EE POWER

2nd EDITION OF THE GUIDE

THE RESISTOR GUIDE

The complete guide to the world of resistors

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TABLE OF CONTENTS

1. WHAT IS A RESISTOR? **3**

2. FUNDAMENTALS **4**
- 2.1 Electrical Resistivity and Resistance 5
- 2.2 Ohm's Law 9
- 2.3 Kirchhoff's Circuit Laws 14
- 2.4 Resistor Properties 18

3. RESISTOR TYPES **32**
- 3.1 Fixed Resistors 35
- 3.2 Variable Resistors 36
- 3.3 Wirewound Resistors 61
- 3.4 Carbon Composition Resistors 66
- 3.5 Carbon Film Resistors 68
- 3.6 Metal Film Resistors 70
- 3.7 Metal Oxide Film Resistors 71
- 3.8 Thin and Thick Film Resistors 72

4. RESISTOR STANDARDS **77**
- 4.1 Resistor Color Code 78
- 4.2 Preferred Values 83
- 4.3 SMD Resistors 86
- 4.4 Resistor Sizes and Packages 89
- 4.5 Resistor Symbols 92

5. APPLICATIONS **95**
- 5.1 Resistors in Series 97
- 5.2 Resistors in Parallel 99
- 5.3 Resistors in Series and Parallel 100
- 5.4 Heater Resistors 101
- 5.5 Resistors in LED Circuits 104
- 5.6 Power Resistors 109
- 5.7 Pull-up and Pull-down Resistors 112
- 5.8 Blower Resistors 115
- 5.9 Shunt Resistors 117

6. APPENDIX **121**

7. ABOUT THE AUTHORS **130**

1. WHAT IS A RESISTOR?

A resistor is a passive electrical component that creates resistance in the flow of electric current. Resistors can be found in almost all electrical networks and electronic circuits. Resistance is measured in ohms (Ω). One ohm is the resistance of a device with a one volt drop across its terminals when a current of one ampere passes through it. The current is proportional to the voltage across the terminal ends. This ratio is represented by Ohm's law:

$$R = \frac{V}{I}$$

Resistors are used for many purposes, including but not limited to: delimiting electric current, voltage division, heat generation, matching and loading circuits, controlling gain, and fixing time constants. They are commercially available with resistance values covering a range of more than nine orders of magnitude. Resistors can be large enough to be used as electric brakes to dissipate kinetic energy from trains or be smaller than a square millimeter for electronics.

> *A resistor is a passive electrical component whose primary function is to limit the flow of electric current.*

The international IEC symbol is a rectangular shape with leads at both ends. In the USA, the ANSI standard, which represents a resistor with a zigzag line with leads at both ends, is commonly used.

Fixed resistor symbols: IEC standard (left) and ANSI standard (right)

2 FUNDAMENTALS

2.1 Electrical Resistivity and Resistance 5

2.1.1 What is Electrical Resistivity? 5
2.1.2 Electrical Resistance 5
2.1.3 Wire Resistance 6
2.1.4 Sheet Resistance 7
2.1.5 Resistive Properties of Materials 8

2.2 Ohm's Law 9

2.2.1 Ohm's Law and Resistors 10
2.2.2 Ohm's Law Equations 11
2.2.3 Ohm's Power Law 12

2.3 Kirchhoff's Circuit Laws 14

2.3.1 Kirchhoff's Current Law (KCL) 14
2.3.2 Kirchhoff's Voltage Law (KVL) 15
2.3.3 Kirchhoff's Laws—Applications 16

2.4 Resistor Properties 18

2.4.1 Resistance 18
2.4.2 Power Rating 18
2.4.3 Inductance 20
2.4.4 Capacitance 23
2.4.5 Noise 26
2.4.6 Temperature Coefficient 27
2.4.7 Other Resistor Properties 30

2. FUNDAMENTALS

2.1. Electrical Resistivity and Resistance

2.1.1. What is Electrical Resistivity?

Electrical resistivity is a measure of a material's property to oppose the flow of electric current. This is expressed in ohm-meters (Ω·m). The symbol for resistivity is usually the Greek letter ρ (rho). A high resistivity means that a material does not conduct electric charge well. Electrical resistivity is defined as the relation between the electrical field inside a material and the electric current running through it as a consequence:

$$\rho = \frac{E}{J}$$

in which ρ is the resistivity of the material (Ω·m), *E* the magnitude of the electrical field in the material (V/m), and *J* the magnitude of the electric current density in the material (A/m^2). If the electrical field (*E*) permeating a material is very large, and the flow of current (*J*) very small, the material has a high resistivity.

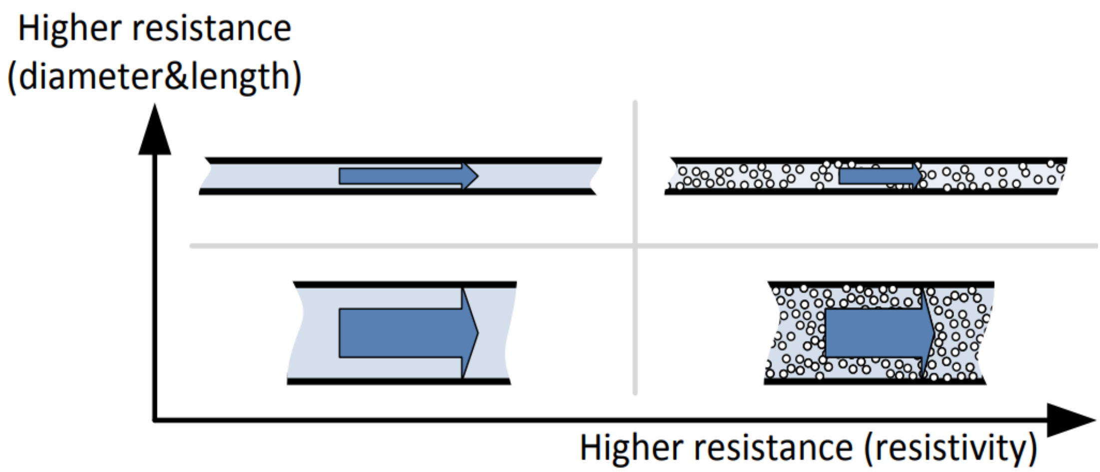
Electrical conductivity is the inverse of resistivity and is a measure of how well a material conducts electric current:

$$\sigma = \frac{1}{\rho} = \frac{J}{E}$$

in which σ is the conductivity of the material, expressed in Siemens per meter (S/m). In electrical engineering, κ (kappa) is often used instead of σ.

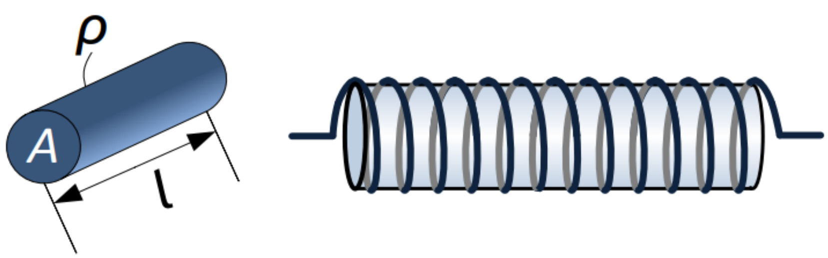
2.1.2. Electrical Resistance

Electrical resistance is expressed in ohms and is not the same as resistivity. While resistivity is a material property, resistance is the property of an object. The electrical resistance of a resistor is determined by the shape and the resistivity of the material. For example, a wirewound resistor with a long, thin wire has a higher resistance than one with a short, thick wire. A wirewound resistor made from a material with high resistivity has a higher resistance value than one with low resistivity. An analogy with a hydraulic system can be made, where water is pumped through a pipe. The longer and thinner the pipe, the higher the resistance will be. A pipe filled with sand will resist the flow of water more than a pipe with no sand (resistivity property).



Hydraulic analogy of electrical resistance

2.1.3. Wire Resistance



Wire resistance parameters

The resistance value of a wire depends on three parameters: resistivity, length, and cross-sectional area.

$$R = \rho \frac{l}{A}$$

in which:

R is the resistance (Ω),
ρ is the resistivity of the material (Ω·m),
l is the length of the material (m),
A is the cross-sectional area of the material (m^2).

As an example, consider a wirewound resistor with a wire of Nichrome with a resistivity of 1.10×10^{-6} Ω·m. The wire has a length of 1500 mm (1.5 m) and an area of 0.5 mm^2 (0.5×10^{-6} m^2). With these three parameters, the resistance value is calculated:

$$R = \rho(\frac{l}{A}) = 1.1 \cdot 10^{-6} \cdot \frac{1.5}{0.5 \cdot 10^{-6}} = 3.3\Omega$$

Nichrome and Constantan, discussed in further detail below, are often used as resistance wire. For resistivity values of other commonly used materials, see the table in section 2.1.5. Resistive Properties of Materials below.

2.1.4. Sheet Resistance

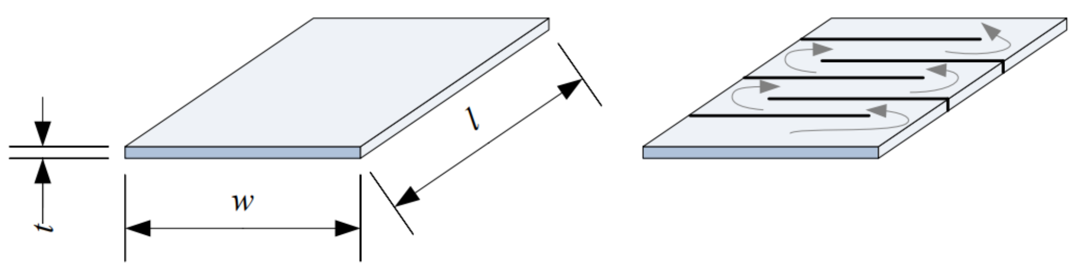
The resistance value for a sheet is calculated the exact same way as for wire resistance. The cross-sectional area can be written as the product of the width, *w*, and thickness, *t*:

$$R = \rho(\frac{l}{A}) = \rho(\frac{l}{wt})$$

For some applications, such as thin films, the ratio between resistivity and film thickness is called sheet resistance R_S in which R_S is in ohms/square (Ω/□). The film thickness needs to be uniform for this calculation:

$$R = \rho(\frac{l}{wt}) = R_s(\frac{l}{w})$$

The electrical resistance of a sheet depends on its length, width, film thickness, and resistivity. Often, resistor manufacturers increase resistance by cutting a pattern into the film to lengthen the electric current's path.



The resistance of a sheet can be increased by cutting a pattern into it.

2.1.5. Resistive Properties of Materials

The resistivity of a material is dependent on temperature, and is typically recorded at a standard 20 °C. The temperature coefficient is a measure of the change in resistivity in response to increases or decreases in heat. Thermistors, commonly used in a range of domestic and industrial applications, make use of resistivity change to measure temperature, often in extreme conditions.

Still, the fluctuating nature of resistivity is not always desirable. In precision electronics, temperatures must be highly stabilized. For this reason, metal foil resistors, constructed from many different materials and alloys, are used. Nichrome, for instance, is an alloy of nickel and chromium, high in resistivity, that does not oxidize at high temperatures, although it is not solderable. Constantan, another popular material, is easily soldered and also has a low temperature coefficient.

Resistive properties of materials

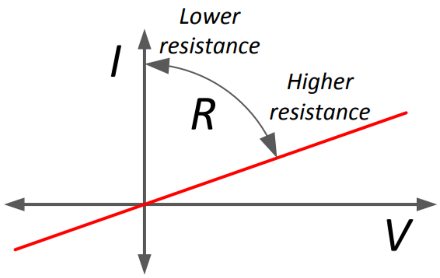
Material	**ρ (Ω·m) at 20°C**	**σ (S/m) at 20°C**	**Temperature Coefficient (1/°C) x10⁻³**
Silver	1.59×10^{-8}	6.30×10^{7}	3.8
Copper	1.68×10^{-8}	5.96×10^{7}	3.9
Gold	2.44×10^{-8}	4.10×10^{7}	3.4
Aluminum	2.82×10^{-8}	3.50×10^{7}	3.9
Tungsten	5.60×10^{-8}	1.79×10^{7}	4.5
Zinc	5.90×10^{-8}	1.69×10^{7}	3.7
Nickel	6.99×10^{-8}	1.43×10^{7}	6
Lithium	9.28×10^{-8}	1.08×10^{7}	6
Iron	1.00×10^{-7}	1.00×10^{7}	5
Platinum	1.06×10^{-7}	9.43×10^{6}	3.9
Tin	1.09×10^{-7}	9.17×10^{6}	4.5
Lead	2.20×10^{-7}	4.55×10^{6}	3.9
Manganin	4.82×10^{-7}	2.07×10^{6}	0.002
Constantan	4.90×10^{-7}	2.04×10^{6}	0.008
Mercury	9.80×10^{-7}	1.02×10^{6}	0.9
Nichrome	1.10×10^{-6}	9.09×10^{5}	0.4
Carbon (amorphous)	$5\text{-}8 \times 10^{-4}$	$1.25\text{-}2 \times 10^{3}$	-0.5

2.2. Ohm's Law

Ohm's law, named after its German discoverer, the physicist Georg Ohm, states that the electrical current coursing through a conductor is proportional to the potential difference across it. Furthermore, the electrical resistance of the conductor is constant. Thus, the mathematical equation:

$$R = \frac{V}{I}$$

where *I* is the current in amperes, *V* the voltage in volts, and *R* the resistance in ohms. To illustrate: a resistor of 1 Ω subjected to a current of 1 A has a voltage difference of 1 V across its terminals.



Georg Ohm's discovery of the relationship between resistance, voltage, and current

German Gustav Kirchhoff, known for his series of circuit laws, made a generalization that is more commonly used in physics:

$$\sigma = \frac{1}{\rho} = \frac{J}{E}$$

where σ is the conductivity parameter (material-specific), *J* the current density in a location of that material, and *E* the electric field in that location.

GEORG SIMON OHM (1789-1854)

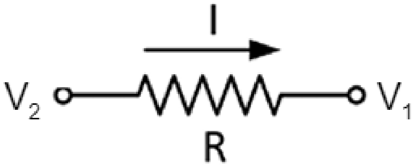
Georg Simon Ohm

In 1827, Georg Simon Ohm published his complete theory of electricity, "The Galvanic Circuit Investigated Mathematically." There, he described the long series of experiments that led him to discover his namesake law.

Although now accepted as one of the fundamental tenets of electrical engineering, Ohm's law was originally met with marked skepticism. Criticism from his colleagues at Cologne was so severe, in fact, that Ohm decided to resign. Though he later went on to become a professor of experimental physics at the University of Munich, Ohm would have to wait nearly fifteen years before recieving proper recognition for his work in 1841.

2.2.1. Ohm's Law and Resistors

Resistors are passive elements that introduce resistance to the flow of electric current in a circuit. A resistor that functions according to Ohm's law is called an Ohmic resistor. When current passes through an Ohmic resistor, the voltage drop across the terminals is proportional to the magnitude of resistance. Ohm's law is described in the figure below:

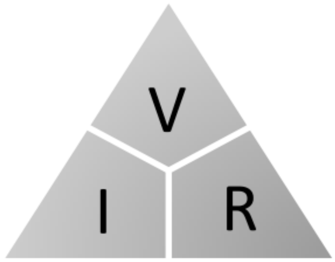


$$V_2 - V_1 = I \cdot R$$

Ohm's formula remains valid for circuits with varying voltage or current, so it can be used for alternating current (AC) circuits as well. Ohm's formula is also valid for circuits with multiple resistors that can be connected in series, parallel or both (as discussed in Chapter 5). For capacitors and inductors the law can of course not be used, since their I-V curves are inherently nonlinear (non-ohmic).

2.2.2. Ohm's Law Equations

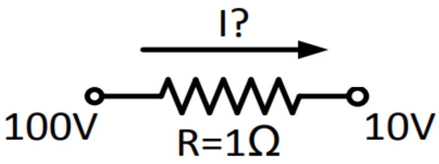
Ohm's formula can be used when two of three variables are known, namely resistance, current, and voltage. The relation between these can be written in different ways, so it may be helpful to utilize the Ohm triangle calculator. Two examples below will demonstrate how to use this tool.



$$R = \frac{V}{I} \quad \textit{or} \quad V = \mathrm{I} \cdot \mathrm{R} \quad \textit{or} \quad I = \frac{V}{R}$$

Example 1

Consider a 1 Ω resistor in a circuit with a voltage drop from 100 V to 10 V across its terminals. What is the current through the resistor?

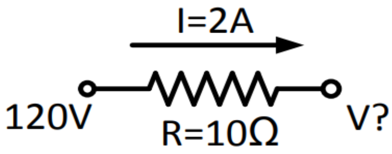


The triangle reminds us that:

$$\mathrm{I} = \frac{\mathrm{V}}{\mathrm{R}} = \frac{100 - 10}{1} = 90\mathrm{A}$$

Example 2

Consider a 10 Ω resistor in a circuit subject to a current of 2 A and a voltage of 120 V at one end. What is the voltage at the opposite end of the resistor?



Using the triangle, we can see that:

V = I • R = 2 • 10 = 20 V

The voltage drop across the resistor is 20 V. Therefore, the voltage at the opposite end of the resistor is 120 - 20 = 100 V.

2.2.3. Ohm's Power Law

A resistor dissipates power when a current passes through it. The energy is released in the form of heat. The power is a function of the current *I* and the applied voltage *V*:

$$P = V \cdot I$$

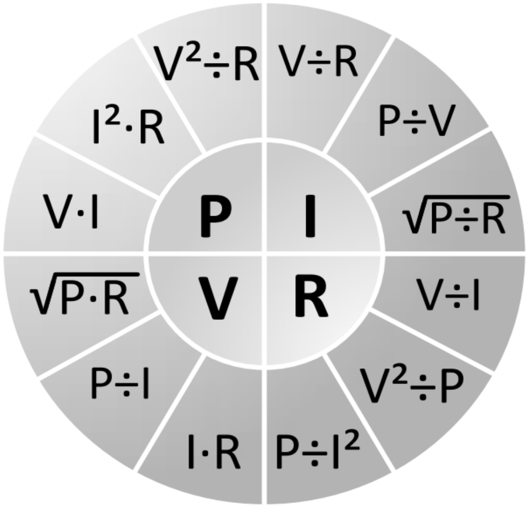
where *P* is the power in watts. When combined with Ohm's law, the power law can be rewritten:

$$P = R \cdot I^2 \qquad P = \frac{V^2}{R}$$

Ideal resistors dissipate all energy and do not store electric or magnetic energy. Each resistor is limited in the power it can dissipate without creating damage. This limit is called the power rating. In practice, these are seldom indicated, though the majority of resistors are rated at 1/4 or 1/8 watt.

Ambient temperatures can reduce power rating. For example, a resistor enclosure or a higher ambient temperature will reduce the amount of energy the resistor can dissipate. This effect is called derating, and can be visualized with a power derating chart.

Using the equation wheel below, we can quickly determine the relation between electric power, current, voltage, and resistance. For each of the four parameters, the wheel demonstrates how to calculate the desired value, provided the other circuit values are known.

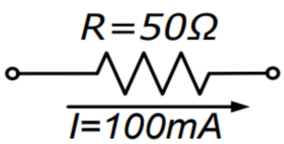


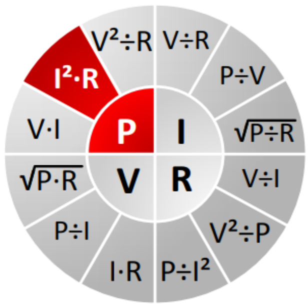
Power law equation wheel

Several examples of Ohm's law problems are given below. You can try to solve the problems yourself before reading the answers.

Example 1

What must be the minimum power rating of this resistor?





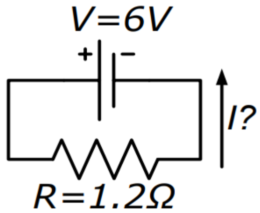
Using the wheel to select the correct formula, we have:

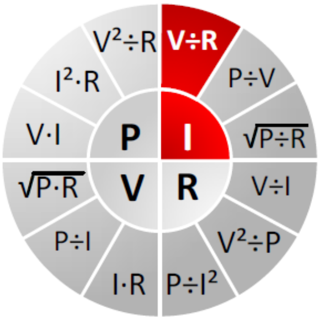
$P = I^2 \times R = 0.100^2 \times 50 = 0.5$ W

So the minimal power rating is 0.5 W. That said, to provide extra reliability and extend operating lifetime, choosing a higher value is recommended.

Example 2

What is the current in the following circuit?



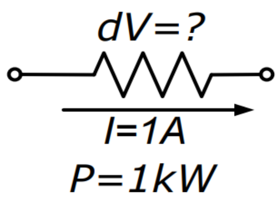


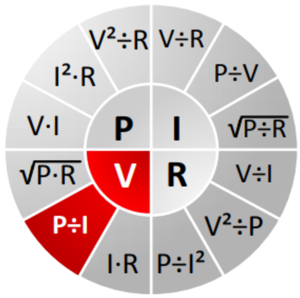
This is a basic example of Ohm's law. The voltage and resistance are known, so we can calculate the current using the equation:

$I = V / R = 6 / 1.2 = 5$ A

Example 3

An electric heater (resistor) with a consumption of 1 kW is connected in a circuit with an 8 A current. What is the voltage drop over the heater?





Voltage can be expressed as a function of the current and power with the formula:

V = P / I = 1000 / 8 = 125 V

2.3. Kirchhoff's Circuit Laws

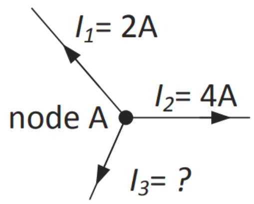
Kirchhoff's circuit laws, formulated in 1845 by German scientist Gustav Kirchhoff, are essential to resistor network theory. The laws describe the conservation of energy and charge in electrical networks. Kirchhoff's Current Law (KCL) and Kirchhoff's Voltage Law (KVL) are described in detail below.

2.3.1. Kirchhoff's Current Law (KCL)

Kirchhoff's Current Law (KCL) states that the sum of all currents leaving or entering a node in any electrical network is always equal to zero. It is based on the principle of conservation of electric charge. The law is also referred to as Kirchhoff's first law. In formula form, KCL is given by:

$$\sum_{i=1}^{n} I_i = 0$$

KCL is easier to understand with an example. Look below at the figure of an arbitrary "node A" from a resistor network.



Three branches are connected to this node. Two of the currents are known: I_1 is 2 A and I_2 is 4 A. The current law states that the sum of I_1, I_2, and I_3 must be zero:

$$I_1 + I_2 + I_3 = 0$$

$$I_3 = -I_1 - I_2$$

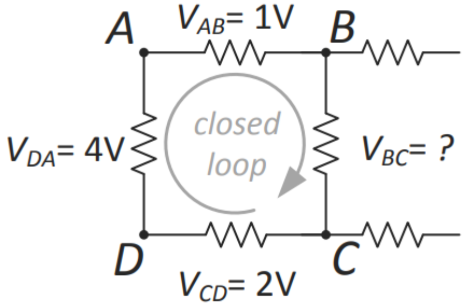
$$I_3 = -2 - 4 = -6A$$

2.3.2. Kirchhoff's Voltage Law (KVL)

Kirchhoff's Voltage Law (KVL) states that the sum of the rise and drop in voltage over all elements in a closed loop is equal to zero. In formula form:

$$\sum_{i=1}^{n} V_i = 0$$

Let's look at an example to explain. Consider a part of a resistor network with an internal closed loop, as shown in the figure below; we want to know the voltage drop between nodes B and C (V_{BC}).



Kirchhoff's Voltage Law around a closed loop

The sum of voltage drops in the loop ABCD must be zero, so we can write:

$$V_{ab} + V_{bc} + V_{cd} + V_{da} = 0$$

$$V_{bc} = -V_{ab} - V_{cd} - V_{da}$$

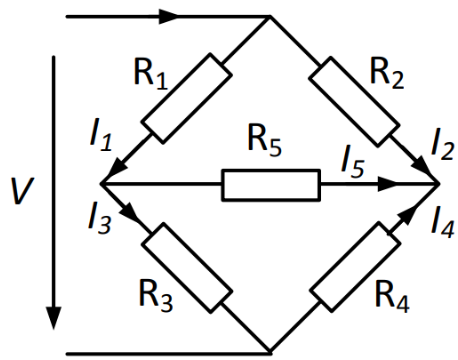
$$V_{bc} = -1 - 2 - 4 = -7V$$

2.3.3. Kirchhoff's Laws—Applications

Kirchhoff's laws form the basis of network theory. Taken together with Ohm's law and the equations for resistors in series and parallel, more complex networks can be solved. Several examples of resistor circuits are provided to illustrate how Kirchhoff's laws can be used.

Example 1: The Bridge Circuit

Bridge circuits are a very common tool in electronics. They are used in measurement, transducer, and switching circuits. Consider the bridge circuit below; with it, we will demonstrate how to use Kirchhoff's laws to determine the cross current I_5. The circuit has four bridge sections with resistors $R_1 - R_4$. There is one cross bridge connection with resistor R_5. The bridge is subject to a constant voltage V and current I.



Kirchhoff's current law states that the sum of all currents in one node is zero. This results in:

$$I = I_1 + I_2$$

$$I = I_3 + I_4$$

$$I_1 = I_3 + I_5$$

Kirchhoff's voltage law states that the sum of all voltages in a loop is zero. This leads to:

$$V - I_1R_1 - I_3R_3 = 0$$

$$I_1R_1 + I_5R_5 - I_2R_2 = 0$$

$$I_3R_3 - I_5R_5 - I_4R_4 = 0$$

The six sets of equations above can be rewritten using normal algebra to find the expression for I_5 (the current in the cross branch):

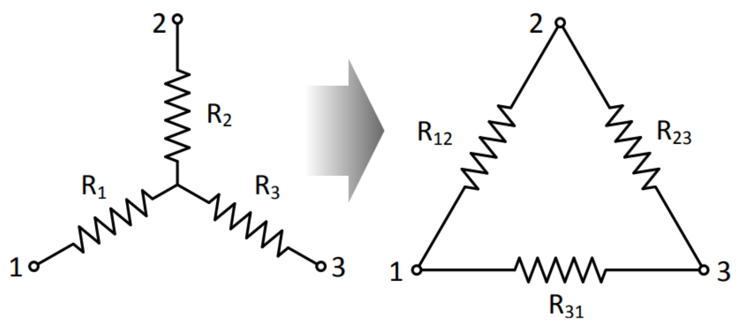
$$0 = I_5 = \frac{V(R_2R_3 - R_1R_4)}{R_5(R_1 + R_3)(R_2 + R_4) + R_1R_3(R_2 + R_4) + R_2R_4(R_1 + R_3)}$$

The equation shows that the bridge current is equal to zero and the bridge is balanced when:

$$R_2R_3 = R_1R_4$$

Example 2: The Star-Delta Connection

Kirchhoff's laws can be used to convert a star connection to a delta connection, as illustrated in the following figure:



Star-delta network transformation

This is often done to solve complex networks. A widely used application for star-delta connections is limiting the starting current of electric motors, whose high starting current causes large voltage drops in the power system. To solve this, the motor windings are connected in the star configuration upon startup, and subsequently convert to the delta connection. As shown above, the star connection has the same voltage drops and currents as the delta connection only when these equations, listed on the following page, are valid:

$$R_1 = \frac{R_{31}R_{12}}{R_{12}+R_{23}+R_{31}}$$

$$R_{12} = R_1 + R_2 + \frac{R_1R_2}{R_3}$$

$$R_2 = \frac{R_{12}R_{23}}{R_{12}+R_{23}R_{31}}$$

$$R_{23} = R_2 + R_3 + \frac{R_2R_3}{R_1}$$

$$R_2 = \frac{R_{23}R_{31}}{R_{12}+R_{23}+R_{31}}$$

$$R_{31} = R_3 + R_1 + \frac{R_3R_1}{R_2}$$

2.4. Resistor Properties

2.4.1. Resistance

The resistance of a resistor, measured in ohms, is dependent on its material and shape. Some materials have higher resistivity, and thus a higher value. The resistance value is often printed on the resistor in the form of a number or color code. For a detailed overview of resistivity, see section 2.1. Electrical Resistivity and Resistance.

2.4.2. Power Rating

The resistor's power rating defines the maximum energy a resistor can safely dissipate. As is stated by Joule's first law, generated electrical power is related to voltage and to current:

$$P = V \bullet I$$

When the electrical power equals the dissipated heat (by radiation, convection, and conduction), the temperature of the resistor will stabilize. Temperature is not equal across the resistor; the body is slightly hotter than the terminals, with the highest temperature centered at its core.

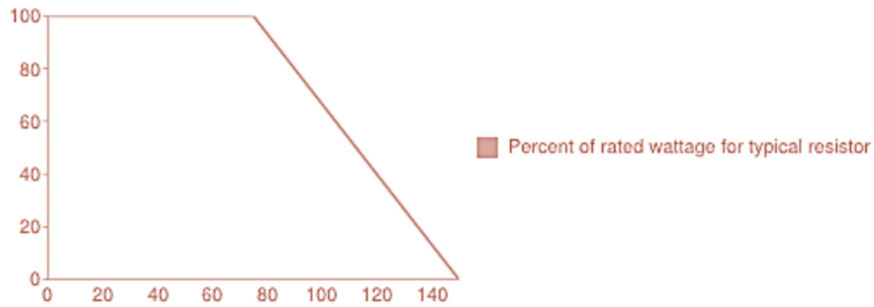
The higher the rate of heat dissipation to the environment, the lower the temperature rise will be. Larger resistors with more surface area can generally dissipate heat at a higher rate. If the (average) power dissipation is greater than the power rating, the resistor may be damaged. This can have several consequences: the resistance value can shift permanently, the lifetime can be significantly reduced, or the component may be completely damaged resulting in an open circuit.

In extreme cases, excessive power can even cause a fire, though special flameproof resistors are available that cause a circuit-break before temperatures climb dangerously high.

2.4.2.1. Resistor Derating

The nominal power rating is defined for a certain ambient temperature in free air. Note that the amount of energy a resistor can dissipate without causing damage, in practice, is strongly dependent on the operating conditions, and therefore not necessarily equal to the nominal power rating.

For example, a higher ambient temperature can significantly reduce the power rating. This effect is referred to as derating. The designer should take this into account. Often, the nominal power rating is a more important factor when selecting a resistor than the maximum power rating. Typically, resistors are rated for full power operation up to a temperature of 70 °C; above this, the resistor starts to derate. This means that above this temperature the resistor can only utilize a reduced power level. This is illustrated by a derating curve, shown below.



Resistor Derating Chart – The vertical axis represents the percentage of nominal rating for a given ambient temperature. In this case, the resistor's full power rating is given up to 70 °C.

In addition to the influence of ambient temperature, there are several other factors that impact derating. The most important are detailed below.

- **Enclosures**

  A resistor's capacity to dissipate heat is limited if insallted in an enclosure. Enclosures restrict air flow and, therefore, the removal of heat by convection. As well, an enclosure's walls act as a thermal barrier, making it more difficult to discharge radiated heat. The extent of these effects is, of course, strongly dependent on an enclosure's material makeup, in addition to its size, shape, orientation, and the thickness of its walls.

- **Forced cooling**
  Increasing the heat transfer by forced convection allows for higher power dissipation than through natural convection. This can be achieved via air or even liquid cooling. Some resistors are designed with conductive air fins, which add additional surface to enhance heat dissipation.

- **Component grouping**
  On a circuit board, resistors are often positioned close to each other, and thus the heat radiated from one resistor will be received by the next. This mutual heating will further increase temperature for a given power consumption.

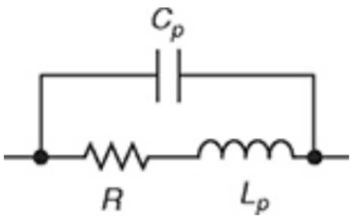
- **Altitude**
  Resistors expel heat via radiation and convection, the latter of which is affected by air density. Above 30 km, the air is so thin that convection ceases entirely, leaving radiation as the sole option for jettisoning heat.

2.4.2.2. Power Resistors

For most electronic circuits, the power rating is not a key parameter, since their resistors dissipate low amounts of energy (typically one watt or less). In power electronics, though, the power rating is important. Generally speaking, when the power rating is one watt or higher, a resistor is referred to as a power resistor. Typical applications include power supplies, dynamic brakes, power conversion circuits, power amplifiers, and heaters.

2.4.3. Inductance

Inductance is an electrical property of conductors, by which an electrical current passing through the conductor induces an electromotive force in the conductor itself (self-inductance) and other conductors nearby. Since resistors are made of conductive materials, they too exhibit inductance as an unwanted, parasitic effect (dubbed, naturally, "parastic inductance"). This effect is especially noticeable if the resistor is made out of wire formed into a coil shape.



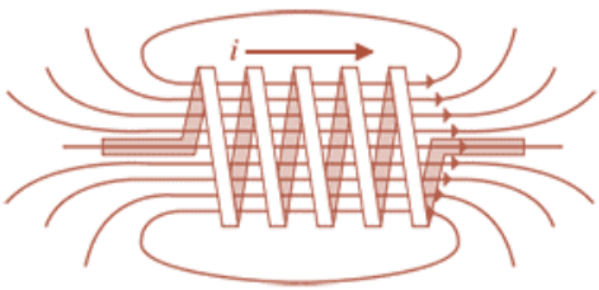
Parasitic inductance and capacitance of a resistor

Depending on the application, resistor inductance might be easily disregarded, especially in DC circuits. However, parasitic resistor inductance can be a significant factor in high-frequency AC applications. This is because the impedance of a resistor increases with the applied voltage frequency, due to the increase in its reactance from the parasitic inductance.

2.4.3.1. Inductors and Resistors

Electrical loads can be divided into two types: real (or resistive) loads, and reactive loads. Real loads are used to convert electrical power into heat. An ideal resistor is a purely resistive load, which means that all the electrical power applied to the resistor is dissipated as heat.

Alternatively, reactive loads convert electrical power into a magnetic or electric field and temporarily store it before returning it to the rest of the circuit. Reactive loads can be inductive or capacitive. Inductive loads store energy in the form of a magnetic field, while capacitive loads store energy in the form of an electric field.



The B-field of an inductor coil

The main difference between ideal resistors and ideal inductors is therefore that resistors dissipate electrical power as heat, while inductors turn electrical power into a magnetic field. Ideal resistors have zero reactance and as a result zero inductance. Unfortunately, electrical devices are not ideal in practice, and even the simplest resistors have a slight parasitic inductive reactance.

2.4.3.2. Parasitic Inductance

Resistors are used when a purely resistive load is required, so inductance is often parasitic—an unwanted side-effect. All real resistors exhibit parasitic inductance to a greater or lesser degree, depending on the design and construction of the resistor. Parasitic inductances in an AC circuit can cause unwanted couplings between system blocks, or can be the cause of altered circuit response at high frequencies. The source of these parasitic inductances can be either self-inductance, which exists even when the resistor is far from other conductors, or mutual inductance, which is observed when other high-frequency devices are nearby. Self-inductance may distort the signal at high frequencies, while mutual inductance may introduce noise in the signal path.

Because of their coil shape, helical wirewound resistors are especially prone to having significant parasitic inductance. To avoid the coil consctruction, resistors designed specifically for use at high frequencies are made of metal film.

2.4.3.3. Reactance and Inductance Calculations

In AC circuits, electrical impedance is the measure of the opposition a circuit presents to the passage of a current when voltage is applied. Impedance is given by the formula:

$$Z = R + j \cdot X$$

where Z is the impedance, R the resistance, X the reactance of a circuit, and j the imaginary unit. For a resistor with only parasitic inductance (no capacitive component), the impedance is given by:

$$Z = R + j \cdot \omega \cdot L$$

As can be seen from the above equations, the impedance of the resistor rises with the voltage frequency because the resistor acts as both a resistor and inductor. This increase is usually negligible, but in some applications is quite significant.

Inductance for different resistor types

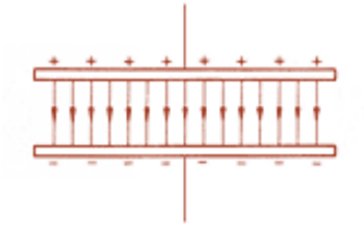
Resistor Type	**Inductance**
Wirewound	0.03 - 56 μH
Foil	< 0.08 μH
Metal oxide	3 - 200 nH
Film	< 2 nH

2.4.3.4. Applications Where Parasitic Effects Play a Role

Parasitic inductance usually manifests itself either in resistors with inferior properties, such as helical wirewound resistors, or in other resistors at very high frequencies. As an example of the high frequency problem, let's consider a foil resistor of 220 Ω with an inductance of 0.05 μH operating at 1 GHz. The magnitude of the impedance is 383.5 Ω at 1 GHz, which is an increase of nearly 75% above the nominal DC value. An engineer would not expect this change if parasitic effects were not taken into account. Microwave and RF applications are particularly sensitive to parasitic effects.

2.4.4. Capacitance

Capacitance is the ability of a body to store electrical energy in the form of electrical charge. Practical resistors always exhibit capacitance as a parasitic property, though depending on the application this may be easily disregarded, especially in DC circuits.



Energy storage of a capacitor

In some applications, such as snubber resistors, the capacitive parasitic effect is actually desirable. Still in others, such as high-frequency AC applications, it can be problematic. This is because the impedance of a resistor with a parasitic parallel capacitance will decrease as the applied frequency increases. The higher the frequency, the lower the impedance, meaning the resistor can no longer be treated as a constant element at high frequencies, and instead becomes a frequency-dependent element.

2.4.4.1. Capacitors and Resistors

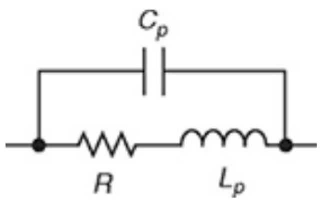
As described in our discussion of inductors and resistors in Section 2.4.3.1 above, electrical loads can be divided into two types: real (or resistive) loads, and reactive loads. Real loads are used to convert electrical power into heat. Reactive loads, which can be inductive or capacitive, convert electrical power into either a magnetic or electric field and temporarily store it before returning it to the circuit. Inductive loads store energy in a magnetic field; capcitive loads store energy in an electric field.

So, as with inductors, the main difference between ideal resistors and ideal capacitors is therefore that resistors dissipate electrical power as heat, while capacitors turn electrical power into an electric field. Ideal resistors have zero reactance and, as a result, they have no capacitance. Unfortunately, this too does not play out in practice; even the simplest resistors have a slight parasitic capacitive reactance.

2.4.4.2. Parasitic Capacitance

Resistors are used when a purely resistive load is required, so capacitance too is often an unwanted side-effect, and in this context is known as “parasitic capacitance.” All real resistors exhibit parasitic capacitance to a greater or lesser extent, depending on the design and construction of the resistor.

Parasitic capacitances in an AC circuit can cause unwanted couplings between system blocks, or can be the cause of an altered circuit response at high frequencies. There are resistors designed specifically for use at high frequencies, which are advertised as low-capacitance resistors, though exact figures for the capacitances are hard to find in data sheets.



Parasitic inductance and capacitance of a resistor

2.4.4.3. Reactance and Capacitance

In AC circuits, electrical impedance is the measure of the opposition a circuit presents to the passage of a current when voltage is applied. Since parasitic capacitance is connected parallel to the resistor (the capacitance shunts the resistor), the complex impedance for such a resistor is given by the parallel connection formula:

$$Z = \frac{Z_R \cdot jX_C}{Z_R + jX_C}$$

where *Z* is the complex impedance, *R* the resistance, *X* the reactance of a circuit, and *j* the imaginary unit. In this subsection, it will be assumed that the parasitic reactance of a real resistor is purely capacitive, so the reactance is:

$$X_C = -\frac{1}{\omega C}$$

Therefore, the complex impedance of a resistor with purely capacitive parasitic effects is:

$$Z = \frac{-R \cdot j\frac{1}{\omega C}}{R - j\frac{1}{\omega C}}$$

where ω is the angular frequency and *C* is the resistor's parasitic capacitance.

For DC or low-frequency applications, we are only concerned with the magnitude of this complex impedance, which can be calculated using the following equation:

$$|Z| = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + (2\pi f C)^2}}$$

where,

R = resistance in ohms,
f = frequency in hertz,
C = capacitance in farads.

Further analyzing the above equation, we can see that the total impedance of a resistor with capacitive parasitic effects decreases as the voltage frequency increases. This decrease is usually negligible, but in some applications may become quite significant.

2.4.4.4. Capacitance of Different Resistors

As previously mentioned, manufacturers rarely make available the typical capacitance values for their resistors. As a general rule, SMD (surface mount device) resistors have much lower parasitics than through-hole resistors, because even ideal conductors under ideal conditions have a certain ability to store charge. Metal leads that connect the resistor to the rest of the circuit are an example of such conductors. The longer the leads, the more charge can be stored and the higher the parasitic capacitance. So SMD resistors, with their shorter leads, have fewer parasitic effects for a given resistance value.

If low capacitance is desired, the resistor should be kept as small and compact as possible. Wirewound resistors should be avoided because the windings generate intercoil capacitance, making them unusable above 50 kHz. Carbon type resistors are usable up to around 1 MHz. Foil resistors provide superior performance at frequencies up to 100 MHz because they usually have a parasitic capacitance of less than 0.05 pF.

2.4.4.5. Parasitic Effects in Applications

Parasitic effects are most prominent at high frequencies. For instance, a metal foil 1 kΩ resistor with 0.05 pF capacitance at 100 MHz would, in fact, behave as a 0.9995 kΩ resistor. This is an example of a good frequency response for a resistor. For comparison, a wirewound resistor is typically only usable up to 50 kHz, because of both inductive and capacitive parasitic effects. Even when bifilar (non-inductive) winding methods are used, the intercoil capacitance limits the maximum usable frequency. Applications that are sensitive to parasitic effects include high-frequency amplifier circuits, GHz clock generators, and microwave circuits.

An example of a circuit component that takes advantage of the capacitive parasitic effect is the snubber resistor. A snubber resistor is used to protect switching elements (switches and thyristors) from voltage spikes generated by inductive loads, such as electric motors during current cut-off. Snubber resistors are most often made as bifilar wirewound resistors to reduce the inductance. For snubber applications, resistors are designed so that the capacitance is in series with the resistor, not in parallel as with standard parasitic capacitances.

2.4.5. Noise

Noise is an unwanted phenomenon for resistors, and for some applications its properties are important. Examples include high-gain amplifiers, charge amplifiers, and low-level signals. Resistor noise is often specified as microvolts noise per volt of applied voltage, for a 1 MHz bandwidth.

Thermal noise is the predominant source of noise for resistors. It is dependent on three variables: resistance, temperature, and bandwidth. The relation between these three parameters is described by the formula:

$$E = \sqrt{4 \cdot R \cdot k \cdot T \cdot \Delta F}$$

where E is the RMS noise signal in volts, R the resistance in ohms, K is Boltzmann's constant, T the temperature in Kelvin, and ΔF the bandwidth in Hz. The equation shows that the noise level can be decreased by reducing the resistance, the temperature, or the bandwidth. After entering Boltzmann's constant, the formula is simplified to:

$$E = 7.43\sqrt{R \cdot T \cdot \Delta F}$$

where E is now the noise voltage in nanovolts, R the resistance in kΩ, and ΔF the bandwidth in kHz.

2.4.5.1. Thermal and Current Noise

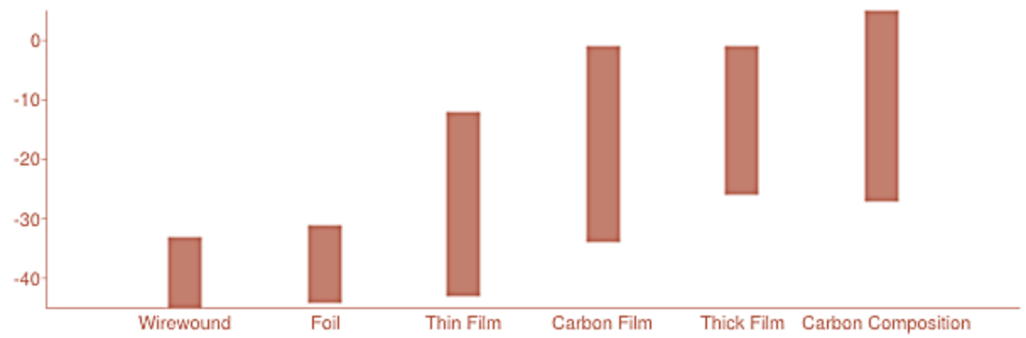
There are two types of noise: thermal noise and current noise. In all materials, electrons are constantly in motion. As temperature increases, so too does their movement. The vibrations of the electrons create a time-varying electric signal. These vibrations are completely random, and so the electrical signal is noise, in this case what we call thermal or Johnson noise. This is the main contributor to resistor noise, and is constant over a wide frequency range. Current noise, however, decreases with increasing frequency. Additionally, thermal noise increases with a larger resistance value, while current noise decreases.

2.4.5.2. Noise Standards

The correct method for measuring resistor current noise is defined in standard IEC 60195, which makes the comparison of resistors from different manufacturers possible. A resistor's current noise is described by the current noise index with a code number.

2.4.5.3. Low Noise Resistor

Thin film, metal foil, and wirewound resistors have preferable noise characteristics. As such, they are often specified in low-noise amplifying applications. Carbon composition and thick film resistors, on the other hand, are among the least preferable; they have high noise due to their construction and materials.



Noise index (dB) for main resistor types

2.4.5.4. Noise in Resistor Applications

In every amplifier circuit, the input resistor is critical. Any noise at the input signal will be amplified by the full gain. It is therefore of crucial importance to choose a low-noise resistor, as well as one low in resistance, for the first stage. This is not valid, though, for a load resistor, since the gain obtained from high resistance outweighs the higher noise level. Because thermal noise is temperature-dependent, it is also highly effective to cool the input stages for low-noise performance.

2.4.6. Temperature Coefficient

The temperature coefficient of resistance, or TCR, is one of the most important parameters characterizing a resistor. The TCR defines the change in resistance as a function of the ambient temperature. The common way to express the TCR is in ppm/°C (or equivalently ppm/°K), which stands for parts per million per degree Celsius (or Kelvin). The TCR is calculated as follows:

$$TCR = \frac{R2 - R1}{R1(T2 - T1)} 10^{-6}$$

where *TCR* is in ppm/°C (ppm/°K), *R1* is the resistance in ohms at temperature *T1* (typically room temperature) in °C or °K, and *R2* is the resistance in ohms at operating temperature *T2* in °C or °K. In place of TCR, α is often used.

2.4.6.1. Positive vs. Negative TCR

Resistors are available with a TCR that is negative, positive, or stable over a certain temperature range. Choosing the right resistor can make temperature compensation unnecessary. In some applications, temperature measurement for example, a large TCR is desirable. Resistors for these applications are called thermistors, and can have a positive (PTC) or negative (NTC) temperature coefficient.

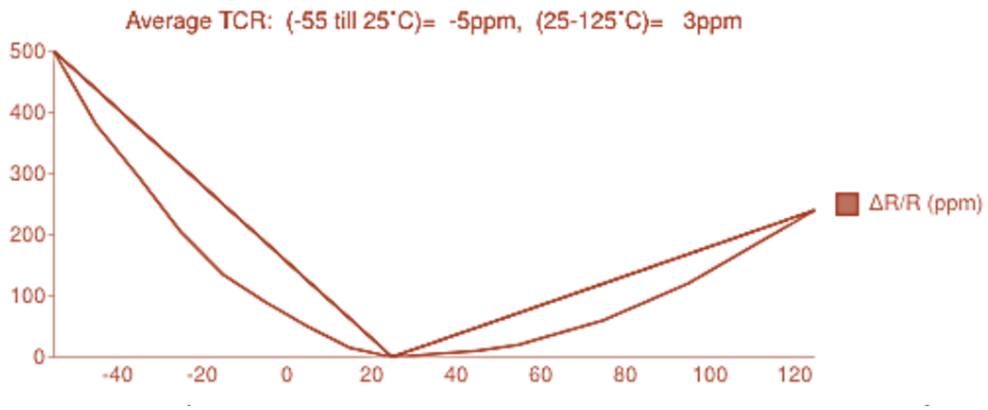
2.4.6.2. TCR Measurement Methods

The temperature coefficient of resistance for a resistor is determined by measuring the resistance values over an appropriate temperature range. The TCR is calculated as the average slope of the resistance value over this interval. This is accurate for linear relations, since the TCR is constant at every temperature.

However, many materials have a nonlinear coefficient. For example, Nichrome, a popular alloy for resistors, has a nonlinear relation between the temperature and the TCR. Because the TCR is calculated as average slope, it is therefore very important to specify the TCR as well as the temperature interval.

The proper method for measuring TCR is standardized in MIL-STD-202 Method 304. With this method, TCR is calculated from between -55 and 25 °C and between 25 and 125 °C. Since the highest measured value is defined as the TCR, this method often results in overspecifying a resistor for less demanding applications. The figure on the following page provides a representative TCR curve for these two temperature bands.

In the table that follows, the TCR is given for a wide variety of materials. Note that the exact value of the TCR depends on the purity of the material as well as the temperature.



Average TCR ΔR/R in ppm for a temperature range of -55 to 25 ℃ and 25 to 125 ℃

Temperature coefficient of resistance for common resistor materials

Material	**TCR (1/°C) x10^{-3}**
Silicon	-75
Germanium	-48
Carbon (amorphous)	-0.5
Manganin	0.002
Constantan	0.008
Nichrome	0.4
Mercury	0.9
Gold	3.4
Zinc	3.7
Copper	3.9
Aluminum	3.9
Lead	3.9
Platinum	3.92
Calcium	4.1
Tungsten	4.5
Tin	4.5
Iron	5
Nickel	6
Lithium	6

2.4.7. Other Resistor Properties

2.4.7.1. Wire Insulation

Wirewound resistors are insulated with enamel (sometimes wound with synthetic fiber, silk or cotton) and the oxide layer of the material itself.

2.4.7.2. Protection Against Influences From the Environment

For applications in very hot and humid climates, the resistor is enclosed in an airtight metal case. If the complete body is covered, for example with enamel paint, special care has to be taken that all expansion coefficients are approximately equal. If this is not the case, the enamel layer may burst after the baking process.

2.4.7.3. Maximum Allowed Voltage

If the maximum allowed voltage is exceeded, it may cause a disruptive discharge and permanently damage the wire insulation. This discharge could as well pass through the solid insulating material and damage other nearby parts.

2.4.7.4. Long-Term Stability

Stability indicates the maximum tolerable change in the resistance value, which fluctuates over time due to mechanical, electrical, and thermal loads. In standards, several stability classes are determined, as defined by established tests. Short-term tests include exposure to overloading, rapid temperature variations, and vibrations. Long-term tests include the damp heat test and load-life tests (constant 70 °C with a certain electrical load).

Resistance change by stability class

Stability Class	Long-Term Test	Short-Term Test
2	± (2.0% x R + 0.10 Ω)	± (0.50% x R + 0.05 Ω)
1	± (1.0% x R + 0.05 Ω)	± (0.25% x R + 0.05 Ω)
0.50	± (0.50% x R + 0.05 Ω)	± (0.10% x R + 0.01 Ω)
0.25	± (0.25% x R + 0.05 Ω)	± (0.05% x R + 0.01 Ω)
0.10	± (0.10% x R + 0.02 Ω)	± (0.05% x R + 0.01 Ω)
0.05	± (0.05% x R + 0.01 Ω)	± (0.025% x R + 0.01 Ω)

2.4.7.5. Pulse Stability

Pulse stability describes the effect on the long-term variation of the resistance value when the resistor is loaded with short-term pulses, instead of constant load. The pulses can be much higher than the normal power rating, without having an effect on long-term stability. Special tests with pulses are defined in standards such as IEC 90115-1, 4.27. To specify a resistor with sufficient pulse stability, the following requirements must be met:

- The average load must not exceed the power rating at the normal ambient operating temperature
- The maximum allowed pulse loading as a function of the duration must not be exceeded
- The pulse voltage at the resistor must be lower than the allowed pulse peak voltage

2.4.7.6. Resistance Value Tolerance

Resistors are manufactured with a certain tolerance. Depending on the application, the tolerance must be specified.

2.4.7.7. Mechanical Strength

The complete construction must be designed for the planned operating temperature (think, for example, of heating elements).

2.4.7.8. Thermo-Electric Effect

As different materials are typically used for the mounting wire and the resistor material, the thermo-electric effect causes unwanted electric currents. Precision resistors are carefully manufactured to minimize this effect.

3 RESISTOR TYPES

3.1 Fixed Resistors **35**
3.1.1 Identifying Fixed Value Resistors 35
3.1.2 Fixed Resistor Symbols 36

3.2 Variable Resistors **36**
3.2.1 Linear Potentiometer 38
3.2.2 Digital Potentiometer 44
3.2.3 Rheostat 46
3.2.4 Trimpot 48
3.2.5 Thermistor 49
3.2.6 Varistor 51
3.2.7 Magneto Resistor 55
3.2.8 Photoresistor 57

3.3 Wirewound Resistors **61**
3.3.1 Construction and Materials 62
3.3.2 High-frequency Effects: Inductance and Capacitance 63
3.3.3 Types 64
3.3.4 Applications 66

3.4 Carbon Composition Resistors **66**
3.4.1 Advantages and Disadvantages 66
3.4.2 Applications 67
3.4.3 Manufacturing 68
3.4.4 History 68

3.5 Carbon Film Resistors **68**
3.5.1 Advantages and Disadvantages 68
3.5.2 Applications 69
3.5.3 Manufacturing 69

3.6 Metal Film Resistors **70**
3.6.1 Construction 70
3.6.2 Applications 71
3.6.3 Reliability 71

3 RESISTOR TYPES

3.7 Metal Oxide Film Resistors 71
3.7.1 Properties 71
3.7.2 Applications 72
3.7.3 Construction 72
3.7.4 History 72

3.8 Thin and Thick Film Resistors 72
3.8.1 Thin Film Technology 73
3.8.2 Thick Film Technology 74
3.8.3 Thin Versus Thick Film Resistors 75

3. RESISTOR TYPES

Resistors can be divided by construction type as well as resistance material. Here is a breakdown of resistors by type:

- Fixed resistors
- Variable resistors, such as the:
  - Potentiometer
  - Rheostat
  - Trimpot
- Resistance-dependent based on a certain physical characteristic:
  - Thermistor (NTC and PTC) — resistance fluctuates with temperature
  - Photo resistor (LDR) — resistance is a function of light level
  - Varistor (VDR) — resistance values vary with applied voltage
  - Magneto resistor (MDR) — resistance changes with a changing magnetic field
  - Strain gauge — resistance is a function of mechanical load

And here is a breakdown based on material and manufacturing process:

- Carbon composition
- Carbon film
- Metal film
- Metal oxide film
- Wirewound
- Foil

The choice of material technology is specific to use case. Often it is a trade-off between cost, precision, and other requirements. Carbon composition, for example, is a very old technique with low precision, but is still used for specific applications where high-energy pulses occur. Carbon composition resistor bodies have a mixture of fine carbon particles and a non-conductive ceramic.

The carbon film technique leads to better tolerance. Resistors of this type are constructed of a non-conductive rod surrounded by a thin layer of carbon film. This layer is treated with a spiral cut to increase and control the resistance value.

Metal and metal oxide films are in wide use today. These have better properties for stability and tolerance, and are also less influenced by temperature variations. They are constructed similarly to carbon film resistors, with a resistive film around a cylindrical body. Metal oxide film is generally more durable.

Wirewound resistors are the oldest type, and can be used for both high-precision and high-power applications. They are constructed by winding a special metal alloy wire, such as nickel chrome, around a non-conductive core. They are durable, accurate, and can have very low resistance values, though they suffer from parasitic reactance at high frequencies.

To meet the highest requirements for precision and stability, metal foil resistors are used. They are constructed by cementing a special alloy of cold-rolled film onto a ceramic substrate.

3.1. Fixed Resistors

Fixed value resistors have a defined ohmic resistance and are not adjustable. They are the most commonly used, and in general are one of the most used electronic components. Fixed resistors are available in axial leaded and surface mount packages, as well as more customized packages depending on their application. While axial leaded resistors used to be the most common, nowadays the advantages of surface mount devices (SMD) make SMD resistors the preferred choice.

> *A fixed resistor has a static, defined electrical resistance that is not adjustable.*

In an ideal world, a perfect resistor would have a constant ohmic resistance under all circumstances. This resistance would be independent of, for example, frequency, voltage, or temperature. But in practice, no resistor is perfect and all have a certain stray capacitance and inductance, resulting in an impedance value different from the nominal resistance value. Resistor materials, for instance, have a certain temperature coefficient, and this influences the resistor value. The type of resistor and its material, though, determine the degree to which the resistance value is dependent on these external factors. As such, specific resistors and materials are selected based on the required accuracy, power dissipation, and noise requirements of the intended application.

3.1.1. Identifying Fixed Value Resistors

In the next table, an overview of general purpose resistors is given. The types listed here are among the most commonly used. Carbon film is the most common axial leaded resistor, and is used for applications where an exceedingly good tolerance and temperature coefficient are not necessary. Metal film is the general axial leaded resistor of choice for higher precision applications. For high-power applications, wirewound resistors are often used, with the aluminum housing depicted in the picture below common for power ratings between 10 and 2500 W. SMD resistors are, in general, constructed from thick or thin film material. The properties listed in the table indicate common value ranges, followed by the most common value between brackets. These values should not be seen as limiting, however, as several special purpose resistors with decidedly different characteristics exist.

Properties of general purpose fixed resistors: range and (typical) values

Type	Carbon film	Metal film	Wirewound	Surface mount
				
Tolerance (%)	2-10 (5)	0.1-5.0 (1)	0.1-5.0 (1)	0.1-5.0 (1)
Power rating (W)	0.125-2 (1/4)	0.1-5 (1/4)	1-200 (10)	0.0125-0.25 (0.1)
Temp coeff (ppm/K)	250-450 (450)	10-250 (50)	20-400 (50)	25-200 (100)

3.1.2. Fixed Resistor Symbols

The following resistor symbols are often used to depict resistors with a fixed value. The most used is the international IEC resistor symbol displayed on the left, but the American resistor symbol displayed on the right is also still used.

International IEC resistor symbol (left) and American ANSI resistor symbol (right).

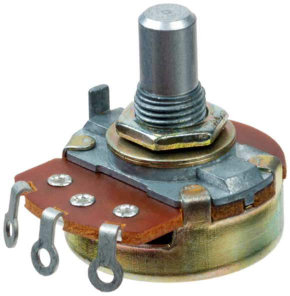
3.2. Variable Resistors

A variable resistor is a resistor whose electric resistance value can be adjusted. A variable resistor is in essence an electro-mechanical transducer, and normally works by sliding a contact (wiper) over a resistive element. When a variable resistor is used as a potential divider by using three terminals, it is called a potentiometer. When only two terminals are used, it functions as a variable resistance and is called a rheostat. Variable resistors that can be controlled electronically, rather than by mechanical action, are also available. These resistors are called digital potentiometers.

> *A variable resistor's resistance value can be adjusted mechanically (potentiometer, rheostat) or electronically (digital potentiometer).*

3.2.1. Potentiometer

A potentiometer is a manually adjustable variable resistor with three terminals. Two terminals are connected to both ends of a resistive element, and the third terminal connects to a sliding contact, called a wiper, moving over the resistive element. The position of the wiper determines the output voltage of the potentiometer. The potentiometer essentially functions as a variable voltage divider.



Potentiometer example

The resistive element can be seen as two resistors in series (potentiometer resistance), where the wiper position determines the resistance ratio of the first resistor to the second resistor. A potentiometer is also commonly known as a potmeter or pot. The most common form of potmeter is the single turn rotary potmeter. This type of pot is often used in audio volume control (logarithmic taper) as well as many other applications. Different materials are used to construct potentiometers, including carbon composition, cermet, wirewound, conductive plastic, or metal film.

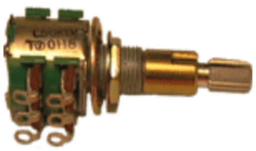
> *A potentiometer is a manually adjustable, variable resistor with three terminals. Two terminals are connected to a resistive element; the third terminal is connected to an adjustable wiper. The position of the wiper determines the output voltage.*

A wide variety of potmeters exist. Manually adjustable potmeters can be divided into rotary or linear movement types. The tables below list the available types and their applications. Besides manually adjustable pots, electronically controlled potentiometers also exist, often called digital potmeters.

3.2.1.1. Rotary Potentiometer

The most common type of potentiometer has a wiper that moves along a circular path. Some of the most common types of rotary potentiometers are described in the following table, with a few pictured here.

Dual-gang potentiometer



Concentric potentiometer

Multi-turn potentiometer

Types of rotary potentiometers

Type	Description	Applications
Single-turn	Single rotation of approximately 270 degrees, or 3/4 of a full turn.	Most common pot type. Used in applications where a single turn provides enough control resolution.
Multi-turn	Multiple rotations (typically 5, 10, or 20) for increased precision. Constructed either with a wiper that follows a spiral or helix form, or by using a worm-gear.	Used where high precision and resolution are required. Worm-gear, multi-turn pots are often used as trimpots on PCBs.
Dual-gang	Two potentiometers combined on the same shaft, enabling the parallel setting of two channels. Single turn potentiometers with equal resistance and taper are most common. More than two gangs is possible, but not common.	Used in stereo audio volume control, or other applications with two channels that must be adjusted in parallel.
Concentric	Dual potmeter where the two potentiometers are individually adjusted by means of concentric shafts. Enables the use of two controls on one unit.	Often encountered in older car radios where the volume and tone controls are combined.
Servo	A motorized potmeter that can also be automatically adjusted by a servo motor.	Used where manual and automatic adjustment is required. Often seen in audio equipment where the remote control can turn the volume control knob.

3.2.1.2. *Linear Potentiometer*

Linear potentiometers have a wiper that moves along a linear path. They are also known as sliders, slide pots, or faders.

Slide potentiometer

Motorized fader

Multi-turn linear trimpot

Types of linear potentiometers

Type	Description	Applications
Slide	Single linear slider potentiometer for audio applications; known also as a fader. High-quality faders are often constructed from conductive plastic.	For single channel control or measurement of distance.
Dual-slide	Dual-slide potentiometer with a single slider controlling two potentiometers in parallel.	Often used for stereo control in professional audio, or other applications where dual parallel channels are controlled.
Multi-turn slide	Constructed from a spindle that actuates a linear potentiometer wiper. Multiple rotations (typically 5, 10, or 20) provide increased precision.	Used where high precision and resolution are required. Multi-turn linear pots are used as trimpots on PCBs, but less commonly than worm-gear trimmer potentiometers.
Motorized fader	Fader that can be automatically adjusted by a servo motor.	Used where manual and automatic adjustment are required. Common in studio audio mixers where the servo faders can be automatically moved to a saved configuration.

3.2.1.3. Digital Potentiometer

Digital potentiometers are potentiometers that are controlled electronically. In most cases, they consist of an array of small resistive components in series. Every resistive element is equipped with a switch that can serve as the tap-off point or virtual wiper position. A digital potmeter can be controlled by, for example, up/down signals or protocols such as I^2C and SPI. See section 3.2.2. Digital Potentiometer for more information.

3.2.1.4. Materials Used For Potentiometers

Materials used for potentiometers

Material	Properties
Carbon composition	Carbon composition ink molded onto a substrate of phenolic resin. This is the most common material, as it is low-cost and provides reasonable noise and wear characteristics.
Wirewound	Can handle high power, are long lasting, and can be very precise, but have limited resolution and a rough feel. Most often used in high-power applications (rheostats are often wirewound) or as precision pots.
Conductive plastic	Very smooth feel and high resolution. Can be constructed to perform millions of cycles, but can only handle limited power and are expensive. Often used in high-end (audio) equipment where high resolution and low noise are important.
Cermet	Very stable, low temperature coefficients, and handle high temperatures well. On the other hand, very expensive and often support a limited number of cycles, though special long-life cermet pots do exist. Widely used for trimpots that do not have to be adjusted often.

3.2.1.5. Potentiometer Standard Values

Because potmeters are variable, there is no need for a wide range of values. While potentiometers can be manufactured in every resistance value one can think of, most potmeters have values in the following range of multiples.

Common potentiometer multiplier values

10	20	22	25	47	50

By far the most used value for potentiometers is 10 kΩ. Other common values are 1, 5, and 100 kΩ.

3.2.1.6. Potentiometer Characteristics

Taper

Potentiometer taper is the relationship between mechanical position and resistance ratio. Linear taper and logarithmic (audio) taper are the most common forms of taper. More information on taper is provided in section 3.2.1.8. Potentiometer Taper.

Marking Codes

Potentiometer values are often marked with a readable string indicating the total resistance, such as “100k” for a 100 kΩ potentiometer. Sometimes a three-digit coding system similar to SMD resistor coding is used. In this system, the first digits indicate the value and the last digit indicates the multiplier. For example, a 1 kΩ would be coded as 102, meaning 10 Ω x 10^2 = 1 kΩ.

The taper of a potentiometer is normally indicated with a letter. The following table lists the coding used for potentiometer taper. Different standards use the same letters, which can be confusing. It is always a good idea to double check the taper by measuring.

Potentiometer marking codes

Taper	String	Asia (common)	Europe	America	Vishay
Linear	LIN	B	A	B	A
Log / Audio	LOG	A	C	A	L
Anti-log	–	–	F	C	F

Resolution

The resolution of a potentiometer is the smallest possible change in resistance ratio. Conductive plastic potmeters have the best resolution, while it is often lower in wirewound resistors whose wire turns introduce discrete steps in resistance.

The resolution can be influenced by the wiper configuration; a wiper consisting of several spread contact points increases the potentiometer resolution.

Hop-on and Hop-off Resistance

At the start and end of travel, the resistive track of a potentiometer is connected to low-resistance metal parts that connect the resistive element to the end terminals. The change in resistance when the wiper enters or exits the resistive track is known as the hop-on and hop-off resistance.

3.2.1.7. Applications for Potentiometers

Potentiometers are used in a diverse range of industries and applications. It would be difficult to list all of the applications here. They can be used for control input, position measurement, as a calibration component, and much more.

User-controlled Inputs

Where a variable input from the user of a machine or application is required, potentiometers are often used. In automotive applications, the throttle pedal is often a potentiometer; normally, this is a dual gang pot to increase system redundancy. Joysticks for machine control are yet another application of pots.

Audio Control

Volume control is often performed with a (motorized) potentiometer in audio applications. For balance control, a dual-gang potentiometer can be used, where one gang has a logarithmic taper and the other gang has an inverse logarithmic taper. In professional audio equipment, faders are often used.

Position or Angle Transducer

Potentiometers are often used as a position or angle transducer to measure distances or angles.

Calibration and Tuning

In fabrication and calibration, trimpots are often used. Trimpots are preset potentiometers that are frequently mounted on a circuit board and can be used to tune or adjust the circuit's performance. They are used only during system calibration and generally have a fixed position. Trimpots, also known as presets, trimmers, or trimming potentiometers, are often actuated by a small flat-head screwdriver.

3.2.1.8. Potentiometer Taper

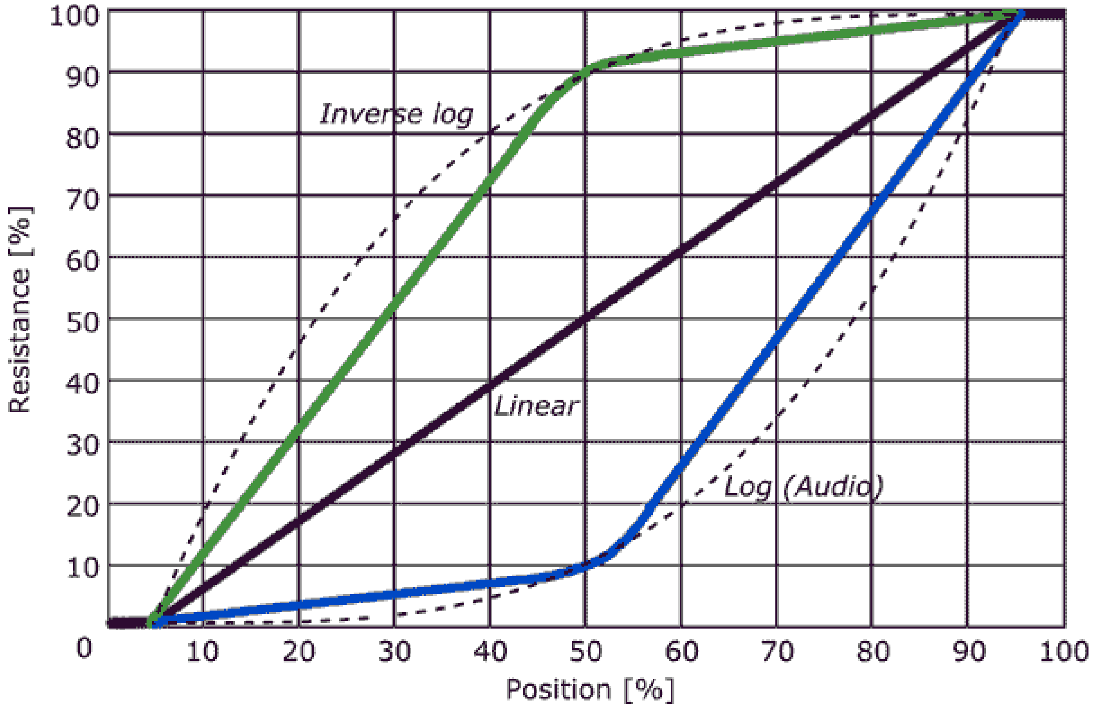
Potentiometer taper, as mentioned above, is the relation between the position and the resistance of a pot. For the majority of variable resistors available, this is a linear relationship, meaning that the relative position is equal to the resistance ratio. For example, when the potmeter is at the middle position, the output voltage is half of the full voltage over the potentiometer. For some applications, and especially audio volume control, nonlinear, logarithmic tapers are used.

> *Taper is the relation between the position of the potentiometer and the resistance ratio.*

Linear Taper

The simple linear taper is the most common form. The graph below shows the relationship between the resistance and the taper position for the most commonly used tapers. The first and last few percent of travel are often only mechanical with no change in resistance.

The region between 5 and 95%, where the electrical resistance changes, is called the electrical travel. The available travel for rotary pots is often denoted in degrees; a mechanical travel of 300° combined with an electrical travel of 270° is common.



Resistance as a function of position for common taper types

Logarithmic or Audio Taper

The most used nonlinear taper is the logarithmic (log) or audio taper. This is mainly used for audio volume control, to obtain a more natural "linear" perception in sound intensity change when you adjust the volume. Because the human ear is sensitive to sound intensity in a logarithmic fashion, at low intensities a slight change in intensity is perceived as a substantial change in loudness, while at high intensities a significant change in intensity is required for the same register.

To compensate for the ear's logarithmic behavior, audio taper pots were developed. While called logarithmic, these actually follow an exponential curve (the opposite of the logarithmic behavior of the human ear). Sometimes inverse logarithmic (anti-log) pots are used, for example in audio controls that turn counterclockwise, but also in some other specialized applications.

The dashed lines in the graph above show the "real" logarithmic curves. In practice, logarithmic types used for audio applications do not actually behave in a precisely exponential way, but follow the curve stepwise. The bottom thick line shows the actual taper curve of an audio potentiometer. This approximation is done because it simplifies the manufacturing process. Instead of a continuously varying resistance track, two different tracks are used that overlap at the middle position.

As audio volume control is in general a non-critical operation, this satisfies for these applications. For special applications, there exist tapered potentiometers with real exponential curves.

3.2.1.9. Potentiometer Symbols

The following symbols are used for potentiometers.

Potentiometer symbols: IEC standard (left) and ANSI standard (right)

3.2.2. Digital Potentiometer

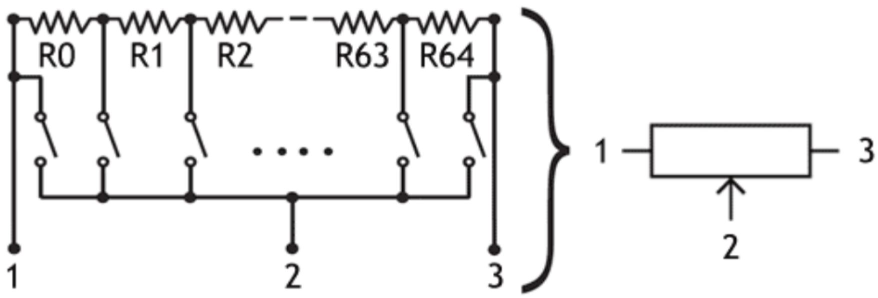
A digital potentiometer (also known as digital resistor) has the same function as a normal potentiometer, but instead of mechanical action it uses digital signals and switches. This is done by making use of a “resistor ladder,” a string of small resistors in series.

Dual-inline package (DIP) often used to package digital potentiometers

> *A digital potentiometer is a variable resistor that is controlled by digital signals instead of by mechanical movement.*

In one simple implementation, at every step of the ladder an electronic switch is present. Only one switch is closed at a time and, in this way, the closed switch determines the “wiper” position and the resistance ratio. The amount of steps in the ladder determines the resolution of the digital pot.

The diagram below shows the working principle of a digital potentiometer with 64 steps. Digital resistors can be controlled by using simple up/down signals or by serial communication protocols such as I^2C or SPI.



Resistor ladder implementation of a digital potentiometer

3.2.2.1. Properties of Digital Potentiometers

Digital potentiometers are integrated circuits (ICs). Some variants have a nonvolatile memory (EEPROM), which remembers the wiper position. When there is no on-board memory, the initial position of the wiper is often the middle position. Because of their relatively small size compared to conventional potentiometers, multiple potentiometers can be packed on a chip, and ICs with up to six channels are available.

Digital resistors are available in a range of values, but 10 kΩ is the most common. Other common values are 5, 50, and 100 kΩ. The standard tolerance is 20% but digital potentiometers with a tolerance down to 1% are available. The amount of steps available determines the resolution of the digital potentiometer. The following table lists common step values, including the bit count:

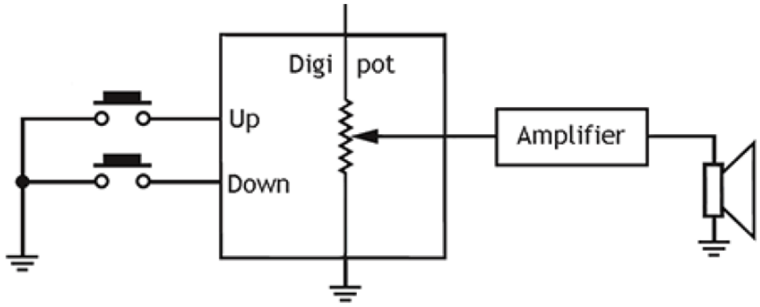
Common step values and bit counts for digital potentiometers

Bits	5	6	7	8	9	10
Steps	32	64	128	256	512	1024

Something to take into account when you start working with digital potentiometers is that most of them are rated at 5 V or less (to power the logic circuits). This can make it a bit tricky to use them as a direct replacement for conventional potentiometers.

3.2.2.2 Digital Potentiometer Applications

Digital pots can be used in any application where normally a trimming potentiometer or preset resistor is used. Their chief advantage is that they can be controlled in a closed loop. They are used in applications that include: brightness and contrast control in monitors, gain control, Wheatstone bridges, and even digital-analog converters. When used for tuning, re-calibration can be performed via a microcontroller at defined intervals. The image below shows a digipot being used for volume control; The potentiometer can be controlled via up/down signals, buttons, or a rotary encoder.



Digital potentiometer used for a volume control application.

3.2.3. Rheostat

A rheostat is a variable resistor used to control current. They are able to vary the resistance in a circuit without interruption, and their construction is very similar to the construction of potentiometers. They use only two connections, even when three terminals (as in a potentiometer) are present. The first connection is made to one end of the resistive element and the second to the wiper (sliding contact).

> *A rheostat is a variable resistor used to control the current flowing in a circuit.*

In contrast to potentiometers, rheostats have to carry a significant current. Therefore, they are mostly constructed as wirewound resistors. Resistive wire is wound around an insulating ceramic core and the wiper slides over the windings.

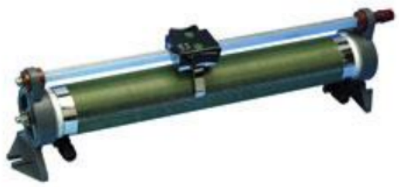
Rheostat variable resistor

In the past, rheostats were often used as power control devices, for example to control light intensity (dimmer), speed in motors, heaters, and ovens. They are rarely used for these functions now because of their relatively low efficiency. In power control applications, they have been replaced by switching electronics. As a variable resistance, they are often used for circuit tuning and calibration. In these cases, they are adjusted only during fabrication or circuit tuning (preset resistor). Here, trimpots are often used, wired as a rheostat. But dedicated two-terminal preset resistors also exist.

3.2.3.1. Types of Rheostats

Several types of rheostats exist. The rotary type is the most often used in power control applications. Most of these rheostats use an open construction, but enclosed types are also available. Just as with potentiometers, multi-gang types also exist. They are used to control multiple applications in parallel, or to increase the power rating or adjust the range. Optionally, rheostats can be equipped with a mechanical stop to limit the minimum or maximum resistance. For special applications, they can also be built with tapered windings.

Rotary rheostat



Slide rheostat

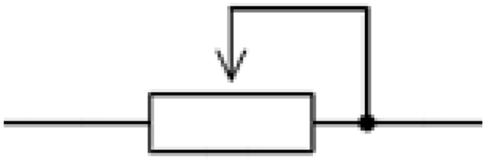
Preset resistor

Slide rheostats are often used for education and in laboratory environments. Linear or slide types are constructed of resistive wire wound on an insulating cylinder. A sliding contact is used to increase or decrease the resistance.

Trimmers used as a variable resistance are very common on printed circuit boards. While dedicated preset resistors with two terminals exist, the three-terminal trimmer potentiometer is more common and often used wired as a rheostat.

3.2.3.2. How to Wire a Potentiometer as a Rheostat

Any three-terminal potentiometer can be wired as a rheostat by connecting to one end of the resistive track and to the wiper. It is best practice to connect the wiper to the other end of the resistive track. Doing this prevents circuit interruption in case the wiper loses connection with the resistive track, and also reduces noise during adjustment.



Potentiometer wired as a variable resistance

3.2.3.3. Rheostat Symbols

The following IEC standard symbols are used to represent rheostats and preset resistors.

IEC standard symbols for a rheostat (left) and preset resistor (right)

3.2.4. Trimpot

A trimpot or trimmer potentiometer is a small potentiometer that is used for adjustment, tuning, and calibration in circuits. When they are used as a variable resistance (wired as a rheostat), they are called preset resistors. Trimpots or presets are normally mounted on printed circuit boards and adjusted by using a screwdriver.

> *Trimmer potentiometers and preset resistors are small variable resistors that are used in circuits for tuning and (re)calibration.*

The material they use as a resistive track varies, but the most common is either carbon composition or cermet. Trimpots are designed for occasional adjustment and can often achieve a high resolution when using multi-turn setting screws. When trimmer potentiometers are used as a replacement for normal potentiometers, care should be taken as their designed lifespan is often only 200 cycles.

3.2.4.1. Types of Trimpots

Several different versions of trimpots are available with different mounting methods (through-hole, SMD) and adjustment orientations (top, side), and are available in single and multi-turn variations.

Single Turn Trimpots

Single turn trimmers/presets are very common and are used where a resolution of one turn is sufficient. They are the most cost-effective variable resistors.

Open, carbon track

Enclosed, side adjust

Enclosed, SMD

Multi-Turn Trimpots

For higher adjustment resolutions, multi-turn trimpots are used. The number of turns varies roughly from five to 25. Common values are 5, 12, or 25 turns. They are often constructed using a worm-gear (rotary track) or lead screw (linear track) mechanism to achieve high resolution. Because of their complex construction and manufacturing, they are more costly than single-turn preset resistors. The lead screw packages can achieve higher power ratings because of their increased surface area.

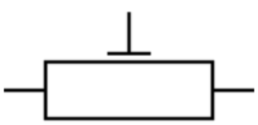
Top adjust, worm-gear

Side adjust, worm-gear

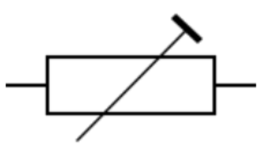
Side adjust, lead screw

3.2.4.2. Trimpot Symbols

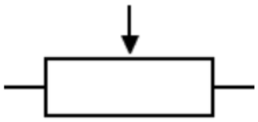
The following IEC symbols are used for trimpots and preset resistors. Although these are the official symbols for occasionally adjusted resistors, the more generic symbols for a potentiometer or rheostat are also often used.



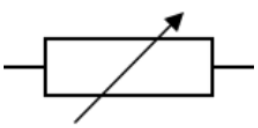
Trimpot



Preset resistor



Potentiometer



Rheostat

3.2.5. Thermistor

A thermistor is a temperature-sensitive resistor often used as a temperature sensor. The term "thermistor" is a contraction of the words "thermal" and "resistor." All resistors are somewhat dependent on temperature, which is described by their temperature coefficient. In most cases for fixed or variable resistors, the temperature coefficient is minimized, but in the case of thermistors a high coefficient is desirable.

> *A thermistor is a resistor whose resistance changes significantly with a change in temperature.*

Unlike most other resistors, thermistors usually have negative temperature coefficients (NTC), which means their resistance decreases as the temperature increases. These types are called NTC thermistors. Thermal resistors with a positive temperature coefficient are called PTC thermistors (Positive Temperature Coefficient).

Thermistors

3.2.5.1. Thermistor Types and Applications

Thermistors are ceramic semiconductors. In most cases, they are composed of metal oxides that are dried and sintered to obtain the desired form factor. The types of oxides and additives determine their characteristic behavior. Cobalt, nickel, iron, copper, and manganese are common oxides for manufacturing NTC thermistors. Barium titanate, strontium titanate, and lead titanate are commonly used for PTC thermistors.

3.2.5.2. NTC Thermistors

NTC thermistors are used when a change in resistance over a wide temperature range is required. They are often used as temperature sensors between -55 and 200 °C, although they can be produced to measure temperatures much lower or higher. Their popularity can be credited to their quick response, reliability, robustness, and low cost.

3.2.5.3. PTC Thermistors

PTC thermistors are used when a sudden change in resistance at a certain temperature is required. They exhibit a sudden increase in resistance above a defined temperature, called the switching, transition, or Curie temperature. The most common PTC switching temperatures are in the range of 60 to 120 °C. PTC thermistors are often used for self-regulating heating elements and self-resetting, overcurrent protection.

Comparison of NTC and PTC Thermistors

Thermistor Type	NTC	PTC
Temperature coefficient	Negative	Positive
Metal oxides	Cobalt, nickel, iron, manganese, titanium	Barium titanate, lead titanate, strontium titanate
Common temperature ranges	-55 to +200 °C	60 to 120 °C (switching temp)
Applications	Temperature sensing and control, in-rush current limiting, flow measurement	Overcurrent protection, self-regulating heaters, time-delays, liquid level sensing

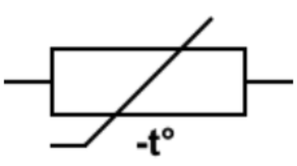
3.2.5.4. Thermistor Packages

Several package types and sizes are available; the radial leaded type is the most common and mostly constructed from epoxy. For applications in harsh environments, glass-encapsulated packages are more suitable. Integrated packages are also available, such as threaded housings, lugs or probes for easy mounting. The following figure shows some examples of available package types.

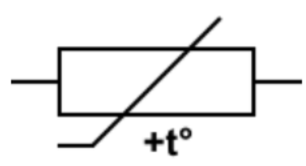
Radial leaded *Axial leaded* *Glass* *Threaded* *Probe*

3.2.5.5. Thermistor Symbols

The following symbols for NTC and PTC thermistors are used in accordance with the IEC standard.



NTC thermistor symbol



PTC thermistor symbol

3.2.6. Varistor

A varistor is a voltage-dependent resistor (VDR). The term “varistor” is derived from the words “variable” and “resistor.” The resistance of a varistor varies as a function of the voltage applied. Varistor resistance decreases when the voltage increases. In case of excessive voltage increases, resistance drops dramatically. This behavior makes varistors suitable for protecting circuits during voltage surges. Causes of a surge can include lightning strikes and electrostatic discharges. The most common type of VDR is the metal oxide varistor, or MOV.

Varistor examples

> *Varistors are nonlinear, two-element semiconductors that drop in resistance as the voltage increases. Voltage dependent resistors are often used as surge suppressors for sensitive circuits.*

3.2.6.1. Varistor Packages

The following figure includes examples of different varistor package styles. The block packages are used for higher power ratings.

Disc

Block

Radial leaded

Axial leaded

3.2.6.2. Varistor Characteristics

As a voltage-dependent resistor, the varistor has a nonlinear varying resistance, dependent on the voltage applied. The impedance is high under nominal load conditions, but will sharply decrease when a specific voltage threshold—the breakdown voltage—is exceeded.

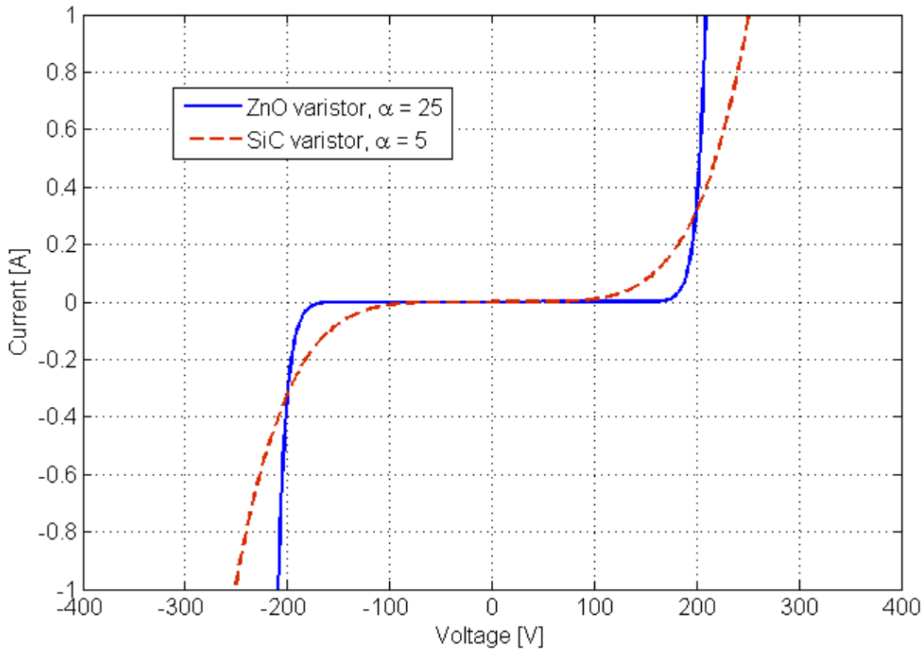
Varistors are often used to protect circuits against excessive transient voltages. When the circuit is exposed to a high voltage transient, the varistor begins to conduct significantly more current and clamps the transient voltage to a safe level. The energy of the incoming surge is partially conducted and partially absorbed, protecting the circuit.

The most common type of varistor is, again, the MOV. MOVs are constructed of a sintered matrix of zinc oxide (ZnO) grains. The grain boundaries provide P-N junction semiconductor characteristics, similar to a diode junction; the matrix of randomly oriented grains can be compared to a large network of diodes in series and parallel. When a low voltage is applied, very little current, caused by the reverse leakage through the junctions, is able to flow.

When a high voltage that exceeds the breakdown voltage is applied, though, the junctions experience an avalanche breakdown and a large current can flow. This behavior results in the nonlinear current-voltage characteristics. The relationship between the current, *I*, through the varistor and the voltage, *V*, across the terminals is typically described by:

$$I = k \cdot V^{\alpha}$$

where α describes the degree of nonlinearity. The figure below shows the characteristic curves of an MOV with high α and a silicon carbide (SiC) varistor with low α.



I-V curve for a metal oxide varistor (MOV)

Important varistor selection parameters include: clamping voltage, peak current, maximum pulse energy, rated AC/DC voltage, and standby current. When used on communication lines, stray capacitance is also an important parameter. A high capacitance can act as a filter for high frequency signals or induce crosstalk, limiting the available bandwidth of the communications line.

Varistors are useful for short duration protection against high transient voltage surges in the order of 1-1000 microseconds. They are, however, not suited for handling sustained surges. If the transient pulse energy in joules (*J*) is too high and significantly exceeds the absolute maximum ratings, the varistor can melt, burn, or explode.

MOVs degrade when exposed to repeated surges. After each surge, MOVs' clamping voltage moves a little lower. The magnitude of this change in the clamping voltage depends on the joule rating of the MOV in relation to the pulse. As the clamping voltage falls lower and lower, a possible failure mode is a partial or complete short circuit in which the clamping voltage falls below the protected line voltage. This situation could lead to a fire hazard. To prevent fire hazards, MOVs are often connected in series with a thermal fuse that disconnects the MOV in case of overheating. To limit degradation, it is advisable to use a clamping voltage as high as the protected circuit allows, to limit the amount of exposure to surges.

3.2.6.3. Varistor Applications

The nonlinear characteristic of varistors makes them ideal for use as surge protection devices against high-voltage transients, sources of which can be lightning strikes, electrostatic discharge, or inductive discharge from motors or transformers. As such, varistors are often used in surge protector power strips. Special types with a low capacitance protect communication lines. These and other additional applications of voltage-dependent resistors are listed below:

- Telephone and other communication line protection
- Radio communication equipment transient suppression
- Surge protector power strips
- Cable TV system surge protectors
- Power supply protection
- Microprocessor protection
- Electronics equipment protection
- Low-voltage board-level protection
- Transient voltage surge suppressor (TVSS)
- Car electronics protection
- Industrial high-energy AC protection

3.2.6.4. Types of Varistors

The most important varistor types are:

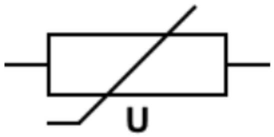
- **Metal oxide varistor** – Described previously, the MOV is a nonlinear transient suppressor composed of zinc oxide (ZnO).
- **Silicon carbide varistor** – Before the MOV came to market, this was the most common variety. These varistors utilize silicon carbide (SiC) and have been extensively used in high-power, high-voltage applications. Their disadvantage is that they draw a significant standby current. Therefore, a series gap is required to limit the standby power consumption.

Alternative types of surge-suppressing devices include:

- **Selenium cells** – These suppressors use selenium rectifiers allowing a high-energy reverse breakdown current. Some selenium cells have self-healing properties that allow them to withstand high-energy discharges. They do not, though, have the clamping ability of modern MOVs.
- **Zener diodes** – A transient suppression device that utilizes silicon rectifier technology. Zener diodes have constant voltage clamp ability. But their major drawback is that they have limited capability to dissipate energy.
- **Crowbar devices** – A crowbar device short-circuits a surge to ground. This short-circuit will continue until the current reaches below a certain level, generally very low, creating a lagging or power-following effect. Examples of crowbar devices include:
    - **Gas discharge tube (GDT) or spark gap** – These devices conduct after a conducting spark is created. Their advantage is their large current-carrying capabilities, though they take a relatively long time to trigger.
    - **Thyristor surge protection device (TSPD)** – These devices have similar characteristics to a GDT, but can act much faster.

3.2.6.5. Varistor Symbol

The following symbol is used for a varistor, in this case one dependent on voltage, U.



Varistor symbol (IEC standard)

3.2.7. Magneto Resistor

Magneto resistors have a variable resistance that is dependent on magnetic field strength. A magneto resistor can thus be used to measure magnetic field presence, strength, and direction. They are also known as magnetic-dependent resistors (MDR). A magneto resistor is a subfamily of magnetic field sensors, or magnetometers.

> *A magneto resistor is a resistor whose electrical resistance changes when an external magnetic field is applied.*

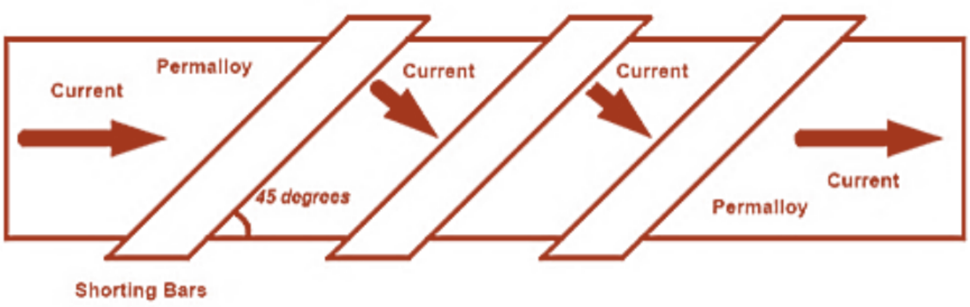
3.2.7.1. Magneto Resistor Characteristics

Magneto resistors make use of the magnetoresistance effect, first discovered in 1856 by William Thomson, also known as Lord Kelvin. The effect is seen in ferromagnetic materials and is dependent on magnetic field strength, as well as the angle between the direction of electric current and the magnetic field. It is therefore known as anisotropic magnetoresistance (AMR).

Other, more recently discovered magnetoresistance effects are the giant magnetoresistance effect (GMR), colossal magnetoresistance effect (CMR), and tunnel magnetoresistance effect (TMR). Because most conventional magneto resistors utilize the AMR effect, the other effects will not be discussed in this guide.

Permalloy, an alloy consisting of 81% nickel (Ni) and 19% iron (Fe), has a high AMR and a low magnetostriction (change in size due to magnetic fields). Therefore, it is a preferred material for magneto resistors.

Magneto resistors are often constructed of long thin films of permalloy. To increase the sensitivity of a permalloy magneto resistor, shorting bars of aluminum or gold are placed on the thin permalloy films at an angle of 45 degrees. This forces the current to flow in a direction of 45 degrees relative to the length of the film. This is called a barber pole configuration.



Permalloy film magnetoresistor using barber pole pattern of shorting bars

A typical AMR magnetoresistive sensor is constructed of a combination of four permalloy thin film magnetoresistors, connected in a Wheatstone measurement bridge.

3.2.7.2. Magneto Resistor Applications

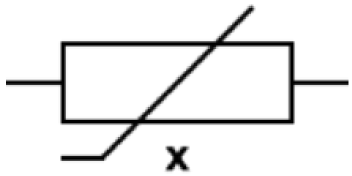
Various applications are possible for magnetic field-sensing devices, including:

- Electronic compasses
- Magnetometry—the measurement of magnetic field intensity and direction
- Position sensors
- Angle position sensors

- Rotary position sensors
- Linear position sensors
- Ferrous metal detection
- Vehicle and traffic detection

3.2.7.3. Magneto Resistor Symbol

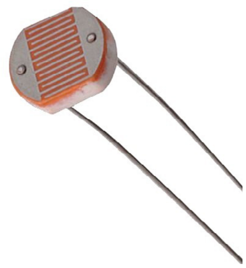
The following symbol is used for a magneto resistor. It is shown as a variable resistor that is dependent on magnetic flux, indicated by the letter 'x'.



Magneto resistor symbol (IEC standard)

3.2.8 Photoresistor

Photoresistors, also known as light-dependent resistors (LDR), are light-sensitive devices that are most often used to indicate the presence or absence of light, or to measure its intensity. In the dark, their resistance is very high, sometimes up to 1 MΩ. When the LDR sensor is exposed to light, the resistance drops dramatically, even down to a few ohms, depending on the light's intensity.



Photoresistor

LDRs are nonlinear devices whose sensitivity varies with the wavelength of the applied light. They are used in many applications, but are occasionally replaced by other devices such as photodiodes and phototransistors. Some countries have banned LDRs made of lead or cadmium over environmental safety concerns.

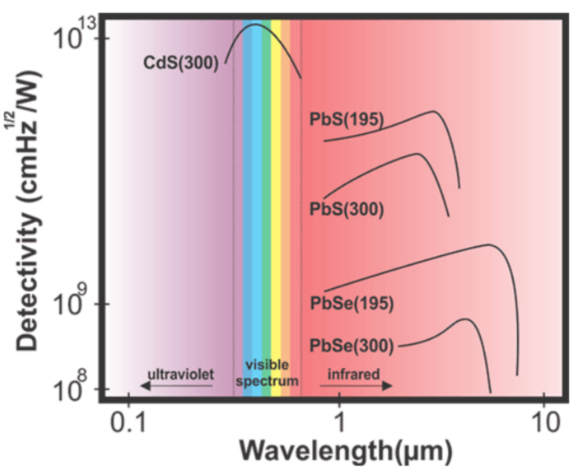
> *Photoresistors are light-sensitive resistors whose resistance decreases as the intensity of light they are exposed to increases.*

3.2.8.1. Types of Photoresistors and Working Mechanisms

Based on the materials used, photoresistors can be divided into two types: intrinsic and extrinsic. Intrinsic photoresistors use undoped materials such as silicon or germanium. Photons that fall on the device excite electrons, causing them to move from the valence band to the conduction band. This generates more free electrons in the material, which increases its current-carrying capability and, therefore, lowers its resistance. Extrinsic photoresistors are made of materials doped with impurities, also called dopants. The dopants create a new energy band above the existing valence band, populated by electrons. Thanks to the smaller energy gap, these electrons need less energy to make the transition to the conduction band. The result is a device sensitive to different wavelengths of light. That said, both types will exhibit a decrease in resistance when illuminated. The higher the light intensity, the larger the resistance drop. Therefore, the resistance of LDRs is an inverse, nonlinear function of light intensity.

3.2.8.2. Wavelength Dependency

The sensitivity of a photoresistor varies with the light wavelength. If the wavelength is outside a certain range, it will not affect the resistance of the device at all; it can be said that the LDR is not sensitive in that light wavelength range. Different materials have particular spectral response curves of wavelength versus sensitivity. Extrinsic light-dependent resistors are generally designed for longer wavelengths of light, with a tendency toward the infrared (IR). When working in the IR range, care must be taken to avoid heat buildup, which could affect measurements by changing the resistance of the device via thermal effects. The figure shown here represents the spectral response of photoconductive detectors made of different materials, with the operating temperature expressed in K and written in parentheses.



Photoresistor spectral response for different material types

3.2.8.3. Sensitivity

Light-dependent resistors have lower sensitivity than photo diodes and photo transistors. Photo diodes and photo transistors are true semiconductor devices, which use light to control the flow of electrons and holes across PN junctions, while light-dependent resistors are passive components, lacking a PN junction. If light intensity is kept constant, resistance may still vary because of changes in temperature. This makes LDRs unsuitable for precise light intensity measurements.

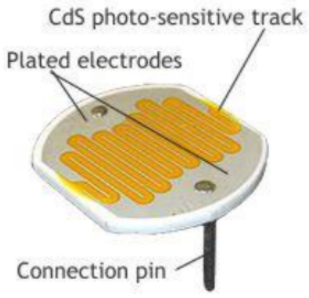
3.2.8.4. Latency

Another interesting property of photoresistors is the latency between changes in illumination and changes in resistance. This phenomenon is called the resistance recovery rate. It usually takes about 10 ms for resistance to drop completely when light is applied after total darkness, while it can take up to 1 second for resistance to rise back to the starting value after the complete removal of light. For this reason, LDRs cannot be used either for recording rapid fluctuations of light or to actuate control equipment. Still, this latency is exploited in several devices, such as audio compressors, where the function of the light-dependent resistor is to smooth the response.

3.2.8.5. Photoresistor Construction and Properties

Since the discovery of selenium photoconductivity, many other materials have been found with similar characteristics. In the 1930s and 1940s, the materials PbS, PbSe, and PbTe were studied following the development of silicon and germanium photoconductors. Modern light-dependent resistors are made most commonly of cadmium sulfide and cadmium selenide, but also of lead sulfide, lead selenide, and indium antimonide.

Cadmium sulfide types are often indicated as CdS photoresistors. To manufacture a cadmium sulfide LDR, highly purified cadmium sulfide powder and inert binding materials are mixed. This mixture is then pressed and sintered. Then, electrodes are vacuum evaporated onto the surface of one side to form interleaving combs, and the leads are connected. The disc is then mounted in a glass envelope, or encapsulated in transparent plastic, to prevent surface contamination.



Cadmium sulfide photoresistor

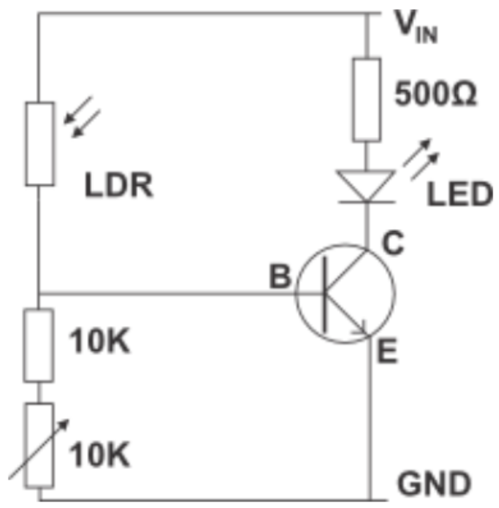
The spectral response curve of cadmium sulfide matches that of the human eye. The peak sensitivity wavelength is about 560-600 nm, which is in the visible part of the spectrum. It should be noted that devices containing lead or cadmium are not RoHS-compliant and are banned for use in countries that adhere to RoHS laws.

3.2.8.6. Typical Applications for Photoresistors

Photoresistors are most often used as light sensors. They are frequently utilized when it is necessary to detect the presence and absence of light, or to measure light intensity. A few examples are night lights and photography light meters. An interesting hobbyist application for light-dependent resistors is the line-following robot, which uses a light source and two or more LDRs to determine the needed change of course. Sometimes, they are used beyond sensing applications, for example in audio compressors, because their reaction to light is not instantaneous, and so the function of the LDR is to introduce a delayed response.

3.2.8.7. Light Sensors

If a basic light sensor is needed, an LDR circuit such as the one depicted below can be used. The LED lights up when the intensity of the light reaching the LDR resistor is sufficient. The 10 kΩ variable resistor is used to set the threshold at which the LED will turn on. If the LDR light is below the threshold intensity, the LED will remain in the off state. In real-world applications, the LED would be replaced with a relay, or the output could be wired to a microcontroller or some other device. If a darkness sensor is needed, where the LED would turn on in the absence of light, the LDR and the two 10 KΩ resistors should be swapped.



Light sensor circuit example

3.2.8.8. Audio Compressors

Audio compressors are devices that reduce the gain of the audio amplifier when the amplitude of the signal is above a set value. This is done to amplify soft sounds while preventing loud sounds from clipping. Some compressors use an LDR and a small lamp (LED or electroluminescent panel) connected to the signal source to create changes in signal gain. This technique is believed by some to add smoother characteristics to the signal, because the response times of the light and the resistor soften the attack and release. The delay in the response time in these applications is roughly 0.1 seconds.

3.2.8.9. Light-dependent Resistor Symbol

The following symbol is used to depict light-dependent photoresistors according to the IEC standard. Sometimes the resistor symbol is circled, with the arrows outside the circle.

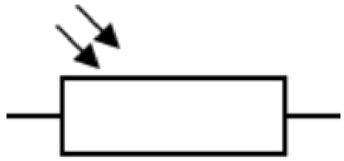
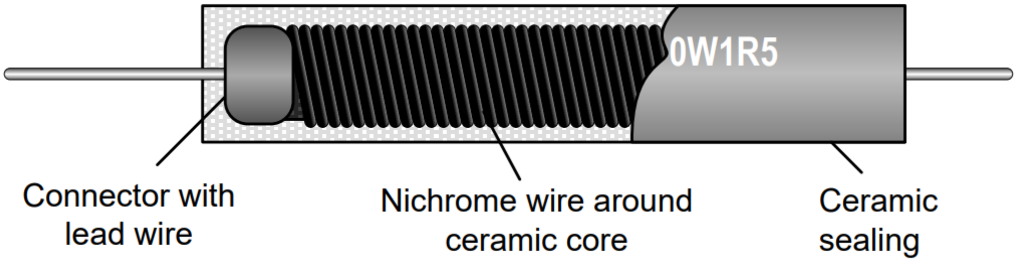


Photo resistor symbol (IEC standard)

3.3. Wirewound Resistors

A wirewound resistor is an electrical passive component that limits current. The resistive element is constructed by winding an insulated metallic wire around a core of non-conductive material.



Schematic view of a wirewound resistor

The wire material has a high resistivity and is usually made of an alloy such as Nickel-chromium (Nichrome), or a copper-nickel-manganese alloy called Manganin. Common core materials include ceramic, plastic, and glass. Wirewound resistors are the oldest type still manufactured today. They can be produced with a high degree of accuracy, and have excellent properties for low resistance values and high power ratings.

> *A wirewound resistor is a resistor in which a wire with high resistivity is wrapped around an insulating core to provide the resistance.*

3.3.1. Construction and Materials

Wirewound resistor construction varies widely. The manufacturing and choice of materials used is dependent on the way the resistor will be used in a circuit. All are made by winding a wire around a core. The resistance value is dependent on the resistivity of the wire, the cross section, and the length. Since these parameters can be accurately controlled, high precision can be achieved. For high tolerance requirements, the resistance value is measured to determine exactly the length at which to cut the wire.

To create high resistance, the wire's diameter needs to be very small and its length very long. As such, wirewound resistors are mainly produced for lower resistance values.

For low power ratings, very thin wire is used. The handling of the wire during manufacturing is critical. Any damage may sever contact. After winding, the wire is well-protected from moisture, which can cause electrolytic corrosion.

There are also wirewound resistors with high power ratings of 50 W or more. These high-power resistors have quite a different construction. The diameter of their wires is relatively large, making them more robust than other resistor types such as metal film.

Wirewound resistors are mainly produced with alloys, since pure metals have a high temperature coefficient of resistance (TCR). For high temperatures, though, pure metals such as tungsten are used. The temperature coefficient is an indicator of how much the resistance will change as the temperature changes. TCR is measured in units of ppm/˚C. If a manufacturer rates a resistor at 50 ppm/˚C, the resistor will not change more than 50 Ω in resistance for each 1 MΩ of the resistor's given value, for a temperature change of 1 ˚C. Typical alloys that are used as resistor wire are:

- Copper alloys
- Silver alloys
- Nickel Chromium alloys
- Iron Chromium alloys
- Iron Chromium Aluminum alloys

In the following table, the properties of the most common alloys are given.

Properties of common resistor alloys

Alloy Group	Material	Composition (%)	Resistivity (10^{-6} Ω/m)	TCR (10^{-3} Ω/°)	Max Operating Temp (°C)
Copper	Constantan	54Cu - 45Ni - 1Mn	0.485	0.2	400
	Nickelin	67Cu - 30Ni - 3Mn	0.4	0.11	300
	Manganin	86Cu - 2Ni - 12Mn	0.442	0.02	300
Silver	N.B.W. 109	82Ag - 10Mn - 8Sn	0.55	0-0.04	
	N.B.W. 139	78Ag - 13Mn - 9Sn	0.61	0-0.08	0-150
	N.B.W. 173	80Ag - 17Mn - 3Sn	0.58	0-0.105	0-200
Nickel Chromium	Nichrome	20Cr - 77/80Ni - 0/2Mn	1.105	0.17	1100/1150
Iron Chromium	CrNiFe 1	70Ni - 20Cr - 8Fe - 2Mn	1.11	0.9	1050/1100
	CrNiFe 2	63Ni - 15Cr - 20Fe - 2Mn	1.12	0.89	1050/1100
Iron Chromium Aluminum	Kanthal A	72Fe - 20Cr - 5Al -3Co	1.45	0.06	1300
	Cekas	75Fe - 20Cr - 5Al	1.4	0.04	1300
	Megapyr	65Fe - 30Cr - 5Al	1.4	0.025	1350
Pure Metals	Tungsten	100 W (sintered)	0.0553	4.5	1500/1700

3.3.2. High-frequency Effects: Inductance and Capacitance

Wirewound resistors naturally have some capacitance and inductance. Given this, they influence the flow of current in an alternating current circuit. This effect is usually not desirable. Since wirewound resistors are designed essentially as coil inductors, they have the worst high-frequency properties of all resistor types.

There are several ways to apply the winding, depending on resistor application. With a DC current, fewer issues arise with the winding than with an AC current, because of parasitic capacitance and self-inductance. To reduce these effects, several winding types exist:

- Bifilar winding
- Winding on a flat former
- Ayrton-Perry winding

These types of winding are applied for measurement devices and decade banks. The drawback of these methods is the difficulty of the manufacturing process.

Bifilar winding

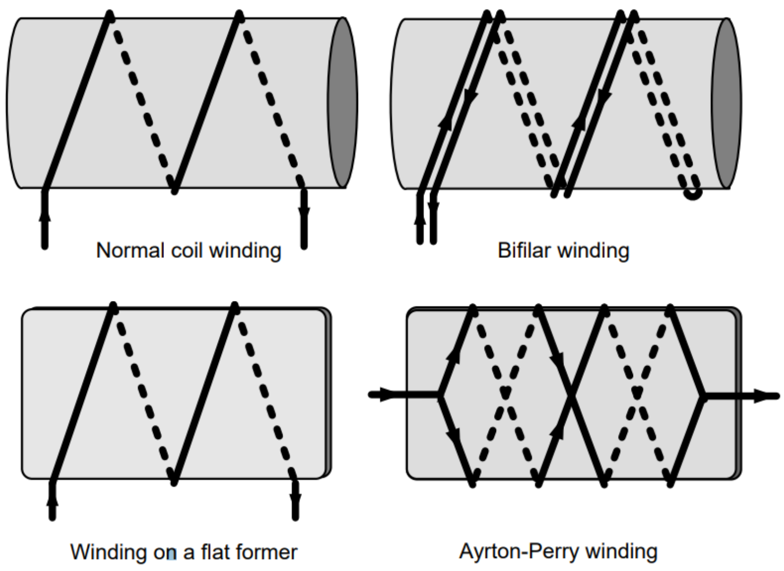
- A bifilar winding is a type of winding where the wire is folded double, and from this double wire a capacitor is made, as in the image below. This type of winding results in decidedly low self-inductance, but the parasitic capacitance between the wires is high.

Simple winding on a flat former

- One way to reduce the capacitance that arises with a bifilar winding is via simple winding on a flat former. The thinner the card, the closer together are the wires in the front and back. They cancel each other's field and, thus, reduce the inductance.

Ayrton-Perry winding

- Resistors with Ayrton-Perry winding are used for the most demanding circuits. This type of winding is similar to simple winding on a flat former, but in this case, two opposite windings are applied. The wires whose currents flow in opposite directions are close together, so that the winding is free of self-inductance. The intersections are on the same potential, so as to minimize the capacitance.



Winding methods to reduce parasitic effects

3.3.3. Types

Wirewound resistors can be roughly classified into two types: precision and power. These versatile resistors can be modified for use in current sensors, temperature sensors, and potentiometers, and can be used in a wide range of additional applications.

3.3.3.1. Precision Wirewounds

High-precision wirewound resistors are typically used in precision audio frequency (AF) attenuators, measuring bridges, and calibration equipment. A typical value for their resistance tolerances is 0.1% or better. Their temperature coefficients of resistance lie around 5 ppm/°C, which is considerably better than most metal film resistors (around 25 ppm/°C). Their stability is fairly good, with ppm changes as low as 35 over a year of operation at full power rating. And their temperature rise is usually below 30 °C, so they can be coated by epoxy resin materials.

In practice, a designer might decide that a resistor needs to be within ±0.05% of the design value for a particular circuit application. To account for aging, TCR, and other parameters, the designer might then specify a tolerance of ±0.01%. This ensures that the resistor stays within the required resistance range over time and varying circuit conditions.

3.3.3.2. Power Wirewounds

Wirewound resistors also exist for exceptionally high-power applications, with a range varying from 0.5 W to more than 1000 W. Power wirewound resistors can be divided into types according to coating. Silicone resins are used for the lowest power dissipation levels. These are compact resistors that can withstand temperatures up to 300 °C above the ambient temperature.

Another type of coating is vitreous enamel. This traditional coating has good insulating properties at low temperatures, but is less commonly used because the insulation is considerably less effective at full rated temperature. Its maximum working surface temperature is 400 °C, its TCR varies from 75 to 200 ppm/°C, and its typical resistance values are in the range of 1 to 10 kΩ.

Most power wirewound resistors have a ceramic core and a ceramic coating to protect the winding. The ceramic coating combines high insulation and physical protection with good heat dissipation. Typical power ratings are between 4 and 17 W. The maximum surface temperature is around 300 °C, and the TCR varies from 250 to 400 ppm/°C. Resistance values are between 10 and 22 kΩ. Usually, these resistors are manufactured with leads that allow for vertical or horizontal mounting.

For the highest dissipation values, resistors are ensconced in an aluminum case with fins. These fins provide a larger surface area from which to dissipate heat, allowing the resistor to handle more power without being damaged. These resistors have a ceramic core and a silicone resin coating, encased in an aluminum extrusion. The surface is anodized to maintain satisfactory insulation resistance. These resistors have a typical power rating of 25 to 50 W, assuming the resistor will be mounted on a metal surface so the heat can better dissipate. Maximum surface temperature is around 300 °C, and the TCR is low with around 25 ppm/°C for ohmic values above 50 Ω. Usually, the TCR is higher for lower resistance values.

3.3.3.3. Potentiometer Wirewound

Potentiometers are often wirewound resistors. A potentiometer is a resistor with three terminals, one of which is attached to a movable contact that varies the amount of resistance. Wirewound resistors are suitable as potentiometers due to their durability.

3.3.4. Applications

Wirewound resistors are often used in circuit breakers or as fuses. To make a fusible resistor, the manufacturer attaches a small spring to one of its ends. A small amount of solder will hold this spring in place. If the current and heat passing through the resistor reach high enough levels, the solder will melt and the spring will pop up and open the circuit. As for circuit breakers, wirewound resistors are common in these applications due to their high-power capabilities. They may be used as components in a large circuit breaker device, or may act as circuit breakers themselves.

When fusible wirewound resistors are sold for use in high-power applications, they are often labeled as circuit breakers. Wirewound resistor potentiometers can be made to offer both high power and high precision. These potentiometers are often used in stereo systems for their precision, and in high-power applications like transducers and televisions. Wirewound resistors can also be used as temperature sensors. In this case, a metal with a positive temperature coefficient is used. This ensures that as the metal's temperature rises, so too will its resistance. This varying resistance can be measured and converted back to a temperature value.

Enhancing the inductive effect that is natural to wirewound resistors can unlock them for use as current sensors. Inductive reactance is determined by the inductance of the device and the current flowing through it. Current-sensing devices measure this reactance and convert it to a current reading. These are used in situations where a high-current condition may occur, and it is desirable to correct it before tripping a breaker. Large water-cooling pumps and freezer units are examples of this type of application.

3.4. Carbon Composition Resistors

Carbon composition resistors (CCR) are fixed form resistors. They are made out of fine carbon particles mixed with a binder (clay, for example). After baking, the mixture has a solid form. Although carbon composition resistors are widely applied in circuits, the majority of resistors today are made via the deposition of a metal or carbon film over a ceramic carrier.

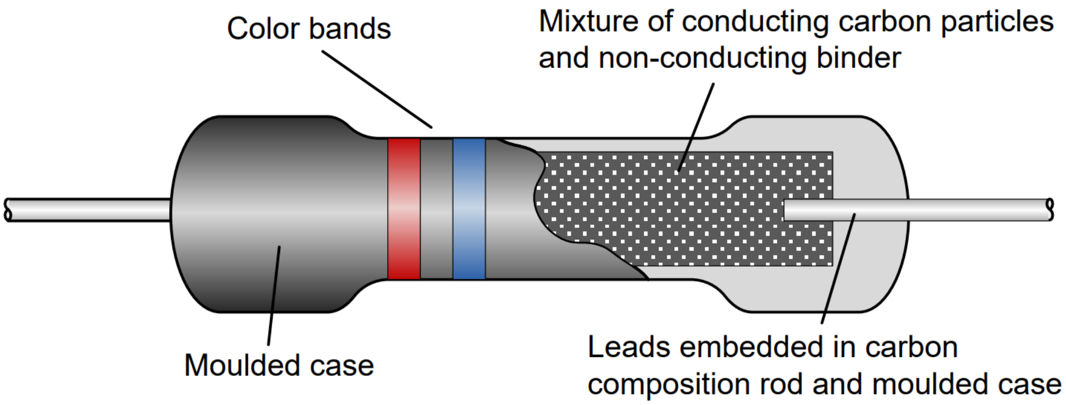
3.4.1. Advantages and Disadvantages

The foremost advantage of carbon composition resistors is their ability to withstand high-energy pulses. When current flows through the resistor, the entire carbon composition body conducts the energy. A wirewound resistor, for example, has a comparatively small volume of wire to conduct current, whereas a carbon composition resistor has much more thermal mass, and thus much higher energy capacity.

Carbon resistors are capable of higher resistances than wirewound resistors, and are considerably cheaper. They are inferior, though, in terms of temperature coefficient, noise, voltage dependence, and load. Decades ago, carbon composition resistors were widely used in consumer electronics.

But due to the low stability of their resistance values, this type of resistor is not suitable for any modern high-precision application. For example, the resistance value can change up to 5% over a shelf life of one year. With heavy use, it can change even more: up to 15% for a 2000-hour test at full rating operation at 70 °C. Soldering can also cause a 2% change.

This instability is inherent to the resistor's design. The carbon composition contains materials with differing heat expansion properties; when the conducting carbon particles and the non-conducting binder heat up or cool down, stresses arise in the resistor body. The mechanical contact between the conducting particles will therefore change, and this leads to a change in resistance value.



Carbon composition resistor structure

In addition, carbon composition resistors' noise properties are poor due to the mixture of different materials; noise level increases when current flows. Resistors of between 0.25 and 0.5 W have a maximum voltage of 150 and 500 V, respectively. Insulation resistance is also poor, with approximately 109 Ω, an order of magnitude lower than other types. One more reason for the decreasing use of this type of resistor is their high temperature coefficients, around 1200 ppm/°C. Their operating temperature range is around -40 to 150 °C, but they begin to derate above 70 °C.

3.4.2. Applications

Carbon composition resistors are able to withstand high-energy pulses, while having a relatively small size. For this reason, they are still used in many applications today, including but not limited to: circuit protection (surge or discharge protection), current limiting, high-voltage power supplies, high-power or strobe lighting, and welding.

One additional example is the medical defibrillator. This sensitive measurement equipment, attached to the patient, needs to be protected against high-energy pulses of around 30 Joule. Carbon composition resistors are applied in the equipment or the leads and have to withstand all of this pulse energy.

3.4.3. Manufacturing

The resistive material in carbon composition resistors is a blend of graphite, ceramic dust, and resin. This mixture is pressed into sticks under high pressure and temperature, and the connecting wires are centrally pressed into both ends of the resistor. Alternatively, metal caps are fitted onto both rod ends, which form the attachment for the wire leads. After the baking process, a massive resistance body is created.

One drawback of this process is the difficulty in predetermining the resistance value, which is established by varying the length of the carbon composition body to create an adequate path for current. As well, the resistor's body is porous, and therefore a coating is required, though in the past some were made without.

To diversify power dissipation, resistors in general are made with different diameters providing a large enough surface to dissipate heat. Commercially available carbon composition resistors have dissipation values between 1/8 (0.125) W and 1/4 (0.25) W. Back in the 1980s, these resistors were available up to 5 W. Although many suppliers have since switched to producing other types, some still specialize in carbon composition resistors.

In the table below, electrical resistivity is shown for separate resistor materials.

Resistivity for different carbon composition resistors

Material	Resistivity (Ω/m)
Graphite	$4 \times 10^{-6} - 11 \times 10^{-6}$
Amorphous carbon	$35 \times 10^{-6} - 50 \times 10^{-6}$

3.4.4. History

The carbon composition resistor has existed for over a hundred years. In the beginning of the twentieth century, it was produced without coating, and the lead wires were directly soldered onto the resistor body. Until the 1960s, carbon composition and wirewound resistors were the only types available. Then in the 60s and into the 70s, there was a shift away from the use of carbon composition resistors to other types, such as the carbon or metal film resistor.

3.5. Carbon Film Resistors

3.5.1. Advantages and Disadvantages

Carbon film resistors are a significant improvement over carbon composition resistors. In comparison to metal film and metal oxide film, though, their commercially available range is smaller. Metal film and metal oxide film resistors are also less expensive to produce and have better overall properties.

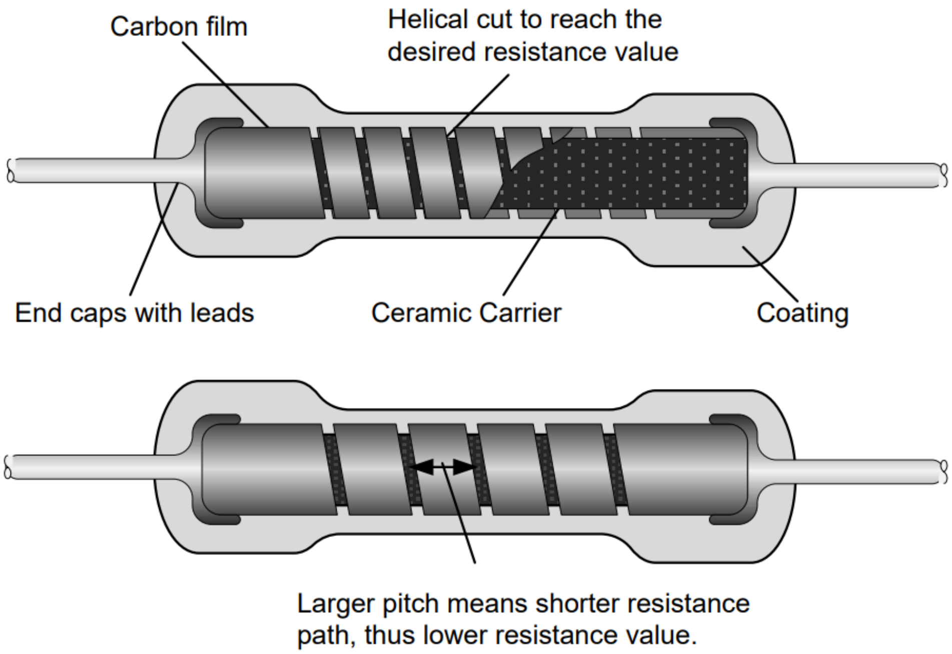
3.5.2. Applications

Typical uses for carbon film resistors are in high-voltage and high-temperature applications, given operating voltages up to 15 kV with a nominal temperature of 350 °C are feasible. Some examples include: high-voltage power supplies, radar, x-rays, and lasers.

3.5.3. Manufacturing

Carbon film resistors are made via a deposition process. At high temperature and under high pressure, a ceramic carrier is held in a hydrocarbon gas. The gas, methane or benzene, is cracked at 1000 °C, and the crystalline carbon is pyrolytically deposited onto the ceramic substrate. Thanks to the precise distribution of the pure graphite without binding, these carbon resistors have low noise.

The desired resistance value can be obtained by choosing the right layer thickness, and by cutting a spiral shape into the carbon layer. The helical cut in the film, as depicted below, increases the length of the current path. By decreasing the pitch of the helix, we increase the length of the resistive path, which in turn increases the resistance value. What's more, by fine-tuning the cut of the spiral, we can make the value more accurate. As for tolerance values in carbon film resistors, they are typically 2, 5, 10, and 20%.



Carbon film resistor construction

As a result of the use of pure carbon, carbon film resistors have higher negative temperature coefficients than carbon composition resistors. Resistive temperature coefficients lie between 2.5×10^{-4} Ω/°C and -8×10^{-4} Ω/°C. Widely used in electronics, this type of resistor is protected against chemical influences with a silicone coating.

These small resistors have a parasitic capacitance of approximately 0.5 pF, with self-inductance around 0.01 µH for uncut resistors and up to several µH for spiral-cut resistors. They are available in values between 1 and 10,000 MΩ, and have a power rating of 1/16, 1/8, 1/4, 1/2, 1, or 2 W.

3.6. Metal Film Resistors

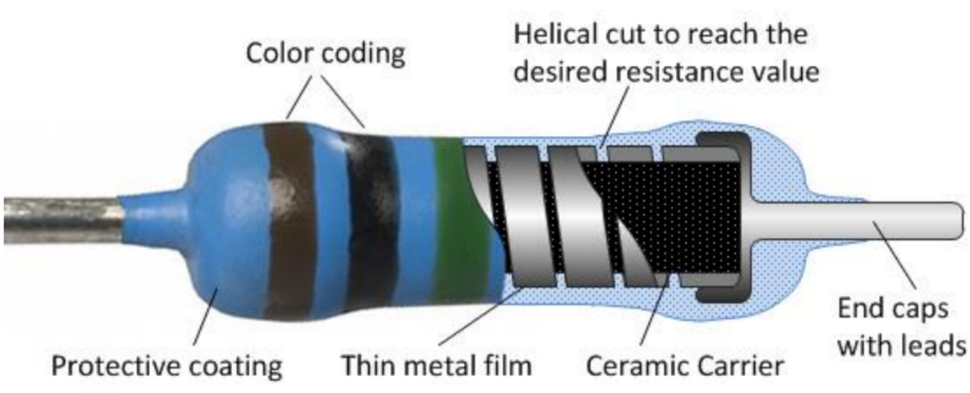
Metal film resistors, which have a thin metal layer as the resistive element on a non-conducting body, are among the most common types of axial resistors. Other film type resistors include carbon film and thick and thin film. Most literature that refers to a metal film resistor is referring to a cylindrical axial resistor, though thin film chip resistors use the same manufacturing principle for the metal layer. Metal film resistors are similar in appearance to carbon film resistors, but have considerably better properties for stability, accuracy, and reliability.

> *Metal film resistors are axial resistors with a thin metal film as the resistive element. This thin film is usually deposited on a ceramic body.*

3.6.1. Construction

The resistive element, a thin metal layer, is usually sputtered (vacuum-deposited) onto a cylindrical high-purity ceramic core; techniques besides sputtering are sometimes used. The deposited metal is artificially aged by extended low-temperature storage, resulting in a resistor with greater accuracy. At both ends, a metal cover is pressed with the connection leads, before the desired resistance is achieved via the cutting of a spiral-shaped slot in the thin metal layer. Today, this is usually done with lasers, though in the past sandblasting and grinding techniques were used.

The resistor's stability and resistance are strongly dependent on the thickness of the metal film (50-250 nm). A thicker layer results in better stability and a lower resistance value. The resistive material is often nickel chromium (NiCr), but for special applications other alloys are used, such as tin and antimony, gold with platinum, and tantalum nitride.



Carbon film resistor construction

Finally, the resistor is covered with several coating layers that are baked individually. This coating protects against moisture and mechanical stress, and, preferably, has high dielectric strength.

The resistor value is marked by color code bands or with text. Metal film resistors are available with tolerances of 0.1, 0.25, 0.5, 1, and 2%. The TCR is usually between 50 and 100 ppm/K.

3.6.2. Applications

Metal film resistors have favorable characteristics for tolerance, stability, and TCR. Thanks to a low voltage coefficient, they also feature low noise properties and high linearity. As such, in circuits where tight tolerance, a low temperature coefficient, and low noise properties are important, metal film resistors are often used. Examples of applications include active filters and bridge circuits.

3.6.3. Reliability

To prioritize reliability, metal film resistors are normally operated between 20 and 80 percent of their specified power rating; reliability is generally increased further by derating 50%. In very specific situations, though, reliability will decrease at lower than 20% of the power rating while in a humid environment. Compared to wirewound and carbon composition resistors, these resistors are more easily damaged by voltage surges and power overloads.

3.7. Metal Oxide Film Resistors

Metal-oxide film resistors are fixed form, axial resistors. They are made of a ceramic rod that is typically coated with a thin film of tin oxide, which is contaminated with antimony oxide to increase resistivity. Metal oxide film resistors must not be confused with metal oxide varistors, which are made of zinc oxide or silicon carbide.

3.7.1. Properties

Metal oxide film resistors exceed the performance of metal film and carbon film resistors for the following properties: power rating, voltage rating, overload capabilities, surges, and high temperatures (see the following table). Their noise properties are similar to those of carbon resistors. Designers often select metal oxide film resistors for high-endurance applications.

Temperature performance comparison of film resistor types

Material	Carbon film	Metal film	Metal oxide film
Temperature	200 °C / 390 °F	250-300 °C / 480-570 °F	450 °C / 840 °F

The stability of metal oxide film resistors is often inferior to metal film resistors. Metal oxide film resistors also have poor properties for low resistance values and tolerance. Their temperature coefficient is around 300 ppm/°C, which is higher than for metal film types.

3.7.2. Applications

Many properties of metal oxide film resistors are similar to those of metal film resistors. For basic use, both metal film and metal oxide film are currently the predominant resistor types. They are just as cheap as carbon film resistors, though for applications requiring power above 1 W or improved stability, carbon film may still be preferred.

3.7.3. Construction

The metal oxide film is mostly produced with chemical deposition methods. Almost always, a ceramic carrier is used as the substrate. The deposition process involves the reaction of a pure metal with a gas at high temperature and at low pressure.

A very common metal oxide film is tin oxide, which is established by heating the resistor body in a tin chloride vapor. First, a thin metal film is applied, which is then catalyzed with oxygen. The resistance of a test piece is measured to achieve the desired composition. A note—other metal oxide films typically use a different deposition process.

After the film is applied to the resistor body, a helical cut is made to realize the final resistance value. This cut lengthens the resistance path and reduces the cross section, and in so doing can increase the resistance value by a magnitude of up to a thousand. What's more, precise cutting can accurately control that end value, which is why resistance is measured throughout the cutting process to allow for small corrections. Today, as with metal film, this is typically done with lasers, though in the past grinding and sandblasting were used.

3.7.4. History

Metal oxide film resistors were the first alternatives to carbon composition resistors. In the past, they were easier to manufacture than metal film resistors, though today they are less commonly used.

3.8. Thin and Thick Film Resistors

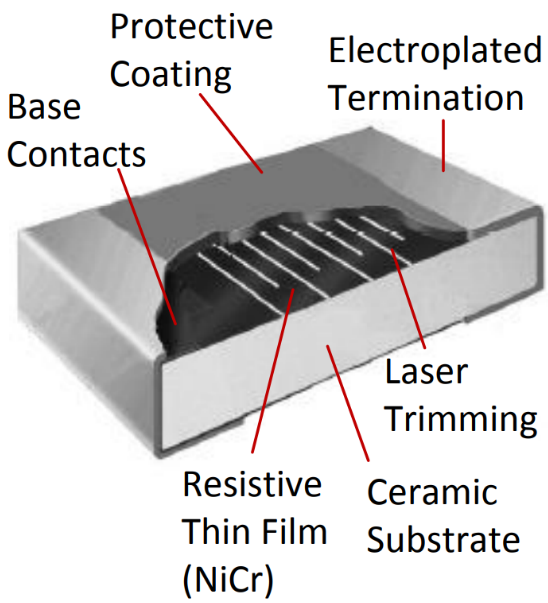
Thin and thick film resistors are the most common types on the market. They are characterized by a resistive layer on a ceramic base. Though they may appear to be highly similar, their properties and manufacturing process differ significantly. Most obvious, thin film has a thickness on the order of 0.1 µm or less, while thick film is thousands of times thicker.

The main difference, though, is the method in which their resistive films are applied onto their respective substrates. Thin film resistors have a metallic film that is vacuum-deposited onto an insulating substrate. Thick film resistors, in contrast, are produced by firing a special paste onto the substrate. This paste is a mixture of glass and metal oxides.

Thin film is more accurate, has a better temperature coefficient, and is more stable. It therefore competes with other technologies that feature high precision, such as wirewound or bulk metal foil. Thick film is preferred for applications where these precise requirements are not critical, since prices are much lower.

3.8.1. Thin Film Technology

As described above, in thin film construction the resistive layer, often an alloy of nickel and chromium called Nichrome, is sputtered (vacuum-deposited) onto a ceramic base. This creates a dense, uniform metallic film of around 0.1 μm thick. This dense, uniform quality makes it possible to trim the resistance value via a subtractive process.



Thin film resistor construction

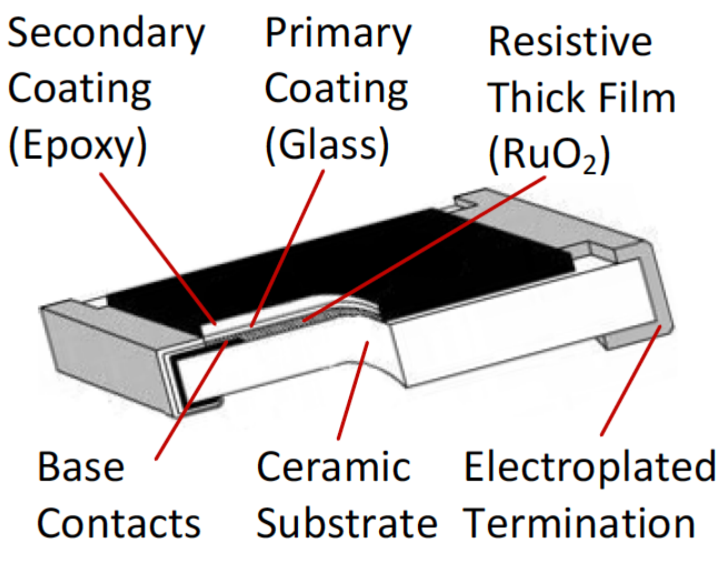
Using photo etching or laser trimming, patterns are created to lengthen the resistive path and to calibrate the resistance value. Thin film resistors are produced with different layer thicknesses to accommodate a range of resistance values. Their base is often alumina ceramic, silicon, or glass. Usually, thin film resistors are produced as a chip (SMD) resistor, but the film can also be applied onto a cylindrical base with axial leads. In this case, the term “metal film resistor” is more often used.

Thin film resistors are usually used for precision applications. They feature relatively high tolerances, low temperature coefficients, and low noise. In addition, thin film performs better than thick film in high-frequency applications, owing to its typically lower inductance and capacitance. The parasitic inductance of thin film can also be higher if it is executed as a cylindrical helix (metal film resistor). This higher performance comes with a cost, though, as resistors of this type can be magnitudes more expensive than thick film resistors. Typical applications for thin film include use in medical equipment, audio installations, precision controls, and measurement devices.

3.8.2. Thick Film Technology

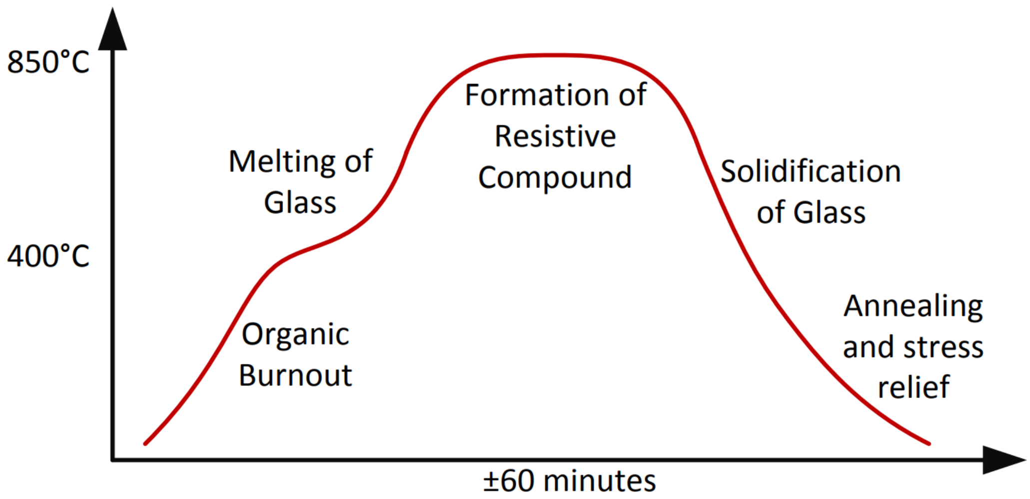
In the 1970s, thick film started to gain popularity in resistor manufacturing. Today, these are by far the most commonly used resistors in electrical and electronic devices. Usually produced in an SMD chip resistor form factor, they are also the least expensive.

In production, the resistive material is a special paste consisting of a mixture of a binder, a carrier, and the metal oxides to be deposited. The binder is a glassy frit, and the carrier consists of organic solvent systems and plasticizers. Modern resistor pastes are based on oxides of ruthenium, iridium, and rhenium; this is also referred to as a cermet (ceramic–metallic). The resistive layer is printed onto a substrate, which is often 95% alumina ceramic, at 850°C. After the firing of the paste onto the carrier, the film becomes glass-like, which makes it well-protected against moisture.



Thick film resistor construction

The complete firing process is schematically depicted in the graph below. Unlike thin film, this process is additive. This means that the resistive layers are added sequentially to the substrate to create the conducting patterns and resistance values. The final thickness is on the order of 100 μm. This is approximately 1000 times more than that of thin film.



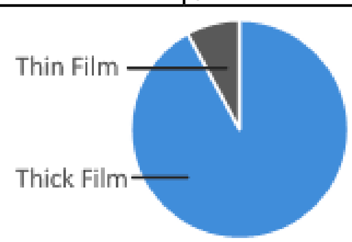
Thick film resistor firing process

The temperature coefficient typically ranges from 50 ppm to 200 ppm/K. Tolerances are between 1% and 5%. Because costs are low, thick film is generally preferred in applications that can accept wider tolerances, higher TCR, or lower stability. As such, these resistors can be found in almost any device with an AC plug or a battery. Beyond their lower cost, thick film resistors are also able to handle more power, provide a wider range of resistance values, and can withstand high surge conditions.

3.8.3. Thin Versus Thick Film Resistors

In the table below, the main differences between these two technologies are listed. The components may look similar, but their construction and electrical properties are undoubtedly different.

Thin film and thick film resistor comparison

Characteristic	Thin Film	Thick Film
Appearance	While their manufacturing process and properties differ greatly, the chip resistors for thin and thick film are often similar in appearance.	
	Construction	
Film thickness (µm)	±0.1	±100
Manufacturing process	Sputtering (vacuum deposition)	Screen and stencil printing
Trimming	Abrasive or laser, for complex pattern photo-etching	Abrasive or laser
Resistive Material	Uniform metallic film, usually Nichrome	Paste of ruthenium oxide or other alloy
	Properties	
Resistance Values (Ω)	0.2 – 20 M	1 – 100 M
Tolerance (%)	±0.1 – ±2	±1 – ±5
Temperature Coefficient (ppm/°C)	±5 – ±50	±50 – ±200
Maximum Operating Temp (°C)	155	155
Max Operating Voltage Vmax (V)	50 – 500	50 – 200
Nonlinearity (dB)	>110	>50
Current Noise (µV/V)	<0.1	<10
Power Rating P_{70} (W)	1/16 – 1	1/16 – 1/4
Stability at P_{70} (1000 h) ΔR/R %	±0.15 – ±0.5	±1 – ±3
Moisture resistance	Thick film is more resistant to moisture, since it is glass-like.	
High-frequency behavior	Thin film features lower parasitic inductance and capacitance. That said, inductance may be high if the thin film is manufactured with a cylindrical shape that is spiral cut.	
	Applications	
Typical areas of use	High-precision: measuring or monitoring equipment, medical or audio applications, precision controls	Wide: almost any electrical device with a battery or AC connection. The average PC contains well over 1000 thick film chip resistors.
Market Share		
Cost	More expensive than thick film	Lowest cost resistor. Preferred when performance requirements are low.
Estimated use in analog circuits		

4 RESISTOR STANDARDS

4.1 Resistor Color Code **78**
4.1.1 Resistor Color Code Chart 79
4.1.2 Tips for Reading Resistor Codes 80
4.1.3 Four-band Resistor 80
4.1.4 Five-band Resistor 81
4.1.5 Six-band Resistor 81
4.1.6 Color Code Exceptions 82

4.2 Preferred Values **83**
4.2.1 E-Series 84

4.3 SMD Resistors **86**
4.3.1 SMD Resistor Packages 87
4.3.2 SMD Resistor Codes 87
4.3.3 The Three and Four-digit System 87
4.3.4 The EIA-96 System 88

4.4 Resistor Sizes and Packages **89**
4.4.1 SMD Resistor Sizes 90
4.4.2 Solder Pad and Land Pattern 91
4.4.3 Axial Resistor Size 91
4.4.4 MELF Resistor Package Sizes 92

4.5 Resistor Symbols **92**

4. RESISTOR STANDARDS

Standardization is a key element in the design of electronic components. Standards for resistor sizes, values, markings, symbols, and measurement methods save manufacturers massive amounts of effort and money. Although international standards such as the IEC (International Electrical Commission) and national standards such as ANSI (American National Standards Institute) are widely accepted, resistor manufacturers often use their own definitions. Given this, it is always important to carefully check the manufacturer's documentation.

4.1. Resistor Color Code

Resistor values are often indicated with color codes. Most leaded resistors with a power rating up to one watt are marked with color bands. These color bands specify the resistance value, the tolerance, and sometimes the reliability or failure rate. The number of bands varies from three to six. At a minimum, two bands indicate the resistance value, with one band serving as a multiplier.

Color bands on an axial leaded resistor

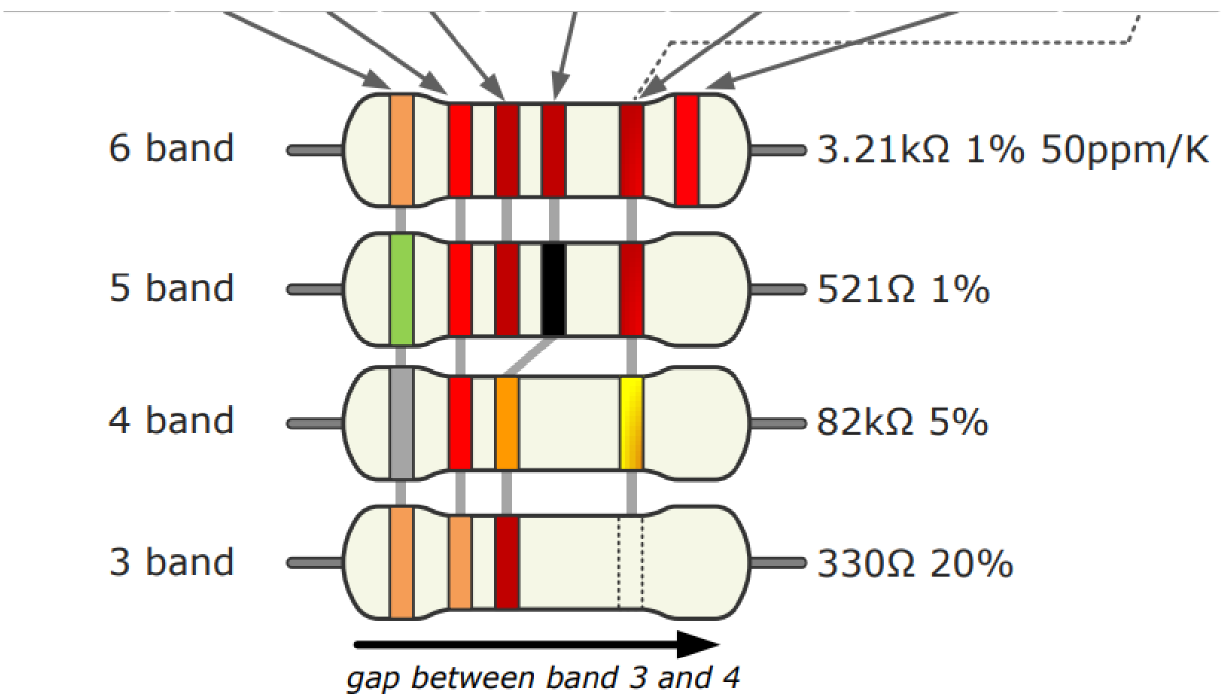
Color coding is defined in the international standard IEC 60062. This standard describes the marking codes for resistors and capacitors, as well as the numerical codes often used for SMD resistors. The resistance values are also standardized. These standard values are called preferred values.

4.1.1. Resistor Color Code Chart

The table below describes the relationship between the number and color of the bands and the resistor values. An online resistor calculator can also be used.

Resistor color code chart

Color	Significant figures			Multiplier	Tolerance (%)	Temp Co (ppm/K)	Failure rate (%)	Memory Mnemonic
Black	0	0	0	x 1		250 (U)		**B**ad
Brown	1	1	1	x 10	1 (F)	100 (S)	1.0	**B**eer
Red	2	2	2	x 100	2 (G)	50 (R)	0.1	**R**ots
Orange	3	3	3	x 1K		15 (P)		**O**ur
Yellow	4	4	4	x 10K		25 (Q)		**Y**oung
Green	5	5	5	x 100K	0.5 (D)	20 (Z)		**G**uts
Blue	6	6	6	x 1M	0.25 (C)	10 (Z)		**B**ut
Violet	7	7	7	x 10M	0.1 (B)	5 (M)		**V**odka
Grey	8	8	8	x 100M	0.05 (A)	1 (K)		**G**oes
White	9	9	9	x 1G				**W**ell
Gold			3rd digit only for bands 5 and 6	x 0.1	5 (J)			**G**et
Silver				x 0.01	10 (K)			**S**ome
None					20 (M)			**N**ow



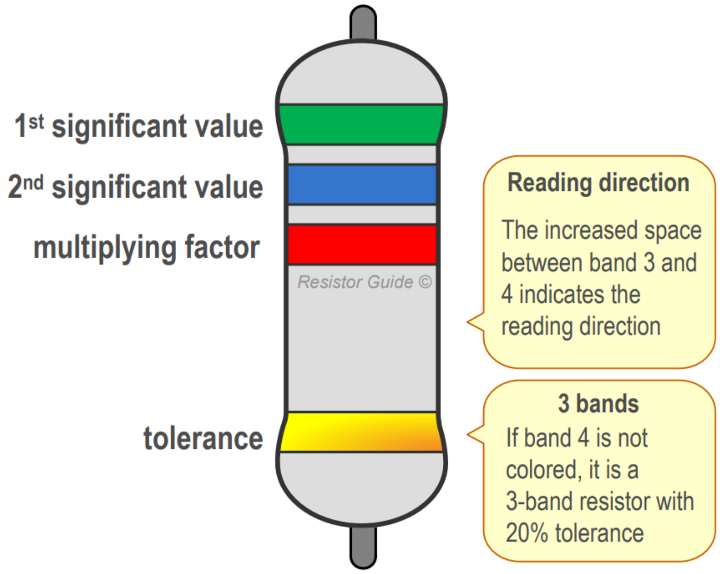
4.1.2. Tips for Reading Resistor Codes

In the sections below, examples are given for different numbers of bands, but first here are some basic tips for reading color codes:

- The reading direction might not always be clear. Sometimes, the increased space between bands 3 and 4 gives away the reading direction.
- The first band is usually the closest to a lead.
- A gold or silver band (the tolerance) is always the last band.
- It is good practice to check the manufacturer's documentation to determine the color coding system employed.
- Even better is to measure the resistance with a multi-meter. In some cases, such as when the color bands are burnt off, this may be the only way to determine the value.

4.1.3. Four-band Resistor

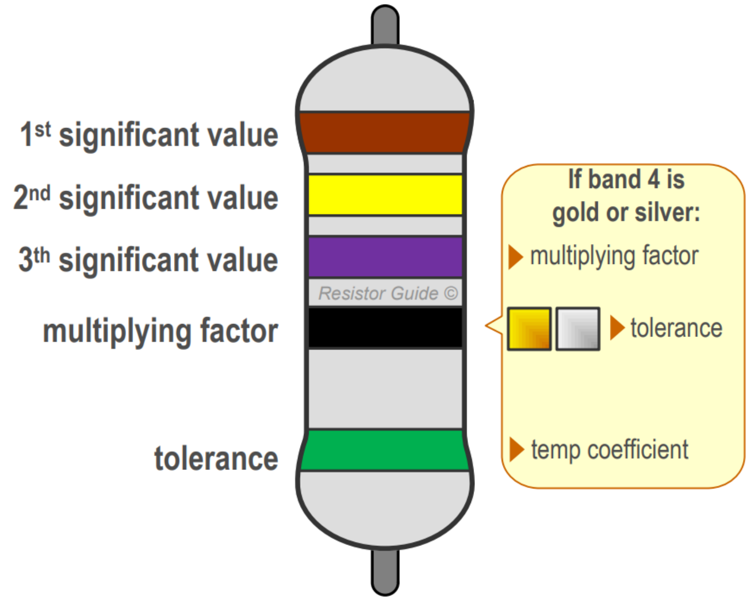
The four-band color code is the most common variation. These resistors have two bands for the resistance value, one multiplier band, and one tolerance band. In the example below, these bands are green, blue, red, and gold. By using the color code chart, we can determine that green stands for 5 and blue for 6. The red band represents a multiplier of 2 (10^2 = 100). The value is thus 56 x 100 = 5600 Ω (5.6 kΩ). The gold band indicates the resistor has a tolerance of ±5%. The resistance value lies therefore between 5320 and 5880 Ω. If the tolerance band is left blank, the result is a three-band resistor. This means that the resistance value remains the same, but the tolerance is 20%.



Four-band resistor color code example:
blue (5), green (6), red (2), and gold (5%) = 56 x 10^2 = 5600 Ω ± 5%

4.1.4. Five-Band Resistor

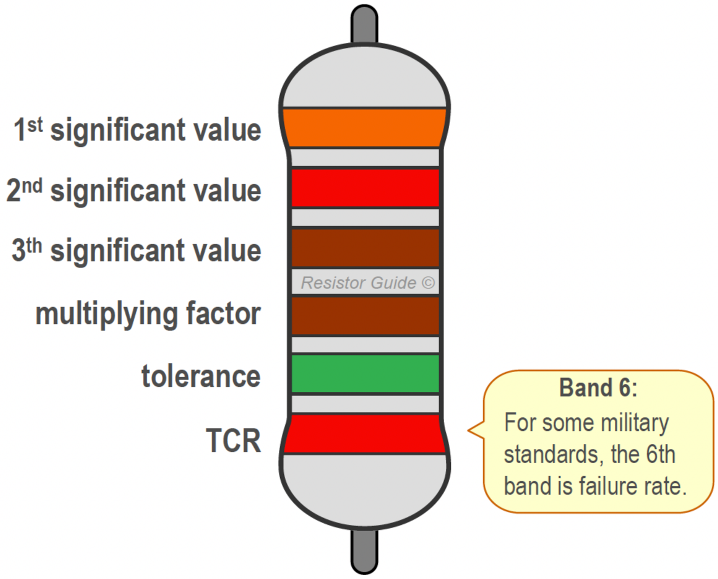
High-precision resistors have an extra band to indicate a third significant digit. Therefore, the first three bands indicate the significant digits, the fourth band is the multiplication factor, and the fifth band represents the tolerance. That said, there are exceptions. For example, on occasion the extra band indicates the failure rate (military specification) or the temperature coefficient (older or specialized resistors). Please refer to section 4.1.6. Color Code Exceptions for more information.



Five-band resistor color code example:
brown (1), yellow (4), violet (7), black (0), and green (0.5%) = 147 x 10^0 = 147 Ω ± 0.5%

4.1.5. Six-band Resistor

Resistors with six bands are usually high-precision resistors that have an additional band to specify the temperature coefficient (ppm/K). The most common color for the sixth band is brown (100 ppm/K). This means that for a temperature change of 10 ˚C, the resistance value can change 0.1%.



Six-band resistor color code example:
orange (3), red (2), brown (1), brown (1), green (0.5%), and red (50 ppm/°C)
$321 \times 10^1 = 3210\ \Omega \pm 0.5\%$, 50 ppm/°C

4.1.6. Color Code Exceptions

Reliability band

- Resistors that are produced according to military specifications sometimes include an extra band to indicate reliability. This is specified in failure rate (%) per 1000 hours of service, a measurement rarely used in commercial electronics. Most often, this reliability band can be found on four-band resistors. Further information regarding reliability can be found in the US military handbook MIL-HDBK-199.

Single black band or zero-ohm resistor

- A resistor with a single black band is called a zero-ohm resistor. It is essentially a wire link that functions to connect traces on a PCB. It is advantageous to use the resistor package, as it allows the same automated machines to place components on a circuit board.

Five-band resistor with a fourth band of gold or silver

- Five-band resistors with a fourth band of gold or silver form an exception, used on specialized and older resistors. The first two bands represent the significant digits, the third the multiply factor, the fourth the tolerance, and the fifth the temperature coefficient (ppm/K).

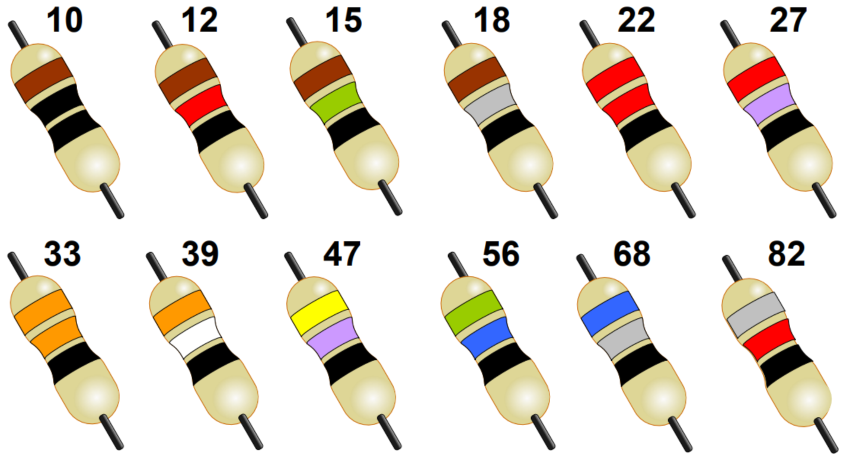
Deviating colors

- For high-voltage resistors, the colors gold and silver are often replaced with yellow and gray. This is to avoid the use of metal particles in the coating.

4.2. Preferred Values

In 1952, soon after resistors became mass-produced, the IEC (International Electrotechnical Commission) developed a system of preferred values, which standardized resistance and tolerance, to minimize the necessary number of sizes manufacturers needed to deliver. These preferred values, or E-series, are published in standard IEC 60063:1963.

Resistors are manufactured with a certain tolerance, and the preferred value system is set up so that the tolerance of each resistor just overlaps with the previous resistor in the series. In this way, manufacturing and inventory costs can be reduced. Different E-series, such as the E-12 and E-24, have a different tolerance.



Example preferred value standard resistor sequence: the E12 series of resistor values, including their color codes

These standard values are also valid for other components such as capacitors, inductors, and Zener diodes. Though preferred values for resistors were established in 1952, the concept of the geometric series was previously introduced in the 1870s by French Army engineer Charles Renard.

The standardization of resistor values serves several important purposes. When manufacturers produce resistors with different resistance values, they end up approximately equally spaced on a logarithmic scale. This helps the supplier limit the number of different values that have to be produced or kept in stock. In addition, standard values ensure that different manufacturers' resistors are compatible for the same design, which is helpful for the electrical engineer.

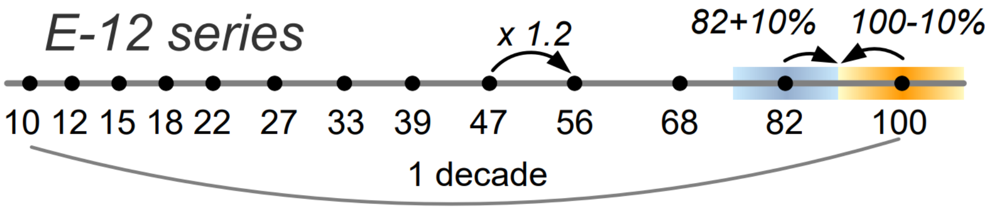
Aside from the preferred values, many other resistor standards exist. Examples include those governing sizing, as well as the use of color and numerical codes. Resistor power ratings are not defined in a norm, and as such often deviate from the above described series.

4.2.1. E-Series

To understand the E-series sets of preferred values, we will examine the E12 in detail. E12 means that every decade (0.1-1.0, 1-10, 10-100, etc.) is divided into 12 steps on a logarithmic scale. The size of every step is equal to:

$$10^{\left(\frac{1}{12}\right)} = 1.21$$

Thus, every value is 21% or 1.21 times greater than the last (rounded). Because of this, all resistors with adjacent E-series values and a tolerance of ±10% have overlapping ranges. The E12 series is as follows: 1.0 – 1.2 – 1.5 – 1.8 – 2.2 – 2.7 – 3.3 – 3.9 – 4.7 – 5.6 – 6.8 – 8.2. And then repeating: 10, 12, 15, etc., for the next series. All of these E12 values can be powers of ten (1.2, 12, 120, etc.).



E12 series demonstrated on a number line

While the E12 series is the most common, other series are also available. It is good practice to specify resistors from a low series when tolerance requirements are not high. The most common series are:

- E6: ±20% tolerance
- E12: ±10%
- E24: ±5% (also available with 1%)
- E48: ±2%
- E96: ±1%
- E192: ±0.5% (also used for resistors with 0.25% and 0.1%)

E6 Series

The E6 series has six values in each decade. The tolerance is ±20%.

E6 series resistor values (tolerance of ±20%)

10	15	22	33	47	68

E12 Series

The E12 series is the most common, and is available for almost every resistor type The tolerance is ±10%.

E12 series resistor values (tolerance of ±10%)

10	12	15	18	22	27	33	39	47	56	68	82

E24 Series

E24 series resistor values (tolerances of ±5% and ±1% available)

10	11	12	13	15	16	18	20	22	24	27	30
33	36	39	43	47	51	56	62	68	75	82	91

E48 Series

Each decade is divided into 48 values. A third significant digit is added (just as it is for the E96 and E192 series).

E48 series resistor values (tolerance of ±2%)

100	105	110	115	121	127	133	140	147	154	162	169
178	187	196	205	215	226	237	249	261	274	287	301
316	332	348	365	383	402	422	442	464	487	511	536
562	590	619	649	681	715	750	787	825	866	909	953

E96 Series

E96 series resistor values (tolerance of ±1%)

100	102	105	107	110	113	115	118	121	124	127	130
133	137	140	143	147	150	154	158	162	165	169	174
178	182	187	191	196	200	205	210	215	221	226	232
237	243	249	255	261	267	274	280	287	294	301	309
316	324	332	340	348	357	365	374	383	392	402	412
422	432	442	453	464	475	487	499	511	523	536	549
562	576	590	604	619	634	649	665	681	698	715	732
750	768	787	806	825	845	866	887	909	931	953	976

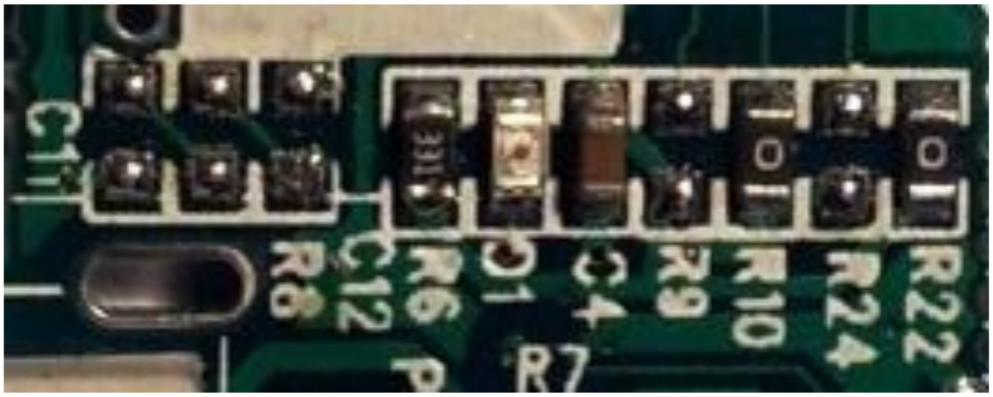
E192 Series

E192 series resistor values (tolerances of ±0.5%, ±0.25% and ±0.1% available)

100	101	102	104	105	106	107	109	110	111	113	114
115	117	118	120	121	123	124	126	127	129	130	132
133	135	137	138	140	142	143	145	147	149	150	152
154	156	158	160	162	164	165	167	169	172	174	176
178	180	182	184	187	189	191	193	196	198	200	203
205	208	210	213	215	218	221	223	226	229	232	234
237	240	243	246	249	252	255	258	261	264	267	271
274	277	280	284	287	291	294	298	301	305	309	312
316	320	324	328	332	336	340	344	348	352	357	361
365	370	374	379	383	388	392	397	402	407	412	417
422	427	432	437	442	448	453	459	464	470	475	481
487	493	499	505	511	517	523	530	536	542	549	556
562	569	576	583	590	597	604	612	619	626	634	642
649	657	665	673	681	690	698	706	715	723	732	741
750	759	768	777	787	796	806	816	825	835	845	856
866	876	887	898	909	920	931	942	953	965	976	988

4.3. SMD Resistors

SMD stands for “Surface Mounted Device.” An SMD is any electronic component that is made for use with SMT, or “Surface Mount Technology.” SMT was developed to meet the ongoing desire for PCB manufacturers to assemble ever smaller components to PCBs more quickly, more efficiently, and at lower cost.



SMD resistors on a printed circuit board

SMDs are smaller than their traditional counterparts. They are often square, rectangular or oval in shape, with very low profiles. Rather than wire leads that go through the PCB, SMDs have small leads or pins that are soldered to pads on the surface of the board. This eliminates the need for holes in the board and allows both sides of the board be more fully utilized.

The manufacture of PCBs using SMT is similar to that of components with leads. Small pads of silver or gold plate, or tin-lead, are placed on the board for attaching the components. Solder paste, a mixture of flux and small balls of solder, is then applied to the mounting pads by a machine similar to a computer printer.

Once the PCB is prepared, SMDs are placed on it using a machine called a pick-and-place. The components are fed to the machine in long tubes, on rolls of tape, or in trays. These machines can attach thousands of components per hour (cph), with one manufacturer advertising a rate as high as 60,000 cph. The board is then sent through a reflow soldering oven, where it is slowly brought up to a temperature that will melt the solder. Once cooled, the board is cleaned to remove solder flux residue and stray solder particles. A visual inspection checks for missing or out-of-position parts, and ensures the board is clean.

4.3.1. SMD Resistor Packages

The term “package” refers to the size, shape and/or lead configuration of an electronic component. For instance, an IC chip that has leads in two rows down opposite sides of the chip is called a Dual Inline Package (DIP) chip. For SMD resistors, resistor package designators describe the length and width of the resistor; these may be given in inches as well as in millimeters. It is therefore important to check the manufacturer’s documentation. The table in section 4.4.1. SMD Resistor Sizes lists the most common packages in imperial units with the metric equivalents. Furthermore, an approximation is given for the typical power ratings.

4.3.2. SMD Resistor Codes

Because of SMD resistors’ small size, there is often no room for the traditional color bands, which is why new SMD-specific codes were developed. The most commonly used codes are the three and four-digit system, and an Electronic Industries Alliance (EIA) system called EIA-96.

4.3.3. The Three and Four-digit System

In this system, the first two or three digits indicate the numerical resistance value of the resistor, and the last digit is a multiplier. This digit indicates the power of ten by which to multiply the given resistor value. The letter ‘R’ is used to indicate the position of a decimal point for resistance values lower than 10 Ω. Thus, 0R5 would be 0.5 Ω and 0R01 would be 0.01 Ω. Here are a few more examples of values under this system:

Three-digit system

- 450 = 45 Ω x 10^0 is 45 Ω
- 273 = 27 Ω x 10^3 is 27,000 Ω (27 kΩ)

Four-digit system

- 7992 = 799 Ω x 10^2 is 79,900 Ω (79.9 kΩ)
- 1733 = 173 Ω x 10^3 is 173,000 Ω (173 kΩ)

4.3.4. The EIA-96 System

The EIA-96 marking system was developed for indicating high-precision resistance values on very small SMD resistors. It is based on the E96-series, and thus aimed at resistors with 1% tolerance. In this system, the marking consists of three digits: two numbers to indicate the resistor value and one letter for the multiplier. The first two numbers represent a code that indicates a resistance value with three significant digits. In the table below, the values for each code are given, which are essentially the values from the E96 series. For example, code 04 represents the value 107 Ω, and code 60 represents the value 412 Ω.

EIA-96 SMD resistance code value table (tolerance of 1%)

Code	Value	Code	Value	Code	Value	Code	Value	Code	Value	Code	Value
01	100	17	147	33	215	49	316	65	464	81	681
02	102	18	150	34	221	50	324	66	475	82	698
03	105	19	154	35	226	51	332	67	487	83	715
04	107	20	158	36	232	52	340	68	499	84	732
05	110	21	162	37	237	53	348	69	511	85	750
06	113	22	165	38	243	54	357	70	523	86	768
07	115	23	169	39	249	55	365	71	536	87	787
08	118	24	174	40	255	56	374	72	549	88	806
09	121	25	178	41	261	57	383	73	562	89	825
10	124	26	182	42	267	58	392	74	576	90	845
11	127	27	187	43	274	59	402	75	590	91	866
12	130	28	191	44	280	60	412	76	604	92	887
13	133	28	196	45	287	61	422	77	619	93	909
14	137	30	200	46	294	62	432	78	634	94	931
15	140	31	205	47	301	63	442	79	649	95	953
16	143	32	210	48	309	64	453	80	665	96	976

The multiplying factor provides the resistor's final value, and again uses codes, as shown in the following table:

SMD resistor multiplication factors

Code	Multiplication Factor
Z	0.001
Y / R	0.01
X / S	0.1
A	1
B / H	10
C	100
D	1000
E	10,000
F	100,000

Taking the resistance code and the multiplier code together, we can calculate the final resistance value. Here are a few examples:

- 01A ⇒ Code 01 = 100 with Multiplier A = 1 ⇒ 100 x 1 = 100 Ω ±1%
- 38C ⇒ Code 38 = 243 with Multiplier C = 100 ⇒ 243 x 100 = 24,300 Ω ±1%
- 92Z ⇒ Code 92 = 887 with Multiplier Z = 0.001 ⇒ 887 x 0.001 = 0.887 Ω ±1%

The use of a letter prevents confusion with other marking systems. Pay attention, though, as the letter R is used in multiple systems. For resistors with tolerances other than 1%, different letter tables exist.

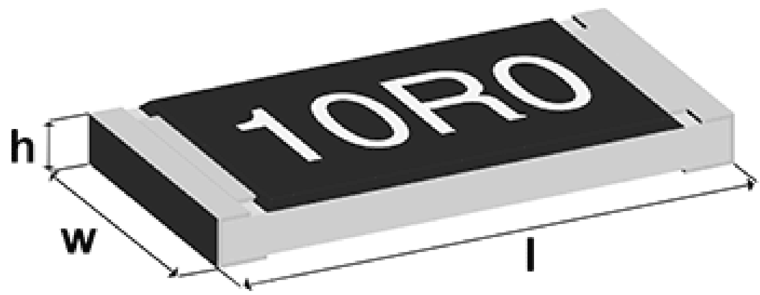
As with package codes, these resistance value codes are common. Still, a manufacturer may use a code variation of its own, or even something completely different. It is therefore always important to verify the manufacturer's marking system.

4.4. Resistor Sizes and Packages

Resistors are available in a large number of different packages. Today, the most commonly used are rectangular surface mount resistors, but the ever reliable axial resistor is still utilized extensively in through-hole designs. Information regarding the dimensions of SMD, axial, and MELF packages is provided below, in addition to some recommended land patterns for MD components, for solder attachment to PCBs.

4.4.1. SMD Resistor Sizes

Surface mount resistors' shape and size are standardized, with most manufacturers employing JEDEC standards. Size is indicated by a numerical code, such as 0603. This code describes the length and width of the package, and can be given in imperial or metric units. So in this case, using the imperial code, 0603 indicates a length of 0.06" and a width of 0.03".



SMD resistor dimensions

In general, the imperial code is more often used to indicate package size. Confusingly, in modern PCB design, metric units (mm) are often used to define layout dimensions, even though package size is defined by an imperial code. You can expect to find this oddity in most cases. But as always, refer to the manufacturer's specifications prior to designing with any of these components.

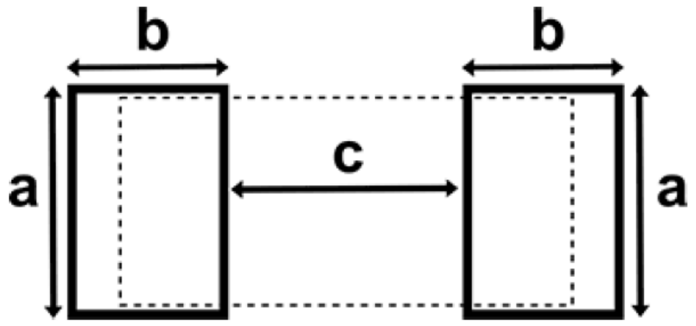
The size of an SMD resistor depends mainly on the required power rating. The following table lists the dimensions and specifications of commonly used surface mount packages.

SMD resistor sizes

Code		Length (l)		Width (w)		Height (h)		Power
Imperial	Metric	inch	mm	inch	mm	inch	mm	W (typical)
01005	0402	0.016	0.4	0.008	0.2	0.005	0.13	1/32 (0.03)
0201	0603	0.024	0.6	0.012	0.3	0.010	0.25	1/20 (0.05)
0402	1005	0.04	1.0	0.02	0.5	0.014	0.35	1/16 (0.06)
0603	1608	0.06	1.55	0.03	0.85	0.018	0.45	1/10 (0.10)
0805	2012	0.08	2.0	0.05	1.2	0.018	0.45	1/8 (0.125)
1206	3216	0.12	3.2	0.06	1.6	0.022	0.55	1/4 (0.25)
1210	3225	0.12	3.2	0.10	2.5	0.022	0.55	1/2 (0.50)
1812	3246	0.12	3.2	0.18	4.6	0.022	0.55	1
2010	5025	0.20	5.0	0.10	2.5	0.024	0.6	3/4 (0.75)
2512	6332	0.25	6.3	0.12	3.2	0.024	0.6	1

4.4.2. Solder Pad and Land Pattern

When designing with surface mount components, the right solder pad size and land pattern should be used. The following table shows recommended land pattern dimensions for common surface mount packages, and also lists dimensions for reflow soldering. For wave soldering, smaller pads are used.



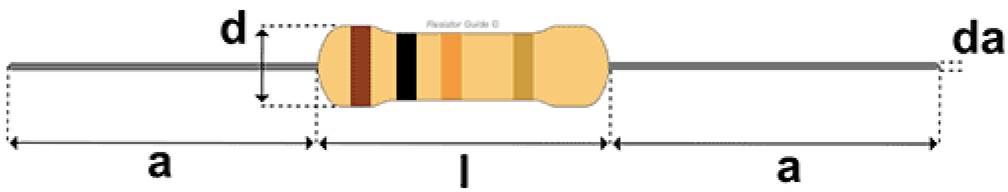
Solder pad dimensions

Code		Pad length (a)		Pad width (b)		Pad gap (c)	
Imperial	Metric	inch	mm	inch	mm	inch	mm
0201	0603	0.012	0.3	0.012	0.3	0.012	0.3
0402	1005	0.024	0.6	0.020	0.5	0.020	0.5
0603	1608	0.035	0.9	0.024	0.6	0.035	0.9
0805	2012	0.051	1.3	0.028	0.7	0.047	1.2
1206	3216	0.063	1.6	0.035	0.9	0.079	2.0
1812	3246	0.19	4.8	0.035	0.9	0.079	2.0
2010	5025	0.11	2.8	0.059	0.9	0.15	3.8
2512	6332	0.14	3.5	0.063	1.6	0.15	3.8

4.4.3. Axial Resistor Size

The size of axial resistors is not as standardized as that of SMD resistors, and different manufacturers often use slightly different dimensions. As well, an axial resistor's size depends both on the power rating and its type, such as carbon composition, wirewound, carbon, or metal film.

The following drawing and table describe the dimensions of common carbon film and metal film axial resistors. Whenever exact size needs to be known, check the manufacturer's data sheet for the component.



Axial resistor power ratings and dimensions

Power rating	Body length (l)	Body diameter (d)	Lead length (a)	Lead diameter (da)
W	mm	mm	mm	mm
1/8 (0.125)	3.0 ± 0.3	1.8 ± 0.3	28 ± 3	0.45 ± 0.05
1/4 (0.25)	6.5 ± 0.5	2.5 ± 0.3	28 ± 3	0.6 ± 0.05
1/2 (0.5)	8.5 ± 0.5	3.2 ± 0.3	28 ± 3	0.6 ± 0.05
1	11 ± 1	5 ± 0.5	28 ± 3	0.8 ± 0.05

4.4.4. MELF Resistor Package Sizes

Metal electrode leadless face (MELF) is another type of surface mount resistor package. The main advantage of using MELF rather than standard SMD packages is a lower thermal coefficient and better stability. The TCR of thin film MELF resistors is often between 25-50 ppm/K, while standard thick film SMD resistors often have a TCR of > 200 ppm/K.

This is possible thanks to MELF resistors' cylindrical construction, though this same construction also gives the package distinct disadvantages. Chief among these is the added difficulty of pick-and-place component placement; because of their round shape, a special suction cup and more vacuum is required. There are three common MELF package sizes: MicroMELF, MiniMELF, and MELF. The following table lists these types' characteristics.

MELF resistor package dimensions and ratings

Name	Abbr.	Code	Length	Diameter	Power
			mm	mm	(W)
MicroMELF	MMU	0102	2.2	1.1	0.2 - 0.3
MiniMELF	MMA	0204	3.6	1.4	0.25 - 0.4
MELF	MMB	0207	5.8	2.2	0.4 - 1.0

4.5. Resisor Symbols

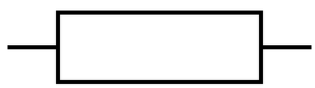
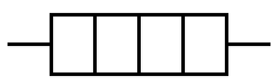
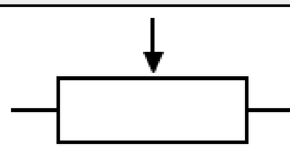
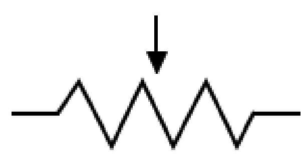
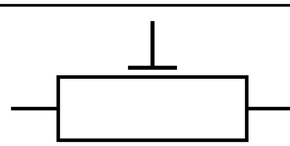
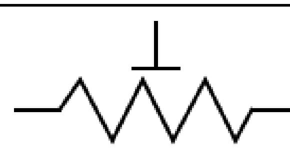
All resistor types have their own symbol for use in a circuit diagram drawing. Several standards exist, which describe how the different components should be displayed. In the past, numerous countries and even industries used their own standards, which could be confusing.

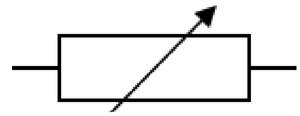
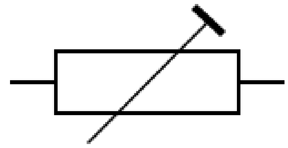
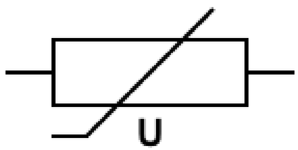
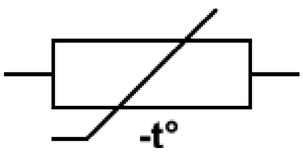
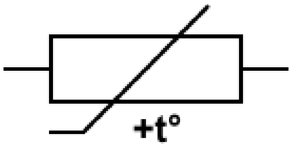
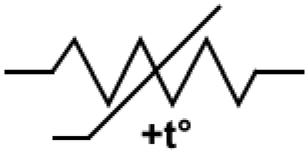
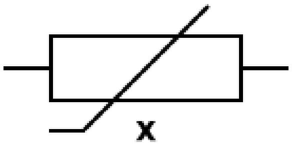
Today, the IEC 60617 standard is the international standard for these electronic symbols. That said, local standards are still used from time to time. The ANSI standard, for example, is still common in the United States, and is listed here along with others:

- IEC 60617 (International)
- ANSI Y32 / IEEE 315 (US) — old
- DIN 40900 (Germany) — old
- AS 1102 (Australia) — old

Sometimes, the symbol for a particular device is different when it is used in another field of application. For example, different symbols are used in electronics from those in architecture and construction. In addition, many local deviations from the international standards exist. The following table shows the most common resistor symbols for electronics design.

Resistor schematic symbols

Type	Abbreviation	IEC (International)	ANSI (US)
Fixed resistor	R		
Heater resistor			
Variable resistors			
Potentiometer			
Trimming potentiometer			

Type	Abbreviation	IEC (International)	ANSI (US)
Rheostat			
Preset resistor			
Dependent resistors			
Photoresistor or Light-dependent resistor	LDR		
Varistor, Voltage-dependent resistor, or Metal oxide varistor	VDR RV MOV		
NTC thermistor	NTC RT		
PTC thermistor	PTC RT		
Magneto, or Magnetic-dependent, resistor	MDR		

5 APPLICATIONS

5.1 Resistors in Series **97**

5.2 Resistors in Parallel **99**

5.3 Resistors in Series and Parallel **100**

5.4 Heater Resistors **101**
- 5.4.1 Radiant Heating 102
- 5.4.2 Convection and Forced-air Heating 103
- 5.4.3 Liquid Heating 103
- 5.4.4 Other Types of Heater Resistors 104

5.5 Resistors in LED Circuits **104**
- 5.5.1 Multiple LEDs in a Series Circuit 106
- 5.5.2 Multiple LEDs in a Parallel Circuit 107
- 5.5.3 How Does an LED Work? 107
- 5.5.4 Using LEDs as Photodiodes 108
- 5.5.5 LED Symbol 108

5.6 Power Resistors **109**
- 5.6.1 Types and Construction 109
- 5.6.2 Typical Applications 111

5.7 Pull-up and Pull-down Resistors **112**
- 5.7.1 What Is a Pull-up Resistor? 112
- 5.7.2 What Is a Pull-down Resistor? 113
- 5.7.3 Pull-up and Pull-down Resistor Values 114
- 5.7.4 Typical Applications 115

5.8 Blower Resistors **115**
- 5.8.1 Construction 115
- 5.8.2 Troubleshooting 116
- 5.8.3 Identifying the Fault 116

5 APPLICATIONS

5.9 Shunt Resistors 117

5.9.1 Shunt Resistors for Measuring Current 117

5.9.2 Shunt Circuit Position When Measuring Current 118

5.9.3 Specifying a Shunt Resistor 119

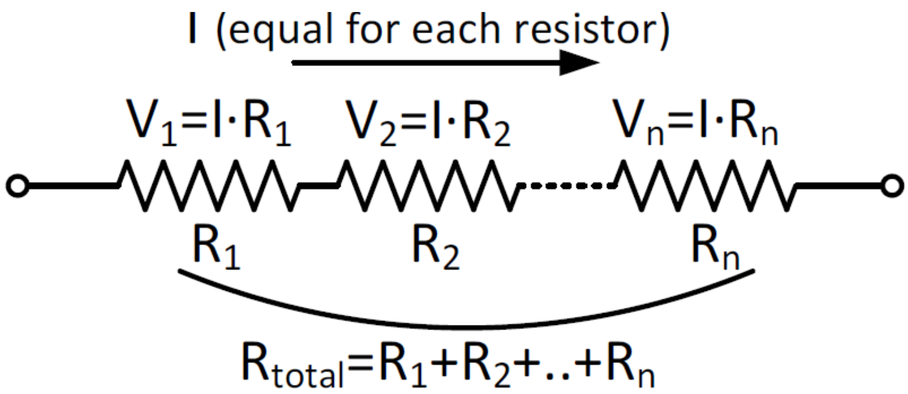
5.9.4 What Is a Shunt in Electronics? 119

5.9.5 Safety Checks When Measuring Resistance 120

5. APPLICATIONS

5.1. Resistors in Series

In many electrical circuits, resistors are connected in series or parallel. A designer might for example combine several resistors with standard values (E-series) to reach a specific resistance value. For a series connection, the current flowing through each resistor is equal because there is only one path for the current to follow. The voltage drop is proportional to the resistance of each individual resistor.



Series connection of resistors

The equivalent resistance of several resistors in series is given by:

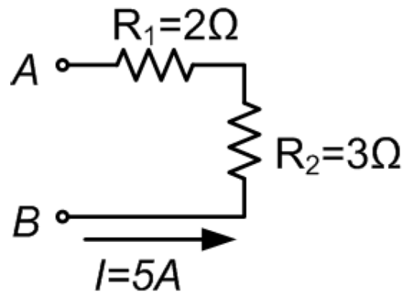
$$R_{eq} = \sum_{i=1}^{n} R_i = R_1 + R_2 + .. + R_n$$

The voltage across each resistor is calculated with Ohm's law:

$$V_i = I \cdot R_i$$

Example

Consider the circuit shown in the picture below. Two resistors R_1 and R_2 connected in series are subject to a constant current, *I*, of 5 A.



Series resistance calculation example

How can we calculate the voltage drop for each resistor, and how can we determine the equivalent resistance value for the two resistors? The current through each resistor is equal. Knowing this and using Ohm's law, we can find the voltage drop for R1 and R2:

$$V_{resistor1} = I \cdot R_1 = 5 \cdot 2 = 10V$$

$$V_{resistor2} = I \cdot R_2 = 5 \cdot 3 = 15V$$

$$V_{eq} = V_{resistor1} + V_{resistor2} = 10 + 15 = 25V$$

The equivalent resistance is equal to the sum of R1 and R2:

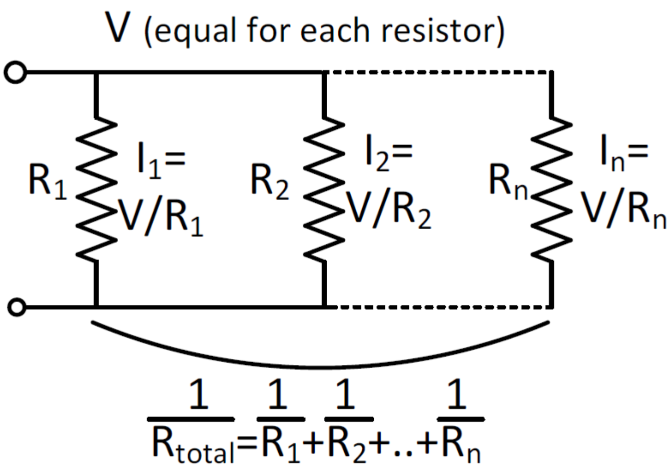
$$R_{eq} = R_1 + R_2 = 2 + 3 = 5\Omega$$

This corresponds with the voltage drops that we calculated:

$$V_{eq} = I \cdot R_{eq} = 5 \cdot 5 = 25V$$

5.2. Resistors in Parallel

Resistors are often connected in series or parallel to create more complex networks. An example of three resistors in parallel is shown in the following figure.



Resistors connected in parallel

The voltage across resistors in parallel is the same for each resistor. The current running through each branch of the circuit, however, is proportional to the resistance of each individual resistor. The equivalent resistance of several resistors in parallel is given by:

$$\frac{1}{R_{eq}} = \sum_{i=1}^{n} \frac{1}{R_i} = \frac{1}{R_1} + \frac{1}{R_2} + .. + \frac{1}{R_n}$$

And the current through each resistor is given by:

$$I = \frac{V}{R_i}$$

Example

A circuit designer needs to install a resistor with 9 Ω and can choose from the E12 series of preferred values (.., 10, 12, 15, 18, 22, 27, 33, 39, 47, 56, 68, 82, ..). The value of 9 Ω is, unfortunately, not available in this series. He decides to connect two standard values in parallel to create an equivalent resistance of 9 Ω. The equivalent resistance value for two resistors in parallel is calculated using the following steps:

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$\frac{1}{R_{eq}} = \frac{R_2}{R_1 R_2} + \frac{R_1}{R_1 R_2}$$

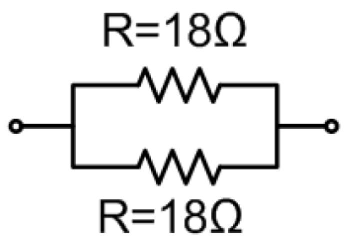
$$\frac{1}{R_{eq}} = \frac{R_1 + R_2}{R_1 R_2}$$

$$R_{eq} = \frac{R_1 R_2}{R_1 + R_2}$$

The above equation shows that if R_1 is equal to R_2, R_{eq} is half the value of one of the two resistors. For an R_{eq} of 9 Ω, R_1 and R_2 should therefore have a value of 2×9=18 Ω. This happens to be a standard value from the E-series.

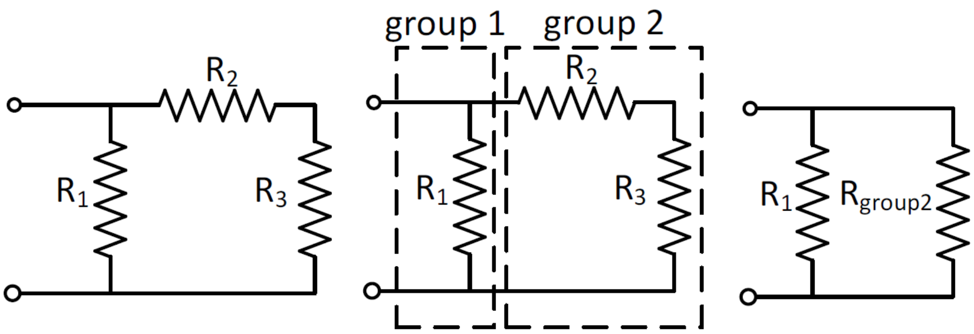
$$R_{eq} = \frac{R_1 R_2}{R_1 + R_2} = \frac{18 \cdot 18}{18 + 18} = 9\Omega$$

As a solution, the designer connects two resistors of 18 Ω in parallel, as shown in the figure below.



5.3. Resistors in Series and Parallel

A more complex resistor network can be solved by systematically grouping resistors. In the figure below, three resistors are connected. Resistors R_2 and R_3 are connected in series. They are in parallel with resistor R_1. To solve the network, the resistors are separated into two groups. Group 1 consists of only R_1. Group 2 consists of R_2 and R_3.



The equivalent resistance of group 2 is easily calculated by the sum of R_2 and R_3:

$$R_{group2} = R_2 + R_3$$

This leads to the simplified circuit with two resistors in parallel. The equivalent resistance value of this circuit is easily calculated as follows:

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_{group2}}$$

$$R_{eq} = \frac{R_1 \cdot R_{group2}}{R_1 + R_{group2}}$$

$$R_{eq} = \frac{R_1 \cdot (R_2 + R_3)}{R_1 + R_2 + R_3}$$

5.4. Heater Resistors

Heater resistors are used whenever an electronic device needs for some reason to generate heat. To provide a reliable and controllable source of it, they are designed as a special type of power resistor.

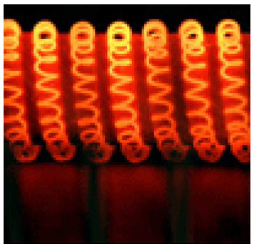
Symbol for a heater resistor

A heating resistor can produce convective heat, meaning it heats up the surrounding air, or radiant heat, meaning it heats other objects directly through a phenomenon called infrared radiation. Radiant heating requires that the heater resistor be placed within line of sight of the object that is to be heated, while in convective heating fans might be utilized to blow air over the heater resistors, enhancing their effectiveness.

> *Heater resistors are a special type of power resistor whose main purpose is to convert electrical energy into heat.*

5.4.1. Radiant Heating

5.4.1.1. Wirewound Radiant Heater



Wirewound radiant heaters are essentially wirewound power resistors. The glowing hot wire emits infrared energy that is then absorbed by the heated object. Some of the energy is given off as light in the visible spectrum as well. A reflector is often added behind the resistance heating element in order to direct as much heat as possible in the desired direction. The wire can be exposed or enclosed in a tube to protect it from damage. This is especially useful if there is a risk of water drops falling on the element, which could cause thermal stress damage. Wirewound radiant heaters are often used in bathrooms or outdoors, where the intent is to heat a person without having to heat up the surrounding air first.

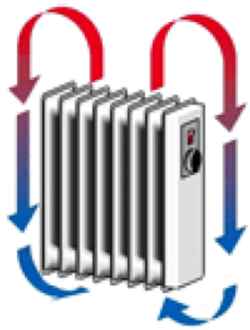
5.4.1.2. Halogen Radiant Heater

Halogen radiant heaters, often called quartz heaters, are similar in design to halogen light bulbs. They most often consist of a quartz tube containing a tungsten resistive filament. The air from the tube is evacuated and replaced with an inert gas such as argon or nitrogen, and a small amount of halogen gas is added. This halogen gas prolongs the heater's lifespan by protecting and cleaning the filament, in a chemical process called the halogen cycle. A reflector is added behind the heating element to direct its heat energy in the desired direction. To prevent fires, halogen heaters are often equipped with safety mechanisms that turn off the heater if it is tipped over. They are often used in applications requiring contact-less heating, such as chemical processes, paint drying, and food processing and thawing, as well as in incubators and for heating augmentation in cold rooms.

5.4.2. Convection and Forced-air Heating

5.4.2.1. Electric Convection Heater

Electric convection heaters contain a heating element that is exposed to air. Upon contact the air heats up and, because hot air is lighter than cold air, it rises, leaving space for more cool air to come in contact with the heater from below. This process is called air convection. Some electric convection heaters do not heat air directly, as is the case with oil radiators. In such devices, the heating element is in direct contact with a special oil that spreads the heat throughout the radiator. The heat is then transferred to the surroundings via air convection. A special subtype of convection heating is floor heating, where resistive wires are used to heat a floor's entire surface. The heat is then transferred to the air through convection, though the difference between the heat of the floor and that of the air is kept under a few degrees, to avoid unpleasant air convection currents.



5.4.2.2. Fan Heater

Fan heaters are similar to electric convection heaters, except that air is forced over the heating element by means of an electrical fan. These heaters are used to heat up closed spaces, such as rooms or vehicle interiors, while the engine is still warming up to operating temperature. The downside to using fan heaters is that they are noisy compared to traditional convection heaters, although recent advances in technology have made fans quieter. The heating element is often a PTC thermistor.

5.4.3. Liquid Heating

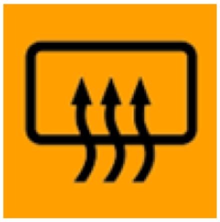
5.4.3.1. Submersible Heater

Submersible heater elements are resistive heaters used to heat up liquids. They are electrically insulated to maintain safety and prevent liquid electrolysis. Many applications call for the use of submersible heaters, such as water heaters, water boilers, and aquarium heaters, which are equipped with a thermostat to maintain constant temperature. If a submersible heater element is constantly in contact with hard water, as is the case with household water heaters, limescale (calcium carbonate deposits) eventually builds up on its surface. As the element is cycled on and off, its thermal expansion and contraction breaks the limescale, which then falls to the bottom of the container. Over time, this process can significantly reduce the liquid capacity of the heater.

5.4.3.2. Industrial Liquid Heating

Industrial liquid heaters are custom-designed and built for the application. Examples of industrial applications that call for electrical heating include, but are not limited to: asphalt heating/melting, bio-diesel processing, clean steam generation, food processing, textiles, and pharmaceutical processing.

5.4.4. Other Types of Heater Resistors



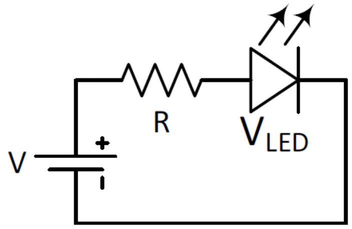
Heating resistance wire has an overwhelming variety of interesting applications, and only some will be listed here. As one example, heater resistors can be used to heat motorcycle hand grips for driving in cold weather. Heater resistors can also be embedded in, or sometimes applied to, the surface of a car window. This is most often seen on the rear, where, in the form of resistive tracks, they are used for de-fogging and de-frosting.

Surveillance cameras provide another useful application. Here, a heater resistor is placed near the glass cover and lens. The resistor's heat keeps the glass temperature above the dew point, which prevents fogging and snow buildup. This keeps the camera useful in all weather conditions.

To accurately develop photographic films, precise and constant temperature is required; otherwise, colors will degrade. In a similar way, many chemical processes need constant temperature, which may require heating. Some pieces of medical equipment, such as blood analyzers, also need constant temperature to operate correctly.

5.5. Resistors in LED Circuits

An LED (Light-emitting Diode) emits light when an electric current passes through it. The simplest circuit to power an LED is a voltage source with a resistor and an LED in series. Such a resistor is often called a ballast resistor. The ballast resistor is used to limit the current passing through the LED and prevent excess current from damaging it. If the voltage source is equal to the voltage drop of the LED, no resistor is required.



LED circuit with a current-limiting resistor

The resistance of the ballast resistor is easy to calculate with Ohm's law and Kirchhoff's circuit laws. The rated LED voltage is subtracted from the voltage source, and then divided by the desired LED operating current:

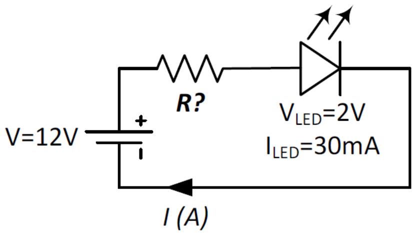
$$R = \frac{V - V_{LED}}{I}$$

where V is the voltage source, V_{LED} is the LED voltage, and I is the LED current. This way, you can find the right resistor for an LED.

This simple circuit might be used as a power-on indicator for a DVD player or a computer monitor. Though widely used in consumer electronics, it is not particularly efficient, since the voltage source's surplus energy is dissipated by the ballast resistor. As such, more complex circuits are sometimes employed to improve energy efficiency.

Example of a Simple LED Circuit

In the following example, an LED with a voltage of 2 V and a current rating of 30 mA must be connected to a 12 V supply.



LED circuit example for calculating series resistance

The ballast resistor can be calculated using the formula:

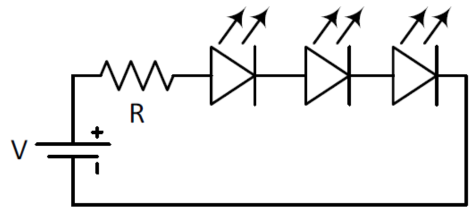
$$R = \frac{V - V_{LED}}{I}$$

$$R = \frac{12 - 2}{0.03} = 333$$

Therefore, the resistor must have a resistance of 333 Ω. If the precise value is not available, choose the next highest value to prevent excess current that may damage the LED.

5.5.1. Multiple LEDs in a Series Circuit

Often, multiple LEDs are connected to a single voltage source with a series connection; in this way, multiple resistors can share the same current. As the current flowing through all LEDs in series is equal, they should be of the same type. Note that lighting one LED in this circuit will require just as much power as multiple LEDs in series. The voltage source must provide a large enough voltage for the sum of the LED voltage drops, plus the resistor.

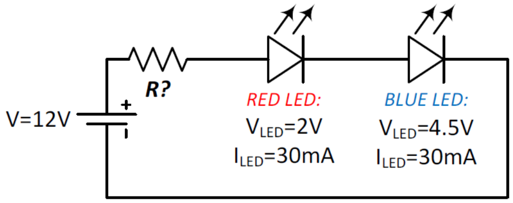


LEDs connected in series

Typically, the source's voltage is 50% greater than the sum of the LED voltages. In contrast, it is sometimes preferable to select a source with lower voltage. Here, the lower brightness is compensated by the larger number of LEDs. In addition, thermal loss is reduced, and the lower load leads to longer LED lifespans.

Example of LEDs in Series

In this example, two LEDs are connected in series. One is red, with a voltage of 2 V, and one is blue, with a voltage of 4.5 V. Both have a rated amperage of 30 mA.



Example circuit of multiple LEDs connected in series

Kirchhoff's circuit laws state that the sum of voltage drops across the circuit is zero. Therefore, the resistor voltage must be equal to the voltage source minus the sum of the LED voltage drops. With Ohm's law, we can calculate the resistance value of the ballast resistor:

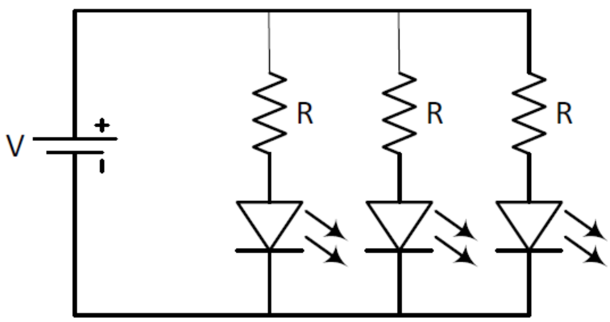
$$R = \frac{V - V_{LED1} - V_{LED2}}{I}$$

$$R = \frac{12 - 2 - 4.5}{0.03} = 183.3$$

The resistor must have a value of at least 183.3 Ω. Note that the voltage drop across the resistor is 5.5 V. Given this, it would have been possible to connect additional LEDs in the circuit.

5.5.2 Multiple LEDs in a Parallel Circuit

It is possible to connect LEDs in parallel, but this creates more issues than with series LED circuits.

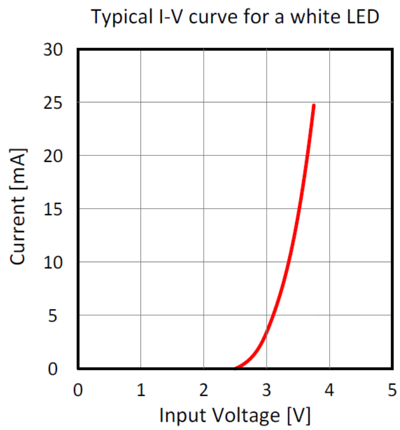


LEDs connected in parallel

The forward voltages of the LEDs must closely match. Otherwise, only the lowest voltage LED will light up, and may be burned by the larger current. Even if the LEDs have the same specification, they can have poorly matching I-V characteristics due to variations in the production process; this leads them to pass differing currents. To minimize this difference in current, LEDs in parallel normally have a ballast resistor for each branch.

5.5.3. How Does an LED Work?

An LED (Light-emitting Diode) is a semiconductor device; it is essentially a P-N junction with a lead attached to each side. An ideal diode has zero resistance when forward-biased and infinite resistance when reverse-biased. In real diodes, though, a small amount of voltage must be present across the diode to make it conduct. This voltage, in addition to other characteristics, is determined by the material makeup and construction of the diode. When enough forward bias voltage is applied, excess electrons from one side of the junction combine with holes on the other side. When this occurs, the electrons fall into a less energetic state and release energy.



LED I-V Characteristic Curve

In LEDs, this energy is released in the form of photons. The materials from which the LED is made determine its wavelength, and therefore the color of the emitted light. The first LEDs were made with gallium arsenide and lit red. Today, an LED can be made from a variety of materials and can emit a range of colors. Voltages vary from about 1.6 V for red LEDs to about 4.4 V for ultraviolet ones. Knowing the correct voltage is important because applying too much voltage across the diode can cause more current than the LED can safely handle.

LEDs today are available in low and high power. LEDs typically give off less heat and use less power than incandescent bulbs of equal brightness. They therefore last longer than equivalent light bulbs, and are used in a wide range of lighting and light-sensing applications.

5.5.4. Using LEDs as Photodiodes

LEDs can be used as photodiodes, which are semiconductors that behave in the opposite manner. Whereas an LED will emit light as it conducts, a photodiode will generate current when exposed to the correct wavelength of light. An LED will exhibit this characteristic when exposed to light at a wavelength below its normal operational wavelength. This allows LEDs to be used in light sensor and fiber optic communication circuits.

5.5.5. LED Symbol

The schematic symbol for an LED is based on that of the standard diode, but with additional arrows pointing away from the diode to represent the emitted light.

LED Symbol

5.6. Power Resistors

Power resistors, which in general have a power rating of at least 5 W, are designed to withstand and dissipate large amounts of power. They are made from materials with high thermal conductivity, which allows for efficient cooling, and are often designed to be coupled with heat sinks. Under maximum load, some may even require forced air or liquid cooling. Some are wirewound, some are made from wire grids for ease of cooling, but all are built to dissipate maximum power while minimizing size. An example application for power resistors is in load banks, which dissipate power generated during engine braking in vehicles using electric motors, such as locomotives or trams.

> *A power resistor is a resistor designed and manufactured to dissipate large amounts of power in a compact physical package.*

5.6.1. Types and Construction

The following table provides key characteristics for various types of power resistors.

Power resistor characteristics

Type	Typical power dissipation	Size	Vibration resistance
Helical wound	<50 W	Small-medium	Low
Edgewound	<3.5 kW	Small-medium	Medium
Grid	<100 kW	Medium-large	High
Chip/SMD	<5 W	Small-very small	High
Water	<500 MW (30 s)	Medium-large	Medium

5.6.1.1. Wirewound Resistors

Wirewound resistors are made by winding a metal wire around a solid form, often made of ceramic, fiberglass, or plastic. There are several winding methods, including helical, bifilar, and edge winding.

Edge wound resistor

Helical winding, in which a wire is wound in a helix around a cylindrical core, is conventional. Since this wire is coil-shaped, wirewound resistors have a certain inductance. To avoid potential interference with other devices and the generation of unwanted magnetic fields, bifilar winding is employed. Here, the wire is wound in two directions, which reduces the electromagnetic fields created by the resistor. Edgewound resistors, which are usually coreless, air-cooled and able to dissipate more power than helicals, are made by winding a strip of metal via its wider edge.

Once wound, metal caps and metallic leads are attached to each end. The body of the device is then often coated with a non-conductive paint or enamel, to offer some protection from the environment. Wirewound resistors can be built to withstand high temperatures, sometimes up to 450 °C. In addition, these resistors are often built to tight tolerances thanks to their material, an alloy of nickel and chrome called Nichrome.

5.6.1.2. Grid Resistor

Grid resistors are large matrices of metal strips connected between two electrodes. Though they vary in size, they can be as large as a refrigerator. It is not uncommon to see grid resistors valued at under 0.04 Ω that can withstand currents of over 500 amperes. They are used as brake resistors and load banks for railroad vehicles, as neutral grounding resistors, in generator load testing, and in harmonic filtering for electric substations.

Grid Resistor

5.6.1.3. Chip/SMD Resistors

Chip resistors are resistors that look like integrated circuit chips. Surface mount power resistors are made from many different materials, such as pressed carbon, ceramics and metal (cermet resistors), or metal foil. Wirewound chip resistors are also available.

Chip / SMD resistor

SMD resistors are actually smaller form, surface mounted chip resistors. The resistor itself consists of a metal oxide film deposited onto a ceramic substrate; the film's thickness and length determine the resistance. They have power dissipation ratings much lower than those of grid resistors or water resistors, and can usually dissipate no more than a few watts, provided they have appropriate cooling.

5.6.1.4. Water Resistors

Water resistors consist of tubes filled with a saline solution, with an electrode at both ends. The salt concentration in the solution controls the resistance of the resistor. Water in the tube provides large heat capacity, which allows for high power dissipation. Some high-power water resistors used in pulsed modes utilize copper sulfate solutions, rather than saline.

5.6.1.5. Liquid Rheostats

Liquid rheostats, or saltwater rheostats, are a type of variable resistor, in which resistance is controlled by submerging the electrodes into a saline solution. Resistance may be raised or lowered by adjusting the electrode's position inside the liquid. To stabilize the load, the mixture must not be allowed to boil. Liquid rheostats are slightly outdated, but are still constructed for use in some diesel generators.

5.6.2. Typical Applications

Power resistors are used when there is a need to safely convert large amounts of energy into heat, using electrical energy as a medium. They are used as controllable power dissipation devices, protective devices, and devices that simulate real-world loads.

5.6.2.1. Engine Braking

High-power resistors are used in locomotives and trams to safely convert the vehicle's kinetic energy to heat. Since the energy required to stop heavy vehicles moving at high speeds is massive, classic disc brakes would wear too quickly and be too expensive to maintain. Given this, regenerative braking tends to be used instead. In regenerative braking, kinetic energy is transformed to electrical energy and then fed back into the supply network. When regenerative braking is not available, power resistors are used. Resistance brakes offer controlled braking power without introducing wear to the parts. It is often necessary to dissipate many kilowatts for extended periods of time.

5.6.2.2. Load Banks

Load bank resistors are devices used to safely simulate a real-world load. They are used to load-test generators, turbines and battery UPS systems. Resistive load banks provide a known, adjustable resistance value in a compact package, as opposed to real loads, which can be dispersed over a large area, are random in value, and may have an inductive or capacitive component in addition to their resistance. AC load banks can withstand and dissipate as much as 6 megawatts of power, but such banks can be the size of a room. To prevent thermal damage, they are equipped with active cooling.

5.6.2.3. Neutral Grounding Resistors

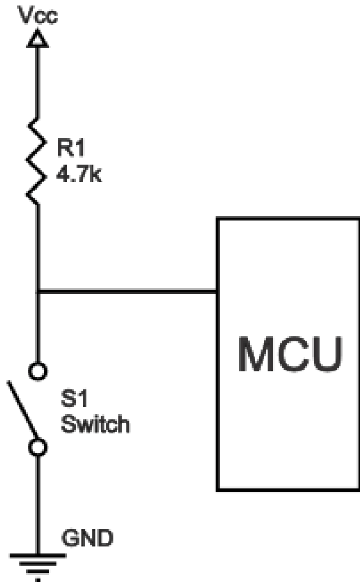
Neutral grounding resistors are power resistors used in the power grounding of Y-connected generators. They are used to limit the fault current as well as transient over-voltages, and allow protective relays to be used in such applications. Neutral grounding resistors are rated at up to 8 kA and are primarily used in medium-voltage AC distribution systems. When these resistors are used, even if a grounding fault occurs, it is much easier to locate the fault location.

5.7. Pull-up and Pull-down Resistors

5.7.1. What Is a Pull-up Resistor?

Pull-up resistors are resistors used in logic circuits to ensure a well-defined logical level at a pin under all conditions. As a reminder, digital logic circuits have three logic states: high, low, and floating (or high-impedance). The high-impedance state occurs when the pin is not pulled to a high or low logic level, but is instead left “floating.”

The unconnected input pin of a microcontroller offers a good illustration. It is neither in a high nor low logic state, and the microcontroller might unpredictably interpret the input value as either a logical high or logical low. Pull-up resistors are used to solve the microcontroller’s dilemma, by pulling the value to a high logic state, as seen in the figure below. Without a pull-up resistor, the MCU’s input would be floating when the switch is open, and lowered only when the switch is closed.



Pull-up resistor circuit

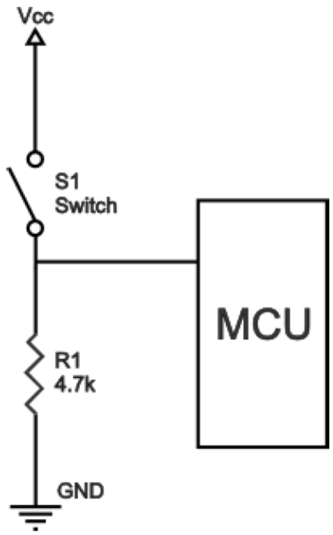
Pull-up resistors are not a special kind of resistor; they are simply fixed-value resistors connected between the voltage supply (typically +5 V, +3.3 V or +2.5 V) and the appropriate pin, which results in a defined input or output voltage in the absence of a driving signal. A typical pull-up resistor value is 4.7 kΩ, but these can vary depending on the application.

> *Pull-up resistors are resistors that are used to ensure that a wire is pulled to a high logic level in the absence of an input signal.*

5.7.2. What Is a Pull-down Resistor?

Pull-down resistors work in the same manner as pull-up resistors, but instead pull the pin to a low logic state. They are connected between ground and the appropriate pin on a device. An example of a pull-down resistor in a digital circuit can be seen in the figure below. A push button switch is connected between the supply voltage and a microcontroller pin.

In such a circuit, when the switch is closed, the microcontroller input is at a logical high value. But when the switch is open, the pull-down resistor pulls the input voltage down to ground (logical zero value), preventing an undefined state at the input. The resistor must have a resistance larger than the impedance of the logic circuit, or else it may pull the voltage down too far, leading the input voltage at the pin to remain at a constant logical low value, regardless of switch position.



Pull-down resistor circuit

5.7.3. Pull-up and Pull-down Resistor Values

The appropriate value for a pull-up (or pull-down) resistor is defined by two factors. The first is power dissipation. If the resistance value is too low, a high current will flow through the pull-up resistor, heating the device and consuming an unnecessary amount of power when the switch is closed. This condition is called a strong pull-up, and is avoided when low power consumption is a requirement. The second factor is pin voltage when the switch is open. If the resistance value is too high, in combination with a large leakage current of the input pin, the input voltage can become insufficient when the switch is open. This condition is labeled a "weak pull-up." The actual value of the pull-up's resistance depends on the impedance of the input pin, which is closely related to the pin's leakage current.

A rule of thumb is to use a resistor that is at least 10 times smaller than that of the input pin impedance. In bipolar logic families operating at 5 V, the typical pull-up resistor value is 1-5 kΩ. For switch and resistive sensor applications, the typical pull-up resistor value is 1-10 kΩ. If in doubt, a good starting point when using a switch is 4.7 kΩ. Some digital circuits, such as CMOS families, have a small input leakage current, which allows for much higher resistance values of around 10 kΩ to 1 MΩ. The disadvantage when using a larger resistance value is that the input pin responds more slowly to voltage changes. This is the result of the coupling between the pull-up resistor and the total pin and wire capacitance at the switching node that forms an RC circuit. The larger the product of R and C, the more time is needed for the capacitance to charge and discharge, and consequently the slower the circuit. In high-speed circuits, a large pull-up resistor can sometimes limit the speed at which the pin can reliably change state.

5.7.4. Typical Applications

Pull-up and pull-down resistors are often used when interfacing a switch—or some other input—with a microcontroller or other digital gates. Most microcontrollers have built-in programmable pull-up/down resistors so fewer external components are needed. It is possible to interface a switch with such microcontrollers directly. Pull-up resistors are, in general, used more often than pull-down resistors, though some microcontroller families have both pull-up and pull-downs available. They are often used to provide controlled current flow into a resistive sensor, prior to analog-to-digital conversion of the sensor output voltage signal. Another application is the I^2C protocol bus, where pull-up resistors are used to enable a single pin to act as an input or an output. When not connected to a bus, the pin floats in a high-impedance state. Pull-down resistors are also used on outputs to provide a known output impedance.

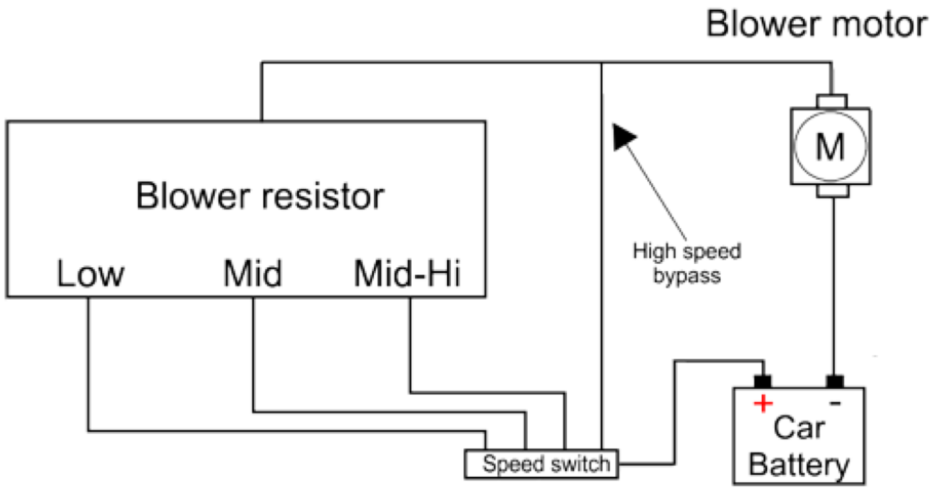
5.8. Blower Resistors

Blower resistors are resistors that are used to control the fan speed of automotive blowers. The fan speed can be changed either by manipulating the resistor resistance mechanically, using a rotating lever, or electronically via the air conditioning system. This change in resistance then limits the current coursing through the motor, which dictates the speed at which the blower fan runs. Blower resistors, being mechanical components, are prone to wear and are the most common point of failure in a car's heating system.

5.8.1. Construction

A blower fan is connected to the negative battery terminal (also called ground) on one end and to the positive battery terminal, through a blower resistor, on the other. The blower resistor is connected in series with the blower fan, meaning the current is running through the blower motor, and thus its speed is controlled by the resistor value. The user chooses a suitable fan speed by utilizing a selector to connect one of the resistors in the blower resistor pack. Blower resistors consist of several resistors with different resistances.

There are, as well, two additional circuits used for the off state and the highest fan speed. In the off state, the blower motor is disconnected from the power supply. At the fan's highest speed, the blower resistor is bypassed completely and the fan is connected directly to the car's battery, which allows maximum current through the motor. The lower the resistance of the selected resistor in a pack, the higher the current that flows through the blower fan, and the faster the fan will turn.



Automotive blower motor circuit schematic

5.8.2. Troubleshooting

The individual resistors inside a pack are usually wirewound and may burn out. They may also fail because of the mechanical stresses and vibrations typically found in an automotive environment. When a blower resistor is faulty, the fan will usually operate at one speed only, usually the highest possible. On occasion, only some of the speed settings will be faulty while others continue to function.

5.8.3. Identifying the Fault

When trying to diagnose a blower fan motor, the following steps should be followed:

- If a car's blower motor doesn't work at all, there are several components to check in the system:
- Check the fuse for power on both ends using a multimeter. If there is power on one end of the fuse but not the other, the fuse needs to be replaced.
- Check the fan relay, if the car is equipped with one. Such relays can be tested by switching the fan's control on and off. Clicking from the relay is an indication that it is almost certainly working correctly.
- Check the fan itself for power by turning on the fan control and checking for +12 V at its terminals. To do this, switch your multimeter to voltage-measuring mode and verify that the voltage difference between the fan's terminals is 12 V. If there is no power present at the fan, suspect a wiring fault. In this case, it's best to take the car to a certified auto electrician. If power is present at the fan's terminals and the fan is not working, the blower fan is defective.

- If the fan operates at some speed settings, but not at others, the blower resistor is faulty and should be replaced.
- Find the blower resistor and detach it from the rest of the circuit. For its precise location, consult the repair manual for your car's make and model. Some common locations: near the blower fan motor, under or behind the dashboard, and around the passenger footwell.
- Once the resistor is located and detached, it is often possible to judge by physical appearance alone whether the resistor has burned out. A burned-out resistor should be replaced with an appropriate model from your car manufacturer.
- If the resistor's appearance is normal, it is necessary to measure its resistance across each individual resistor. The resistors are all connected to a common point. Switch the multimeter to the resistance measuring mode, attach one probe of the multimeter to that common point and use the other probe to measure resistances at other points. If any of these resistances show an open circuit (infinite resistance), the blower resistor needs to be replaced.

A word of caution: blower resistors get very hot during normal operation, so care must be taken to avoid burns and other injuries.

5.9. Shunt Resistors

A shunt resistor is used to measure electric current, alternating or direct. This is done by measuring the voltage drop across the resistor. The term "shunt" is also used in the electronics industry, where it describes a circuit component that redirects excess current around another component to prevent damage.

5.9.1. Shunt Resistors for Measuring Current

A device for measuring electric current is called an ammeter. Most modern ammeters measure the voltage drop over a precision resistor with a known resistance. The current flow is calculated by using Ohm's law:

$$I = \frac{V}{R}$$

Most ammeters have a built-in resistor to measure current. When the current is too high for the ammeter, though, a different setup is required. Here, an ammeter is placed in parallel with an accurate shunt resistor, which is sometimes referred to as an "ammeter shunt."

Usually, this is a high-precision manganin resistor with low resistance. The current is divided over the shunt and the ammeter, such that only a small (known) percentage flows through it. In this way, large currents can still be measured, and by correctly scaling the ammeter, the actual amperage can be directly measured. Using this configuration, in theory, the maximum amperage that can be measured is endless.

In actuality, though, the voltage rating of the measurement device must not be exceeded. In addition, the resistance value should be as low as possible to limit interference with the circuit. That said, a smaller resistance value results in a smaller voltage drop and a lower resolution.

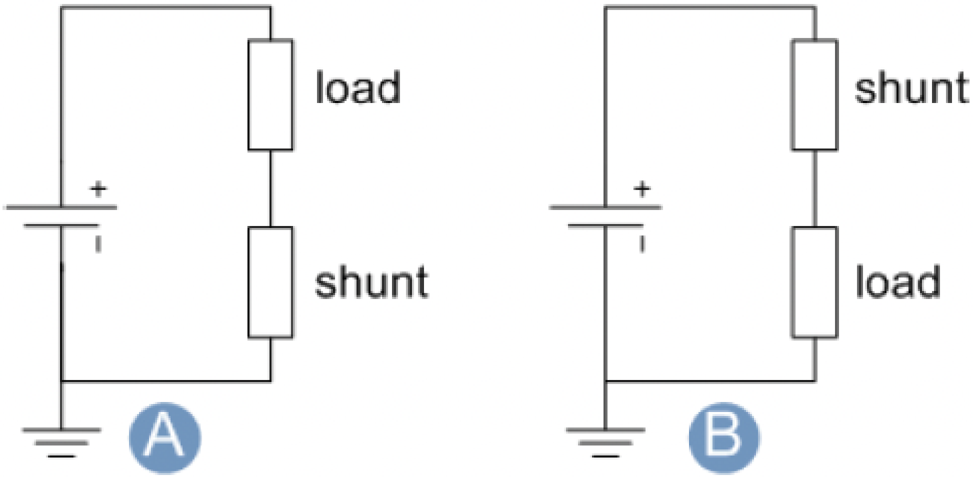
Example

A shunt resistor with a resistance of 1 mΩ is used. The resistor is placed in a circuit, and a voltage drop of 30 millivolts is measured across the resistor. This means that the current is equal to the voltage divided by resistance, or: $I = V / R = 0.030 / 0.001 = 30$ A. If one were to know the current and voltage values, the same calculation could be made to determine resistance. This is used to calibrate shunt resistance.

5.9.2. Shunt Circuit Position When Measuring Current

It is important to carefully choose the position of the shunt in the circuit. When the circuit shares a common ground with the measurement device, it is advisable to place the shunt as close to the ground as possible. This protects the ammeter from the common mode voltage, which might be too high and thus damage the device, or lead to erroneous results.

A disadvantage here is that leakages that bypass the shunt might not be detected. If the shunt is placed in the ungrounded leg, it must be isolated from the ground or include a voltage divider, or an isolation amplifier, to protect the instrument. Other methods are viable, including using a Hall Effect sensor to avoid connecting the measurement instrument directly to the high-voltage circuit. Still, current shunts are generally more affordable. Two variations on shunt placement are depicted in the figure on the following page.



A. Often, the shunt is placed in the grounded side to eliminate the common mode voltage.
B. In this configuration, the common mode voltage could be too high for the ammeter.

5.9.3. Specifying a Shunt Resistor

In specifying a shunt resistor, several parameters are important. Shunt resistors have a maximum current rating, and their resistance values are given by the voltage drop at this maximum. For example, a shunt resistor rated at 100 A and 50 mV has a resistance of 50 / 100 = 0.5 mΩ. The voltage drop at maximum current is typically rated 50, 75 or 100 mV.

Other important parameters include the resistance tolerance, the temperature coefficient of resistance, and the power rating. The power rating indicates the amount of electric power that the resistor can dissipate at a given ambient temperature without damaging or changing the resistor parameters. The produced power can be calculated with Joule's law.

Shunt resistors usually have a derating factor of 66% for continuous operation. This is defined for a runtime longer than two minutes. High temperatures negatively influence the accuracy of the shunt; above 80 °C, thermal drift starts. This drift worsens with rising temperature, and above 140 °C the resistor will be damaged. At this level of heat, the resistance value may also be permanently changed.

5.9.4. What Is a Shunt in Electronics?

This section has been focused on shunt resistors, whose primary purpose is to measure current. But the term "shunt" has broader meaning in electronics. A shunt is an element that is used in a circuit to redirect current around another portion of the circuit. Its areas of application vary widely. In some applications, electrical devices other than resistors can be used. A few examples are provided below to illustrate the shunt's versatility.

- **Protecting a circuit against overvoltage**
  One method for protecting a circuit from overvoltage is to use a crowbar configuration. When the voltage becomes too high, a device will short circuit. This results in the current flowing parallel to the circuit, which causes an immediate voltage drop. High current through the shunt should trigger a circuit breaker or fuse.
- **Bypassing a defective device**
  When one element in a series circuit fails, it will break the complete circuit. A shunt can be used to overcome this problem. The failure will lead to a higher voltage, which in turn will cause the shunt to short out. The electricity will then pass around the defective element. A good example of this is Christmas lighting.
- **Bypassing electrical noise**
  Shunts with a capacitor are sometimes applied in circuits where high-frequency noise is a problem. Before the problematic signal reaches the circuit elements, the capacitor redirects it to the ground.

5.9.5. Safety Checks When Measuring Resistance

1. Before connecting the ohmmeter leads, turn off the power in the circuit.

2. When connecting the leads to a DC current or voltage, make sure to correctly choose plus and minus.

3. Adjust the meter to the correct settings (AC, DC, ohms, etc.)

4. Verify that the meter's range is high enough for the test circuit.

5a. If measuring current or voltage, turn on power and inspect the meter value.
5b. If measuring resistance, leave the power off.

6. Switch off the power and then remove the test leads from the circuit.

7. If measuring current, reconnect the circuit as appropriate.

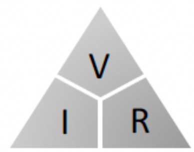
6. APPENDIX

Resistor Formulas and Laws

Ohm's Law

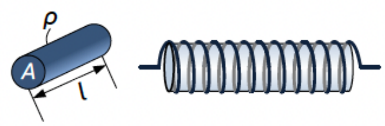
$$R = \frac{V}{I}$$

$$\rho = \frac{E}{J}$$



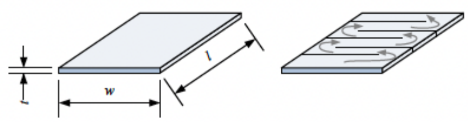
Wire resistance

$$R = \rho \frac{l}{A}$$



Sheet resistance

$$R = \rho \frac{l}{A} = \rho \frac{l}{t \cdot w}$$



Resistors in parallel

$$\frac{1}{R_{eq}} = \sum_{i=1}^{n} \frac{1}{R_i} = \frac{1}{R_1} + .. + \frac{1}{R_n}$$

Current through each resistor:

$$I = \frac{V}{R_i}$$

Resistors in series

$$R_{eq} = \sum_{i=1}^{n} R_i = R_1 + .. + R_n$$

Voltage across each resistor:

$$V_i = I \cdot R_i$$

1st law or current law: In 1 node, the sum of all entering or leaving currents is zero.
2nd law or voltage law: In a closed loop, the sum of voltage rises or drops is zero.

Resistor Color Code

Color	Significant figures			Multiplier	Tolerance (%)	Temp Co (ppm/K)	Failure rate (%)	Memory Mnemonic
Black	0	0	0	x 1		250 (U)		**B**ad
Brown	1	1	1	x 10	1 (F)	100 (S)	1.0	**B**eer
Red	2	2	2	x 100	2 (G)	50 (R)	0.1	**R**ots
Orange	3	3	3	x 1K		15 (P)		**O**ur
Yellow	4	4	4	x 10K		25 (Q)		**Y**oung
Green	5	5	5	x 100K	0.5 (D)	20 (Z)		**G**uts
Blue	6	6	6	x 1M	0.25 (C)	10 (Z)		**B**ut
Violet	7	7	7	x 10M	0.1 (B)	5 (M)		**V**odka
Grey	8	8	8	x 100M	0.05 (A)	1 (K)		**G**oes
White	9	9	9	x 1G				**W**ell
Gold			3rd digit only for bands 5 and 6	x 0.1	5 (J)			**G**et
Silver				x 0.01	10 (K)			**S**ome
None					20 (M)			**N**ow

Resistor SMD Codes

Three and four-digit resistance code systems

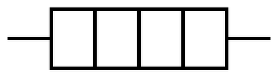
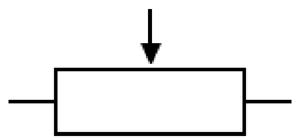
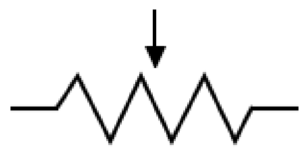
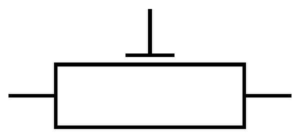
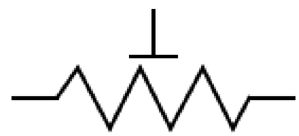
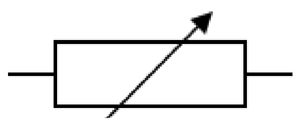
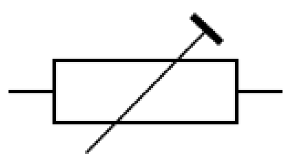
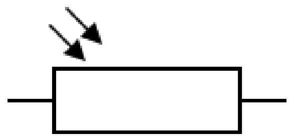
	Three-digit code	Four-digit code
Code	A B C	A B C D
Value	AB x 10^C	ABC x 10^D
Example	450: 45 x 10^0 = 45 Ω	7992: 799 x 10^2 = 79.9 kΩ

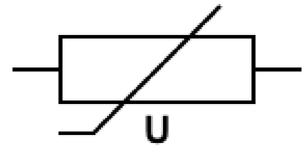
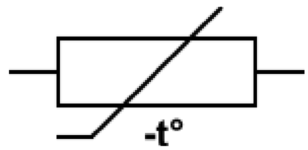
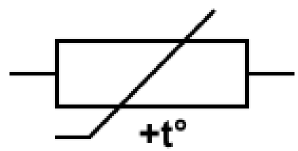
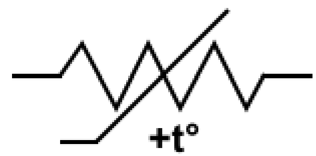
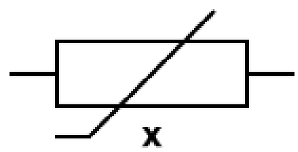
EIA-96 resistance code system

Code	Multiplication factor
Z	0.001
Y / R	0.01
X / S	0.1
A	1
B / H	10
C	100
D	1000
E	10,000
F	100,000
Examples	
Code	**Value**
01A	100 Ω ±1%
38C	24300 Ω ±1%

Code	Value	Code	Value	Code	Value	Code	Value	Code	Value	Code	Value
01	100	17	147	33	215	49	316	65	464	81	681
02	102	18	150	34	221	50	324	66	475	82	698
03	105	19	154	35	226	51	332	67	487	83	715
04	107	20	158	36	232	52	340	68	499	84	732
05	110	21	162	37	237	53	348	69	511	85	750
06	113	22	165	38	243	54	357	70	523	86	768
07	115	23	169	39	249	55	365	71	536	87	787
08	118	24	174	40	255	56	374	72	549	88	806
09	121	25	178	41	261	57	383	73	562	89	825
10	124	26	182	42	267	58	392	74	576	90	845
11	127	27	187	43	274	59	402	75	590	91	866
12	130	28	191	44	280	60	412	76	604	92	887
13	133	28	196	45	287	61	422	77	619	93	909
14	137	30	200	46	294	62	432	78	634	94	931
15	140	31	205	47	301	63	422	79	649	95	953
16	143	32	210	48	309	64	453	80	665	96	976

Resistor Schematic Symbols

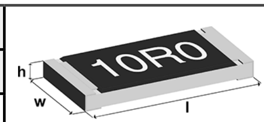
Type	Abbreviation	IEC (International)	ANSI (US)
Fixed resistor	R		
Heater resistor			
Variable resistors			
Potentiometer			
Trimming potentiometer			
Rheostat			
Preset resistor			
Dependent resistors			
Photo, or Light-dependent, resistor	LDR		

Type	Abbreviation	IEC (International)	ANSI (US)
Varistor, Voltage-dependent resistor, or Metal oxide varistor	VDR RV MOV		
NTC thermistor	NTC RT		
PTC thermistor	PTC RT		
Magneto, or Magnetic-dependent, resistor	MDR		

Resistor Sizes and Symbols

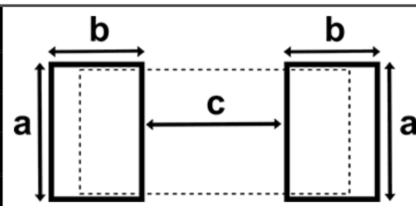
SMD Resistor

Code		Length (l)		Width (w)		Height (h)		Power
Imperial	Metric	inch	mm	inch	mm	inch	mm	W
01005	0402	0.016	0.4	0.08	0.2	0.005	0.13	1/32 (0.03)
0201	0603	0.024	0.6	0.012	0.3	0.010	0.25	1/20 (0.05)
0402	1005	0.04	1.0	0.02	0.5	0.014	0.35	1/16 (0.06)
0603	1608	0.06	1.55	0.03	0.85	0.018	0.45	1/10 (0.10)
0805	2012	0.08	2.0	0.05	1.2	0.018	0.45	1/8 (0.125)
1206	3216	0.12	3.2	0.06	1.6	0.022	0.55	1/4 (0.25)
1210	3225	0.12	3.2	0.10	2.5	0.022	0.55	1/2 (0.50)
1812	3246	0.12	3.2	0.18	4.6	0.022	0.55	1
2010	5025	0.20	5.0	0.10	2.5	0.024	0.6	3/4 (0.75)
2512	6332	0.25	6.3	0.12	3.2	0.024	0.6	1



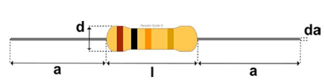
Solder Path and Land Pattern

Code		Pad length (a)		Pad width (b)		Pad gap (c)	
Imperial	Metric	inch	mm	inch	mm	inch	mm
0201	0603	0.012	0.3	0.012	0.3	0.012	0.3
0402	1005	0.024	0.6	0.020	0.5	0.020	0.5
0603	1608	0.035	0.9	0.024	0.6	0.035	0.9
0805	2012	0.051	1.3	0.028	0.7	0.047	1.2
1206	3216	0.063	1.6	0.035	0.9	0.079	2.0
1812	3246	0.19	4.8	0.035	0.9	0.079	2.0
2010	5025	0.11	2.8	0.059	0.9	0.15	3.8
2512	6332	0.14	3.5	0.063	1.6	0.15	3.8



Axial Resistor

Power rating	Body length (l)	Body dia (d)	Lead length (a)	Lead dia (da)
W	mm	mm	mm	mm
1/8 (0.125)	3.0 ± 0.3	1.8 ± 0.3	28 ± 3	0.45 ± 0.05
1/4 (0.25)	6.5 ± 0.5	2.5 ± 0.3	28 ± 3	0.6 ± 0.05
1/2 (0.5)	8.5 ± 0.5	3.2 ± 0.3	28 ± 3	0.6 ± 0.05
1	11 ± 1	5 ± 0.5	28 ± 3	0.8 ± 0.05



MELF Resistor

Name	Abbr.	Code	Length	Diameter	Power
			mm	mm	(W)
MicroMELF	MMU	0102	2.2	1.1	0.2 - 0.3
MiniMELF	MMA	0204	3.6	1.4	0.25 - 0.4
MELF	MMB	0207	5.8	2.2	0.4 - 1.0

Preferred Resistor Values

E6 series resistor values (tolerance of ±20%)											
10		15		22		33		47		68	
E12 series resistor values (tolerance of ±10%)											
10	12	15	18	22	27	33	39	47	56	68	82
E24 series resistor values (tolerance of ±5% and ±1%)											
10	11	12	13	15	16	18	20	22	24	27	30
33	36	39	43	47	51	56	62	68	75	82	91
E48 series resistor values (tolerance of ±2%)											
100	105	110	115	121	127	133	140	147	154	162	169
178	187	196	205	215	226	237	249	261	274	287	301
316	332	348	365	383	402	422	442	464	487	511	536
562	590	619	649	681	715	750	787	825	866	909	953
E96 series resistor values (tolerance of ±1%)											
100	102	105	107	110	113	115	118	121	124	127	130
133	137	140	143	147	150	154	158	162	165	169	174
178	182	187	191	196	200	205	210	215	221	226	232
237	243	249	255	261	267	274	280	287	294	301	309
316	324	332	340	348	357	365	374	383	392	402	412
422	432	442	453	464	475	487	499	511	523	536	549
562	576	590	604	619	634	649	665	681	698	715	732
750	768	787	806	825	845	866	887	909	931	953	976
E192 series resistor values (tolerance of ±0.5%, ±0.25%, and ±0.1%)											
100	101	102	104	105	106	107	109	110	111	113	114
115	117	118	120	121	123	124	126	127	129	130	132
133	135	137	138	140	142	143	145	147	149	150	152
154	156	158	160	162	164	165	167	169	172	174	176
178	180	182	184	187	189	191	193	196	198	200	203
205	208	210	213	215	218	221	223	226	229	232	234
237	240	243	246	249	252	255	258	261	264	267	271
274	277	280	284	287	291	294	298	301	305	309	312
316	320	324	328	332	336	340	344	348	352	357	361
365	370	374	379	383	388	392	397	402	407	412	417
422	427	432	437	442	448	453	459	464	470	475	481
487	493	499	505	511	517	523	530	536	542	549	556
562	569	576	583	590	597	604	612	619	626	634	642
649	657	665	673	681	690	698	706	715	723	732	741
750	759	768	777	787	796	806	816	825	835	845	856
866	876	887	898	909	920	931	942	953	965	976	988

Resistive Properties of Materials

Material	ρ (Ω-m) at 20°C	σ (S/m) at 20°C	Temperature Coefficient (1/°C) x 10^{-3}
Silver	1.59 $\times10^{-8}$	6.30 $\times10^{7}$	3.8
Copper	1.68 $\times10^{-8}$	5.96 $\times10^{7}$	3.9
Gold	2.44 $\times10^{-8}$	4.10 $\times10^{7}$	3.4
Aluminum	2.82 $\times10^{-8}$	3.50 $\times10^{7}$	3.9
Tungsten	5.60 $\times10^{-8}$	1.79 $\times10^{7}$	4.5
Zinc	5.90 $\times10^{-8}$	1.69 $\times10^{7}$	3.7
Nickel	6.99 $\times10^{-8}$	1.43 $\times10^{7}$	6
Lithium	9.28 $\times10^{-8}$	1.08 $\times10^{7}$	6
Iron	1.00 $\times10^{-7}$	1.00 $\times10^{7}$	5
Platinum	1.06 $\times10^{-7}$	9.43 $\times10^{6}$	3.9
Tin	1.09 $\times10^{-7}$	9.17 $\times10^{6}$	4.5
Lead	2.20 $\times10^{-7}$	4.55 $\times10^{6}$	3.9
Manganin	4.82 $\times10^{-7}$	2.07 $\times10^{6}$	0.002
Constantan	4.90 $\times10^{-7}$	2.04 $\times10^{6}$	0.008
Mercury	9.80 $\times10^{-7}$	1.02 $\times10^{6}$	0.9

AUTHORS

The authors of the Resistor Guide were **M.Sc. J.W. Pustjens** and **M.Sc. P.F. Van Oorschot.** Confronted with the problem that there was little unbiased, quality information available in one reference, either on the Internet or in book form, over seveal years they consolidated the most important educational topics. Van Oorschot had previously worked in research on the feasibility of electric vehicles. Pustejns had previously worked in the specification of packaging machinery.

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2nd EDITION OF THE GUIDE

THE

RESISTOR GUIDE

The complete guide to the world of resistors

P.F. VAN OORSCHOT & J.W. PUSTJENS

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