Module 001: What is Resistance?

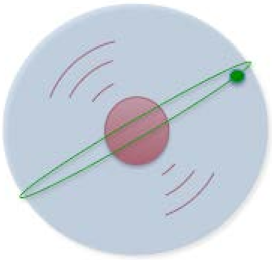
All materials have the ability to support some movement of charged particles, that is, to support "current". The measure of this ability is termed *conductivity* and is typically designated by the Greek letter σ ("sigma"). The higher the conductivity, the more readily that material supports current. The *resistivity* of a material is designated ρ ("rho") and is inversely related to the conductivity $\rho = 1/\sigma$. Some materials are very good at conducting current. Most of these are metals - elements like copper, silver, and gold. Some materials conduct current very poorly like glass or many types of plastic.

So what makes an electronic device a "resistor"? As the name implies, a resistor is a device that resists current flowing through it. In doing so, some of the electrical energy supplied to the circuit is dissipated as heat. With the proper choice of material resistivity and fabrication geometry, resistors can be manufactured that accurately *control* the amount of current flowing through the device. Resistors are circuit elements that closely follow Ohm's law $V = RI$. Many values of resistances are commercially available. Read more at http://www.resistorguide.com/resistor-values/.

We commonly perceive a wire as providing low loss connections between circuit elements. Wires are made of materials, most-commonly highly-conductive metallic elements like copper, and are typically fabricated into long strands of varying thickness. However, even the wire "traces" on most integrated circuit chips are made of the same metal as the wiring in your house. The conductivity of these metals is many orders of magnitude greater than the conductivity of the materials used to make most resistors. Whether a metal or a "resistor", at a microscopic level, we find that the physics is the same.

Conductivity is a bulk property of materials that depends on parameters associated with the atoms/molecules of the material, and the geometry of how the atoms/molecules are bonded, as well as externally imposed parameters like temperature. Let's look at a *representation* of what takes place inside a solid material at a microscopic scale to see how the conductivity and current flow are related.

Atoms are typically represented with a positively charged, relatively-heavy, nucleus (red) vibrating with an energy proportional to the temperature of the material (red lines) and the orbiting negatively-charged electrons (blue shell surrounding the nucleus). The representations are never really to-scale. The conductivity of a material is primarily a function of the ease at which electrons can be removed from the influence of nucleus. If you look at a periodic table and look at all of the materials we call metals they all share the same property – the outermost shell contains only one or two electrons. It is shielded from the positive charge in the nucleus by all of



Example of single atom with one electron in the outermost shell.

Gold with an atomic number of 79 is such a good conductor because the positively charged nucleus in almost completely shielded by the 78 electrons in stable orbits.

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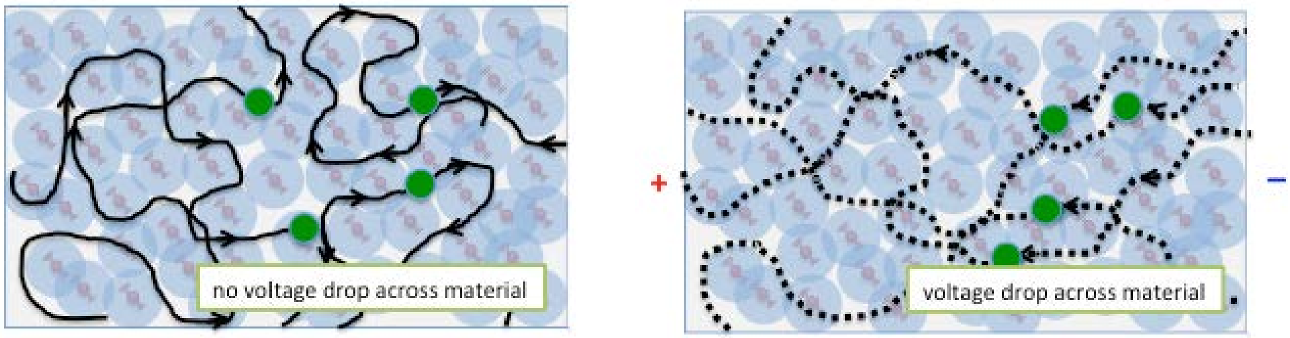
the other electrons making it easy to dislodge at room temperatures. These escaped electrons are represented by the green dots in the figures below.

If you were to look inside a piece of this substance you would see a lattice of atoms or molecules bonded in a structure that depends on the material. Even at room temperature the free electrons have sufficient kinetic energy to escape the influence of the atoms in the lattice. A region of that lattice missing an electron is positively charged. If a wandering electron comes close enough it can be re-captured. The electrons that have broken free navigate this minefield. Electrons are constantly recaptured while others break free. When a voltage is applied across the material, any free electrons feel a force (proportional to the voltage drop) tugging them in the direction of the terminal with the higher voltage. A very simplified view of the movement of these electrons in the absence of an electric field and in the presence of an electric field (voltage drop) is illustrated in the Figure 2(a).



(a) (b)

Figure 2: Artist's description of electron movement in a material (a) with no electric field applied and (b) in the presence of an electric field.

Without a voltage drop, the free electrons can move through the empty spaces in the material at close to the speed of light, but most are not energetic enough to be totally free of the influence of the positively charged regions. As an electron approaches a positively charged site its trajectory is modified (much like a comet approaching the sun). If the encounter is too close to the positively charged nuclei, the electron can get re-captured or even transfer some of its energy to a trapped electron knocking it free. Because the free electrons are influenced *randomly* by the thermal fluctuations in the vibrating lattice there is no net electric current.

Once a voltage is applied across the device the free electrons are still buffeted by the lattice, some are still captured by the lattice sites while others break free, but there is a net *trend* inside the material for the electrons to drift in a direction towards the higher voltage – Figure 2(b) illustrates this behavior. While each electron moves very quickly in the free space between lattice sites, the

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organized drift velocity is surprisingly slow. For a piece of copper (one of the better conducting materials) carrying a current of almost 50 A and sustaining a voltage drop of 1V, an individual electron (which can move at ~.5% the speed of light), might experience a drift velocity (movement due to the voltage) at most of a few millimeters per second. Unlike many of the software demonstrations of current flow, electric current is not a few free electrons racing around a circuit path, but instead current is countless electrons slowly drifting in the direction of (negative) current flow in the circuit path.

Material	Resistivity **ρ** (Ohm-m)	Conductivity **σ** (1/Ohm-m)
Teflon	$> 10^{23}$	
Air	$\sim 10^{16}$	
Salt Water	.2	5
Carbon Graphite – thin film graphite	$3x10^{-3}$ $5x10^{-6}$	$3.3x10^{2}$ $3x10^{5}$
Carbon Amorphous - carbon filled	$5x10^{4}$	$2x10^{5}$
Nichrome - wirewound	$1x10^{-6}$	$1x10^{6}$
Aluminum		$3.5x10^{7}$
Copper		$6x10^{7}$
Silver		$6.3x10^{7}$

Table 1: Resistivity and conductivity of several common materials.

The table above shows the resistivity and its inverse the conductivity of common materials. As you can see the range of resistivity/conductivity spans a range of over 10^{30}. The grey cells indicate materials commonly used to make resistors.

The main factors that determine the conductivity are:

i) The ease at which the electrons can be dislodged – For a given volume of material the easier it is to remove electrons the more electrons there are to make up current.

ii) The distance between the atoms in the lattice of the material – The more closely the spaced the atoms in the lattice the more often the free electrons are scattered or captured reducing their velocity and randomizing their direction of travel.

iii) The temperature of the material – As the temperature increases the atoms in the lattice vibrate with greater amplitude lowering the mobility of the free electrons.

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Electrical conductivity is often correlated with the thermal conductivity. Some of the same mechanisms that make a material a good conductor of heat also make them good electrical conductors. The units of resistance are Ohms. In SI units an Ohm is equal to *Volt/Amp* which, taking into account that Amp=*charge/time* is *Volt*Sec/Coulombs*.

Procedures

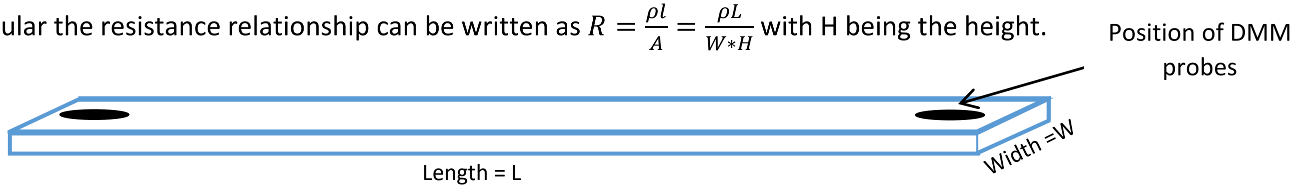
Modeling the behavior of a Resistor

Even though the physical behavior of current flowing through a resistor is enormously complicated if considered at scales much greater than quantum scales the bulk properties are surprisingly simple to quantify as Georg Ohm found in the early 1800's while putting together one of the first comprehensive books on connecting electromagnetics and circuit theory. This simple relationship between the voltage across a piece of material and the current flowing through the material $V = RI$ was met with derision at first. This linear relationship was empirically derived but Ohm constructed the mathematical framework to show how it fit with the rather new subject of electromagnetics. It was apparently worthy of descriptions such as "web of naked fancies" by the then-minister of Education in Germany.

Today we use Ohm's law as our simplest model of the I-V characteristics of a resistor. A resistor fails when a large enough voltage is placed across it, it draws a larger current (according to Ohm's Law), and dissipates power beyond its rated use until the resistor is destroyed in a puff of really bad smelling brown smoke. At this point your resistor likely contains an air gap and the resistivity is better given by that of air in the previous table!

The resistance of a piece of material can be computed if the resistivity is known and the geometry of the piece of material is also known. Most resistors are made using materials that are formed into easy to use geometries – like a cylinder. For any shape whose cross-sectional area does not change along its length the resistance R can be computed as $R = \frac{\rho l}{A} =$ resistivity*length/(cross-sectional area).

Some resistors are rectangular. Resistance is varied by altering the length and width. Since their cross-section is approximately rectangular the resistance relationship can be written as $R = \frac{\rho l}{A} = \frac{\rho L}{W*H}$ with H being the height.



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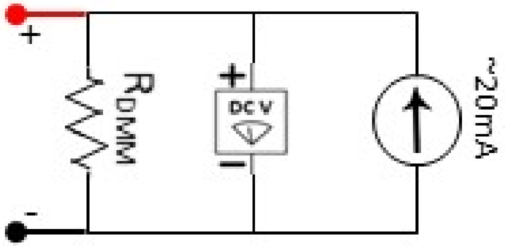
Experimenting with Making a Resistor

The devices we call “resistors” are designed through the choices of **material and geometry**. With easy-to-use materials – graphite in pencil lead and aluminum wire – you will explore this relationship. ***NOTE:*** *The measurement device you will use during this lab– the Digital Multimeter - only measures resistance Ω NOT resistivity ρ.* As you work through the procedures it will become clear how resistance and resistivity are related.

Let us illustrate how the Digital Multimeter (DMM) makes the resistance measurement. This voltage is provided by a nearly ideal current source in parallel with a resistance of R_{DMM}=1MΩ and an ideal voltmeter. A very small amount of current flows between the probes creating a voltage across R_{DMM}. The ideal voltmeter then measures the voltage across this internal resistor. The figure below shows a schematic of this simple model.



- ✓ Set the Digital Multimeter in the mode used to measure resistance.

All materials have the ability to conduct current. Conduction is the property associated with the resistivity. Measure the resistance of things around you – a pencil, your arm (don’t pierce the skin), the bench material, etc. – but heed this warning: **the DMM ohmmeter uses a voltage source to inject a small amount of current to make the measurement**. Use good judgment – trying to find the resistance of your partner’s eye is bad judgment. Record your measurements in the questions at the end of this document.

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Question 1: Write down the things you measured in Table 2 and whether they have high resistance (display reads OVLD), low resistance (display reads 0), or a measurable resistance (record the value).

Material	Resistance	Configuration and Comments

Table 2: Your measured resistances of various materials and structures.

Since you will be probing arbitrary surfaces, the measurements process can be tricky. The banana cables were designed to interface with a device with conducting leads. For example, if I hold one connector between my thumb and index finger and the other between my ring and little finger the resistance is 5-15 MΩ depending on how tightly I squeeze the connectors.

Question 2: Did the results surprise you? Most people can guess which materials are good conductors – materials with a low resistivity/resistance - by knowing which materials are good thermal conductors. There is often a high correlation between thermal and electrical conductivity. What property of the skin might make people decent conductors?

- ✓ Using any pencil, shade in the rectangle below. Make sure the line is fairly uniformly filled. Line dimensions: 6” x .25”

Question 3: Place one probe at one end of the line. With the other probe, take measurements along the line at different points. Label each point at which you took your measurement and write the resistance as measured by the DMM next to your mark.

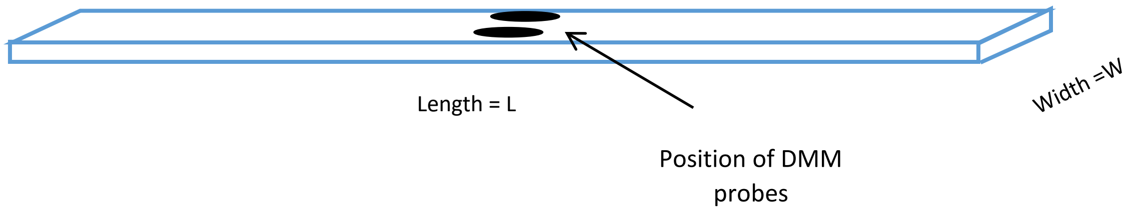
- ✓ Color the rectangle below with approximately the same darkness as before. The length of this second box is the same as the first but it is twice as wide. Line dimensions: 6” x .5”

Question 4: Repeat Question 3 using the larger rectangle. Try to make the measurements at approximately the same points.

Question 5: When you were probing the line at different points along the length of the rectangle you were actually measuring the same resistance as a rectangle snipped to that shorter length. Why does the resistance depend on where along the line you position the probe?

Question 6: Do your measurements agree with the formula $R = \frac{\rho l}{A} = \frac{\rho L}{W*H}$?

- ✓ Probe the line you drew for question 4 as shown in the figure below.



Question 7: Write down the result. Why is the value measured in this way different from that measured by probing the line at the ends.

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