Resistance :

If we look a little more closely into how charge flows in a conductor, we see that the electron is essentially free to move about the metal conductor material. The electron roams about the conductor, dropping in and out of various valance shells of the metal atoms or wanders between the atoms. Note, as the electron moves about and eventually hits another metal lattice atom and absorbed into its valence shell, it will give up some of its energy in the form of heat. Since no voltage has been applied to the conductor the process will be totally random with no total electron flow in any one direction. Under these conditions, the current is said to be zero.

In summary, when a free electron hits a lattice atom, energy is lost as heat and the electron winds up in the valence shell. So the lattice atom in a sense offers a resistance to the flow of charge or free movement of the electron about the conductor material. The conductor material that exhibits this property is then said to be resistive. Components that are designed to offer varying degrees of resistance to the flow of charge are called Resistors. The electrical symbol used for a Resistor is shown in fig.- 14.

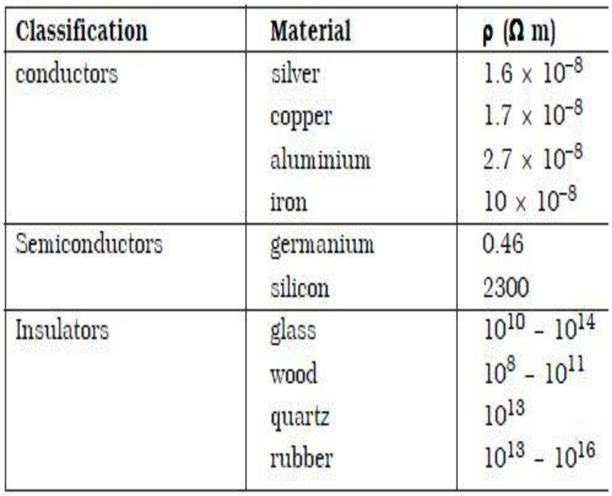
Fig. – 16

Even though conductors have been discussed here, it can be said that the resistance is essentially a function of the material used. So this resistance can apply to any material in general that includes semi-conductors and insulators. The semi-conductor can offer a very wide range of resistance going from that of metal conductor to an insulator. So the highest resistance to the flow of charge would be that of an insulator and why they are used as insulation material to cover metal conductors that need to be isolated electrically from other objects. The plastic material the covers electrical house wiring would be an example of that.

The resistance of a metallic conductor is directly proportional to the length of the conductor and inversely proportional to its cross-sectional area. Therefore the resistance of a specific type of conductor material would be a function of what was just stated and the type of material used, called its resistivity (ρ). Stated in equation form,

$$R = \rho\left(\frac{L}{A}\right) \quad \text{units are “Ohms”} \qquad (14)$$

The terms **ρ** is the Resistivity of the material in Ohm-Meters, **L** is the length in Meters and **A** the cross-sectional area in square Meters. Note, the Resistivity is a physical property of the material which is dependent on temperature. The table in Figure 17 list the Resistivity of some typical materials ranging from metals to insulators. In Figure 18 is a scale drawing comparing some solid wire sizes with reference to their wire gage number (AWG) and a end view of a segment of stranded wire. Note in this case the stranded wire is made up of seven smaller gage solid wire segments that are twisted around a central wire, all making electrical contact where each wire touches each other.



Classification	Material	ρ (Ω m)
conductors	silver	1.6×10^{-8}
	copper	1.7×10^{-8}
	aluminium	2.7×10^{-8}
	iron	10×10^{-8}
Semiconductors	germanium	0.46
	silicon	2300
Insulators	glass	10^{10} - 10^{14}
	wood	10^{8} - 10^{11}
	quartz	10^{13}
	rubber	10^{13} - 10^{16}

Fig.- 17

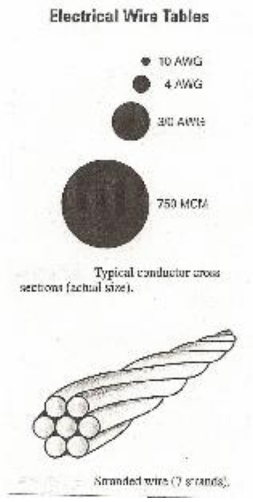
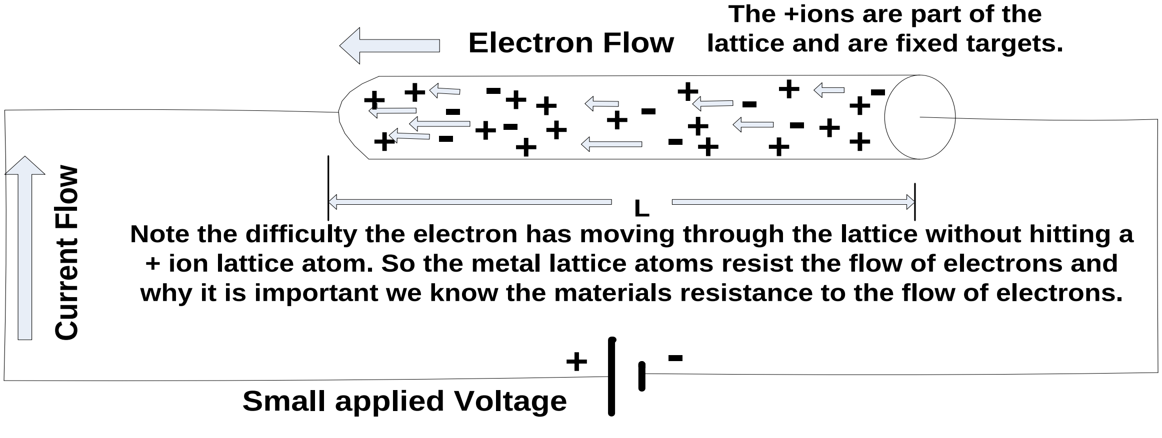


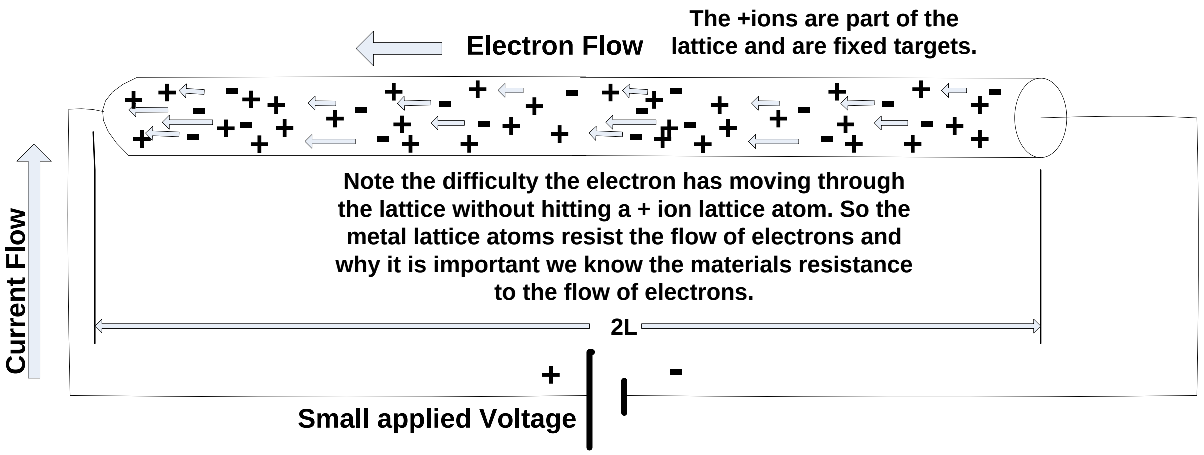
Fig. – 18

Looking at equation 14 it is noted that the resistance is proportional to the length of a conductor. So as the conductor gets longer with the area remaining constant, its resistance goes up. Does this make sense ? The answer is yes. In order to investigate this further lets first apply a voltage across both ends of a metal conductor. This applied voltage will then apply a force to the charge in that conductor forcing the charge to drift (flow)in one direction. This defines the current in this conductor and its numeric value is determined by how difficult it is for the charge make its way through the conductor. Remember the conductor lattice atoms present targets for the electron (charge) to hit thus slowing down the progress of the electron traveling through the conductor. Now if the length (L) of the conductor Fig. 19 was doubled (2L) Fig. 20, area remaining constant, the difficulty to travel down the conductor would be doubled, verifying the above proportionality statement.



Note the difficulty the electron has moving through the lattice without hitting a + ion lattice atom. So the metal lattice atoms resist the flow of electrons and why it is important we know the materials resistance to the flow of electrons.

Fig.- 19

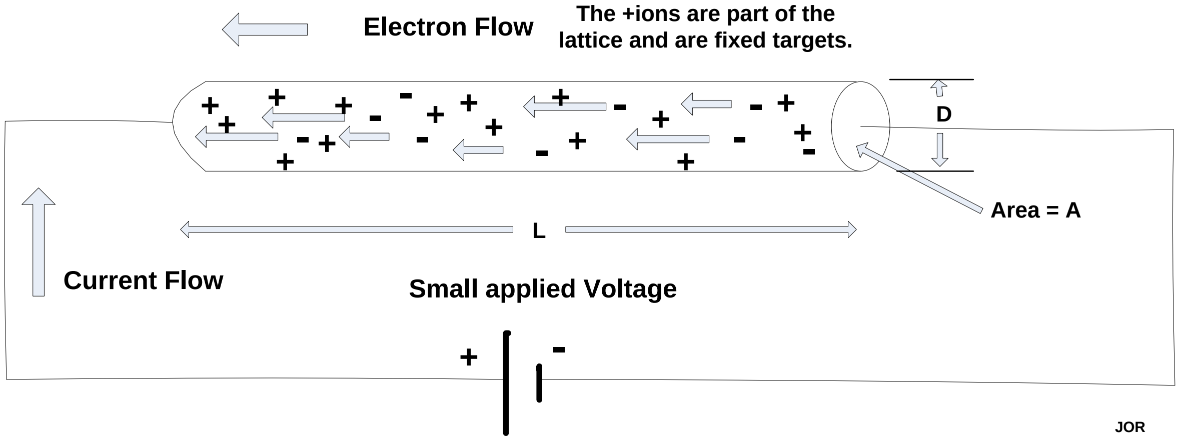


The +ions are part of the lattice and are fixed targets.

Note the difficulty the electron has moving through the lattice without hitting a + ion lattice atom. So the metal lattice atoms resist the flow of electrons and why it is important we know the materials resistance to the flow of electrons.

Fig.- 20

The resistance is also inversely proportional to the cross-sectional area of the conductor. If the wire diameter gets wider the cross-sectional area will get larger making it much easier for the electrons to move between the lattice atoms. Since the electrons are no longer confined to a narrow cross-sectional area it has a better chance of moving between the lattice atoms lowering its resistance to flow through the wire.



The +ions are part of the lattice and are fixed targets.

Fig.- 21

For example, in figure 21 above, the electrons free path before a collision with a lattice atom is about one quarter that of the conductor in figure 22. Looking at that from another point of view. It can also be said that the free path of the electron before a collision with a lattice atom in figure 22 is four times that of the conductor in figure 21.

In figure 21,

$$\text{Area} = A = (\pi)(r^2) = (\pi)\left(\frac{D}{2}\right)^2 \qquad (15)$$

$$R_1 = \rho(\frac{L}{A}) = \rho(\frac{L}{(\pi)(\frac{D}{2})2}) = 4(\frac{\rho L}{\pi D^2}) \quad \text{for wire diameter = D} \qquad (16)$$

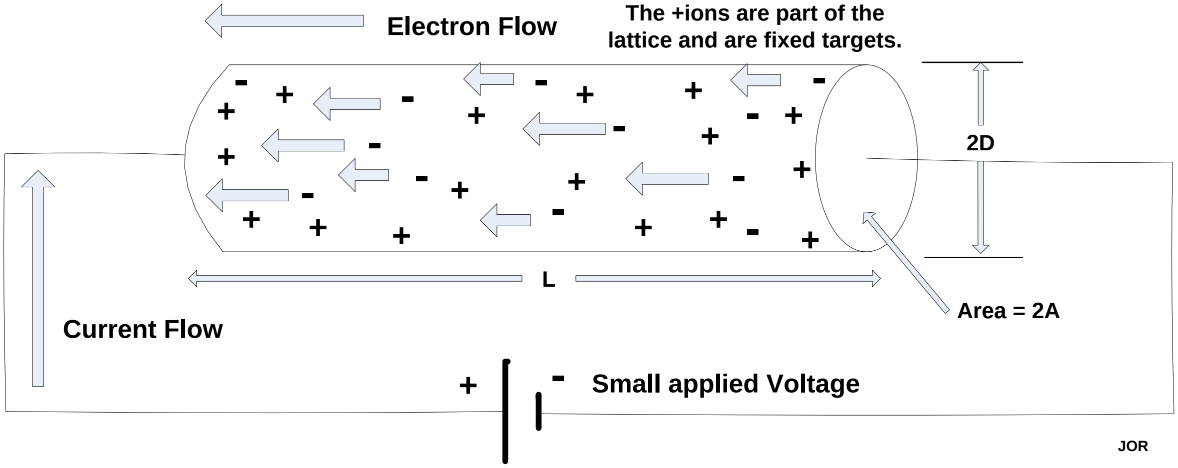


Fig.- 22

$$R_2 = \rho(\frac{L}{A}) = \rho(\frac{L}{(\pi)(\frac{2D}{2})2}) = 4(\frac{\rho L}{\pi 4D^2}) = (\frac{\rho L}{\pi D^2}) \quad \text{for wire diameter = 2D} \qquad (17)$$

$$R_2 = \frac{1}{4} R_1 \qquad (18)$$

This result says the wire with twice the diameter (2D) has one quarter the resistance as the shorter diameter (D) wire.

In summary, for a fixed diameter wire, the resistance goes up proportionally as the wire length increases. Given a fixed length wire, the resistance goes down as the diameter increases. Remember in this case the resistance is inversely proportional to the cross-sectional area, not the diameter directly.

What does all this mean ? It means that the longer the electron is free in a conductor the lesser the resistance to its flow. This effectively means its resistance is smaller than a conductor that has a shorter electron free path.

The Practical Calculation of Resistance :

The resistance of any material with a uniform cross-sectional area maybe determined by the following four factors :

1. Length.
2. Type of Material.
3. Its Temperature.
4. Its cross-sectional area.

For a fixed temperature of 20^0C, the Resistance may be expressed as,

$$R = \rho(\frac{L}{A}) \qquad (19)$$

Example : An engineer needs to find the resistance of 100 feet of solid copper wire. Using a micrometer he determines the diameter is 0.1 inches.

Converting the diameter to meters,

$$D = 0.1 \text{ in} = (0.1\text{in})(2.54 \text{ cm/in}) = 0.245 \text{ cm} = 2.54 \times 10^{-3} \text{ m}$$

Converting the length to meters,

$$100 \text{ ft} = (12)(100) = (1200 \text{ in})(2.54 \text{ cm/in}) = 3048 \text{ cm} = 30.48 \text{ m}$$

Defining the resistivity in MKS units,

$$\rho = 1.68 \times 10^{-8} \ \Omega\text{-m} \text{ or } 1.7 \times 10^{-8} \ \Omega\text{-m}$$

Calculating the area,

$$A = \frac{\pi D^2}{4} = \frac{\pi(0.00254)^2}{4} = 5.064\text{x}10^{-6}$$

Finally, calculating the resistance,

$$R = \rho(\frac{L}{A}) = \rho(\frac{L}{A}) = (1.7 \text{ x}10^{-8})(\frac{30.48}{5.064\text{x}10^{-6}}) = 0.102 \text{ ohms}$$

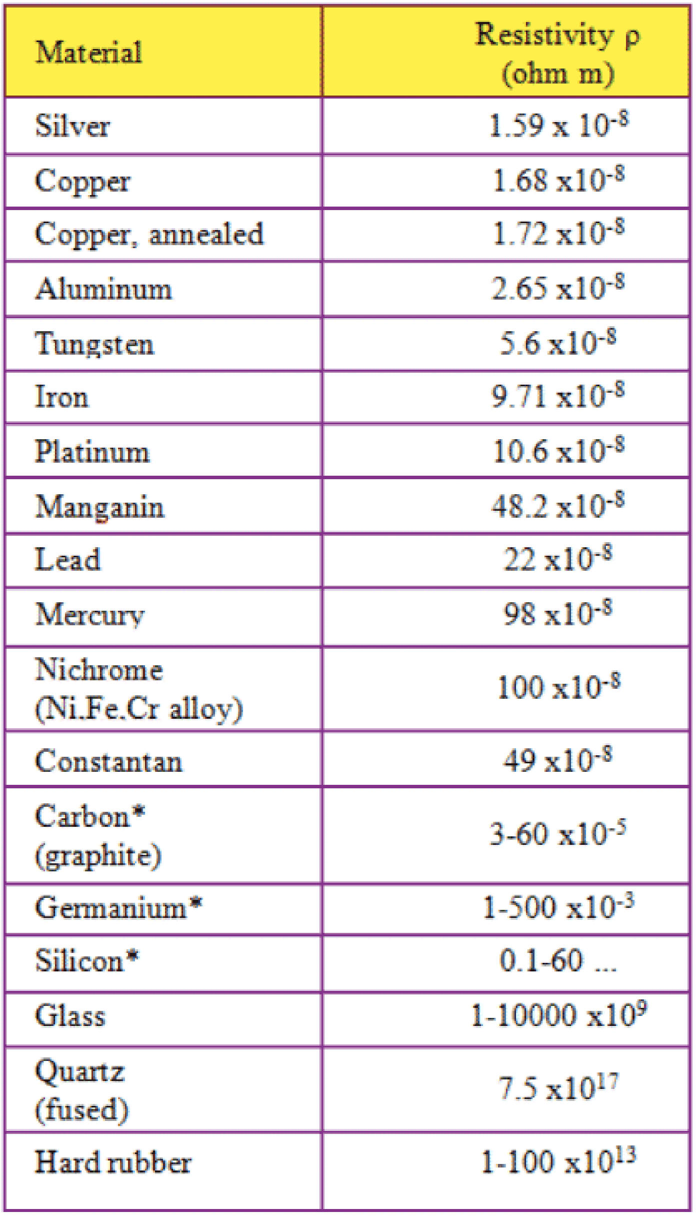
The Table on the next page shows the wire gauge(AWG), diameter, area and the current carrying capacity of various sizes of copper wire. This table is very useful since wire is purchased and identified by the AWG (wire gauge number) not its diameter. The AWG also notes the safe current carrying capacity of that size wire which is also a function of the insulation that is covering the wire in question, which is not noted in this table.

A common use of this table is to look up the maximum current that would be flowing in your circuit and then pick the next size up wire gauge (AWG) which is a lower AWG. Please note, the larger the AWG number the smaller the wire and lower current carrying capacity.

This table is for standard copper wire at temperature = 20°C.

Size	Diameter		Area		Resistance	Current Capacity
(AWG)	(inches)	(mm)	(CM,	(mm²)	(Ω/1000 ft)	(A) AMPS
56	0.0005	0.012	0.240	0.00012	43 200	
54	0.0006	0.016	0.384	0.00019	27 000	
52	0.0008	0.020	0.608	0.00030	17 000	
50	0.0010	0.025	0.980	0.00049	10 600	
48	0.0013	0.032	1.54	0.00077	6 750	
46	0.0016	0.040	2.46	0.00125	4 210	
45	0.0019	0.047	3.10	0.00157	3 350	
44	0.0020	0.051	4.00	0.00243	2 590	
43	0.0022	0.056	4.84	0.00245	2 140	
42	0.0025	0.064	6.25	0.00317	1 660	
41	0.0028	0.071	7.84	0.00397	1 320	
40	0.0031	0.079	9.61	0.00487	1 080	
39	0.0035	0.089	12.2	0.00621	847	
38	0.0040	0.102	16.0	0.00811	648	
37	0.0045	0.114	20.2	0.0103	521	
36	0.0050	0.127	25.0	0.0127	415	
35	0.0056	0.142	31.4	0.0159	331	
34	0.0063	0.160	39.7	0.0201	261	
33	0.0071	0.180	50.4	0.0255	206	
32	0.0080	0.203	64.0	0.0324	162	
31	0.0089	0.226	79.2	0.0401	131	
30	0.0100	0.254	100	0.0507	104	
29	0.0113	0.287	128	0.0647	81.2	
28	0.0126	0.320	159	0.0804	65.3	
27	0.0142	0.361	202	0.102	51.4	
26	0.0159	0.404	253	0.128	41.0	0.75*
25	0.0179	0.455	320	0.162	32.4	
24	0.0201	0.511	404	0.205	25.7	1.3*
23	0.0226	0.574	511	0.259	20.3	
22	0.0253	0.643	640	0.324	16.2	2.0*
21	0.0285	0.724	812	0.412	12.8	
20	0.0320	0.813	1 020	0.519	10.1	3.0*
19	0.0359	0.912	1 290	0.653	8.05	
18	0.0403	1.02	1 620	0.823	6.39	5.0†
17	0.0453	1.15	2 050	1.04	5.05	
16	0.0508	1.29	2 580	1.31	4.02	10.0†
15	0.0571	1.45	3 260	1.65	3.18	
→ 14	0.0641	1.63	4 110	2.08	2.52	15.0† ←
13	0.0720	1.83	5 180	2.63	2.00	
12	0.0808	2.05	6 530	3.31	1.59	20.0†
11	0.0907	2.30	8 230	4.17	1.26	
10	0.1019	2.588	10 380	5.261	0.998 8	30.0†
9	0.1144	2.906	13 090	6.632	0.792 5	
8	0.1285	3.264	16 510	8.367	0.628 1 →	45
7	0.1443	3.665	20 820	10.55	0.498 1	
6	0.1620	4.115	26 240	13.30	0.395 2 →	65
5	0.1819	4.620	33 090	16.77	0.313 4	
4	0.2043	5.189	41 740	21.15	0.248 5 →	85
3	0.2294	5.827	52 620	26.67	0.197 1 →	100
2	0.2576	6.543	66 360	33.62	0.156 3 →	115
1	0.2893	7.348	83 690	42.41	0.123 9 →	130
1/0	0.3249	8.252	105 600	53.49	0.098 25 →	150
2/0	0.3648	9.266	133 100	67.43	0.077 93	175
3/0	0.4096	10.40	167 800	85.01	0.061 82	200
4/0	0.4600	11.68	211 600	107.2	0.049 01	230

Material	Resistivity ρ (ohm m)
Silver	1.59×10^{-8}
Copper	1.68×10^{-8}
Copper, annealed	1.72×10^{-8}
Aluminum	2.65×10^{-8}
Tungsten	5.6×10^{-8}
Iron	9.71×10^{-8}
Platinum	10.6×10^{-8}
Manganin	48.2×10^{-8}
Lead	22×10^{-8}
Mercury	98×10^{-8}
Nichrome (Ni,Fe,Cr alloy)	100×10^{-8}
Constantan	49×10^{-8}
Carbon* (graphite)	$3\text{-}60 \times 10^{-5}$
Germanium*	$1\text{-}500 \times 10^{-3}$
Silicon*	0.1-60
Glass	$1\text{-}10000 \times 10^{9}$
Quartz (fused)	7.5×10^{17}
Hard rubber	$1\text{-}100 \times 10^{13}$



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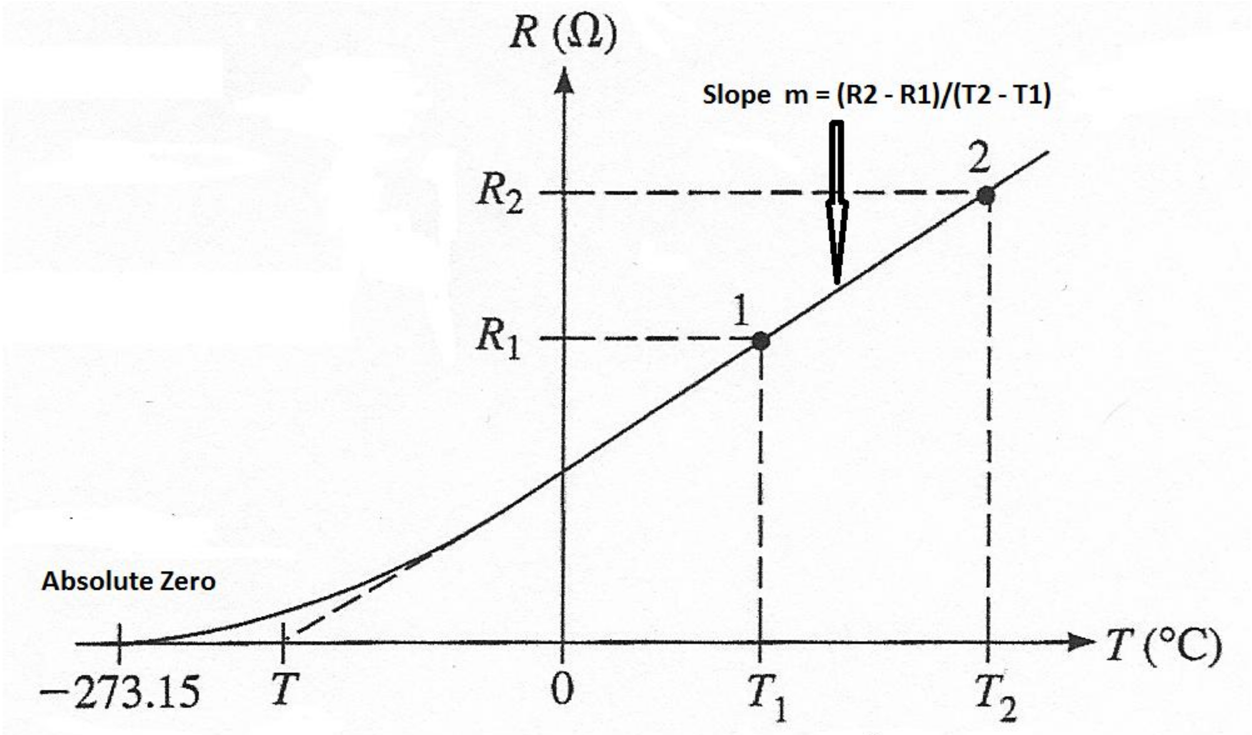
Glass	$1\text{-}10000 \times 10^{9}$
Quartz (fused)	7.5×10^{17}
Hard rubber	$1\text{-}100 \times 10^{13}$

Temperature effects on Resistance :

The resistance of a conductor does chance with temperature. This effect is more noticeable as the applied voltage increases, the current that is flowing through the conductor increases. When both the voltage and current increase, the power dissipated in the conductor increases. This power is dissipated as heat in the conductor causing its temperature to rise. What is discovered from this effect is that the resistance of the conductor also increases an effect that is not always discussed. So in general it is important that know what the relationship between resistance and temperature looks like. This relationship is shown in the plot below.



Resistance Change with Temperature

This plot shows that the resistance increases as the temperature is increased from approximately absolute zero (**T**) to temperature ($\mathbf{T_2}$). Note the plot in the positive temperature range is linear which allows us to find a simple analytic solution in terms of resistance and temperature.

Using similar triangles, the following relation is obtained,

$$\frac{R_2 - 0}{T_2 - T} = \frac{R_1 - 0}{T_1 - T} \qquad (20)$$

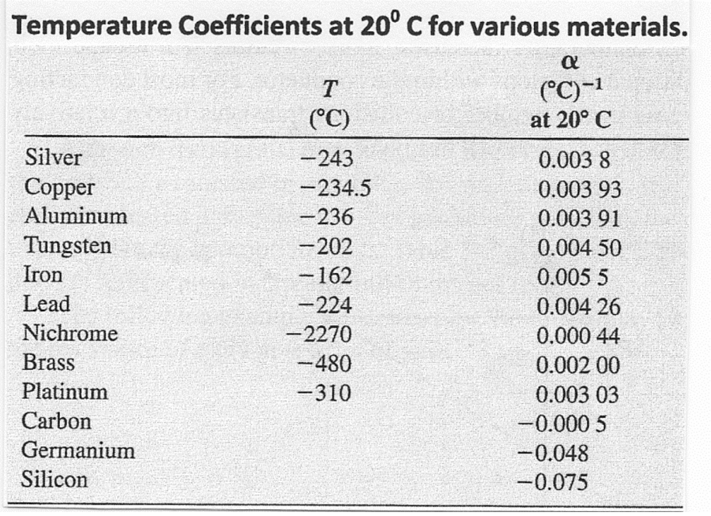
Which yields,

$$R_2 = R_1\left(\frac{T_2 - T}{T_1 - T}\right) \qquad (21)$$

This equation yields one method which references absolute zero for its solution. There is another method which uses the temperature coefficient of resistance **(α)** to find a **R_2** at some temperature **T_2** knowing the resistance **(R_1)** at a temperature **(R_1)**.

$$\mathbf{R_2 = R_1 [1 + \alpha (T_2 - T_1)]} \qquad \mathbf{(22)}$$

Where α is the temperature coefficient of resistance for different materials. Note equation 22 does not require the need to know the absolute zero temperature of the material, just it temperature coefficient to calculate **R_2**. The table below lists the temperature at absolute zero and the coefficient for various materials at 20^0 C.



Temperature Coefficients at 20^0 C for various materials.

	T (°C)	α $(°\mathrm{C})^{-1}$ at 20° C
Silver	−243	0.003 8
Copper	−234.5	0.003 93
Aluminum	−236	0.003 91
Tungsten	−202	0.004 50
Iron	−162	0.005 5
Lead	−224	0.004 26
Nichrome	−2270	0.000 44
Brass	−480	0.002 00
Platinum	−310	0.003 03
Carbon		−0.000 5
Germanium		−0.048
Silicon		−0.075

To get a better feel for the effect temperature has on resistance lets do a couple of examples.

Example 1 :

A Copper coil has a resistance of 10 ohms at room temperature (20^0C). What would be its resistance at a temperature of 100^0C ?

Solution :

From the table for Temp. Coeff's, $\alpha = 0.00393$ at 20^0C.

$R_2 = R_1 [1 + \alpha (T_2 - T_1)] = 10[1 + 0.00393(100 - 20)] = 10[1 + 0.00393(80)] = 10[1 + 0.3144] = 13.14\ \Omega$

Hence the resistance of the coil has gone up by 3.14 ohms, a little over 30% from the room temperature resistance of 10 Ω.

Example 2 :

At what temperature would the resistance double in the example above from a given resistance of 20 ohms at 20^0C.

Solution :

Solving the equation in example 1 for T_2 instead of R_2 where R_2 = 20 ohms,

$$\mathbf{T_2 = \frac{1}{\alpha} [\frac{R_2}{R_1} - 1] + T_1} \qquad \mathbf{(23)}$$

$$T_2 = \frac{1}{0.00393} [\frac{20}{10} - 1] + 20 = = \frac{1}{0.00393} [2 - 1] + 20 = 254.5 + 20 = 274.5^0C$$

Here the temperature would need to be raised to 274.5^0C for the resistance of the coil to double.

In conclusion, it is important to understand that temperature affects the resistance of materials. How it affects the resistance depends on the materials used. The materials mentioned here all have positive temperature coefficients, meaning as the resistance goes up as the temperature goes up. Semiconductors for example have negative temperature coefficients, meaning as the resistance goes down as the temperature goes up. Also not mentioned was the effect the power dissipated in the conductor material has on its temperature. This then defines specific ratings of temperature and power dissipation that can be safely used with these materials protecting the material property from destruction.

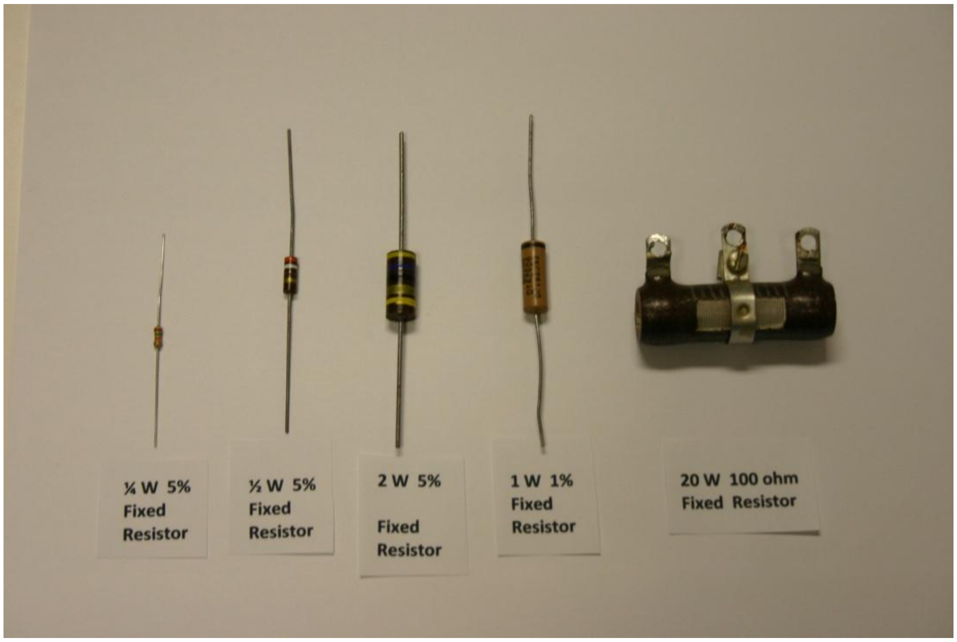
Types of resistive components and devices :

The resistor that has been discussed up to this point comes in two types, fixed and variable.

Fixed resistors :

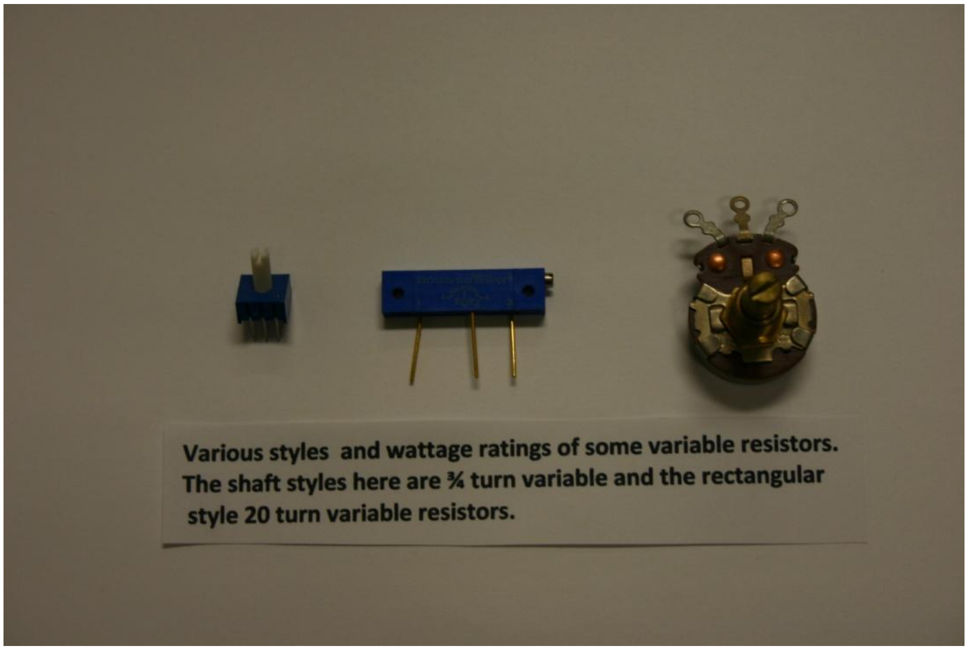
The resistors that are used in most everyday applications are carbon film, metal film and wire wound. These resistors are used in circuits to limit current, divide voltages or generate heat. They are available in a large selection of values that are defined by the manufacturing process. These values are consistent across the industry for specific type and tolerance. The accuracy of these fixed values is dependant on the tolerance. Some typical tolerances are 1%, 5%, 10%, 20% where 5% being most common in typical electronic circuits. The resistance value and tolerances are defined by either a color code or numeric identification on the resistor. These resistors come now in two types, component body with leads or surface mount. This type of resistor is generally low power carbon or metal film ranging in power from about 1/8th watt to 2 watts.

Power resistors are generally wire wound consisting of nickel chromium wire which is about 675 ohms per circular mil foot. So this is special resistive wire used to make the most common types of power resistors. The actual resistance value is of course a function of the area and length and/or the geometry on the material making up the resistor. Another words the resistor could be a flat bar of nickel chromium material not looking at all like a typical wire wound resistor.



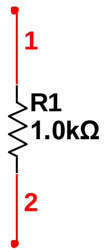
Variable resistors :

Variable resistors are designed so that their ohmic values can be easily adjusted mechanically. This resistance is varied physically by moving a metal contact wiper element over either a carbon or metal resistive deposit on a ceramic base or over single turns of resistive wire. These devices also come in a variety of precisions, power ratings and mechanical accuracy settings.

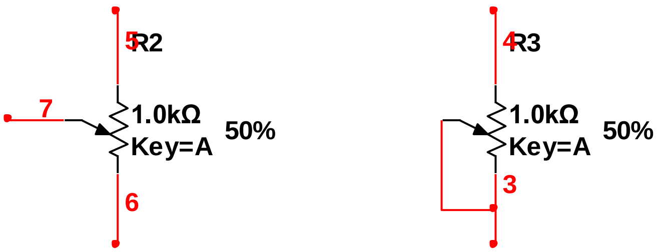


Various styles and wattage ratings of some variable resistors. The shaft styles here are ¾ turn variable and the rectangular style 20 turn variable resistors.

The standard schematic symbols for fixed and variable resistors are shown below.



Standard Fixed Resistor Symbol used in Multisim.

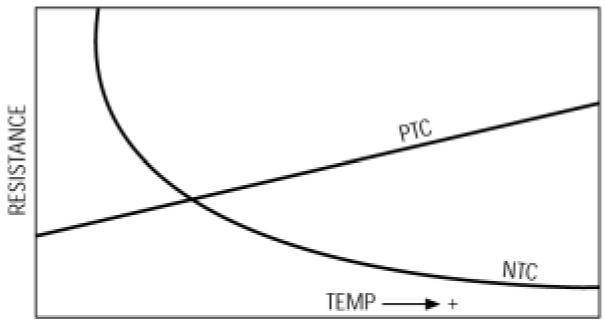


Standard Variable Resistor Symbols used in Multisim. The symbol to the right is setup to be used as a simple in series two terminal variable resistor.

Special types of resistive devices :

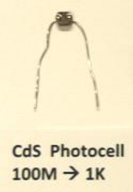
Thermistor :

The negative temperature coefficient (NTC) thermistor is essentially a semiconductor resistive device, whose resistance varies directly with temperature. This means the resistance goes down as the temperature goes up.

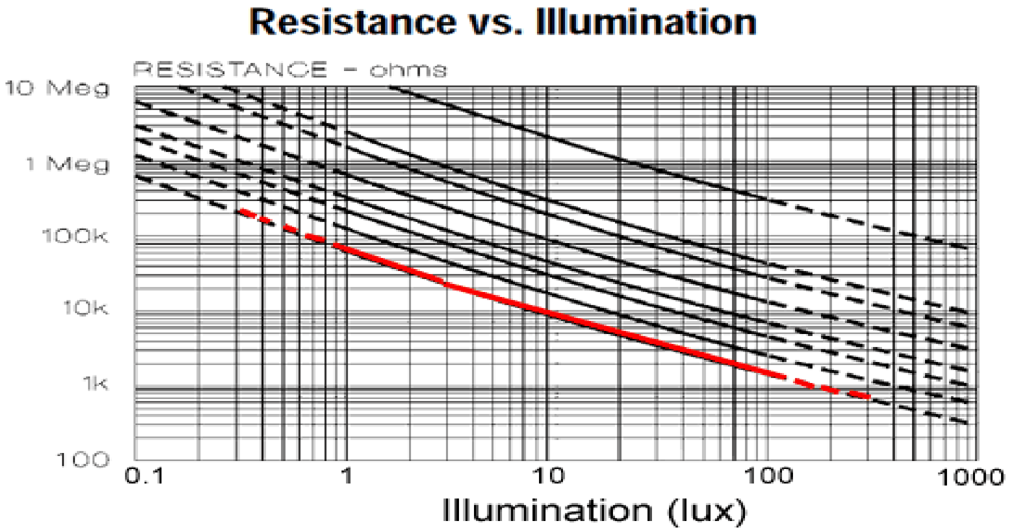


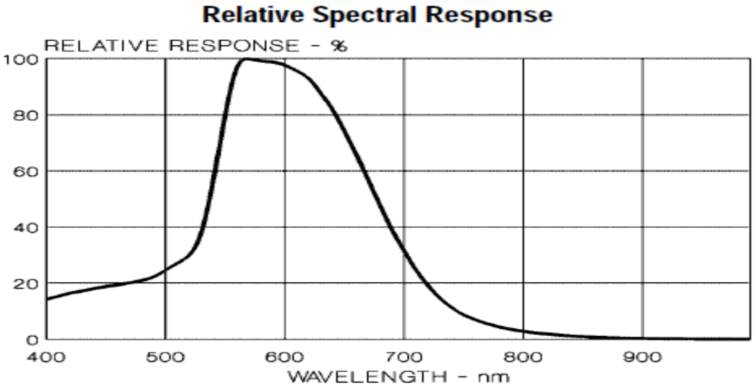
The range of operation for different thermistors is from -200°C to +1000°C and come in a variety of package types, glass bead, disc, probe and chip, depending on the application. The NTC type is used when a continuous change of resistance is required over a wide temperature range. The PTC types are used when it is desired to switch something on or off at some temperature usually ranging from 60°C to 180°C. They are commonly used for protection of windings in transformers and electric motors.

Photoconductor : The photoconductor is a light sensitive resistor or sometimes called a light dependent resistor (LDR). The LDR exhibits Photoconductivity since its resistance decreases with increasing incident light intensity. The typical LDR is made from cadmium sulfide (CdS) which in the dark acts like a high resistance semiconductor. When light falls on the LDR of high enough frequency, photons will be absorbed by the CdS material giving valence band electrons enough energy to be released into the conduction band. These free electrons contribute to conduction, lowering its resistance. A typical CdS cell is shown below.

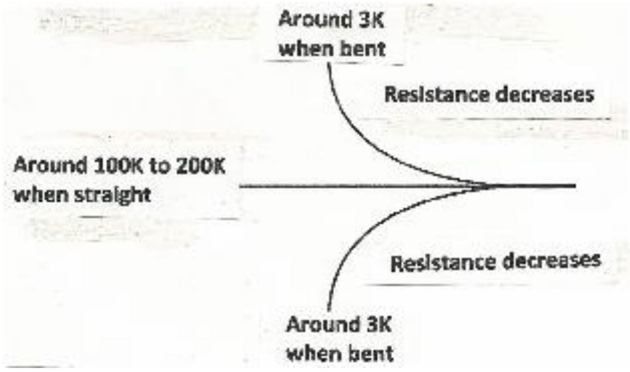


There are also LRD’s made of Lead Sulphide (PbS) and indium antimonide(InSb) which are used to detect light in the mid infrared spectrum and Ge:Cu in the far infrared spectrum.





Flex or Strain Gauge : This unique bi-directional sensor changes its resistance when bent. The un-flexed sensor has a nominal resistance ranging from 10M ohms down to 10K ohms depending on the specific device. Its lowest bent resistance could be down to 1K ohm or so. Note the bent resistance can be anywhere from meg ohms to K ohms depending on how much it is bent. The flex sensor is also pressure sensitive and can be used to sense a force applied to the sensor.



Incandescent Lamp(bulb) : The incandescent bulb produces light by heating up a wire filament to a temperature high enough to cause the filament to glow. When a small voltage is applied to this filament, a current will flow. Since the filament has resistance it will initially give off energy in the form of heat. When the voltage increases, the current will also increase, causing more power to be dissipated in the filament, making it hotter. At some point as the voltage increases, the filament will get so hot that it will start to glow and give off light. This process continues until the voltage and current values reach the power rating of the filament. Once this is reached, the bulb will be at its maximum rated light output. For typical household bulbs this is defined by a wattage, like 60 watts, 100 watts etc. The filament type bulb resistance becomes non-linear when it starts to give of light.