GATE Material for Electrical Engineering

ELECTRICAL ENGINEERING

- **Basic Concepts**

Quanties:

You are using charge now, believe it or not.

These lessons have been designed to be read electronically, not on paper.

To read them electronically means using a monitor.

A monitor uses charge to make the screen emit light of various colors, and to control that light so that it forms letters and windows, etc.

To produce the light that the monitor emits, and to control the appearance of that light, voltage is used to control the path of charge that is emitted at the back of the monitor and which strikes the monitor screen.

A caveat! If you are reading this lesson using a flat panel display, then these statements are not true. In that case imagine that you are using a CRT monitor.

Here is a little pictorial model of what happens. Click the appropriate phrase to show how the electrons (which carry charge!) move up, move down, or travel a flat path. Note the following:

When there is positive charge on the top plate there is also negative charge on the bottom plate. The electron is simultaneously attracted to the positive charge and repelled by the negative charge.

The same attraction/repulsion is obtained when the charges are reversed.

Current

Like people, the most interesting charge is the charge that is in motion, moving about rather than sitting still.

Charge in motion is referred to as current.

Current can exist in many different physical forms because there are many different physical situations in which charge can flow.

The most common manifestation of charge in motion is the movement of electrons in a wire such as the wire leading to the computer that is running this lesson. That's one form of current. Here's a simulation that lets you see how charge flows around an electrical circuit through several elements.

Goals For This Lesson

There are lots of different forms of current, and you need to understand current - the flow of charge if you want to understand the electrical devices you use.

Objectives for this system include the following:

For yourself

To develop a mental model that helps you picture and understand current in an electrical circuit.

In an electrical circuit

Be able to define and measure currents in any element.
Be able to use units of current correctly.

Current - continued

There are a number of different ways of thinking about current. In different situations you might want to use different ways of thinking about current to help you figure out what's going on.

Water flowing in a pipe is analogous to current. The water flows in the interior of the pipe, and current actually flows through the empty spaces between atoms in a wire, but the analogy can be useful. It helps if you have some sort of analogy that lets you use something you already know about to help you think about new things like current.

Current is an information carrying signal. There will be times when you don't care so much about the charge that's being transported as current flows but you will care about the information that is being sent using current.

There will be times when the charge that is being transported is what is important, and there are times when you will have to think in a backwards sort of way about that. Semiconductor engineers do this all the time when they talk about holes moving in semiconductors. They have invented a concept that is based on missing electrons and the

spaces they should occupy in an atomic lattice, and they work with ideas of missing electrons - holes - that move about in semiconductors.

Most of the time, when you are dealing with current you are dealing with electrons moving through metallic wires of electronic devices. At this point, we will begin discussing electron flow through wires.

Current usually flows through wires, and electrical engineers usually idealize the situation. The figure below shows a wire carrying current, and the idealized representation we use - the arrow that points in the direction the current flows. Note that the current in the idealization is symbolized by an arrow along the idealized wire, and the arrow points in the direction that positive charge flows.

Voltage

We usually try to start each lesson by giving reasons why you want to learn the lesson topic. However, if you have ever had the misfortune of grabbing a live wire with more than a few volts you might already have the answer to why you want to learn about voltage. You've probably seen the signs that say "Danger High Voltage", and you've probably talked about things or people being "High Voltage". A high voltage individual is one with a lot of energy and drive. That's apropos.

Still voltage is important - and not just to electrical engineers - because it is the medium used to transmit information and energy in our world.

What Is Voltage? - Ways Of Thinking About Voltage

Voltage is a physical variable that can be thought of in different ways. Here are a few ways you can think about voltage.

Voltage can be thought of as the driving force (although it is not really a "force".) behind current. Things like batteries are voltage sources. The voltage across the terminals of a battery tends to stay pretty constant. When you connect a device across the battery terminals a current flows through the device.

Current flows through electrical elements when a voltage appears across the terminals of the element, just like water flows through a pipe when a pressure difference appears across the pipe. You can use that analogy to get started thinking about voltage.

More ways of thinking about voltage are:
Voltage is an across variable (Whereas current is a through variable, remember?). Water pressure that causes water flow is also an across variable. We talk about pressure differences and voltage differences.

Voltage is a concept that is related to potential energy. Voltage is the electrical potential energy a charge has by virtue of its position in space. Where the charge is affects the energy it has because other charges exert forces on it. When forces are exerted on the charge, then it may require energy to move the charge between two points, or, conversely, the system may release energy as the charge moves between two points.

Because there are electrical forces there are concepts like potential energy that can be used in electrical systems. What's more, the electrical forces obey an inverse square law, just like gravitational forces, so a lot of concepts carry over. Those gravitational force field concepts are important. Electrical fields have much in common with gravitational fields, and a number of those concepts carry over to electrical fields.

The electrical force law and the gravitational are both inverse square laws. Because the fundamental force law is the same, many of the concepts developed for gravitational forces can be taken over to electrical concepts because the underlying mathematics is the same. Those electrical concepts will be almost exactly the same except that charge will play the role in electrical forces that mass plays in gravitational forces. Here are some of the important ideas that carry over.

Potential energy that is a function only of position is a direct result of the inverse square force law. Both gravitational masses and electrical charges obey an inverse square law.

Potential energy can be converted into other forms of energy. In a gravitational field, masses can fall together (due to mutual attraction) and the potential energy can be converted to heat and kinetic energy.

A mass can acquire kinetic energy in an gravitational field and later that kinetic energy could be converted to heat. Charges attached to masses can acquire energy in an eletrical field, and that kinetic energy can be converted to heat.

The many concepts that carry over from gravitational systems help to make voltage a much richer concept. Think of some of the implications.
If you pull two masses apart (by lifting a weight to a higher position on the earth, for example) you put potential energy into the system. If you pull two attracting charges apart you put potential energy into the system.

That potential energy can be converted into other forms of energy. If you have a charge with potential energy, you can generate light, heat, mechanical motion and you can even store chemical energy.

Voltage Concepts

In electrical fields, we will want to think in terms of the potential energy per unit of charge. Near the earth's surface the potential energy of a mass, m, h meters above the surface is mgh. The potential energy per unit mass is just gh. Voltage is the potential energy per unit charge for a charge in an electrical force field.

There are consequences of the inverse square law for electrical forces. Generally, those consequences are similar to what happens in gravitational systems.

In an electrical field, or in any conservative field like a gravitational field, we will have to do the same amount of work to move the charge between any two points A and B, no matter what path we take in moving the charge. Work done in a conservative field is said to be "path independent".

The potential energy in a gravitational field and the voltage in an electrical field (potential energy per unit of charge) are functions of position only.

One important consequence is a relationship between energy put into a charge as it moves.
If we move a charge from point A to point B, and put a given number of joules of work into the charge, we will recover exactly the same number of joules from the charge if it moves back from point B to point A. If we move the charge through any closed path or circuit, there will be no net energy input to the system and no net energy recovered from the charge.

If we move a charge from point A to point B, the number of joules of work we put into the charge can be calculated by multiplying the charge, Q, by the voltage difference between points A and B, Vab.

Kirchhoff's Laws

Kirchhoff's Current Law - Introduction

Kirchhoff's Current Law - KCL - is one of two fundamental laws in electrical engineering, the other being Kirchhoff's Voltage Law (KVL).

- KCL is a fundamental law, as fundamental as Conservation of Mass in mechanics, for example, because KCL is really conservation of charge.
- KVL and KCL are the starting point for analysis of any circuit.

- KCL and KVL always hold and are usually the most useful piece of information you will have about a circuit after the circuit itself.
- People and computer programs both use KVL and KCL for circuit analysis. Spice (in all its incarnations) starts with KCL.

Power & Energy

An Introduction To Electrical Power And Energy

Why Do You Need To Know About Electrical Energy?

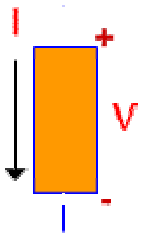
A power station is a place where other forms of energy - coal, gas, potential energy in water and nuclear energy - are turned into electrical energy for transmission to places that use electrical energy. Electrical engineering is concerned with transmission and ultilization of two things - energy and information. Here, in this lesson, we are going to focus on power and energy. In this lesson you will want to learn the following.

Given an electrical circuit or device

- Be able to compute instantaneous rate of energy use (power).
- Be able to compute how much energy is used over a period of time.
- Be able to compute how much energy is stored in an electrical storage device like a battery or a capacitor.

What Is Electrical Power?

Electrical power is conceptually simple. Consider a device that has a voltage across it and a current flowing through it. That situation is shown in the diagram at the right.



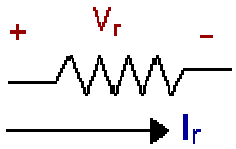
- The voltage across the device is a measure of the energy - in joules - that a unit charge - one couloumb - will dissipate when it flows through the device. If the device is a resistor, then the energy will appear as heat energy in the resistor. If the device is a battery, then the energy will be stored in the battery.
- The current is the number of couloumbs that flows through the device in one second.j

- If each couloumb dissipates V joules, and I couloumbs flows in one second, then the rate of energy dissipation is the product, VI.
- That's what power is - the rate at which energy is expended. The rest of the story includes these points.
- It doesn't matter what the electrical device is, the rate at which energy is delivered to the device is VI as long as the voltage and current are defined as shown.
- The power can be negative. If the device is a battery, then current - as defined in the figure - can easily be negative if, for example, a resistor is attached to the battery. If the power is negative, then the rate at which the device expends energy is negative. That really means that it is delivering energy in that situation.

Power in Electrical Devices

A resistor is one device for which you can compute power dissipation.

- A symbol for a resistor is shown below, along with a voltage, V_r, across the resistor and a current, I_r, flowing through the resistor.



- We can compute the power delivered to the resistor. It's just the product of the voltage across the resistorand the current through the resistor, V_rI_r.

But there's more to the story.

- In a resistor, there is a relationship between the voltage and the current, and we can use that knowledge to get a different expression - one that will give more insight.
- We know that $V_r = Ri_r$, so the power is just:
    - Power into the resistor = $V_rI_r = (RI_r)I_r = R(I_r)^2$.
- We can also use the expression for the current $I_r = V_r/R$,
    - Power into the resistor = $V_rI_r = V_r(V_r/R) = (V_r)^2/R$.

At different times, these two results - which are equivalent - can be used - whichever is appropriate. Besides being a useful result tthese are also illuminating results (And that's not a reference to the fact that a typical light bulb is aresistor that dissipates power/energy.).

- The power dissipated by a resistor is always positive. That means that it does not (and in fact it could not) generate energy. It always dissipates energy - uses it up - contributing to the heat death of the universe.
- We know the power is positive because R is always positive (and it will always be for any resistor that doesn't have hidden transistors) and because the square of the current has to be a positive number.

Circuit Diagrams

A Short Note About Circuit Diagrams & Symbols

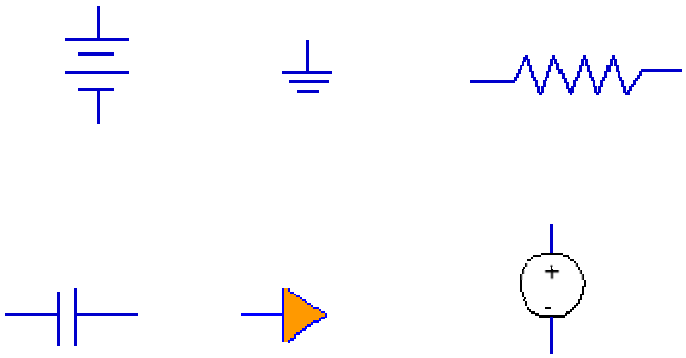
You probably already know that electrical engineers do not draw pictorial diagrams for every circuit. Instead, they draw symbolic diagrams that represent a physical situation.

Now, imagine that the element shown as a yellow rectangle is a battery. We would draw this circuit as shown at the right. Notice the symbol for the battery, with the "+" and "-" signs. Notice also the two elements, shown here as rectangles. Later, we will examine some symbols for particular elements.



These diagrams may not look like the physical system, but they form a sort of language that allows precise communication between engineers about exactly what comprises a particular circuit. Different kinds of electrical elements have different symbols. Sometimes new symbols have to be invented when someone invents a new electrical device.

Here are some symbols that are used for some common components.



Signals

An Introduction to Signals

Why Do You Need To Know About Signals?

Electricity has been with us for a while now, and we use it in many ways that were never anticipated when we began to use electricity.

- After electricity was discovered and understood, almost all of the first applications were ones that involved power. The application may have been an electric light or it may have been a motor. In either case, theapplication of electricity involved the use of large amounts of energy and power.
- However, other early applications of electricity were used to transmit information. The telegraph, and later the telephone, had a very significant effect on the history of the United States.
- As things progressed it became necessary to design an build systems to distribute large amounts of electrical power.
- The city of Sunbury, PA, was the first to have an electrical distribution system for lighting on July 4, 1883. That system was a DC system.
- Later, AC systems were developed. Edison, who installed that first DC system in Sunbury, and who had begun installing DC systems in many other cities bitterly fought the introduction of AC systems. Edison put out advertisements that showed an electric chair and asked the public if they wanted AC in their home since it was used in the electric chair for killing people.

AC systems prevailed, despite Edison's protestations. AC systems were based on a time varying voltage. (AC stands for Alternating Current.) As people learned to deal with these time varying voltages they realized that time varying voltages could be used to transmit information. With the invention of radio it was realized that information could be transmitted by controlling the parameters of a sinusoidally varying voltage.

Today, we have vast industries that use electricity to distritute information. Those industries are the TV networks (over the air, cable and satellite), phone systems, the internet and other radio communciation systems, for example.

If you want to understand the basics of how the information distribution industry works you will need to know about the various forms of electrical signals.

Electrical Signals

There are many different kinds of electrical signals. If we look at how signals are generated, we find that there are many different kinds of electrical signal sources. Here are some.

- Microphones
- Fax machines
- Thermocouples
- Remote controls for television sets

What could possibly all of these signals have in common? Well, they are all electrically generated signals, and electrical engineers have to deal with them.

- If you are a sound engineer, you will have to deal with the small voltages produced by microphones and you will have to worry about processing the signal so that you can reproduce the sound signals accurately.
- If you design fax machines you will need to ensure that your signals are transmitted accurately so that information is not corrupted when it is sent.
- If you need to control temperature in an industrial process, you will need to worry about the small signal from a thermocouple - how to amplify it - how to process it.
- TV remotes are designed to set the channel accurately. They set the channel, adjust volume, etc. by sending signals to the TV.

What is common through all of this is the need to be able to manipulate signals in different ways. That might include doing one or more of the following.

- Amplify a signal - make it larger
- Remove noise from a signal
- Change a signal to emphasize certain characteristics -for example adding bass boost to a sound signal.

When you start to operate on signals in this way you are entering the realm of signal processing. Today, signal processing is often done after digitizing a signal - making a digital version of the signal - and the processing that is done there is referred to as digital signal processing, or simply DSP.

If you will be dealing with signals, then you will need to have some sort of model for the signals you work with. Usually that will be some sort of mathematical representation.

The simplest representation for a signal is to represent the signal as a function of time. For example, the voltage that appears across the terminals of a microphone will vary in time when the microphone "picks up" a sound. Then, we might say something like:

Microphone voltage = $V_{\mathbf{mike}}(t)$

Representing a signal as a time function is so common that there are many instruments and data gathering devices that give you a picture of a voltage time function. The most common instrument that gives a picture of a voltage time function is the oscilloscope.

At this point, we can consider some specific kinds of signals. We'll start with periodic signals, and in particular we'll start with sinusoidal signals.

Periodic Signals

Periodic signals are signals that repeat in time with a certain period. The most fundamental periodic signal is the sinusoidal signal. Any other periodic signal can be thought of as a combination of sinusoidal signals added together. That approach is based on the Fourier Series and you can go to that topic when you know enough about sinusoidal signals.

In this section you will begin to learn about sinusoidal signals. Sinusoidal signals, based on sine and cosine functions, are the most important signals you will deal with. They are important because virtually every other signal can be thought of as being composed of many different sine and cosine signals. They form the basis for many other things you will do in signal processing and information transmission. Eventually you will deal with signals as different as voice signals, radar signals, measurement signals and entertainment signals like those found in television and radio. Sinusoidal signals are the starting point for almost all work in signal processing and information transmission.

In this part of this lesson you will learn:

- What Sinusoidal Signals are and How they are Represented
- The Parameters of a Sinusoidal Signal
- How to Measure the Parameters of a Sinusoidal Signal.

Representation of Sinusoidal Signals

If you put a voltage signal into an oscilloscope you can get a picture of how the signal varies in time. Sinusoidal signals are often voltages which vary sinusoidally in time. (Sinusoidal signals could be, however, other physical variables like current, pressure, or virtually any other physical variable.) Here's a simulator that will let you put various kinds of signals on a simulated oscilloscope. Click the Startbutton to see a typical sinusoidal signal.

You can write a mathematical expression for the voltage signal as a function of time. Call that mathematical expression V(t). V(t) will have this general form.

$V(t) = V_{\mathbf{max}}\sin(\mathbf{w}t + \mathbf{f})$

This signal has three parameters, the maximum voltage, or amplitude, denoted by $V_{\mathbf{max}}$, the angular frequency denoted by **w** and the phase angle denoted by **f**. We'll examine these separately.

Circuits

There are a number of tools you can use for very small electrical circuits. For example, given a small electrical circuit you can do any or all of the following.

- Look for resistor combinations - either series or parallel,
- Look for sourcesthat you can find a Thevinin or Norton equivalent for,
- Look for embedded voltage dividers,
- Hope that all of the above will lead to a very simple circuit that you can analyze.

But - - - what happens when you do all of that and you still can't figure out what goes on?

- You need some general method that you know will get you to a result.

In other words, what you may need is a method that has a high probability of success - one that is almost guaranteed to work for a large variety of circuits. There are two general methods you might try in that situation:

- The method of node voltages,
- The loop equation method.

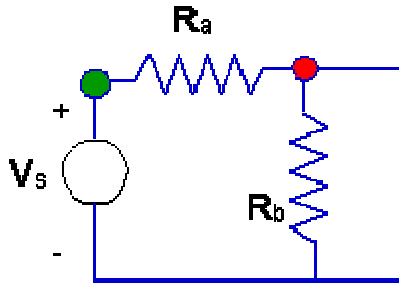
In this lesson you will begin to learn some general methods for analysis of electrical circuits. When you learn those analysis methods you will have increased the numberof tools in you analysis toolbox. We ask you to be thoughtful as you do that. If your regular toolbox is empty and someone gives you a hammer, then pretty soon everything will start to look like a nail. Not only do you have to learn the tools for analysis, you also have to learn when you need to use them, and how to choose from the tools in your toolbox.

Node Voltage Equations

We are going to start with the method of NodeVoltages. The name of the method tells you exactly what you are going to do.

- The method of Node Voltages starts with writing the KCL equations for the nodes in a circuit. Thoseequations are written in terms of node voltages (even though you are writing the Current Law, the variables are voltages!) thus the name!

That's a little simplified, but that is the essence of the method. We'll start with a simple circuit, and we will try to discover what you have to do. Here's a very simple circuit. It is a voltage divider. We notice some very simple facts about this circuit.



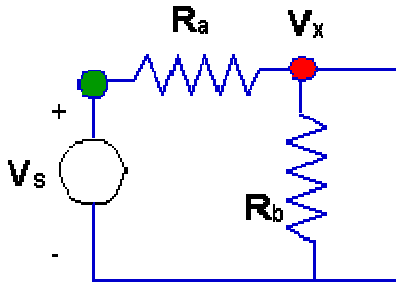
- There are two nodes in this circuit. One is marked with a red dot, the other is marked with an green dot.
- There is a difference between the two nodes. If we know V_s - the source voltage - then we know the voltage at the node marked with an green dot.
- We don't know the voltage at the node marked with a red dot unless we do some analysis.

Now, what we are really saying about this circuit is the following.

- Since there is only one node where we do not know the voltage, when we write the equations for this circuit, we really only need one equation.
- There's one unknown and there's going to beoneequation.
- The equation we need to write is KCL at the node with the unknown voltage

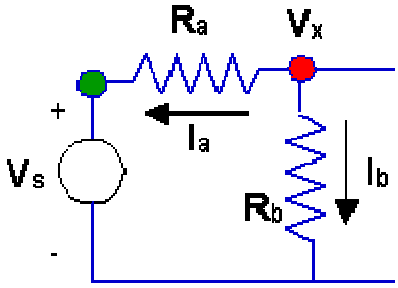
Now, we will write the equation at the node with the unknown voltage.

- We need to define a symbol for the unknown voltage. We'll call it V_x.
- Then we write KCL at the node where V_x appears.
- Finally, we solve whatever equation results from writing KCL.



Now, we will write the equation at the node with the unknown voltage.

- To write KCL we need to define two currents for this case. They are shown below.



- Then KCL is written as:
  - $I_a + I_b = 0$ since both currents are leaving the node.
- We need to get expressions forI_a and I_b. The expressions we need are:
  - $I_a = (V_x - V_s)/R_a$
  - $I_b = (V_x - 0)/R_b$

In both cases the voltage across the resistor causing the current to flow in the indicated direction is:

Voltage at the node - Voltage at other resistor end.

- Note that one end of R_b is connected to ground, so a zero appears in that expression.
- It is important to be sure you understand how each current is calculated, and the exact expression for the current. The current through a resistor, R, connected to a node is:

(Voltage at the node - Voltage at other resistor end)/R

- Then, since:
    - $I_a = (V_x - V_s)/R_a$ and
    - $I_b = (V_x - 0)/R_b$
- We can write the complete KCL equation.
    - KCL gives us: $I_a + I_b = 0$.
- So, we have:
    - $(V_x - V_s)/R_a + (V_x - 0)/R_b = 0$

Now, remember the algorithm for using node voltages.

- Define a symbol for the unknown voltage. We've done that.
- Write KCL at the node where Vx appears. Done that also.
- Solve whatever equation results from writing KCL. We need to do that.

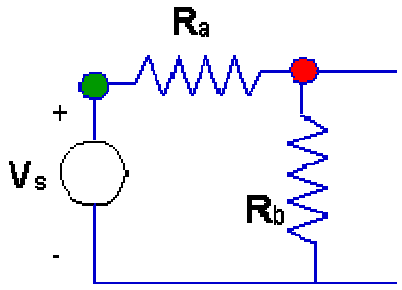
We need to learn how you can solve these kinds ofequations. It's not hard to solve the equation we have:

$(V_x - V_s)/R_a + (V_x - 0)/R_b = 0$

The result is:

$V_x = V_s*R_b/(R_a + R_b)$

Actually, this circuit was pretty easy.

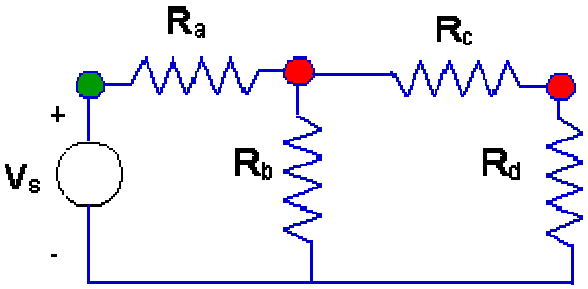


- This circuit has one unknown node voltage.
- We wrote one KCL equation.
- We had one equation with one unknown.

Now, we'll look at a more complicated circuit.

Here is a more complicated circuit. This ladder circuit is more complex for one simple reason.

- This circuit has two unknown node voltages.
    - The nodes with unknown voltages are marked with red dots.
    - Once again, we have a node where the voltage is known, and it is marked with an green dot

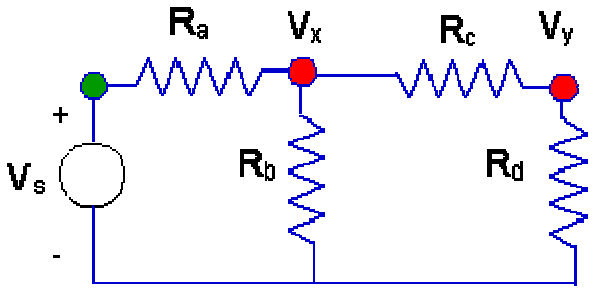


We use the same solution algorithm as before.

- Define symbols for the unknown voltages. We'll use$V_x$andV_y.
- Then we write KCL at the nodes whereV_x and$V_y$appear.
- Finally, we solve whatever equations result from writing KCL.

For the first step:

- Define symbols for the unknown voltage -V_x andV_y. They are shown on the diagram below.

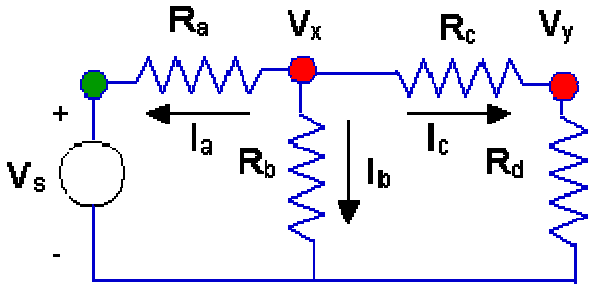


V_x and V_y are shown at the respective nodes. Notice again that the voltage and the node with the orange dot is already know to be V_s volts when measured with respect to ground.

For the second step:

- Write KCL at the nodes where $V_x$and $V_y$appear.

Again, currents need to be defined. Let's work on node x first. Define currents as in the figure below, and write KCL.



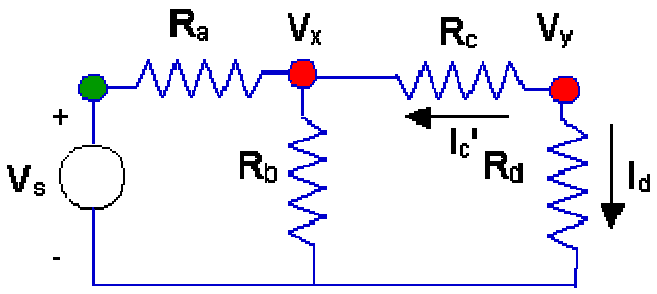
$I_a + I_b + I_c = 0$.

- Then express each current in terms of the nodevoltages.
    - $I_a = (V_x - V_s)/R_a$
    - $I_b = (V_x - V_s)/R_a$
    - $I_c = (V_x - V_s)/R_a$

So, if we put these current expressions into the KCL equation, we get:

$(V_x - V_s)/R_a + (V_x - V_s)/R_a + (V_x - V_s)/R_a = 0$

Now, we need to solve this equation. This is one equation, but it has two unknowns, V_x and V_y. We need a secondequation, and clearly it is obtained by writing KCL at node y. Writing KCL at node y we get:



$I_c' + I_d = 0$

- We use I_c' because it is not the same asI_c. Actually$I_c' = - I_c$.
- Still, using these definitions, we get:
  - $I_c' = (V_y - V_x)/R_c$
  - $I_d = (V_y - 0)/R_d$

Combining the expressions for the terms in KCL at node y, we have:

$(V_y - V_x)/R_c + (V_y - 0)/R_d = 0$

And, the equation we had from node x is:

$(V_x - V_s)/R_a + (V_x - 0)/R_b + (V_x - V_y)/R_c = 0$

Now, we're going to write out both equations and combine $V_x$and V_y terms. Here's the result of rearranging the equationsthat way.

$V_x(1/R_a + 1/R_b + 1/R_c) - V_y/R_c = V_s/R_a$

$V_y(1/R_c + 1/R_d) - V_x/R_c = 0$

These are close to what we want. We are going to rearrange these equations to show the coefficients of V_x and V_y better next.

$V_x(1/R_a + 1/R_b + 1/R_c) - V_y/R_c = V_s/R_a$

$-V_x/R_c + V_y(1/R_c + 1/R_d) = 0$

There are several things to note here, even though we only have a set of equations to solve, and we haven't solved those equations yet.. First, the equations can be easily obtained from the circuit diagram. We'll work on that in a while, but you may already have noticed that there is a kind of symmetry to the equations, and there are clear relationships between the nodes the resistors are connected to, and how those resistance values enter into the equations.

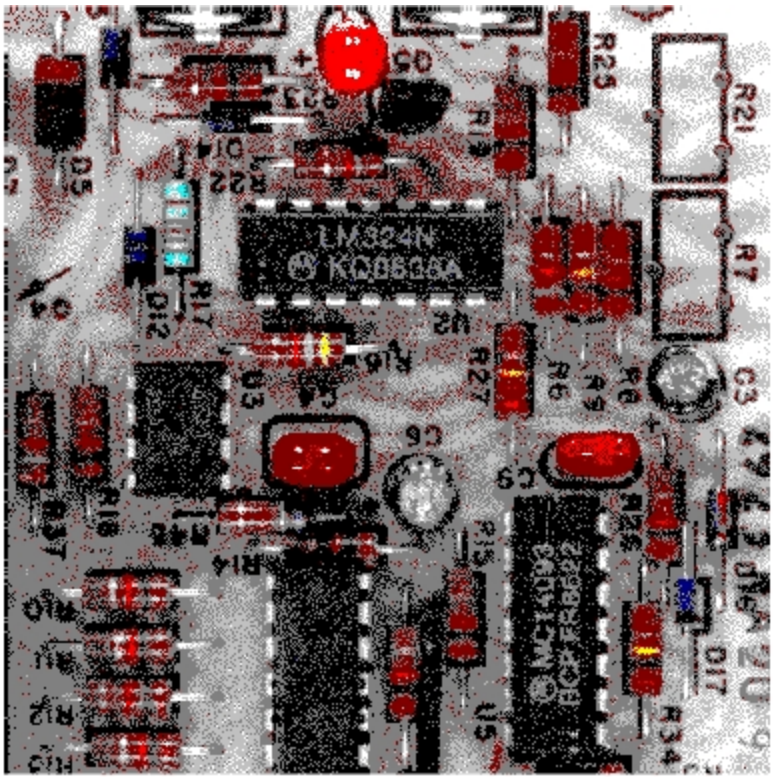
You may also have noted that the equations that result are simultaneous linear equations. Basically, you have two unknown node voltages, and the equations you write result intwo equations in those two unknown node voltages. You know everything else in the equations, including resistance and source voltage values.

Finally, you may already know several algorithms for solving simultaneous linear equations.

Electrical Elements

Resistors

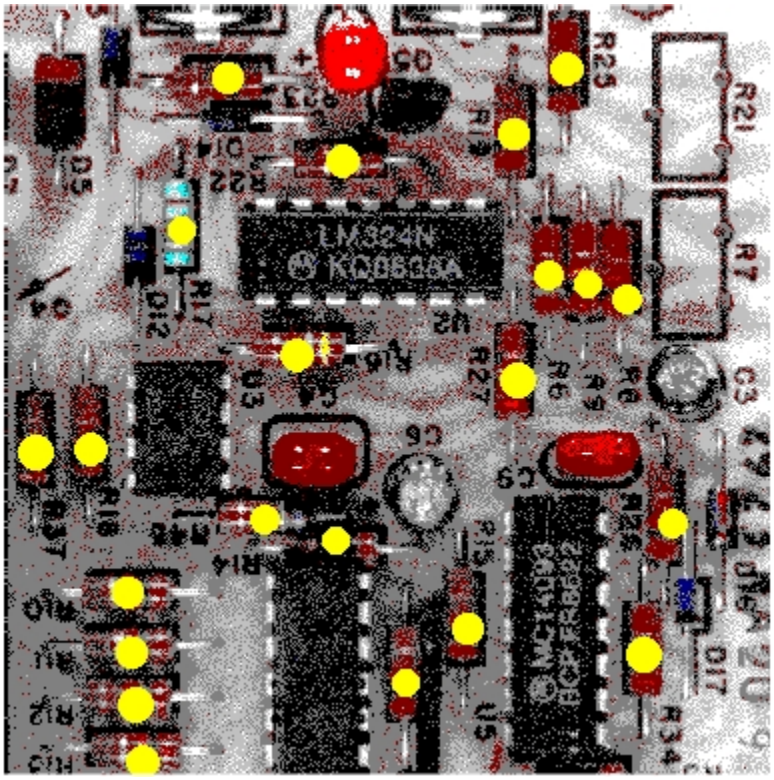
There are many different types of electrical components. Shown below is a photograph of part of a circuit board. On this circuit board are many electrical components including some resistors.



There are resistors, capacitors, diodes and integrated circuits. Using plated copper and solder on the reverse side of the board, these components are interconnected and when a supply voltage is provided, these components can interact. Electrical engineers need to know how to design larger circuits like this and to control those interactions to achieve some purpose.

In this lesson you are going to learn about the simplest sort of electrical component, the resistor. What you learn about resistorsis a starting point. That knowledge helps you as you begin to learn about all of the other kinds of electrical/electronic components. Still, although resistors are basic

elements, they occur everywhere. On the board below, all of the resistors are marked with a yellow dot.



Almost every electrical product is constructed from a collection of fundamental electrical components. For example,

- a radio,
- a portable tape player,
- a television,
- a telephone,
- a cellular phone,
- the electronic ignition in a car,
- a computer circuit board

are all built from smaller electrical components. There are many different kinds of components, including

- resistors,
- capacitors,

- inductors,
- transistors,
- microwave generating tubes,
- and many more.

These devices can be combined to form many different kinds of circuits and devices including all of the appliances listed earlier as well as all the various forms of computers we use daily. If you want to be able to design electrical and electronic circuits to perform a useful function you need to start by learning about components, and we will start with resistors.

The array of electrical components now available includes a vast and diverse number of components with varying shapes and numbers of leads. Here are some more electrical components you may be familiar with:

- light bulbs,
- computer chips,
- solar cells,
- inductors,
- heating elements on stoves,
- Light Emitting Diode (LED) displays on calculators,
- operational amplifiers,
- thermistors,
- and many others.

Some of the electrical devices on our list have something in common. There are many ways of categorizing them. For example, you might look for elements with two leads or those with three leads. You might also look for those elements which interact with other physical variables (for example, speakers which produce sound in a stereo, or a light bulb which generates light).

One way of categorizing the items on the previous page is that all of the items above produce heat as a by-product of their operation. Here are some more devices that produce heat when a voltage is applied - a stove heating element, a toaster and two light bulbs.

There are numerous places where resistors are used. Here are some places where resistors are used.

- Heating Applications:
    - Home baseboard heaters
    - Toasters
    - Clothes Dryers
- Measurement Applications:
    - Photoresistors to measure light intensity (Photgraphic light meters in a camera)
    - Thermistors to measure temperature
    - Strain gages to measure strain (Used in bathroom scales, measurements on bridges)

Resistors are ubiquitous today. They are literally everywhere, not only in electronic equipment but are they are in many of the ordinary devices we rely on like toasters, irons, stoves and light bulbs.

To really understand resistors you need to understand the law they obey - Ohm's Law - which gives a relationship between the current through a resistor and the voltage across the resistor. That's something you may not have considered yet. A resistor is a device that establishes a unique relationship between a current and a voltage.

Ohm's Law - What You Need To Know About Resistors.

The Genesis of Electrical Devices and Theories

Work on electrical devices all started with resistors and resistance. The concept of resistance was first enunciated by Georg Simon Ohm who was the first to point out that voltage and current in a wire were related mathematically. That's an important idea. Since Ohm's time many different devices have been discovered and generalizations of Ohms' Law are used to describe those devices.

Ohm found that mathematics could be applied to what was going on in resistors, and the mathematical relation he found was just the start of the application of mathematics to electrical phenomena.

The Application of Mathematics to Electrical Science

You are probably accustomed to the idea that physical phenomena can be described using the language of mathematics. That's an idea that wasn't always accepted, and when Ohm first

proposed to describe electrical phenomena using mathematics he was taken to task vehemently. (That happened even though Newton had described mechanical phenomena mathematically two hundred years earlier, and had, in fact, invented calculus in order to do that!)

Ohm didn't even have the concepts of current and voltage to work with. He had to invent the concepts and then show that there was an experimental relationship between voltage and current, and that that relationship could be described mathematically.

It all sounds simple today, especially since we have nice cleanconcepts of voltage and current as we discussed in the first chapter. In Ohm's time, things were not so clear, and his discoveries really include clarification of the concepts of voltage and current as well as resistance.

Working with very primitive instruments that he designed and constructed himself, Ohm discovered that voltage and current were linearly related in wires. That means that if you measure voltage across a wire and plot that against the current through the wire you get a straight line in the plot.

Working with very imprecise measurements, Ohm was able to determine that voltage and current for any fixed geometrical structure built from conducting material satisfied a relationship:

$V = I R$

where

- V is the voltage across the device,
- I is the current flowing through the device,
- R is a constant.
- R depends upon the material from which the device is constructed and the geometry of the material.

There are several different ways that Ohm's Law can be represented.

- Graphically:
    - We can draw/sketch/diagram/plot the relationship.
- Mathematically:
    - We can represent the relationship mathematically with anequation:
        - $V_r = I_r R$
- Symbolically:

- We can devise a symbol for the resistor and use it in circuit diagrams to stand for any element that satisfies Ohm'sLaw. The standard symbol is shown below along with polarity definitions for the voltage and current.

We will use the symbol R for any resistor, although there will occasionaly be devices (like light bulbs) that are really resistorsbut which have a special symbol that can be used for them. Still, you can use this symbol for an resistive device.

Sources

Ideal Sources

Why Are Sources Important?

Electrical sources, in practice, include things like:

- batteries,
- the ever-present wall plug,
- power supplies (like those little things you use with yourcalculator and other things)
- and many other kinds of electrical devices that deliver electrical energy.

They are the starting point for any circuit you design. You have to have an electrical source in any circuit if it is going to do anything.

What Is An Electrical Source?

You probably suspect an electrical source has to be something that gives you a voltage or a current, and you would be correct. In fact, there are two different kinds of ideal electrical sources - voltage sources and current sources. In this lesson, we'll look first at voltage sources, but we don't want to overlook current sources. They will be discussed after ideal voltage sources.

What Is An Ideal Voltage Source?

Looking at voltage sources first, let's consider the concept of an ideal voltage source. When you buy a battery you buy a nine (9) volt battery, or a 1.5 v battery, or a twelve (12) volt car battery - or some other battery that has a specified voltage. Clearly those batteries - electrical sources - are assumed to have a certain voltage - whatever it is - that doesn't change much.

When you buy a power supply for your calculator or a telephone answering machine or some other device you need to look at the voltage you need for the power supply. They usually come in a few specified voltages. It seems clear that many sources are designed to give you some particular voltage and to attempt to maintain a constant voltage.

Below we'll consider simple models for voltage sources thatmaintain a constant voltage and we'll take a look at how you can represent that kind of device. A voltage source that canmaintain a constant voltage - no matter what you do to it, like drawing a lot of current, or putting it in a situation where current flows through it - is an ideal voltage source. That's what we are going to examine in this lesson. We'll leave it for another lesson to look at sources that are not ideal. So, let's answer that question above. What is an ideal voltage source? And there's another question implied. Why worry about an ideal voltage source since nothing like that exists in the real world. We'll take those questions in order.

Ideal Voltage Sources

The concept of an ideal voltage source is pretty simple, and it was really embedded in the previous discussion.

- An ideal voltage source is a voltage source that maintains the same voltage across the source'sterminals no matter what current is drawn from theterminals of the source or what current flows into theterminals.

That's it in a nutshell. If the source is a DC Source, we can plot a voltage current plot for an ideal voltage source. The plot is shown below. However, we need to define terms. Here is a circuit symbol for an ideal voltage source. In this symbol, we assume the following.

Capacitors

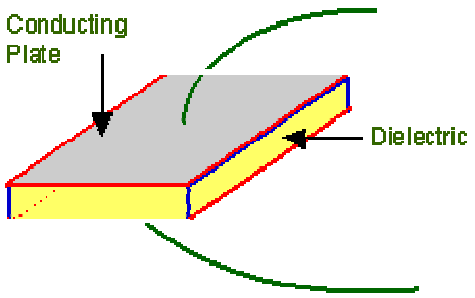
Why Are Capacitors Important?

The capacitor is a widely used electrical component. It has several features that make it useful and important:

- A capacitor can store energy, so capacitors are often found in power supplies.
- A capacitor has a voltage that is proportional to the charge (the integral of the current) that is stored in the capacitor, so a capacitor can be used to performinteresting computations in op-amp circuits, for example.
- Circuits with capacitors exhibit frequency-dependentbehavior so that circuits that amplify certain frequencies selectively can be built.

What Is A Capacitor?

Capacitors are two-terminal electrical elements. Capacitors are essentially two conductors, usually conduction plates - but any two conductors -



separated by an insulator - a dielectric - with conection wires connected to the two conducting plates.

Capacitors occur naturally. On printed circuit boards two wires running parallel to each other on opposite sides of the board form a capacitor. That's a capacitor that comes about inadvertently, and we would normally prefer that it not be there. But, it's there. It has electrical effects, and it will affect your circuit. You need to understand what it does.

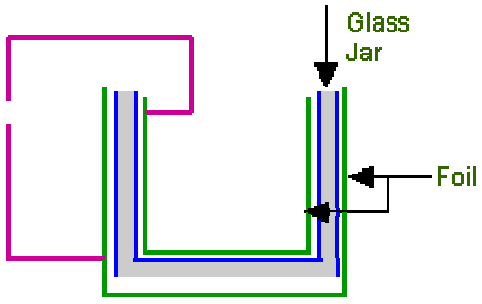
At other times, you specifically want to use capacitorsbecause of their frequency dependent behavior. There are lots of situations where we want to design for some specific frequency dependent behavior. Maybe you want to filter out some high frequency noise from a lower frequency signal. Maybe you want to filter out power supply frequencies in a signal running near a 60 Hz line. You're almost certainly going to use a circuit with a capacitor.

Sometimes you can use a capacitor to store energy. In a subway car, an insulator at a track switch may cut offpower from the car for a few feet along the line. You might use a large capacitor to store energy to drive the subway car through the insulator in the power feed.

Capacitors are used for all these purposes, and more. In this chapter you're going to start learning about this important electrical component. Remember capacitors do the following and more.

- Store energy
- Change their behavior with frequency
- Come about naturally in circuits and can change a circuit's behavior

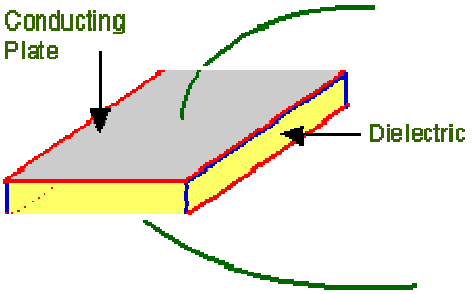
Capacitors and inductors are both elements that can store energy in purely electrical forms. These two elements were both invented early in electrical history. The capacitor appeared first as the legendary Leyden jar, a device that consisted of a glass jar with metal foil on the inside and outside of the jar, kind of like the picture below. This schematic/picture shows a battery attached to leads on the Leyden jar capacitor.



Although this device first appeared in Leyden, a city in the Netherlands sometime before 1750. It was discovered by E. G. von Kleist and Pieter van Musschenbroek. Although it has been around for about 250 years, it has all of the elements of a modern capacitor, including:

- Two conducting plates. That's the metallic foil in the Leyden jar.

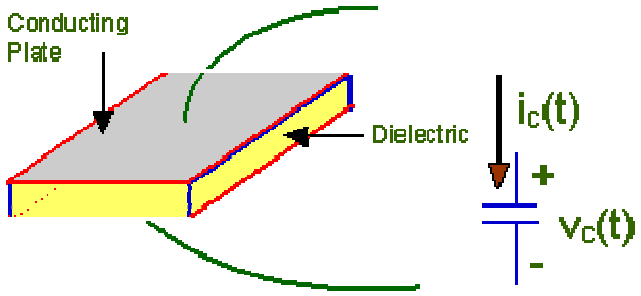
- An insulator that separates the plates so that they make no electrical contact. That's the glass jar - the Leyden jar.



The way the Leyden jar operated was that charge could be put onto both foil elements. If positive charge was put onto the inside foil, and negative charge on the outside foil, then the two charges would tend to hold each other in place. Modern capacitors are no different and usually consist of two metallic or conductingplates that are arranged in a way that permits charge to be bound to the two plates of the capacitor. A simple physical situation is the one shown at the right.

If the top plate contains positive charge, and the bottom plate contains negative charge, then there is a tendency for the charge to be bound on the capacitor plates since the positive charge attracts the negative charge (and thereby keeps the negative charge from flowing out of the capacitor) and in turn, the negative charge tends to hold the positive charge in place. Once charge gets on the plates of a capacitor, it will tend to stay there, never moving unless there is a conductive path that it can take to flow from one plate to the other.

There is also a standard circuit symbol for a capacitor. The figure below shows a sketch of a physical capacitor, the corresponding circuit symbol, and the relationship between Q and V. Notice how the symbol for a capacitor captures the essence of the two plates and the insulating dielectric between the plates.



Now, consider a capacitor that starts out with no charge on either plate. If the capacitor is connected to a circuit, then the same charge will flow into one plate as flows out from the other. The net result will be that the same amount of charge, but of opposite sign, will be on each plate of the capacitor. That is the usual situation, and we usually assume that if an amount of charge, Q, is on the positive plate then -Q is the amount of charge on the negative plate.

The essence of a capacitor is that it stores charge. Because they store charge they have the properties mentioned earlier - they store energy and they have frequency dependent behavior. When we examine charge storage in a capacitor we can understand other aspects of thebehavior of capacitors.

In a capacitor charge can accumulate on the two plates. Normally charge of opposite polarity accumulates on the two plates, positive on one plate and negative on the other. It is possible for that charge to stay there. The positive charge on one plate attracts and holds the negative charge on the other plate. In that situation the charge can stay there for a long time.

That's it for this section. You now know pretty much what a capacitor is. What you need to learn yet is how the capacitor is used in a circuit - what it does when you use it. That's the topic of the next section. If you can learn that then you can begin to learn some of the things that you can do with a capacitor. Capacitors are a very interesting kind of component. Capacitors are one large reason why electrical engineers have to learn calculus, especially about derivatives. In the next section you'll learn how capacitors influence voltage and current.

Digital Signals and Logic Chapter

- Gates
- Minterms
- Karnaugh Maps
- Flip-Flops
- Counters
- Memory

Data Representations in Computer programs

Representations and Conversions

Integers A single byte can store an integer that takes on a value from 0 to 255.
The interpretation of the bits in the byte uses normal binary representations for numbers. You might not see thisrepresentation often.
unsigned char x;

A single bytecan also store an integer that takes on a value from -128 to +127. In this case, one bit in the byte is used as a sign bit. In C, an integer of this type is declared using:

char x;
or
short int x; Larger integers can be stored using two bytes. Two bytes can store 2^{16} - 1 or 65536 numbers from 0 to 65535. Thenumbers represented can run from 0 to 65535. In C, an integer of this type is declared using: unsigned int x; Signed integers take two bytes and use one bit to store the sign (plus or minus), and have a range from -32768 to +32767, and are declared

like this: int x;NOTE: In some cases, the declaration above will give you an integer that takes four bytes, and which can have much larger values.

Finally, there is a long integer that is used for large integers. A long integer takes four bytes, and will handle integers from -2,147,483,648 to -2,147,483,647. The form of the declaration is:

long int x; Now, none of these representations will handle something like 2.59 - a number that is not an integer. You need to use a floating point representation for those numbers.

Data Type	Number of Bytes	Number of Bits
Float	4	32
Double	8	64
Long Double	12	96

float 4 32
double 8 64
long double 12 96

Floating Point Numbers

IEEE has written a standard for floating point numbers. The simplest IEEE representation uses a 32 bit word (four bytes) and looks something like this:

S	E	E	E	E	E	E	E	E	S	F	F	-	-	F	F	F	F	F	F	F	F	F	F
0	1							8	9														31

- This representation is short a few bits - just to be sure that it will "fit".
- There are two sign bits in the representation. The exponent can be positive or negative, and the mantissa can have either sign as well.

This representation can be difficult to unravel, but S is the sign bit, and the eight bit "E" number is a signed integer representing the exponent. The "F" number determines the mantissa and is actually the floating point part in a 1.X representation, where X is thenumber represented by F. A four bit floating point number has a declaration like this.

float x;

What you need to remember is that a floating point number is stored as an exponent and a mantissa along with a sign. That means that - in the four byte representation - there are only 24

bits devoted to the mantissa (significant figures) and you have to remember not to overestimate how precise the representation is.

If you want a more precise representation of a number, you can use a double precision floating point representation that uses eight (8) bytes. The declaration is:

double x;

ASCII coded numbers

Numerous instruments transmit measurement data using ASCII coded numbers. In an ASCII coded number. For example, ameasurement that yields a value 3.145 would be transmitted to a computer with the following sequence of characters.

- An ASCII character 3,
- An ASCII character ., (That's a period!)
- An ASCII character 1,
- An ASCII character 4,
- An ASCII character 5,
- A separator that could be either one of these:
    - If the next piece of data is stored in another column, then the next character in the file should be an ASCII character Tab, (A tab character) That would produce a "Tab-delimited" file since the delimiter is a tab character.
        - There are times when "Comma-delimited" files are used. In that situation, the tab character is replaced by a comma.
    - If the next piece of data starts another row, then it is often the case that two characters are used. Those characters are an ASCII character CR, (Carriage return) and an ASCII character LF, (Line Feed). (In manual typewriter days, the carriage return took the carriage back to the first position at the left of the page, and the line feed advanced to the next line.)

An Introduction To Network Concepts

Introduction

At this point you should know how to do computer controlled measurements. However, the computer you use is probablyconnected to a network, and that connection allows for

someinteresting possibilities. In particular, you can take measurements and do control remotely. However, there are a few topics you should be conversant with before you try that.

Why learn about Basic Network Concepts?

Using computer measurement and control across a network allows for possibilities of operation in remote or otherwise inaccessible locations, and it allows for measurement and control of multiple locations from a single location. To takeadvantage of those possibilities, you need to have a basic familiarity with networked computers. You need to learn about basic concepts of network addressing and how to determineaddresses. When you are finished with this unit you should be able to use a program (LabVIEW) to perform measurements and control across a network and you will learn about URLs, and IP addresses, and how to determine them. In addition, you will learn about some basic network concepts (servers, etc.)

Some Basic Network Concepts

Let's start with what happens when you "go to" www.SomeCompany.com to get information about their products. Actually, you don't go anywhere, but you do send some information across the network. The information you send does the following.

- First, the URL (www.SomeCompany.com) gets sent over the network to a special computer - a name server - that translates this URL into an address of the form below. This form (all numbers) is the numeric IP address.
    - www.xxx.yyy.zzz
- Next, computers on the network (routers, etc.) try to send the message along so that it will get to the right computer - i.e. the one that has the IP address you are sending to. (Routers route messages along the network, that's why they are called routers.
- When the message gets to the correct computer - the server, wherever in the world it might be - the server sends the file - often written in HTML - back to your computer - the client.

This is an over-simplified picture of what goes on, but it contains all the basic ideas about what happens. There are several points that you should note in this sequence of events.

- The message you - the client - send to the server has to have the server's address, otherwise the message will not get to the correct server.
- The message you send to the server must also contain the address of your computer, otherwise the information that the server sends out on the network will not make it back to you.

- The message you send to the server will also include a command. The command to get an HTML file is GET. When you are in a browser and you send a request for a file, you send a GET command along with the name of the file you want to GET.
- The message you send to the server may not go out as a single message. It may be broken into packets, and each packet needs to contain enough information that the complete information request can be reassembled by the server.
- The information sent back by the server may not arrive as a single message. It will probably be broken into packets, and each packet needs to contain enough information to permit your computer to reassemble the complete file/set of information sent by the server.
- In the above process when packets are sent over the network, there are no guarantees that they will arrive in the correct order, and computers on either end - both the client and the server - have to have the capability of reassembling all of the information. In the case of the client, you will often want that information displayed as a web page.

That is a short summary of what takes place in a typical client-server situation.

Measurements

An Introduction To Electrical Measurements

Electrical measurements often come down to either measuring current or measuring voltage. Even if you are measuring frequency, you will be measuring the frequency of a current signal or a voltage signal and you will need to know how to measure either voltage or current.

In this short lesson, we will examine those two measurements - starting with measuring voltage. However, first we should note a few common characteristics of the meters you use for those measurements.

Many times you will use a digital multimeter - a DMM - to measure either voltage or current. Actually, a DMM will also usually measure frequency (of a voltage signal) and resistance. You should note the following about typical DMMs.

Polarity is important. Usually the terminals of the DMM will be coded to indicate polarity. Often that polarity is indicated by a red terminal (positive) and a black terminal (negative). In other cases, the polarity could be indicated by printed notes on the terminals.

Often one of the terminals on the DMM may be connected to the ground. That would normally be the black terminal, or it may be indicated with a ground symbol.

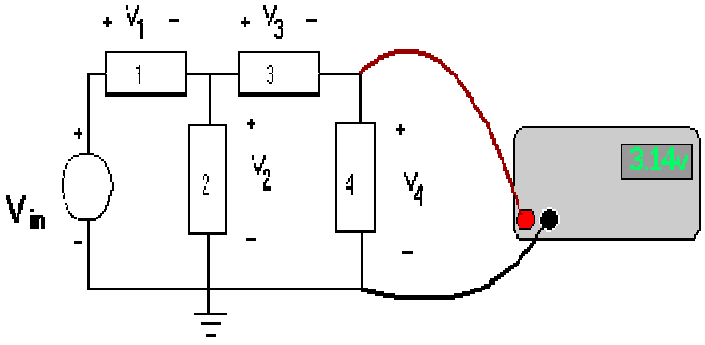
With that in mind, let's get on to measuring voltage.

Measuring Voltage

Voltage is one of the most common quantities measured. That's because many other variables - like temperature, for example - are measured by generating a voltage with a sensor. So, even if you want to measuretemperature you might end up having to measure a voltage and convert that reading into the temperature reading you wanted.

Voltage is measured with a voltmeter. However, digital multimeters (DMMs) - which can function as voltmeters - often have considerably more capability and can measurecurrent, resistance and frequency. And, there are other instruments - like oscilloscopes - that measure voltage and should be thought of as voltmeters. No matter what the instrument is, if it measures voltage you have to treat the instrument as a voltmeter.

When you measure voltage you have to remember thatvoltage is an across variable. When you measure voltage you have to connect the voltmeter to the two points in a circuit where you want to measure voltage. Here is a circuit with a voltmeter connected to measure the voltage across element #4.



Note the following about this measurement.

- Notice that the voltmeter measures the voltage across element #4, $+V_4$. (And, the plus sign is important. Remember the polarity issue.)
- Notice the polarity definitions for V_4, and notice how the red terminal is connected to the "+" end of element #4. If you reversed the leads, by connecting the red lead to the "-" terminal on element #4 and the black lead to the "+" end of element #4, you would be measuring $-V_4$.

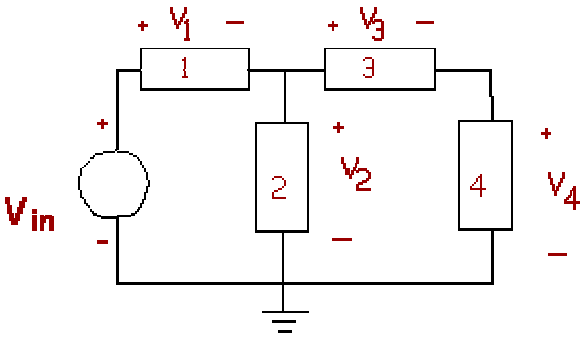
And, remember this as well.

- When you measure voltage, the voltmeter should not disturb the circuit where you are attempting to measure the voltage. In the circuit above, that disturbance is the current drawn by the voltmeter. You want that current to be as close to zero as it can possibly be. That means that you need to have the resistance of the voltmeter as large as possible.

There's more discussion of that effect in the lesson on measuring voltage. Ideally, the resistance of a voltmeter would be infinite.

Measuring Current

Current is measured with an ammeter. While voltage is a more common measurement, it is often necessary tomeasure current. When measuring current, it is important to remember that current is a flow variable. Current flows through electrical elements, and if you want to measurecurrent you have to get it to flow through the ammeter. Here's the same circuit we used in the example above. Consider what we would have to do to measure the current flowing through element #4.



If we want to measure the current through element #4, we have to get that current to flow through the ammeter. Here's a way to insert an ammeter into the circuit to measure that current.

A Short Note on What Happens in a GPIB Voltmeter.

When you convert data in a GPIB voltmeter, there are some interesting things that happen. In the process the data takes on many forms, and the way the data takes on those forms and is processed needs to be understood so that you can understand meter accuracy.

Step 1 - Data Conversion

The first step in using a GPIB voltmeter is to do the conversion. The input from a voltage source being measured first goes to an A/D converter. That converter will produce an integer that is representative of the voltage being converted. In the figure below, the analog input voltage(shown as a narrow line) produces an integer (and since that could be 8 bits, or 12, bits, etc., we show that with a thick line). if you want to see a simulator for an A/D converter.



Step 2 - Compute the Voltage from the Count Value

The integer produced by the A/D depends upon theinput voltage, but it is not usually the case that the integer is equal to the voltage input to the A/D. You need to compute the actual voltage - and that is going to be a floating pointnumber. The voltmeter will need to have some sort of computational capability to perform the computation. That's going to be something like this:

V_{calc} = Lower Limit + Count*(Higher Limit - Lower Limit)/($2^{\#Bits}$)

Example

If the voltmeter is really an oscilloscope with 8 bits, and the lower limit is -4v with an upper limit of +4 volts, you would get

V_{calc} = -4 + Count*8/(256)

That is the computation that would be done on an oscilloscope with an 8 bit A/D, set on 1v/Div, when there are 8 divisions (4 up and 4 down from the center of the scope).

Step 3 - Generate an ASCII String

In many cases, GPIB instruments send data to a computer as an ASCII string, so there has to be some further data manipulation to complete the process and get the data to the computer. The entire operation would look something like that shown in the figure below.

