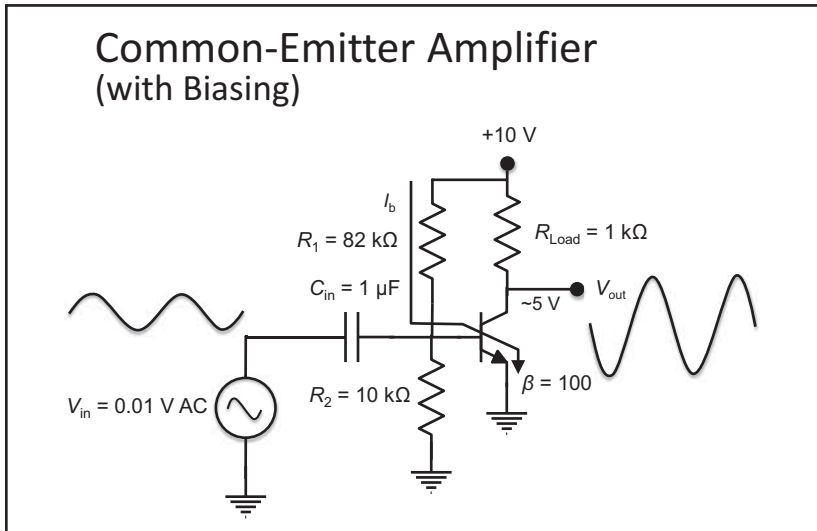
Common-Emitter Amplifier



A transistor is a three-terminal device that allows one circuit to control another. Because it has only three terminals, one of those terminals must

be shared by both circuits. We can build a transistor amplifier in which the collector is common, the base is common, or the emitter is common. The common emitter (CE) is probably the most often-used configuration. The diagram here shows a first attempt at a CE amplifier—but this circuit won't work because the transistor's base-emitter junction becomes reverse biased when the AC input signal V_{in} goes negative.

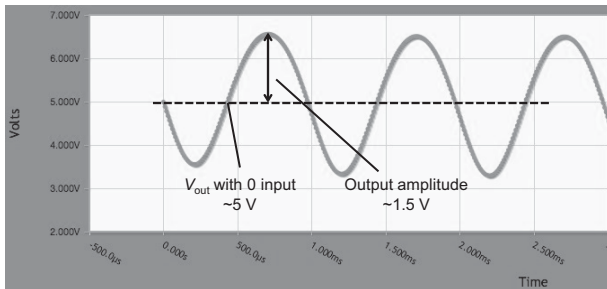
Biasing



A functioning CE amplifier requires circuitry for *biasing*, which provides a steady base current even when there's no input. Biasing is generally chosen so that the output, taken at the transistor's collector, is about half the supply voltage when there's no input voltage. With biasing, the base-emitter junction is always conducting, and the output swings lower and higher as the input swings higher and lower. The output swing will be greater than the input swing, making this circuit a *voltage amplifier*.

Common-Emitter Amplifier

V_{out} from CircuitLab

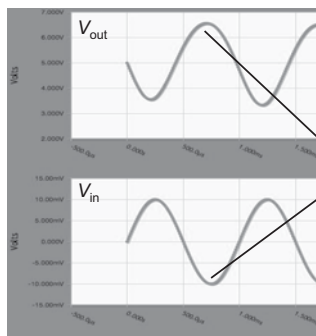


Output amplitude: 1.5 V
 Input amplitude: 0.01 V \Rightarrow $|Gain| = 1.5 \text{ V} / 0.01 \text{ V} = 150$

A probe in CircuitLab shows the collector voltage of the transistor in a properly biased CE amplifier. This is the voltage labeled V_{out} , here a sine wave swinging 1.5 V either side of 5 V. We can calculate the gain of this amplifier as follows: The output amplitude (the peak of the output swing) is 1.5 V; the input amplitude is 0.01 V. The gain, then, is: $1.5/0.01 = 150$.

Common-Emitter Amplifier

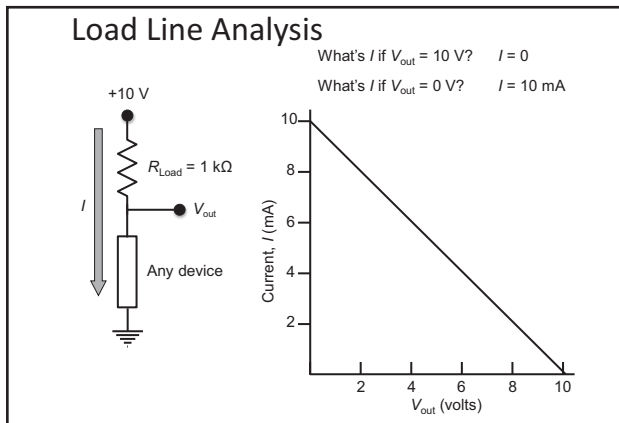
V_{out} and V_{in} from CircuitLab



Input and output
 are out of phase
 Inverting amplifier
 Gain = -150

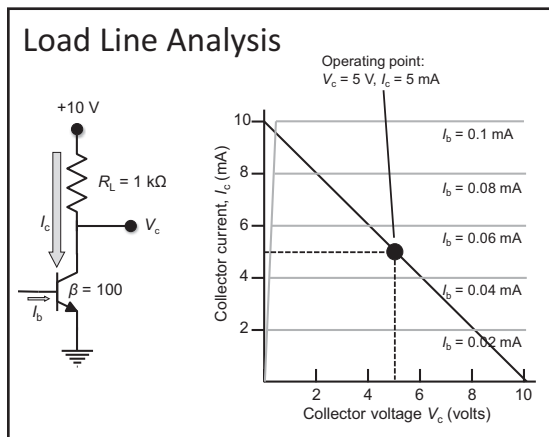
Because the input and output are out of phase, we have an inverting amplifier, which means the gain is actually -150.

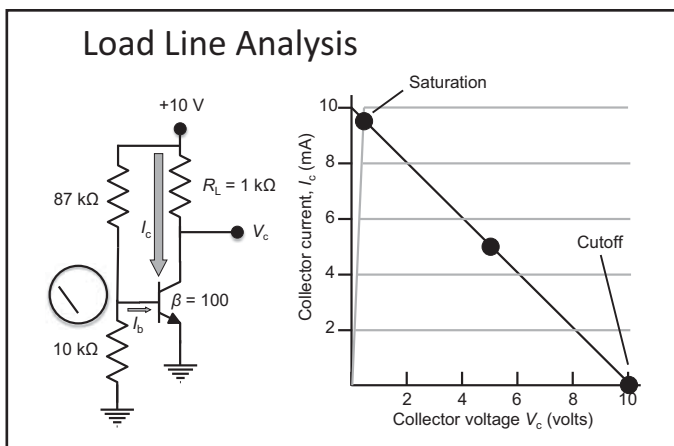
Load Line Analysis and Distortion



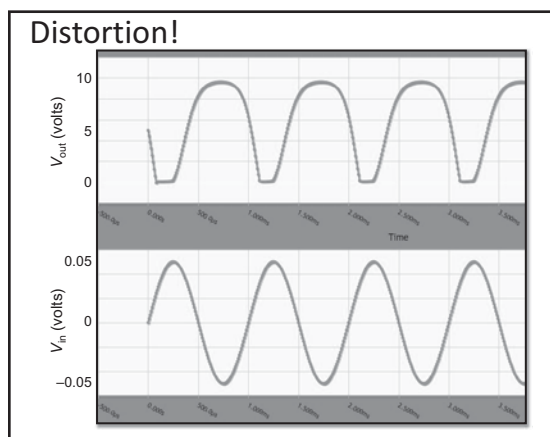
To understand how this amplifier works and learn its limitations, we conduct *load line analysis*. Imagine an arbitrary device in series with a resistor (called the *load resistor*) and a battery or power supply. We can draw a plot of V_{out} —the voltage across the arbitrary device—versus I , the current through the device. If the output were 5 V , we would have 5 mA flowing through the load resistors and through the arbitrary device. In general, V_{out} and I must lie on a line that goes from the maximum current (10 mA here, when $V_{\text{out}} = 0$) to the maximum voltage (10 V here, when $I = 0$). This line is the *load line*.

We now replace the arbitrary device with the collector-to-emitter portion of a transistor. We choose a biasing circuit whose steady base current puts the collector voltage at about half of the power supply voltage; this establishes the *operating point*, as shown here.





When we apply an input signal, the base current varies and, therefore, so does the collector current. But the output voltage must remain on the load line. So the voltage swings down and up the load line as the input voltage goes up and down. But the voltage swing is limited by two special points: cutoff, where there's no current flowing through the transistor and there's maximum possible voltage at the output, and saturation, where there's the most possible current and very little voltage. No matter what happens at the input, the output can't go beyond these points. If it's pushed beyond those limits, the amplifier will exhibit distortion, and if it's an audio amplifier, you'll hear that distortion.



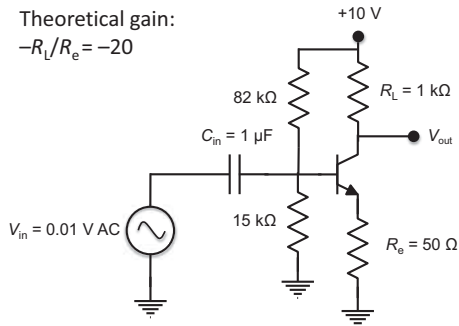
Distortion of V_{out} shows clearly in these CircuitLab plots of output voltage (top) and input voltage (bottom).

Better Biasing

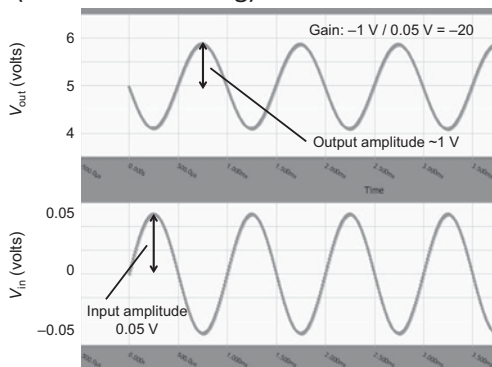
Common-Emitter Amplifier
(with Better Biasing)

Theoretical gain:

$$-R_L/R_e = -20$$



A better biasing scheme adds a small (here, 50 Ω) resistor in the emitter lead. Adding this resistor gives us a fixed gain that is approximately independent of the transistor's own characteristics. In fact, that gain becomes the resistance of the load divided by the resistance of the emitter resistor, in this case: $1000/50 = 20$.

Common-Emitter Amplifier
(with Better Biasing)

The output from CircuitLab for this CE amplifier shows that it has, in fact, a gain of -20 .

Suggested Reading

Introductory

Lowe, *Electronics All-in-One for Dummies*, book II, chapter 6, pp. 302–306.

Shamieh and McComb, *Electronics for Dummies*, 2nd ed., chapter 6, pp. 135–137.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 2, section 2.2.6.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 4, section 4.3, pp. 440–442.

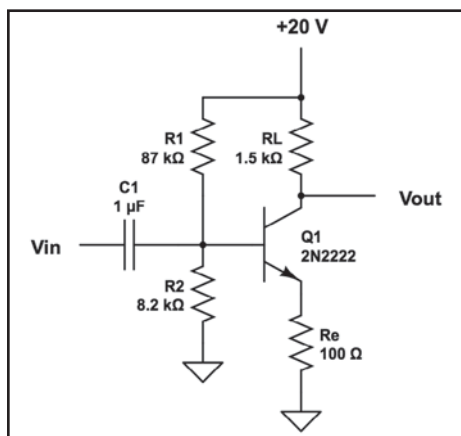
Project

Audio Preamplifier

Simulate a CE amplifier using a 2N2222 transistor, power supply voltage $V_{cc} = 15$ V, and a gain of -10 . Use trial and error to bias with an operating point within 0.5 V of $V_{cc}/2$. Verify the gain and operating point. Determine the input voltage range for which distortion isn't visually obvious.

Questions to Consider

- *1. What should be the voltage gain of the amplifier shown below?
2. Why is it necessary to bias the transistor in a CE amplifier?
- *3. What circuit quantities determine the load line's (a) slope and (b) intersection with the voltage axis?



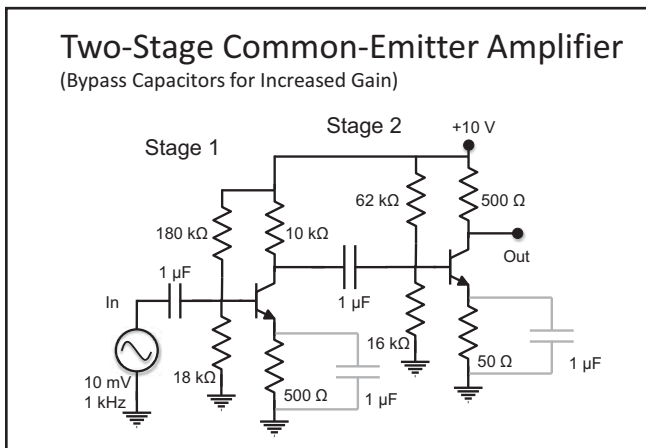
Building an Audio Amplifier

Lecture 9

In this lecture, we'll continue our ongoing exploration of audio amplifier circuits. A complete audio amplifier requires several stages of voltage amplification, followed by a power output stage to drive a loudspeaker. As we put together a complete audio amplifier in this lecture, we'll learn about two new amplifier circuits: the emitter follower and the complementary symmetry configuration. We'll cover the following key topics:

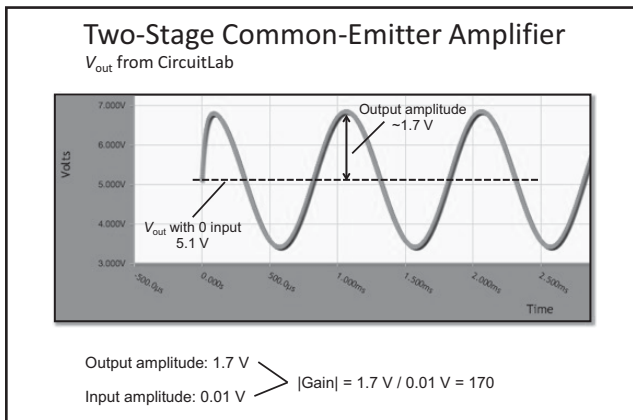
- Multistage amplifiers
- Coupling common-emitter stages for voltage gain
- The emitter follower
- Complementary symmetry
- Eliminating distortion.

Multistage Amplifiers

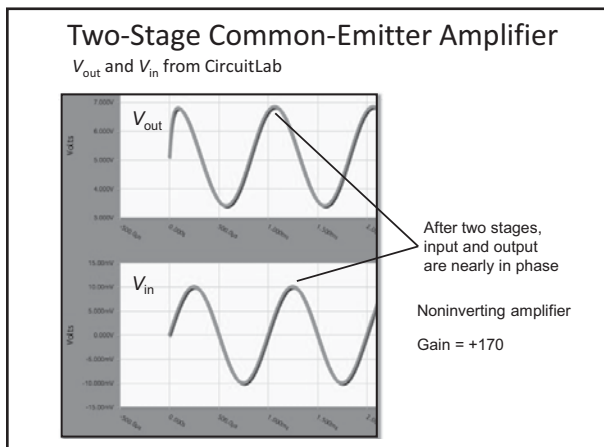


Both the stage 1 and stage 2 CE amplifiers shown here are voltage amplifiers. Their primary purpose is to increase the input voltage. Because the output of the first stage swings about its operating point rather than about 0 V, we need to couple the two stages with a capacitor that blocks DC but lets the varying AC signal through. We've also added bypass capacitors around the emitter

resistors. The AC signal “sees” these capacitors as lower-resistance paths to ground than the emitter resistors, and this recaptures some of the gain we lost by adding those resistors.



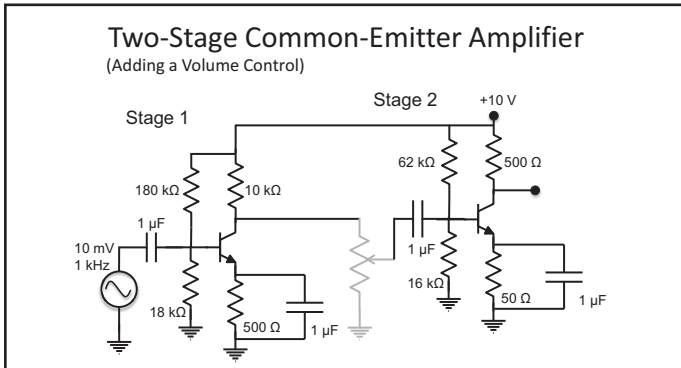
The output from a simulation of this amplifier shows that the voltage is swinging roughly around 5 V; that’s the operating point. The output amplitude is 1.7 V; the gain is 170.



We can see that this is a noninverting amplifier because the signal went through one CE amplifier, which inverts the input signal (here, a sine wave).

When the input goes high, the output goes low. That low output is then fed into the second stage, and when the output of the first stage goes low, the output of the second stage goes high, giving us a positive gain overall.

Volume Control



We can add a volume control using a *potentiometer*, which is a kind of variable resistor that acts as a variable voltage divider. Here, we've put the volume control between the two amplifier stages. Turning the knob moves the variable contact (the arrow on the potentiometer symbol), tapping off anywhere from zero to all of the first-stage output and supplying the corresponding voltage as input to the second stage.

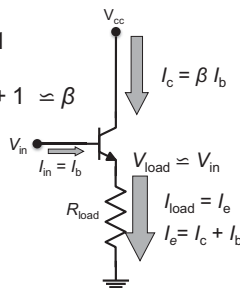
The Emitter Follower

The Emitter Follower

A Current Amplifier

Voltage gain: $V_{\text{load}}/V_{\text{in}} \simeq 1$

Current gain: $I_{\text{load}}/I_{\text{in}} = \beta + 1 \simeq \beta$

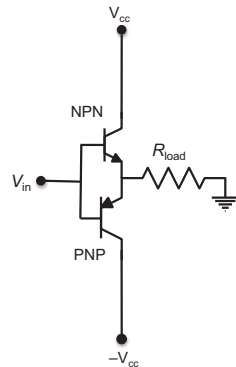


An emitter follower is a current amplifier. It's also called a common-collector configuration because the collector of the transistor is connected directly to the power supply, which along with ground, is another common point in the circuit.

Complementary Symmetry

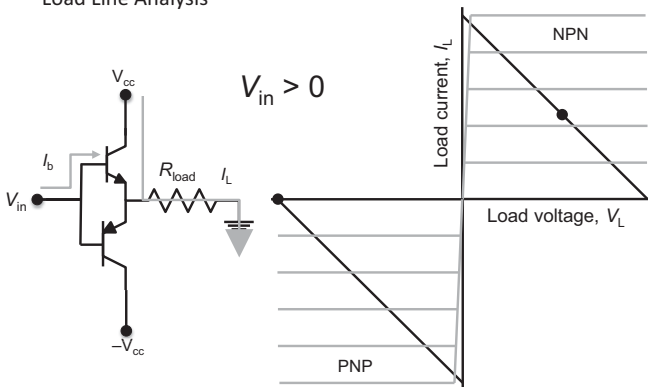
To reach the final stage of our amplifier to drive a speaker, we can make use of the complementarity of NPN and PNP BJTs by developing a complementary-symmetry (CS) circuit.

Complementary Symmetry



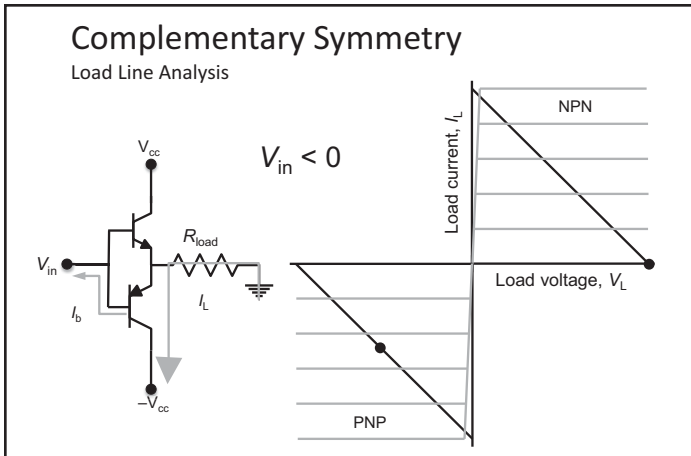
Complementary Symmetry

Load Line Analysis



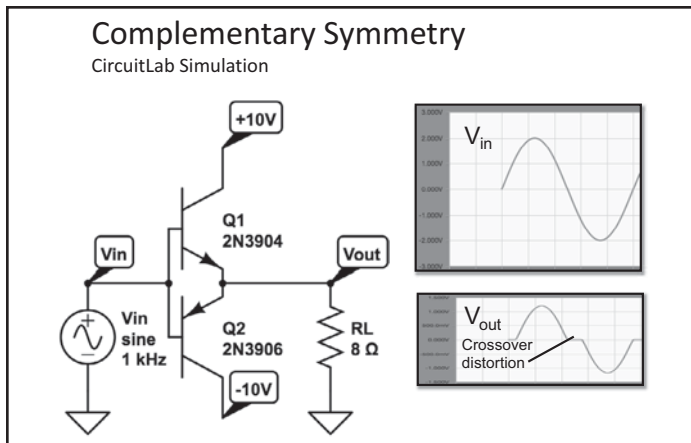
Here, a positive input voltage turns on the NPN transistor (the upper transistor in the diagram), which amplifies the positive-going half of the AC cycle. A negative voltage turns on the PNP (lower) transistor. Together, the

two transistors amplify the entire cycle. Each transistor is biased at its cutoff and moves into the active region of the load line only when it's conducting.

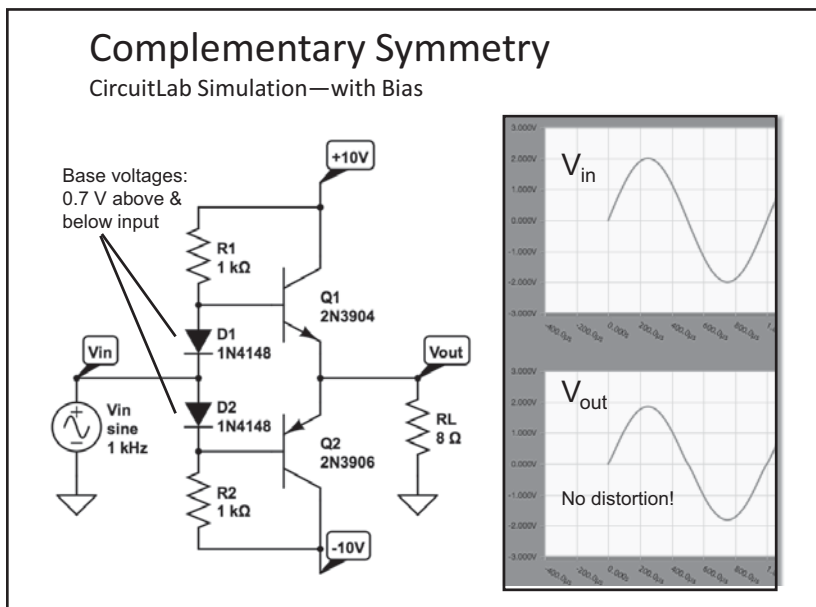


This device will amplify when the input signal goes positive by turning on the NPN transistor and when the input signal goes negative by turning on the PNP transistor. When there's no input, neither transistor is on, and we're not dissipating power.

Eliminating Distortion



We still have a problem that causes minor distortion in the output voltage and, thus, the sound from our amplifier. This glitch occurs because turning on the NPN transistor doesn't require just a positive voltage; it requires a voltage going above the 0.7 V needed to turn on the base-emitter junction. And turning on the PNP transistor requires the input going below that same 0.7 V. *Crossover distortion* is caused by the transistors turning off during the interval when the input voltage is between +0.7 V and -0.7 V.



An easy trick for eliminating crossover distortion is to simply add a couple of diodes and resistors in a string from +10 V down to -10 V. What the diodes do, effectively, is bias the base of the NPN transistor at +0.7 V, so it's just on the verge of turning on. The lower diode biases the base of the bottom transistor, the PNP transistor, at -0.7 V, also just on the verge of turning on. If the input signal swings even the slightest bit positive, the upper transistor turns on. If the input swings even the slightest bit negative, the lower transistor turns on, and there's no crossover distortion.

Suggested Reading

Introductory

None of the introductory books treats the transistor amplifier circuits introduced in this lecture. For practical amplifier construction, you would start with integrated-circuit amplifiers, and you wouldn't have to know how their internal circuitry works.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 2, sections 2.2.1 and 2.4.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 4, section 4.3, pp. 439–440.

Project

Gain and Power

Simulate the combination of a two-stage CE amplifier with a diode-biased CS output stage to make a complete audio amplifier. Use the two-stage CE amplifier from earlier in this lecture and the CS amplifier. Couple the CE and CS amplifiers with a 1- μ F capacitor. For input, use a 0.025-V, 1-kHz sine wave. Find the voltage gain and calculate the power delivered to R_L .

Questions to Consider

1. Why is it necessary to use a capacitor between two stages of a multistage audio amplifier?
2. Why is a CS output stage in an audio amplifier more energy efficient than a single-transistor output stage?

The Ideal Amplifier

Lecture 10

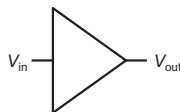
In the preceding two lectures, we learned about transistor amplifiers that are designed specifically to amplify in the range of audio frequencies. But it's important to note that amplifiers have other functions besides those related to audio, including instruments for scientific, medical, or consumer use; electronic thermometers are an example of the latter. In this lecture, we'll look more theoretically at the characteristics we would ideally like to have in an amplifier. Then, we'll see how surprisingly close we can come to an ideal amplifier at a remarkably low expense. Key topics to be covered include:

- An ideal amplifier
- DC amplification:
the differential amplifier
- An integrated-circuit
operational amplifier
- The op-amp as a comparator
- Application: battery tester.

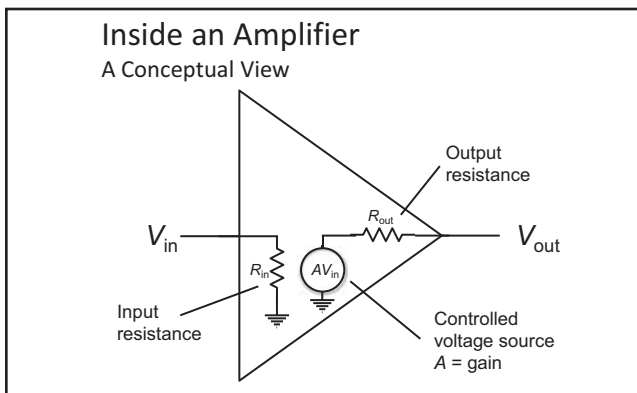
An Ideal Amplifier

Desired Amplifier Characteristics

- High gain: $V_{\text{out}} = \text{Gain} \times V_{\text{in}}$
 - Or gain easily controlled to desired level
 - Ideal: infinite
 - Tempered with negative feedback
- Low output resistance
 - Source or sink substantial current
 - Ideal: zero
- High input resistance
 - Draw minimum current from input source
 - Ideal: infinite



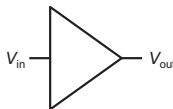
Among the qualities we'd like to have in an amplifier are high gain, low output resistance, and high input resistance. Ideally, we'd like to have infinite gain, zero output resistance, and infinite input resistance.



A conceptual view of an amplifier shows the following: The input comes in and controls the output, giving an output voltage that is the gain (A) multiplied by the input voltage. If there's current at the output, either coming from the amplifier or going into it, that current must go through the output resistance. A real amplifier approximates the goals of an ideal one to the extent that the input resistance is very high, the output resistance is very low, and the gain is very large—much larger than 1.

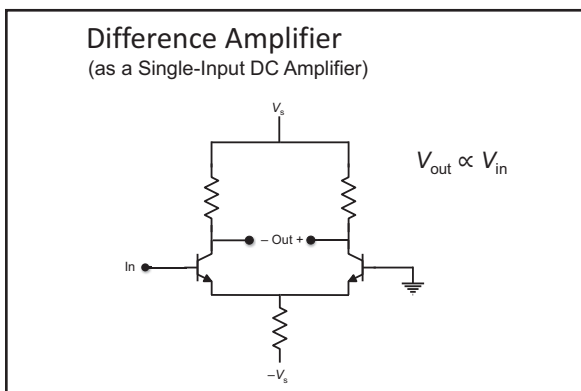
Desired Amplifier Characteristics

- High gain: $V_{\text{out}} = \text{Gain} \times V_{\text{in}}$
- Low output resistance
- High input resistance
- Wide frequency response
 - Depends on application
 - Audio: 20 Hz–20 kHz
 - Instrumentation: DC to high frequencies



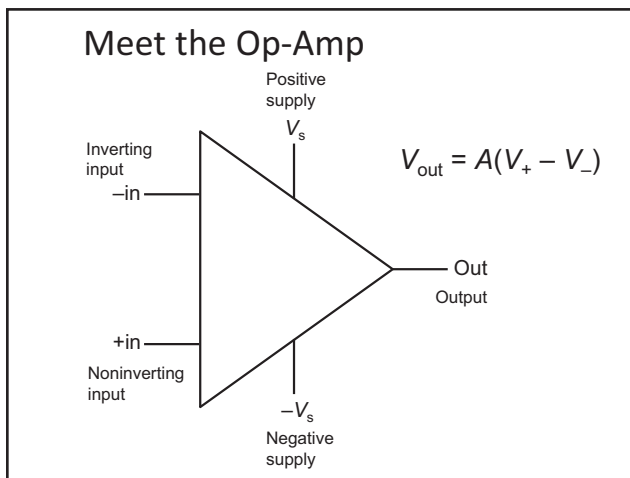
In addition to high gain, low output resistance, and high input resistance, we usually want an amplifier to have a wide and flat frequency response, meaning it amplifies a broad range of frequencies with the same gain across the whole range. That is, for the range of frequencies we're interested in amplifying, we would like the amplifier not to amplify one frequency more than another.

DC Amplification: The Differential Amplifier



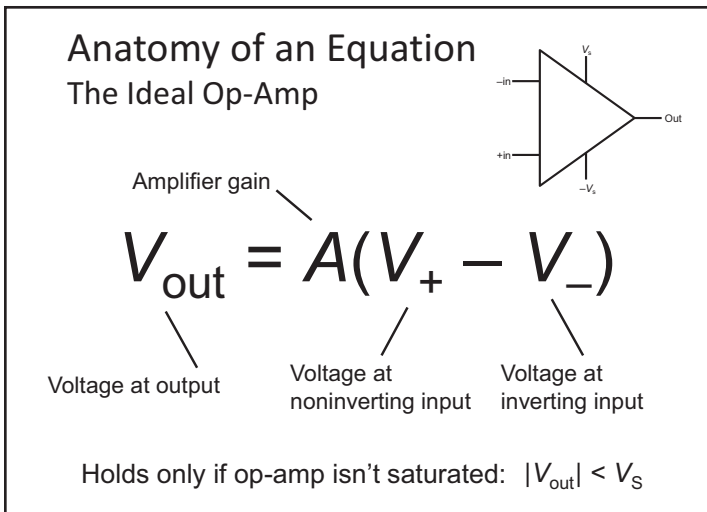
Our two-stage common-emitter preamplifier won't work for DC. Capacitors are open circuits to DC; they respond only to variations in voltage. To address this problem, we need a *difference amplifier*, which has two inputs. In the implementation of a difference amplifier shown here, we have two NPN transistors with separate load resistors and a common emitter resistor. The difference amplifier gives us an output proportional to the difference between its two inputs.

An Integrated-Circuit Operational Amplifier



The *operational amplifier* (*op-amp*) is a difference amplifier, usually built on a single, compact integrated circuit, that approaches the ideal amplifier. It has two inputs, both with high input resistance, a single low-resistance output, high gain, and a broad frequency response that includes DC (zero frequency). Originally, op-amps were designed to do mathematical operations and build analog computers; they're still used for many applications in analog electronics.

An op-amp has two power supply connections, one to a positive power supply, typically +15 V, and one to a negative power supply, typically -15 V. It has a noninverting input, also called the *plus input*; an inverting input, also called the *minus input*; and one output.

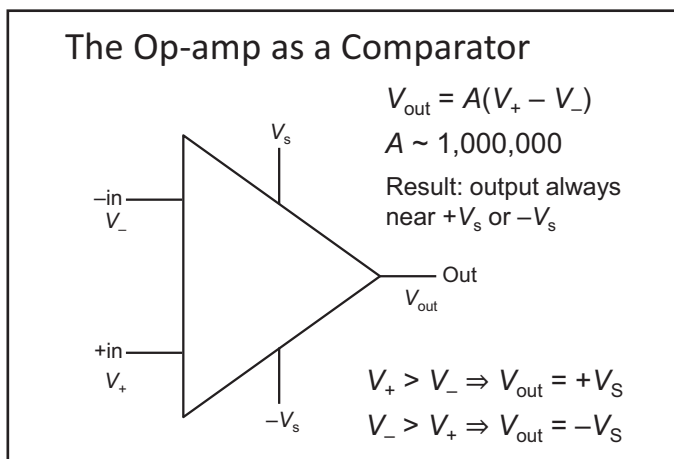


As we can see from the expression for the output of an op-amp, it's a difference amplifier: $V_{\text{out}} = A(V_+ - V_-)$. It amplifies the difference between V_+ and V_- by the factor A , which is the amplifier's gain. The ideal op-amp has a very large A .

Op-Amp	Gain	R_{in}	I_{in}	Bandwidth	Cost	Comments
TL081	200,000	$10^{12} \Omega$	40 mA	3 MHz	\$0.22	CircuitLab default
DC	1,000,000					DoCircuits generic
411	200,000	$10^{12} \Omega$	20 mA	4 MHz	\$0.70	Horowitz & Hill default
741	200,000	2 M Ω	25 mA	1 MHz	\$0.22	Workhorse, but becoming obsolete
L165	10,000	0.5 M Ω	2 A		\$1.00	Power op-amp
Notes: All values are "typical" and may vary. Quantity pricing is shown; individual pricing may be several times higher.						

The table shows specifications for five op-amps.

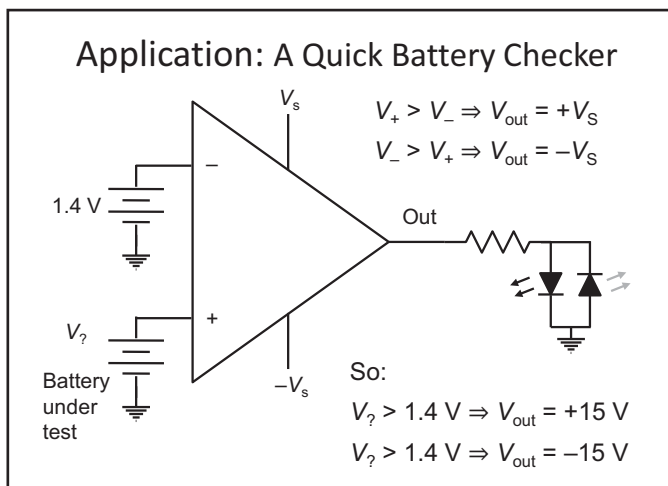
The Op-Amp as a Comparator



An op-amp in the comparator configuration simply compares V_+ and V_- to find which one is larger. Its output goes to (or near) either the positive

or negative supply voltage. It only gives information about which input is larger but doesn't tell any more about the specific input voltages or their difference—only whether that difference is positive or negative.

Application: Battery Tester



One application of a comparator is the simple battery checker shown here, which compares the voltage of the battery test against a standard voltage, here chosen as 1.4 V.

Suggested Reading

Introductory

Brindley, *Starting Electronics*, 4th ed., chapter 9 through p. 146.

Lowe, *Electronics All-in-One for Dummies*, book III, chapter 1; chapter 3 through p. 382; pp. 387–390.

Shamieh and McComb, *Electronics for Dummies*, 2nd ed., chapter 7, pp. 157–158.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 4, section 4.1, stressing the introduction to op-amps.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 8, section 8.3.

Projects

Differential Amplifier Simulation

Simulate the two-transistor differential amplifier shown in this lecture. Use $\pm 15\text{-V}$ supplies and $56\text{ k}\Omega$ for all three resistors. Put a voltmeter between the two output terminals and check to have it display its voltage. Find the differential voltage gain:

- Attach voltage sources to both inputs (transistor bases)
- Set both initially to 0
- Run DC simulation and record output voltage shown on meter
- Raise one input by 5 mV, drop the other by 5 mV, and record output
- Continue until you have about six measurements
- Make a graph of output versus differential input and use it to find the gain.

Low-Battery Warning Circuit

A plug-in smoke detector has a 4.5-V backup battery (three 1.5-V AA batteries in series). It has built-in $\pm 15\text{-V}$ DC power supplies that normally operate its circuitry unless there's a power failure and the battery has to take over. No other power supplies are available.

- Design a low-battery warning circuit that will light an LED if the battery voltage drops below 4 V. The LED should draw 15 mA of current when it's lit. No need to build this one; just sketch a circuit.
- Hint: Consider using an op-amp and either a voltage divider or a zener diode.

Questions to Consider

1. Why can't the audio amplifier circuits of Lecture 9 be used to amplify DC or slowly varying signals?
2. The ideal amplifier should have a *high* input resistance but a *low* output resistance. Why the difference?
3. With any reasonable voltage (more than a few microvolts) across the inputs of an op-amp, the output is sure to be at one of its two limiting values. Why?

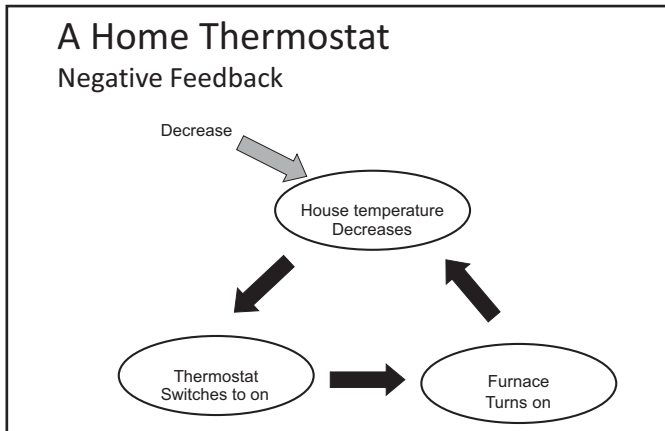
Feedback Magic

Lecture 11

The term *feedback* refers to a change in a system that follows as a result of some earlier change. There are two kinds of feedback: negative, in which the additional change has the effect of diminishing the original change, and positive, in which the additional change enhances the original change. Negative feedback is stabilizing; if something goes one way, the feedback brings it back the other way. Positive feedback is destabilizing; it can lead to runaway effects. In this lecture, we'll look at some intriguing demonstrations involving negative feedback. Key ideas include the following:

- The feedback concept
- Electromechanical feedback: a servomechanism
- Optical feedback: the intelligent light bulb
- Thermal feedback: a constant-temperature system.

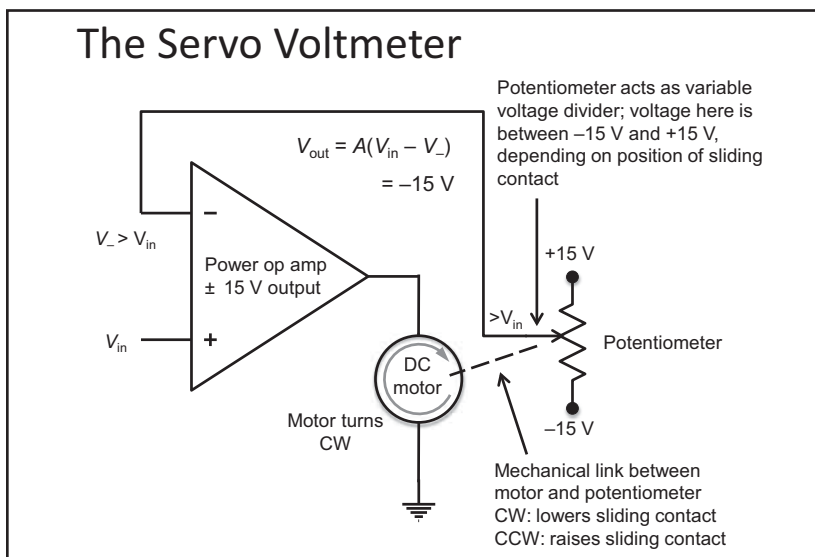
The Feedback Concept



Your home thermostat is a negative feedback system based on a temperature-sensitive switch. If your house temperature decreases below the level you've

set, the switch turns on. That turns on the furnace, which produces heat, and the house temperature increases. If it gets too hot, the switch turns off, turning off the furnace and dropping the house temperature.

Electromechanical Feedback: A Servomechanism

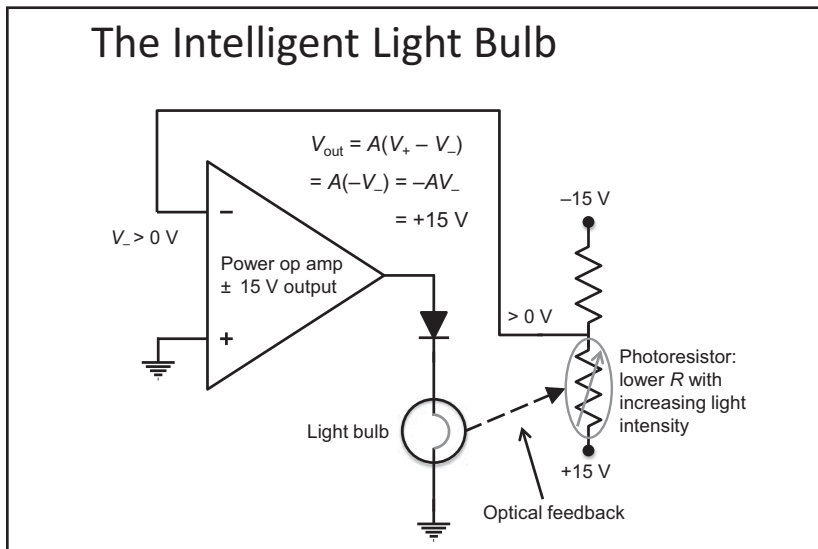


The demonstration servo voltmeter consists of a single op-amp with its inverting input connected to a potentiometer—a variable voltage divider. At the output, there's a DC electric motor that runs on $\pm 15\text{ V}$, turning one way if the voltage is positive and the other way if it's negative. The feedback loop consists of a mechanical connection between the shaft of the potentiometer and the motor shaft.

A variable input voltage is supplied to the noninverting input of the op-amp. If this input voltage is greater than the voltage at the inverting input, the motor turns in such a way that it moves the movable tap on the potentiometer toward higher voltages, thus increasing the voltage at the inverting input. If the voltage at the inverting input exceeds the voltage at the noninverting input, then the motor goes the other way, lowering the voltage at the noninverting input. Thus, the position of the potentiometer's movable contact corresponds

to the voltage at the noninverting input. An indicating needle is connected to the motor-potentiometer shaft, indicating the input voltage. The mechanical feedback causes the voltage at the inverting input to “follow” the voltage applied at the noninverting input. The system is called a *servomechanism* because the position of the indicating needle slavishly follows the position of your hand as you turn the knob on the input voltage. Similar systems are used for accurate control of heavy machinery or in prosthetic limbs.

Optical Feedback: The Intelligent Light Bulb

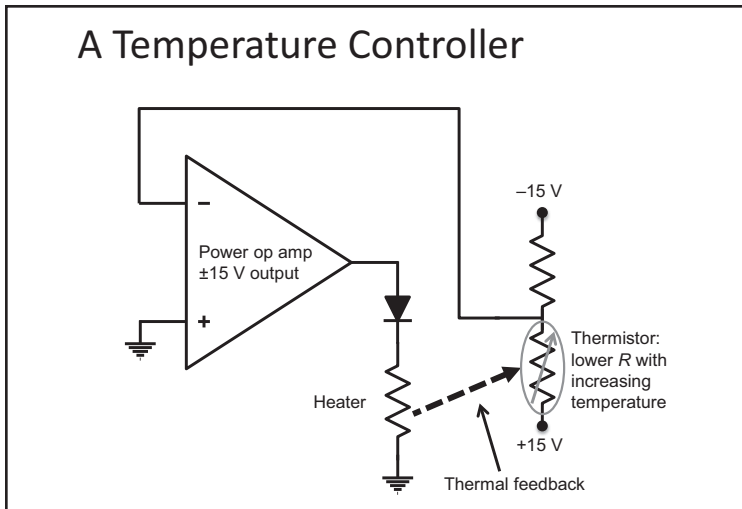


We can morph the servo voltmeter into another circuit with the same power op-amp, but instead of the potentiometer, this circuit has a resistor and a photoresistor in series across the $\pm 15\text{-V}$ power supplies. The photoresistor’s resistance depends on the intensity of light falling on it, decreasing with increasing intensity. Optical feedback occurs because the light bulb at the op-amp output shines on the photoresistor. The system is analogous to the mechanical-feedback servo voltmeter, except here, the feedback acts to keep the light intensity at the photoresistor constant—even if it’s moved closer to or further from the light bulb. This circuit might be used as a

sensor in an energy-efficient office building to sense and adjust levels of ambient lighting.

Another optical feedback system is “funny face,” a circuit with two photoresistors in a “face” mounted on the shaft of a motor connected to the output of an op-amp. Feedback causes the face to turn so that it follows a bright light.

Thermal Feedback: A Constant-Temperature System



If we replace the photoresistor with a *thermistor*—a thermal resistor whose resistance drops with increasing temperature—then we create a temperature-control feedback system.

Suggested Reading

Introductory

None of the introductory books covers feedback at the level of this lecture.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 4, section 4.1, stressing feedback.

Project

Reverse Engineering

Design a plausible circuit for “funny face.” Hint: You need only the following components:

- Power op-amp
- Two photoresistors
- DC motor, reversible with polarity change
- Power supply for op-amp (assumed).

Questions to Consider

1. Give several examples of negative feedback, not necessarily electronic.
- *2. Identify the nature of the feedback loop in the following devices that were discussed in this lecture: servo voltmeter, intelligent light bulb, and temperature controller. Is the feedback electronic, thermal, optical, or mechanical?

Electronic Feedback

Lecture 12

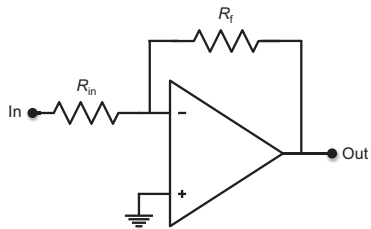
The preceding lecture showed a number of demonstrations involving negative feedback: mechanical, optical, and thermal. In all those cases, the circuits had op-amps whose outputs swung between two limits, +15 V and -15 V. But they did so in a way—because of negative feedback—that kept the voltage at the negative input close to the value it had at the positive input. In this lecture, we'll look at circuits in which the feedback mechanism is electronic. That gives rise to a remarkable versatility in op-amp circuits, including circuits that “tame” the op-amp's huge intrinsic gain. Important topics in this lecture include the following:

- Op-amp circuits with negative feedback
- The inverting amplifier: a detailed analysis
- Op-amp rules: simplifying op-amp circuit analysis.

Op-Amp Circuits with Negative Feedback

An inverting amplifier is a simple op-amp circuit that uses negative feedback. The noninverting (+) input of this op-amp is at ground, 0 V. We have an input resistor, R_{in} , and we'll connect the voltage we want to amplify to the point marked “In.” We'll connect a feedback loop from the output of this amplifier back to the inverting (-) input. For this configuration, we want to know the gain: What's the ratio of V_{out} to V_{in} ?

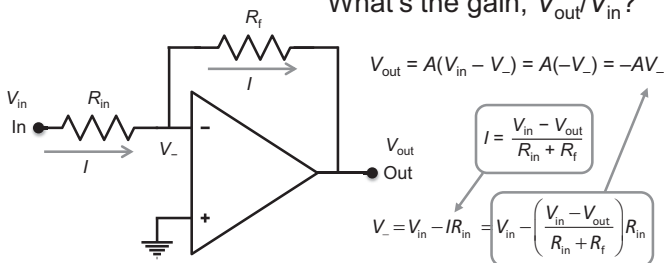
An Inverting Amplifier



The Inverting Amplifier: A Detailed Analysis

An Inverting Amplifier

What's the gain, V_{out}/V_{in} ?



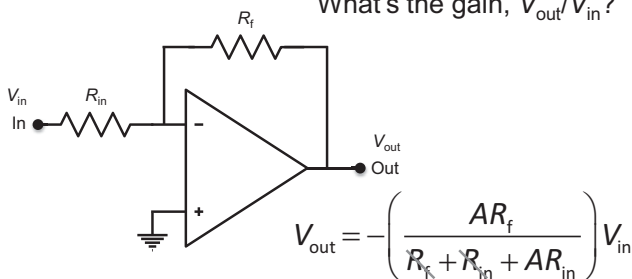
$$V_{out} = -AV_- = -A \left(V_{in} - \left(\frac{V_{in} - V_{out}}{R_{in} + R_f} \right) R_{in} \right)$$

Algebra \rightarrow

$$V_{out} = - \left(\frac{AR_f}{R_f + R_{in} + AR_{in}} \right) V_{in}$$

An Inverting Amplifier

What's the gain, V_{out}/V_{in} ?



Ideal op amp: $A \gg 1$

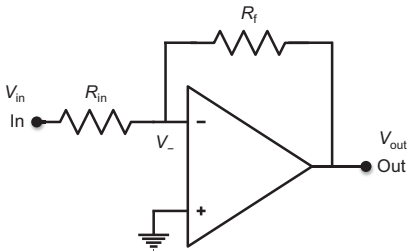
$$V_{out} = - \left(\frac{AR_f}{AR_{in}} \right) V_{in}$$

$$V_{out} = - \frac{R_f}{R_{in}} V_{in}$$

To answer this question, we must walk through some heavy mathematics, but doing so will allow us to analyze other op-amp circuits almost trivially. Because of the fact that the amplifier's gain is huge ($A \gg 1$), we get the

remarkably simple result $V_{\text{out}} = -R_f/R_{\text{in}}$. Negative feedback has “tamed” the huge gain and allowed us to make an amplifier with any gain we want! And the value of A doesn’t matter at all—as long as it’s big.

An Inverting Amplifier



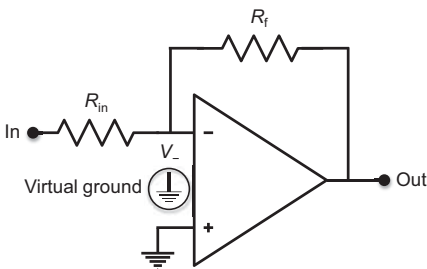
$$V_{\text{out}} = -\frac{R_f}{R_{\text{in}}} V_{\text{in}}$$

What's V_- ?

$$V_{\text{out}} = A (V_+ - V_-) = -A V_-$$

$$V_- = -\frac{V_{\text{out}}}{A} \approx 0$$

An Inverting Amplifier



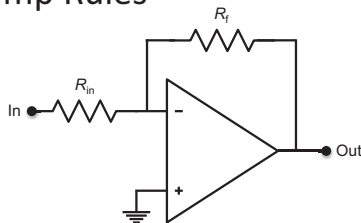
$$V_{\text{out}} = -\frac{R_f}{R_{\text{in}}} V_{\text{in}}$$

$$V_- \approx 0$$

To find the voltage at the inverting input to the op-amp itself, we again go through some math; the result is $V_- \approx 0$. Because of that, we say that V_- is at *virtual ground*. It’s as if that point were connected to ground, or 0 V—but it isn’t really. Rather, the negative feedback works actively to keep V_- at very nearly 0 V.

Op-Amp Rules: Simplifying Op-Amp Circuit Analysis

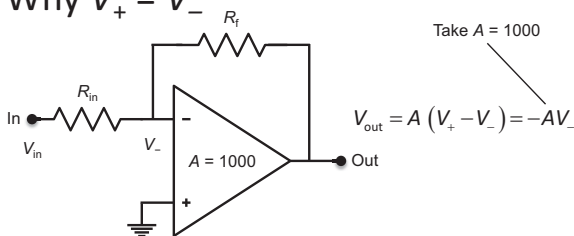
Op-amp Rules



1. No current flows into op-amp inputs
 - Huge input resistance
 - Enhanced by negative feedback
2. With negative feedback, $V_+ = V_-$
 - $V_- > V_+$ makes V_{out} negative; feedback pushes V_- down
 - $V_- < V_+$ makes V_{out} positive; feedback pushes V_- up

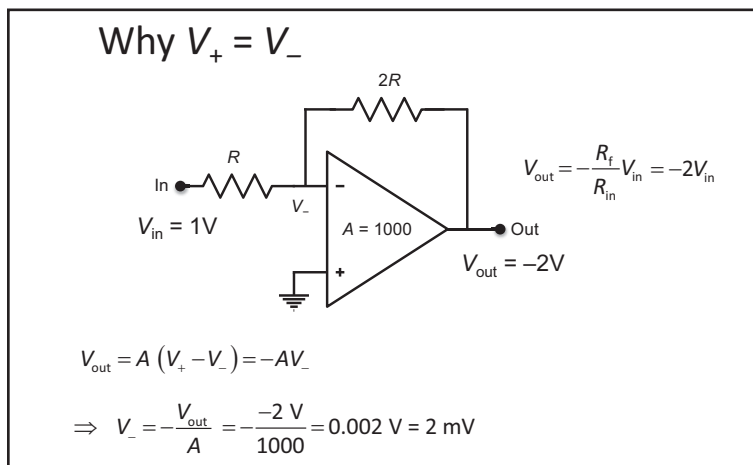
We can identify two simple rules for analyzing op-amps: (1) No current flows into the op-amp inputs, and (2) whenever negative feedback is in control, V_+ and V_- are almost identical. (For the inverting amplifier, V_+ was 0, so V_- became very nearly 0, as well.)

Why $V_+ = V_-$



- Suppose $V_- = 1 \text{ V}$
- Then V_{out} "wants" to be -1000 V
- V_{out} heads toward negative supply voltage of -15 V
- Because of feedback resistor, V_- also heads downward
- As soon as V_- goes negative, V_{out} heads toward $+15 \text{ V}$
- That drives V_- positive, and the cycle repeats
- Feedback is \sim instantaneous, so V_- assumes a small average value

If V_- were greater than V_+ , we get a large negative output, which, through the feedback resistor, would be felt at the inverting input. That decreases the inverting-input voltage until it's no longer greater than V_+ . If V_- becomes less than V_+ , the output goes positive, and that results in increasing V_- . This all happens almost instantaneously, with the result that V_+ and V_- remain essentially equal.



Again, a mathematical analysis gives us confirmation of op-amp rule 2: that V_+ and V_- are very nearly equal. The difference voltage $V_+ - V_-$ is, therefore, very small, and for that reason, we get an output voltage that is not at one of the limits but somewhere between those limits.

Suggested Reading

Introductory

Brindley, *Starting Electronics*, 4th ed., chapter 9, pp. 150–152.

Lowe, *Electronics All-in-One for Dummies*, book III, chapter 3, pp. 382–385.

Advanced

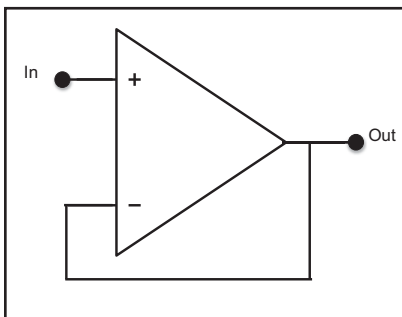
Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 4, sections 4.1.3 and 4.2.1.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 8, section 8.4 through p. 642.

Projects

Delving into Math

The op-amp in the circuit shown has gain A . Note that the op-amp has been flipped, so the positive input is at the top. Analyze the circuit to find the exact relation between V_{out} and V_{in} . Show that when A is very large ($A \gg 1$), you get a simpler relation that doesn't depend on A . With $A = 1000$ and $V_{\text{in}} = 1$ V, find the “error signal,” $V_+ - V_-$.

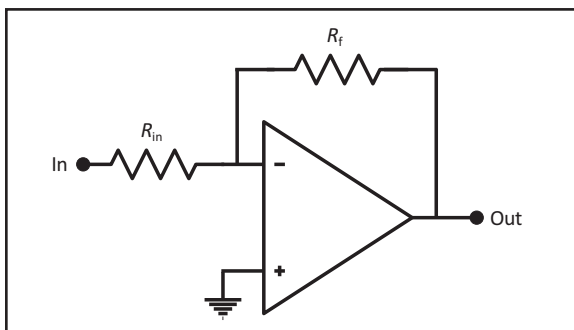


Gain-of-3 Inverting Amplifier

Design a gain-of-3 inverting amplifier, simulate it, and verify its gain both for DC and AC. How big is the “error signal”? Check the (time-dependent) voltage at the op-amp's inverting input.

Questions to Consider

1. Why is the circuit shown below called an *inverting* amplifier?



2. In the circuit above, identify the point called *virtual ground* and explain this term.
3. State the two op-amp rules.

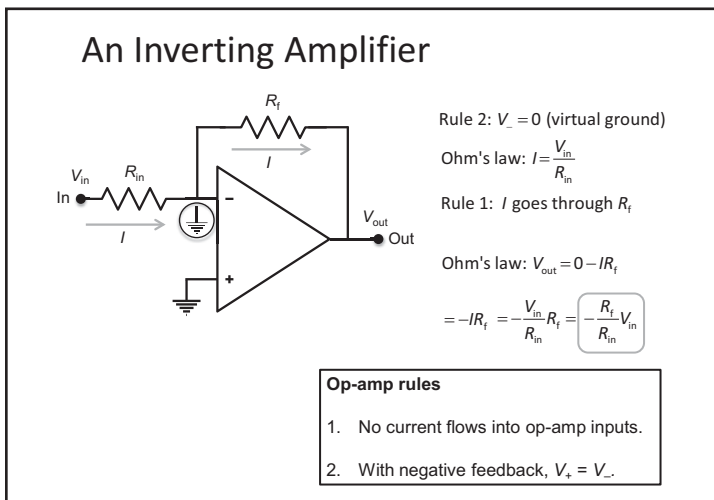
Amplifier Circuits Using Op-Amps

Lecture 13

All the math we did in the preceding lecture enables us to analyze a number of interesting op-amp circuits because we now understand the two simple rules that govern the behavior of op-amps: (1) There is no current flowing into the op-amp inputs, and (2) with negative feedback, the two inputs—inverting and noninverting—must be at the same voltage. With this lecture, then, we'll begin looking at increasingly complex circuits involving op-amps and circuits that perform other functions than simply amplify. Important topics include the following:

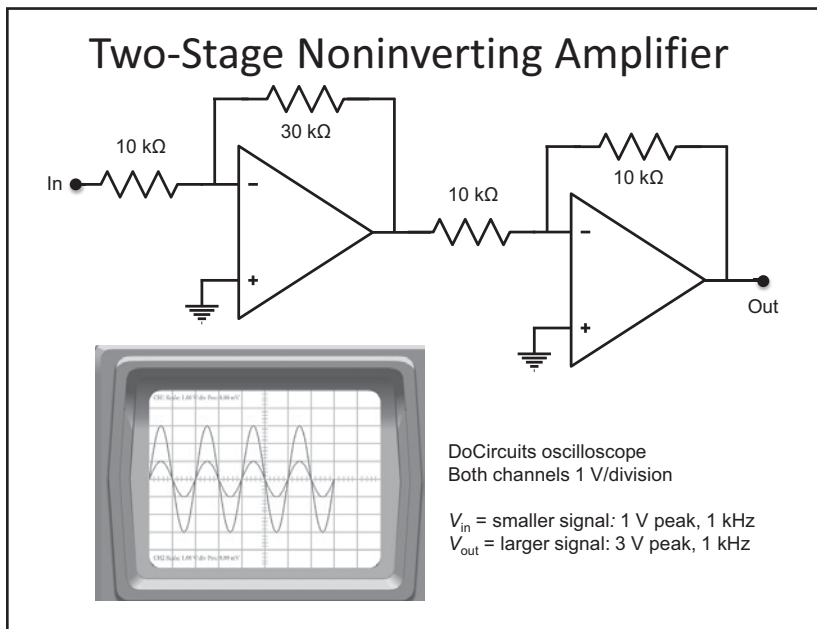
- The inverting amplifier via op-amp rules
- Summing amplifiers
- Current-to-voltage converters
- Application: a light meter.

The Inverting Amplifier via Op-Amp Rules



We begin by analyzing the same inverting amplifier we looked at in the preceding lecture, now using the simple op-amp rules. Recall that those rules

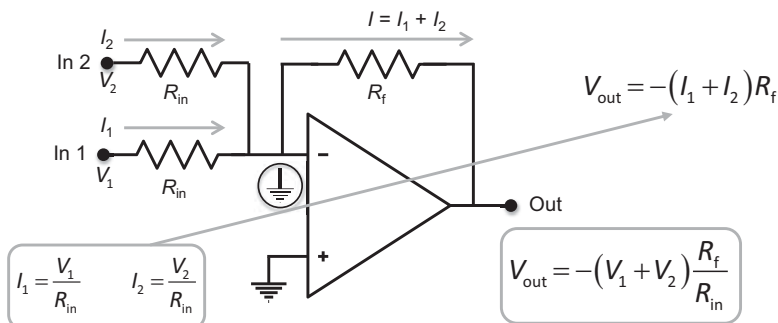
came from the complicated math we did in the previous lecture, followed by the assumption that the intrinsic gain (A) of the op-amp was much greater than 1. That gave us the second rule: $V_+ = V_-$. Note that it now takes only a few steps of simple math to get to the result that the gain is $-R_f/R_{in}$.



If we don't want our amplifier to invert, we can add a second inverting amplifier. Here, we see one op-amp stage with a 10-k Ω input resistor and a 30-k Ω feedback resistor; it has a gain of -3 . The output of this stage goes into a 10-k Ω input resistor of another op-amp in the same inverting configuration but with a feedback resistor equal to its input resistor; it has a gain of -1 . (This second stage is called a *unity-gain inverter*.) Thus, the second amplifier simply inverts the output of the first amplifier. We had -3 for the gain of the first amplifier and -1 for the gain of the second amplifier; the whole two-stage amplifier has a gain of $+3$.

Summing Amplifiers

Summing Amplifier



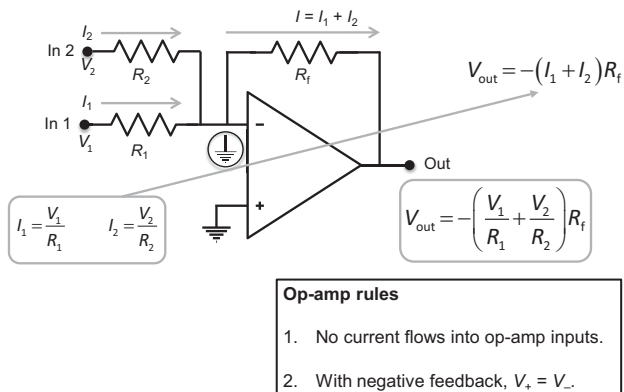
Op-amp rules

1. No current flows into op-amp inputs.
2. With negative feedback, $V_+ = V_-$.

A summing amplifier begins as the same inverting amplifier we've just seen. It has an input voltage, V_1 , and an input current, I_1 , flowing through the lower resistor marked R_{in} to virtual ground at the op-amp's inverting input. We then connect a second, identical input resistor with a second input voltage, V_2 , driving current I_2 to the same virtual ground. The currents that come in through those two resistors act as if they're going to ground, so each is completely independent of the current flowing in other input resistors.

According to op-amp rule 1, no current can flow into the op-amp. Thus, the currents I_1 and I_2 actually flow through the feedback resistor, and that feedback-resistor current is the sum of the two input currents. Applying Ohm's law then shows that the output is basically the sum of the input voltages negated, inverted, and multiplied by R_f/R_{in} .

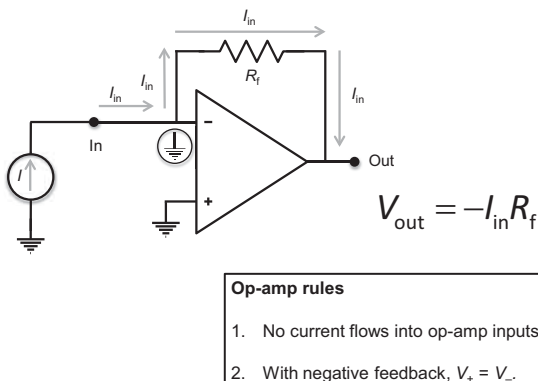
Weighting the Sum



We could also configure a summing amplifier so that one input counts more than the other, giving an amplifier that produces a weighted sum.

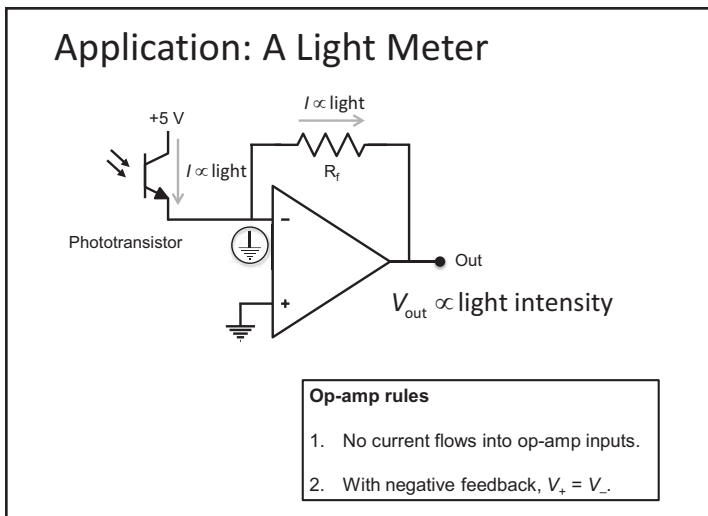
Current-to-Voltage Converters

Current to Voltage



A current-to-voltage converter is like an inverting amplifier, except that it doesn't have an input resistor because it gets a current directly at its input.

Application: A Light Meter



A light meter is built in the same configuration as the current-to-voltage converter, except that the current source is a light-sensitive *phototransistor*, which produces a current proportional to the light intensity. Thus, at the output, we get a voltage proportional to the light intensity. Light meters are used in cameras and many other applications.

Suggested Reading

Introductory

Brindley, *Starting Electronics*, 4th ed., chapter 9, pp. 147 to end.

Lowe, *Electronics All-in-One for Dummies*, book III, chapter 3, pp. 385 to end.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 4, sections 4.2.2, 4.2.3, 4.3.1.3, 4.3.1.4.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 8, section 8.4, pp. 641–642 (top).

Project

Temperature Sensor

A temperature sensor produces an output voltage whose value in mV is equal to the temperature in degrees Celsius. Design an op-amp circuit with this sensor at the input that produces an output whose value in mV is 100 times the temperature in degrees Fahrenheit (i.e., when it's 70°, the circuit's output should be 7000 mV, or 7.0 V). Your op-amp(s) use $\pm 15\text{-V}$ power supplies, and these are the only power sources available to you. As an option, simulate the circuit and verify its operation; try the DC sweep simulation.

Questions to Consider

1. In the current-to-voltage converter, a source of current is connected directly to the inverting input of the op-amp. Where does the current actually go?
2. Why is it important that the resistors in a summing amplifier be precisely matched?
3. What's a phototransistor, and why doesn't it have a connection to its base?

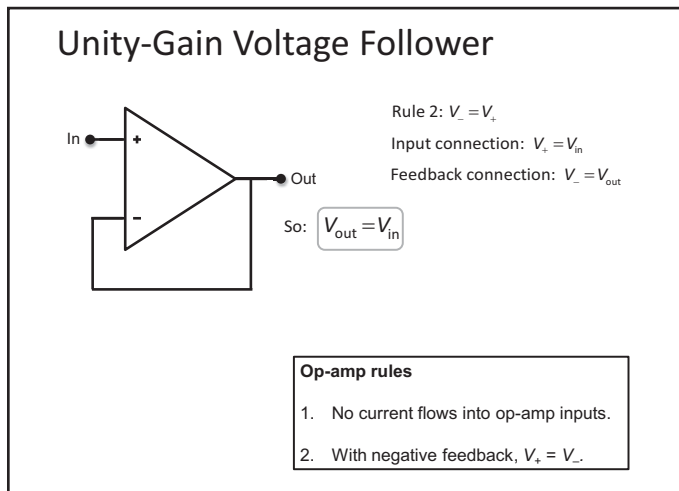
More Fun with Op-Amps

Lecture 14

So far, we've used op-amps to build inverting amplifiers, configurations in which the input of the circuit is brought in, ultimately, to the inverting input to the amplifier. Although these amplifiers are versatile, there are a few disadvantages. For example, their input resistance is determined by the input resistor and tends to be fairly low; thus, they draw significant current from their input source. That can be a problem with weak input sources. Further, another inversion is required if we don't want an inverting amplifier. In this lecture, we'll look at a wide range of circuits using op-amps, beginning with noninverting configurations. Important topics we'll cover include the following:

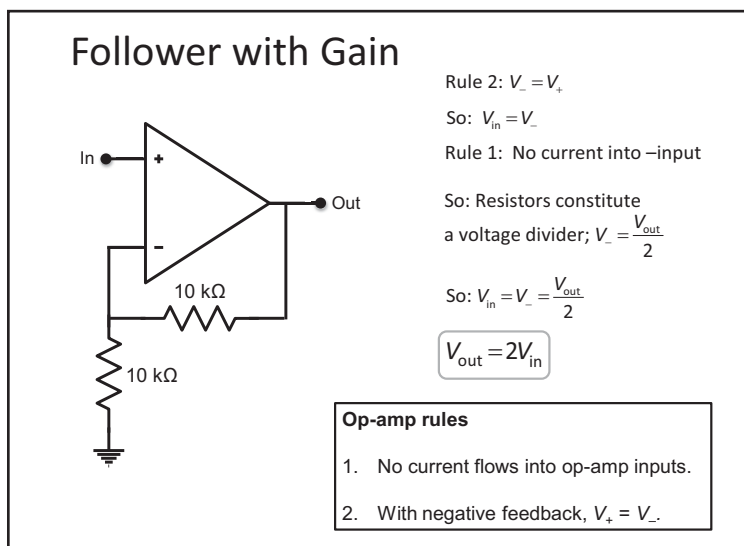
- The unity-gain voltage follower
- Followers with gain
- Difference amplifiers
- Peak detectors
- Schmitt triggers
- Application: Freezer alarm.

The Unity-Gain Voltage Follower



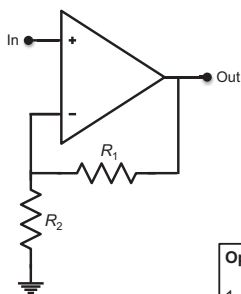
The unity-gain voltage follower consists of just one op-amp. A quick analysis of this circuit shows that $V_{\text{out}} = V_{\text{in}}$; the output is equal to the input. This device might be useful in situations in which we have a very weak signal source, but that source can't, for example, power a loudspeaker or drive a large meter. Because the input goes directly to the op-amp's input, op-amp rule 1 shows that this circuit draws essentially zero current from its input source. A unity-gain voltage follower doesn't change the voltage, but it does allow us to deliver more current to the output. We should note that this circuit is subject to *common mode response* issues because neither input is at ground.

Followers with Gain



This circuit is called a *follower with gain*. It's similar to the unity-gain follower, except it multiplies the voltage. Notice that it takes two equal resistors to make a follower with gain of 2. In the inverting configuration, two equal resistors would give us unity gain.

Noninverting Amplifier (Follower with Gain)



Rule 1:

Voltage Divider; $V_- = \left(\frac{R_2}{R_1 + R_2} \right) V_{out}$

Rule 2: $V_- = V_+$ ($= V_{in}$)

$$V_{out} = \underbrace{\left(\frac{R_1 + R_2}{R_2} \right)}_{\text{Gain}} V_{in}$$

Op-amp rules

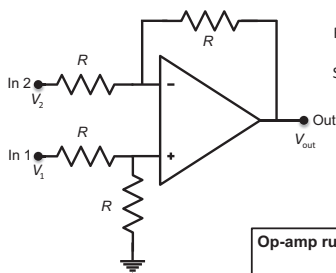
1. No current flows into op-amp inputs.
2. With negative feedback, $V_+ = V_-$.

We can analyze this circuit with arbitrary resistances R_1 and R_2 . Using the voltage divider equation, we find that the output and input voltages are related by the ratio of the sum of the resistors divided by the first resistor. That gives us a gain, which we can set to anything we want simply by choosing appropriate resistors.

Difference Amplifiers

Difference Amplifier

Find V_{out} versus V_1 and V_2



Rule 1: Both resistor pairs are voltage dividers

$$\text{So: } V_+ = \frac{V_1}{2} \quad \text{and: } V_- = \frac{V_2 + V_{out}}{2}$$

Rule 2: $V_+ = V_-$

$$\text{So: } \frac{V_1}{2} = \frac{V_2 + V_{out}}{2} \Rightarrow V_2 + V_{out} = V_1$$

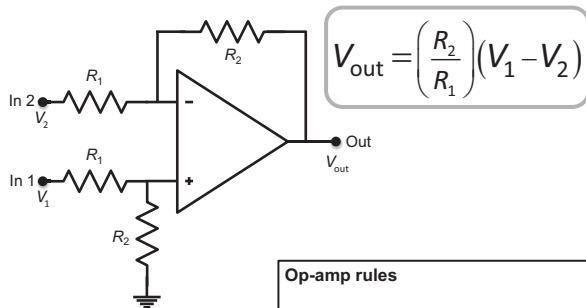
$$V_{out} = V_1 - V_2$$

Op-amp rules

1. No current flows into op-amp inputs.
2. With negative feedback, $V_+ = V_-$.

In a difference amplifier, the output voltage is the difference between the two input voltages.

Difference Amplifier with Gain

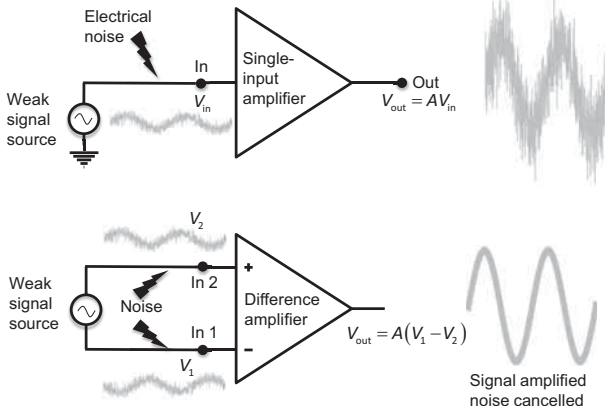


Op-amp rules

1. No current flows into op-amp inputs.
2. With negative feedback, $V_+ = V_-$.

We can expand on the basic circuit for a simple difference amplifier by making the two input resistors the same but the feedback resistor and the resistor to ground different; that provides gain given by R_2/R_1 .

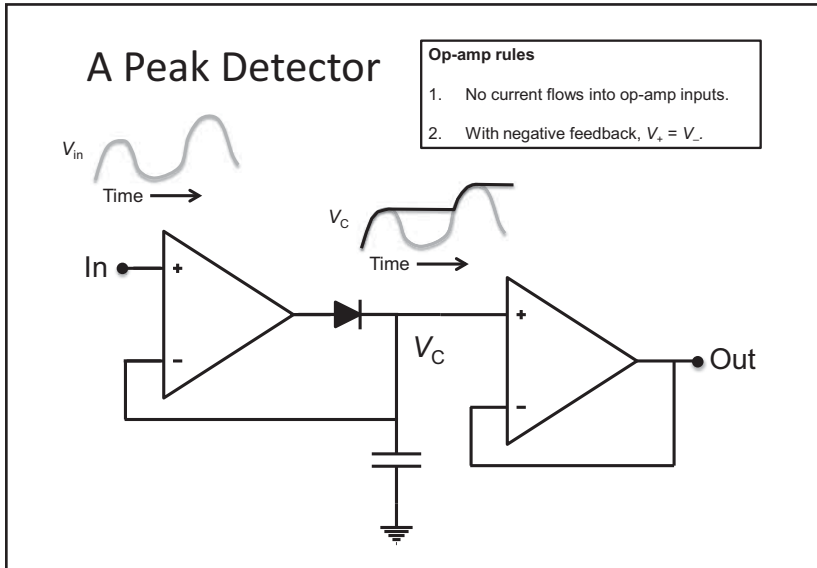
Application: Noise Reduction



One common application of difference amplifiers is in very sensitive circuitry where it's necessary to eliminate any electronic noise that might

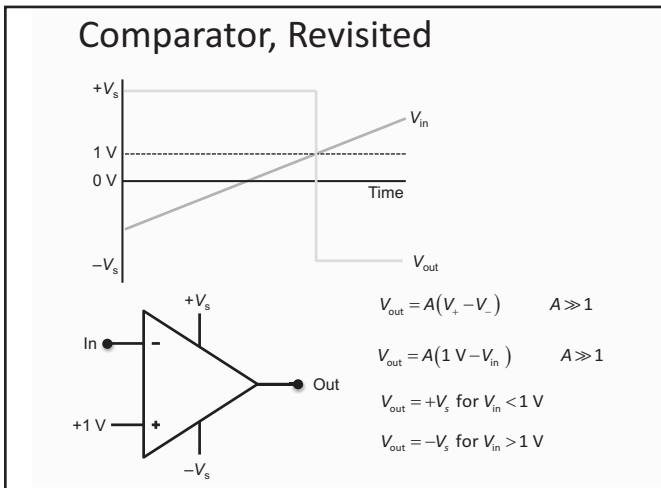
creep in to the input signals. If the noise is on both input lines, a difference amplifier will cancel it while amplifying the desired signal.

Peak Detectors

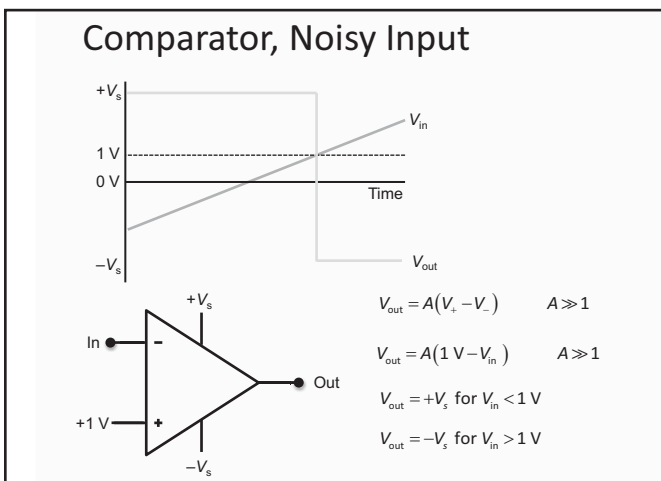


A peak detector is useful when we have a signal that's varying and we would like to know its maximum value. It's an op-amp connected basically in the unity-gain follower configuration, except it has a diode. That means that the amplifier feedback works only if the input voltage goes positive relative to the voltage at the negative input. Otherwise, the diode is reversed biased; we don't have feedback; and the output of the op-amp will go to its limit. A capacitor is added to serve as a memory device of sorts, and the second op-amp, in a voltage follower configuration, presents a very high input resistance that allows the capacitor to hold its charge for significant times.

Schmitt Triggers



Earlier, we saw an op-amp as a comparator; it looked at its two inputs and went to one limit or the other, depending on which input was greater.

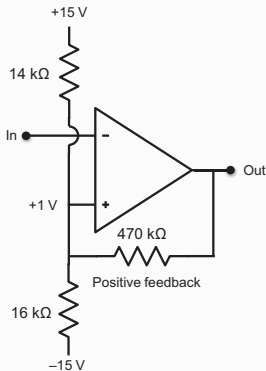


Imagine we have a voltage that is slowly rising with time, and we'd like to know when it reaches 1 V. Ideally, as soon as V_{in} reaches 1 V, the output

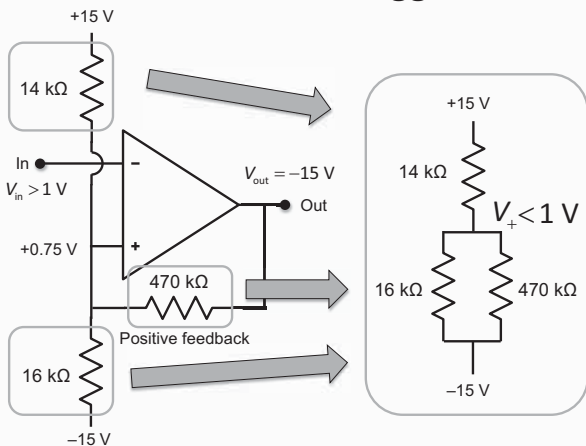
should switch abruptly down and become the negative limit. But if V_{in} has some noise on it, instead of giving us a clean break from one level to another, it wiggles back and forth.

We can deal with this problem by using a circuit called a *Schmitt trigger*, which incorporates some positive feedback.

Solution: The Schmitt Trigger

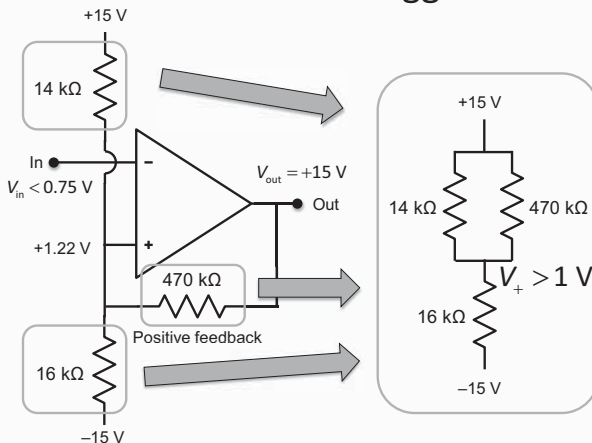


Solution: The Schmitt Trigger



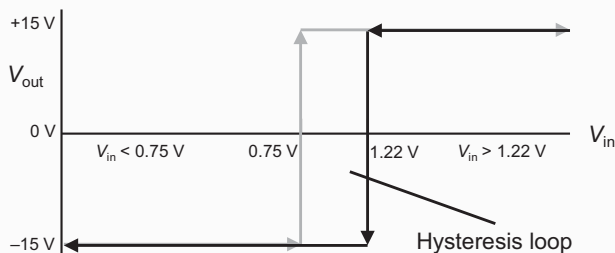
An extra resistor lowers the comparison voltage to about 0.75 V when the output is negative. That means that the voltage must fall below 0.75 V before another transition takes place. Once it falls below 0.75 V, the output swings to +15 V, which raises the comparison voltage at the + input to 1.22 V.

Solution: The Schmitt Trigger



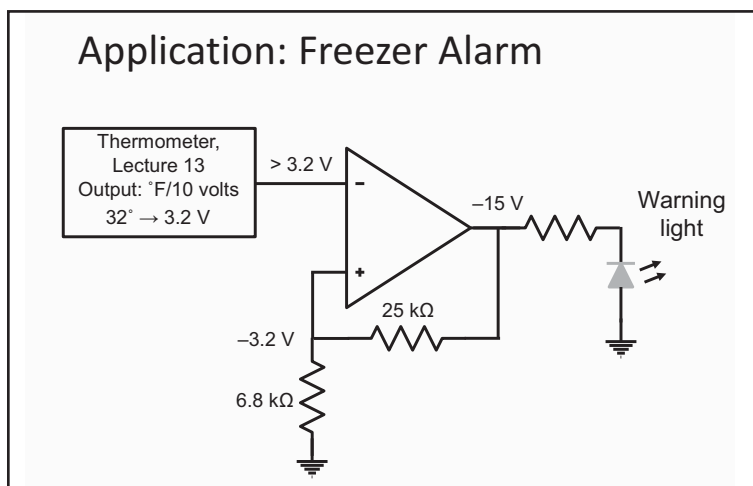
What we've done, effectively, is to change the levels that we're switching to two slightly different levels. That phenomenon is called *hysteresis*.

"Remembering"—Hysteresis



If we have a circuit that's supposed to switch back and forth between two levels, such as a thermostat in a home, hysteresis tells us not to always switch right at the same level; we wait until one level gets a little too high and the other gets a little too low. This allows us to avoid the problem of multiple switching.

Application: Freezer Alarm



One practical example of hysteresis is an alarm that would let you know if the temperature in your freezer goes above 32° if you're away from your house for an extended time. Here, the warning light comes on when the temperature goes above freezing, and the positive feedback provided by the 25-kΩ resistor prevents it from turning off again even when the freezer temperature returns to normal.

Suggested Reading

Introductory

None of the introductory books covers the material in this lecture.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 4, sections 4.2.4, 4.3.2.2, and 4.5.1.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 8, section 8.4, p. 642 (bottom).

Projects

Schmitt Trigger

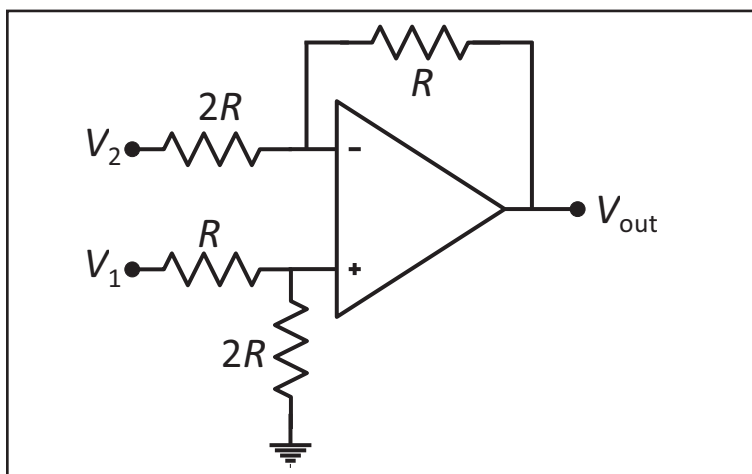
Verify the 0.75-V and 1.22-V thresholds in the Schmitt trigger circuit shown in this lecture.

Difference Amplifier

Design a difference amplifier with a gain of 10 and very high input resistances (such as $10^{12} \Omega$, typical of an op-amp). You'll need to combine several circuits from this lecture. Simulate it and verify that it works.

Questions to Consider

- *1. In the circuit below, what is V_{out} in terms of V_1 and V_2 ?



2. Explain how a difference amplifier can be used to reduce electrical noise.
3. What is meant by the term *hysteresis*?

Using Op-Amps with Capacitors

Lecture 15

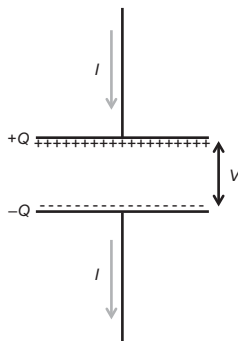
In this lecture, we'll look at capacitors used with op-amps. In the previous lecture, we used a capacitor to detect the peak of a voltage, but the capacitor wasn't really active with the op-amp. The op-amps were present to help the capacitor get and hold the charge. Now, we want to use capacitors actively with op-amps, which means putting them in the feedback loop of the op-amp. Among the key topics we'll cover in this lecture are the following:

- Capacitors: charge, voltage, current
- A capacitor as a feedback component
- An op-amp integrator
- Application: an integrating light meter
- A triangle/square wave-function generator.

Capacitors: Charge, Voltage, Current

Capacitor Review

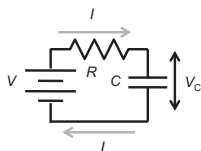
- Capacitor: a pair of conductors separated by an insulator
- Charge on capacitor plates is proportional to voltage between them: $Q = CV$
- Charge delivered by current I flowing in wires leading to capacitor
- Rate of charge buildup on capacitor proportional to I
- Voltage proportional to charge, so rate of voltage increase proportional to I



As you recall, a capacitor is a pair of conductors separated by an insulator. Remember that a capacitor is not like a resistor. It doesn't obey Ohm's law, because capacitor voltage and current aren't proportional. Rather, current is proportional to the *rate of change of voltage*.

Charging a Capacitor with a Battery

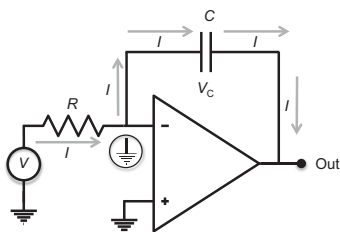
- Capacitor initially uncharged; $V_C = 0$
- Current flows, delivering charge to capacitor
 - Current depends on voltage across R
 - As V_C increases, voltage across R decreases
- So rate of charge buildup on capacitor decreases
- So rate of increase of capacitor voltage decreases
- Eventually $V_C \rightarrow V$
 - Timing depends on "time constant" RC



A simple way to put charge onto a capacitor is with a battery. We then get a voltage that rises rapidly at first, but as the capacitor charges and the voltage across the resistor decreases, the rate of voltage rise decreases. There are many situations in which we would like to have a steady voltage rise, as in a cathode ray tube oscilloscope.

A Capacitor as a Feedback Component

Charging a Capacitor with an Op-Amp



Op-amp rules

1. No current flows into op-amp inputs.
2. With negative feedback, $V_+ = V_-$.

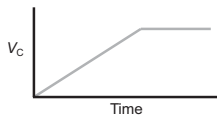
Rule 2: $V_- = 0$ (virtual ground)

Ohm's law: $I = V/R$

Rule 1: Current carries charge to/from capacitor plates

Current is constant, so capacitor charge and voltage increase at a steady rate...
...until the op-amp reaches its voltage limit

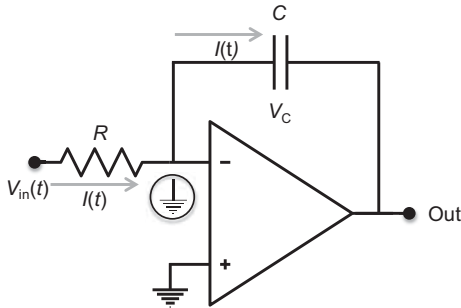
Inverting configuration: $V_{out} = -V_C$



A simple inverting configuration shows what happens when we put a capacitor in the feedback loop of an op-amp and supply a constant input voltage. The circuit gives an output voltage that increases steadily with time.

An Op-Amp Integrator

Time-Dependent Input Voltage



Op-amp rules

1. No current flows into op-amp inputs.
2. With negative feedback, $V_+ = V_-$.

Rule 2: $V_- = 0$ (virtual ground)

Ohm's law: $I(t) = V_{in}(t)/R$

Rule 1: Current carries charge to/from capacitor plates

Capacitor accumulates the total charge Q that flows through R

Capacitor: $V_C = Q/C$

$\Rightarrow V_{out} = -V_C = -Q/C$

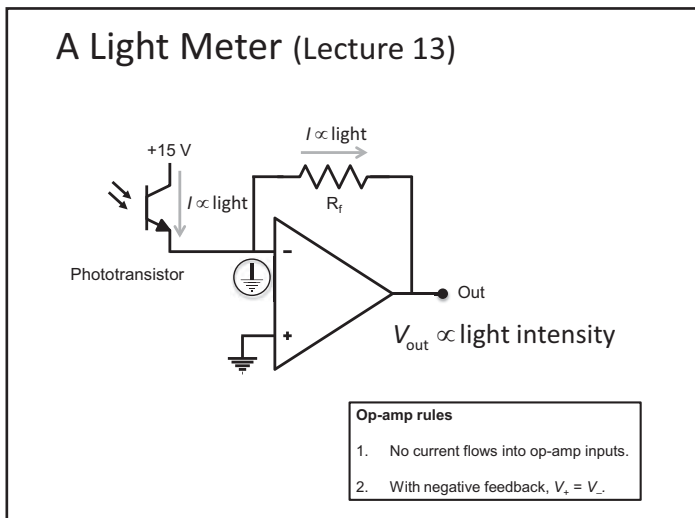
Circuit is an *integrator*;
it sums the total input current over time

Had calculus?

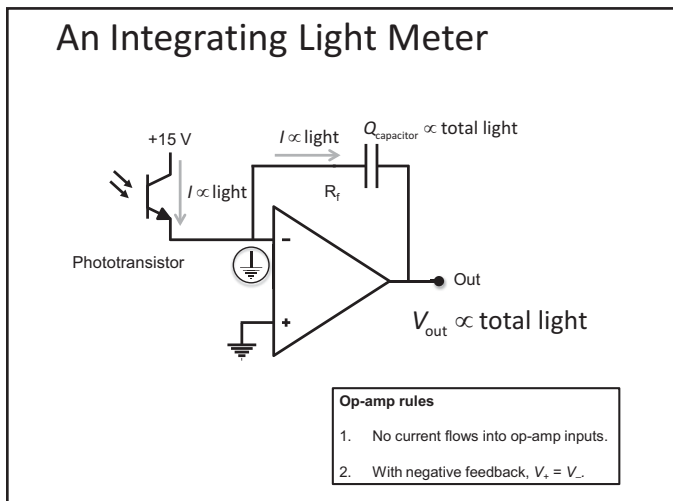
$$V_{out} = -\frac{1}{RC} \int V_{in} dt$$

Instead of a constant voltage at the input, which results in a linear rise or fall (depending on the sign of the input voltage at the output), we can use time-dependent input voltage. Here, as long as current flows in the direction shown, the capacitor charge keeps building up; the capacitor accumulates the algebraic sum of all the current. Consequently, we get a situation in which the output voltage of the circuit is proportional to the total charge that has accumulated on the capacitor. This circuit is an *integrator*; it integrates, or adds up, the algebraic sum of the charges delivered by all the currents over time.

Application: An Integrating Light Meter

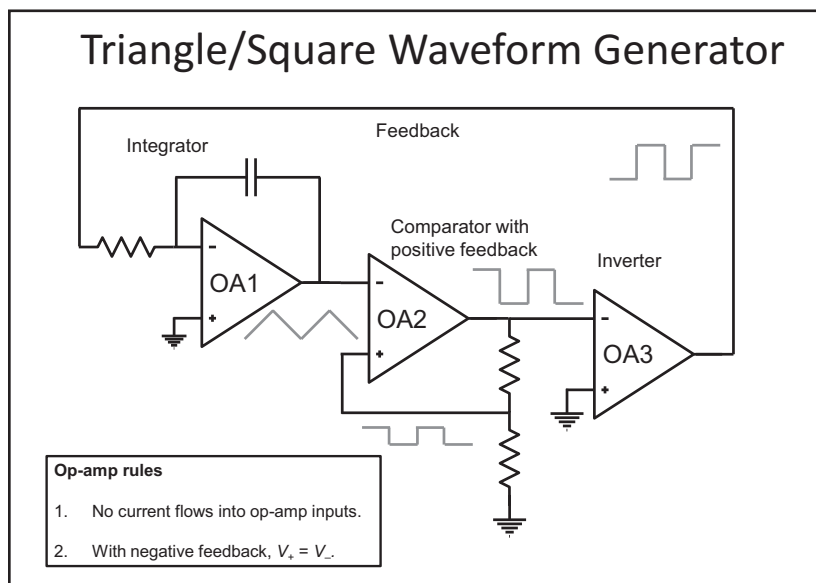


We've seen a light meter twice so far: first, as a device that gave an output proportional to the amount of light falling on it, then, as a peak detector that recorded the maximum light intensity.



An integrating light meter is a third type; this light meter records the total amount of light that falls over time. Such a device might be used to determine the amount of solar energy accumulated over a certain period or to close a camera shutter after a specific amount of light had come through the camera's lens.

A Triangle/Square Wave-Function Generator



In general, to make a circuit that undergoes some kind of periodic back-and-forth oscillation, we typically need a combination of both positive and negative feedback, as we see in this simple triangle/square wave-function generator. This waveform-generator circuit consists of three op-amps: an integrator, a simple version of a Schmitt trigger, and a comparator.

Suggested Reading

Introductory

None of the introductory books covers the material in this lecture.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 4, sections 4.2.6 and 4.3.3.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 8, section 8.4, pp. 643–644.

Project

Triangle/Square Generator

Simulate the triangle/square generator described in the lecture. Use 10 k Ω for all resistors, 0.1 μ F (100 nF) for C. Use 741 op-amps in CircuitLab, with explicit ± 15 -V power supplies. Simulate for 5 ms with 0.01 ms step; choose “Yes” to Skip Initial. Look at the outputs of the integrator and either other op-amp. As a challenge: Can you add a control for frequency adjustment?

Questions to Consider

1. Why, when charging a capacitor from a battery and a resistor, does the capacitor voltage not rise at a steady rate?
2. How does using a capacitor in the feedback loop of an op-amp allow the capacitor to charge at a constant rate?
3. What is meant by an *integrating* light meter? (Although the term *integrate* comes from calculus, you don’t need to know calculus to answer this.)

Digital versus Analog

Lecture 16

To this point in the course, we've been working with analog electronics, but with this lecture, we switch to digital electronics. Digital circuits use voltages to represent two distinct states: 1 and 0. Strings of 1s and 0s represent binary numbers or encode other information, such as letters, and these digital quantities can be manipulated and combined with simple logic operations. This lecture will lay the foundation for understanding digital electronics before we move on to developing digital circuits. Important topics include the following:

- Digital versus analog
- Binary numbers
- Logic operations: AND, OR, NOT
- Truth tables and Boolean notation
- Logic gates and symbols
- The NAND and NOR operations
- Everything from NAND or NOR!

Digital versus Analog

Analog	Digital
Continuous range of voltages and currents	Two states
Electrical quantities are analogs of physical quantities	Values of physical quantities are encoded as binary numbers
Irreversible degradation in transmission and copying	Error-free transmission and copying

Here are some important differences between analog and digital. Analog is the old way of doing things in electronics, and, increasingly, digital is the new way.

Analog quantities take on a continuous range of values. These include most physical quantities, such as temperature, voltage, speed, weight, time, intensity of sound, and so on. In fact, most of the quantities in the physical world are analog quantities. We can't get away from the fact that we live in a largely analog world, but today's electronics are largely digital.



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Some real-world quantities are intrinsically digital, taking only discrete values. One example from everyday life is money.

Continuously varying analog quantities can be converted to digital. For example, an electronic thermometer “discretizes” the temperature. It might read 98.6° or 98.7°, but it won't read 98.7392° because it doesn't have that many digits, and it can't cover the continuously varying range of temperature. We represent these analog quantities as digital quantities with limited numbers of digits. And, ultimately, those digits are reducible to 0s and 1s.



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Binary Numbers

Binary Numbers

- Two binary digits (bits)
 - 0 "zero," "no," "false," "low"
 - 1 "one," "yes," "true," "high"

Places: 8 4 2 1

$$\begin{aligned}
 &1001_2 \\
 &= 1 \times 8 + 0 \times 4 + 0 \times 2 + 1 \times 1 \\
 &= 9_{10}
 \end{aligned}$$

Every quantity in the world of digital electronics is represented with two binary digits: 0 and 1.

Representing Text

- ASCII
 - American Standard Code for Information Interchange
 - Assigns each character an 8-bit binary representation

01000100 01001111 01000111
 D O G


	Binary representation
A	0100 0001
B	0100 0010
C	0100 0011
D	0100 0100
E	0100 0101
F	0100 0110
G	0100 0111
...
O	0100 1111
...

Text is represented with the American Standard Code for Information Interchange (ASCII).


Logic Operations: AND, OR, NOT

Logic Operations

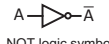
- **AND**
 - Output is 1 only if both inputs are 1
 - Boolean algebra: $A \cdot B$
- **OR**
 - Output is 1 if either input is 1
 - Boolean algebra: $A + B$
- **NOT**
 - Output is opposite of input
 - Boolean algebra: \bar{A}



AND logic symbol



OR logic symbol





NOT logic symbol


At the heart of processing digital information is the science of digital logic—a combination of mathematics and philosophy that governs everything in digital electronics. Just as we add, subtract, multiply, and divide in mathematics, we can do simple operations, known as AND, OR, and NOT, in digital logic. These operations are represented with the logic symbols shown above. The output of an AND operation is 1 only if both inputs are 1. The output of OR is 1 if either input is 1. The output of NOT is the opposite of the input.

Truth Tables and Boolean Notation

Truth Tables

- **AND**

A	B	$A \cdot B$
0	0	0
0	1	0
1	0	0
1	1	1
- **OR**

A	B	$A + B$
0	0	0
0	1	1
1	0	1
1	1	1
- **NOT**

A	\bar{A}
0	1
1	0

Logic operations can be represented with *truth tables*.

Logic Gates and Symbols

Logic “Gates”

• AND



A	B	A·B
0	0	0
0	1	0
1	0	0
1	1	1

B=0: A irrelevant to output; A can't "get through"

• OR



A	B	A+B
0	0	0
0	1	1
1	0	1
1	1	1

B=1: A irrelevant to output; A can't "get through"

Circuits that implement logic operations are called *logic gates*. Consider an AND operation in which the B input is 0. If that's the case, then the output must be 0 because for an AND operation, the output is 0 if either of the inputs is 0; both inputs must be 1 for the output to be 1. Thus, the A input is irrelevant to the output in this case; whatever A is, it doesn't have any effect on the input. The operation is like a gate that's closed; A can't "get through."

Logic “Gates”

• AND



A	B	A·B
0	0	0
0	1	0
1	0	0
1	1	1

B=1: Output = A; A "gets through"

• OR



A	B	A+B
0	0	0
0	1	1
1	0	1
1	1	1

B=0: Output = A; A "gets through"

On the other hand, if B = 1, then the output is the value of A. Now A "gets through" and the gate is open. A similar gating happens with the OR operation.

The NAND and NOR Operations

More Logic Gates

- **NAND (NOT AND)**

- Output is 0 only if both inputs are 1
- Boolean algebra: $\overline{A \cdot B}$



NAND logic symbol

A	B	$A \cdot B$	$\overline{A \cdot B}$
0	0	0	1
0	1	0	1
1	0	0	1
1	1	1	0

- **NOR (NOT OR)**

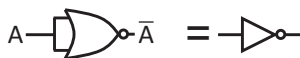
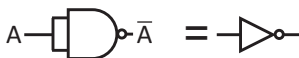
- Output is 0 if either input is 1
- Boolean algebra: $\overline{A+B}$



NOR logic symbol

A	B	$A+B$	$\overline{A+B}$
0	0	0	1
0	1	1	0
1	0	1	0
1	1	1	0

- **NOT from NAND, NOR**



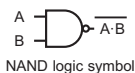
NAND and NOR gates are somewhat more obscure to think about but much more useful than AND and OR gates. NAND stands for NOT AND, and its output is 0 only if both inputs are 1; it's exactly the opposite of the AND gate. NOR stands for NOT OR, and its output is 0 if either input is 1; the only possible state in which the NOR gate has a non-0 output is when both inputs are 0. Once we have NAND or NOR gates, we can also make NOT gates by connecting together the two inputs of a NAND or a NOR gate.

Connecting the two inputs in the AND gate truth table rules out the middle two rows, which have different values for A and B. We have either 00, in which case we get 1 at the output, or 11, in which case we get 0; thus, the AND has become a NOT gate. NANDs and NORs are useful because we can use them to build other gate operations.

More Logic Gates

• NAND (NOT AND)

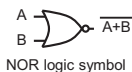
- Output is 0 only if both inputs are 1
- Boolean algebra: $\overline{A \cdot B}$



A	B	A·B	$\overline{A \cdot B}$
0	0	0	1
0	1	0	1
1	0	0	1
1	1	1	0

• NOR (NOT OR)

- Output is 0 if either input is 1
- Boolean algebra: $\overline{A+B}$



A	B	A+B	$\overline{A+B}$
0	0	0	1
0	1	1	0
1	0	1	0
1	1	1	0

• AND, OR from NAND, NOR



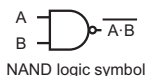
NAND and NOR can make NOT; if we want to make an AND gate, we start with a NAND and add a NOT. If we invert the output of a NAND gate, we get back to an AND gate. We could build that structure with two NANDs, with the second one connected as a NOT gate. Equivalently, we can make an OR gate from NOR and NOT.

Everything from NAND or NOR!

Everything from NAND

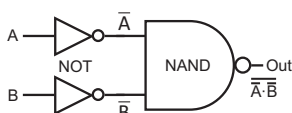
• NAND (NOT AND)

- Output is 0 only if both inputs are 1
- Boolean algebra: $\overline{A \cdot B}$

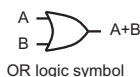


A	B	A·B	$\overline{A \cdot B}$
0	0	0	1
0	1	0	1
1	0	0	1
1	1	1	0

• What's this?



A	B	\overline{A}	\overline{B}	Out
0	0	1	1	0
0	1	1	0	1
1	0	0	1	1
1	1	0	0	1




A	B	A+B
0	0	0
0	1	1
1	0	1
1	1	1

We can build everything from the NAND operation. For example, we can make NAND gates into inverters, put the inverters on the front of the input to another NAND gate, and get an OR gate. We can also get NOT from a NAND gate, and we can get NOR from NAND by inverting the OR gate we just built.

Everything from NOR

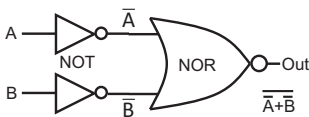
- NOR (NOT OR)**
 - Output is 0 if either input is 1
 - Boolean algebra: $\overline{A+B}$




NOR logic symbol

A	B	A+B	$\overline{A+B}$
0	0	0	1
0	1	1	0
1	0	1	0
1	1	1	0

- What's this?**



A	B	\bar{A}	\bar{B}	Out
0	0	1	1	0
0	1	1	0	0
1	0	0	1	0
1	1	0	0	1



AND logic symbol

A	B	A·B
0	0	0
0	1	0
1	0	0
1	1	1

Similarly, we can get everything from NOR if we put inputs into the NOR and invert them. These versatile NAND and NOR gates are the basic building blocks of digital circuits.

Suggested Reading

Introductory

Brindley, *Starting Electronics*, 4th ed., chapter 10.

Lowe, *Electronics All-in-One for Dummies*, book IV, chapters 1–2.

Shamieh and McComb, *Electronics for Dummies*, 2nd ed., chapter 7 through p. 151.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 10, section 10.1.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 12, sections 12.1–12.2.2.

Projects

Digital Logic

How many two-input logic operations are possible? How many were introduced in this lecture?

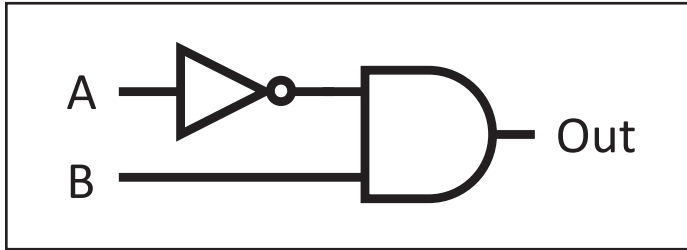
Using any combination of AND/OR/NAND/NOR/NOT, design a three-input AND gate.

Using only NAND gates, design an Exclusive OR gate—whose output is 1 if one of its two inputs is 1, but not both. Challenge: What's the minimum number of gates you can use?

Questions to Consider

1. Why are NAND and NOR more useful logic operations than the more familiar AND and OR?

- *2. Construct the truth table for the following logic circuit and write a symbolic expression for the output in terms of the two inputs, A and B.



Electronics Goes Digital

Lecture 17

In the preceding lecture, we were introduced to logic operations and Boolean algebra. In this lecture, we'll transfer that knowledge to electronics. For electronic circuits to be digital, they must be able to implement the abrupt transition between the two possible states—0 and 1—with nothing in between. The fundamental electronic device that is able to do that is a switch, which is either on or off, open or closed, high or low, yes or no, true or false, or 1 or 0. We'll begin this lecture with a demonstration of how the logic operations we saw in the last lecture can be implemented using circuits with manual switches. Then, we'll move on to see how it's done with electronic switches, such as diodes and transistors. Key topics we'll cover include the following:

- AND, OR, NOT: simple electrical implementations
- Diode logic
- Transistor-transistor logic
- CMOS logic: today's mainstream
- Logic families

AND, OR, NOT: Simple Electrical Implementations

In a demonstration, we see a light bulb representing the output of three logic gates. If the light bulb is on, we're in the 1 state. If the light bulb is off, we're in a 0 state. We have a source of power and two switches connected in series. The switches represent the A and B input. An open or off switch represents the 0 state; a closed switch represents the 1 state. In the AND operation, the two switches are in series, so both A and B must be closed for the bulb to light—that is, for a 1 at the output. In the OR operation, the switches are in parallel and either A or B or both must be closed for the output to be a 1. In the NOT operation, an open



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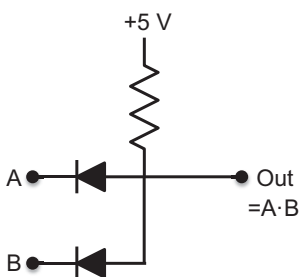
switch—a 0 state—produces a 1 state at the output; a closed switch—a 1 state—produces a 0 state at the output.

Diode Logic

Diode Resistor AND Gate

Logic definitions: 0 V = Logic 0; 5 V = Logic 1

Ideal diodes: on ($R = 0$) or off ($R = \infty$); no voltage drop



A	A	B	B	Out	Out
0 V	0	0 V	0	0 V	0
0 V	0	5 V	1	0 V	0
5 V	1	0 V	0	0 V	0
5 V	1	5 V	1	5 V	1

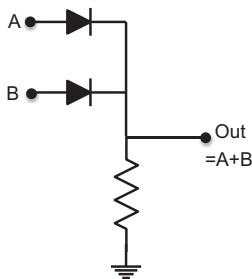
AND

Analogous to the gates using light bulbs, batteries, and switches is a diode-resistor implementation AND gate. The logic levels in this circuit are: 0 = 0 V and 1 = 5 V. Looking at the truth table for this circuit, we see that if both A and B are 0, both diodes are on because the 5 V can send a current through either diode into ground (0 V), which is connected to A and B. In fact, if A is 0, B is 0, or both are 0, we get 0 at the output because one or both of the diodes will be on. The only way we won't get 0 at the output is if both A and B are 1 (5 V); then, the diodes are shut off.

Diode Resistor OR Gate

Logic definitions: 0 V = Logic 1; 5 V = Logic 0

Ideal diodes: on ($R = 0$) or off ($R = \infty$); no voltage drop



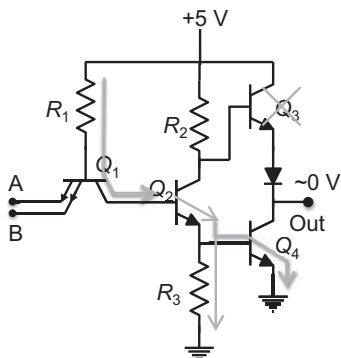
A	A	B	B	Out	Out
0 V	1	0 V	1	0 V	1
0 V	1	5 V	0	0 V	1
5 V	0	0 V	1	0 V	1
5 V	0	5 V	0	5 V	0

OR

A diode resistor implementation OR gate works similarly. If both A and B are 0, the output is 0. If either A or B is 1 or both are 1, the output is 1.

Transistor-Transistor Logic (TTL)

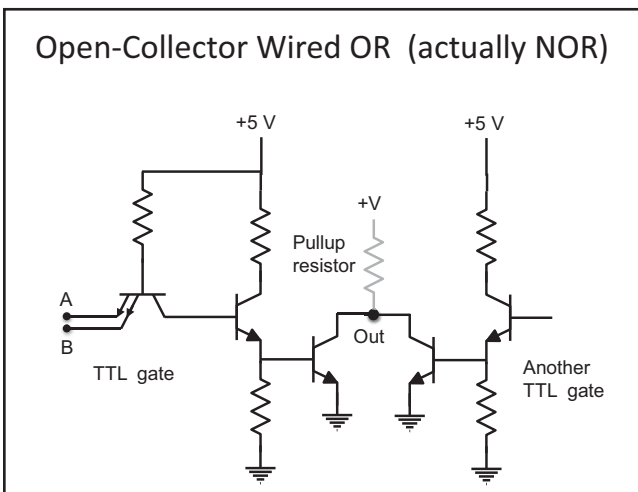
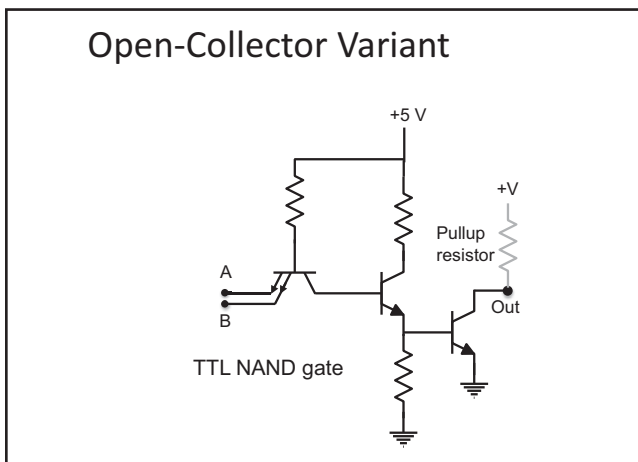
TTL



A and both B unconnected
or connected to +5 V
Transistor Q_1 not "transisting"
Current flows through Q_1 's
base-collector junction
Current continues through
 Q_2 's base-emitter junction;
 Q_2 on
Voltage at Q_2 's collector is
low; Q_3 off
Current continues through
 R_3 and Q_4 ; Q_4 on
Output goes low (~ 0 V)

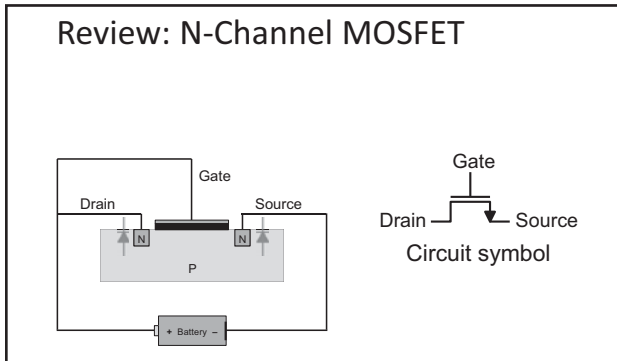
TTL is a form of logic that was developed in the 1970s. It's still in use on occasion, although it is being superseded by circuits based on MOSFETs.

Here, we have a transistor with two emitters, each of them behaving like the emitter of a BJT. In this circuit, the output goes high if either of the inputs is low.



A variant on TTL called *open collector output* is useful for connecting the outputs of two TTL gates directly. The result is a wired OR (actually NOR) situation.

CMOS Logic: Today's Mainstream



As we saw in an earlier lecture, a MOSFET consists of two electrodes (a *source* and a *drain*), which in this case, are incursions of N-type semiconductor material in a block of P-type material. There's another electrode, the *gate*, which is a thin metal layer insulated from the block of semiconductor by a layer of silicon dioxide. This transistor can be considered a switch that's turned on by putting positive charge on the gate. We can also build complementary MOSFETs that have N-type blocks and P-type incursions; they're turned on by putting 0 volts on the gate.

CMOS**Complementary Metal-Oxide Semiconductor**

- Uses N-channel and P-channel MOS transistors in series combinations
- Except when switching state...
 - One transistor in series combination is off
 - Draws essentially no current
 - Consumes essentially zero power
- When switching
 - Current flows to charge gate capacitance
 - Power consumption increases with switching rate
- Ubiquitous in computers and consumer electronics

CMOS stands for *complementary metal-oxide semiconductor*. These circuits are ubiquitous in consumer electronics and computers.

CMOS Inverter

Logic levels:

Logic 0: 0 V

Logic 1: V_s

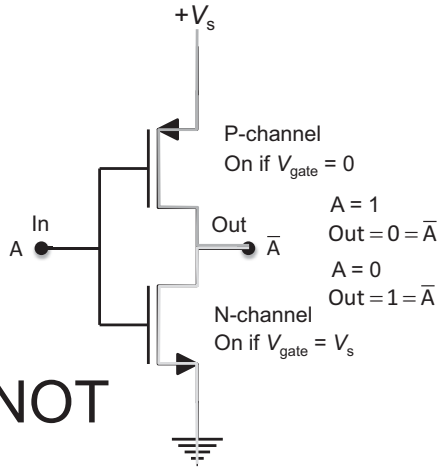
$$V_{in} = V_{gate} = V_s$$

$$A = 1$$

$$V_{in} = V_{gate} = 0$$

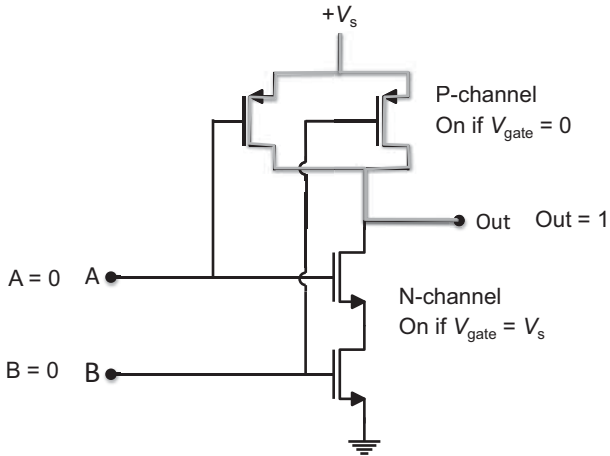
$$A = 0$$

NOT



This CMOS inverter (a NOT gate) is a simple example of a CMOS circuit.

CMOS NAND Gate



A CMOS NAND gate is slightly more complicated.

Logic Families

Logic Type	Power per Gate	Speed (MHz)	Supply Voltage	Logic Voltages	Comments
Bipolar Original TTL (7400 series)	10 mW	35	4.5–5.5 V	0–0.8 V 2–5 V	Robust, but obsolete High power consumption Relatively slow
Bipolar 74LS TTL	2 mW	45	4.5–5.5 V	0–0.8 V 2–5 V	Lower power, faster than original TTL
CMOS 74HC	3 μ W quiescent 0.6 mW, 1 MHz	45	2–6 V	0–1 V 3.5–4.4 V	Logic levels listed are for 5 V supply
CMOS 74HCT	3 μ W quiescent 0.6 mW, 1 MHz	45	4.5–5.5 V	0–0.8 V 2–5 V	TTL compatible variant of 74HC
CMOS 74LVC	3 μ W quiescent 0.8 mW, 1 MHz	200	2–3.6 V	0–0.8 V 2–3.3 V	Increasingly popular; used with fast, large-scale integrated logic; surface mount only

The table above shows a number of logic families. The CMOS 74HCT series is compatible with the older TTL and can serve as a modern replacement in most applications.

Suggested Reading

Introductory

Brindley, *Starting Electronics*, 4th ed., chapter 11 through p. 187.

Lowe, *Electronics All-in-One for Dummies*, book IV, chapter 3 and chapter 4 to pp. 565–569.

Shamieh and McComb, *Electronics for Dummies*, 2nd ed., chapter 14, pp. 323 to end.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 10, sections 10.2–10.3.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 12, sections 12.4 and 12.11.

Project

Digital Circuit Design

Design a digital circuit with four inputs and one output, whose input represents a 4-bit binary number and whose output is 1 only when the input is the binary equivalent of 2, 6, or 8. Use any gates in the table of basic logic gates.

Questions to Consider

1. What does the *C* in *CMOS* stand for? How does this relate to the basic fact that there are two types of doped semiconductors?
2. Why does CMOS logic consume much less power than TTL?
3. Why is CMOS logic more sensitive to static electricity damage than TTL?

Flip-Flop Circuits

Lecture 18

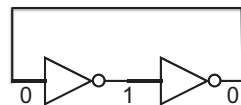
So far in this course, the digital circuits we've considered have typically had one or two inputs. Those two inputs produced an output, which we described by means of a truth table. The output responded directly to the inputs. In this lecture, we'll move to more sophisticated circuits—circuits that “remember.” These circuits constitute the core of computer memory and many other applications. We'll begin by looking at the basic bistable circuit—a circuit that has two stable states—and we'll see how we change those states. Such circuits are sometimes called *flip-flops*. Key concepts here include the following:

- The basic bistable circuit
- Gating the inputs: set and reset
- Application: debouncing
- Clocking
- Master-slave flip-flops.

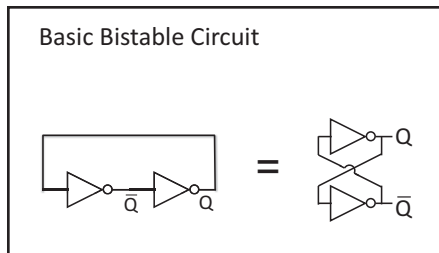
The Basic Bistable Circuit

The two inverters here are in a stable, consistent state: 0 at the input to the first inverter, 1 at the output of the first inverter, and 0 at the output of the second inverter, connected back to the input of the first. We could also have 1 at the input to the first inverter, 0 at its output, and 1 at the output of the second inverter. This circuit can only be in one of those states.

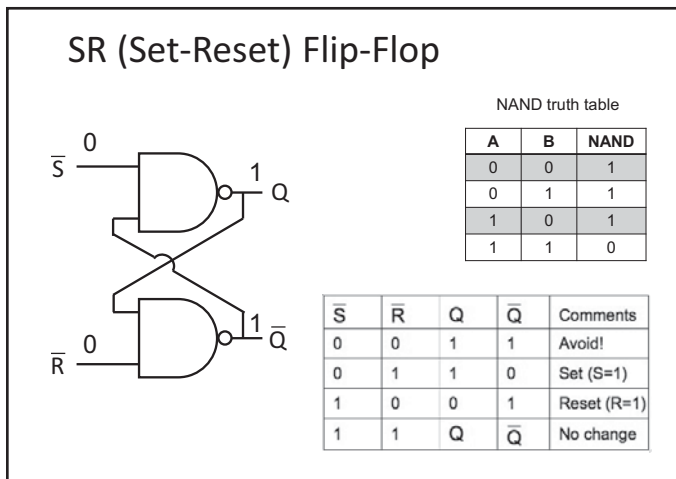
Basic Bistable Circuit



In a more symmetric drawing of the same circuit, the output of the upper inverter (called Q) is connected to the input of the lower inverter, whose output is \bar{Q} (meaning *not* Q). But this circuit isn't useful because we have no way to change its state. To make the circuit useful, we replace the inverters with logic gates. The extra inputs to the gates will allow us to change the state of the bistable circuit.

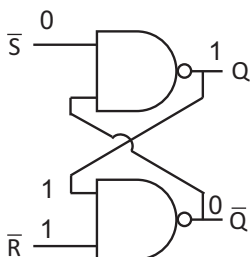


Gating the Inputs: Set and Reset



In this circuit, called a *set-reset (SR) flip-flop*, we replace the inverters with NAND gates. Recall that a NAND gate has a truth table that is the inverse of AND. The only time its output is 0 is when both its inputs are 1. Note that the inputs here are labeled \bar{S} (*not set*) and \bar{R} (*not reset*). If we set both inputs to 0, both outputs (Q and \bar{Q}) have to be 1. This is not a bistable state storing a 1 in one output and a 0 in the other; thus, this is a situation that we'd like to avoid.

SR (Set-Reset) Flip-Flop



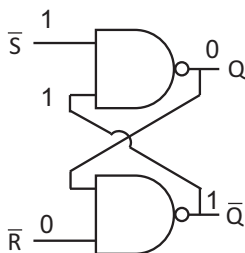
NAND truth table

A	B	NAND
0	0	1
0	1	1
1	0	1
1	1	0

\bar{S}	\bar{R}	Q	\bar{Q}	Comments
0	0	1	1	Avoid!
0	1	1	0	Set ($S=1$)
1	0	0	1	Reset ($R=1$)
1	1	Q	\bar{Q}	No change

If we put a 0 at the \bar{S} input and a 1 at the \bar{R} input, we get a 1 at Q. That 1 is cross-connected back to the other input of the lower NAND gate. Consequently, we have 1 and 1 at the inputs to the lower NAND gate, and its output is 0. That is a legitimate state of the flip-flop.

SR (Set-Reset) Flip-Flop



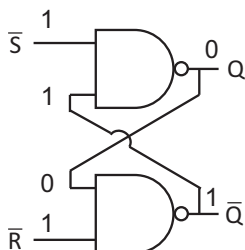
NAND truth table

A	B	NAND
0	0	1
0	1	1
1	0	1
1	1	0

\bar{S}	\bar{R}	Q	\bar{Q}	Comments
0	0	1	1	Avoid!
0	1	1	0	Set ($S=1$)
1	0	0	1	Reset ($R=1$)
1	1	Q	\bar{Q}	No change

We can also do the opposite: Set \bar{S} to 1 and \bar{R} to 0. That gives us 0 at Q and 1 at \bar{Q} . We have reset the flip-flop.

SR (Set-Reset) Flip-Flop



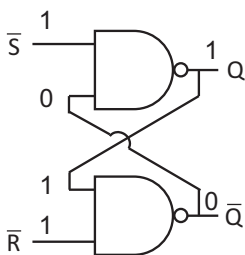
NAND truth table

A	B	NAND
0	0	1
0	1	1
1	0	1
1	1	0

\bar{S}	\bar{R}	Q	\bar{Q}	Comments
0	0	1	1	Avoid!
0	1	1	0	Set (S=1)
1	0	0	1	Reset (R=1)
1	1	Q	\bar{Q}	No change

Finally, we have the state in which we set both \bar{S} and \bar{R} to 1. This is consistent with either $Q = 1$ and $\bar{Q} = 0$ (as shown above), or $Q = 0$ and $\bar{Q} = 1$ (as shown below). So having $\bar{S} = \bar{R} = 1$ leaves the state of the flip-flop unchanged.

SR (Set-Reset) Flip-Flop

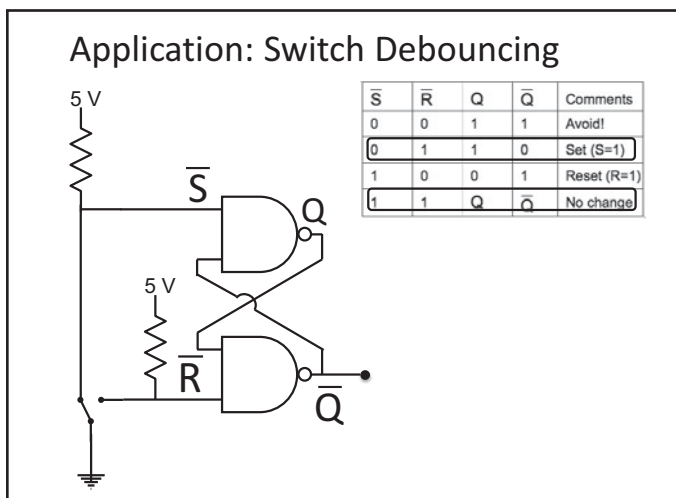


NAND truth table

A	B	NAND
0	0	1
0	1	1
1	0	1
1	1	0

\bar{S}	\bar{R}	Q	\bar{Q}	Comments
0	0	1	1	Avoid!
0	1	1	0	Set (S=1)
1	0	0	1	Reset (R=1)
1	1	Q	\bar{Q}	No change

Application: Debouncing



One of the simplest uses of an SR flip-flop is to stop the bouncing that occurs when a mechanical switch is turned on. In this case the flip-flop “latches up” in the $Q = 1$ state the first time the switch closes, and it can’t change until the switch is again thrown all the way to its right-hand position.

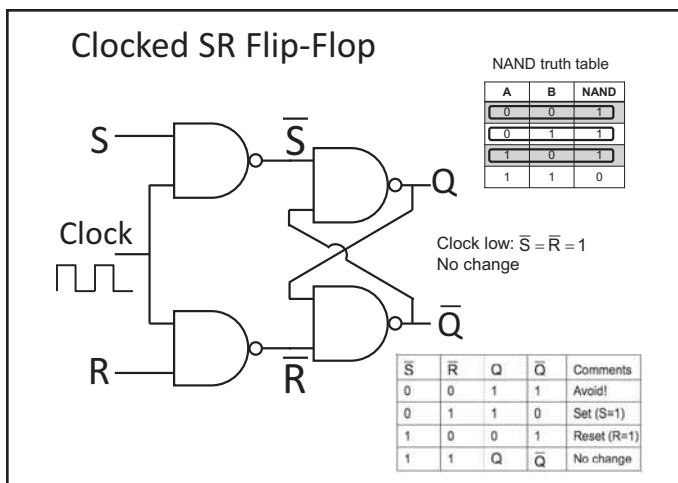
Clocking

The simple SR flip-flop uses *asynchronous logic*; the output changes as soon as the input changes. But if we have large-scale circuits with numerous flip-flops, as in a computer, we need to use *synchronous*, or

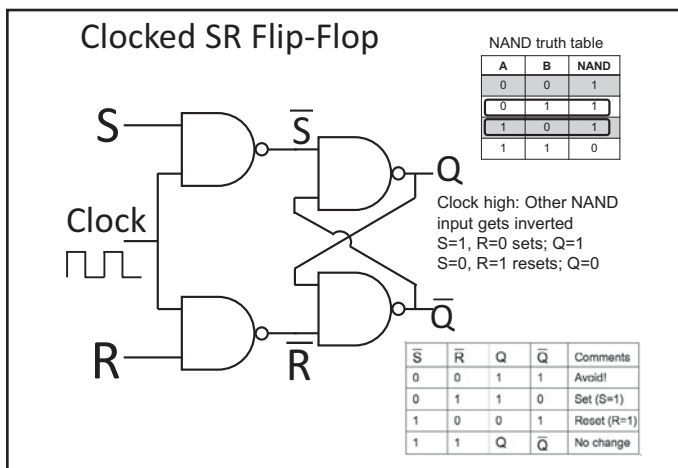
clocked, logic. Here, a central clock governs all the logic switching. The clock is a square-wave generator running at a fixed rate, with its voltage swinging between the two logic levels (0 and 5 V in the circuits we’re discussing).

Synchronous versus Asynchronous

- Asynchronous logic
 - Output changes as soon as inputs change
 - Chaos in large-scale circuits!
- Synchronous (clocked) logic
 - Central clock governs all logic switching
 - Clock is a square-wave generator
 - Today’s computers: clock frequency ~several GHz



To make our simple SR flip-flop into a synchronous circuit, we add two NAND gates in front of it. Whenever we have a NAND gate, if both inputs are high, the output is low, and if either input is low, the output is high. Thus, if the clock is low (the clock constitutes one input to the NAND gates), the outputs of both NAND gates are high. That's the state in which the SR flip-flop doesn't change, so the flip-flop can't change state unless the clock is high. That's what makes all the flip-flops in a circuit change synchronously.



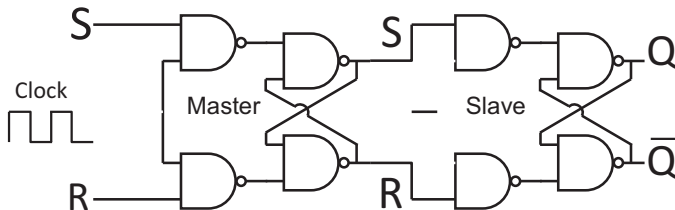
When the clock is high, the left-hand NAND gates act as inverters, and their S and R inputs become the \bar{S} and \bar{R} inputs to the bistable circuit at right.

Master-Slave Flip-Flops

Master-Slave Flip-Flop

SR truth table
 Q_n = value of Q
 after n^{th} clock pulse

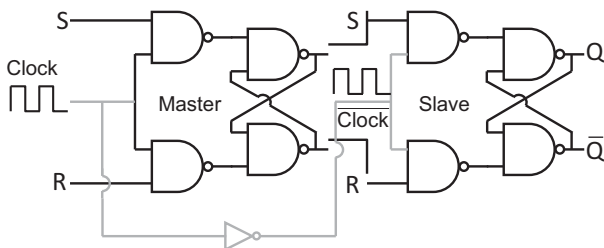
S	R	Q_{n+1}
0	0	Q_n
0	1	0
1	0	1
1	1	?



There are still some issues with the clocked flip-flop. The whole time the clock is high, the flip-flop is subject to change. Thus, if there's any noise in the system, it's possible that during the high phase of the clock, the flip-flop could flip back and forth several times. A more orderly situation would be if it changed only once per cycle. Further, a flip-flop that involves feedback from Q back to the set input could be subject to oscillation. One approach to solving that problem is a master-slave flip-flop.

We started with a basic bistable circuit. We then replaced the inverters with NAND gates so that we could set and reset. Then, we added another pair of NAND gates for the clocking. To make a master-slave flip-flop, we build the exact same circuit again.

Master-Slave Flip-Flop

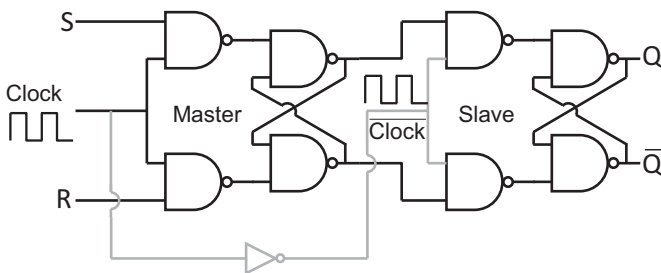


To this configuration, we add one more gate—an inverter. It goes from the clock input to the master flip-flop into the clock input of the slave flip-flop, but there's an inversion in between.

Master-Slave Flip-Flop

Clock high: Master accepts inputs

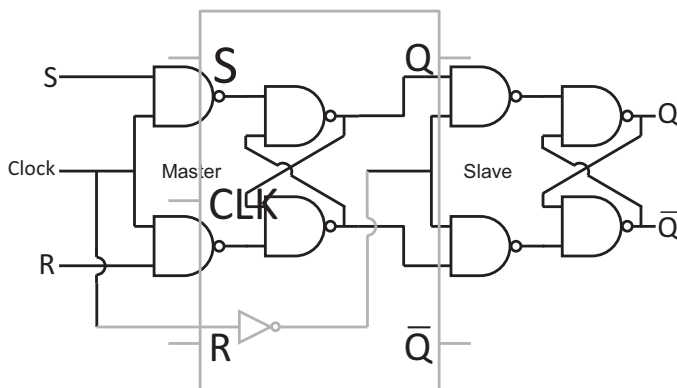
$\overline{\text{Clock}}$ low: Slave isolated; can't change state



When the clock is high, the master flip-flop can change state. But at the same time, the clock input to the slave flip-flop is low, so the slave can't change

state. Only when the clock goes low does the clock input to the slave go high, and at that point, the contents of the master are transferred to the slave.

Master-Slave Flip-Flop



The master-slave flip-flop is a device that gives us increasing order in a complicated electronic system. It allows the clock to control the states when the flip-flops can change state. Further, the master-slave arrangement allows that change to occur only once per clock cycle. For our purposes, we'll represent the eight NAND gates and one inverter in this master-slave flip-flop as a single rectangle with the appropriate inputs and outputs. Similar rectangles will be our symbols for different kinds of flip-flops.

Suggested Reading

Introductory

Brindley, *Starting Electronics*, 4th ed., chapter 11, pp. 187–194.

Lowe, *Electronics All-in-One for Dummies*, book IV, chapter 5 through p. 595.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 10, section 10.4.1.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 12, section 12.6 through 12.6.2.

Projects

SR Flip-Flop Design

Design an unclocked SR flip-flop using NOR gates. Be sure to label the inputs correctly. Determine its truth table. How does it differ from the NAND-based flip-flop presented in this lecture?

SR Flip-Flop Simulation

Simulate either your design or the NAND-based SR flip-flop from this lecture and verify that it works.

Questions to Consider

1. In the unclocked flip-flop introduced at the start of this lecture, we labeled the inputs S and R. Later, after adding gates for clocking, the inputs became S and R. Why the change?
2. Why do we use clocked logic in complex circuits, such as those in computers?
3. What advantage do master-slave and edge-triggered flip-flops offer over the simpler clocked flip-flop without the master-slave configuration or edge triggering?

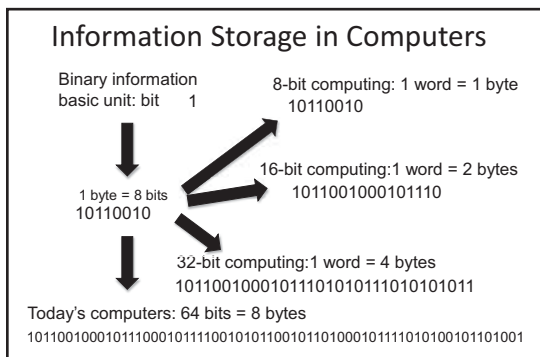
Shift and Divide—Your USB and Your Watch

Lecture 19

The simple SR flip-flop stores 1 bit of information, and that information is available at its Q output, whose value is either logic 1 or logic 0. Any piece of information that can be addressed with a yes/no, true/false response can be stored as 1 bit. But we've seen that computers and other circuits use many bits. For example, the ASCII system represents each character in the alphabet by an 8-bit sequence, and computers in general store information in strings of many bits (called *words*). Further, as computers have evolved, those words have gotten longer. For all these reasons, we need more than just one flip-flop storing 1 bit. In this lecture, we'll begin to learn how to link flip-flops to store and process multiple bits of information. Key topics include the following:

- Organizing data:
 - The computer word
 - Meet the D flip-flop and shift registers
 - Serial-to-parallel conversion
 - Parallel-to-serial conversion
- A computer communicates
 - Inside your USB
 - Meet the T flip-flop
 - Frequency dividers: what's inside your quartz watch.

Organizing Data: The Computer Word



The basic information unit in binary is the bit, which can be either a 1 or a 0. The next largest unit is the *byte*, containing 8 bits. Early computers used 8-bit words; each word was 1 byte. Today's computers are

mostly 64-bit units; smaller microcomputers in smart devices may still use 8- or 16-bit words.

Two Approaches to Digital Communications

- Parallel
 - Send a whole word at once
 - Requires N wires, with N the word length
 - Increasingly impractical as N has grown
- Serial
 - Send one bit at a time
 - Requires parallel-to-serial conversion at sender...
 - ...and serial-to-parallel conversion at receiver

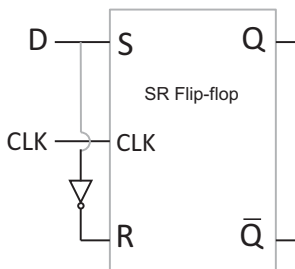
There are two approaches to computer communication: *parallel* and *serial*. In parallel, an entire word is sent at once down a cable that contains one wire for each bit. Parallel transmission occurs almost instantaneously, but as the length of the word has grown, parallel communication has become impractical. In serial communication, 1 bit is sent at a time. This method requires far fewer wires, reducing the cost and bulkiness of the cable, but it comes at the expense of slower transmission and the need to convert from parallel to serial on the sending end and back to parallel on the receiving end. Flip-flops can be used for that purpose.

Meet the D Flip-Flop and Shift Registers

For a data (D) flip-flop, we start with an SR flip-flop, and we connect the set input to the reset input through an inverter. If we put a 1 at the D input (the set input), we get a 0 at the reset input, and Q goes to 1. If we put D to 0, we get 1 at the reset, and Q goes to 0. One of the advantages of the D flip-

D (Data) Flip-Flop

D = 1: Q \rightarrow 1 on clock (set)
D = 0: Q \rightarrow 0 on clock (reset)

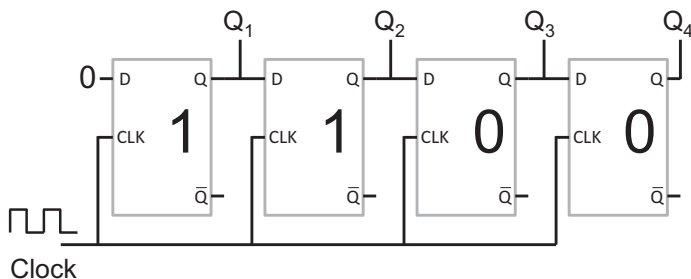


flop is that it eliminates the state with 1 on both inputs, which we've seen is to be avoided.

Shift Registers

Initial register contents: 1100 ($= 12_{10}$)

0 at first D input



Each clock pulse shifts contents of each flip-flop one place to right

A *shift register* is a number of D flip-flops connected so the Q output of each flip-flop feeds the D input of the next flip-flop. All flip-flops are connected to the same clock, and when the clock pulse occurs, each flip-flop delivers the contents of its D input to its Q output. As a result, each clock pulse shifts the contents of the entire register one place to the right.

Suppose the initial register content is 1100 (12 in base 10). If we put a 0 to the first input, after the first shift, 0 will load into the leftmost D flip-flop, leaving us with 0110 (6 in base 10) after the first clock pulse. After the second clock pulse, we get 0011 (3 in base 10).

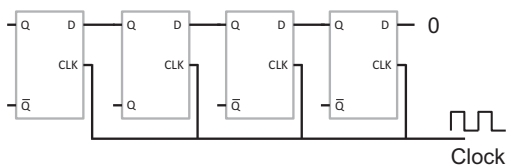
Shift Register: A Divide-by- 2^n Circuit

Initial register contents: 1100 ($= 12_{10}$)

After first clock pulse: 0110 ($= 6_{10} = 12 \div 2$)

After second clock pulse: 0011 ($= 3_{10} = 6 \div 2 = 12 \div 4$)

What's this do?



Each clock pulse shifts contents of each flip-flop one place to left: multiplies by 2

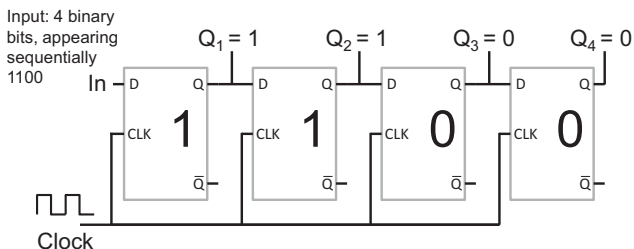
If we interpret the contents of the shift register as a binary number, notice that we are dividing that binary number by 2 with each shift. We can imagine taking as many flip-flops as we want and dividing by any power of 2. Thus, a shift register is one way of doing arithmetic in a computer. If we reverse the directions of the flip-flops, as shown in the bottom of the figure above, then we get a circuit that multiplies by 2 with each clock pulse.

Serial-to-Parallel Conversion

Serial-to-Parallel Conversion

Each clock pulse shifts contents of each flip-flop one place to right

After four clock pulses: 4 bits available in parallel at outputs



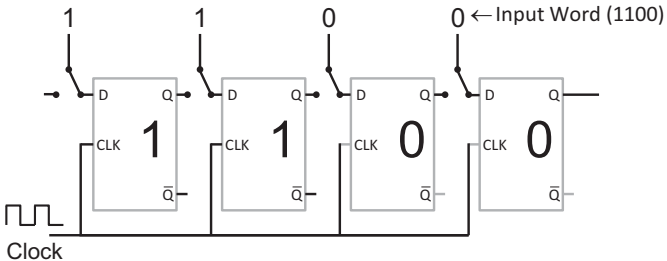
To accomplish serial-to-parallel conversion, we start with a register consisting of four D flip-flops. If we want to load 1100, we bring in each digit sequentially to the left-hand flip-flop. As we do that, on the clock, everything shifts to the right. After four clock pulses, we end up with 1100 stored in the register.

Parallel-to-Serial Conversion

Parallel-to-Serial Conversion

Each clock pulse shifts contents of each flip-flop one place to right

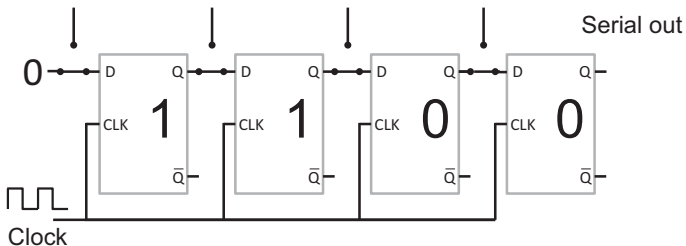
Step 1: Set switches (logic gates!) up; load 4-bit word



Parallel-to-Serial Conversion

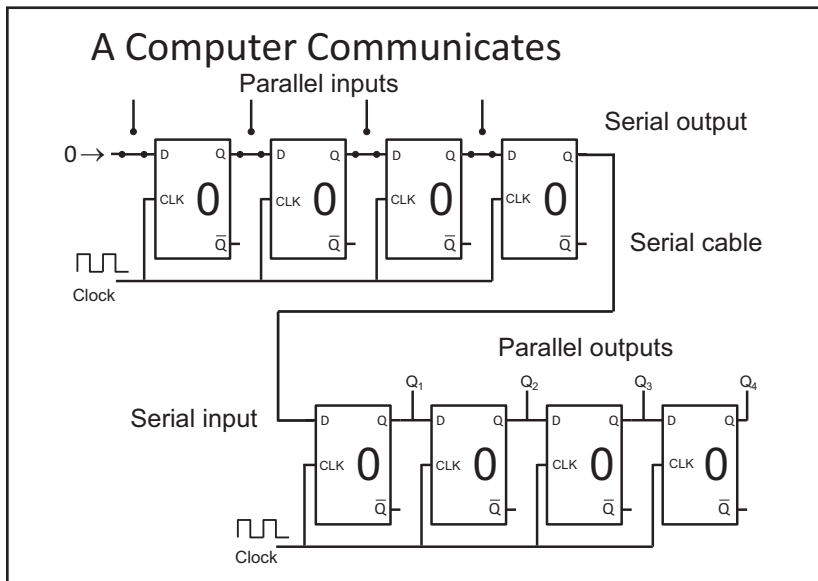
Each clock pulse shifts contents of each flip-flop one place to right

Step 2: Set switches (logic gates!) left; start shifting right



Parallel-to-serial conversion is a little more complicated, requiring some switches. Here, the switches at the top of the diagram are first connected to the information we want to bring in. Again, our input is 1100. With the switches in their upper position, we load the 4-bit word into the register. Then, we move the switches to the other position so the Ds are connected to the Qs again, as we had earlier in our shift register. This allows us to start the process of shifting the word to the right. The bits appear in sequence, one at a time, at the serial output.

A Computer Communicates



We can now see how a computer communicates with external devices via a serial connection. The information to be communicated (here, the 4-bit sequence 1100) is loaded in from the computer in parallel, sent serially over a cable, and converted back to parallel for use in another device, such as a printer or another computer.

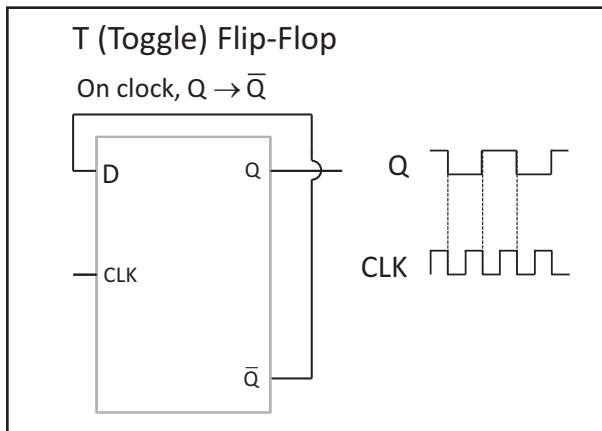
Inside Your USB

Inside Your USB

- USB 2
 - Four wires; two for signal, two for 5-V power
 - Max data rate: 480 megabits/second
 - Unidirectional data transfer
 - Send/receive happen separately
 - Max current supplied: 500 mA
- USB 3
 - Nine wires; seven for signal, two for 5-V power
 - Max data rate: ~5 gigabits/second
 - Simultaneous send/receive
 - Max current supplied: 900 mA

USB stands for *universal serial bus*; a *bus* is something that carries signals typically over substantial distances in electronic circuits.

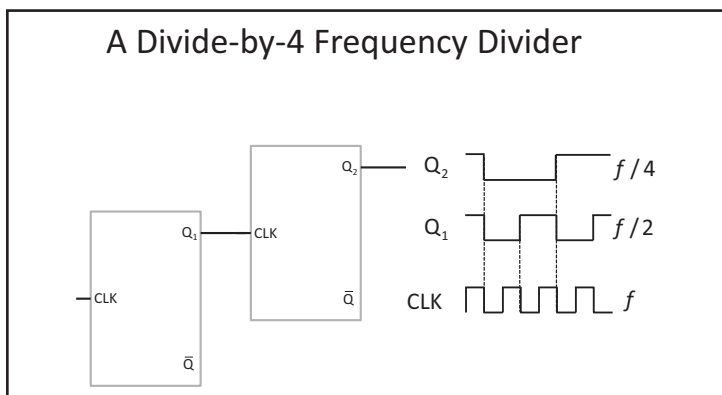
Meet the T Flip-Flop



The T flip-flop represents an interesting use of negative feedback. We start with a D flip-flop, then connect the \bar{Q} output to the D input. If $Q = 1$, then

$\overline{Q} = 0$ and so the D input will have 0. When the clock pulse arrives, that 0 is loaded into Q, and Q changes to 0. On the other hand, if $Q = 0$, then $\overline{Q} = 1$, because those two are always opposites. So if $Q = 0$, there's a 1 at the D input. When the clock pulse arrives, that 1 is loaded into Q. The point is that this flip-flop toggles between its two possible states. Whatever state Q is in, on the next clock pulse, Q goes to \overline{Q} . T flip-flops are the building blocks of many circuits, including frequency dividers and digital counters.

Frequency Dividers: What's inside Your Quartz Watch



Earlier, we saw a divide-by-2 frequency divider with one T flip-flop. If we take the Q output of that T flip-flop and put it into the clock input on the next T flip-flop, the second flip-flop acts exactly like the first, except now, it's working on a signal that's coming in at half the clock frequency. That gives us a divide-by-4 frequency divider.

Inside a quartz timepiece, there is a small crystal of quartz that can be set vibrating by applying a voltage across it. Typically, the crystal is engineered to vibrate at a frequency of 32,768 Hz (cycles per second)—which is 2^{15} Hz. That frequency is chosen because when it's divided by 15, the result is 1 Hz, and that 1 Hz drives the second hand or the digital display of the timepiece.



Suggested Reading

Introductory

Brindley, *Starting Electronics*, 4th ed., chapter 11, pp. 194 to end.

Lowe, *Electronics All-in-One for Dummies*, book VI, chapter 5, pp. 596 to end.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 10, sections 10.4.2, 10.5.1, 10.5.3; chapter 14, section 14.2.4.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 12, sections 12.6.3, 12.6.4, 12.6.5 through p. 780; section 12.8.

Projects

T Flip-Flop Simulation

Simulate a T flip-flop using your circuit simulator's built-in \underline{D} flip-flop and verify that it works. Note: CircuitLab's D flip-flop has no \overline{Q} output. How will you deal with that?

Frequency Divider

Make a frequency divider that divides the input frequency by 8 and verify that it works. Use your flip-flop(s) from the project above, CL's built-in T flip-flop with a 1 at the T input or DC's JK flip-flop with all J, K inputs to 1.

Questions to Consider

1. Why has parallel data transmission become increasingly impractical as computers have evolved?
2. What's a T flip-flop do? And what does the *T* stand for?
3. What's special about the number 32,768, which is the frequency of the quartz crystal vibrations in a quartz watch?

Digital Memory

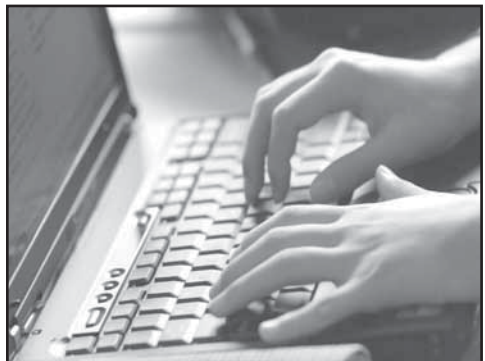
Lecture 20

We've already discussed flip-flops as circuits that can “sort of” remember, but in this lecture, we'll build them into substantial memories, such as would be used in computers and other kinds of devices to remember both data and program instructions. We will look in some detail at different kinds of memory, how memory is used, and how memory can be made using flip-flops. We'll also discuss other kinds of memory that aren't based on flip-flops. Key topics in this lecture include the following:

- Volatile versus nonvolatile memory
- Random-access versus sequential memory
- Memory addressing
- A simple flip-flop-based memory
- Static versus dynamic memory
- Flash memory.

Distinctions in Electronic Memory

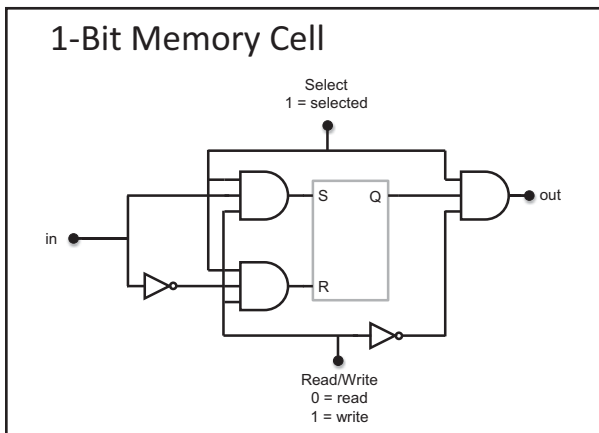
We need to make two important distinctions concerning memory. Memory can be volatile, meaning that information is lost if the power is lost, or it can be nonvolatile, meaning that information is retained even without power. Second, memory comes in two forms: random-access memory (RAM) and sequential memory. RAM is memory that can be accessed equally quickly, no matter what piece of data is being accessed. Most semiconductor-based memory is RAM. Sequential memory requires passing through a sequence of memory items before you can access the one you want. Examples of sequential memory devices include magnetic tape, hard disks, CDs, and DVDs.



Memory Addressing

Another issue with memory is how we address it. Think of a single item of memory storing a bit, a 1 or a 0. If you want that bit, you must know where that memory is—its address. The amount of memory available is usually expressed in bytes (1 byte = 8 bits). The maximum amount of memory that can be addressed is ultimately set by word length; it's 2 raised to the number of bits. With a 32-bit word, we can address up to 2^{32} individual memory locations. That's only about 4 billion addresses—a rather small amount of memory for a modern computer. With 64-bit words, we can address about 20 trillion billion locations. In dealing with memory, we also need to know whether the memory location is being read or written to.

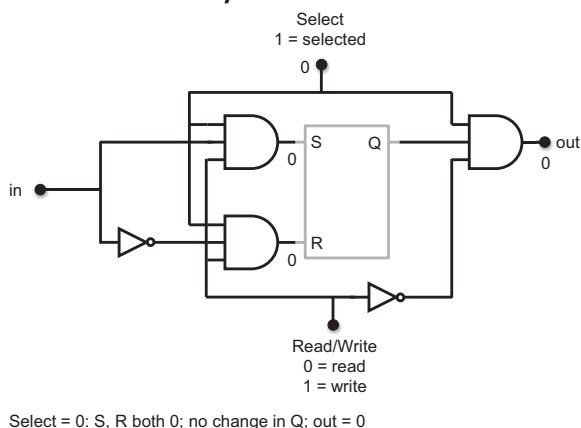
A Simple Flip-Flop–Based Memory



We can build a single memory cell that stores 1 bit based on the SR flip-flop. To this SR flip-flop, we add a pair of three-input AND gates. Remember, with this type of gate, the only way to get a 1 at the output is to have a 1 in all three inputs. The output circuitry consists of another three-input AND gate. The information in the memory cell is stored as the value of Q.

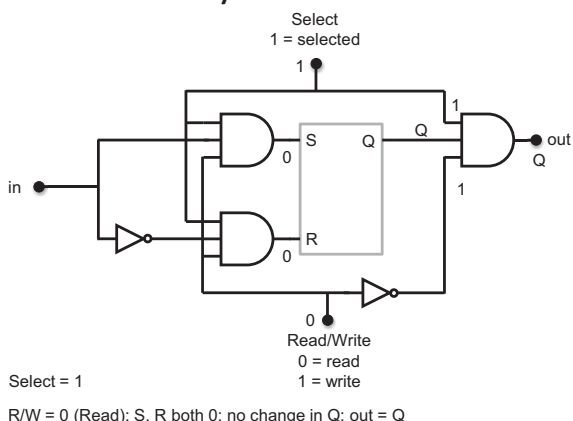
A 1 at the select line means that this memory cell is selected to be read or written to. A 0 at the select line means that the memory cell is inert. The read/write line tells us whether we want to read the information that's in the memory or write new information to the memory.

1-Bit Memory Cell

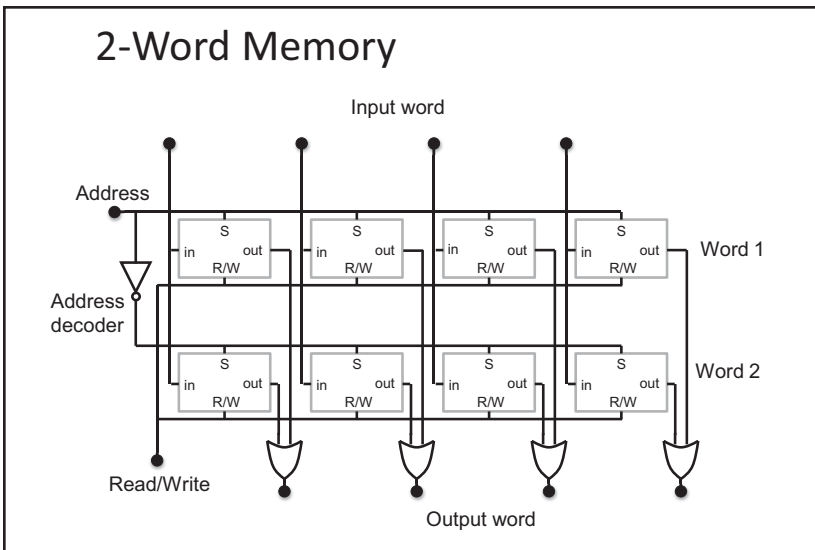


A 1 is needed to select this memory cell. If there is a 0 on the select input, the AND gate outputs (the S, R inputs to the flip-flop) are both 0, and Q can't change. Further, the output is 0 regardless of what Q is because the output AND gate has a 0 at one of its inputs.

1-Bit Memory Cell



What if we select this cell and set the read/write to 0 (meaning *read* in this configuration)? Now, the output AND gate is open, in the sense that the value of Q “gets through” to the output of the memory cell. If Q is 1, we get 1 at the output because all three inputs to the AND gate are 1. If Q is 0, we get 0 at the output. Here, we’re reading the memory cell. We can’t change Q in this configuration, but we can find out what Q is. On the other hand, if we set the read/write input to 1, the output gate is closed, and we can’t tell the value of Q from the output. But in this state, the input to the memory cell “gets through” the input AND gates, and we set or reset the flip-flop, loading the input into Q. Thus, we’ve written information to the memory cell.



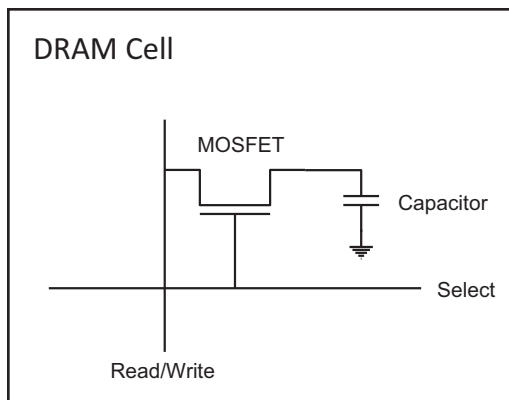
Computers have many (billions!) of words, usually of 64 bits each. Above is a simple example of a multiple-word memory, in this case containing two words of 4 bits each. Each word has a select line, and the select lines of all the memory cells in each word are tied together. The output lines of the corresponding bits from each word are tied together through OR gates. Thus, whichever word is selected, we can read or write from/to that word only.

Here, the address requires just a 1 or a 0 because there are two input words. If it's a 1, we address the upper word because the address line is connected

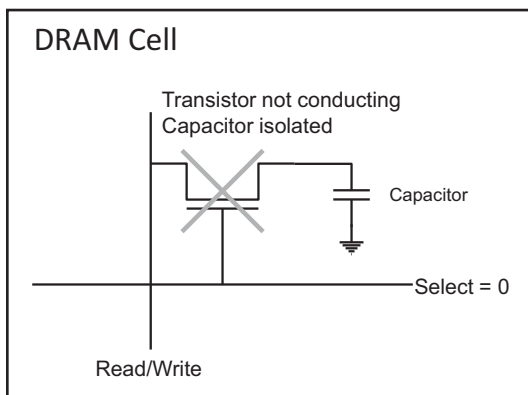
directly to all the selects of Word 1. If it's a 0, the inverter causes us to select Word 2. The address decoding logic gets much more complicated with billion-word memories, but the idea is the same.

Static versus Dynamic Memory

In static memory, the basic information storage unit is a flip-flop. It's a volatile memory, but it's energy efficient and fast. It also takes up space, however, and it's a bit expensive. The memory used in most computers, dynamic RAM (DRAM), is much simpler. Its basic information storage unit is the capacitor.



DRAM has two lines—a select line and a read/write line. It has a capacitor that is built onto the integrated circuit chips. A MOSFET turns on or off, in this case, depending on whether we put a 1 or a 0 on its gate.



If we put a 0 on the select line that is connected to the gate, then the capacitor is isolated because the transistor is off. Putting a 1 on the select line turns on the MOSFET transistor. We can then write to the memory cell by putting charge through the MOSFET

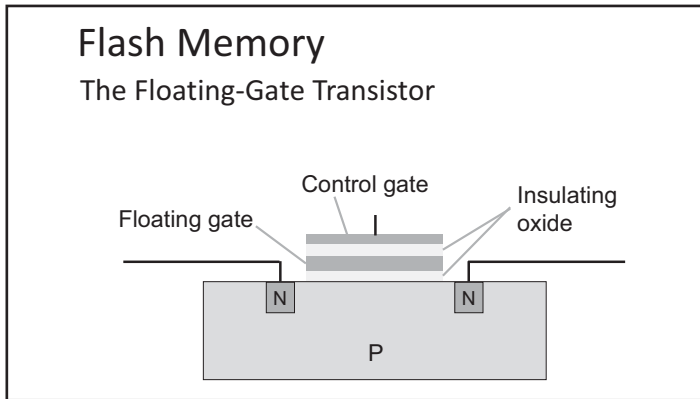
and onto the capacitor. Or we can read the memory by sensing whether or not there's a voltage on the capacitor.

But capacitors gradually lose their charge, and so we need to go through the entire memory periodically and read the state of each capacitor. If a capacitor is in the 1 state, we boost it back up to maximum charge. This is typically done about 15 times each second. It's this "dynamic refreshing" of the memory that accounts for the *D*, for *dynamic*, in the term *DRAM*.

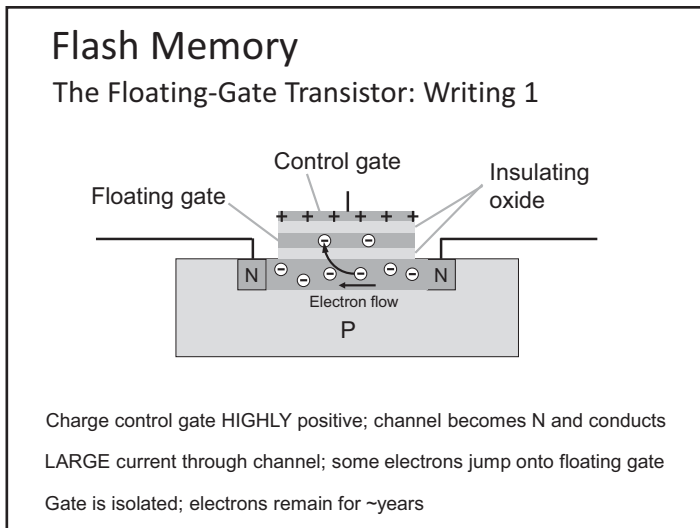
Types of Memory

Type	Speed	Volatile	Access	Uses/Comments
SRAM	Fastest	Yes	Random	Small, high-speed memory
DRAM	Fast	Yes	Random	Main memory in computers, etc.
ROM PROM EPROM	Slower	No	Random	Storing permanent information, startup sequences, etc.
Flash	Slower	No	Random	Long-term storage in smart devices, tablets, "flash drives," increasingly in computers
Magnetic disk	Slow	No	Sequential	Long-term storage in computers Uses spinning magnetic disk Rapidly giving way to flash storage
Optical disc	Slow	No	Sequential	CDs, DVDs for music, video, computer data Data read/written by laser
Tape	Very slow	No	Sequential	Backup and archives
Magnetic core	Slow	No	Random	Obsolete; used tiny magnetic rings on intersecting wires

Flash Memory

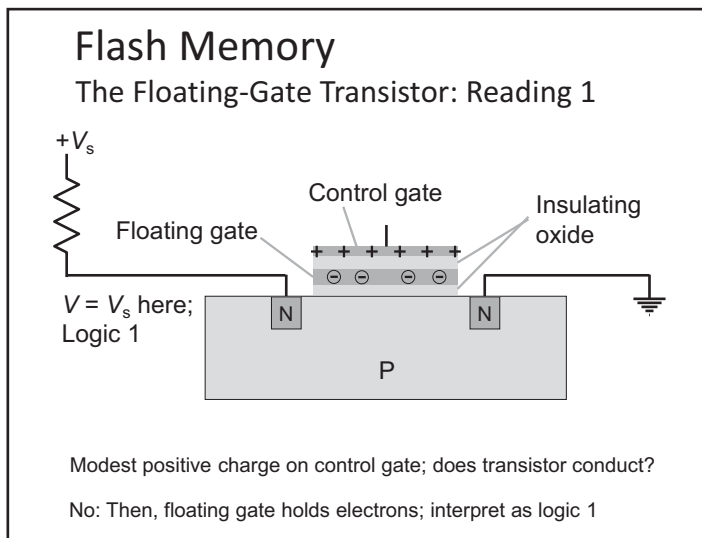


Flash memory uses transistors that look similar to MOSFETs, except they have an extra gate, called a *floating gate*, sandwiched between two layers of insulation.



If we want to write a 1 to this floating-gate transistor, we put a highly positive charge on the control gate. That voltage pulls electrons into the channel, which becomes N-type and conducts. Some of the electrons that are

conducted through the channel undergo a process called *quantum tunneling*, in which they leap onto the insulated gate. The presence of those electrons tells us that we have a 1 stored in that memory unit. If we want to write a 0, we put a highly negative charge on the control, and if there are any electrons in the floating gate, they're pushed out through the insulation and into the substrate.



If we want to read this transistor, we put a modest charge on the control gate. If the transistor doesn't conduct, that means the floating gate has some electrons on it. That situation is interpreted as a logic 1. If the transistor does conduct, then the floating gate doesn't have any electrons; that's a logic 0.

Suggested Reading

Introductory

Brindley, *Starting Electronics*, 4th ed., chapter 11, pp. 194 to end.

Lowe, *Electronics All-in-One for Dummies*, book VI, chapter 5, pp. 596 to end.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 14, sections 14.2.2–14.2.3.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 12, section 12.12.

Projects

Memory Cell Simulation

Simulate the 1-bit memory cell described in this lecture. In CL, you'll need to make three-input AND gates; DC allows you to select the number of gate inputs. Clock the read/write input and the data input at a slower rate (1/4 as fast is good).

4-Word, 4-Bit Memory

Consider a 4-word by 4-bit memory, similar to the 2-word memory described in this lecture. Design (but don't build) an address decoder for this memory. You'll need two address lines to address four words.

Questions to Consider

1. Both RAM and your hard drive or solid-state drive (SSD) are forms of memory. How are they different, and what's the purpose of each in your computer?
2. What's the difference between volatile and nonvolatile memory?
3. Find out how much RAM is in your computer, as well as the capacity of its SSD or hard drive.
4. Your phone, tablet, flash or USB drive, and many other devices use flash memory for long-term storage. Describe the physical principle behind flash memory.
5. How is a computer's word length related to the maximum amount of RAM that can be installed in the computer?

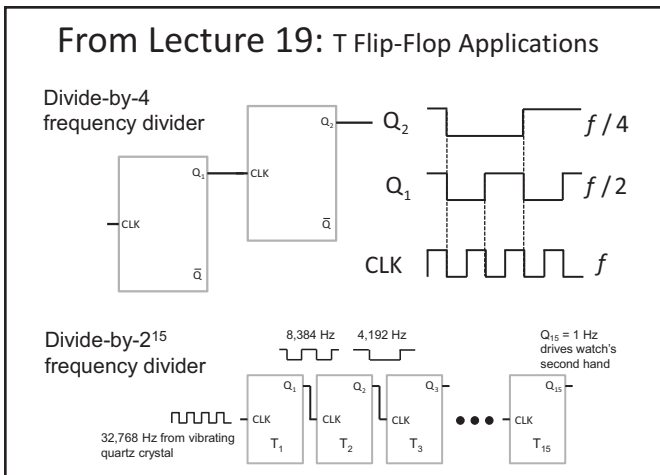
Digital Counters

Lecture 21

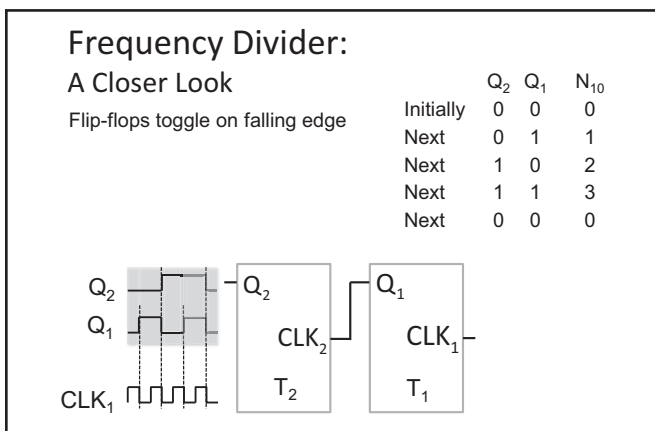
In the last lecture, we enabled digital circuits to remember information; in this lecture, we'll enable them to count. Of course, counting has many applications: in business (counting products on the assembly line), in the medical profession (counting blood cells), in physics, even in archaeology (counting atoms for carbon dating). Counters also have other, less obvious uses, such as making conversions between the analog and the digital realms. We'll begin our exploration of counters by looking at some of the questions and subtleties involved in building electronic counters. Important topics we'll cover include:

- Frequency dividers and counters
- A 2-bit binary counter
- n -bit binary counters
- Decade counters
- Asynchronous versus synchronous counters and the JK flip-flop
- Application: a practical counting device.

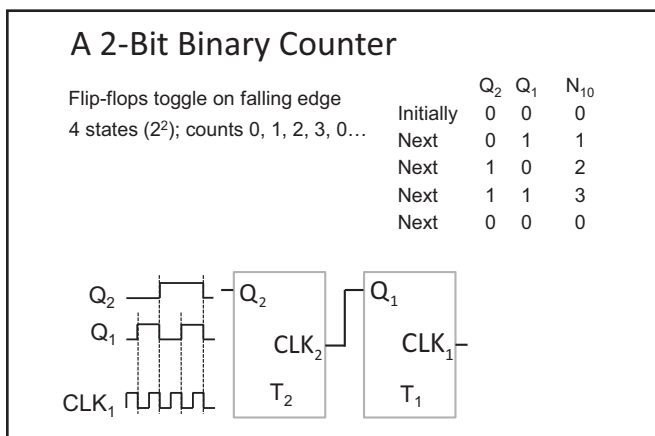
Frequency Dividers and Counters



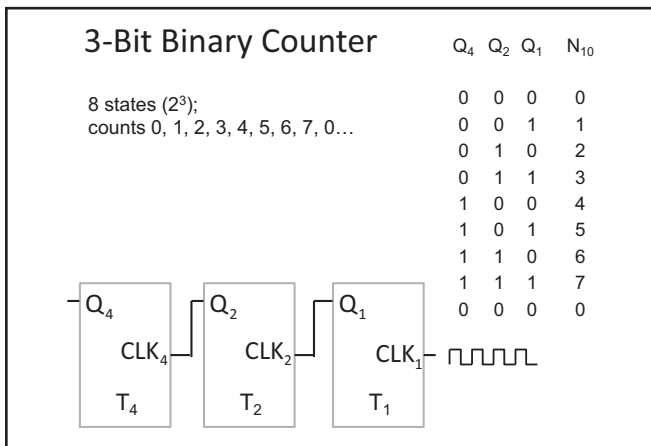
In Lecture 19, we saw the divide-by-4 frequency divider, which consisted of two toggle flip-flops connected so that the output of one went to the clock input of the other, and each one went at half the rate of the clock signal coming into it.



Here, the frequency divider is redrawn with the flip-flop on the right (T_1) receiving the clock input (CLK_1). We'll treat that as binary digit 1, the digit in the 1s column. The output of T_1 , the Q_1 connection, is connected to the clock input of T_2 ; its output is Q_2 . The 2 here stands for the 2s bit, the number we would multiply by 2 to find the decimal representation of the binary number in this flip-flop combination.



When we translate the intermediate outputs to decimal numbers, we can see that this device is not only a frequency divider but also a counter. With two flip-flops, we have two binary digits, which leads to only four possible combinations. These represent the decimal numbers 0 to 3. If we have n flip-flops, the number of combinations is 2^n .

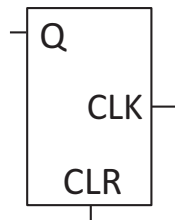


With a 3-bit binary counter, we can represent 2^3 , or 8, states. These represent the decimal numbers 0 to 7.

Decade Counters

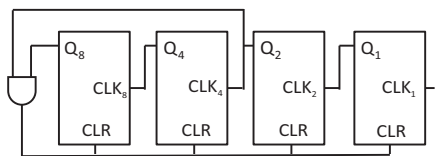
What if we want to count some number of states that isn't a power of 2? Logic gates help with that problem, along with a flip-flop that has a minor modification. On this toggle flip-flop with clear (CLR), if we put a 1 on CLR, no matter what else is happening, Q goes right to 0.

Toggle Flip-Flop with Clear



1 at CLR sets $Q = 0$ regardless of what else is happening

Decade Counter (BCD Counter)



Gates cause reset at 10

States of a
4-Bit Binary Counter

Q ₈	Q ₄	Q ₂	Q ₁	N ₁₀
0	0	0	0	0
0	0	0	1	1
0	0	1	0	2
0	0	1	1	3
0	1	0	0	4
0	1	0	1	5
0	1	1	0	6
0	1	1	1	7
1	0	0	0	8
1	0	0	1	9
1	0	1	0	10
1	0	1	1	11
1	1	0	0	12
1	1	0	1	13
1	1	1	0	14
1	1	1	1	15

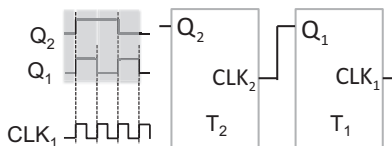
A decade counter consists of four T flip-flops with CLR connected to the output of an AND gate. If we encounter a condition in which both Q₈ and Q₂ go high, corresponding to the decimal number 10, the counter is set back to 0. So this counter counts from 0 to 9, but on the next clock pulse, it goes back to 0. A decade counter is also called a *binary coded decimal* (BCD) counter.

A 2-Bit Binary Down Counter

Flip-flops toggle on rising edge

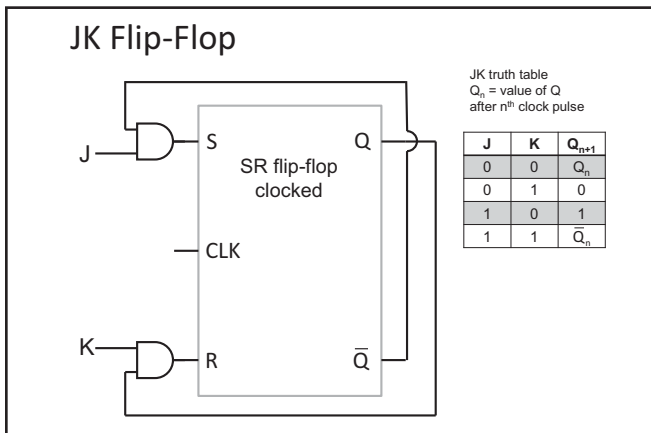
4 states (2²); counts 0, 3, 2, 1, 0...

	Q ₂	Q ₁	N ₁₀
Initially	0	0	0
Next	1	1	3
Next	1	0	2
Next	0	1	1
Next	0	0	0

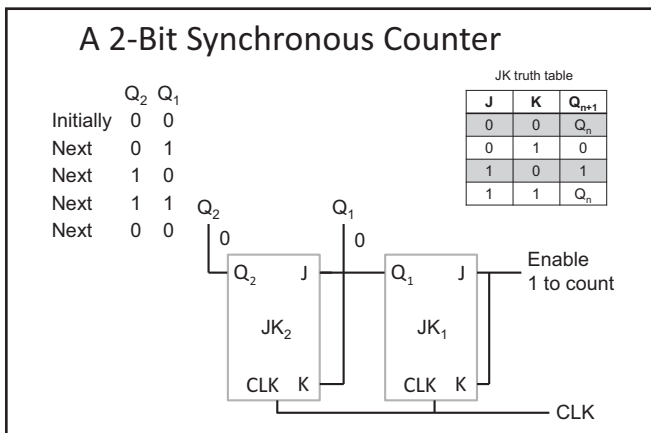


The easiest way to count down is to change the flip-flop to change state on the rising edge of the clock.

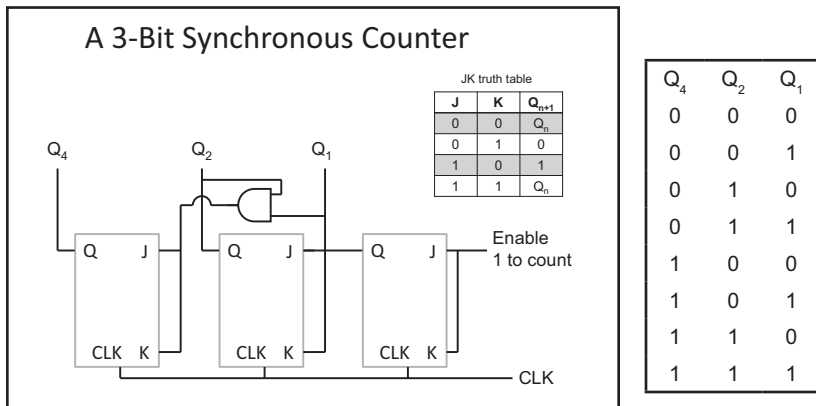
Asynchronous versus Synchronous Counters and the JK Flip-Flop



Digital gates have a *propagation time*, typically measured in nanoseconds, for the input to change the state of the flip-flop. Because of this, the count ripples through from one flip-flop to the next. Briefly, while it's rippling, the output lines have intermediate states that are not the correct count. A solution to this problem is to build a *synchronous counter* that clocks all the flip-flops together so that they all change at the same time. That requires either gating or more sophisticated flip-flop design or both. The JK flip-flop is a versatile flip-flop that can be used to build the synchronous counter.

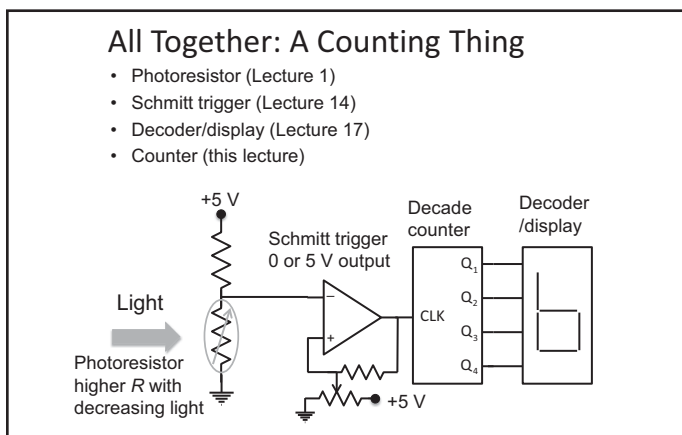


If the J and K inputs to a JK flip-flop are both 0, nothing happens. If J and K are both 1, then the device becomes a T flip-flop and toggles on the clock pulse. Here JK_1 is wired so it toggles on each clock pulse, but JK_2 toggles only when $Q_1 = 1$, making this a 2-bit synchronous counter.



A 3-bit synchronous counter is more complicated because it also requires gating. The key point to remember with any synchronous counter is that all the flip-flops have their clocks connected, so they change state at once.

Application: A Practical Counting Device



A circuit for a practical counting device consists of a photoresistor, a Schmitt trigger, a decoder/display, and a counter. It works by having the objects to be counted interrupt a light beam. This causes the Schmitt trigger to produce a single output pulse, which feeds the clock input of the counter. Thus, the device counts the number of interruptions of the light beam.

Suggested Reading

Introductory

Shamieh and McComb, *Electronics for Dummies*, 2nd ed., chapter 7, p. 165.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 10, section 10.5.2.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 12, pp. 781–802.

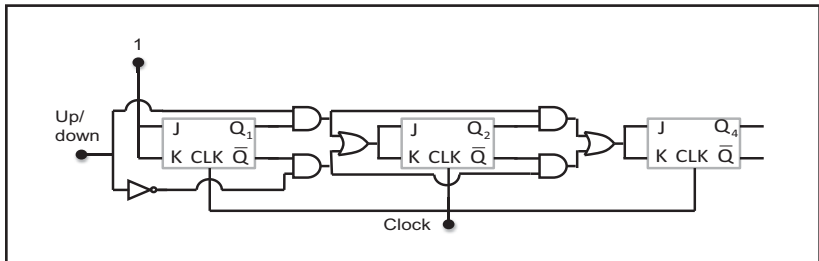
Projects

Exploring JK Flip-Flops

Explore your circuit simulator's built-in JK flip-flop. Is it rising- or falling-edge triggered? Verify the JK truth table.

Counter Simulation

Simulate the 3-bit synchronous up/down counter shown below. Verify that it counts both up and down.



Questions to Consider

1. What does *BCD* stand for, and what distinguishes a BCD counter from a 4-bit binary counter?
2. What's the difference between ripple and synchronous counters? What's the advantage of the latter?

Digital to Analog

Lecture 22

These days, electronics is increasingly digital. It's easier to store and process digital information; digital information gives us more bandwidth; and we can deal with more information at once in digital form. But we need to convert signals from the analog world—sound, light intensity, electrical voltages, speed, temperatures—to digital. In this lecture and the next, we'll look at how to do that conversion, starting with the easier topic, digital to analog. Key topics we'll cover include the following:

- Phones, music, and more: why we need analog/digital conversions
- Digital-to-analog converters (DACs)
- A weighted-resistor DAC
- A ladder DAC
- In your phone: the delta-sigma DAC.

Phones, Music, and More

When you talk on a cell phone, analog sound comes out of your mouth, is picked up by the microphone in the phone, and goes through an analog amplifier. Then, an analog-to-digital converter converts the sound intensities into a series of digital numbers. That information goes to a modulator, which uses it to alter a radio frequency signal produced by a transmitter inside the phone. That signal goes to the phone's antenna and out over the airwaves to a cell tower.

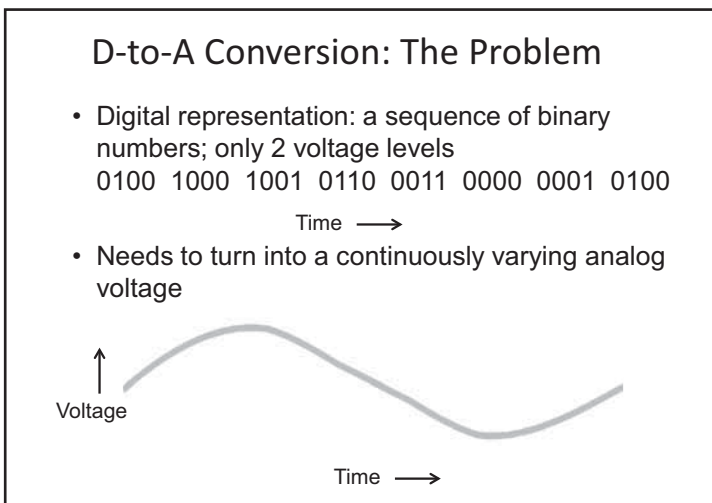


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The cell tower picks up the signal, cleans it up, amplifies it, and rebroadcasts it, using filters to distinguish it from nearby frequencies of other incoming

phone calls. The radio receiver in the recipient's phone picks up the signal and sends it through a demodulator, which extracts the stream of 1s and 0s that represents the digital information. That bitstream goes through a digital-to-analog converter (DAC), whose output is an analog signal—a continuously varying voltage. That signal then goes through an audio amplifier and on to a speaker or headphones, which produce analog sound. Almost all modern phones use this digital conversion and exchange data in digital form.

Digital-to-Analog Converters (DACs)

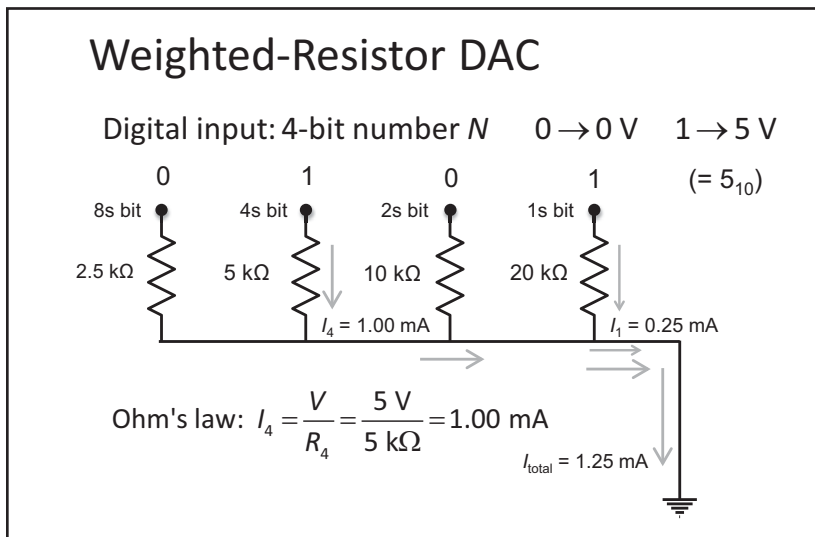


The digital representation of a quantity, such as a time-varying sound intensity or a time-varying voltage, is a sequence of binary numbers. A CD, for example, stores sound intensities as 16-bit numbers. It records these 16-bit numbers at the rate of about 44,000 times every second. Playing the sound requires a digital-to-analog converter. The DAC produces a continuously varying analog voltage that is amplified and played through loudspeakers or headphones.

The problem here is that there are always gaps in the conversion of analog information to digital. We know, for example, the sound intensity at one time and the sound intensity at a later time, but we don't know it in between. We

have to assume that those gaps are filled in continuously. We thus turn the string of digital numbers into an appropriate analog waveform. In the figure above, that waveform, resulting from the string of 4-bit numbers shown, is approximately sinusoidal.

A Weighted-Resistor DAC



One of the easiest ways to perform digital-to-analog conversion is with *weighted currents*: We use each bit in the binary number to produce a current, and we weight those currents by the significance of the bit. The 1s bit is the least significant bit (LSB), and the maximum number of bits (e.g., the 8s bit when we're dealing with 4-bit numbers) is the most significant. We then sum those weighted currents and convert the result to an analog voltage, which corresponds to the binary number originally fed into the device. This process is implemented with precision-weighted resistors, which make different currents flow for the same voltage.

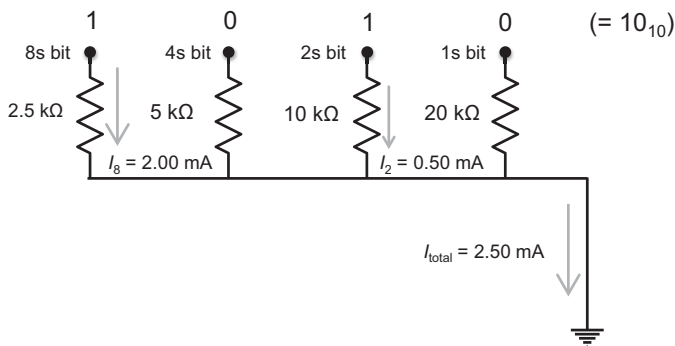
In the DAC shown here, the 8s bit goes to ground through a 2.5-k Ω resistor; the 4s bit goes to ground through a 5-k Ω resistor, which means that a 1 at the 4s bit will produce half the current of a 1 at the 8s bit. The 2s bit

goes through a 10-k Ω resistor to ground, and the 1s bit goes through a 20-k Ω resistor.

It's crucially important that these resistors all go to ground. If there were any resistance in the common ground connection, then the current in each resistor would be influenced by other currents. Also, it's important to feed the DAC with precise voltages, either 0 V or 5 V in the figure shown. Using the outputs of logic circuits (which we'll use in order to simplify our circuits) isn't as accurate because there are voltage ranges, rather than precise voltages, for each of the two logic levels.

Weighted-Resistor DAC

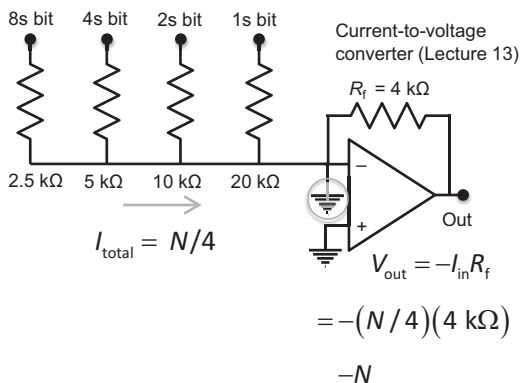
Digital input: 4-bit number N 0 \rightarrow 0 V 1 \rightarrow 5 V



What happens when we put in the decimal number 10, represented in binary as 1010? That puts 5 V across the 2.5-k Ω resistor, causing 2 mA to flow. It puts 5 V across the 10-k Ω resistor, causing 0.5 mA to flow. Those two currents merge, giving a total current of 2.5 mA. This is a DAC that produces a current, in milliamps, whose value is $\frac{1}{4}$ of the input number ($N/4$).

Weighted-Resistor DAC

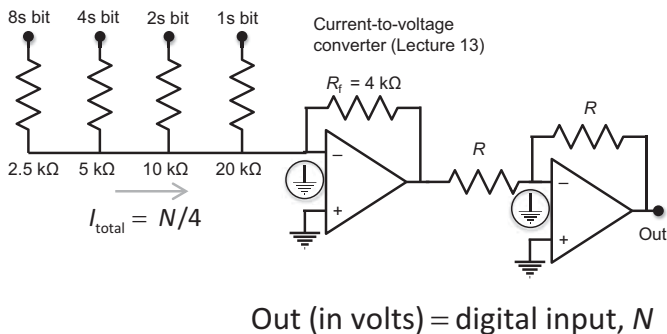
Digital input: 4-bit number N $0 \rightarrow 0\text{ V}$ $1 \rightarrow 5\text{ V}$



We can turn that into a combined current-to-voltage converter. As we saw in Lecture 13, $V_{\text{out}} = -I_{\text{in}} R_f$. In this case, the current coming in is $N/4$; with the $4\text{-k}\Omega$ feedback resistor, this yields a voltage whose numerical value is equal to the negative of the input binary number: $-N$.

Weighted-Resistor DAC

Digital input: 4-bit number N $0 \rightarrow 0\text{ V}$ $1 \rightarrow 5\text{ V}$

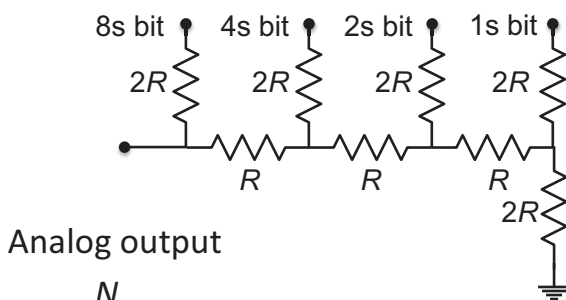


If we want to eliminate the negative result, we can add a unity-gain inverter. As you recall, this circuit produces a gain of R_f/R_{in} ; here, that ratio is -1 . So the output in volts is equal to the digital input number, N .

A Ladder DAC

A Better DAC: R – $2R$ Ladder

Digital input N : 4 bits, 0 or V volts; logic 0 or logic 1

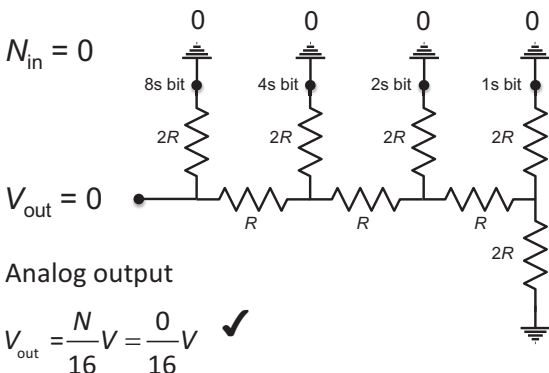


$$V_{\text{out}} = \frac{N}{16} V$$

Weighted-resistor DACs are not the best DACs because it's hard to match resistors that have very different values. Using a $20\text{-k}\Omega$ resistor and a $2.5\text{-k}\Omega$ resistor and getting the two resistances right is very difficult. Further, the more bits to be converted, the wider the range of resistors that must be used. A better DAC is the R – $2R$ ladder. This device is much easier to match because it uses only two different resistor values. Its analog output is a voltage rather than a current.

A Better DAC: R - $2R$ Ladder

Digital input N : 4 bits, 0 or V volts; logic 0 or logic 1

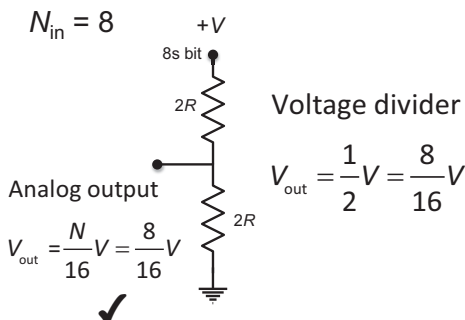


Because this device is a linear circuit—all the components have currents and voltages that are linearly related—mathematically, all we need to do is determine how it works for two values, and then we'll know it works linearly for all other values.

The output of this device is $N/16$ volts; we need to show that this is true for two input values, and then, because of linearity, it will be true for all values. If we input 0000, we get $0/16$, which is 0.

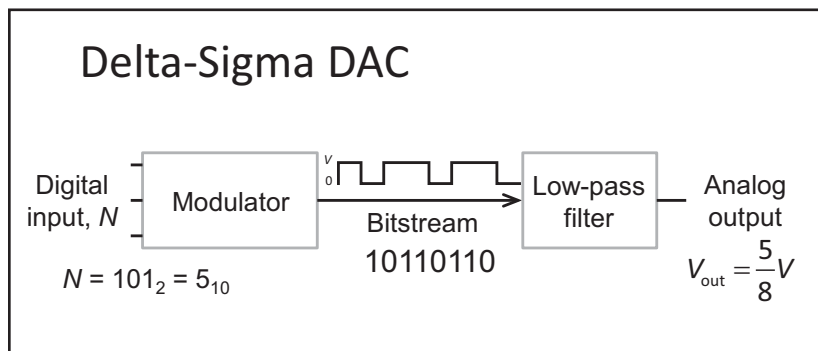
A Better DAC: R - $2R$ Ladder

Digital input N : 4 bits, 0 or V volts; logic 0 or logic 1



For a second value, consider inputting the number 8 (1000). By going through multiple reductions of series and parallel resistor combinations, we end up with a voltage divider with a division by 2. The output, then, must be half the input, or $\frac{8}{16}V$, where V is the supply voltage.

In Your Phone: The Delta-Sigma DAC



The delta-sigma DAC has a digital input corresponding to N bits and a modulator. The modulator is a circuit that looks at that digital number and produces a bitstream (a stream of 1s or 0s), making the relative proportion of 1s in that stream proportional to the value of the input number. The digital output is then passed through a low-pass filter, which smooths out the variations and produces an analog output that is basically the average of all those bits; the more 1s, the higher that average. This is how the DACs in most common electronic devices work.

Suggested Reading

Introductory

Shamieh and McComb, *Electronics for Dummies*, 2nd ed., chapter 7, p. 166.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 13, sections 13.1–13.4.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 12, section 12.10.5.

Project

DAC Simulation

Simulate the 4-bit weighted-resistor DAC described in this lecture, including the two op-amps. Test with one of the following options:

- Apply all 16 different combinations of binary inputs and run a DC simulation for each combination.
- Connect the DAC inputs to the outputs of the counter simulated in the project for Lecture 21.
- Simulate a counter with four clocks or square-wave generators running at different frequencies.

Questions to Consider

1. Why is a weighted-resistor DAC less practical than an R - $2R$ ladder DAC?
2. Why are the inputs of a DAC labeled 1, 2, 4, 8 rather than 1, 2, 3, 4?
3. When a counter is used to feed the inputs of a DAC, the output of the DAC as viewed on an oscilloscope resembles a staircase. Why?

Analog to Digital

Lecture 23

In this lecture, we will build the most sophisticated circuits we'll work with in this course. They'll combine material from throughout the course, including op-amps, counters, DACs, and more. We'll put these all together as we work on analog-to-digital conversion, the more difficult part of the process of moving from the analog world into digital electronics and back to analog again. Key topics include the following:

- Characterizing analog-to-digital converters
- Sampling and the Nyquist criterion
- Flash converters
- Integrating converters
- Feedback converters.

Characterizing Analog-to-Digital Converters

Analog-to-Digital Specifications

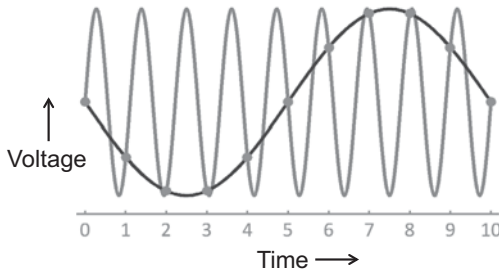
- Speed
 - How much time to convert?
 - How many conversions per second?
 - Are time/rate fixed or dependent on input value?
- Precision
 - How many bits or digits does the A-to-D converter produce?
 - CD: 16 bits
 - Typical camera: 3 colors, 8 bits each
 - Digital scales: 3–4 digits

Analog-to-digital converters (ADCs) are characterized by speed and precision.

Sampling and the Nyquist Criterion

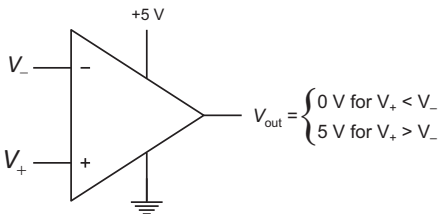
Sampling: The Nyquist Criterion

For accurate representation of an analog signal, the minimum sample rate must be at least twice the highest frequency of interest.



The Nyquist criterion states: For accurate representation of an analog signal, the minimum sample rate must be at least twice the highest frequency of interest. If the rate is lower, reconstructing the analog signal from the digitized values may result in an entirely different waveform, as suggested in the figure above. A CD, for example, samples at 44.1 kHz. The ADC in the recording system determines the analog sound intensity 44,100 times per second and stores each result as a 16-bit binary number representing one of 2^{16} possible sound levels. The 44.1 kHz is chosen because the upper limit of what we can hear is on the order of 20 kHz; thus, we're digitizing at somewhat more than twice that rate, enabling us to accurately capture the highest audible frequencies.

Logic-Level Comparator

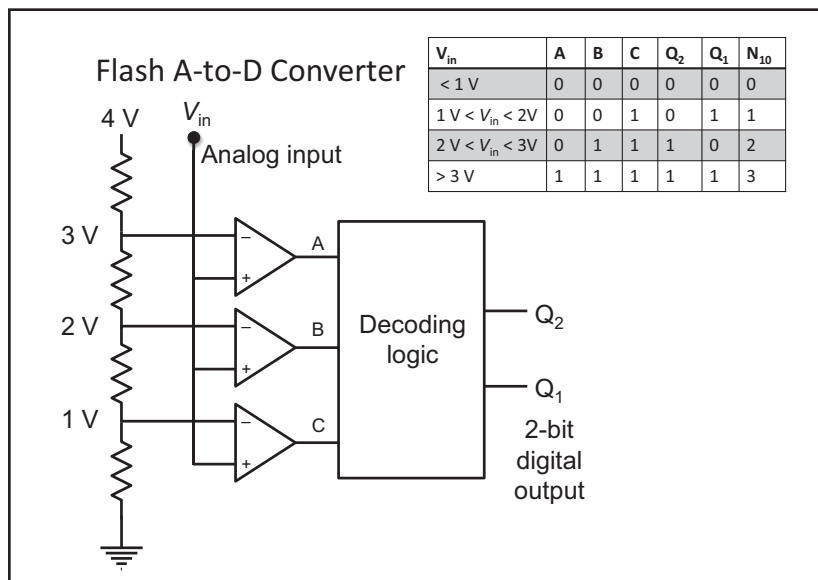


Logic-Level Comparator

A logic-level comparator resembles a regular op-amp except it runs off a 5-V power supply if it's being used with TTL. The other end of the power supply is not -15 V but ground. As a result, the comparator's

output swings between 0 V and 5 V. If we run it open loop—that is, with no feedback—we get 0 V at the output if V_+ is less than V_- and 5 V, or logic level 1, at the output if V_+ is greater than V_- . There's some latitude in those numbers, but they're good enough to determine definitively whether we have logic 0 at the output or logic 1. We'll make use of the logic-level comparator in several ADC designs.

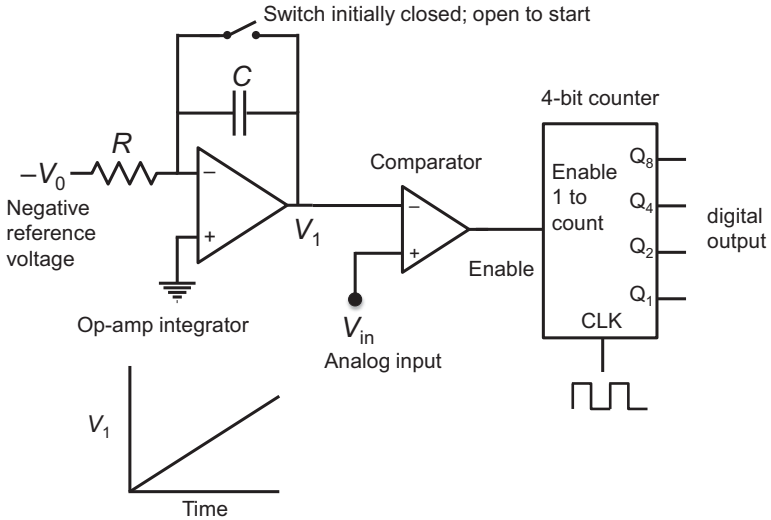
Flash Converters



The flash ADC compares an analog input against a range of discrete voltages that are built into the converter. The process of conversion in this circuit is almost instantaneous. If there are just a few bits and we don't need high precision, this is a simple converter to use, but it gets complicated quickly if we have many bits.

In this flash ADC, we have three comparators whose outputs are three binary digits that tell us whether the input voltage is greater or less than the threshold voltage for each comparator. We then need a logic circuit that decodes that set of bits into a binary representation of the input voltage.

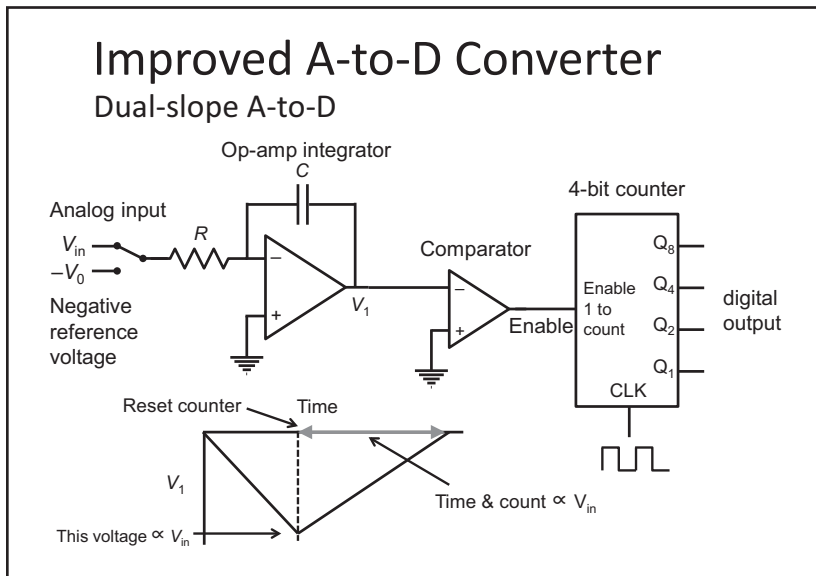
Integrating A-to-D Converter



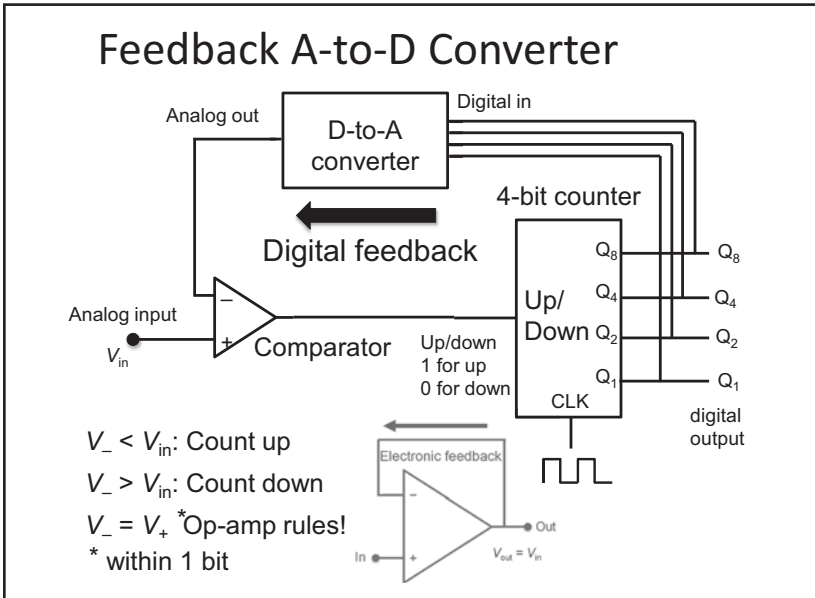
We talked about integrators when we put capacitors together with op-amps. In particular, we saw that if we applied a steady voltage to an integrator, we got a voltage at the output of the op-amp that rose or fell at a steady rate. What integrating ADCs do is charge the capacitor at a steady rate, using a known reference voltage or an unknown analog voltage.

If we charge the capacitor at a steady rate using a known reference voltage, run a counter while the capacitor is charging, and have a comparator that tells the counter to stop when the capacitor voltage reaches the analog input, then the time that the counter has been running will be proportional to that analog input voltage, and thus, the output of the counter will be a digital number proportional to the analog input.

In this integrating ADC, we have an integrator to which we apply a negative reference voltage. When we open the switch across the capacitor, the capacitor voltage starts to rise at a steady rate. When the capacitor voltage rises above the analog input voltage, the comparator has a larger voltage at its negative input, and its output goes to zero, disabling the counter. The count is then a digital representation of the input voltage.



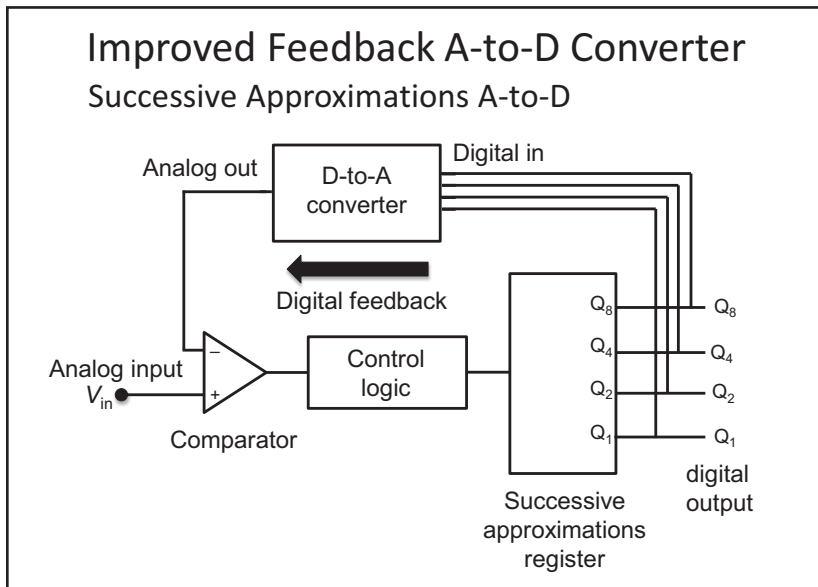
The dual-slope ADC uses the same basic technique, but it integrates, first, the unknown voltage until the counter is completely full. Then, it switches and integrates a reference voltage. The time it takes to do that depends on what that initial input voltage was, and the count that comes out at the end is, therefore, proportional to the input voltage. Dual-slope integrators are widely used in applications where precision is required, in part because small variations in resistance, capacitance, or clock frequency don't affect the conversion.



With a feedback ADC, we essentially make an ADC by putting a DAC in a feedback loop. We see here an analog input coming into the noninverting input of a comparator. We also see a 4-bit up/down counter. We then put a DAC into the feedback loop of the op-amp. Part of the feedback circuitry is the digital output of the counter going in to the digital inputs of the DAC. The analog output of the DAC goes to the inverting input of the comparator. This gives us a complete feedback ADC.

This circuit should remind you of the simple voltage follower we developed (also shown in the figure above) in which we took the output of an op-amp and connected it directly via electronic feedback to the negative input of the op-amp. The output voltage followed the input voltage. According to the op-amp rules, the two voltages at the positive and negative were essentially the same. This more complicated circuit for the ADC does essentially the same thing. It has an op-amp that is a comparator connected with a digital feedback loop. With our understanding of negative feedback, we could guess

that this circuit tries to keep the inverting input—the output of the DAC—at the same voltage as the unknown voltage we’re bringing in. For that to happen, the input to the DAC must be the binary equivalent of the analog input voltage. This simple circuit “bobbles” back and forth between two binary outputs whose values are either side of the actual analog input. This is like the servo voltmeter demonstrated in Lecture 11, whose needle kept “bobbling” back and forth.



A *successive approximations ADC* is an improved version of the feedback ADC whose conversion time is independent of the analog input voltage.

Suggested Reading

Introductory

Shamieh and McComb, *Electronics for Dummies*, 2nd ed., chapter 7, p. 166.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 13, sections 13.5–13.7.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 12, section 12.10.6.

Project

Feedback ADC Simulation

Simulate a 3-bit version of the feedback ADC described in this lecture. Use your DAC/3-bit counter combination if you built it in Lecture 22. Add a comparator (CL: under Digital Gates). Plot the DAC output on one graph and $Q_{1,2,4}$ on another. You can add 6 V and 12 V to Q_2 , Q_4 for clearer graphics. Verify operation for several DC input voltages. As a challenge, change the input to AC (but offset for positive only); adjust clock frequency (to what value, compared with AC input frequency?); and verify that the digital output follows the AC input.

Questions to Consider

1. Name at least six devices in your household or among your possessions that must contain ADCs.
- *2. A 10-bit ADC has how many distinct digital levels?
3. What makes a flash ADC faster than an integrating or feedback type of converter?
- *4. A digital kitchen scale shows three decimal digits. What's the minimum number of bits in the ADC in this scale?

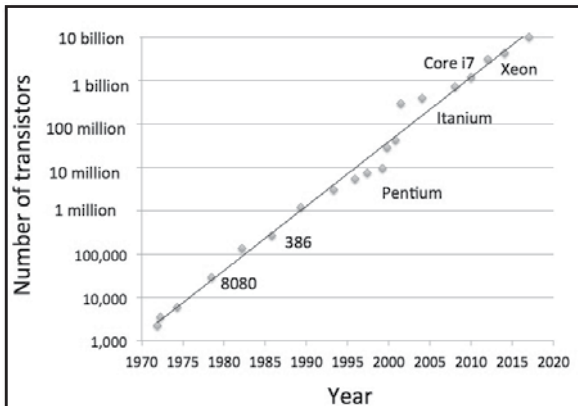
Your Future in Electronics

Lecture 24

In this lecture, we will look at two aspects of your future in electronics—as a consumer and as a creator. Even if you're not interested in building electronics, as a consumer, you will buy more electronics in the future than you have in the past because more electronic devices will be developed, and they will be, for the most part, faster and cheaper. If you've done some of the projects in this course, you may also become a creator of electronics. We've learned a number of basic building blocks, including amplifiers, flip-flops, counters, op-amps, and more. And we've seen how you can build these up from simpler circuits, ultimately based in transistors and other components. In this lecture, we will explore where your new knowledge of electronics will take you in the future.

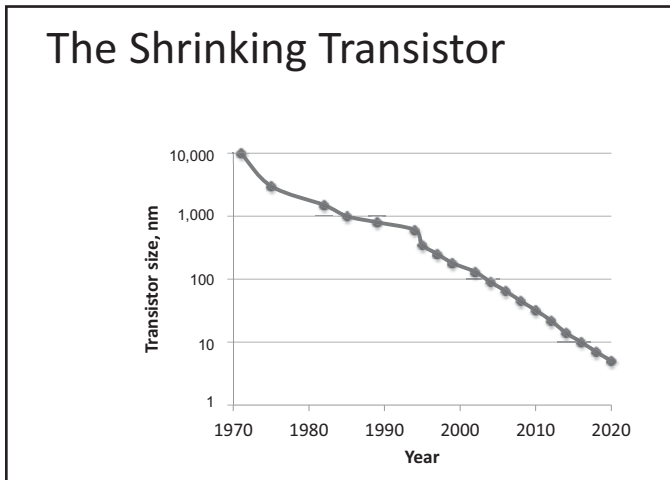
Moore's Law Revisited

Moore's Law Continues!



As we saw in an earlier lecture, in the 1960s, Gordon Moore, an engineer at Intel, predicted that the number of transistors on a given integrated circuit would

double every 18 months. Actually, since 1965, it's been approximately true that the number of transistors on an integrated chip has doubled about every two years. But we may be headed to some sort of limit around the year 2020, when transistors are shrunk down to about a nanometer (one-billionth of a meter).



We can also think about Moore's law in terms of the size of transistors. As the graph shows, that size is heading down toward the range of 10 to 1 nanometers. Of course, as transistors continue to shrink, we can fit more on a chip, which enables us to store and process more information and perform complex operations faster. Ultimately, we will develop nanoscale-size transistors.

A Quantum Limit?

- Gordon Moore: "When [during a 2005 visit to Intel] Stephen Hawking was asked what are the fundamental limits to microelectronics, he said the speed of light and the atomic nature of matter."
- Limiting transistor size:
 - Compton wavelength of the electron
 $h/m_e c = 0.0024 \text{ nm}$
 - Extrapolate: will reach in year 2036

According to Stephen Hawking, fundamental limits to microelectronics are imposed by the speed of light and the atomic nature of matter.

Future Electronic Devices

Self-driving cars have already driven hundreds of thousands of miles on the public highways of California and may be for sale around the year 2020. Such cars are an example of the kind of complexity enabled by the miniaturization of electronic circuits and computing power and by the miniaturization and reduced cost of sensors of all types. The future of electronics will see greater numbers of smart systems of all kinds.



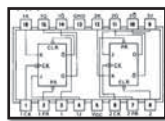
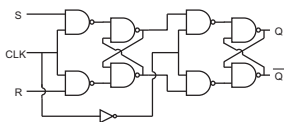
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Your Future as a Builder of Electronics

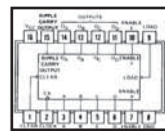
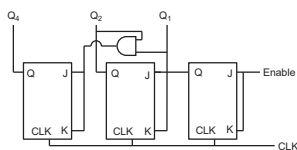
Your Electronic Future...

...as a designer/builder/doer of electronics

Don't build—buy!



7476 dual JK flip-flop



74160-series counters

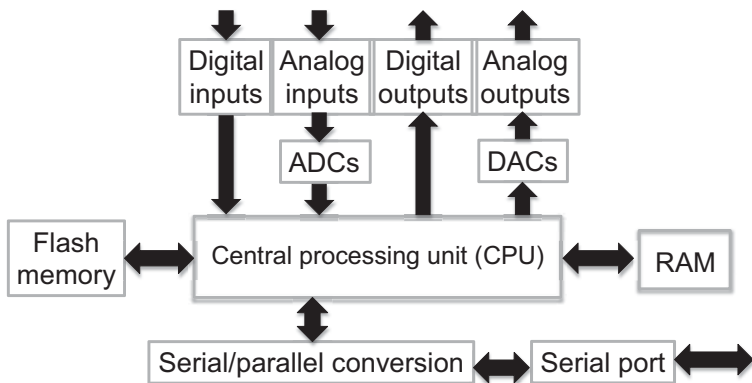
One of the most important lessons we've learned throughout this course is to buy—not build—basic circuits. For example, we saw how to build up

from a simple bistable circuit to an RS master-slave flip-flop, but if you're actually building your own electronics, you should buy an integrated circuit that already has flip-flops on it, such as a 7476 dual JK flip-flop.

Microcontrollers

Meet the Microcontroller

A Tiny Computer on a Chip















A microcontroller has a central processing unit, consisting of logic gates set up to compare, add, and perform other functions with binary numbers. It has flash memory, which we can think of as its hard drive, where it stores data and programs. It also has RAM and a serial-parallel converter and a serial port that can bring data in or out. Typically, it has both digital inputs and analog inputs that go through analog-to-digital converters. It also has digital-to-analog converters to provide analog outputs.

Arduino Code

```
int sensorPin = A0; // input pin for the potentiometer
int ledPinred = 13; // pin for red LED
int ledPingreen=12; // pin for green LED
int sensorValue = 0; // value coming from the sensor

void setup() {
  // declare the ledPin as an OUTPUT:
  pinMode(ledPinred, OUTPUT);
  pinMode(ledPingreen, OUTPUT);
}

void loop() {
  // read the value from the sensor:
  sensorValue = analogRead(sensorPin);
   if (sensorValue > 100)
   // turn the red ledPin on
   {digitalWrite(ledPingreen, LOW);
   digitalWrite(ledPinred, HIGH);
   // stop the program for <sensorValue> milliseconds:
   delay(sensorValue);
   // turn the red ledPin off:
   digitalWrite(ledPinred, LOW);
   // stop the program for for <sensorValue> milliseconds:
   delay(sensorValue);
  }
   else
   {digitalWrite(ledPingreen, HIGH);
  }
}
```

Electronics hobbyists around the world use microcontroller development boards, such as the Arduino microcontroller, to build many kinds of devices. These development boards have power receptacles, a USB input, a power input, five or six 10-bit ADCs, and digital and analog inputs. They are programmable with a rather simple coding language that you can learn very quickly. One approach to learning this programming is to download the software for your microcontroller and adapt its simple code examples for your own purposes.

Summing Up Our Course

A device built by a student at Middlebury College to track the Sun by looking for the brightest point in the sky serves as a fitting end to our course. This device is an example of electronics in the service of our planet, a way to maximize our ability to extract clean, free, nonpolluting energy from the Sun.



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Suggested Reading

Introductory

Lowe, *Electronics All-in-One for Dummies*, book VII, especially chapter 1.

Platt, *Make: Electronics*, chapter 5, experiments 34–36.

Advanced

Horowitz and Hill, *The Art of Electronics*, 3rd ed., chapter 15.

Scherz and Monk, *Practical Electronics for Inventors*, 3rd ed., chapter 13.

Questions to Consider

1. What are the ultimate limits to the shrinking size of electronic components in integrated circuits?
2. What is a microcontroller, and what relation does it bear to your laptop computer?

Answers to Selected Questions to Consider

Lecture 1

2. (a) 6 A; (b) 1440 W

Lecture 2

1. R_7, R_8, R_{12} all in parallel; R_{10}, R_{13} in parallel; R_{14}, R_{15} in series.
2. 5.7 V

Lecture 3

1. Neither measurement is successful. The ammeter's zero resistance "shorts out" R_3 , so the voltage across it becomes zero, and that's what the voltmeter reads. The current through R_3 is also zero, but that's not what the ammeter reads, because the meter isn't in series with R_3 . It reads the current through the series combination of R_1 and R_2 , which is $V/(R_1 + R_2)$. The ammeter will be damaged (or blow its fuse) if this current exceeds the maximum current the meter can handle.
2. Time.

Lecture 5

1. (a) It acts as an open circuit or very high resistance; (b) it acts as a short circuit or very low resistance.

Lecture 7

3. 5.8 k Ω

Lecture 8

1. -15
3. (a) The load resistance; (b) the supply voltage.

Lecture 11

2. Mechanical, optical, thermal.

Lecture 14

1. $V_{\text{out}} = V_1 - V_2/2$

Lecture 16

2. $\bar{A} \cdot B$

A	B	Out
0	0	0
0	1	1
1	0	0
1	1	0

Lecture 23

2. 2^{10} , which is 1024.
4. The minimum number is 10 because a three-digit scale reads from 0–999, and $2^{10}=1024$, the next higher power of 2. But if the conversion itself is done in binary-coded decimal, for instance, by using BCD counters, then 12 bits will be needed—4 for each decimal digit.

Bibliography

Notes: *Understanding Modern Electronics* is designed to be a standalone course introducing you to the concepts and devices behind modern electronics. Nevertheless, you can increase your knowledge of electronics with additional readings. I've chosen six books for suggested readings, although there are plenty of other good books available that you may also find helpful. You don't need to read any of the suggested books, and you certainly don't need to read them all. However, if you want to do some supplementary reading, I suggest starting with one of the introductory-level books; then, if you want to go deeper, look for one of the more advanced books.

The books I recommend here fall into two categories. First are four introductory-level books, Keith Brindley's *Starting Electronics*, Charles Platt's *Make: Electronics*, and two books in the *For Dummies* series. (Don't be put off by the *Dummies* titles; these are actually quite good introductions to electronics.) These beginning books don't go into as much detail on how electronic components work, and most don't get as far as the more sophisticated circuits discussed in the course. However, they're good for their simple analogies that help you understand electronic devices and circuits, and they get you quickly into building practical circuits without a great deal of theoretical background. They're especially helpful with advice on practical aspects of electronic circuit construction—tools, soldering, circuit boards, sources of electronic components, and so on. Because this course doesn't cover those topics, the books can be especially helpful if you're interested in pursuing actual construction of, and experimentation with, electronic circuits—something I hope you'll be inclined to try after viewing the course. (You'll also get some experience “building” circuits with software simulation if you undertake the projects associated with each lecture.)

None of the books follows the same sequence as this course, which means that the suggested readings jump around somewhat, and you'll sometimes

find the same suggested readings repeated because a given chapter in the introductory books covers the material of several lectures in a way that makes it hard to break out specific sections to associate with specific lectures. Not every book includes suggested readings for every lecture.

In addition to the introductory books, I've included two more advanced books: Paul Scherz and Simon Monk's *Practical Electronics for Inventors* (3rd edition) and Paul Horowitz and Winfield Hill's *The Art of Electronics* (3rd edition). Both are oriented toward practical circuit design but without the construction tips included in the introductory books. Both go into electronics at significantly greater depth than does this course. Scherz and Monk's book is generally at a slightly lower level than that of Horowitz and Hill and may be easier to read cover to cover (and it's less expensive). For decades, Horowitz and Hill has been a standard reference tool for doing practical electronic circuit design, and I recommend it highly for serious electronics experimenters—especially if you can find a used edition. That may be a bit difficult given that the third edition was published in 2014, although the 1989 second edition remains a valuable reference book despite the fact that some of the individual components it describes have become obsolete.

Finally, I've included in the bibliography several more introductory-level books that you might find helpful, although they aren't listed specifically in the suggested readings.

Boysen, Earl, and Harry Kybett. *Complete Electronics: Self-Teaching Guide with Projects*. Indianapolis, IN: John Wiley & Sons, 2012. As the name implies, this book embodies a self-teaching approach to electronics. It covers only analog electronics, corresponding roughly to Lectures 1 through 15 of the course, although it goes deeper into some topics, such as resonant circuits. The book incorporates numerous self-tests, quizzes, and do-it-yourself projects.

Brindley, Keith. *Starting Electronics*. 4th ed. Oxford, UK: Newnes Publishing, 2011. An introductory-level book that covers, approximately, the material through Lecture 18 of this course. A good mix of practice and

theory. Because the book is published in England, its lists of parts suppliers aren't particularly useful to readers outside the United Kingdom.

Horowitz, Paul, and Winfield Hill. *The Art of Electronics*. 3rd ed. Cambridge, UK: Cambridge University Press, 2014. The definitive reference guide to the theory and practice of electronic circuit design. Emphasizes practical considerations and real devices, not just underlying theory. Great graphic collages of good circuit ideas, as well as “bad circuits” that illustrate how not to design circuits. A great reference tool for the serious electronics enthusiast.

Jung, Walter. *IC Op-Amp Cookbook*. Indianapolis, IN: H. W. Sams, 1986. Ancient by electronics standards, this book is nevertheless a delightful and practical introduction to op-amps and the dazzling array of circuits they enable.

Lancaster, Don. *TTL Cookbook*. Indianapolis, IN: H. W. Sams, 1974. Even more dated than the op-amp cookbook and based on an early and now obsolete logic family, *TTL Cookbook* remains a classic introduction to digital logic. May be difficult to find.

Lowe, Doug. *Electronics All-in-One for Dummies*. Hoboken, NJ: John Wiley & Sons, 2012. Billed as “8 books in 1,” this is a thorough and practical look at a wide range of electronic circuits. It covers most of the basic components used in the course and goes further into such topics as radio and infrared devices.

Mims, Forrest M. *Getting Started in Electronics*. 4th ed. Niles, IL: Master Publishing, 2012. Billed as “a complete electronics course in 128 pages,” this book reads less like a narrative than a series of introductions to electronic components and circuits you can build with them. Charmingly produced, with hand-lettered text and hand drawings. Includes many practical tips and some components not covered in the course.

Platt, Charles. *Make: Electronics*. Sebastopol, CA: MakerMedia, 2009. Another good hands-on introduction to electronics; at a fairly elementary level but encompassing some reasonably sophisticated projects, including a microcontroller-driven robot relevant to Lecture 24.

Shamieh, Cathleen, and Gordon McComb. *Electronics for Dummies*. 2nd ed. Hoboken, NJ: John Wiley & Sons, 2009. Another electronics book in the *For Dummies* series. Less comprehensive than Lowe's *Electronics All-in-One* but still a good, quick introduction with a nice chapter on integrated circuits.

Scherz, Paul, and Simon Monk. *Practical Electronics for Inventors*. 3rd ed. New York: McGraw-Hill, 2013. Designed to give practical advice to inventors wanting to incorporate electronics into their inventions, this book also serves nicely as a general introduction to electronics at a level somewhat more advanced and more comprehensive than this course.