



# Understanding Electronics

## A Beginner's Guide with Projects

Written and Illustrated by  
Jonathan Baumgardner





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Printed by Amazon.com



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LumiDax Electronics LLC  
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*Dedicated to my Awesome Family  
Estelle,  
Alex,  
and  
Racheal*

## Acknowledgments

I would like to thank Clifford Dax for his input and editing of this first edition. Clifford has worked at the University of Oregon for over 20 years, and has worked for prestigious companies such as Rockwell Engineering. His proven background in electronics has been indispensable for this author, without whom this book would not have been written. Clifford is still working for the Technical Science Administration at the University of Oregon, teaching a course in analog electronics for students of the sciences. People come to him every day to solve complicated technical problems, such as MRI coil design.

I would also like to thank Steve Weimholt for his input and assistance and editing advice. Steve is also an employee of the University of Oregon in the Camcor <sup>TM</sup> facility, and is an electron microscope engineer. He maintains the equipment in the facility, and assists the research scientists with their laboratory setups.

Finally, I would like to thank John Boosinger, who works in the machine shop at the University of Oregon. He is an instructor who teaches students how to machine plastic and metal parts using lathes, milling machines, and other equipment. Students get hands-on training from John, who supports and guides their research projects.

## Table of Contents

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<b>Chapter 1 – Fundamental Concepts.....</b>	<b>1</b>
Chapter 1.1: What is Electricity?.....	2
Chapter 1.2: An Introduction to Circuits, Schematics, and Basic Terms.....	4
Chapter 1.3: Features of the LumiDax ® Bakerboard Analog Trainer.....	7
Chapter 1.4: Vocabulary Review.....	12
Chapter 1.5: Lab Activity 1 – Building a Basic Circuit.....	12
Chapter 1.6: Exercises.....	16
 <b>Chapter 2 – Ohm's Law: Resistance.....</b>	 <b>18</b>
Chapter 2.1: Connecting Voltage, Current, and Resistance Together.....	19
Chapter 2.2: Resistor Types, Values, and Sizes.....	20
Chapter 2.3: Reading Resistor Color Bands.....	21
Chapter 2.4: Measuring Voltage, Current, and Resistance.....	22
Chapter 2.5: Resistors in Series and Parallel.....	26
Chapter 2.6: Potentiometers, Thermistors, and CdS Cells.....	32
Chapter 2.7: Computing Power Dissipation in DC Loads.....	33
Chapter 2.8: Vocabulary Review.....	34
Chapter 2.9: Lab Activity 2 – Resistor Networks.....	35
Chapter 2.10: Exercises.....	40
 <b>Chapter 3 – Capacitance and Inductance.....</b>	 <b>42</b>
Chapter 3.1: Introduction to Capacitors.....	43
Chapter 3.2: Capacitors in Series and Parallel.....	46
Chapter 3.3: Capacitor Charge, Discharge, and the RC Time Constant.....	47
Chapter 3.4: Introduction to Inductors.....	49
Chapter 3.5: Inductors in Series and Parallel.....	52
Chapter 3.6: Inductor Charge, Discharge, and the RL Time Constant.....	53
Chapter 3.7: Basic Transformer Theory.....	56
Chapter 3.8: Vocabulary Review.....	59
Chapter 3.9: Lab Activity 3 – Exploring RC Circuits.....	59
Chapter 3.10: Exercises.....	65

<b>Chapter 4 – AC, Filters, Diodes, and Power Supplies.....</b>	<b>67</b>
Chapter 4.1: AC RMS Voltage – The Real Story.....	68
Chapter 4.2: Amplitude, Frequency, and Phase.....	70
Chapter 4.3: Other Waveforms.....	72
Chapter 4.4: Producing and Measuring Waveforms in the Laboratory.....	73
Chapter 4.5: Reactance, Impedance, and Complex Numbers.....	77
Chapter 4.6: Filters and Resonance.....	85
Chapter 4.7: The Diode and DC Power Supplies.....	94
Chapter 4.8: Vocabulary Review.....	101
Chapter 4.9: Lab Activity 4 – AC Signals, Filters, and Rectification.....	102
Chapter 4.10: Exercise.....	107
 <b>Chapter 5 – Transistors and Op Amps.....</b>	 <b>109</b>
Chapter 5.1: The Bipolar Junction Transistor.....	110
Chapter 5.2: Useful Transistor Circuits.....	114
Chapter 5.3: Operational Amplifiers.....	124
Chapter 5.4: Vocabulary Review.....	138
Chapter 5.5: Lab Activity 5 – Oscillators and Amplifiers.....	139
Chapter 5.6: Exercises.....	142
 <b>Chapter 6 – Tips, Tricks, and Applications.....</b>	 <b>145</b>
Chapter 6.1: Quick Remedies to Common Problems.....	146
Chapter 6.2: Tips and Tricks.....	150
 <b>Chapter 7 – The Digital World.....</b>	 <b>155</b>
Chapter 7.1: A Brief Not So Brief History of Digital Logic.....	155
Chapter 7.2: Boolean Algebra.....	155
Chapter 7.3: Introduction to Logic Gates.....	157
Chapter 7.4: Logic Design and Minimization.....	162
Chapter 7.5: Number Systems.....	169
Chapter 7.6: Finite State Machines.....	172
Chapter 7.7: Latches and Flip-Flops.....	175
Chapter 7.8: Sequential Logic Design and Minimization.....	178
Chapter 7.9: Clock Oscillators and One-Shots.....	180



Chapter 7.10: Counters.....	183
Chapter 7.11: Parallel to Serial Conversion.....	186
Chapter 7.12: Vocabulary Review.....	189
Chapter 7.13: Lab Activity 7 – Serial Transmitter / Receiver.....	190
Chapter 7.14: Exercises.....	192
 <b>Appendix A – Schematic Symbols.....</b>	 195
 <b>Appendix B – Formulas, Conversions, and Units.....</b>	 196
 <b>Appendix C – Where to Buy Parts.....</b>	 197
 <b>Solved Problems.....</b>	 198

## Chapter 1 – Fundamental Concepts

In this chapter, you will...

- ➡ Learn about where charge comes from.
- ➡ Explore concepts of voltage and current.
- ➡ Discover the way circuits work.
- ➡ Find out about schematic diagrams.
- ➡ Build and test your first circuit.

Humans have always been fascinated by the raw power of electricity. From the heating, to lighting, to plating metals, civilization has been taking advantage of this universal form of energy. Indeed, civilization could not exist as it does today without electricity.

But why do some materials seem to work better than others when it comes to making electricity flow? What is a volt, an amp, DC, AC? What is actually moving in the wire when a lamp is plugged into an outlet?

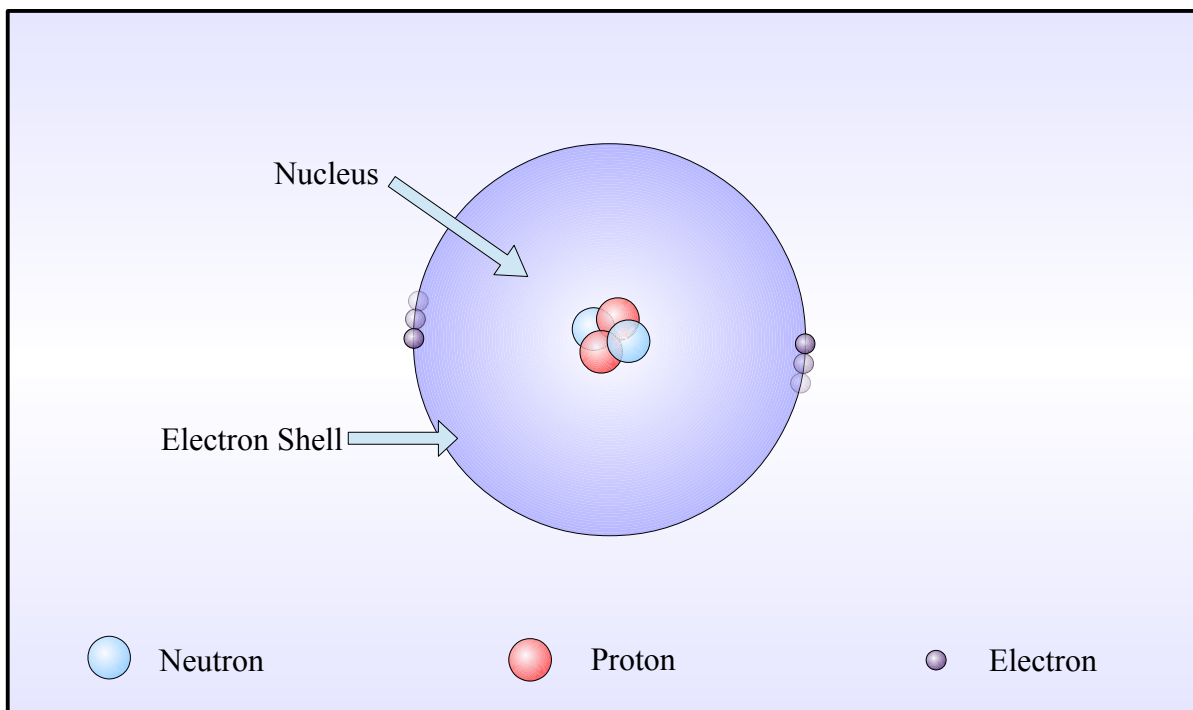
In this chapter, we will explore the phenomenon that gives rise to electricity: charge. We will discover where charge comes from, and how it is made to move. We will explore why some materials block electricity, while other materials allow it to flow freely. Finally, we will try building our first circuit.

## Chapter 1.1: What is Electricity?

---

Energy is all around us. It is present in the form of heat, light, and motion. Energy is defined as the ability to do work. Civilization would not have advanced as far as it has if not for the discovery of electricity. So what makes electricity? *Electricity* is defined as the buildup and motion of *electric charges*. Opposite charges want to combine, while like charges repel one another. So if we have a charged particle, we can move it by applying an *electric field*, which is an invisible force-field.

Electric charge comes from the particles in *atoms*, the building blocks of matter. Atoms are composed of three types of particles. These are the *proton*, the *neutron*, and the *electron*, as shown below in **Figure 1**. Protons have a *positive charge*, neutrons have zero charge, and electrons have a *negative charge*. Protons and neutrons make up the *nucleus* (center) of the atom, and electrons “orbit” around this nucleus in layers called *shells* or *orbitals*. Protons and neutrons are far heavier than electrons, but in spite of this protons and electrons have equal and opposite charges. Therefore, the number of protons must be equal to the number of electrons for an atom to have a net charge of zero. An atom which has lost or gained an electron can have a positive or negative charge, respectively.

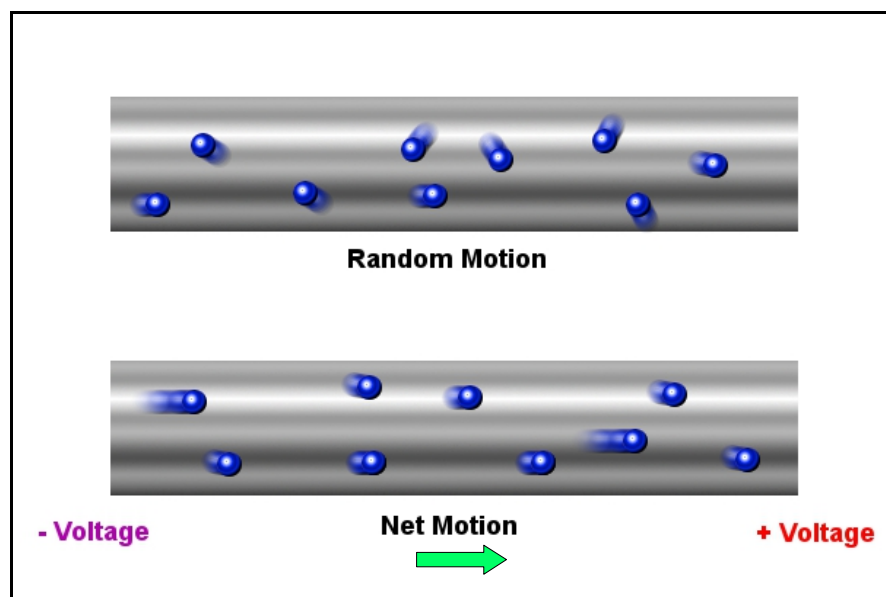


**Figure 1: Protons, neutrons, and electrons in an atom.**

An atom at *ground state* (lowest energy) will have a net charge of zero. This is because the positive charges from the protons in the nucleus are equally balanced with the negative charges from the electrons in their *orbitals*. Some atoms have lots of protons and electrons, and the electrons furthest away from the nucleus can be “bumped off” easily when the atom gains energy. The outer shells of atoms are called *valence orbitals*, and the electrons in the outer shell are called *valence electrons*.

Valence electrons that gain enough energy can escape their valence orbitals and become free electric charges. They can move around in all directions between the spaces of the atoms, occasionally settling into a free valence orbital, only to be bumped off again. Materials where there is an abundance of free electric charges are called *conductors*. Metals have an abundance of free electrons, so they are excellent conductors of electricity.

*Electrical conduction* occurs when we cause all the free electrons to drift in the same direction, like water in a pipe. The electrons are still moving in random directions, but they have a *net motion* in the direction of the positive charge. The *electromotive force* (sometimes abbreviated EMF) that causes the electrons to move is called *electric potential* (denoted by capital E,) and is measured in *volts* (abbreviated V.) A *potential difference* applied to a wire from a battery will cause the free electrons to drift in the direction of the positive charge, and away from the negative charge, as shown in **Figure 2**.



**Figure 2:** An applied potential difference on a wire causes electrons to drift.

When electric charges are in motion, we call this *electric current* (denoted by capital  $I$ ). Electric current has units of *amperes* or *amps* (abbreviated A.) One amp is one *coulomb* of electric charge passing through a given point in a conductor per second. A *coulomb* (abbreviated C) is a very large number of discrete charges, so it is more convenient to use amperes. So voltage is the “pressure” that moves the electrons in a conductor, and current is the motion of the electrons.

The electrical devices found in your home have ratings for voltage and current. A typical light bulb in a lamp requires 120 volts AC, or 120 VAC (we will discuss alternating current later.) Fuses and circuit breakers are designed to shut off a circuit when maximum current has been exceeded. These may be rated anywhere from 10 A to 20 A for residential power. The USB cables from your computer provide +5 VDC (volts, direct current) to phones and other devices for charging. And the remote control on your coffee table may operate on AA or AAA batteries, which provide 1.5 V each. But there is a big difference between the power coming out of your wall socket and battery power. We will discuss this difference in the next section.

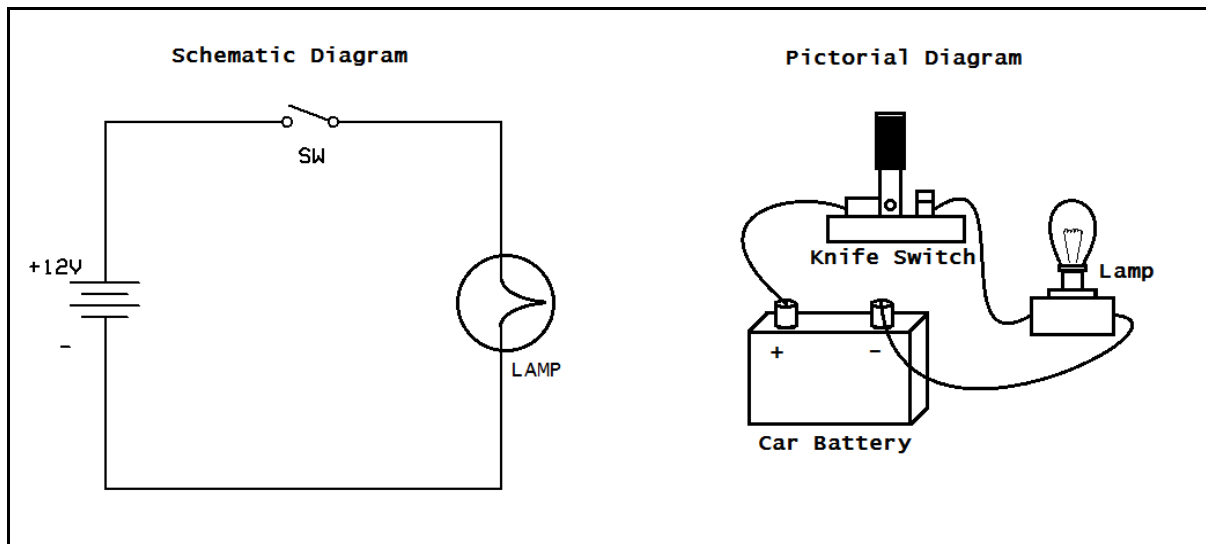
## Question

Fuses and circuit breakers are safety devices. What is it that fuses and circuit breakers prevent during an overload?

### **Chapter 1.2: An Introduction to Circuits, Schematics, and Basic Terms.**

---

In the previous section, we discussed how free charges can be made to flow in a conductor. In order for charges to flow, a complete path must be provided. Electricity must flow in a *circuit*, that is, it must flow in a closed loop from the power source to the device being powered, and then back to the power source. If we break the wires anywhere between the power source and the circuit, no current will flow. The air around you has very few free electrons, so air is a pretty good *insulator*. Insulators keep unwanted electrical contacts from occurring. The plastic and rubber on wires are an example of insulators. So opening a switch breaks the contact and current will stop flowing.

**Schematic and Pictorial Diagrams**

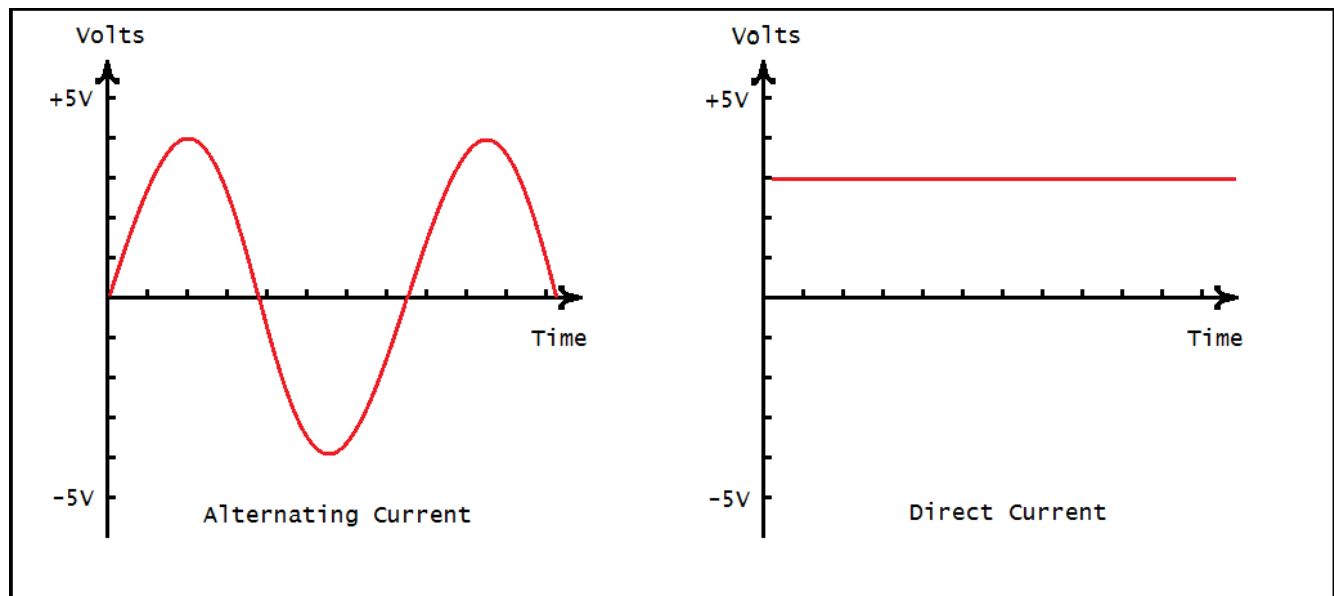
**Figure 3: A basic electric circuit; schematic diagram and pictorial diagram.**

The drawings shown in **Figure 3** above are special types of drawings that electronics engineers and technicians use. They are called *pictorial diagrams* and *schematic diagrams*. Pictorial diagrams show the physical layout for parts placement, and schematic diagrams show symbolic circuit connections. You should learn all the schematic symbols in **Appendix A** so that you can begin building circuits by reading these diagrams, since schematics are used far more often in electronics. Both the schematic diagram and pictorial diagram shown above describe exactly the same circuit. It may seem difficult at first, but don't worry. You will be learning all about schematics as you progress through this course.

The circuit shown in **Figure 3** is a simple light with a switch to turn it on and off. A battery supplies power to the circuit. Though the electrons are moving through the wire away from the negative terminal and towards the positive terminal, engineers consider current flow to start at the positive terminal (this is backwards!) In electronics, it is conventional to show current flowing from positive to negative. This is due entirely to historical reasons. This can be confusing at first, but all schematic symbols are understood to use *conventional current*. Therefore, diodes and other directional devices are shown pointing in the direction opposite of actual current flow. Understanding conventional current is very important, but just remember that electrons are moving in the opposite direction. Don't worry, you'll get the hang of it. Conventional current will be used throughout this text.

### **Alternating Current and Direct Current**

You have probably heard the terms *alternating current* and *direct current*, or abbreviated AC and DC. Direct current does not change direction. The constant voltage and current that a battery provides is a good example of DC. Alternating current changes direction *periodically*, or in a repeating fashion. See **Figure 4** below. The wall sockets in your home provide alternating current. You may be asking why alternating current is used rather than direct current to provide power to your appliances. This has to do with the way power is delivered. The electric company transmits power on high voltage power lines that run for many miles. This is because high voltages are needed to overcome the *resistance* of the transmission lines. But the voltage must be stepped down using power line transformers, and transformers require alternating current to operate.



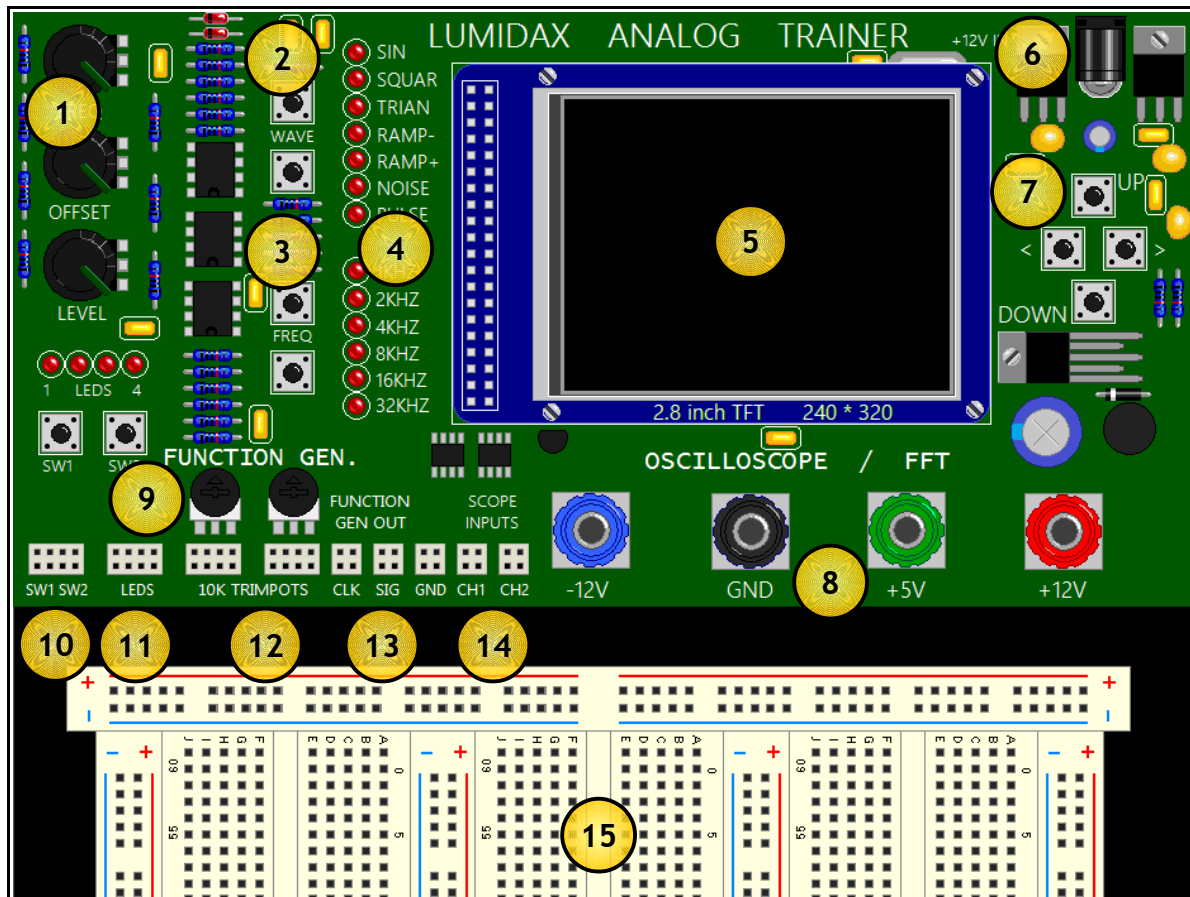
**Figure 4: Alternating vs. direct current.**

From the figure above, we can see that an AC signal has a voltage that periodically changes from positive to negative, from +4 V to -4 V. The figure above also shows a constant DC voltage of +3 V, on the right. This is usually a *sine wave* (as in the trigonometric function) but can be any function. Direct current is current that flows in only one direction, and is usually constant. The study of alternating and direct current circuits is called *analog circuit theory*, and we will be going into this in detail later. There is quite a bit of ground to cover first, but we'll be getting to analog circuit theory in Chapter 4.

### Chapter 1.3: Features of the LumiDax ® Bakerboard Analog Trainer

The Bakerboard is equipped with several useful pieces of test equipment in one convenient package.

**Figure 5**, shown below, is a diagram showing the layout of the Bakerboard Analog Trainer.



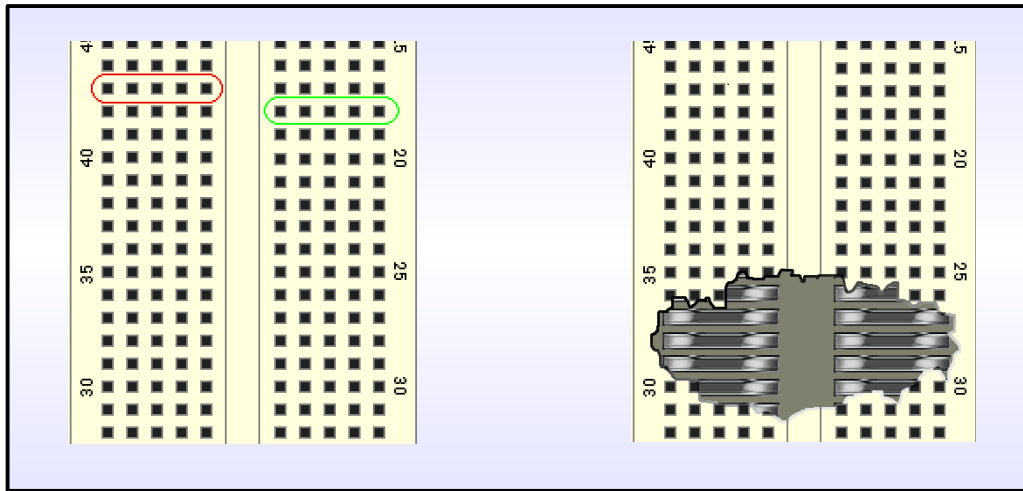
**Figure 5: A tour of the LumiDax ® Bakerboard features.**

- |  |   |
|--|---|
| 1) Function Generator control knobs.             | 9) Project LEDs, switches, and potentiometers.      |
| 2) Function Generator waveform select keys.      | 10) Quick-connects for project switches.            |
| 3) Function Generator range select keys.         | 11) Quick-connects for project LEDs.                |
| 4) Function Generator waveform, range indicator. | 12) Quick-connects for project potentiometers.      |
| 5) Full color 2.8" TFT display.                  | 13) Function Generator signal and clock output.     |
| 6) DC jack for power supply (included.)          | 14) Oscilloscope inputs for Channel 1, Channel 2.   |
| 7) Oscilloscope / Spectrum Analyzer cursor keys. | 15) Solderless breadboard for prototyping circuits. |
| 8) Built-in power supplies for -12V, +5V, +12V.  |   |



### **Solderless Breadboard**

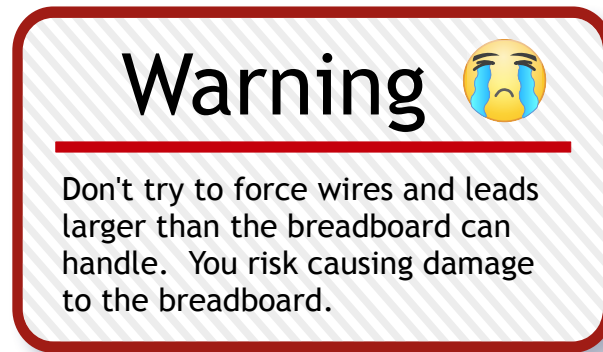
One of the most useful features of the Bakerboard is the solderless breadboard, which allows you to build and test circuits without the need for solder and soldering irons. The solderless breadboard is designed such that the holes will accept leads for most electronics components and wires, holding them firmly and securely. Simply bend the leads, trim them with a pair of diagonal cutters, and push the wires into the holes. Removal is easy too - just gently pull. Take a look at **Figure 6**, shown below.



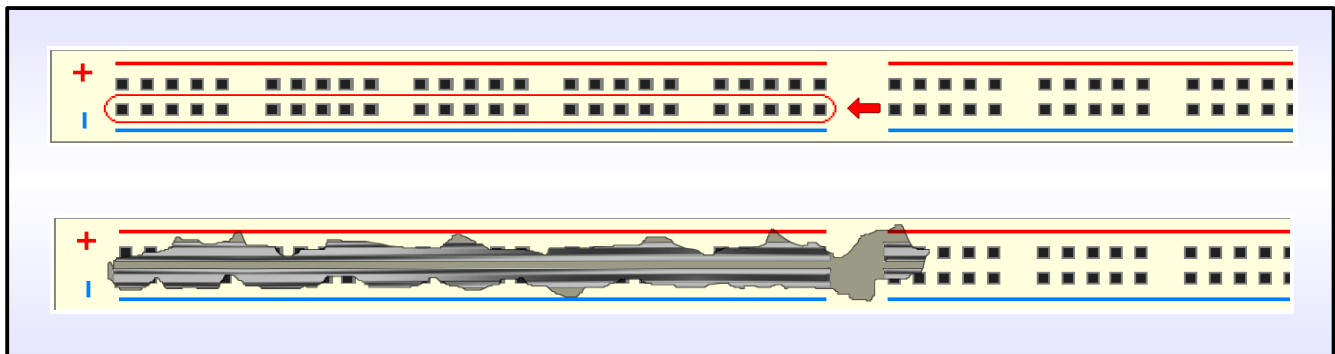
**Figure 6: Solderless breadboard tie-points and how they work.**

In the figure above, we can see that the breadboard has rows of *tie-points*. The gap that runs down the middle is just the right width to place *integrated circuits*, which we will cover in a later section. The breadboard has rows of five holes on either side of the gap in the middle. Each row of five tie-points is connected horizontally, so plugging wires and leads into the same row makes an instant connection. As shown in the above figure on the left, one row is circled in red, and another separate row is circled in green. The diagram on the right shows how the metal prongs are arranged internally.

The prongs that make the tie-points are spring-loaded, and can accept wires up to 22 AWG wire. They will work for lead thicknesses of most components. However, it is important that you be gentle when inserting wire into the tie-points. Components such as rectifier diodes have leads that are thicker to handle the higher current. But if the lead won't fit, rethink how to attach it to your circuit. Repeatedly forcing large leads into the holes will force the spring-loaded prongs apart over time, and your wiring connections will be loose and unreliable.



There are also power distribution strips provided for convenience. These are located on the top of the breadboard, and running down the sides and between the breadboard panels. They are identified by the red and blue markings indicating plus and minus, respectively. **Figure 7** shows a power distribution strip.



**Figure 7: Power distribution breadboard strip.**

The power distribution strips on your breadboard are different from the row connectors in **Figure 6**. The difference is that the tie-points are all connected in a line. There are red and blue markings on the power distribution strip to help you understand how they are connected internally. The red and blue lines show common connections. The arrow in the top drawing of **Figure 7** points to a strip of tie-points that are all connected. Notice that the red and blue lines are broken in the middle of the power distribution strip. In **Figure 7**, the bottom drawing shows an inside-view. That broken line means that the connections do not run all the way down. Don't forget this gap in the future, as this knowledge will save you from much confusion later. Power is not automatically provided on these distribution strips.

### Power Supplies

The LumiDax ® Bakerboard is equipped with three *regulated* DC power supplies. These are +5V, -12V, and +12V, and all share a *common ground*. The +5V power supply is ideal for digital circuits, while the -12V and +12V supplies are great for *op-amp* circuits, which require dual power supplies. The +5V and +12V power supplies can deliver up to one amp of current, and the -12V supply can deliver a maximum of 0.5 amps. A desktop power supply cord is provided with the kit for powering your trainer. **Figure 8** shows the power supplies, located near the top of the breadboard area. The binding posts can accept banana jacks, or wires can be secured by screwing the binding post down onto your wires. As shown below, the blue binding post provides -12V, black is the common ground (the concept of grounding will be discussed later,) green is +5V, and red is +12V.

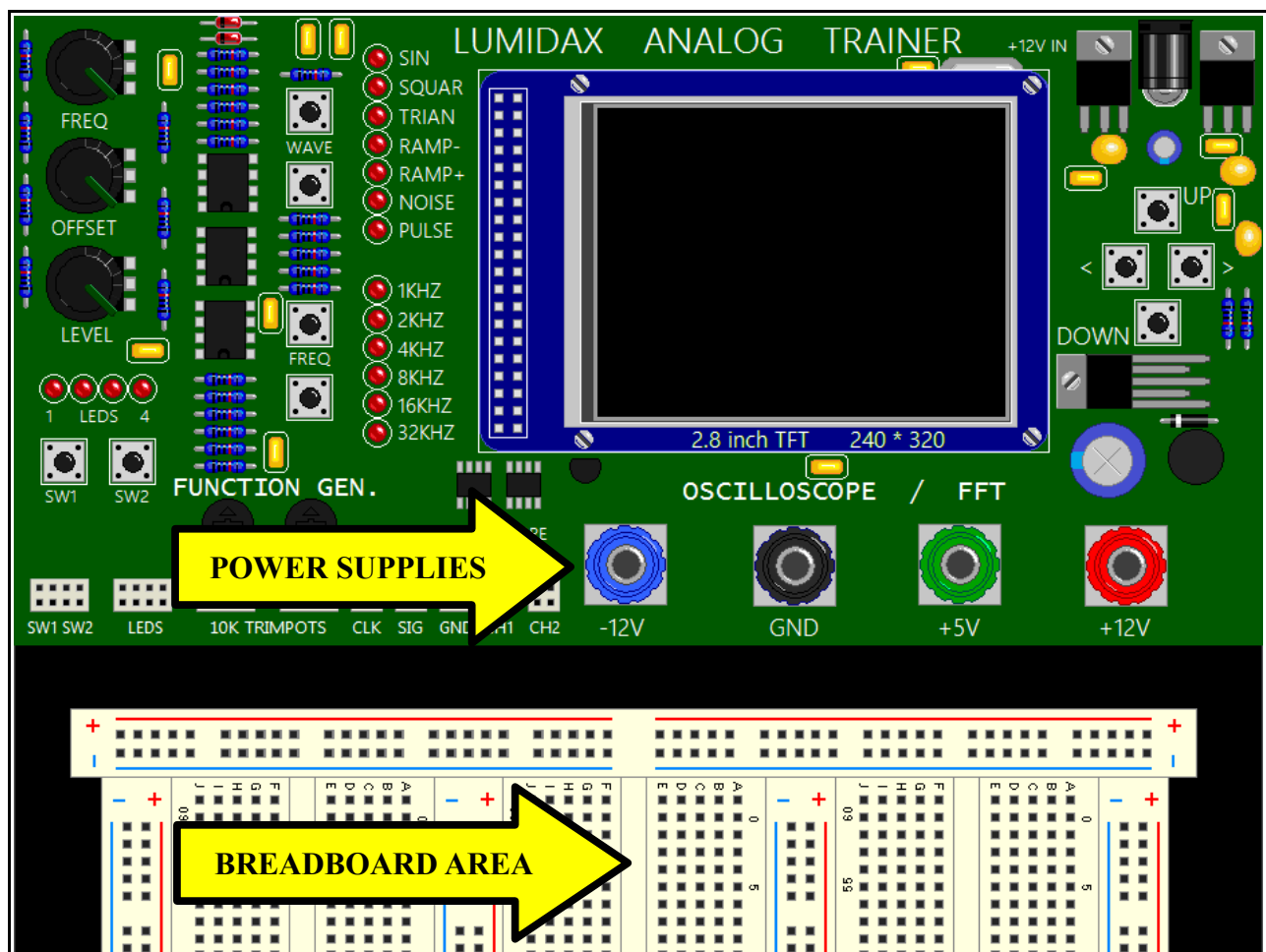
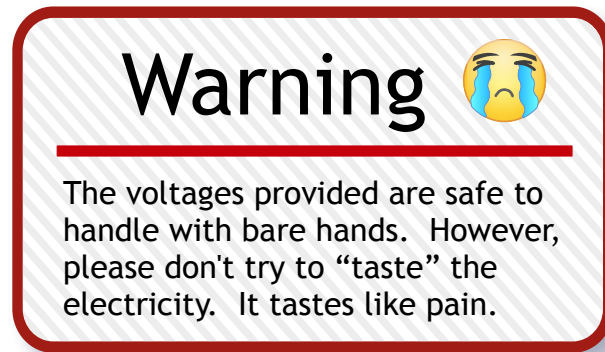


Figure 8: Breadboard area and power supply positions on the Bakerboard.



**There are certain things to keep in mind when using these power supplies:**

- Do not ever connect the power supplies together directly, or connect them directly to ground. This will cause damage to your power supplies.
- Make sure your components can handle the power they are trying to dissipate. If a part gets hot on your breadboard, it may melt the plastic and cause an unsightly burn...not to mention permanently damaging your unit. The +12V supply can deliver up to 12 watts of power, which is more than enough to smoke a part. Also, resistors smell really bad when they burn.
- These voltages are safe to handle with bare hands. Even so, please use caution. Don't poke around with screwdrivers, or wear watches, rings, or necklaces. This may cause shorts.
- Don't spill liquids on the unit or expose to high levels of moisture.
- Do not EVER use power supplies other than those provided with your unit. If you use a higher voltage or current power supply, you risk damaging the test equipment, the breadboard, and your health. It may be tempting to make a 120V relay circuit to control your lights, but please don't do it.
- Try to keep your wiring neat. Loose wires and leads that are too long will encourage shorting.
- When removing integrated circuits (ICs,) use an IC puller. Using a screwdriver may appear to work, but you will also damage the breadboard.
- Don't eat over the Bakerboard Analog Trainer. Food will enter the tie-point holes, and will be very hard to clean.
- Try to keep the Bakerboard Analog Trainer in a safe place. A fall may damage the unit.
- If you get a white screen, you have a short. Quickly unplug the unit and check your circuit.

## Chapter 1.4: Vocabulary Review

alternating current: current that changes direction periodically	net motion: a general direction of motion of a system
ampere, amp: defined as one coulomb / second of current	neutron: a zero-charged particle found in atoms
analog circuit theory: the study of AC and DC circuits	nucleus: center of atoms composed of protons, neutrons
atom: an elemental building block of matter	op-amp: an integrated circuit that amplifies signals
circuit: a complete path of conduction	oscilloscope: a device that displays fast changes in voltage
conductor: a material that conducts electricity easily	periodic: repeating in time
conventional current: a standard that accepts flow from + to -	pictorial diagram: a diagram showing physical layout
coulomb: unit of charge, 1 C is defined as $6.24 \times 10^{18}$ electrons	positive charge: protons exhibit a positive, or + charge
direct current: current that flows in only one direction	potential difference: a voltage difference between two points
electric charge: a property of subatomic particles	power supply: a device that supplies voltage and current
electric current: the flow of electrons, measured in amperes	proton: a positively charged particle found in atoms
electric field: the area of influence around a charge	regulated: resistant to changes, constant
electric potential: a buildup of charge, measured in volts	resistance: impedance to the flow of current
electrical conduction: motion of charges in a conductor	schematic diagram: a symbolic representation of a circuit
electricity: the buildup and flow of electric charges	shell, orbital: regions where electrons are allowed
electromotive force: a force that causes charges to move	sine wave: a trigonometric function, $f(x) = \sin(x)$
electron: a negatively charged particle found in atoms	solderless breadboard: a tool for prototyping circuits
function generator: a device that produces signals	spectrogram: a picture of spectral energies changing in time
ground state: lowest energy state of an atom	spectrum analyzer: a device that graphs frequencies
ground: the common points of connection between systems	tie-point: connectors that easily connect wires together
insulator: material that prevents contact between conductors	valence electron: electrons furthest away from the nucleus
integrated circuit: a complete circuit in a tiny package	valence shell, valence orbital: outermost orbital or shell
negative charge: electrons exhibit a negative, or - charge	volt: a unit of measure, defined as one joule / coulomb

## Chapter 1.5: Lab Activity 1 – Building a Basic Circuit

### Introduction

In this chapter, we went over some of the basic terminology of electricity. This lab will introduce you to the LumiDax ® Bakerboard Analog Trainer, and show you how to build basic circuits. You will be constructing a very simple light circuit similar to the one you read about. In this lab, you will be wiring an LED (light emitting diode,) a resistor, and a switch to the +5V power supply by reading a schematic diagram, and verify that your circuit works by testing it.

An LED is a device that lights when a small current (usually 0.015 amperes.) LEDs are directional, that is, they light up when current flows in one direction only. We will cover diode characteristics in a later chapter. LEDs require about two volts across them in the forward direction to light up.

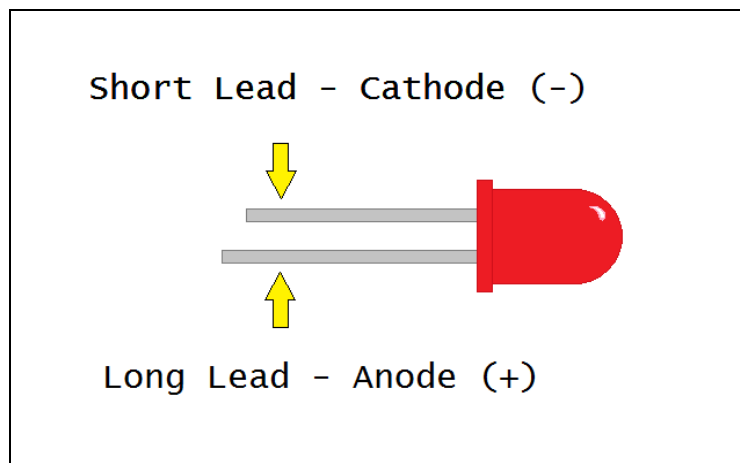
**Materials**

The materials required for this lab are listed in the table shown below.

Lab Activity 1 – Parts List	
Quantity	Item
1	Red light-emitting diode (LED), 5mm
1	470 ohm ¼ watt resistor (yellow, purple, brown, and gold striped)
1	LumiDax ® wiring kit
1	LumiDax ® Bakerboard Analog Trainer
1	Pair of wire cutters.

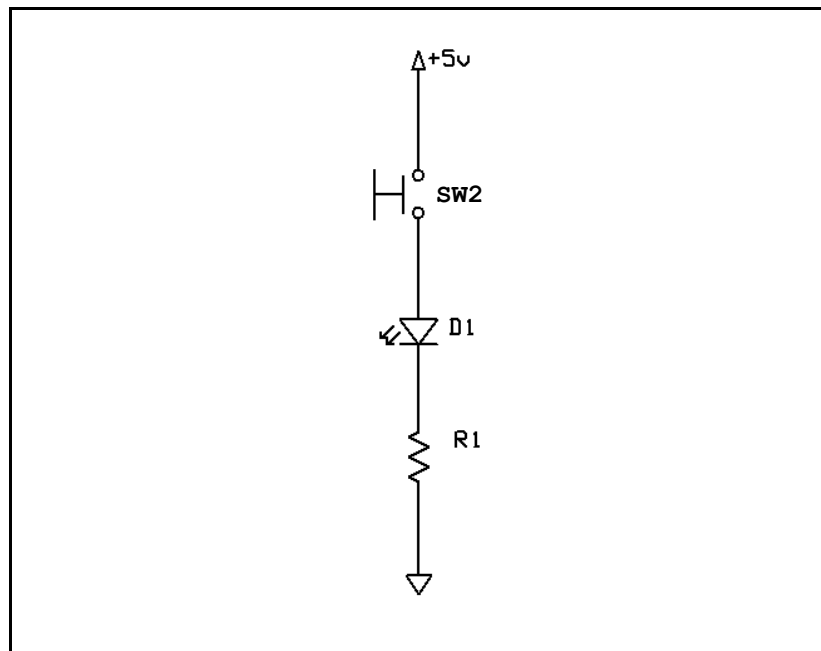
**Procedure**

Make sure power is not applied to the trainer until your circuit is wired and ready to test. We will now get the components ready to use for constructing the circuit. Take a look at your LED. Notice that one lead is longer than the other one. **Figure 9**, shown below, shows a typical LED.



**Figure 9: A typical LED, showing the anode and cathode leads.**

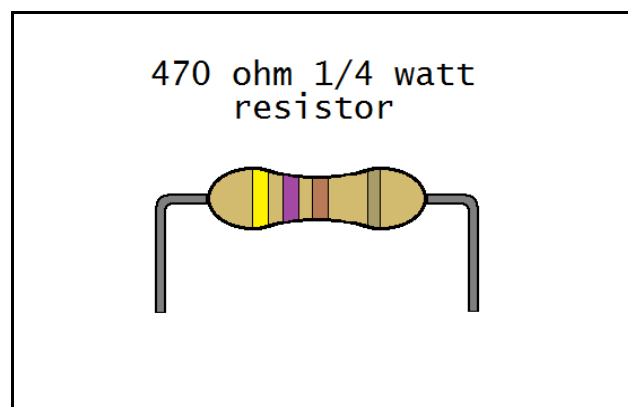
It must be remembered that a diode conducts in the forward direction (from positive to negative,) and blocks current in the other direction. Therefore, if you insert the LED into the circuit backwards, then the LED will not light. For this lab activity, we will not trim the leads on the LED. Notice that one of the leads is longer than the other one on the LED. The longer lead is the positive lead, called the *anode*. The shorter lead is the negative lead, which is called the *cathode*.



**Figure 10: Lab Activity 1 schematic diagram.**

Observe the schematic shown in **Figure 10**, shown above. The circuit to be wired will start at the +5V power supply. The current will flow through switch SW2 when the button is pushed, through the LED, and through resistor R1, and finally to *ground*. The circuit will be completed when the switch is pressed, and broken with the switch is released.

1. The components have to be crimped and trimmed to use with the solderless breadboard. Gently bend the leads of the resistor and trim them so that your resistor appears as in **Figure 11**.



**Figure 11: Resistor with leads bent and trimmed.**

2. Place the LED with the long lead towards the top of the trainer, and the short lead in a different row towards the bottom of the trainer. Place the 470 ohm resistor as shown in **Figure 12**.
3. You will need to place jumper wires (orange) on the power distribution strips to connect them across.
4. Place a wire from the positive power distribution strip to one connection of switch SW2 as shown in **Figure 12**.
5. Wire from the other connection of switch SW2 to the positive lead of the LED (anode.)
6. Since the negative lead of the LED (cathode) is on the same row as the resistor, then these are connected. The last connection goes from the other lead of the resistor back to ground (the negative power distribution strip).

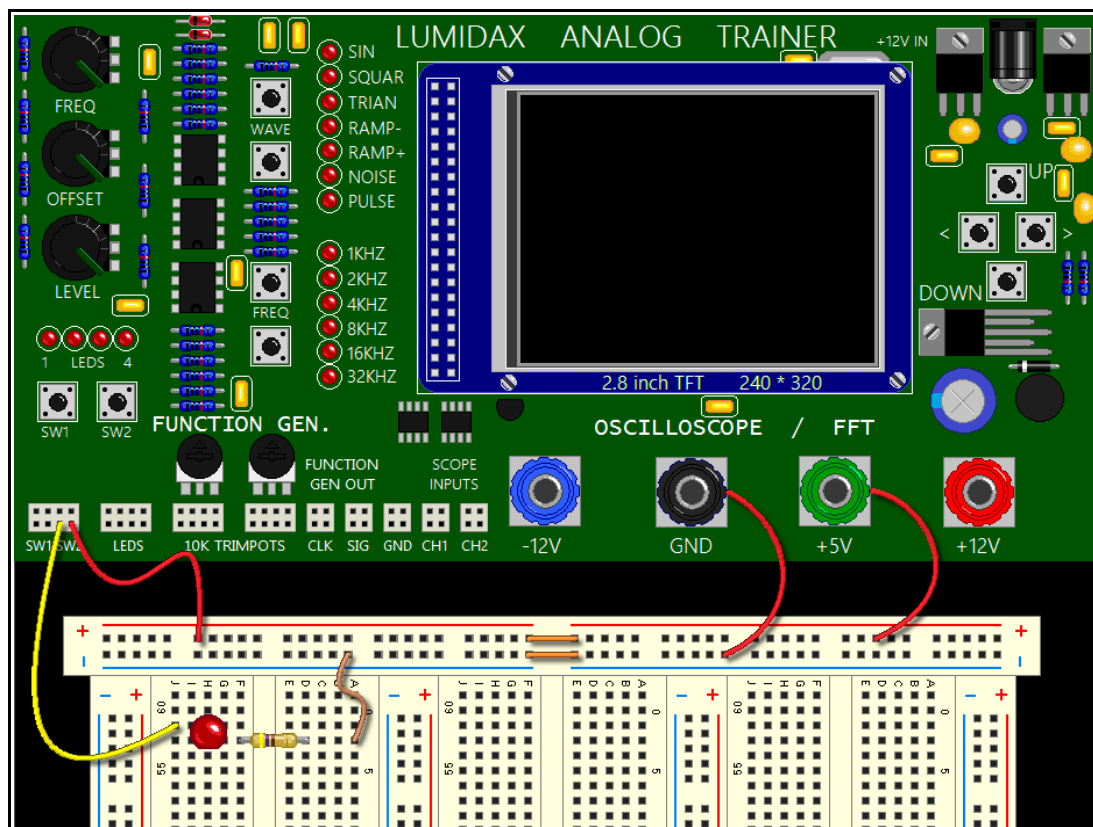


Figure 12: Lab activity pictorial diagram.



7. Carefully inspect the circuit before applying power. This step is extremely important, as finding wiring errors now will prevent you from causing damage to the trainer or your components. Get into the habit of performing a visual check before plugging in the power supply to your unit.
8. Plug in the power supply to your trainer. Verify that the LED lights up when you press the push-button switch SW2. Did it light up?
9. If the LED didn't light, make sure it isn't backwards. An LED won't light if it is placed in the circuit backwards.

### **Lab Activity 1 – Conclusion**

In this activity, you learned about using LumiDax ® Bakerboard. You read a schematic diagram and built a physical representation of the circuit. You verified that the LED lights up when the circuit is completed by pressing the switch SW2. You also used a resistor, a device that limits current. LEDs are devices that need between 0.01 amperes and 0.02 amperes. Without the resistor, the LED would have burned out due to excess current. In a later section, you will learn how to calculate the resistances needed for any such circuit.

## **Chapter 1.6: Exercises**

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### **Vocabulary Questions**

1. The building blocks of matter are called \_\_\_\_\_.
2. The \_\_\_\_\_ (or center) of an atom, contains protons, and may contain neutrons.
3. \_\_\_\_\_ have positive charge, while \_\_\_\_\_ have negative charge.
4. A \_\_\_\_\_ has an abundance of free electric charges that can flow.
5. When electrons are encouraged to drift in a direction, this flow is called \_\_\_\_\_.
6. \_\_\_\_\_ is current that changes direction periodically.
7. The unit of measure of electric potential is the \_\_\_\_\_.
8. The unit of measure of electric current flow is the \_\_\_\_\_.
9. An \_\_\_\_\_ prevents current flow, and keeps conductors from making contact.

10. \_\_\_\_\_ electrons are electrons found in the outermost orbitals of atoms.
11. The unit of electric charge is the \_\_\_\_\_, abbreviated C.
12. A \_\_\_\_\_ is a symbolic diagram showing electrical connections.

**True or False**

- |  |   |   |
|--|---|---|
| 1. Alternating current is a steady, constant current.                    | T | F |
| 2. Neutrons have a charge of zero.                                       | T | F |
| 3. A circuit is a complete path for current to flow.                     | T | F |
| 4. Electrons are heavier than protons and neutrons.                      | T | F |
| 5. Valence orbitals are found closest to the nucleus of atoms.           | T | F |
| 6. Insulators are made of non-conductive materials.                      | T | F |
| 7. Conventional current is understood to flow from positive to negative. | T | F |
| 8. The ground state of an atom is it's lowest energy state.              | T | F |
| 9. Like charges attract, and opposite charges repel one another.         | T | F |
| 10. The electrical outlets in your home provide direct current.          | T | F |

## Chapter 2 – Ohm's Law: Resistance

In this chapter, you will...

- ➡ Take a look at Ohm's Law.
- ➡ Use Ohm's Law in circuit design.
- ➡ Learn how to read resistor color codes.
- ➡ Make use of a multimeter.
- ➡ Master series and parallel circuits.

Your first exploration into the world of electronics components will invariably include the humble *resistor*. This component is by far the simplest - a resistor impedes the flow of current.

*Ohm's Law* is a physical law. It connects voltage, current, and *resistance* in a very elegant way. With Ohm's Law, you can evaluate *series* and *parallel* circuits with ease. Though Thevenin's Theorem, Norton's Theorem, and Kirchhoff's Laws are beyond the scope of this book, these ideas will be touched upon for clarity and completeness.

All *loads* may be represented by an *equivalent resistance*. A load is the circuit or device being powered. Ohm's Law makes dealing with loads easy. You only need multiplication and division to calculate. With this tool in your toolbox, you will be able to find the proper resistor value for any application.

## Chapter 2.1: Connecting Voltage, Current, and Resistance Together

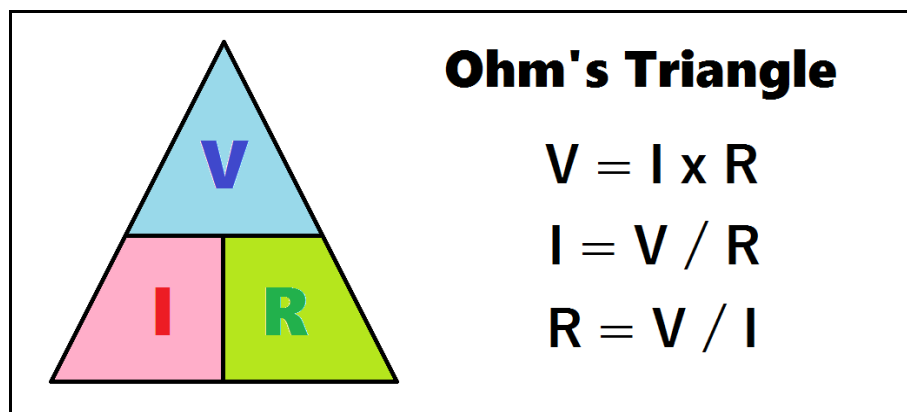
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We have already discussed voltage and current in Chapter 1, which have units of volts and amperes, respectively. Resistors also have a unit of measure, and this is the *ohm*, represented by the Greek letter omega ( $\Omega$ ). Resistors come in a huge variety of fixed values from zero ohms all the way up to millions of ohms.

One ohm is defined as the resistance of a conductor across which a potential difference of one volt produces a current of one ampere.

$$1\ \Omega \equiv \frac{1\text{ V}}{1\text{ A}}$$

Ohm's Law is a powerful tool. Using Ohm's Law, you will be able to calculate unknown values when you analyze or design circuits. For example, you might need a resistor to limit current for an LED to operate properly. Even some sensors are just specialized resistors! Ohm's Law is usually depicted as the triangle diagram shown below in **Figure 13**. Remember that capital I stands for current.



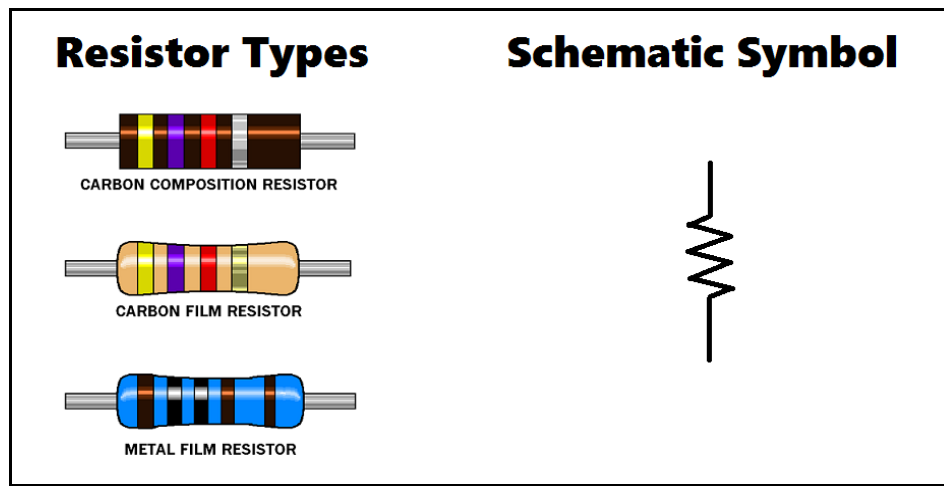
**Figure 13: Using Ohm's Triangle.**

To use *Ohm's Triangle*, place your thumb over the unknown value, and the uncovered part of the triangle tells you which equation you need to use. These three equations will help you solve *resistor networks* of any complexity. Resistor networks will be covered later in this chapter.

## Chapter 2.2: Resistor Types, Values, and Sizes

---

Resistors come in many varieties and shapes depending on their application, but we'll focus on the most common resistors you will encounter. These are *carbon composition resistors*, *carbon film resistors*, and *metal film resistors*. Shown below in **Figure 14** are some typical resistors and the general schematic symbol for a resistor.



**Figure 14: Common resistor types and the schematic symbol for resistors.**

### Carbon Composition Resistors

An older type of resistor is the carbon composition resistor. It is made by pressing resistive material with a plastic binder into a small rod. By varying the amount of resistive material mixed with the binder, the resistance can be changed. Carbon composition resistors are cheaper to make, less accurate, and in some cases produce electrical noise. Therefore, they are mostly used for noncritical applications. Carbon composition resistors come in a cylindrical package (as opposed to the peanut-shaped packages of carbon film and metal film resistors) and are usually dark brown in color.

### Carbon Film Resistors

Carbon film resistors are made by covering a ceramic rod with carbon film and precisely cutting it away with a laser until the desired resistance is achieved. Their construction makes them less prone to thermal effects. Therefore, they are better suited for applications where accuracy and low-noise are important. Carbon film resistors are usually beige in color, and vaguely peanut-shaped. Most commonly, they are available in *tolerances* of 5% (gold band,) which is fine for most applications.

### Metal Film Resistors

Metal film resistors are made in a similar manner to their carbon film cousins. However, they are far more accurate and stable. They are also more expensive. Metal film resistors are used in situations where resistance values must be very accurate, such as in scientific instrumentation. They are usually blue or green in color and have an extra stripe. This extra stripe is an extra digit of accuracy before the multiplier band. Tolerances of 1% are typical for metal film resistors.

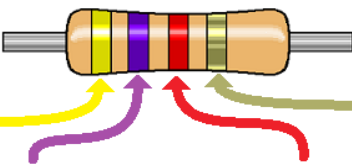
### Resistor Power Ratings

Resistors come in several *power ratings*. These ratings are 1/8 watt, 1/4 watt, 1/2 watt, 1 watt, etc. A resistor's power rating is based on its physical size. The larger the resistor's body, the more heat it can handle. So a resistor's physical size determines how much power (in the form of heat) it can safely dissipate. We will cover the topic of *power dissipation* later. As a rule of thumb, carbon film resistors in the 1/4 watt range are used by experimenters when breadboarding circuits.

## Chapter 2.3: Reading Resistor Color Bands

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Resistors are too small to allow for printing their resistance values on them directly. So in the industry, engineers came up with a *color code* to make it easier to read resistor values. Below in **Figure 15** is a chart to help you read resistor color codes.



1st Digit	2nd Digit	Multiplier	Tolerance
0	0	1	
1	1	10	1%
2	2	100	2%
3	3	1000	
4	4	10000	
5	5	100000	
6	6	1000000	
7	7		
8	8	0.1 Gold	5% Gold
9	9	0.01 Silver	10% Silver

**Figure 15: Resistor color codes**

In **Figure 15** shown above, we have an example resistor with a yellow band, a purple band, a red band, and a gold band. The gold band is the *tolerance band*, which always appears last. You begin reading from the band furthest away from the tolerance band. So for the example in **Figure 15**, yellow corresponds to 4, purple corresponds to 7, the red band is the multiplier indicating  $\times 100$ , and the final band is gold, meaning 5% tolerance. So the resistor shown is a  $4700\ \Omega$  resistor. We may also write this  $4.7\ \text{K}\ \Omega$ , or 4.7 kilo-ohms. Tolerance is an indication of how accurate the resistor's actual value is compared to the markings. At 5% tolerance, the actual resistance may be anywhere between  $4465\ \Omega$  and  $4935\ \Omega$ .

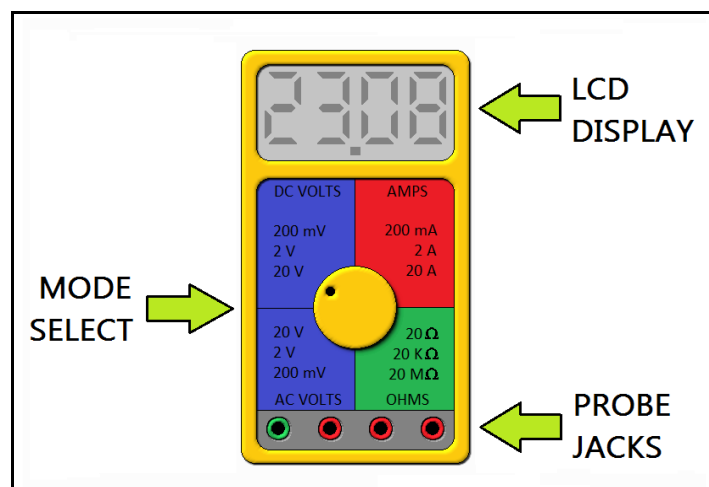
## Question

You have a resistor with a blue band, a grey band, a black band, and a silver band. What would the resistance and tolerance be?

### Chapter 2.4: Measuring Voltage, Current, and Resistance

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Of the many types of test equipment you will use in your electronics career, there are few instruments as versatile as the *multimeter*. In **Figure 16** below, a typical multimeter is shown.

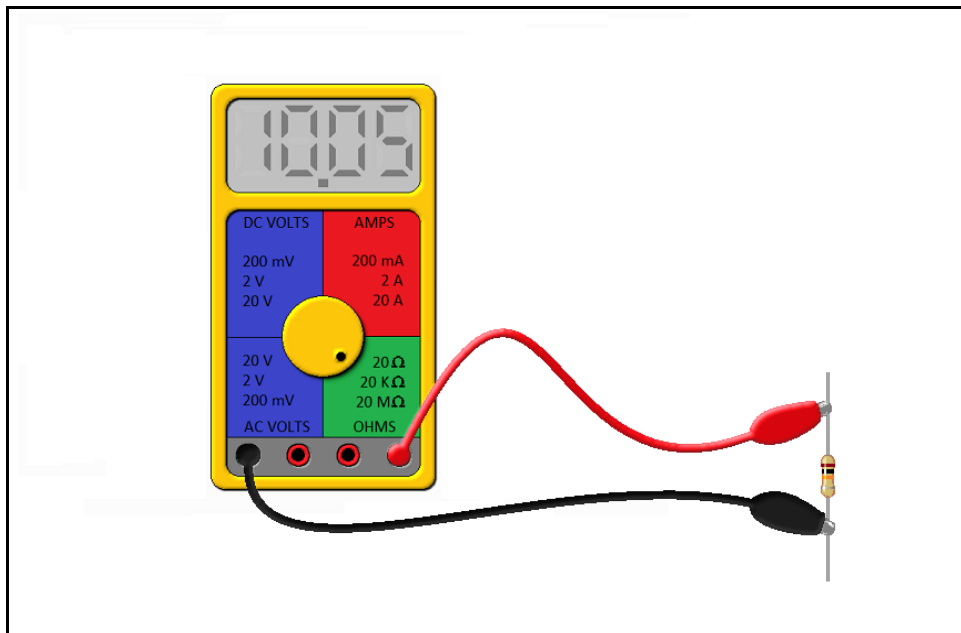


**Figure 16: A typical multimeter.**

A multimeter is a meter that can measure voltage, current, resistance, and even test transistors and diodes. Multimeters are available at most hobby and tool stores, and can be purchased for under \$20.00. Having one on your bench is recommended, as they can be invaluable tools for *continuity testing* (for shorts or open circuits) and for determining unknown resistances.

### **Using a Multimeter to Measure Resistance**

To use the multimeter to measure resistance, place the resistor in the test clips as shown below in **Figure 17**. You may also measure transformer coils and motor coils to check for *continuity* in this way. You will find that even your skin has a measurable resistance! Don't worry, you won't feel anything! The multimeter uses an internal battery (usually +9V) to measure resistance.



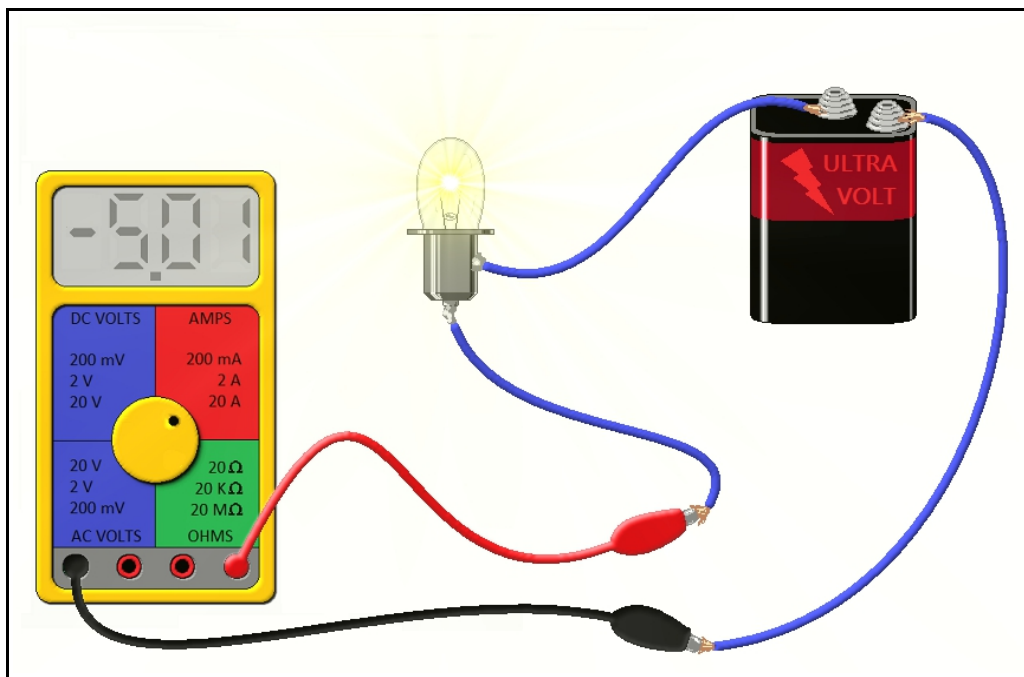
**Figure 17: Using a multimeter to measure resistance.**

It should be noted that it is unwise to measure resistors that are placed in a circuit, regardless of whether the circuit is under power or not. A multimeter will use an internal battery to inject a small current through the resistor under test to measure its resistance. To get an accurate reading, and to ensure that no damage occurs to surrounding components or your meter, you should unsolder one leg of the resistor you would like to measure to remove it from the circuit temporarily.



### Measuring Current with a Multimeter

To measure current with a multimeter, we must place it in *series* with the circuit under test. In this configuration, the meter becomes a part of the circuit. In **Figure 18**, you will see the correct way to use a multimeter in the ammeter mode. Pay special attention to the jacks on the multimeter, as each multimeter varies. If you know you are measuring alternating current, use the AC ammeter setting. If you are measuring direct current, use the DC ammeter setting. You may notice that the current is negative in the diagram. Can you offer an explanation as to why that is? Hint: The outer terminal on a 6V battery like the one shown is positive.

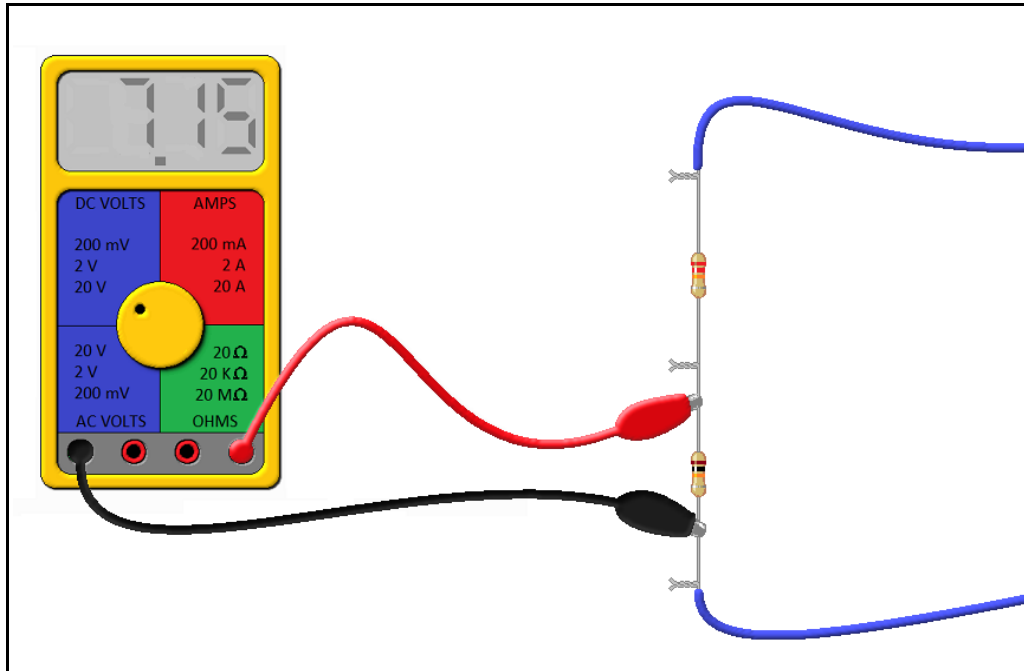


**Figure 18: How to use a multimeter as an ammeter.**

There is usually more than one positive (red) jack for your test leads on the front panel of the multimeter. The jacks on a multimeter are fused for protecting the meter during current measurements. So make sure you are using the right jack for the circuit under test and for the current mode setting on your meter. Failure to do so may blow a fuse in the meter, or worse. For example, if you are in 10 Amp mode, use the jack marked "10 A." And finally, be aware that if you place the test clips in the circuit backwards in DC ammeter mode, you will not hurt the meter. You will instead see a negative current indication.

### Measuring Voltage with a Multimeter

To measure voltage across a component with a voltmeter, you place it in *parallel* with the component under test. A voltmeter draws almost no current at all, so this measurement will not interfere in the operation of the circuit under test. **Figure 19** shows a voltmeter being used to check a resistor in a circuit.



**Figure 19. Measuring voltage across a component with a multimeter.**

Make sure that you are measuring the voltage on the right setting. You won't hurt your meter if you are measuring an AC voltage with the meter set to DC mode, but you may not read the voltage you expect. In fact, the meter will report the DC average – which is zero for an AC waveform!

## Warning 🥲

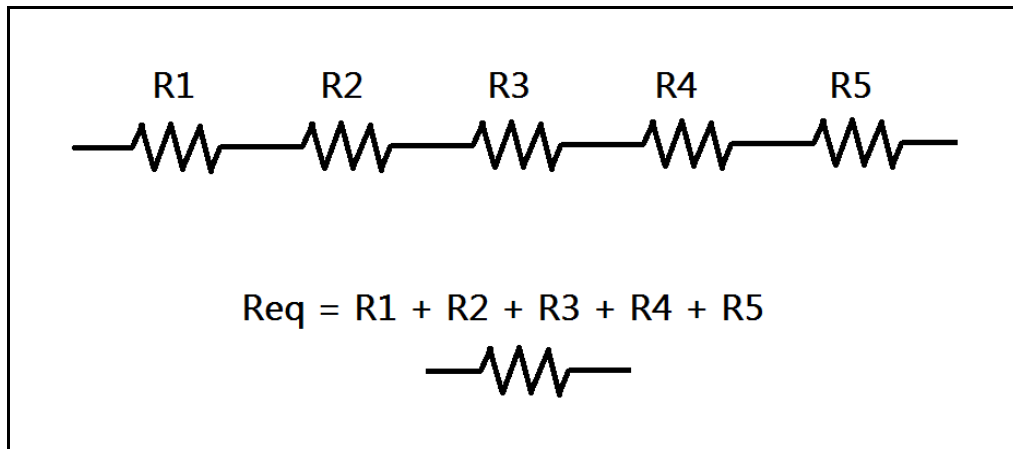
Though most voltmeters can measure voltages in excess of 500VAC, don't tempt fate. Leave the house wiring to the pros.

## Chapter 2.5: Resistors in Series and Parallel

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### **Resistors in Series: Equivalent Resistance**

What happens when we place two or more resistors in series? We end up with an *effective resistor* that is the sum of all the individual resistors. In **Figure 20** shown below, we have five resistors. Their *equivalent resistance* is the sum of all their individual resistances.



**Figure 20: Resistors in series add up to an effective resistor.**

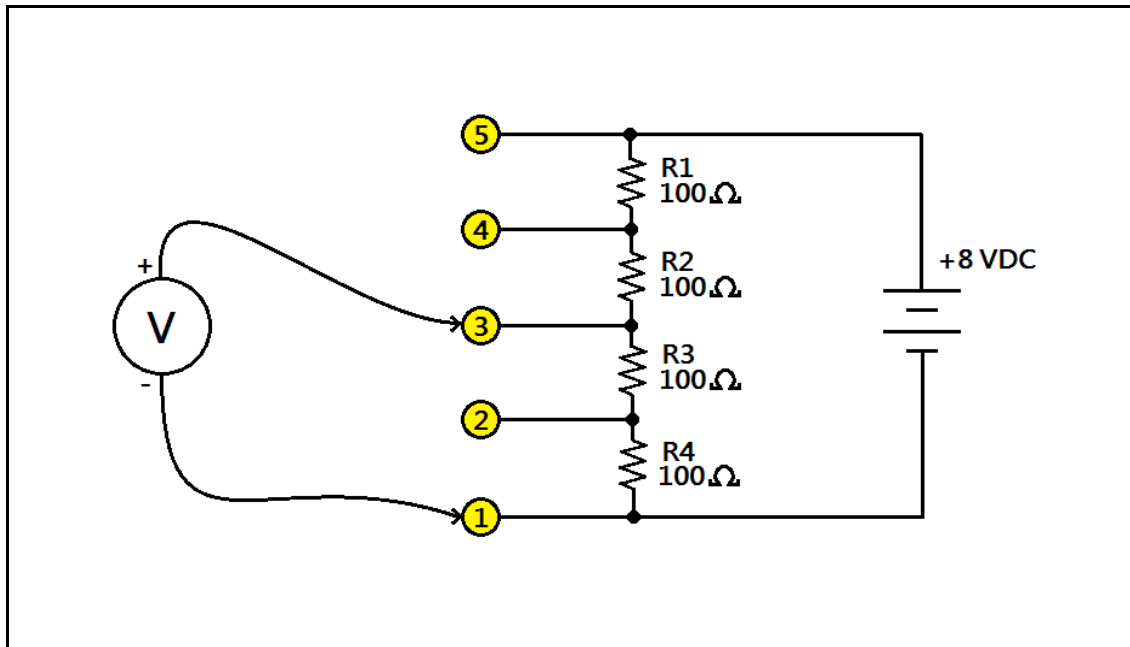
We may now be a bit more rigorous and extend this to any number of resistors.

If given N arbitrary resistors connected in series, they will have an equivalent resistance given by the following formula:

$$R_{eq} = R_1 + R_2 + \dots + R_{N-1} + R_N$$

### **Resistors in Series: The Voltage Divider**

Something curious happens when we place resistors in series. We certainly do end up with an equivalent resistor, but something happens with the individual resistors as well. The voltage from the power source is divided up among the resistors. In fact, the voltages across each resistor add to the source voltage! This configuration of resistors is called a *voltage divider*, and it is a very useful circuit. The voltage divider appears again and again in electronics. We will now demonstrate how it works.



**Figure 21: A basic voltage divider circuit with four resistors and a voltage source.**

Take a look at **Figure 21**, shown above. We have four resistors with identical values. Let's calculate the equivalent resistance. Once we have the equivalent resistance, we'll use it to find the current.

$$R_{eq} = R_1 + R_2 + R_3 + R_4 = 100\ \Omega + 100\ \Omega + 100\ \Omega + 100\ \Omega = 400\ \Omega$$

Now that we have the equivalent resistance, we can calculate the current using Ohm's Law:

$$I = \frac{V_{Source}}{R_{eq}} = \frac{8\text{ V}}{400\ \Omega} = 0.02\text{ A, or } 20\text{ mA (milliamperes)}$$

We may now determine the voltage across each resistor. Since all the resistors are equal, and the current is the same everywhere, they will each drop the same voltage:

$$V_{R1} = V_{R2} = V_{R3} = V_{R4} = 100\ \Omega \times 0.02\text{ A} = 2\text{ V}$$

Therefore, if we measure between points 1 and 2, points 2 and 3, points 3 and 4, and points 4 and 5, we will measure 2 V every time. If we measure at points 1 and 3, what happens? We get the voltage across R4 plus the voltage across R3, or 4 V. And what about point 1 and point 4? We measure 6 V. We have divided the source voltage down to 2 V, 4 V, and 6 V if we measure with respect to point 1. Of course, the voltage between point 1 and point 5 is just 8 V, the source voltage.

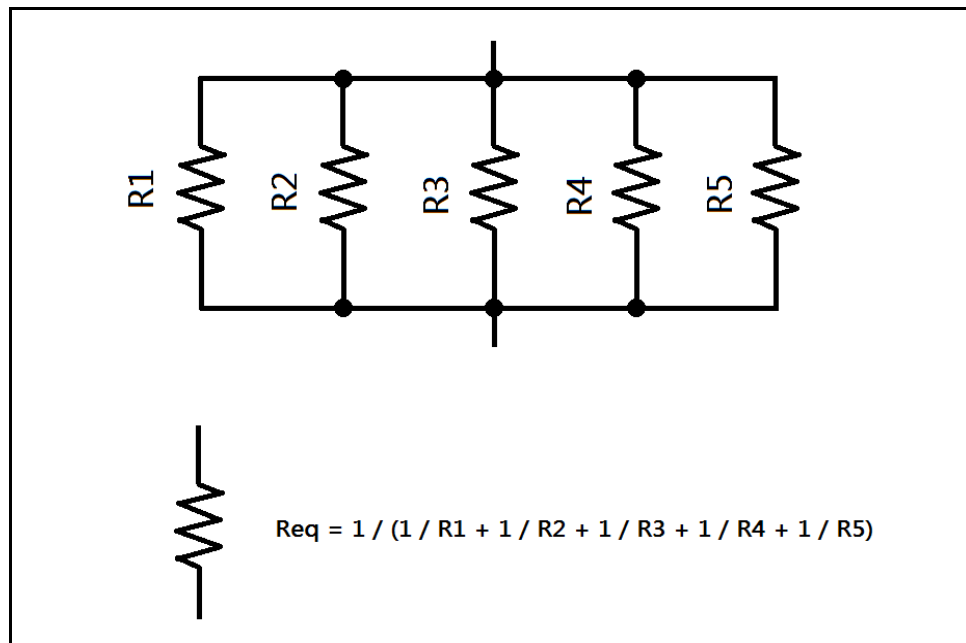
**Resistors in Parallel: Equivalent Resistance**

Finding the equivalent resistance for resistors in parallel is a little trickier. Because we end up with a *current divider*, the approach to the problem is a little more complex. We have to take the reciprocal of the sum of the reciprocals of the resistances. Let's look at the equation for resistors in parallel.

If given  $N$  resistors in parallel of arbitrary resistance, the equivalent resistance may be found by using the following equation:

$$R_{||} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_{N-1}} + \frac{1}{R_N}}$$

Let's see what this looks like in schematic format. In **Figure 22** shown below, we have five resistors of arbitrary value in parallel. We may represent this network with a single resistor.



**Figure 22: Five resistors in parallel, and their equivalent resistance.**

Intuitively, resistors in series are additive. What do you suppose happens when resistors are connected in parallel? It turns out that the equivalent resistance is *less* than the lowest resistance in the parallel network! Now we will cover a quick trick for resistors of equal value in parallel.

If  $N$  resistors of equal value  $R$  are in parallel, then the equivalent parallel resistance can be calculated quickly by using the following formula:

$$R_{\parallel} = \frac{R}{N}$$

For example, suppose we connect five resistors in parallel, each with the value  $100\ \Omega$ . What is the equivalent resistance? The answer is  $100\ \Omega / 5$ , or  $20\ \Omega$ .

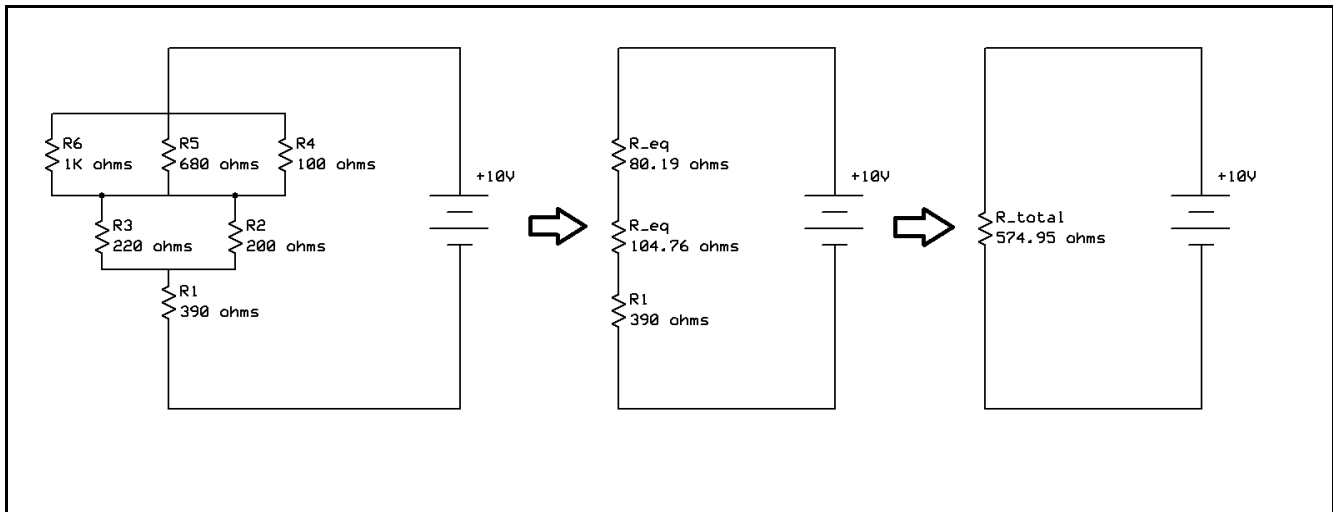
### Series-Parallel Resistor Networks

It should be noted that resistors in parallel have the same voltage across them. This fact is useful when dealing with more complicated networks. Notice the connection! Resistors in series have the same *current* through them (they have to!) and resistors in parallel have the same *voltage* across them. Remembering this fact will make it easy to analyze resistor networks of any complexity.

## Question

If the total voltage from a power supply is divided among resistors in series, what happens to total current for resistors in parallel?

We may tackle resistor networks by remembering that we can replace parallel or series resistors with their equivalent resistance during the analysis of the network. Let's try our hand at analyzing a complex network. In **Figure 23**, shown below, we are given a resistor network, shown in the leftmost schematic. We are provided with a  $10\text{ V}$  battery, and we are given the resistance values. We are asked to find the voltages and currents for each of the resistors in the network. We start by finding the total current for the circuit, and to do that we need to find the equivalent resistance for the entire resistor network, and simplify it into one equivalent load. Then we can apply Ohm's Law to find the current for that load, and this will give us our starting point.



**Figure 23: Analyzing a resistor network.**

Take a look at the schematic on the left. This is the resistor network that we must analyze. We begin by noting that resistors R3 and R2 form a parallel network, and that R6, R5, and R4 form a separate parallel network. We begin by finding their equivalent resistances.

$$R_3 \parallel R_2 = \frac{1}{\frac{1}{220\Omega} + \frac{1}{200\Omega}} \approx 104.76\Omega$$

$$R_6 \parallel R_5 \parallel R_4 = \frac{1}{\frac{1}{1000\Omega} + \frac{1}{680\Omega} + \frac{1}{100\Omega}} \approx 80.19\Omega$$

We note that these equivalent resistances form a series network (middle schematic.) Therefore,

$$R_{total} = 80.19\Omega + 104.76\Omega + 390\Omega \approx 574.95\Omega$$

And by Ohm's Law, the total current can be found (see the schematic at right in the above figure)

$$I_{total} = \frac{10V}{574.95\Omega} = 0.0174A, \text{ or } 17.4mA$$

Now that we have the total current, we can use the reduced series network (the middle schematic in **Figure 23**) to find the voltages. Remember that parallel networks will have the same voltage.

Finding the voltage across  $R_1$  is easy. We simply use Ohm's Law again:

$$V_{R1} = 17.4 \text{ mA} \times 390 \Omega \approx 6.78 \text{ V}$$

Since the parallel network  $R_3 \parallel R_2$  has equivalent resistance  $104.76 \Omega$ ,

$$V_{R3} = V_{R2} = 17.4 \text{ mA} \times 104.76 \Omega \approx 1.82 \text{ V}$$

Finally, since the parallel network  $R_6 \parallel R_5 \parallel R_4$  has equivalent resistance  $80.19 \Omega$ ,

$$V_{R6} = V_{R5} = V_{R4} = 17.4 \text{ mA} \times 80.19 \Omega \approx 1.40 \text{ V}$$

And we note that the voltages across each equivalent series resistance sum to the source voltage:

$$6.78 \text{ V} + 1.82 \text{ V} + 1.40 \text{ V} = 10.0 \text{ V}$$

Now we may easily calculate the individual resistor currents by using Ohm's Law again:

$$I_{R1} = 17.4 \text{ mA (which was the total current we found,)}$$

$$I_{R2} = \frac{1.82 \text{ V}}{200 \Omega} \approx 0.0091 \text{ A, or } 9.1 \text{ mA}$$

$$I_{R3} = \frac{1.82 \text{ V}}{220 \Omega} \approx 0.0083 \text{ A, or } 8.3 \text{ mA}$$

$$I_{R4} = \frac{1.40 \text{ V}}{100 \Omega} \approx 0.0140 \text{ A, or } 14.0 \text{ mA}$$

$$I_{R5} = \frac{1.40 \text{ V}}{680 \Omega} \approx 0.0020 \text{ A, or } 2.0 \text{ mA}$$

$$I_{R6} = \frac{1.40 \text{ V}}{1000 \Omega} \approx 0.00014 \text{ A, or } 1.4 \text{ mA}$$

And finally, note that the sum of the currents for the individual parallel networks is the total current:

$$I_{total} = I_{R1} = I_{R2} + I_{R3} = I_{R4} + I_{R5} + I_{R6} = 17.4 \text{ mA}$$

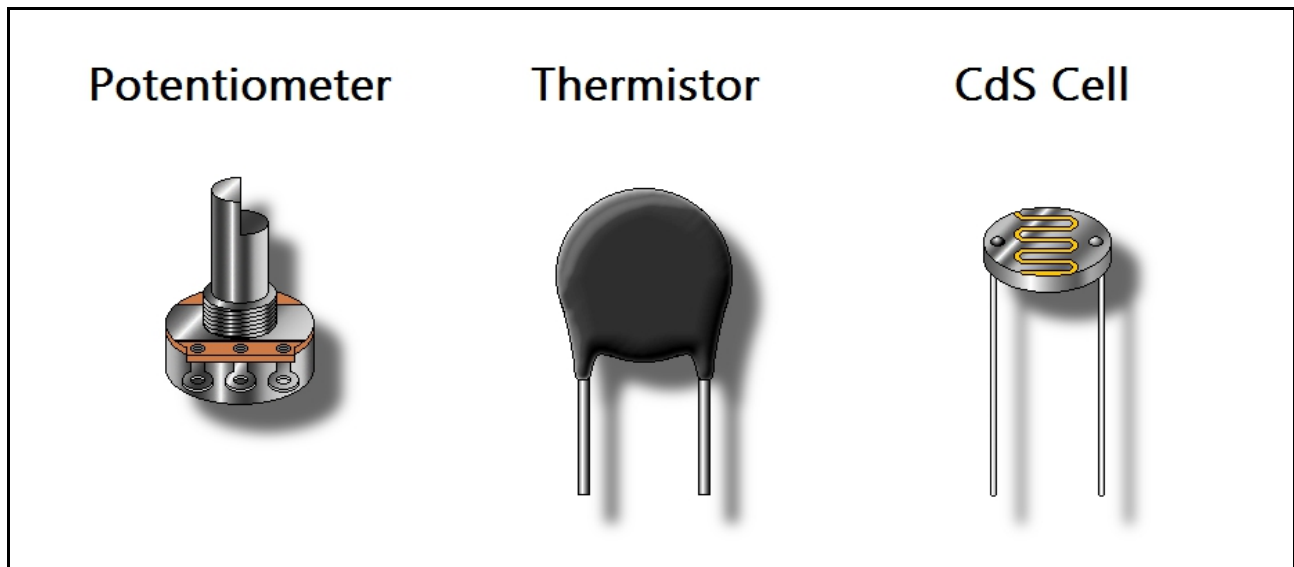
We verified some interesting things. First, we verified that the voltage divider concept is true even for series-parallel circuits. Second, we saw that parallel resistor networks divide the total current.



## Chapter 2.6: Potentiometers, Thermistors, and CdS Cells

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We've covered the basics when it comes to fixed resistors. But there is a bigger world of electronics components out there left to be discovered. We mentioned earlier that there are special purpose resistors. Some of these are shown in **Figure 24**, below.



**Figure 24: Potentiometers, thermistors, and CdS cells, oh my!**

*Potentiometers* are variable resistors. The middle tab is a connection to an internal wiper. With it, you can vary resistance by turning the knob. Think of it as a voltage divider that you can adjust. Some have a *linear taper*, which means they vary in a linear way when turned, while others may have an *audio taper*, which is an exponential variation. They are available in a wide range of values. They can be used as variable resistors, or even as position sensors, such as in joysticks and guitar pedals.

Next in our list is the *thermistor*. A thermistor decreases its resistance drastically as temperature increases. This makes it an ideal thermostat. Thermistors are used as safety devices to prevent *current inrush*. They, too, come in a wide variety of resistances and temperature characteristics.

Finally, we have a *cadmium sulfide cell*, or *CdS cell* for short. It changes resistance as light levels change, making it ideal for use as a light detector – such as in a burglar alarm or a light-game.

## Chapter 2.7: Computing Power Dissipation in DC Loads

---

We would prefer our circuits not to catch fire. In order to design circuits which can safely dissipate heat, we have to choose the proper *wattage* for the resistor value we select. As a rule of thumb, we want our resistor's wattage to be twice the value it will be expected to dissipate. Though we will cover AC power in a later chapter, we will introduce DC power equations here. The unit of measure of power is the *Watt*, abbreviated W. It is the amount of energy in *Joules* dissipated per second.

We may compute DC power dissipation of a resistive element by any of the following equations:

$$P_{watts} = V \times I,$$

$$P_{watts} = \frac{V^2}{R},$$

$$P_{watts} = I^2 \times R$$

For example, if we compute a power dissipation of 0.5 W (half a watt) for a given resistor, we should select a 1 W (one watt) resistor. Let's try an example. Take a look at **Figure 25**.

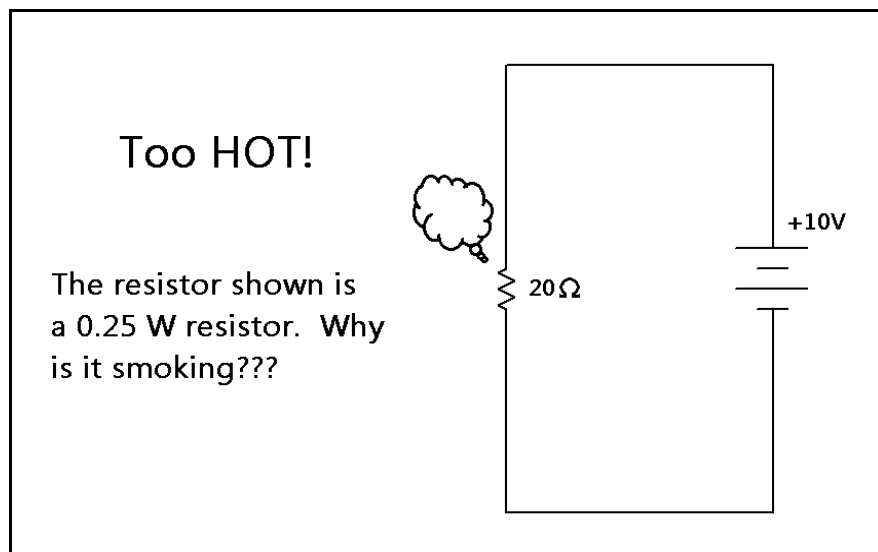


Figure 25: Is it hot in here, or is it just my resistor?

We have selected a quarter-watt resistor for our circuit. But there seems to be a problem – it's smoking! Let's compute the power dissipation of the resistor in the above figure to find out what has gone wrong.

We compute the power dissipation of the resistor in the above diagram:

$$\frac{V^2}{R} = \frac{(10\text{ V})^2}{20\ \Omega} = 5\text{ W}$$

Our little quarter-watt resistor cannot handle 5 watts of power! It will certainly catch fire. The resistor is trying to dissipate 20 times the amount of power it was designed to handle! If we need a 20  $\Omega$  resistor in this circuit, then we should use a 20  $\Omega$ , 10 W resistor (remember we need a power rating double the amount of power it will be expected to dissipate.) Why a factor of two? Well, engineers are human. And, well, engineers can also make mistakes. The more complicated the circuit, the less sure we are about how it will act when the circuit is being used out in the field. The “fudge factor” is a built-in safety precaution that ensures our circuit can handle excess current without bursting into flame should the unthinkable happen...because it certainly can happen!

## Chapter 2.8: Vocabulary Review

audio taper: exponential variation used in some potentiometers	Ohm: unit of measure of resistance
cadmium sulfide cell: a light-sensing resistor	Ohm's law: a physical law connecting volts, amps, and ohms
carbon composition resistor: a resistor made from carbon and binder	Ohm's Triangle: an tool for remembering equations
carbon film resistor: a resistor made with ceramic and carbon film	parallel: connected together side-by-side
CdS cell: abbreviation for cadmium sulfide cell	potentiometer: a variable resistor that can act as a voltage divider
color code: a code used for identifying resistor values by color band	power dissipation: energy emitted by a device in the form of heat
continuity test: checking for open circuits or short circuits	power rating: the amount of power a device is designed to dissipate
continuity: a condition meaning that a conductive path exists	power: a unit of energy, measured in Watts or Joules per second
current divider: a parallel circuit that divides current among branches	resistance: the property of conductors to impede the flow of current
current inrush: a sudden current spike when power is applied	resistor network: a group of resistors connected in a complex way
effective resistor: a resistor with the same resistance as a network	series: connected in a line, or part of the same current path
equivalent resistance: the combined resistance of a network	thermistor: resistor sensor that changes resistance with temperature
Joule: a unit of measure of energy used in physics and electronics	tolerance band: the color code on a resistor indicating tolerance
linear taper: linear variation used in some potentiometers	tolerance: a measure of accuracy of a resistor's indicated value
load: the device or circuit powered by a power supply	voltage divider: a circuit that provides a fraction of a source voltage
metal film resistor: a resistor made of ceramic and metal film	Watt: unit of measure of power, equal to one Joule per second
multimeter: test equipment for measuring volts, amps, and ohms	wattage: amount of power a device is designed to dissipate

## Chapter 2.9: Lab Activity 2 – Resistor Networks

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### Introduction

We explored series and parallel circuits involving resistor networks. We will now verify what we learned by using a multimeter. We will create our own resistors by wiring our existing resistors in series and parallel to obtain resistance values we don't have in our kit. We will construct a simple voltage divider to get voltages not found on the Bakerboard. Finally, we will create a resistor network.

### Materials

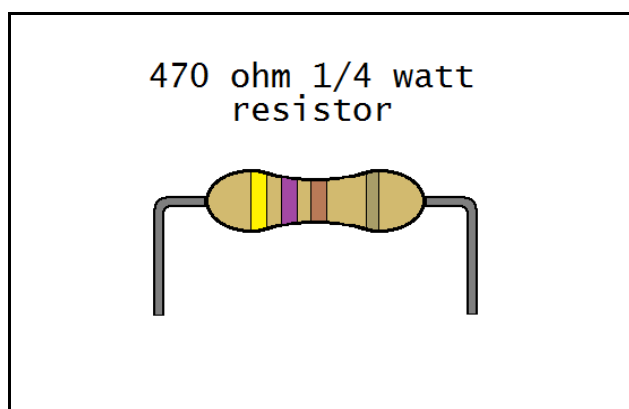
The materials required for this lab are listed in the table shown below.

Lab Activity 2 – Parts List	
Quantity	Item
1	220 $\Omega$ ¼ watt resistor (red, red, brown, and gold striped)
2	470 $\Omega$ ¼ watt resistor (yellow, purple, brown, and gold striped)
3	1000 $\Omega$ ¼ watt resistor (brown, black, red, and gold striped)
1	Multimeter (any multimeter model will suffice, as long as it can measure resistance)
1	LumiDax ® wiring kit
1	LumiDax ® Bakerboard Analog Trainer
1	Pair of wire cutters.

### Procedure

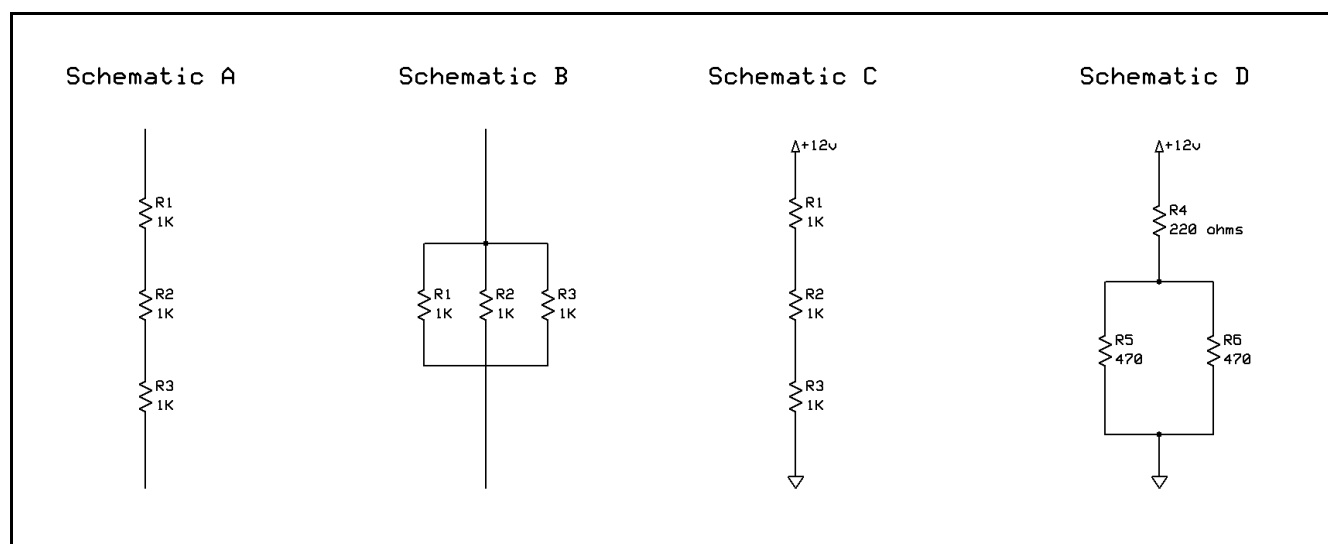
Make sure power is not applied to the trainer until your circuit is wired and ready to test. We will now get the components ready to use for constructing the circuit.

1. If your resistors are brand new, they will have long, straight leads. These will need to be gently bent and trimmed to fit into the breadboard properly. **Figure 26**, below, shows a properly prepared resistor. With your fingers gently applying pressure, bend the leads to a right angle with respect to the resistor body. Use the diagonal cutters to trim the leads to about half an inch, or about 1.5 centimeters. They should be short enough to allow the resistor to sit flush on the breadboard, yet long enough that the leads can be inserted into the tie-points in the breadboard securely.



**Figure 26:** What your resistors should look like after they are trimmed properly.

Observe the schematics shown below in **Figure 27**. You will be referring to these schematics for the duration of this lab exercise. We will be constructing our own resistors using the 1000  $\Omega$  resistors, and finally construct a series-parallel network to verify what we covered in this chapter.



**Figure 27:** Lab Activity 2 Schematic Diagram

2. We will begin constructing a 3000  $\Omega$  resistor by using three of the 1000  $\Omega$  resistors. Connect the three 1000  $\Omega$  resistors in series as shown in **Schematic A** in **Figure 27**, above. Your work should look like the diagram in **Figure 28** below. Do not apply power to this circuit. Make sure that you follow the diagram and insert the resistor leads into the rows as shown.

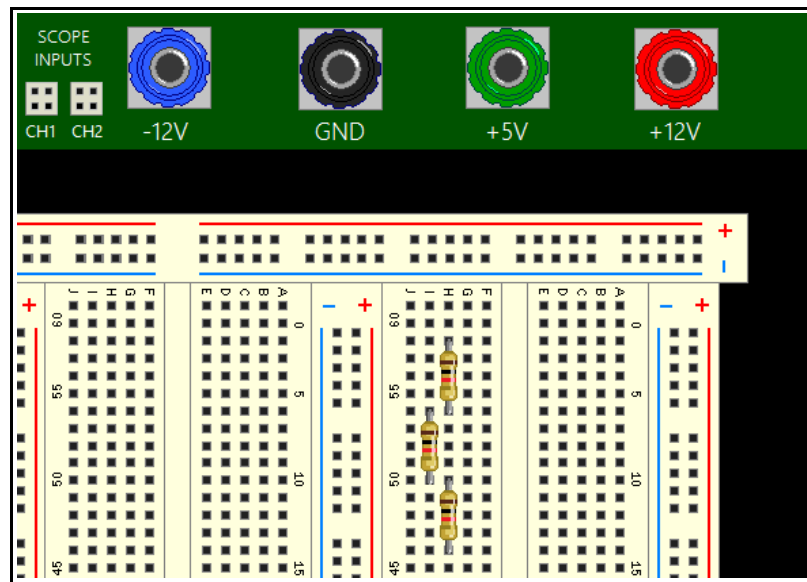


Figure 28: Three 1 KΩ resistors in series.

Turn on your multimeter and set the mode to ohms. Now use your multimeter probes to measure across all three resistors. Did you read a resistance close to 3000 Ω?

3. Apply +12 V to your series resistors, as shown in **Schematic C** in **Figure 27**, above. **Figure 29** shows what your circuit should look like when it is wired correctly. Turn on the power to the Bakerboard when you are finished wiring. Change the mode of your multimeter to DC volts.

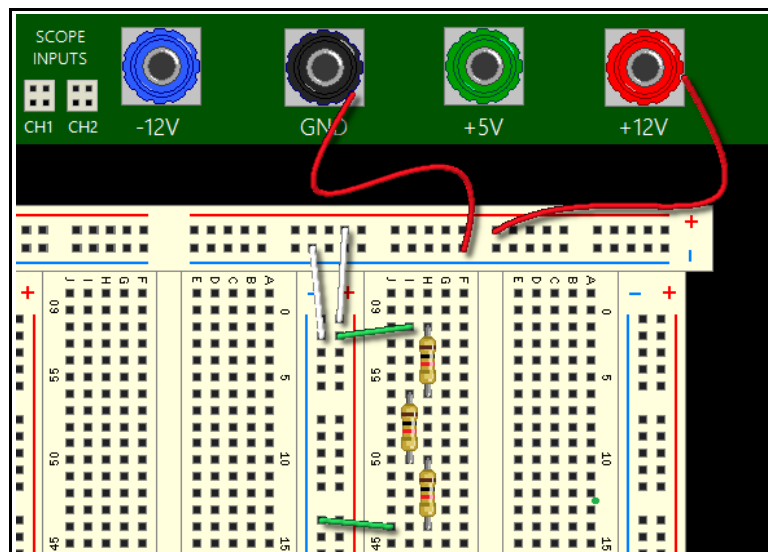
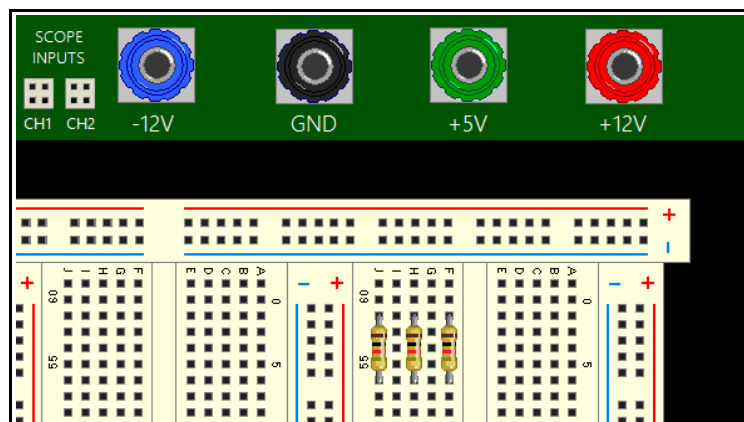


Figure 29: Series resistors being used as a voltage divider.

Measure the voltage across each resistor with your multimeter. Did you read +4 V across each resistor? Now we will verify that the voltage divider is working. Place the negative probe (black) of the multimeter on the lower lead of the bottom resistor. This is called measuring with respect to *ground*, as ground is the lowest potential in the circuit. Place the positive probe (red) of the multimeter between the bottom and middle resistors where they are connected. Did you read +4 V? Keep the negative probe at ground and put the positive probe between the middle and top resistors where they are connected. Did you read +8 V? Now, measure across all three resistors. Did you read the source voltage of +12 V?

Why is it that each resistor drops +4 V? The answer is that the current is everywhere the same in a series circuit, and that the resistors are all equal in value. Therefore, each will drop 1/3 of the source voltage. You will calculate this as an exercise following the lab.

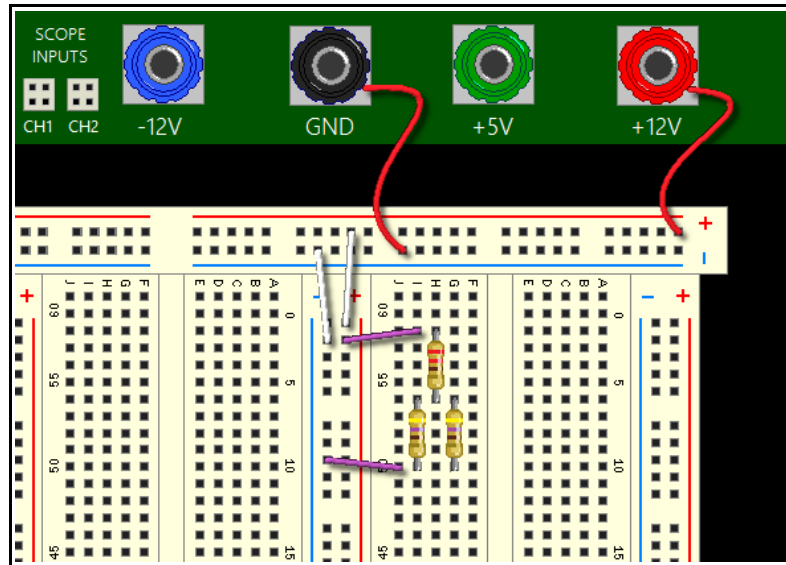
4. Next we will construct a  $333\ \Omega$  resistor by placing three  $1000\ \Omega$  resistors in parallel. Refer to **Schematic B** shown in **Figure 27**, above. If your Bakerboard is still powered from the previous step, unplug it. Remove the wires and resistors from the breadboard and rearrange the three  $1000\ \Omega$  resistors as shown in **Figure 30**. Make sure to follow the diagram as shown to ensure the resistors are properly connected in parallel. Do not wire this circuit to the power supplies.



**Figure 30: Three 1 K $\Omega$  resistors in parallel.**

Change the mode of your multimeter back to ohms. Measure across the resistors in parallel with your multimeter. Did you read approximately  $333\ \Omega$ ? Why is the resistance lower than  $1000\ \Omega$ ? Can you calculate the resistance quickly?

5. Now we will wire a resistor network with the  $220\ \Omega$  resistor and the two  $470\ \Omega$  resistors. Dismantle the parallel circuit you just built with the  $1000\ \Omega$  resistors and return them to your parts kit. Refer to **Schematic D** in **Figure 27**, above. Wire the series-parallel circuit; the circuit is shown completely wired below, in **Figure 31**.



**Figure 31: Series-parallel circuit diagram for Schematic D.**

Make sure not to power the unit until you have thoroughly checked your circuit. With the circuit under power, set your multimeter back to DC volts mode and measure the voltage across each of the  $470\ \Omega$  resistors. Did you measure a voltage close to +6 V? Is it the same for both  $470\ \Omega$  resistors? Can you make a guess as to the equivalent resistance of the  $470\ \Omega$  resistors in parallel?

### **Lab Activity 2 – Conclusion**

In this activity, you learned how to use a multimeter to measure voltage and resistance. You built your own resistors with values you do not have in your parts kit. You also verified voltage dividers, and some of the properties of series and parallel circuits.

You also learned the schematic symbol for your first component: the resistor! Being able to breadboard your own circuits from a schematic is a very important skill to have. As we progress through this course, you will find yourself getting better and better at wiring circuits. Eventually, you will be designing your own circuits!



## Chapter 2.10: Exercises

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### Vocabulary Questions

1. A useful mathematical tool connecting voltage, current, and resistance is \_\_\_\_\_.
2. A \_\_\_\_\_ circuit has elements connected one after another in the same current path.
3. A \_\_\_\_\_ circuit divides current among its branches.
4. A circuit or device under power is often referred to as the \_\_\_\_\_.
5. A simplified resistor that has the same resistance as a resistor network: \_\_\_\_\_.
6. A \_\_\_\_\_ is a resistor made with resistive material and a binder.
7. \_\_\_\_\_ is a measure of resistor value accuracy.
8. \_\_\_\_\_ is a measure of the energy dissipated by a resistor, in Watts.
9. A \_\_\_\_\_ is a device that can measure voltage, current, or resistance.
10. A \_\_\_\_\_ is a variable resistor.
11. We may use a \_\_\_\_\_ to get a fraction of the total voltage from a power supply.
12. A \_\_\_\_\_ changes resistance drastically with changes in temperature.

### True or False

- |  |   |   |
|--|---|---|
| 1. Carbon composition resistors are low-noise, very accurate resistors.              | T | F |
| 2. A Joule is a measure of resistance.   | T | F |
| 3. Series circuits have the same current throughout the current path.                | T | F |
| 4. Parallel circuits are also known as voltage dividers.                             | T | F |
| 5. A cadmium sulfide cell changes resistance with changes of light intensity.        | T | F |
| 6. One watt is equal to one joule per second of power dissipation.                   | T | F |
| 7. A resistor's wattage should be smaller than the expected power it will dissipate. | T | F |
| 8. To measure voltage, a multimeter must be connected in series with the circuit.    | T | F |
| 9. A resistor impedes the flow of current in a circuit.                              | T | F |
| 10. Some resistors can have values of millions of ohms.                              | T | F |

**Problems**

1. You are given a 200  $\Omega$  resistor, a 330  $\Omega$  resistor, and a 470  $\Omega$  resistor. Calculate the series combination for these resistors.
2. Calculate the parallel resistance of the resistors from the **Problem 1**.
3. Calculate the currents and voltages for all resistors from **Schematic D** in **Figure 27** of the lab exercise you just completed. What happens to the current when it encounters the two 470  $\Omega$  resistors in parallel?
4. You are tasked with providing a dropping resistor for an LED. The LED drops 1.7 V in the forward (lit) direction. You will power the LED from a +15 V power supply. You are asked to make sure the LED has a current of 15 mA (0.015 A). What value resistor should you use in series with the LED to make sure it does not burn out?
5. In **Problem 4** you found a dropping resistor for the LED. But you are unsure about what wattage to use. Calculate the power dissipated by the dropping resistor. Will a  $\frac{1}{4}$  W resistor work? Remember that your resistor wattage should be a factor of two higher than the expected power dissipation.
6. Calculate the voltages and currents in each resistor from **Schematic C** of **Figure 27** from the lab exercise.
7. You need a 25  $\Omega$ , 1 W resistor, but all you have are four 100  $\Omega$ ,  $\frac{1}{4}$  W resistors. Explain how you can make the 25  $\Omega$ , 1 W resistor with what you have. What is the power dissipated by each resistor with respect to total current? Will it work?

## Chapter 3 – Capacitance and Inductance

In this chapter, you will...

- ➡ Learn about capacitors.
- ➡ Explore the properties of capacitors.
- ➡ Look at magnetism and inductance.
- ➡ Learn about the Right Hand Rule.
- ➡ Discover transformer theory.

You learned about your first *passive* component in the last chapter: the resistor. Now you will learn about *capacitors*, *inductors*, and *transformers*.

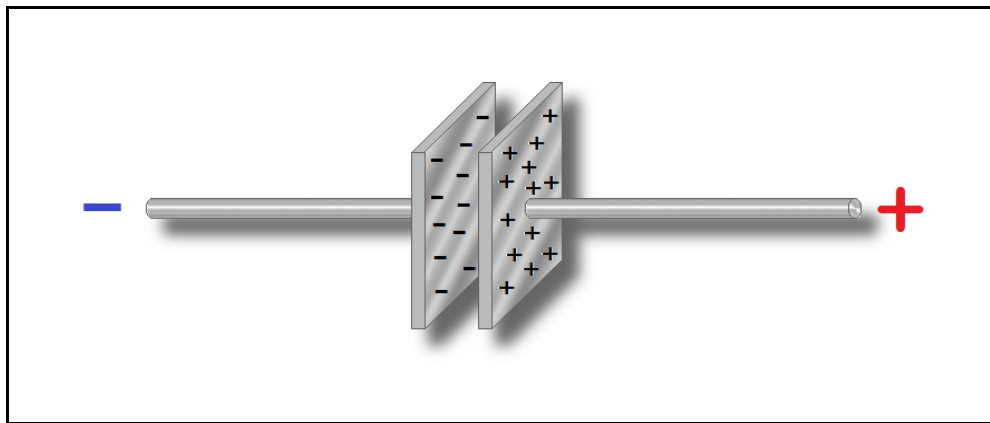
A capacitor is a component that can store charge. The amount of charge a capacitor can store is called its *capacitance*. Inductors are *electromagnetic* components that can also store energy. But instead of storing charge, they store energy in a *magnetic field*. Transformers can convert from one AC voltage to another by using an internal magnetic field.

These components are used in electronics to smooth waveforms, block DC or AC, to convert from one AC voltage to another, and in *filters*. A filter is a circuit that removes unwanted *frequencies* from a *signal*, or selects a narrow *band* of signals from a wider *spectrum*. Your radio tuner works by using a filter.

## Chapter 3.1: Introduction to Capacitors

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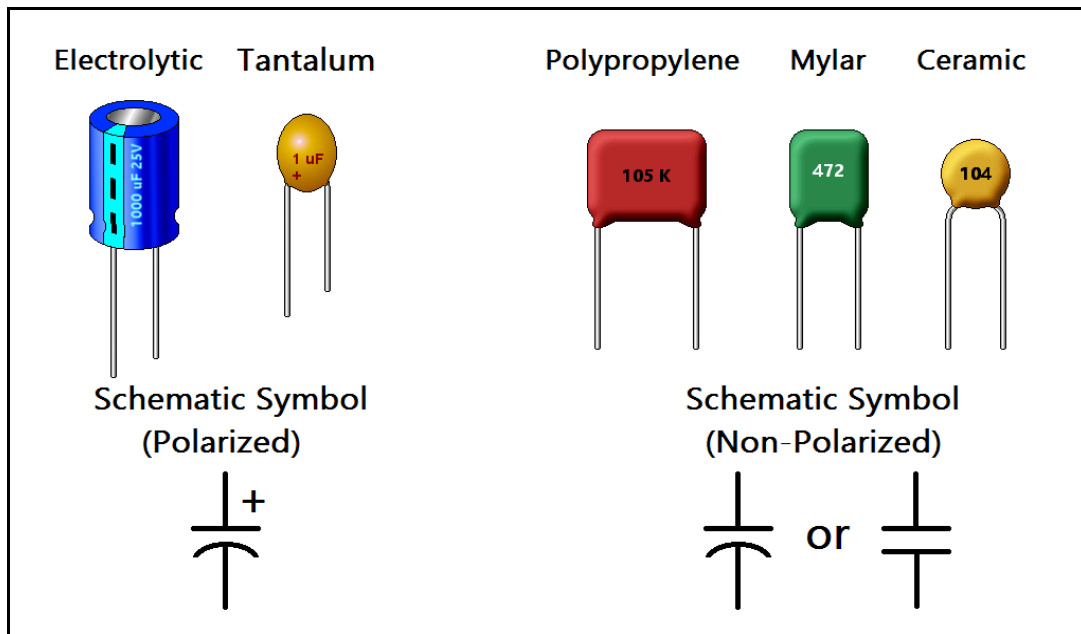
A capacitor is a component that can store electric charge. In their simplest possible form, capacitors are nothing more than two conductive plates separated by empty space, air, or some insulating material called a *dielectric*. If we apply an electric field to the plates with a potential difference, negative charges will build on the negative side, and positive charges will build up on the positive side by *charge induction*. If we then remove the potential difference, the capacitor will remain in a charged state since the charges on the plates cannot equalize due to the insulating gap. The energy is stored in the electric field between the plates. Let's take a look at **Figure 32**, below.



**Figure 32: A parallel-plate capacitor showing charge distribution.**

Calculating capacitance for such a system of plates is beyond the scope of this book. However, we will say that a capacitor's ability to store charge depends on how close the plates are, the properties of the insulator between the plates, and the surface area of the plates. Bigger plates, closer distances, and better insulators all contribute to higher capacitance. Advances in the material sciences have produced better insulators, making modern capacitors much smaller and more reliable.

Capacitors have a unit of measure called the *farad*. But a farad is quite large, so we usually use microfarads (abbreviated  $\mu\text{F}$ .) A microfarad is one millionth of a farad, or  $1 \times 10^{-6} \text{ F}$ . Capacitors are commercially available from tens of farads (the so-called “super caps”) down to fractions of a picofarad (as low as  $5 \times 10^{-14} \text{ F}$ !) Capacitors are rated for their *working voltage*. If a capacitor's working voltage is exceeded, there is risk of failure called *dielectric breakdown*.



**Figure 33: A few of the most common types of capacitors.**

Capacitors come in a dizzying array of types and styles. But you will most commonly encounter the capacitors shown in **Figure 33**, above. These are the *electrolytic capacitor*, *tantalum capacitor*, *polypropylene capacitor*, *mylar capacitor*, and the *ceramic disc capacitor*.

### Aluminum Electrolytic Capacitors

Aluminum electrolytic capacitors are made by rolling plates of aluminum foil together with an electrolyte-impregnated tissue to separate the plates. They are typically dark blue (but occasionally other colors) and cylindrical in shape. These capacitors are *polarized*. That is, they have a negative lead (marked by a stripe) and a positive lead. This has to do with the internal chemistry of the capacitor. Charging these capacitors backwards may result in permanent damage to the capacitor and a face-full of stinky smoke. They range from one microfarad to thousands of microfarads. Because of their leakage and poor tolerance, they are mainly used for power supply filtering and low frequency applications. They are also rated at lower working voltages than other types.

### Tantalum Capacitors

Tantalum capacitors are very small, but offer increased capacitance for their size. They are much smaller than electrolytic capacitors, making them ideal for use in circuits where size is a factor. Like electrolytic capacitors, they are polarized. And like aluminum electrolytic capacitors, they do not like

reverse voltage. In fact, tantalum capacitors have a nickname: “bullet caps.” They will self-destruct rather spectacularly if inserted into a circuit backwards, often exploding. Therefore, pay attention to the little plus sign on these capacitors, as that tells you which lead is the positive lead.

### **Film Capacitors**

Polypropylene capacitors, or “poly caps,” are made using a thin sheet of plastic material as the insulating dielectric. They are usually red and rectangular in shape. They come in ranges from tens of microfarads to fractions of a microfarad. These capacitors have improved tolerance and better characteristics than their mylar cousins. They are non-polarized, and have a wider range of applications due to their better all-around ratings. These capacitors do not vary as much due to temperature and voltage applied, and are a better choice for audio applications. Mylar capacitors can be recognized by their green rectangular packaging. They suffer from dielectric absorption, and do not perform as well as polypropylene capacitors. However, they are cheaper than polypropylene capacitors. They are useful for non-critical applications where cost is a factor.

### **Ceramic Disc Capacitors**

These capacitors are easy to recognize due to their familiar round shape, flat profile, and their yellow, orange, or red coloring. They are cheap, dependable, and are by far the most commonly used type of capacitor. They offer good performance well into RF (*radio frequency*) ranges. They typically come in values from picofarads (0.000001 microfarads) up to 0.1 microfarads. These capacitors also have extraordinarily high working voltages, from hundreds to thousands of volts. As such, they can be used for high voltage applications such as voltage multiplier circuits.

### **A Note on Reading Capacitor Values**

Aluminum electrolytic and tantalum capacitors are easy to read. However, poly, mylar, and ceramic disc capacitors are often stamped with a three-digit numeric code. This code refers to the capacitance in picofarads, and is very similar to the way resistors are coded. The first two numbers are the first digits of the capacitance, and the last number is the multiplier. For example, a numeric code of 473 means  $47 \times 1000$ , or 47000 picofarads (47 nF.) The code 104 means  $10 \times 10000$ , or 100000 picofarads (0.1 microfarads.) The code 681 means  $68 \times 10$ , or 680 picofarads. And rarely you will see a 105 code, meaning 1000000 picofarads, or 1  $\mu$ F. Consequently, 1000 picofarads equals one nanofarad, and 1000 nanofarads equals one microfarad. You will see these values frequently written pF (picofarad,) nF (nanofarad,) and  $\mu$ F (microfarad.)

## Chapter 3.2: Capacitors in Series and Parallel

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We will start with series-connected capacitors. It seems counter-intuitive, but capacitors do *not* add up when placed in series as resistors do. Let's look at the equation to gain some insight.

To compute the equivalent capacitance for N arbitrary capacitors placed in series,

$$C_{eq} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \dots + \frac{1}{C_{N-1}} + \frac{1}{C_N}}$$

The equivalent capacitance for series-connected capacitors will be lower than the lowest capacitor's value. Why? Remember that the closer the plates of a capacitor are, the higher the capacitance. By placing capacitors in series, we are increasing the effective plate distance of the equivalent capacitor, thereby reducing the overall capacitance! Our quick trick for resistors in parallel will also work for capacitors in series.

To compute the equivalent capacitance for N capacitors of equal capacitance C in series,

$$C_{eq} = \frac{C}{N}$$

We now turn our attention to capacitors in parallel. This configuration is so common that it has a special term: *capacitor bank*. Capacitors in parallel add together (due to the increased effective plate area.) Therefore, computing equivalent capacitance for capacitors in parallel is quite easy.

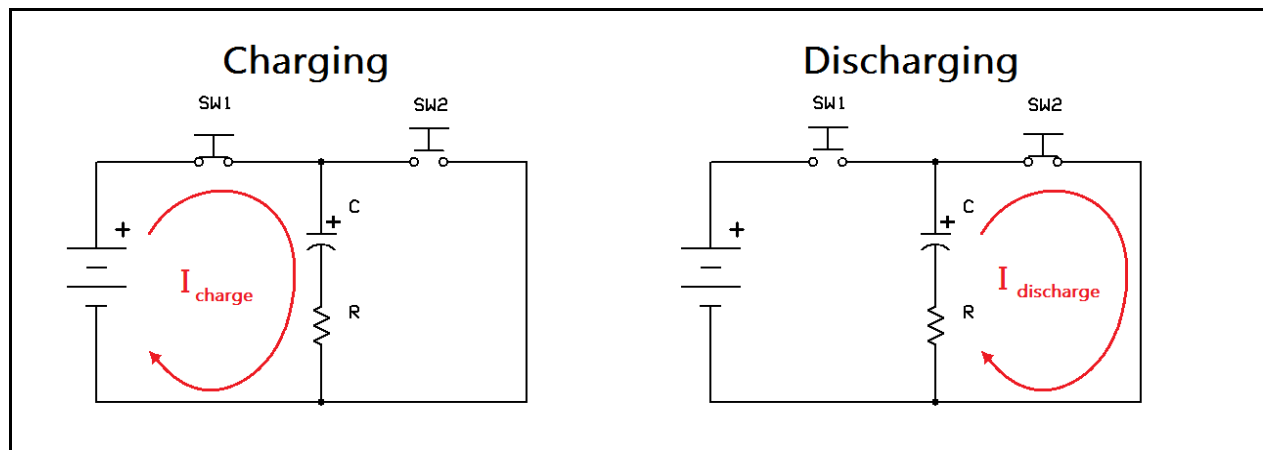
To compute the equivalent capacitance for N arbitrary capacitors in parallel,

$$C_{eq} = C_1 + C_2 + \dots + C_{N-1} + C_N$$

Power supplies are a common place to find banks of capacitors for filtering DC. Capacitors can discharge very quickly, producing huge current impulses. Therefore, capacitor banks are also used in *pulse circuits* to achieve very high current, high speed discharges, such as in a rail-gun system.

### Chapter 3.3: Capacitor Charge, Discharge, and the RC Time Constant

When we charge or discharge capacitors, they do not charge or discharge instantly. They take a certain amount of time to charge or discharge completely. The amount of time to charge a capacitor depends on the capacitance and the resistance in the circuit. Take a look at **Figure 34**, shown below.



**Figure 34: Charging and discharging a capacitor through a resistor.**

When we depress and hold the push-button switch SW1, the capacitor begins charging (the schematic at left.) *Instantaneously*, the capacitor begins to flood with charges, and looks like a *dead short*. The only thing limiting current at this point is the resistor. As the charge begins to build up in the capacitor, the current decreases. Finally, after a certain amount of time, the current stops altogether and the capacitor is fully charged. The amount of time it takes to do this depends on the *time constant* of the capacitor and resistor, called the *RC time constant*, which we will now define.

The RC time constant  $\tau_{RC}$  is defined the following way,

$$\tau_{RC} \equiv R \times C$$



The Greek letter  $\tau$  (lowercase tau) is used to represent the time constant  $R * C$ , and is measured in seconds. After the switch SW1 in **Figure 34** is pressed and held, the capacitor is said to be fully charged after about  $5\tau$ , or “five tau.” If we release switch SW1 at this point, the capacitor will retain the charge until a discharge path is created. We will now give the capacitor charging function for the voltage across a capacitor with respect to time.

The voltage across a capacitor when charging from 0 V can be expressed by the following function, with given values of  $R$  and  $C$  in series,

$$V(t) = V_0(1 - e^{\frac{-t}{\tau_{RC}}}) = V_0(1 - e^{\frac{-t}{RC}})$$

Where  $V_0$  is the initial applied voltage and  $t$  is the elapsed time in seconds.

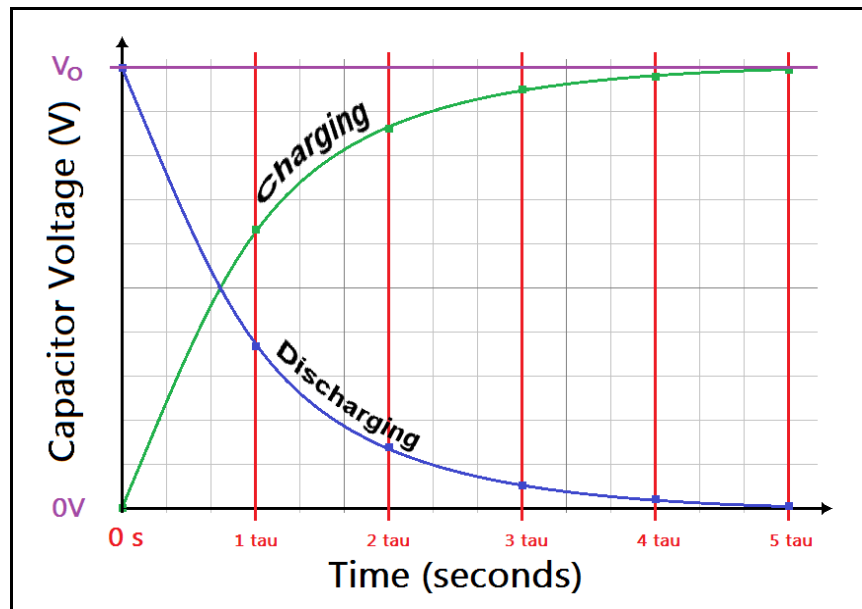
When we discharge a capacitor, it begins to dump its stored charge into the discharge path, acting as a temporary voltage source. In **Figure 34**, look at the schematic on the right. If we depress and hold switch SW2, the charge stored in the capacitor is given a discharge path through the resistor. Once again, it takes about  $5\tau$  to discharge the capacitor to 0 V. We now give the capacitor discharging function for voltage across a capacitor with respect to time.

The voltage across a capacitor when discharging from initial voltage  $V_0$  can be expressed by the following function, with given values of  $R$  and  $C$  in series,

$$V(t) = V_0 e^{\frac{-t}{\tau_{RC}}} = V_0 e^{\frac{-t}{RC}}$$

Where  $V_0$  is the capacitor's starting voltage and  $t$  is the elapsed time in seconds.

What do you suppose happens to the energy when the capacitor discharges? It is dissipated as heat by the resistor in the discharge path. Therefore, both energy and charge are conserved. Capacitors are said to resist changes in voltage. This is due to their being able to store charges when the applied voltage increases, and to deliver those stored charges when the applied voltage decreases. This is what makes them useful for filtering. They also block DC, since no current flows when fully charged.



**Figure 35: Resistor-capacitor (RC) charge and discharge curves.**

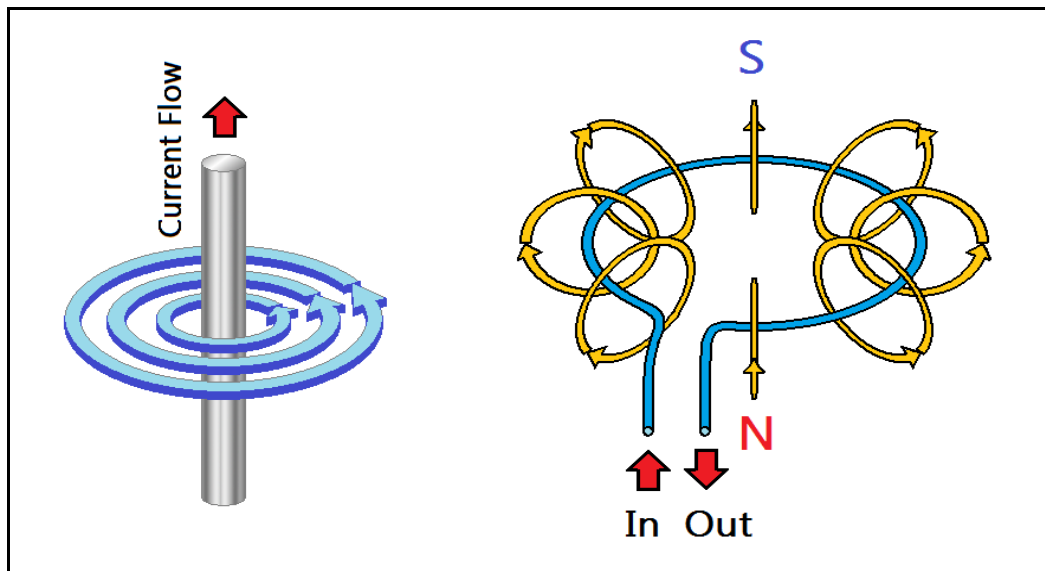
We just described the functions for charging and discharging capacitors with a series resistance. Let's look at **Figure 35**, shown above. We can clearly see the exponential nature of charge and discharge curves in this graph. After a time of  $1\tau$ , a charging capacitor is charged to about 63% of the applied voltage, while a discharging capacitor is discharged to about 36% of its initial voltage. We may use these facts to measure an unknown capacitance if the series resistance is known. We will examine charging and discharging behavior for RC circuits later in the lab exercise at the end of this chapter.

## Chapter 3.4: Introduction to Inductors

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An inductor is nothing more than a coil of wire. It might be an *air-core* inductor, or have a solid core of iron or *ferrite*. Ferrites are made from a *magnetic* powder that is pressed into either a cylinder shape or a doughnut shape called a *toroid*. Inductors use the properties of electricity and certain materials to concentrate a *magnetic field*. *Inductance* is measured in *henries*, represented by a capital H, and come in values from a few microhenries ( $\mu\text{H}$ ) to tens of henries.

Any wire with a current flowing through it generates a magnetic field. This is due to a physical law that states that charges in motion must develop a magnetic field. Therefore, we refer to this phenomenon as *electromagnetism*, as both electricity and magnetism are intimately linked.

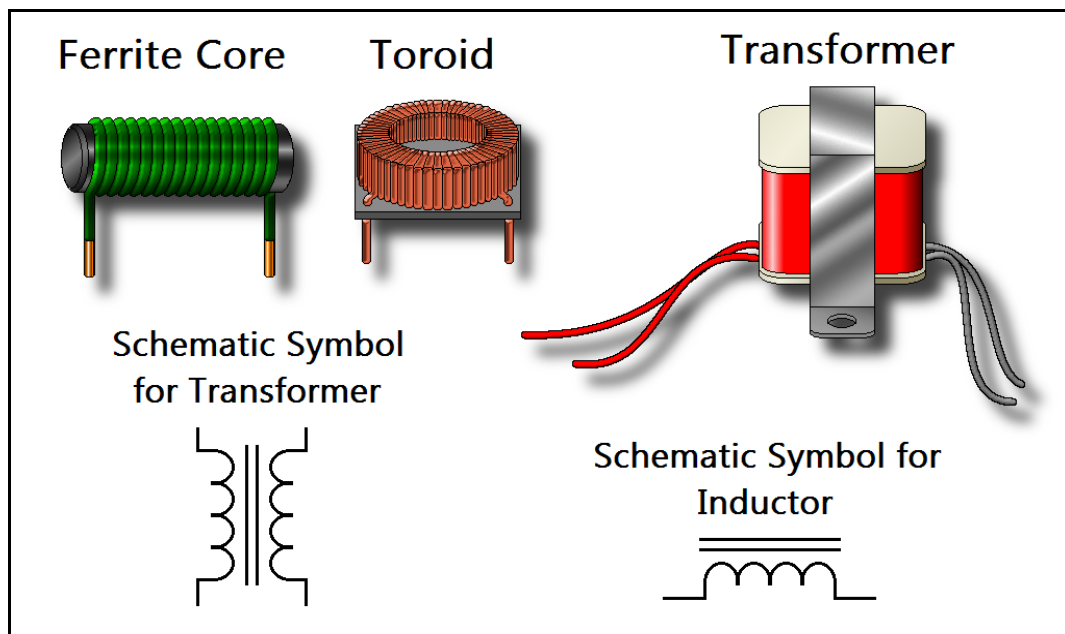


**Figure 36: Visualizing the Right Hand Rule.**

We may understand the relationship between current flow and magnetic fields by using the *Right Hand Rule*. In **Figure 36**, above, observe the conductor on the left. A current is shown flowing in the upward direction. Now, imagine grasping this conductor with your right hand, with your thumb pointing in the direction of current flow, and observe the curl of your fingers. Your fingers will curl in the direction of the circular magnetic field around the conductor.

If we bend a straight conductor into a circle, we have essentially created a one-turn coil. Coils concentrate the circular magnetic field, leading to a north-south polarization. Observe the coil on the right, and pay attention to the circular field lines, with arrows depicting the direction of the field. When arranged in a coil, the field lines appear to come out of the bottom of the coil, and move toward the top of the coil. If we reverse the direction of current flow in this coil, the direction of the magnetic field will change, leading to a north magnetic pole at the top of the coil, and a south magnetic pole at the bottom of the coil.

Computing the inductance of a coil is beyond the scope of this text, and can be rather involved depending on the material used for the core, the number of turns of the coil, the geometric configuration, etc. Even the physical proximity of one coil to another can give rise to *mutual inductance*, further complicating matters. Therefore, we will place more stress on the uses of inductors rather than going heavily into theory.



**Figure 37: Inductor examples – a coil, a toroid, and a transformer.**

Shown above in **Figure 37**, we have some examples of the inductors you will come across. A transformer is also shown, because it is also a device that uses electromagnetism. Transformers “transform” one voltage to another, and to provide *isolation*. Transformers are just one example of the many types and styles of inductors you might come across. Let's look at a few of them.

### **RF Inductors**

Radio frequency (RF) inductors are found in high frequency circuits such as communications equipment. They are typically wound on cardboard, ferrite, or have a wax, plastic, or air core. These have small inductance values, and are used in conjunction with capacitors to make RF filters. These are usually in the millihenry (mH) or microhenry ( $\mu\text{H}$ ) range.

### **Chokes**

*Chokes* are high-current inductors that have a low inductance. They are used for cleaning up AC power lines by “choking off” high frequency signals, and to keep these unwanted signals from being wicked into sensitive electronics. The ferrite core coil and toroid in **Figure 37** are examples of chokes, though some may actually look more like transformers with only one winding. They are typically wound with large diameter *magnet wire* on powdered ferrite cores. Larger, heavier inductors are used in power conditioning equipment and in heavy industrial applications, and have iron cores.

**Transformers**

Transformers use mutual inductance to convert one AC voltage to another. They are created by winding a coil called the *primary winding* on a magnetic core, and then winding an electrically isolated coil on top of the first called the *secondary winding*. As the magnetic field from the primary winding expands, it *induces* electromotive force in the secondary. That is, the magnetic field lines cut across the secondary, and the moving magnetic field gives rise to current flow in the secondary via *magnetic induction*.

There are many types of transformers. Some tiny transformers are used in high frequency communications circuits (RF transformers.) Larger transformers are used for power supplies, providing safer voltages and isolation from power lines. Some types of transformers do not isolate the secondary winding and primary, but integrate the two in series. These are called *autotransformers*.

**Chapter 3.5: Inductors in Series and Parallel**

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We will start with series-connected inductors that are *not* magnetically coupled. As it turns out, inductors add together in series just as resistors do. We will now define the equation for adding inductors in series.

To compute the equivalent inductance for N arbitrary inductors in series (no magnetic coupling,)

$$L_{eq} = L_1 + L_2 + \dots + L_{N-1} + L_N$$

For inductors in parallel with no coupling, the equation has the same form as for resistors in parallel.

To compute the equivalent inductance for N arbitrary inductors in parallel (no magnetic coupling,)

$$L_{eq} = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \dots + \frac{1}{L_{N-1}} + \frac{1}{L_N}}$$

And, of course, our quick trick for resistors in parallel works for inductors of equal value in parallel.

To compute the equivalent inductance for  $N$  inductors of equal inductance  $L$  in parallel (no magnetic coupling,)

$$L_{eq} = \frac{L}{N}$$

### Chapter 3.6: Inductor Charge, Discharge, and the RL Time Constant

Inductors do not store energy in the form of charges like capacitors do. Instead, inductors store energy in the magnetic field that they produce. Even though a capacitor can store charge for a long time, inductors cannot do so. As soon as current is removed, the magnetic field invariably begins to collapse. If there is no path for the discharge, very high “kickback” voltages can be generated!

Inductors resist changes in current (remember that capacitors resist changes in voltage.) Therefore, when the field collapses, a *back EMF* is generated, as the inductor is trying to continue current flow in the same direction. It is the collapsing magnetic field that generates this back EMF by cutting across the coil as it collapses. So the voltage across the inductor reverses during discharge to keep current flowing in the same direction in the inductor. Let's take a closer look at how this works in **Figure 38**.

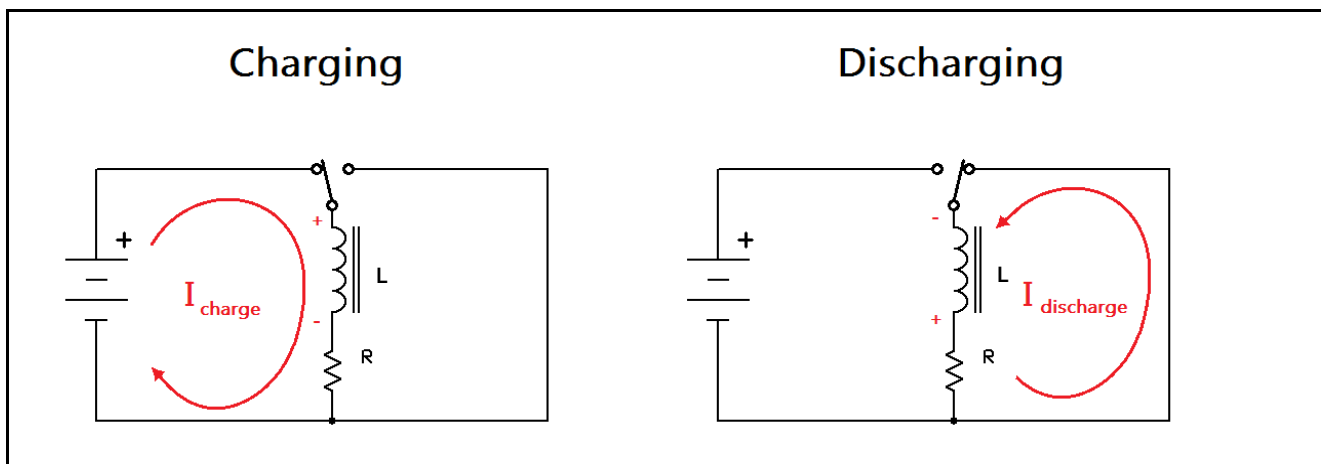


Figure 38: Inductor charging and discharging.

Look at the switch in the middle of the schematic, shown above. We are going to make this switch infinitely fast for our discussion. When the switch is flipped over to the voltage source, no current flows at first. The inductor is resisting the sudden increase in current. The inductor appears as an open circuit, and drops all the voltage from the power supply. As the magnetic field builds in the inductor, current slowly increases until maximum current is achieved. Following the current flow from the power supply, it moves down through the inductor (down the page) and the resistor towards the negative terminal of the power supply. When maximum current is established, the inductor looks like a short circuit and drops no voltage, and the only resistance in the circuit is provided by the resistor. As it turns out, RL circuits have a time constant as well as RC circuits, which is also called tau ( $\tau$ .) It takes about  $5\tau$  for the current to reach maximum for a series RL circuit. We define the *RL time constant* below.

The RL time constant  $\tau_{RL}$  is defined the following way,

$$\tau_{RL} \equiv \frac{L}{R}$$

We will now give the inductor charging function for inductor current with respect to time, given a series resistance R in the current path, as in **Figure 38**.

The current through an inductor when charging from an initial current of 0 A can be expressed by the following function, with given values of R and L in series,

$$I(t) = I_f \left(1 - e^{\frac{-t}{\tau_{RL}}}\right) = \frac{V_0}{R} \left(1 - e^{\frac{-Rt}{L}}\right)$$

Where  $V_0$  is the initial applied voltage,  $I_f$  is the final current, and  $t$  is the elapsed time in seconds.

When our infinitely fast switch is flipped to the other position, the inductor suddenly creates a back EMF to resist the reduction of current. It acts as a temporary voltage source of opposite polarity, trying to continue the current flow down the page. It has a discharge path through the resistor, and the

current decays exponentially to zero. Where does the energy from the magnetic field go? It is dissipated by the resistor as heat. Therefore, energy is conserved here, too. Again, the discharge of the inductor takes about  $5\tau$ .

We now give the inductor discharging function for current through an inductor with respect to time, given a series resistor  $R$  in the discharge path as in **Figure 38**.

The inductor discharge current when discharging from initial current  $I_0$  can be expressed by the following function, with given values of  $R$  and  $L$  in series,

$$I(t) = I_0 e^{\frac{-t}{\tau_{RL}}} = I_0 e^{\frac{-Rt}{L}}$$

Where  $I_0$  is the inductor's starting current and  $t$  is the elapsed time in seconds.

In **Figure 39**, we show the charge and discharge curves for inductor current with respect to time. And inductors will reach about 63% of maximum current in one tau when charging.

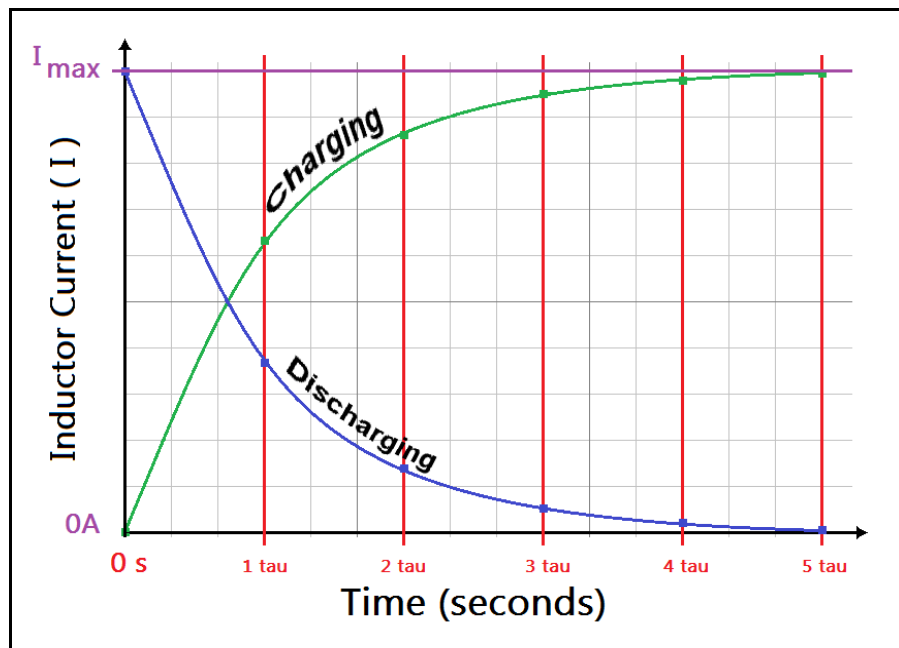


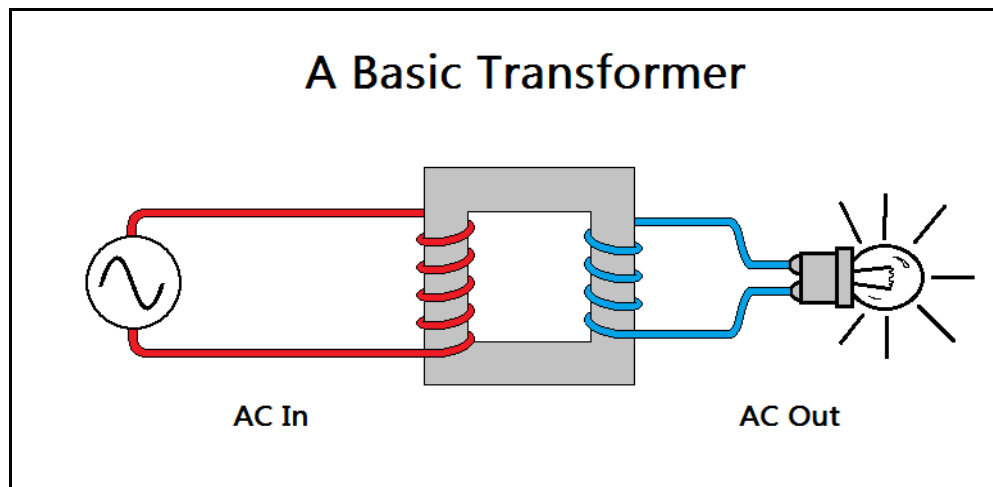
Figure 39: Resistor-inductor (RL) charge and discharge curves.



## Chapter 3.7: Basic Transformer Theory

### Transformer Turns Ratio

It was stated earlier in this chapter that transformers use mutual inductance to transform one AC voltage to another. We will now take a closer look at transformers and give some useful hints on how to use them. Let's look at **Figure 40**, shown below.



**Figure 40: A transformer isolating a load from the AC source.**

Whether transformers step an input AC voltage up or down based the *turns ratio* of the secondary to the primary windings. On the left side of the diagram above, an AC input waveform is being applied to the primary, shown in red. The magnetic field created by this alternating current is confined to the core, which is represented by the gray square in the diagram. The *flux* in the core induces current flow in the secondary, shown in blue. We now state a relationship between turns ratio and voltage.

The ratio of output voltage to input voltage for a transformer is equal to the ratio of the number of turns in the secondary to the number of turns in the primary,

$$\frac{V_{secondary}}{V_{primary}} = \frac{N_{secondary}}{N_{primary}}$$

Where  $V_{secondary}$  is the secondary AC voltage,  $V_{primary}$  is the primary AC voltage, and  $N_{secondary}$  and  $N_{primary}$  are the number of turns in the secondary and primary, respectively.

Look again at **Figure 40**. From the drawing, we can see that the turns ratio is 3 : 4. Normally, transformers will have many times that number of turns, but it is the ratio itself in which we are interested. We can do a little math to find out how our transformer will step up or down the voltage we input into the primary.

From the equation, we may rewrite the expression to solve for the unknown secondary voltage.

Solving for  $V_{secondary}$ ,

$$V_{secondary} = V_{primary} \frac{N_{secondary}}{N_{primary}}$$

So if we multiply the primary voltage by the turns ratio, we obtain the secondary voltage. Let's do an example using the ratio from the diagram in **Figure 40**.

Given a 16 VAC input on the primary, we may calculate the secondary voltage,

$$V_{secondary} = (16 VAC) \frac{3}{4} = 12 VAC$$

### **Transformer Power Capacity**

Transformers are rated according to how much power they can deliver to a load. This is referred to as a transformer's *volt-ampere characteristic*. Let's say we have a transformer with a VA rating of 100 VA, and a secondary voltage of 10 VAC. Dividing the volt-ampere rating by the primary or secondary operating voltages will yield the maximum current the primary and secondary can handle.

Consider a transformer with a VA rating of 100 VA, a primary voltage rating of 100 VAC, and a secondary voltage of 10 VAC. For the secondary the maximum current is,

$$I_{max} = \frac{100 VA}{10 VAC} = 10 A$$

And for the primary, the maximum current is,

$$I_{max} = \frac{100 VA}{100 VAC} = 1 A$$

**Transformer Load Transfer**

If given the secondary voltage and current (in RMS AC volts and amperes, which we will cover later) we can compute the unknown current in the primary via load transfer. This works because of the law of conservation of energy. If power is being delivered to the load via the secondary winding, then the primary sees this load as an impedance. We will cover impedance in the next chapter.

Power (energy) is conserved when power is delivered from the primary of a transformer to the secondary load.

$$P_{primary} = P_{secondary} \Rightarrow V_{primary} I_{primary} = V_{secondary} I_{secondary}$$

From the equation, we can calculate for an unknown primary current by solving for it in terms of the known primary voltage, the secondary voltage, and the secondary current.

Solving for the primary current transferred via the secondary and load,

$$I_{primary} = \frac{V_{secondary}}{V_{primary}} I_{secondary}$$

As long as the load doesn't draw more than the maximum, then the transformer will perform as expected. However, exceeding this maximum current will cause heating in the transformer, possible shorting in the windings, and reduce the life of the transformer.

**How to Select a Power Transformer**

Should you be one of the types to build a power supply from scratch, you will be wanting to know how to select a power transformer. You must first analyze your load circuit to determine the expected load. Choose your transformer secondary current to be at least 150% of that load current. Transformer primary and secondary voltages are given in RMS (root-mean-square) voltages. Though we will cover RMS calculation in the next chapter, it is important to know that if you are selecting a transformer for a DC power supply, that the secondary voltage will have a higher peak voltage than the stated RMS voltage. If you multiply the RMS voltage by 1.414, you will obtain the peak voltage. For example, a transformer secondary marked 12 VAC will have a peak voltage of  $12 * 1.414$  V, or 16.968 V.

## Chapter 3.8: Vocabulary Review

air core inductor: an inductor that is not wound on a core	magnet wire: a type of wire with an enamel insulator
autotransformer: a transformer with a non-isolated secondary	magnetic: being able to admit or generate magnetic fields
back EMF: reverse voltage caused by a collapsing magnetic field	magnetic field: a "force field" that exists around magnets
band: a group of related frequencies in a spectrum	magnetic induction: causing a current to flow via a magnetic field
capacitance: the measure of a capacitor in farads	mutual inductance: see magnetic induction
capacitor: a component that can store energy as an electric field	mylar capacitor: a capacitor made from mylar film dielectric
capacitor bank: a group of capacitors placed in parallel	polarized: having a positive and a negative terminal
ceramic disc capacitor: a high voltage, small value capacitor	polypropylene capacitor: capacitor made from polypropylene
charge induction: causing an object to become charged via a field	primary winding: the input winding of a transformer
choke: a high current inductor that can block high frequency AC	pulse circuit: a circuit that generates extremely fast current pulses
dead short: an electrical connection with near zero ohms	radio frequency: greater than frequency of 100 KHz
dielectric: an insulator that can increase capacitance between plates	RC time constant: value of tau, product of $R * C$ , in seconds
dielectric breakdown: a destructive event / capacitor failure	RF: abbreviation for radio frequency
electrolytic capacitor: a capacitor made using electrolytic paste	Right Hand Rule: a tool to remember the direction of fields
electromagnetic: dealing with the properties of moving charges	RL time constant: the quotient of $L / R$ , in seconds
electromagnetism: see electromagnetic	secondary winding: the output winding of a transformer
farad: unit of measure of capacitance	signal: a frequency or group of frequencies of interest
ferrite: an inductor core made from powdered magnetic material	spectrum: the entire range of all possible frequencies
filter: a circuit that blocks unwanted frequencies	tantalum capacitor: a capacitor made from a tantalum pellet
flux: the "lines of force" of a magnetic field	time constant: a measure of charge and decay time
frequency: how fast a signal is oscillating, measured in Hertz (Hz)	toroid: a doughnut shaped coil or core
henry: unit of measure of inductance	transformer: a component that converts one AC voltage to another
inductor: a component that stores energy in a magnetic field	turns ratio: the ratio of secondary to primary turns for transformers
inductance: measure of an inductor in henries	VA: see volt-ampere characteristic
instantaneous: infinitely fast	volt-ampere characteristic: a power rating for transformers
isolation: electrical separation	working voltage: the maximum voltage for a capacitor

## Chapter 3.9: Lab Activity 3 – Exploring RC Circuits

### Introduction

We have covered a lot of ground in this chapter. We will be focusing on capacitor circuits in this lab. We will first be building a simple charge and discharge circuit to demonstrate the ability of capacitors to store charge. We'll then continue by familiarizing ourselves with the LumiDax ® Bakerboard Analog Trainer. We'll explain what a function generator does, and how an oscilloscope is used. We'll try out our test equipment by building a demonstration circuit that rapidly charges and discharges a capacitor using the function generator. Then we'll use the oscilloscope to look at the input and output waveforms to verify what we learned in this chapter.

**Materials**

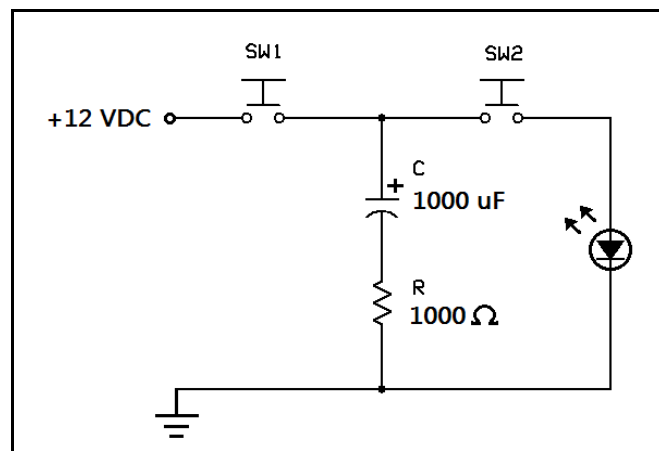
The materials required for this lab are listed in the table shown below.

Lab Activity 3 – Parts List	
Quantity	Item
1	1000 $\mu\text{F}$ 35V electrolytic capacitor
1	0.1 $\mu\text{F}$ ceramic disc capacitor
1	1000 $\Omega$ $\frac{1}{4}$ watt resistor (brown, black, red, and gold striped)
1	10 K $\Omega$ $\frac{1}{4}$ watt resistor (brown, black, orange, and gold striped)
1	LED of any color (choose your favorite!)
1	LumiDax $\text{\textregistered}$ wiring kit
1	LumiDax $\text{\textregistered}$ Bakerboard Analog Trainer
1	Pair of wire cutters.

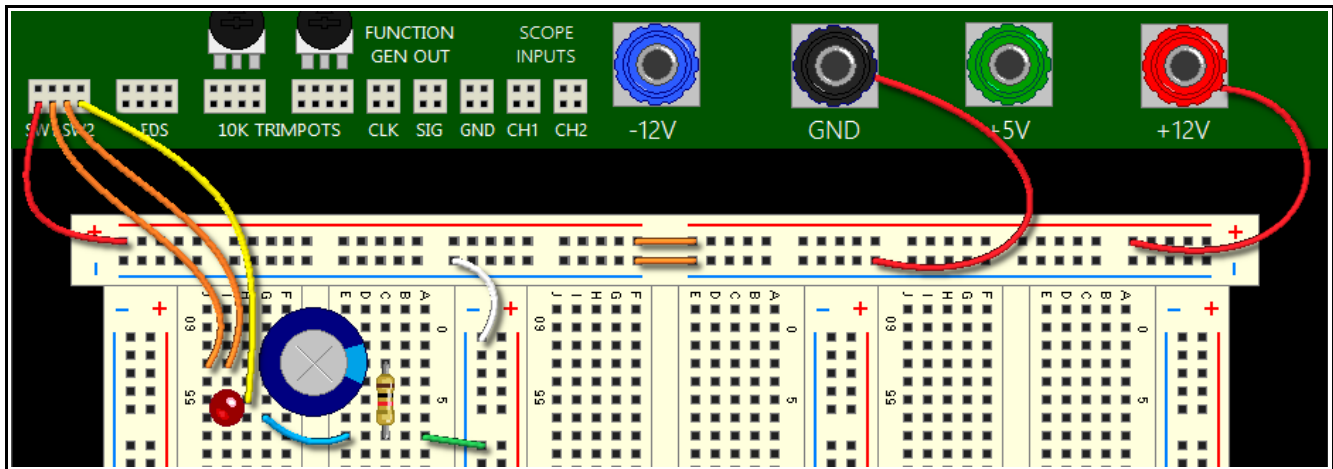
**Procedure**

Make sure power is not applied to the trainer until your circuit is wired and ready to test. Leave the LED untrimmed, as you will want to be able to identify the anode and cathode. The longer lead will be positive (anode.)

1. Begin by wiring the circuit shown in the schematic in **Figure 41**. You will be wiring the example charge / discharge circuit covered earlier in this chapter. Make sure to pay attention to the polarity of the capacitor and the LED. **Figure 42** shows what your circuit should look like fully wired.



**Figure 41: Charging and discharging demonstration.**



**Figure 42: What your circuit should look like when finished.**

Since the capacitor is large, you will have to straddle over the gap that separates the rows. This will make it easier to place the other components nearby.

2. When you are ready, apply power to your Bakerboard Analog Trainer. Let's do some math before we try our circuit out. We need to see how long it will take to charge our 1000 microfarad capacitor via the 1000 ohm resistor.

$$\tau_{RC} = R \times C = 1000\mu\text{F} \times 1000\Omega = 1 \text{ second,}$$

$$\text{and } 5\tau_{RC} = 5 \text{ seconds.}$$

3. Press the switch SW1 to charge the capacitor, and hold it for five seconds. The capacitor should now be fully charged to the source voltage of +12 VDC. **DO NOT PRESS BOTH SWITCHES AT THE SAME TIME!** Release switch SW1. The capacitor should be fully charged.

3. Now press and hold switch SW2, and observe the LED light up as the capacitor discharges through the resistor and LED. Did it take about five seconds for the light to completely dim? If the LED did not light, make sure it is not inserted backwards. Release switch SW2.

4. When you are finished charging and discharging your capacitor circuit, disconnect power to the Bakerboard Analog Trainer, and dismantle the circuit. We will now look at charge / discharge curves.

5. We will begin the next part of this lab by familiarizing ourselves with the function generator and the oscilloscope. A function generator is a piece of test equipment that creates signals. We will cover the function generator in greater detail in the next chapter, but for now we will use it for our experiment. Wire the circuit shown in **Figure 43**. **Figure 44** gives an idea of what your circuit should look like. Wire the circuit shown in **Figure 43**. **Figure 44** gives an idea of what your circuit should look like.

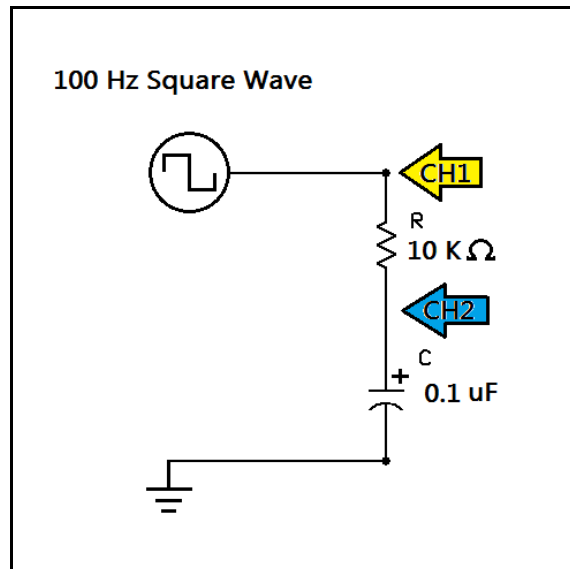


Figure 43: RC charge / discharge curve demo circuit

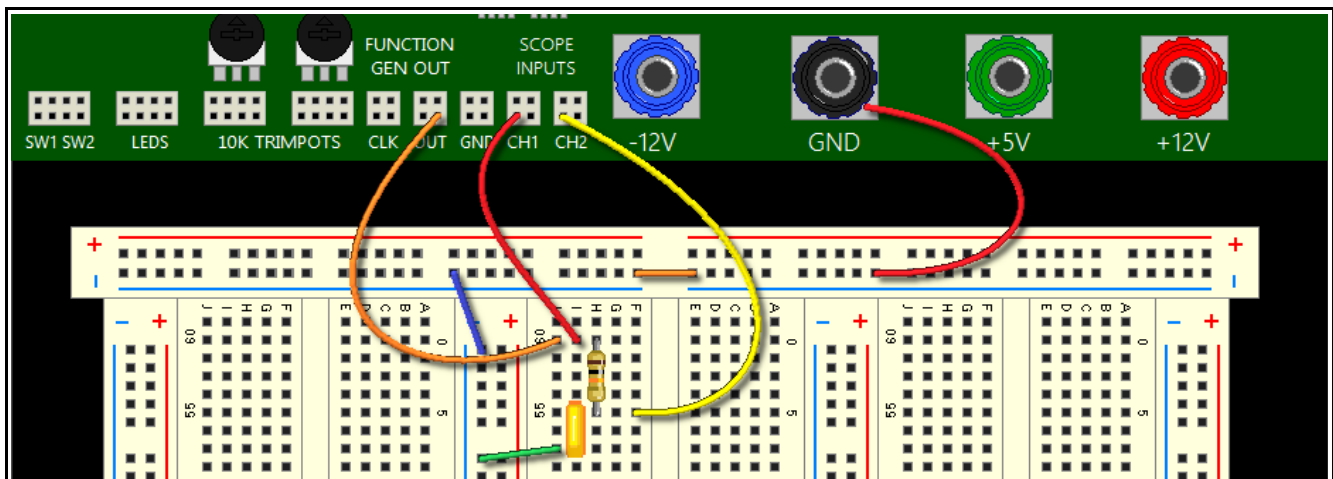
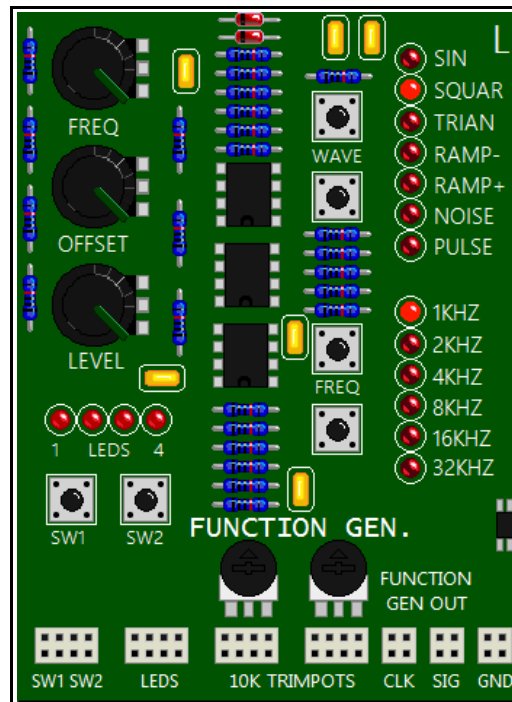


Figure 44: What the RC charge / discharge demo circuit should look like.

6. We are going to use the function generator to supply a 100 Hz (100 cycle-per-second) square wave (a waveform that “turns on and off.”) Go ahead and apply power to the Bakerboard Analog

Trainer, and we will set up the function generator and the oscilloscope. Use the WAVE and FREQ keys on the function generator shown in **Figure 45** to select a square wave in the 1 KHZ range. The 1KHZ LED should be lit, and the LED marked SQUAR should be lit, as shown below.

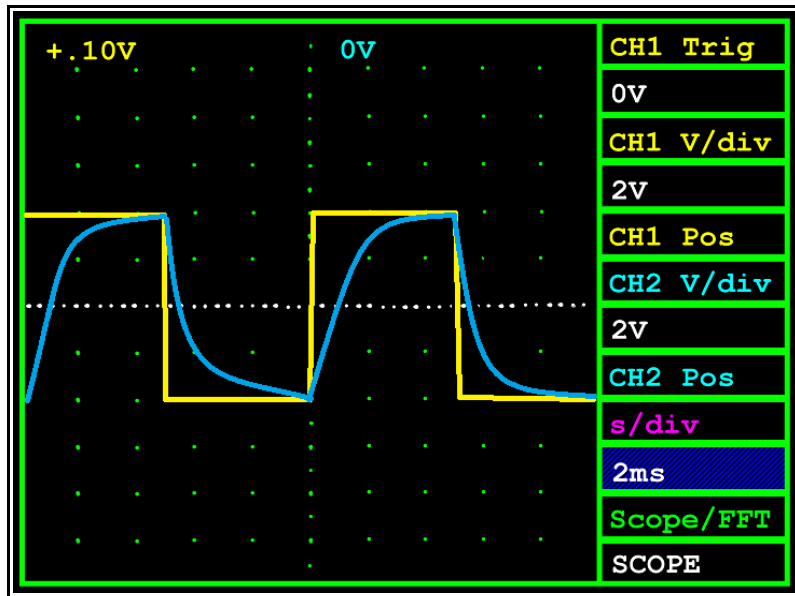


**Figure 45: Function generator control panel.**

Now look at the knobs on the left. The FREQ knob controls the frequency of the signal, or how fast the “waves are waving.” The OFFSET knob controls the DC voltage that the waveform “rides on.” Finally, the LEVEL knob controls amplitude, or “how big” the signal is in volts. Make the waveform about four vertical dots high using the LEVEL knob. Center the waveform using the OFFSET knob. Do not worry about setting the frequency at this point. We will cover that next.

7. To the right of the oscilloscope screen, there are four cursor keys. These are used to adjust the settings of the oscilloscope during use. We will cover what these settings mean later. Right now we are just using the oscilloscope to look at a waveform. Use the up and down cursor keys to highlight the window under **s/div** on the right of the oscilloscope display. Now, use the right and left keys on the keypad to select 2ms. Use the FREQ knob on the function generator to get about two charge / discharge curves into the window.. **Figure 46** shows what your oscilloscope should look like.





**Figure 46:** What the oscilloscope should look like when finished.

8. Now observe the blue trace. When the square wave is high, or “on,” the capacitor begins to charge. When the square wave is low, or “off,” the capacitor is discharging. Compare the curves to **Figure 35** from earlier in this chapter. Do they look similar?

### **Lab Activity 3 – Conclusion**

In this activity, you learned about charging and discharging capacitors. You got some hands on experience, experimenting with energy storage in a capacitor. You also learned how to use the function generator and the oscilloscope on the Bakerboard Analog Trainer. Using the function generator, you input a signal into an RC circuit and used the oscilloscope to view the input and output waveforms.

You will be using the function generator and the oscilloscope more and more as we progress in this course. Familiarizing ourselves with the test equipment will help us understand how to measure signals, and what they are telling us.

## Chapter 3.10: Exercises

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### Vocabulary Questions

1. A capacitor is measured in units called \_\_\_\_\_.
2. A \_\_\_\_\_ is a capacitor made from electrolyte, and is polarized.
3. The RC \_\_\_\_\_ tells us how fast an RC circuit can charge and discharge.
4. A \_\_\_\_\_ can convert from one AC voltage to another.
5. An \_\_\_\_\_ is a coil of wire that concentrates a magnetic field.
6. A \_\_\_\_\_ is an inductor that keeps out high frequencies from equipment.
7. Inductors use a \_\_\_\_\_ to store energy.
8. The \_\_\_\_\_ is the “input” winding on a transformer.
9. The \_\_\_\_\_ is the unit of measure of an inductor.
10. The \_\_\_\_\_ is the insulating material used between the plates of a capacitor.
11. To prevent damage, the \_\_\_\_\_ of a capacitor should never be exceeded.
12. The \_\_\_\_\_ characteristic of a transformer tells us it's power capacity.
13. We may use the \_\_\_\_\_ to visualize the magnetic field around a wire.

### True or False

- |  |   |   |
|--|---|---|
| 1. It is acceptable to put capacitors in backwards if they are polarized.        | T | F |
| 2. The henry is the unit of measure for capacitors.                              | T | F |
| 3. A farad is very large, and microfarads are used most often.                   | T | F |
| 4. Capacitors in series add together.  | T | F |
| 5. A magnetic field is created by charges in motion.                             | T | F |
| 6. A capacitor can store energy even if the charging voltage is removed.         | T | F |
| 7. An inductor cannot store energy the same way capacitors can.                  | T | F |
| 8. An inductor can develop hundreds of volts if current is suddenly interrupted. | T | F |
| 9. A step-up transformer can be turned around and used in step-down mode.        | T | F |
| 10. A capacitor can explode if excessive voltage is applied.                     | T | F |

**Problems**

1. Calculate the time constant of a series RL circuit with a 20 mH inductor and a 20 K $\Omega$  resistor.
2. A capacitor with a series resistor of 10 K $\Omega$  charges from zero to 99.5% of the applied voltage in 100 milliseconds. What is the capacitor's approximate value?
3. A transformer is used to step down 120 VAC to 24 VAC. What is the turns ratio? If the VA rating for this transformer is 480 VA, what is the maximum secondary current?
4. Calculate the equivalent capacitance of a 470  $\mu$ F capacitor, a 100  $\mu$ F capacitor, and a 1000  $\mu$ F capacitor in series.
5. You need an inductor that is 15 mH. But you only have three 10 mH inductors. Can you create a series-parallel equivalent inductor to get a 15 mH inductor, given no magnetic coupling?
6. You need a 1000  $\mu$ F capacitor, but you only have five 200  $\mu$ F capacitors. Is there a way to create an equivalent capacitor to get 1000  $\mu$ F?

## Chapter 4 – AC, Filters, Diodes, Power Supplies

In this chapter, you will...

- ➡ Learn about RMS voltage and current.
- ➡ Discover new waveforms.
- ➡ Look at how to build filter circuits.
- ➡ Meet your first semiconductor, the diode.
- ➡ Find out about making power supplies.

You have come a long way on your journey, but new shores await you. We have put off the study of AC circuits until now because there was some ground we had to cover first. Now we are ready to enter into the real *analog* world.

*Analog electronics* covers both DC and AC waveforms. In this chapter, we will look at signals in detail. We'll find out what *RMS* really means, as well as all the waveforms you'll encounter. We will also be discussing *filter circuits*, *reactance*, *phase*, and *impedance*.

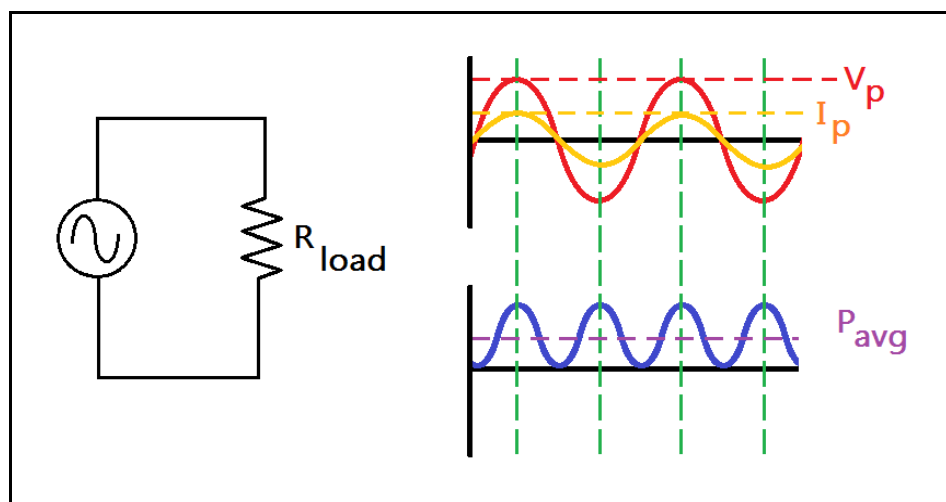
To complete our journey, we will meet our first *semiconductors* - the *diode* and the *voltage regulator*. We'll examine the types and uses of diodes. We'll then put everything together, and cover power supplies, which will make use of the diode to change an AC waveform to DC.

## Chapter 4.1: AC RMS Voltage – The Real Story

It was mentioned in the last chapter that AC voltages are usually measured in RMS, or “root-mean-square” volts, and this is actually lower than the *peak voltage* of an AC *sinusoid*. Now we will discuss the reasoning for this initially confusing standard by deriving this relationship in terms of power delivery. We will not be using *calculus*, but we can arm ourselves with a little graphical analysis first.

What we want to find is a way to relate the AC voltage to a *steady-state* DC voltage that will have the same heating effect in the load resistance, which will coincide with the same power dissipated by the load resistance over time. This way, all of our power calculations will be correct, as with DC circuits. So there is some scaling factor by which we can “scale back” the applied AC voltage to something that makes sense from a power delivery standpoint.

We may employ some simple tricks to help us in our derivation. Take a look below at **Figure 47**. Here, we have a *purely resistive* load, so voltage and current are always *in phase*. That is, when voltage is positive (red,) current is positive (orange,) and when voltage is negative, current is also negative. The waveforms “track along” together in time. Though we have a voltage and current that are *periodically* changing direction, the power dissipated by the load resistance (purple) is always positive, though fluctuating. We also note that the average of the power delivered is half the total “height” (purple dashed line.) So visually, the *average power* is half the *peak instantaneous power*.



**Figure 47: The power delivered to the load is always positive.**

We begin by noting, qualitatively, that the average power is half the peak instantaneous power, and by setting this equal to an expression in terms of the effective DC voltage.

$$P_{avg} = \frac{V_{peak} I_{peak}}{2} = \frac{V_{eff}^2}{R_{load}}$$

We multiply by R, and obtain the following equation,

$$\frac{V_{peak} I_{peak} R_{load}}{2} = V_{eff}^2$$

We can express the product of peak current and the load resistance as  $V_{peak}$ .

$$\frac{V_{peak}^2}{2} = V_{eff}^2$$

Therefore, we can simplify the expression, without having used calculus,

$$\frac{V_{peak}}{\sqrt{2}} = V_{eff} = V_{RMS}$$

We can use Ohm's Law now to deal with RMS voltages and currents just as we could in the realm of DC, and the power calculations will make sense as well.

We have just uncovered two very useful expressions, which can help us easily convert from an AC RMS voltage to the peak voltage, and from the peak value of an AC voltage to AC RMS volts.

$$V_{RMS} = 0.707 \times V_{peak}$$

$$V_{peak} = 1.414 \times V_{RMS}$$

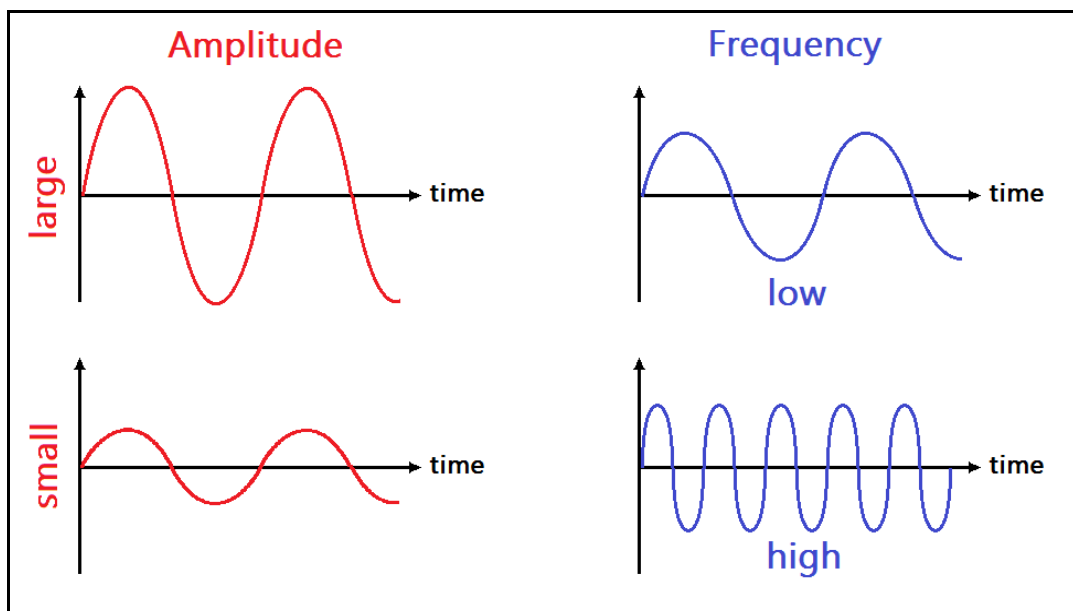
We found in the previous chapter that these equations are needed to design DC power supplies, because the *rectified* DC voltage will be higher than we might expect if we knew nothing about the difference between AC peak voltage and AC RMS voltage. Rectification means forcing all parts of the waveform to be positive, or “flipping over” the negative half of the waveform. There is a special

semiconductor component that can help us accomplish this, as we will see later. It will also behoove us to know any AC peak voltages if we are selecting a working voltage for our capacitors! Remember that capacitors need twice the working voltage than any voltage to which they will be subjected.

## Chapter 4.2: Amplitude, Frequency, and Phase

---

All periodic waveforms have measurements that are of importance in electronics. Musically, we can describe a note by its pitch and how loud it is. In electronics, there are similar concepts. These are *frequency* and *amplitude*. Take a look at **Figure 48**.



**Figure 48: Amplitude vs. frequency.**

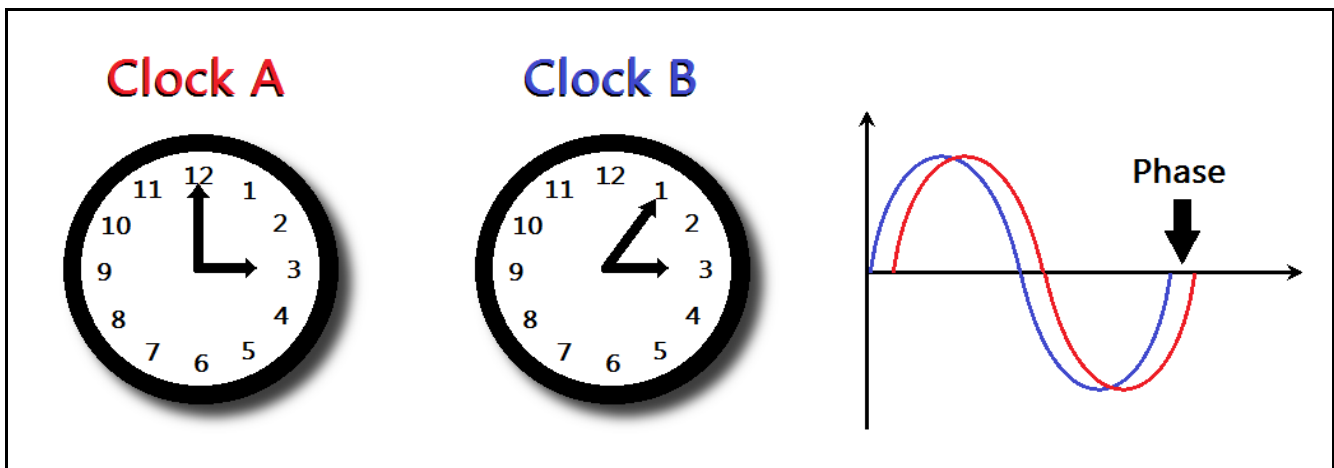
From the above figure, amplitude is the measure of “how big” or “how loud” the signal is. Think of ocean tides. At low tide, the ocean waves are smaller in amplitude, and at high tide, the ocean waves are much bigger in amplitude. Frequency, on the other hand, tells us how fast the signal is *oscillating*, or how fast it is changing with respect to time. A “slow wave” will have a lower frequency, while a “fast wave” will have a higher frequency. Think of low frequencies as low pitches on a piano, and high frequencies as the really high pitches on a piano. There is a simple connection between frequency and *period*. Period is the time it takes to complete one full cycle (one full up and down motion,) represented by a capital T, and is measured in seconds.

Period is inversely proportional to frequency,

$$F = \frac{1}{T}$$

Where  $T$  is the time it takes to complete one full cycle, and  $F$  is the frequency in cycles per second, or Hz (Hertz.)

*Phase*, on the other hand, is a different measurement. Phase is only valid for two signals of the *same frequency*. The amplitudes can be different, but the frequencies must be the same to make mathematical sense. Phase is measured in degrees or radians, and has to do with how much one signal is leading or lagging behind another one in time. We may think of two clocks; one with the current time, and one that is set five minutes fast. Let's look at this analogy in **Figure 49**.



**Figure 49: Clock analogy for phase shift for one hour, or cycle.**

From the diagram, we see that “Clock B” is five minutes faster than the current time, represented by “Clock A.” If we plot the vertical motion of the minute hands of the clocks, we get the figure shown to the right. Clock B, represented by the blue trace, is five minutes faster than Clock A, represented by the red trace. Both minute hands are moving at the same speed – one revolution around the clock per hour. But Clock B will always be leading Clock A by five minutes. This relationship is called a *phase difference* or a *phase shift*. We measure the phase shift in degrees or radians.



For example, if there are 360 degrees in a clock face, then five minutes would correspond to an angle of 30 degrees. Therefore, Clock B has a *leading phase* of 30 degrees. We may also say that Clock A has a *phase lag* of 30 degrees with respect to Clock B. We'll cover phase in detail later.

### Chapter 4.3: Other Waveforms

When we say the words “alternating current,” we are actually referring to a much wider category of signals than just pure sinusoids. There are quite a few *waveforms* used in electronics that are so common that they have been given special names. Let's take a look at a few of them.

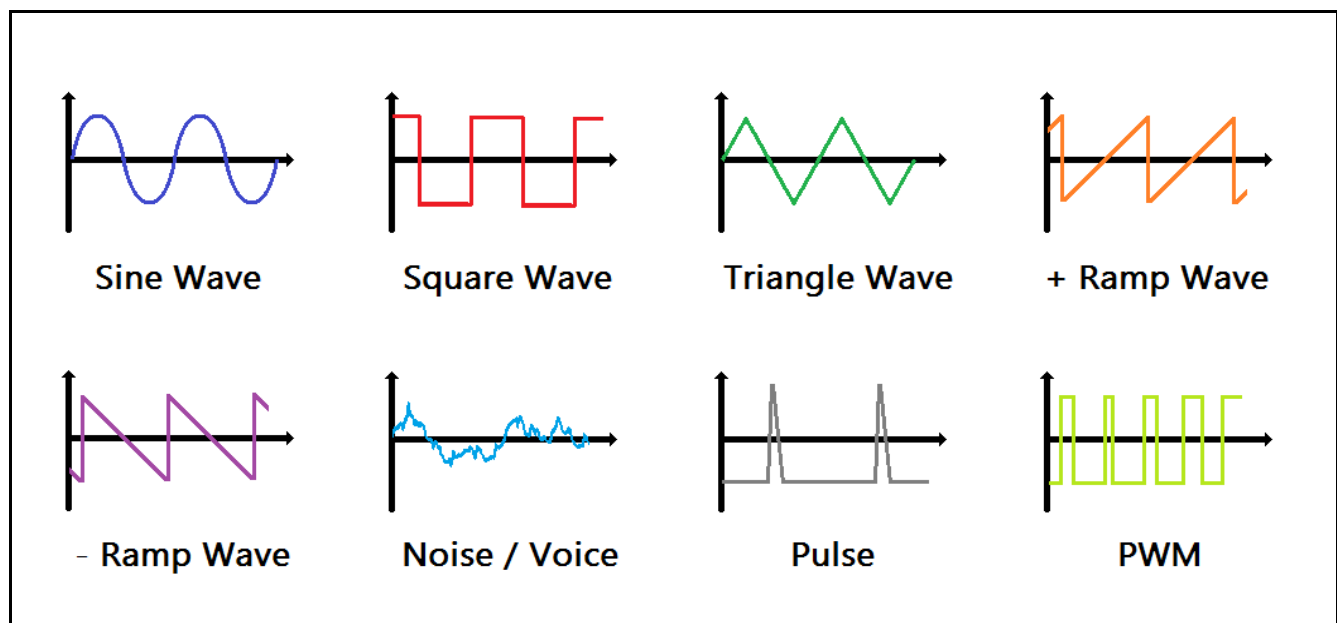


Figure 50: An extended family of electronic signals.

In **Figure 50**, shown above, we have eight example waveforms that are discussed frequently in electronics. The *sine wave* (dark blue) is the one you will most commonly come across. Proceeding from left to right, we have a *square wave* (red.) Square waves are often found in digital electronics circuits. Most *TTL oscillators* output this type of waveform. Next, we have a *triangle wave* (green,) and two *ramp waves* (orange, and purple.) These types of signals are used for motor positioning, and some systems will report position information this way. Next we have *noise* (light blue.) This type of signal will be seen in voice, music, or in nature. Noise is a combination of many signals of different frequencies and amplitudes. Noise can be extremely useful as an input to a filter to see what

frequencies upon which the filter is acting. The next waveform is the *pulse* waveform (gray.) Pulses are used for timing, and some sensors may output this type of signal, such as an RPM gauge. Finally, we have a *PWM* waveform (light green.) PWM, or *pulse-width modulation*, is used to control power to a load without using resistors to reduce voltage or current. LED drivers use a waveform like this one to control brightness due to the higher efficiency of power delivery.

These waveforms appear everywhere in electronics in various incarnations. The LumiDax® Bakerboard Analog Trainer can produce most of these waveforms, and we will be exploring them later on in the lab activity. But in order to do so, we must familiarize ourselves with some of the test equipment used in electronics.

## **Chapter 4.4: Producing and Measuring Waveforms in the Laboratory**

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There is test equipment that can produce and measure AC waveforms. These are the *function generator*, the *frequency counter*, the *oscilloscope*, and the *spectrum analyzer*.

### **Function Generators**

Let's say we have just built an amplifier, but we don't know if it is going to work. What should we do to test it? We have to inject some sort of signal into the input, but we have to be careful not to overpower the input. The best solution is to use a function generator. A function generator can produce common waveforms and carefully control the frequency and the amplitude of the signal.

### **Frequency Counters**

A frequency counter can count the number of cycles per second of a periodic waveform. Frequency counters can't tell you what a waveform looks like. But frequency counters can, often very precisely, tell you how fast a periodic signal is oscillating. Recent advances in technology have made the frequency counter an integral function in modern oscilloscopes and multimeters.

### **Oscilloscopes**

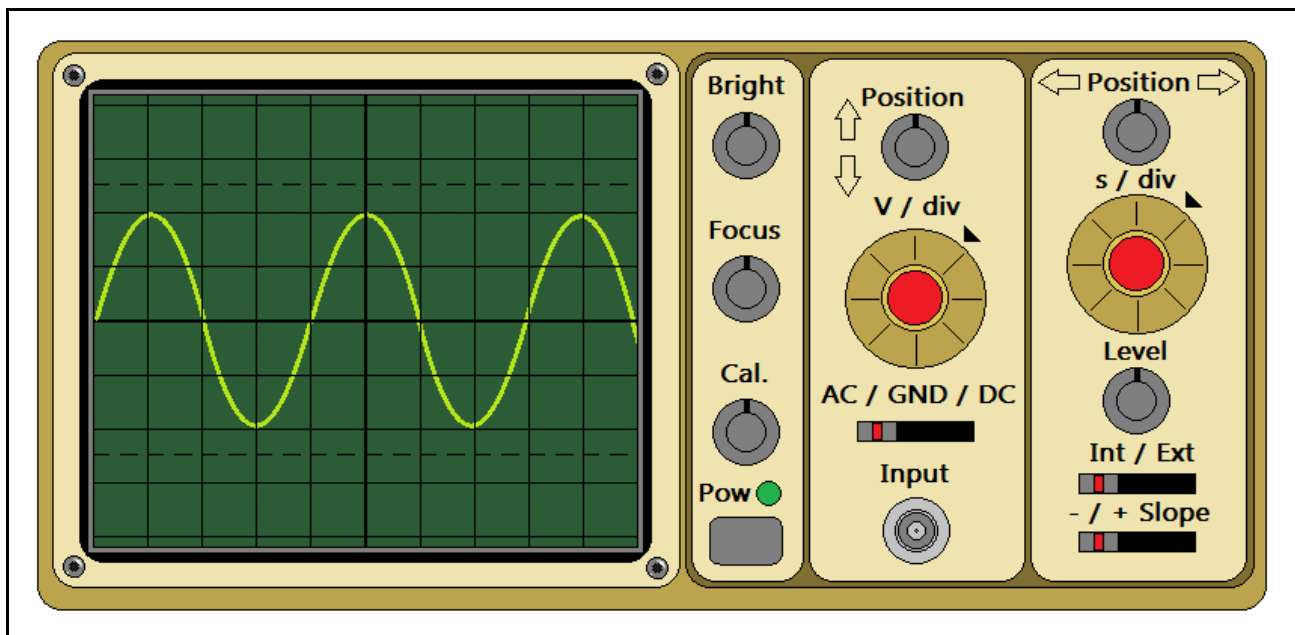
Unlike frequency counters, not only can an oscilloscope measure frequency, but also amplitude, phase shift, and even display the shape of the waveform. Oscilloscopes are indispensable in the electronics lab, as they can show you at a glance exactly what is happening to a signal in detail.

### Spectrum Analyzers

A spectrum analyzer is a special piece of test equipment that shows what is happening to multiple frequencies at once. Rather than showing a signal in the *time domain*, spectrum analyzers show what is happening in the *frequency domain*, over the entire spectrum of interest. They show a graph that represents how much of each signal is present in a *histogram*. Spectrogram data is a very powerful *signal analysis* tool, as it can show you at a glance what is happening to multiple frequencies simultaneously. They can be used to generate *frequency response* plots for filters and amplifiers, or put more simply, what groups of frequencies are favored over others by a filter or amplifier circuit.

### Using an Oscilloscope

Function generators and frequency counters are fairly straightforward to use. Oscilloscopes, on the other hand, are more complicated. We'll now cover their adjustment and use, since oscilloscopes are by far the most common and the most useful tool on an electronics bench. In **Figure 51**, we are given a common analog oscilloscope interface. We will now go over the interface and how to use it. You will likely encounter an oscilloscope like the one below, so knowing how to use it will serve you later. We will be looking at a single channel example, but there are two channel oscilloscopes, and some even have four inputs. These oscilloscopes can display multiple waveforms at the same time.



**Figure 51:** A typical single-input analog oscilloscope.

### **Cathode Ray Tube or LCD Screen**

Observe **Figure 51**. On the left is the screen. Modern oscilloscopes use an LCD screen, but older analog oscilloscopes will have a phosphor screen like the one shown above. CRT (cathode ray tube) oscilloscopes use an electron beam to excite a phosphor screen. These scopes are still available and widely used, though the more expensive LCD oscilloscopes are quickly gaining popularity.

### **Screen Reticule**

The CRT has a reticule, or grid, that helps during measurement of a signal. The reticule helps in signal measurement by giving us a frame of reference when we are measuring voltage or time. The reticule is used in conjunction with the V / div and time / div settings, giving the reticule subdivisions (the grid lines) a numeric meaning.

### **Beam Controls**

The first set of controls will be located somewhere near the screen. Our example oscilloscope drawing has beam controls just to the right of the CRT. There will be an intensity or brightness control, and a focus control. This is also typically where the main power button will be found. These controls are not found on LCD oscilloscopes, as they do not use electron beams to draw traces.

### **Signal Input Controls**

Typically, the next panel to the right will be the signal input cluster of controls. These controls are used to adjust the volts per division (V / div,) or how many volts correspond to the vertical ticks in the screen reticule. There will be a vertical positioning knob to move the signal trace up and down to help align with the reticule for measurements. This panel will also have an input coupling switch. Set this to ground first to position the trace, then choose either AC or DC coupling to observe your signal. AC coupling will place an input capacitor in the signal path and block the DC signal component. There will be a BNC style connector on this panel or somewhere near it for attaching signal probes.

### **Timing and Trigger Controls**

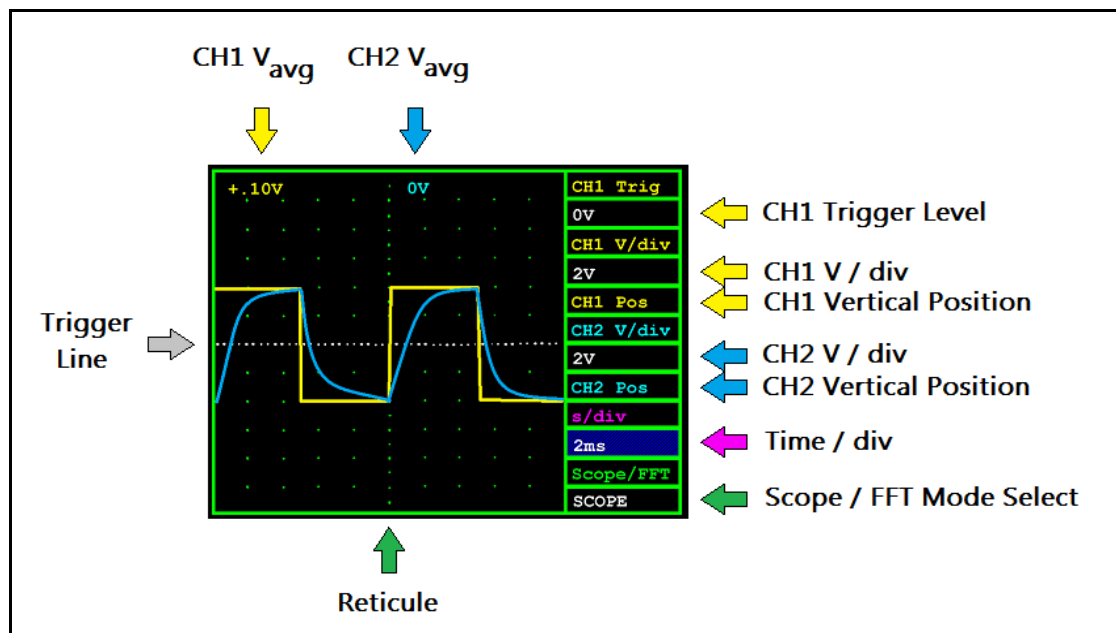
Oscilloscopes feature a cluster of controls for timing and triggering behavior. The time per division knob, (s / div,) controls how much time to which each horizontal tick on the reticule corresponds. There will trigger controls in this panel as well. Triggering refers to which voltage the scope will watch for before drawing the trace, and this level is set by the level control. The horizontal positioning knob at the top right of our example oscilloscope gives the user the option of moving the trace left or right.

### Interpreting a Signal on an Oscilloscope

Observe the waveform displayed on the oscilloscope screen in **Figure 51**. Let's say that the vertical setting is 5 V / division, and the horizontal setting is 10 milliseconds per division. What is the peak to peak voltage (the total height) of the example waveform shown in the figure? Since the entire waveform spans four vertical ticks, it is 20 V<sub>pp</sub>. What is the AC peak voltage? It is 10 V if measured from the axis of the waveform (the center line.) Note that V<sub>pp</sub> is 2 X V<sub>p</sub>. Finally, what is the time for one complete cycle? It is 40 milliseconds, since a complete cycle spans four horizontal ticks.

### The LumiDax ® Bakerboard Analog Trainer Oscilloscope

The LumiDax ® Bakerboard Analog Trainer has a dual-channel digital oscilloscope built right in. You read the screen the same way – by setting the volts per division for the vertical scale, and the time per division for the horizontal scale. There are no knobs, but instead you use the up and down keys to the right of the scope to highlight the field you want to change, and then press left or right. You will be reading the oscilloscope on the Bakerboard Analog Trainer when you perform the lab exercise at the end of this chapter. **Figure 52** shows the features of the Bakerboard's oscilloscope. This image should be familiar to you – it was your previous lab! Can you guess the amplitude and frequency of the yellow trace by reading the settings of the oscilloscope? What is the AC peak voltage? What is the peak-to-peak voltage? What about the frequency? What is the trigger level setting?



**Figure 52: The LumiDax ® Bakerboard Analog Trainer oscilloscope.**

## Chapter 4.5 Reactance, Impedance, and Complex Numbers

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We are going to have a look at filter circuits after we learn how to calculate reactance and impedance. Reactance is the pure scalar “AC resistance” of a capacitor or inductor, and is measured in ohms ( $\Omega$ .) We covered RC and RL circuits before in Chapter 3, but only for charging and discharging to some steady-state current or voltage. But it turns out that we may use the properties of inductors and capacitors to filter out unwanted frequencies in a signal.

### Reactance of Pure C and Pure L

We noted in the last chapter that capacitors block DC, and that inductors block AC, but this is only part of the story. It turns out that the “AC resistance” of a capacitor or inductor is frequency dependent. We use the capital letter  $X$  to denote reactance.

For capacitors, we may calculate capacitive reactance with the following equation,

$$X_C = \frac{1}{2\pi f C}$$

And for inductors, we have the following equation for inductive reactance,

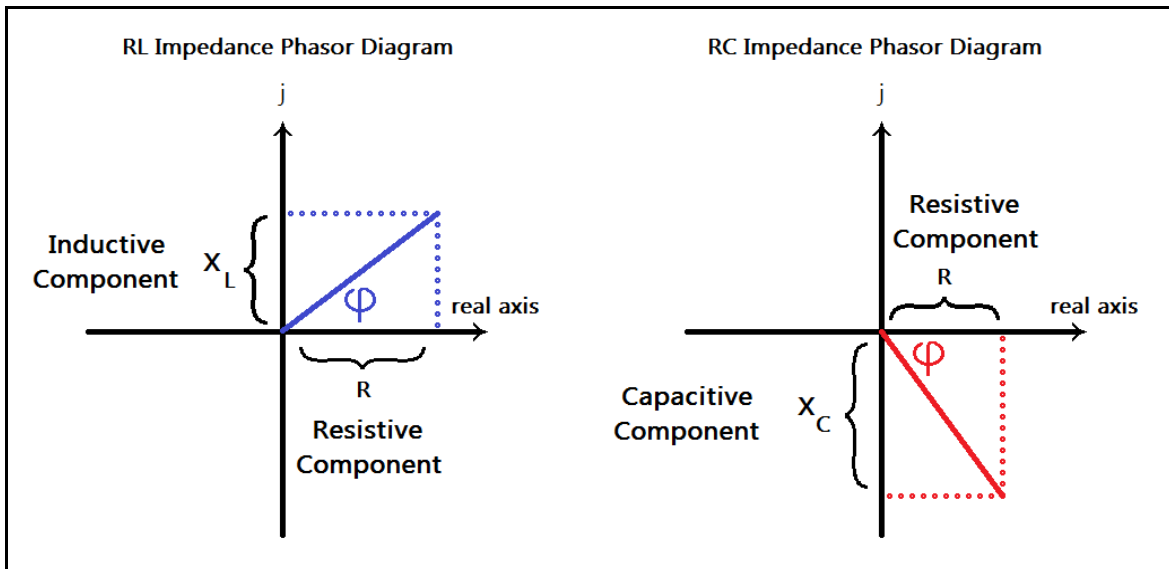
$$X_L = 2\pi f L$$

Where  $X_C$  and  $X_L$  are the reactance for capacitors and inductors in ohms, respectively,  $C$  is capacitance in Farads,  $L$  is inductance in henries, and  $f$  is the frequency of the applied signal in cycles per second, or  $Hz$ .

### Impedance, Phase, and Phasor Diagrams

Though the reactance is a pure scalar value, we must take into account that capacitors and inductors do not behave as pure resistors. They cause a phase shift of up to +/- 90 degrees between voltage and current. An easy way to remember which component does what is with the mnemonic “**ELI the ICE man.**” In inductive circuits, the voltage leads and the current lags, hence **ELI**. In capacitive circuits, the current leads and the voltage lags...**ICE**. Impedance is a complex resistance (represented by capital  $Z$  and measured in ohms) due to this phase shift introduced by the reactive elements. We

may visualize this with a *phasor diagram*, with reactance on the *imaginary axis* (denoted by  $j$ ) and pure resistance on the *real axis* (the horizontal axis.) Pure resistance will always lie on the real axis in the positive direction. Take a look at the phasor diagrams in **Figure 53**, below. Remember that  $X_L$  is always “up,” and  $X_C$  is always “down,” when you are drawing a phasor diagram.



**Figure 53: Phasor diagrams showing inductive vs capacitive impedance.**

The reactance ( $X_C$  or  $X_L$ ) and the pure resistance ( $R$ ) form the opposite and adjacent sides of a right triangle, respectively. The phase shift of the total RC or RL series combination is the angle  $\phi$  (phi.) The length of the hypotenuse is the *magnitude* of the total impedance, in ohms. It may seem strange to want to express impedance as a *complex number*, but it turns out that impedance gives us a more complete picture of Ohm's Law, which also works for complex numbers! In electronics, you will have to remember that we use lowercase  $j$  for imaginary numbers, not  $i$ , which is reserved for current. Let's now define total impedance in terms of the total reactance and the pure resistance.

We define impedance to be a complex number with a real part corresponding to a pure resistance, and an imaginary part corresponding to the difference of  $X_L$  and  $X_C$ .

$$Z \equiv R + j(X_L - X_C)$$

## Question

Why do we subtract the capacitive reactance from the inductive reactance to define the total impedance in the above equation?  
Hint: Look at **Figure 53** for a clue.

### Complex Arithmetic Review

We have just introduced impedance as a complex number. Next is a review of complex arithmetic, which may be skipped. It is included as a primer for dealing with the generalized form of Ohm's Law for impedance. There are some things to remember when dealing with complex numbers. First, complex numbers have a *real part* and an *imaginary part*. There is a property of the imaginary quantity  $j$  to be aware of when evaluating expressions with complex numbers.

The definition of an imaginary number  $j$  is,

$$j \equiv \sqrt{-1}, \text{ which implies that } j^2 = -1$$

A complex number can be expressed as the sum of its real part and imaginary part. We call this the *rectangular form*, or *Cartesian form*, of a complex number. Some forms of complex numbers are easier to work with than others, given the situation. So knowing how to express a complex number in different forms can help us. As long as we remember that  $j^2$  is equal to -1 when we are evaluating complex expressions in rectangular form, the rest is just algebra.

A complex number in rectangular form can be expressed as the sum of its real and imaginary components.

$$Z = a + jb$$



We may add or subtract complex numbers by adding or subtracting their respective real and imaginary parts. Treat the imaginary value  $j$  like you would a “variable,” and use it when collecting like terms.

To add or subtract complex numbers, we use the rectangular form.

Given  $Z_1 = a_1 + jb_1$  and  $Z_2 = a_2 + jb_2$ ,

$$Z_1 + Z_2 = a_1 + jb_1 + a_2 + jb_2 = (a_1 + a_2) + j(b_1 + b_2)$$

$$Z_1 - Z_2 = a_1 + jb_1 - (a_2 + jb_2) = (a_1 - a_2) + j(b_1 - b_2)$$

When multiplying or dividing complex numbers, we may either keep them in rectangular form or convert them to *polar form*, though polar form is preferred for this. We'll cover polar form shortly.

To multiply complex numbers in rectangular form, expand as you would a factored expression, with the exception that  $j^2 = -1$ .

Given  $Z_1 = a_1 + jb_1$ , and  $Z_2 = a_2 + jb_2$ ,

$$Z_1 Z_2 = (a_1 + jb_1)(a_2 + jb_2) = a_1 a_2 + ja_1 b_2 + ja_2 b_1 - b_1 b_2$$

$$\Rightarrow Z_1 Z_2 = (a_1 a_2 - b_1 b_2) + j(a_1 b_2 + a_2 b_1)$$

This is rather inelegant. To divide complex numbers in rectangular form (which is even more inelegant,) we need the *complex conjugate*. We'll define it first before covering division of complex numbers in rectangular form. We use *star notation* to denote the complex conjugate.

We define the complex conjugate as follows,

Given a complex number  $Z = a + jb$

$$Z^* \equiv a - jb$$

Now that we have the conjugate, we can evaluate quotients involving complex numbers in rectangular form. Why we would *want* to do this is another story, entirely: we wouldn't. Let's see why.

To evaluate a complex quotient in rectangular form where the divisor (denominator) is complex, multiply both the dividend (numerator) and the divisor by the complex conjugate of the divisor, such that  $Z_2 \neq 0$ .

$$\frac{Z_1}{Z_2} = \frac{a_1 + jb_1}{a_2 + jb_2} = \frac{(a_1 + jb_1)}{(a_2 + jb_2)} \cdot \frac{(a_2 - jb_2)}{(a_2 - jb_2)} = \frac{a_1 a_2 - ja_1 b_2 + ja_2 b_1 + b_1 b_2}{a_2^2 + b_2^2}$$

$$\Rightarrow \frac{Z_1}{Z_2} = \frac{(a_1 a_2 + b_1 b_2) + j(a_2 b_1 - a_1 b_2)}{a_2^2 + b_2^2} = \frac{(a_1 a_2 + b_1 b_2)}{(a_2^2 + b_2^2)} + j \frac{(a_2 b_1 - a_1 b_2)}{(a_2^2 + b_2^2)}$$

Which is downright **ugly**! Clearly, multiplying and dividing complex numbers in rectangular form is not going to make things easier. Therefore, we will next cover converting from rectangular to polar form. To do this, we need the magnitude or *modulus* (the hypotenuse in **Figure 53**) and the angle.

We compute the magnitude (modulus) of a complex number by using the Pythagorean Theorem,

Given complex number  $Z = a + jb$ ,

$$|Z| = \sqrt{a^2 + b^2}$$

We may now find the angle by recognizing that the modulus, real, and imaginary parts compose the three sides of a right triangle, and employ trigonometry. Watch those negative signs!

We may compute the polar angle  $\phi$  made by the modulus of complex number  $Z = a + jb$  with respect to the real axis,

$$\phi = \arctan\left(\frac{b}{a}\right)$$

Now we can use polar form to express a complex number by using the last two equations.

A complex number in polar form is written in magnitude-angle format,

$$Z = a + jb = |Z| \angle \phi$$

Converting from rectangular form to polar form makes multiplication and division of complex numbers much easier. Observe the simplicity and elegance of the equations shown below.

When multiplying complex numbers in polar form, we multiply the magnitudes and add the angles,

$$Z_1 Z_2 = |Z_1| |Z_2| \angle (\phi_1 + \phi_2)$$

and when dividing complex numbers, we divide the magnitudes and subtract the angles,

$$\frac{Z_1}{Z_2} = \frac{|Z_1|}{|Z_2|} \angle (\phi_1 - \phi_2)$$

Converting from a complex number expressed in polar form back to rectangular form makes use of trigonometry. This will complete our review of complex numbers.

To convert a complex number in polar form to rectangular form,

$$Z = |Z|(\cos \phi + j \sin \phi)$$

### **Putting Complex Numbers to Use**

Now that we have defined some useful mathematical relationships, we can put them to use when dealing with impedance. Ohm's Law will require you to multiply and divide, and simplifying series-parallel impedance networks will require these concepts. Remember, computing the phase angle of current or voltage will be much more straightforward if you express complex numbers in polar form.

We may restate Ohm's Law for impedance, if voltage and current are in RMS values.

We may state Ohm's Law in a generalized format when dealing with impedance,

$$Z = \frac{V}{I}, \quad V = IZ, \quad I = \frac{V}{Z}$$

Where  $Z$  is a complex resistance and  $V$ ,  $I$  are given in effective RMS values.

Let's do an example. Let's say that we have an RC circuit with a 0.1  $\mu\text{F}$  capacitor and a 10  $\text{K}\Omega$  resistor in series with an AC voltage source, such as a function generator. The applied AC voltage is 10 V RMS. What is the current in the series combination, given that the frequency of the applied AC voltage is 1 KHz? What is the phase angle of the current with respect to the applied AC voltage?

We are given 10 V AC at 1 KHz, and a resistor of 10  $\text{K}\Omega$  and a capacitor of 0.1  $\mu\text{F}$ .

We first compute the reactance of the capacitor to express impedance in rectangular form.

$$Z = R - j \frac{1}{2\pi f C} = 10 \text{ K}\Omega - j 1592 \Omega \text{ (the imaginary part is negative due to } X_C \text{)}$$

We may express this impedance in polar form,

$$\phi = \arctan\left(\frac{-1592}{10000}\right) \approx -9.05^\circ, \text{ and the modulus is } |Z| = \sqrt{10000^2 + 1592^2} \approx 10126 \Omega,$$

We may express the applied RMS voltage with angle  $0^\circ$ . Now we can solve for the current,

$$I = \frac{V}{Z} = \frac{10 \text{ V} \angle 0^\circ}{10126 \angle -9.05^\circ} \approx 0.000988 \angle 9.05^\circ \text{ A} = 988 \mu\text{A} \angle 9.05^\circ (\text{RMS})$$

As we can see, the current leads the voltage, as we would expect from the capacitive reactance (remember Eli the Ice man?) In this case, it is leading by a phase angle of 9.05 degrees. Remember that when writing an impedance in rectangular form that inductance will yield a positive imaginary part, and a capacitance will yield a negative imaginary part.

As long as we remember that the impedance is a complex number, we may also treat impedance as we do resistors in series and parallel. Therefore, we may reduce complicated reactive networks easily by using the same rules that apply for resistors in series and parallel! We will define them formally.

For N arbitrary impedances in series, the equivalent impedance (for constant frequency  $f$ ) may be found using the following equation,

$$Z_{eq} = Z_1 + Z_2 + \dots + Z_{N-1} + Z_N$$

And the equivalent parallel combination of N arbitrary impedances (for constant frequency  $f$ ) is given by the following equation,

$$Z_{\parallel} = \frac{1}{\frac{1}{Z_1} + \frac{1}{Z_2} + \dots + \frac{1}{Z_{N-1}} + \frac{1}{Z_N}}$$

Using these two relationships will enable you to handle any series-parallel combination of complex resistance (for a constant frequency  $f$ ) by using the same network analysis techniques introduced in Chapter 2. Recall from earlier in this section that the capacitive and inductive reactance are frequency dependent. That is, capacitors have a reactance inversely proportional to the applied frequency, and inductors have a reactance that is directly proportional. Therefore, impedance must also be frequency dependent, and this forms the basis for *filter theory*.

Before moving on to resonance and filters, there is one caveat that we must address. That is, though reactance is measured in ohms, capacitors and inductors do not ideally dissipate power. This is because their voltage and current are out of phase, be it a leading phase or a lagging phase. So pure reactance dissipates practically no power. Therefore, we must exercise caution when trying to state how much power is actually dissipated in a reactive network by merely multiplying voltage and current. Only a pure resistance (voltage and current in phase) will dissipate any power.

The three types of AC power are *real power* (due to the pure resistances,) *apparent power*, and *reactive power*. Calculating reactive and apparent power is beyond the scope of this text. It is left to the reader as a research exercise to find out more about these different ways to measure AC power.

## Chapter 4.6 Filters and Resonance

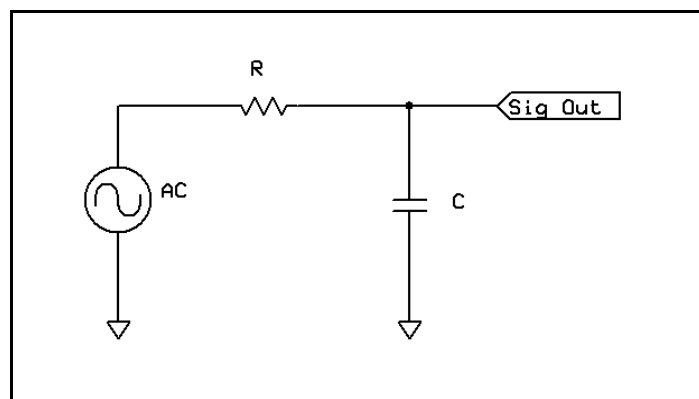
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Filters, as previously mentioned, selectively pass some frequencies while diminishing others. They are also used for smoothing DC to reduce “AC *hum*.” Filter analysis is a huge area in electronics engineering theory, so we won't be doing a comprehensive approach. Instead, we'll investigate some of the most common filters as a primer, and offer a few simple equations to remember.

We define the terms *low pass*, *high pass*, *bandpass*, and *band reject*. Low pass filters block higher frequencies, but allow lower frequencies. High pass filters do just the opposite – they pass high frequencies and block low frequencies. Bandpass filters allow a group of frequencies in a window, but reject frequencies outside of this window. Band reject filters do effectively the opposite of bandpass filters – they suppress frequencies inside a window and pass all other frequencies. We may use combinations of resistors, capacitors, and inductors to create what are called *passive filters*. Passive filters do not use any amplification to boost the signals. We'll meet *active filters* later in this text.

### First Order RC Low Pass Filters

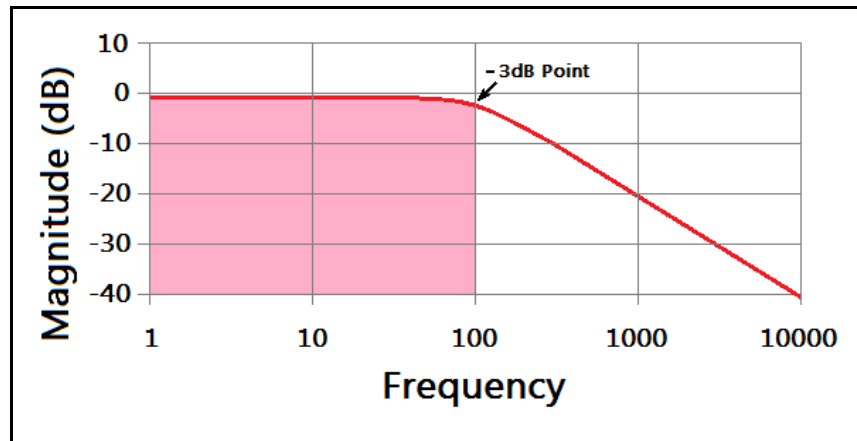
Low pass filters can be constructed by keeping in mind that capacitors look like a short circuit to high frequencies. **Figure 54** shows a low pass RC filter. This is a one stage filter, so it is called *first order*.



**Figure 54: A first order RC low pass filter.**

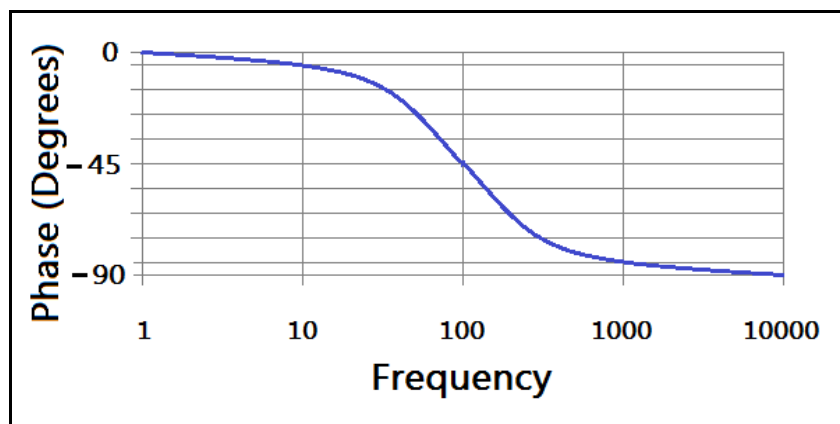
If we take the signal output across the capacitor, the voltage across the capacitor will diminish with increasing frequency. This is due to the reciprocal nature of the capacitive reactance  $X_C$ . We are now going to introduce a new type of graph called a *Bode plot* (pronounced “BO-dee.”) A Bode plot

displays signal *gain* or *attenuation* in *decibels*, or dB, on the vertical axis, and frequency on the horizontal axis. It is a way to see at a glance how a filter will behave over the entire spectrum. Frequency is usually shown with a *logarithmic scale*. **Figure 55** shows an example Bode plot for a low pass RC filter. The area in pink is the range of frequencies passed by the action of the filter.



**Figure 55: The Bode plot for a first order low pass RC filter.**

Filters have point at which they begin to roll-off, called the *cutoff frequency*. This is the point where the power of the signal being filtered is  $\frac{1}{2}$  the input power, hence the term “*half-power point*.” Because half-power also corresponds to an attenuation (reduction) of -3 dB, this is also called the “*3 dB point*.” The half-power point in our example above is at 100 Hz. Something also happens to the phase of the input signal. A Bode plot is often accompanied by a *phase plot*. **Figure 56** shows the phase plot for the above Bode plot. Notice what happens to the phase at the cutoff frequency of 100 Hz.



**Figure 56: The phase plot for the Bode plot shown in Figure 55.**

The reason the cutoff frequency is also called the 3dB point will become clearer when we express the power “gain” as a logarithm (this “gain” is actually a loss, hence the negative vertical scale in the plot of **Figure 55**.) Try evaluating the expression below by making  $P_{out} / P_{in} = 0.5$ .

We may express the gain as the logarithm of the ratio of output power to the input power.

$$G_{dB} = 10 \log_{10} \left( \frac{P_{out}}{P_{in}} \right) = 20 \log_{10} \left( \frac{V_{out}}{V_{in}} \right)$$

We will now give the equation for the cutoff frequency without derivation.

The cutoff frequency  $f_c$  for a low pass first order RC filter is given by,

$$f_c = \frac{1}{2\pi RC}$$

Where R and C are the resistance and capacitance of the filter.

We will now do some quick verification to calculate the voltage across the capacitor, and use this to define the *transfer function* of the filter. The transfer function tells us the relationship of the output signal to the input signal. We will simultaneously get the phase. This part may be skipped.

We start with a first order low pass RC filter with resistor R, capacitor C, and applied signal  $V_{in}$ . The current (RMS) in the series combination is,

$$I = \frac{V_{in}}{Z_{total}} = \frac{V_{in}}{\sqrt{R^2 + X_C^2} \angle \arctan\left(\frac{-X_C}{R}\right)}, \text{ and } V_{out} = V_C = I Z_C$$

$$V_{out} = \frac{V_{in}}{Z_{total}} Z_C = \frac{V_{in}}{\sqrt{R^2 + X_C^2} \angle -\arctan\left(\frac{X_C}{R}\right)} (X_C \angle -90^\circ)$$



Thus, we arrive at the transfer function for this filter in polar form, with the phase.

$$H(f) = \frac{V_{\text{out}}}{V_{\text{in}}} = \frac{X_C}{\sqrt{R^2 + X_C^2}} \angle \left( -90^\circ + \arctan\left(\frac{X_C}{R}\right) \right)$$

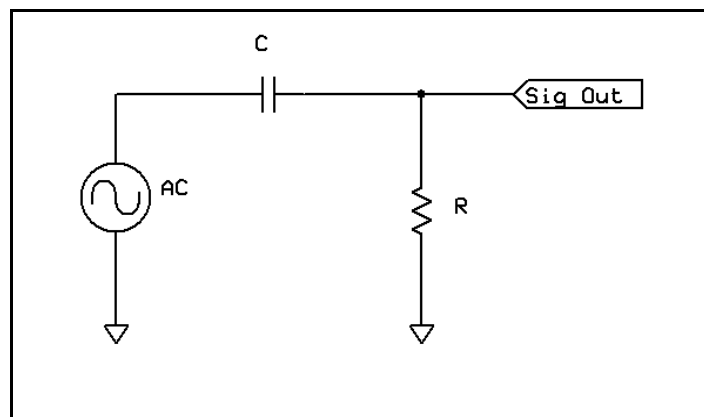
Clearly, at low frequencies the phase is nearly zero and  $V_C$  is at maximum. As frequency increases, the phase angle approaches  $-90^\circ$  and the output voltage diminishes, since

$$\lim_{f \rightarrow \infty} \frac{X_C}{\sqrt{R^2 + X_C^2}} = 0. \text{ (Recall that } X_C = \frac{1}{2\pi f C} \text{).}$$

If this was confusing, then you can simplify matters by just remembering the cutoff frequency equation and not worrying about phase or even the transfer function. We gave this example to show how to use the impedance generalization of Ohm's Law to evaluate the transfer function for a given filter. From now on we will only be focusing on the qualitative Bode plots and skip the calculations.

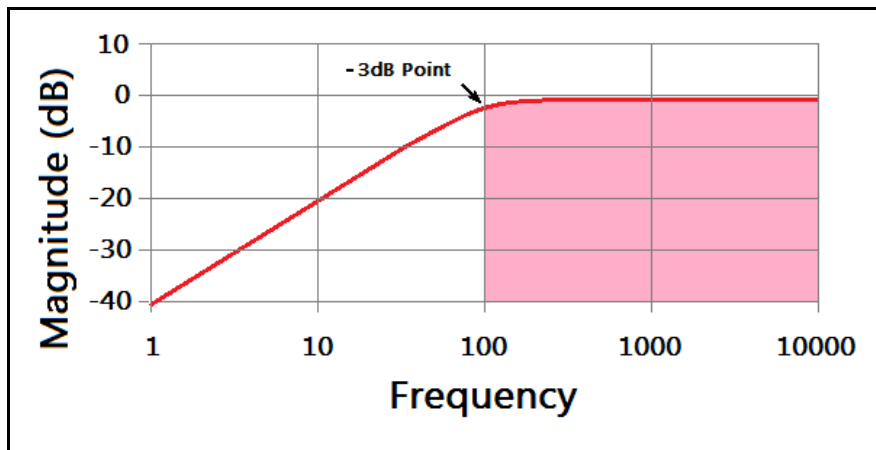
### **First Order RC High Pass Filters**

The RC high pass filter reverses the position of the resistor and capacitor. Output is taken across the resistor. **Figure 57** shows an RC high pass filter. The position of the capacitor blocks DC.



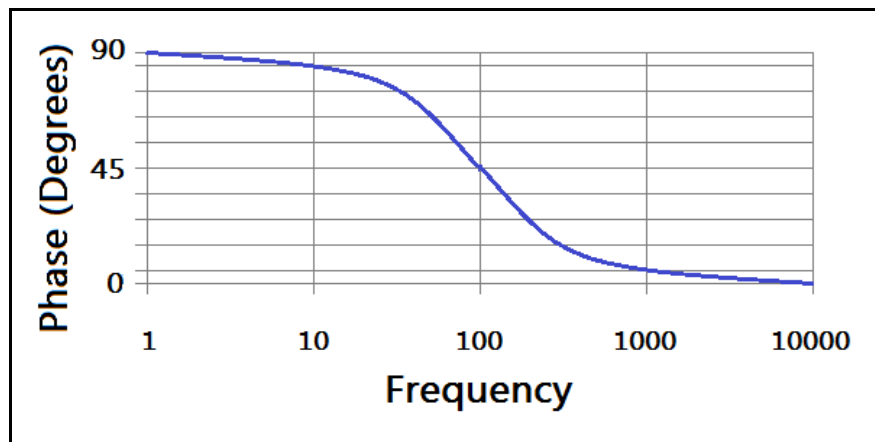
**Figure 57: A first order RC high pass filter.**

We now offer the Bode plot for a high pass filter. Notice that it looks similar to the plot for a low pass filter, but it is reversed. **Figure 58** shows an example high pass RC filter plot with a cutoff frequency of 100 Hz. We will show one more phase diagram to accompany **Figure 58**.



**Figure 58: The Bode plot for a first order high pass RC filter.**

The phase plot for the figure above is given in **Figure 59**, below. Note that the phase changes are now reversed. Yet the phase passes through an inflection point (corresponding to a phase shift of 45 degrees) again near the cutoff frequency. For low frequencies, the capacitor's reactance is much higher than the series resistance. At high frequencies the capacitor has almost no reactance at all, and the phase shift goes to zero, meaning the circuit is almost purely resistive.



**Figure 59: The phase plot for the Bode plot shown in Figure 58.**

Not surprisingly, the cutoff frequency will be of the same form as for the low pass filter. This is entirely due to the time constant of the series RC combination. Simply transposing the R and C elements in the circuit has no effect on the time constant. The gain equation will work for this configuration as well, provided that you have calculated the correct transfer function. We leave this as an exercise.

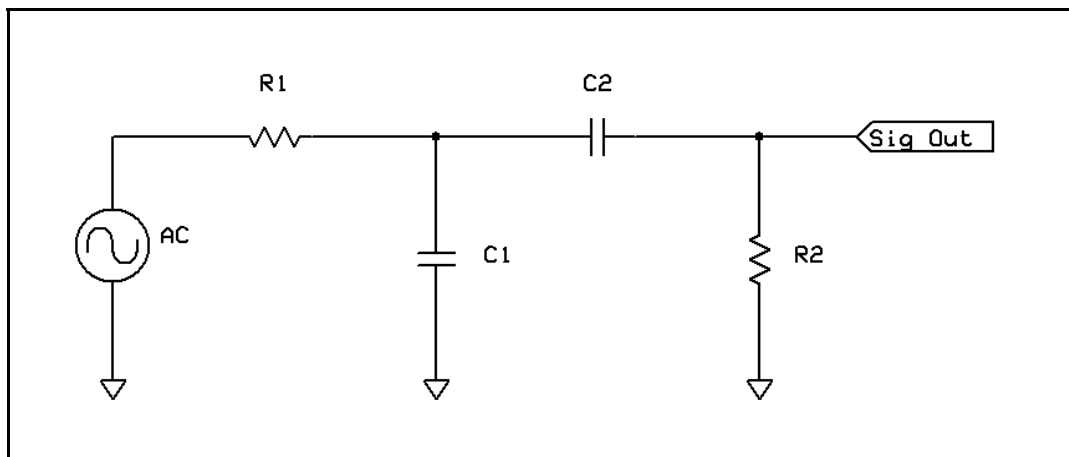
The cutoff frequency  $f_c$  for a high pass first order RC filter is given by,

$$f_c = \frac{1}{2\pi RC}$$

Where R and C are the resistance and capacitance of the filter.

### **RC Bandpass Filter**

Suppose we have a high pass filter and a low pass filter, one right after the other. Now, let's say the high pass filter's cutoff frequency is much lower than the low pass filter's cutoff frequency, such that the pass regions overlap. We would have a filter that has a hump-shaped Bode plot. This arrangement has a special name – the bandpass filter. It suppresses all frequencies above and below the window defined by the two cutoff frequencies. **Figure 60** shows a simple RC bandpass filter.



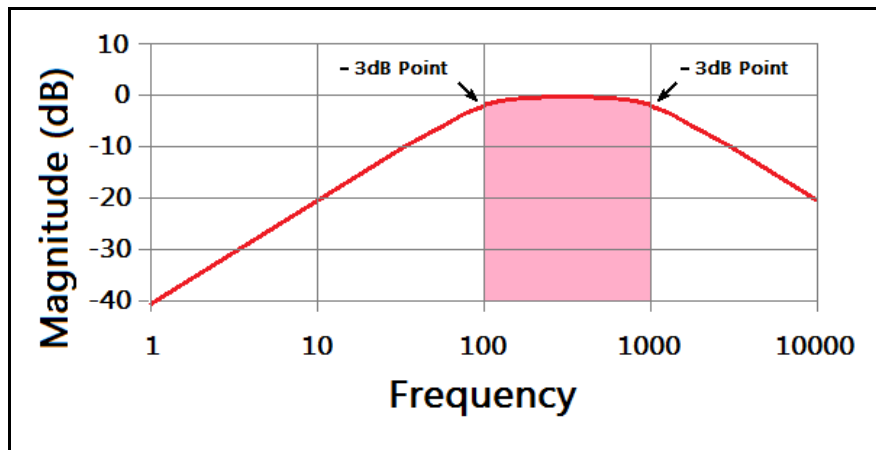
**Figure 60: An RC bandpass filter.**

A bandpass filter will have two cutoff frequencies determined by each separate filter.

From **Figure 60** shown above, we calculate two distinct cutoff frequencies,

$$f_{c1} = \frac{1}{2\pi R_1 C_1}, \text{ and } f_{c2} = \frac{1}{2\pi R_2 C_2}$$

Where  $f_{c2} \ll f_{c1}$ .



**Figure 61: Bode plot for a first order RC bandpass filter.**

In the Bode plot in **Figure 61**, we have combined a high pass filter with a cutoff frequency of 100 Hz, and a low pass filter with a cutoff frequency of 1 KHz. The region of overlap of these two filters is denoted by the pink region in the plot above, and is a combination of each filter's frequency response. We may define the *bandwidth* of a bandpass filter using the two cutoff frequencies.

Given the low frequency cutoff  $f_l$  and the high frequency cutoff  $f_h$  of a bandpass filter, we define the bandwidth  $BW$  as the difference of  $f_h$ ,  $f_l$ .

$$BW = f_h - f_l$$

### **RLC Filters and Resonance**

RC bandpass filters are fine for some applications. However, there is an issue with these filters: they are simply not *selective* enough if we only want a narrow band. That is, the roll-off on either side of an RC bandpass filter isn't steep enough to give us a sharp peak to pick out only a narrow range of frequencies. It would be like trying to tune in a radio station that is too close to other radio stations.

We'd hear all the stations around the station of interest, and we would not be able to **ROCK OUT** because our tunes would be washed out by sports broadcasts. By using RLC *resonant filters*, we can increase selectivity and create better performing bandpass or band reject filters. *Resonance* is a property of a vibrational system where, if we introduce small oscillations of the right frequency, the oscillations in the system will build and gain energy.

We are concerned only with finding the resonant frequency of the LC part of the filter. Computing the bandwidth of such filters can be involved, and is beyond the scope of this text. The bandwidth, or sharpness of the filter, is due to the series parasitic resistance of the inductor.

We note that the reactive impedance  $j(X_L - X_C)$  is equal to zero at the resonant frequency.

$$|Z_{LC}| = 2\pi f_r L - \frac{1}{2\pi f_r C} = 0$$

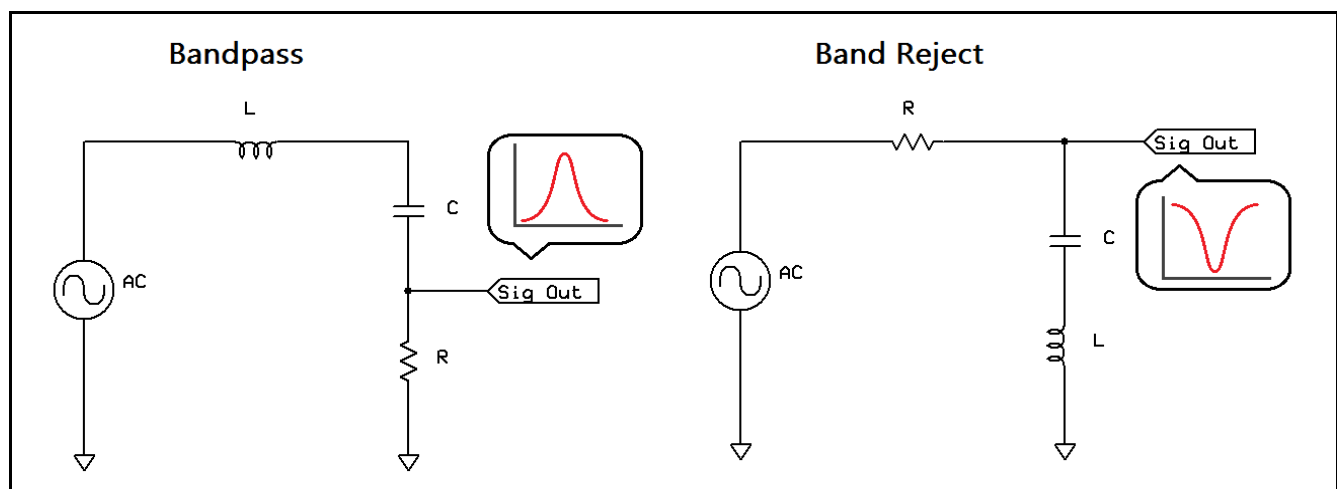
$$\text{Solving for } f_r, \quad 2\pi f_r L = \frac{1}{2\pi f_r C} \Rightarrow f_r^2 = \frac{1}{4\pi^2 LC} \Rightarrow f_r = \frac{1}{2\pi\sqrt{LC}}$$

The resonant frequency for an RLC filter is given by the relation,

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

### Series RLC Filters

Observe **Figure 62**, shown below. A series LC combination will have zero impedance at the resonant frequency. In other words, a series LC combination will look like a dead short at the resonant frequency. Therefore, we may use this to our advantage and construct the filters shown below.



**Figure 62: Series RLC bandpass and band reject filters.**

Let's compute the series combination of the inductor and the capacitor to verify that their combined impedance goes to zero at resonance.

Recall that impedances in series add,

$$Z_{eq} = Z_C + Z_L = j(X_L - X_C), \text{ and } Z = 0 \text{ if } X_L = X_C$$

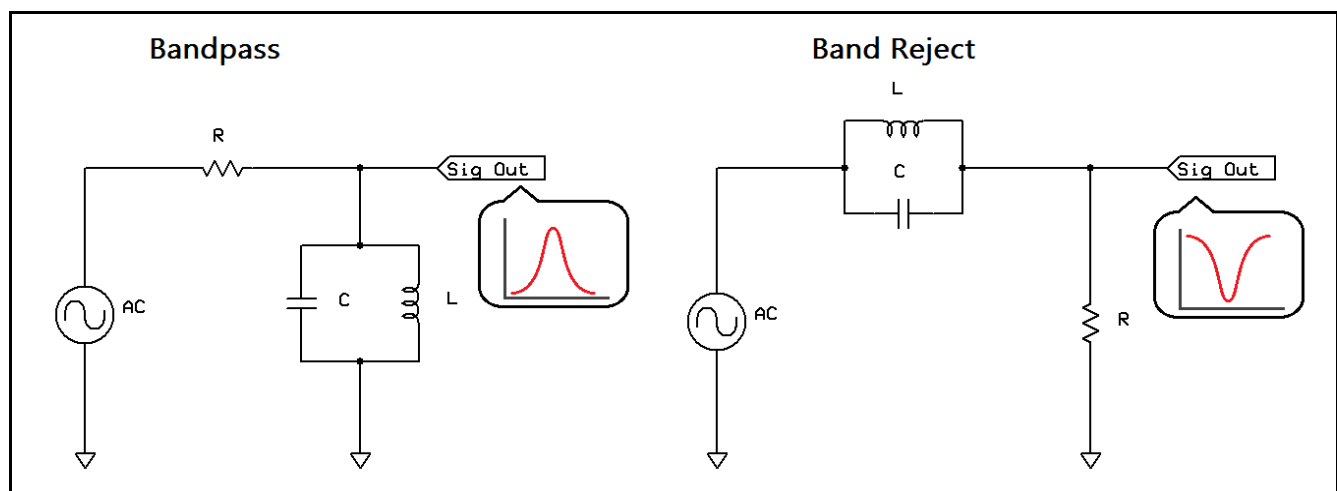
As we mentioned before, the inductor has a parasitic resistance due to the length of wire introduced by the coil. Therefore, the combined impedance does not actually go to zero. There is a factor called “Q,” which refers to the *quality* of the inductor. A high series resistance will mean a lower “quality,” which will damp oscillation and increase the bandwidth of the filter (this is unwanted in most cases.)

### **Parallel RLC Filters**

Placing an inductor and a capacitor in parallel produces a special arrangement, called a *tank circuit*. Tank circuits have the unique property that, at resonance, their combined impedance becomes very large. This is due to the energy exchange between the capacitor and inductor at the resonant frequency. The energy “sloshes” back and forth between the inductor and the capacitor.

We may use tank circuits to make bandpass and band reject filters as we did with series RLC circuits.

**Figure 63**, below, shows a bandpass and band reject filter utilizing the parallel tank circuit configuration. Tank circuits are common in communications equipment, such as portable radios.



**Figure 63: Tank circuit bandpass and band reject filters.**

We can compute the parallel impedance to verify that it approaches some large value at resonance. We should not be fooled, however. As we found with series resonant filters, inductors have parasitic resistance, and therefore the impedance will not be infinite at resonance.

We use the parallel impedance equation,

$$\frac{1}{Z} = \frac{1}{jX_L} - \frac{1}{jX_C} \Rightarrow \frac{1}{Z} = j\left(\frac{1}{X_C} - \frac{1}{X_L}\right),$$

$$\text{Therefore, } Z = j\left(\frac{X_C X_L}{X_C - X_L}\right), \quad |Z| \rightarrow \infty \text{ as } (X_C - X_L) \rightarrow 0$$

## Chapter 4.7 The Diode and DC Power Supplies

### Diode Construction

Diodes are semiconductor devices that are made from *silicon* or *germanium*, which are *doped* with various elements like arsenic and boron to create *PN junctions*. A PN junction consists of a semiconductor doped with *charge donors* (*N-type semiconductor*) in contact with a semiconductor doped with *charge acceptors* (*P-type semiconductor*.) The result is that a special junction is created which admits current flow in one direction, but blocks it in the other direction! Let's look at **Figure 64**.

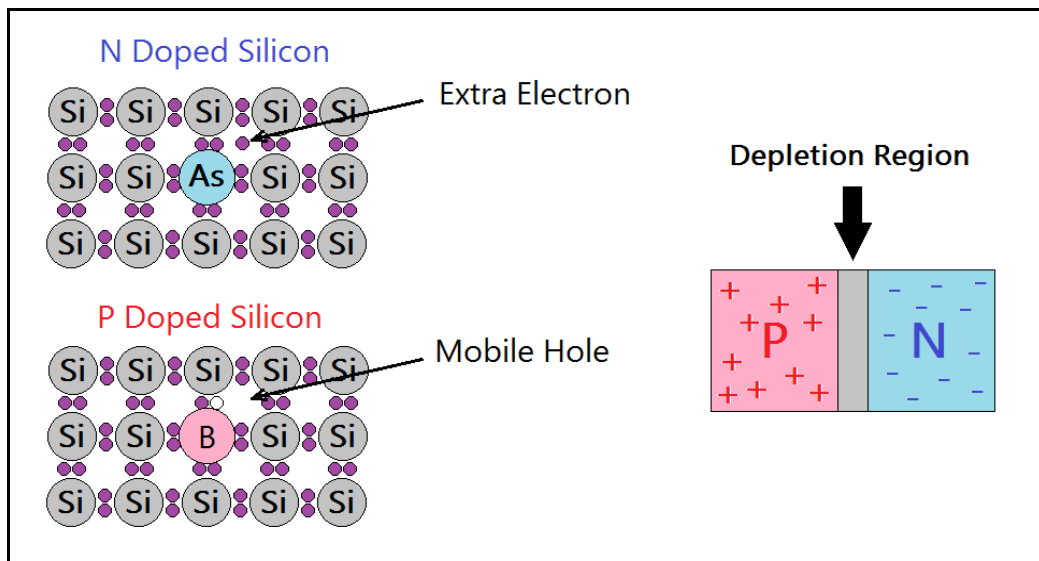


Figure 64: Doped semiconductors, and the PN junction.

In a P-type semiconductor there are mobile “holes,” and in an N-type semiconductor, there are free electrons. These are collectively referred to as *charge carriers*. In diodes, the positive terminal is called the *anode*, and the negative terminal is called the *cathode*. Current flows in the forward direction, from anode to cathode. The electrons move towards the anode to combine with available holes, and holes “move” towards the cathode. (These holes don't really move, but the electrons occupying them do move in the direction of the positive terminal, so the holes appear to propagate in the opposite direction.) The real story happens where the charge carriers meet at the junction.

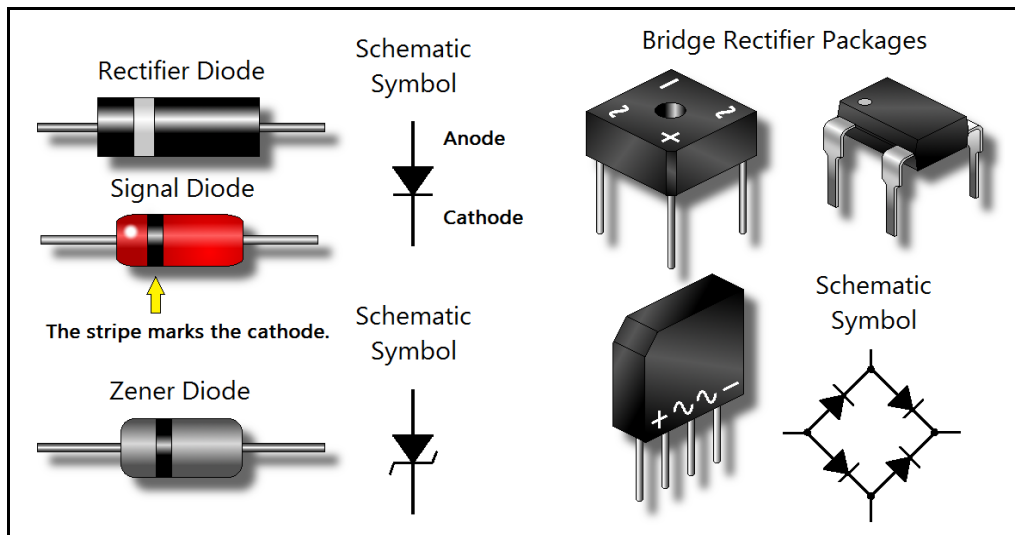
In the above diagram, there is a region defined by a gray area where the P-type and N-type semiconductor meet. This is called the *depletion region* (because there are fewer charge carriers here.) When the diode has no applied voltage, some of the electrons from the N-type semiconductor jump across to the P-type semiconductor to occupy free holes. As more and more electrons do this, the depletion region becomes wider, so the electrons find it harder and harder to jump across the gap. When this depletion region becomes large enough, the electrons cannot make it across the gap to fill the holes on the other side.

When the diode is *forward biased*, more charge carriers are introduced, and the depletion region becomes smaller. Since the electrons can make it across this gap easily, current is allowed to flow. However, if the diode is *reverse biased*, the depletion region becomes wider since charge carriers are removed. Therefore, very little current can flow in the reverse direction. Due to the *quantum* effects in the semiconductor crystal, the diode will drop a small voltage in the forward direction. This voltage is usually about 0.7 V for silicon diodes, and about 0.3 V for germanium.

### **Types of Diodes**

Since diodes can block current flow in one direction, but allow it to flow in another direction, diodes can be used to *rectify* an AC voltage. Diodes specially made for this purpose are called *rectifier diodes*. Some diodes have the unique property of dropping a very steady voltage when they are reverse biased. These are called *zener diodes*, and can be used in power supplies to carefully control DC voltage. This process is called *voltage regulation*. And *signal diodes* or *switching diodes* are used in radio circuits because they are extremely fast. Because diodes drop a small voltage in the forward direction, they dissipate a small amount of heat. They also have limits to the amount of reverse voltage they can stand off before failing. Therefore, diodes are rated for *PIV*, or *peak-inverse-voltage* and for their current capacity. **Figure 65** shows some common diode packages.





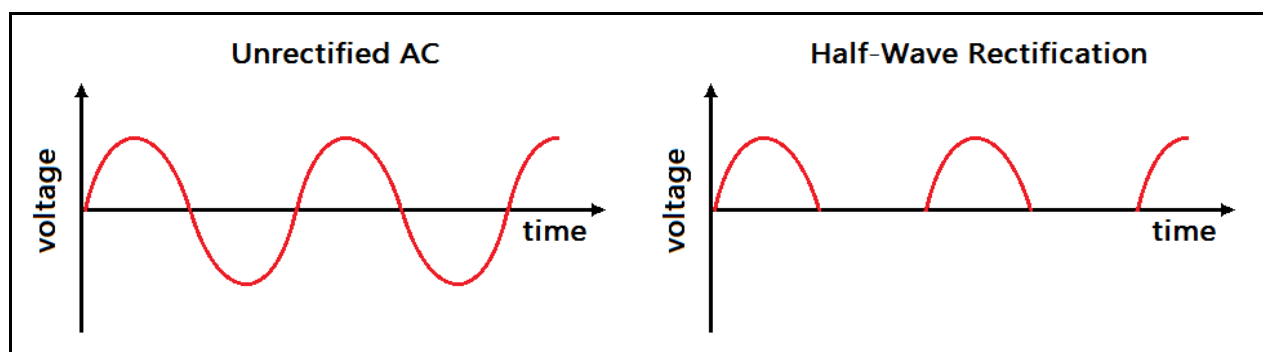
**Figure 65: Common diode packages and their schematic symbols.**

### Common Diodes to Remember

Most diodes have a “1N” prefix. A good all-around performer is the 1N4007 rectifier. It has a PIV rating of 1000 VDC (700 VAC,) making it an excellent choice for most circuits. Next is the 1N4148 switching diode. They are rated for 300 mA of forward current, and have a PIV rating of 100 VDC. Use the 1N4148 in circuits that require very fast rectification, such as in radio and digital circuits. As for zener diodes, you select these by their current capacity and *zener voltage*. These diodes also typically have a “1N” prefix such as the 1N5230 4.7 V zener. We'll meet the zener diode later.

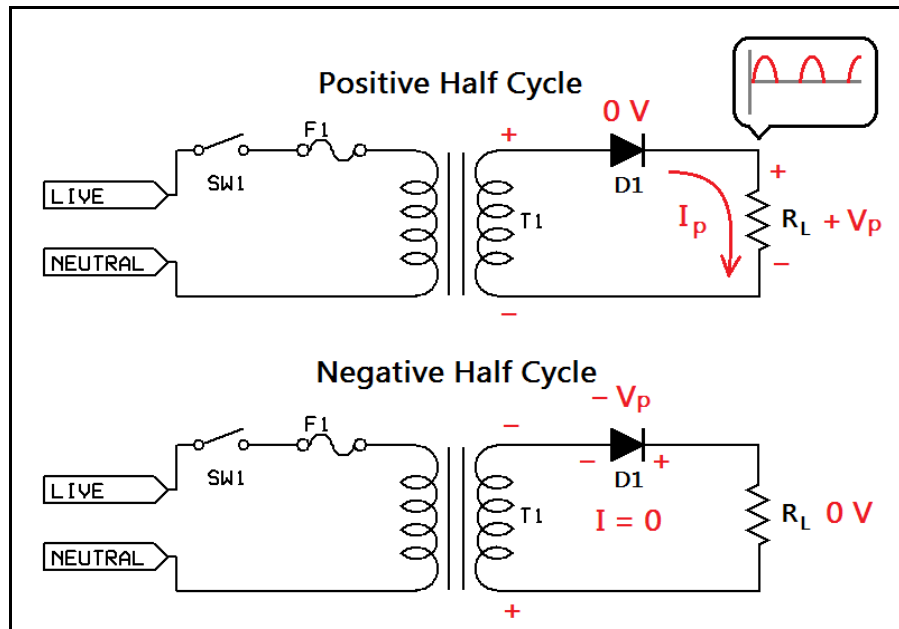
### Diode Rectification and Power Supply Design

Suppose you are building a power supply and have purchased a transformer. It outputs 12 VAC (RMS) on the secondary, but how do you convert AC to DC? Take a look at **Figure 66**, below.



**Figure 66: Half-wave rectification of an AC sine wave.**

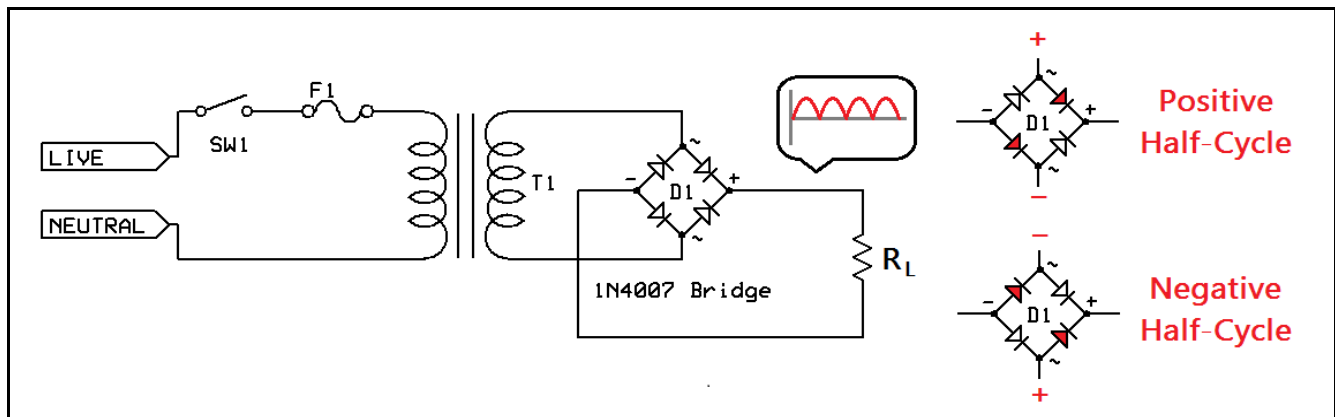
On the left, we have an unrectified AC sine wave. Notice that the voltage swings up and down through the zero axis. Suppose we had a switch that automatically opened the circuit when the voltage went negative, giving us the waveform on the right. That is precisely what a diode does. Let's take a look at a simple circuit in **Figure 67**, called a *half-wave rectifier*, which can accomplish just that.



**Figure 67: A basic half-wave rectifier circuit.**

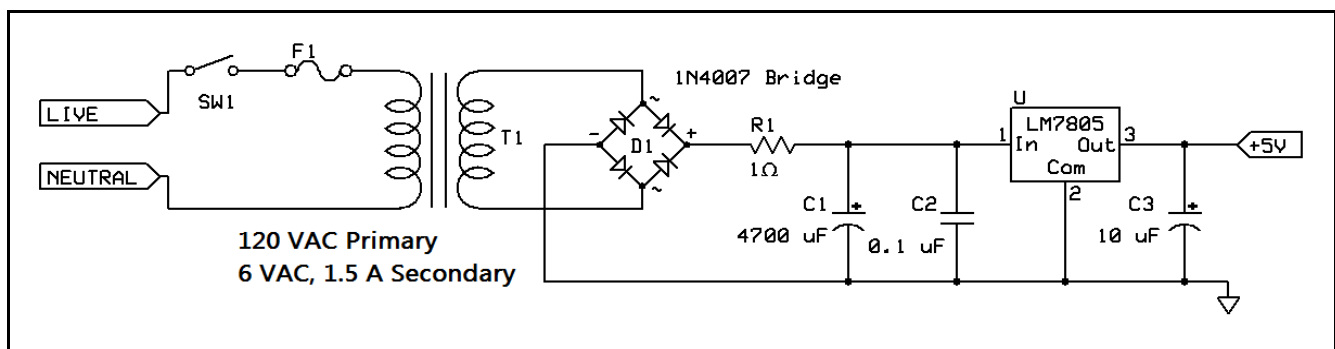
We have a drawing showing the same circuit for different parts of the applied waveform, showing the diode's conducting and blocking action. Because the diode D1 only conducts in the forward direction, the output voltage across  $R_L$  is always positive. Current increases in the load with increasing voltage up to the peak voltage, and then decreases to zero. During the negative half-cycle, the diode is reverse-biased and drops all of the negative voltage, meaning no current flows and the diode's resistance is essentially infinite. An *ideal diode* is shown for clarity (an ideal diode does not have a forward voltage drop, and reverse current is zero.)

The above circuit is fine if we can live with the gaps in voltage, but it doesn't look like the smooth, constant DC we would expect from, say, a battery. We need to improve the above situation by reducing the gaps in the voltage delivered to the load. If only we could flip over the negative half-cycles to reduce those gaps! It turns out there is a circuit that can do just that. But we need a special configuration of diodes called a *full-wave bridge rectifier*. **Figure 68** shows a full-wave bridge rectifier.



**Figure 68: A full-wave rectifier with a diagram showing diode conduction.**

The diamond of diodes is a bridge rectifier composed of 1N4007 rectifier diodes. During conduction, only two diodes are forward biased at a time. Each pair of diodes takes turn in conducting, one for the positive half-cycle, the other for the negative. This way, no matter what the polarity of the applied voltage, the diodes will force the output to always be in one direction. Therefore, we flip over the negative half-cycles and force them to be positive as well! We have filled in the gaps, which is an improvement over the half-wave rectifier from before. However, the output voltage is still “bumpy.” The frequency of the bumps will depend on what AC frequency drives the transformer (60 Hz in the United States.) We can smooth the bumps out with a low pass RC filter.



**Figure 69: A complete DC power supply with +5 VDC regulated output.**

If we use a low pass RC filter on the output, as in **Figure 69**, we get a reasonably good power supply. The series resistor is a low-value, high wattage resistor that suppresses the large current inrush caused by the large capacitor, and contributes to a low RC time constant (we want a low-pass filter with a cutoff below 60 Hz.) There will be a slight ripple on the output, depending on the load.

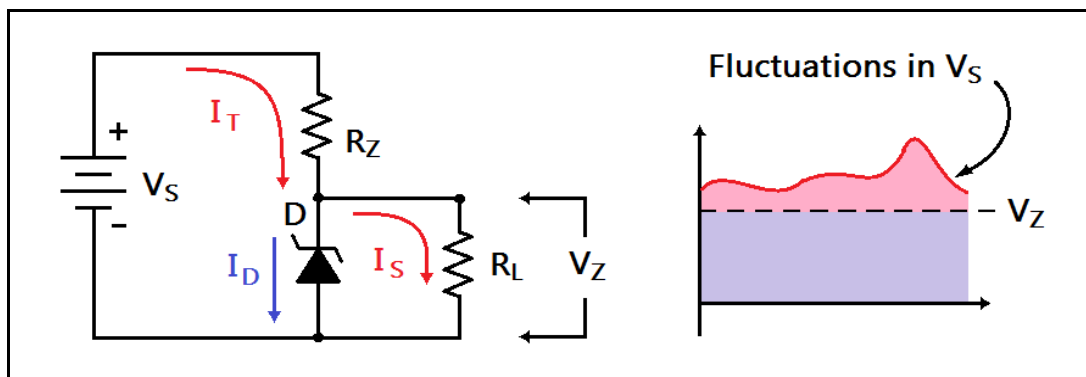
## Question

Can you compute the cutoff frequency of the low pass RC filter used in the power supply in **Figure 69**? Is it lower than 60 Hz?

### Voltage Regulation

You may be wondering about the square marked “LM7805” in **Figure 69**. The low pass RC filter definitely smooths things out for our example power supply. But there is still a slight ripple voltage, which is especially noticeable when we have a load. In order to smooth out the ripple voltage in the power supply, we need what is called a *voltage regulator*. A voltage regulator can maintain a very stable voltage, even with changes in the input voltage such as a ripple or hum.

Before looking at voltage regulator ICs (integrated circuits,) we are going to cover zener diodes first. We may regulate voltage with a simple zener circuit. Recall that if we reverse-bias a zener diode, it will drop a very stable, precise voltage. This is due to a special condition called *avalanche mode*. These diodes are designed to operate this way, and due to quantum effects, they drop a very precise, constant voltage. **Figure 70** shows how to use a zener diode. As long as some small current flows through the zener, it will maintain a steady zener voltage across the load. The total current branches off through the diode and through the load. This type of regulator is called a *shunt regulator*.

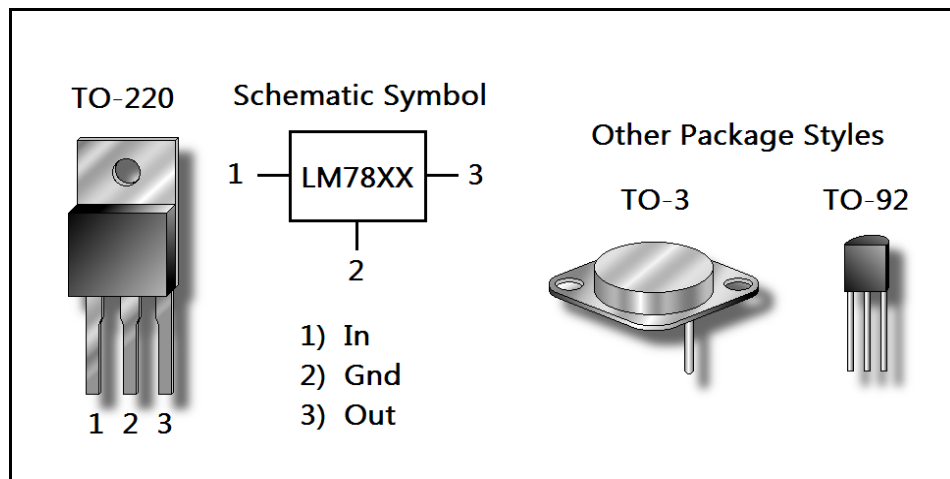


**Figure 70. A zener diode shunt regulator.**

There's a problem with this circuit. Can you see it? When we disconnect the load resistor, where does the total current flow? It flows through the diode...*all of it*. This circuit is impractical because if we disconnect the load, we risk burning up the diode. Why? Suppose we have one amp of current, and a 10 V zener diode providing regulation to the load, and the load suddenly disappears. Since the zener diode will take all that current, it will dissipate  $10\text{ V} \times 1\text{ A}$ , or 10 W! Holy cats! That diode is going to be hot! So zeners are fine as a *voltage reference*, but not so good for power supplies.

### Voltage Regulator ICs

We *could* use a shunt regulator for our power supply, but it wouldn't be practical. We need a magical device that can provide regulation, but not just burn power away while we have no load connected. The LM78XX and LM79XX series of IC regulators is the answer. The LM78XX series of regulators are positive regulators, and the LM79XX series are negative regulators. So if we construct a power supply with positive and negative voltages available, these are the devices that can regulate output voltage for our outputs. The last two digits on the package conveniently tell us the regulated output voltage for the device. For example, an LM7805 is a +5 VDC regulator. An LM7912 is a -12 VDC regulator. Common voltage regulators are shown in **Figure 71**.



**Figure 71: Common voltage regulator packages. TO-220 pin-out shown.**

The TO-220 package is the most common in use. They are one ampere devices that have a tab for attaching to a *heatsink*. The tab is usually grounded, and physically attached to pin 2. The unregulated voltage goes on pin 1, and the output is taken on pin 3. These regulators need ~2 VDC of “overhead.” For example, if you want +5 VDC output, they need at least +7 VDC input.

## Chapter 4.8: Vocabulary Review

<p>3dB point: the point where a filter begins to roll-off</p> <p>AC hum: a small ripple voltage on a DC voltage</p> <p>active filter: a filter that uses amplifiers to improve performance</p> <p>amplitude: the measure of a signal's magnitude or "loudness"</p> <p>analog electronics: the study of AC and DC circuits</p> <p>analog: a signal that can take on any voltage, i.e. not digital</p> <p>anode: the positive terminal of a diode</p> <p>apparent power: power due to phase shift in voltage and current</p> <p>attenuation: reduction in magnitude or power</p> <p>avalanche mode: type of diode conduction in reverse, see zener</p> <p>average power: the total power delivered over time</p> <p>band reject: suppression of frequencies in a band or window</p> <p>bandpass: suppression of frequencies outside a band or window</p> <p>bandwidth: a measure of a bandpass filter's window size</p> <p>Bode plot: plot of magnitude or power to frequency</p> <p>calculus: a branch of mathematics dealing with rates of change</p> <p>Cartesian form: rectangular form of a complex number, <math>a + jb</math></p> <p>cathode: the negative terminal of a diode</p> <p>charge acceptor: an dopant element that generates a hole</p> <p>charge carrier: any unit of charge that is mobile</p> <p>charge donor: an dopant element that generates free electrons</p> <p>complex conjugate: change of sign of imaginary part, <math>a - jb</math></p> <p>complex number: sum of a real number and an imaginary number</p> <p>cutoff frequency: point where a filter begins to roll-off</p> <p>decibel: unit of measure of signal strength, logarithmic</p> <p>depletion region: zone in PN junction devoid of charge carriers</p> <p>diode: semiconductor device that blocks current in one direction</p> <p>dopant: element that adds free electrons or creates holes</p> <p>doped: semiconductor that has dopant elements added</p> <p>filter circuits: circuits that can suppress unwanted frequencies</p> <p>filter theory: study of filter circuits via transfer functions</p> <p>first order: only one filter element per frequency of interest</p> <p>forward bias: applying a voltage to a diode that causes current flow</p> <p>frequency counter: test equipment that can measure frequency</p> <p>frequency domain: measure of amplitude vs frequency</p> <p>frequency response: how a filter will respond to input, Bode plot</p> <p>frequency: the measure of how fast a signal is oscillating</p> <p>full-wave rectifier: a circuit that can flip over negative half-cycles</p> <p>function generator: test equipment that can generate signals</p> <p>gain: the measure of amplification or attenuation of a signal</p> <p>germanium: a semiconductor used to make diodes</p> <p>half-power point: point where a filter begins to roll-off</p>	<p>half-wave rectifier: a circuit that blocks negative half-cycles</p> <p>heatsink: a piece of metal with fins that can dissipate heat effectively</p> <p>high pass: filter that can block low frequencies</p> <p>histogram: a graph of bins or boxes</p> <p>hole: a positive charge carrier in P-type semiconductor</p> <p>ideal diode: a diode with no voltage drop in forward direction</p> <p>imaginary axis: represented by the imaginary quantity <math>j</math></p> <p>imaginary part: part of a complex number on the imaginary axis, <math>j</math></p> <p>impedance: complex resistance with real part and reactive part, <math>Z</math></p> <p>in phase: waves that track along together in time</p> <p>leading phase: one wave that is ahead of another one</p> <p>logarithmic scale: measuring in powers of ten per tick mark</p> <p>low pass: a filter that can suppress high frequencies</p> <p>magnitude: how big a signal appears</p> <p>modulus: the square root of the sum of the squares of real, imag</p> <p>N-type: semiconductor doped with charge donors</p> <p>noise: many frequencies in one signal, such as a hiss</p> <p>oscillation: changing amplitude with respect to time periodically</p> <p>oscilloscope: test equipment that can visually represent signals</p> <p>P-type: semiconductor doped with charge acceptors</p> <p>passive filter: filter composed of passive R, L, C components</p> <p>peak instantaneous power: snapshot of peak power in time</p> <p>peak voltage: snapshot of when voltage is at maximum</p> <p>peak-inverse-voltage: maximum safe reverse voltage for diodes</p> <p>period: the time it takes to complete one cycle, <math>1 / \text{frequency}</math></p> <p>periodic: each cycle looks the same</p> <p>phase difference: measured in degrees or radians, phase shift</p> <p>phase lag: how much one signal trails another one in degrees</p> <p>phase plot: plot of phase vs frequency for a filter</p> <p>phase shift: measured in degrees, lead or lag between two signals</p> <p>phase: see phase shift</p> <p>phasor diagram: geometric representation of an impedance</p> <p>PIV: peak-inverse voltage</p> <p>PN junction: silicon doped with charge donors and acceptors</p> <p>polar form: complex number with magnitude-angle notation</p> <p>pulse-width modulation: rapid pulses to control power</p> <p>pulse: a narrow sliver of applied voltage or current</p> <p>pure resistance: a resistance with no reactive elements</p> <p>PWM: pulse-width modulation</p> <p>Q, quality: quality of an inductor that increases with lower resistance</p> <p>quantum: having to do with energies in atoms</p> <p>ramp wave: a linear, periodic waveform</p>
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<p>reactance: scalar value of AC resistance</p> <p>reactive power: power due to a phase shift between voltage, current</p> <p>real axis: the horizontal axis where pure resistance is plotted</p> <p>real part: the part of a complex number without the imaginary unit <math>j</math></p> <p>real power: the power dissipated by pure resistance in a circuit</p> <p>rectangular form: form of complex numbers, <math>Z = a + jb</math></p> <p>rectified AC: AC with negative half-cycles flipped positive</p> <p>rectifier diode: a diode specially made for rectifying for power</p> <p>rectifier: a diode used to block negative half-cycles</p> <p>resonance: a frequency where L and C reactance are equal</p> <p>resonant filter: a filter that has improved selectivity</p> <p>reverse bias: a backwards voltage applied to a diode, no current</p> <p>RMS: root-mean-square, DC equivalent voltage for AC</p> <p>selectivity: how well a filter can tune to a small band of frequencies</p> <p>semiconductor: silicon or germanium, used to make diodes, etc.</p> <p>shunt regulator: a regulator using a zener diode to shunt current</p> <p>signal analysis: theory of how filters respond to input signals</p> <p>signal diode: a very fast diode that can rectify at high frequencies</p> <p>silicon: semiconductor used to make diodes, transistors, etc.</p>	<p>sine wave: common waveform used in power transmission</p> <p>sinusoid: sine-wave shaped waveform</p> <p>spectrum analyzer: device that measures amplitude vs frequency</p> <p>square wave: digital on / off signal that has a square appearance</p> <p>star notation: used to denote a complex conjugate</p> <p>steady-state: not changing appreciably with respect to time</p> <p>switching diode: very fast diode that can rectify at high frequencies</p> <p>tank circuit: parallel LC circuit with high impedance at resonance</p> <p>time domain: changing amplitude with respect to time</p> <p>transfer function: how a filter will react given input frequency</p> <p>triangle wave: a linear waveform resembling a sawtooth</p> <p>TTL oscillator: produces accurate square waves at high frequency</p> <p>voltage reference: used as a stable reference in other circuits</p> <p>voltage regulation: act of smoothing to a pure DC voltage</p> <p>voltage regulator: device that can provide very stable output voltage</p> <p>waveform: the shape of a periodic signal</p> <p>zener diode: diode operated in reverse to obtain stable voltages</p> <p>zener voltage: the voltage a zener diode provides</p>
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## Chapter 4.9: Lab Activity 4 – AC Signals, Filters, and Rectification

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### Introduction

You have come far, traveler! You have passed the lands of signals and phases, through the valley of filter circuits, and have traversed the treacherous mountain passes of diodes and power supplies. You defeated the complex number dragons, and the reactance monster X. Now that you have completed your journey, your reward is a challenging lab exercise!

In this lab exercise, we'll be learning how to use a function generator and an oscilloscope to create our own waveforms. We'll look at how to change frequency, offset, and amplitude from the function generator, and measure our output on the oscilloscope. Then we will create high pass and low pass RC filters to apply what we learned. As the input frequency is changed, we will see how the output changes by using both channels of the oscilloscope. Finally, we will be building our own rectifier circuit to verify diode action.

## Materials

The materials required for this lab are listed in the table shown below.

Lab Activity 4 – Parts List	
Quantity	Item
1	0.1 $\mu\text{F}$ ceramic disc capacitor
1	10 K $\Omega$ ¼ watt resistor (brown, black, orange, and gold striped)
1	1N4007 Diode
1	LumiDax ® wiring kit
1	LumiDax ® Bakerboard Analog Trainer
1	Pair of wire cutters.

## Procedure

Make sure power is not applied to the trainer until your circuit is wired and ready to test.

1. We will first be exploring the function generator and the oscilloscope functions. Wire the output marked SIG from the function generator to the CH1 input for the oscilloscope, then wire the output marked CLK to the CH2 input, as shown in **Figure 72**.

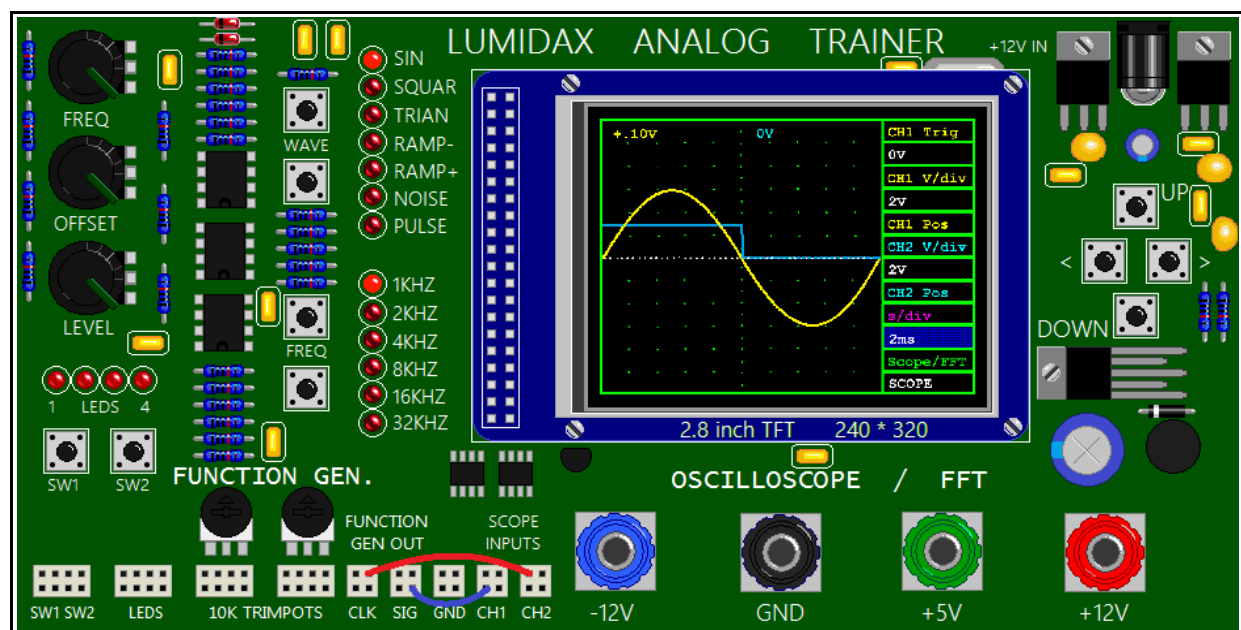
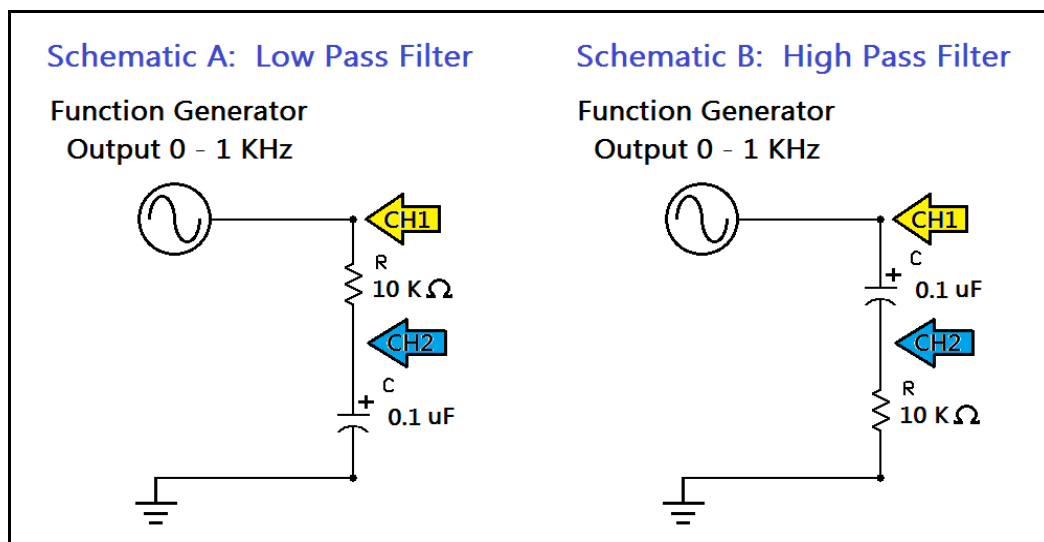


Figure 72: Testing the function generator with the oscilloscope.

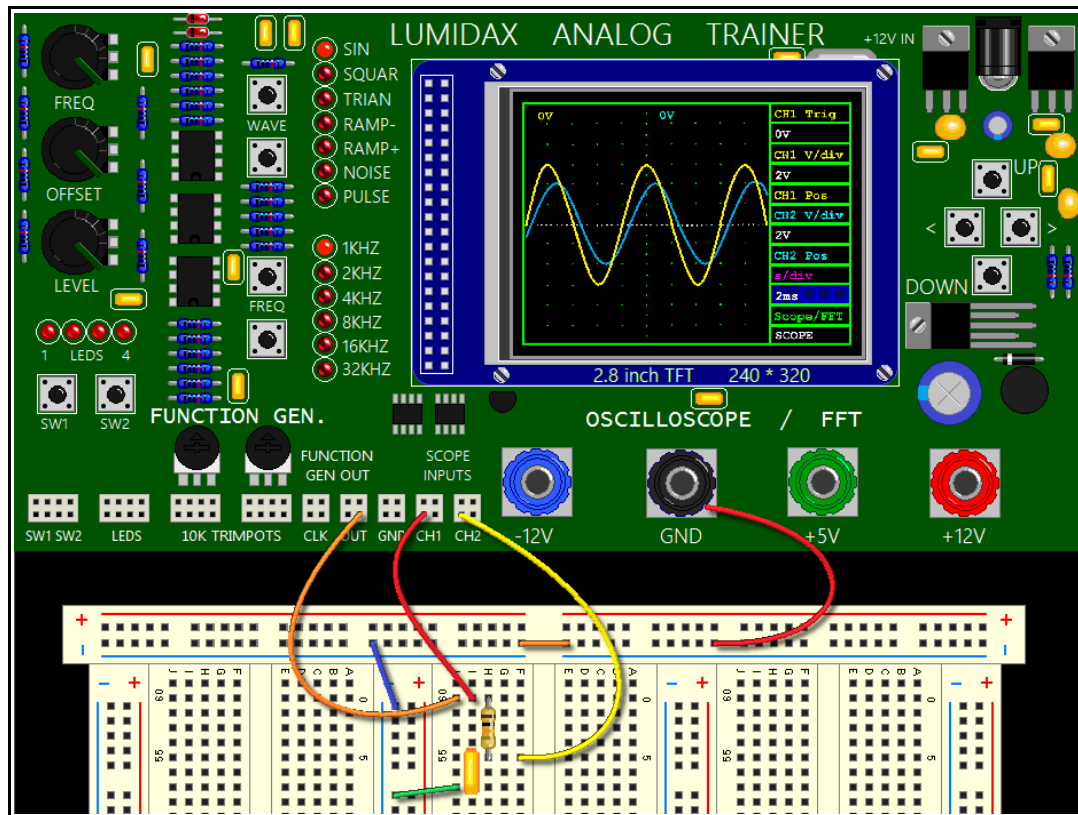


2. Apply power, and use the cursor keys set the oscilloscope s / div setting to 2 ms / div.
3. Set the function generator to 1 KHz range, and use the WAVE keys to run through all the waveforms. Look at the yellow trace. Can you identify any of these signals by name? Use the FREQ knob to adjust frequency, the OFFSET knob to control the DC voltage that the output signal “rides on top of,” and set the LEVEL knob to adjust amplitude. See what each knob does to the output signal. Then, use the knobs to adjust the waveform to the one shown in **Figure 72**. Try to adjust the function generator to display one full cycle of the sine wave input.
4. Can you tell what the frequency is by reading the trace? What about the peak voltage? The peak to peak voltage? Can you calculate the RMS voltage from the peak voltage? Record your findings.
5. The blue trace is the “CLK,” or clock output. It is a digital signal that turns “on” when the waveform is positive, and “off” when the waveform is negative. It is a +3.3 V “LVTTL” clock that you can adjust with the frequency control! Remove power from the Bakerboard Analog Trainer, and remove the wires.
6. Construct the circuit marked “Schematic A” in **Figure 73**. You will be verifying the filtering action of a low pass filter.



**Figure 73: Test filters with oscilloscope connections and variable input frequency.**

7. Set the oscilloscope, again, to 2 ms / division. Set the function generator to SIN (sine wave) mode, and set the frequency range to 1 KHz, as before. Adjust the input (yellow trace) to have an amplitude of about 6 V peak, and make sure the offset is set to 0 V to center the output on the screen. Your setup should look like the one in **Figure 74**.

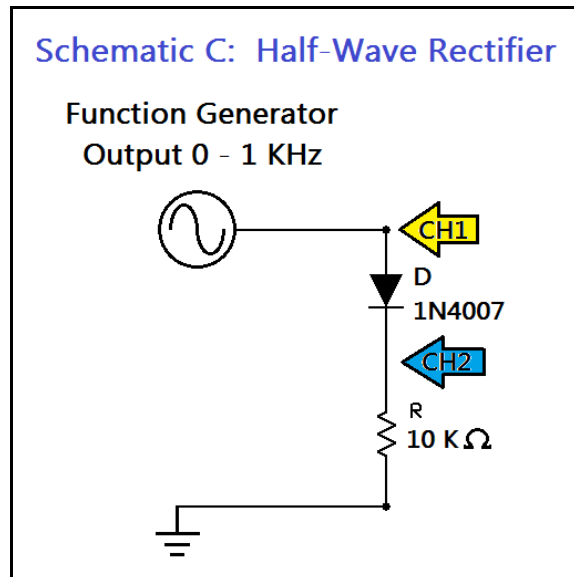


**Figure 74: Low pass filter with input and output.**

8. Vary the input frequency and observe the phase shift and the output amplitude (blue trace.) If it is difficult to see the blue trace, it may be moved up and down by highlighting the CH2 Pos window and using the left and right arrow keys. Moving the trace only affects how it is displayed, not the input signal. Does the output amplitude (blue) decrease when you turn the FREQ knob? What happens to the phase?

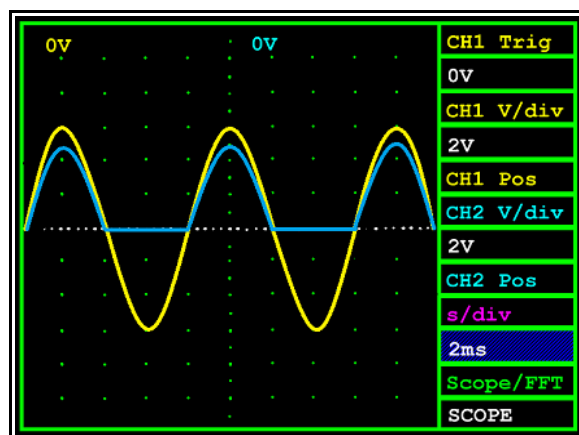
9. Turn off the power, and switch the positions of the capacitor and the resistor to create a high pass filter, as shown in Schematic B of **Figure 73**. Plug in the power once more, and set the time / div setting to 2 ms / division again. Vary the frequency, as before. Does the filter work as predicted?

10. Unplug the power again and dismantle the filter circuit. Next we will be verifying diode action. Build the circuit Schematic C, shown in **Figure 75**. We will be using a 1N4007 diode and resistor load to measure the output voltage across the load. This is the half-wave rectifier we covered in the text.



**Figure 75: Diode Half-Wave rectifier circuit.**

11. Turn on the power again, and adjust the oscilloscope as before to 2 ms / division. Make sure to set the function generator to SIN mode again, and that your output range is set to 1 KHz. Vary the frequency to get at least two full cycles on the input trace (yellow.) If you cannot see the blue trace, move it up or down using the CH2 Pos function. Does the output look like **Figure 76**?



**Figure 76: Half-wave rectifier showing diode blocking action.**

**Lab Activity 4 – Conclusion**

In this activity, you learned about how to use the function generator and the oscilloscope on the Bakerboard Analog Trainer. You created your own signals and saw them on the oscilloscope screen. Then you built low pass and high pass RC filters. You varied the input frequency to the filters and watch as their output changed with input frequency. Finally, you constructed a half-wave rectifier circuit using a 1N4007 diode and a load resistor. Congratulations, and welcome to the analog world!

**Chapter 4.10: Exercises**

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**Vocabulary Questions**

1. The measure of how fast a signal is oscillating is called \_\_\_\_\_.
2. The \_\_\_\_\_ of a signal is how “loud” it is, or how large it is.
3. The \_\_\_\_\_ of a bandpass filter is a measure of the size of the frequency window.
4. A parallel LC combination is also called a \_\_\_\_\_.
5. The \_\_\_\_\_ of a coil is also called Q, and is a defining factor for bandwidth.
6. A \_\_\_\_\_ is a special diagram that helps us visualize impedance.
7. The \_\_\_\_\_ of a complex number negates the imaginary part.
8. \_\_\_\_\_ could be called the “AC resistance” of a reactive component.
9. \_\_\_\_\_ is a complex resistance, and is the sum of real and imaginary parts.
10. A \_\_\_\_\_ consists of a PN junction, and can block current in one direction.
11. A \_\_\_\_\_ is used backwards (reverse bias,) and drops a precise voltage.
12. A \_\_\_\_\_ can flip over the negative half-cycles of a sine wave for rectification.
13. A \_\_\_\_\_ is often found as a digital signal, such as TTL oscillator output.

**True or False**

- |   |   |   |
|---|---|---|
| 1. Impedance can be real, complex, or 0.                                  | T | F |
| 2. Reactance varies with frequency.                                       | T | F |
| 3. A high pass filter blocks high frequencies and passes low frequencies. | T | F |
| 4. Polar form can be expressed $Z = a + jb$ .                             | T | F |
| 5. The RMS voltage and the peak voltage of a sine wave are the same.      | T | F |

- |   |   |   |
|---|---|---|
| 6. Amplitude is a measure of how fast a signal is oscillating.  | T | F |
| 7. A tank circuit takes on a very high impedance at resonance.  | T | F |
| 8. Capacitors and inductors do not ideally dissipate any power. | T | F |
| 9. PWM is used to control power by varying pulse width.         | T | F |
| 10. A series RLC circuit is purely resistive at resonance.      | T | F |

### **Problems**

1. You are given a sine wave with a peak voltage of 10 Vp and a frequency of 10 KHz. What is the period (the time it takes to complete one cycle?) What is the RMS voltage? What is the peak-to-peak voltage?
2. A DC voltage of +24 V powers a load, which draws 2 W of power. What is the RMS voltage of an AC sine wave that would dissipate the same power? Would the peak voltage of the AC waveform be higher than the DC voltage?
3. A transformer with a 12 VAC (RMS) secondary feeds a bridge rectifier. Given that the diodes in the bridge are silicon type diodes, what is the peak of the output rectified waveform? Hint: consider that only two diodes conduct at one time in series.
4. If the current delivered by the power supply in **Figure 69** is one amp maximum, calculate the wattage of the resistor R1 needed for safe operation.
5. A 2.5 KHz, 10 VAC sine wave is used as an input to a 2200  $\Omega$  resistor and a 4.7 nF capacitor in series. Calculate the voltages across both the resistor and capacitor, and the total current for the network. Give your answer in polar form, showing the phase shift.
6. Design a bandpass RC filter with a lower cutoff frequency of 20 KHz and an upper cutoff frequency of 200 KHz.

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## Chapter 5 – Transistors and Op Amps

In this chapter, you will...

- ➡ Meet the transistor and the op amp.
- ➡ Learn about how to use transistors.
- ➡ Discover the secrets of op amps.
- ➡ Make use of transistors in applications.
- ➡ Build your own amplifier.

So far, we have made use of a few *passive* components. That is, we have used components that do not *amplify*. Diodes can't amplify on their own. They can only block current from flowing in one direction. And resistors, capacitors, and inductors can only attenuate.

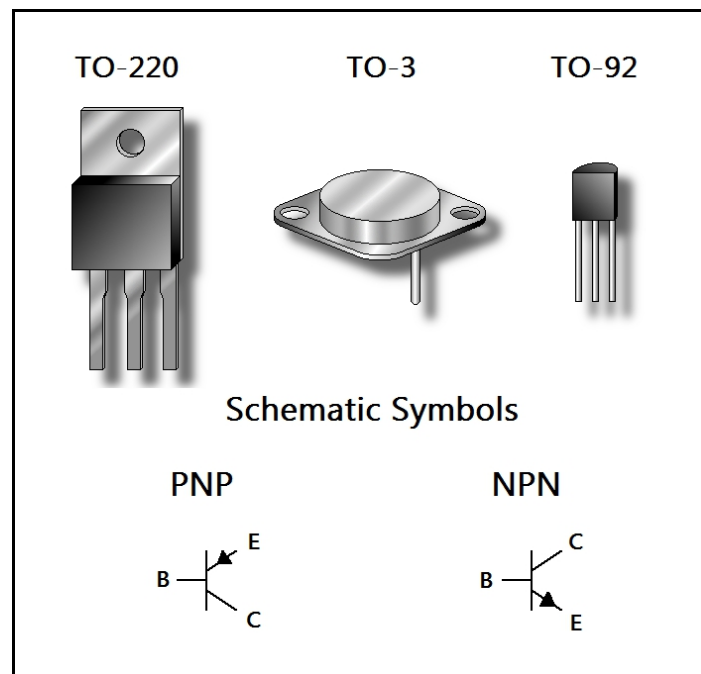
The most basic amplifier imaginable would act much like a valve. Imagined that way, a huge flow of water could be controlled by a small turn of a valve. A *transistor* is a three terminal device that can control a large current with a tiny current. So they may be thought of as valves in this respect.

We will explore the world of transistors and their uses. Later, we will cover *differential amplifiers*, and then discover that *operational amplifiers* are nothing more than differential amplifiers in a convenient *integrated circuit*, or *IC* for short.

## Chapter 5.1: The Bipolar Junction Transistor (BJT)

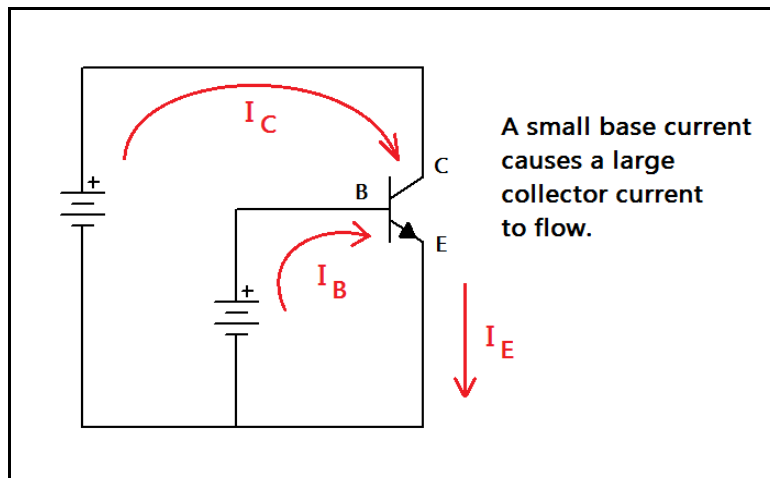
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We met the diode in the last chapter, which is a PN junction. But suppose we wanted to control the current in the diode with another, much smaller current. The solution is to add another semiconductor junction, forming a “PNP or NPN sandwich.” By doing so, we create special devices called transistors. These are referred to as *bipolar junction transistors*, or *BJTs*. A bipolar junction transistor is a three-terminal device that can switch large currents with a small control current. **Figure 77** shows common transistor packages, and the schematic symbols for *PNP* and *NPN* transistors.



**Figure 77: Bipolar junction transistor packages, and their schematic symbols.**

The schematic symbols in the figure are marked with the letters E, B, and C, which stand for *emitter*, *base*, and *collector*, respectively. You can see a resemblance to the diode's schematic symbol. This gives some idea of the polarity of the transistor. An NPN transistor needs a positive base voltage to turn on, and a PNP transistor needs a negative base voltage. We'll cover this later. But for now, just think of a transistor as a switch, as this is the most basic use of a transistor. In order to “turn on” a transistor, we must supply a small current to the base of the transistor. In **Figure 78**, we have an NPN transistor showing the flow of current in order to turn the transistor on.



**Figure 78: Basic operation of an NPN transistor.**

Transistors have a property called *gain*. For bipolar junction transistors, this is referred to as *beta gain*, represented by the Greek symbol beta ( $\beta$ ). Beta is the *current gain*, because the collector current may be expressed as the product of the base current and this amplifying factor.

The current amplification factor of a transistor is defined the following way,

$$\beta \equiv \frac{I_C}{I_B}$$

A gain of 100 – 300 is typical for small signal transistors. Let's say we have a gain of 100 and a base current of 10 mA. The collector current is given by the following equation:

$$I_C = \beta I_B = 100 \times 0.01 A = 1 A$$

So we can cause a current of one ampere to flow in the collector of the transistor with a tiny current of 0.01 amperes flowing in the base of the transistor. Current gain is also denoted by  $h_{FE}$  in transistor *datasheets*. You should read the component datasheet so you can use the transistor safely and effectively in your circuits. Datasheets can also tell us the *pinout* of the part. However, there is a fairly common standard for transistor pin designations, as shown in **Figure 79**. The common pinouts for TO-220 and TO-92 devices are given. (TO means “transistor outline” and refers to package style.)



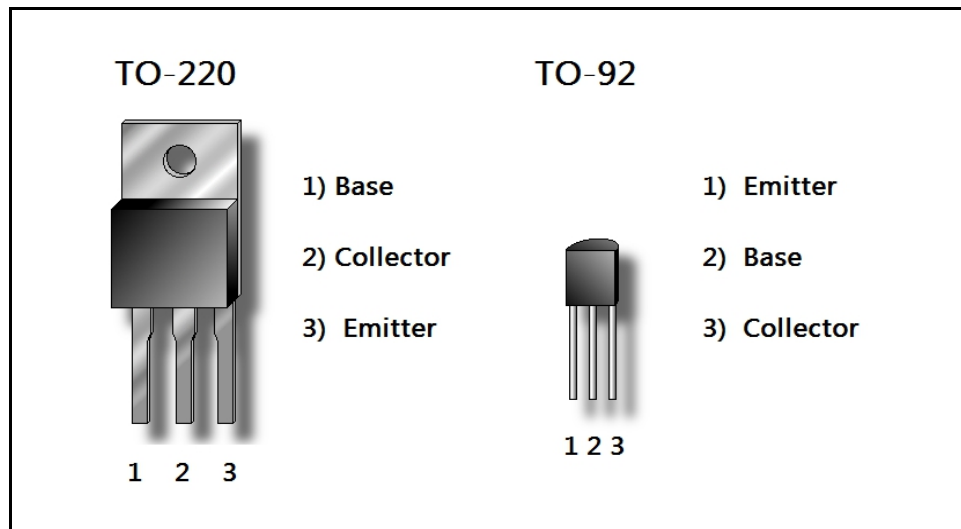


Figure 79: Common pinouts for bipolar junction transistors.

### **Common Transistors to Remember**

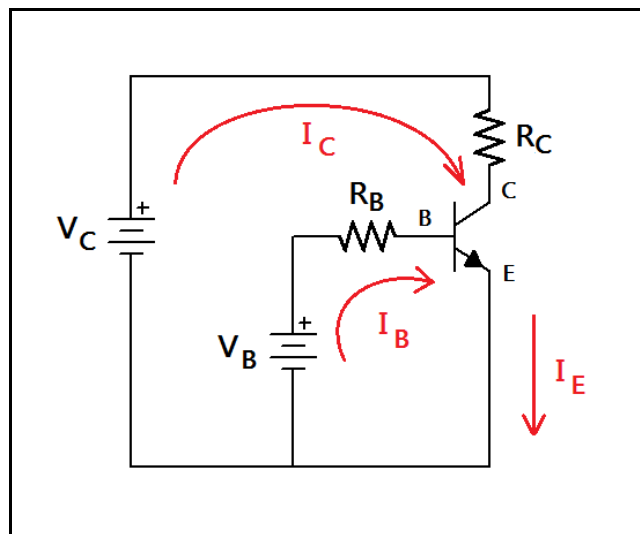
There are a handful of transistors you should memorize. Some useful transistors have part numbers that begin with a “2N” or “TIP” prefix. Very useful transistors are *small signal* transistors in the TO-92 package. A pair of NPN and PNP transistors with closely matched performance are the 2N3904 NPN, and the 2N3906 PNP general purpose transistors. These are inexpensive, all-around good performers for low power amplifier circuits. They can safely handle up to 200 mA of current, and operate at voltages up to 40 V. They typically have a gain of about 100.

If you need a powerful transistor that can switch large currents, consider the TIP 31 NPN transistor and the TIP 32 PNP transistor. These come in a TO-220 package, and can safely handle up to 3 A of current. However, they have smaller gain – a gain of 25 is typical for these. Then there are *Darlington* transistors, which we will cover later. But here, we'll introduce the TIP 121 NPN Darlington and the TIP 126 PNP Darlington transistors. They have a much higher gain of about 1000, and are the correct choice for switching large currents of up to 5 A with a small signal such as a digital output. Being power devices, the TIP 121 and TIP 126 Darlington transistors come in a TO-220 package.

A point of caution: TO-220 transistor packages have the collector directly connected to the *heatsink tab*. Unlike voltage regulators, which make this tab a ground connection, you would do well to remember that you need an insulator if you must heatsink your transistor to a grounded case. Failure to do so will short circuit your power supply! When you buy a TO-220 transistor, buy insulators too.

### **Basic Bipolar Junction Transistor Operation**

Bipolar junction transistors can be used for a wide variety of applications. Let's cover a little theory before we move on to common transistor circuits. The maximum collector current is controlled by whatever resistance is in the current path of the transistor's collector. In other words, there is a point where the transistor ideally looks like a short circuit from emitter to collector, called *saturation*, where collector current is maximum. This maximum current is set by the load  $R_C$ . There is another point called *cutoff*, where the transistor is completely turned off. Since there is a *diode drop* from the emitter to the base, if we do not apply greater than +0.7 V to the base, no current flows and the transistor is completely turned off. Because the transistor can be operated either fully saturated, or in full cutoff, it looks much like a switch. Let's look at **Figure 80** to see why that is.



**Figure 80: Basic NPN transistor switch with collector and base resistors.**

Calculating maximum collector current is as critical design step. If the transistor is in full saturation, then we can assume it acts as a short circuit from collector to emitter (an ideal transistor.) We can compute the base current that will give rise to this condition, given the other parameters in the circuit.

The maximum collector current may be computed by assuming that the transistor acts as a short circuit between the collector and the emitter. See **Figure 80**.

$$I_{C\text{-sat}} \approx \frac{V_C}{R_C}, \text{ and the saturation base current follows, } I_{B\text{-sat}} = \frac{I_{C\text{-sat}}}{\beta}$$

The cutoff point, of course, is when the source voltage  $V_B < +0.7\text{ V}$ .

We may compute the voltage across  $R_B$  at saturation.

$$I_{B\text{-sat}} R_B = V_{R_B},$$

and adding the diode drop gives the necessary source voltage applied to the base resistor to achieve saturation.

$$V_{R_B} + 0.7\text{ V} = V_B$$

This gives us a range of voltages and currents in the base resistor from saturation to cutoff. The resistor network on the base of the transistor forms a *bias* by which we may carefully control when the transistor is in saturation and when it is in cutoff. If we bias the transistor to be “half-on,” we end up with an amplifier that can amplify AC signals. We’ll meet that circuit later.

## Chapter 5.2: Useful Transistor Circuits

### Switching Loads with TTL

TTL is a very common control method for devices and systems. Most *digital* and *microcontroller* circuits output voltage levels that are either *logic low* (0 V) or *logic high* (+5 V.) Sometimes the loads we need to switch are too high in voltage or current for TTL to handle. After all, we can’t drive much more than an LED with TTL. We need to use transistors between our digital circuit and the load.

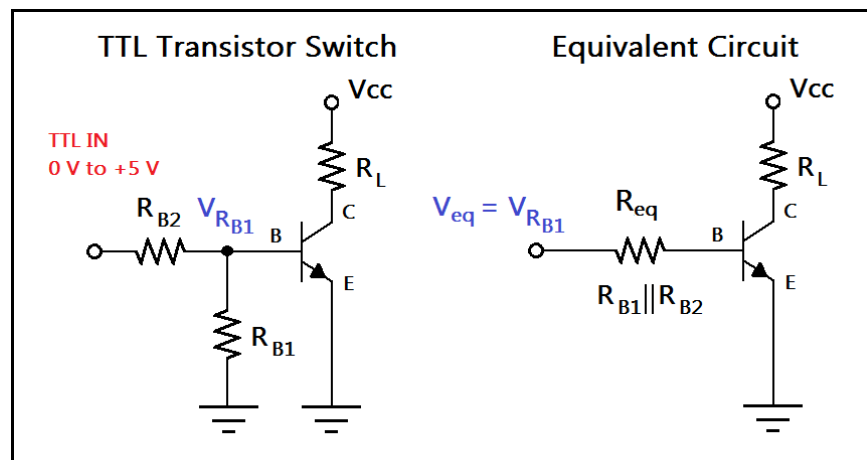


Figure 81: TTL actuated transistor switch.

Why do we need a voltage divider to bias the transistor in **Figure 81**? This is due to logic levels not being precisely 0 V for logic low and logic high not being quite +5 V. A logic high can be considered legally high at +3.0 V, and a logic low can be legal at +0.8 V. This is problematic for us. We need to make sure that when we present a logic low to the base of the transistor, that it turns off. As +0.8 V is greater than +0.7 V for  $V_{CE}$ , then we have to pull these levels down a bit. Let's do some calculating.

We may find an equivalent circuit for the voltage divider bias. This comes from Thevenin's theorem, but just remember that the equivalent resistance of a voltage divider bias is the parallel combination of  $R_{B1}$  and  $R_{B2}$  seen by the base of the transistor. Refer to **Figure 81**.

$$V_{eq} = V_{RB_1} = V_{TTL} \frac{R_{B1}}{R_{B1} + R_{B2}} \text{ and } R_{eq} = \frac{R_{B1} R_{B2}}{R_{B1} + R_{B2}}$$

Assuming that  $R_{B1} = R_{B2}$ ,  $V_{eq}$  can be either 0 V to +0.4 V for logic low, and +1.5 V to +2.5 V for logic high. These levels will ensure cutoff for a legal logic low.

We can compute the base current required to fully saturate the transistor by using the lower bound for the logic high output voltage, +1.5V, assuming  $V_{CE} = 0V$  at saturation.

$$I_{C-sat} = \frac{V_{CC}}{R_L}, \text{ and assuming } \beta \approx 100, I_{B-sat} = \frac{I_{C-sat}}{\beta} = \frac{V_{CC}}{\beta R_L}$$

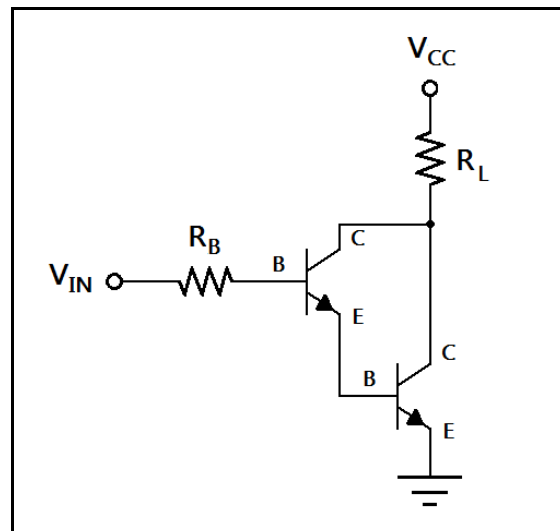
We wish to choose  $R_{eq}$  such that,

$$\frac{V_{eq} - 0.7V}{R_{eq}} = I_{B-sat} \Rightarrow R_{eq} = \frac{1.5V - 0.7V}{I_{B-sat}} = \frac{0.8V}{I_{B-sat}}$$

And remembering that we assumed  $R_{B1} = R_{B2}$ ,

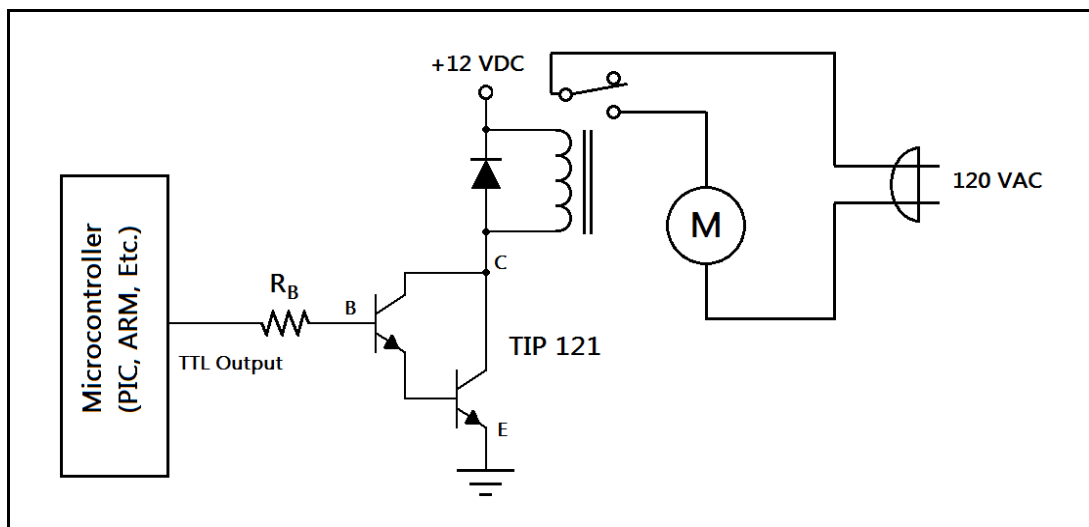
$$R_{B1} = R_{B2} = 2 R_{eq}$$

The caveat here is that you cannot expect to draw more than 15 mA from a TTL output. TTL is not intended for driving loads. Furthermore, you will have to remember that small signal transistors cannot drive more than 200 mA or so. Therefore, our analysis is telling us that if we wish to drive a larger current than 200 mA, we need a special transistor. We need a transistor that will, for sure, have a much higher gain and a higher current capability. Enter the Darlington pair. A Darlington pair is a special arrangement of two transistors in one package that yields improved gain.



**Figure 82: An NPN Darlington configuration, yielding higher gain.**

With an NPN Darlington pair, things get easier when switching large loads with TTL. For starters, the gain is much higher (about 1000.) Why? Look at **Figure 82**. The base current of the transistor on the right is controlled by the transistor on the left. Therefore, the gain is the product of the individual transistor gains. We won't have to worry about drawing more than 15 mA from a TTL output. Also, notice that there are two diode drops instead of one. This means that the voltage applied to base resistor  $R_B$  must be greater than +1.4 V. This very conveniently makes interfacing to TTL outputs easier, because now we don't have to worry about the logic levels too much. Let's do an example.



**Figure 83: Darlington based relay controller circuit with TTL input.**

Suppose we have a 12 VDC relay that we want to switch with a TTL output. The relay controls a motor such as a fan or pump on an AC circuit. The coil draws 2 A of current when energized – a pretty normal coil current for a power relay. Let's use a TIP 121 NPN Darlington transistor circuit, as shown in **Figure 83**. The diode in the circuit suppresses the inductive kick from the transistor switching action in the coil. We can compute the value of the base resistor needed.

The output from the digital system is +3 V to +5 V for logic high. We will assume worst case and use +3 V for logic high output. We need 2 A saturation current,

$$I_{C-sat} = \beta I_{B-sat} \Rightarrow 2 A = 1000 I_{B-sat} \Rightarrow I_{B-sat} = 2 mA$$

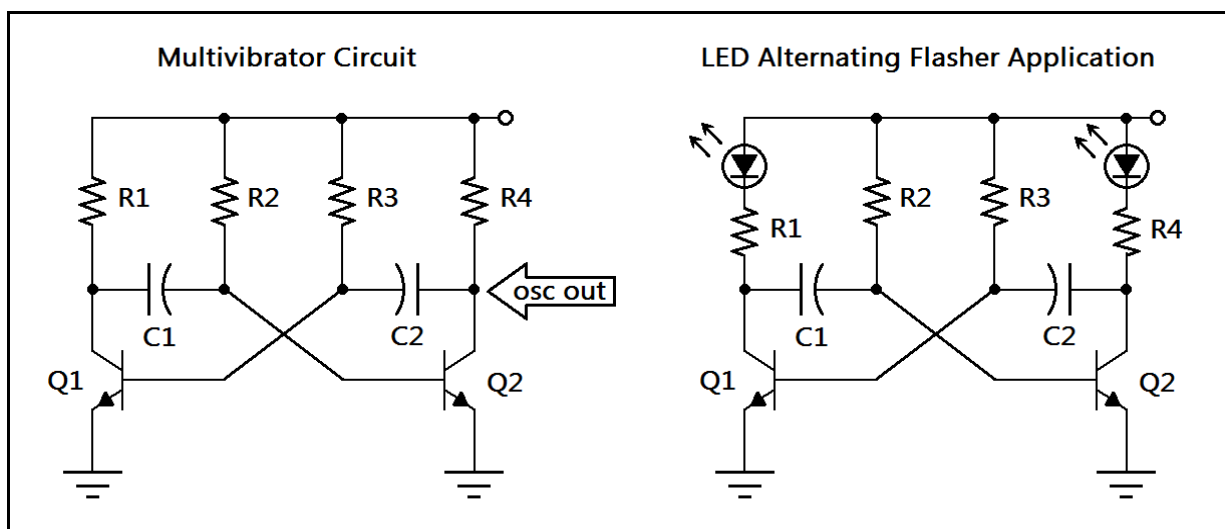
Now we may compute the base resistor's value,

$$\frac{V_{in} - 1.4 V}{I_{B-sat}} = \frac{+1.6 V}{2 mA} = 800 \Omega$$

If given +5 V as logic high and a base resistor of  $800 \Omega$ , the maximum base current is  $4.5 mA$ . This is well within the specifications of the transistor and most TTL devices.

### The Two-Transistor Oscillator

A two transistor *oscillator*, called a *multivibrator*, can be used to generate a square wave. It works by using two RC charge-discharge time constants and two transistors. **Figure 84** shows a multivibrator circuit. We won't discuss the theory of operation, but we will give some useful equations.



**Figure 84: Two transistor multivibrator circuit with LED “blinky light” application.**

The transistors in the circuit take turns at powering their respective loads,  $R_1$  and  $R_4$ . The *duty cycle*, or the percentage of time that one of the transistors is on, is related to the RC time constants  $R_2C_1$  and  $R_3C_2$ . Therefore, these time constants control the total period (the “on time” for both transistors) and therefore the frequency of oscillation. You will be building this circuit in the lab exercise.

The total period of oscillation of a multivibrator is given by the following equation,

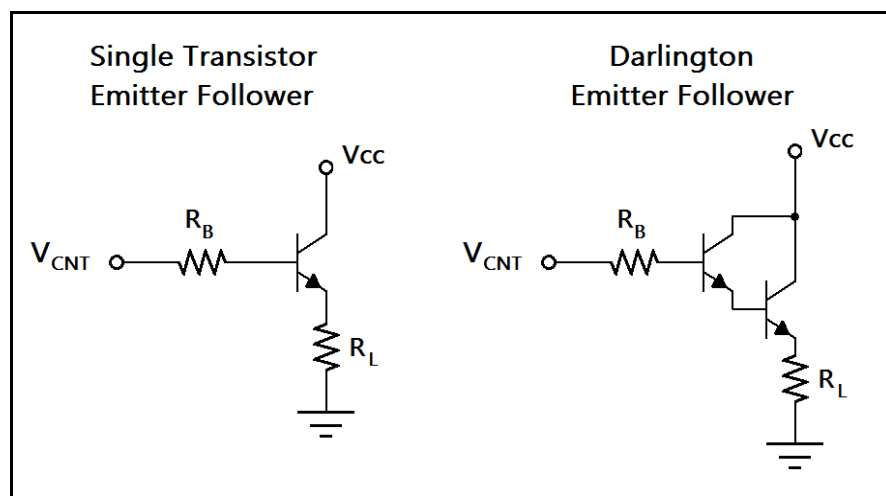
$$T_{total} = t_1 + t_2 = \ln(2)R_2C_1 + \ln(2)R_3C_2$$

and the frequency of oscillation is given by,

$$f_{osc} = \frac{1}{T_{total}} = \frac{1}{\ln(2)(R_2C_1 + R_3C_2)} \approx \frac{1}{0.693(R_2C_1 + R_3C_2)}$$

### The emitter-follower

Let's suppose you have an adjustable 0 V to +12 V regulated power supply that can deliver up to one ampere of current. It is fine for your small projects, but what if you want to test a new 12 VDC motor that draws 3 A? There is a very useful circuit that can boost current and provide a controlled output voltage to a load if given a good reference voltage. This circuit is called the *emitter-follower*, or *voltage follower*, and is useful for buffering high-current loads. **Figure 85** shows a single transistor emitter-follower, and a Darlington version of the same circuit.



**Figure 85: Single transistor and Darlington emitter-follower circuits.**

The output voltage of the circuit presented to the load will be approximately equal to the input control voltage, minus the diode drop. The voltage across the base resistor should be negligible.

The input resistance to the circuit is high, due to transimpedance, or the load 'viewed' through the emitter. Therefore, the control voltage source will not be loaded too greatly.

$$R_{in} = R_B + \beta R_L \approx \beta R_L, \text{ since } R_B \ll \beta R_L$$

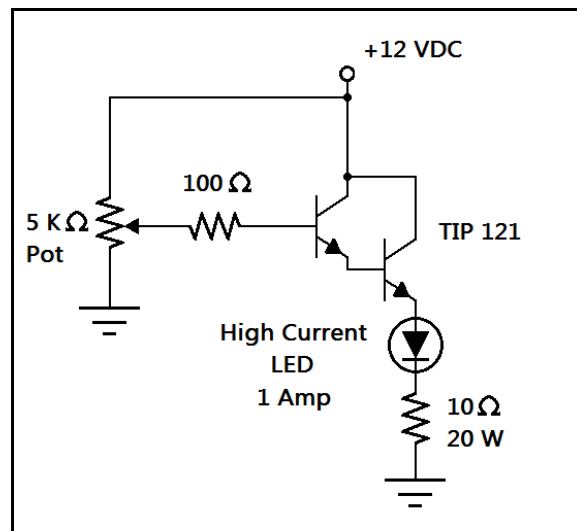
The base current will be approximately the current in the load divided by  $\beta$ .

$$I_B \approx \frac{I_L}{\beta}$$

We may select a maximum for the desired load current and choose  $R_B$  accordingly. The output resistance  $R_{out}$  is the parallel combination,

$$R_{out} = R_E \parallel \frac{R_B}{\beta} \approx \frac{R_B}{\beta}, \text{ since } R_E \gg \frac{R_B}{\beta}.$$

Let's make a high-power LED controller with a TIP 121 Darlington transistor using an emitter-follower. We'll supply up to one ampere of current to the LED by setting a control voltage with a potentiometer. The transistor will get warm, so make sure to use a heatsink (such as a clip-on style heatsink.) The diode's brightness will be fully controllable via the potentiometer. Let's take a look at **Figure 86**.



**Figure 86: High power LED brightness controller using an emitter-follower.**

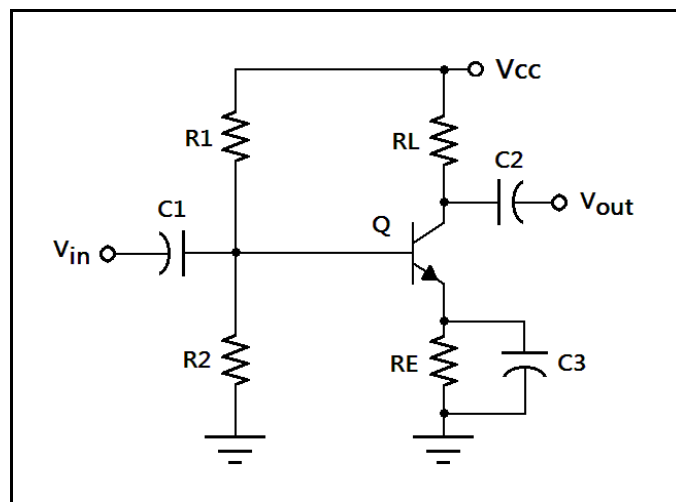


The key points to remember:

- The output voltage will be the input voltage minus the diode drop. This will be  $V_{in} - 0.7\text{ V}$  for a single transistor, and  $V_{in} - 1.4\text{ V}$  for a Darlington pair.
- The collector voltage supply  $V_{CC}$  must be higher than the control voltage.
- Choose a base resistor that will prevent overcurrent in the base of the transistor.
- It is desirable to have some large emitter resistor in parallel with the load in case the load is removed. This will prevent a floating condition on the emitter.  $10\text{ K}\Omega$  to  $100\text{ K}\Omega$  works.
- The voltage presented to the load is invariant to changes in  $V_{CC}$ . The voltage presented to the load is only dependent on the control voltage. The power supply  $V_{CC}$  should be high-current.

### The Common-Emitter Amplifier

All of the circuits we have looked at so far have been geared towards switching, current control, and voltage control. We haven't really looked at anything that amplifies. Now we will explore transistor amplifiers and how to build them. One of the most common single-transistor amplifiers is the *common-emitter amplifier*. Let's take a look at **Figure 87**.



**Figure 87: A common-emitter amplifier with AC coupling capacitors.**

The common-emitter amplifier works by using a stiff voltage divider bias to set the amplifier at the *quiescent point*, or a point where it is turned on halfway. Therefore, small AC signal applied to the base via the coupling capacitor  $C1$  will cause a large change in current in the collector. The coupling capacitors are absolutely necessary, since we don't want to upset the bias voltages.

Let's start designing the circuit. Take note of the emitter resistor  $R_E$ . The emitter resistor is there to prevent a condition called *thermal runaway*. We design the circuit such that 1 V is dropped across  $R_E$  at the quiescent point. We will be referring to **Figure 87** for the design process that follows.

We would like to set the maximum load current. The voltage across the transistor at saturation is ideally 0 V. We first need to find the load resistor  $R_L$  for current  $I_{C-sat}$ . Assume  $V_{R_E} = 1\text{ V}$  and  $V_{BE} = 0.7\text{ V}$ .

$$V_{R_L} = V_{CC} - V_{R_E}, \quad R_L = \frac{V_{CC} - V_{R_E}}{I_{C-sat}}$$

We select a quiescent point where the current is half the maximum.

$$I_{C(Q)} = \frac{V_{CC} - V_{R_E}}{2R_L}$$

This will give us the quiescent base current  $I_{B(Q)}$  if we assume a gain of 100.

$$I_{B(Q)} = \frac{I_{C(Q)}}{\beta}$$

Now we note that the emitter current is the sum of  $I_{B(Q)}$  and  $I_{C(Q)}$  and calculate resistor  $R_E$ .

$$R_E = \frac{V_{R_E}}{I_{E(Q)}} = \frac{V_{R_E}}{I_{B(Q)} + I_{C(Q)}}$$

Now that we have that part, we turn our attention to the voltage divider bias circuit. We want the bias voltage across  $R_2$  to equal  $V_{R_E} + V_{BE}$ , and the divider current to be  $10 I_{B(Q)}$ .

$$R_2 = \frac{V_{R_E} + V_{BE}}{10 I_{B(Q)}}$$

And finally, the value of  $R_1$  can be found by noting it has a current of  $11 I_{B(Q)}$ . (Why?)

$$R_1 = \frac{V_{CC} - (V_{R_E} + V_{BE})}{11 I_{B(Q)}}$$

The AC coupling capacitors  $C_1$  and  $C_2$  are usually  $1\text{ }\mu\text{F}$  to  $10\text{ }\mu\text{F}$  (polypropylene capacitors are good) and  $C_3$  is chosen such that the reactance  $X_{C3} = R_E / 10$  at lowest operating signal frequency.

### The Push-Pull Amplifier

We will briefly mention the *push-pull* amplifier. We may stack an NPN and PNP transistor together such that we may achieve an output that can swing positive or negative. This is sometimes called a *totem-pole* configuration. These amplifiers are often used as output driver stages for audio.

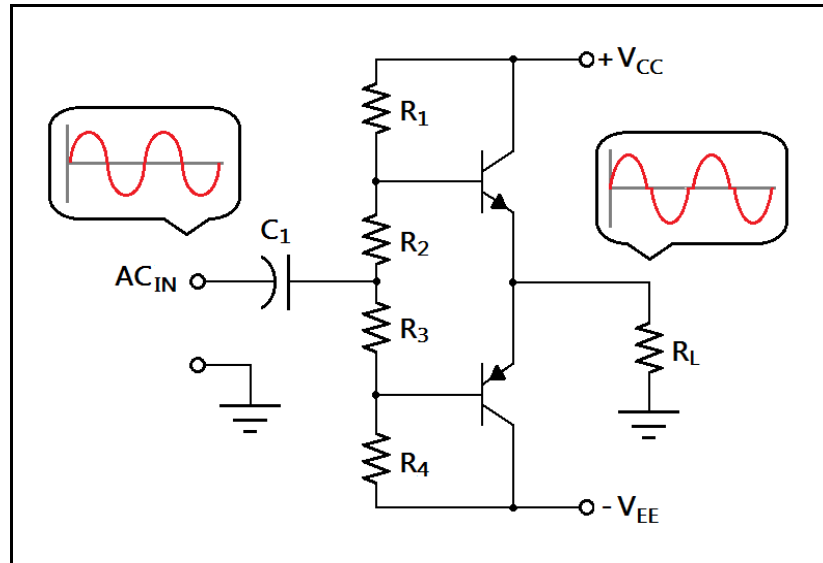


Figure 88: A push-pull amplifier with crossover distortion.

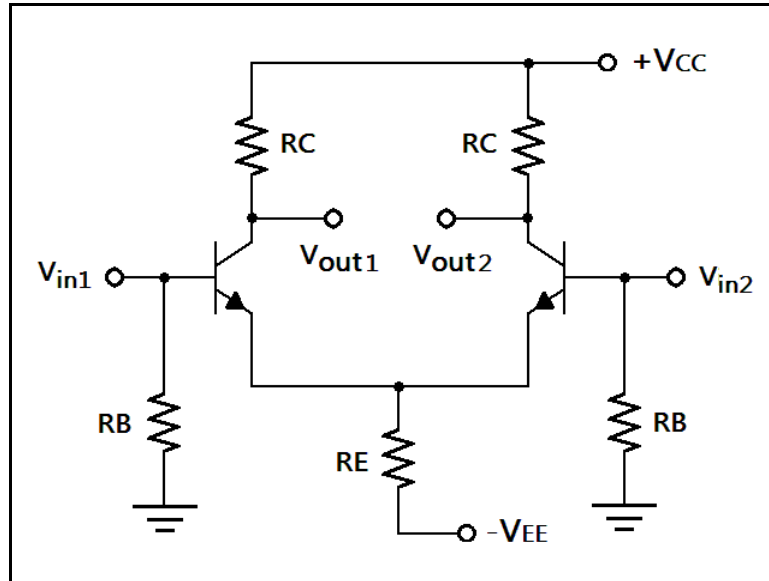
A naïve approach to push-pull amplifier design will result in **Figure 88**, above. Resistors  $R_2$  and  $R_3$  set the bias points for the NPN and PNP transistors, with the NPN transistor handling the positive half-cycles and the PNP transistor handling the negative half cycles. The circuit has a problem due to the combined diode drops of the emitters, yielding a distortion in the output signal called *crossover distortion*. A solution might be to replace  $R_2$  and  $R_3$  with forward biased diodes, but a word of warning:

## Warning

Regardless of the biasing scheme, a push-pull amplifier can run away and destroy itself. There are better designs than **Figure 88**.

### The Differential Amplifier

A *differential amplifier* is an amplifier that can give an output voltage that is the difference of two input voltages times the *voltage gain*. We will only be touching upon them briefly as we move on to operational amplifiers, or op amps, as they are essentially an improved version of this circuit. Let's take a look at **Figure 89**.



**Figure 89: A differential amplifier using two transistors.**

In this circuit, we have two transistors being fed current through the emitter resistor RE in the diagram. At the quiescent point, both transistors are turned on equally and share the current through RE. The difference between the two terminals marked  $V_{out}$  is zero. If  $V_{in1} \neq V_{in2}$ , then one transistor conducts more than the other one, and the difference of the input voltages (times the gain) appears between the output terminals. Therefore, we can directly apply a differential AC signal between  $V_{in1}$  and  $V_{in2}$ . The transistors are biased via negative feedback provided by RE. AC coupling capacitors are not required due to this self-biasing, so an AC signal may be directly applied to the inputs.

To test the quiescent properties of the circuit, a *galvanic* (DC) path is needed from the base to ground for both transistors, which in the diagram is provided by RB. If you would like to build and test a differential amplifier, let  $RE = RC = RB = 10\text{ K}\Omega$ , and use 2N3904 NPN transistors. The Bakerboard Analog Trainer conveniently features positive and negative 12 VDC power supplies for testing such circuits.

## Chapter 5.3: Operational Amplifiers

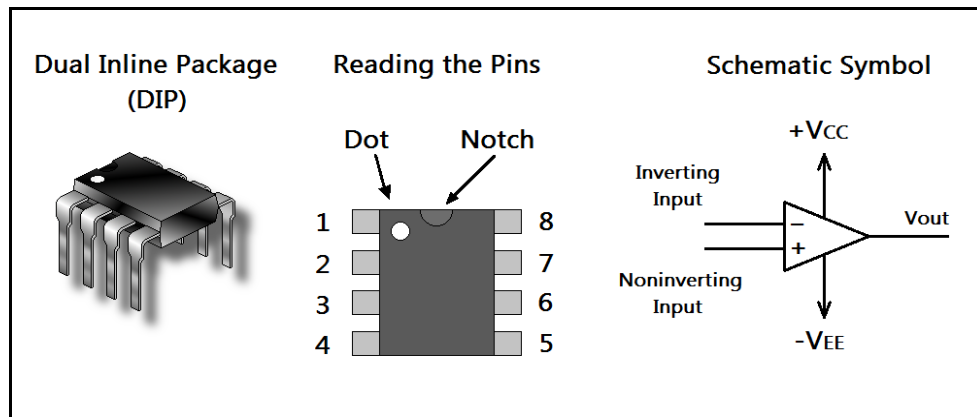
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### Op Amps at a Glance

Building transistor amplifiers from scratch is fine for experiments, but for practical small signal applications there are simpler solutions. We can use a device called an operational amplifier to speed up the design process. They are ideal for small signal amplifier circuits because they have some surprising properties. Op amps can have an *open loop voltage gain* of one million or more! They have very high input impedance, so they can be used with sensors that output very tiny voltages without loading them down, such as a *piezo transducer*. Also, op amps have a low output impedance, meaning they can drive low-impedance loads such as a 0.1 W, 8  $\Omega$  loudspeaker. The gain can be controlled very easily with two resistors, and they can be configured to perform just about any small-signal processing task you might imagine, from oscillators to active filters. Op amps have a range of frequencies where they are effective amplifiers, but have only *unity gain* at a special frequency called the *gain bandwidth product*. Use op amps well below this frequency for best results.

An operational amplifier is a differential amplifier much like the one we covered in the previous section. However, they perform much better than the two transistor version. Like the transistor differential amplifier, op amps have two differential inputs, called the inverting input and non-inverting input. They are intended to be powered by a positive and negative voltage supply, though they can be configured for single-ended designs. Some op amps have a trim control for fine-tuning the bias on the output. Operational amplifiers are used to perform mathematical operations on an input voltage. They can output the sum or difference of input voltages, multiply and divide, compare voltages, act as a trigger, and even perform calculus operations such as differentiation and integration.

Op amps are integrated circuits. An integrated circuit is any miniaturized, functional drop-in circuit element that is available in a package called a *dual inline package*, or *DIP*. A DIP package is perfect for *through-hole* construction, as these are easily soldered by hand. **Figure 90** shows an op amp DIP package and schematic symbol. DIPs have a small notch or white dot to show where to begin counting pins. Pin 1 will always be to the immediate left of either of these markers. The pins count upward in a counter-clockwise fashion from the first pin. Op amps, like all integrated circuits, have different pinouts for their internal connections. Consult the datasheet for the op amp you are using to see how the pins are connected.



**Figure 90: An op amp in a DIP package, with schematic symbol shown.**

### Common Op Amps to Remember

There are a few op amps you should memorize so you can design your own circuits. They typically have prefixes like LM, CA, or TL, depending on the manufacturer. LM stands for “linear module.” You will see this prefix on many op amp ICs. The LM741 op amp is an old standard, but has been replaced by more recent, better performing op amps. One benefit is that the output of the LM741 is short circuit protected. It has a gain bandwidth product of 1 MHz. The CA3140 is a newer op amp with a gain bandwidth product of 4.5 MHz. This makes it better suited for high frequency operation. The LM386 is an audio amplifier especially suited to battery powered devices. It can drive low impedance loads such as a speaker to deliver from 250 mW to 1 W of power. There are also pin-compatible equivalent devices to the LM741 like the TL081, the TL061, and the TL071.

### The Non-Inverting Amplifier

We can create an amplifier where the output signal that is non-inverted. The common-emitter amplifier discussed before inverts the input signal, such that the input signal and output signal are 180 degrees out of phase. In some cases, this is undesirable. **Figure 91** shows a non-inverting amplifier. The gain is set by the feedback resistor  $R_f$  and the ground resistor  $R_g$ .

The voltage gain of a non-inverting amplifier is given by,

$$A_{Vout} = 1 + \frac{R_f}{R_g}$$

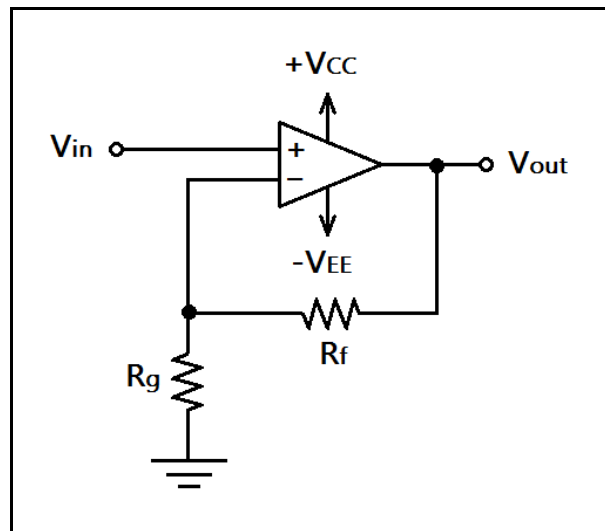


Figure 91: A non-inverting amplifier using an op amp.

### The Voltage Follower

There is a special case of the above amplifier where the output voltage is equal to the input voltage. That is, it is said to have unity gain, or a gain of one. It is a very simple circuit. Though this amplifier may seem useless at first, consider that the op amp has high input impedance, and low output impedance. **Figure 92** shows the basic circuit and an example application.

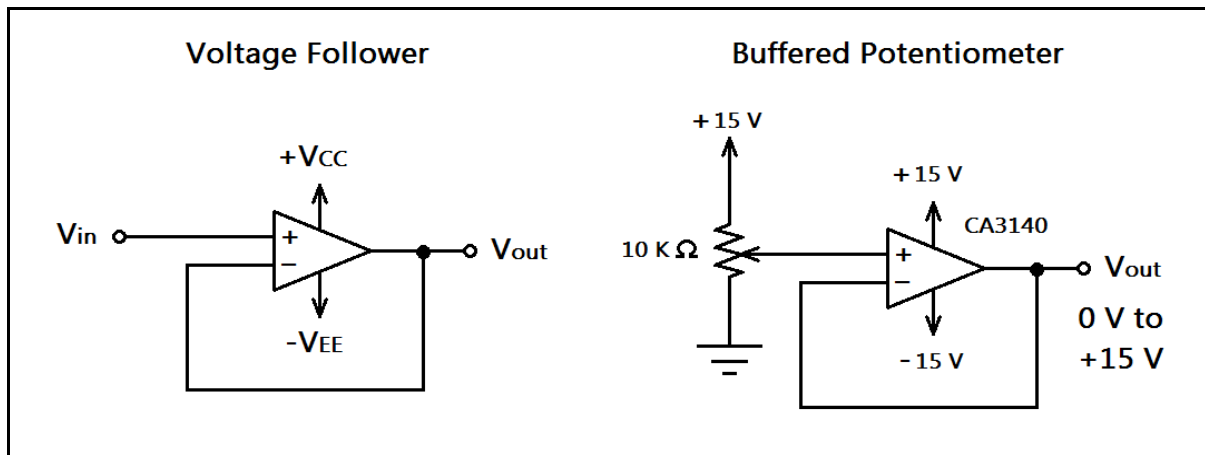


Figure 92: Voltage follower circuit and a buffered potentiometer application.

The application circuit is useful because the potentiometer is not loaded. Since most potentiometers aren't necessarily rated for delivering a lot of power to a circuit, using a buffer such as the one shown is often desirable. The application shown above could be used as a brightness or level control.

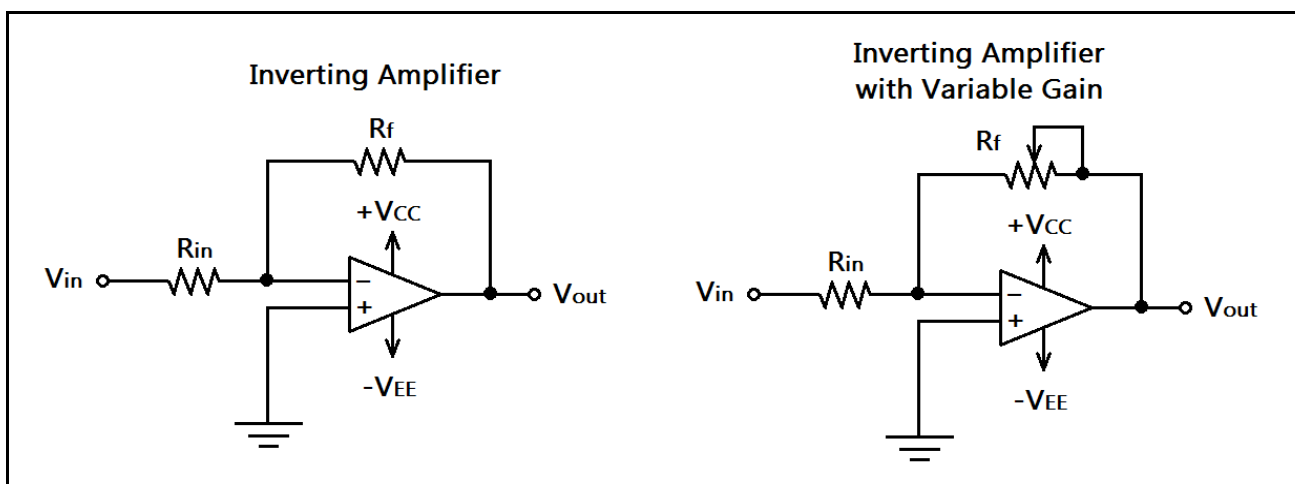
### The Inverting Amplifier

If we are unconcerned with the output signal voltage being 180 degrees out of phase with the input signal voltage, we may use an inverting amplifier. It is stable due to the negative feedback. The voltage gain of the inverting amplifier is determined by the ratio of the feedback resistor  $R_f$  to the input resistor  $R_{in}$ . **Figure 93** shows an inverting amplifier circuit.

The voltage gain of an inverting amplifier is given by,

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

The inverting amplifier can have a variable gain which can be set by a potentiometer when used as the feedback resistor. By varying the potentiometer, you can dynamically control the gain and therefore scale the input signal to the desired level. This would make a good volume control for an audio preamp or a guitar “stomp-box.” If the potentiometer is noisy, this can be cured by connecting small capacitors across the terminals of the potentiometer, such as 0.01  $\mu\text{F}$  ceramic disc capacitors. These capacitors may affect the frequency response of your amplifier. If the feedback resistor is less than the input resistor, the op amp will actively attenuate the input signal. This holds since the voltage gain equation holds for *any* resistor values, including when  $R_f < R_{in}$ .

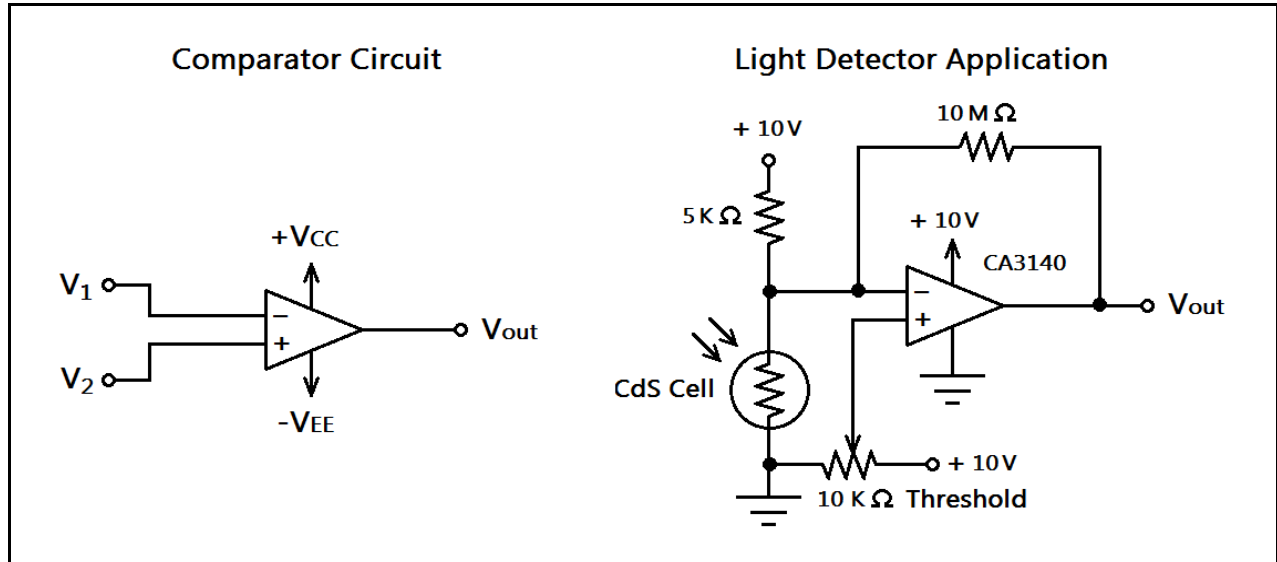


**Figure 93: An inverting amplifier with a variable gain amplifier application.**



### The Comparator and Level Detection

We may use the incredibly high voltage gain of an op amp to give us a voltage comparator function. This can be used to set trigger levels for alarms and sensors, as well as converting a sine wave to a square wave, and other functions. We can use a light level sensor as an example. **Figure 94** shows a basic comparator and a light detector application.

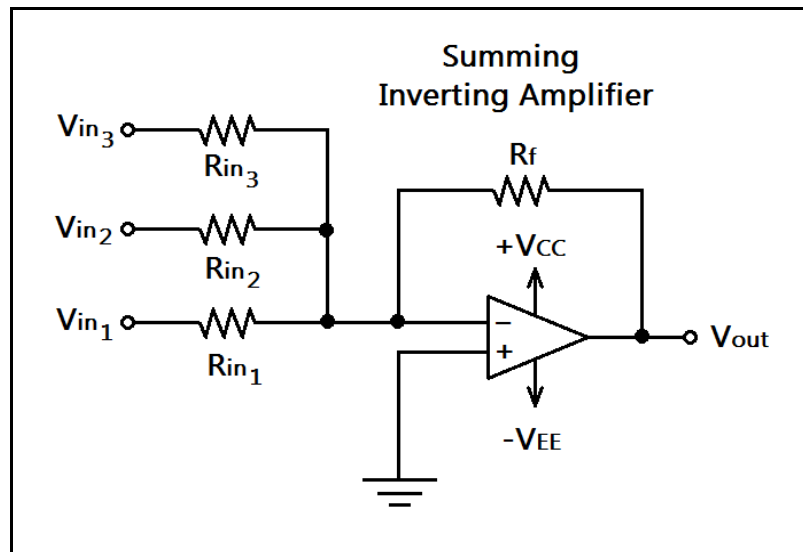


**Figure 94: A comparator circuit and a light detection circuit.**

The circuit works by using the op amp's high gain, which is in the millions. In the application, we show a 10 MΩ resistor providing negative feedback, which prevents oscillations. Comparators are very prone to oscillation, so consider this when you design with them. When the voltage at input  $V_2$  is greater than the voltage at  $V_1$ , the amplifier tries to amplify the difference as much as possible, meaning the output voltage  $V_{out}$  will have two states, either  $V_{EE}$  or  $V_{CC}$ . We refer to this as “rail to rail” operation. This on / off switching action can be used to activate a circuit should a sense voltage cross some threshold. The light sensor in the example is a CdS cell that has a dark resistance of 10 KΩ, which decreases with increasing incident light. This could be used as a burglar alarm or nightlight.

### The Inverting Summing Amplifier (Signal Mixer)

We can mix signals easily with an op amp. In fact, creating an inverting summing amplifier is nothing more than adding more input resistors to an inverting amplifier. This type of amplifier could be used in guitar circuits to mix special effects, or for modulation.



**Figure 95:** A summing inverting amplifier that can mix signals.

In **Figure 95** we have an inverting summing amplifier. The feedback resistor  $R_F$  sets the gain of each input channel via their respective input resistors. The equation for the output voltage is surprisingly simple if we have equal values for the input resistors. There are three inputs shown in the figure, but this can be scaled to accommodate any reasonable number of inputs.

The output voltage of an inverting amplifier with N inputs is given by,

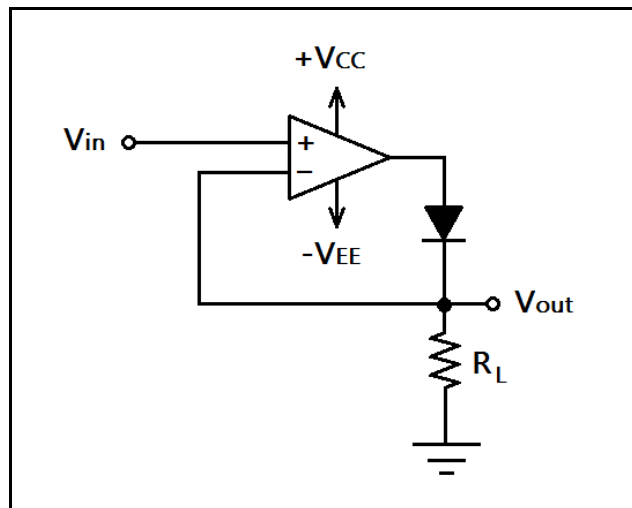
$$V_{out} = -\left( V_{in1} \frac{R_f}{R_{in1}} + V_{in2} \frac{R_f}{R_{in2}} + \dots + V_{in\ N-1} \frac{R_f}{R_{in\ N-1}} + V_{in\ N} \frac{R_f}{R_{inN}} \right)$$

The equation simplifies if we have equal value input resistors.

$$V_{out} = -\frac{R_f}{R_{in}} (V_{in1} + V_{in2} + \dots + V_{in\ N-1} + V_{in\ N})$$

### **The Super Diode**

Recall from our discussion of diodes that they will drop a non-negligible forward voltage. For silicon diodes, this is usually about +0.7 V. It turns out that if the forward voltage is less than this value, the diode will not conduct ideally. This makes using a diode to rectify a tiny signal problematic.

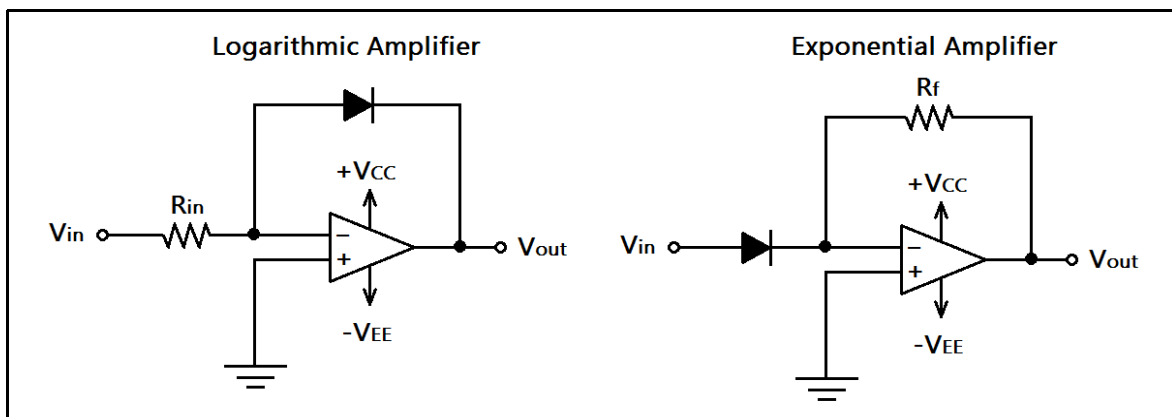


**Figure 96: The ideal diode, or “super diode.”**

In **Figure 96**, we have an op amp with negative feedback. This negative feedback will force the output to try to make the input voltages equal. When the input voltage is negative, the diode is reverse-biased and no current flows in the load. When the output voltage is positive, the op amp overcomes the drop across the diode by driving its output slightly higher.

### **Logarithmic and Exponential Amplifiers**

Consider the gain of the inverting amplifier. We may calculate the output voltage as the product of the input voltage and the ratio of the feedback resistor to the input resistor. This gives the inverting amplifier a *linear* relationship. However, not all sensors will yield a perfectly linear output. If we need to linearize a sensor's output, we may use a logarithmic amplifier or an exponential amplifier.



**Figure 97: A logarithmic amplifier and an exponential amplifier.**

In **Figure 97**, we have two amplifiers that take advantage of the diode's peculiar characteristics. In diodes, when the applied forward voltage is less than +0.7 V, very little current flows. As the applied forward voltage begins nearing +0.7 V, the current increases in an exponential fashion. This is dependent on the “thermal voltage” of the diode  $V_T$ , which is about 25 mV at room temperature, and the reverse-bias saturation current  $I_S$ . Check the diode's datasheet, as these values will be listed.

The output voltage of a logarithmic amplifier is given by,

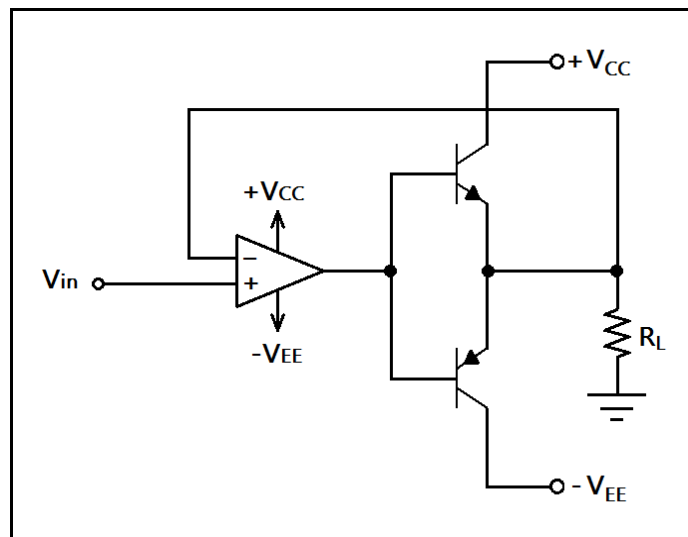
$$V_{\text{out}} = -V_T \ln \left( \frac{V_{\text{in}}}{I_S R_{\text{in}}} \right)$$

The output voltage of an exponential amplifier is given by,

$$V_{\text{out}} = -I_S R e^{\frac{V_{\text{in}}}{V_T}}$$

### An Improved Push-Pull Amplifier

Recall that the transistor push-pull amplifier in **Figure 88** had as serious flaw. It is unsafe due to the possibility of thermal runaway in the transistors. The biasing issue can be solved, producing a safe amplifier with no crossover distortion. To do this, we use an op amp. Let's look at **Figure 98**.

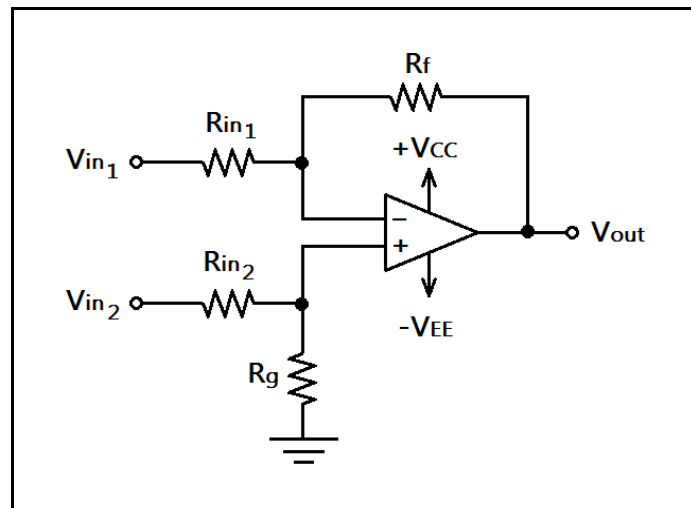


**Figure 98: A greatly improved push-pull amplifier.**

The circuit works because the operational amplifier uses the two transistors as voltage followers. When the input is positive, the PNP transistor is in cutoff, and the NPN transistor begins to conduct,. When the input swings negative, the NPN transistor is in cutoff, and the PNP transistor conducts. Therefore, the output can swing negative or positive. The output is used for feedback to the inverting input. Because of this, the op amp will force its output to overcome the diode drops of the two transistors, creating distortionless output. If greater power is required, such as an audio amplifier or a DC motor driver, Darlington pairs may be substituted.

### The Differential Amplifier

We may wish to amplify the difference between two signals. However, we do not want to amplify a signal that appears on both, such as electrical noise. This might happen if we have long transmission lines running across the lab. So we need a circuit that has a high *common mode rejection ratio*, or *CMRR*. We can use a differential amplifier configuration to solve the problem. **Figure 99** shows a differential amplifier. We want to choose the resistors such that  $R_F / R_{in1} = R_g / R_{in2}$ .



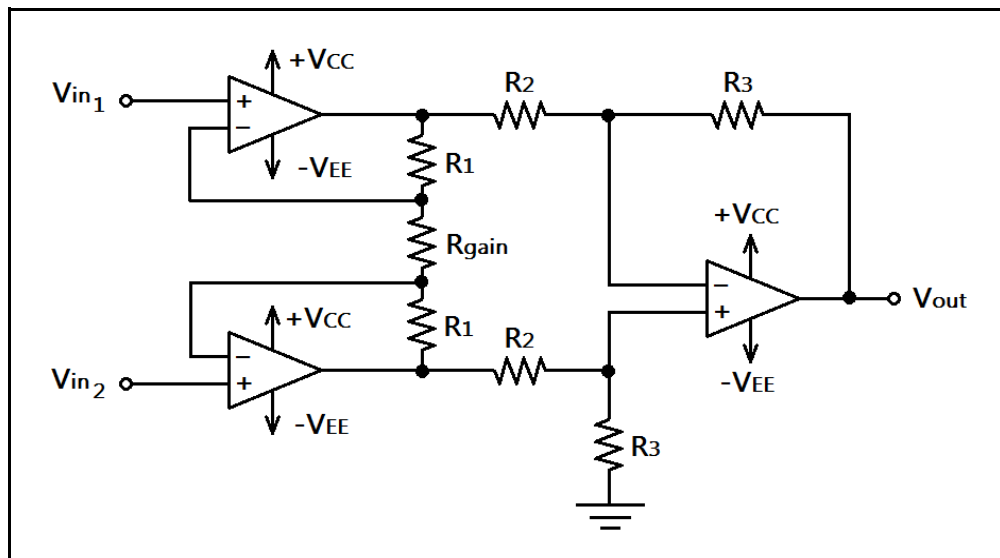
**Figure 99. A differential amplifier.**

The output voltage of a differential amplifier with  $R_F / R_{in1} = R_g / R_{in2}$  is given by,

$$V_{out} = \frac{R_F}{R_{in1}} (V_2 - V_1)$$

### The Instrumentation Amplifier

Up until now, we have been focusing on single op amp solutions. However, we will mention a useful amplifier that uses three op amps. A differential amplifier can be improved by buffering the inputs with the addition of two op amps, creating an instrumentation amplifier. Then very small sensor signals can be used as inputs without loading them, and the high CMRR will ensure low noise. This circuit is perfect for measuring very small signals in the lab setting. Let's look at **Figure 100**.



**Figure 100: An instrumentation amplifier.**

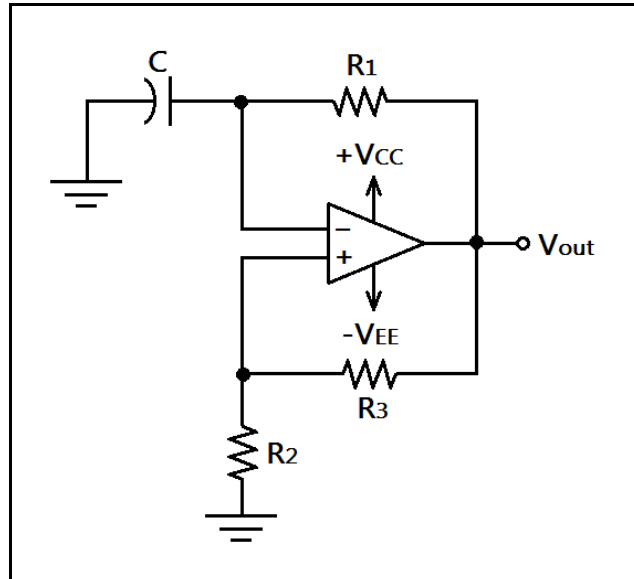
We may easily control the gain of the above circuit by replacing the resistor  $R_{gain}$  with a potentiometer or a set of resistors switched by a single-pole rotary switch. This does away with the need for matched, ganged resistors or potentiometers. Any signal presented which is common to both inputs will be rejected by the amplifier, provided that the equal valued resistors are closely matched. Use 1% tolerance resistors in these amplifiers. The gain equation is rather complex.

The output voltage for the circuit shown in **Figure 100** is given by,

$$V_{out} = \left( 1 + \frac{2R_1}{R_{gain}} \right) \frac{R_3}{R_2} (V_{in2} - V_{in1})$$

### The Op Amp Oscillator

An op amp can be configured as an oscillator, yielding an op-amp based function generator. The frequency of oscillation is easy to control with a simple RC circuit. This type of oscillator is called a *relaxation oscillator*, and the output is a square wave from  $V_{CC}$  to  $V_{EE}$ . **Figure 101** shows an op amp relaxation oscillator.



**Figure 101: Op amp square wave oscillator.**

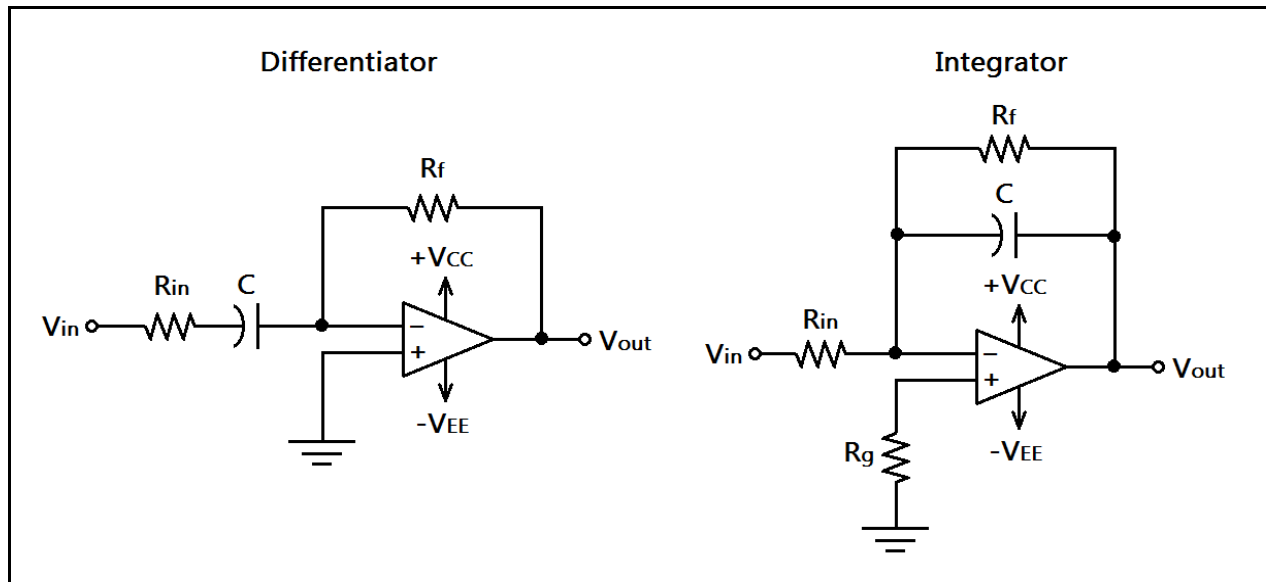
Observe  $R_2$  and  $R_3$  in the circuit shown above. This forms a voltage divider, which sets a reference voltage across  $R_2$ . Let's start the op amp with a positive output at  $V_{CC}$ . The capacitor charges through  $R_1$  until it becomes greater than the voltage across  $R_2$ . At that point the op amp outputs a negative voltage near  $V_{EE}$ . The capacitor then begins to discharge through  $R_1$  until it's voltage is more negative than the voltage across  $R_2$ , and the process repeats. The frequency is dependent on the RC time constant formed by  $R_1C$ , and the voltage divider formed by  $R_2$  and  $R_3$ .

The frequency of the op amp circuit in **Figure 101** is given by,

$$\alpha = \frac{R_2}{R_2 + R_3}, \quad f_{osc} = \frac{1}{2 R_1 C \ln \left( \frac{1 + \alpha}{1 - \alpha} \right)}$$

**Op Amp Integrator and Differentiator**

Though we have not been using calculus in this text, two circuits will be presented that will perform calculus operations on an input signal, namely differentiation and integration. Let's look at two circuits that can perform calculus operations on an input signal in **Figure 102**.



**Figure 102: Op amp differentiator and integrator circuits.**

The differentiator reports the rate of change of the input signal. This also corresponds to the slope of the signal function.  $R_{in}$  is introduced to stabilize the gain at high frequencies.  $R_{in}$  and capacitor  $C$  determine the *corner frequency* (where the differentiator starts losing gain.) The corner frequency should be at least 10 times higher than the maximum expected input frequency.

The output voltage of the differentiator in **Figure 102** is given by,

$$V_{out}(t) = -R_f C \frac{d}{dt} V_{in}(t)$$

The corner frequency is given by,

$$f_c = \frac{1}{2\pi R_{in} C}$$



The integrator can be used to find the “area under the curve” of the input signal. It is somewhat more complicated than the differentiator, since the capacitor must be provided with a discharge resistor to prevent an unwanted DC offset.  $R_g$  has a value equal to  $R_{in}$ . In order for good performance, the input signal should be at least 10 times higher than the corner frequency.

The output voltage of the integrator in **Figure 102** is given by,

$$V_{out}(t_1) = V_{out}(t_0) - \frac{1}{R_{in}C} \int_{t_0}^{t_1} V_{in}(t) dt$$

The corner frequency is given by,

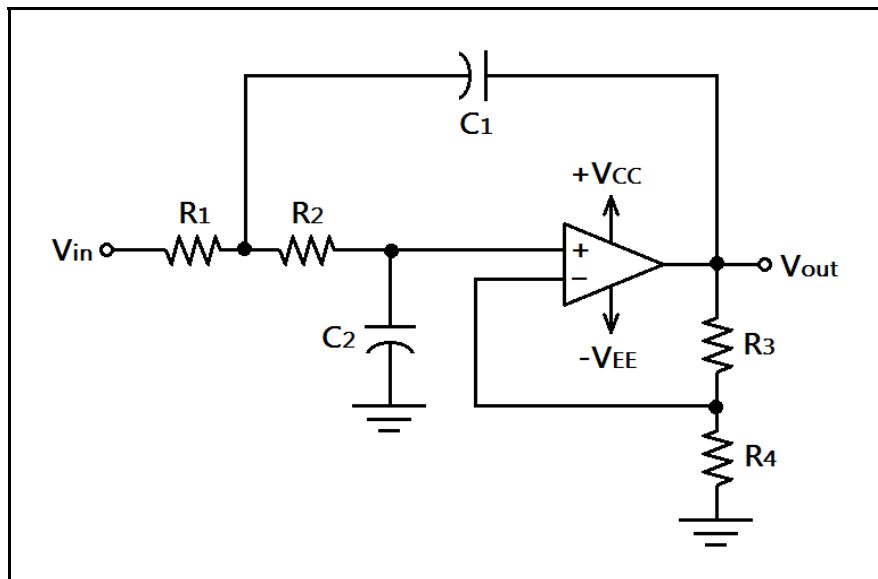
$$f_c = \frac{1}{2\pi R_f C}$$

Observe that the corner frequency equation, for both the differentiator and integrator, are of the same form as the equations for low pass and high pass filter cutoff frequency. In fact, the differentiator and integrator are active filters! The differentiator is a high pass active filter, and the integrator is a low pass active filter. But they are only first order filters. We can do better.

### **Active Filters: Sallen-Key Low and High Pass Filters**

Active filter theory is a huge area of study. We won't go into detailed analysis, but we will present two simple second order filters that will make active filter design easy. Active filters can give increased performance over passive filters because they can be made with steeper roll-off. They also have the added bonus of providing gain – something that passive filters cannot do. Active filters can be cascaded together to yield steeper roll-off, and even to create narrow bandpass filters – an improvement over RC bandpass filters.

Though there are literally hundreds of filter design possibilities, we will focus on a simple second order filter configuration that is easy to remember, has an easy cutoff frequency equation, and also a simple Bode plot. We will obtain a frequency response similar to the RC filters we discussed in the previous chapter, but with twice the steepness of the roll-off. These simplified filters are called Sallen-Key filters, and can be made with only four resistors, two capacitors, and one op amp. Therefore, they are not only easy to remember and apply, but are inexpensive to build as well.



**Figure 103: A Sallen-Key low pass filter.**

We will start with a low pass, second order Sallen-Key filter, as shown in **Figure 103**. We will make things easy on ourselves and choose  $R_1$  and  $R_2$  to have equal resistance values, and  $C_1$  and  $C_2$  to have equal capacitance values. The resistors  $R_3$  and  $R_4$  set the gain. Let's look at the equations for gain and cutoff frequency, which work for both low pass and high pass Sallen-Key filters.

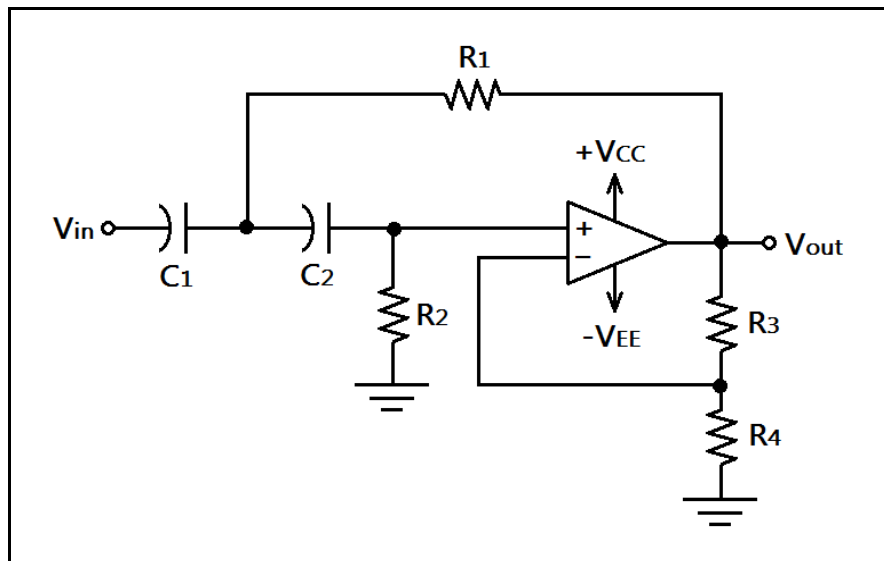
The cutoff frequency of a Sallen-Key active filter, with  $R_1 = R_2$  and  $C_1 = C_2$  is given by,

$$f_c = \frac{1}{2\pi R_1 C_1}$$

And the gain is given by,

$$A_v = 1 + \frac{R_3}{R_4}$$

The Bode plot for this filter looks much like that of a passive RC filter, but the roll-off is steeper. To obtain a high pass filter, all we must do is transpose  $R_1$  and  $R_2$  with  $C_1$  and  $C_2$ !  $R_3$  and  $R_4$  play the same role at setting gain. As stated before, we may use the above equation for cutoff frequency and gain for the high pass filter as well! Observe the high pass Sallen-Key filter in **Figure 104**.



**Figure 104: A Sallen-Key high pass filter.**

If we wish to cascade two of these filters for an even steeper cutoff, we should use two filters with the same cutoff frequency. This will make a fourth order filter. Or, we may choose a high pass filter and a low pass filter to create a bandpass filter that is far better than the passive RC bandpass filter. The design process for bandpass filters is the same, choosing the high pass filter's cutoff frequency to be lower than the low pass filter's cutoff frequency.

## Chapter 5.4: Vocabulary Review

<p>amplify: to increase the amplitude of a voltage or current</p> <p>base: the terminal on a transistor used for control current</p> <p>beta gain: the current gain factor for a transistor amplifier</p> <p>bias: a voltage on the base of a transistor to set the quiescent point</p> <p>bipolar junction transistor: an NPN or PNP transistor</p> <p>BJT: bipolar junction transistor</p> <p>CMRR: common mode rejection ratio</p> <p>collector: the "output" terminal of a BJT</p> <p>common emitter amplifier: an amplifier with a voltage divider bias</p> <p>common mode rejection: ability of an op amp to reject noise</p> <p>common mode: driving two differential lines with same phase noise</p> <p>corner frequency: cutoff frequency for integrator, or differentiator</p> <p>crossover distortion: distortion caused by emitter-base diode drop</p> <p>current gain: increase in current amplitude</p> <p>cutoff: point where a transistor is biased such that it will not conduct</p> <p>Darlington: two transistors configured for high gain</p>	<p>datasheet: industrial document showing properties of a device</p> <p>differential amplifier: amplifies the difference between two inputs</p> <p>digital: having two states – logic high and logic low</p> <p>diode drop: about +0.7 V drop from emitter to base of a transistor</p> <p>DIP: dual inline package – a common package for integrated circuits</p> <p>dual inline package: see DIP</p> <p>duty cycle: amount of time a square wave is on compared to period</p> <p>emitter-follower: a voltage follower constructed with a BJT</p> <p>emitter: terminal of a BJT that provides current to base and collector</p> <p>gain bandwidth product: point where op amps have unity gain</p> <p>gain: factor of amplification that is the ratio of output to input</p> <p>galvanic: a physical electrical connection</p> <p>heatsink: attaching a device to a piece of metal for heat removal</p> <p>IC: integrated circuit</p> <p>integrated circuit: a convenient drop-in circuit module</p> <p>logic high: the "on voltage" for digital logic</p>
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logic low: the “off voltage” for digital logic microcontroller: a tiny self-contained programmable computer multivibrator: an oscillator with two stable states NPN: transistor that needs positive voltage on base to conduct op amp: operational amplifier that can perform math operations open loop gain: very high gain of an op amp with no feedback path operational amplifier: see op amp oscillator: circuit that produces a periodic waveform passive: does not amplify, only attenuates piezo transducer: a sensor that measures pressure or vibration pinout: how pins are internally connected on an IC or package PNP: transistor that needs negative voltage on base to conduct push-pull amplifier: amplifier that can swing positive or negative	quiescent point: the balance point of an amplifier with no input relaxation oscillator: oscillator that uses a threshold saturation: point where a transistor is turned on all the way small signal: having to do with small voltages and currents thermal runaway: destructive increase in current due to heating through-hole: construction technique good for hand soldering totem-pole: two transistors stacked in same current path. transistor: three-terminal semiconductor amplifier TTL: two transistor logic, with 0 V and +5 V levels unity gain: a gain of 1 voltage follower: amplifier that reproduces input voltage voltage gain: a gain in voltage amplitude, $A_v$
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## Chapter 5.5: Lab Activity 5 – Oscillators and Amplifiers

### Introduction

We have learned about amplifiers and oscillators in this chapter. Now we will create an oscillator that flashes LEDs, and use an op amp to create an inverting amplifier. Then we will examine the op amp's high open loop gain with a comparator circuit.

### Materials

The materials required for this lab are listed in the table shown below.

Lab Activity 5 – Parts List	
Quantity	Item
2	47 $\mu$ F electrolytic capacitor
3	10 K $\Omega$ ¼ watt resistor (brown, black, orange, and gold striped)
2	560 $\Omega$ ¼ watt resistor (green, blue, brown, and gold striped)
2	2N3904 or 2N2222 transistors
2	LEDs of your favorite colors
1	LM741 or pin-compatible operational amplifier
1	LumiDax ® wiring kit
1	LumiDax ® Bakerboard Analog Trainer
1	Pair of wire cutters

**Procedure**

Make sure power is not applied to the trainer until your circuit is wired and ready to test.

1. We will first build a cute little LED flasher by using the multivibrator circuit shown in **Figure 105**. This circuit will flash two LEDs alternately at a rate of about 1 Hz to 3 Hz. Use the pictorial diagram in **Figure 106** to get an idea of what your breadboarded circuit should look like.

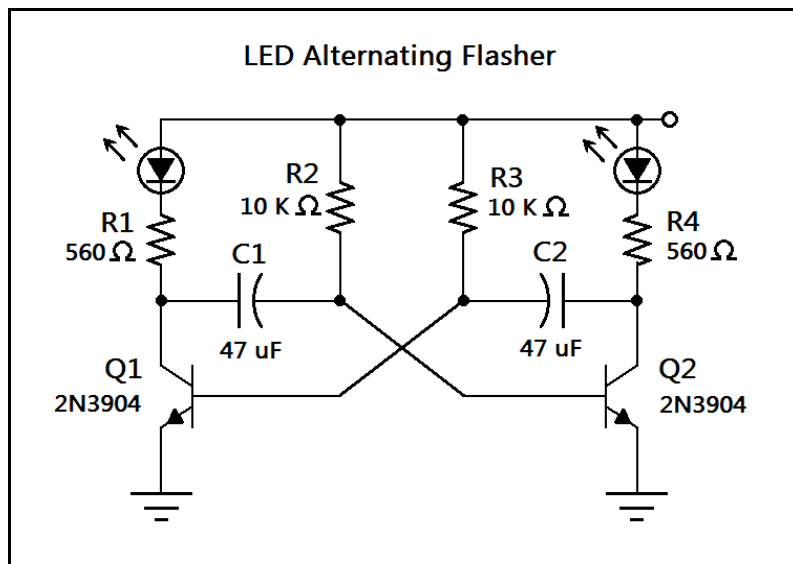


Figure 105: LED flasher circuit.

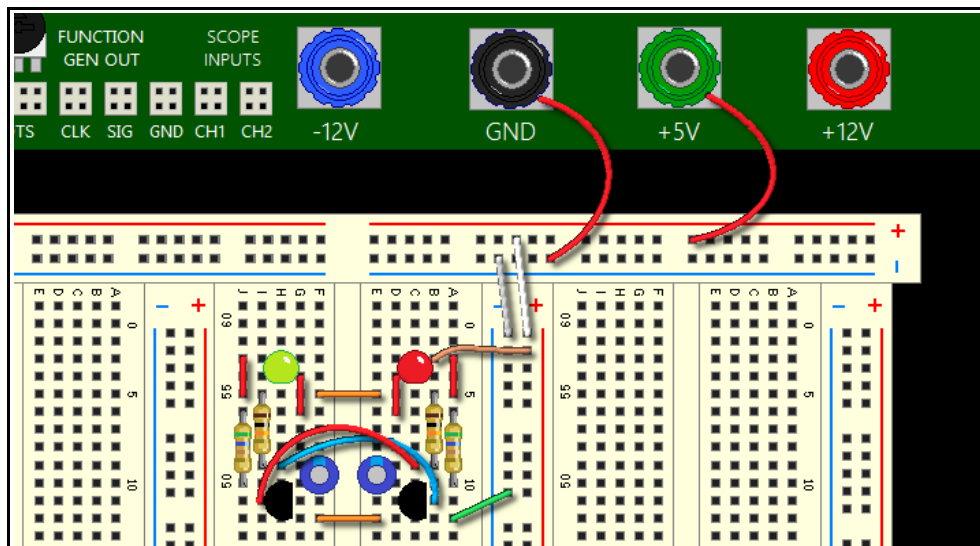


Figure 106: The LED flasher circuit on the breadboard.

2. Apply power to the LED flasher. Are the LEDs blinking alternately? The rate of flashing should be slow enough to see with your eyes. Can you calculate the frequency of oscillation from the values of the resistors and capacitors? Hint: Check the equation on page 118.
3. Remove the power and dismantle the circuit. We will now build our first amplifier, the inverting op amp. We will use the function generator and the oscilloscope to try some experiments. Wire the schematic shown in **Figure 107**. Use the pictorial diagram in **Figure 108** as a guide.

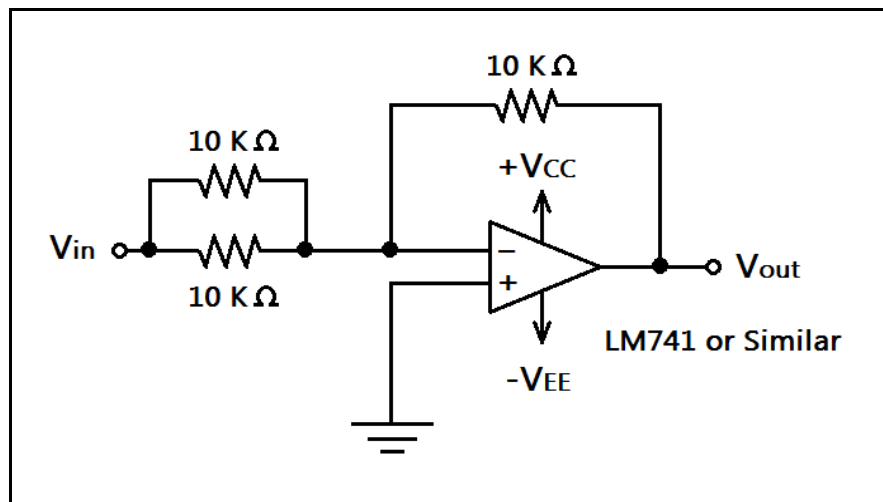


Figure 107: An inverting amplifier with a gain of two.

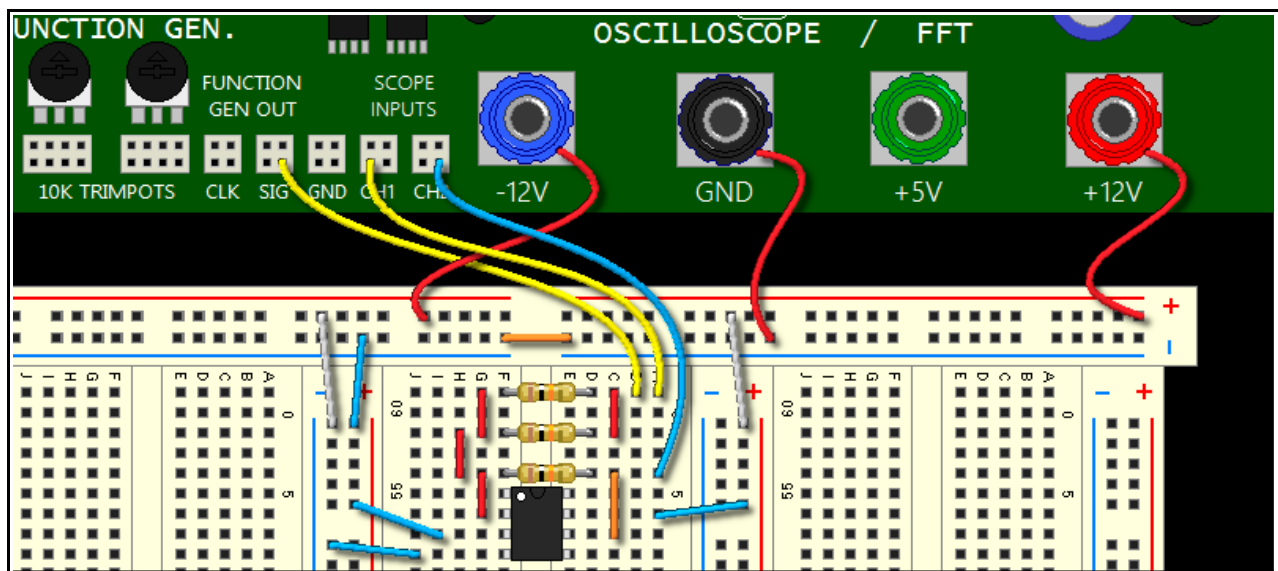


Figure 108: The breadboarded inverting amplifier.

4. Notice the input resistors on the input in parallel. The equivalent resistance for the input is half the resistance of the feedback resistor. What is the gain? Adjust the function generator offset to center the waveform, and select sine wave output. Make the sine wave amplitude  $2 V_p$ . Verify your gain calculation by comparing the output voltage to the input.
5. Now disconnect the feedback resistor (the 10 K $\Omega$  resistor closest to the op amp in **Figure 108**.) What happens to the output waveform? By removing the feedback resistor, the gain of the circuit goes to about one million. This circuit is now nothing more than a comparator with a series input resistor.
6. Select the triangle waveform on the function generator. Use the level control on the function generator to move the triangle wave up and down slightly around the center line. What happens to the output waveform? Can you control the duty cycle this way?

### **Lab Activity 5 – Conclusion**

In this lab, you used two transistors to build an oscillator circuit that flashes two LEDs. You also built your first inverting amplifier using an op amp IC. Then, you used a comparator to convert a triangle wave to a square wave, and adjusted the square wave duty cycle by changing the level of the input. Now, you can try some of the other circuits in this chapter on your own. In the next chapter, we will be giving example circuits for you to try yourself!

## **Chapter 5.6: Exercises**

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### **Vocabulary Questions**

1. The ratio of output voltage to input voltage is called the \_\_\_\_\_ of an amplifier.
2. The BJT, or \_\_\_\_\_, is a transistor that can either be NPN or PNP.
3. An \_\_\_\_\_ is a functional drop-in circuit module available in DIP packages.
4. Current gain is also called \_\_\_\_\_.
5. The \_\_\_\_\_ is a circuit that has a gain of unity.
6. A \_\_\_\_\_ is a circuit that has two output states, usually rail-to-rail operation.
7. An \_\_\_\_\_ is an amplifier that flips the output waveform phase 180 degrees.
8. The \_\_\_\_\_ is a pair of transistors in one package with high gain.

9. The \_\_\_\_\_ of an op amp can be a million or more.
10. The \_\_\_\_\_ is the frequency where an op amp has a gain of unity.
11. A \_\_\_\_\_ is a second order filter that uses four resistors and two capacitors.
12. The \_\_\_\_\_ is a measure of how well an op amp can block signals common to both inputs.
13. A \_\_\_\_\_ is used to set a transistor's quiescent point.

### **True or False**

- |  |   |   |
|--|---|---|
| 1. Transistors have a voltage gain called $\beta$ .                          | T | F |
| 2. Op amps can amplify signals higher than their gain bandwidth product.     | T | F |
| 3. A push-pull amplifier is better and safer if driven with an op amp.       | T | F |
| 4. A transistor can switch loads on their collector or their emitter.        | T | F |
| 5. An integrator circuit is also a first order high pass filter.             | T | F |
| 6. Op amps have incredibly high open loop gain in the millions.              | T | F |
| 7. Op amps have low input impedance and very high output impedance.          | T | F |
| 8. Transistor amplifiers must be biased very carefully to amplify correctly. | T | F |
| 9. Active filters may be cascaded to increase the filter order.              | T | F |
| 10. Unity gain means a gain factor of zero.                                  | T | F |

### **Problems**

1. Design a summing amplifier that has a gain of 10 on each input channel, and has four inputs.
2. Compute the value of a base current that will yield a collector saturation current of 500 mA given a transistor with a gain of 150. What input voltage is needed to achieve this saturation current if given a 1 K $\Omega$  resistor on the base? Do not neglect the diode drop.
3. Design a circuit that uses a Darlington NPN transistor to turn on a 24 VDC lamp with an on-current of one ampere, if given a TTL input. Assume a gain of 1000, and that the load is on the collector side. Do not use a relay. What value of base resistor will work for legal TTL levels?
4. Design a Sallen-Key low pass filter with a cutoff frequency of 10 KHz.



5. Create a relaxation oscillator with a frequency of 1 KHz using an op amp. Choose any resistor or capacitor combination to achieve this.
6. Design a second order bandpass filter with a lower cutoff frequency of 10 KHz and an upper cutoff frequency of 100 KHz.
7. Design a non-inverting amplifier with a gain of 100.
8. A differential amplifier has a gain of 1000 and an output voltage of -10 V. What is the difference of the input signals? What does the negative output voltage mean?

## Chapter 6 – Tips, Tricks, and Applications

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In this chapter, you will...

- ➡ Learn cool electronics tricks.
- ➡ Put what you've learned to use.
- ➡ Discover new and exciting circuits.
- ➡ Find out how to solve common issues.
- ➡ Get a grasp of good design practice.

You have come a long way, indeed. In the last chapter, you learned about amplifiers and transistors. Now that you have some theory and hands-on experience, it is now time to look at some common tips, tricks, and special purpose circuits.

The world of electronics design is now open to you. As you continue to progress, you will come across certain issues that will perplex you. But with a little common sense, and inexpensive components, we'll see how to master any situation that may present you with difficulty.

This section is not only for the hobbyist, but for the science professional as well. Being able to design sensors and amplifiers to take data is critical to success. This means understanding where noise comes from, and how to design amplifiers to minimize noise issues.

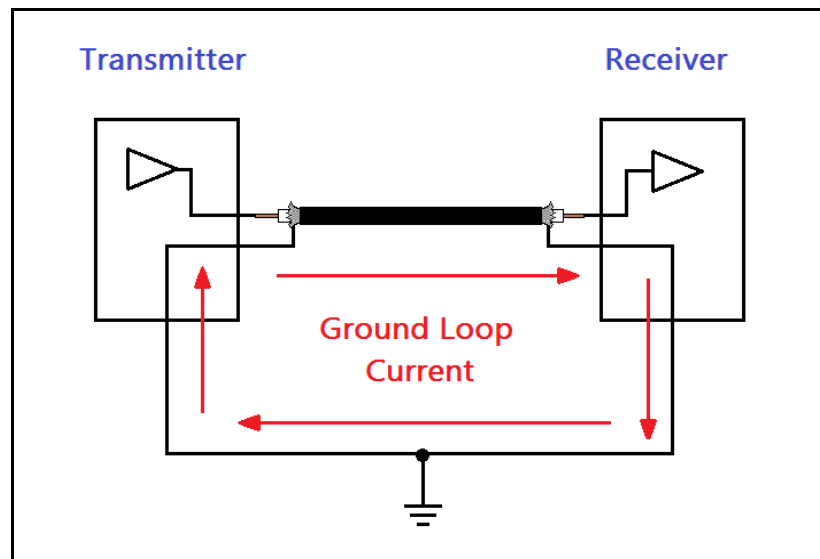
## Chapter 6.1: Quick Remedies to Common Problems

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Electronics is certainly a field where gotchas can occur. An op amp may decide to oscillate on its own. Or, a potentiometer may cause crackling sounds. Grounding issues can cause serious noise problems. Sometimes, there are quick fixes that will lend themselves to circuit design. We'll take a look at a handful of these situations, and learn how to remedy them.

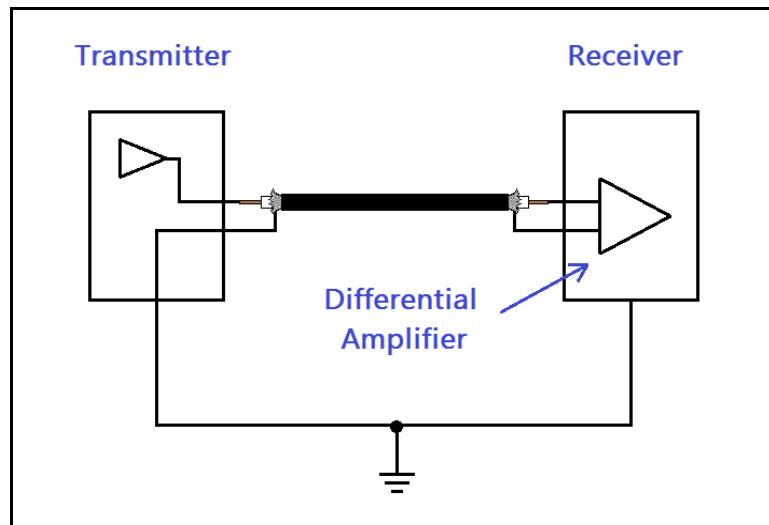
### Grounding Problems and How to Avoid Them

A circuit must have a rock-solid ground. However, as the complexity of a system increases, ground loops may accidentally be introduced. A ground loop occurs when a complete circuit is unintentionally made in a ground system, causing unwanted stray signals to be wicked into amplifiers. This may cause hum and unwanted oscillations in amplifiers. **Figure 109** shows a ground loop.



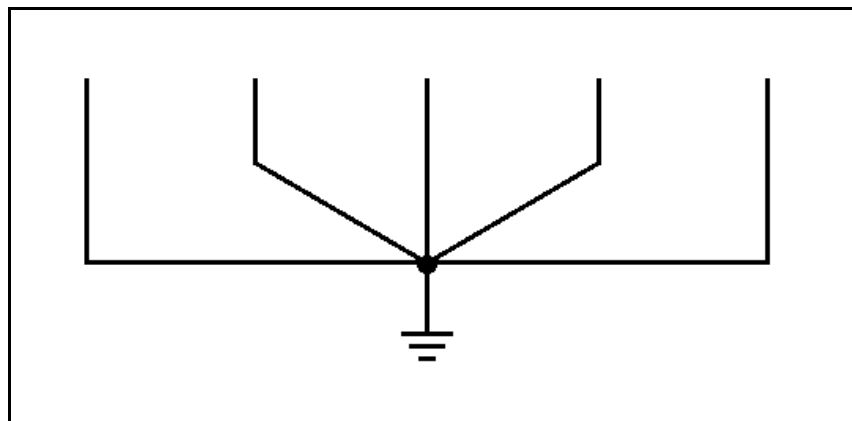
**Figure 109: A ground loop showing current flow.**

AC ground lines can have about 4 mV of hum. Instead of using a single-input amplifier in the receiver shown above, the best solution is to use a differential amplifier on the receiver preamp. This will eliminate the ground loop, which can introduce serious noise problems if the cable is of an appreciable length. **Figure 110** shows a differential line receiver. We generally don't want our signal to be the same level as the *noise floor*. So having a transmitter that is “loud enough” to be at least one order of magnitude higher than the noise floor is desirable.



**Figure 110: Using a differential amplifier to solve ground loop issues.**

Of course, designing our circuits not to have ground loops in the first place is good practice. We want to use what is called a *star ground*. This is a configuration such that each ground going to a part of the circuit originates at the same point. That way, ground loops are prevented in the system. A star ground is shown schematically in **Figure 111**.

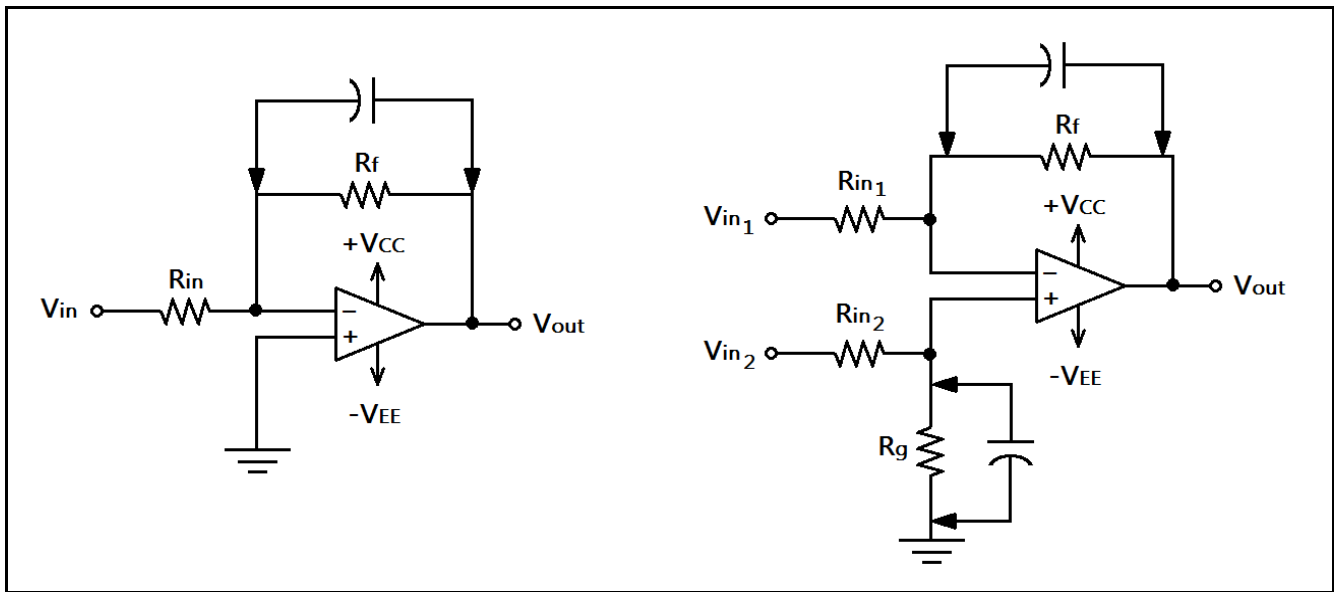


**Figure 111: A star ground shown schematically.**

When grounding, make sure that the connections are not *ohmic*. That is, make sure they have as little resistance as possible. This means cleaning terminals that have oxidation, as this can cause the connection to develop a resistance and float the entire circuit above ground. Also, use common sense for transmission lines. A twisted shielded pair is the best to use for long transmission lines.

### How to Solve Op Amp Oscillation

Op amps are very prone to oscillation due to feedback. This is especially true for high gain configurations. More than likely, you will encounter this problem. There is a very easy fix, fortunately. A capacitor of small value (such as 0.01  $\mu\text{F}$ ) may be placed across the feedback resistor. If you are using a differential amplifier, use the same capacitor value across the ground resistor as well. **Figure 112** shows where to place the capacitor to suppress oscillation.

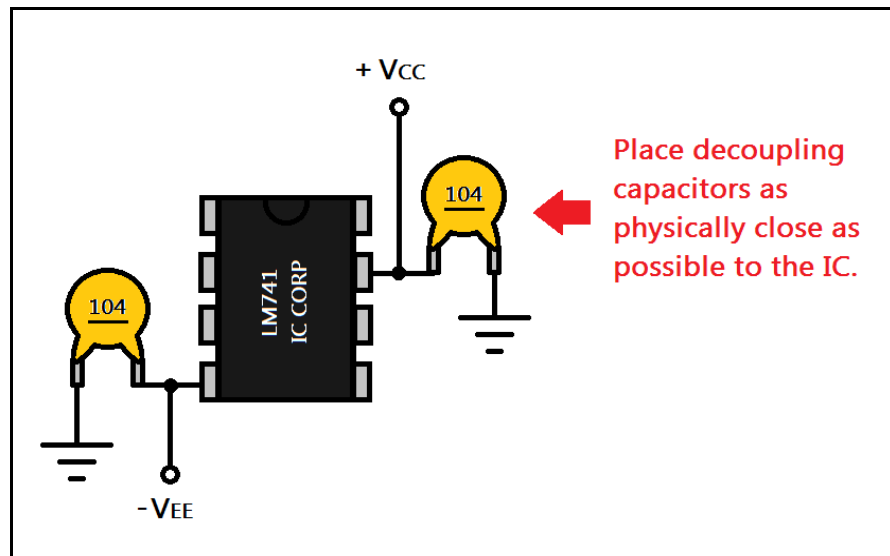


**Figure 112: Using capacitors to stop oscillation in op amp circuits.**

On the left in the figure above, we have an inverting amplifier which is oscillating when it interacts with the rest of the circuit. On the right, we have a differential amplifier that is also having issues. By placing capacitors as shown, it will be possible to stop the unwanted oscillation.

### Use Decoupling Capacitors and Short Leads

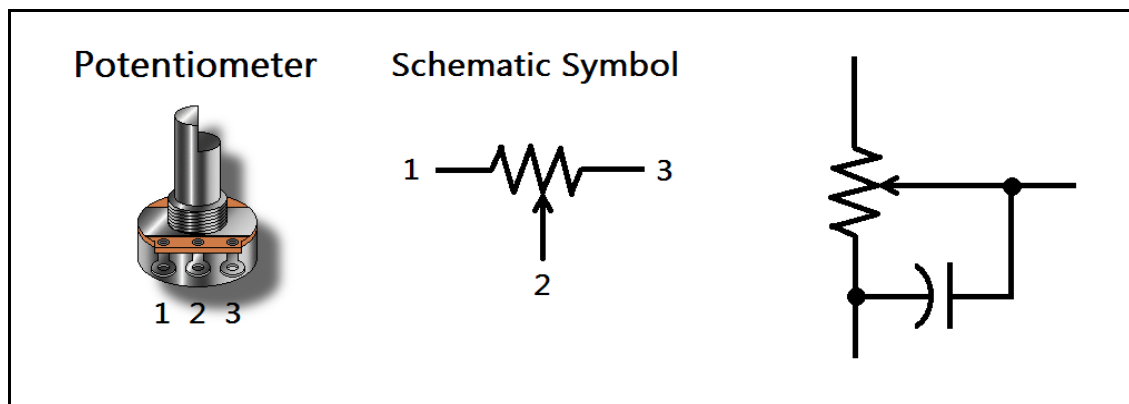
A wire is an inductor, as we explained earlier in this text. As such, power supply circuit paths may present problems in systems where there is fast switching. Keeping leads and traces as short as possible may help, but it is always good practice to use *decoupling capacitors*. Decoupling capacitors are small, with typical values of 0.1  $\mu\text{F}$ . They are placed as close as possible to every integrated circuit, and go from the power supply to ground. This goes for operational amplifiers as well as digital and microcontroller ICs. When designing schematics, always remember to indicate the value and placement of decoupling capacitors. **Figure 113** shows examples of decoupling capacitor placement.



**Figure 113:** An op amp with decoupling capacitors on both rails.

### Dirty, Noisy Potentiometers

It may be surprising to learn that spray lubricant can fix a dirty potentiometer. By squirting a small amount into the body of the potentiometer and working the wiper back and forth, an old and dirty potentiometer can be restored. A light mineral oil such as WD-40™ will work wonders.



**Figure 114:** Curing potentiometer noise with a capacitor.

A capacitor can also be used to help with noise problems in potentiometers. In **Figure 114** shown above, look to the right. Notice the placement of the capacitor. The capacitor will cure the noise from the wiper element of the potentiometer by forming a low-pass filter and shunting the crackling noise to ground. It is recommended for potentiometers used as a threshold setting. 100 nF should work fine.

### Easy Switch Debounce

Switch *bounce* is caused by the mechanical elements in switches. When a switch is actuated, the connection isn't instant. The contacts will vibrate, making and breaking contact until settling. This will definitely cause problems in digital systems. Fortunately, there is an easy solution for this. We can use a 100 nF capacitor to *debounce* a switch. **Figure 115** shows an example of debouncing a switch.

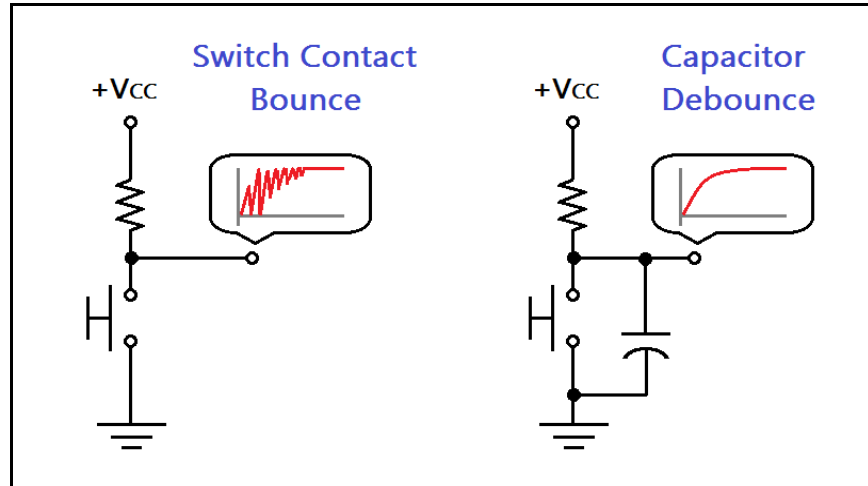


Figure 115: Debouncing a switch with a capacitor.

## Chapter 6.2: Tips and Tricks

### Obtaining Higher Voltages

If we need higher DC voltages than we can get from standard power supplies, as often happens in the lab setting, we may use a special circuit called a *voltage multiplier*. A voltage multiplier may be used to rectify an AC input voltage, and multiply it to very high DC levels. Look at the circuit in **Figure 116**.

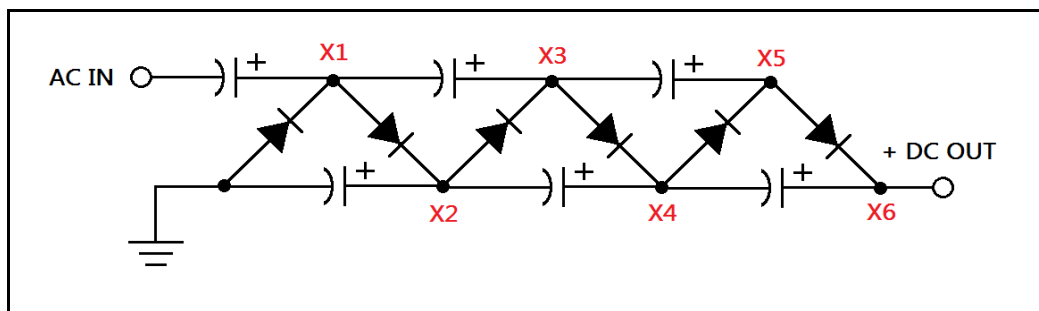
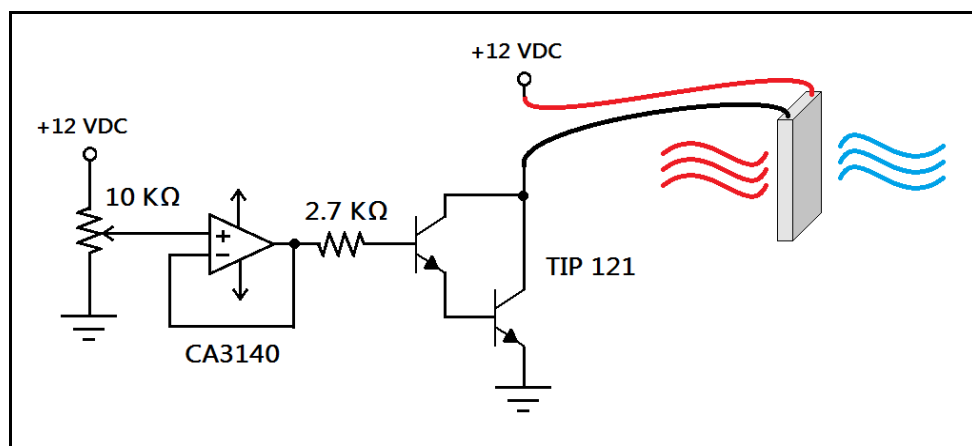


Figure 116: A voltage multiplier ladder yielding six times the input voltage.

If we use 10 VAC RMS input, the peak voltage is 14.14 V, and the above ladder multiplies this to almost 85 VDC! The working voltages for the capacitors and the PIV ratings for the diodes don't have to be greater than the maximum output voltage. However, they do have to be rated for their share of the total output voltage. The figure, above, shows how each stage multiplies the input AC voltage. The circuit can be cascaded to obtain even higher voltages. Just keep adding diodes and capacitors! This circuit can produce hundreds to thousands of volts.

### Heating and Cooling with Peltier Junctions

A *peltier junction* is a device that can act as a heat pump. They are flat, squarish looking devices with two leads, usually red and black for positive and negative. Typical small peltier junctions can deliver up to 90 BTUs (British temperature units) of heating or cooling. When current flows, the device gets hot on one side, and cold on the other! To make a cooling device, a heatsink should be used on the hot side.



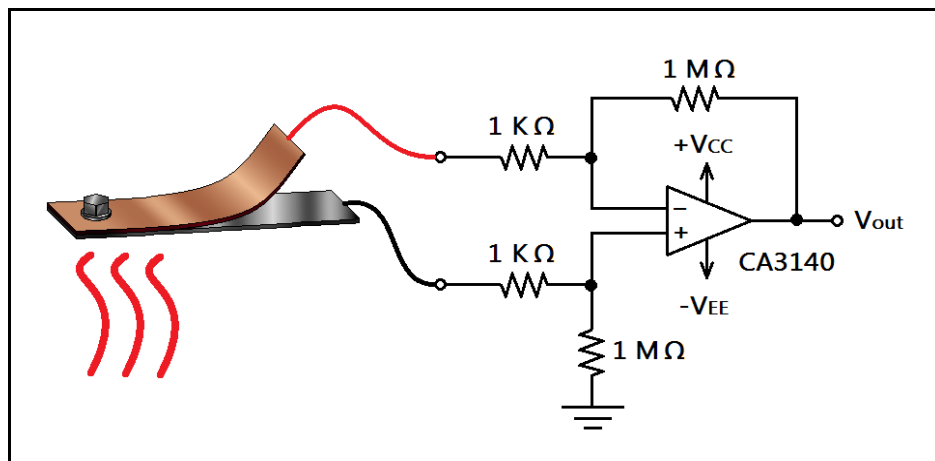
**Figure 117: Peltier junction driver circuit with variable cooling / heating control.**

These devices can be driven by low voltages, and typical devices will require a few amperes of current. They are not terribly efficient, but they can provide effective cooling. The heat pumping action can be controlled depending on how much current is used to drive the device. **Figure 117** shows an example driver circuit. The maximum current that can flow at saturation is determined by the base resistor, and yields about 4 A maximum supplied to the peltier junction. The buffered potentiometer controls the base current supplied to the Darlington transistor, which in turn controls the temperature. Such a circuit could be used to chill water in a bath, or even to act as a heatsink booster.



### Sensing Temperature with a Thermocouple

Temperature can be measured with a device called a *thermocouple*. A thermocouple is nothing more than two dissimilar metals in contact with one another. Due to the chemistry of the metals, a voltage will be developed at the junction as temperature increases. A good example would be a strip of steel bolted, brazed, or spot-welded to a strip of brass. The voltage developed is in the microvolts, so a differential amplifier is required to amplify the thermocouple output. Temperatures in the hundreds of degrees can be measured, provided that the thermocouple does not oxidize. Voltages will vary depending on the types of metal used. **Figure 118** shows a thermocouple with an amplifier circuit.



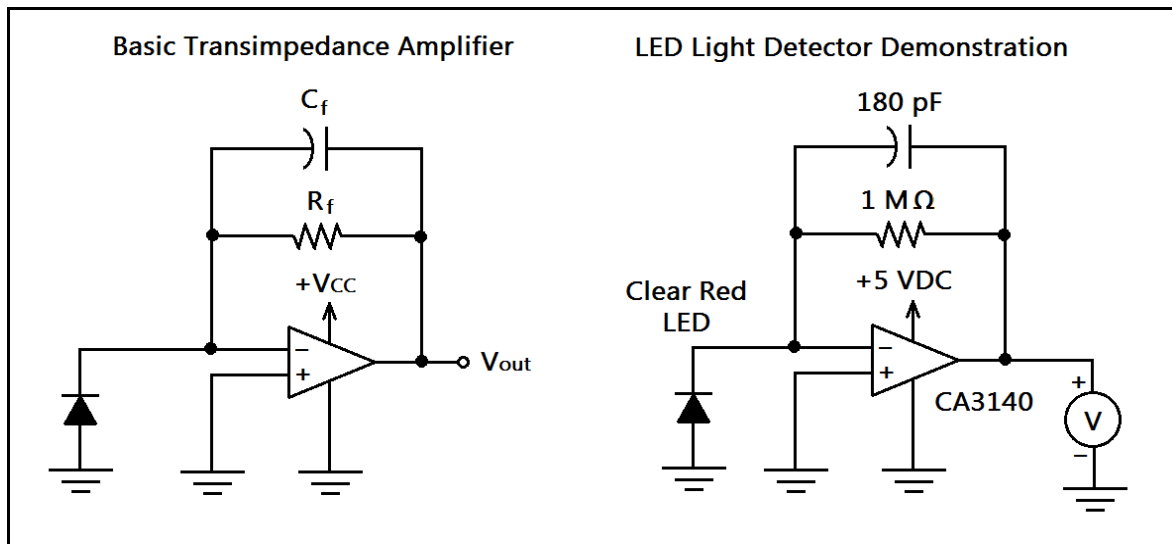
**Figure 118:** An example thermocouple circuit.

### Sensing Light using an LED

LEDs can produce light, of course, when current is provided. It may surprise you, however, to know that LEDs can also produce a tiny current when light shines on them. We need a special kind of circuit, however, to be able to sense light using LEDs. We can use a *transimpedance amplifier*. The LED should be connected such that the anode is at ground potential, and the cathode feeds the inverting input of the op amp. The output voltage is proportional to the feedback resistor's value. **Figure 119** shows a basic transimpedance amplifier and a demonstration circuit.

The output voltage of a transimpedance amplifier is given by,

$$V_{out} = I_{in} R_f$$



**Figure 119: A transimpedance amplifier with a demonstration circuit.**

Use LEDs in a clear package. LEDs will not detect light of a longer wavelength than they emit. This makes it possible to detect color. If the circuit oscillates, try increasing the value of the capacitor. And of course, if more gain is desired, increase the value of the resistor. The frequency response of the circuit depends on the low-pass filter in the feedback path, and the equivalent resistance and capacitance of the depletion region of the diode.

### **High Wattage Resistors from Scratch**

High wattage resistors are not as widely available as the  $\frac{1}{4}$  W and  $\frac{1}{2}$  W varieties. They can also be expensive. If we are in a pinch and need a high wattage resistor, we may make our own. Recall that we may add  $N$  equal value resistors in series such that  $R_{eq} = R * N$ , and that we may combine  $N$  equal value resistors in parallel such that  $R_{eq} = R / N$ . By using equal value resistors, we are assured that each resistor will dissipate its share of the total power. For example, if we need a 100  $\Omega$  2 W resistor, we may use eight 800  $\Omega$   $\frac{1}{4}$  W resistors in parallel.

## Chapter 7 – The Digital World

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In this chapter, you will...

- ➡ Master Boolean algebra.
- ➡ Learn about different types of logic.
- ➡ Discover logic symbols and circuits.
- ➡ Try your hand at logic design.
- ➡ Understand sequential logic circuits.

Up until now, we have been working in the analog world. Analog simply means “continuous.” That is, we may vary voltage continuously and infinitely, choosing any value we like.

*Digital* circuits behave differently. Digital *outputs* are only confined to two *states* - either on or off. By using small circuit elements, called logic gates, we may build systems of any complexity by taking advantage of this two-state behavior.

The world of digital logic is ruled by time. Gate outputs do not turn on instantaneously, but take a certain (often tiny) amount of time to activate. And some gates will not see an input signal at all if that signal changes too fast. All of these delicate *timing* issues must be analyzed if the digital system you are designing is going to be reliable and dependable.

## Chapter 7.1: A Brief Not So Brief History of Digital Logic

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The history of digital logic is not as short as you might think. The concept of solving problems using symbols originated in Persia, with al-Khwarizmi's writings detailing how to solve algebraic problems using algorithms, circa 800 C.E. In the 1800s, mechanical gears and switches were used to build calculating machines. The advancements in radio technology in the 1910s led to the development of tube devices; However, the invention of the bipolar junction transistor in 1947 changed everything.

## Chapter 7.2: Boolean Algebra

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Before we dive into playing with logic ICs and push-button switches, we need to go over a little theory first. Boolean algebra gives us a list of rules for how a *logic gate* will behave for a set of given *inputs*, and how to design digital circuits using *Boolean expressions*. Each type of gate has a special name, and by combining the different types of gates together, we may construct even more complex functions. Therefore, knowing how to solve Boolean expressions will make design much easier.

### **What is Boolean Algebra?**

Just as with ordinary high-school algebra, we may devise a symbolic system such that we may minimize (factor) expressions and solve for unknowns involving Boolean values. When we say the word *Boolean*, we are referring to the fact that our “variables” may take on only two values in the set  $\{0, 1\}$ . That is, a variable can either be ON or OFF (TRUE or FALSE, respectively.) There is no in-between state, and no “2.” We will cover number systems and binary arithmetic later in this chapter.

### **Positive vs. Negative Logic**

As we have just stated, logic variables may have one of two states. By convention, we use ON (1) as *logic high* and OFF (0) as *logic low*. This is referred to as *positive logic*. However, we may also make the OFF state (0) represent logic high and the ON state logic low. When the roles are reversed in this way, we are said to be using *negative logic*. Both systems are used in electronics. For example, the IC you are using may have positive logic inputs and outputs for data, but negative logic inputs for controlling the various functions of the IC. It is very common, so be sure to pay attention!

### Boolean Operators

A *Boolean operator* is just like any algebraic operator. In algebra, we have addition ( + ), subtraction ( - ), multiplication ( \* or X ) and division ( / ), and these operators tell us how to calculate the result. Not surprisingly, we may find analogs (pun intended) to these operations in Boolean algebra: we have an operation very similar to addition, which is represented by the *OR operator*, represented by a plus sign (  $A + B$ , say “A or B.” ) And we may also “multiply” Boolean values together with the *AND operator* (  $A * B$ , say “A and B.” ) Instead of a negative sign, we may negate with bar notation or with an exclamation point (  $\bar{A}$ , !A , say “A-bar” or “not A.” ) Finally, we have a sort of oddball function called *exclusive OR*, which can be built using the other functions. Exclusive OR is represented by a circle with a plus inside (  $\oplus$  ), and is a specialized form of the OR function.

### Properties of Boolean Expressions

In the table shown below, we outline the basic properties and laws of Boolean algebra. Notice some of the similarities to laws you already know with regards to numeric expressions. Memorize the contents of this table. It will be on the midterm. Just kidding.

Law	Expression	What It Says
Law of Identity	$A = A$ , $!A = !A$	A Boolean value is equal to itself.
Commutative Law	$A * B = B * A$ $A + B = B + A$	Order does not matter where AND or OR are used.
Associative Law	$A * (B * C) = (A * B) * C$ $A + (B + C) = (A + B) + C$	How we group variables being ANDed / ORed together doesn't matter.
Idempotent Law	$A * A = A$ , $A + A = A$	This identity is useful for <i>minimization</i> .
Double Negative Law	$!(!A) = A$	Negating a negation.
Complementary Law	$!A * A = 0$ $!A + A = 1$	ANDing a variable with its negation. ORing a variable with its negation
Intersection Law	$A * 0 = 0$ $A * 1 = A$	Multiplying by 0 or 1 also happens to work in Boolean algebra.
Union Law	$A + 1 = 1$ $A + 0 = A$	The 1 forces this to be always true. Adding nothing to A yields A.
DeMorgan's Law	$!(A * B) = !A + !B$ $!(A + B) = !A * !B$	Helpful for minimization.
Distributive Law	$A * (B + C) = A * B + A * C$ $A + (B * C) = (A + B) * (A + C)$	What you know about factoring and distributing also works for Boolean.

Chapter 7.3: Introduction to Logic Gates

Logic gates are electronic circuits that implement Boolean operations. They are the building blocks of *combinational logic*. Combinational logic tells us how to combine basic Boolean functions to obtain more complicated behavior. Logic gates produce an output instantaneously when their inputs change. That is, logic gates are time-independent; the output is purely a function of the present input state(s.)

The Logic Buffer Gate

At first blush, this gate looks like it does extremely little. Looking at the *truth table*, which is a tabular way to show how digital inputs and outputs relate to each other, our suspicion is confirmed. The output of this gate simply reproduces the input. It may not seem like a terribly useful function. However, the diagram shown below is not telling us the whole story. Take a look at **Figure 120**.

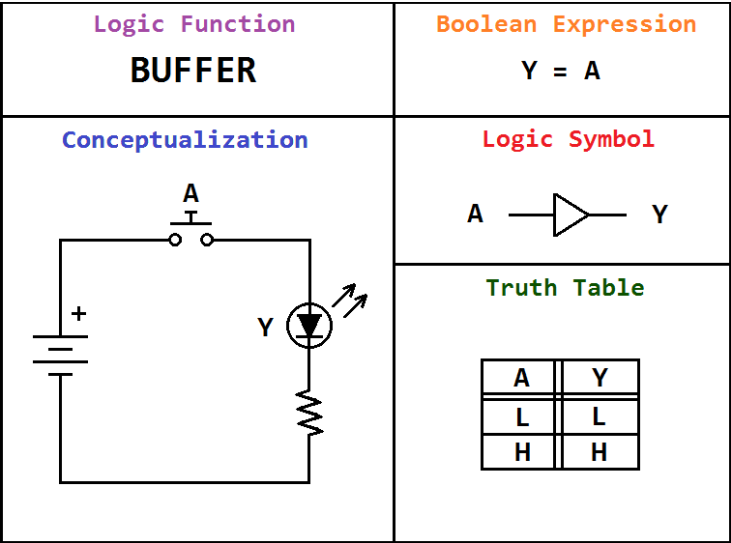


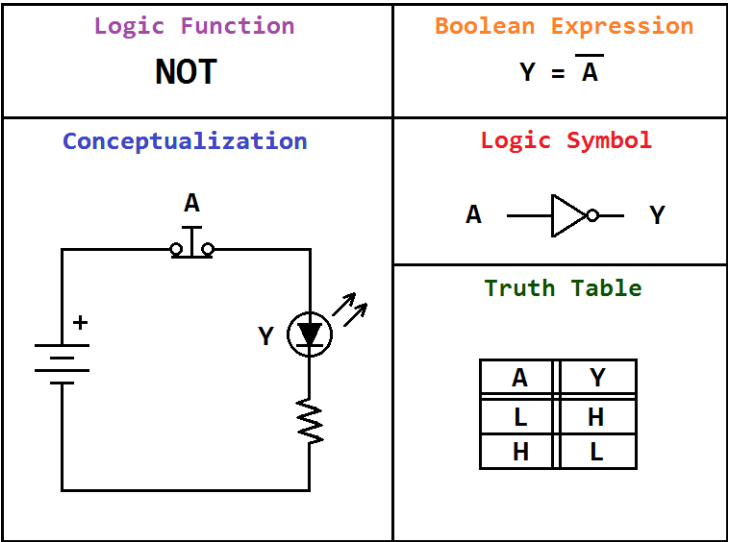
Figure 120: The logic buffer - conceptual circuit, equation, schematic symbol, and truth table.

A logic gate consists of transistors, diodes, etc. It takes a finite amount of time to turn on a transistor, so it will take some time for a change on a digital input to propagate through the gate to the output. This is called *propagation delay*, and is a measure of how fast a chip can change an output for a given input change. Now suppose we are interfacing to a system where we are given two input signals – with one signal line slightly lagged behind the other - causing *glitches*. (A glitch is a timing error where pulses may not be concomitant.) We may insert a *buffer gate* to provide a slight delay path on the

faster signal to correct the problem. Another use of logic buffers is where we must feed many logic inputs with only one output, or as a line driver to transmit data. Logic gates really aren't designed for driving more than a few mA of current. If there are a lot of logic gates in the system, your logic output may have to *fan out* to perhaps even hundreds of other inputs. If the output cannot *source* (act as Vcc) or *sink* (act as ground) the current required, a buffer with greater drive capability can be used for this output to boost the fan-out capability. A TTL hex-buffer is the 74LS07 (*open-collector driver*.)

**The Inverter Gate**

We could make a slightly more interesting version of the logic buffer by making the output do the opposite of what the input is doing. This logic gate is called an *inverter*, and is shown below in **Figure 121**. Note the “invert bubble” on the logic symbol. A TTL hex-inverter is the 74LS04.



**Figure 121:** The inverter gate - conceptual circuit, equation, schematic symbol, and truth table.

**The NAND Gate**

Beyond the operations we may carry out on a single signal line, or *bit* of information, we may construct gates for two (or more) inputs. We will cover the *NAND* (NOT AND) gate first, since it is one of the most important. This chip was one of the first available TTL digital logic chips. Designated on TTL parts as 74LS00, it has the unusual property that it can be used to create any other logic function (look at DeMorgan's Law to understand why.) If given two inputs, we may create a function which outputs false only if both inputs are true. Let's have a look at **Figure 122**. Note the invert bubble.

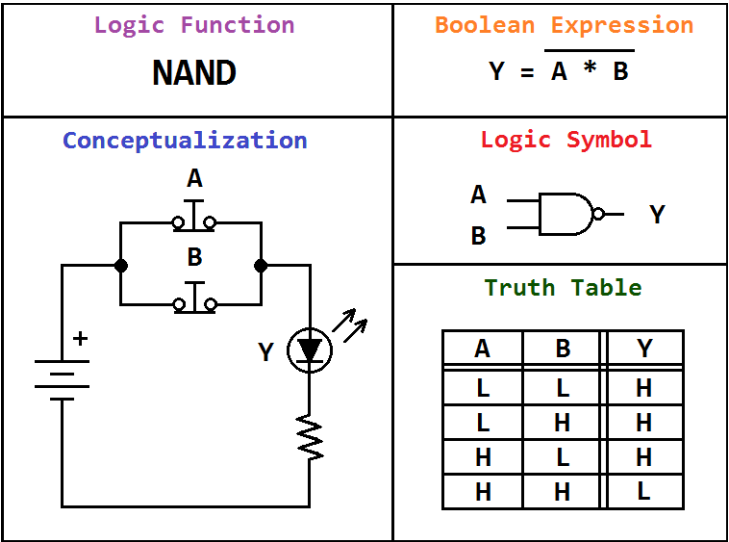


Figure 122: The NAND gate - conceptual circuit, equation, schematic symbol, and truth table.

**The AND Gate**

The previous example was a “not-and” function. We showed it before the AND gate due to historical considerations. We now turn our attention to the *AND* gate, its cousin. An AND gate is a logic gate which outputs true only if *both* inputs are true at the same time. **Figure 123** shows the AND function. A TTL quad, two-input AND gate is the 74LS08.

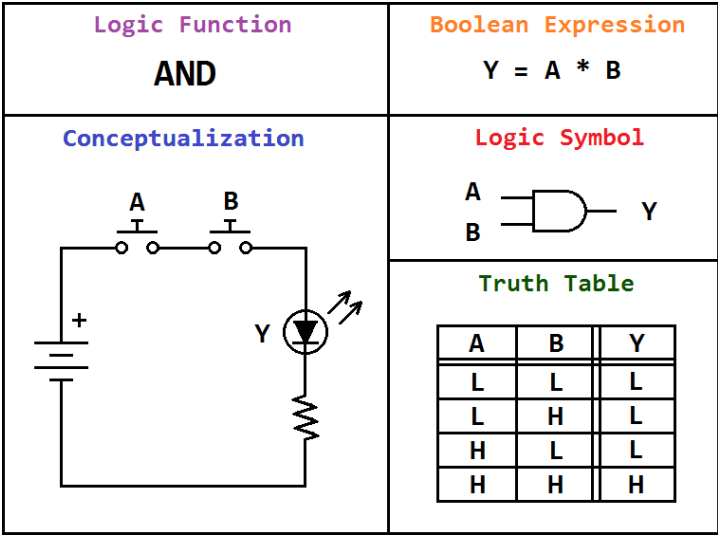


Figure 123: The AND gate - conceptual circuit, equation, schematic symbol, and truth table.



### The OR Gate

The *OR* gate outputs true if *any* or *all* of the inputs are true. If at least one input is logic high, the function will output a logic high as well. **Figure 124** shows the function for the OR gate. A TTL quad, two-input OR gate is the 74LS32.

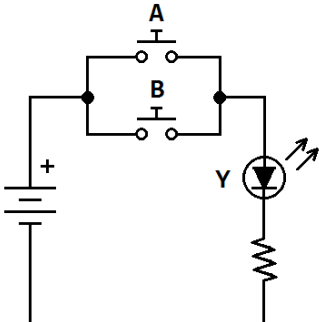

<p>Logic Function</p> <p><b>OR</b></p>	<p>Boolean Expression</p> <p><math>Y = A + B</math></p>															
<p>Conceptualization</p> 	<p>Logic Symbol</p> 															
	<p>Truth Table</p> <table><tr><th>A</th><th>B</th><th>Y</th></tr><tr><td>L</td><td>L</td><td>L</td></tr><tr><td>L</td><td>H</td><td>H</td></tr><tr><td>H</td><td>L</td><td>H</td></tr><tr><td>H</td><td>H</td><td>H</td></tr></table>	A	B	Y	L	L	L	L	H	H	H	L	H	H	H	H
A	B	Y														
L	L	L														
L	H	H														
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H	H	H														

Figure 124: The OR gate - conceptual circuit, equation, schematic symbol, and truth table.

### The NOR Gate

We may negate the OR gate to get a *NOR* gate. A NOR gate outputs true only when *all* inputs are false. **Figure 125** shows the NOR function. A TTL quad, two-input NOR gate is the 74LS02.

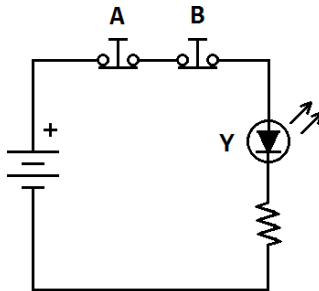

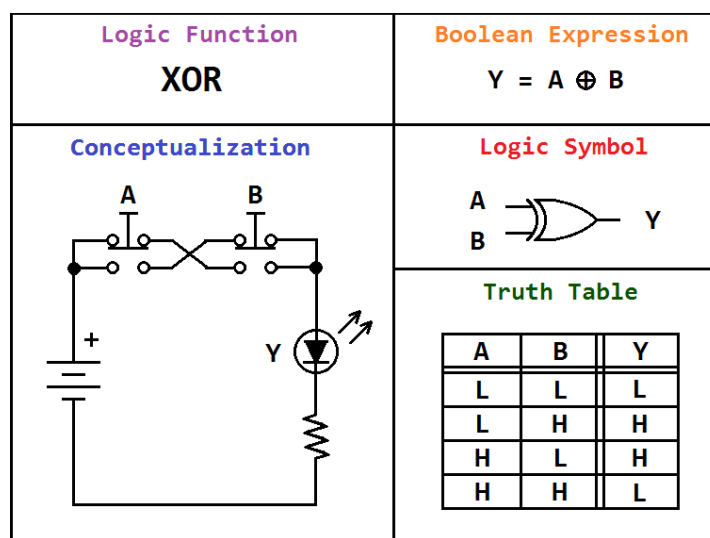
<p>Logic Function</p> <p><b>NOR</b></p>	<p>Boolean Expression</p> $Y = \overline{A + B}$															
<p>Conceptualization</p> 	<p>Logic Symbol</p> 															
	<p>Truth Table</p> <table><tr><th>A</th><th>B</th><th>Y</th></tr><tr><td>L</td><td>L</td><td>H</td></tr><tr><td>L</td><td>H</td><td>L</td></tr><tr><td>H</td><td>L</td><td>L</td></tr><tr><td>H</td><td>H</td><td>L</td></tr></table>	A	B	Y	L	L	H	L	H	L	H	L	L	H	H	L
A	B	Y														
L	L	H														
L	H	L														
H	L	L														
H	H	L														

Figure 125: The NOR gate - conceptual circuit, equation, schematic symbol, and truth table.

### The Exclusive OR (XOR) Gate

We note from the OR gate, shown above, that the function outputs true if *either* or *both* of the inputs are true. However, what if we wanted to create a mutually-exclusive function that outputs true if *only one* input is true at a time, but *not both simultaneously*? The logic gate for this special case of the OR function is called the *exclusive OR*, or *XOR gate*. **Figure 126** shows an XOR gate.



**Figure 126:** The XOR gate - conceptual circuit, equation, schematic symbol, and truth table.

Think of it this way – the XOR gate compares the inputs, and outputs true only if they have different logic levels. This type of operation is used in high-speed security systems that can encrypt data using the XOR function in hardware. It may also be used as a one-bit difference detector for constructing *magnitude comparators*, *arithmetic logic units*, etc. The XOR function is interesting in that if applied twice, it *undoes* itself. A TTL quad, two-input XOR gate is the 74LS86.

### The Exclusive NOR (XNOR) Gate

The *exclusive NOR gate*, or XNOR gate, is similar to its cousin, except the output is negated. Think of it this way – the XNOR gate compares the inputs, and outputs true only if they are simultaneously the same logic level. **Figure 127** shows the exclusive NOR gate. The XNOR gate also finds use in ALU design. A TTL quad, two-input XNOR gate is the 74LS266.

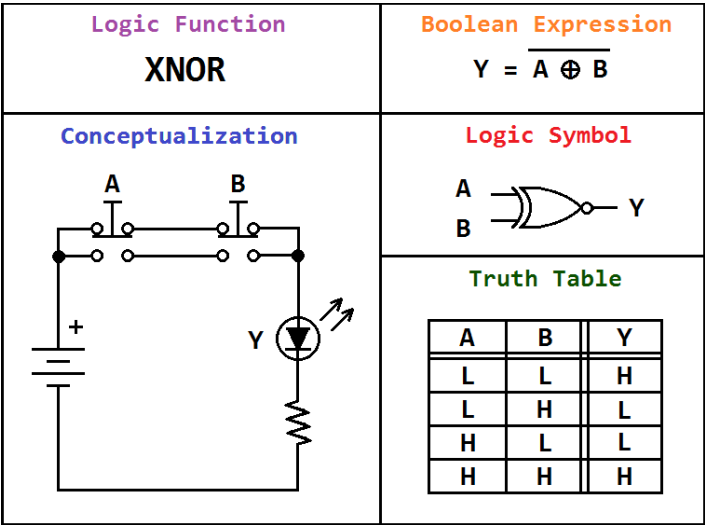


Figure 127: The XNOR gate - conceptual circuit, equation, schematic symbol, and truth table.

Chapter 7.4: Combinational Logic Design and Minimization

We have covered the basic properties of Boolean algebra and have introduced logic gates. Now we will begin exploring digital design concepts and *minimization* techniques. Minimization is an important area of study in digital design. By using minimization techniques, the goal is always to make the system you are designing as small as possible with the fewest number of logic gates. If the same function can be done with fewer gates, not only do you save money, but time, board space, etc.

Designing with Truth Tables and Algebraic Minimization

Just as numeric expressions can be factored and simplified in algebra, we may employ the same techniques to simplify Boolean algebraic expressions. We'll start with an easy design example to get a feel for the process, and an understanding of why minimization is important.

Design Example 1

Suppose you are designing an alarm system for a house that has one door and one window. The alarm siren sounds when the system is armed and the front door opens, or when the system is armed and the window is open, or both cases. Write a truth table, Boolean equation, and draw the circuit.

**Solution:**

Before we attempt to write a Boolean equation for this problem, making a truth table will help us prevent making a mistake. To write a truth table for the above problem, we create a list of variables representing the digital inputs and outputs of our hypothetical circuit. We have three input signals – alarm armed, door open, and window open. We may designate Boolean variables to represent these signals **A**, **D**, and **W**, respectively. We place the input variables in columns on the left, and the functional result on the right. We list every possible combination of input conditions (sometimes called *stimulus vectors*,) and map each case to give the desired output state in the right column, as shown below in **Figure 128**. We simply put an H or a 1 in the column when we want the siren (**S**) to activate, and an L or a 0 where we want it to be silent. (Just be consistent with how you show it.)

A	D	W	S
L	L	L	L
L	L	H	L
L	H	L	L
L	H	H	L
H	L	L	L
H	L	H	H
H	H	L	H
H	H	H	H

**Figure 128:** Truth table for the above design problem.

We may count the number of logic high states in the output column to know how many terms will be in our equation. By going down the output column on the right, it seems there are three terms in our equation (since there are three cases on the inputs which yield a logic high output.)

To convert a truth table into a Boolean expression is actually quite easy. You only need to list those combinations of input variables that result in a logic high output (indicating that the conditions stated in the problem were met in that combination.) You AND all the inputs on that line, negating them if they are logic low (L.) List your output variable on the left, then an equals sign, and then OR all of the ANDed terms together. This format is called *sum of products* or *SOP*. From the truth table above, we can now formulate an equation that will turn on a siren if the required input conditions are met.

$$S = (A * !D * W) + (A * D * !W) + (A * D * W)$$

We begin factoring:

$$S = A * (D * W + !D * W + D * !W) \Rightarrow$$

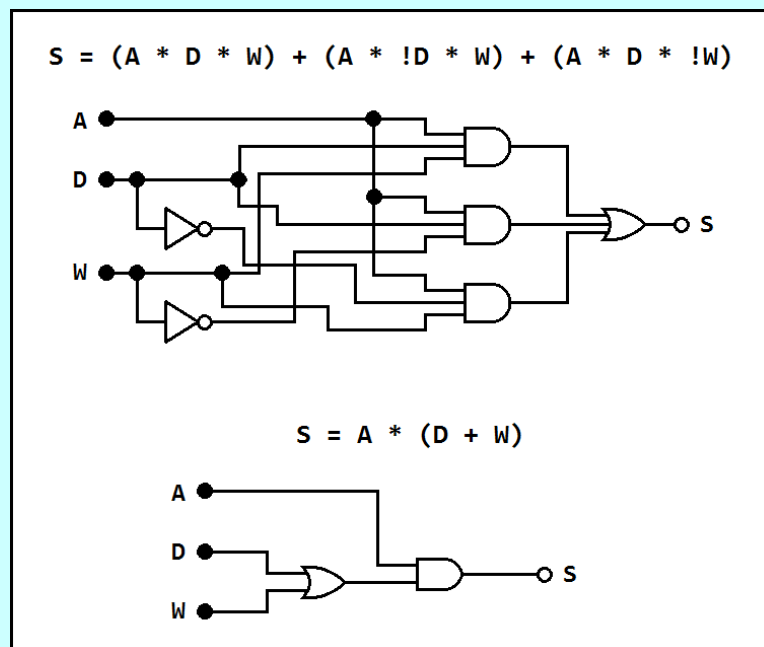
$$S = A * (D * (W + !W) + !D * W) \Rightarrow S = A * (D + !D * W)$$

We may distribute **D** over the AND operator:

$$S = A * (D + !D) * (D + W) = A * 1 * (D + W)$$

$$\Rightarrow S = A * (D + W)$$

You may have noticed that there are three product terms in the original equation. A truth table will give you an equation in SOP form, or sum of products form, but it may not be minimized. By simplifying the original equation, we have obtained the same functionality with the fewest possible logic gates. Both the minimized equation and the SOP form equation say the same thing, and both circuits will *behave* the same way, but minimizing has made a world of difference *structurally* when we try to draw these circuits for comparison, as shown in **Figure 129** below.



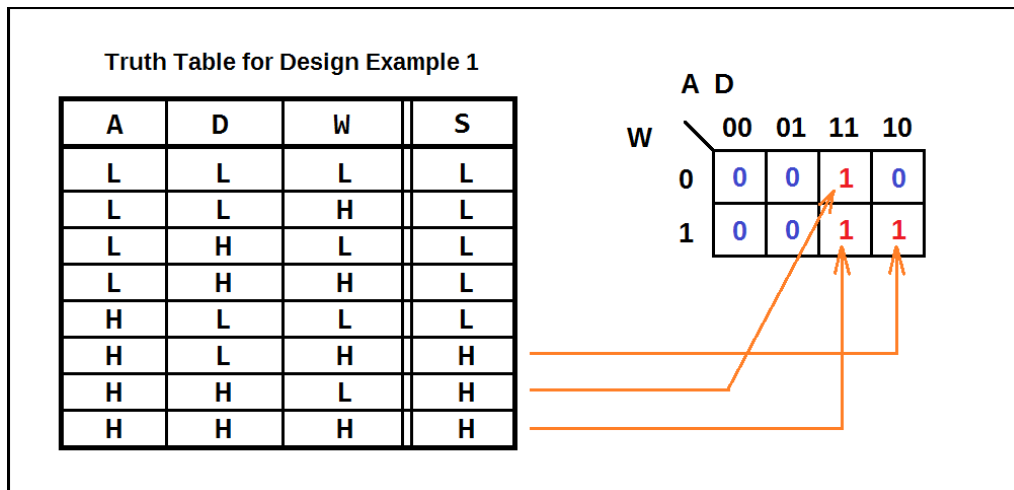
**Figure 129:** Schematic diagram for the design example above.

### Further Minimization Techniques

It is unfortunate that we can end up with at most eight product terms in our equation for only three input variables. That is a lot of factoring to do by hand to arrive at the minimized equation for so few inputs. One may get lucky depending on the circumstances. However, dealing with more than three input variables makes for a nasty set of factoring. Four variables means up to 16 product terms in our resultant Boolean equation, and five variables yields a Boolean equation with up to 32 product terms. What to say of larger systems such as a data bus?

### Constructing Karnaugh Maps from Truth Tables

If we have four or more variables, we may want to consider using a *Karnaugh map* (say “KAR - no”). They are a little cumbersome to set up, but produce elegant results. Furthermore, Karnaugh maps also show us additional information, such as the existence of *race conditions* (structural glitches caused by propagation delay.) We will explore three-variable and four-variable Karnaugh maps. Let's take a look at **Figure 130** to get an idea of how a Karnaugh map works. We'll start with the three variable system we covered in **Design Example 1**. We will use the truth table to populate the Karnaugh map and demonstrate that it generates minimized Boolean equations.



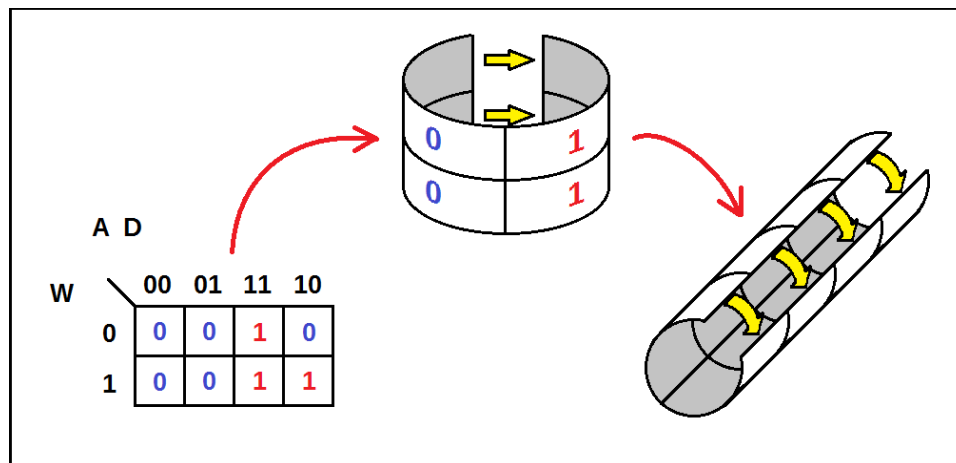
**Figure 130: A three-variable Karnaugh map representation of Design Example 1.**

We construct a truth table and begin looking for those patterns of **A**, **D**, and **W**, that yield a high (or true) output. Then, we make a grid of either 4X2 or 4X4, depending on the number of input variables. In the case of **Design Example 1**, we have three input variables, therefore we need a 4X2 map. We label the variables in groups of two at most, such that all input variables are represented exactly once

(it is convenient to do this in the top left corner with a little diagonal line, as shown in the figure.) Next, we label the columns and rows using *Gray code*. Gray code is a means of counting in binary such that only one digit is changing at a time between adjacent states. If we have two variables in a column or row, we start at the top left corner, and write 00, 01, 11, 10 along the cells of the column or row. If there is only one variable on a column or row, you may simply list the two possible values 0, 1. When finished, mark all outputs in the truth table that are true, and look for the combination of input variable states for that entry. Find the combination of high and low states for the input variables on the grid, and mark those positions in the Karnaugh map with a 1. All other positions in the map receive 0.

### **Minimizing with Karnaugh Maps and Minterms**

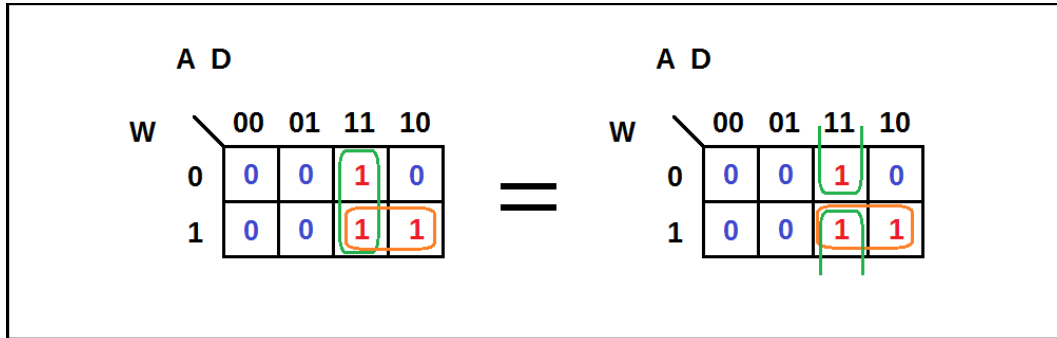
Now that we have covered how to construct a Karnaugh map from a truth table, we are ready to begin using it to solve our Boolean equation. We start by looking for *laterally or vertically connected* groups of 1s that are powers of two in number. A Karnaugh map is said to be *toroidally connected*. That is, not only are the cells adjacent within the map, but the edges connect as well, as if the whole map were located on the surface of a donut. **Figure 131** shows how the Karnaugh map we created for **Design Example 1** can be folded to show adjacency.



**Figure 131: The adjacency of edge cells in a Karnaugh map.**

Thus, we may have groups of one, two, four, eight, etc. The rules are that we may wrap around the edges of the torus, but we may only connect *adjacent* and *complete* groups of 1s. We may not include any zeros. When we are thus grouping 1s in a Karnaugh map, we end up with a sum of products (SOP) equation, and are said to be working with the *minterms* of the truth table. If we were grouping

zeros, we would be working instead with *maxterms*, and have a Boolean equation of a different form (*product of sums* or *POS*.) It should be noted that to use maxterms is a different process and is beyond the scope of this text. We will only cover solving for the minterms of a truth table, and leave solving for maxterms as a research exercise. Let's take a look at how to group the minterms from the truth table in **Design Example 1**. Have a look at **Figure 132**.



**Figure 132: Two different ways of grouping minterms with the same result.**

Minterms may be grouped contiguously, as shown on the left in the figure above. However, because of the rules of adjacency, we may also obtain the grouping on the right. Even though we have started with the top cell and drawn our circle to wrap around to the lower cell (green circle) we will obtain the same equation, as long as we are careful to make groups of powers of two.

Once all groups of minterms are circled, it is time to write an equation from the map. The way this is done is by looking at the groups you have circled, and then looking at the Gray code for all variables in the columns and rows for that group. Let's start with the vertical, green-circled grouping. We note that the values for **A** and **D** do not change, but **W** does change as we move vertically in the group. Therefore **W** is discarded. The first product term is **A \* D**. Now we look at the horizontal, orange-circled grouping. We see that **W** does not change as we move horizontally in the group, but looking at the Gray code we can see that **D** does in fact change. So we eliminate that from the group, yielding the second product term **A \* W**. Therefore, we arrive at the following equation:

$$S = A * D + A * W = A * (D + W)$$

Look familiar? This is precisely the same equation we had found before. If we had left this expression alone instead of factoring, we would have three gates instead of two, but the result produced by the



Karnaugh map is more symmetrical. Therefore, the Karnaugh map has bypassed a lot of the steps we had to take algebraically, making the problem far more manageable. When doing Karnaugh maps for five variables, two 4x4 grids are required. But for six variables, we obtain a 4X4X4 Karnaugh map, which requires an additional two 4X4 maps. But even at five input variables, we must think of grouping minterms in three-dimensional space, which is challenging. Keep it in mind.

### Using Don't-Cares to Aid in Minimization

Race conditions exist where we have disconnected (non-overlapping) groups of minterms in our Karnaugh map. If a race condition exists in your circuit, there is the possibility of generating minute pulses when transitioning input states. Sometimes it is advantageous to add additional placeholders in a Karnaugh map. That way, we can make an output a “don't-care,” such that we will never provide that input to the logic function; therefore we are unconcerned with the output in that case. **Figure 133** shows a Karnaugh map with a “don't-care” (denoted by an X) to help with minimization, as well as to prevent an existing race condition. But one must be absolutely certain that the inputs that generate the don't-care aren't ever presented in the design.

		A B			
		00	01	11	10
C D	00	0	0	1	0
	01	0	0	1	0
	11	0	0	X	0
	10	1	1	1	1

**Figure 133: Using a don't-care to aid in minimization.**

Notice in the above figure that without the don't-care, we could not have grouped the vertical minterms into a column of four. We would have ended up with a possible race condition, remedied only by adding another product term to ensure overlap. Donuts, anyone? *[professor must provide donuts]*

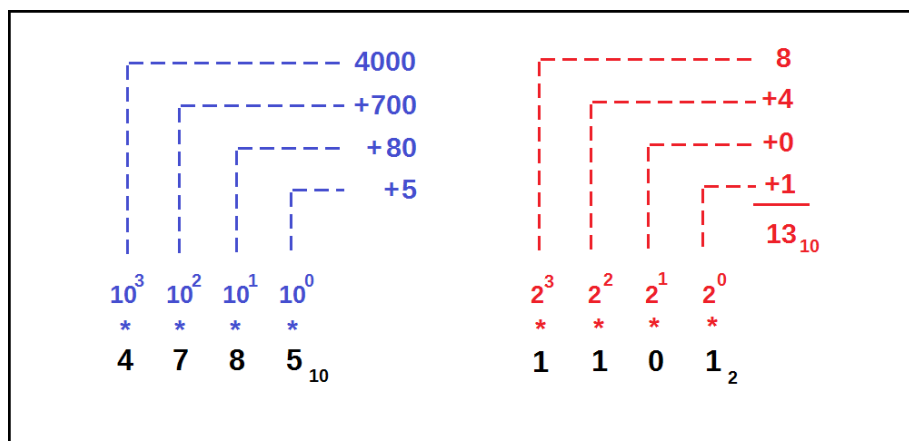
## Chapter 7.5: Number Systems

### The Decimal, Binary, and Hexadecimal Number Systems

Most people are familiar with the *base 10 number system*, also known as the *decimal number system*. Counting in base 10 is so very human, after all. The human body typically has 10 fingers. And the number 10 has such wonderful properties. But did you ever wonder why? It is a pattern generated by our choice of counting with 10 symbols.

In base 10 arithmetic, we may count physical objects or symbolic tokens by using the symbols in the Arabic set of numerals {0, 1, 2, 3, 4, 5, 6, 7, 8, 9} to represent the count. The placement of digits progresses from right to left for each power of 10 we add, such that the placement tells us how many 1s, 10s, 100s, etc., we need to build a number. So we may think of increasing powers of ten starting at the rightmost (least significant) digit, starting with  $10^0$ ,  $10^1$ ,  $10^2$ , etc., in each position as weights or multipliers. News to you, right?

Now we consider the *base 2 number system*, also known as the *binary number system*. Binary numbers only allow us to count using the numerals in the set {0, 1}. But we may build numbers in much the same way as we do in the decimal number system, only we move in powers of two, not powers of 10. In **Figure 134**, shown below, we can see the decimal number 4785 being broken down into thousands, hundreds, tens, and ones. We now turn our attention to the number on the right. We can see the binary number 1101 being broken down into multiples of powers of two. To convert a binary number to decimal, we need only sum as shown.

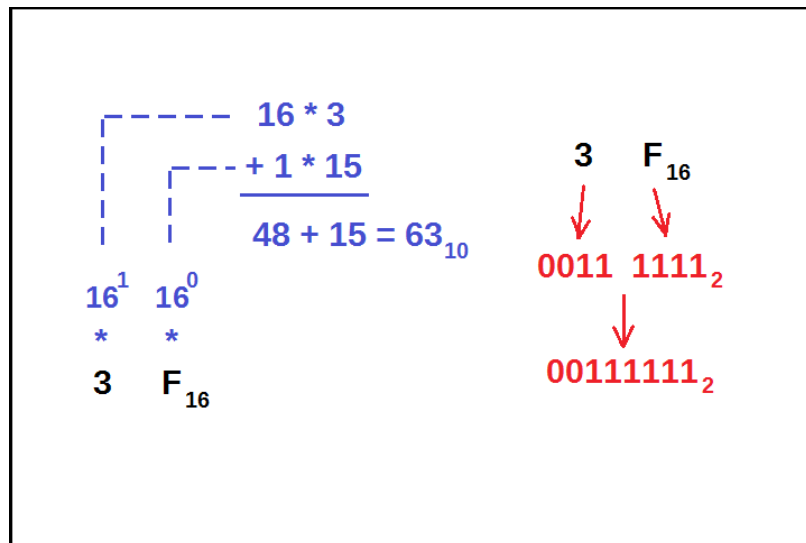


**Figure 134: Comparing the decimal number system to the binary number system.**

In our example above, we show two four-digit numbers in the decimal and binary number systems. Let's look at the decimal number 13 being represented by the binary number 1101. First of all, we read the binary number “one, one, zero, one.” We don't ever say “one thousand, one hundred and one” when we are speaking binary. No, we read aloud every digit like the geeks we know we are. It can get rather tedious. But we notice something curious too. If we confine ourselves to four digits, we may limit our binary droning, but we can only count from 0 to 15. Four digits to count to 15 is not efficient. If we group very long binary numbers into chunks that are four bits (binary digits) wide, we can do binary arithmetic on larger numbers in a more convenient way. We need a set of digits that can go from 0 to 15, but we run out of digits after decimal number 9.

Well, a bunch of smart guys a long time ago came up with the idea of using alphabetic characters to count past 9. Thus, A = 10, B = 11, C = 12, D = 13, E = 14, and F = 15. Bingo, now we can represent groups of four bits (called a *NIBBLE*) into a more compact way of representing binary numbers. It is called the *hexadecimal number system*. **Figure 135** demonstrates how hexadecimal numbers are graphically expressed, and now to convert to the decimal and binary number systems.

It may surprise you to know that converting from binary to hexadecimal is quite simple. All you have to do is make groups of four binary digits, starting at the LSb (“*least significant bit*”) on the right, and moving towards the MSb (“*most significant bit*”) on the left. Pad extra zeros on the left until you get a grouping that is a multiple of four. Then assign a hexadecimal letter or number to each quartet.



**Figure 135: Conversion from the hexadecimal number system to decimal and binary.**

With a two digit hexadecimal number, we may count from 0 to 255. Not bad – we can not only represent eight digits (bits) of a long binary number, but we can also count fairly high as well. This convenient package of eight binary digits is called a *BYTE*. Therefore, a *BYTE* is simply a two-digit hexadecimal number. A *WORD* consists of two bytes, equaling 16 total binary digits, and a *DWORD* consists of four bytes, equaling 32 total binary digits. Those bearded fellows who are familiar with microcontroller development will recognize these as standard bus widths.

### **A Quick Conversion Table**

Now we will give a useful table for converting between the decimal, binary, and hexadecimal number systems. You should commit this table to memory. In time, you will develop the ability to recognize the hexadecimal and binary equivalents immediately. Take a look at **Figure 136**.

Decimal	Hexadecimal	Binary
0	0x0	0b0000
1	0x1	0b0001
2	0x2	0b0010
3	0x3	0b0011
4	0x4	0b0100
5	0x5	0b0101
6	0x6	0b0110
7	0x7	0b0111
8	0x8	0b1000
9	0x9	0b1001
10	0xA	0b1010
11	0xB	0b1011
12	0xC	0b1100
13	0xD	0b1101
14	0xE	0b1110
15	0xF	0b1111

**Figure 136: A table showing decimal, hexadecimal, and binary values from 0 to 15.**

When writing hexadecimal or binary numbers, it is often more convenient to prepend a 0x to a hexadecimal number, and a 0b to a binary number, instead of using a base subscript. This is the way binary and hexadecimal values are represented in software and firmware programs.

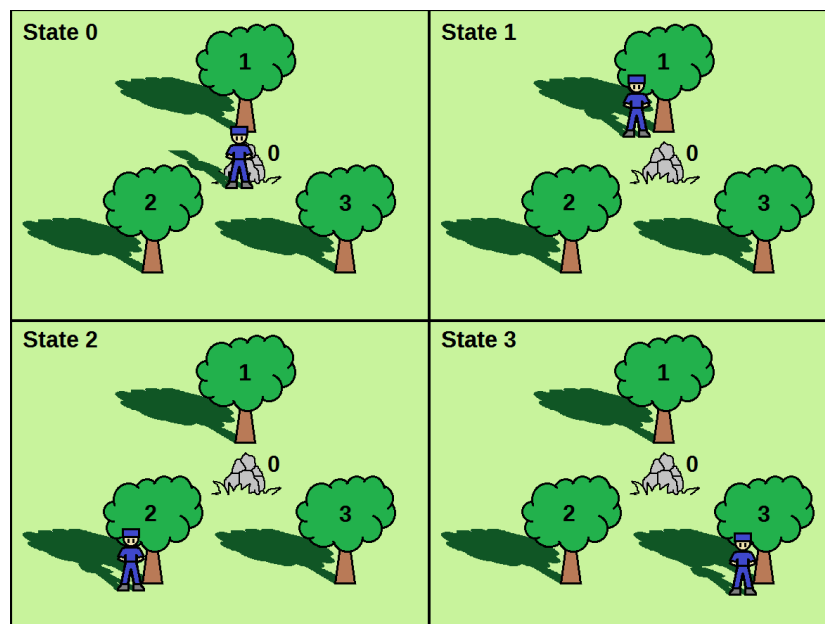
## Chapter 7.6: Finite State Machines

In Chapters 7.1 – 7.5, we discussed logic gates that are time-independent. Combinational logic gates have no *memory* of their state. If you change the inputs, the outputs will also change instantaneously. Sequential circuits are *time-dependent*, and have some form of timing mechanism (a clock,) a memory for holding the present-state (*registers* or *flip-flops*,) a *feedback network* of combinational logic for the *next-state*, and output logic. Such systems are generally referred to as *finite state machines*.

### What Do Finite State Machines Do?

Finite state machines help us to understand and design complex rules for the behavior of a sequential circuit. Let's say we are training a soldier, as shown in **Figure 137**. The soldier runs whenever he hears us blow our whistle at regular intervals. On the training ground, we have a circle of three trees and a stone. We make up rules for the training exercise and explain them to the soldier:

- 1) *The stone in the center is home. If you hold up your right hand while blowing the whistle, the soldier is to move to the central stone. If the soldier is already at the stone and your hand is up, he stays there.*
- 2) *If at home, he can only move to the top tree (tree #1 in the diagram) when your right hand is down and the whistle blows. If at a tree, he may only move anti-clockwise to the next tree. He must move!*
- 3) *The soldier is only to move when the whistle blows. He may not move out of turn or backwards.*

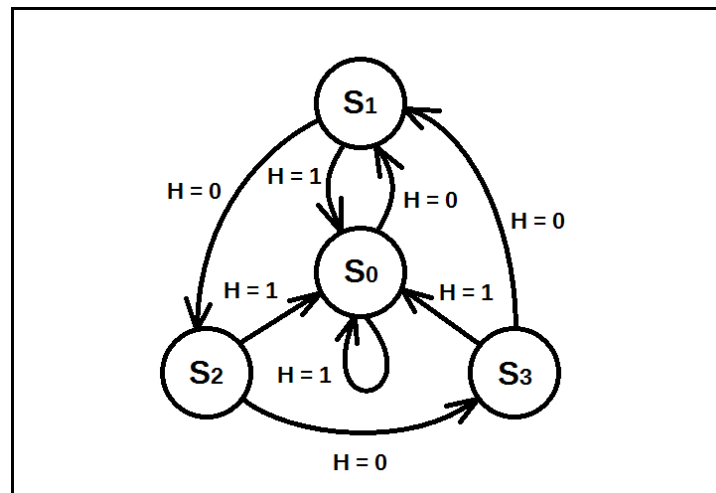


**Figure 137: Finite state machine example.**

The soldier in the above diagram can either be at the stone, or any of the three trees. Therefore, he has exactly four states he can occupy. Our picture certainly helps us to understand *where* the soldier may be standing, but not how he got there. We need a symbolic diagram that not only shows the soldier's possible locations, but also how he may move from place to place.

### State Transition Diagrams

We will now discuss *state transition diagrams*. We'll be using the soldier example from **Figure 137** to draw a better representation of the rules we outlined in the previous section. We start by drawing circles to represent our states and labeling them. Then, we connect the state bubbles with arrows showing how we may transition from state to state. Finally, we label the arrows with the conditions that allows for that transition. **Figure 138** shows a state transition diagram for the example above.



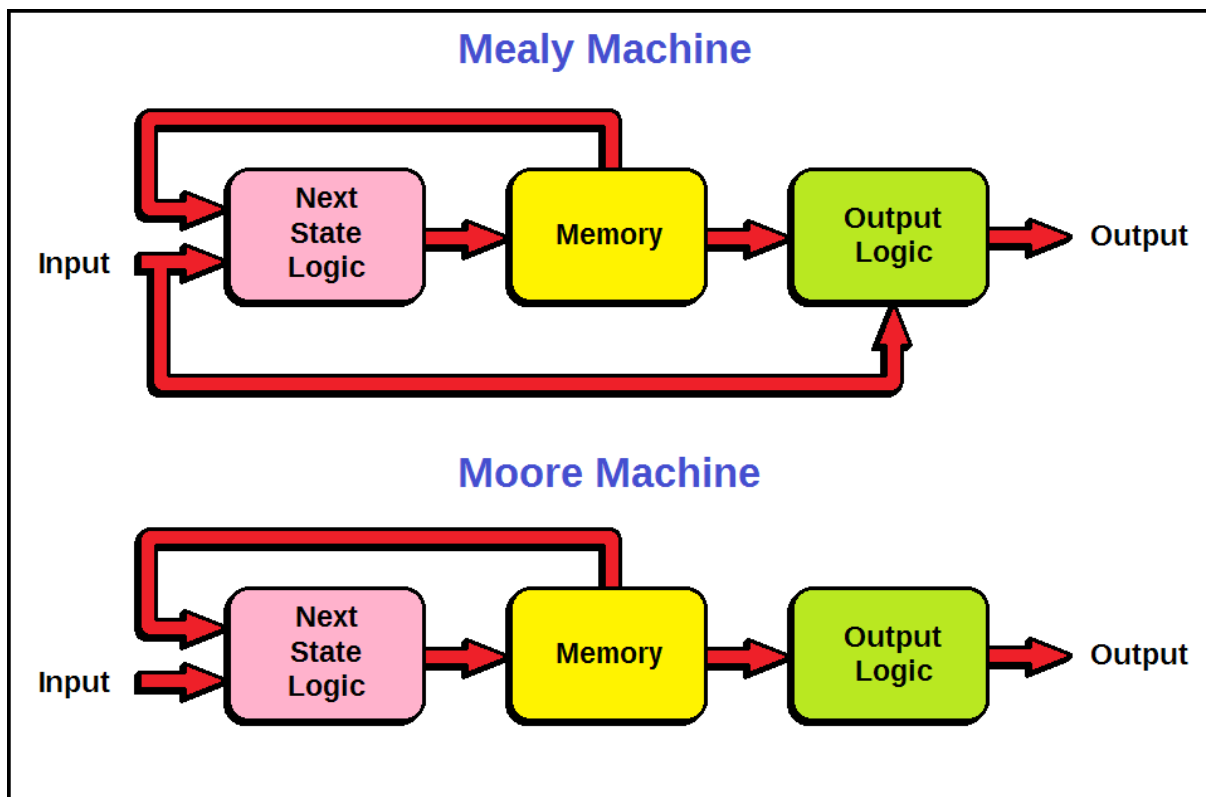
**Figure 138: A state transition diagram for the soldier problem.**

From the figure, we see a more detailed picture of the rules for moving our soldier. Starting at state **S<sub>0</sub>**, if we have our right hand down (**H = 0**), there is only one place for the soldier to move – state **S<sub>1</sub>**. From state **S<sub>1</sub>**, we may move to state **S<sub>2</sub>** if **H = 0**, or we may move back to state **S<sub>0</sub>** if **H = 1**, and so on. Notice that state **S<sub>0</sub>** is also an *idle state* (one of the arrows loops back on itself at state **S<sub>0</sub>**.) That is, we remain at state **S<sub>0</sub>** if **H = 1**. The example shown above is synchronous. That is, the soldier we are training only moves when we blow our whistle. We might throw our right hand up while the soldier is in motion, but he must finish moving to his destination along one of the transition arrows before the next whistle. Only when he has arrived does he look at your hand for what to do next.

**Finite State Machine Architecture**

To gain an understanding of the types of finite state machines we may encounter, we must employ some imagery. We have two basic types of finite state machines: Mealy machines and Moore machines. In Mealy architecture, the output can change based on the current state in memory or *asynchronously* with an input change. That is, a change on the outputs may be affected by a change on the inputs regardless of how the system clock may be ticking. Moore machines have outputs that are only dependent on the tick of the system clock. For Moore machines, a change on the inputs will have to wait for the next tick of the clock to produce a change on the output in a synchronous fashion.

**Figure 139** shows the structural differences between a Mealy Machine and a Moore Machine.



**Figure 139:** Mealy and Moore finite state machine architecture.

The soldier problem from earlier would be an example of a Moore machine. Why? Because the soldier ignores our hand motions when he is moving. Our soldier only acts when he has reached his destination and is ready for another whistle blow. He certainly doesn't want to do push-ups!

Chapter 7.7: Latches and Flip-Flops

As we mentioned before, a finite state machine must have some form of memory to hold the present-state. A *flip-flop* is a type of memory that can change states when given a pulse on an input, and can store one bit of information. A register is a collection of one or more ordered bits (flip-flops) that indicate a numeric value associated with a state in finite state machines.

The Set-Reset Latch

We will begin with the *set-reset latch*, or *SR latch*. A latch is a type of memory that can retain its output state as long as power is applied. Latches have two inputs, both of which are *active low* (negative logic.) If both inputs are logic high, the output state remains unchanged. However, they cannot be simultaneously *asserted* (brought low,) or the device will behave unpredictably. Due to the feedback in the figure above, the latch will set the output Q equal to 1 when input !S is brought low. Output Q will maintain that value even if !S is brought high again. Likewise, asserting !R will set output Q to 0, even if !R is brought high again. SR latches can be constructed using only two NAND gates. A latch. **Figure 140** shows how an SR latch is constructed. A common TTL part is the 74LS279.

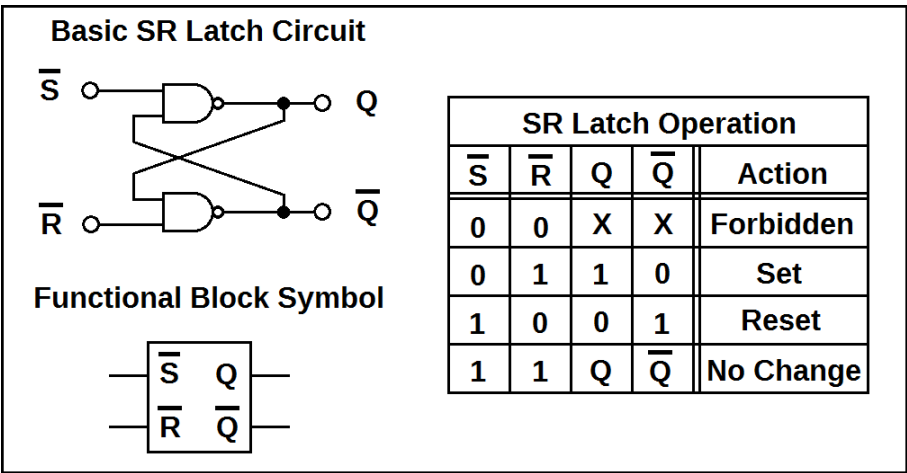


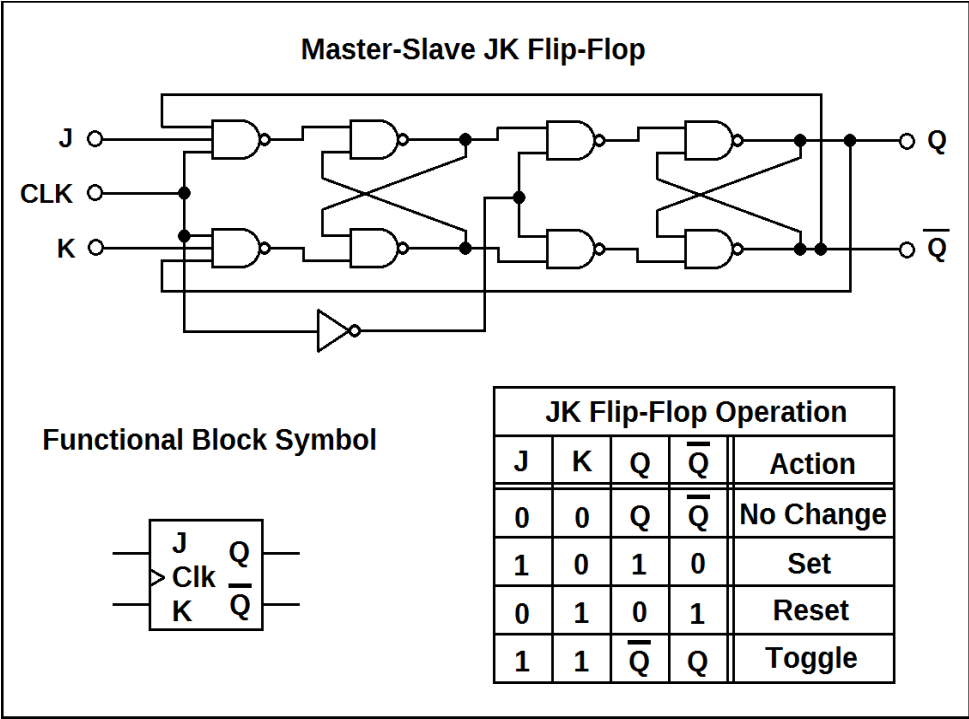
Figure 140: A set-reset latch with truth table and logic symbol.

The problem with this latch is that it is *metastable* if we try to assert !S and !R simultaneously (the output is unpredictable.) Also, there is no clocking mechanism – so this latch is said to be a *transparent latch*. That is, once data has been presented to the !S input (after a reset,) it latches immediately and is stored until reset. There is no way to control the latching action synchronously.



**The Master-Slave JK Flip-Flop**

The SR latch had some serious issues. The *master-slave JK flip-flop* is a huge improvement over the SR latch: it uses two SR latches in tandem. A master-slave JK flip-flop requires a clock pulse to be presented in order to latch the data. The JK flip-flop will not pass data from the master SR latch to the slave until a *rising edge* occurs. On the next *falling edge* of the clock, the data is then latched to the slave and all other changes are ignored until the next clock pulse. That makes the master-slave JK flip-flop a *negative edge triggered* synchronous device. Like the SR latch, the JK flip-flop has both a set function (J) and a reset function (K.) However, the inputs are *active high* (positive logic.) Furthermore, it has no issues with forbidden states or requiring specialized pulse circuits. **Figure 141** shows a master-slave JK flip-flop. A common master-slave JK flip-flop is the 74LS112.

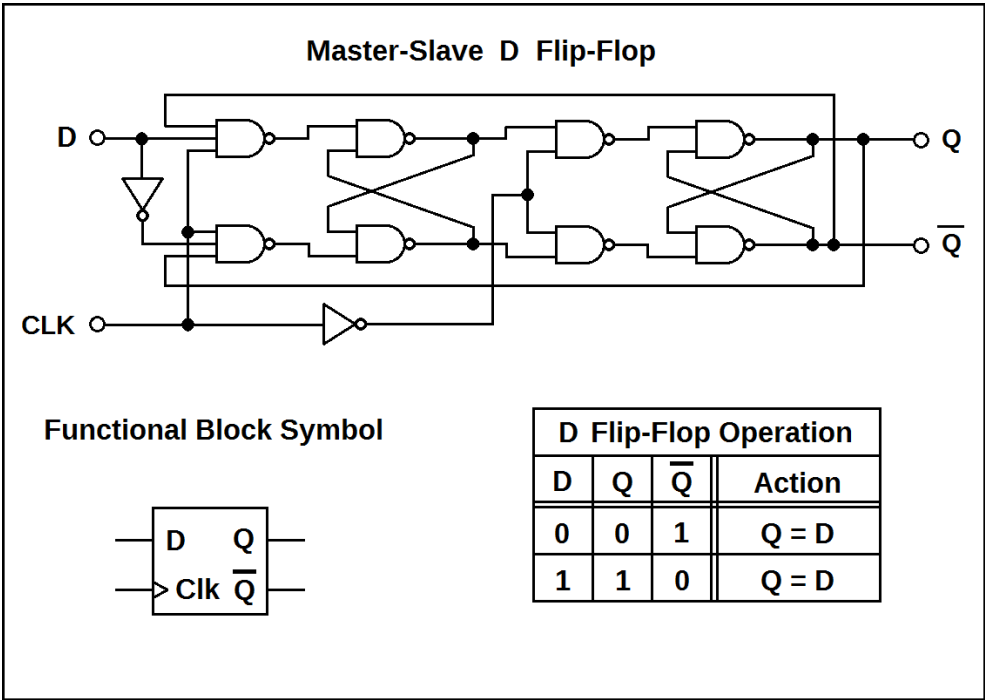


**Figure 141: A master-slave JK flip-flop with truth table and logic symbol.**

An interesting point is that this flip-flop can toggle output states. If a logic high is presented to both J and K when a clock pulse occurs, the master-slave JK flip-flop will invert output states. In other words, it takes the data present at the output and negates it (flip-flop!) The master-slave JK flip-flop will be revisited later, but we have one more type of register to learn about before we move on.

**The Master-Slave D Flip-Flop**

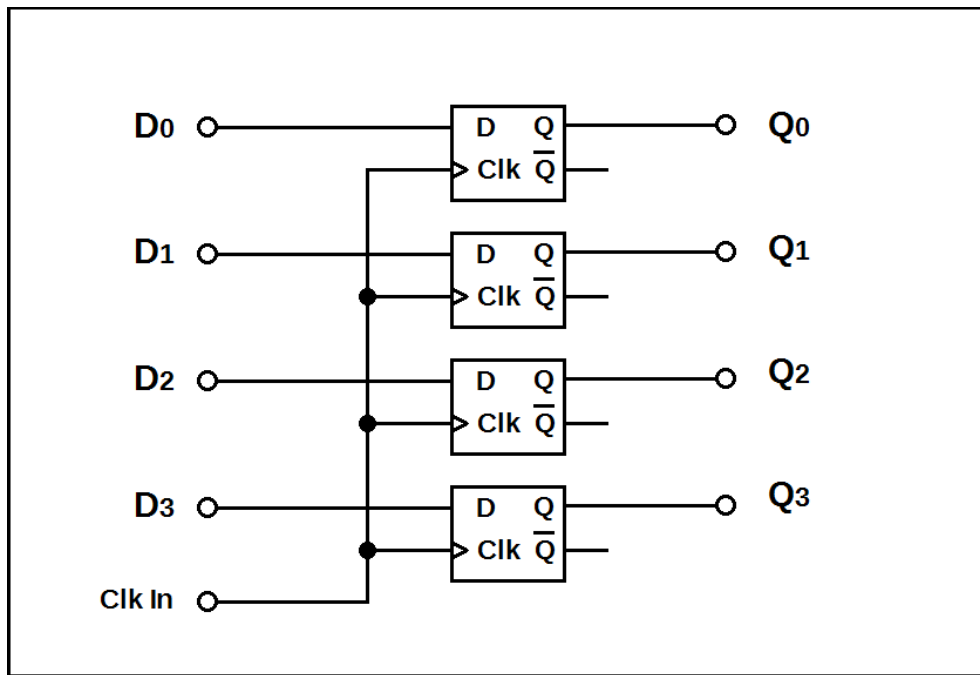
We finally turn our attention to the *master-slave data flip-flop*, or D flip-flop. This flip-flop not only solves all the problems of the SR latch, but also has fewer inputs. We simply present a 1 or 0 to an input and the clock latches the data to the output, holding the output logic level until the next clock. The master-slave D flip-flop is based on the master-slave JK flip-flop, but adds an inverter to prevent the toggle state, which also reduces the number of inputs. Data presented to the latch is clocked on the falling edge, just as with the master-slave JK flip-flop. **Figure 142** shows a master-slave D type flip-flop. A common octal D type flip-flop is the 74LS574.



**Figure 142: A master-slave D flip-flop with truth table and logic symbol.**

**Using Flip-Flops to Build Larger Registers**

When we are designing a state machine, we must have an idea for the number of states we will include in our design. When we have some idea of the number of states, we can then select the number of bits required to construct a memory register for the state machine. We want to choose a power of two that is just large enough to cover the number of states in our design. For example, if we have 13 states in our state machine, we will need a four-bit register, since  $2^4 > 13 > 2^3$ . **Figure 143** shows how to construct a four-bit register using D type flip-flops.



**Figure 143: A four-bit register built with D flip-flops.**

With the register shown above, it will be possible to latch four bits of input data simultaneously. Complementary outputs are provided to ease the design requirements for the next-state logic. Registers of any size may be constructed as above by ganging the clock inputs and adding flip-flops.

## Chapter 7.8: Sequential Logic Design and Minimization

Now that we have shown how a set of flip-flops can be grouped to make a memory register, we can move on to state machine implementation. The design process for sequential circuits is much like that of combinational circuits. We must start with a specialized truth table that shows the inputs, the present and next states, and any desired outputs. With this table, we use the present-state variables to design feedback logic for the next state inputs.

### Design Example 2

*We will implement the soldier problem from earlier. The “whistle” will be a clock pulse, and our hand up / down will be represented by a single input variable, **H**. Draw a state transition diagram and state-table. Write Boolean equations for the feedback logic, and draw a schematic of your design.*

**Solution:**

We need to count the states and assign numeric values to each. We count  $S_0$ ,  $S_1$ ,  $S_2$ , and  $S_3$ , equaling four total states. Since we have already shown the state transition diagram for this problem, we will simply reference **Figure 138** for this problem. Make sure to label the state bubbles, their numeric values, and draw arrows with labels for your inputs.

We will need two D flip-flops for our memory register inputs, and assign them the designations  $D_0$ ,  $D_1$ , and their respective outputs  $Q_0$ ,  $Q_1$ . Next, we need to identify the inputs. In this case, we will choose **H** as before to represent our hand position, with UP = 1 and DOWN = 0. Since we chose **H** as an input variable, we will populate our state table with 1s and 0s for the sake of disambiguation. There are actually two truth tables implied in the state table, one for each bit of the memory register. **Figure 144** shows the state table for the soldier problem.

Inputs	Present State		Next State	
	Q1	Q0	D1	D0
0	0	0	0	1
0	0	1	1	0
0	1	0	1	1
0	1	1	0	1
1	0	0	0	0
1	0	1	0	0
1	1	0	0	0
1	1	1	0	0

**Figure 144: State table for the soldier problem.**

By examining the table, we find we are fortunate. The feedback network for both  $D_0$  and  $D_1$  are relatively simple due to the small number of minterms for each. We will skip using Karnaugh maps and must stick with Boolean algebraic minimization, but if you wish to use them to solve sequential problems, keep in mind you need to solve a separate map for each bit in the memory register.

We have omitted the output logic section, but the design procedure is exactly the same. You would just create another network much the same way as for the feedback logic. If the output logic depends on any of the inputs in addition to the present state, the result will be Mealy architecture.

We write the equations and minimize:

$$D_1 = !H * (!Q_1 * Q_0 + Q_1 * !Q_0) = !H * (Q_1 \oplus Q_0); \text{ (due to mutual exclusion)}$$

$$D_0 = !H * (!Q_1 * !Q_0 + Q_1 * !Q_0 + Q_1 * Q_0) \Rightarrow$$

$$D_0 = !H * (!Q_1 * !Q_0 + Q_1 * (Q_0 + !Q_0)) = !H * (!Q_1 * !Q_0 + Q_1)$$

Now that we have defined the equations for the feedback logic, it is time to draw a schematic showing the memory registers, the next-state logic, and the inputs and outputs. **Figure 145** shows our implementation, though we have omitted the output logic section for brevity.

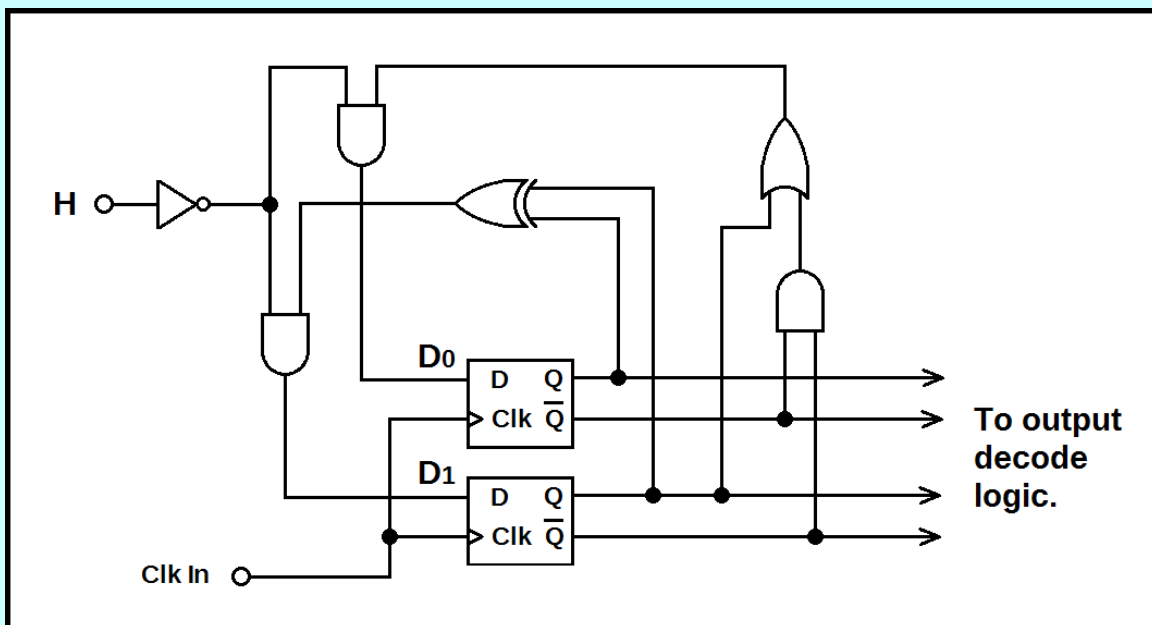


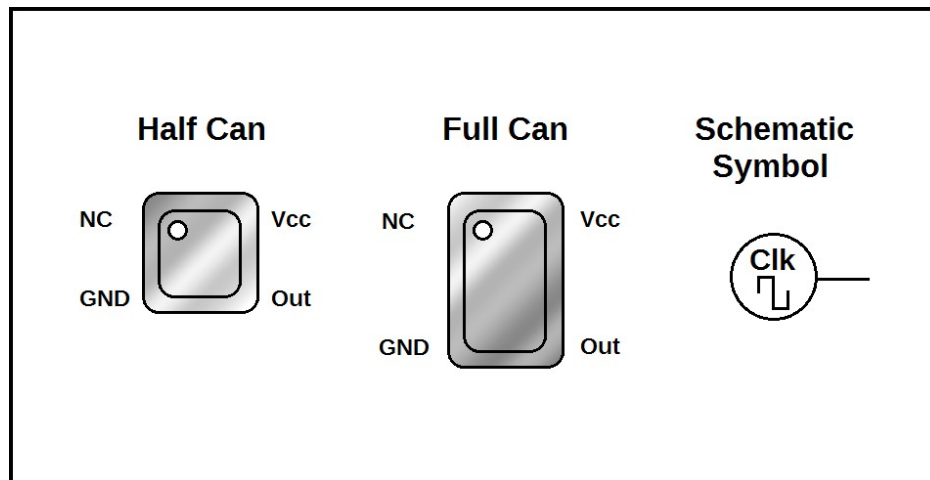
Figure 145: Schematic diagram for the implementation of the soldier problem.

## Chapter 7.9: Clock Oscillators and One-Shots

Most sequential circuits will require a clock (though there are exceptions.) It is not practical to build a clock oscillator from scratch, though for special purpose applications this may be a design requirement. It is a must that the system clock generates *isochronous* pulses in a steady stream with very little error or drift. Systems which take data must do so in absolutely equal time intervals.

### TTL Crystal Oscillators

TTL crystal oscillators are available for use in TTL circuits to provide a symmetrical square wave clock. They are inexpensive, four-pin devices that are made to fit DIP through-hole patterns. They come in either DIP or SOIC packages, or metal packages in two sizes – *full-can* (fits 14-pin DIP hole patterns) and *half-can* (fits eight-pin DIP hole patterns.) No special circuitry is required – just power, ground, and clock output. TTL crystal oscillators come in frequencies that range from 10 KHz to hundreds of MHz. **Figure 146** shows two typical TTL crystal oscillators with typical *pinout*. This should be your first choice for a system clock - they are rock-stable oscillators. They can be purchased in TTL (5V) or LVTTL (3.3V) varieties. Sometimes the NC connection (pin 1) has other functions – be careful!



**Figure 146:** Full-can and half-can TTL crystal oscillators.

### The LM555 Timer

LM555 timers are versatile eight-pin devices that can be used to provide a clock for TTL systems. LM555 timers are based on *CMOS technology* (ceramic metal oxide semiconductor.) CMOS has a wider operating voltage range: the LM555 can operate with supply voltages from +5V to +15V. The LM555 has two modes of operation: *astable mode*, and *monostable mode*.

In astable mode, the LM555 is a *free-running* oscillator. That is – once power is applied to the circuit, it will run continuously. The duty cycle and frequency of oscillation can be carefully controlled by choosing various values for the four required external components – two resistors and two capacitors. **Figure 147** shows an LM555 configured for free-running oscillation. Consult the data sheet for more information on timing with the LM555.

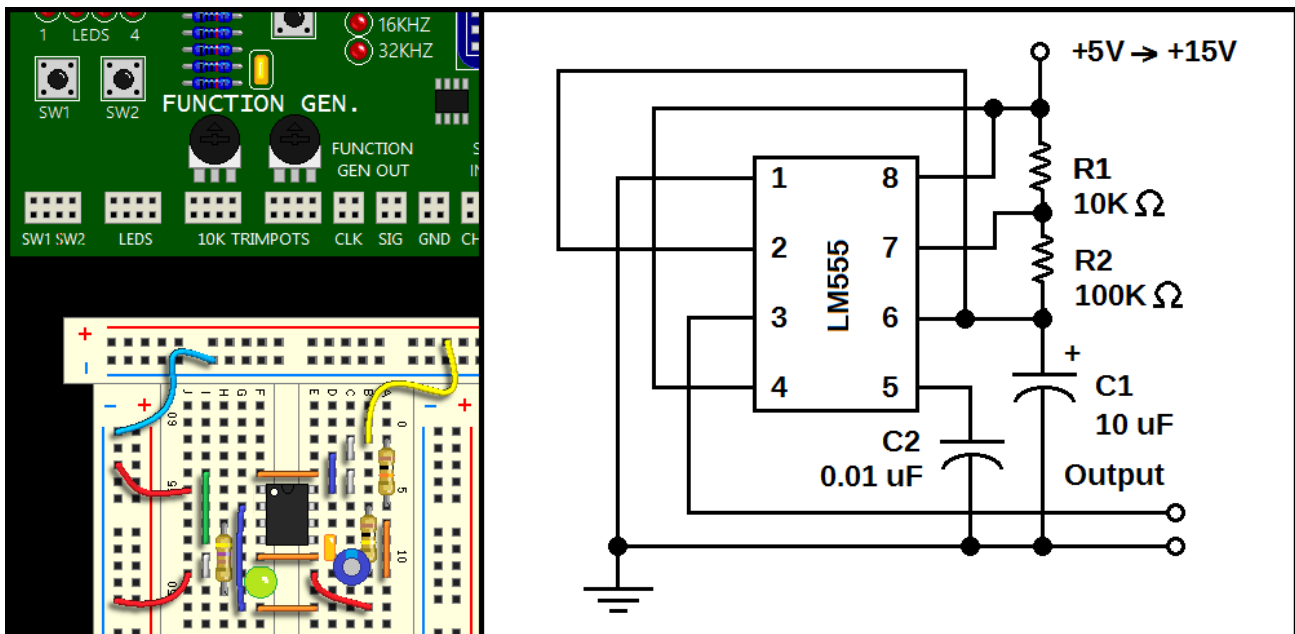


Figure 147: LM555 timer configured as a free-running oscillator.

Monostable mode differs from astable mode in that it does not run freely. The output will idle low until the circuit is triggered. Then, the output goes high and ignores all other trigger events until the circuit times out and the output goes low again. When the pulse times out, it is ready for another trigger.

**Figure 148** shows a monostable pulse circuit with a pulse delay of 0.627 seconds.

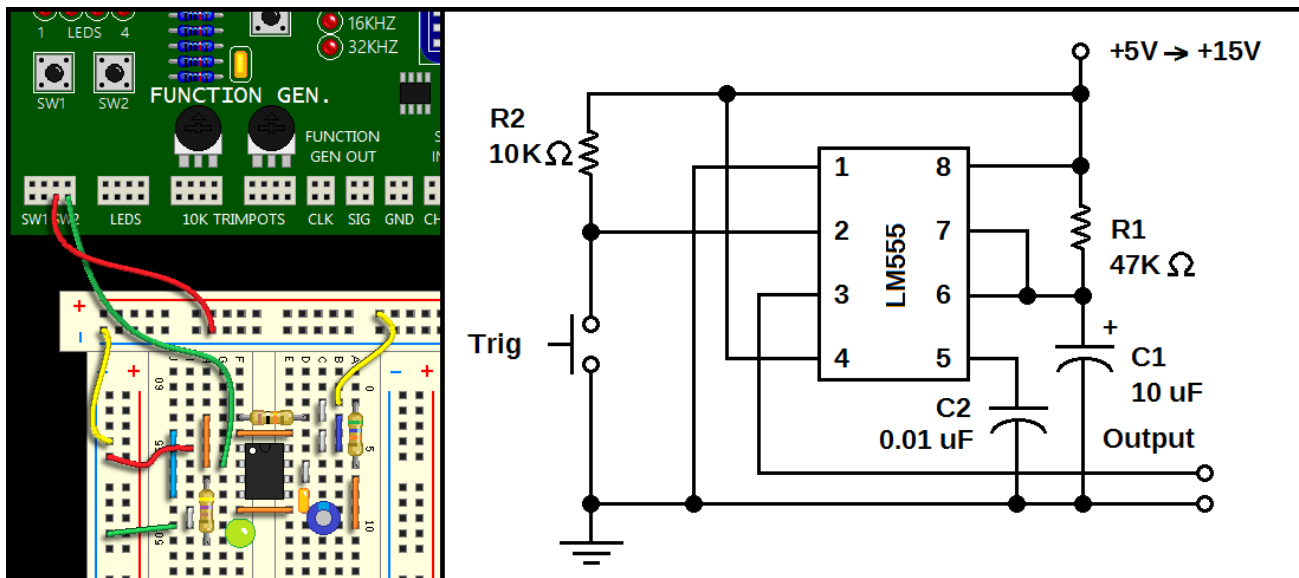


Figure 148: LM555 one-shot (monostable) timer being used as a switch debounce.

Monostable (one-shot) mode oscillator circuits have a wide variety of uses. They can be used to turn on / off a piece of equipment or circuit for a specific amount of time. The on-time of the pulse can be adjusted from fractions of a second to hours – making these ICs useful for auto-shutoff (“green technology”) circuits. Alternatively, they can be used to *debounce* switches. (Switch bounce is caused by mechanical vibrations as the switch mechanism closes.)

## Chapter 7.10: Counters

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*Counters* are digital devices that are composed of flip-flops that can *increment* or *decrement* a binary value. They often feature an up / down control line to control the count direction, and also other functions such as enable and clear. Counters are useful for keeping track of events that are too fast to tally by hand. They are also useful for measuring time – a window counter can very accurately measure time intervals. Let's have a look at how counters are constructed.

### Binary Ripple Counters

There is a simple method for constructing counters of any size. **Figure 149** shows how to gang D flip-flops into an n-bit counter (in this case we created a four-bit counter with a *carry line*.) Ripple counters are so-called, since it takes a finite amount of time for the count to *ripple* through all the flip-flops. This being so, they are useful for lower-speed applications, since propagation delay is an issue.

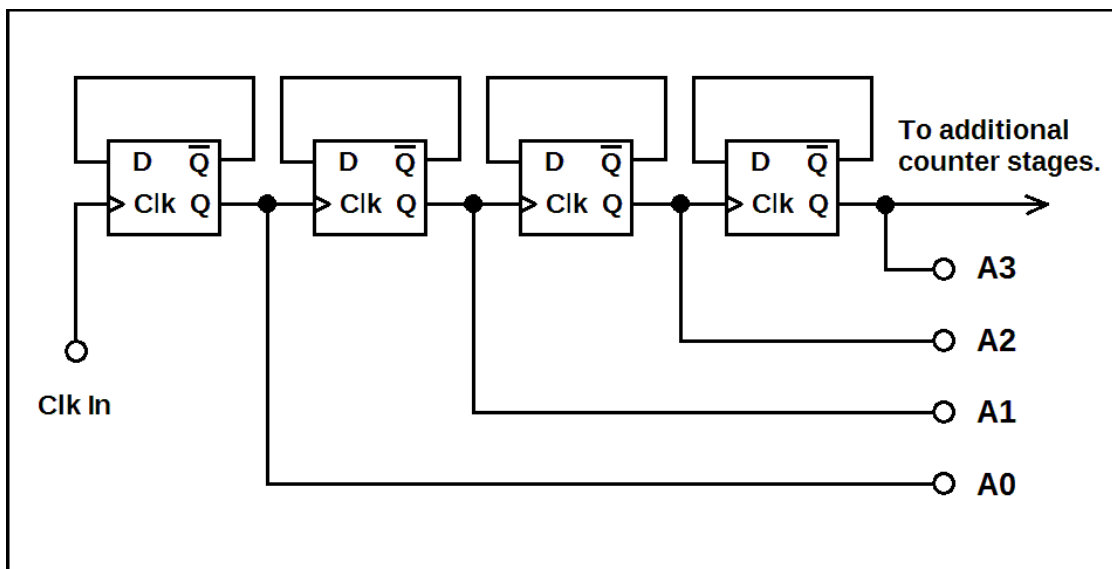
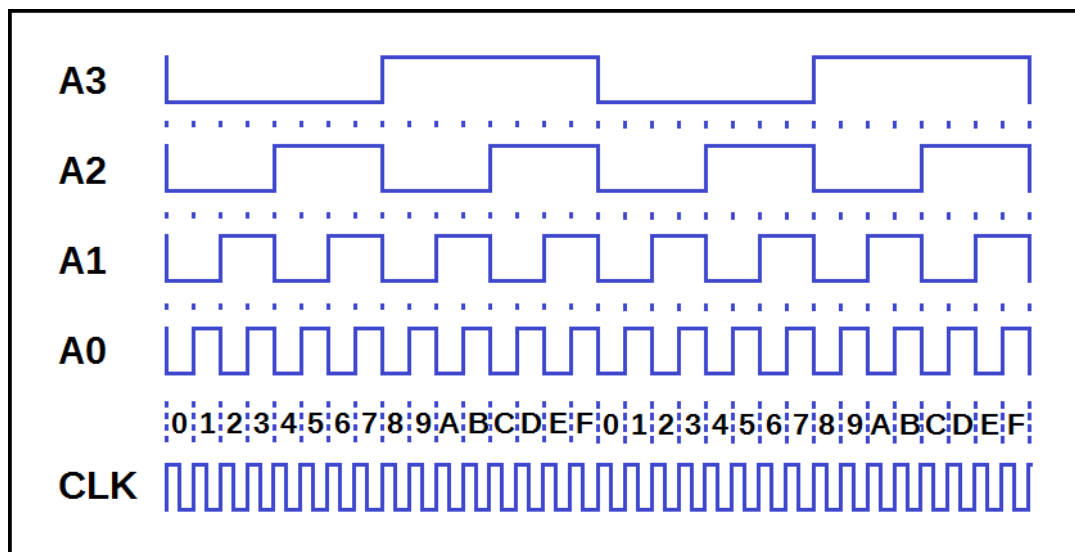


Figure 149: A ripple up counter constructed of D type flip-flops.



Each flip-flop divides its input clock frequency by two, which is how the toggling action of the D flip-flops in the diagram work. Whatever the current output  $Q$ , we are guaranteed to latch the negation of  $Q$  on the very next clock, generating a square wave at  $\frac{1}{2}$  the input clock frequency. If we plot the input signals, output signals, and clock in a graph, we obtain a *timing diagram* for the above circuit. Let's take a look at **Figure 150**. Hexadecimal values are indicated for each count. Note that the timing diagram does not show propagation delays. A TTL binary ripple counter is the 74LS93.



**Figure 150: Timing diagram for the four-bit ripple up counter from Figure 149.**

### Synchronous Binary Counters

Due to the ripple counter's problem with propagation delay, it is unsuitable for high speed applications. We may use a special type of counter called a *synchronous binary counter*. A synchronous binary counter includes a feedback logic network to handle reset and *rollover* for each discrete flip-flop. This way, we don't have to wait for the changes to propagate through all the flip-flops from LSB to MSB (least significant bit to most significant bit.)

It is convenient to use JK flip-flops to build a synchronous counter. Though deriving the equations for each bit in the counter is beyond the scope of this text, it is an interesting exercise! Remember that J and K are both inputs, and to list both in the state transition table. **Figure 151** shows a synchronous binary counter. These counters are much faster than ripple counters, and therefore are better to use in data capture equipment. A common TTL part number is the 74LS163.

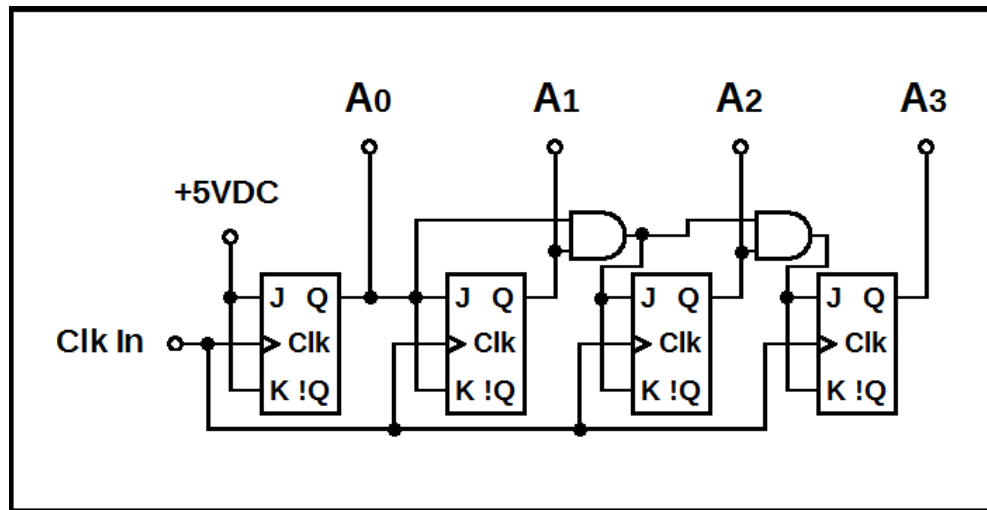


Figure 151: A synchronous up counter constructed using JK flip-flops.

### Decade Counters and Binary Coded Decimal

The 74LS90 is a special counter with divide-by-five and divide-by-two hardware. In tandem, these can be used for divide-by-ten. The output lines proceed from 0b0000 to 0b1001, and then the reset hardware loops this back to 0b0000. By using four binary lines to represent digits from digits {0 – 9}, this method of representing a number is called *binary coded decimal*, or *BCD*. **Figure 152** shows a typical test circuit. When the switch is depressed and released, the counter will increment.

The BCD scheme is useful for designing circuits that count events, such as a frequency counter or an event counter. This scheme is also useful for creating readouts for timers. Multiple counters can be cascaded to count units, tens, hundreds, etc. In order to decode the binary count, a *BCD to seven segment decoder* chip is needed. In the figure shown below, we can see the venerable 74LS47 BCD decoder / driver. If you are seeing some kind of alien writing instead of numbers, there are two possibilities: 1) the display is the wrong type (common cathode?) 2) you are displaying counts from 10 – 15. The 74LS47 will not display hexadecimal characters.

The circuit on the following page was constructed using a LT513RA common anode LED display. These are usually found in a 14 pin DIP style package. The manufacturer has omitted pins 4, 5, and 12 from the package, but count the pins just as you would any ordinary integrated circuit. Hold the display right-side-up with the number facing you, and pin 1 will be at the top left. LED displays often have nonstandard pin designations, though the example shown is typical.

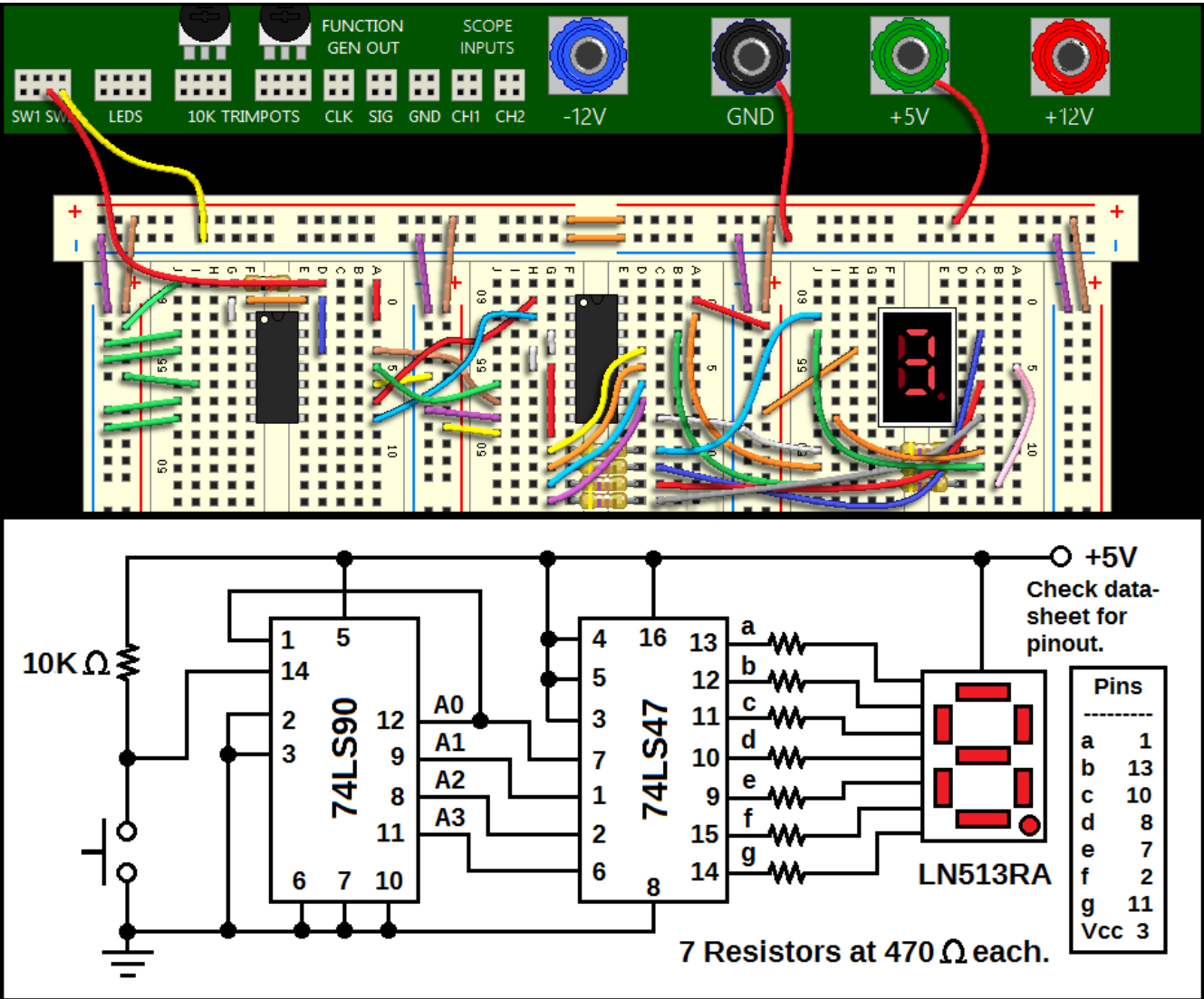


Figure 152: 74LS90 BCD counter and 74LS47 BCD decoder test circuit.

Chapter 7.11: Parallel to Serial Conversion

It is far more efficient to use one or two lines to transmit data, rather than bringing out every line from a data bus. But we are faced with a problem now – how do we tell the equipment down at the other end of the transmission line how to decode our data? Did we start at the right side or the left side of our binary number? There's more to this whole serial thing than meets the eye! And there are so many types of protocols, from UART (universal asynchronous transmit and receive,) to SPI (serial peripheral interface,) to USB (universal serial bus.) Indeed, you are surrounded by serial devices.

### Selecting One of Many Data Lines – The Multiplexer

In **Figure 153** below, we have a special circuit called a *multiplexer*. A multiplexer gives us a way to select from multiple lines of data, or for reading a particular bit in a register. The  $S_0$  and  $S_1$  inputs form a two-bit binary number that *addresses* one of four data lines  $A_0$  through  $A_3$ . Therefore, this is a 4:1 mux (read “four to one mux.”) Notice that if we present a two-bit binary value and cycle through the addresses {00, 01, 10, 11, 00, etc.} we can “read off” the bits sequentially. This way, we may construct a *data selector* that can single out only those bits or data lines of interest. An 8:1 TTL multiplexer is the 74LS151.

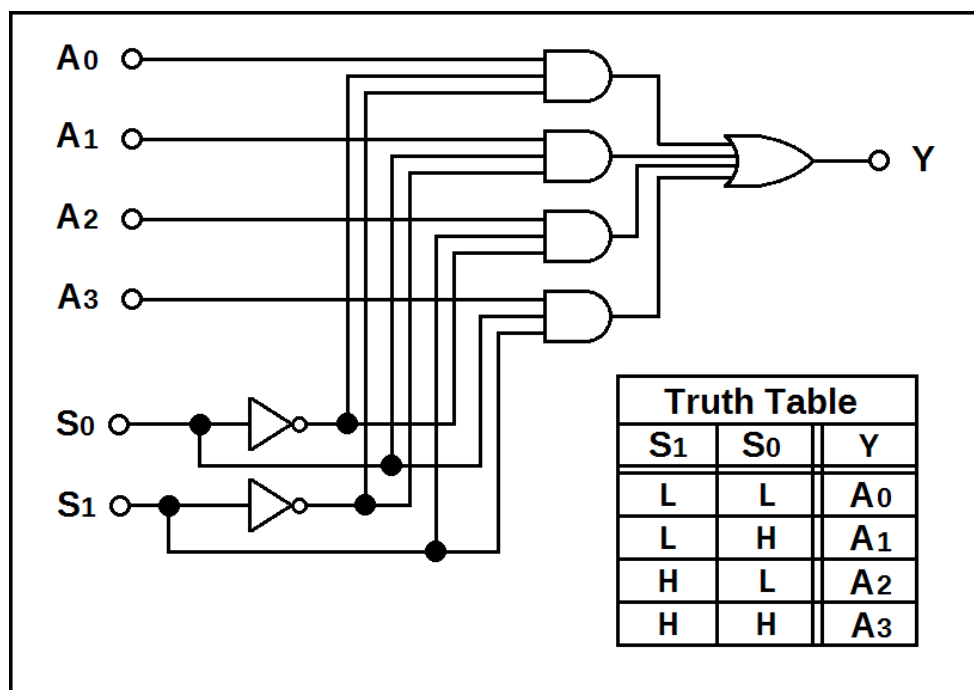
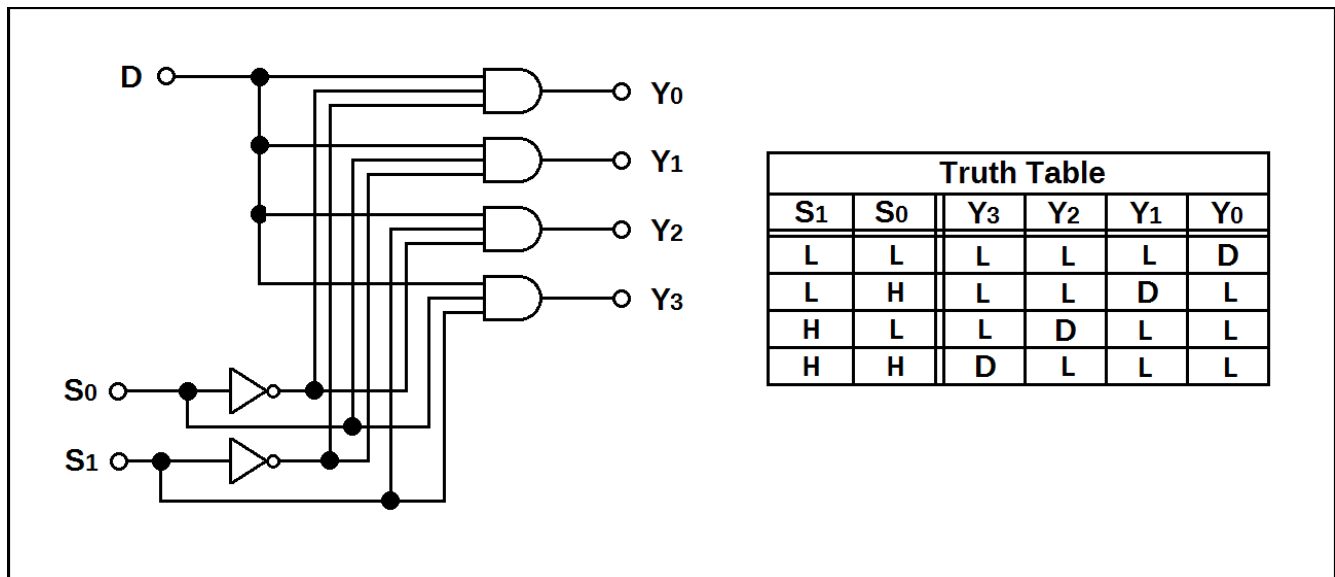


Figure 153: A 4:1 data selector / multiplexer.

### Demultiplexers and One-Hot-State Decoding

In **Figure 154** below, we have another special circuit called a *demultiplexer*. A demultiplexer gives essentially the opposite function of a multiplexer, in that it reads a single signal line and routes it to one of several receiving channels. A demultiplexer needs to know something about the current count (what bit is this?) in order to reconstruct the signals. The demultiplexer also has address lines (we will also show a 1:4 demultiplexer (say “one of four demux”) to route the input signal to the proper location.



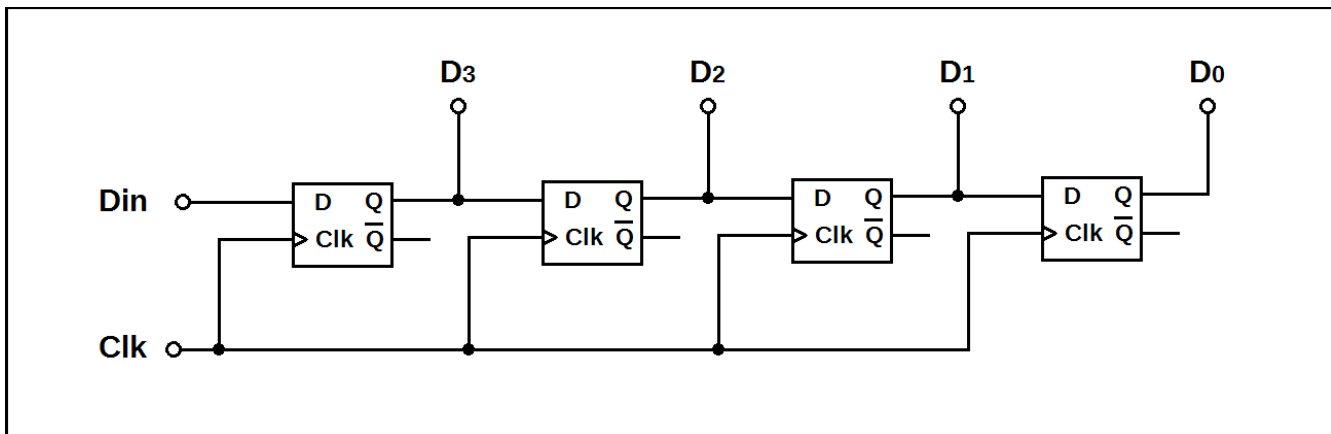
**Figure 154: A one-to-four demultiplexer.**

From the diagram above, we have a one line to four line demultiplexer. The truth table reveals that we may select one of four possible addresses for the incoming data **D**. Interestingly, we find that if we tie the input to a logical high, we can make a circuit that lights only one LED at a time. This same scheme is useful if you are needing to select one *chip enable* at a time. It is called a *one-hot-state decoder* because only one of the output lines is high at any given time. You might also feed a binary counter into the address lines and make a cute little chase light. ♥ A TTL one-to-eight demultiplexer is the 74LS138.

### **Shift Registers**

Multiplexers and demultiplexers are great – but by themselves that cannot help us with timing when converting from serial to parallel – we need a synchronous circuit. We may employ flip-flops to convert between parallel and serial communications, since we may chain them together to store serial bits as they arrive. **Figure 155** shows a serial to parallel *shift register*, four bits wide.

The D type flip-flops are used in a sort of bucket brigade to shift data. When data is present at the input **Din**, it is clocked and passed to the next flip-flop in the chain. This shift register takes four clock cycles to transmit all data presented to the input, so after four clock cycles, the serial data is now available on lines D0 – D3 in parallel. Note also that for a register of N flip-flops, we require N clocks to fully shift the data. A TTL universal shift register is the 74LS194.



**Figure 155: A four-bit shift register composed of D type flip-flops.**

## Chapter 7.12: Vocabulary Review

active low: negative logic where 0 is true and 1 is false  
 active high: positive logic where 1 is true and 0 is false  
 AND: logical function that is true if all inputs are true  
 BCD: binary coded decimal  
 bit: smallest unit of information in the digital world  
 Boolean: method of solving logic problems using symbols  
 Boolean expression: an expression where values may be true/false  
 buffer gate: a special gate that can boost an output  
 carry: a digital output used as an input to the next stage  
 combinational logic: complex functions from simple gates  
 counter: a circuit that can increment or decrement a value  
 CMOS: ceramic metal oxide semiconductor  
 debounce: a circuit that eliminates mechanical switch bounce  
 decrement: to reduce by one, to subtract from a count  
 digital: pertaining to the use of logic gates to build electronic circuits  
 falling edge: high to low transition of a clock pulse  
 fan out: the number of inputs an output must service  
 free running: an oscillator not requiring start conditions  
 finite state machine: a model of a complex time-dependent behavior  
 glitch: pulses caused by propagation delays  
 increment: to increase by one, to add to a count  
 inputs: digital logic inputs that represent variables in a logic function  
 inverter: makes the logic level opposite of the input  
 Karnaugh map: a powerful technique for minimization  
 logic gate: an electronic implementation of a Boolean logic function  
 logic high: an electrical signal meaning true ( +5V for TTL )  
 logic low: an electrical signal meaning false ( 0V for TTL )  
 minimization: reducing a Boolean expression to simplest form

minterm: any term in a truth table that yields a true in the outputs  
 NAND: not AND  
 negative logic: active low  
 next-state: the output of the feedback logic network  
 NOR: not OR  
 NOT: invert  
 open collector: a current sink output that can drive a larger load  
 operator: symbol in an expression instructing which function to use  
 OR: logic function that is true if any inputs are true  
 outputs: digital logic outputs that carry the result of a logic function  
 POS: product of sums form  
 positive logic: active high  
 propagation delay: rising edge: low to high transition of a clock pulse  
 present-state: the current state of inputs and outputs in a FSM  
 ripple counter: a counter where changes ripple from LSB to MSB  
 sink: the ability of an output to act as ground  
 SOP: sum of products form  
 source: the ability of an output to provide current  
 state: a condition or mode in a system of complex behaviors  
 state table: a table showing inputs, present state, outputs, etc.  
 state transition diagram: a bubble representation of a FSM  
 stimulus vectors: sets of input variables  
 synchronous: happening in time, not skipping a beat  
 timing: having to do with temporal effects of electronic circuits  
 timing diagram: a labeled picture of waveforms showing timing  
 transparent: data appears immediately at outputs without a clock  
 truth table: a table of high and low values used in logic design  
 XOR / XNOR: exclusive OR, exclusive NOR

## Chapter 7.13: Lab Activity 7 – Serial Transmitter / Receiver

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### Introduction

We covered serial to parallel conversion just before ending the chapter. Now we will design our own serial protocol and construct a serial transmitter / receiver pair. We will need one line for data, one line for a clock, and a data ready line. Therefore, this will be a three-wire interface.

Our protocol will transfer four bits, starting with the MSB. We will start with a set of four DIP switches, and feed these into the parallel load register of the 74LS195. A modulo-5 counter will control loading and data transfer for both registers. Therefore, this is a three-wire protocol. Once the data is loaded from the switches into the transmitter, the system clock shifts the contents of the register towards the MSB, thus sending all four bits in the nibble. The receiver uses bit shifting to reconstruct the nibble in the receiver. On each “data ready” pulse, the receiver loads its contents into a D type octal register.

### Materials

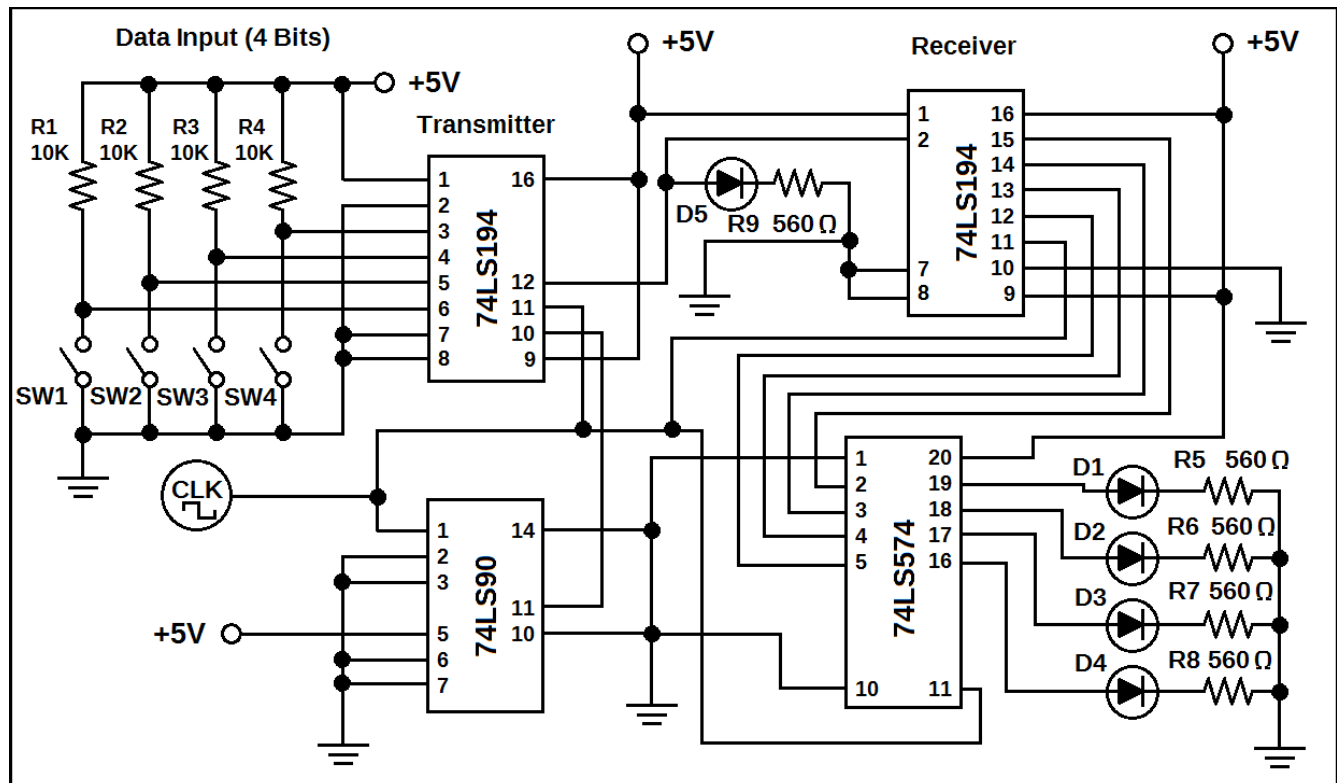
The materials required for this lab are listed in the table shown below.

Lab Activity 7 – Parts List	
Quantity	Item
1	74LS574 octal D type latch
4	10 K $\Omega$ ¼ watt resistor (brown, black, orange, and gold striped)
5	560 $\Omega$ ¼ watt resistor (green, blue, brown, and gold striped)
1	4-gang DIP switch
2	74LS194 universal shift register
5	LEDs of your favorite colors
1	74LS90 decade counter
1	LumiDax ® wiring kit
1	LumiDax ® Bakerboard Analog Trainer
1	Pair of wire cutters

**Procedure**

Make sure power is not applied to the trainer until your circuit is wired and ready to test.

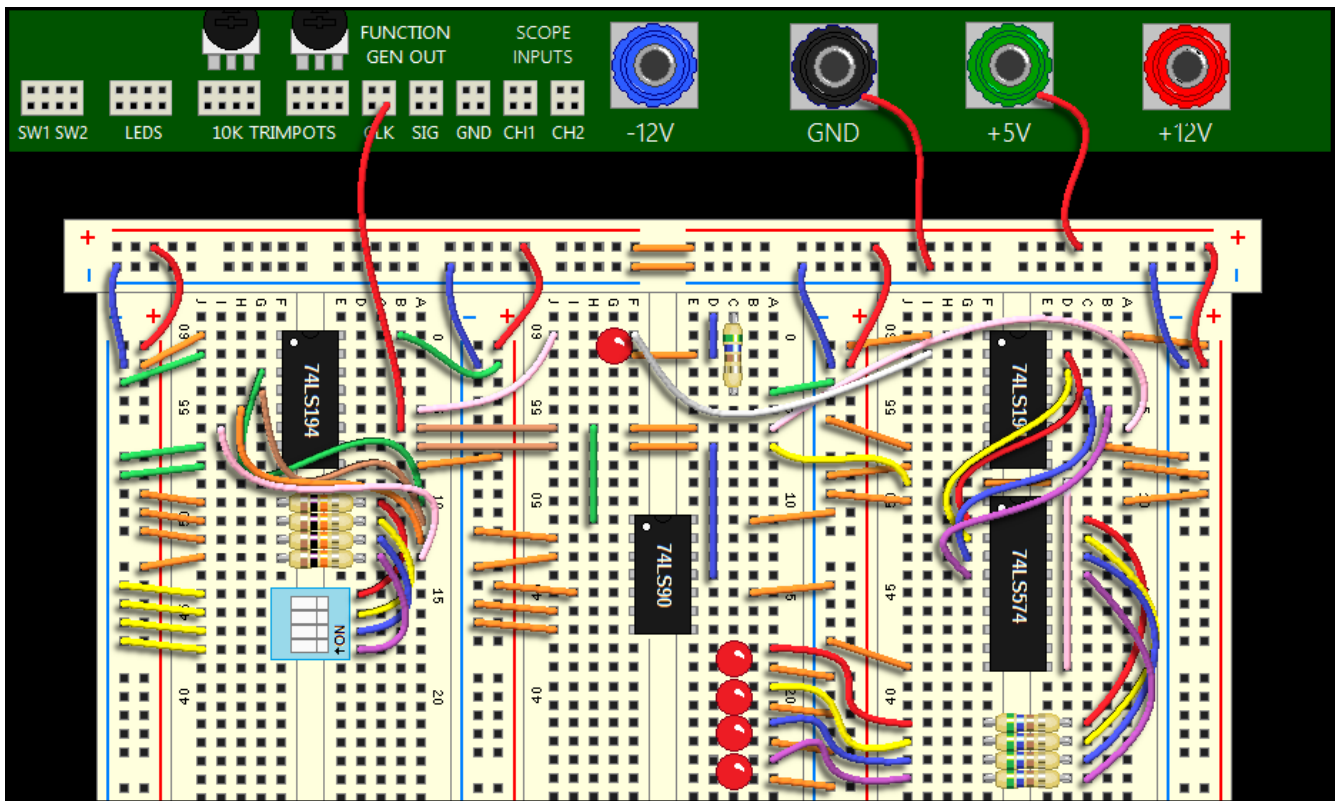
1. We will be constructing the circuit shown in **Figure 156**. Observe that the circuit has two parts – a transmit section and a receive section. Use **Figure 157** as a guide for wiring and parts placement.



**Figure 156: Serial transmitter and receiver circuit.**

2. Make sure to use the CLK output from the Bakerboard such that the frequency can be changed. Set the function generator output to the lowest setting. Apply power to the Bakerboard.
3. Note that we are using a divide-by-five counter. On the first four counts, the last data is sent on the serial line by the shift register (the LED **D5** monitors the signal line.) On the fifth count, the next data is latched to the shift register from the switches. Then, the process repeats.
4. Hook up CH1 of the scope input to pin 11 of the **74LS90** counter chip, and CH2 of the scope input to pin 12 of the **74LS194**. Adjust the frequency so that a single transfer can be seen.





**Figure 157: Physical wiring of the circuit shown in Figure 156.**

5. Try slowing the system down and changing the input switch configuration. Watch the scope traces and see how changing the input data changes the serial signal.
6. Now speed up the function generator to the fastest setting and change the switch configuration. Is the result more or less instantaneous?

### **Lab Activity 7 – Conclusion**

In this lab, you constructed a very challenging and ambitious circuit. You used a counter to count in modulo, and successfully sent data over a single signal line with a serial to parallel. And you were able to decode the signal you sent to yourself with a parallel to serial converter.

## Chapter 7.14: Exercises

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### Vocabulary Questions

1. If we use 0 as logic high and 1 as logic low, this is \_\_\_\_\_ logic.
2. When designing digital logic, minimization is helped with \_\_\_\_\_ maps.
3. A \_\_\_\_\_ uses flip-flops to increment or decrement a value.
4. When we put many signals on one line, this is called \_\_\_\_\_.
5. A \_\_\_\_\_ decoder allows only one state to be logic high at a time.
6. A \_\_\_\_\_ is a collection of latches or flip-flops for storing data.
7. \_\_\_\_\_ is a branch of mathematics concerned with true or false values.
8. \_\_\_\_\_ logic uses simple gate logic to construct complex circuits.
9. \_\_\_\_\_ logic is time-dependent and involves one or more states.
10. \_\_\_\_\_ are used to map out complex behavior in a sequential circuit.
11. The \_\_\_\_\_ outputs a logic high only when both inputs are high.
12. The \_\_\_\_\_ negates the value appearing on its input.
13. An \_\_\_\_\_ outputs high if one and only one of its two inputs is high.

### True or False

- |   |   |   |
|---|---|---|
| 1. Both positive and negative logic are used in electronics.              | T | F |
| 2. A logic high is +5V.   | T | F |
| 3. A logic low is 0V.   | T | F |
| 4. A shift register is used for changing from positive to negative logic. | T | F |
| 5. 10 could be 16, ten, or two, depending on the number system. ;-)       | T | F |
| 6. We may cascade AND and OR gates to get more inputs. (Think!)           | T | F |
| 7. Minimizing is an unnecessary step. (Careful...)                        | T | F |
| 8. We may connect two outputs together without incident.                  | T | F |

**Problems**

1. Design an XOR gate using only AND, OR, and INVERT.
2. Design a feedback network that can detect the binary number 14 on a four bit register.
3. Design a simple shift register using six D-type flip-flops.
4. Convert the following binary number to decimal and hexadecimal: 0b01101001.
5. Simplify the following Boolean expression:  $A(!B * C + B * !C) + !A(!B * C + B * !C)$
6. Draw a state transition diagram for your daily routine. Indicate any arrows or conditions.
7. In your own words, describe the process of converting from serial to parallel.

## Appendix A: Schematic Symbols

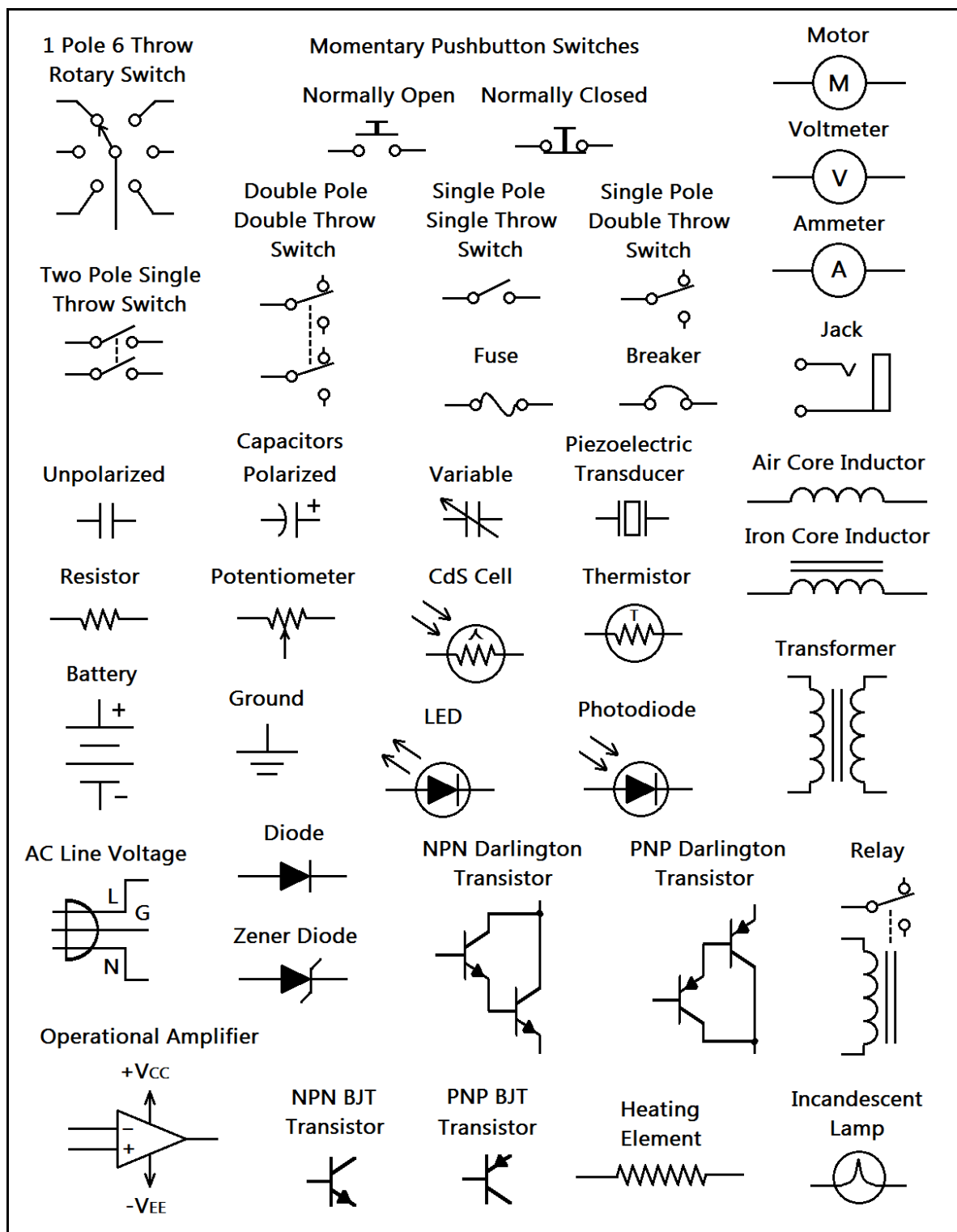


Figure 158: Common schematic symbols to remember.

## Appendix B: Formulas, Conversions, and Units

### Unit Prefix Notation

$1 \times 10^{12}$ (tera) T	$1 \times 10^{-3}$ (milli) m
$1 \times 10^9$ (giga) G	$1 \times 10^{-6}$ (micro) $\mu$
$1 \times 10^6$ (mega) M	$1 \times 10^{-9}$ (nano) n
$1 \times 10^3$ (kilo) K	$1 \times 10^{-12}$ (pico) p

### Units

1 Volt = 1 Joule / 1 Coulomb  
 1 Ampere = 1 Coulomb / 1 second  
 1 Ohm = 1 Volt / 1 Ampere  
 1 Watt = 1 Joule / 1 second = 1 Volt X 1 Ampere  
 10 dBW =  $10 \log_{10} (P_{out} / P_{in})$   
 1 Farad = 1 Coulomb / 1 Volt  
 1 Henry = 1 Weber / 1 Ampere  
 1 Coulomb =  $6.24 \times 10^{18}$  charges  
 1 Hertz = 1 cycle / second  
 1 Joule = 1 kilogram X (meters / seconds)<sup>2</sup>

### Cartesian - Polar Form Conversions

Given polar form phasor  $|Z| \angle \phi$   
 $a = |Z| \cos(\phi)$ ,  $b = |Z| \sin(\phi)$ ,  $Z = a + jb$

Given Cartesian form phasor  $Z = a + jb$   
 $|Z| = \sqrt{a^2 + b^2}$ , and  $\phi = \arctan\left(\frac{b}{a}\right)$

### Power Dissipation, DC & AC

$P = V * I$  (pure resistive power)  
 $Q = V^2 / X = I^2 * X$  (reactive power, units are VAR)  
 $S = V^2 / Z = I^2 * Z$  (apparent power, units are VA)

### DC Ohm's Law and Generalized Ohm's Law

For DC circuits with pure resistance,  
 $V = I * R$

For generalized AC impedances,  
 $V = I * Z$

### Gain Formulas

Voltage Gain (op amps):  $A_v = V_{out} / V_{in}$   
 Current Gain (transistors):  $\beta = I_c / I_b$   
 Inverting Op Amp:  $A_v = R_f / R_{in}$   
 Non-Inverting Op Amp:  $A_v = 1 + R_f / R_{in}$   
 Differential Op Amp:  $V_{out} = R_f / R_{in} (V_2 - V_1)$

### Passive Components in Series

$R_{eq} = R_1 + R_2 + \dots + R_{N-1} + R_N$   
 $L_{eq} = L_1 + L_2 + \dots + L_{N-1} + L_N$   
 $1 / C_{eq} = 1 / C_1 + 1 / C_2 + \dots + 1 / C_{N-1} + 1 / C_N$

### Passive Components in Parallel

$1 / R_{eq} = 1 / R_1 + 1 / R_2 + \dots + 1 / R_{N-1} + 1 / R_N$   
 $1 / L_{eq} = 1 / L_1 + 1 / L_2 + \dots + 1 / L_{N-1} + 1 / L_N$   
 $C_{eq} = C_1 + C_2 + \dots + C_{N-1} + C_N$

### Time Constants, Reactance, and Resonance

$\tau_{RC} = RC$   
 $\tau_{RL} = L / R$   
 $f_c = 1 / (2\pi RC)$  (for RC filters)  
 $f_R = 1 / (2\pi \sqrt{LC})$   
 $X_C = 1 / (2\pi f C)$   
 $X_L = 2\pi f L$

### AC Average Voltage, Peak to Peak, and RMS

$V_p = 1.414 \times V_{AC \text{ RMS}}$  (AC sinusoid)  
 $V_{RMS} = 0.707 \times V_p$  (AC sinusoid)  
 $V_{AVG} = 0.637 \times V_p$  (AC sinusoid)

### Digital Logic Levels

In theory,  
 Logic low = 0 V, Logic high = +5.0 V

In practice,  
 Logic low  $\leq$  +0.8 V, Logic high  $\geq$  +3.0 V

## Appendix C: Where to Buy Parts

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### **Jameco Electronics** <sup>TM</sup>

Jameco should be your first stop for buying kits. They have a wide variety of parts kits and grab bags, and many weekly deals. You can stock up on the cheap. [www.jameco.com](http://www.jameco.com)

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### **Futurlec** <sup>TM</sup>

Futurlec is an overseas company. But I would like to point out that this author had a very good experience with these folks. I ordered, but forgot my shipping payment. They sent me the parts anyway. So kind! Such good treatment is worthy of note here in this text. [www.futurlec.com](http://www.futurlec.com)

### **Agilent Technologies** <sup>TM</sup>

Agilent sent us a shipment of sample LEDs. They also have die-hard customer service, so they deserve special mention in this text. I appreciate what they have done for us. [www.agilent.com](http://www.agilent.com)

### **Electronix Express** <sup>TM</sup>

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## Solved Problems

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### Chapter 1 Solved Problems

#### Vocabulary

1. The building blocks of matter are called atoms.
2. The nucleus (or center) of an atom, contains protons, and may contain neutrons.
3. Protons have positive charge, while electrons have negative charge.
4. A conductor has an abundance of free electric charges that can flow.
5. When electrons are encouraged to drift in a direction, this flow is called current.
6. Alternating current is current that changes direction periodically.
7. The unit of measure of electric potential is the volt.
8. The unit of measure of electric current flow is the ampere.
9. An insulator prevents current flow, and keeps conductors from making contact.
10. Valence electrons are electrons found in the outermost orbitals of atoms.
11. The unit of electric charge is the Coulomb, abbreviated C.
12. A schematic diagram is a symbolic diagram showing electrical connections.

#### True or False

1. Alternating current is a steady, constant current. F
2. Neutrons have a charge of zero. T
3. A circuit is a complete path for current to flow. T
4. Electrons are heavier than protons and neutrons. F
5. Valence orbitals are found closest to the nucleus of atoms. F
6. Insulators are made of non-conductive materials. T
7. Conventional current is understood to flow from positive to negative. T
8. The ground state of an atom is it's lowest energy state. T
9. Like charges attract, and opposite charges repel one another. F
10. The electrical outlets in your home provide direct current. F

### Chapter 2 Solved Problems

#### Vocabulary

1. A useful mathematical tool connecting voltage, current, and resistance is Ohm's Law.
2. A series circuit has elements connected one after another in the same current path.

3. A parallel circuit divides current among its branches.
4. A circuit or device under power is often referred to as the load.
5. A simplified resistor that has the same resistance as a resistor network: equivalent resistor.
6. A carbon composition resistor is a resistor made with resistive material and a binder.
7. Tolerance is a measure of resistor value accuracy.
8. Power is a measure of the energy dissipated by a resistor, in Watts.
9. A multimeter is a device that can measure voltage, current, or resistance.
10. A potentiometer is a variable resistor.
11. We may use a voltage divider to get a fraction of the total voltage from a power supply.
12. A thermistor changes resistance drastically with changes in temperature.

**True or False**

1. Carbon composition resistors are low-noise, very accurate resistors. F
2. A Joule is a measure of resistance. F
3. Series circuits have the same current throughout the current path. T
4. Parallel circuits are also known as voltage dividers. F
5. A cadmium sulfide cell changes resistance with changes of light intensity. T
6. One watt is equal to one joule per second of power dissipation. T
7. A resistor's wattage should be smaller than the expected power it will dissipate. F
8. To measure voltage, a multimeter must be connected in series with the circuit. F
9. A resistor impedes the flow of current in a circuit. T
10. Some resistors can have values of millions of ohms. T

**Problems**

1. You are given a 200  $\Omega$  resistor, a 330  $\Omega$  resistor, and a 470  $\Omega$  resistor. Calculate the series combination for these resistors.

$$R_{eq} = 200\Omega + 330\Omega + 470\Omega = 1000\Omega$$

2. Calculate the parallel resistance of the resistors from the Problem 1.

$$\frac{1}{R_{eq}} = \frac{1}{200\Omega} + \frac{1}{330\Omega} + \frac{1}{470\Omega} \Rightarrow R_{eq} = 98.4\Omega$$



3. Calculate the currents and voltages for all resistors from Schematic D in Figure 27 of the lab exercise you just completed. What happens to the current when it encounters the two 470  $\Omega$  resistors in parallel?

$$\frac{12V}{220\Omega + \frac{470\Omega}{2}} = 26.4mA, \text{ so } I_{R4} = 26.4mA \text{ and } I_{R5} = I_{R6} = 13.2mA$$

$$V_{R4} = 26.4mA \times 220\Omega = 5.81V, \text{ and } V_{R5} = V_{R6} = 12V - 5.81V = 6.19V$$

4. You are tasked with providing a dropping resistor for an LED. The LED drops 1.7 V in the forward (lit) direction. You will power the LED from a +15 V power supply. You are asked to make sure the LED has a current of 15 mA (0.015 A). What value resistor should you use in series with the LED to make sure it does not burn out?

$$\frac{15V - 1.7V}{15mA} \approx 887\Omega$$

5. In Problem 4 you found a dropping resistor for the LED. But you are unsure about what wattage to use. Calculate the power dissipated by the dropping resistor. Will a ¼ W resistor work? Remember that your resistor wattage should be a factor of two higher than the expected power dissipation.

$$(15mA)^2 \times 887\Omega \approx 200mW; \text{ Marginally okay, but } 1/2 \text{ W will be better.}$$

6. Calculate the voltages and currents in each resistor from Schematic C of Figure 27 from the lab exercise.

Each resistor is 1000  $\Omega$ , and  $R_{eq} = 3000\Omega$

$$\frac{12V}{3000\Omega} = 4mA, \text{ and the current through each is the same.}$$

$$V_{R1} = V_{R2} = V_{R3} = 1000\Omega \times 4mA = 4V$$

7. You need a 25  $\Omega$ , 1 W resistor, but all you have are four 100  $\Omega$ , ¼ W resistors. Explain how you can make the 25  $\Omega$ , 1 W resistor with what you have. What is the power dissipated by each resistor with respect to total current? Will it work?

Yes. If we need a 1 W resistor, we may combine the four equal 1/4 W resistors in parallel.

$$\frac{100\Omega}{4} = 25\Omega, \text{ and the total dissipated power is equally divided among the resistors.}$$

**Chapter 3 Solved Problems****Vocabulary Questions**

1. A capacitor is measured in units called Farads.
2. An electrolytic capacitor is a capacitor made from electrolyte, and is polarized.
3. The RC time constant tells us how fast an RC circuit can charge and discharge.
4. A transformer can convert from one AC voltage to another.
5. An inductor is a coil of wire that concentrates a magnetic field.
6. A choke is an inductor that keeps out high frequencies from equipment.
7. Inductors use a magnetic field to store energy.
8. The primary is the “input” winding on a transformer.
9. The henry (H) is the unit of measure of an inductor.
10. The dielectric is the insulating material used between the plates of a capacitor.
11. To prevent damage, the working voltage of a capacitor should never be exceeded.
12. The volt-ampere rating characteristic of a transformer tells us its power capacity.
13. We may use the right hand rule to visualize the magnetic field around a wire.

**True or False**

1. It is acceptable to put capacitors in backwards if they are polarized. F
2. The Henry is the unit of measure for capacitors. T
3. A Farad is very large, and micro-Farads are used most often. T
4. Capacitors in series add together. F
5. A magnetic field is created by charges in motion. T
6. A capacitor can store energy even if the charging voltage is removed. T
7. An inductor cannot store energy the same way capacitors can. T
8. An inductor can develop hundreds of volts if current is suddenly interrupted. T
9. A step-up transformer can be turned around and used in step-down mode. T
10. A capacitor can explode if excessive voltage is applied. T

**Problems**

1. Calculate the time constant of a series RL circuit with a 20 mH inductor and a 20 KΩ resistor.

$$\tau_{RL} = \frac{L}{R} = \frac{20\text{ mH}}{20\text{ K}\Omega} = 1\mu\text{s}$$

2. A capacitor with a series resistor of  $10\text{ K}\Omega$  charges from zero to 99.5% of the applied voltage in 100 milliseconds. What is the capacitor's approximate value?

A capacitor will charge to about 99.5% in five  $\tau$ , with given series resistor.

$$\frac{100\text{ ms}}{5} = 20\text{ ms}, \quad RC = 20\text{ ms} \Rightarrow C = \frac{20\text{ ms}}{10\text{ K}\Omega} = 2\text{ }\mu\text{F}$$

3. A transformer is used to step down 120 VAC to 24 VAC. What is the turns ratio? If the VA rating for this transformer is 480 VA, what is the maximum secondary current?

The turns ratio is given by the ratio of primary voltage to secondary voltage,

$$TR = \frac{120\text{ V}}{24\text{ V}} = 5:1, \text{ and the maximum secondary current is } \frac{480\text{ VA}}{24\text{ V}} = 20\text{ A}$$

4. Calculate the equivalent capacitance of a  $470\text{ }\mu\text{F}$  capacitor, a  $100\text{ }\mu\text{F}$  capacitor, and a  $1000\text{ }\mu\text{F}$  capacitor in series.

$$\frac{1}{C_{eq}} = \frac{1}{470\text{ }\mu\text{F}} + \frac{1}{100\text{ }\mu\text{F}} + \frac{1}{1000\text{ }\mu\text{F}} \Rightarrow C_{eq} \approx 76.2\text{ }\mu\text{F}$$

5. You need an inductor that is 15 mH. But you only have three 10 mH inductors. Can you create a series-parallel equivalent inductor to get a 15 mH inductor, given no magnetic coupling?

Yes, by placing two in parallel, and one in series,

$$L_{eq} = 10\text{ mH} + \frac{1}{\frac{1}{10\text{ mH}} + \frac{1}{10\text{ mH}}} = 15\text{ mH}$$

6. You need a  $1000\text{ }\mu\text{F}$  capacitor, but you only have five  $200\text{ }\mu\text{F}$  capacitors. Is there a way to create an equivalent capacitor to get  $1000\text{ }\mu\text{F}$ ?

Yes, by placing the five  $200\text{ }\mu\text{F}$  capacitors in parallel.

$$C_{eq} = 5 \times 200\text{ }\mu\text{F} = 1000\text{ }\mu\text{F}$$

## **Chapter 4 Solved Problems**

### **Vocabulary Questions**

1. The measure of how fast a signal is oscillating is called frequency.
2. The amplitude of a signal is how "loud" it is, or how large it is.
3. The bandwidth of a bandpass filter is a measure of the size of the frequency window.
4. A parallel LC combination is also called a tank circuit.
5. The quality of a coil is also called Q, and is a defining factor for bandwidth.

6. A phasor diagram is a special diagram that helps us visualize impedance.
7. The conjugate of a complex number negates the imaginary part.
8. Reactance could be called the “AC resistance” of a reactive component.
9. Impedance is a complex resistance, and is the sum of real and imaginary parts.
10. A diode consists of a PN junction, and can block current in one direction.
11. A zener diode is used backwards (reverse bias,) and drops a precise voltage.
12. A full-wave rectifier can flip over the negative half-cycles of a sine wave for rectification.
13. A square wave is often found as a digital signal, such as TTL oscillator output.

### True or False

1. Impedance can be real, complex, or 0. T
2. Reactance varies with frequency. T
3. A high pass filter blocks high frequencies and passes low frequencies. F
4. Polar form can be expressed  $Z = a + jb$ . F
5. The RMS voltage and the peak voltage of a sine wave are the same. F
6. Amplitude is a measure of how fast a signal is oscillating. F
7. A tank circuit takes on a very high impedance at resonance. T
8. Capacitors and inductors do not ideally dissipate any power. T
9. PWM is used to control power by varying pulse width. T
10. A series RLC circuit is purely resistive at resonance. T

### Problems

1. You are given a sine wave with a peak voltage of 10 V<sub>p</sub> and a frequency of 10 KHz. What is the period (the time it takes to complete one cycle?) What is the RMS voltage? What is the peak-to-peak voltage?

$$T = \frac{1}{10 \text{ KHz}} = 100 \mu s, V_{RMS} = 10 V_{AC} \times 1.414 = 14.14 V_p, V_{pp} = 2 \times V_p = 28.28 V$$

2. A DC voltage of +24 V powers a load, which draws 2 W of power. What is the RMS voltage of an AC sine wave that would dissipate the same power? Would the peak voltage of the AC waveform be higher than the DC voltage?

Trick question. The AC RMS voltage *is* the effective DC voltage.

$$V_{RMS} = 24 V_{AC}, V_p \text{ is higher. } V_p = 24 V_{RMS} \times 1.414 = 33.94 V$$

3. A transformer with a 12 VAC (RMS) secondary feeds a bridge rectifier. Given that the diodes in the bridge are silicon type diodes, what is the peak of the output rectified waveform? Hint: consider that only two diodes conduct at one time in series.

The peak output of the bridge rectifier is the peak voltage minus the diode drops,  
 $12 V_{AC} \times 1.414 - 2 \times 0.7 V = V_p - 2 V_{diode} = 15.57 V_p$

4. If the current delivered by the power supply in Figure 69 is one amp maximum, calculate the wattage of the resistor R1 needed for safe operation.

The resistor is  $1 \Omega$ . At  $1 A$  maximum current,

$$P_{R1} = (1 A)^2 \times 1 \Omega = 1 W, \text{ and we want twice this power rating: } 2W.$$

5. A 2.5 KHz, 10 VAC sine wave is used as an input to a  $2200 \Omega$  resistor and a  $4.7 nF$  capacitor in series. Calculate the voltages across both the resistor and capacitor, and the total current for the network. Give your answer in polar form, showing the phase shift.

The impedance in rectangular form is given by,  $Z_{total} = R + j(X_L - X_C)$

$$Z_{total} = 2200 \Omega - j13545 \Omega, |Z_{total}| = \sqrt{2200^2 + 13545^2} \Omega \approx 13723 \Omega,$$

$$\phi = \arctan\left(-\frac{13545}{2200}\right) \approx -80.7^\circ, \text{ and in polar form, } Z_{total} = 13723 \angle -80.7^\circ$$

$$I_{RC} = \frac{V}{Z_{total}} = \frac{10 V \angle 0^\circ}{13723 \Omega \angle -80.7^\circ} \approx 729 \mu A \angle 80.7^\circ, \text{ current leads.}$$

$$V_R = I_{RC} Z_R = 2200 \Omega \angle 0^\circ \times 729 \mu A \angle 80.7^\circ = 1.604 V \angle 80.7^\circ,$$

$$V_C = I_{RC} Z_C = 13545 \Omega \angle -90^\circ \times 729 \mu A \angle 80.7^\circ = 9.874 V \angle -9.3^\circ, \text{ voltage lags.}$$

6. Design a bandpass RC filter with a lower cutoff frequency of 20 KHz and an upper cutoff frequency of 200 KHz.

We make sure to stay away from  $pF$  range capacitors and  $M \Omega$  range resistors.

The high pass filter should have the lower cutoff frequency. We select a  $10 nF$  capacitor.

$$f_{CL} = \frac{1}{2\pi RC} \Rightarrow R = \frac{1}{2\pi \times 10 nF \times 20 KHz} \approx 796 \Omega$$

The low pass filter should have the upper cutoff frequency. We select a  $1 nF$  capacitor.

$$f_{CH} = \frac{1}{2\pi RC} \Rightarrow R = \frac{1}{2\pi \times 1 nF \times 200 KHz} \approx 796 \Omega$$

**Chapter 5 Solved Problems****Vocabulary Questions**

1. The ratio of output voltage to input voltage is called the voltage gain of an amplifier.
2. The BJT, or bipolar junction transistor, is a transistor that can either be NPN or PNP.
3. An integrated circuit is a functional drop-in circuit module available in DIP packages.
4. Current gain is also called beta gain, or  $\beta$ .
5. The voltage follower (or emitter follower) is a circuit that has a voltage gain of unity.
6. A comparator is a circuit that has two output states, usually rail-to-rail operation.
7. An inverting amplifier is an amplifier that flips the output waveform phase 180 degrees.
8. The Darlington pair is a pair of transistors in one package with high gain.
9. The open loop voltage gain of an op amp can be a million or more.
10. The gain bandwidth product is the frequency where an op amp has a gain of unity.
11. A Sallen-Key filter is a second order filter that uses four resistors and two capacitors.
12. The CMRR is a measure of how well an op amp can block signals common to both inputs.
13. A bias network is used to set a transistor's quiescent point.

**True or False**

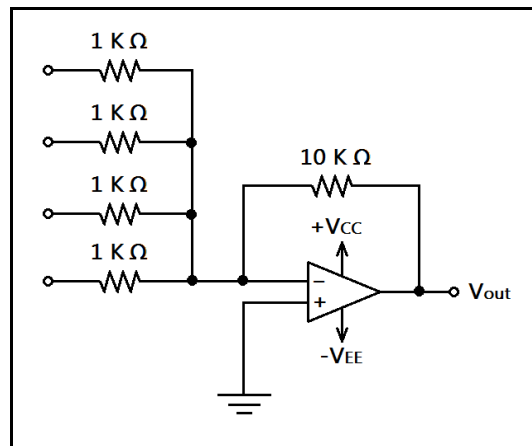
1. Transistors have a voltage gain called  $\beta$ . F
2. Op amps can amplify signals higher than their gain bandwidth product. F
3. A push-pull amplifier is better and safer if driven with an op amp. T
4. A transistor can switch loads on their collector or their emitter. T
5. An integrator circuit is also a first order high pass filter. F
6. Op amps have incredibly high open loop gain in the millions. T
7. Op amps have low input impedance and very high output impedance. F
8. Transistor amplifiers must be biased very carefully to amplify correctly. T
9. Active filters may be cascaded to increase the filter order. T
10. Unity gain means a gain factor of zero. F

**Problems**

1. Design a summing amplifier that has a gain of 10 on each input channel, and has four inputs.

We refer to **Figure 95**. We select  $10\text{ K}\Omega$  for feedback resistance, and  $1\text{ K}\Omega$  for each of the inputs.

$$A_v = \frac{R_f}{R_{in}} = \frac{10\text{ K}\Omega}{1\text{ K}\Omega} = 10$$



**Figure 159: Circuit design for Problem 1.**

2. Compute the value of a base current that will yield a collector saturation current of 500 mA given a transistor with a gain of 150. What input voltage is needed to achieve this saturation current if given a 1 KΩ resistor on the base? Do not neglect the diode drop.

$$\text{We note that } I_b \beta = I_c \Rightarrow I_b = \frac{I_c}{\beta} = \frac{500 \text{ mA}}{150} = 3.33 \text{ mA}$$

$$\begin{aligned} \text{The resistor voltage drop is, } V_R &= 1 \text{ K}\Omega \times 3.33 \text{ mA} = 3.33 \text{ V}, \\ V_{bias} &= 3.33 \text{ V} + 0.7 \text{ V} = 4.03 \text{ V} \end{aligned}$$

3. Design a circuit that uses a Darlington NPN transistor to turn on a 24 VDC lamp with an on-current of one ampere, if given a TTL input. Assume a gain of 1000, and that the load is on the collector side. Do not use a relay. What value of base resistor will work for legal TTL levels?

We refer to **Figure 83**, replacing the relay coil with a lamp. We need to compute base current.

$$I_b = \frac{I_c}{\beta} = \frac{1 \text{ A}}{1000} = 1 \text{ mA}$$

We choose a worst-case for the logic high voltage: 3.0V.

$$V_{bias} - V_{CE} = V_R, \quad 3.0 \text{ V} - 1.4 \text{ V} = 1.6 \text{ V}$$

$$R_B = \frac{1.6 \text{ V}}{1 \text{ mA}} = 1.6 \text{ K}\Omega$$

Saturation occurs at 3.0V and this resistor will work for any legal high.

4. Design a Sallen-Key low pass filter with a cutoff frequency of 10 KHz.

We refer to **Figure 103**. Select  $R_1 = R_2$  and  $C_1 = C_2$ . Let  $R_3 = R_4 = 1 \text{ K}\Omega$  for a gain of 2.

$$\text{Choose } 10 \text{ nF} \text{ for capacitors. Then } R_1 = R_2 = \frac{1}{2\pi f_c C} = \frac{1}{2\pi \times 10 \text{ KHz} \times 10 \text{ nF}} = 1592 \Omega$$

5. Create a relaxation oscillator with a frequency of 1 KHz using an op amp. Choose any resistor or capacitor combination to achieve this.

We refer to **Figure 101**. We choose  $R_2 = R_3 = 1\text{ K}\Omega$ ,  $\alpha = \frac{R_2}{R_2 + R_3} = \frac{1}{2}$

$$f_{osc} = \frac{1}{2R_f C \ln\left(\frac{3/2}{1/2}\right)} = \frac{1}{2R_f C \ln(3)}, \text{ choose } C = 100\text{ nF}.$$

$$R_f \approx \frac{1}{2.197 \times 1\text{ KHz} \times 100\text{ nF}} = 4551\Omega$$

6. Design a second order bandpass filter with a lower cutoff frequency of 10 KHz and an upper cutoff frequency of 100 KHz.

We may cascade a Sallen-Key low pass filter and a Sallen-Key high pass filter.

The design procedure is similar to that of a passive RC bandpass filter.

We make sure to stay away from  $pF$  range capacitors and  $M\Omega$  range resistors.

We refer to **Figures 103** and **104**.

Choose  $R_1 = R_2$ ,  $C_1 = C_2$  for each filter, and  $R_3 = R_4 = 1\text{ K}\Omega$  for both filters.

The high pass filter should have the lower cutoff frequency. We select a  $10\text{ nF}$  capacitor.

$$f_{CL} = \frac{1}{2\pi RC} \Rightarrow R = \frac{1}{2\pi \times 10\text{ nF} \times 10\text{ KHz}} \approx 1592\Omega$$

The low pass filter should have the upper cutoff frequency. We select a  $1\text{ nF}$  capacitor.

$$f_{CH} = \frac{1}{2\pi RC} \Rightarrow R = \frac{1}{2\pi \times 1\text{ nF} \times 100\text{ KHz}} \approx 1592\Omega$$

The gain within the bandpass window is the product of each filter's gain:  $2\left(1 + \frac{R_3}{R_4}\right) = 4$

7. Design a non-inverting amplifier with a gain of 100.

We refer to **Figure 91**. We choose  $R_f$  and  $R_g$  such that  $\frac{R_f}{R_g} = 99$ , since  $A_v = \left(1 + \frac{R_f}{R_g}\right)$

Let  $R_f = 99\text{ K}\Omega$  and  $R_g = 1\text{ K}\Omega$ ,  $A_v = \left(1 + \frac{99\text{ K}\Omega}{1\text{ K}\Omega}\right) = 100$

8. A differential amplifier has a gain of 1000 and an output voltage of -10 V. What is the difference of the input signals? What does the negative output voltage mean?

With a gain of 1000, that means the difference in the input signals is 10 mV.

The negative sign means the inverting input is positive with respect to the non-inverting input.



**Chapter 7 Solved Problems****Vocabulary Questions**

1. If we use 0 as logic high and 1 as logic low, this is negative logic.
2. When designing digital logic, minimization is helped with Karnaugh maps.
3. A counter uses flip-flops to increment or decrement a value.
4. When we put many signals on one line, this is called multiplexing.
5. A one-hot-state decoder allows only one state to be logic high at a time.
6. A register is a collection of latches or flip-flops for storing data.
7. Boolean algebra is a branch of mathematics concerned with true or false values.
8. Combinational logic uses simple gate logic to construct complex circuits.
9. Sequential logic is time-dependent and involves one or more states.
10. State transition diagrams are used to map out complex behavior in a sequential circuit.
11. The AND gate outputs a logic high only when both inputs are high.
12. The inverter negates the value appearing on its input.
13. An exclusive OR outputs high if one and only one of its two inputs is high.

**True or False**

1. Both positive and negative logic are used in electronics. T
2. A logic high is +5V. F (why?)
3. A logic low is 0V. F (why?)
4. A shift register is used for changing from positive to negative logic. F
5. 10 could be 16, ten, or two, depending on the number system. ;-) T
6. We may cascade AND and OR gates to get more inputs. (Think!) T
7. Minimizing is an unnecessary step. (Careful...) F
8. We may connect two outputs together without incident. F

**Problems**

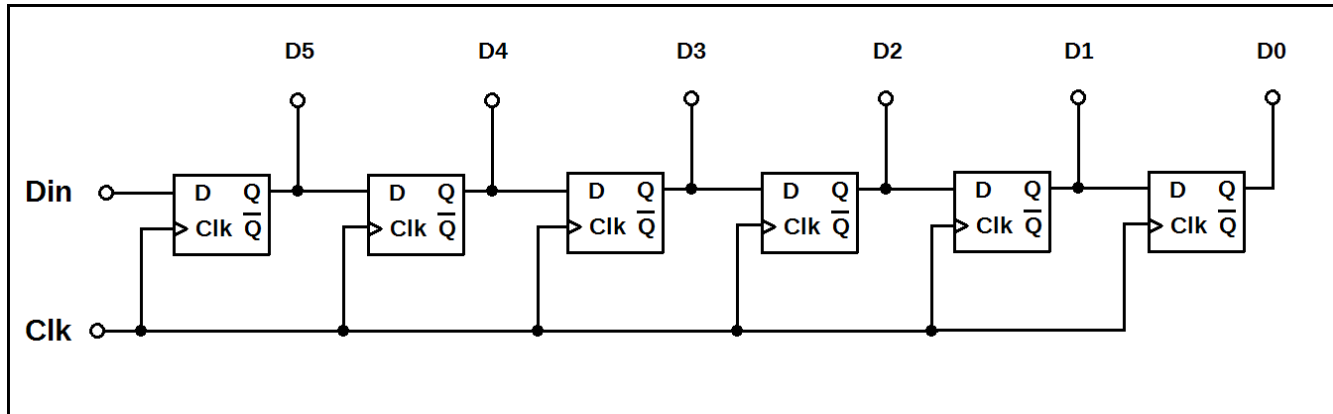
1. Design an XOR gate using only AND, OR, and INVERT.

$$Y = !A * B + A * !B$$

2. Design a feedback network that can detect the binary number 14 on a four bit register.

$$Y = D * C * !B * A$$

3. Design a simple shift register using six D-type flip-flops.



**Figure 160: Six bit register design for problem 3.**

4. Convert the following binary number to decimal and hexadecimal: 0b01101001.

$$0b01101001 = 0x69 = 6 \cdot 16 + 9 = 105_{10}$$

5. Simplify the following Boolean expression:  $A(!B * C + B * !C) + !A(!B * C + B * !C)$

$$\mathbf{B \oplus C}$$

6. Draw a state transition diagram for your daily routine. Indicate any arrows or conditions.

Answers may vary. :-)

7. In your own words, describe the process of converting from serial to parallel.

Answers may vary. :-)