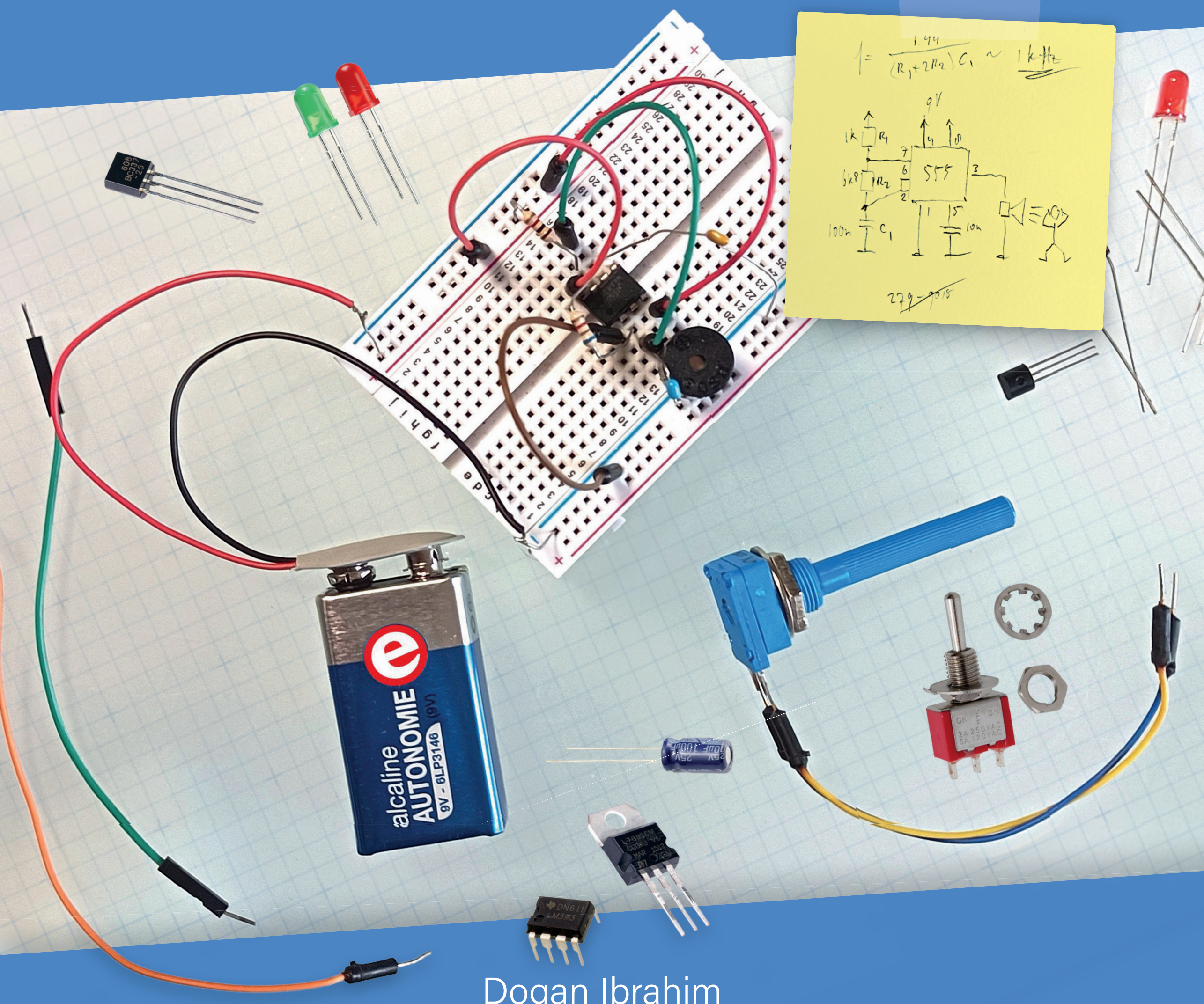
Practical Electronics Crash Course

Learning circuit design the fun way



Dogan Ibrahim
Ahmet Ibrahim

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Learning circuit design the fun way

Dr. Dogan Ibrahim
Ahmet Ibrahim

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Contents

Preface

Welcome to the world of electronics!
In this beginner-friendly book, you will explore and learn the most important electrical engineering and electronics concepts in a fun way by doing various experiments and by simulating circuits. The aim of the book is to teach you the basic electronics without getting into complex technical jargon and calculations.

Learning electronics is not as difficult as it may seem. Using this book, you will be creating your own projects sooner than you might think. The book starts from the very basics, such as what is electricity? What is voltage? What is current? and so on. You will then learn about simple electronic circuits and the symbols used in circuits. No previous knowledge of electronics is required, only some simple algebra is required to be able to make simple calculations. Circuit simulation has been introduced at an early stage to enable readers to experiment with different circuits.

You will learn:

- The concepts of voltage, current, circuit, and power
- AC and DC voltages
- Basic lamp circuits with switches
- Resistors, capacitors, inductors and how to identify them
- Transient circuits
- Electromagnetism
- Loudspeakers, reed switches, and transformers
- Diodes, BJT and MOSFET transistors and switching circuits
- Optocoupler circuits
- Multivibrator and astable/monostable circuits
- Using the 555 chip
- Operational amplifiers and various circuit configurations
- Logic gates
- Amplifiers, oscillators, and electrical filters
- Sensors
- Electrical test and measurement tools
- Microcontroller development boards: Arduino Uno, ESP32, Raspberry Pi Pico, and Raspberry Pi 5
- Electronic component selection and reading data sheets
- Electrical EMC and EMI and norms and regulations

Many tested and working projects and simulations are given in the book to make you familiar with the construction and testing of the basic electronic circuits given in the book.
I hope you enjoy reading the book.

Dr. Dogan Ibrahim, BSc., MSc., PhD
Ahmet Ibrahim, BSc., MSc
London, 2024

Chapter 1 • Electricity

1.1 Overview

We all use electricity in our daily lives, and we cannot do without it. Can you imagine what will happen if electricity was not available for a few days? Imagine life with no heating, no lighting, no radio, no TV, no internet, no computer, no microwave, no fridge… But have you ever asked yourself: What is electricity? What is voltage? What is an electrical circuit? How can I connect lamps in different ways? The aim of this chapter is to answer these questions in detail.

1.2 What is Electricity?

Atoms are the building blocks of matter; they are the smallest units of matter that have the chemical properties of a given substance. Atoms comprise three basic components: protons, neutrons, and electrons (Figure 1.1). The protons and neutrons are in the center of the atom, known as the nucleus, while the electrons orbit at a considerable distance from the nucleus.

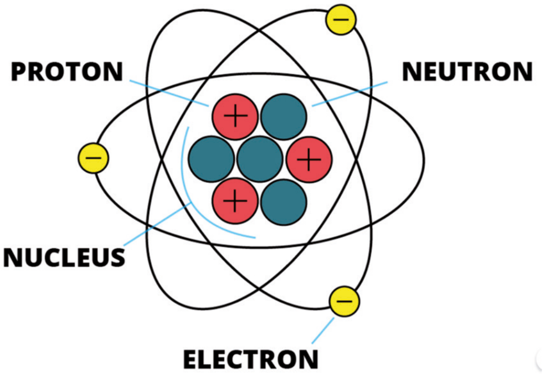


Figure 1.1 An atom. (source: www.vedantu.com)

The atomic number of an atom corresponds to the number of protons in the nucleus. For example, a carbon atom has six protons in its nucleus, therefore its atomic number is six. The sum of the number of protons and neutrons determine the atomic mass of an atom.

Protons are positively charged particles inside the nucleus. The neutrons inside the nucleus do not have charge. The mass of a neutron is more than that of a proton. Electrons are negatively charged particles that orbit the nucleus within orbital shells. They are much smaller than protons and neutrons. The overall charge of an atom is determined by the difference between the number of protons and electrons. For example, if there are more protons than electrons, the net charge is positive. If the number of protons is equal to the number of electrons, the net charge is zero.

Electricity is the set of physical phenomena associated with the presence and motion of electric charge. Electrons can flow only if there are free electrons in a substance. Concerning the flow of electrons, materials fall into three categories:

Insulators: Some materials like wood, paper, plastic, rubber, etc. do not conduct electricity and therefore are good insulators. This is due to the (very) low number of free electrons that are available.

Conductors: Many metals such as copper, iron, silver, steel, etc. are excellent conductors of electricity. This is because they have an abundance of free electrons.

Semiconductors: Materials like germanium, arsenic, boron, and silicon have only a few free electrons. They conduct electricity better than insulators but not as good as conductors do. Semiconductors are used for manufacturing transistors and integrated circuits (ICs).

1.3 Electronic Circuits

For electrons to flow, an electronic (or electrical) circuit is required. A circuit is a closed loop of conducting material such as wire. Of course, every electronic circuit also contains components, but there may not be insulators in the circuit loop. The electrons in an electronic circuit do not move unless they are forced to do so. This force can be a battery or any other type of energy source connected to the circuit. The movement of electrons in a circuit constitutes the current in the circuit. Thus, when a voltage source is applied to a circuit, current can flow through it. The electrons flow from the negative pole towards the positive pole. But, because electrons have a negative charge, it is customary to say that the current flows from plus to minus.

The unit of voltage is volt, denoted by V (sometimes also denoted by U). The unit of current is ampere, A. In most electronic applications, smaller units of volt and ampere may be used. The conversions to smaller units are as follows:

1 V = 1,000 millivolt (1000 mV)
1 mV = 1,000 microvolt (1000 μV)

Similarly,

1 A = 1,000 milliampere (1000 mA)
1 mA = 1,000 microampere (1000 μA)

1.4 DC and AC

There are two types of voltage sources: Direct Current or DC and Alternating Current or AC.

DC

In a DC circuit, the current always flows in the same direction. A DC voltage source does not necessarily have a constant value, but it never changes sign. An example of a DC voltage source is an ideal battery, which provides a constant voltage over time. For example, an ideal PP-3 type battery provides 9 V as shown in Figure 1.2. This is described mathematically as:

$$V_{(t)} = 9 \text{ V}$$

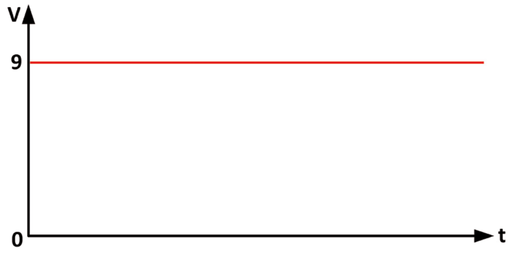


Figure 1.2 9V battery voltage.

Of course, a battery loses its charge over time and its voltage drops as the battery is used, but for the discussion here, we assume that the voltage is constant.

AC

In an AC circuit, the direction of the charge flow and hence the voltage level reverses periodically. Electricity providers supply AC voltages known as the mains voltage to buildings all over the country. However, most electronic devices like mobile phones, computers, radios, TVs, etc. operate with DC voltages and the AC voltage must be converted into DC. As an example, your mobile phone has a battery and operates from a DC voltage, but you plug its charger into an AC wall socket. The charger converts the AC to DC to charge your phone's battery.

AC voltages can have many shapes like sine, square, triangle, sawtooth, etc. The AC voltage supplied by electricity providers is in the form of a sine wave (Figure 1.3), expressed mathematically as:

$$V_{(t)} = V_p \sin(\omega t)$$

where

$V_{(t)}$ is the voltage as a function of time.
V_p is the amplitude (peak value) of the waveform. The waveform spans from $-Vp$ to $+Vp$.
ω is the radian frequency equal to $2\pi f$, where f is the frequency of the waveform in hertz.
t is the time in seconds.

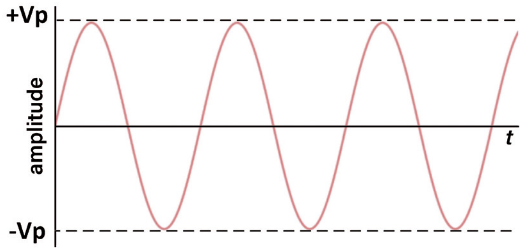


Figure 1.3 Sine waveform.

The period of a sine wave is the time it takes for a cycle to complete and is related to the frequency by the relationship

$$T = 1/f$$

Example
Find the period and hence the frequency of the sine wave shown in Figure 1.4. Write down the mathematical expression of the waveform.

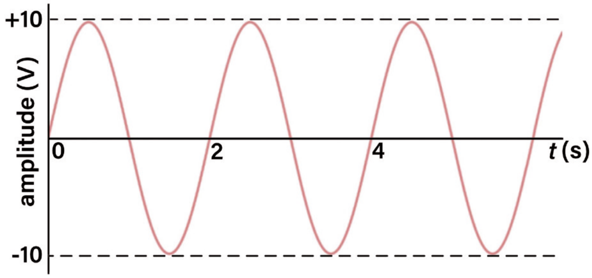


Figure 1.4 Example sine wave.

Solution
The amplitude is 10 V. The period of the waveform is found to be T = 2 seconds. Therefore, the frequency is $f = 1/2 = 0.5$ Hz. The radian frequency is, $\omega = 2\pi f = 2 \times 3.14 \times 0.5 = 3.14$ rad/s. The mathematical expression of the waveform therefore is:

$$V_{(t)} = 10 \sin(3.14t)$$

1.5 Electric Power

Electric power is the rate at which electrical energy is transferred by an electric circuit. In other words, it is the rate of work done per unit of time by an electric circuit. The unit of electric power (P) is watt (W), given by:

$$P = \text{current} \times \text{voltage}$$

Where power is in watt, current is in ampere, and voltage is in volt. Power is sometimes expressed in bigger or smaller units, as follows:

1 kW = 1,000 watt (1000 W)
1 W = 1,000 milliwatt (1000 mW)
1 mW = 1,000 microwatt (1000 µW)

Power can also be calculated from the energy in joule over a period of time. i.e.

P in W = energy/second = joule/second

Example

A mains operated kettle works with 230 V and consumes 2 A. Find the power consumed by this kettle. If the kettle is operated for 10 seconds, how much electrical energy is used?

Solution

From the above equation, $P = 230 \times 2 = 460$ W.
The energy used is $E = P \times t = 460 \times 10 = 4{,}600$ joules.

1.6 Basic Lamp/Switch Circuits

Suppose you have some lamps and a few switches. Let us investigate in how many ways you can connect them in a circuit. In the following circuits, V_{Ln} is the voltage across lamp *n*, and ILn is the current through lamp *n*. Also, it is assumed that the brightness of the lamps is the same as long as current passes through them.

1.6.1 One Switch Only

Series connection of lamps

Figure 1.5 shows a series connection of three lamps and a switch. Here, the same current goes through each lamp. The sum of the voltages across each lamp is equal to the applied voltage. When the switch is closed, all lamps turn on.

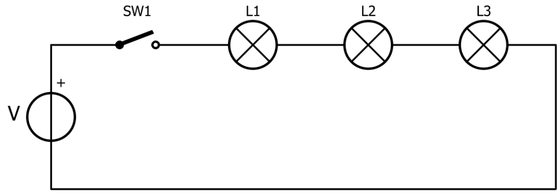


Figure 1.5 Series connection. The same current flows through all the lamps. When the switch is closed, all lamps turn on. $V = V_{L1} + V_{L2} + V_{L3}$

Parallel connection of lamps

Figure 1.6 shows a parallel connection of three lamps and a switch. Here, the same voltage is across each lamp. The sum of the currents through the lamps is equal to the main current. When the switch is closed, all lamps turn on.

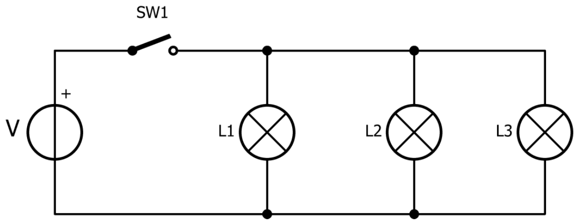


Figure 1.6 Parallel connection. Each lamp has the same voltage across it. When the switch is closed, all lamps turn on. $I = I_{L1} + I_{L2} + I_{L3}$

Series and parallel connection of lamps

Figure 1.7 shows a mixed series and parallel connection of three lamps and a switch. Here, the same voltage is across L2 and L3. The sum of voltages across L1 and L2 (or L3) is equal to the applied voltage. The current through L1 is equal to the sum of the currents through L2 and L3.

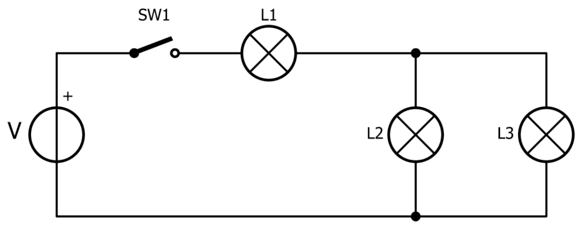


Figure 1.7 Series and parallel connection.
Lamps L2 and L3 have the same voltage across them.
When the switch is closed, all lamps turn on. $V = V_{L1} + V_{L2}$ *or* $V = V_{L1} + V_{L3}$; $I_{L1} = I_{L2} + I_{L3}$

1.6.2 More Than One Switch

Figures 1.8 to 1.10 show various configurations of lamps and switches. The operation of each circuit is described below the circuits.

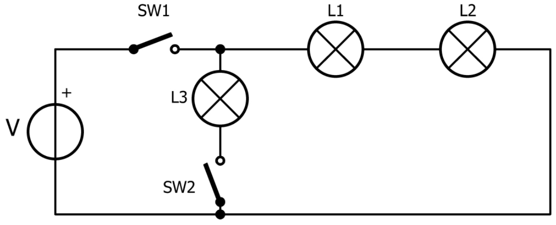


Figure 1.8 L1 and L2 turn on when SW1 is closed. L3 turns on when SW2 is closed.

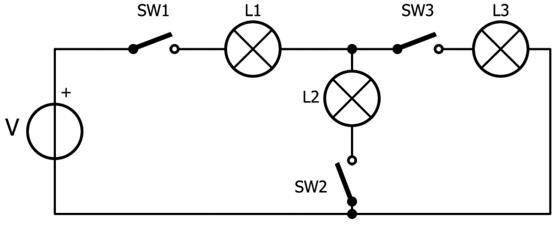


Figure 1.9 L1 turns on when SW1 is closed and also SW2 or SW3 are closed.
L2 turns on when SW1 and SW2 are closed (L1 turns on too).
L3 turns on when SW1 and SW3 are closed (L1 turns on too).
All lamps turn on when all switches are closed.

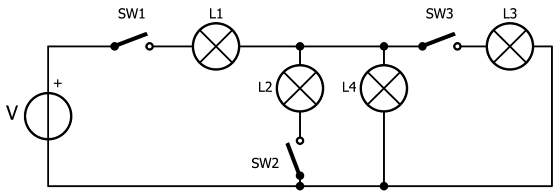


Figure 1.10 L1 and L4 turn on when SW1 is closed. L2 turns on when SW1 and SW2 are closed (L1 and L4 turn on too). L3 turns on when SW1 and SW3 are closed (L1 and L4 turn on too). All lamps turn on when all switches are closed.

1.6.3 Two-Way Switch

You are probably familiar with two-way switches if your home has a staircase or a long hallway. They are also often found in bedrooms. In a two-way switch configuration, a lamp is controlled by two switches, for example one downstairs and one upstairs. If the lamp is off, it can be turned on from the downstairs switch. Once you are upstairs, you can turn it off from the upstairs switch and vice versa. Figure 1.11 shows the schematic of a two-way switch. This circuit uses two switches of type SPDT (Single Pole Double Throw). The operation of various switches is discussed in Chapter 5.

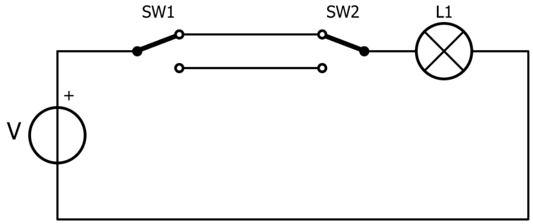


Figure 1.11 Two-way switch. When the lamp is on, you can turn it off with either SW1 or SW2. When the lamp is off, you can turn it on with either SW1 or SW2.

Chapter 2 • Passive Components

2.1 Overview

Passive components are parts like resistors, capacitors, inductors, cables, switches, fans, lamps, antennas, terminals and connectors, coils, transformers, printed circuit boards (PCBs) and so on. These components cannot generate power, but they receive electrical energy, which they can either absorb, dissipate, or store. Passive components do not provide any gain or amplification of electrical signals. They can either be used on their own or connected in series or in parallel with other components in electrical circuits to control the current flow, apply a phase shift to signals, change the voltage across a component and so on. Passive components are bidirectional (they do not have polarity) as they can be connected in either direction within a circuit (except for electrolytic capacitors as they have polarity).

In this chapter, we will be looking at the most commonly used passive components: resistors, capacitors, and inductors, and their combinations in electrical circuits.

2.2 Resistors

Resistors play a crucial role in electrical circuits by impeding the flow of electric current. To comprehend the function of a resistor more easily, one can draw an analogy between electric current and water flowing in a pipe. In this analogy, a resistor is akin to a constriction in the pipe, acting to limit the flow of water through it. The degree of restriction in the pipe correlates with the resistance in the electrical circuit. Simply put, the higher the resistance, the more constrained the flow of electric current becomes. Similarly, in the water analogy, an increased constriction in the pipe results in a reduced volume of water able to pass through.

Resistors have many functions in electrical circuits. Some common uses of resistors are:

- **Potential dividers:** two or more resistors in series are used to reduce an input voltage to a required level.

- **Current limiting:** a resistor is used to limit the current flow in an electrical circuit, usually to protect a device. For example, a current limiting resistor is used in LED circuits to limit the current and hence protect both the current source and the LED.

- **Operational amplifiers:** Here, resistors are used to set the amplifier gain.

- **Active filters:** Resistors are used in active filter circuits to set the filter gain, frequency, and phase responses.

- **Current measurement:** Resistors are used to measure the currents through circuits.

- **In active circuits:** Resistors are used in various active circuits, such as amplifiers, mixers, oscillators, comparators, buffers, transmitters, receivers, etc. to set the circuit characteristics.

Resistor values

Resistor values are in ohms, denoted with the Greek capital letter omega (Ω). For example, 100 ohms or 100 Ω. Larger values are available as kilohms, denoted as kΩ, or megohms, denotes as MΩ. 1 kΩ is equal to 1,000 Ω and 1 MΩ is equal to 1,000,000 Ω. Therefore, 1 MΩ is equal to 1,000 kΩ.

Resistor values have a tolerance, specified as a percentage. For example, the value of a 100 Ω resistor with a 10% tolerance may lie in the range from 90 Ω up to 110 Ω. Common tolerances are 10%, 5% and 1%.

Because it is complicated to produce and stock resistors of every value possible, they have been organised into series of preferred values known as the E-series. The E-series are based on tolerances. The number following the 'E' indicates the number of different values in a series. The E12 series, the most used, is based on 10% tolerance and has 12 values per decade:

1.0, 1.2, 1.5, 1.8, 2.2, 2.7, 3.3, 3.9, 4.7, 5.6, 6.8 and 8.2.

For example, within the E12 series, we can find resistors with the following values in the 1.8 range:

1.8 Ω, 18 Ω, 180 Ω, 1.8 kΩ, 18 kΩ, 180 kΩ, 1.8 MΩ and so on.

The E24 series is based on 5% tolerance and has 24 values per decade:

1.0, 1.1, 1.2, 1.3, 1.5, 1.6, 1.8, 2.0, 2.2, 2.4, 2.7, 3.0, 3.3, 3.6, 3.9, 4.3, 4.7, 5.1, 5.6, 6.2, 6.8, 7.5, 8.2 and 9.1.

Resistors with 1% tolerance are available in the E96 series. Resistors from the E192 series have 0.5% tolerance, but they are more expensive. For completeness' sake, there also exist E3, E6 and E48 series.

If, for example, we need a 185 Ω resistor, the nearest value from the E12 and E24 series would be 180 Ω. Note that for historical reasons, circuits often use resistors with values from the E12 series only, but with a 5% tolerance.

2.2.1 Types of Resistors

Resistors are available in various shapes and configurations.

Fixed-value resistors

As the name suggests, these resistors have fixed resistance values (Figure 2.1 left). A fixed-value resistor is a two-terminal device. They can have different shapes such as rectangular, cylindrical, chassis mounted, resistor arrays, surface mounted, etc. Fixed value resistors are shown in two different ways in electrical circuits: Either as a zigzag line (US style, Figure 2.1 middle) or as a rectangle (European style, Figure 2.1, right). In a schematic, the value of a resistor is written near or inside the symbol in shorthand using multipliers like ‘k’ and ‘M’. The Ω symbol is usually omitted. Values below 1 kΩ are commonly written with the Ω symbol replaced by ‘R’ (ex. 470R). Values with a decimal like 2.2 kΩ or 5.6 MΩ may be written as 2k2 or 5M6. A value of 3.9 Ω may be written as 3R9. When only references such as R1, R2, R3, etc. are shown, the values are listed in a table (the component list) or in the text, for example R1 = 10 kΩ

Figure 2.1 A fixed-value resistor (left), its US-style symbol (middle) and the European-style symbol on the right.

Variable Resistors

Also known as potentiometers (‘pots’) and trimmers, the value of a variable or adjustable resistor is adjusted either by turning a shaft or a screw (Figure 2.2 left) or by sliding a knob. A variable resistor is a three-terminal device. The centre pin, shown with an arrow in electrical circuits (Figure 2.2, right), is known as the wiper and is where the variable resistance is available.

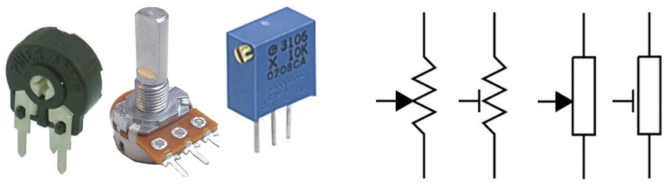


Figure 2.2 Variable resistors and their symbols. When the wiper is drawn as an arrow, it is a potentiometer. Otherwise, it is an adjustable resistor or trimmer.

Resistor Networks

Resistor networks can be used to save space when multiple resistors of the same value are needed. For such applications, it is possible to purchase resistor networks either as single inline (SIL, Figure 2.3 left) or dual inline (DIL, Figure 2.3 right) packages. They can come as multiple individual resistors, or with one pin of each resistor connected to a common contact.

Figure 2.3 Resistor networks come in SIL (left) and DIL (right) packages.

2.2.2 Resistive Materials

Different materials are used in resistor manufacturing. Some commonly used materials, their advantages and disadvantages, are summarized in this section.

Carbon Composition Resistors

Carbon composition resistors are formed by mixing carbon granules with some kind of binding material, shaped as a small cylindrical rod. This type of resistor suffers from temperature changes, change of resistance by ageing, and high noise. Carbon composition resistors, although available in older equipment, are no longer used.

Carbon Film Resistors

These resistors (Figure 2.4a) are used for general-purpose applications. They are constructed by depositing a carbon film onto a cylindrical ceramic substrate. More carbon results in lower resistance. The advantage of this construction is low inductance, making carbon film suitable for high-frequency applications. Also, the ceramic is an excellent heat insulator.

Metal Film Resistors

Metal film resistors (Figure 2.4b) are made by layering certain metals onto an insulating substrate. Their construction is easier than carbon film resistors, and they can be manufactured in large quantities using less effort. The advantages of metal film resistors are lower noise, much tighter tolerances, and better temperature coefficients, meaning that their value doesn't change much when their temperature changes. They are slowly replacing the carbon film types.

Wire-Wound Resistors

Wire-wound resistors (Figure 2.4c) are made by winding a wire on a substrate. They are used in applications requiring very tight tolerances (less than 0.01%) and low-temperature coefficients. Wire-wound resistors are also used in high-power applications. However, due to the wound wire, this kind of resistors has high inductance and is therefore unsuitable for high-frequency applications.

Metal Strip Resistors

These resistors (Figure 2.4d) are used mainly in power supplies for measuring current. They have very low ohmic values and very low-temperature coefficients. Metal strip resistors are constructed by laser trimming a strip of metal.

Metal Oxide Resistors

Metal oxide resistors (Figure 2.4e) are similar to metal film resistors with an oxide of tin as resistive material. They are generally more suitable for high-voltage and high-power applications than metal film resistors. Metal oxide resistors are also more reliable than the metal film types.

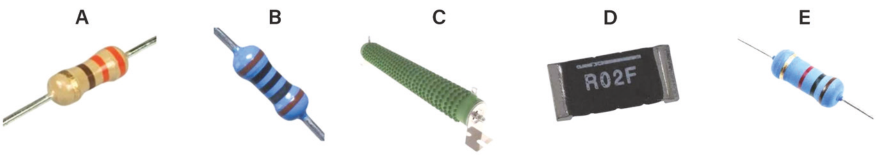


Figure 2.4 Different types of resistors. From left to right: carbon film, metal film, wire-wound, metal strip and metal oxide.

2.2.3 Resistor Specifications

It is important to know the key characteristics and specifications of resistors before they are used in electrical circuits. Some common specifications are given in this section.

Temperature Coefficient

This is a measure of the change of the resistance value due to temperature changes. The temperature can be either positive or negative. In applications where the ambient temperature is subject to large changes, resistors with low-temperature coefficients may be preferred.

Ageing

Ageing is the change of resistance value over time due to environmental stress like humidity, ambient temperature and so on. Typically, the resistance value increases over time.

Thermal Resistance

The thermal resistance is a measure of how well a resistor can dissipate heat. This parameter is important in for instance, high-power applications where the resistor is enclosed and is not in direct contact with free air.

Noise

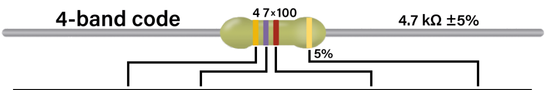
Like all other electronic components, resistors generate noise, and this may become important in low-voltage and precision applications. Most of the noise in resistors is caused by high temperature. The noise level can be reduced by lowering the resistance value, lowering the operating temperature, and by lowering the power applied to the resistor.

Power Rating

This is an essential parameter for every resistor used in a circuit. All resistors have power ratings. In general, the larger the size of a resistor, the more power it can handle. It is important to choose a resistor that can support the maximum power applied to it. The power dissipated by a resistor is determined by the current through it and its resistance (see below). Small resistors used in most electrical circuits are designed not to dissipate more than about 0.25 W or 0.125 W.

2.2.4 Resistor Colour Code

The value of a cylindrical (or through-hole) resistor is indicated by colour bands, see Figure 2.5. Each resistor has three or four bands specifying the value, plus a tolerance band. For a 4-band resistor, the first two bands correspond to numerical values, the third band is a multiplier, and the last band is the tolerance. For a 5-band resistor, the first three bands are numerical values, the fourth band is the multiplier and the last band is the tolerance. Notice that there is a small gap between the tolerance band and other bands.



Colour	Band 1	Band 2	Band 3	Multiplier	Tolerance
None	–	–	–	–	±20
Pink	–	–	–	0.001	–
Silver	–	–	–	0.01	±10
Gold	–	–	–	0.1	±5
Black	0	0	0	1	–
Brown	1	1	1	10	±1
Red	2	2	2	100	±2
Orange	3	3	3	1,000	±0.05
Yellow	4	4	4	10,000	±0.02
Green	5	5	5	100,000	±0.5
Blue	6	6	6	1,000,000	±0.25
Violet	7	7	7	–	±0.1
Gray	8	8	8	–	±0.01
White	9	9	9	–	–

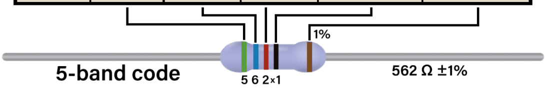


Figure 2.5 Resistor colour codes. Resistors with six bands exist too. The first five bands form a 5-band code, the 6th band indicates the temperature coefficient.

Example 1
A 4-band resistor has the colours red, red, orange, brown. Calculate its value and tolerance. From Figure 2.5 we have:

Red: 2
Red: 2
Orange: 1,000
Brown: 1%

The value is: 22 × 1,000 = 22,000 Ω or 22 kΩ with ±1% tolerance

This value can also be read from right to left, i.e. brown, orange, red, red, which corresponds to 1,300 Ω with ±2% tolerance. The reading direction is indicated by the tolerance band, which is either wider or placed apart from the other bands. In case of doubt, use an ohmmeter.

Example 2
A 4-band resistor has the colours yellow, violet, yellow, gold. Calculate its value and tolerance.

From Figure 2.5 we have:

Yellow: 4
Violet: 7
Yellow: 10,000
Gold: 5%

The value is: 47 × 10,000 = 470,000 Ω or 470 kΩ with ±5% tolerance

Example 3
A 5-band resistor has the colours: brown, black, black, brown, brown. Calculate its value and tolerance.
From Figure 2.5 we have:

Brown: 1
Black: 0
Black: 0
Brown: 10
Brown: 1%

The value is: 100 × 10 = 1,000 Ω or 1 kΩ with ±1% tolerance

This value can also be read from right to left, i.e. brown, brown, black, black, brown, which corresponds to 110 Ω with ±1% tolerance. The reading direction is indicated by the tolerance band, which is either wider or placed apart from the other bands. In case of doubt, use an ohmmeter.

Because of their small sizes, on surface-mount technology (SMT) resistors the value in ohms is printed on them as a 3- or 4-digit number. In a 3-digit representation, the first two digits are the numeric values, and the last digit is the number of zeroes. For example, 102 (Figure 2.6, left) represents ’10 00’ which is 1,000 Ω or 1 kΩ. Similarly, 103 represents ’10 000’ which is 10,000 Ω or 10 kΩ.

For low values, the letter ‘R’ is used as a decimal point. For example, 4R7 means 4.7 Ω (Figure 2.6, right).

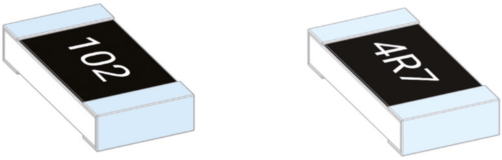


Figure 2.6 1 kΩ and 4.7 Ω surface mount resistors.

For very small-sized resistors the EIA96 system is used, which involves a lookup table where a 3-digit value is used.

2.2.5 Ohm's Law

Ohm's law is one of the fundamental laws in electronics. This law states that the voltage drop (V, in volts) across a resistor is equal to the product of the current (I, in amperes) through the resistor and its value (R, in ohms). Expressed as an equation:

$$V = I \times R \quad \text{or} \quad I = V/R \quad \text{or} \quad R = V/I$$

In many electronic circuits, the currents are measured in milliamperes (mA), which is one thousandth of an ampere. As an example, consider a circuit where the voltage across a resistor is 5 V and the current through this resistor is measured to be 100 mA. The value of the resistor can be calculated as:

$$R = V/I = 5/0.10 = 50\ \Omega$$

2.2.6 Resistors in Series and Parallel

Resistors can be connected in series, parallel, or in a combination of series and parallel. By connecting resistors together, we can obtain larger or smaller values. Also, various special passive electrical circuits can be designed by combining resistors.

Series Connection

Figure 2.7 top shows four resistors connected in series. In a series connection, the total resistance is equal to the sum of the individual values. Hence, in this circuit the total resistance R_T is given by:

$$R_T = R1 + R2 + R3 + R4$$

In a series resistor circuit, the same current flows through all the resistors and the sum of the voltage drops across each resistor is equal to the applied voltage to the circuit.

Example

Three resistors with the values 100 Ω, 150 Ω and 200 Ω are connected in series. Calculate the total resistance.

Solution

The total resistance is given by: $R_T = 100 + 150 + 200 = 450\ \Omega$

Parallel Connection

Figure 2.7 bottom shows four resistors connected in parallel. When resistors are connected in parallel, the *inverse* of the total resistance is equal to the sum of the *inverse values* of the individual resistances. Hence, in this circuit the total resistance R_T is given by:

$$1/R_T = 1/R1 + 1/R2 + 1/R3 + 1/R4$$

In a parallel resistor circuit, the same voltage is across each resistor and the sum of the currents in each branch is equal to the total current in the circuit.