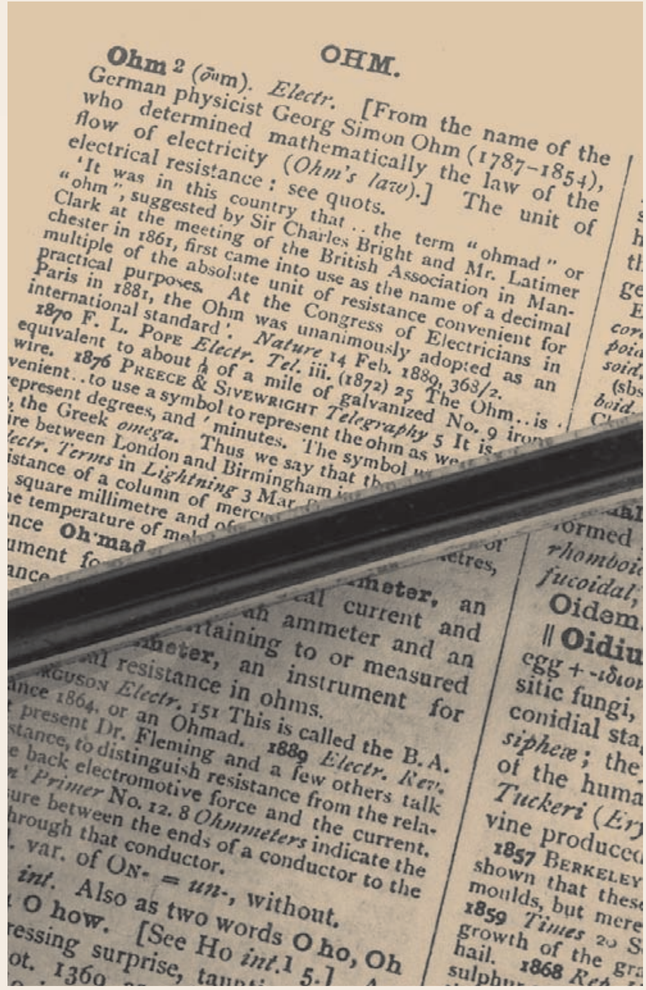
"Simon Says..."



Once there was a fellow named Georg who found out more about electrical circuits than most scientists of the time, and he did it before most ordinary people even realized electrical circuits could occur. His name was Georg Simon Ohm — Herr Professor Doktor Georg Simon Ohm, actually. You should recognize his last name because he first understood what we now call *Ohm's Law*. He was the first to explain how voltage, current and resistance interconnect in an electrical circuit — a significant step forward for the world at the time, even if few people knew it.

What's so impressive about Georg Simon Ohm's achievement is this: He published his findings in *1827*. Think about that for a moment. In those days whale-oil lanterns were the headlights on horse-drawn carriages, for the few people who could even afford to travel at all. Taillights hadn't even been invented yet. Nobody had electric lighting, cellphones, microwave ovens, radios, television or computers. Ships moved by sails or oars; there was hardly a railroad in the world; even the steam engine, perhaps the most important invention in history, was something quite new. Lightning was the only electrical phenomenon most people knew about. In fact, *nothing* useful in everyday life worked by electricity. It was entirely a set of hypotheses at the dim forefront of science.

Most people didn't have the foggiest what it was, yet Georg was already thinking hard and clear about this 'electricity' stuff. Georg Simon Ohm did something that other scientists just didn't think of, even though they were just as smart as he was. The sequence of events and Georg's part in them make for an interesting story.

The story begins with an Italian physicist, Signore Alessandro Guiseppe Antonio Anastasio Volta, who identified and described the electromotive force we now call *voltage*. Alessandro was pretty smart, but he only went so far. He figured out how to generate and demonstrate voltage and published a paper explaining his findings in 1769. He received all kinds of awards for his accomplishment from the governments in Europe. They even named the stuff after him, so he probably figured one discovery was enough. Today we call the unit of electromotive force or potential a *volt* after Volta, in Alessandro's honor. He died a happy man in 1827 with a chest full of medals.

Next came a French physicist, Monsieur Andre Marie Ampere. Andre approached things differently. He'd noticed the connection between electricity and magnetism and thought it through with experiments until he understood it, and his findings were published in a 1820 scientific paper. His work earned him quite a bit of recognition, and to this day the basic unit of electrical current is called the *ampere* or *amp* for short. Andre, too, collected his share of medals before he died in 1836.

Signore Alessandro Guiseppe Antonio Anastasio Volta

Herr Professor Doktor Georg Simon Ohm

Monsieur Andre Marie Ampere

There's a chance that Ampere may have known of Volta's work, because we know the members of the European scientific community got together between the frequent wars and revolutions to debate and discuss their scientific findings. However, there is no evidence that Volta and Ampere ever met face-to-face to discuss their discoveries or to explore how they might work together. It's too bad, because neither could see the big picture. They both had some good ideas that needed to be connected.

This is where Georg Simon Ohm entered the scene. He studied the work of Volta and Ampere and recognized a new connection between the concepts of volts and amps. Relating volts and amps in a direct, quantifiable relationship made sense to Georg, but he didn't yet have it in the form of an equation. Between his thought-experiments and his attempts to formulate the relationship in a mathematical way, he realized there must be a third characteristic of electrical circuits, a characteristic he named *resistance*. Now he had it in an equation! Amazingly, Georg did it all mathematically and conceptually, without the benefit of live circuits to use in his experiments. Quite the calculating guy!

Can you guess what happened next? Nothing! The scientific community rejected his conclusions and ignored him. Georg was very insulted, so he quit his teaching job at Cologne University and went on a long vacation. After all the bruised egos had a chance to heal, the undeniable significance of Georg's discovery became apparent to everyone with an interest in electricity. Georg later wrote a book to further explain his findings and got at least one medal before he went to the great laboratory in the sky in 1854. Georg left behind the great scientific hypothesis, **E = I x R**, which we call *Ohm's Law* in his honor.

Georg figured it all out before most people knew the first thing about this strange stuff called *electricity*. And his conclusions have clarified the relationship between voltage, current and resistance ever since. Pay attention to what Herr Professor Doktor Georg, . . . er, Simon says, and you too can understand. We have an advantage over people in the early 19th Century: We have live circuits to use when applying what 'Simon says' to understand any circuit in any car or truck, whether the vehicle is made in the US, Europe or Asia. Count on it. Now let's see what 'Simon says' about circuits.

Signore Volta would really get a kick out of the battery in **Figure 1** (on next page) because he only had a primitive battery to create the first sample of voltage in his experiments. He would be quite impressed to see how battery technology has progressed. The generator (alternator) in **Figure 1** would probably blow his mind, too.

"The volts witha no acid!? Ha! Notta canna be!" supposes Signore Volta. He wouldn't have a clue how it works until he learned Ampere's interconnection between electricity and magnetism. But he would love to see a generator create voltage. He would exclaim, "Yo! Now we gotta some volts!" Yes we do, but what does the voltage do in a circuit? What happens in a circuit if there is no voltage, or if the voltage is too low or too high? Hmmmm?

Let's see what we can learn from Monsieur Ampere. We connect a circuit to the terminals of the voltage source using some wires, a lamp, a switch and a fuse just in case. We close the switch and the lamp lights.

"*Mais, oui!*" observes Ampere, "but of course. *Naturellement*, just read my book. Current is flowing. *Magnifique, non?*" Yes, it is, Monsieur. But what makes that magnificent current flow? How do you control the current in a circuit, and what happens if the current is too high or too low? Hmmmm?

This is where 'Simon' (Herr Professor Doktor Georg Simon Ohm) set everybody straight. One advantage of Ohm's Law is there are three logically and mathematically equivalent versions to help explain what is happening in a circuit. Let's look at each of the three versions of the Law.

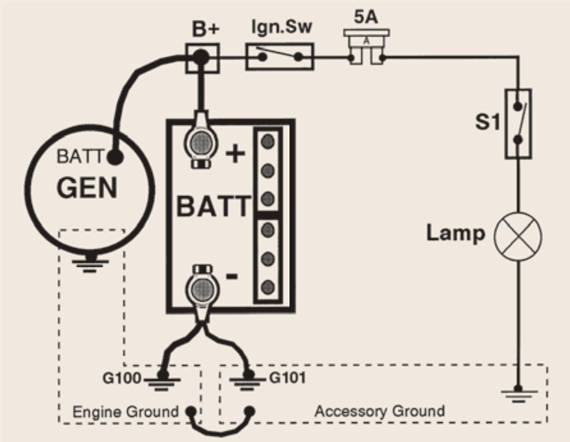


Figure 1: Basic Electrical System

Battery Voltage	vs.	State of Charge
12.66		100%
12.45	-----	75%
12.24		50%
12.06		25%
11.89		0%

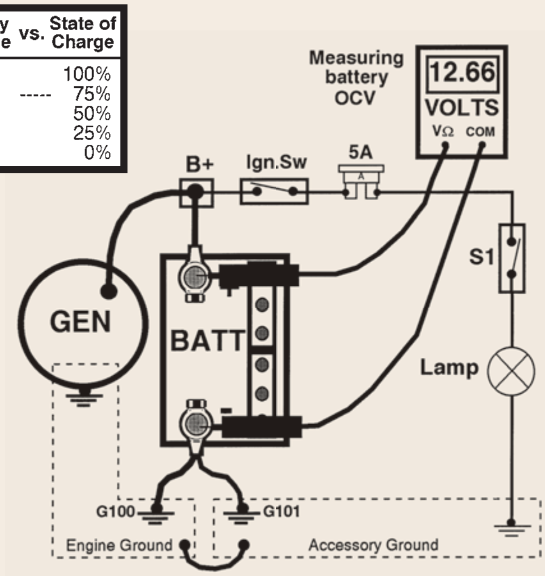
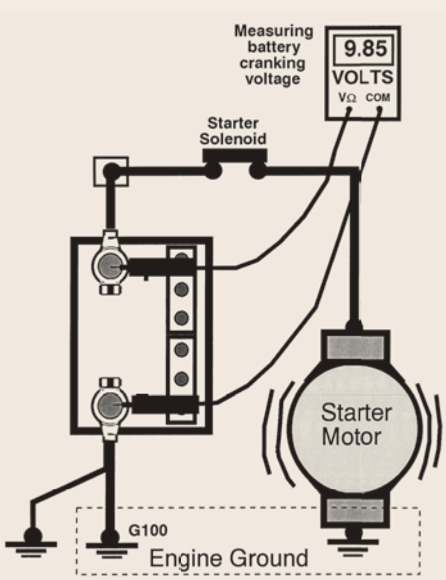


Figure 2: Testing Battery OCV



Minimum Battery Load Test Voltage vs. Battery Temperature	
Voltage	Degrees F
9.90	100
9.80	90
9.70	80
9.60	70
9.50	60
9.40	50
9.30	40
9.10	30
8.90	20
8.70	10
8.50	0

Figure 3: Battery Load Test

Simon Says "E = I x R"

'Simon says' it takes voltage (E) to make current (I) flow through a circuit, but resistance (R) affects how much current can flow. You can calculate voltage if you know the current and the resistance (E = I x R). Volts equal amps times ohms.

'Simon says' if you don't know the voltage, multiply the current by the resistance. Now let's look at this from a practical point of view. The amount of voltage supplied to the circuit is critical. The circuit needs the proper voltage so current can flow and the circuit can operate properly. The voltage source of a vehicle's electrical system consists of a battery and a generator. *Sit down, Signore Volta! Stop clapping and cheering! You're not at the opera! We know you discovered voltage. Just listen to what 'Simon says'!*

Voltage is the electrical pressure driving current through a circuit, just as water pressure drives water through a pipe. Voltage does not flow, any more than pressure. It is simply an electrical force in a circuit that moves current. We call the arrangement of a battery and a generator on present day vehicles a '12-volt' system, even though the operating voltage is greater than 12 volts.

The battery's voltage at rest is 12.66 volts. This is called battery *open circuit voltage* (OCV). A slightly higher battery OCV (in the range of 12.67-12.80 volts) comes from the positive surface charge after a period of engine running, which is normal. An OCV less than 12.66 indicates less than full battery charge, or a battery discharging through a circuit as current flows from the battery. The battery OCV chart in **Figure 2** can help you determine a battery's state of charge based on its OCV.

Besides testing a battery for OCV, we also test how low the battery voltage drops during cranking. This is called a cranking-voltage test. A battery must provide sufficient cranking voltage to crank an engine and get it started, as shown in **Figure 3**. Once the engine begins to run, the generator (alternator) wakes up and takes over producing the vehicle's operating voltage.

A generator produces a charging voltage when the engine is running. Charging voltage operates the vehicle's electric loads and charges the battery at the same time. You should test a charging system for sufficient charging voltage under all modes of vehicle operation and varying electrical demands.

Figure 4 shows how to connect the DMM to test charging voltage. Put the DMM test leads on the battery terminals with the engine running. Typical generator voltage ranges from a low of about 13.8 volts to a high of not more than 15.2 volts.

The charging voltage produced by a properly functioning generator depends on engine rpm (high rpm means higher charging voltage; low rpm means lower voltage) and the amount of electrical demand on the generator (high demand means lower charging voltage; low demand means higher voltage). Practice checking several vehicles to educate yourself on the actual charging voltage for various makes and models for a given ambient temperature.

Simon says "I = E ÷ R"

'Simon (also and equivalently) says' the voltage and resistance in a circuit determine the current. Current (I) – amps – are directly proportionate to the voltage (E) and inversely proportionate to the resistance (R) in a circuit. **I = E ÷ R**.

'Simon says' current (amps) is determined by the voltage (volts) divided by the resistance (ohms).

Current is the movement of electrons through a circuit. **Figure 5** shows electron flow through a lamp circuit flowing from the negative terminal of the voltage source to the positive terminal. Electrons are negative charges, so current always flows from negative to positive through a circuit. Similar charges repel, and opposite charges attract. *Stop interrupting and sit down,* s'il vous plait. *Monsieur Ampere — we know you discovered current! Let's hear what Simon has to say!*

'Simon says' the two things determining the current in a circuit are how much voltage and resistance are present in the circuit. 'Simon says' if the voltage goes up, such as might happen if the charging voltage gets too high because of a generator or regulator problem, the current through the lamp goes up, and the lamp burns brighter. If current gets too high, it could burn out the lamp or at least shorten its life. If the voltage gets too low, the current through the lamp goes down, and the lamp glows dimmer. Any way you look at it, 'Simon says,' voltage and current stay directly proportional as long as the resistance is fixed.

'Simon also says' resistance affects current, so load resistance has a dramatic effect on current because the load is the only significant resistance in most circuits. If the load resistance goes down, load current increases. If load resistance increases — such as when a lamp with higher resistance is placed in the circuit — load current decreases. Any way you look at it, 'Simon says,' current and resistance are inversely proportional as long as the voltage is fixed.

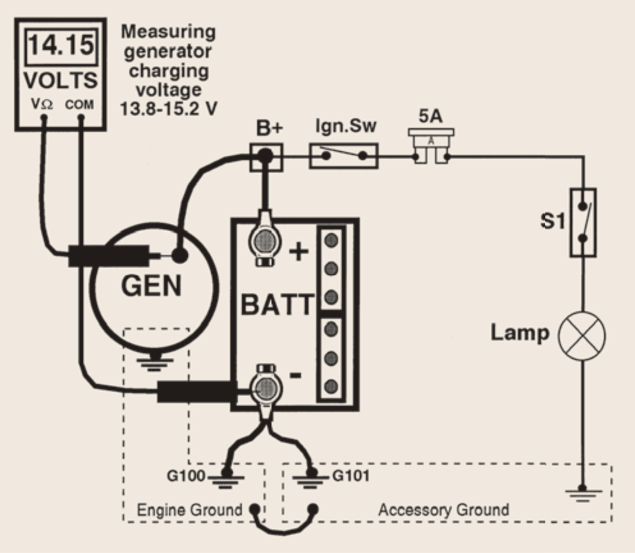


Figure 4: *Measuring Charging Voltage*

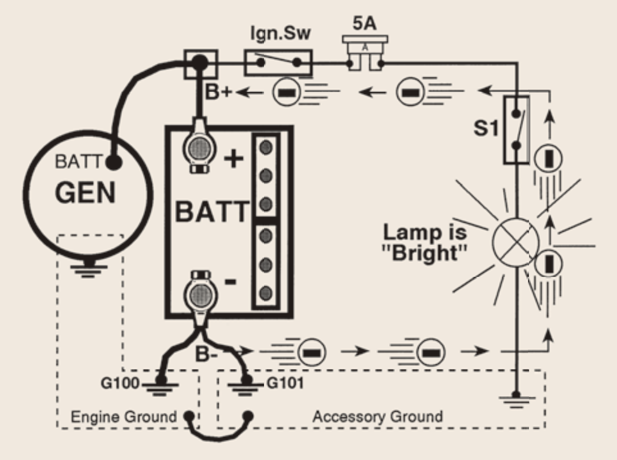


Figure 5: *Electron Flow*

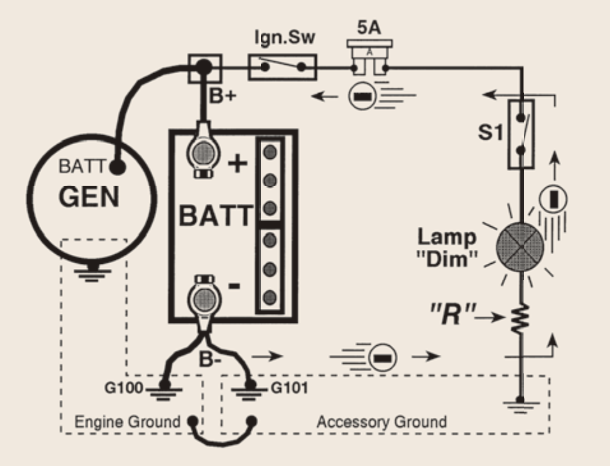


Figure 6: *Circuit Resistance*

"Simon Says..."

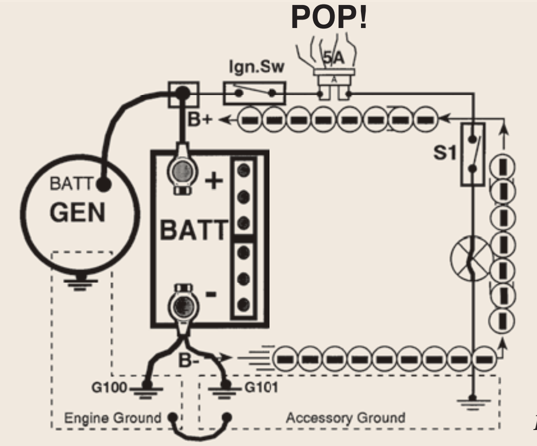


***Figure 7:** Short Circuit*

Simon says "R = E ÷ I"

'Simon says' to calculate the resistance by dividing the voltage by the current. 'Simon says' if you don't know the resistance, divide the voltage by the current. 'Simon also says' if resistance goes up, current must go down, as long as voltage stays fixed. And if resistance goes down, current will go up with the same proviso.

Figure 6 (on page 19) illustrates this inverse relationship. A high-resistance ground has added unwanted resistance to the circuit. The schematic indicates the high-resistance ground with a resistor symbol on the groundside of the lamp, between the lamp and ground. This flags a high resistance ground connection due, perhaps, to corrosion.

The extra resistance added to the circuit increases total circuit resistance and reduces the current through the circuit and the lamp. The extra resistance in the circuit makes the lamp dim because the total circuit current is lower.

'Simon says' the opposite is also true. If resistance goes down and voltage stays the same, current goes up. Suppose the load (our lamp) becomes shorted as illustrated in **Figure 7**. The circuit offers little or no resistance to current, and Simon says current will go very high. We know from our experience that high current will blow the fuse if the circuit is fuse-protected.

I don't believe Simon ever heard of a fuse. Certainly Monsieur Ampere could not have known about fuses because he couldn't make enough current to blow a fuse, even if he had one. *(Pardon, Monsieur Ampere! Sometimes the truth hurts.)* If the circuit is not fuse-protected, high current can heat and melt the wiring to a temperature that can cause an electrical fire.

'Simon also says' if the voltage side of the load is accidentally grounded, the lowered circuit resistance will result in high current. No matter how you look at it, 'Simon says,' current and resistance are inversely proportional. So long as the voltage stays constant, if one goes up the other must go down.

Herr Professor Doktor Georg Simon Ohm was the first guy to combine volts and amps into a complete electrical relationship by adding the missing ingredient — resistance — referred to in units called *ohms* in his honor. Georg Simon Ohm put it all together, and we've been using his concepts to understand how circuits work ever since. Pay attention to what Simon says. He knew what he was talking about, even if he didn't have an actual circuit to prove his argument. If he were here right now, he might ask you, "*Ist alles klar?*" It should be.

In the second part of this article, we'll apply the same principles to explain the operation of more complex circuits. ■

—By Vince Fischelli