BASIC ELECTRICITY

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Historical Background:

The study of electricity revolves around a few common terms that describe the behavior of electrical charge. Electrical charge and its associated phenomena are a fundamental part of the world that we live in. The understanding and use of electricity is largely responsible for the advanced technology that we enjoy today: electric light, heat, digital computers, television, music on CD, DVD video, radar, microwave ovens, cell phones, and on and on and on.

The first recorded studies of "natural attractive phenomena" occurred among the ancient Greeks over 2,500 years ago. That's right, over 2 thousand 5 hundred years ago. Over the last 2 or 3 hundred years, and particularly in the last century, that understanding has grown tremendously. In fact, some of the most interesting work relative to this limited discussion was done over a 40-year span between 1785 and 1826.

The fundamental unit of electric charge is the COULOMB, named for Charles Augustin de Coulomb, a French physicist (1736-1806). The smallest concentration of charge is contained in a single electron, a subatomic particle. The Coulomb is an extremely large amount of charge, or stated more precisely, an electric charge equal to 1 Coulomb requires an extremely large number of electrons. The charge of a single electronic is 0.00000000000000000016 Coulombs. That's 18 zeros in front of the 16. Stated in the notation that scientists prefer, called coincidentally, scientific notation, that amount of charge would be 1.6×10^{-19} Coulombs. So 1 Coulomb of electric charge represents 6.25×10^{18} electrons or 6,250,000,000,000,000,000 electrons. That's a whole bunch of electrons (6.25 billion billion or if you prefer 6.25 million trillion). In fact, if each electron was a large as a marble, with a ½ inch diameter, you could line them up end to end in a straight line and reach from the earth to the moon and back over 100 million times.

So what do we know about electric charge except that the charge on a single electron is pretty small? A collection of electric charges standing still represents an amount of stored, or potential electrical energy. A more convenient way to look at the stored electrical energy within a collection of electric charges standing still is the potential ability for the electric charges to move. In this context we speak about an "electrical potential", described numerically or quantified by an amount of voltage. The fundamental unit of electrical potential is the VOLT, named for Alessandro Volta, an Italian physicist (1745-1827).

Charge Polarity:

To avoid the inevitable confusion resulting from trying to keep track of charge polarity, all discussions of electric charge movement will be described from the perspective of positive charges. Do not be frustrated if you look in either a basic physics or fundamental electronics book and find out that the polarity of in individual electron is negative. Virtually all electronic product application manuals and most electronic instruments indicate either a concentration of positive charge (voltage) or the flow of positive charge (current). This no doubt stems from the historical representations of these phenomena by mathematicians.

Charge in Motion:

If given the opportunity, the positive electrical charge will begin to move in a direction from a higher voltage to a lower voltage. This is just like a ball, or a whole bunch of marbles, rolling down a hill. They will roll from a high point to a low point under the influence of gravity. They will only stop when the ground changes shape to block their motion. This concept is very important to the operation of all electrical appliances, including every piece of high technology equipment mentioned earlier. This fact is also very important when considering how to charge a battery.

What controls the movement of the charge along a path suitable to conduct electricity is two things. First, how much electrical potential is there to force the charge to move and second, how much resistance does the path offer to the movement of electric charge. The resistance of the path is like the shape of the ground. By cleverly constructing the conductive path for electron movement and altering the resistance of that path at strategic locations, a wide variety of interesting electron motions can be produced, resulting in a great number of useful work functions. The fundamental unit of resistance to electric charge movement is the OHM, named for George Simon Ohm, a German physicist (1787 to 1854).

Once the electric charge begins to move, an electric current results. This is probably the most familiar form of electricity to everyone who uses electrical power. Truthfully, it is only when electric charge is in motion that we can extract any useful work or information from the machines that control both the paths through which the electric charge moves and the size of the electric current. The size (or amplitude) of the electric current is

described by the quantity of electric charge that moves past a reference point along a reference conductive path during a fixed reference time period. The fundamental unit of electrical current is the AMPERE, named for Andre Marie Ampere, a French physicist (1775 to 1836). To give you some perspective on the size of an Ampere (or Amp for short), 1 Amp = 1 Coulomb of electric charge moving every second. In more concise mathematical terms, 1 Amp = 1 Coulomb / Second. There are a lot of electrons that make up 1 Amp of electric current (remember 100 million round trips to the moon). That also means that 6.25 billion billion electrons must pass by the reference point every second.

So now that we know the basic parts of electricity, what does this have to do with batteries and battery chargers? First we should talk about how the Volts, Amps, and Ohms are related. Remember, Volts result from charge (Coulombs) sitting still and Amps result from charge moving. So by talking about Volts and Amps, we've covered charge also.

Another thing that George S. Ohm figured out is that the sizes or amplitudes of Volts, Amps, and Ohms are related. There is something called an electric circuit which is also very important when figuring out how to control Volts, Amps, an Ohms. An electric circuit is a collection of conductive paths that could possibly allow electric charge to move.

A CLOSED electric circuit will allow charge to move; an OPEN electric circuit will not. But having a closed path to move through is not enough. There has to be something to push or pull the electric charge through the closed path. That something is voltage (electric potential), in sufficient quantity and with the correct polarity to cause the charge not only to move, but also to move in the correction direction.

Ohm's Law:

Here is where Mr. Ohm made himself famous, or at least it is what he is most remembered for. "Ohm's Law" defines how the electric charge moves by a very simple relationship. The size of an electric current is directly proportional to the size of the voltage pushing it and inversely proportional to the size of the resistance trying to stop it or slow it down, in the same closed electric circuit. Mathematically, if we use the letter "I" to represent current (Amps) and "V" to represent voltage (Volts) and "R" to represent resistance (Ohms), then the equation looks like this: $I = (V/R)$. This is the fundamental form of Ohm's Law. Another German physicist Gustav Robert Kirchoff (1824 to 1887) established the laws governing the voltage and current distribution in complex circuit arrangements. Most electric circuit analysis textbooks refer to Kirchoff's laws with about the same regularity as Ohm's law.
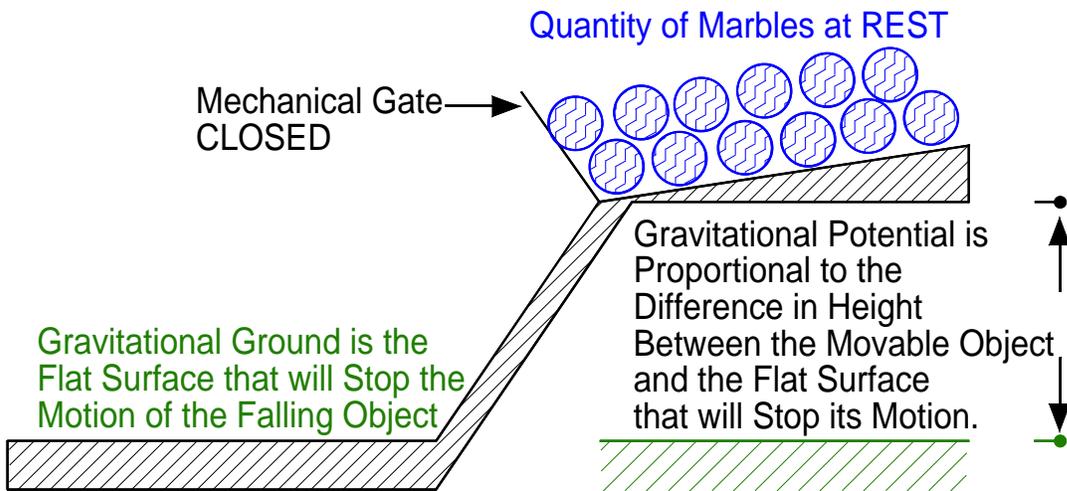
Quantity of Marbles at REST

Mechanical Gate
CLOSED

Gravitational Potential is
Proportional to the
Difference in Height
Between the Movable Object
and the Flat Surface
that will Stop its Motion.

Gravitational Ground is the
Flat Surface that will Stop the
Motion of the Falling Object

Figure 1 Mechanical Analogy, Marbles at Rest

Without belaboring the point too much, please don't be to mystified by the use of the letter "I" to represent electric current. In some texts you will see the letter "E" used to represent voltage. In that case the reasoning is because voltage is equal to Electric potential. Often times the particular symbol used simply result from a limited English alphabet used to represent more than 26 variables. Also, there are foreign language or proper name considerations. The "R" used for resistance could have just as easily been an "O", in honor of Mr. Ohm, or an "A" could have been used for electric current in honor of Mr. Ampere. You get the picture.

To try to get a better understanding of electrical potential and charge motion, consider the analogy between electrical potential and gravitational potential as illustrated by Figure 1 and Figure 2.
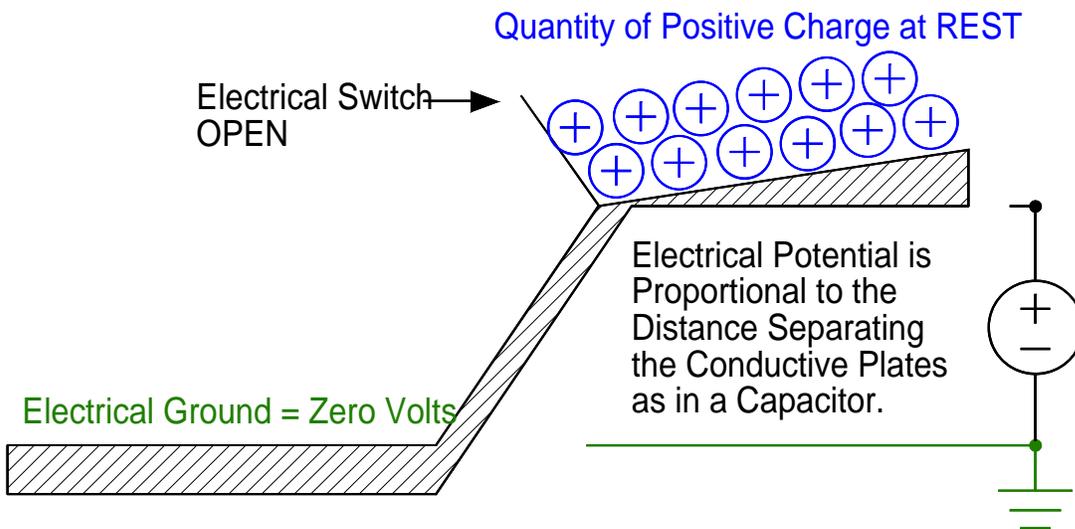
Quantity of Positive Charge at REST

Electrical Switch
OPEN

Electrical Potential is
Proportional to the
Distance Separating
the Conductive Plates
as in a Capacitor.

Electrical Ground = Zero Volts

Figure 2 Electrical Analogy, Charge at Rest
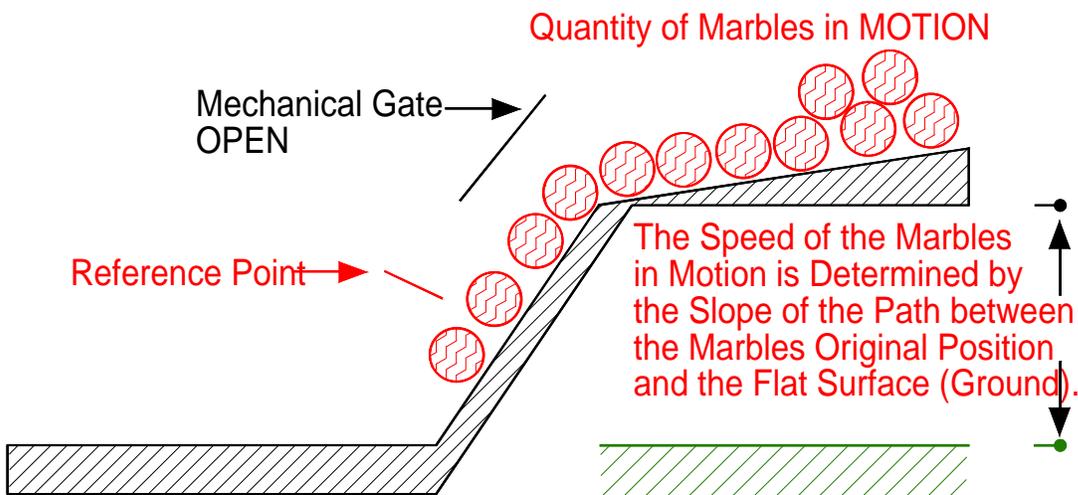
The direct analogy between distance and voltage potential breaks down in any context other than stored charge separated by conductive plates. In the most general sense, the voltage potential due to the accumulation of electric charge is directly proportional to the amount of charge and inversely proportional to the distance from the charge when making the voltage measurement. But for the purposes of this discussion, the parallel plate capacitor analogy is adequate.

Notice the comparison between Figure 1 and Figure 2. The mechanical gate and the electrical switch are physically represented in the same manner. And yet, the context of the words "OPEN" and "CLOSED" are identically reversed. The mechanical system context is the one with which we are most familiar. The electrical circuit context is opposite in the sense that "closed" means to complete a conductive path for charge movement (current flow) and "open" means that the conductive path has been interrupted.

Now let's take the next step and see what happens when things start to move. In Figure 3, it is clear that the amount of objects flowing past the reference point during a fixed period of time is determined by both the quantity of objects at rest prior to the mechanical gate opening and by the speed at which they move past the reference point. The slope of the path connecting the original rest position plane and the mechanical ground plane determines the speed.

Figure 3 Mechanical Analogy, Marbles in Motion

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An interesting fact is that the time it will take an object to reach the ground will be identical whether it travels in a straight, vertical line or along a sloped line. However, the sloped path is physically longer than the straight, vertical line, so that the speed along the sloped is greater than the speed along the straight, vertical line. Remember that speed = distance divided by time. So if the time is the same and the distance is larger, then the speed is larger. All of the relationships dealing with speed and motion in the mechanical system assume that there is no friction.

We've taken a little literary license with the use of speed in Figure 4. As it turns out, the speed of charge movement is very fast, all the time. Actually in all but the most bizarre conductive path configurations, the speed of charge movement is at or very near the speed of light, a mere 186,000 or so miles per second. So on a typical electric circuit board, measuring less than 1 foot in any direction, all parts of the circuit will be energized in a small (very, very small) fraction of a second.
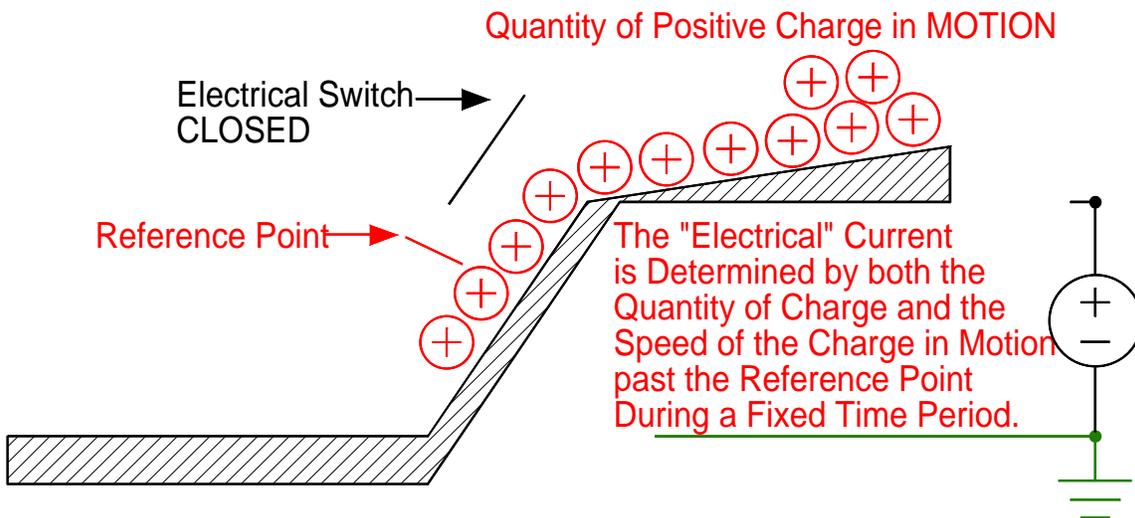

Figure 4 Electrical Analogy, Charge in Motion

Truthfully, it is difficult to come up with a complete, simple analogy to illustrate the behavior of electric charge in motion. Another popular analogy is that of fluid motion. The intuitive comparison between water pressure and voltage is appealing. But when it comes to describing the cause and effect relationships that determine the amplitude of electric current, that analogy breaks down too.

Continuing with the sloped path mechanical analogy, in Figure 3, it is more correct to say that the speed of the marbles is inversely proportional to the slope of the path. The more gradual slope represents a longer distance, and therefore a larger speed. In Figure 4, the true speed of the charge nearly constant everywhere, but for the sake of argument, let's

try to relate the slope of the path to the RESISTANCE to charge motion along the path. Again, beginning with the slope of the mechanical path in Figure 3, the smaller, or more gradual the slope between the initial rest plane and the ground plane, the greater the speed, and therefore the larger the "mechanical" current. In electrical terms, considering Ohm's Law, a larger current results from a smaller resistance. So the mechanical slope is directly proportional to the electrical resistance. You really don't want to think about this too much, because there are many conditions where the analogy breaks down, but hopefully it gives you some perspective on how to relate electrical charge and its motion to something more familiar.

As you have probably already guessed from the previous figures, the electric schematic symbols for ground and voltage sources are shown below:

Schematic Symbol for Electrical Ground

Schematic Symbol for Voltage Source

OR

Figure 5 Schematic Symbols: GND & Voltage Source

The last symbol on the right is also used for a battery. The long and short horizontal lines are used to indicate individual cells. So technically, 6 pairs of large and small horizontal lines would represent a 12 Volt battery. But practically, only 2 pairs of horizontal lines are usually used to represent a battery, regardless of its voltage.
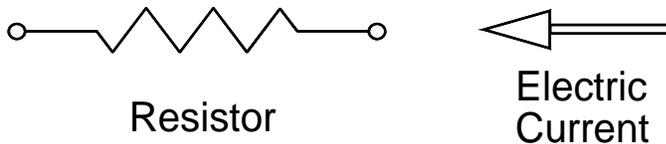
Resistor

Electric Current

Figure 6 Schematic Symbols: Resistor & Electric Current

The symbol on the left in Figure 6 is used to represent resistance in an electric schematic diagram. An arrow pointing in the direction that the positive charge moves depicts current flow.

Battery Chargers & Batteries:

To make use of Ohm's Law when we talk about batteries and battery chargers, we need to add one more little complication. Each of the symbols in the equation ($I = V/R$) represents the TOTAL quantities of current, voltage, and resistance that exist in a single closed circuit path. Fortunately, when we examine the connections between a battery and a battery charger, we can almost always get by with only one closed circuit path.

So what's the mystery about saying TOTAL? You might say that is obvious. Well, we really didn't talk about the effects of charge polarity, positive and negative. Like charges repel and opposite charges attract. So two positive charges or two negative charges push each other away while one positive charge and one negative charge will pull each other closer together. Since electric charges have polarity, voltage must also have polarity, because voltage is just a collection of electric charges sitting around. So after you hook up a battery to a battery charger, the polarity of the battery voltage and the battery charger voltage must be considered to correctly calculate how much voltage (TOTAL) exists in the closed circuit path between those two devices.

When you hook up a battery to a charger, you connect the positive lead from the charger to the positive terminal on battery. The same goes for the negative connection. As it turns out, if the battery and battery charger are connected together correctly, then the polarities of their respective voltages will be identical and each device will tend to push electric charge away from it toward the other device. So what we have here is sort of like a "tug of war", although in this case it might be better to call it a "push of war".

Nominal Voltage Ratings:

Back to Ohm's Law for a minute. To figure out how much voltage is in the closed circuit path between the charger and the battery, you must compute the difference between the two voltages. This is called a "Potential Difference". Fortunately, if you have the correct size battery charger for your battery, you really don't have to compute anything, because the laws of nature that Mr. Ohm (and many, many others) investigated will automatically do it for you. But if you hadn't yet purchased a charger and you weren't sure which one to buy, then you need to think about this a little bit. **Always use a charger that has the same voltage rating as your battery.** Always put a 12 Volt charger on a 12 Volt battery. Never put a 12 Volt charger on a 6 Volt battery!

You might now ask yourself "OK, if I take the difference between the battery voltage and the battery charger voltage, and they are both 12 Volt devices, and 12 minus 12 equals zero, then I have no voltage left to create any electric current. What gives?"

As is so often true, things are not always what they seem to be. It is true that we call a 12 Volt battery a 12 Volt battery and that we call a 12 Volt charger a 12 Volt charger. What is not true is that at any given time, the voltage produced by either of these devices will be exactly 12 Volts. In fact, a 12 Volt battery will change between almost 13 Volts and 11.5 Volts as it goes from being fully charged to fully discharged. Actually, while connected to a load, the 12-volt battery voltage can fall to only 2 or 3 volts, but this represents a severe over discharge. We'll talk more about that a little later. Likewise, a 12 Volt battery charger may produce a voltage as high as 16 or 17 Volts in order to properly recharge a 12 Volt battery. So let's just remember that both a battery and a charger can produce a range of voltages around 12 Volts but that it's just easier to call

them "12 Volt" devices. We refer to 12 Volts as the NOMINAL Voltage rating of the device.

So we can probably guess that at any given time while the battery is being charged, the difference between the battery voltage and the charger voltage is not zero. In fact, if the charger is working properly, the charger voltage will always be larger than the battery voltage, even when it operates in the maintenance or float mode. That means that the electric current (the movement of electric charge) will always be in the direction from the charger to the battery. We might also call that the "direction of positive current flow".

The resistance is the other part of the puzzle that we must now consider. What conducts electric charge? Metals are good: copper, aluminum, silver, gold, titanium, and alloys like brass and steel; all kinds of metals conduct electric charge. Oh by the way, lead is also a metal. That will come in handy when we talk about lead-acid batteries. We call something that conducts electric charge well a "conductor".

What does not conduct electric charge very well? Actually, anything that is not a good conductor would qualify. We call something that is not a good conductor an "insulator". Now if I had first said "insulator" then immediately you probably would have thought of things like rubber, plastic, paper, and so on.

Electric wires and cables are made up of at least two parts. First, there is a conductor to guide the flow of electric charge. Second, there is an insulator, usually wrapped around the conductor to make it safe to handle and to allow many wires to come in close contact without disturbing the electric charge flow in any one of the individual wires.

Resistance:

So what is resistance? Actually, every substance has some resistance to electric charge flow. Conductors have very little resistance. Insulators have a tremendous amount of resistance. In practical closed electric circuit paths, in every electric machine or appliance, there are a wide variety of components that have different amounts of resistance. But again, we need to talk about the TOTAL resistance so that we can calculate how much electric charge will flow. Now I am going to start saying "electric current flow". "Electric charge flow" is more correct, but almost everybody involved in the study or practical application of electricity says "electric current flow".

One practical thing that influences resistance is the physical surface contact between two components in a closed circuit path. Soldering makes the largest percentage of surface contacts between conductors in electric appliances. Effectively, this is a welding process, and if done properly, the resulting conductive path is almost perfect. In that case, there is virtually no resistance across a good "solder joint" as long as the size of the electric current through it does not exceed the rating of the components that were joined together.

It is all the other methods of connecting components besides welding or soldering that usually result in some "contact resistance". For batteries and battery chargers, the size of the interconnecting cables is usually fairly large. Most times either ring terminals or alligator clamps at the end of the battery charger cables are used to make contact with the battery terminals or posts. If the battery terminals are dirty or rusted, then there is a good chance that a higher resistance will be present in the closed circuit path once the charger is connected to the battery. As more resistance is added to the total in the closed circuit path, then less electric current will flow from the charger into the battery.

The other 2 major components of electrical resistance in the closed circuit are the internal resistances of both the battery and the charger. These resistances result from a wide variety of sources and they are difficult to define precisely, just from the knowledge of what is inside each device. This is particularly true in the case of the battery. The exact values of these resistances are usually determined from testing the device. Fortunately, all of the resistances in the battery charging closed circuit are usually small enough that the only limitation on how much electric current will flow is the output current rating, or the current limit, of the charger. Essentially, a battery charger sees a fully discharged battery as almost a short circuit connection. It is only when the battery voltage begins to approach the output voltage of the charger that the small total resistance, including the battery internal resistance, the charger internal resistance, and the cable resistance, becomes significant when calculating how much current will flow from the charger into the battery.

Charging a Battery, Equivalent Electric Circuits:

Now with everything connected, and the charger switched on, anything that happens will be a direct result of Ohm's Law. If the battery voltage is very low, the total voltage difference between the battery and the charger is larger and more electric current will flow into the battery. If the battery voltage is higher, like when it's nearly fully charged, then that difference is smaller and less current will flow. If there is a bad electrical contact in the circuit, then less current, or maybe even no current will flow. If no current flows, then we say that we have an OPEN circuit. So if everything is hooked up correctly, and all the electrical connections are good, then the current flow out of the charger will most likely be right at its rated limit, at least for a time. Later we will discuss some differences in charger types and methods of charge current control.
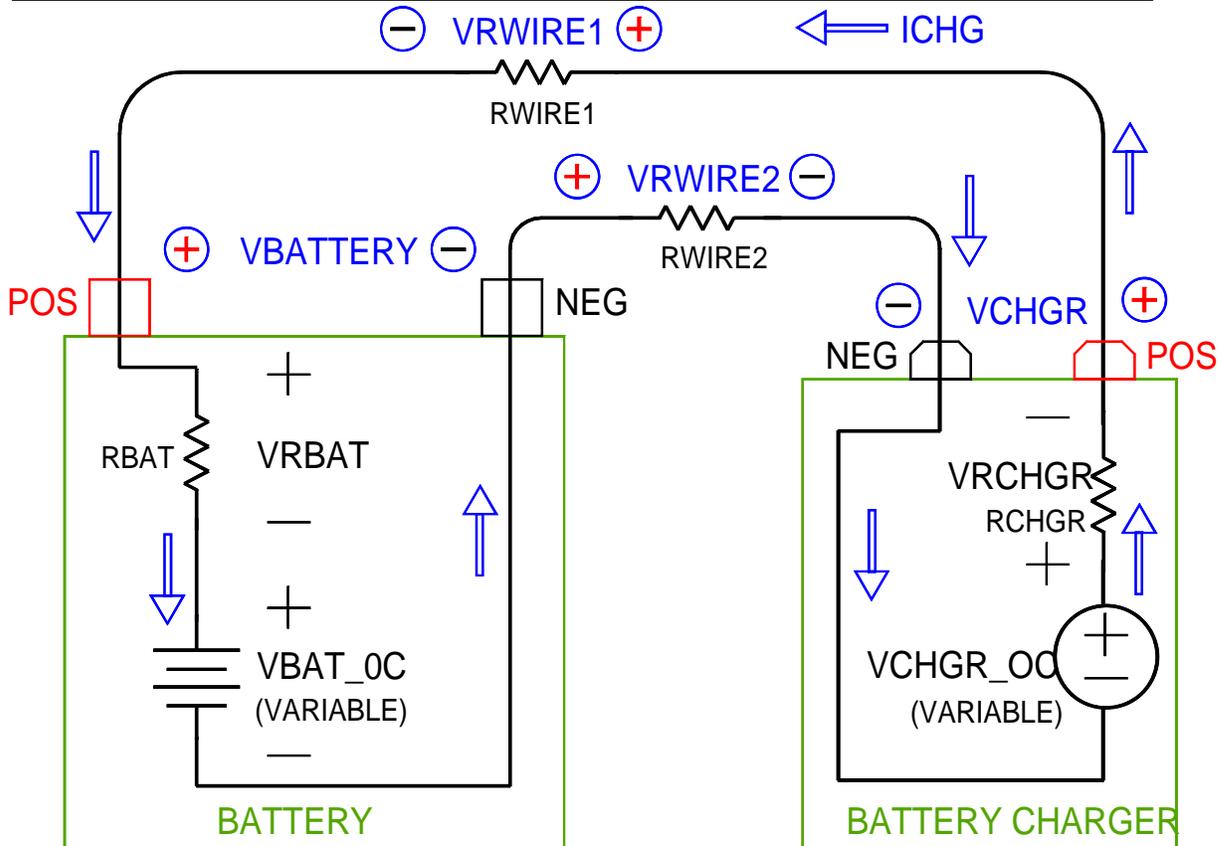
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Figure 7 Battery Charging Model: Detailed

The circuit diagram shown in Figure 7 has a lot of information. First, the 2 green boxes represent the battery and the battery charger. Each box has a voltage source and a resistor inside. Those two elements represent the simplest electrical model for both the battery and the battery charger. Although the model is simple in mathematical terms, it will suffice to help us understand the interaction between the battery and the battery charger.

All voltages external to the battery and the charger are labeled in blue. The external voltages can be measured with a meter. All internal battery and battery charger voltages are labeled in black. The internal voltages CANNOT be measured with a meter. We must deduce their value from our knowledge of the battery and the battery charger behavior and from the values of the voltages that we are able to measure and from the value of ICHG. The nice thing about a series connected circuit is that the electrical current is the same everywhere, so "ICHG" can be measured outside the boxes and we know that it is the same inside the boxes.

The battery voltage source is labeled "VBAT_OC and the charger voltage source is labeled "VCHGR_OC", where the OC stands for open circuit. Notice that each of these

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voltages is variable. VBAT_OC varies with the battery's State of Charge (SOC). VCHGR_OC varies by the actions of the battery chargers internal control electronics that are determined to a great degree by the details of the charging algorithm.

Inside each box there is one resistor that models the internal losses of the battery ("RBAT") and the battery charger ("RCHGR"). Each of these resistors has a voltage associated with it, "VRBAT" and "VRCHGR". Outside the boxes there are two other resistors labeled "RWIRE1" and "RWIRE2". These two resistors model the resistances of the connecting wires and the contact resistance between the battery posts and the charger cable terminations (typically either ring terminals or alligator clamps).

The blue arrows indicate the current flowing from the charger to the battery and back to the charger. The heavy line and all of the voltage sources and resistors connected to it form a closed circuit path. It is interesting to note the orientation of the positive and negative polarities marked on each voltage as you follow the blue arrows around the closed circuit path. The point of the arrow hits the positive polarity symbol first on each element with the exception of the voltage source inside the charger. In this diagram, the battery voltage source behaves like a load because the orientation of its polarity marks is exactly the same as that for the resistors in the loop.

The two external voltages "VBATTERY" and "VCHGR" cannot only be measured with a meter, but they can be calculated from knowledge of the battery and battery charger characteristics. The process of assigning values to these two external voltages is important because it helps us to understand why both of these voltages may have different values from what we might normally expect, as the battery and battery charger are subjected to different operating conditions.

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Vchg_source   Vchg_source

ICHG   ICHG
                           10 A

(+) VBATTERY (−)   (+) VBATTERY (−)

POS   NEG   POS   11.5 V   NEG

VRBAT   0.1 V
RBAT   RBAT   VRBAT = ICHG x RBAT
                           0.01 Ω
                                   (10 A x 0.01 Ω) = 0.1 V

VBAT_0C   VBAT_0C
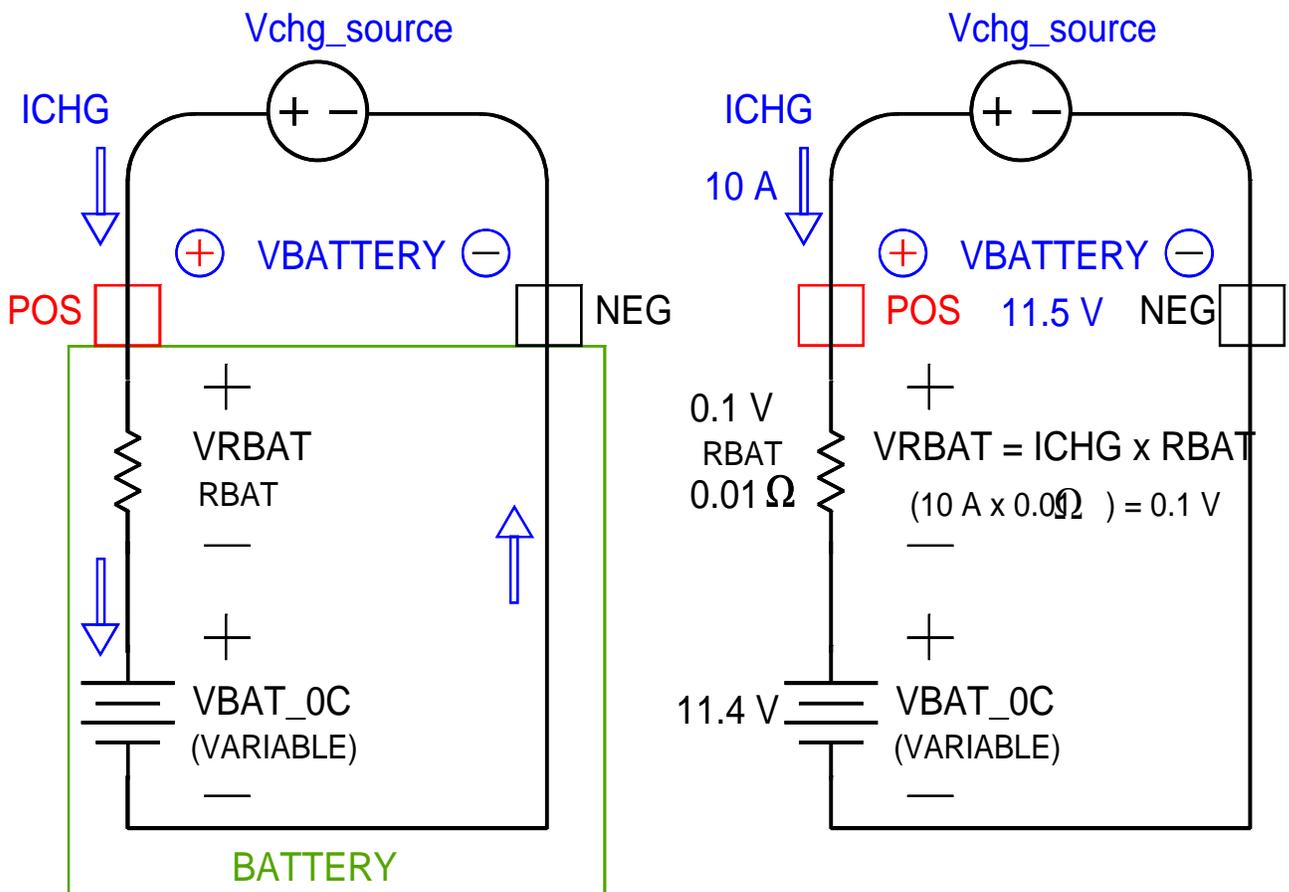(VARIABLE)   11.4 V   (VARIABLE)

BATTERY

Figure 8 Battery Charging Model: Simplified with Numerical Example

To begin this process, consider the 2 circuits shown in Figure 8. Here we have isolated the battery components and represented the remainder of connecting wires and battery charger elements by a single voltage source labeled "Vchg_source". What we want to do is focus on the 2 internal elements that are used to model the battery. As these 2 elements interact with the charge current, the impact on the external voltage VBATTERY will be measurable and predictable.

What happens is that the battery internal resistance develops a voltage because Ohm's law tells us that it will when it has an electric current passed through it. When the electric current goes into the battery while it is charging, the polarity of the voltage on the internal battery resistance is that same as that on the internal, variable voltage source. This means that the two voltages will add together as we take inventory around the closed loop. The external voltage VBATTERY = VRBAT + VBAT_0C. In the circuit on the right in Figure 8, we assigned some values. The result is that as soon as the charge current is applied to the battery, its voltage immediately jumps to a higher value because of the internal battery resistance. As the battery begins to recharge, the value of VBAT_0C will increase, as will the value of VBATTERY. The important thing to

remember is that the voltage that we can measure directly, VBATTERY, will change instantaneously even though the SOC of the battery has not changed.

Discharging a Battery, Equivalent Electric Circuit:

Now let's look at the reverse situation. What happens when the battery delivers current to a load?
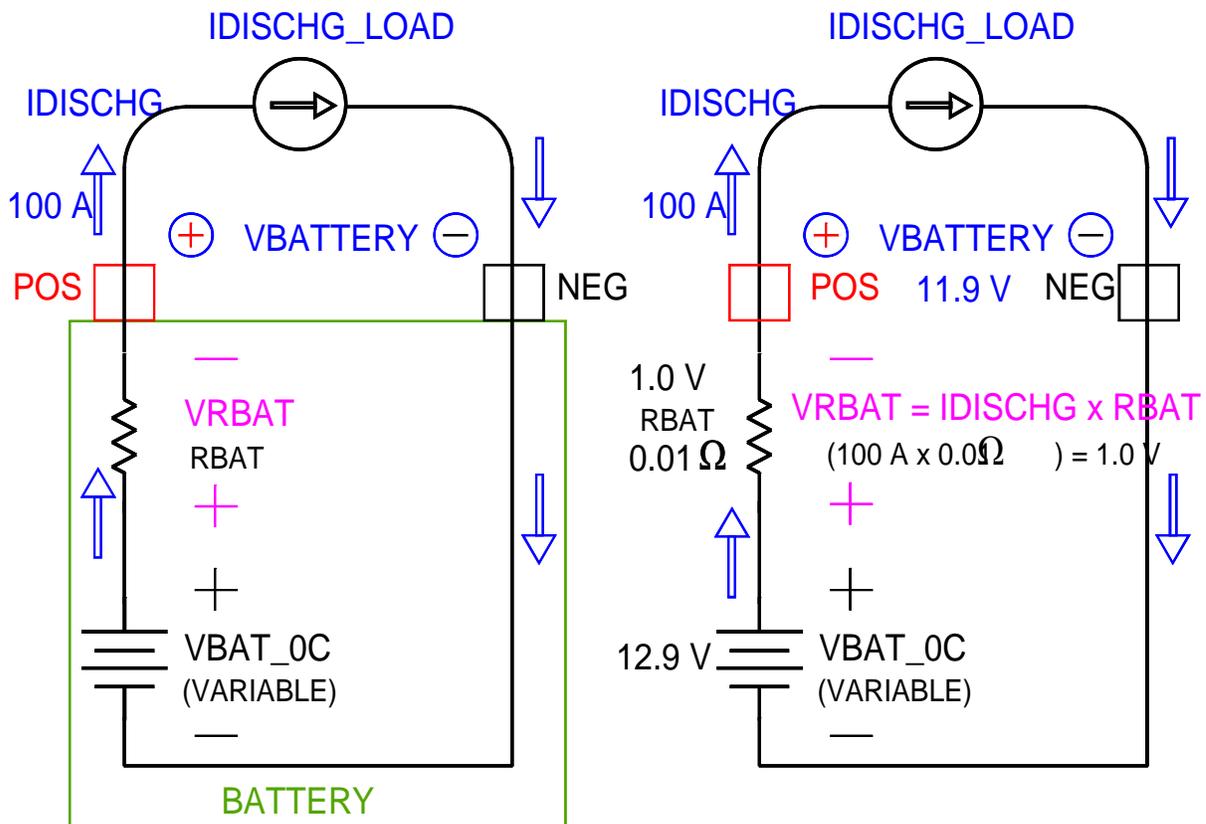

Figure 9 Battery Discharge Model: Simplified with Numerical Example

The 2 diagrams in Figure 9 show what happens to the voltage developed by the internal battery resistance when the battery is delivering current to a load. The diagram on the left shows the basic setup where the load on the battery is modeled as a constant current source, labeled "IDISCHG_LOAD. The diagram on the right assigns numerical values and displays an interesting result. First, the initial VBAT_OC = 12.9 V represents a fully charged 12 Volt battery. Second, the discharge current of 100 amps is beginning to approach size of steady state engine start currents for small engines. (Note: a steady state 100 amp engine start current can easily be associated with a momentary 300 A to 400 A in rush current required to get the starter motor turning.) Third, and most important, notice how the polarity of the voltage developed across the battery internal resistance changes. Now that voltage subtracts from the total measured across the battery terminals. The magnitude of that voltage instantly drops by 1 volt even though the SOC

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of the battery has not changed. Obviously, over time, the equivalent open circuit value of the battery voltage will drop in response to its reduced SOC.

Time Required to Charge a Battery:

Let's take a moment and talk about two of the fundamental electric quantities, Amps and Coulombs. A battery stores charge (Coulombs), and an electric current (Amps) is made up of charge that is moving. Let's ask a very important question: **How long will it take to charge a battery?** *This question is so important that it is repeated in the section titled Frequently Asked Questions.* If you look at the battery specifications and ratings, you won't find Coulombs listed anywhere. What you probably will find is Amp-Hours. Let's look at that term. Amps times Hours = (Coulombs per second) times 3600 seconds (in 1 Hour). So, 1 Amp-Hour = 3600 Coulombs. That's still sort of confusing. The main thing to remember is that Amp-Hours and Coulombs are both units that describe an amount of electric charge.

Let's try something else. Suppose I have a 50 Amp-Hour battery. That's a fairly typical size for an automotive engine start type battery. Now let's say I have a 10 Amp charger. If it's a good charger (like the Battery Tender® products), it will deliver close to 10 amps for as long as it takes to get the battery voltage up to its recharge level. **So how long will it take to actually charge the battery?**
We can make a pretty good guess by just dividing two numbers:

(Battery Capacity) / (Charger Current) = Time

(Amp-Hours) / (Amps) = Hours

for this example:

(50 Amp-Hours) divided by (10 Amps) = 5 Hours.

So we would estimate that it will take a good 10 Amp charger about 5 Hours to recharge a 50 Amp-Hour battery. **Actually this rough estimate usually tells us how long it takes to recharge the battery to about 80% of its capacity.** It turns out that it will probably take an equal amount of time, or another 5 hours to recharge the last 20% of the battery capacity. Keep in mind also that many of the 10 Amp chargers on the market today are what we call taper chargers. They typically sell for $25.00 to $40.00 retail. With those types of chargers the charge times that we just calculated probably need to be doubled.