Electronics for the Car Restorer

INTRODUCTION

This article is designed to provide a bit of insight into the nature of electronics one will typically encounter in trying to fix a car. My intent is to provide enough theoretical background so that you can understand what is going on, and by having that understanding successfully troubleshoot electrical and electronic problems, thus saving yourself some serious frustration or expense, or both. Until pretty recently, say 1980 or so, the level of sophistication of automotive electronics was not great. Sure, there were the occasional engine control computer, but in most cars the most complex piece of electronics was either the voltage regulator or the radio (depending on your point of view). Starting in the late 70s, but gaining momentum through the 80s, we find computer based engine controls creeping into our vehicles. This is of course both good and bad. It’s bad because the controls use many special purpose chips and parts, so even if you can figure out what to replace, the chances of being able to get a replacement part are small (I have repaired one such computer successfully, but it’s rare to attempt to do so). It’s good for two reasons - the computers directly measure important engine parameters such as mass flow in the intake manifold, exhaust chemistry, and engine crankshaft position and thus can adapt the fuel and spark to the exact conditions needed for the particular power cycle rather than relying on average conditions or steady state optimizations we find with carburetted engines. It is certainly beyond the scope of an article like this to provide procedures for troubleshooting an engine control computer, but I hope that a bit of knowledge on what is happening may let you do so yourself. For most “electronic” cars, the dealer’s manual is virtually indispensable, and I strongly recommend you acquire one when you get such a car.

CONDUCTORS AND INSULATORS

There are two types of electricity - static and “regular” (for lack of a better word). Except for the advantages of sticking balloons to the ceiling, providing an electrifying kiss or handshake, and lifting skirts on dry days, we will have little to do with static electricity in our car work. I will mention it periodically as appropriate, just to see if you are paying attention.

We are most directly concerned with electricity in conductors (wires) that we can use to do useful work like light lights and turn motors. Now, it turns out that all material can be divided in to conductors, insulators, and semiconductors. Conductors are usually metals, like copper or aluminum, and insulators are not (sulfur, many organic compounds like plastic, wool and rubber). Semiconductors are weird materials that aren’t really insulators and aren’t really conductors - they are sort of in the middle, and are used for making transistors and integrated circuits (silicon is the most commonly used semiconductor).

You will notice that I used the words conductor, metal, and insulator without much definition. Rather than providing a formal definition (which is probably impossible given the scientific mind), let us explore a bit what makes a conductor conduct. We all know, from high school science if nowhere else, that matter is made up of atoms, and that atoms themselves are made up of a nucleus and a bunch of electrons whirling around the periphery, much like politicians around a pot of money. This image is cute and makes for nice graphics on 1950 era “atomic” coffee cups or nick-nacks, but it is somewhat misleading. When you start dealing with things that are very small, and I assure you electrons are very small, you encounter a “law” of nature commonly expressed as the Heisenberg Uncertainty Principle. Stated in simple English rather than a formula, it says that if you know how fast something is going precisely enough you don’t know where it is, and if you know where it is precisely enough you don’t know its velocity. (Refer to this after a few beers when you can't find the pull tab, or use it to amaze your friends with your newfound erudition - it has rather profound, but irrelevant to this article, implications on philosophy)..

The apparent paradox of the Heisenberg Uncertainty Principle (hey, I can find my car, it's sitting in my driveway) is resolved when you realize that at any scale we can see the uncertainty is well below our threshold of detection. But, when you get to the atomic level, it is significant. And, that is why it's misleading to think of electrons as small balls in a circular orbit. A better way to think about them (if you have to think about them at all) is as a cloud. There is a set of equation in quantum mechanics called Schrodenger's equations which allows you (with a fair amount of mathematical pain) to solve for the probability function of an electron (or other particle). Like all great equations, it is totally impractical to solve the equations for anything significant, but it can be done for very simple structures. What you find is that there are regions around a nucleus where it is likely you will find an electron, and other regions where it is extremely unlikely. Many odd anomalies crop up with these equations, and some of the odd anomalies are in use today to make your computers work (look up a paradox called "Schrodenger's cat" for a mind bending romp through the implausible), but for our purposes, let us envision our atoms more as weather systems than solar systems, with clouds (containing one or more electrons within them) forming roughly spherical rings around a central nucleus (itself a cloud also).

Now, some materials, when a substantial number of atoms are gathered together, form "clouds" that actually spread between the atoms. This happens because of the way the clouds interact. Since the clouds represent places where finding an electron is likely, if we find a material where the cloud can spread between atoms it means that electrons can move around in the material. If we find a material where the clouds don't spread between atoms, it means that electrons are stuck where they started and they can't move around.

Electrons have a electrical property called "charge" - the charge on an electron is defined as being negative. Protons (within the atomic nucleus) have a positive charge. There are other subatomic particles, some with charge, but they aren't relevant to this discussion despite their obscurity and bizarre behaviors. If electrons can be induced to move within a material, then charge will move through the material causing "current".

Remember static electricity??? If you rub a balloon against your cat on a dry day (I love that image), you will cause an unbalance in charge between the balloon and cat by pulling electrons out of the balloon and depositing them on the cat. The balloon thus has a positive charge, and the cat a negative charge. *****Check this - polarity may be reversed *****The latex of the balloon is one of those materials in which the electron clouds don't spread between the molecules - it is an "insulator" - so the excess charge is stuck to the balloon.

Now charge creates a force just like gravity and magnetism (there, that's the three causes of force that are operative at human scales). Like charges repel, opposite charges attract. So, the balloon has a charge, the ceiling doesn't, so the charge difference causes the two to be attracted, thus explaining why the balloon sticks to the ceiling.

Now, if the material into which we injected (or extracted) the electrons was a conductor, the excess (or surfeit) would immediately spread out across the entire conductor. If we could find a source of electrons and a sink for electrons (a sink is a fancy term for a place into which these electrons can flow and be disposed of), then we could make electrons flow along our conductor, creating a current. There are several ways of producing such a source and sink, and commonly they are produced together. An electrochemical reaction (i.e. a battery) is one way.

Now, the confusing part - as if the forgoing wasn't confusing - the electrons have a charge defined as negative. So, since opposites attract and like charges repel, they will physically flow from the negative terminal of the battery to the positive. Current on the other hand (for historical reasons) is defined to flow from the positive terminal to the negative. For most of the rest of this article we will concern ourselves with current and forget about electrons, but occasionally this disparity will become important.

With this background, you should know, in more detail than is needed, how and why current moves through a wire and how and why it doesn't move through an insulator.

WHAT HAPPENS WHEN CURRENT FLOWS THROUGH A WIRE

At this point it is convenient to define some terms and provide a few useful analogies.

Current is measured in Amperes. Charge is measured in Coulombs. One ampere of current is present when one coulomb of charge flows through a conductor (a wire) in a second (steady state).

A convenient analogy to current flowing through a wire is to imagine water flowing through a pipe. In order to make the water flow, you need pressure to push it through the pipe. In plumbing the pressure is measured in pounds per square inch, or bars, or a number of other units. In electronics, the pressure is measured in volts. A volt, named after Count Alessandro Volta (1745-1827), is the potential difference between two points in a conductor carrying one ampere of current when one joule of work (10 million ergs) of work is required to move one coulomb of electricity from one of the points to the other. The unit of electrical work is the watt (named after James Watt, the inventor of the steam engine), representing the consumption of electrical energy at a rate of 1 joule per second. Get the idea that these definitions never end?? What is important to remember is that Amperes or amps represents a unit of current (moving electricity), Volts represents a unit of pressure (potential), and Watts represents a unit of work. Watts is typically calculated by multiplying current times voltage, so if a headlamp draws 15 amps at 6 volts, you have 15X6=90 watts.

There are standards which define these units because it is impractical to untangle the mess otherwise (since everything is defined in terms of everything else). One Amp will deposit .001118 grams of silver per second if passed through a silver nitrate solution. A volt is defended as .98203 times the potential of a standard Weston cell consisting of poles of cadmium amalgam and mecurous sulfate with an electrolyte of cadmium sulfate. And no, none of this is relevant but it’s interesting to read once so you know how it’s done. We will find that we measure voltage with a voltmeter and amperage with an amp meter, and rarely if ever measure wattage - instead we calculate it as shown above.

When current flows through a wire (or anything else for that matter) it creates a magnetic field around the wire (measured in Oersteds, named after Hans Christian Oersted (1777-1851)). This phenomena is extremely important because it is what makes electric motors and transformers work. The magnetic field forms a ring around the conductor, with the field lines pointing according to a “right hand rule”. The right hand rule says that if you place your hand around the conductor, with your thumb pointing in the direction of current flow, your fingers will point in the direction of magnetic field (which of course is defined as pointing from north to south).

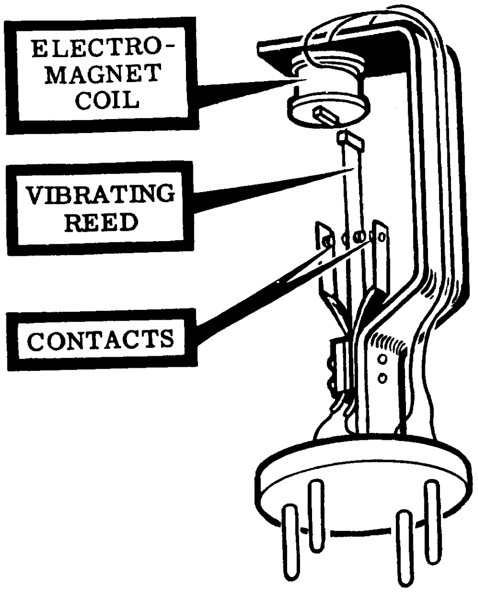

Figure 1 - Vibrator

Now that we have described currents, and the interesting artifact that current flowing through a wire produces a magnetic field, let's see what we can do with it.

First, we should probably define some terms, in particular, AC and DC, currents. If current flows at a constant rate in one direction, it is called "direct current", or DC, whereas, if the current varies as a function of time, in particular if it changes direction regularly, then we call it "Alternating Current", or AC. The current produced by a battery is DC, the current in your house is AC (unless you have an unusual house). There is a good reason for the difference. Electrochemical reactions, such as that which produces current from the dry or wet cell battery, produces current in only one direction. On the other hand, as we will explain in a bit, DC current is both more dangerous and less practical for typical household usage - It is more dangerous because if you have high enough voltage (typically more than 48 Volts is considered potentially dangerous) and you grab the wires, the DC current will make your muscles clench and you can't let go of whatever it is that is killing you. This, of course is bad, but the real reason involves money. It takes heavier wire to carry lots of wattage at a low voltage than at a high voltage, because you need more current (for the same wattage). I will explain why that is in the section on resistance. So, to save money on wire, it is convenient to be able to distribute the electricity as a high voltage (you will find million volt lines in some parts of the country) and then drop the voltage down to whatever is proper near the source. This, until recently, was extremely difficult unless you used a "transformer" (described in a later section), and that needs AC current to work.

RESISTANCE

Now, when current flows through a wire (or anything else), just as when water flows through a pipe, the conductor resists the flow. The resistance per "square" of various interesting metals is shown in Figure 2. I use the term "square" to refer to a uniform thickness of metal that forms a square - it turns out that if you use this particular configuration, the actual dimensions don't matter - a 4" square of copper 1 inch thick has exactly the same resistance (corner to corner, or edge to edge) as a 40 inch square of copper 1 inch thick.

Aluminum (pure)	1.70
Brass	3 . 57
Chromium	1.82
Copper (hard drawn)	1.12
Copper (annealed)	1.00
iron (pure)	5.65
Lead	14.3
Nickel	6.25 to 8.33
Phosphor Bronze	2 75
Silver	0.94
Tin	7.70
Zinc	3.54

Figure 2 - Relative Resistivity of Various Metals

Anyway, what we see here is that the material through which the current flows resists that flow. The water flowing through a pipe analogy is effective here - just as you would use a larger diameter pipe to reduce the restrictions ("resistance") so too you use a larger diameter wire to reduce the resistance to current flow. There is a useful equation (OK, but it's a simple equation):

$$\mathbf{E=IR}$$

Now, remember that scientists want to make everything confusing, so they change the names around. In the equation, E represents "electromotive force", AKA volts, and I represents current (I have no idea why I should represent current, but it does, except under some circumstances when we feel obligated to use the letter "J" instead), and R represents resistance (well, you see, to be truly confusing, you can't change the names all the times, only some of the time. So, what we have is a definition of resistance. The "electromotive force" measured in Volts (named after Volta, remember) is equal to the current (measured in Amps, named after Ampere) times the resistance in Ohms (named after another dead guy). A more useful way to represent it is as I=E/R, which lets you figure out how much current will flow through a circuit if you know its resistance.

When current flows through a resistance, heat is produced. The power dissipated in a resistor is $\mathbf{I^2R}$**,** or $\mathbf{E^2/R}$. This let's you estimate the power that will be dissipated in some circuit if you know the resistance and the current or voltage, or alternatively, if you know you have a 6 volt 36 watt headlight, you can calculate it's resistance (1 ohm, hot, less cold) and it's current draw (6 amps). Of course, since we also know that power in watts is volts times amps, you could have just divided the power by the applied voltage, and had the same answer.

As an interesting aside, the resistance of most metals increases with temperature. That is why a light bulb will measure one resistance cold, yet draw less current hot than you would estimate from the cold resistance. It is also why a "light bulb" load is so problematical to electrical circuits, because there is a dramatic surge of current through the filament while it is heating up. That is also why bulbs typically burn out when you first turn them on, not later. Another interesting fact, if these kinds of things interest you is that light bulb life is dramatically affected by the applied voltage. For those who care, the equations are:

$$\frac{Actual\_Live}{Rated\_Life} = \left(\frac{Rated\_Volts}{Actual\_Volts}\right)^{13}$$

You will note (particularly now that I point it out to you) that the exponent is "13" - what that means is that if you have a light bulb that will last 1 hour at its rated voltage, it will last 8192 hours (i.e. 2^{13}) hours at half voltage (about a year). Or, alternatively, a 6 volt bulb run at 8 volts will have 2% of the life it would have had at it's rated voltage. This phenomena explains why a stuck voltage regulator causes all the bulbs in the car to burn out simultaneously

SWITCHES

Switches are devices that can close or open a circuit, just like a valve can block or permit flow of fluid in a pipe. A switch just makes a metallic path between two terminals when it is closed (i.e. permitting current flow) and "breaks" the path when the switch is "open", or blocking the current flow. The operation of most switches you will find in cars is pretty obvious upon inspection. The usual failure mode of these switches is either pitting of the contacts, or an oxide build up. Headlight switches are particularly prone to problems due to oxide build up. The oxide builds up because there is a lot of current flowing through the switch. The current causes heat, because there is some small resistance even a new and perfect switch. The heat increases the chemical reactivity of the metals in the switch (usually copper and brass) which causes them to oxidize a bit. The oxides have more resistance than the clean shiny metals, so the current flow encounters more resistance, causing more heat, causing more oxide, and so on. If you find your headlights are dim, one thing to check is the switch itself - if it is warm to the touch (or worse, really HOT), then you need to clean off the oxides, solder any swaged connections, and generally clean it up.

I once was troubleshooting dim headlights on my 1956 356 Porsche. I had 7.2 volts at the generator, as I was supposed to. By the time the current went through the wiring, through the headlight switch, through the fuse block, and through even more wires to reach the headlights, there was enough resistance that I ended up with 3.1 volts across the lights. No wonder they were dim. My ultimate solution was to give up on the switch and to install a special relay to handle the current, but it did help a lot to clean the various connections and switches, etc.

Switches have “poles”, or circuits - one, two, or more poles, and they have “throws” or positions. A really simple switch, like a horn switch (or a door bell switch) has one pole (because it only makes a single circuit), and one “throw” (because there is no contact made when the switch is not pushed). Most switches make one set of contacts in the “normal” position, and a different set in the “actuated” position, as shown in Figure 3. If the switch is spring loaded into some “normal” position, as is the case with the horn switch, then the contact which is closed when you press the switch is called the “normally open” contact, and the contact which is broken (or “opened”) when you press the switch is called the “normally closed” contact.

And, of course, because everything should be confusing, switch configurations are identified by acronyms: SPST for “single pole, single throw” - that would be your horn switch. SPDT for single pole double throw, DPST for double pole single throw, DPDT for double pole double throw, and so on. I hear the phrase TPDT occasionally, but above that the number of poles is mentioned, as in “4PDT”. This same notation applies to the contact configuration of relays, by the way.

One important thing to notice on switches is the contact points. In fact, the ignition points within the distributor are just a special switch. If a switch is to carry sensitive signals (like from a phonograph) where the current is minuscule, then the contacts should be gold. If the switch is to carry a few tenths of an amp or more, gold is of no particular value because there is enough current to burn away oxides when the contacts make. For very high currents, hundreds of amps (or thousands of amps), there are special contact configurations. The starter solenoid in your car is and example of such a special high current switch. At high currents, the key problem is to avoid building an arc welder instead of a switch, because as the contacts separate the current will want to keep flowing. The contacts must either be made from an arc resistant material (like tungsten) or have sufficient thermal mass that an arc won’t sustain itself. The other important thing about the contact points is that at currents above a few tenths of an amp the points will weld and tear bits of metal off each time they break, which causes pitting. When the pitting gets bad enough, the contacts don’t mate properly and the current doesn’t flow, or flows intermittently. To fix pitted contacts, just file them flat again.

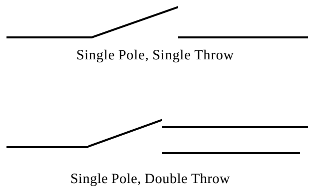

Figure 3 single pole switches

RELAYS AND SOLENOIDS

Relays are just electrically actuated switches, solenoids are coils of wire that can deliver a magnetic force. You remember (don’t you, this is a quiz) that when current flows through a wire (or anything else) it makes a magnetic field around the wire. Well, if you wind that wire around a toilet paper roll, or some other cylinder, you can get a stronger field. Each turn gives you another “wire’s worth” of magnetic field. And, as we all remember, magnetic fields attract iron.

So, if we take a bunch of turns of wire around a cylinder, and put a piece of iron part way into the cylinder and then turn on the current, the magnetic field will suck the piece of iron into the center of the core (oops, of course the right technical term is “attract”, but who’s checking). There are a lot of useful things we can do with this motion. You will find electric trunk and door locks use solenoids, automatic transmissions use solenoids to affect the shift behavior, some carburetors have solenoids to cut off the idle circuit when the ignition is off, and so on. Sometimes, you will find that the solenoid has the center of the coil filled with iron, and the movable piece is outside. From the point of view of the magnetic field, this is really the same thing - the core concentrates the field making an electromagnet, and then it attracts whatever it’s supposed to so that something useful happens.

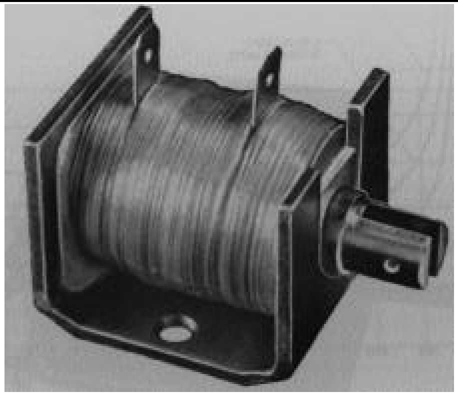
Figure 4 - Solenoid

Perhaps the most interesting example of this type of application of a solenoid is the relay (Figure 5). The relay is just a momentary switch with an electromagnet as an actuator. When current flows through the electromagnet (in the center, bottom, of the picture), it attracts a metal armature which in turn moves the contacts on the relay, thus opening one set of contacts and closing another. Most cars after the late 30’s had relays in the starting circuit to energize the starter motor when the starter switch was pressed. Earlier than that, the voltage regulator was (is) common. The voltage regulator is just a special relay in which the pull in forces of the electromagnet is carefully counterbalanced by an adjustable spring. In this way, the current to the field coils and so on are controlled by balancing magnetic forces against the spring forces. On some of the relays within a voltage regulator, there may be more than one coil (with the current flowing in opposite directions) so that the magnetic fields of the two coils sum (or cancel) under some conditions.

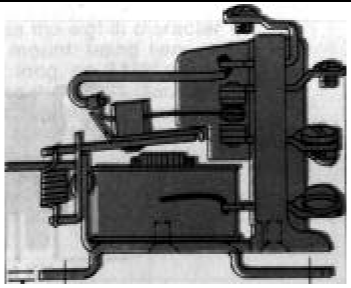
Figure 5 - Relay

A special case of a relay is the vibrator, shown in Figure 1, which is used to turn DC into AC so that a transformer (described later) can be used to create the higher voltages needed by the tubes in a radio. In a vibrator, the relay is made to oscillate by connecting the coil in series with a normally closed contact. When power is applied, the electromagnet moves the armature, which breaks the contact, which then breaks the circuit so no current flows through the magnet. The contacts then return to their original position, which re-energizes the magnet, and the process repeats. This is the same action that takes place in a doorbell or buzzer, except that the purpose of the oscillating armature is to move contacts to make DC into AC rather than to make noise.

MOTORS AND GENERATORS

If you can understand solenoids, you can understand motors and generators. Remember that current flowing through a wire causes a magnetic field around the wire. We showed with solenoids that this magnetic field can attract another magnet or piece of iron. If we hold the magnet fixed and let the solenoid move, we have part of a primitive motor.

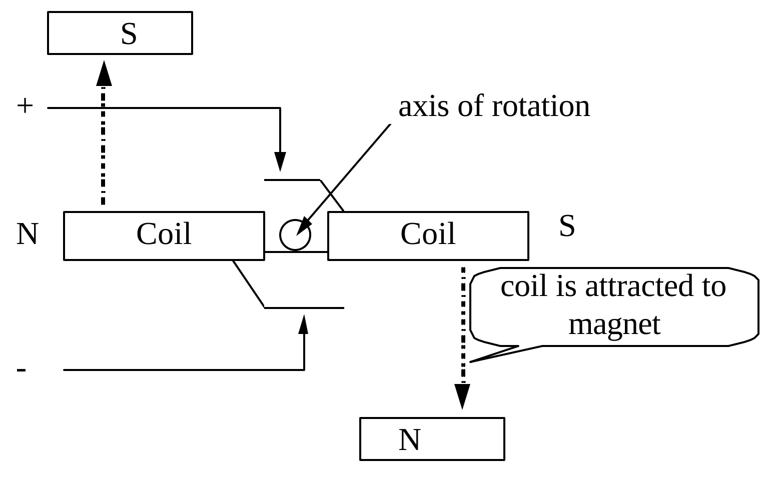

Figure 6 - Simplified Electric Motor

This basic concept is shown in Figure 6. Current flows through two coils in series, causing a magnetic field. A second set of magnets called the pole pieces (or field coils if they are electromagnets), either permanent or electric, set up another magnetic field. The coils are attracted to the opposite fields of the pole pieces, so the "S" end of the armature coil rotates towards the "N" end of the pole piece. As the coils rotate, the current is supplied to the coils through brushes and a commutator. When the motor has rotated far enough, the commutator (a pair of copper strips in this case) breaks the circuit, and then a bit later as the coils continue to rotate, the commutator again makes the circuit. The coils have now reversed position (e.g. 180º), but the commutator has also reversed the direction of current, so the coils are again attracted to the pole pieces.

CAPACITANCE AND INDUCTANCE

TRANSFORMERS

Theory

The Ignition Coil

DIODES AND THEIR USES

TRANSISTORS

INTEGRATED CIRCUITS, MICROPROCESSORS, AND THAT MAGIC CALLED SOFTWARE

SOME STRANGE ABERRATIONS WE FIND IN CARS

Bimetalic Strips

Special Sensors