

CT GUIDE

SAC Engineering

This document provides background information on topics covered in various courses and laboratories taught by Dr. T (his initials are CT, thus the name "CT Guide").

It includes important conceptual topics like units, unit conversion, physics, math, electricity, electric circuits, controls, and more. It also contains practical information on related to the lab: safety, electric circuits, electric components, lab tools, equipment, supplies, and more. The topics in this document apply to multiple courses taught by Dr. T, including, but not limited to, the electric circuits and mechatronics laboratories.

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***** SAFETY & CARE *****

CHAP 1 - SAFETY & CARE

Safety is the NUMBER ONE PRIORITY in any laboratory!

The laboratory MUST be a SAFE environment. Courses with laboratory exercises may involve the use of different tools and equipment. The lab equipment is generally safe to use, but they can still pose a danger to any one if not used properly.

Lecture courses conducted in the laboratory space require students to follow this simple rule:

DO NOT TOUCH ANY OF THE LAB TOOLS OR EQUIPMENT.

It is critical that students understand and follow some basic laboratory practices.

Some SIMPLE COMMON SENSE RULES that will help you be safe in lab

1. Always BE CAREFUL (ABC!)
2. Always THINK about what you are doing.
3. Read about and learn how to use any tools or equipment before using them.
4. If you do not know how to use any tool or equipment, ASK the instructor before using them.

VIOLATIONS

Any student in violation of any safety practices MUST fill out an "Incident Report." Also students are REQUIRED to report any incidents, including any injuries, incidents, or safety violations. An incident report will be provided for your use. Students who fail to follow the instructions above or who repeatedly demonstrate improper practices may be restricted from using the equipment or engaging in laboratory activities.

1.1 General Safety Topics

1. Use common sense
2. THINK – about what you are doing before you do it.
3. BE AWARE of your surroundings. This can save you from a serious accident or injury.
4. NO running or horseplay
5. NEVER use or touch a piece of equipment until you have been trained and released to work on it.
6. NO cell phone use or socializing when using equipment (distractions, loss of focus/awareness)
7. Keep body parts at least several inches from any cutting tools (drills, saws, endmills, cutters).
8. Never "drive" a tool towards your body (e.g., hold an object in hand while using/pushing screwdriver)
9. Never reach into a machine while it is moving.
10. Don't blow air on yourself (you can blow stuff in your eye, or damage your ears).

11. CAUTION – machined/drilled material will leave sharp edges or burrs, which are like small razor blades. Be careful how you handle them
12. If you start to drop a sharp object, do not try to catch it – step back and allow it to fall to the floor.
13. Equipment damaged due to negligence will not be replaced. It will be gone forever, adversely affecting the class.

1.2 Safety Exam

All students must pass a safety exam before they can use the equipment listed here: lasers, 3D printers, drill press, band saw, tensile tester, mill, lathe, robot, PLC system, and scanner. This helps to ensure student safety and equipment care. Students must score at least **90%** on the safety exam before they can use the lab equipment.

1.3 Equipment-that-Moves Safety

Any equipment that moves including machining equipment (drill press, band saw, mill), PLC, robot arm, and power tools can be particularly dangerous.

1. Keep hands and fingers away from moving or rotating machine elements or cutters.
2. NEVER point a finger at a moving/rotating machine element (drill press, mill, lathe, band saw). Instead use a stylus (pencil).
3. Always TIE BACK long hair.
4. Always wear EYE PROTECTION for any activity that can project material into your eye. Eg – this power tools like sanders, hand drills, band saw, drill press, Dremel tools, etc.)
5. NEVER wear any item that can get caught in the machine (see below).
6. NO jewelry (rings, dangling earrings, bracelets, watches) or dangling items (necklaces),
7. ONLY short sleeves, NO long sleeves. NO loose, dangling clothing.
8. Clothing – short sleeve shirts, no collared shirts, no dangling items (ties),
9. Be careful how you handle cutters – they are SHARP.
10. Always take your time on equipment and be deliberate. Never rush!

1.4 Safety on Specific Equipment

In addition to the safety items above, be aware of these ADDITIONAL safety items on specific equipment.

1.4.1 - Laser Engraver

1. Light reflecting off the part is considered safe, but avoid looking at it for more than a few moments.
2. Attend the machine while your jobs runs (don't walk away) as there is a fire risk
3. ALWAYS run the filtration system to keep odors minimized.
4. Never reach into the machine while the laser head is moving (pinching or catch risk).

1.4.2 - Drill Press

1. NEVER leave the chuck key in the chuck! (It can become a projectile. #1 injury in the shop)
2. Clamp down material instead of trying to hold it using your hands.

1.4.3 - Band Saw

1. Use vise for round pieces (don't try to hold with hand)
2. Keep your hands away from the blade (at least 3", use the push stick to push the work piece).

1.4.4 - Soldering Iron

1. Keep all body parts away from the heated end. Severe burns will result.
2. Avoid inhaling fumes. Use the snorkels or a portable filter system.
3. The heated end may take a long time to cool off.
Do not touch the end at all even if you think it has cooled.
4. Wear eye protection. Splattering solder flux can injure the eye.

1.4.5 - Amatrol PLC

1. DO NOT reach into the machine while it runs. Turn it off first.
2. Ensure no people or foreign objects are near the machine before turning it on.

1.4.6 - Fanuc Robot

1. DO NOT reach into the machine while it runs. Turn it off first.
2. Ensure no people or foreign objects are near the machine before turning it on.

1.4.7 - 3D Printer

1. Do not touch the bed or the extruder head as they are heated and can cause severe burns.
2. Keep your hands away from the extruder head or build area when the printer is running.
3. Use a tool to remove break-away support from models.
4. Wear eye protection when removing support material (pieces can fly!)

1.4.8 - Manual or CNC Mill

1. Only 1 operator at a time (no teams)
2. For the CNC, keep doors closed.

1.5 Electricity & Circuit Safety

1. ALWAYS keep power to a circuit disconnected while altering the circuit.
2. NEVER connect a voltage source directly to another voltage source (or ground). (ie - NO short circuits!)
E.g., do not connect the 5V supply on Arduino directly to GND (ground or 0V)!
3. Never stick wires into the cooling vents or holes in a piece of equipment (plugged in or not)

1.6 Care

Students must take care of the following items so that we can continue to offer this lab course to future students.

1. Yourself
2. Others
3. The laboratory and all the stuff in it (equipment, tools, furniture, etc.)

CARE FOR YOURSELF & OTHERS

Be aware of your surroundings and think about everything you are doing. Careless action on your part can endanger you and your classmates.

CARE FOR THE LABORATORY

Please be careful not to mar, cut, chip, or scratch the counters.

Do NOT write on the counters.

Be careful with any lab tools or supplies.

Completely clean up your area when you are done (return tools, supplies to their proper location).

CARE FOR EQUIPMENT

1. ALWAYS carry each piece of electronic equipment with TWO (2) HANDS!
2. NEVER carry more than 1 piece of equipment at the same time (to avoid drops).
3. Make sure equipment is OFF before plugging it in.
4. Never drop or bang the equipment. Sensitive electronics are easily damaged.
5. If you don't know how to use a piece of equipment, ask the instructor beforehand.
6. Never stick wires or any other conductive part into an electrical socket.
7. Our breadboards are designed for 22 AWG or smaller wire sizes (meaning larger AWG number, like 24 AWG). Inserting larger sized wires (20, 18, 16 AWG) can damage the breadboard.

Read the posted handouts on the equipment you are to use.

Also do not perform any operation on a machine unless we have first showed you how to do it. Please do not pull, yank, hammer, push, fiddle, etc. on any portion of the equipment in order to try to accomplish something.

ELECTRICAL POWER

Our equipment will need AC electrical power. Utilize the workbench power plugs or power strips mounted to the workbenches. Please do not unplug power strips.

1.6.2 - Laptop Use

Students are free to use the lab laptops. Refer to the posted instructions on how to check out, use, and return laptops. Students MUST follow these instructions or their laptop use privileges may be revoked.

1.7 Clean Up

Students must clean up after themselves (it is not the instructor's job). It is their responsibility, and it is part of their grade. The instructor will announce clean up time (often about 15 minutes before the end of the lab period) but it can be at any time. At that point, please begin cleaning up your lab workbench immediately. Return all equipment and parts as indicated in other sections. Then clear your work area of any scraps (wire remnants, stripped off insulation, etc.) and place them into the trash (don't just wipe debris onto the floor). Also clean up any scraps that have fallen to the floor in your area. We have brooms and dustpans.

After cleaning up and returning equipment, inform the instructor you are ready to leave.

WIPE DOWN YOUR WORK AREA WITH GLASS CLEANER OR ALCOHOL when you are done.

***** CLEAN UP & STORAGE (250L) *****

CHAP 2 - CLEAN UP & STORAGE (250L)

This entire chapter is applicable to the Engr 250L class.

2.1 Engr 250L Clean Up

Students must clean up after themselves (it is not the instructor's job). It is their responsibility, and it is part of their grade. The instructor will announce clean up time (often about 15 minutes before the end of the lab period) but it can be at any time. At that point, please begin cleaning up your lab workbench immediately. Return all equipment and parts as indicated in other sections. Then clear your work area of any scraps (wire remnants, stripped off insulation, etc.) and place them into the trash (don't just wipe debris onto the floor). Also clean up any scraps that have fallen to the floor in your area. We have brooms and dustpans.

After cleaning up and returning equipment, inform the instructor you are ready to leave.

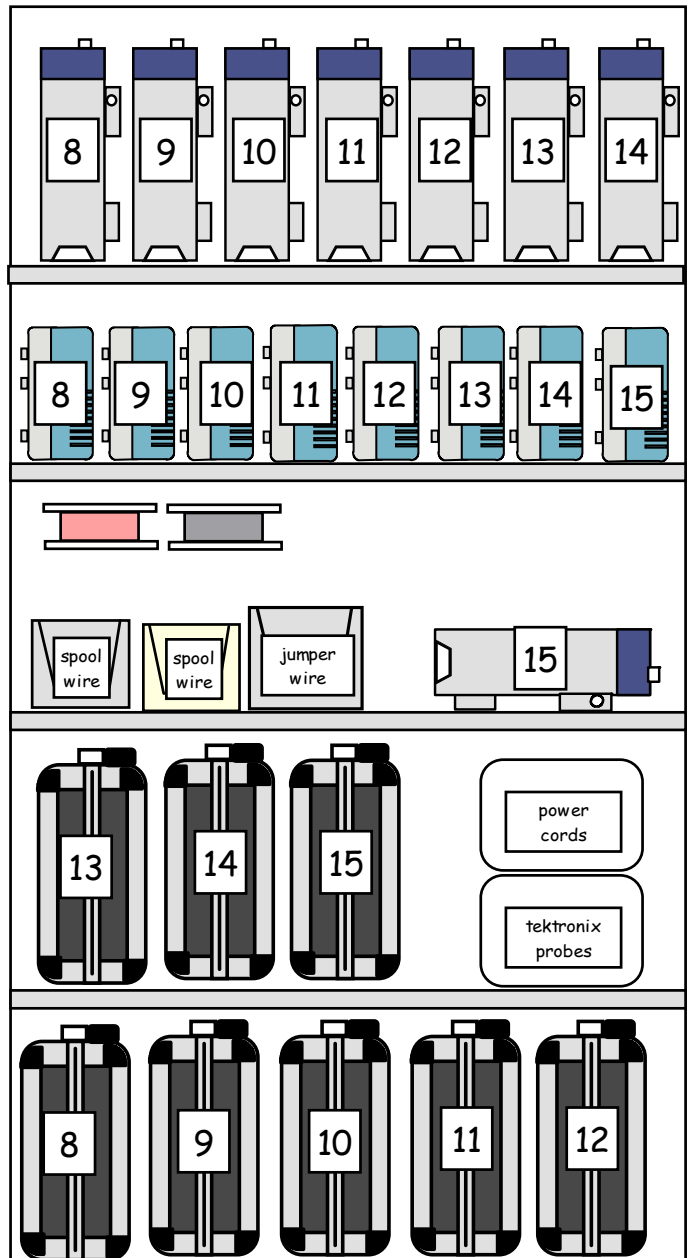
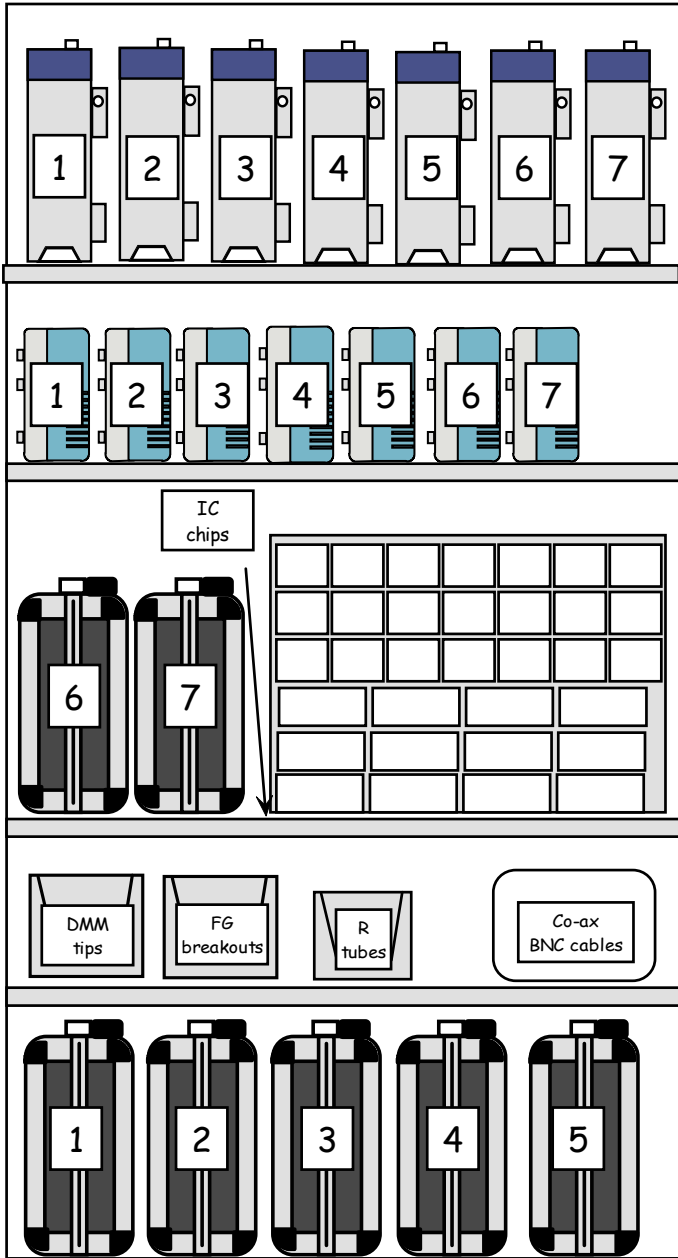
The instructor may institute a "TAG" system for clean up. The process works as follows. After putting away all equipment and cleaning up your area as specified above, each student team must leave a "tag" - a small piece of paper in their work area that indicates their team number (e.g., "TEAM 4") and student names. After students have left, the instructor will go around and inspect the bench areas to ensure proper clean up was done. The paper reveals which team was in the area. If the area is not properly cleaned up, the instructor will be able to know which team it was. Point deductions will apply. If a team fails to leave a team number slip, then there is a deduction as well.

2.2 Special Note - Trainers & Scratching

Unfortunately our trainers have screws on the bottom and the glides are not tall enough to protect the surfaces on which you may place the trainers. **DO NOT DRAG THE TRAINERS ON THE COUNTERS.** If you do, it will scratch them.

2.3 Organization & Storage of Engr 250L Equipment

Equipment such as the oscilloscopes, function generators, and trainers (usually for Engr 250L) must be put away in the correct spot. Students must return equipment to their proper EXACT specified locations when the lab period is over.



TO KNOW FOR EXAM:
 Engr 250L - everything in this chapter
 All other classes - section 2.1 only

***** UNITS *****

CHAP 3 - UNITS

We cannot work with basic engineering concepts, without first understanding concepts of **PHYSICAL QUANTITIES** of **UNITS**.

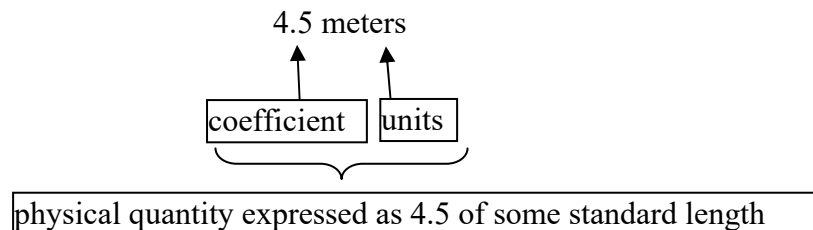
3.1 Physical Quantities and Units

A physical quantity is something that can be measured in the physical world.

A **UNIT** is a quantity defined by convention or law. It is generally used as a standard by which physical quantities are measured. There are different units for measuring different physical quantities. (e.g., foot, meter, second, gram).

A physical quantity is written as a coefficient and a unit that is meant to convey the quantity as a certain number of standard units (example, "4 meters").

EXAMPLE



There are 2 main systems of units used throughout the world: SI (International System of units) and US (or Imperial). Nearly the entire world uses the SI system of units. The U.S. uses the US system. Each unit system has a set of base units.

Base Units

SI: meter (distance), kilogram, kg (mass), second, s (time)

US: feet, ft (distance), pound, lb (force), second s (time)

The SI system of units is a superior system that makes computations simpler and has less ambiguity. But since the United States continues to use the antiquated US system of units, it is necessary to learn how to convert units.

SI PREFIXES

The US system of units has entirely different units when dealing with large versus small quantities. For instance, we use INCHES to measure paper size, FEET to measure a room size, and MILES to measure driving distance.

The SI system uses a more clever way of dealing with quantities of varying magnitude. For instance, the standard unit of distance in SI is the METER. We use centi-meters (cm's) for paper size. "Centi" means 1/100th. We use meters for room size. We use kilo-meters (km) for driving distance. "Kilo" means 1000 times. The prefixes are in base 10, so it's easier to convert. You just have to remember the prefix values.

$$10^{-2} = 1/100 = \text{centi}$$

$$10^{-3} = 1/1000 = \text{milli}$$

$$10^{-6} = \text{micro}$$

$$10^{-9} = \text{nano}$$

$$10^3 = 1000 = \text{kilo}$$

$$10^6 = 1,000,000 = \text{mega}$$

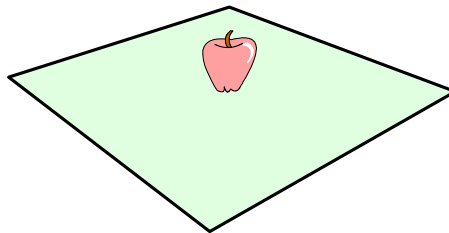
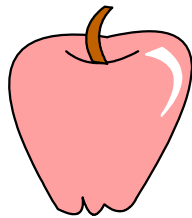
$$10^9 = 1,000,000,000 = \text{giga}$$

SI FORCES

The standard SI unit for force is the NEWTON. It is POUNDS in US units.

1 Newton (N) = 1 kg m/s². (about the weight of a large apple!)

1 Pascal (Pa) = 1 N/m². A unit of pressure.



3.2 Simple Unit Conversion

It is important to know how to convert units, especially for engineers. One must know the conversion factor. Common conversion factors are below

1 ft = .3048 meters

1 lb = 4.448 Newtons (force)

(and many others)

MATHEMATICS OF UNITS

Units multiply and divide just like numbers.

$$2 \times 2 = 2^2.$$

$$\text{Similarly, ft} \times \text{ft} = \text{ft}^2.$$

$$3 \times 5 = 3 \cdot 5$$

$$\text{Similarly lb} \times \text{ft} = \text{lb} \cdot \text{ft}$$

$\frac{2}{4}$ is "2 divided by 4". Similarly $\frac{m}{s}$ (meters divided by seconds, but we say "meters PER second")

Units cancel in fractions just like numbers.

$$\frac{2}{2} = \frac{\cancel{2}}{\cancel{2}} = 1 \quad \text{Similarly, } \frac{ft}{ft} = \frac{\cancel{ft}}{\cancel{ft}} = 1$$

SIMPLE UNIT CONVERSION

Take the example of converting meters per feet. Let's say we have 500 feet and we want to convert that to meters.

1. Write what you are given.

500 feet

2. Look up the conversion factor

$$1 \text{ ft} = .3048 \text{ m}$$

3. Write the conversion factor as a fraction (there are always 2 choices)

$$\left(\frac{.3048 \text{ m}}{1 \text{ ft}} \right) = \left(\frac{1 \text{ ft}}{.3048 \text{ m}} \right)$$

4. Multiply what's "given" with the conversion fraction (pick the one that cancels the units properly)

$$500 \text{ ft} \left(\frac{.3048 \text{ m}}{1 \text{ ft}} \right)$$

5. Combine the coefficients. Cancel and combine the units.

$$500 \cancel{ft} \left(\frac{.3048 \text{ m}}{1 \cancel{ft}} \right) = (500 \cdot .3048) \text{ m}$$

6. Do the arithmetic on the numbers (a calculator is okay)

$$500 \text{ ft} \left(\frac{.3048 \text{ m}}{1 \text{ ft}} \right) = (500 \cdot .3048) \text{ m} = 152.4 \text{ m}$$

3.3 Unit Conversion 2

We can use the same approach for more complicated unit conversions.

AREA - Convert 2.0 square meters (or m^2) to square inches (or in^2)

$$2.0 \text{ m}^2 \left(\frac{100 \text{ cm}}{1 \text{ m}} \right)^2 \left(\frac{1 \text{ in}}{2.54 \text{ cm}} \right)^2 = \left(\frac{2 \cdot 100^2}{2.54^2} \right) \text{ in}^2 = 3100 \text{ in}^2$$

VOLUME - Convert gallons to cubic centimeters. (1 cubic ft = 7.48 ga)

$$1 \text{ gallon} \left(\frac{1 \text{ ft}^3}{7.48 \text{ ga}} \right) \left(\frac{.3048 \text{ m}}{1 \text{ ft}} \right)^3 \left(\frac{100 \text{ cm}}{1 \text{ m}} \right)^3 = \left(\frac{.3048^3 \cdot 100^3}{7.48} \right) \text{ cm}^3 = 3785 \text{ cm}^3$$

PRESSURE - Convert 14.696 lb/in² to kilo-Pascals (kPa) (note 1 Pa = 1 N/m²)

$$14.696 \text{ lb/in}^2 \left(\frac{4.448 \text{ N}}{\text{lb}} \right) \left(\frac{1 \text{ in}}{2.54 \text{ cm}} \right) \left(\frac{1 \text{ in}}{2.54 \text{ cm}} \right) \left(\frac{100 \text{ cm}}{1 \text{ m}} \right) \left(\frac{100 \text{ cm}}{1 \text{ m}} \right) \left(\frac{1 \text{ Pa}}{1 \text{ N/m}^2} \right) \left(\frac{1 \text{ kPa}}{1000 \text{ Pa}} \right) = 101.3 \text{ kPa}$$

TO KNOW FOR EXAM:

What is a unit? What is a physical quantity? What are the 2 main systems of units?

SI system units for: force, distance

SI prefixes: kilo, mega, centi, milli, micro, nano

How to convert units

******* PHYSICS & MATH *******

CHAP 4 - PHYSICS & MATH

Engineers use science and math to do their designs. In this chapter we will cover some basic physics and mathematics principles needed for class and lab.

4.1 Isaac Newton

Physics is sometimes called the "mother of all sciences". Physics, using mathematics as a tool, seeks to explain and predict everything that happens in the physical universe. There are different branches of physics, but the one that is the most important for engineering is CLASSICAL MECHANICS. A key part of classical mechanics is NEWTONIAN MECHANICS.

Isaac Newton published the principles of Newtonian mechanics in his "Principia" in the 1600's. In it, he describes the physics and mathematics (differential calculus) needed to explain how forces affect the movement of large bodies (large enough for humans to see). His formulations are still used today by engineers to design cars, planes, rockets, and satellites. Some people consider Newton to be the greatest scientist to ever live because of his extensive contribution to the body of scientific knowledge (he also

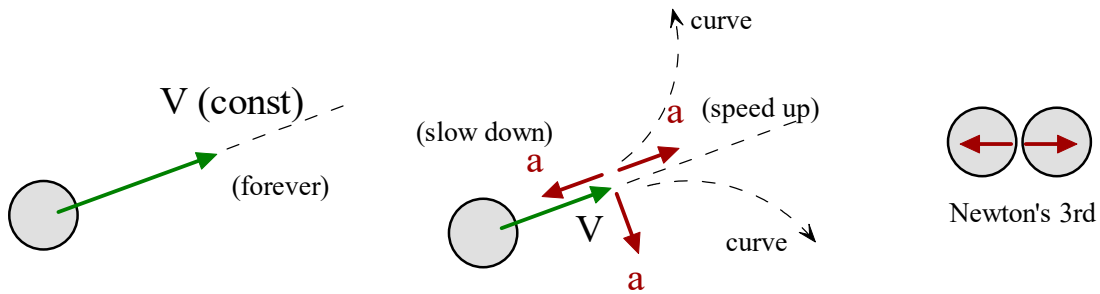
figured out that all the colors of the rainbow are contained in white light, and he formulated his equations for Newtonian gravity).

Newtonian physics can be summed up with a rather simple but powerful equation.

$$F = ma$$

This equation has 3 elements: force F , mass m , and acceleration a . Newtonian physics states that FORCE is a push or pull that causes a MASS to ACCELERATE (in this case, $F=ma$ is being used to define force). Mass is an intrinsic property of a body that characterizes its resistance to acceleration (again, they seem to use the Newton equation above to define mass). Acceleration is the change in velocity or motion. This can mean speeding up, slowing down, or changing direction. A body that is moving at constant speed in a straight line is NOT accelerating, thus the sum of the forces acting on that body are zero.

Newtonian physics is summarized in his THREE LAWS

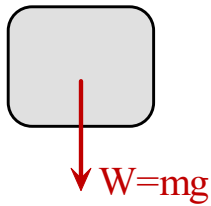


1. The Law of Inertia - a body will move in a straight line at constant speed unless acted upon by an external unbalanced force. This law basically describes the "natural state" of a body's motion.
2. The Law of Acceleration - force causes a mass to accelerate based on the equation $F = ma$.
3. The Law of Reciprocal Actions - for every force there is an equal and opposite force. This basically means that force is an interaction between 2 bodies.

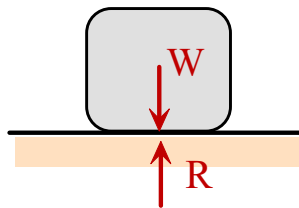
4.2 Forces

Forces push or pull an object, causing it to accelerate. Forces have magnitude and direction. Magnitude tells us how strong the force is. Direction tells us which way the force is pointed. Forces are modeled in math as VECTORS. Vectors (and, thus, forces) can be visualized as arrows in space. The length of the arrow tells us the force's magnitude. The direction the arrow is pointing tells us the force's direction.

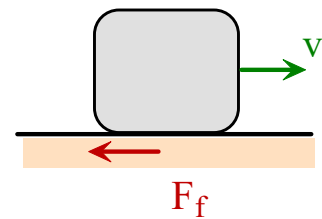
Here are some common forces:



Weight
(force of gravity)



Reaction force
(you push - it pushes back)



Friction
(when surfaces rub)
(always OPPOSES motion)

The SI units for force is the NEWTON, which is about the weight of a large apple (remember Newton with the apple on the head!). In US units, the standard is the POUND - a quantity that Americans probably find more intuitive.

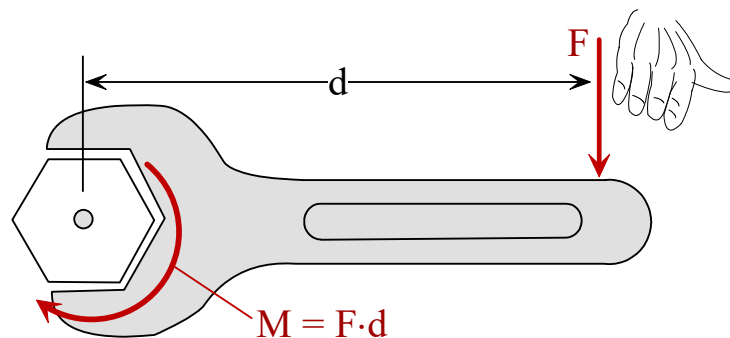
4.3 Statics

The natural result of Newton's Third Law is that if a body is acted upon by two equal and opposite forces, the body will not accelerate (it won't "move"). The body would move exactly the same as if no forces acted on it at all. This scenario describes what is studied in STATICS. STATICS studies situations where forces acting on a body are BALANCED. If balanced, the body is in STATIC EQUILIBRIUM and will not move. This area is essential for the study of bridges and structures (designed by civil engineers).

4.4 Moment of a Force

The study of forces leads to another important concept, that of MOMENTS or TORQUES. You may have heard of a torque wrench. Torque and moment are the same, but physicists and engineers generally use the term MOMENT instead of torque. Moment is simply force at a distance. It tends to cause bodies to rotate. So if we want to tighten a screw, we must generate a moment about the screw's axis in order to make it rotate or turn.

Moment is force times distance.



4.5 Energy

ENERGY is related to WORK. And work is the ability to exert force over a distance. The standard SI unit for work is the JOULE (J). One Joule is one Newton times one meter.

$$1 \text{ JOULE} = 1 \text{ NEWTON} \cdot 1 \text{ METER.}$$

If you push a box across the floor with 1 N of force over a distance of 1 meter, then you have done 1 J of work on the box!

There are different forms of energy. There is KINETIC ENERGY - the energy of a mass in motion. Its equations is

$$T = \frac{1}{2}mv^2$$

POTENTIAL ENERGY (PE) is stored energy. There are different forms of PE.

One form is gravitational potential energy. If you raise a mass in a gravity field, then that mass now has gravitational PE according to the equation

$$V_{gravity} = mgh$$

Another form of PE is ELASTIC PE. A stretched spring or rubber band has stored energy according to the equation

$$V_{spring} = \frac{1}{2}kx^2$$

Similar to elastic PE would be the stored energy of a gas that is compressed into a container.

$$V_{pressure} = PV$$

4.6 Trigonometry

Mathematics is the science of numbers. Numbers have certain characteristics and patterns. Mathematicians seek to understand these characteristics and patterns. An important area of math is TRIGONOMETRY - the math of triangles.

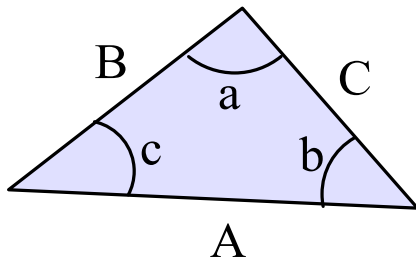
Here are some basic concepts of trig that are used all the time in engineering.

Triangle - a polygon with 3 straight sides

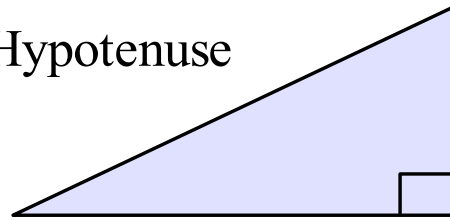
Property – interior angles add up to 180 degrees ($a + b + c = 180$)

Right triangles – one of the angles is 90 degrees (perpendicular or “orthogonal”)

The diagonal is the “hypotenuse”.



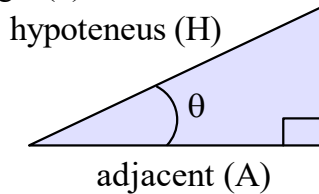
Hypotenuse



Sine, Cosine, Tangent

The angle is one of the 2 angles that is NOT the 90-degree angle.

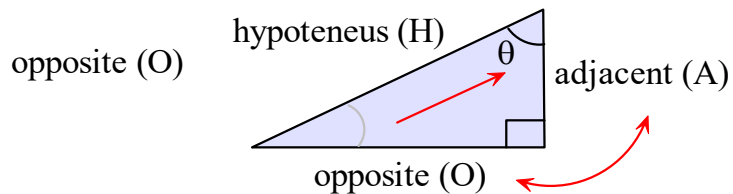
Pick an angle (θ)



$$\sin(\theta) = \frac{\text{opposite}}{\text{hypotenuse}} = \frac{O}{H}$$

$$\sin \theta = \frac{O}{H}$$

$$O = H \sin \theta$$

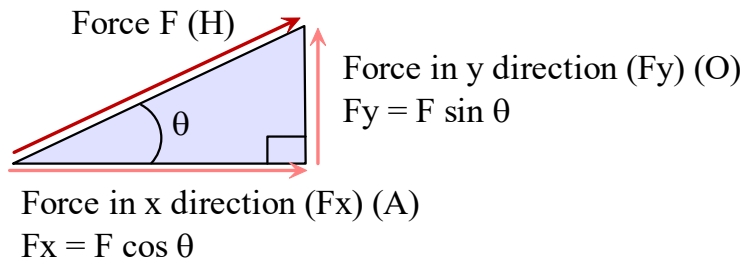


$$\cos(\theta) = \frac{\text{adjacent}}{\text{hypotenuse}} = \frac{A}{H}$$

$$\cos \theta = \frac{A}{H}$$

$$A = H \cos \theta$$

Sine and cosine are used all the time in engineering. We use these trig functions to PROJECT (or break up) forces. Forces are arrows (they have magnitude and direction). A force that is inclined above the horizontal by angle θ has horizontal and vertical projections as shown below.



TO KNOW FOR EXAM:

What are forces? Newton's main equation? Newton's 3 laws

What are vectors? Common forces?

What is moment? What is energy and its units?

What is KE, PE?

What is trig? Triangle's internal angles add to what?

Trig is commonly used in engineering to do what?

***** ELECTRICITY *****

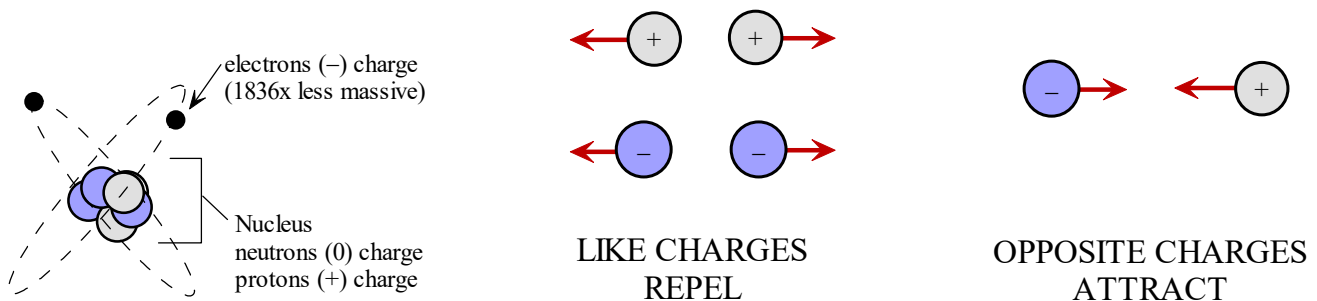
CHAP 5 - ELECTRICITY

5.1 Introduction

Electricity is a FLOW OF CHARGE, specifically a flow of ELECTRONS.

All matter is made up of tiny particles called ATOMS. The components of an atom are the proton, neutron, and electron. The proton and neutron reside in the nucleus and the electron "orbits" the nucleus, much like a planet orbiting the sun. The proton has a (+) charge, the neutron no charge, and the electron a (-) charge.

Electrons are attracted to protons (a basic rule of charge), keeping them from flying away from the nucleus. However electrons can be knocked loose from their nuclei. This is how electricity is produced.



CONDUCTOR & INSULATORS

Some elements hold their electrons tightly and others more loosely. Loosely held electrons are called FREE ELECTRONS. Free electrons are easily knocked free of the nucleus and can form electricity.

Conductors (like metals) have many free electrons.

Insulators (like plastic, rubber) have few free electrons.

5.2 ELECTRICAL QUANTITIES

There are a variety of electrical quantities that we must become familiar with in order to understand electricity. These include charge, current, voltage, resistance, and power.

5.2.1 - CHARGE

Charge (denoted by letter "q") is a property of matter that causes it to experience force when placed in an electro-magnetic field. Charge has units of **COULOMBS** (C). One Coulomb is the charge of 6.4×10^{18} electrons.

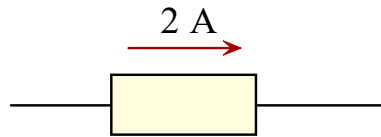
5.2.2 - CURRENT

Current (denoted by "i") is the FLOW RATE of charge.

Current has units of AMPERES (or "Amps") where 1 Ampere = 1 Coulomb per second (C/s).

So current is a measure of how many electrons are passing by a point every second.

We speak of "CURRENT THROUGH AN ELEMENT" (elements are circuit components like resistors, capacitors, and inductors), and we specify current on an electrical schematic using an arrow and a current value.

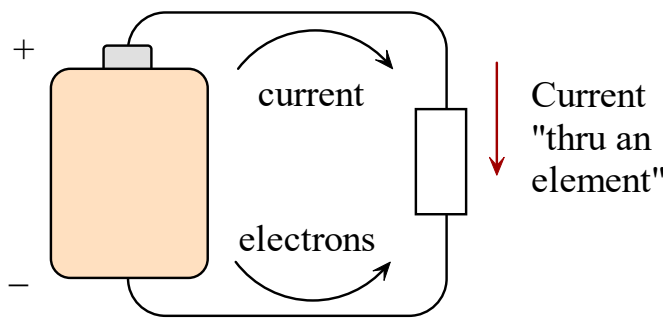


"2 Amps of current thru an element"

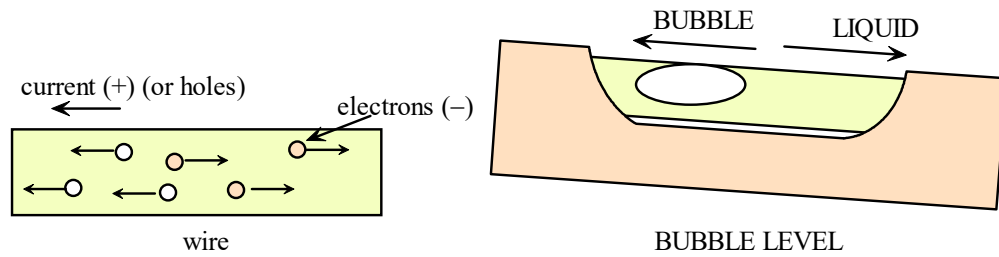
CONVENTIONAL CURRENT

Even though the moving charge in electricity is the negatively-charged electron, we actually follow the "flow" of positive (+) charge in a circuit.

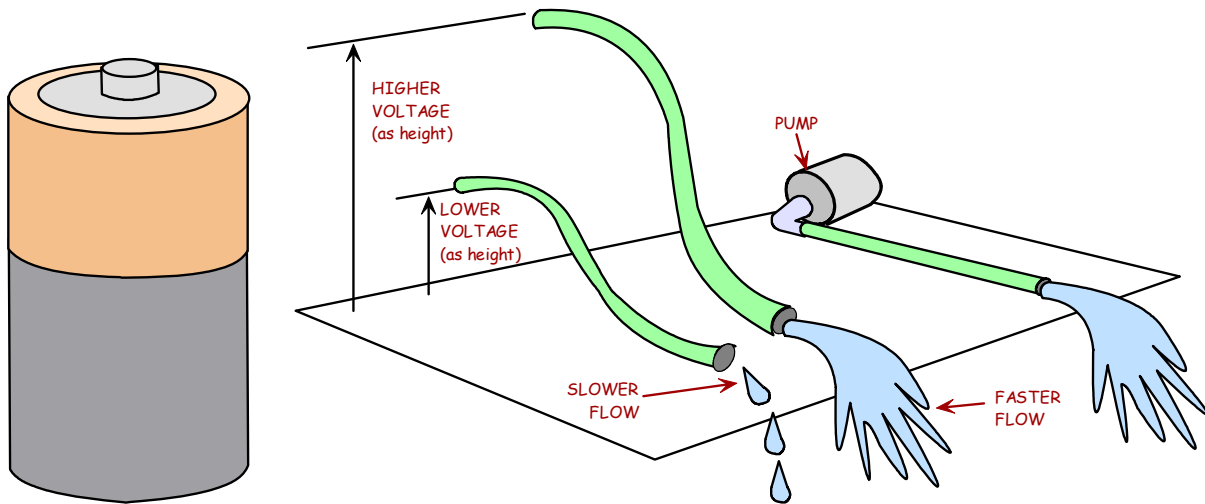
Consider the simple battery circuit. Batteries have a positive (+) and negative (-) terminal. If we connect an element across those terminals, electricity would flow. The electrons would originate from the battery's (-) terminal and flow through the wire, through the element, and into the battery's (+) terminal. But "conventional" current follows the flow of positive charge, which starts from the (+) battery terminal, thru the wire, thru the element, and into the (-) terminal. We use this convention even though there isn't really a moving positive charge!



A great way of thinking about (+) charge flow is a bubble level. A bubble level has a clear glass tube and some colored liquid inside. If the level is tilted down on the right, the bubble moves to the left. What's really happening is that the liquid moved to the right and the bubble is the absence of liquid. It is just like electricity. The liquid is the electrons (moving to right), and the bubble is a "hole" (a vacant spot for an electron). As electrons propagate to the right, holes propagate to the left.



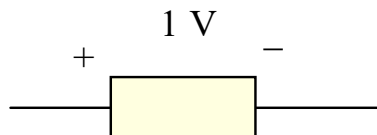
5.2.3 - VOLTAGE



VOLTAGE is ELECTRICAL PRESSURE - something that PUSHES charge and makes it move. Sources of voltage include batteries, power supplies, and AC outlets. Voltage has different names: electrical potential, potential difference, EMF, etc. Voltage is like stored energy - which is why it is sometimes referred to as electrical POTENTIAL. (potential energy is stored energy) Thus voltage can be visualized as either electrical PRESSURE or electrical HEIGHT. Voltage has units of VOLTS.

Voltage is always a DIFFERENCE in electrical potential between 2 points in a circuit. Thus, voltage is always RELATIVE, it is never absolute.

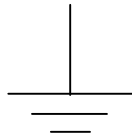
We speak of "VOLTAGE ACROSS AN ELEMENT", and we specify voltage on an electrical schematic by writing a plus (+) and a minus (-) written on either side of an element, and a voltage value. The (+) side has a higher electrical potential relative to the (-) side.



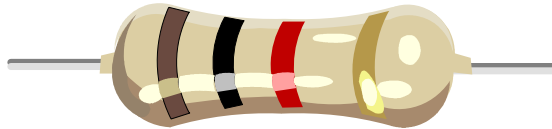
"1V across an element"

GROUND

Although voltage is never absolute, we often wish to measure voltage in a circuit relative to a REFERENCE POINT, which is called GROUND. The ground point in a circuit is a reference point from which all other voltages in the circuit are measured. It is usually the (-) side of the power supply. Ground has the symbol below.



5.2.4 - RESISTANCE

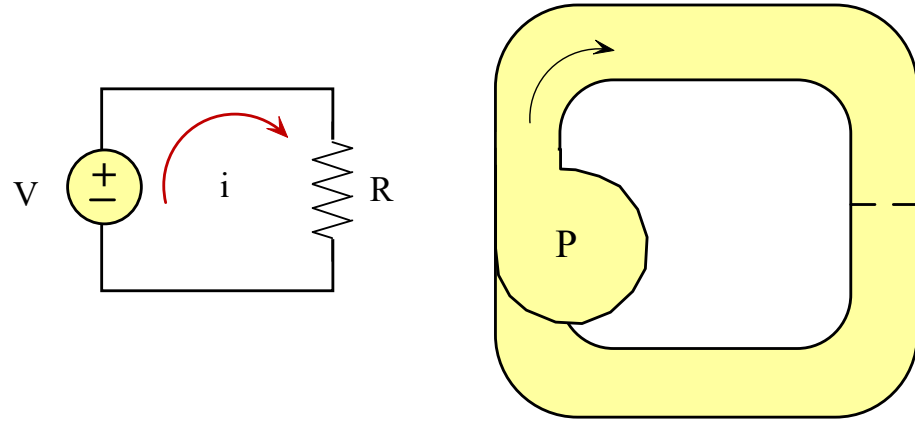
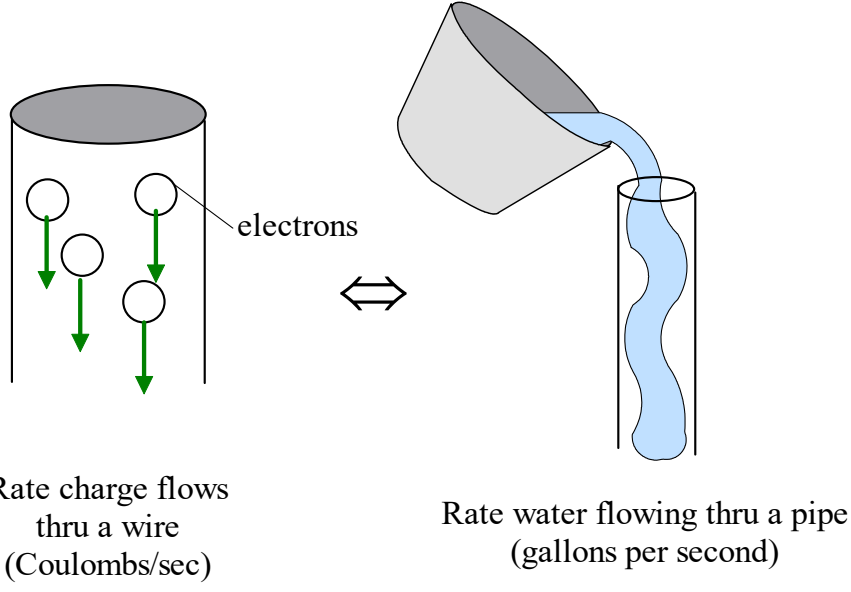
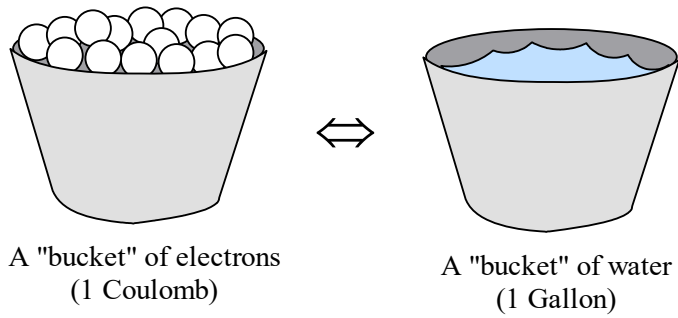


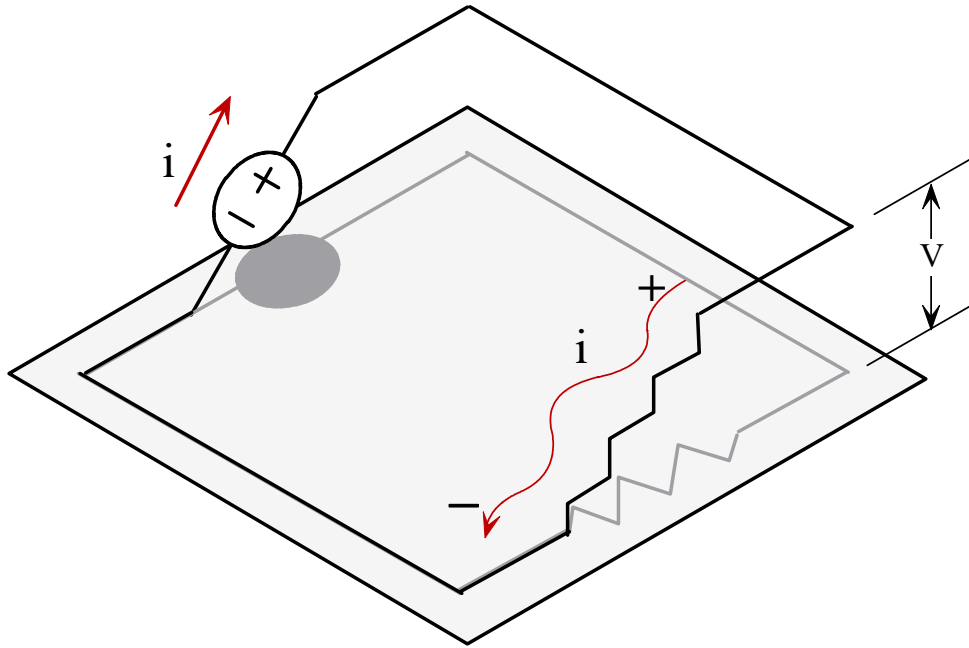
RESISTANCE is opposition to the flow of electric current. It has units of OHMS. Conductors like wire have LOW resistance (though it is not zero). Insulators have high resistance. RESISTORS are used in circuits to add certain amounts of resistance.

5.2.5 - WATER ANALOGY

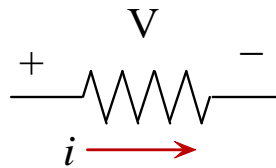
The water analogy helps us better understand electricity. Instead electrons flowing through a wire, you think of water flowing through a pipe. In the water analogy, the water is the charge. Current would be the flow rate of water (e.g., gallons per second). For instance, you can pour water from a jug slowly or quickly, and this would affect the water flow rate. Voltage in the water analogy is water PRESSURE. The water analog for resistance is a restriction in the pipe.

The water analogy for voltage is WATER PRESSURE or HEIGHT. Pressurized water will cause the water to move. A water pump is the analog to a battery. Pumps make water move by creating localized pressure or pump water up in height. If you take a hose filled with water and raise one end, water will flow out the lower side.





5.3 Ohm's Law



Ohm's Law is an equation that relates the voltage (V), current (I), and resistance (R) in a resistor.

There are 3 forms of Ohm's Law. Start with $V = IR$, and you can derive the other 2 equations.

$$V = IR$$

$$I = V / R$$

$$R = V / I$$

Isolate the I

$$V = IR$$

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

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

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

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

Isolate the R

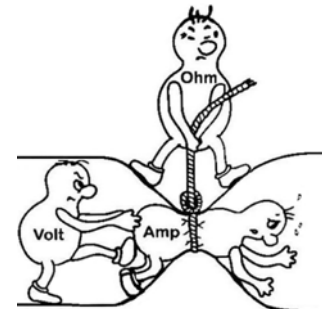
$$V = IR$$

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

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

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

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



CALCULATIONS WITH OHM'S LAW

We often use Ohm's Law to make calculations. As long as the electrical quantities are kept in their standard units (voltage in volts, current in amps, resistance in ohms), you don't have to worry too much about units.

$$V = IR \quad [\text{Volt}] = [\text{Amp}][\text{Ohm}]$$

$$I = \frac{V}{R} \quad [\text{Amp}] = \frac{[\text{Volt}]}{[\text{Ohm}]}$$

$$R = \frac{V}{I} \quad [\text{Ohm}] = \frac{[\text{Volt}]}{[\text{Amp}]}$$

Example: How much current flows when if a 1000 Ω resistor is hooked up to 100V?

$$I = \frac{V}{R} = \frac{100V}{1000\Omega} = \frac{1}{10} \frac{V}{\Omega} = \frac{1}{10} A$$

CALCULATIONS WITH PREFIXES

How much voltage do you need to get 20 mA to flow across a 1kΩ resistor (1k = 1000)?

$$20 \text{ mA} \left(\frac{1 \text{ A}}{1000 \text{ mA}} \right) = .020 \text{ A} \quad 1 \text{ k}\Omega \left(\frac{1000 \Omega}{1 \text{ k}\Omega} \right) = 1000 \Omega$$

$$V = IR = (.020 \text{ A})(1000 \Omega) = 20 \text{ A}\Omega = 20 \text{ V}$$

5.4 Power

Power is the rate that energy is being used or supplied. It applies to any machine, not just electricity. Power is voltage times current

$$p = vi$$

Power has units of WATTS.

$$1 \text{ WATT} = 1 \text{ JOULE} / \text{SECOND} = 1 \text{ VOLT} \times 1 \text{ AMP}$$

For resistors, there are 3 forms of the power equation

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

$$P = IV = I(IR) = I^2R$$

$$P = (V / R)V = V^2 / R$$

EXAMPLE POWER CALCULATION

What is the power dissipated by 50 Ω resistor with 2 A of current flowing thru it?

$$P = I^2R = (2A)^2(50\Omega) = 200A^2\Omega = 200W$$

You have a resistor (R = 2 kΩ) with 10V across it. The resistor is rated at 1/4 W. Does it blow up?

$$P = V^2 / R = (10V)^2 / 2000\Omega = (100 / 2000)V^2\Omega = (1 / 20)W \text{ (does NOT blow up)}$$

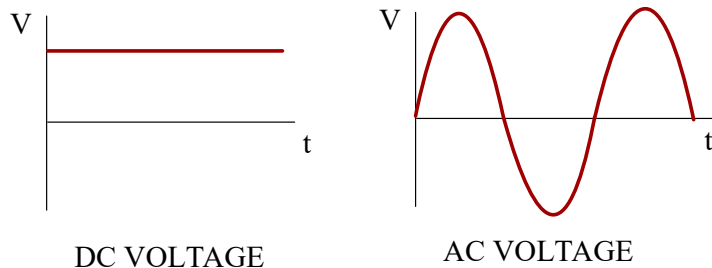
5.5 Types of Electricity

There are 2 basic types of electricity: AC and DC.

DC electricity has constant voltage and current (e.g., batteries)

AC electricity has voltage and current that switches back and forth. There are different types of AC electricity but we will usually deal with sinusoidal AC electricity which oscillates as a sine wave.

AC electricity can oscillate at different frequencies. Residential AC frequency is 60 Hz (cycles/sec).



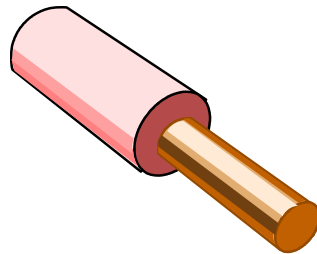
TO KNOW FOR EXAM:

- What is electricity? Rules for charge? Conductors vs. insulators (why are they different)?
- Electrical quantities (charge, current, voltage): what are they, their units, water analogy for them?
- What is ground, resistance (and its units)?
- What is Ohm's law, its equation, and do calc's with it
- What is power, its units, its equation?
- Types of electricity - what is the difference?

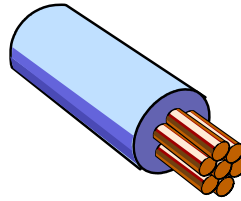
******* ELECTRICAL COMPONENTS *******

CHAP 6 - ELECTRICAL COMPONENTS

6.1 Wire



SOLID WIRE



STRANDED WIRE

Wire is designed to conduct electric current with very little resistance. Wires come in a variety of sizes, styles, and insulator colors. Wire is either solid or stranded. Stranded wire is more flexible but solid can carry more current. AWG (American Wire Gauge) is a common standard for sizing wire. Increasing AWG number corresponds to decreasing wire size. Larger wire is needed if conducting greater current. Wire is generally coated with an INSULATION to prevent short circuits. The color of the insulation does not affect wire function but we will often color code our wire.

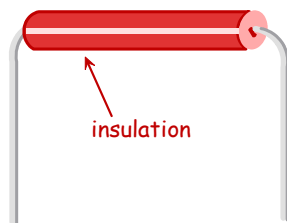
HOT or (+) voltage	red
GND or (-) voltage	black, brown, green

We often model wire as having no resistance, but in reality wire has a small amount of resistance that depends on its length (e.g., 20 AWG copper wire is about 10 mOhms/ft).

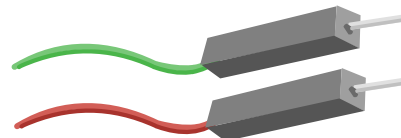
Below is a sample table of AWG wire gage sizes

AWG	Wire Diameter (in)	AWG	Wire Diameter (in)
1	.289	19	.0359
2	.258	20	.0320
3	.229	21	.0285
10	.102	22	.0253
12	.0808	23	.0226
14	.0641	24	.0201
16	.0508	25	.0179
17	.0453	26	.0159
18	.0403	27	.0142

JUMPER WIRE KITS



PRE-CUT PRE-STRIPPED JUMPER WIRE



"DUPONT" WIRE

Jumper wire kits often come in 22 AWG wire that is pre-cut and pre-stripped. We usually use them in their default lengths, pushing the wire down so that it is flush with the breadboard. Or we can cut them to length. Hookup wire comes on a spool (I sometimes refer to it as "spool wire") can also be used if you need longer pieces of wire. Most of our spool wire supply is red or black (for hot and GND).

STRIPPING wire is the process of removing the plastic insulation from the end of a wire to expose the metal wire. The goal is to remove the plastic without cutting the metal.

DUPONT WIRE

Many hobbyist electronics kits include packs of so-called DUPONT wire. These are smaller-sized stranded wire of various insulator colors with male or female connectors crimped on the ends. "MALE" ends have a piece of solid wire that may be inserted into a solderless breadboard or perhaps an Arduino micro-controller port. Female ends have a connector with a small hole into which a wire may be inserted. Most kits contain male-male (M-M) Dupont wire. You can also find male-female (M-F) or female-female (F-F) Dupont wire.

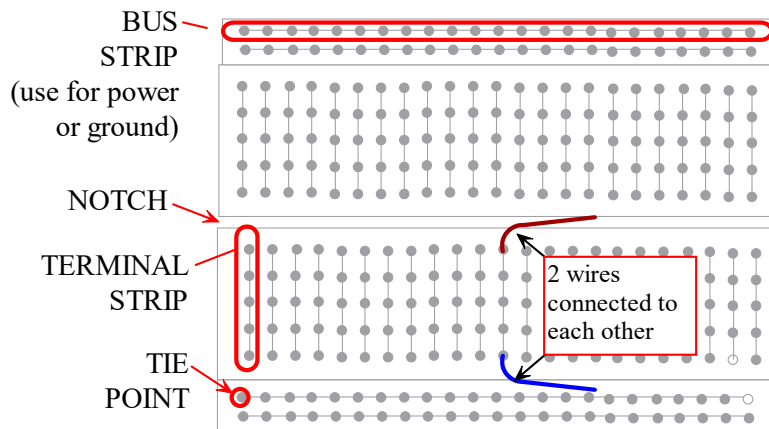
6.2 Solderless Breadboards

Breadboards are used to create circuits. There are different types. "Perf" or solder breadboards require the use of solder to create the circuits. Solderless breadboards allow you to easily wire up and change circuits without using solder. These are useful creating prototype circuits.

The breadboard is made up of a grid of holes, called **TIE POINTS** which have specific connectivity beneath (you can't see the connections, but they are there). Tie points are an industry-standard 0.1 inches apart. This standard allows manufacturers know to make components like IC chips and potentiometers that will match this spacing.

Our breadboards are designed for **22 gauge** wire or smaller (i.e., larger AWG values). If you jam overly-large wires into the board, you will damage the contacts beneath.

Tie points are connected into each other in **TERMINAL STRIPS** and **BUS STRIPS**. Terminal strips are connections of 5 tie points. Bus strips are connected the whole length of the board. In the figure shown the internal connections are shown below in grey lines.



Breadboards may be damaged if too much current flows thru the tie point. This is sometimes evident if the plastic is melted or "browned." If you see a browned area, build your circuit elsewhere.

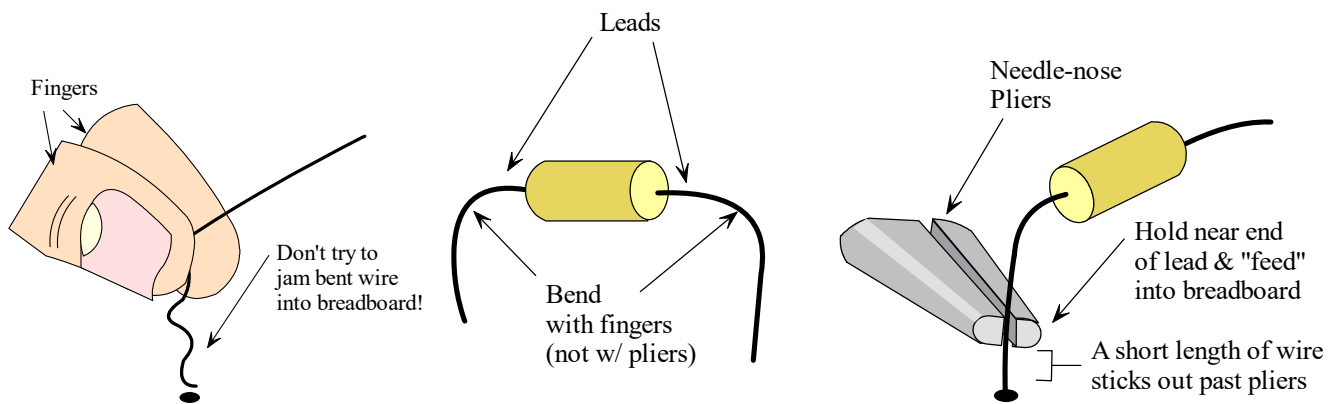
INSERTING RESISTORS AND WIRE INTO BREADBOARD

To insert wire into a breadboard simply push the wire into the hole. Don't try to insert bent up wire into a breadboard (you can damage it). First straighten the wire with needle-nose pliers, or cut the wire off and re-strip to get clean straight wire again.

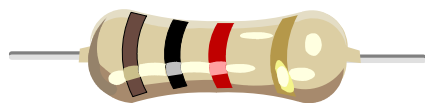
Bend resistor leads using your fingers and make GENTLE, not sharp, bends.

Resistor leads (wire) are very thin. Insert these carefully or they may buckle. It may help to "WALK" the wire into the breadboard. Hold the wire near its end (with fingers or needle-nosed pliers), and push in as far as you can. If using pliers, make sure power is OFF. Then release the wire and hold it a short distance away from the breadboard and push again. Repeat until the wire bottoms out. When resistor leads become all bent up, discard them.

Be sure power is OFF before altering any circuits. Especially dangerous is the use of a metallic tool like the needle nose pliers. You may accidentally short something if using such a tool. That is why power must always be OFF when altering circuits (safer for you & equipment).



6.3 Resistors



Resistors resist current, pull energy from a circuit, and turn that energy into heat. They can be thought of as a frictional element. Resistor values are in OHMS. Key parameters are resistance value, tolerance, and power rating. Power rating indicates the amount of power (energy/time) that the resistor can dissipate without "blowing up." Note if a resistor is dissipating power close to its rating, it will get HOT – hot enough to burn you. Physically small resistors typically have lower power ratings. Electronics often use 1/4-watt resistors. The wires coming out of a resistor are called its LEADS. The water analogy for a resistor is a restriction in the pipe (or an orifice).

RESISTOR COLOR CODE

Resistor "nominal" value is specified using a 4-band color code. Each color represents a number (0 through 9). The first 3 color bands specify the nominal resistor value. The 4th band specifies tolerance (allowable variability in the resistance value).

A mnemonic helps use to remember the colors

(0) Better (1) Be (2) Right (3) Or (4) Your (5) Great (6) Big (7) Vacation (8) Goes (9) Wrong

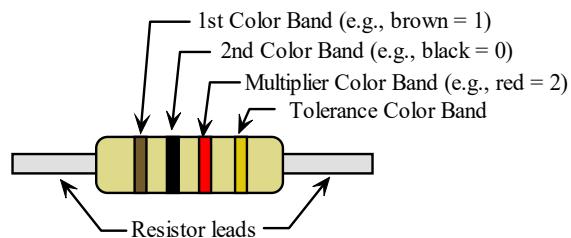
OR: Black Bears Run On Yosemite's Great Big Vertical Granite Walls.

OR: Black Bears Run On Your Grass But Very...

FIRST 3 BANDS			4TH BAND		
No.	Color	No.	Color	Tolerance	Color
0	Black	5	Green	± 20%	no band
1	Brown	6	Blue	± 10%	silver
2	Red	7	Violet	± 5%	gold
3	Orange	8	Gray		
4	Yellow	9	White		

Example: Brown - Black - Red - Gold

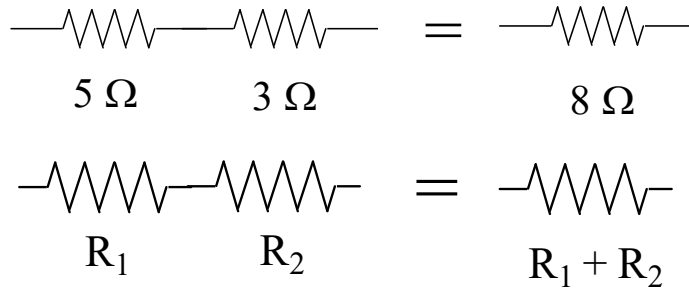
$$\begin{array}{r}
 1 \quad 0 \quad 2 \quad \pm 5\% \\
 \downarrow \quad \downarrow \quad \swarrow \quad \searrow \\
 10 \quad \times \quad 10^2 \quad \pm 5\% \\
 10 \quad \times \quad 100 \quad \pm 5\% \\
 1000 \quad \pm 5\% \\
 1\text{k}\Omega \quad \pm 5\%
 \end{array}$$



A common mistake made by students is to think that the color band encode in scientific notation. For the example above, the first 2 color bands (brown – black) encode the number 10 ("ten"), not 1.0 ("one point zero"). So the resistor value is 10 (TEN) x 10², not 1.0 x 10². Again, the color bands do not code in scientific notation. (forget that decimal!)

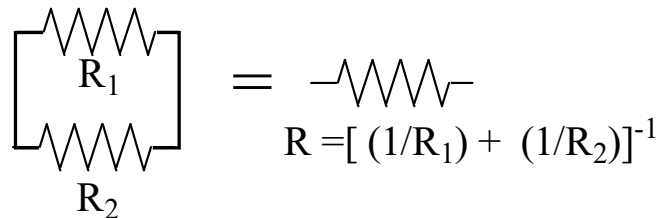
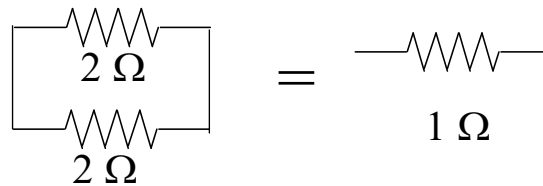
ADDING RESISTORS

Resistors add up in series



Resistors in parallel add up with the "reciprocal" equation

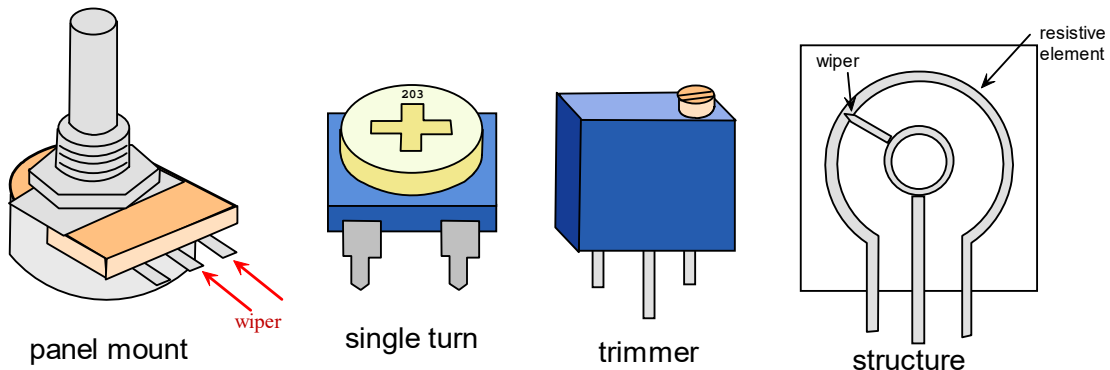
$$\frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{R_{EQ}}$$

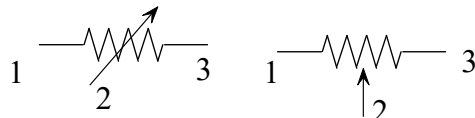


RESISTORS AND POWER

The equation for power dissipated on a resistor is $P = V^2/R$. We will generally work with small 1/4 Watt resistors. Smaller valued resistors used with voltage sources will dissipate more power. Be sure to check whether a smaller valued 1/4 Watt resistor will blow if a given amount of voltage is applied.

6.4 Potentiometers

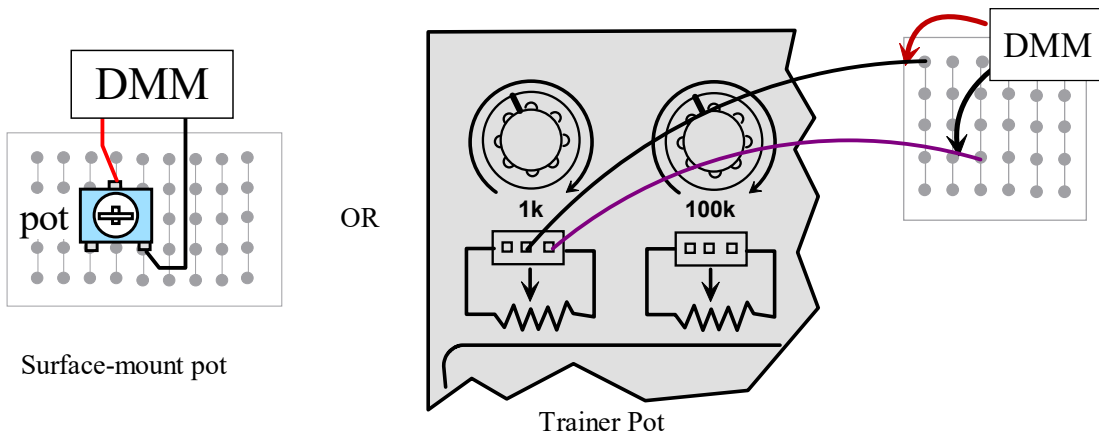




POT SYMBOL

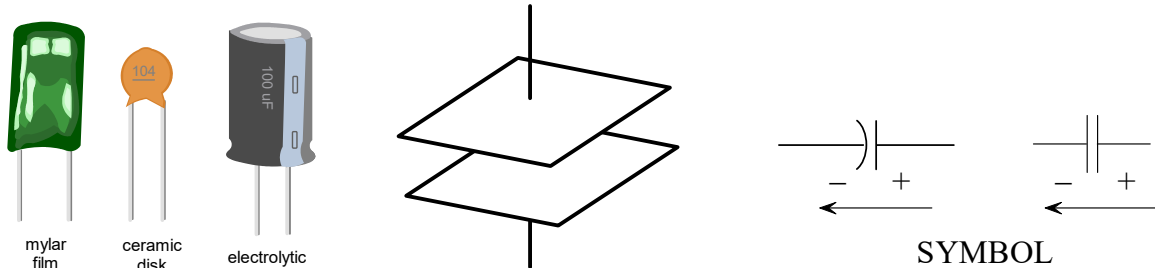
Potentiometers (or "POTS") are 3-terminal resistors which are often configured as dials or sliders. A pot's overall resistance rating is the resistance value (a constant) between its outer leads (1 & 3, see figure). The 3rd terminal (#2) connects to a moving contact called a "wiper". Turning the dial moves the wiper along the potentiometer's windings, causing a change in resistance between the wiper lead (#2) and lead #1 (R_{12}) and also between wiper and lead #3 (R_{13}). The sum of R_{12} and R_{23} always equals the pot overall resistance, but since R_{12} and R_{23} can be altered by turning the dial, the potentiometer can be used as a variable resistor.

When you drop a voltage across terminals 1 and 3, you can use a pot to create a variable voltage. Because the turning of the dial changes the values of R_{12} and R_{23} , it turns out the voltage V_{12} and V_{23} also change as you turn the dial. This happens due to the VOLTAGE DIVIDER RULE.



Pots also have a "taper" or "profile" specification – usually linear or log. Linear pots have a resistance change that is proportional to the turn angle. Log pots (or "audio taper" pots) have a logarithmic relationship to the turn angle. This are used for controlling the volume on a stereo because it turns out the human ear perceives sound loudness logarithmically. That is, something that sounds 2x as loud as something else actually has 100x the electrical power. Trimmer pots like the blue one shown are multi-turn pots – that is, it takes several turns to move the wiper through its entire range.

6.5 Capacitors



Capacitors store electric charge much like a battery but with very different characteristics. The basic structure of a capacitor is 2 conductive plates separated by a space, which is usually filled with a dielectric material which concentrates the electric field produced by the charged plates.

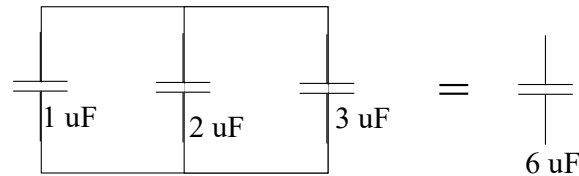
A capacitor's value is CAPACITANCE and it has units of FARADS. They also have a power rating and maximum voltage rating. Capacitors may be POLAR or non-polar. Polar capacitors may only have voltage applied across it in 1 polarity direction. If the voltage polarity is applied in the opposite direction, the capacitor will blow up. Electrolytic capacitors are often used when higher capacitance is needed, but these capacitors are polarized.

Capacitors have the effect of preventing instantaneous CHANGES IN VOLTAGE. For AC circuits, capacitors have a resistive characteristic called CAPACITIVE REACTANCE which can be thought of as frequency-dependent impedance (it DECREASES with increasing frequency).

There are several different types of capacitors.

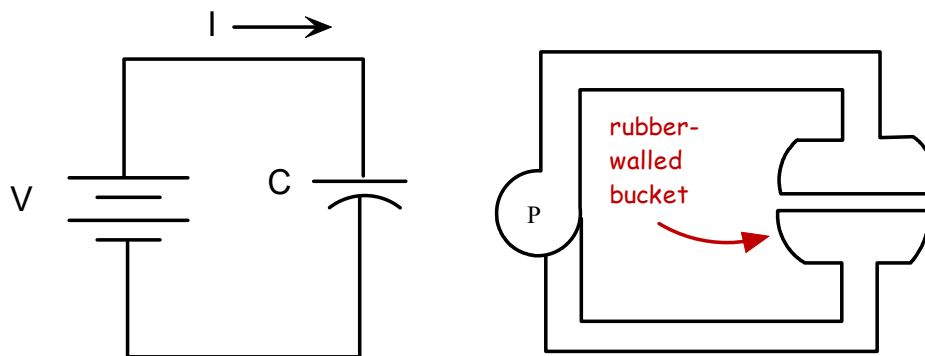
1. Ceramic disk – maximum values of about 0.33 uF (50 V)
2. Mylar film capacitor – max value (< 1 uF)
3. Electrolytic – max values (~ 4700 uF), but are polarized

Capacitors add up in parallel.

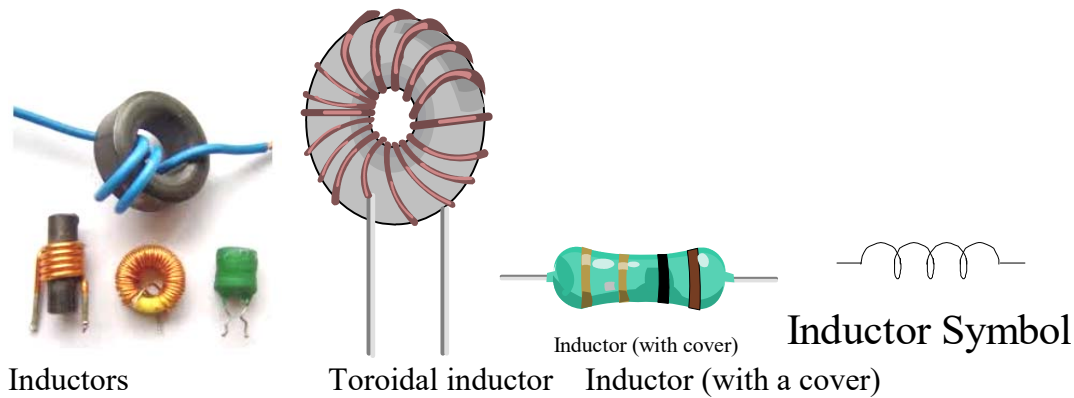


WATER ANALOGY

The water analogy for Cs is a rubber-walled bucket. As water (charge) fills the bucket (C), the rubber walls are stretched, causing water pressure (voltage) to form. Pressure (voltage) in this bucket cannot jump up or down instantly. Instead the walls just stretch or un-stretch, which smoothes out pressure changes.



6.6 Inductors

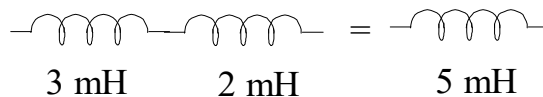


Inductors are coils of conductive wire that store energy in a magnetic field. Inductors may be encased in a cover which hides the coils of wire, making the inductor look like a capacitor. The variable for an inductor is the letter L.

An inductor's value is INDUCTANCE which has units of HENRIES. They also have a power rating and maximum voltage rating.

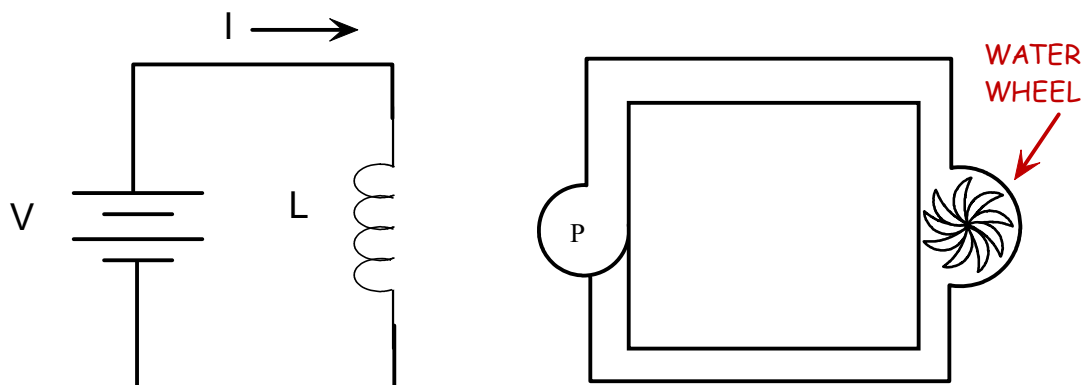
Inductors have the effect of preventing instantaneous CHANGES IN CURRENT. In other words they smooth out changes in current. They can be thought of as adding inertia to electric current. For AC circuits, inductors have a frequency-dependent "resistance" called INDUCTIVE REACTANCE which rises with increasing frequency.

Inductors add up in SERIES



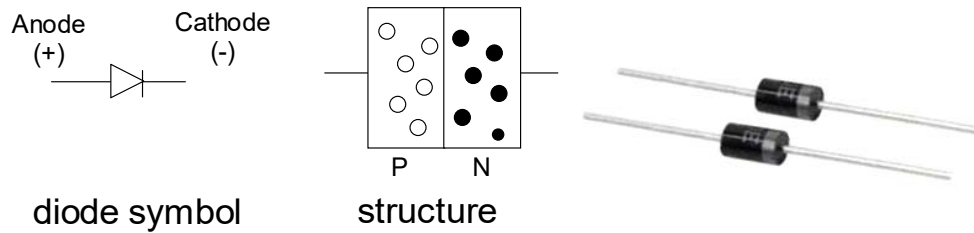
WATER ANALOG

The water analog for L is a massive water wheel. You can think of inductors as giving electric current inertia.



Inductors are used in DC power supplies, transformers, motors, solenoids, and relays (for switches, valves). Sometimes they are called chokes or coils.

6.7 Diodes



Diodes are one-way valves for electricity. They are made from semiconductor elements like silicon or germanium. DOPING processes are used to alter the electrical characteristics of semiconductors. Specifically, semiconductors are doped to become either P or N type semiconductor. N type semi-conductor material is doped with phosphorus (5 valence electrons) to give it an extra free electron. P type semiconductor material is doped with boron (3 valence electrons) to give it extra holes.

N-type semiconductor has extra HOLES (an empty spot for an electron).
P-type semiconductor has extra free ELECTRONS.

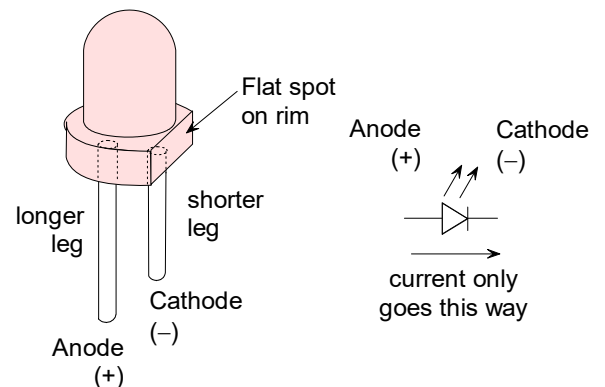
A diode is a sandwich of P and N material. They act as one-way valves for circuits – allowing current to flow in one direction but not the other. Diodes have 2 leads: an anode and a cathode.

When voltage is applied in FORWARD BIAS direction, the higher voltage potential is on the anode side and the lower voltage potential is on the cathode side (the cathode is closer to GND). Current will flow through the diode. In REVERSE BIAS (anode closer to GND), current will not flow.

The water analog for a diode is a one-way valve for water.

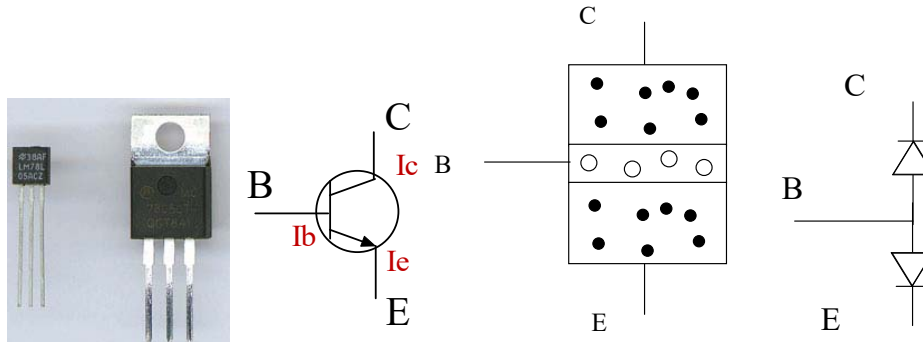
6.8 LEDs

Light-emitting diodes (LEDs) are special diodes that emit light when wired in forward bias configuration. Like a regular diode, an LED has an anode and a cathode. The cathode must be wired closer to ground (forward bias) or the LED will not light. LEDs must have a current-limiting resistor wired in series. Typical LEDs used in electronics have full brightness with 20 mA of current flowing through them (these are traditional DIP-type at 4 Lm/W). Often 5V powers these LED's. Thus, a current-limiting resistor of 220 ohms (red-red-brown) is usually used in series with the LED. Without this resistor, the LED will blow.



LEDs now commonly used in general residential lighting are different than the ones we will use. These household LEDs utilize more efficient and higher-power LEDs (SMD or surface-mount diode (50-100 Lm/W), or LED COB (chip on board, > 100 Lm/W).

6.9 Transistors



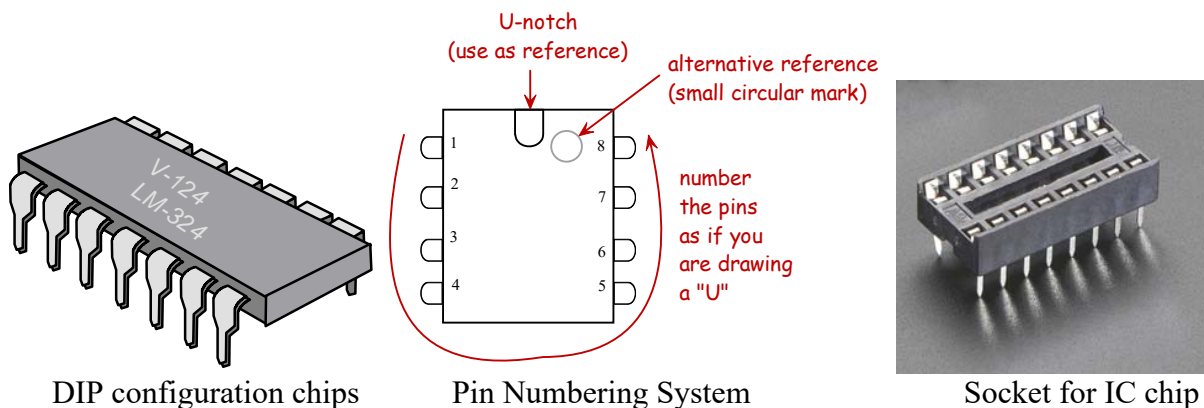
Transistors form the basis for all modern electronics (computers, cell phones, TVs, etc.). A small current applied to one pin controls a much larger current between the other 2 pins. This behavior allows the transistor to operate either as an ELECTRONIC SWITCH or ELECTRONIC SPIGOT. That is, a small signal can control a much larger signal. Typically the small "control" signal comes from a computer or micro-controller, and the larger signal comes from a power supply that powers a large electrical device (e.g, a large motor).

A transistor has 3 "legs". The body of lower-power transistors is shaped like a cut-off cylinder. Higher power transistors box-shaped and have a metallic plate with a hole. This is where you would mount a "heat sink" (piece of metal with cooling fins) which draws heat off the transistor.

BIPOLAR FUNCTION TRANSISTORS (BJT's) are a triple-layer sandwich of semiconductor material. There are two types: NPN and PNP. A BJT has 3 legs: base, collector, and emitter. A small current at the base controls a larger current between the collector and emitter.

MOSFET (metal-oxide semi-conductor field effect transistor) transistors are a higher-performance transistor (also more expensive). They draw much less current than BJT's. There are 2 types: N-channel and P-channel (somewhat analogous to NPN and PNP BJT transistors). The 3 legs of a MOSFET are the gate, drain, and source. A small signal at the gate controls a much larger signal between the drain and source. MOSFETS drawing much less current into the gate than BJT's do into their base. The resistance of the metal-oxide layer at the gate is $\sim 10^{15}$ ohms. Thus, virtually no current flows into the gate!

6.10 Integrated Circuit Chips



DIP configuration chips

Pin Numbering System

Socket for IC chip

There are many different integrated circuit (IC) chips for doing many different functions. They are called "integrated" because all of the components that make up the chip are etched (integrated) into a solid piece of semi-conductor material (often silicon) instead of having discrete wires and components.

Many IC chips have a DIP (dual in-line package) configuration. This means the chip has 2 rows of pins. These pins are numbered and are usually NOT symmetrical. Thus the chip will have a reference point - often a "U" or "O" marking to distinguish the 2 different rows of pins. Orient the chip so the U faces up. The pin in the upper left is #1. Then number the pins as you move around the chip as if drawing the letter "U". Sometimes the chips will have a circular mark instead of the "U".

Examples of IC chips we may use in lab are the LM324 (quad op amp chip), 555 (timer), 741 (single op amp chip), and others.

DIP chips are inserted so their body lies over the channel on the solderless breadboard.

IC chips are also assembled onto printed circuit boards (PCB's). In these cases the IC chip is either directly soldered to the PCB or a SOCKET is soldered to the PCB. When using a socket, a bad IC chip can be simply pulled from the socket to replace it, rather than having to re-solder the IC chip to the PCB.

TO KNOW FOR EXAM:

Wire - types (solid, stranded), insulation (colors, purpose), sizing (AWG, how it works), don't memorize AWG sizing chart numbers

Solderless breadboards (Bb) - terms, identify parts, size of wire that fits,

Resistors - what they do, symbol, units, color code (be able to compute nominal R), color code will be given on exam, how Rs add (in series), equivalent R in parallel,

Potentiometers (pots) - what are they, symbol, value in (ohms), what is a wiper, how they work, they are effectively adjustable Rs

Capacitors - what are they, how they work, symbol, value in (farads), what they do (prevent instant changes in V), water analogy

Inductors - what are they, how they work, symbol, value in (Henries), what they do (prevent instant changes in I), water analogy,

Diodes - what are they, symbol, forward vs. reverse bias, identify cathode vs. anode

LEDs - what are they, symbol, identify cathode vs. anode

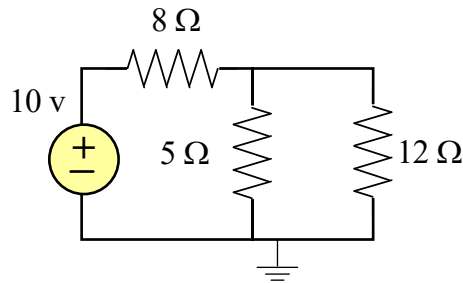
Transistors - what are they, symbol, how work, what they do, identify types, identify legs,

IC chips - what are they, what is DIP,

***** **ELECTRIC CIRCUITS** *****

CHAP 7 - ELECTRICAL CIRCUITS

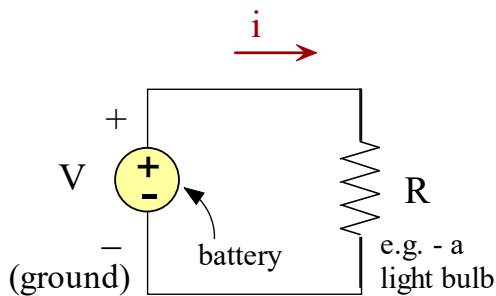
7.1 Intro



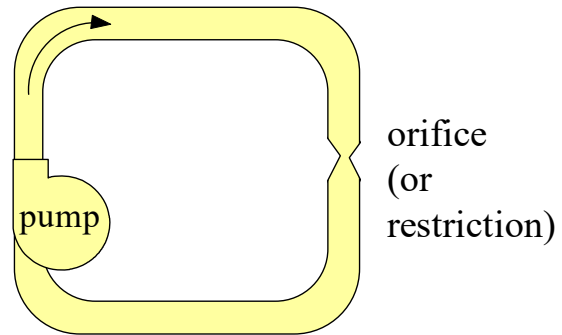
An electric circuit is an interconnection of circuit elements. Circuit components can be wired in a variety of different configurations. These configurations determine, in part, how much voltage and current form in each of the components.

What is needed to get electricity to flow?

1. Circuit (closed path) - charge must start and end at the same point
2. Power source - something to push the charge (voltage)

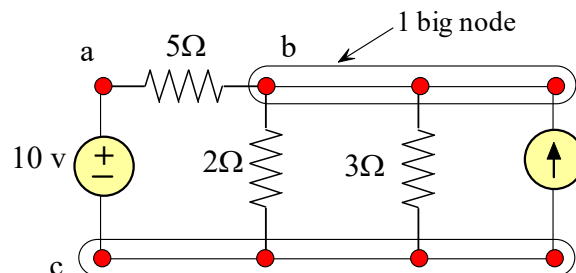


simple circuit



water analog

7.2 Circuit Terms



7.2.1 - Branch

A branch is any 2-terminal element (it has 2 wires sticking out of it) in the circuit.

7.2.2 - Node

A node is a point of connection between 2 or more branches (i.e. – where ever there is wire). If there is no element between 2 nodes, then it is one big node.

7.2.3 - Loop

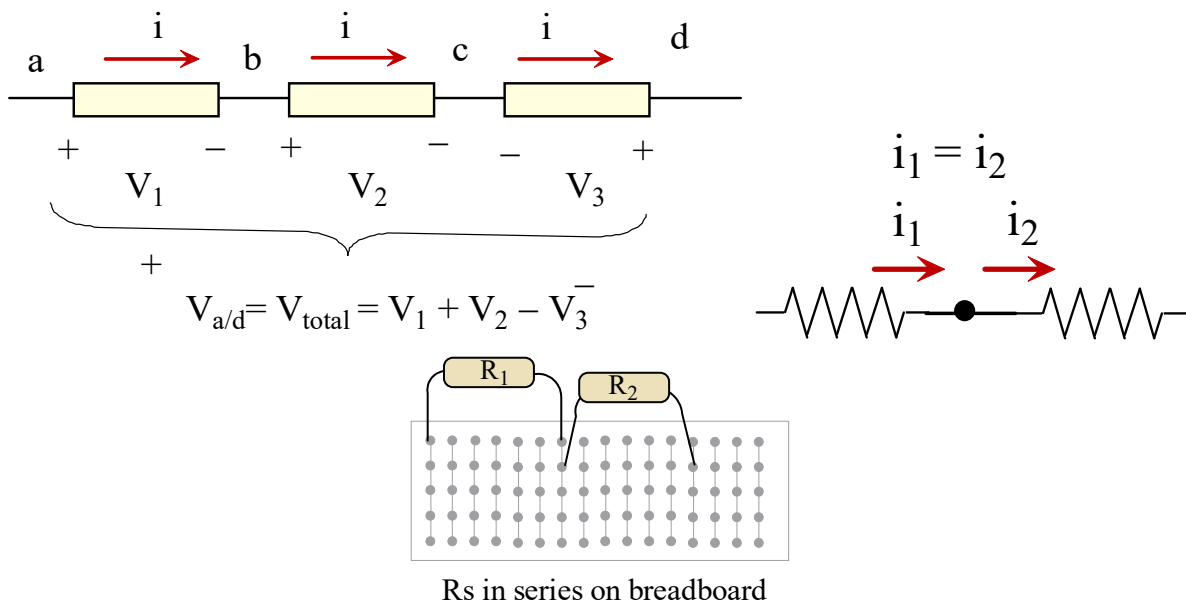
A loop is a closed path in a circuit.

7.3 Series Configuration

In SERIES configuration, elements are wired on after the other (they are "IN SERIES"). As you move from one component to the next, voltage is either added or subtracted.

Voltages add up.

Current is the same.

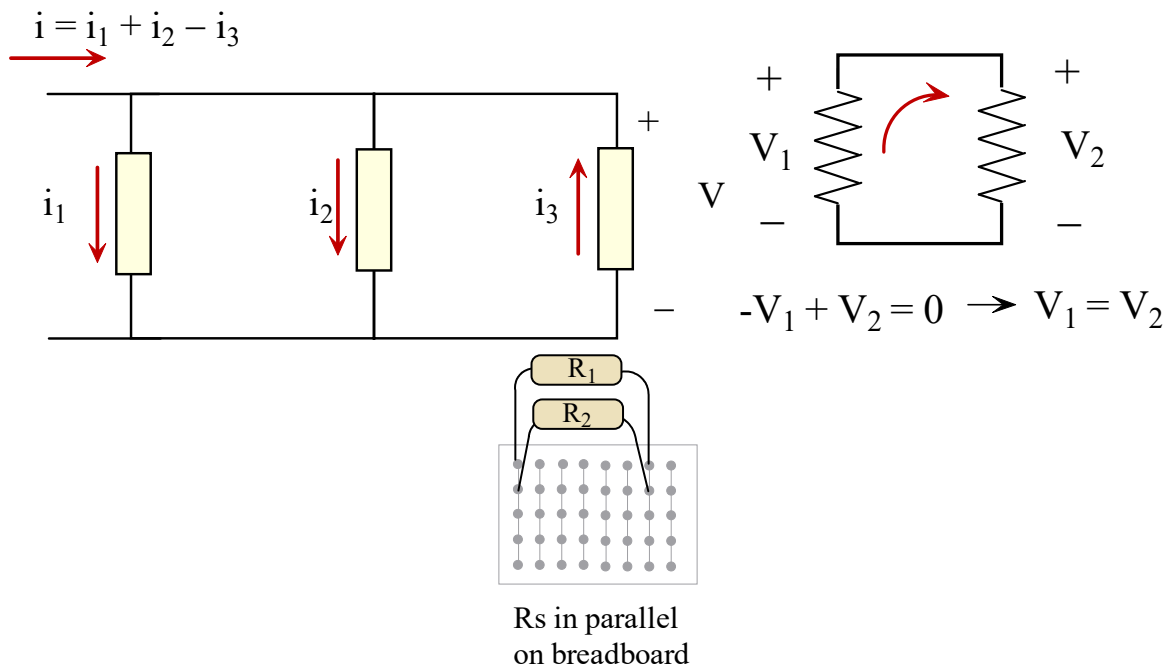


7.4 Parallel Configuration

In PARALLEL configuration, each side of 2 elements is wired to the same "node". Another way of looking at it is that the 2 components are wired in an exclusive loop. That means that if you walk around the loop, you'd pass ONLY thru each component once and you end up where you started.

Currents add up.

Voltages are the same.



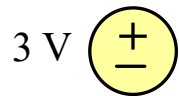
7.5 Kirchhoff's Laws

Kirchhoff's Laws are among the basic laws of circuitry. They can never be violated.

KIRCHHOFF'S CURRENT LAW (KCL)

KIRCHHOFF'S VOLTAGE LAW (KVL)

7.6 Voltage & Current Sources



Voltage source



Current source

Voltage sources (VSs) and current sources (CSs) are the power sources of circuits. The symbols are shown.

Voltage sources maintain a specified voltage across its terminals.
It is DANGEROUS to hook up a VS across a small resistance.

Voltage sources are models for batteries or DC power supplies.

Current sources maintain a specified current through its terminals.
It is DANGEROUS to hook up a CS across a high resistance.

TO KNOW FOR EXAM:

What is a circuit? What is required for electricity to flow?

Terms: branch, node, loop (what are they? Identify them)

Series vs. parallel configuration - what are they, identify the configuration, characteristics of each (eg, current same, voltage adds in series, etc.)

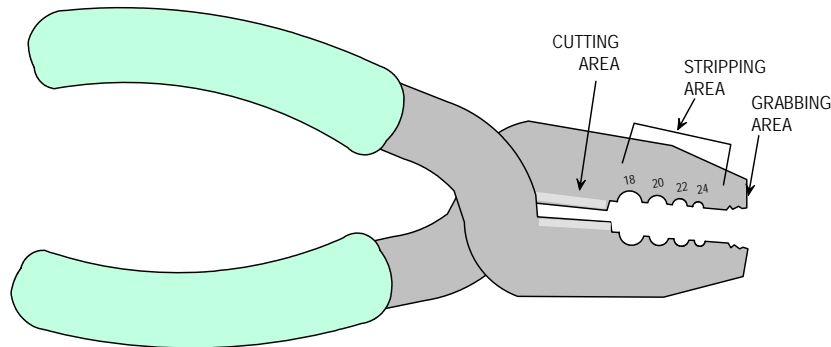
Kirchhoff's Laws - what are they?

Voltage vs. current sources - what are they, symbol

***** TOOLS & OTHER *****

CHAP 8 - TOOLS & OTHER

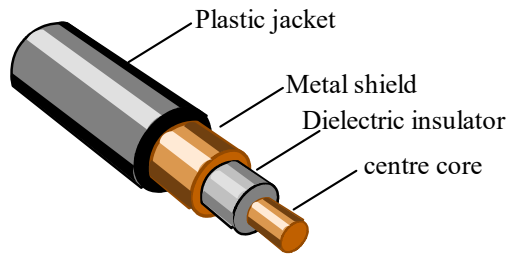
8.1 Wire Cutter / Strippers



The wire cutter/stripper tool is an important tool in circuit construction. A wire cutter/stripper is a tool that has multiple uses. It can cut, strip, and hold wire (see figure). Stripping wire is the process of removing the insulation from the end of a wire to expose the metal wire. The goal is to remove the plastic without cutting the metal. When stripping wire, select the proper size concave "well". Squeeze the tool completely, give a small twist back and forth, back off the squeezing just a bit, and then pull the insulation off. Do not attempt to strip more than 1/4" of insulation at a time. If you need to strip more than that, repeat the stripping process multiple times with shorter lengths.

The cutting area of the tool can cut your fingers. Use care.

8.2 Co-Axial Cables



Co-axial cable construction



BNC connectors

Coaxial cables are specifically designed to reduce noise. Signal is carried on the central conductor (solid or stranded), which is surrounded by a dielectric insulator, and then a metallic shield. The shield is usually grounded to reduce interference (e.g., EM from fluorescent lights would strike the metallic shield first, and would then be immediately grounded).

Applications – coaxial cables are often used in RF signal applications due to their high quality of transmission.

BNC (Bayonet Neill-Concelman) connectors are often used on co-axial cables. These are commonly-used connectors on radio-frequency electronic equipment for frequencies below 3 GHz and below 500V.

Our coaxial (or "co-ax") cables will have "male" BNC connectors at both ends ("male-male"). They may be referred to as BNC cables.

Engaging the connectors involves slipping the male connector over the female connector. The female connector has a protruding portion that must line up with a slot on the sleeve of the male connector. After slipping it over, you must rotate the sleeve until it is secure.

In our lab, BNC connectors are used for the output of the function generator and the oscilloscope.

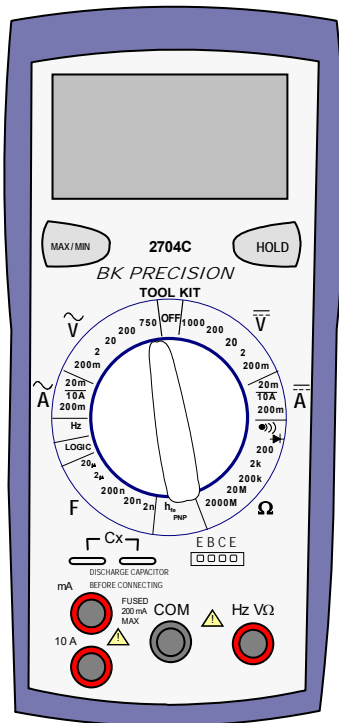
TO KNOW FOR EXAM:

Wire cutter stripper - what it does, identify different areas of the tool and how to use them

Co-ax cables - not covered

***** **DIGITAL MULTI-METERS** *****

CHAP 9 - DIGITAL MULTI-METERS (DMMs)



9.1 General DMM instructions

The DMM ("digital" = display is digital instead of a needle, "multi" = many, "meter" = to measure) is an electronic instrument that can measure several types of electrical signals and display them digitally. DMM's can measure voltage, current, & resistance, capacitance, continuity (to see if there is a "break" in a wire) and other variables. There are many different types of DMM's with widely varying prices, but even cheap ones can be pretty useful. Digital multi-meters may be referred to as "DMM's" or just "multi-meters".

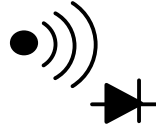
DMM's come with usually two "test leads": one red and one black. The black lead always plugs into the black "COM" ("common" or ground) port. The red lead may go into any of the red ports, but it is usually used in the "VΩHz" port.

The user must first select the SETTING TYPE (are you measuring voltage, current, continuity, etc.)

Then the user must select the RANGE of the value, depending on the type of meter. MANUAL RANGING meters require the user to select the proper RANGE on the dial. For instance the meter may have resistance measuring ranges of 20, 200, 2k, 20k, 200k, 2MΩ. The meter is best set at a range that is JUST greater than

the value being measured. For instance to measure a 2.2kΩ resistor, the range setting would need to be set at 20kΩ. AUTO-RANGING ranging meters automatically set the proper range, though it may take a few moments for the meter to internally switch its circuitry to find the proper range.

CONTINUITY TESTING



Continuity testing involves checking whether 2 points in a circuit have a low resistance between them (typically less than 50 Ω). The meter will tone if this is the case.

Turn the dial on the DMM to the symbol shown. Other DMM's will have a similar symbol, though it may not be exactly the same. The red test lead goes into the " Hz VΩ " port. The black lead is in the COM port. First touch the test leads together to test. The DMM should tone. Then touch the test leads to the 2 points in the circuit you wish to test.

Continuity testing is a good way of testing fuses.

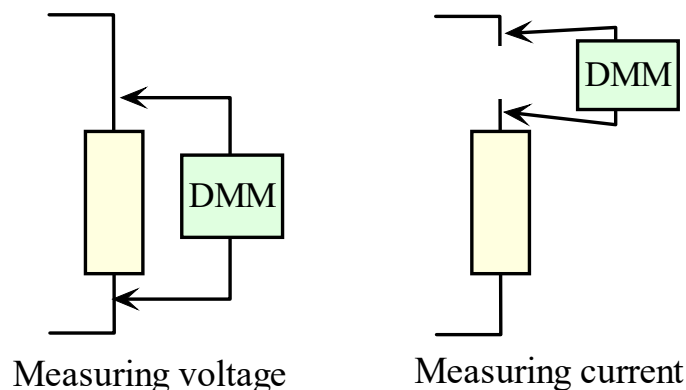
VOLTAGE MEASUREMENT

First select the variable TYPE (DCV or ACV) then select the RANGE. Touch the test leads so that the meter is in PARALLEL with the component across which the voltage is being measured. The red test lead goes to the Hz-V-Ω port.

CURRENT MEASUREMENT

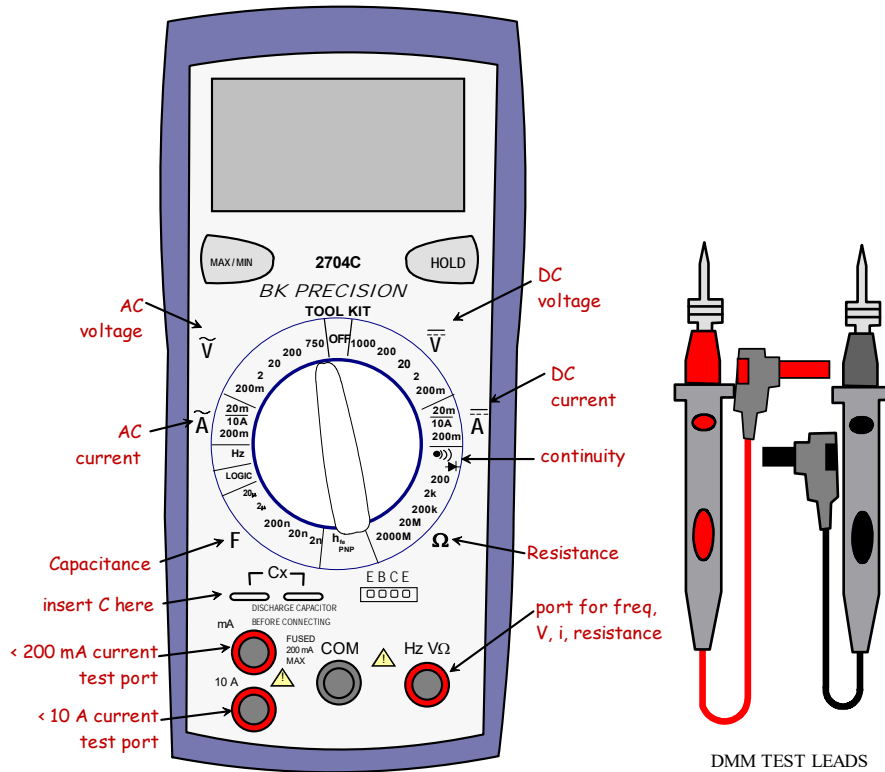
The test lead must be moved to one of the current-measurement ports. One port is fused at 200 mA and the other at 10 A. Insert test lead to the appropriate port depending on the expected current level.

Break open the circuit and touch the test leads so that the meter is in SERIES with a current-resisting component (e.g. – a resistor). This means the branch must be opened and the DMM connected across the opening.



The meter is vulnerable in this setting. The DMM internal resistance is very low to accurately measure current. Thus, if you erroneously connect the meter in parallel with a component (as is done with voltage measurement), then nearly all of the current will pass thru the low resistance (per current divider rule) and the fuse will blow. The BK DMMs seem to indicate a blown fuse by sounding a tone if the lead is in the current port and the dial is set to any voltage measuring section. Generally the instructor will not have students measure current because of this vulnerability

9.2 BK Precision 2704C



SPECS

Variables measurable: DCV, ACV, resistance, DCA, ACA, capacitance, AC frequency, logic, transistor test

Battery: 9V

Fuses:

0.5A/500V fast blow (DC input) ceramic 6.25 x 32 mm

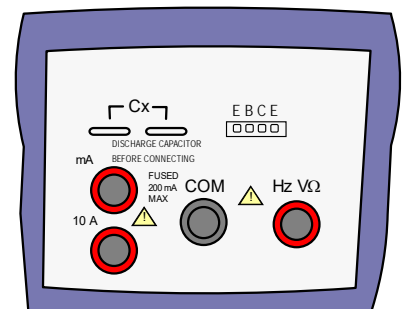
10A/600V fast blow ceramic 6.35 x 25.4 mm

SUMMARY

The BK Precision BK 2704C is one DMM used in lab. This model is about \$60 and is an example of a MANUAL RANGING multi-meter. It is powered with a 9V battery and has 2 internal fast-blow fuses. It comes with a set of "test leads - one black, one red. ONLY use these test leads with this device & no other device.

The black test lead is inserted into the black COM port.

The red test lead is inserted into one of 3 red ports, depending on what is being measured per below:



"Hz VΩ" – when measuring voltage, resistance, frequency

"mA" – when measuring current (up to 200 mA)

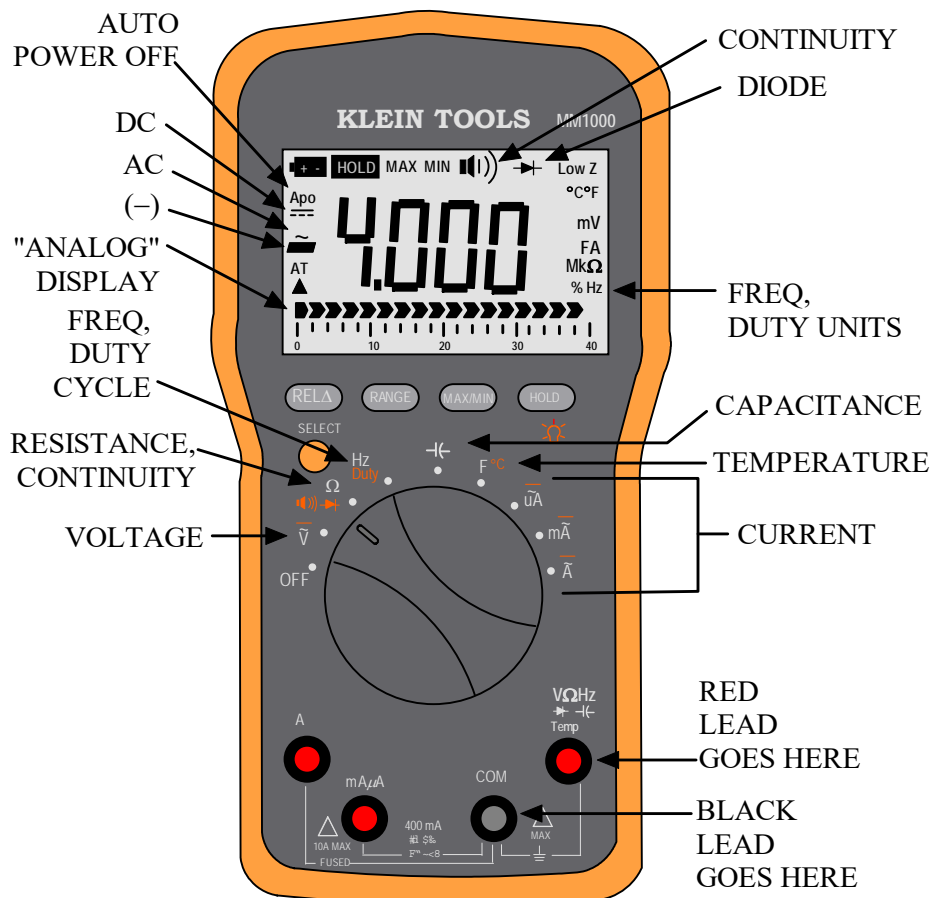
"10A" – when measuring current (up to 10A)

First select the VARIABLE TYPE to be measured: resistance, DC voltage (DCV), DC current, etc.

Then select the RANGE within the setting type. The set range value must be GREATER THAN the measured signal (e.g., to measure a 100 kΩ resistor, set the range to 200K, 2M, or 20M). The best range setting is the smallest one that is still greater than signal's magnitude.

If the measured signal exceeds the range setting, the DMM may display an "OL", meaning " over-range" (or out of limit). If set range is too large compared to the measured signal, then you lose resolution.

9.3 Klein Tools MM 1000



SPECS

Battery 2x AAA batteries
Fuses 440 mA/1000V fast blow
11A/100V fast blow

Display APO = auto power off

The Klein Tools MM1000 (the orange ones) are another DMM we have in lab. These are \$75 meters and are AUTO-RANGING. This means you don't have to set the range value when measuring a variable. When measuring using auto-ranging it takes a few moments for the meter to hone in on a measurement as its internal electronics switch to the proper range.

This DMM has auto-power shut-off (APO), a backlit display, and a pseudo-analog bar meter. It can measure DCV, ACV, DCA, ACA, resistance, continuity capacitance, frequency, duty cycle, diode testing, frequency, and duty cycle. Note using the backlight will draw down the battery fairly quickly.

CONTINUITY / RESISTANCE

Continuity testing is combined with resistance measurement. Adjust dial to " Ω /continuity" setting. Press the orange SELECT button until the continuity symbol appears on the display.

Dial (Ω /continuity) > Press orange button (continuity appears on display)

Resistance measurement is also under the " Ω /continuity" setting. Press the orange SELECT button until the " Ω " symbol appears on the right of the display.

VOLTAGE

Both DC and AC voltage are combined in one setting. First adjust the dial to $\overline{\tilde{V}}$ setting. Then press the orange SELECT button to toggle between DC and AC. The red lead must be in the "V Ω Hz" port. Place test leads in parallel with element across which you wish to measure voltage.

mA CURRENT

Both DC and AC current are combined in one setting. First adjust the dial to "mA" setting. Then press the orange SELECT button to toggle between DC and AC. The red lead must be in the "ma/uA" port. Place test leads so that the DMM is in SERIES with the branch in which you wish to measure current. The limit in this setting is 400 mA.

"A" CURRENT

Both DC and AC current are combined in one setting. First adjust the dial to $\overline{\tilde{A}}$ setting. Then press the orange SELECT button to toggle between DC and AC. The red lead must be in the "A" port. Place test leads so that the DMM is in SERIES with the branch in which you wish to measure current. The limit in this setting is 10 A for a period of about 30 seconds.

(KEEP WORKING ON THIS)

TO KNOW FOR EXAM:

What are DMM's? What does DMM stand for? What do they do?

How do you use them?

Where do you insert the red and black test leads?

How do you measure voltage, resistance, current?

Auto vs. manual ranging - what are these?

What is continuity testing?

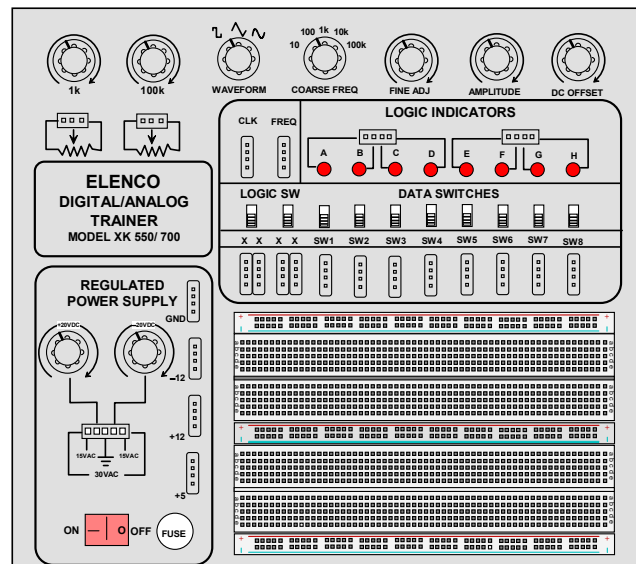
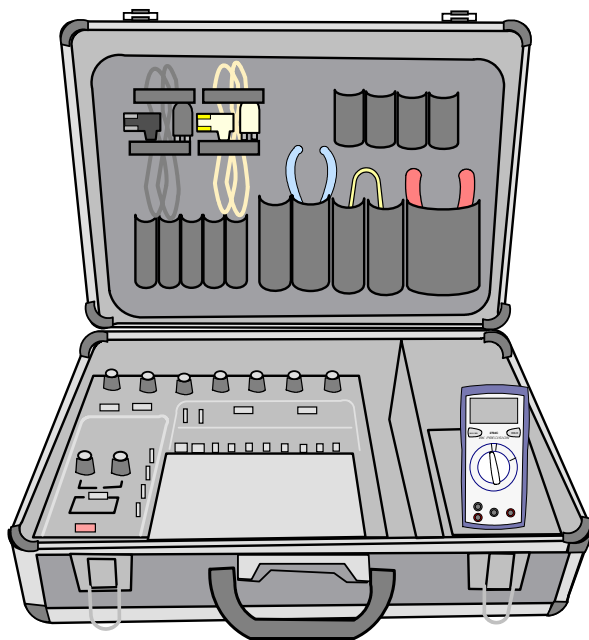
Don't memorize DMM specifications

***** TRAINERS *****

CHAP 10 - TRAINERS

10.1 Intro

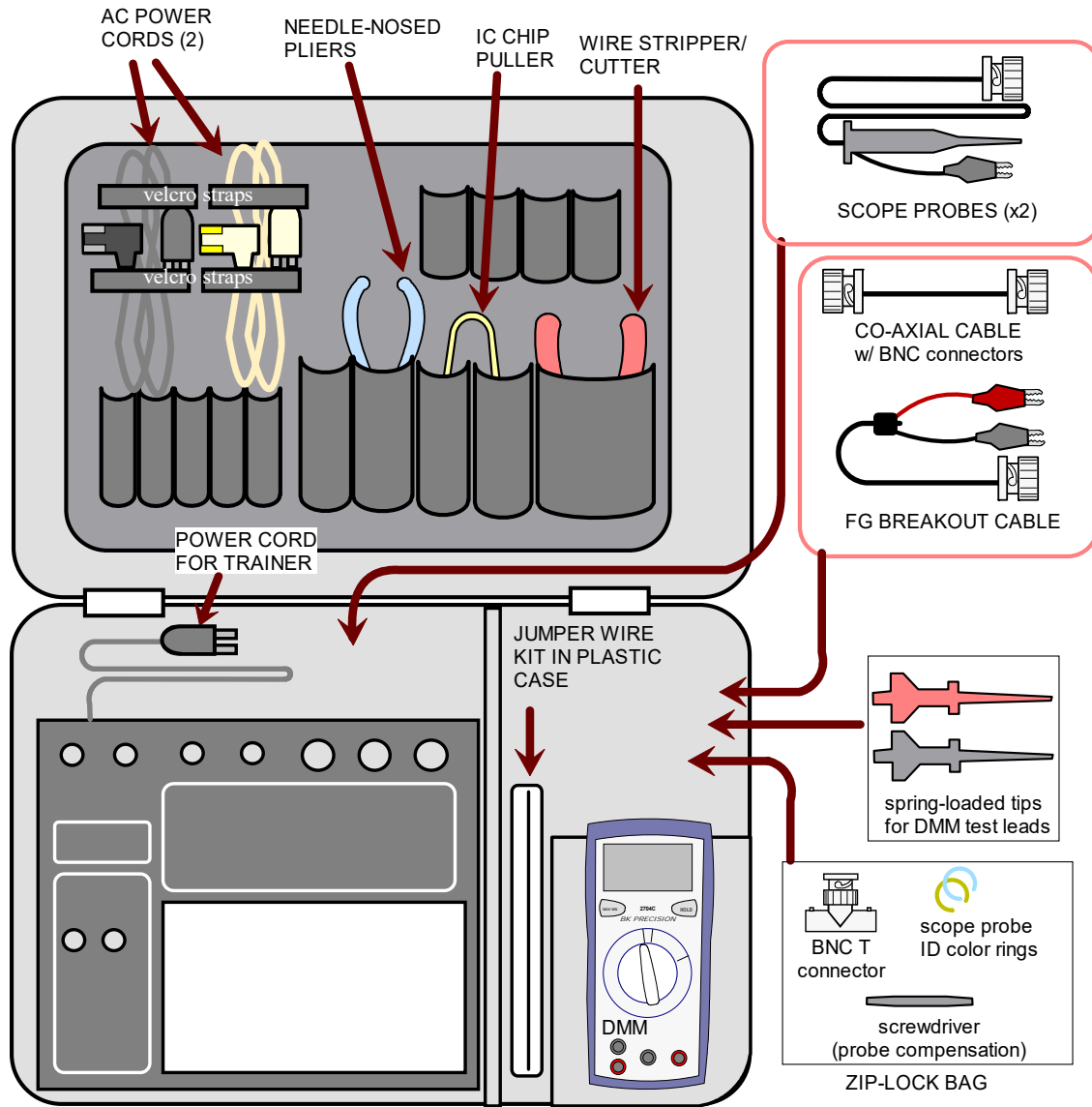
The "trainer" cases (Elenco XK 700) contain tools and supplies for building and testing circuits. The trainers include 5 independent power supplies, an analog trainer, a digital trainer, a function generator, and a solderless breadboard. The XK 700 is housed in a sturdy briefcase and includes a variety of tools.



TRAINER CONTENTS LIST

1. Trainer itself – case with handle solderless breadboard, and electronics chassis
2. Digital multi-meter (DMM)
3. Scope probes (x2) (use ONLY with oscilloscope)
4. DMM test leads (1 red, 1 black)
5. Spring-loaded tips for DMM test leads
6. Power cords (2), (1 for scope, 1 for FG)
7. Co-axial cable with BNC connectors ("BNC cable") (1)
8. BNC-T splitter (1)
9. Jumper wire kit (1 case)
10. Scope probe kit (colored rings, probe compensation screwdriver)
11. Needle-nosed pliers (1)
12. Wire stripper/cutter tool
13. IC chip pulling tool

14. FG "break-out cable" (BNC to alligator clip leads, use ONLY with function generator)



10.2 Trainer Contents (mainly for ENGR 250L)



Scope probes (x2) & scope kit



Wire cutter/stripper



Power cords (2)



BNC-T



Jumper wire kit



Power cords (x2)



DMM leads

BNC-T splitter

FG break-out cable



Co-axial cable
(w/ BNC connectors)



Needle-nose pliers



DMM tips



IC chip puller

10.3 Specifications

Positive variable power supply (0 – 15V at .5A, 15 – 20V at 1A).

Negative variable power supply (same specs as above)

3 fixed voltage (DC) power supplies (+12VDC, -12 VDC, +5VDC, at 1A each)

AC voltage power (15 or 30 VAC)

Fuse type:

Note – supplies are regulated to within 150 mV, and are short-circuit-protected using integrated circuit regulator devices.

10.4 Trainer Fuse

CHECKING THE FUSE

Access the trainer fuse by unscrewing the fuse housing. Visually inspect the fuse to see if it has blown. This can be difficult to see. You can also test the fuse using a continuity test using a DMM.

10.5 Trainer Function Generator

The trainer comes with a built-in function generator. The quality is not quite as good as a standard bench function generator (FG).

Waveforms: sine (the symbol looks a bit like a triangle), triangle, square;

Frequency: 1 Hz – 100 kHz, in 5 steps)

Amplitude: 0 – 15 Vpp

DC offset adjustment (no indexing at 0 V. Verify zero offset by checking V_{avg} on scope (s/b = 0).

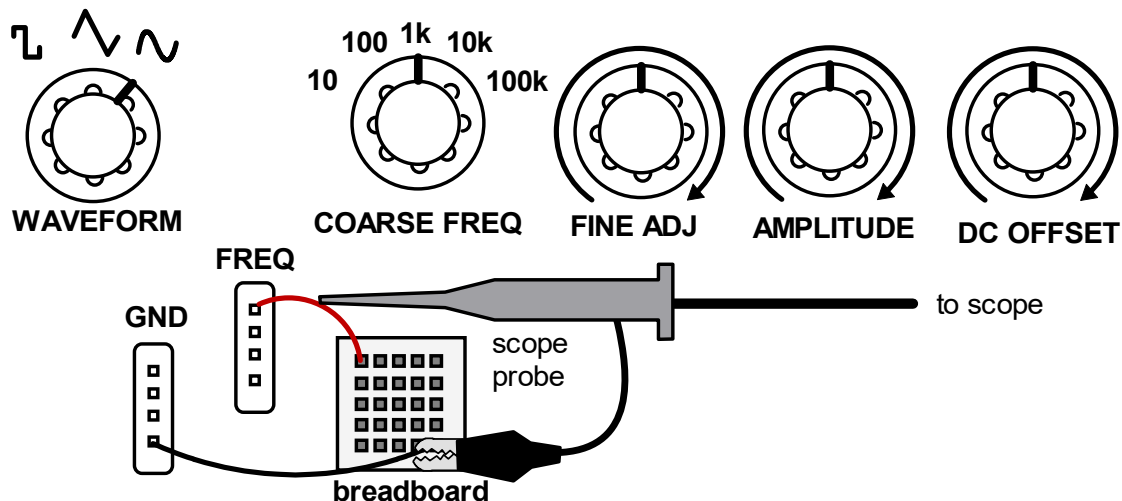
Output impedance: ~ 330 ohms

Function generator output: "FREQ" terminal (relative to GND).

STEPS FOR OBTAINING A WAVEFORM

Let's try to get the trainer FG to output (for example) a 2 Vpp, 1 kHz, 0 volt offset sine wave. The output of the trainer FG is the port labeled FREQ.

1. Run a wire (usually red) from FREQ to the breadboard.
2. Run a black wire from GND to a second location on the breadboard.
3. Hook scope to the FG output (probe to FREQ, probe GND clip to GND).
4. On FG, select the waveform (square, triangle, or sine)
5. Set the COURSE FREQ knob.
6. Turn the FINE ADJ, AMPLITUDE, and DC OFFSET knobs to their 12 o'clock position
7. On scope, adjust the voltage and time scales on the scope (or use AUTOSSET)
8. Set the scope to display Vpp, frequency, and Vmean (or Vavg) (this measures DC offset)
9. Adjust the amplitude knob until you obtain the proper amplitude (Vpp)
10. Adjust the coarse and fine frequency until you obtain the desired frequency (in Hz).
11. Adjust DC offset so that Vmean or Vavg = 0 (for 0 DC offset).



POTENTIOMETER

The trainer has 2 built-in pots - 1k and 100k (panel mounted).
The center port connects to the pot wiper.

DIGITAL SECTION (not used)

BREADBOARD - the trainer has a large solderless breadboard on which to build your circuits. If an area of the breadboard looks burnt (brown) or melted, then do not use that area.

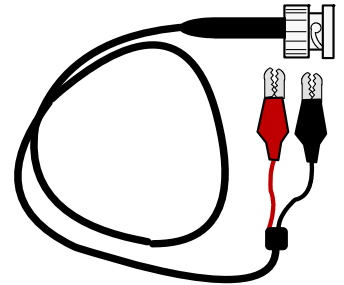
TO KNOW FOR EXAM:

- be able to identify tools and components in trainer
- how to use the trainer's function generator
- how to use the trainer's regulated power supply
- how to use the trainer's pots
- how to remove and check the trainer's fuse
- not covered - specs on the trainer

***** **FUNCTION GENERATOR** *****

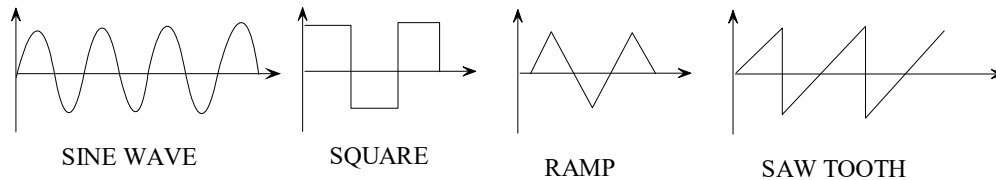
CHAP 11 - FUNCTION GENERATOR

Function generators (FGs) produce voltage signals of different "waveform" patterns (sine, square, ramp, etc.). FG's have numerous knobs and buttons that are used to adjust the various waveform parameters (amplitude, frequency, duty, etc.). The output of an FG may be sent to an oscilloscope. An FG output signal can also be applied to a circuit using a function generator "break out" cable. Do not use this break-out cable with the oscilloscope.

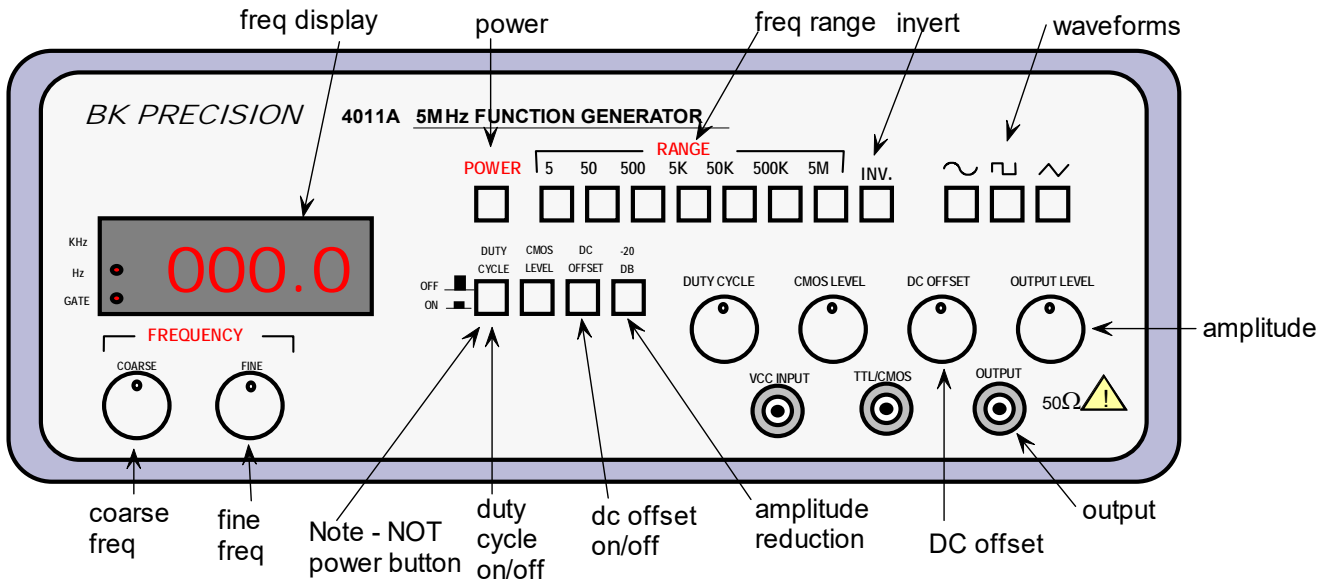


BREAKOUT CABLE

Below are some basic waveform patterns that are often available on an FG.



11.1 BK Precision 4011A



The BK Precision 4011A function generator (~ \$400) produces signals up to 5 MHz.

POWER button - is marked with "POWER" in red (NOT the "DUTY CYCLE" button below)

DC Offset knob - adds or subtracts DC offset (with DC offset button IN).

OUTPUT port - the BNC connector on the FAR RIGHT is the FG output

FREQUENCY CONTROL - first set the coarse and fine knobs to 12 o'clock. Then push the RANGE button (the specified range is ~ max frequency under that setting). Turn COARSE knob for coarse adjustment. Lastly, turn FINE knob for fine adjustment.

FREQUENCY DISPLAY - is slow to refresh. Adjust frequency then wait for the display to refresh.

OUTPUT LEVEL - turn this knob to adjust the AMPLITUDE of the waveform. The minimum amplitude for all waveforms is about 800-900 mV.

-20DB button - pressing this button allows the FG to output below 800-900 mV to roughly ~80-90 mV.

TO KNOW FOR EXAM:

- all topics above

***** OSCILLOSCOPE *****

CHAP 12 - OSCILLOSCOPE

The oscilloscope (or "scope" for short) is an electronic device that senses and plots voltage values as a function of time (e.g., sine wave voltage versus time). There are digital and analog scopes. Older scopes were ANALOG, and modern scopes tend to be DIGITAL (& are generally easier to use).

Analog scopes have a CRT display. These displays work by emitting a stream of electrons against a phosphor-coated screen (like an old tube TV). When the electron strikes the screen, the phosphor glows so we can see it. Scopes are designed to display oscillating signals non-moving on the display. This is achieved with a combination of TRIGGERING and SWEEP. Sweep is related to the horizontal movement on the display. Triggering is what starts (or triggers) the horizontal sweep so that sweep begins at the same relative point of a repeating signal. Triggering, sweep, and vertical deflection (caused by voltage) produce a non-moving trace on the display.

Users may benefit from using an analog scope. The analog scope forces users to better understand how the scope works & what its controls do. Analog scopes are often preferred by experienced electronics technicians because they are very responsive & are thus able to display some "irregular" signals that may provide clues to what is wrong in a circuit.

Digital scopes are essentially computerized sensing devices that use software and LCD displays. Their software provides a multitude of tools to process and display sensed waveforms and their parameters. Digital scopes can also store and export display graphics and sampled data.

Oscilloscopes MEASURE voltage. Thus, their scope PROBES are connected to a point on the circuit to measure the voltage there. The user then manipulates the various dials, buttons, and controls on the scope to obtain the desired trace on the display. These controls also allow one to display the measured parameters (e.g., V_{pp} , V_{avg} , etc.) TIME and VOLTAGE SCALE controls the size of the trace on the screen but they do not actually change voltage and frequency values.

12.1 General Topics for All Scopes

SCOPE PROBES

Oscilloscopes use scope probes to connect to the circuit. The probes typically have a spring-loaded tip and a grounding clip. The user connects the probe tip to the desired point on the circuit. The ground clip is ONLY to a ground point on the circuit. Unlike DMMs, scopes cannot generally measure voltage relative to non-ground reference points. Connecting the ground clip to a non-ground point in circuit alters the circuit, rendering the scope reading wrong.

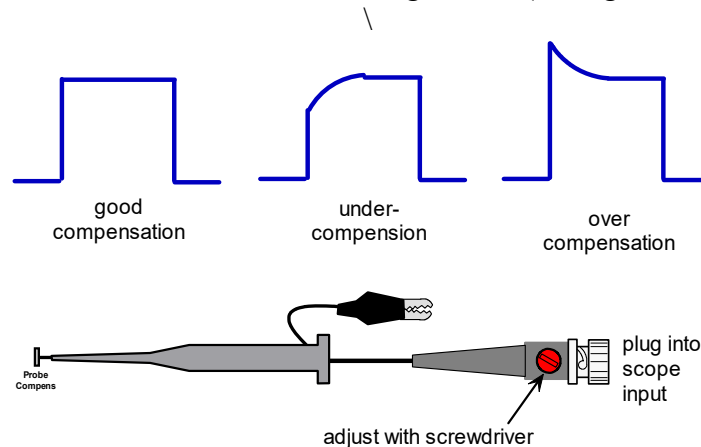


PROBE COMPENSATION

The scope probe has inherent internal capacitance that affects the accuracy of its readings. The scope and scope probes provide a way to compensate for this to improve measurement accuracy. The scope has a port that produces a known square wave. Hook up the probe to the port and make the probe compensation adjustments. The probe compensation steps must be done for EACH PROBE, and the probe compensation should be periodically rechecked.

STEPS

1. Connect scope probe to a scope input. Turn on the channel.
2. Connect spring-loaded probe tip hook to probe compensation output.
3. Press AUTOSET to get the square wave displayed.
4. Use scope calibration screwdriver (a very small plastic one that comes with scope) to turn the adjustment screw on the probe near the BNC connector.
5. Adjust the screw until the waveform horizontal edge is flat (see figure below).



PROBE ATTENUATION

Like any other measuring device, the scope can affect the variable being measured. The best measuring devices try to minimize this effect. Oscilloscopes provide a way to reduce resistive and capacitive loading. This is done by using the "10x scope probe" attenuation setting. First set the switch ON THE PROBE to "x10". Then duplicate that setting on the appropriate channel on the scope (e.g., press CH 1 to get the CH 1 menu. Set probe compensation to "x10". These settings must always match.

When using the co-axial cable, set the attenuation to 1x. A common mistake for users is to forget to change the probe attenuation when switching between using the scope probe and the co-ax cable.

COUPLING

An AC signal may or may not have a "DC offset" or DC component. Sometimes we want the scope to display that offset, but other times we don't. This is controlled with COUPLING.

There are generally 3 coupling modes: AC, DC, and GND.

AC coupling - trace only shows only AC component of signal with DC component zeroed out. Signal should appear vertically centered on screen. Even if a signal with DC offset is being measured, the scope under AC coupling will not show that DC offset (eg - V_{mean} will show as ~ 0).

DC coupling - trace includes DC component of signal, so waveform will be displaced vertically, not centered (i.e., V_{mean} will show as not equal to 0)

GND - the signal is grounded. The trace should be a horizontal line on the x-axis.

TRIGGER

Scopes use TRIGGERING to get oscillating signals to appear static on the screen. The trigger setting specifies which channel you are triggering off of, and the trigger "level", which is the voltage value that will be placed on the y axis. On the Instek the trigger level is denoted by a small arrow on the right of the trace. This arrow must be set within the limits of the repeating signal. Otherwise the trace will become unstable. You can only trigger on one of the channels. Thus, if you have for example 2 sine waves of different frequencies being input to the scope, only one of the traces will appear static on the display (the one being used to trigger). The other traces will appear to roll on the screen. This is normal.

SCALE & POSITION CONTROLS

Oscilloscopes have numerous buttons and knobs to allow us to get the trace to appear on the screen as we like. Scopes are MEASUREMENT devices, so any adjustments here do NOT change the signal - they just change their appearance on the scope display.

VOLTS/DIV - controls "voltage scale" (it does NOT change the voltage value)

TIME/DIV - controls "time scale" (it does NOT change the frequency of the signal)

VERTICAL POSITION - moves the trace up and down (it does NOT add or subtract DC offset)

HORIZONTAL POSITION - moves the trace side to side

MEASUREMENTS

With analog scopes, you must figure out frequency and voltage values by counting divisions. Digital scopes will calculate and display these values for you. Examples of signal values that you may wish to display are: V_{pp} (peak-to-peak), V_p (peak), V_{max} (amplitude), V_{mean} (avg or dc offset of signal), frequency, period, and more.

AUTOSET

Autoset is a quick and easy way to get traces to appear nicely on the scope's screen. It will automatically set voltage scale, time scale, trigger level, position, and other settings.

Do NOT over-use this function. A user should be able to get waveforms to appear nicely by adjusting scale, position, and trigger without using Autoset.

If displaying 2 signals Autoset will usually offset the 2 traces vertically. If you wish to OVERLAY the 2 traces, Autoset will not help.

Autoset also works poorly with DC voltage readings on the scope. DC voltage appears as a straight horizontal line on a scope. Pressing Autoset while measuring DC voltage will often result in the scope ZOOMING IN attempting to read any signal variations. Often the zoom scale is extreme, causing the scope to merely show the NOISE present in the DC signal (probably not what you wanted). Thus, do not use Autoset when measuring DC signals on the scope.

SAVING DISPLAY TRACE TO USB

Digital storage oscilloscopes (DSO's) can usually save a digital copy of the trace. Insert a USB flash drive into the scope. The drive likely must be formatted per scope requirements. Many scopes use **FAT32**, which is an older formatting. It is often limited to **USB drives sized 2-32 Gb**. Most scopes offer options such as file type and **ink saver mode**. Ink saver will invert the colors so the background is white instead of black. This saves ink & toner if you are printing the images. Saving the image to a cell phone or computer gives you more options to adjust the images (like brightness and contrast). You can invert colors, brighten, change contrast, etc. in programs like MS Paint or GIMP (a free graphics program). You can then copy the altered images to MS Word for any reports.

FORMAT DRIVE FAT32

Insert USB drive into a computer. In Windows, open File Explorer. Right click the USB drive & select Format... If FAT32 is not an option, then there is a work-around. You can format the drive using the command prompt. Open cmd.exe. Then follow steps below.

```
type: diskpart
type: list disk
      result:
      Disk #
      -----
      Disk 0
      Disk 1

type: select disk #
type: list disk (the selected disk has * - ensure it is what you want)
      result:
      Disk #
      -----
      Disk 0
      *Disk 1

type: create partition primary
      result:
      DISKPART > DiskPart succeeded in creating the specified partition

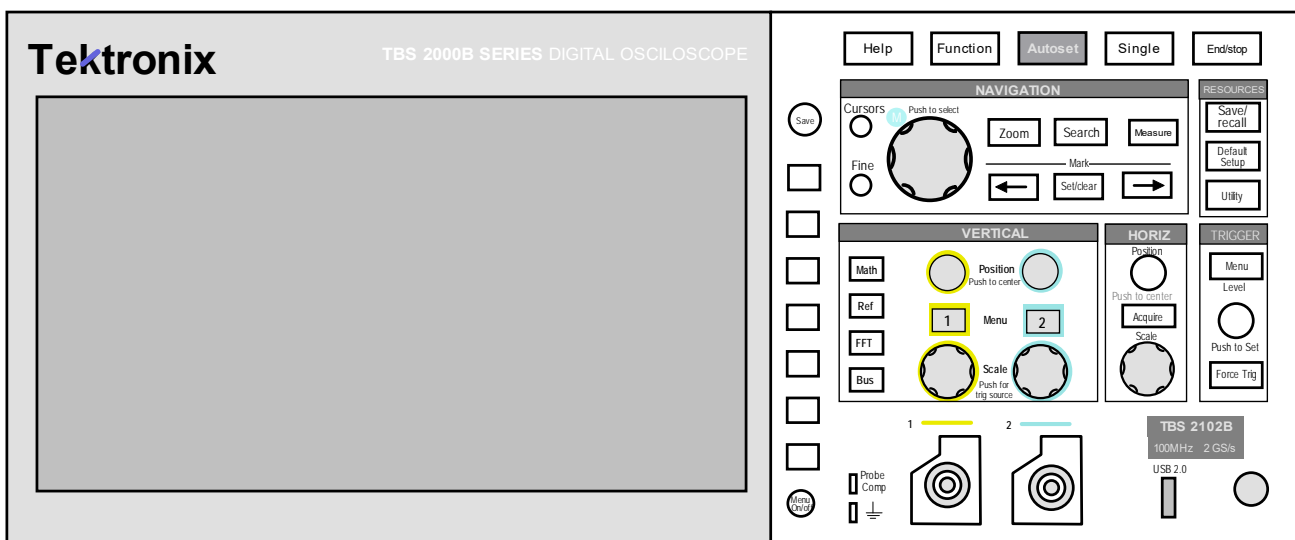
type: select partition 1
      result:
      Partition 1 is now the selected partition
```

type: format fs=fat32 quick
result:
100 percent completed
DiskPart successfully formatted the volume

(optional?)
type: active
DiskPart marked the current partition as active.

12.2 Tektronix Scopes

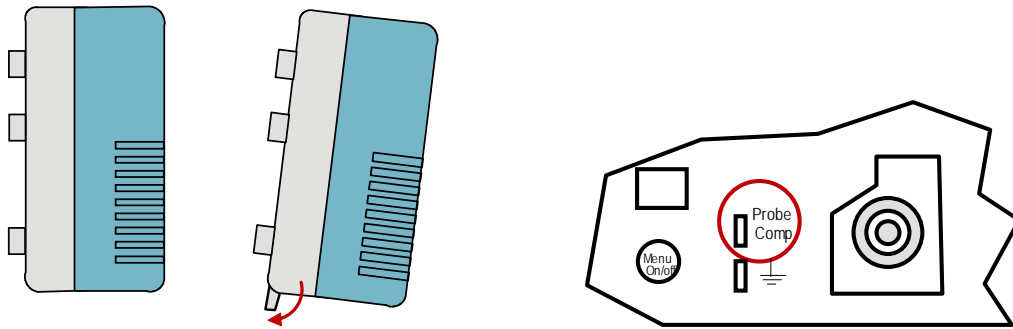
The Tektronix TBS 2102B is a general-purpose 2-channel digital storage oscilloscope (DSO) can measure signals of up 200 MHz frequency (cost ~ \$1.8k). Specs: sampling frequency 2 GSa/s, 9-inch display.



12.2.1 - Getting Started

POWER UP

Place the scope on a secure, level surface. Plug power plug into back of unit and plug into AC outlet. The front power button will light YELLOW. Flip out "tilt stand" legs if desired to incline the scope slightly. Press POWER key on the front panel. Wait a few moments for the scope to "boot" up.



PROBE COMPENSATION

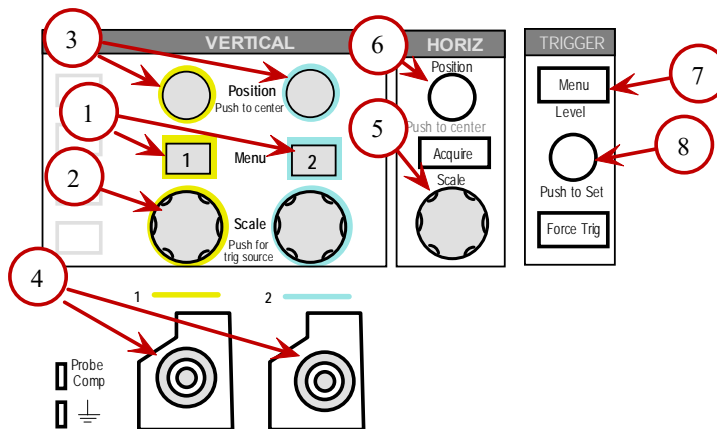
The probe compensation port is to the left of the CH 1 BNC connection port (see figure above left). Perform probe compensation as described above.

PROBE ATTENUATION

Some scope probes can switch between x and 10x, but apparently the Tektronix scopes are fixed at 10x attenuation. So ensure that scope inputs are set accordingly when using the probes.

12.2.2 - Basic Trace Control

The functions below work pretty much as described in the section "General Topics for All Scopes". The turning knobs on the Tektronix scope are PUSH-KNOBS (you adjust the knob then push the knob like a button to confirm your selection).



CHANNEL MENU (1) - toggles the respective channel on and off. Accesses channel settings: probe attenuation, DC coupling, and more

VERTICAL SCALE (2) - adjusts volts/division. A division is 1 vertical square defined by the dotted lines. It does NOT change the signal's amplitude.

VERTICAL POSITION (3) - shifts the trace up and down (it does NOT add DC voltage offset)

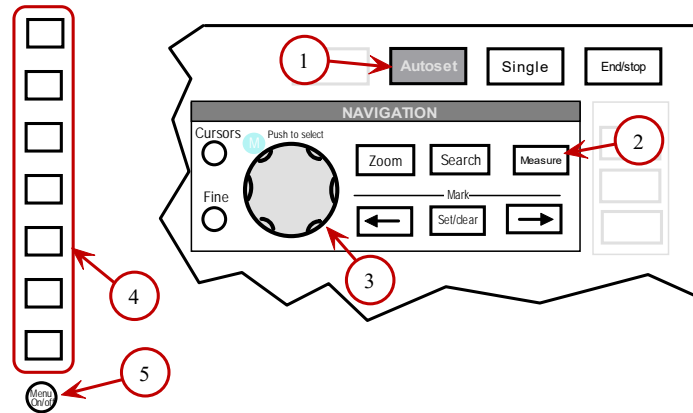
PROBE INPUT PORTS (4) - where to plug in scope probes for channels 1 and 2

HORIZ SCALE (5) - adjusts the time scale (time/division). A division is 1 horizontal square of dotted lines

HORIZ POSITION (6) - shift trace left and right

TRIGGER MENU (7) - trigger settings: type (edge), source (channel), slope (rising), level
TRIGGER LEVEL (8) - turn to adjust trigger level (must be within range of signal)

12.2.3 - Autoset, Measure, Menus, Saving to USB

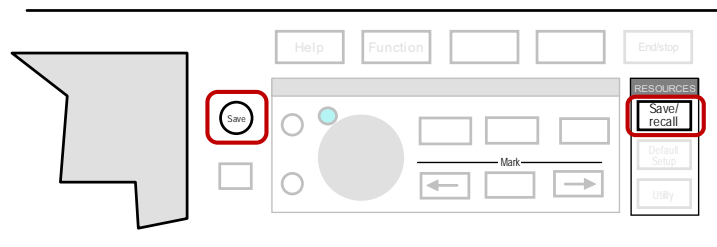


AUTOSET (1) - press to automatically set scale, position, and trigger

MEASURE (2) - press this button to add measurements to the display (eg, V_{pp} , V_{max} , V_{avg} , frequency). Once in the measure menu, turn the SELECTION KNOB (3) to highlight desired measurement. Ensure the desired channel (1 or 2) is selected. Push the select knob (it is a button too) to select the measurement.

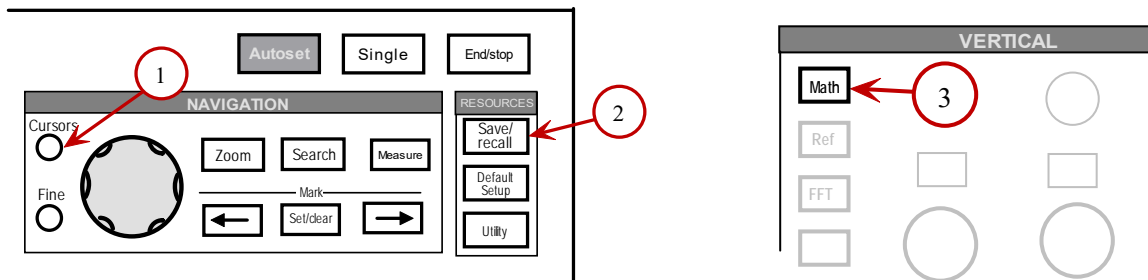
MENUS & SOFTKEYS - various scope functions will bring up a menu system on the right side of the display. Navigate the menu using the selection knob (3) and the SOFT KEYS (4) which are to the right of the display. Exit the menus by pressing the MENUS ON/OFF BUTTON (5)

SAVING TO USB



You can save your data (as CSV) and display (as image file) to a USB flash drive. First obtain a USB flash drive formatted FAT32. See section above for how to do that. Once formatted insert the USB drive into the USB 2.0 port of scope. A message will appear indicating that the scope knows a USB drive is inserted. Press SAVE/RECALL. Set filetype to JPG. Set INK SAVER to ON. Now press SAVE whenever you wish to save the screen to the USB drive.

12.2.4 - Cursors, Reset

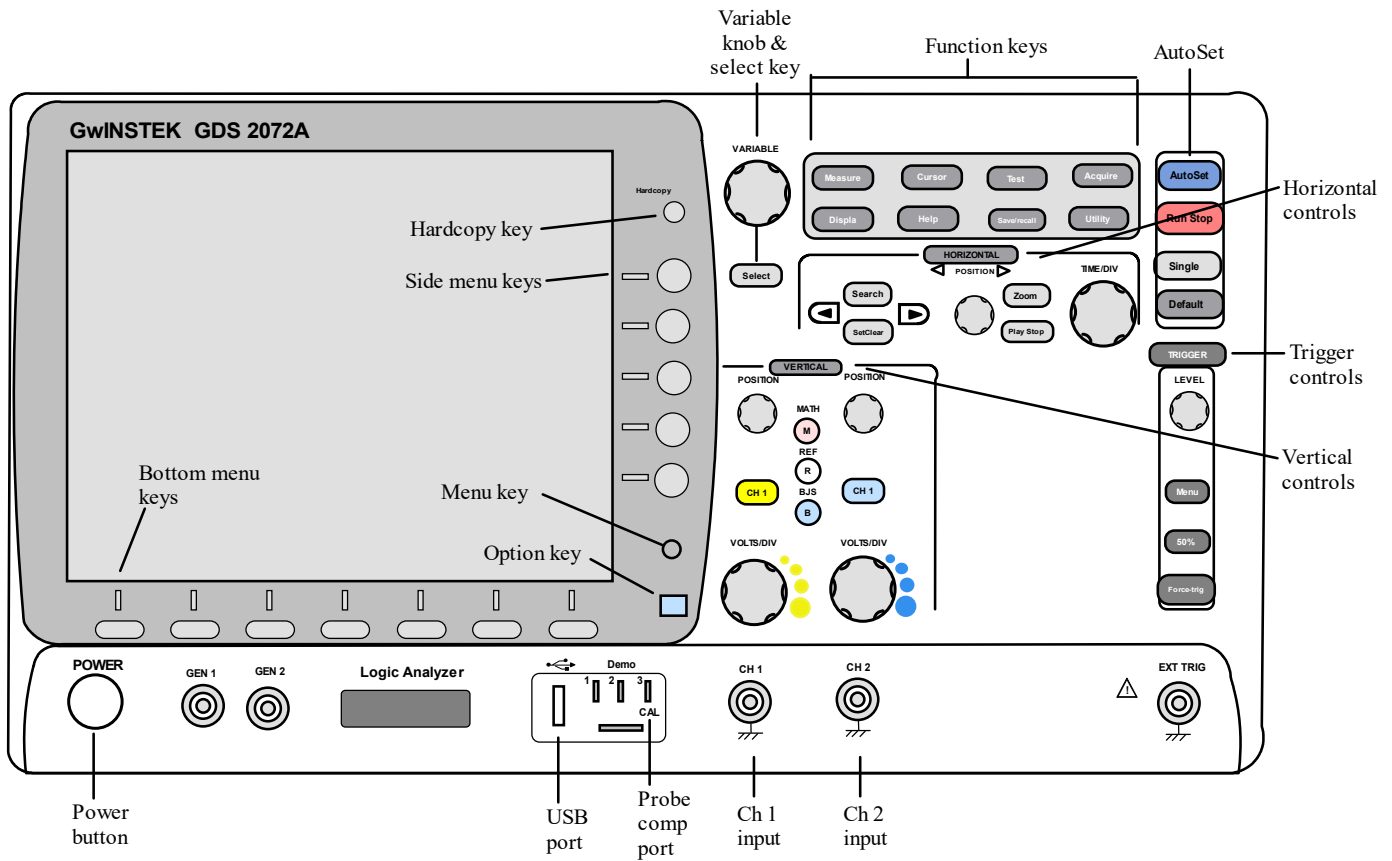


CURSORS (1) - press to use the cursors. Cursors allow you to "point" to certain locations on a trace and obtain voltage or time values or differences (eg - to get time constants, voltage or time differences between 2 points on the trace).

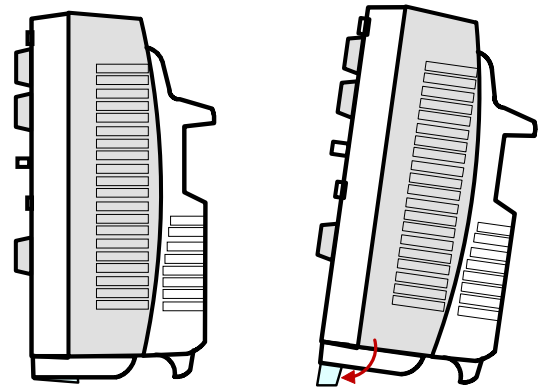
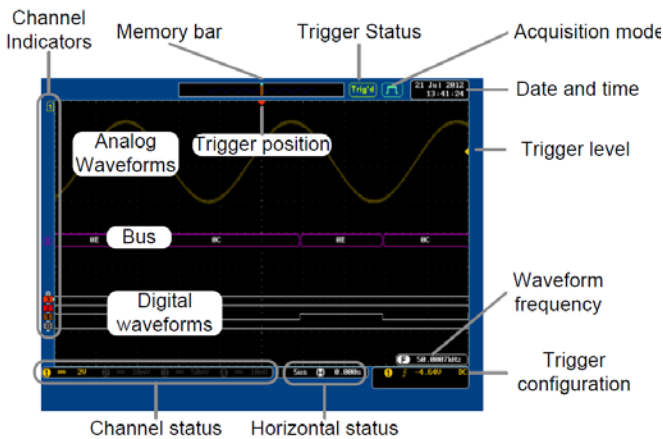
SAVE/RECALL (2) - resets the scope to factory default settings. This may be helpful if a setting is wrong and you can't seem to find where that setting is to fix it.

MATH (3) - press to access math functions. The scope can perform math operations on the measured signals. For instance you may wish to subtract channel 2 from channel 1 ($MATH = CH\ 2 - CH\ 1$) and see the resulting trace and its value (eg V_{mean}) on the screen.

12.3 Instek GDS-2072A (70MHz, 2-channel, 2 GSa/s)



The Instek GDS-2072A is a generic purpose digital storage oscilloscope (DSO) that can measure signals of up to 70 MHz frequency. It is a 2-channel scope with a sampling frequency of 2 GSa/s (giga-samples per second). It has an 8-inch color TFT SVGA LCD display at 800 x 600.



FRONT PANEL CONTROLS

- Power button
- Bottom menu keys - to select menus that appear along bottom
- Menu key - hide on screen menu system
- Option key - to access any installed options
- Hardcopy key – is the quick-save or quick-print key
- USB port - for USB flash drive for saving screenshots & data

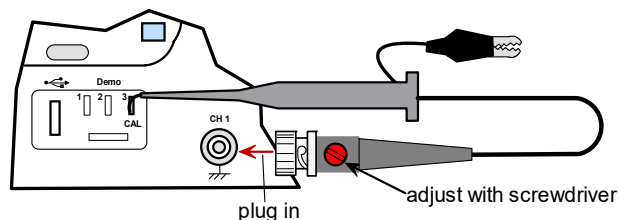
- Ports - #3 is for probe compensation
- CH 1 & CH 2 inputs - for scope probes
- Side menu keys - for selecting menus that appear along side
- Vertical controls - to set vertical (voltage) position and voltage scale (volts/div)
 - Math - set & configure math functions
 - Ref
- Horizontal controls - set time base settings (horizontal position, time scale (time/div)
 - Zoom – press in combination with horizontal position knob
- Trigger controls
 - Level knob (set trigger level), menu key (enter trigger menu), 50% (set trigger to half-way pt)
 - Force-trig - force an immediate trigger of waveform
- AUTOSET - automatically set trigger, voltage & time scales
- Run/stop – press to "freeze" or continue ("run") signal acquisition
- Default setup – resets scope to default settings
- Function keys - to configure & run the different functions on the scope
 - Measure (display automatic measurements)
 - Cursors, test, acquire (configure acquisition mode), display (settings), help, save/recall,
 - Utility (configure hardcopy key, display time, language, calibration, etc.)
- Variable knob - use knob to increase/decrease values or move between parameters.
- Select Key – to make selections

GETTING STARTED

Place the scope on a secure, level surface. Flip out "tilt stand" legs to incline the scope slightly. Connect the power cord to the rear panel. Press POWER key on the front panel. It takes some time for the scope to "boot" up.

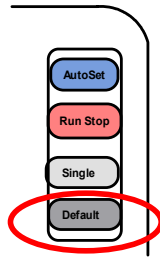
PROBE COMPENSATION

1. Connect scope probe to one of the scope CH inputs.
2. Turn on the channel.
3. Connect spring-loaded probe tip hook to probe compensation output 3 (a 2 Vpp, 1kHz square wave).
4. Press AUTOSET to get the square waveform to display.
5. Press DISPLAY, set TYPE to "Vectors"
6. Use scope calibration screwdriver to turn adjustment screw on the probe near the BNC connector.
7. Adjust until the waveform horizontal edge is flat.



PROBE ATTENUATION - when using the scope probe, set attenuation to 10x (see above)

RESTORING FACTORY SETTINGS - press DEFAULT key



MEASUREMENTS

To display any voltage or time parameters, perform the following steps

MEASURE > Add measurement (lower left, use bottom menu keys) > V/I Mean (use side menu keys) > select Pk-Pk (turn VARIABLE knob) > SELECT button (under VARIABLE knob). Menu Off to remove menu items.

SAVING SCOPE TRACE

Digital scopes have a nice feature where the display's screen can be captured digitally and set to a USB flash drive. In addition, you can also save the sampled data values to a *.csv, or spreadsheet, file. Capture the scope trace using the following steps:

1. Hardcopy > xxx (2 options):
 - a.) "Ink Saver" ON (gives you white background, but trace is very light)
 - b.) "Ink Saver" OFF (gives black background), but then open in graphics program like "MS Paint" Then select all, and "Invert Color". Then paste into MS Word
2. F2 (save all) saves the *.bmp file and the *.csv (excel file with sampled data).
3. Verify the image saved properly by plugging in the flash drive in a PC (some drives have issues).
4. Note - for the Instek GDS-2072A, the USB flash drive must be formatted as FAT32.

DISPLAY ALL

The scope is able to display all of the variables on the screen at once.

To activate, press MEASURE twice, then F1 (display all). Around 22 different variables will display across the screen (it will take up the whole screen).

Sometimes students activate this accidentally. To remove, do the following

Press MEASURE (to activate the "measure" menu).

Press OFF (F5)

TO KNOW FOR EXAM:

- how to use the scope - get it to show a trace with proper scaling
- how to display desired parameters
- how to set probe attenuation and adjust probe compensation
- instructor will specify which scope you must know these items above for

***** 3D PRINTING *****



CHAP 13 - 3D PRINTING

13.1 About 3D printing

3D printing has become a very popular technique for producing models with complex geometry. There are different 3D printing technologies, but perhaps the most popular involves feeding a plastic filament into an extruder head where it is melted. The extruder head then moves under computer control to deposit the melted plastic onto a "build plate" and then continues to build the model one layer at a time. As the model builds up, the build platform moves down. The result is a 3-dimensional part. The official term for this process is "**fused deposition modeling**" (or FDM). FDM is a type of **additive** manufacturing.

There are many different manufacturers of 3D printers now. There are consumer-level and professional / industrial-level printers. Consumer level printers are as cheap as \$100 (build it yourself) to several thousand dollars. The professional/industrial level printers are at least \$30K. "Stratasys" is a famous professional-level manufacturer. They possess a patent on the temperature-controlled 3D-printing chamber. This temperature control is important to stabilize first layers of plastic, prevent deformation, and separation of the first layer from the build plate (peeling). Stratasys has 2 main printer types: FDM & Polyjet. Polyjet sprays a liquid photo-polymer and then cures it with a flash of UV light. It is much faster than FDM but the material is very expensive.

There are 2 basic categories of printing support: (1) break-away support or (2) soluble support. If a model has over-hanging geometry, then the printer must create a supportive scaffolding to support the overhang. This scaffolding is modeled in the "slicing" software. With BREAK-AWAY support, the support is the same material as the model. After completion the support must be "broken away" by cutting or prying. Small protrusions are often left after support removal, and these must be sanded down to create a smooth model. With SOLUBLE SUPPORT, printer uses one material for the model and another material for the support. The support material is soluble in water. A common soluble support material is PVA (polyvinyl alcohol). After completion the model and support are submerged into a warm water and detergent or soap mixture that eventually dissolves the support away. Breaking and prying are not needed. Soluble support

3D printers must have at least 2 extruding heads so that one head can extrude model material, and the second head can extrude support material.

13.2 3D Models

Websites such as thingiverse.com and grabcad.com have repositories of 3D models that you can download for free. You may need to register with these sites. Typically an **STL file** is used to encode the 3D geometry. Many of these models are either created from 3D modeling software or from 3D scans. Find a cool 3D model online and bring it in to be scanned. You may also create your own model in a CAD program like Solidworks. After creating the model, do a "Save As" an STL.

13.3 Cura Slicing Software

Import the STL file into a slicing software. Ultimaker printers use the **Cura** software. In that software you will specify many parameters. Here are some important ones:

1. Object size and orientation
2. Material type
3. Printer model
4. Layer thickness, and shell thickness
5. Type of support, infill, etc.

13.4 Lab 3D Printers

Examples of high-end consumer level 3D printers are Ultimaker and Raise. The SAC mechatronics lab has a couple of Ultimaker 3D printers. These are dual-head printers which enables them to either print in two different colors, or to print with soluble support.

REFER to the separate ULTIMAKER GUIDES on how to operate these machines.

13.5 3D Printer Problems

3D printing is an amazing technology, but it is not perfect (NO manufacturing process is). Most printing errors are related to temperature control issues. Consumer-grade 3D printers usually do not have enclosed temperature-controlled chambers. This can cause issues. Typically the first few layers are warmer as they are in contact with the heated platform. But the layers above are not in direct contact so they cool and shrink. This tends to cause the upper layers to pull on the lower layers. Often this causes the first layer to PEEL up from the platform. This will often cause the print to fail.

This phenomenon is more pronounced when you are printing models with large print areas. The material type affects this as well. ABS and Nylon tend to warp more; PLA less.

It is a good idea to attend the print for the first few layers to verify they do not peel off the build plate. If they do, the print has failed and you should abort the job.

Ways to avoid this problem include:

1. Use a 3D printer with a heated bed.
2. Use adhesive on the build plate (stick glue, hair spray etc.). The UM printers are fine without anything.
3. Ensure bed is leveled.
4. Attempt to control temperature in the chamber (avoid drafts), etc.
5. Ensure z-offset is in sweet spot (use "baby stepping" – adjust while machines runs – if printer does it)
 - if you can see gaps between then set nozzle CLOSER to bed.
 - if nozzle is digging thru previous lines, then set nozzle HIGHER from bed (it's squishing the material)
6. Slow down the first layer
7. Use raft, brim, and skirt.

Other Problems:

Running out of material – make sure there is enough material on the spool to complete your model.

Old material – filaments begin to degrade (causing print errors) after they are removed from the sealed packages. We must try to use up a filament spool as soon as possible after it is opened.

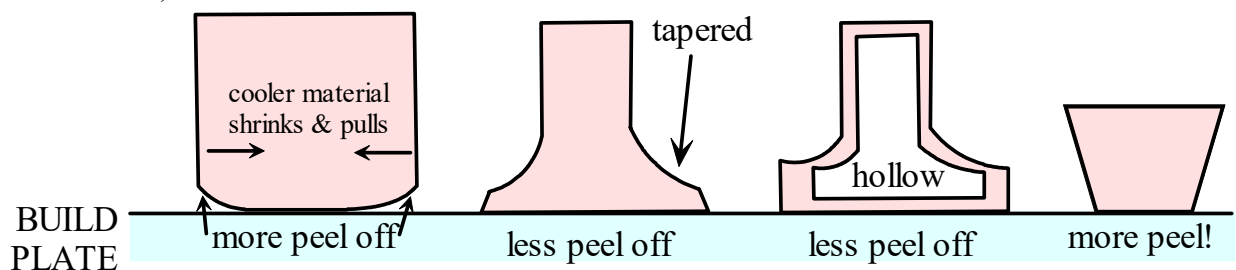
Tangles in spool – will also cause the print to fail as the filament will stop feeding into the extruder head.

13.6 Modeling for 3D Printer Manufacturability

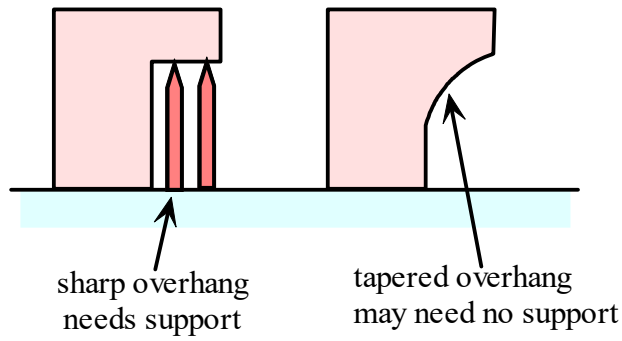
Good design ALWAYS considers how the designed part will be fabricated. This is called **design for manufacturability**. A design for a machined part must consider tool radius & tool path or access. Molded parts must have a draft angle that allows the part to be ejected from the mold. 3D printed parts are no different. Judicious changes in geometry can improve the results of your 3D print.

Reduce chances of warping or peeling

1. Tapered walls are less likely to cause peel off compared to vertical walls (lower shrinking forces) (note – tapering "out" can make this worse)
2. Hollow (less infill, < 20%) parts also have less shrinking forces & will peel less.
3. Use fillets and rounds instead of sharp edges and corners (which result in greater temperature differences).



Reduce support – support is necessary to hold up overhanging geometry. But support spoils the surface finish of the part, requiring sanding. Support also increases print time and material usage. You can reduce the need for support though by tapering overhangs.



TO KNOW FOR EXAM:

What is 3D printing? FDM (and what it stands for)?

Model file type (stl)?

What is a slicing software and what does it do?

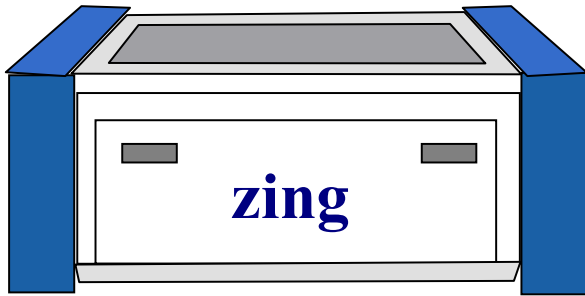
Breakaway vs. soluble support?

Common problems?

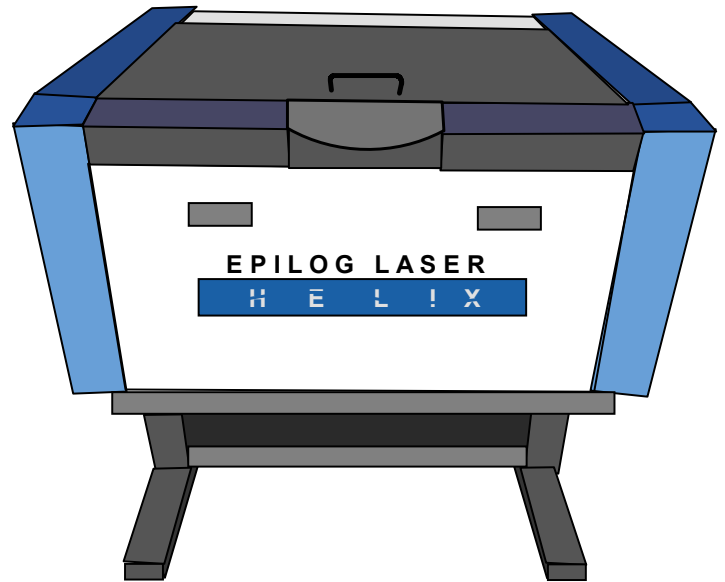
Best ways to avoid problems?

Ways to adjust your design to improve 3D printer manufacturability

***** LASER CUTTING *****



Epilog Zing 24



Epilog Helix

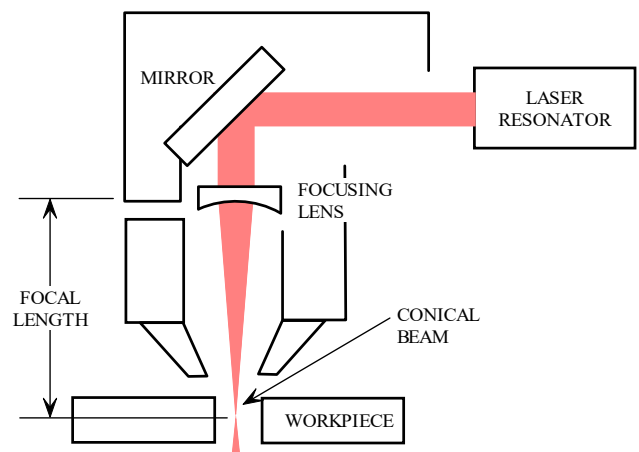
CHAP 14 - LASER CUTTING / ENGRAVING

14.1 About Laser Cutting / Engraving

Laser cutting works by directing the output of a high-powered laser. The laser optics and computer-controlled motion are used to move either the laser or the material. The focused laser beam is directed at the material which either melts, burns, or vaporizes away, and is blown away by a jet of gas. KERF is the small amount of width that is destroyed in the material in the cutting process. Note that the laser beam CONE shaped due to the focusing lens. Thus, deep cuts with the laser may not yield vertical walls.

The same laser cutting system can be used to engrave instead of cut. This is done by making adjustments to the laser's power, speed of motion, and focus.

Note that the laser does not fire continuously. Instead it fires in discrete pulses. The rate of firing is often controllable in the laser settings.



Laser cutters/engravers can work with a variety of materials, such as: wood, plastic, paper, glass, and metal (strong lasers).

14.2 Raster vs. Vector

There are 2 basic modes of operation for the laser: RASTER or VECTOR. These modes are based on 2 basic types of graphics: raster and vector.

RASTER graphics work mainly with BITMAP images which break up the image into small dots or pixels. Raster graphics file types include bmp, jpg, gif, tif, etc. The laser can take raster graphics and ENGRAVE that image into a material. RASTER setting is for engraving the material with some type BITMAP image (jpg, tif, gif, etc.). It is typically best to have a very HIGH CONTRAST image (black and white, with few or no greys). In raster mode the laser will sweep back and forth to cover an entire area. During that motion the laser will pulse at precise moments to engrave the raster image.

VECTOR graphics are typically lines that are encoded as a set of equations. These graphics can be scaled without loss of quality. In vector mode, the laser will move along a specified path rather than move back and forth. The laser will PULSE at a high rate (frequency setting). Higher frequencies produce higher amounts of heat. Objects and text must be UNFILLED in this mode. When vector cutting, you generally want a *.dxf file (eg – from Solidworks). The laser can either vector CUT or ENGRAVE. The vector cut settings require lower speeds and high power. Vector engraving involve higher speeds and lower power.

REFER to the laser equipment handout for detailed information on the laser.

TO KNOW FOR EXAM:

What is laser cutting/engraving? How does it work?

What is kerf? Know that laser fires in pulses, not continuously

Raster vs. vector?

***** **SOLDERING** *****

CHAP 15 - SOLDERING

It is common to first build new or prototype circuits on solderless breadboards. Solderless breadboards allow for quick and easy changes to a circuit. However, these circuits are likely to fall apart if shaken or dropped. So once we have a circuit that we know works and will likely not be changed again, it is time to build that circuit using solder. Soldered circuits are usually built on a **SOLDER BREADBOARD, PERF BOARD**, or printed circuit board (PCB). A circuit that is soldered is much more secure than one built on a solderless breadboard. Soldering onto these types of boards is sometimes called **through-hole soldering**.

15.1 Soldering

Solder is a low-melting point metallic alloy that is used to bond circuit elements together. Traditional solder is a metallic alloy that is a mixture of **tin** (Sn) and **lead** (Pb), usually 60Sn40Pb (60% tin, 40% lead). Tin has a lower melting point than lead. Solder sticks best to CLEAN metal (not oily or oxidized), so we must have a clean substrate. The substrate is the material onto which you are applying solder.

Solder often includes different **flux cores** – acid or rosin. Flux cleans the surface and allows the solder to stick better. Acid core is used in plumbing and should not be used for electronics. **ROSIN CORE** is used for electronics. Regular rosin core is sticky and hard to clean off. Water-based flux leaves a white film & is easier to clean off. "No-clean" – burns or boils off. Extra flux can also be applied to the substrate to aid in soldering. This can be applied with a brush or needle bottle dispenser.

Lead-free solder is more commonly used now due to health and environmental concerns with using laded solder. However, lead-free solder can be a bit harder to work with since it has a **HIGHER MELTING POINT**. Components of lead-free solder include: tin, copper, silver, nickel, zinc, and other elements.

A soldering iron is used to melt the solder. Nicer soldering stations have a temperature controller and a digital readout to show the set and actual temperature. The power rating of the soldering iron is important. Most solder melts at 180 – 190 C (or 360 – 370 F). The best temperature is the lowest temperature needed to melt the solder and work quickly. Typical set temperatures for electronic soldering are around 600 - 650 F for lead-based solder, 650 - 700 F for lead-free solder.

Large blocks of material are harder to heat up and will require higher power soldering irons. With electronics the blocks of material tend to be smaller and do not usually require high power soldering irons.

15.2 Soldering Safety

Soldering irons get VERY HOT and will seriously BURN you if you touch them.

The fumes coming off of a soldering iron are not safe to breathe. Use ventilation or a portable smoke absorber or a snorkle (like those in the SC-134 lab) when soldering.

Finally, always wear eye protection while soldering. Even if you wear glasses, we suggest wearing goggles. Splattering flux can pit your glasses lens.

15.3 General Procedures

There are a variety of soldering iron tips. A fine tip is good for smaller jobs in electronics.

Heat the soldering iron to an adequate temperature for the solder you are using.

Keep the soldering iron tip clean and tinned. Prepare a wet sponge (use distilled or DI (de-ionized) water to reduce accumulation of minerals on the iron) or towel to clean the soldering iron tip. First heat the tip and then "**prime**" or clean the tip by wiping it on the wet sponge. Then tin the tip. This means apply some

solder to the tip, allow it to melt, and then wipe it on the wet sponge again. The wiping action will remove most of the solder but leave a thin shiny silver layer of solder on the tip.

Do NOT melt the solder by directly touching the iron to the solder. This technique can often cause **COLD JOINTS** which are solder joints that appear to be good, but actually have poor mechanical connection (a slight pull on the wire and they pull apart) or poor electrical connection.

The correct technique is to touch the iron to the substrate. Wait a few moments for the iron to heat the substrate. Then touch the solder wire to the opposite side. The heated substrate should melt the solder (not the iron directly). The melted solder will flow into the substrate using capillary action. This produces the best solder joints.

When soldering wire to a PCB, hold the tip against both the lead and contact point/pad for a few seconds to bring up soldering temperature at the same time. Touch the solder wire to the lead and contact point/pad a few times until solder flows around the lead and contact.

A nice tip is to apply a small drop of solder to the iron and touch that to the substrate. This improves thermal heat transfer from the tip to the substrate. The solder drop must be small though. It is not intended to coat the substrate, just improve heat transfer.

It is best to work quickly. The longer you heat your electronic components the more likely it is the heat will damage the electrical/electronic components.

15.3.1 - Tinning Wire

Tinning is the process of applying melted solder around stranded electrical wire. Tinning helps keep the thin strands of wire together making it easier to connect stranded wire to screw terminals or other connectors.

STEPS

1. Set soldering iron temperature to 600 - 650 F.
2. Twist stranded wire to keep the strands together (if doing stranded)
2. Apply a small amount of solder to the iron (to improve thermal heat transfer)
3. Place the hot iron on one side of the stranded wire
4. Apply the solder on opposite side. The heated wire will melt solder.
Capillary action will draw the solder into the strands.
5. Ensure the length of the exposed wire is soldered.

This is a decent video on tinning wire

<https://www.youtube.com/watch?v=pRPF4wpXX9Q>

15.3.2 - Soldering 2 wires together

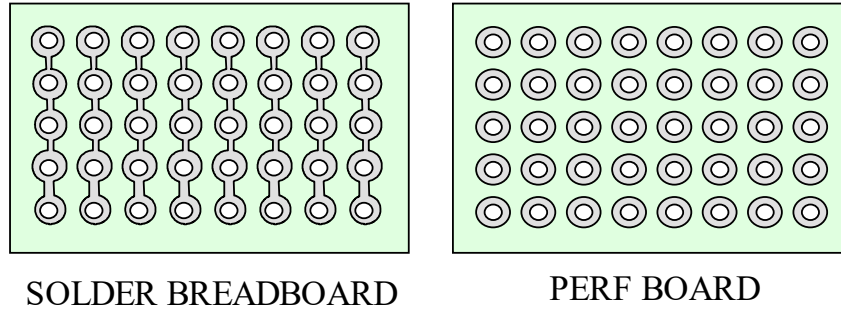
Sometimes you will wish to solder 2 wires together to create a permanent connection. If using heat shrink tubing, do not forget to slide the tubing onto the wire BEFORE soldering!

Set soldering iron to 600-650F.

Here is a nice video on soldering 2 wires together

15.4 Perf and Solder Breadboards

Soldered circuits may be built on PERF boards (have individual hole pads that are NOT connected to each other) or on SOLDER BREADBOARDS (have hole pads that are connected just like solderless breadboards). There are also printed circuit boards (PCB's) that you can have custom-made by many companies.



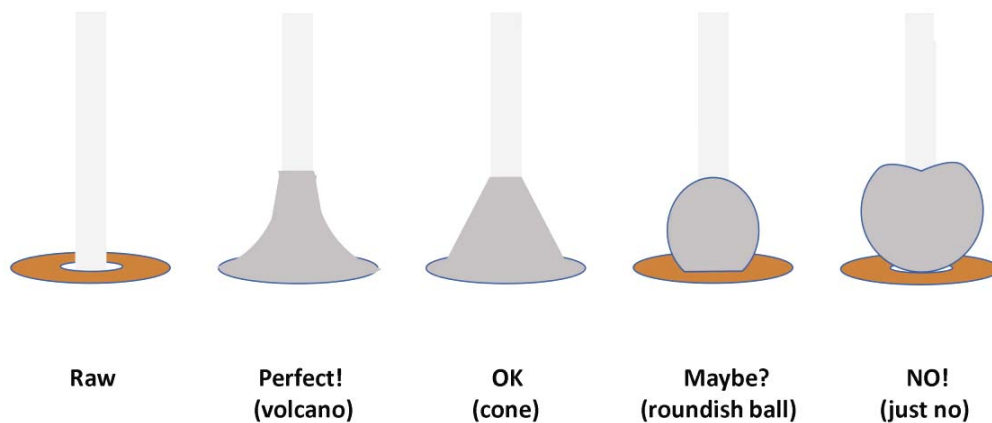
Through-hole soldering is the term used for the soldering of components onto solder, perf boards or PCB's where the component leads are pushed through the board holes and soldered on the other side.

Typical soldering iron temperatures are 700 F.

The following videos are pretty good guides for doing circuit board soldering
<https://www.youtube.com/watch?v=AqvHogekDI4>

<https://www.youtube.com/watch?v=VxMV6wGS3NY>
<https://www.youtube.com/watch?v=vAx89WhpZ3k>

The goal is to get a good solder joint that has a nice **solder fillet**.



If you are using perf board having individual hole/solder pads you may wish to create a **solder bridge** that connects multiple holes (much like a terminal strip in a solderless breadboard). Unintended solder bridges can be fixed by removing solder. This can be done using a wick or de-soldering pump.

<https://www.youtube.com/watch?v=19Kbr8cPqOE>

TO KNOW FOR EXAM:

Almost everything in this section is fair game for an exam.

***** MOTORS *****

CHAP 16 - MOTORS

Electric motors are a common way to produce movement. These **actuators** convert electrical energy into mechanical energy (movement). Most motors use magnetic INDUCTION to produce movement. Induction motors have WINDINGS (wires wrapped up into many turns) that will produce a magnetic field when electricity flows through them. Motion is produced by the interaction of the stator and rotor magnetic fields. An interesting fact about motors is that they can be operated in reverse. If you turn a motor, electricity will be produced at its terminals.

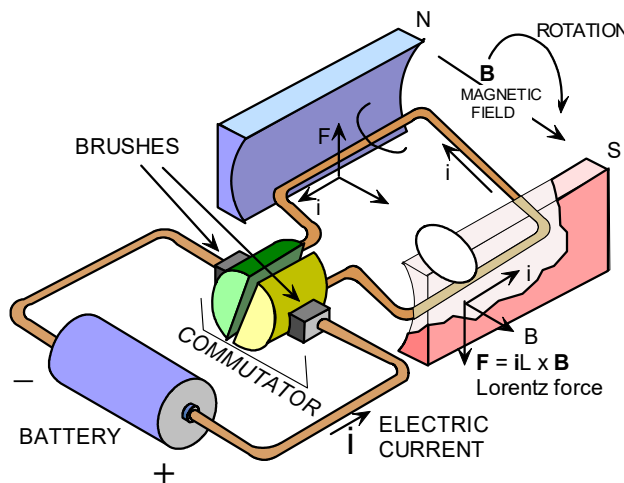
There are many different kinds of motors, and these may be categorized in many different ways.

DRIVE MECHANISM - induction vs. non-induction. Some non-induction motors include piezo-electric and ultrasonic motors do not use magnetic fields to produce movement. Most other motors do use magnetic fields.

ELECTRICITY-DRIVE TYPE - within induction motors are AC, DC, and universal motors. AC motors are driven by AC (usually sinusoidal) electrical signals. DC motors are driven by constant voltage signals. Universal motors can operate using either AC or DC electricity.

BRUSHED or BRUSHLESS TYPE - DC motors can be brushed or brushless. Brush motors have a **commutator** which serves to reverse the direction of current through the motors windings so that the motor continues to move in one direction. Brushless DC motors have no commutator. Instead, the motor controller senses the motor angular position and switches the current through the windings to produce continuous movement. All AC motors are brushless.

16.1 Brushed DC Motors



DC motors can be found everywhere. They produce rotational motion when DC electricity is applied to their input pins. There are many different kinds of motors so we will focus on brushed DC motors. The simplest DC motor is pictured above. The **STATOR** (the stationary part of the motor) has permanent magnets that produce a magnetic field. The **ROTOR** (or armature) is the rotating part of the motor. In this simple case, the armature is a simple coil of wire (sometimes called a loop or winding). The armature is connected to DC power through a **COMMUTATOR**. When electric current flows through the coil an electromagnetic **LORENTZ** force is induced in it by the magnetic field. This force causes the coil to rotate. The commutator serves to switch the direction of electric current so that the forces turn the armature in the same direction regardless of its orientation. The commutator uses graphite brushes that ride along the contacts. Because of friction, these brushes eventually wear out.

Here's a nice video that describes how DC motors work:

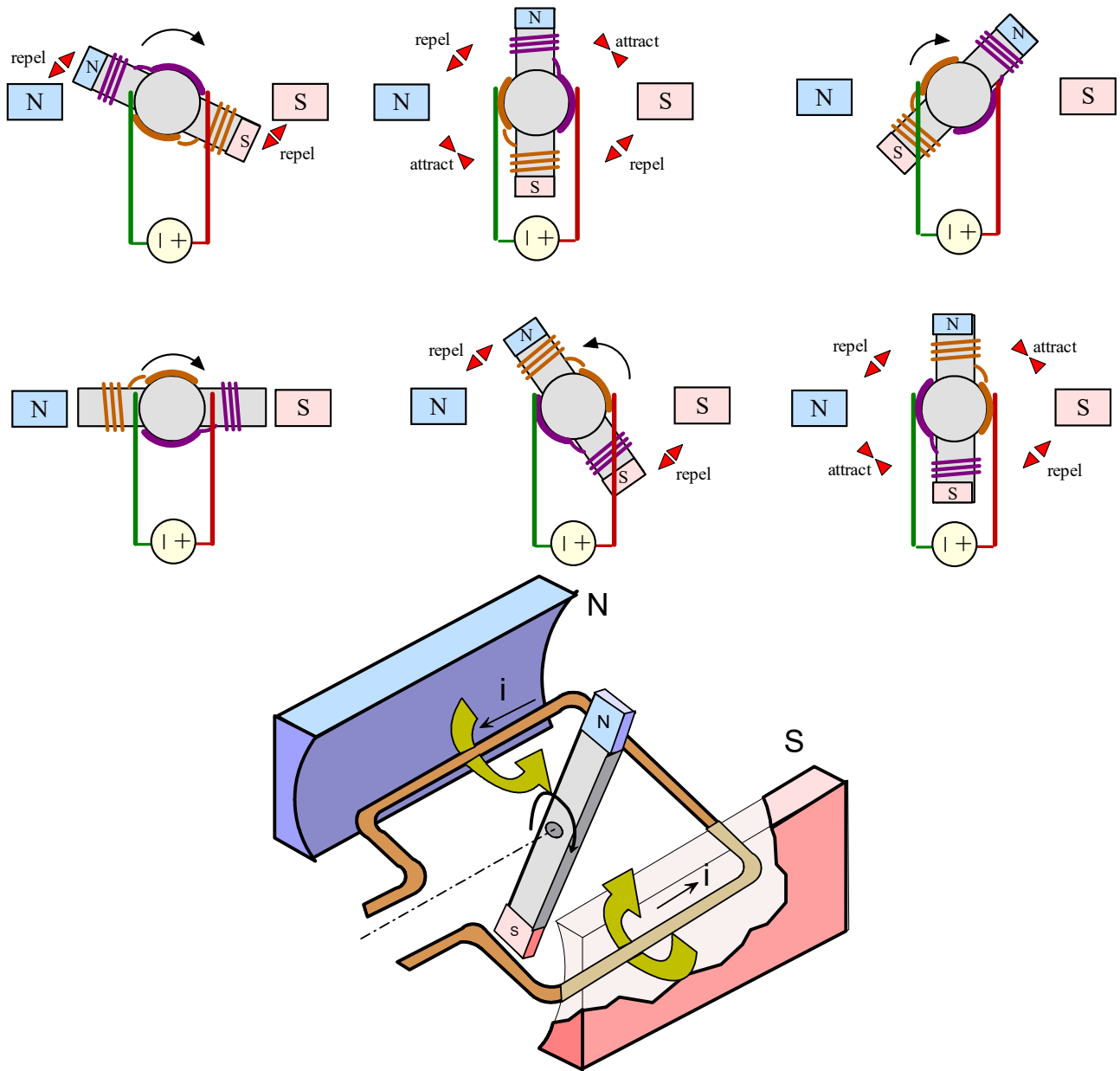
<https://www.youtube.com/watch?v=LAtPHANefQo>

Another way to envision the motor's operation is in terms of the interaction of 2 magnetic fields - one produced by the stator permanent magnet and the "electro-magnet" produced in the armature. Magnetics have a north (N) and south (S) pole. N repels N. S repels S. N attracts S. The electro-magnetic field produced in the armature can be thought of as a bar magnet whose N & S poles switch based on the rotor's angle via the commutator. The commutator switches rotor's magnetic poles in a way that keeps the rotor turning.

There's a nice video that helps illustrate this: (<https://www.youtube.com/watch?v=wxG3cwugXgs>).

An armature with just 1 loop of wire would only produce a very weak magnetic field. So in real motors the armature has many windings of wire wrapped around an iron core (or some ferro-magnetic material). The multiple windings and the iron core strengthens the magnetic field.

The result of this is that more electric current (or more voltage) results in a faster turning motor. In general, torque of a DC motor is proportional to the current flowing through its windings. In order to change the direction that the motor spins, the voltage "polarity" applied to the motor must be reversed.



More realistic motors will have several POLES to smooth movement and prevent

MOTOR CONTROLLERS

Motor controllers take a CONTROL SIGNAL and convert it into a higher power electrical signal that can power the motor. Controllers also control motor turning direction.

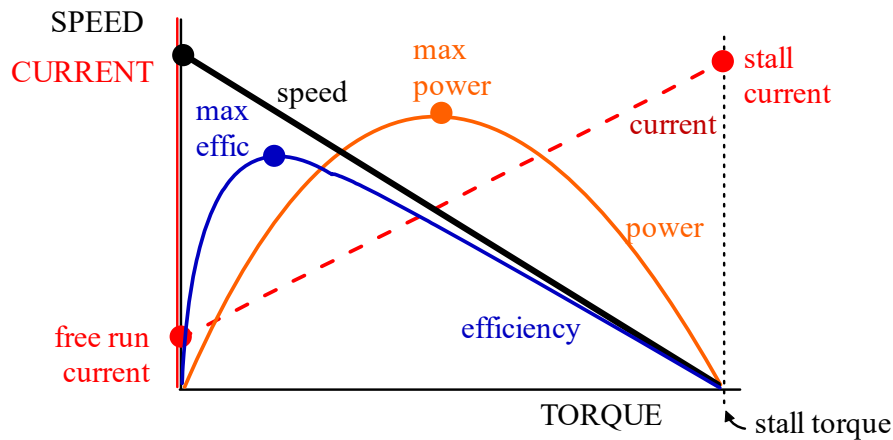
SPECIFICATIONS

1. Nominal voltage – corresponds to the motor's highest efficiency. Operation outside of this value reduces the motor's efficiency. An operating range (eg, 3-9 V) may also be indicated.

2. No-Load RPM – speed of motor shaft with no load connected with the nominal voltage applied. The spec refers to shaft speed after any "gear down".
3. Power rating – $P = IV$ with $I =$ no load current, $V =$ nominal voltage. The motor can only operate at this power for short periods of time. P also \sim stall current \times nom voltage
4. Stall torque – maximum torque motor can apply with shaft held motionless. Motors are damaged if stalled for more than a few seconds. Do not operate a motor at great than 1/4 of stall torque.
5. Stall current – current drawn by motor at stall conditions. This can be a very high value. A motor controller that cannot provide this value can fry if you operate at this condition. If stall or nominal current specs are not provided, you can estimate this with motor power & nominal voltage ($I = P/V$).
6. No-Load Current

MOTOR TORQUE / SPEED CURVE (& POWER)

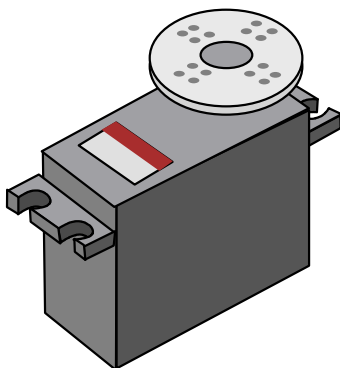
A motor's performance depends on its operating conditions. In general, the more torque it must produce the slower the motor can turn. The faster a motor turns the less torque it can produce.



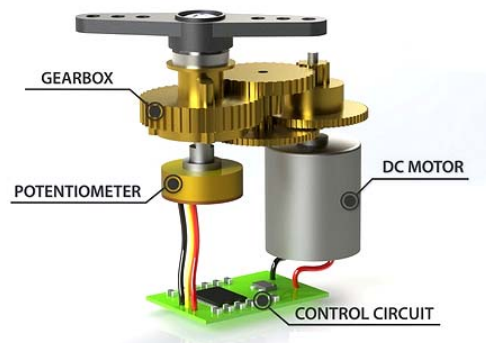
ACCESSORIES

Hubs and shaft couplers provide a means of connecting the motor shaft to a drive shaft.

16.2 DC Servo Motors



Hobby Servo



We will tend to work with hobby servo motors due to their availability and low cost. There are also commercial-level servos which are much nicer but much more expensive. The 2 basic types of hobby servos we will use are standard (the black motor pictured) and "micro" servos (the blue one pictured).

Hobby servo motors ("servos") contain a brushed DC motor, internal control circuitry, and often a "gear head". They are designed to rotate its shaft to a specific orientation (or "motor shaft angle") based on a pulse-width signal received. The internal control circuitry senses the actual shaft angle and corrects errors by driving the shaft in the opposite direction of the error. Servo motors generally have a rotating range of either 90° or 180°. Hobby servos are designed to move radio-controlled airplane flaps, boat rudders, and car steering among other applications.

Servos usually have 3 electrical connections: power, ground, and control signal (a pulse-width signal). An important servo-motor spec is the supply voltage value (5 VDC is common for hobby servos). This spec means you must apply that much voltage for the motor's power. **ONLY APPLY VOLTAGE TO THE MOTOR THAT IS WITHIN ITS SPECIFICATIONS!** A higher voltage will blow out the motor! For instance if you apply 12V or more to a motor rated for 5-7V, you will likely destroy that motor.

Servos are controlled using PWM (pulse-width modulation) signals, which are digital pulses that are high (5 VDC) for a specific amount of time and lower otherwise (0 VDC). The pulses must occur at 50 Hz (cycles per second) for hobby servos.

Arduino makes things easy by having a "servo" library that has many of the functions we need to drive a servo-motor. For instance, we can command the motor to a certain angle using the function `servo.write(angle)`, where you specify the motor angle instead of the pulsewidth value. In addition, the functions in the servo library can run in the background while the CPU does other things. This is GOOD, and makes our programming easier! It does this by interrupting the execution of other code when it needs to send those pulses, and it does so very quickly so it is almost unnoticeable. This is an example of multi-tasking programming.

Servos draw varying amount of current depending on the "loading" conditions. A high load condition for instance would be when something is physically resisting the motor's rotation. A freely turning motor draws much less current. Examples of current draw are below.

Servo	Idle	Turning @ No Load	Stall
Hitech	8 mA	150 mA	800 mA
SG 90 (micro-servo)	5 mA	100 mA	700 mA

Arduino may be able to power a freely-turning micro-servo for a short period of time. However, it cannot do so for very long. Any motor bigger than a micro-servo, or any servo being resisted at all cannot be directly powered by Arduino.

It is generally better to use an alternate source of power for servos instead of relying on Arduino's power. DC voltage regulators are often used because they output a constant voltage signal. They generally take a higher DC voltage input (e.g. 9 VDC, from say a battery) and output a very consistent output voltage (e.g. 5 VDC) that is slightly lower than the input voltage. Often you can forego the voltage regulator and draw power from a battery pack. The motor will still work but it may not position as accurately. You can use

alkaline batteries, but many RC control hobbyists use rechargeable NiCd, nickle-metal-hydrde, or lithium polymer batteries. Yet another option is to use a transistor. If your motor only turns 1 direction, you may be able to control this motion with 1 transistor. If your motor turns in 2 direction, or must do position control, then you can use 2 transistors in a "push-pull" configuration (e.g., NPN and PNP transistor).

16.3 Continuous Rotation Servos

Continuous rotation servos turn continuously at certain speeds and directions - as opposed to being limited to 90 or 180 degrees in motion. Continuous rotation servos receive the same control signals as regular servos, but they are used in other applications, such as wheels and pulleys.

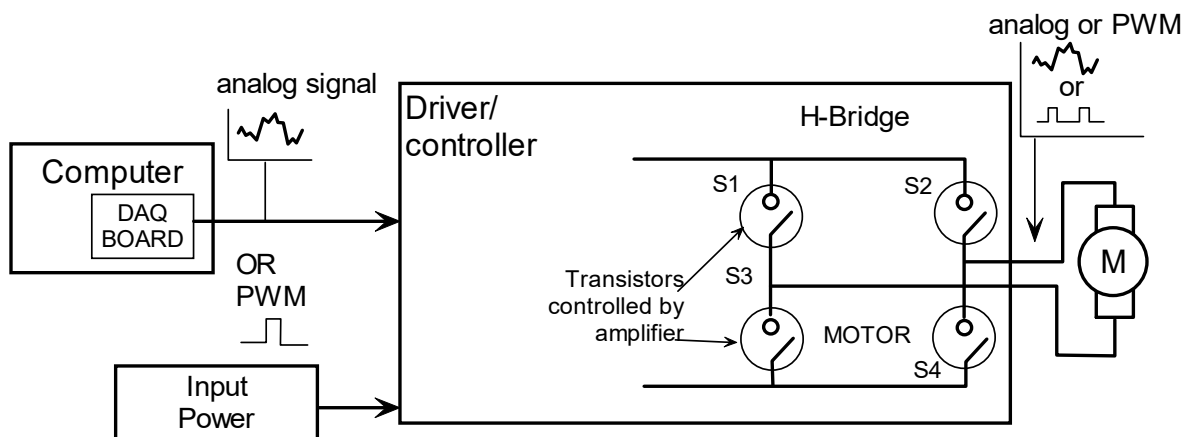
These are often modified (or hacked) RC servos. Hard stops are removed and the controller feedback is hard wired to think it's always in the middle position, regardless of the actual position of the motor shaft. A non-middle-position pulse tricks the controller into correcting the motor position forward or backward. So the motor will turn continuously as it tries to correct for a desired position it can never reach.

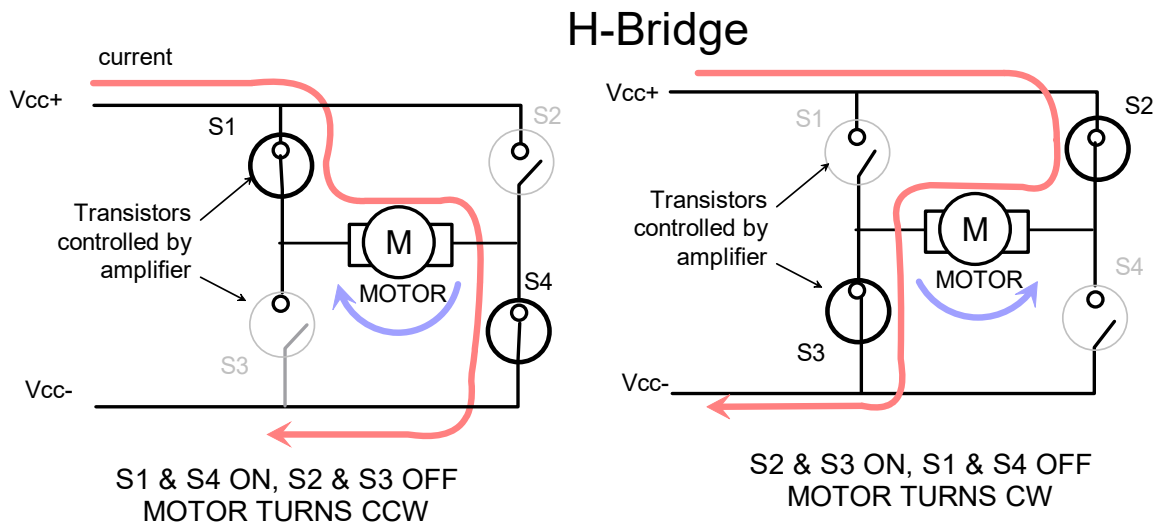
Due to variations in the analog circuitry, it can be tricky to find the precise 'neutral' point in the control signal where the motor stops moving. Usually there's a little trim potentiometer you can hand-adjust in a process called **CENTERING**.

16.4 Motor Controllers

Motors are generally driven using MOTOR CONTROLLERS. Based on the control signal coming from the computer (like an Arduino), the controller must modulate how much electricity is routed from the power source to the motors. This will effectively control how the motor turns. In addition, the controller must control motor DIRECTION. A common technique to control direction is to use an H-BRIDGE. The H-bridge can control the direction of electricity going through the motor by switching a set of transistor switches.

- 1. Close switches S1 & S4 to make the motor go forward
- 2. Close switches S2 & S3 to make the motor go backward





16.5 Stepper Motors

1. Have several electrical terminals (say 6 or 8)
2. Energize separate coils separately & sequentially to move the motor

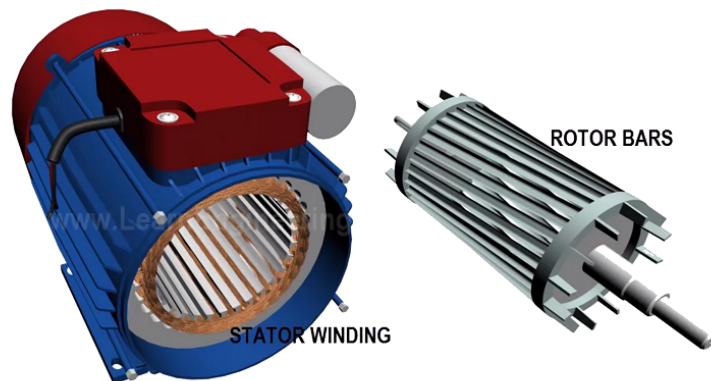
(TO DO)

16.6 Brushless DC Motors (BLDC's)

Brushless DC motors have NO COMMUTATOR.
 Instead switching is done electronically by the motor controller/amplifier.
 Motor sensing is done with "back EMF" (sensor-less) or Hall-effect sensors.

(TO DO)

16.7 AC Motors



AC motors rotate when powered by AC electricity. These motors tend to be simple, reliable, and durable. You tend to see AC motors used when continuous rotation is needed, such as fans, laundry machines, and

dryers. Tesla cars are powered with AC motors. One drawback with AC motors is that it is difficult to control their speed. Often speed control is achieved using advanced controllers such as VFD's (variable frequency drives). It is even more difficult to control position with AC motors. However, many industrial robots, like Fanuc robots use AC servo motors (AC motors equipped with feedback sensing and positioning controllers).

There are different types of AC motors. Single-phase and 3-phase AC motors are very common.

SINGLE-PHASE AC MOTOR

The stator of a single-phase AC motor has 2 windings: the main and the auxiliary (which is perpendicular to the main winding). A capacitor is connected in the auxiliary winding. The AC current through the stator winding produces a fluctuating magnetic field. If the rotor has an initial rotation, the rotating magnetic field will produce a moment that follows the rotating magnetic field. The auxiliary winding and capacitor are used to START the rotation of the rotor. Without it, the main winding cannot get a rotor (that has zero initial rotation) started.

Fans - shaded pole motors

SLIP

3-PHASE AC MOTOR

The basic principle behind these motors is that multiple electro-magnetic fields are produced in the stator windings that appear as a single rotating magnetic field. The rotor will follow the ...

Rotating speed is based on the LINE FREQUENCY of the applied AC voltage, the number of poles,

$$N = 120 * f / P$$

AC motor speed cannot be effectively controlled with:

1. Variacs - these change the amplitude of the applied AC signal, not its frequency
2. Dimmer switches - often these use PWM and are effective at dimming lights, but not slowing down motors
3. Rheostats - variable resistors, that serve to reduce voltage and current, but

VARIABLE FREQUENCY DRIVES (VFD's)

VFD's are really one of the only effective ways of controlling AC motor speed. They work by changing the frequency of the AC signal. They are commonly used with 3-phase motors, but they may not be available for single-phase motors.

(TO DO)

16.8 Other Motors

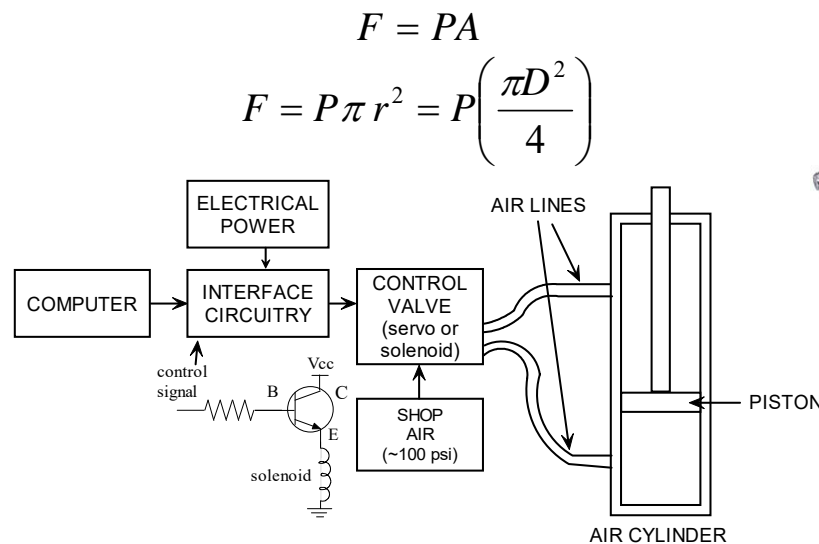
Most motors are INDUCTION motors, whose motion is produced using magnetic induction. However, there are motors that don't use induction. Piezo-electric or ultra-sonic motors produce motion without use of a magnetic field.

(TO DO)

16.9 Pneumatic Air Cylinders

While motors are probably the most common type of actuator, there ARE other types of actuators. Pneumatic and hydraulic actuators are another type of actuator. Pneumatic systems use **AIR PRESSURE** to produce force. A pneumatic air cylinder consists of a piston and rod moving on a linear path inside of a closed cylinder. The piston divides the cylinder into 2 chambers. Pressure differences across the piston cause the cylinder to actuate OUT or BACK. Air pressure is often provided by "shop air" which can be about 100 to 150 psi (lb/in²).

Pneumatic actuation is **VERY STRONG** compared to electric motors. However **bandwidth** (how fast you can move back & forth) is **limited** due to compressibility of air and the fact that time is required for air to travel through tubes and into the air cylinder chambers.



CONTROL VALVES are used to control air flow to the air cylinder. There are 2 basic types of control valves:

- 1.) Solenoid valves - on/off only. Direct acting or servo-assisted
- 2.) Servo valves - continuous change

SOLENOID VALVE OPERATION

Solenoid valves only open or close. There is no in between. When electricity is sent to the valve, it drive the valve to either open or close (there are normally-open valves (NO) and normally-closed (NC) valves). A solenoid moves a metallic component by creating a magnetic field. The magnetic forces must overcome a spring force. Thus, substantial electric current is needed. Thus an Arduino cannot directly drive a solenoid valve. A transistor (or controller) and a separate power supply would be needed

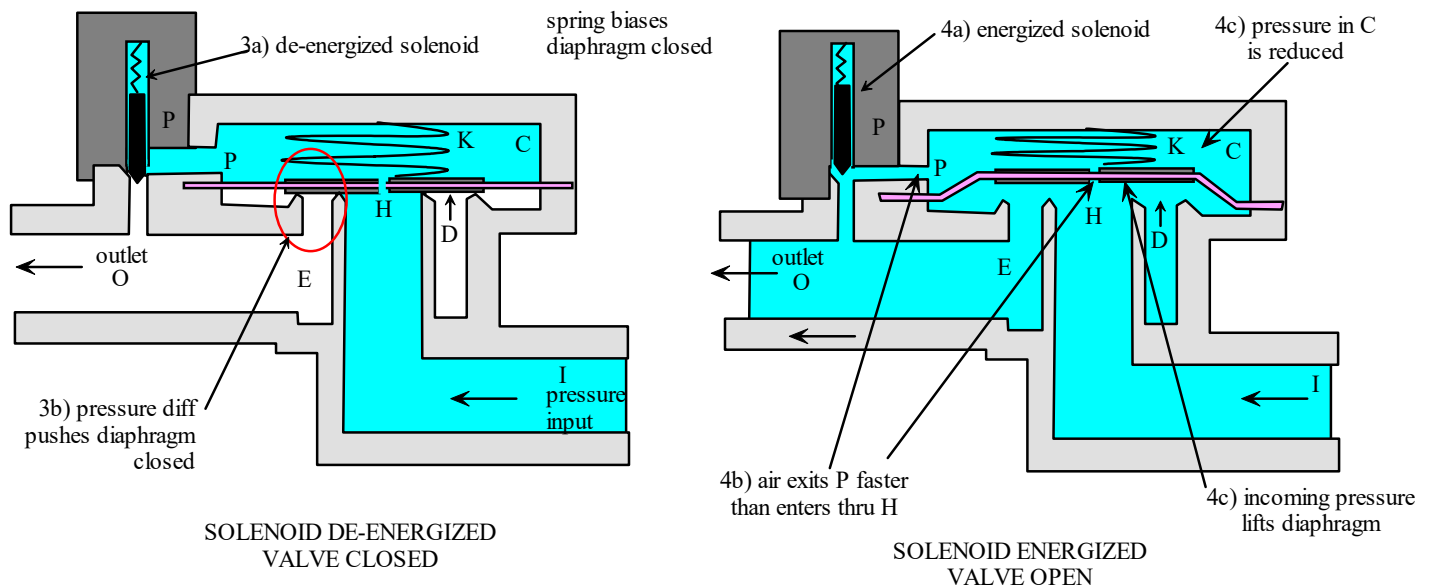
Below is a picture and sequence of events that controls an "internally-piloted" solenoid (on/off) valve.

VALVE OPENING:

1. Pressure originates at input I
2. Weak spring K lightly pushes elastic diaphragm D.
3. D has pinhole H allowing fluid pressure to pass into chamber C.
Thus pressure equalized across diaphragm D.
4. De-energized solenoid causes pin to block drain passage P (spring pushes pin).
5. Thus outlet chamber O has lower pressure
Thus pressure difference at E ensures diaphragm pushed down & sealed (spring is irrelevant)
6. Energize solenoid so pin unblocks passage P.
7. Air exits at P faster than it enters at pinhole H.
8. Pressure in chamber C is reduced and incoming pressure lifts diaphragm.
9. Valve is open.

VALVE CLOSING

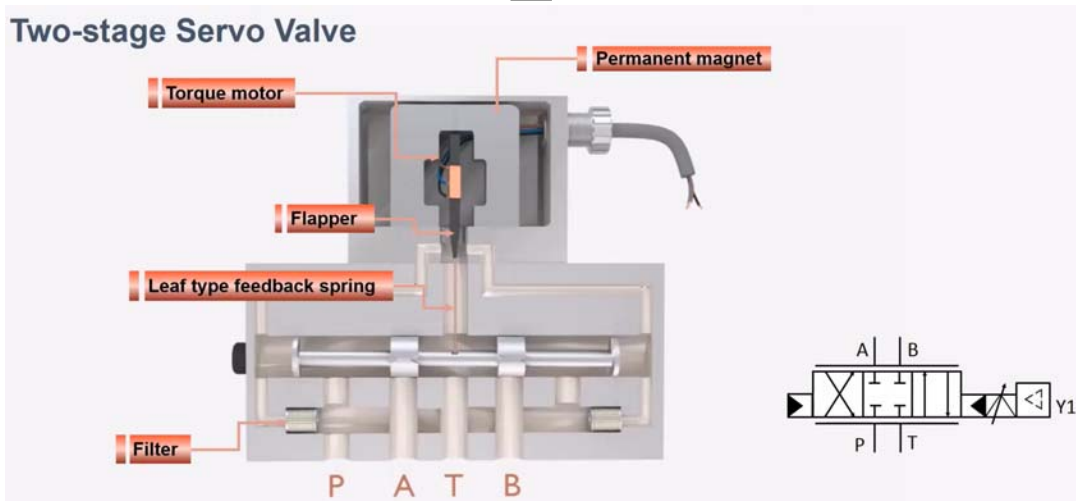
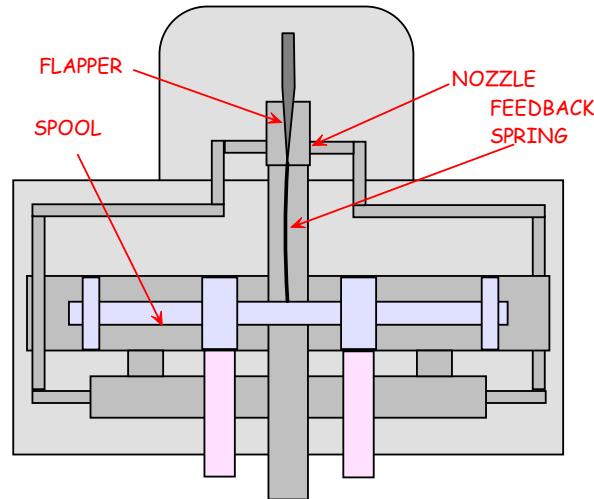
1. De-energize solenoid so pin now blocks G again.
2. Pressure in chamber C becomes equal to I (pinhole). So pressure is equal across diaphragm D.
3. Spring K biases diaphragm D down, sealing the valve.
4. Outlet pressure at O becomes less than in chamber C, cause diaphragm D to tightly seal.
5. Valve is closed.



SERVO VALVES

Servo valves are able to **METER** air flow continuously to the air cylinder (slow, fast, etc.). They are much more expensive, and the principles of their operation are a bit more complex. Servo valves are highly accurate and responsive. Servo valves receive an analog signal and they deliver air to a port proportional to that signal. Metered air flow is achieved by sliding the valve's **SPOOL** (the key component of the servo valve) to different continuous positions. In doing so, the spool opens and closes various PORTS to varying degrees. This allows for the continuous adjustment of air to the different ports.

(SERVO VALVE OPERATION HERE)



An air cylinder's linear position can be controlled if you use servo valves (you could make a pneumatic robot!). It would be necessary to equip the air cylinder with a linear position sensor (LVDT, linear encoder, etc.) to sense the cylinder's translational position. The sensor's signal would be sent to a computer (perhaps an Arduino). The computer would compute a command signal using various control laws and then send that signal to the servo valve. Like the solenoid valve, Arduino cannot directly control a servo valve. The electrical control signal must first be amplified using a controller or transistor.

16.10 Hydraulic Cylinders

Hydraulic actuators are basically the same idea as pneumatics (air) except power comes from pressurized hydraulic oil (pressure about 3000 psi!!). Forces exerted by hydraulic actuators is much higher than motors or pneumatics due to the extremely high oil pressures. The bandwidth is also higher than pneumatics since the oil does not compress. One drawback is that hydraulic oil is messy and tends to leak from control valves. Control valve design is basically the same as with pneumatic valves, but they have seals to prevent oil leakage.

16.11 Other Actuators

There are many other actuators besides motors, pneumatics, and hydraulics. Living organisms move using MUSCLES which are a type of actuator. They work by SHORTENING in response to an electrical signal (a nerve impulse).

Here are some other actuators:

- Electroactive polymers (EAP) – change shape when voltage is applied to them
- Nitinol (Ni-Ti)
- Pneumatic artificial muscles (McKibben)– bladder fills with air and shortens.
- and more...

TO KNOW:

DC motors - how they work, identify their parts and their purpose, what is the commutator? What forces makes them move?

DC servo motors - what parts do they have? 3 wires - identify how to properly connect them, what voltage can be applied to them, how does the control signal work (PWM, frequency), how do we power the motor (can arduino do that?), understand that motors draw more current when resisted

Motor controllers - what they do? How they control direction (H bridge)

Continuous rotation servos - not now

Stepper motors - not now

BLDC's - not now

AC motors - not now

Other motors - not now

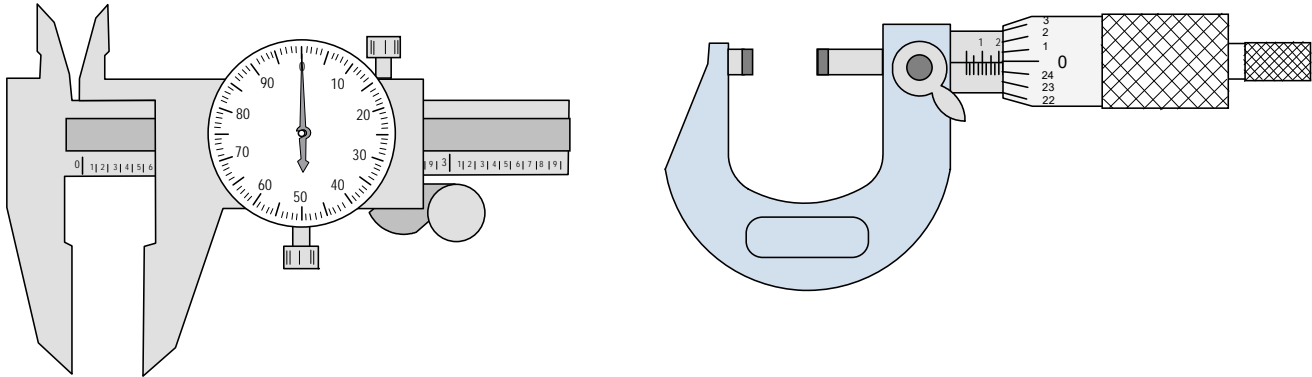
Other actuators

Pneumatics - why use (strong)?, uses 'shop air' pressure, low bandwidth, 2 types valves

Hydraulics - very strong, uses hydraulic oil pressure, high bandwidth

***** MEASURING TOOLS *****

CHAP 17 - MEASURING TOOLS



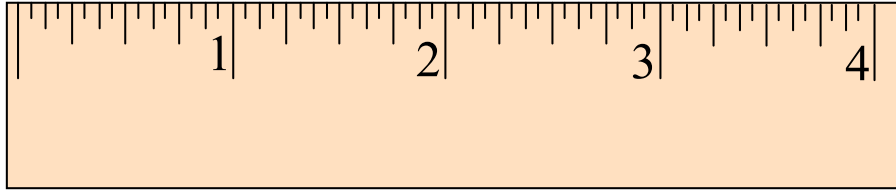
An important part of manufacturing is **INSPECTION**. Manufactured parts must be inspected to ensure that they will properly fit and function. At manufacturing companies inspection usually falls under the QA (or Quality Assurance) or QC (quality control) department. Within QA, there is a special department called "metrology". They are responsible for the calibration of any measuring tools and equipment. Three common measuring tools are the RULER, CALIPER, and MICROMETER. The caliper and micrometer are commonly used to measure machined parts. The caliper may read to a resolution of 0.0005 (half a thousandth of an inch) and an accuracy of 0.001" (one thousandth of an inch). A piece of paper is about 0.004" (4 thousandths) thick! A micrometer has a resolution of about 0.0001" and an accuracy of about 0.0001" (one ten-thousandths of an inch), making it more accurate than the caliper.

Non-digital calipers and micrometers require one to learn how to read the measurement. Micrometers will commonly also use a **VERNIER** as a way of obtaining an extra decimal place on the reading. Micrometers tend to either use a ratchet or a friction thimble to consistently control how much to "squeeze" part it is measuring.

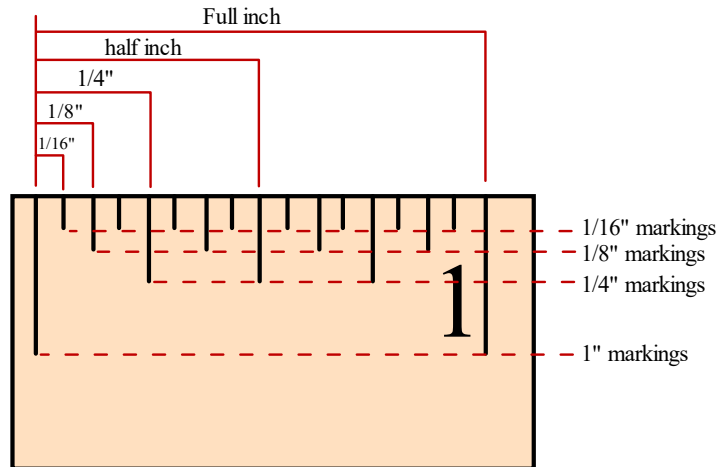
Some nicer calipers and micrometers have electronics and display the measurement digitally. These of course are much easier to use.

Watch videos linked on the GUIDES webpage (ruler, caliper, and micrometer).

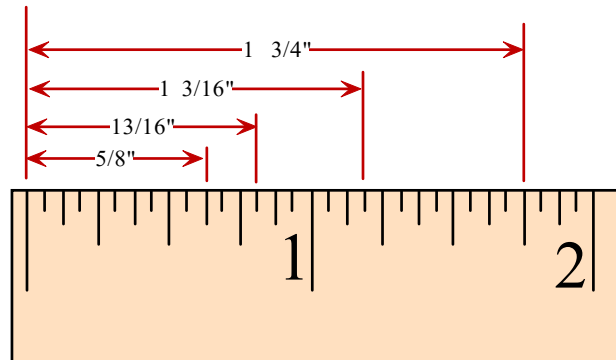
17.1 Ruler



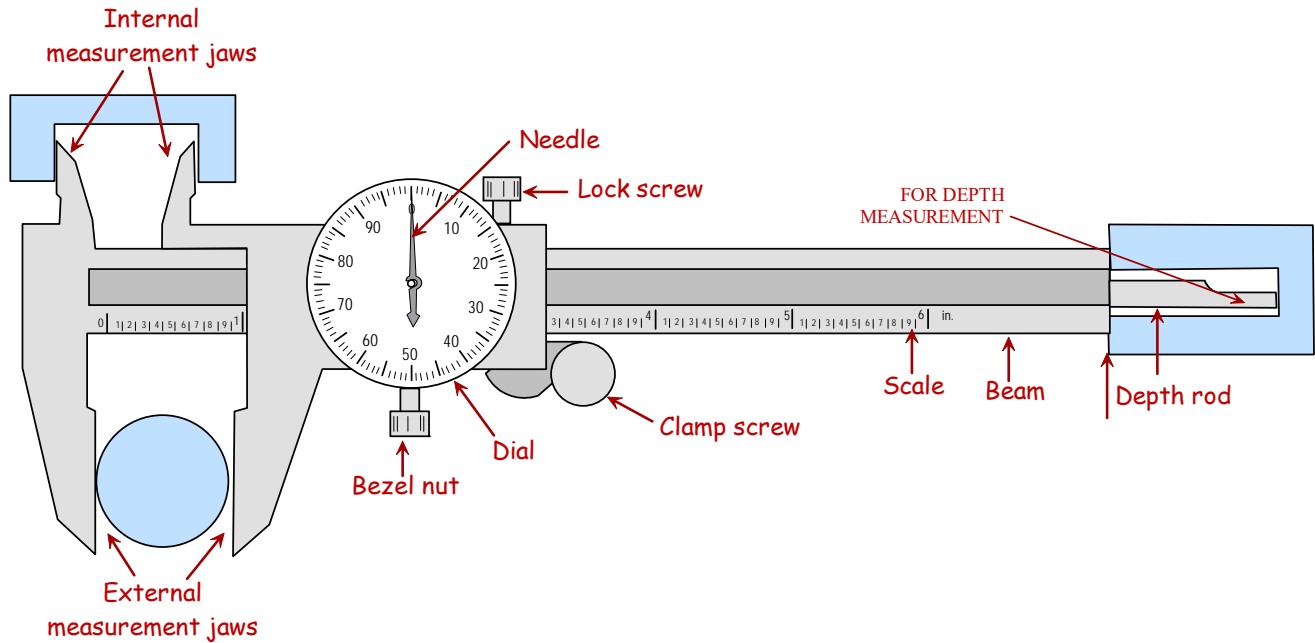
Every kid has used a ruler in grade school! They are not just used to draw straight lines. They are also an important tool used to measure distances. Some rulers break up inches into tenths and others into fractions. Here we'll look at how to read a fractional ruler.



Example measurements are shown below



17.2 Dial Calipers



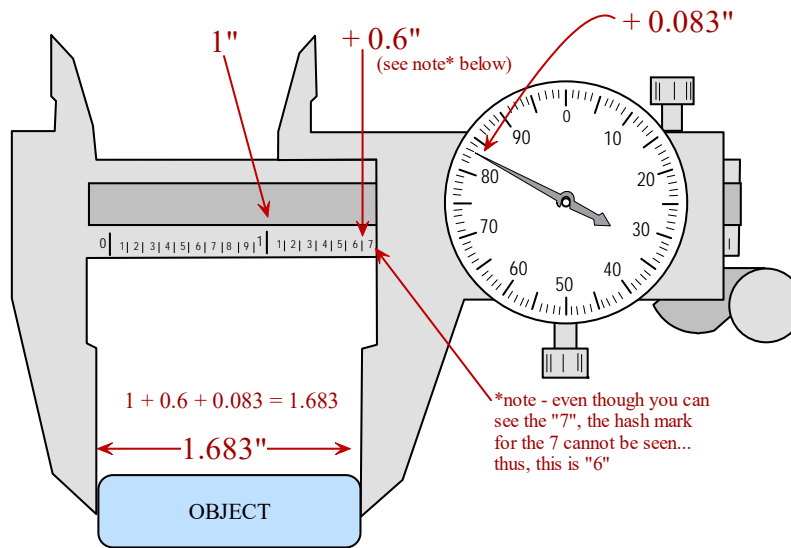
A **caliper** is a device used to measure the distance between opposite sides of an object. There are different types, including "dial calipers" and those with a digital display. There are calipers that are set for SI (mm) and US units (inches).

Dial calipers are usually set up to measure in inches, tenths (.10), hundredths (.01), and thousandths (.001) of an inch. The accuracy of a dial caliper is typically about 0.001" (one one-thousandths of an inch). This is about 1/4th of the thickness of a piece of paper!

The caliper is able to measure outer dimensions, inner dimensions, and depth (see above). You must be careful to keep the caliper perpendicular to the dimension being measured, or else the reading will be off.

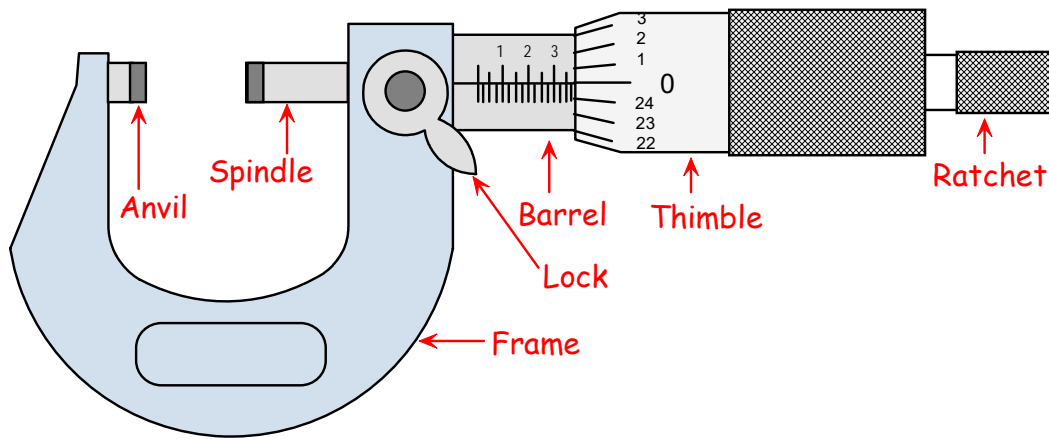
Famous caliper companies include Mitutoyo and Starrett.

READING A CALIPER



A caliper can also be set up to measure differences in distance. First measure the reference dimension. Loosen the set screw for the display and rotate it until the "0" (zero) lines up with the pointer. Then measure the other dimension and read the dial display. With digital calipers, you set the reference distance, press the "zero" button, and now you are measuring relative to that reference distance.

17.3 Micrometers



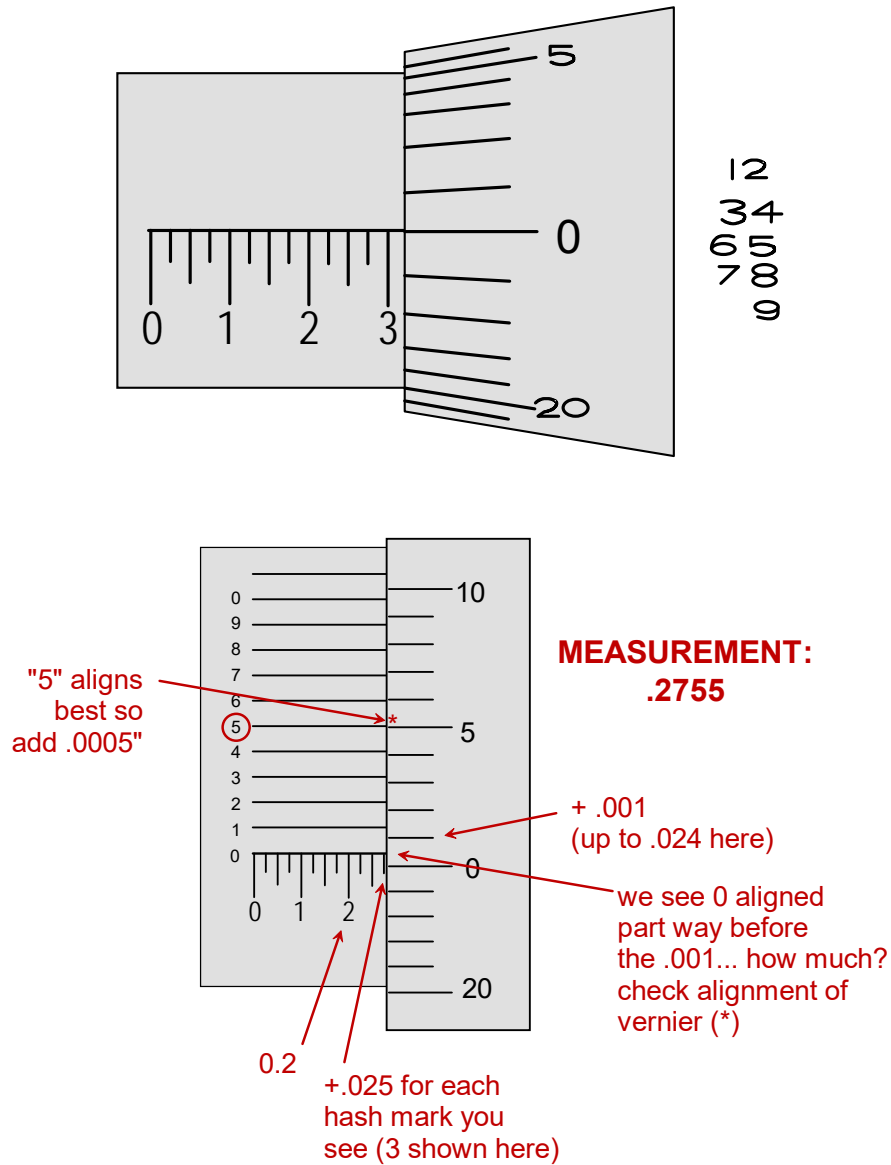
A **micrometer**, sometimes known as a micrometer screw gauge, is a device incorporating a calibrated screw widely used for accurate measurement of components in mechanical engineering and machining as well as most mechanical trades, along with other metrological instruments such as dial, vernier, and digital caliper.

Micrometers may display measurements digitally (these need batteries). Or they may use a vernier to measure fractions of an inch.

Sometimes it is necessary to be careful and consistent with the amount of force applied to the measured part. Micrometers will have either a ratchet or friction thimble to make the force applied more consistent.

READING A VERNIER MICROMETER

Generally the micrometer will measure down to the ten-thousandths of an inch (0.0001"). Machinists refer to one ten-thousandths of an inch as "a tenth".



TO KNOW FOR EXAM:

- parts of a caliper and micrometer
- how to read a ruler
- how to use and read caliper and micrometers?

***** PID CONTROL *****

CHAP 18 - PID CONTROL

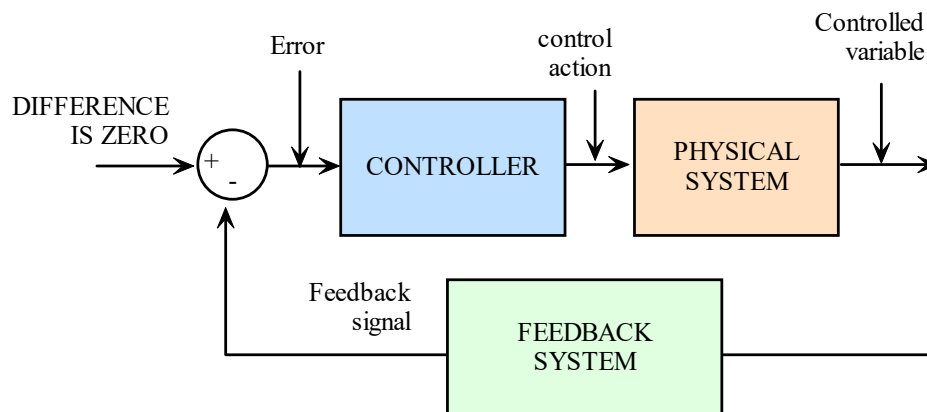
18.1 Control Systems

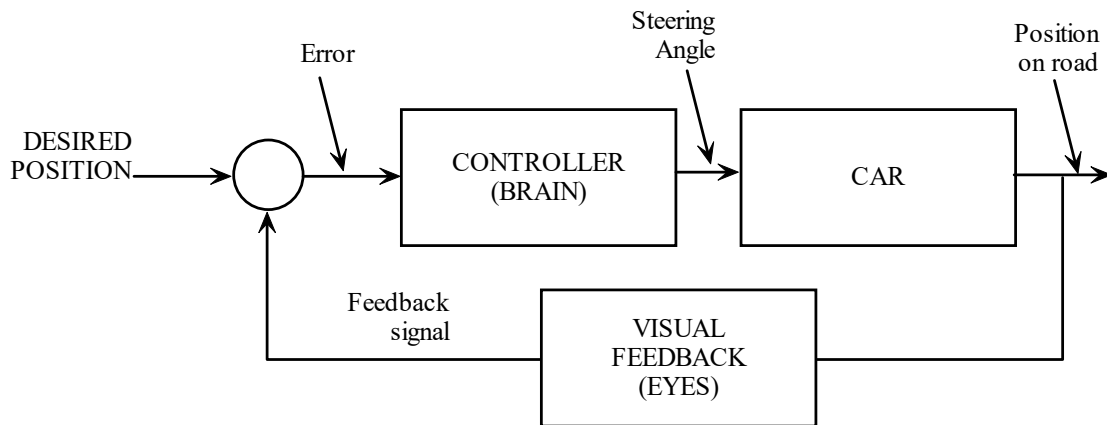
A control system manages or regulates the behavior of a SYSTEM (the physical thing being controlled) using a controller. A thermostat is an example of a simple control system that controls the temperature in a room. Control systems are used to control robots, industrial machinery, aircraft, and many other things. Even living organisms like human beings use control systems to manage their own movements.

Controllers are often classified as either **OPEN LOOP** or **CLOSED LOOP**. Open loop controllers do not use information about the "system." An example of this would be a sprinkler for a lawn which only turns on for a certain amount of time. The controller does not get or use any information about the lawn (e.g., moisture of the soil), and it does not work well if there are **DISTURBANCES**. A closed-loop controller, on the other hand, takes sensor data from the system and uses it to compute the control action. This controller is sometimes called a **FEEDBACK** controller because information about the system is fed back to the controller. An example of this would be when a driver tries to keep his car in the center of a lane. Visual feedback is used to guide the control action (in this case the movement of the steering wheel) to correct for errors (drifting left or right in the lane). Feedback helps correct for disturbances or changes in condition. For instance, a curved or banked road will cause the car to depart from the center (the "desired position"). When this happens, the driver will visually sense this and then make the correction (turn the steering wheel).

A general approach to control involves comparing a measured system variable (actual position, temperature, etc.) with a desired value (desired position, desired temperature, etc.). The control system will modulate the control action to push the system variable towards the desired value.

The control process is often visualized using **BLOCK DIAGRAMS** as shown below, including an example.





There are different CONTROL LAWS but the most commonly used one is probably the PID controller.

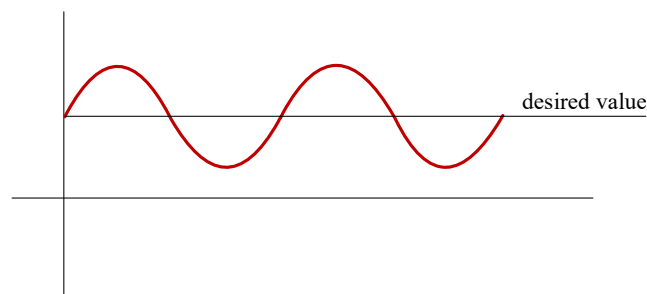
18.2 PID Controller

The PID controller (or its variations P, PI, and PD) is the most commonly used controller. The PID controller is simple and effective under most conditions.

P stands for Proportional.
 I stands for Integral
 D stands for Derivative.

18.3 Proportional (P) Control

P control measures a system variable, compares it to a desired variable, calculates error (actual minus desired), and imposes a control action that is PROPORTIONAL to that error (it multiplies negative error by a GAIN). The gain adjusts the controller's sensitivity to the error. Higher gain produces more aggressive correction for the same amount of error. P controllers tend to cause the system to oscillate about the desired system variable. The resulting behavior is much like a spring. P controllers help speed response. P-control can be thought of as correcting for PRESENT error.



One must first identify the SYSTEM VARIABLE one would like to control. Below the system variable is denoted by "x". The system variable can be almost anything. For a thermostat, it would be temperature. For a robot arm it could be a joint angle. For a solar tracker, it would be the difference in 2 different light signals. Once we identify the system variable, we must understand that there are 2 versions of it. First there is the "actual" variable. Keep in mind that the actual variable is really the MEASURED variable, one that is obtained by using some kind of a sensor. In the equations below actual is "x". The second version is the DESIRED VARIABLE (denoted " x_d "). This is a value that we wish our system variable to be equal to. For a solar tracker, the variable (which, again, is the DIFFERENCE in 2 sensed light values), is zero (i.e., we

want the difference in the 2 light sensor values to be 0). For a thermostat, perhaps it is 70 degrees F. For a robot arm, perhaps it is an angle of 30 degrees.

The equation for P control is below (x = actual variable value, x_d = desired variable value)

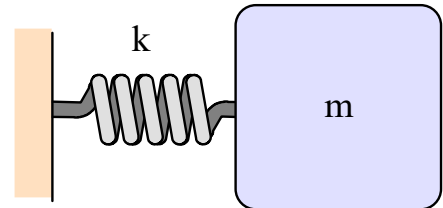
$$u_p = K_p(-e) \quad \text{where } K_p = \text{proportional gain and } e = \text{error.}$$

But error is $x - x_d$, where x = actual variable value and x_d = desired value. Thus,

$$u_p = K_p(-e) = K_p[-(x - x_d)] = K_p(x_d - x)$$

The equation for the force applied by a spring is

$$F_{sp} = K(l_o - l) \quad \text{where } K \text{ is the spring constant,}$$



Where

K is the spring constant

l_o is the unstretched spring length

l is the actual spring length

You can see the P control equation is basically the same as the spring equation. That is why P control produces behavior similar to that of a spring (that is, oscillating movement). In addition, if you drive a motor with P control and you then rotate the motor shaft, it will resist you in a way that feels just like a spring!

18.4 Derivative (D) Control

D control imposes control action that is proportional to the rate of change of error (or DERIVATIVE of error, for those of you who have had calculus). The derivative of the system variable is denoted x' in the equations below. The equation for D-control is analogous to that of a damper (or shock absorber). This effectively helps damp out the oscillations of a P controller. D-control helps reduce transient error. D-control can be thought of as correcting for predictions of FUTURE error.

The equation for D control looks like below (x' = derivative of error or error rate).

$$u_D = K_D \left(\frac{dx_d}{dt} - \frac{dx}{dt} \right) = K_D(x'_d - x')$$

and if $x'_d = 0$, then you get

$$u_D = -K_D x' = -K_D v$$

This equation is similar to that of the equation for force exerted by a shock absorber (or damper), which is

$$F_B = -Bv \quad \text{where } v \text{ is the speed of the damper.}$$

18.5 Integral (I) Controller

I-control imposes control action that is proportional to the error INTEGRATED (or added up) over time. If you have not had calculus yet, integrating just means to add up over time. I-control helps correct for persistent error that P control is not going away. As that error persists in time, the control action of I-control builds up. I-control is useful when the system has persistent disturbance or force (e.g., controlling height of a drone... gravity forces are persistent in this case). I-control can be thought of as correcting for memory of PAST errors.

$$u_I = K_I(-\int e) = K_I[-\int (x - x_d)] = K_I \int (x_d - x)$$

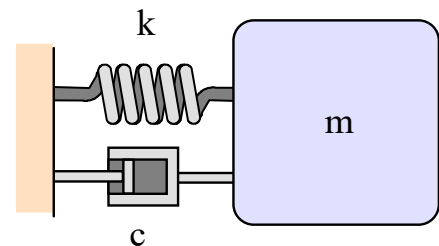
18.6 PD Control

P, I, and D control can be applied in different combinations, such as PD, PI, and PID control.

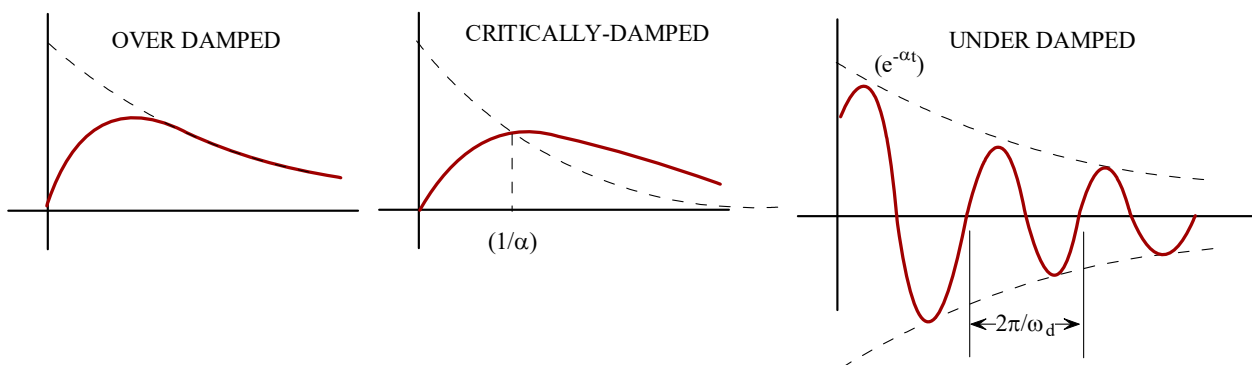
It is common to start with P control to get your system "in the ballpark". However, increasing the P gain often causes oscillations. Adding D control can help. A PD (proportional-derivative) controller can get a system to oscillate about a desired value and also "damp" (or reduce) the oscillations. Its behavior is analogous to a mass-spring-damper system. The spring (P control) keeps the system close to a desired value, and the damper (D control) removes the oscillations. A PD controller cannot drive error to zero if there is a constant disturbance (or force). There would always be an error. You could get it to be pretty small, but it would never be zero.

$$u_P = K_P(x_d - x) + K_D(x'_d - x') \quad \text{PD controller}$$

$$F_B = -Bv \quad \text{where } v \text{ is the speed of the damper.}$$



The response of a PD controller depends on the strength of the damper. If under-damped the system will undergo oscillations that decay with time. If critically or over-damped, the system will undergo "exponential decay".



18.7 PI Control

A PI (proportional-integral) controller can get a system to oscillate about a desired value and also correct for constant disturbances, but it may have trouble getting rid of oscillations. PI control is often used when you have a persistent disturbance or force. PI control might work well with, for instance, elevation control on a drone. Gravity is a constant persistent force that always pushes the drone down. A PI controller may work well to control the drone's elevation.

$$u = K_P(x_d - x) + K_I \int (x_d - x)$$

18.8 PID Control

The PID (proportional-integral-derivative) controller incorporates all 3 components.

$$u = K_P(x_d - x) + K_I \int (x_d - x) + K_D(x'_d - x')$$

18.9 Potential Complications

P CONTROL PROBLEMS

But as you might suspect, there can be complications. Increasing K_P can reduce error, but it cannot be increased arbitrarily high. If set too high, K_P can cause system instability. You will often see the system oscillate, and then spontaneously oscillate more violently. This is system instability.

D CONTROL PROBLEMS

The D term can also cause problems. In theory D control adds friction to the controller, which should absorb energy and settle the system down. In practice, the D control can have the opposite effect. All sensor signals have noise. It turns out that taking derivatives AMPLIFY noise. This can produce unwanted effects and cause the D control to do exactly the opposite of what you want. That is, it can potentially create instability, especially as you increase K_D gain.

I CONTROL PROBLEMS

I control can have instability problems too. I control uses error that is added up over time. This can have the problem of INTEGRAL WINDUP. This occurs if the system has an error that has built up over time. This happens if your actuator is saturated because some force acting on the system is too strong for it. If that happens over a period of time, the error will add up. If the force is removed, the actuator is now strong enough to drive system to zero error. But because of the built-up correction in the I control, the controller will push the system past zero error (producing negative error) until the error "UNWINDS". There are computational methods for reducing this problem. For instance, we can CLAMP the integral term, limiting how much it accumulates. Or we can zero out the accumulated integral error if the error switches sign.

CLAMPING

Here we might implement a controller saturation limit to match the saturation of the actuator. Then we'd want to do 2 checks:

1. Check the controller output before and after the clamping saturation limit and compare them. If they are not equal then that means the output is saturating.

2. Check the sign of the error and the sign of the control to see if they are equal.

Clamping would be implemented if:

1. The output is saturating AND
2. The error is the same sign as the controller output.

SUMMARY

So while PID control works well in most cases, the challenge is to TUNE the gains (K_p , K_I , K_D) to get the desired performance.

Watch the videos below (it's a very nice explanation):

<https://www.youtube.com/watch?v=wkfEZmsQqiA>

<https://www.youtube.com/watch?v=NVLXCwc8HzM>

<https://www.youtube.com/watch?v=7dUVdrs1e18>

A nice video showing someone tuning PID gains for a DC motor

<https://www.youtube.com/watch?v=fusr9eTceEo>

TO KNOW FOR EXAM:

What is a control system? What is PID control and how does it work?

What is: open loop vs. closed loop, block diagrams,

What does P-I-D stand for?

How do each of the P, I, and D controls work?

How does PI, PD work?

What are the potential problems?

(No need to know the PID equation which has calculus in it)

***** **SENSORS** *****

CHAP 19 - SENSORS

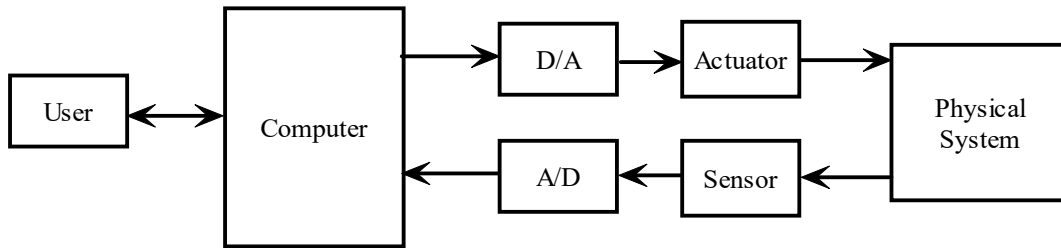
19.1 Intro

A SENSOR is a device that measures a physical quantity and converts it into a signal which can be read by an observer or by an instrument. Sensors are often used to inform a machine about its environment or its own state. Robots need sensors to effectively operate.

A TRANSDUCER is a device that converts one type of energy or physical attribute to another type.

Modern sensors typically measure a physical variable (movement, pressure, temperature, etc.) by producing an electronic signal (usually a voltage) that is related to that physical measurement.

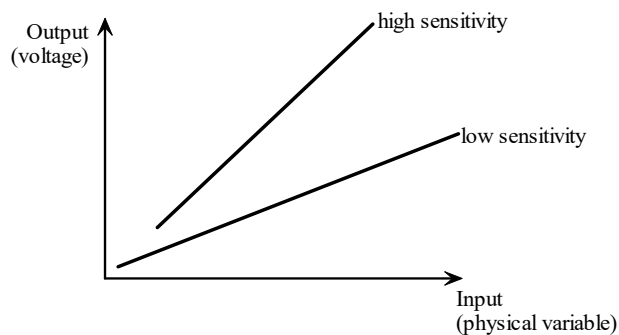
Signals are usually analog & are converted to digital using A/D conversion. Besides A/D conversion, it is often necessary to CONDITION a sensor's signal before sending it on to the computer (including amplification, filtering, etc.).



19.2 Characteristics

Desired properties of a sensor are:

1. Sensitive to measured property.
2. Insensitive to other properties.
3. Does not influence the measured property.



19.3 Calibration, sensitivity and Range

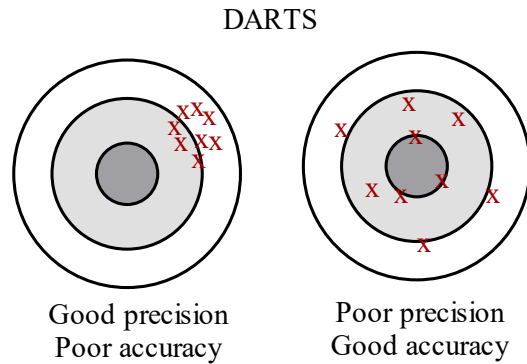
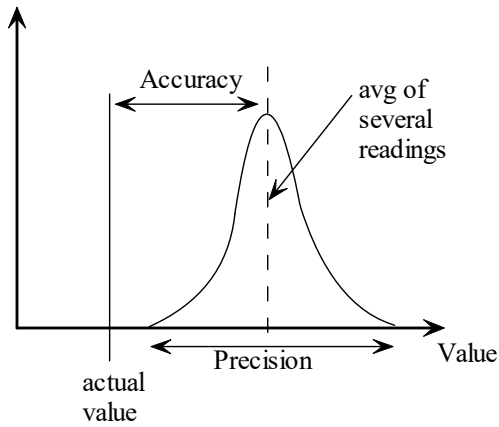
TERMS

1. Sensitivity – degree of output change as measured quantity changes.
2. Range – maximum & minimum values that can be measured.

19.4 Deviation in measurement

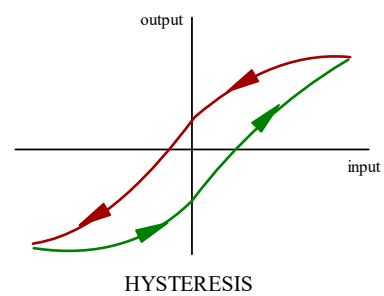
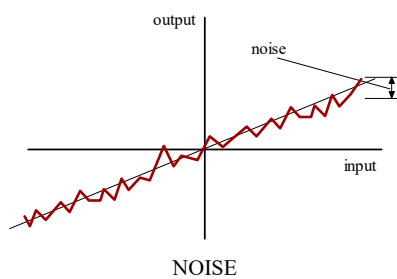
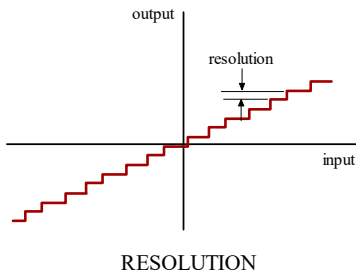
TERMS

1. Accuracy – closeness of a measurement to its true value.
2. Precision – repeatability.



3. Resolution – the smallest change detectable in the physical quantity being measured.
4. Noise – undesired random signal that is added to the desired signal
5. Hysteresis – sensor output depends on past input.

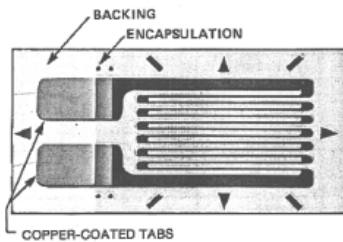
The output may differ depending on the direction you are coming from.
This results in uncertainty and error.



19.5 Examples

FORCE OR CONTACT SENSORS

1. Weight sensors - scales
2. Strain gages - measures the strain (or deformation) of an object
3. Load cells - use strain gages, multi-axis
4. Micro-switches (bumper or contact sensors)



Strain gage



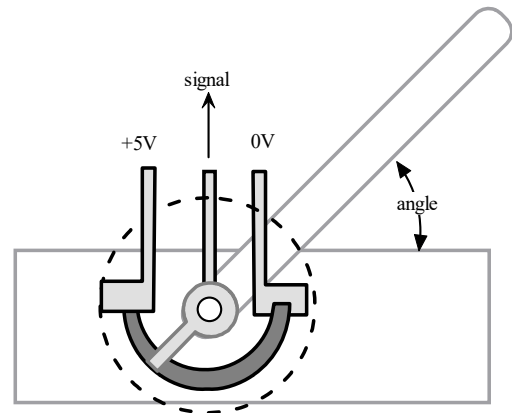
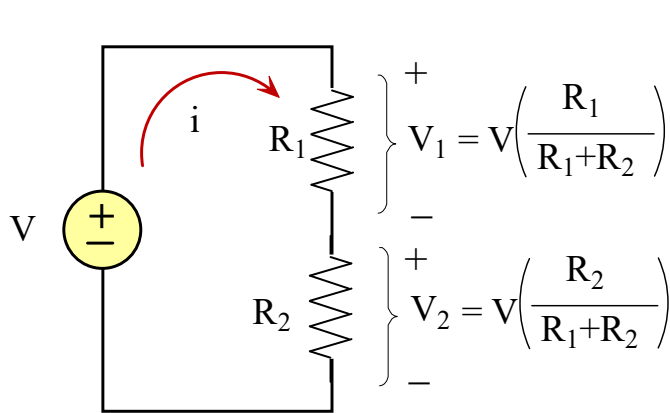
Load cell



Micro-switch

POSITION & ORIENTATION SENSORS

1. Potentiometer - pots are angle sensors (drop V across them & use voltage divider rule)



2. Digital encoders

Digital encoders measure angular rotation. A code wheel with “spokes” is mounted to a rotating shaft. An LED is mounted on one side of the code wheel. A light sensor is mounted on the other side of the code wheel. As the shaft (& code wheel) turn the spokes interrupt the light received by the sensor. Electronics condition the signal and send out a pulse each time the light is interrupted. Electronics or programming will count the pulses.

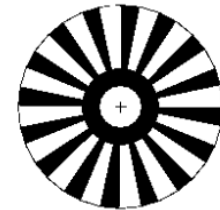
Incremental encoders cannot find absolute position on their own. They must be “homed”. Absolute encoders DO know absolute position.



Pot



Encoder



Encoder wheel

3. Hall Effect sensors - output voltage varies in response to a magnetic field
4. LVDTs (linear variable displacement transformers)
5. Orientation – tilt sensors, gyros, and compass (uses magnetism)

Movement Sensors

- Accelerometers – measure acceleration (actually measures force, or really actually deformation).
- Gyroscopes – measure angular rotation rate.
- Speed sensing – sense position and take a time derivative

LIGHT SENSORS

1. Photo-resistors – resistors whose R decreases with light exposure. Use in voltage divider circuit
2. Phototransistors – light switches transistor ON, allowing current to flow (more light \square more current)
3. Photodiodes – like an LED in reverse
4. Near-IR sensors – for proximity (there or not there)

SOUND SENSORS

Microphone, piezoelectric film sensors, sonar, etc.

TEMPERATURE

Mercury-in-glass thermometer – thermal expansion of Hg in a tiny tube.

Thermocouple – junction between 2 different metals that produces a voltage related to a temperature difference (based on thermo-electric effect, $T \uparrow \rightarrow V \uparrow$) (e.g. – chromel-alumel)

Thermistor – a resistor whose resistance varies with temperature.

OTHER

Pressure – 2 chambers with a membrane in between and a strain gage adhered to the membrane.

Flow – turbine flow meters have vanes that spin inside the flow (faster flow \rightarrow faster turbine spin)

Humidity

TO KNOW FOR EXAM:

- Sensor vs. transducer
- Characteristics of a good sensor
- What is: sensitivity, range, accuracy, precision, resolution, noise, hysteresis
- Examples of sensors: force, position/orientation, movement, light, sound, temperature,

***** COMPUTERS *****

CHAP 20 - COMPUTERS

Computers are machines that manipulate data according to a set of instructions. Those instructions are commonly called a COMPUTER PROGRAM.

20.1 History

A long time ago clever people realized you could do logic computations (and thus mathematical computations) using switches.

The oldest known computers were mechanical (using mechanical switches).

Later, computers were created using vacuum tubes (thru 1960's) (the tubes served as the switches).

Modern computers are electronic. Transistors form the basis for modern computers. Transistors are electronics switches. (note - an i7-Ivy Bridge E has almost 1.9 BILLION transistors)

2600 BC Abacus

1500 Mechanical calculator (DaVinci)

1642 Pascaline, the first mechanical calculator (Blaise Pascal) (+/- 2 numbers)

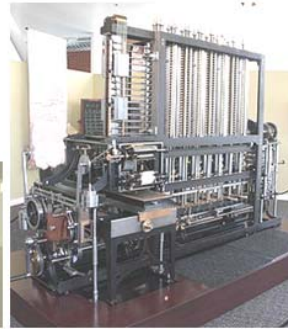
- 1822 Difference engine – a large mechanical calculator (Charles Babbage) (divided differences to interpolate/tabulate fns using polynomial coeffs)
- 1837 Analytical engine (Charles Babbage) (same logical structure as modern computers)
- 1904 Vacuum tubes (John Ambrose Fleming) (pre-semi-conductor diodes, triodes)
- 1947 Electronic transistor (Shockley, Bardeen, Brittain)
- 1968 Integrated circuit (Intel, Robert Noyce)



Abacus



Pascaline



Difference engine

20.2 Basic components of a computer

Processor (or “central processing unit”, CPU) – executes instructions.

Memory – stores instructions and data

RAM – random access memory. Is volatile (data is lost when power is off), but FAST.

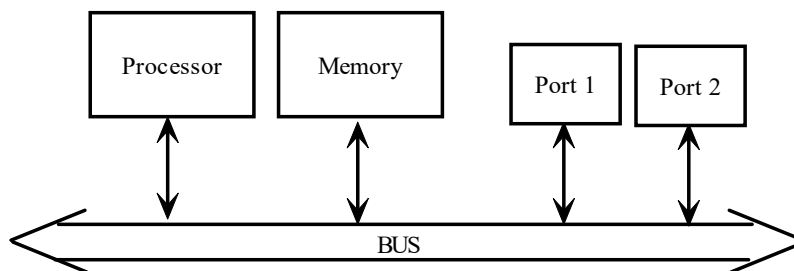
ROM – read-only memory

PROM – programmable read-only memory

EEPROM – electronically erasable programmable read-only memory (memory is retained even w/o power)

Ports – connect the computer to the outside world

Bus – communication pathway between the processor, memory, and ports



TO KNOW FOR EXAM:

- What is a computer?
- Basic components of a computer (eg, bus, processor, etc.)

***** MATERIALS *****

CHAP 21 - MATERIALS

Mechanical parts must be made out of some kind of material. The design engineer will, of course, select material based on a variety of factors including: material properties, cost, material availability, strength, corrosion resistance, and many other factors.

21.1 Basic Material Types

The basic classification of materials include

1. Metals
2. Polymers (plastics, man-made material consisting of repeating sub-units)
3. Ceramics (hard brittle inorganic nonmetallic, e.g., baked clay)
4. Composites (combinations of materials)

There is also wood and concrete, which tend to be used as construction materials in civil engineering design.

21.2 Material Properties

Materials are selected for any number of their properties.

1. Physical
 - Density (ρ) – mass per unit volume (kg/m^3) (basically, how heavy is the material)
 - Elastic modulus (E) – stiffness/springiness of material (high value = stiffer) (F/A)
2. Mechanical properties - strength, impact resistance (toughness), fatigue
 - Strength (σ) – how strong is the material, measured in force per unit area (lb/in^2 , N/m^2).
 - There are different types of strength - see below

$$\sigma = \text{force over area} = F/A$$

3. Thermal properties
 - Thermal conductivity - how easily heat moves thru it
 - Specific heat, melting point
 - Coefficient of thermal expansion (CTE) - how much material grows with temperature
4. Chemical properties - corrosion resistance
5. Electrical - electrical conductivity

METALS

Metals are known for their lustre, strength, hardness, thermal & electrical conductivity, malleability (can be formed). Alloys are combinations of different metals. Steel is a combination of iron and carbon (2 - 3%). The added carbon resides in the interstitial sites, increasing the strength and rigidity of iron.

Copper and its alloys (brass).

Aluminum – high specific strength (often used in aerospace industry where density is a concern)

Stainless steels

Regular iron will chemically react with oxygen to form iron oxide - rust. Such corrosion can be reduced by adding certain elements to iron. These new compounds are sometimes called STAINLESS STEELS or corrosion resistance steel. There are different types of stainless steels.

AUSTENITIC STAINLESS STEEL (300 series)

Austenitic stainless contains carbon, chromium, molybdenum, and nickel. These tend to be non-magnetic

FERRITIC (400 series)

These alloys contain mainly chromium and other trace elements. They are magnetic.

MARTENSITIC

These alloys contain mainly chromium and some with small amounts of molybdenum.

CERAMICS

Brittle, high thermal & electrical resistance (insulators), high corrosion resistance, high temperature stability

POLYMERS

Long-chained macro-molecules, ductile/soft, low thermal stability, poor conductor (heat & electricity)

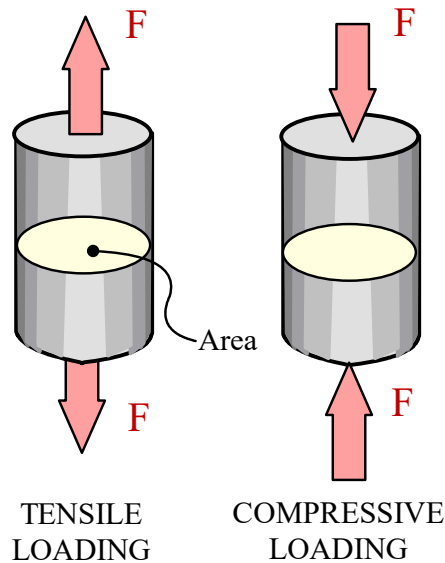
WOOD

Wood is cheap and abundant. It is typically used in construction (civil designs), not in mechanical design.

Wood is ANISOTROPIC, which means its properties are different in different directions. You may already be aware that wood is strong in the direction of its grains. It is much weaker between the grains. Thus it is much easier to break a piece of wood along the grains rather than across them. This is to be distinguished from ISOTROPIC materials which have the same properties in all directions.

21.3 Material Strength

Materials are selected for any number of their properties. One important one is material strength. Strength is often quantified in terms of STRESS which is FORCE over AREA, so it has the same units as pressure.



BASSWOOD (used for bridge project)

Properties of basswood (it varies).

Wood is tricky in that its properties depend on direction relative to the wood grain (called "anisotropic").

Characteristic	Value in SI units	Value in US units
Density (ρ)	.320 – .657 g/cc	.0116 - .0237 lb/in ³
Ultimate tensile strength (σ)	~ 70 MPa	10,150 lb/in ² .
Compressive yield strength (σ_c)	32.6 MPa (// to grain)	4730 psi (or lb/in ²)
Elastic modulus (E)	7.10 – 10.3 GPa	1030 –1490 ksi (1k lb/in ²)

21.4 Common Polymers

Polymers are generally man-made and typically have the following properties: chemically inert, fair strength, and low density.

Here is a list of commonly-used plastics.

1. Polyamides (nylons)
2. Polycarbonate – lenses, windows
3. Polyesters – fabrics
4. Polyethylene – inexpensive (low, med, high density), bags
5. Polypropylene (PP)
6. Polystyrene
7. Polyurethanes – foam
8. Polyvinyl chloride (PVC) – piping,
9. Acrylonitrile butadiene styrene (ABS) – 3D printers
10. Polylactic acid (PLA) – 3D printers
11. Polyoxymethylene (POM), Acetal, or Delrin) – high stiffness, low friction,
12. Polytetrafluoroethylene (PTFE or Teflon) – non-stick coatings
13. Polymethyl methacrylate (PMMA or acrylic or Plexiglass)

21.4.2 - Plastics with Low Friction

Plastics that typically have lower coefficients of friction are:

1. PTFE (polytetrafluoroethylene)
2. PEEK
3. PPS
4. Nylon
5. Acetal (delrin)
6. Polyester

These plastics are often used for bearing and wear materials.

***** **MECHANICAL DESIGN** *****

CHAP 22 - MECHANICAL DESIGN

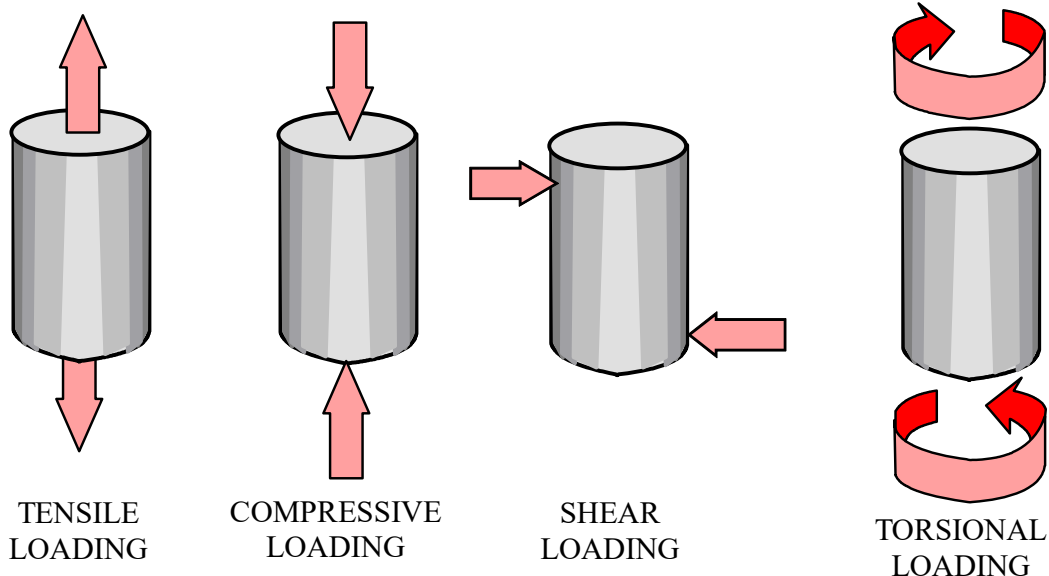
Mechanical design involves the design of structures, machines, or mechanisms. Mechanical design must consider the forces (loads) that are being supported by the structure, machine, or mechanism.

22.1 Loading

Loading is another term for the forces applied to a structure, machine, or mechanism. This is one reason why engineers must take advanced math and physics courses.

A basic mechanical component is called a MEMBER.

A member may be loaded in a variety of different ways (illustrated below)



TENSILE - the member is being pulled apart
COMPRESSIVE - the member is being "squished"
SHEAR - the member is being "sliced"
TORSIONAL - the member is being twisted (like wring out a rag)

The strength of a material is an essential consideration in design. Material selection is based on the material's properties, including its strength. Strength values are evaluated using materials testing equipment such as tensile testers. Famous brands of materials testing equipment include Instron and Tinius Olsen.

22.2 Structures & Support Loads

Structures (like frames and machines) are generally designed to support loads (forces).

TRUSSES

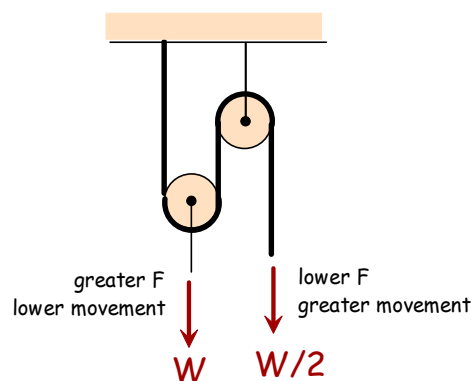
A famous structure that is commonly used in shorter bridge design is the TRUSS. It is characterized by having long straight slender members joined at the ends by rotating joints. Loads are only applied at the joints. In addition, a rigid truss is configured so the members form triangular shapes. Trusses are tremendously strong and are able to support loads many times greater than their own weight. This is possible because the truss design protects the members from bending loads, which are the easiest way to break a member.

22.3 Force Amplification or Reduction

Frames and machines can be configured to amplify or reduce forces. One simple example of force amplification is the nut cracker. A smaller force at the end of the handle produces a much larger force where the nut is placed.

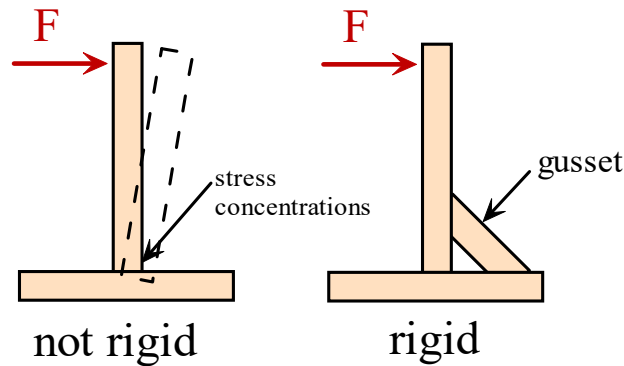
One can always design a mechanism that takes a small force over large displacement and convert it into a large force over a small displacement. The opposite is true too. Mechanisms may be designed that convert a small force over a large displacement into a small force over a large displacement. This is what happens with a nutcracker.

This principle should always work. Take the example of a pulley system. Many are designed to reduce forces. But this ALWAYS comes at the expense of increased displacement.



22.4 Side forces, Moments, and Gussets

Often we wish to mount a member perpendicular to another member. As can be seen on the figure shown, a small side force will easily displace the vertical piece. A small side force near the top will produce high stress concentrations near the base (like the nutcracker). The way to solve this problem is to add a GUSSET (a brace, often angled at 45 degrees). This reduces the stress concentrations at the base and makes the structure much more rigid.



Curved surfaces are more rigid (and stronger) than flat surfaces (e.g, an egg)

Joints allow movement in a desired way.

Rotating – need a yoke (fork)

Bearings – reduce friction, movement smoother

Bearings reduce friction and produce smoother movement.

22.5 Simple Machines

- A. Levers
- B. Pulleys
- C. Screws
- D. Gears
- E. Linkages
- F. 4-Bar Mechanisms

22.6 Gears

Gears are toothed cogs used to transmit motion. Gears are often part of a TRANSMISSION SYSTEM of a machine with the purpose of transferring energy from a power source to the output of the machine. For instance cars have transmissions, and the sprocket/chain system of a bicycle is a gear system.

22.6.1 - Gears

Angular velocity (ω) - speed of rotation (use Greek letter omega)

Units - [degrees/second], [cycles/second], [radians/second]

π radians = 180 degrees

Torque (τ) - twisting force (Greek letter "tau")

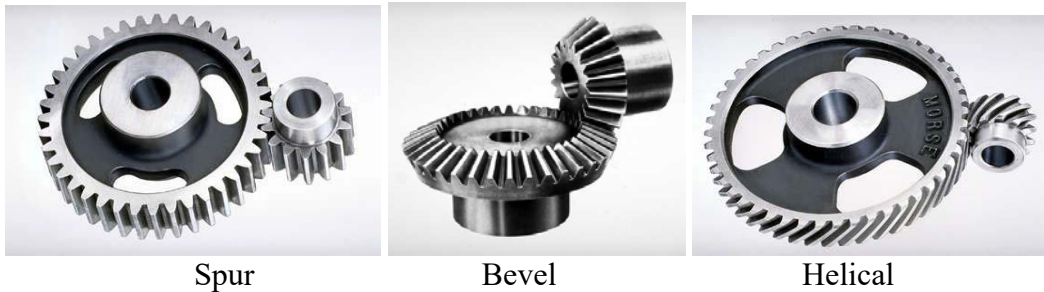
Units: [lb-ft], [N - m]

Power (p) - rate at which work is done

Units: Watts (W) or [N-m/s] = [Joule/second]

22.6.2 - Gear Types

1. Spur gears – for parallel shafts.
2. Bevel gears – for perpendicular shafts.
3. Helical gears – for non-parallel shafts. Angled teeth produce gradual meshing (quieter, smoother)



Spur

Bevel

Helical

22.6.3 - Gear Ratio

Consider 2 meshed gears

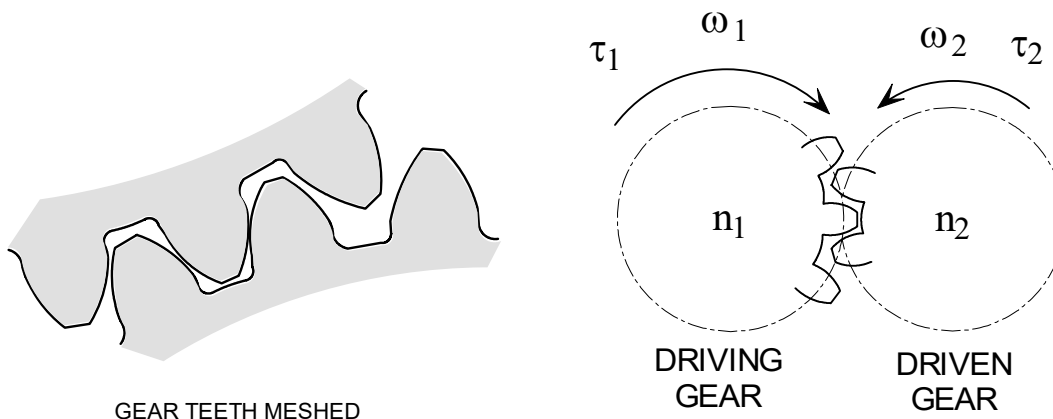
1. Let gear 1 be the “driving” gear (it’s connected to a motor)
2. Let gear 2 be the “driven” gear (it moves only if gear 1 moves it)
3. Note – pitch diameter = effective diameter of a gear
4. Each gear has:

n = number of teeth on gear

r = radius of gear

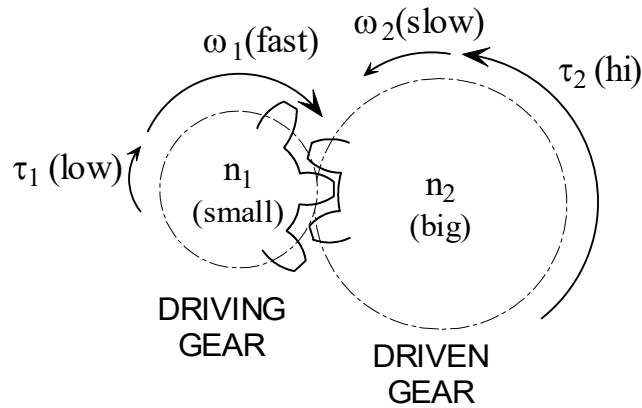
ω = turning speed (e.g., in RPM)

τ = torque (twisting force, in ft-lbs or N-m)



GEAR RATIO

1. Ratio of number of teeth of “driven” gear (n2) to that of “driving” gear (n1).
2. Equations below



$$\text{Gear Ratio } R = \left(\frac{n_2}{n_1} \right) = \left(\frac{r_2}{r_1} \right) = \left(\frac{\omega_1}{\omega_2} \right) = \left(\frac{\tau_2}{\tau_1} \right)$$

↑ teeth
 ↑ radius
 ↑ turning
 ↑ torque

EXAMPLE

Gear ratio $R = (n_2/n_1) = (40/20) = 2$.
 $R = r_2/r_1 = 2$ means that gear 2 is 2x as big as gear 1.
 Gear 2 turns half as fast as gear 1
 Gear 2 has 2x as much torque as gear 1

"Gearing Down" a motor
 Motors are good at turning fast but with low torque
 Gears can reduce the speed and increase the torque

Configurations

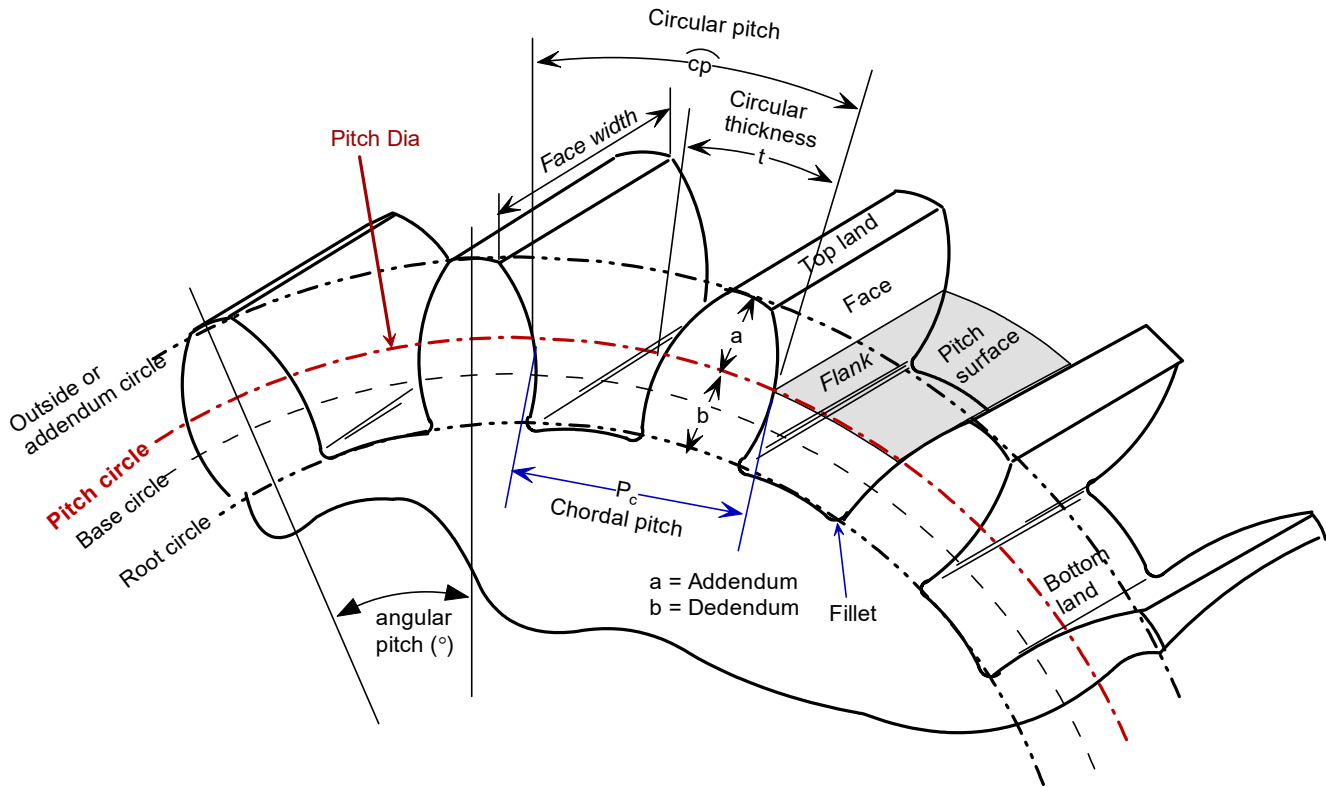
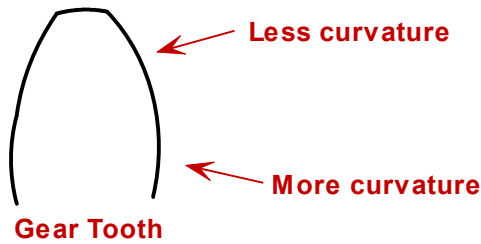
What if we want driven gear to turn in the same direction (CW, CCW) as driving gear?
 Use idler gear, or a chain (or belt).

22.6.4 - Involute Gear Profile

Gear teeth roll on each other during meshing. During the roll, the contact point MOVES relative to the gear centers, causing dynamic changes in gear ratio. This causes turning speed of driven gear to fluctuate up & down, causing vibration and noise.

Designers came up with the INVOLUTE PROFILE for gear teeth to minimize this, producing more steady rotation speeds. Note that this comes at the cost of gear teeth rubbing slightly against each other.

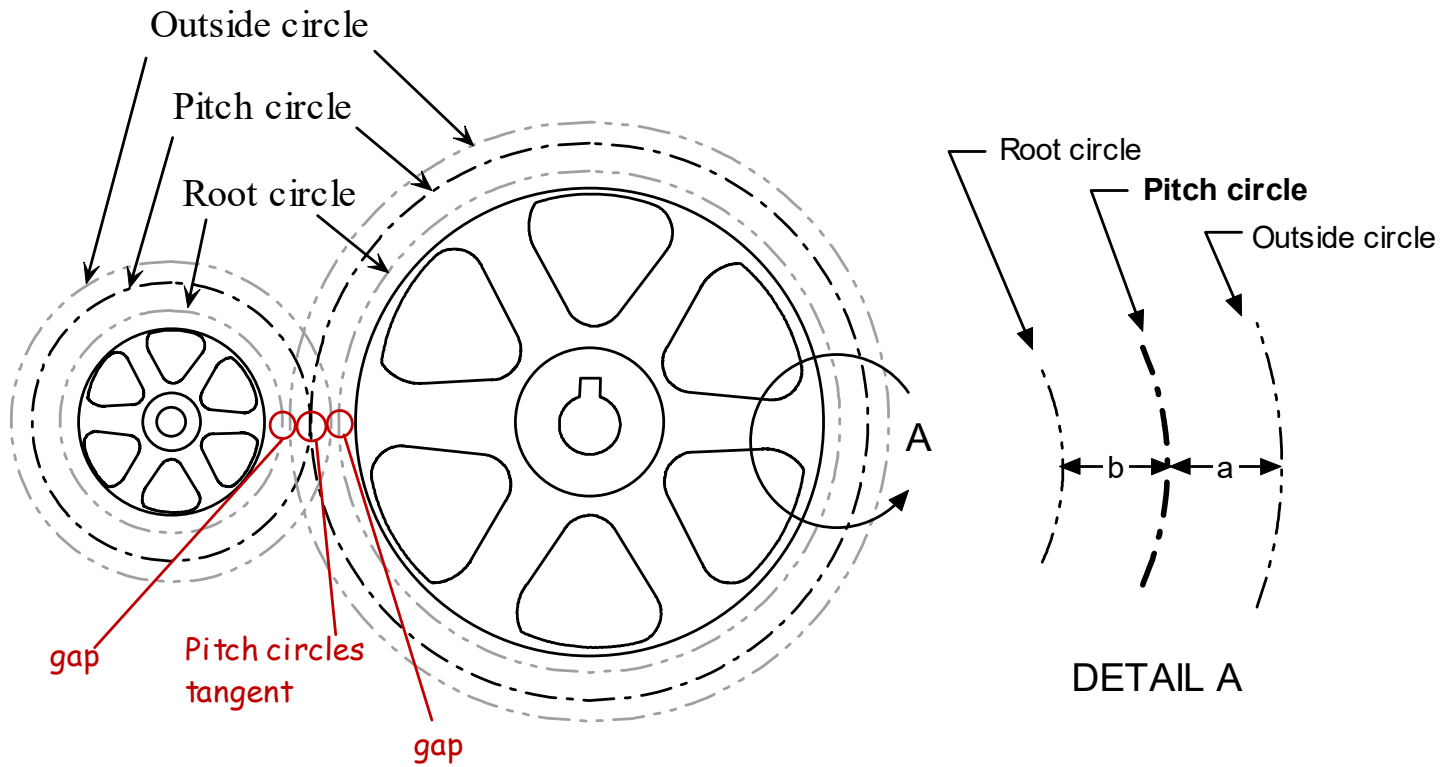
The involute profile is a spiral shaped curve traced by a point on a taut cord unwound from the BASE circle. The curve becomes straighter as the cord unwinds.



N = number of teeth
 PD = pitch diameter
 pressure angle (pa) = 14.5 (or 20, or 25 deg)

Diametral pitch, DP = N / PD (# teeth per inch) (must match for meshed gears)
 a = $1/DP$ (addendum) (distance from pitch circle to outside circle)
 b = $1.157/DP$ (dedendum) (distance from pitch circle to root circle)
 Outside circle dia OD = $PD + 2a$
 Root circle dia (rD) = $PD - 2b$
 Base circle dia (bD) = $PD \cos(\text{pressure angle})$
 Angular pitch, ap = $360 / (2*N)$ (degrees) (angle between teeth)

$$x(t) = (bD/2) * (*$$



***** MISC *****

CHAP 23 - MISC

XXX

23.1 Analog Measuring Devices

Old-school measurement devices were analog.

VOLTMETERS

Older analog voltmeters measure voltage, but the display uses a needle-type gauge. This type of display requires you to "interpolate" or "extrapolate" to figure out the voltage value. Many expert technicians like to use the analog meters when they are measuring irregular signals. The movement of the needle may help them assess problems in an electrical circuit. Irregular signals can be more difficult to see on a digital meter

23.2 SAC Equipment

Elenko XK 700 (\$250)
Oscilloscope, Instek GDS 2062 – (\$900)
Function generators, BK Precision xx – (\$400)
Digital multi-meters, BK Precision XX – (\$60) – X

```
// 0531_ServoSloMoCCW.ino -----  
// pulse LEDs at 1/100th servo rate
```

***** APPENDIX *****

CHAP 24 - APPENDIX

The following documents reference this one:

1. 100A notes (with section #s),
2. 250L labs - lab safety,
3. 131 NOTes,
4. Arduino (+ sections)
5. xx
- 6.

Arduino --> C prog,
Blink --> Arduino, lab guide,
C prog --> Arduino

24.2 xx