Brass Tacks

An in-depth look at a radio-related topic

Conductors

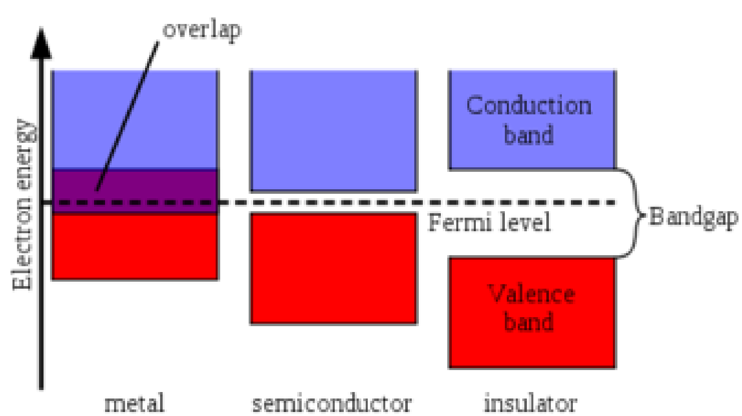
When discussing electronics or electrical topics, it seems easy to become so deeply involved with a subject that I often overlook a significant one that's hiding in plain sight : the wires. In fact, not just wires, but anything that can conduct electricity. The word ***conductor*** can refer to a material that can permit the transfer of thermal (heat) energy, sound, kinetic energy, and ionic movement, but our discussion is strictly electrical.

An electrical conductor is a material that permits the flow of electrical current through it. *A word of caveat: I've linked this paragraph to the Wikipedia article that attempts to describe an electrical conductor, but I personally find the article woefully inaccurate in places and sorely lacking in detail, so I encourage you to access more than one source for education and verification.*

How a conductor conducts

The nucleus of each atom is normally orbited by one or more electrons. They don't all travel around in perfectly spherical patterns, as is often depicted, but the outermost electrons reside within two occupation regions, known as ***energy bands***. These are so-called because electrons must be excited (absorb more energy) to move from one region to occupy an outer region. The inner of these two is the valence band and the outer is the conduction band, with a band gap (the "forbidden" band) in between them, in which no electron can exist.

An electron in the valence band tends to remain within its region until sufficient energy is provided by a nearby atom or other energy source (such as light or heat) to allow it to be either shared or moved out altogether. When an electron is shared, it eventually returns to the atom where it came from, and we call that a covalent bond between the two atoms. In the case for which the electron doesn't return to the atom where it came from, it simply travels into the conduction band, then to another atom while receiving a replacement electron, a process we call electric current because each electron contributes to a "river" that "flows" from one atom to another.



The larger the band gap in an atom, the more energy is required to move an electron across it into the conduction band, where it can freely move to another atom. In some atoms,

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the band gap is large, and we call the materials made from them ***insulators***. In some, the band gap is very small or non-existent, and we call the materials made from them ***conductors***. Most metals are made from atoms with no band gap, so their electrons require very little energy to move from one band to the next, and therefore from one atom to the next.

An imperfect world

Because the band gaps differ in width between different conductors, each conductor differs in its ***conductivity*** from that of other conductors. The greater a material's conductivity over that of another, the more easily it conducts electricity, a property we refer to as ***conductance***, typically symbolized by the uppercase ***G*** and measured in siemens (S, or Ω^{-1}). Silver is the metal exhibiting the greatest conductivity, with copper and gold following closely.

In a previous article we discussed the property of resistance in terms of a material's ability to reduce the flow of electrons in a conductor. It turns out that resistance is the reciprocal of conductance, or **R** = **1**/**G** for a given material. The following table lists the resistivity (Ω-m) and conductivity (Ω^{-1}/m, or S/m) of a few materials, especially metals:

Material	Resistivity	Conductivity
Silver	1.59×10^{-8}	6.30×10^{7}
Copper	1.68×10^{-8}	5.96×10^{7}
Gold	2.44×10^{-8}	4.10×10^{7}
Aluminum	2.82×10^{-8}	3.5×10^{7}
Calcium	3.36×10^{-8}	2.98×10^{7}
Zinc	5.90×10^{-8}	1.69×10^{7}
Lithium	9.28×10^{-8}	1.08×10^{7}
Iron	1.0×10^{-7}	1.0×10^{7}
Lead	2.2×10^{-7}	4.6×10^{6}
Titanium	4.2×10^{-7}	2.4×10^{6}
Stainless steel	6.9×10^{-7}	1.45×10^{6}
Mercury	9.8×10^{-7}	1.02×10^{6}
Sea water	0.2	4.8
Silicon	6.4×10^{2}	1.56×10^{-3}
Distilled water	1.8×10^{5}	5.5×10^{-6}
Glass	1.0×10^{10}	1.0×10^{-11}
Air (average)	1.3×10^{16}	3.0×10^{-15}

The conclusion you might reach from this table is that ***there is no perfect conductor*** and ***there is no perfect insulator***. Even a superconductor has its limitations.

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Wires

Although we amateurs are likely familiar with many forms of electrical conductors, such as a patio awning, a car body, or a lake, a wire is probably the one ***designed to conduct electricity*** with which we are most acquainted. Others designed for electric current might include an antenna, a household electrical plug, or a battery terminal, but for a moment I'd like to focus on the omnipresent special case that we often use for connecting one electrical component with another.

A wire is often seen as a long, thin cylinder of metal, yet can appear in other shapes, as on a printed circuit board or a ribbon cable. Often, a wire can be collectively considered, such as a conductive bundle of thinner wires in a thicker *stranded* set, which is often regarded as a single wire, such as a high-voltage power line or one side of an extension cord to an outlet.

In whatever form they're manifest, each wire is typically specified by a rating system centered around its ***ampacity***, or current-carrying capacity up to a maximum temperature for its specific cross-sectional area. The following table lists the *American Wire Gauge* sizes for copper (the most common household wire material) and their associated ampacities:

Gauge	Diameter (in)	Current to 60°C	Current to 90°C
00	0.3648	145 A	195 A
0	0.3249	125 A	170 A
2	0.2576	95 A	130 A
4	0.2043	70 A	95 A
6	0.1620	55 A	75 A
8	0.1285	40 A	55 A
10	0.1019	30 A	40 A
12	0.0808	20 A	30 A
14	0.0641	15 A	25 A
16	0.0508	12 A	18 A
18	0.0403	10 A	16 A
22	0.0253	3 A	N/A *

* 22 AWG wire isn't rated for 90°C because that's not a practical heat application for most terminals at that size, not because the wire itself is unable to handle the heat.

Other conductor types

Numerous types of conductors have been manufactured for electrical use besides wires and leads, such as ground rods, block terminals, and bus (not "buss" which is a company name) bars. I tend to categorize most of these for "conventional" use; that is, they don't require any

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chemical or physical modification to perform their intended function. This can be true for connectors, contacts, sockets, switches, slots, straps, foil, braid, panels, hardware (nuts, bolts, screws, washers, etc.) and much more.

I often categorize some electrical conductors by "special" use case, such as the following:

- **Semiconductors** : including transistors, diodes, LEDs (light-emitting diodes), and ICs (integrated circuits, which function according to applied voltages or currents to chemically modified insulators)
- **Fuses** : intended to melt and open a circuit immediately after a specific amperage level is exceeded (fast-blowing) or after a specified period of time (slow-blowing)
- **Solder** : intended to melt and electrically fuse wires and/or terminals together as though they were a single conductor; welds might also fit into this category
- **Incandescent filaments** : the little, curly wire that glows (and outputs light or heat or both) once an appropriate amount of voltage is placed across its terminals; the heating filaments in electric ovens and Styrofoam cutting wires also apply

Properties that affect conductivity

As previously mentioned, we tend to rate ampacities of wires according to their diameters for a particular material. But conductors aren't always perfectly round, and in fact their conductivity and other electrical capacities can depend on their dimensions, or ***geometry***. In particular, the resistance of a conductor is directly proportional to its material resistivity and length, and inversely proportional to its cross-sectional area.

Amtrak conductor

The above chart indicates allowable amperage for each wire up to a specific temperature, because heat affects the conductivity of materials as well. As temperature in a metal rises, its atoms and molecules vibrate farther apart, resulting in its physical expansion, which is directly related to its increase in resistivity, and therefore its reduction in conductivity.

The inherent (built-in because of the material type) resistivity of a material is dependent on the complete mixture of the material if the material is made of multiple substances. Several metals mixed as an alloy, or a combination of conductive substance and a ceramic like in a resistor, possess a unique resistivity distinct from that of any single substance. Therefore, material composition uniformity and material density uniformity also contribute to material resistivity, and therefore conductivity.

While addressing resistivity and conductivity, we must also consider conductor impedance when we include frequency-dependent compound conductors, such as coaxial cable and other transmission lines in the discussion. In other words, while a particular conductor exhibits a set resistance in direct current conditions, its opposition to current flow might be very different in the presence of an alternating current.

Furthermore, we must take the skin effect into account for a conductor in which the flowing

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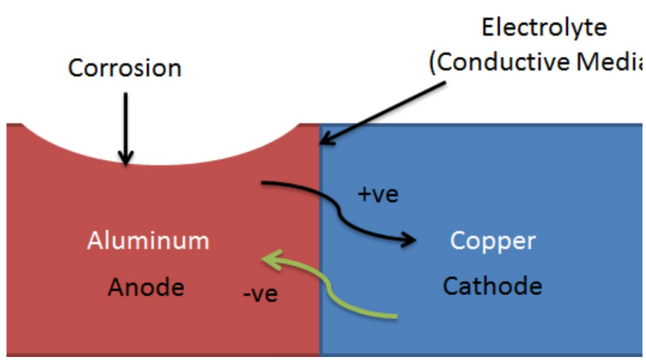
current alternates at a particular frequency. The higher the alternating frequency, the less current actually flows in the center of the conductor, increasing the percentage of the total current flowing closer to the conductor “skin” or surface. And because less conductor cross-section is available for carrying electrical current, the greater its resistance.

Conductor considerations

Stretch and sag : Many conductors, especially metals, possess the *plastic* property of malleability; that is, they can be molded, hammered, rolled, and pressed. Unfortunately for us amateurs, it also means they can stretch and sag. If I cut a wire for 80 meters and leave it hanging from two supports, I expect that wire to maintain the same length forever. Unfortunately, some metals, like copper, stretch easily, and not only do my antenna elements become too long with time, they can sag far enough to come undesirably close to other objects. Some wire manufacturers combine metals to prevent sag, like for long-distance high-voltage power lines.

Corrosion : It’s common practice to combine metals for strength and other reasons, but that combination often comes with a cost. When two metals made of different substances contact each other while carrying electrical current, they often suffer the effects of dissimilar metals, known as *galvanic corrosion*. This can turn a perfectly good-conducting connector into a near-insulator, especially if left out in the weather, where water becomes an effective electrolyte between the two.



The result of galvanic corrosion can be high SWR, intermittent connection, or even arcing; a friend might complain about a hum in your signal that wasn’t there previously. As much as possible, avoid making or purchasing devices made with visible electrical conductors of two different metals in contact with each other, like coax with overlapping shielding of dissimilar metals or copper rods tightened onto a steel plate. Where these are exposed to humidity while electrical current is running through them, galvanic corrosion can result, in many cases causing one or both conductors to eventually disintegrate at the joint.

Oxidation : Not unlike galvanic corrosion, *metallic oxidation* plays a role in conductor behavior, whether or not an electrical current is involved. Oxidation is the chemical change of a metal exposed to air or water, like rust for iron. Metal oxides actually help protect the conductor from further exposure to a small extent, but they also prevent a good connection with another conductor. Before connecting metal conductors that have been sitting unused for many days, sand or scrape the oxide from their contact locations as much as you can. Using stainless

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hardware can be a good preventive measure against oxidation.

Bare vs. insulated : One question that seems to surface occasionally is whether to use bare or insulated wires for various purposes. Technically, an insulated wire does possess slightly different electrical characteristics from that of a bare wire, such as velocity factor, capacitance, and inductance, but in most cases these differences are negligible. The largest considerations for deciding between insulated and uninsulated wire use are typically corrosion and electrical danger. If you mount a dipole low enough for people to touch from the ground, it's probably best to use insulated; otherwise, it really makes no noticeable difference. If you bury a radial wire, its best to use insulated, which will still contact the Earth through capacitive coupling, but bare wire will eventually require you to replace the radial because of the oxidation and corrosion combination.

Human body : Pure water is a poor conductor, as seen in the chart above. But most water we encounter is not very pure, especially that in our bodies. Because of that, we human beings are conductors, not very good conductors, but conductors we are. This is because many substances dissolve and dissociate in water, thereby ionizing it into a conductive medium. As a result, a high enough voltage placed across the optimum locations on a human body for a sufficient amount of time can cause enough current to flow through the organs that are most dear to us, disrupting their normal functions.

Velocity factor

Similar to light through glass or water, electricity travels through different conductors at different speeds, each measured as a percentage of the speed of light. This percentage is a frequency-independent and unitless property known as ***velocity factor*** (VF), and can play an important role in amateur radio, primarily in antenna phasing harnesses and feed lines (coaxial cable and other signal transmission lines). Understand that *electricity* refers to the electrical energy that's being propagated in a wire, not to electrons, which travel much slower than the speed of sound, let alone the speed of light. The following table lists the **signal loss per 100 feet** and velocity factor for a few common 50-ohm coaxial cable models:

Coax type	Power (2 meters)	Loss (20 meters)	Loss (2 meters)	VF
RG-58	240 W	1.7 dB	5.6 dB	0.66
RG-8X	150 W	1.3 dB	4.5 dB	0.82
LMR-240	660 W	0.9 dB	3.0 dB	0.84
RG-213	840 W	0.7 dB	2.4 dB	0.66
RG-8	840 W	0.7 dB	2.4 dB	0.66
LMR-400	1480 W	0.5 dB	1.5 dB	0.85

Because signals in a wire or cable travel slower than the speed of light, the slower propagation speed makes the conductor appear shorter than it actually is. This effect gives rise to the wire's ***electrical length***, which is a percentage of its physical length, reflected by the velocity factor. For example, the length of a single dipole element (wire or aluminum tube for instance)

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is **234** ÷ **f** (MHz) = **L** (feet) if the element was a perfect conductor. But since electrical energy takes time to travel its length, if the element is cut to **L** feet long, it'll be too long, resulting in excessive signal reflection and therefore potentially high SWR. If you cut it for **L** x **VF** feet, however, it'll be resonant at **f** MHz for your dipole, minimizing its SWR.

Velocity factor is largely due to the dielectric for a two-conductor cable; in fact, the VF equals *the reciprocal of the square root of the dielectric constant* for a particular two-conductor cable, such as coax. For a single-conductor wire, the voltage on the wire is often referenced to ground, so the ground can be considered the "other conductor" in the supposed pair, and the dielectric would therefore be air, making the VF very close to 0.99 or higher.

Finally

We tend to take conductors for granted, and in most cases that's not a problem. Most people don't really care how or why a conductor conducts electricity, only that it does. For the curious, however, these paragraphs might provide a few insights on how that works, including some of the theory that supports its relevance to electrical knowledge in general, if not specifically amateur radio.

Our discussion on conductors probably wouldn't be complete without some reference to insulators, their seeming opposite. An electrical insulator is a material through which electrical current does not flow freely or easily. (A particular type of electrical insulator, one typically used for outdoor long-distance power delivery lines, is a special case of our general insulator discussion.) In many cases, insulation is installed or applied in an effort to inhibit the flow of electrical current, which is essential for electrical shock prevention or other safety measure. To help maintain signal integrity, insulators also keep conductors from accidentally contacting each other, like inside an electrical appliance or electronic device.

Like conductors, insulation is rated for their ability to maintain electrical separation, especially in electrical power applications, such as with power supplies, house wiring, or extension cords. Insulation ratings are determined largely by breakdown voltage (maximum voltage the insulator can reliably prevent arcing) and temperature for the particular material in question. Insulation is also classed for separation ability from weather, chemical, or other non-electrical and undesirable environmental hazards.

Summary

An electrical conductor is a material that permits the flow of electrical current. One material conducts electricity better than another because less energy is required to move electrons from its valence region to its conduction region. Conductivity varies widely among different materials, but there is no perfect conductor and no perfect insulator. The available conductor variety requires us to select an appropriate material for a particular application. The electrical wire is perhaps the conductor most familiar to radio amateurs. Geometry affects a material's conductivity, but so does temperature and signal frequency.

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