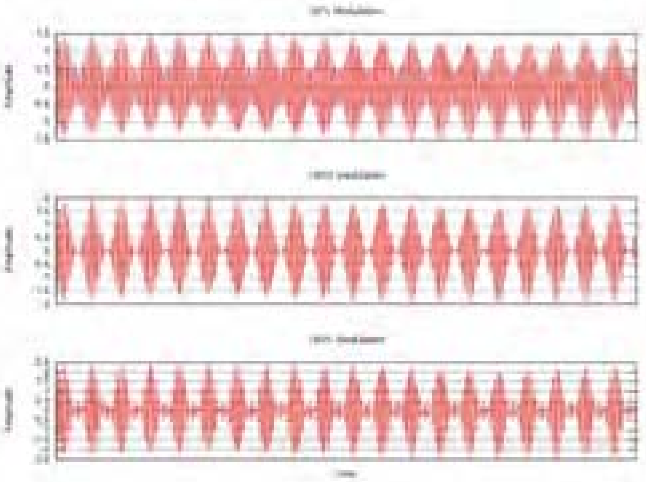
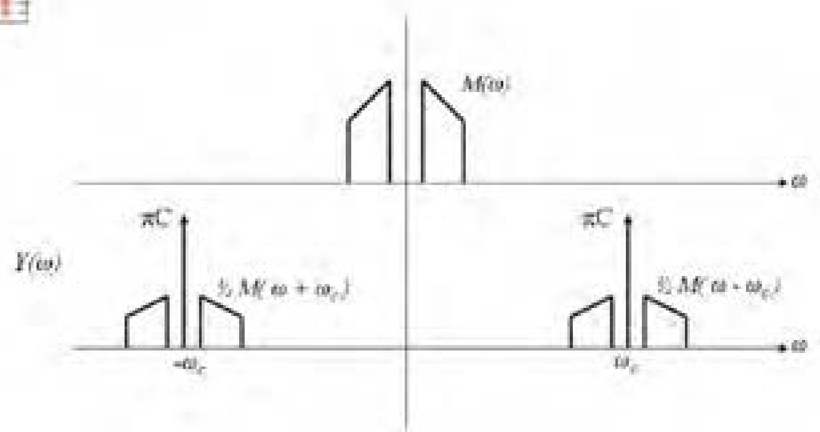
Basic Electronics

Charles Taylor





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Electronics

The field of **electronics** comprises the study and use of systems that operate by controlling the flow of electrons (or other charge carriers) in devices such as thermionic valves and semiconductors. The design and construction of electronic circuits to solve practical problems is an integral technique in the field of electronics engineering and is equally important in hardware design for computer engineering. All applications of electronics involve the transmission of either information or power. Most deal only with information.

The study of new semiconductor devices and surrounding technology is sometimes considered a branch of physics. This article focuses on engineering aspects of electronics.

Overview of electronic systems and circuits

Commercial digital voltmeter checking a prototype

Electronic systems are used to perform a wide variety of tasks. The main uses of electronic circuits are:

1. the controlling and processing of information

2. the conversion to/from and distribution of electric power

Both these applications involve the creation and/or detection of electromagnetic fields and electric currents. While electrical energy had been used for some time prior to the late 19th century to transmit data over telegraph and telephone lines, development in electronics grew exponentially after the advent of radio.

One way of looking at an electronic system is to divide it into 3 parts:

- Inputs – Electronic or mechanical sensors (or transducers). These devices take signals/information from external sources in the physical world (such as antennas or technology networks) and convert those signals/information into current/voltage or digital (high/low) signals within the system.

- Signal processors – These circuits serve to manipulate, interpret and transform inputted signals in order to make them useful for a desired application. Recently, complex signal processing has been accomplished with the use of Digital Signal Processors.

- Outputs – Actuators or other devices (such as transducers) that transform current/voltage signals back into useful physical form (e.g., by accomplishing a physical task such as rotating an electric motor).

For example, a television set contains these 3 parts. The television's input transforms a broadcast signal (received by an antenna or fed in through a cable) into a current/voltage signal that can be used by the device. Signal processing circuits inside the television extract information from this signal that dictates brightness, colour and sound level. Output devices then convert this information back into physical form. A cathode ray tube transforms electronic signals into a visible image on the screen. Magnet-driven speakers convert signals into audible sound.

Electronic devices and components

An electronic component is any indivisible electronic building block packaged in a discrete form with two or more connecting leads or metallic pads. Components are intended to be connected together, usually by soldering to a printed circuit board, to create an electronic circuit with a particular function (for example an amplifier, radio receiver, or oscillator). Components may be packaged singly (resistor, capacitor, transistor, diode etc.) or in more or less complex groups as integrated circuits (operational amplifier, resistor array, logic gate etc). Active components are sometimes called *devices* rather than components.

Types of circuits

Analog circuits

analog circuits

Hitachi J100 adjustable frequency drive chassis.

Most analog electronic appliances, such as radio receivers, are constructed from combinations of a few types of basic circuits. Analog circuits use a continuous range of voltage as opposed to discrete levels as in digital circuits. The number of different analog circuits so far devised is huge, especially because a 'circuit' can be defined as anything from a single component, to systems containing thousands of components.

Analog circuits are sometimes called linear circuits although many non-linear effects are used in analog circuits such as mixers, modulators etc. Good examples of analog circuits include vacuum tube and transistor amplifiers, operational amplifiers and oscillators.

Some analog circuitry these days may use digital or even microprocessor techniques to improve upon the basic performance of the circuit. This type of circuit is usually called 'mixed signal'.

Sometimes it may be difficult to differentiate between analog and digital circuits as they have elements of both linear and non-linear operation. An example is the comparator which takes in a continuous range of voltage but puts out only one of two levels as in a digital circuit. Similarly, an overdriven transistor amplifier can take on the characteristics of a controlled switch having essentially two levels of output.

Digital circuits

Digital circuits are electric circuits based on a number of discrete voltage levels. Digital circuits are the most common physical representation of Boolean algebra and are the basis of all digital computers. To most engineers, the terms "digital circuit", "digital system" and "logic" are interchangeable in the context of digital circuits. In most cases the number of different states of a node is two, represented by two voltage levels labeled "Low" and "High". Often "Low" will be near zero volts and "High" will be at a higher level depending on the supply voltage in use.

Computers, electronic clocks, and programmable logic controllers (used to control industrial processes) are constructed of digital circuits. Digital Signal Processors are another example.

Building-blocks:

- logic gates
- Adders
- Binary Multipliers
- flip-flops
- counters
- registers
- multiplexers
- Schmitt triggers

Highly integrated devices:

- microprocessors
- microcontrollers
- Application specific integrated circuit(ASIC)
- Digital signal processor (DSP)
- Field Programmable Gate Array (FPGA)

Mixed-signal circuits

Mixed-signal circuits refers to integrated circuits (ICs) which have both analog circuits and digital circuits combined on a single semiconductor die or on the same circuit board. Mixed-signal circuits are becoming increasingly common. Mixed circuits contain both analog and digital components. Analog to digital converters and digital to analog converters are the primary examples. Other examples are transmission gates and buffers.

Heat dissipation and thermal management

Thermal management of electronic devices and systems

Heat generated by electronic circuitry must be dissipated to prevent immediate failure and improve long term reliability. Techniques for *heat dissipation* can include heatsinks and fans for air cooling, and other forms of computer cooling such as water cooling. These techniques use convection, conduction, & radiation of heat energy.

Noise

Noise is associated with all electronic circuits. Noise is generally defined as any unwanted signal that is not present at the input of a circuit. Noise is not the same as signal distortion caused by a circuit.

Electronics theory

Mathematical methods in electronics

Mathematical methods are integral to the study of electronics. To become proficient in electronics it is also necessary to become proficient in the mathematics of circuit analysis.

Circuit analysis is the study of methods of solving generally linear systems for unknown variables such as the voltage at a certain node or the current though a certain branch of a network. A common analytical tool for this is the SPICE circuit simulator.

Also important to electronics is the study and understanding of electromagnetic field theory.

Electronic test equipment

Electronic test equipment

Electronic test equipment is used to create stimulus signals and capture responses from electronic Devices Under Test (DUTs). In this way, the proper operation of the DUT can be proven or faults in the device can be traced and repaired.

Practical electronics engineering and assembly requires the use of many different kinds of electronic test equipment ranging from the very simple and inexpensive (such as a test light consisting of just a light bulb and a test lead) to extremely complex and sophisticated such as Automatic Test Equipment.

Computer aided design (CAD)

Electronic design automation

Today's electronics engineers have the ability to design circuits using premanufactured building blocks such as power supplies, resistors, capacitors, semiconductors (such as transistors), and integrated circuits. Electronic design automation software programs include schematic capture programs such as ORCAD or Eagle Layout Editor, used to make circuit diagrams and printed circuit board layouts.

Construction methods

Many different methods of connecting components have been used over the years. For instance, in the beginning point to point wiring using tag boards attached to chassis were used to connect various electrical innards. Cordwood construction and wire wraps were other methods used. Most modern day electronics now use printed circuit boards or highly integrated circuits.

Consumer electronics are electronic equipment intended for use by everyday people. Consumer electronics usually find applications in entertainment, communications and office productivity.

Some categories of consumer electronics include telephones, audio equipment, televisions, calculators, and playback and recording of video media such as DVD or VHS.

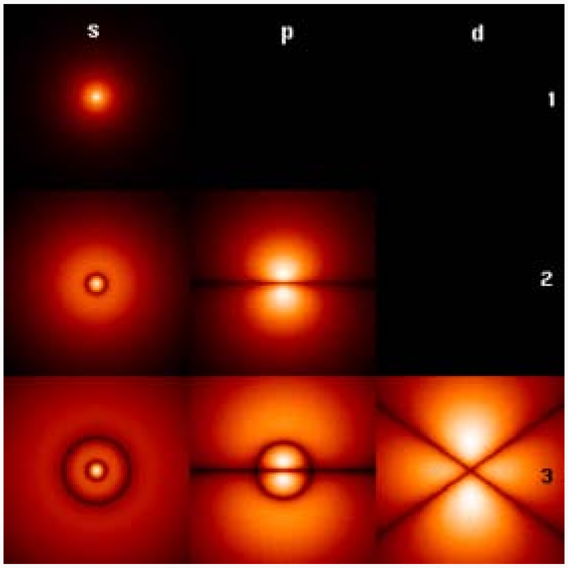
Consumer electronics are manufactured throughout the world, although there is a particularly high concentration of manufacturing activity in the Far East, in particular China.

One overriding characteristic of all consumer electronic products is the trend of ever-falling prices. This is driven by gains in manufacturing efficiency and automation, coupled with improvements in semiconductor design. Semiconductor components benefit from Moore's Law, an observed principle which states that, for a given price, semiconductor functionality doubles every 18 months.

Many consumer electronics have planned obsolescence, resulting in E-waste.

Electron

Electron



Theoretical estimates of the electron density for the first few hydrogen atom electron orbitals shown as cross-sections with color-coded probability density

Composition:	Elementary particle
Family:	Fermion
Group:	Lepton
Generation:	First
Interaction:	Gravity, Electromagnetic, Weak
Antiparticle:	Positron
Theorized:	G. Johnstone Stoney (1874)
Discovered:	J.J. Thomson (1897)
Mass:	$9.109\,3826(16) \times 10^{-31}$ kg $5.485\,799\,0945(24) \times 10^{-4}$ u $^{1}/_{1822.888\,4849(8)}$ u 0.510 998 918(44) MeV

Electric charge:	–1.602 176 53(14) × 10^{-19} C
Spin:	½

The **electron** is a fundamental subatomic particle that carries an electric charge. It is a spin-½ lepton that participates in electromagnetic interactions, and its mass is less than one thousandth of that of the smallest atom. Its electric charge is defined by convention to be negative, with a value of −1 in atomic units. Together with atomic nuclei, electrons make up atoms; their interaction with adjacent nuclei is the main cause of chemical bonding.

Overview

The word *electron* was coined in 1891 by George Johnstone Stoney and is derived from the term *electric force* introduced by William Gilbert. Its origin is in Greekήλεκτρον (elektron), meaning *amber*. J.J. Thomson is credited with having first measured the charge/mass ratio and is considered to be the discoverer of the electron.

Within an atom, electrons surround a nucleus composed of protons and neutrons in an electron configuration. The variations in electric field generated by differing numbers of electrons and their configurations in atoms determine the chemical properties of the elements. These fields play a fundamental role in chemical bonds and chemistry.

Electrons in motion produce an electric current and a magnetic field. Some types of electric currents are termed electricity.

Our understanding of how electrons behave has been significantly modified during the past century, the greatest advances being the development of quantum mechanics in the 20th century. This brought the idea of wave-particle duality, that is, that electrons show both wave-like and particle-like properties, to varying degrees. Equally important, particle physics has furthered our understanding of how the electron interacts with other particles.

Classification

The electron is one of a class of subatomic particles called leptons, which are believed to be fundamental particles (that is, they cannot be broken down into smaller constituent parts).

As with all particles, electrons can also act as waves. This is called the wave-particle duality, also known by the term *complementarity* coined by Niels Bohr and can be demonstrated using the double-slit experiment.

The antiparticle of an electron is the **positron**, which has the same mass but positive rather than negative charge. The discoverer of the positron, Carl D. Anderson, proposed calling standard electrons **negatrons**, and using *electron* as a generic term to describe both the positively and negatively charged variants. This usage never caught on and is rarely if ever encountered today.

Properties and behavior

Electrons have a negative electric charge of -1.6022×10^{-19} coulombs, a mass of 9.11×10^{-31} kg based on charge/mass measurements and a relativistic rest mass of about 0.511 MeV/c^2. The mass of the electron is approximately $^1/_{1836}$ of the mass of the proton. The common electron symbol is $\mathbf{e^-}$.

According to quantum mechanics, electrons can be represented by wavefunctions, from which a calculated probabilistic electron density can be determined. The orbital of each electron in an atom can be described by a wavefunction. Based on the Heisenberg uncertainty principle, the exact momentum and position of the actual electron cannot be simultaneously determined. This is a limitation which, in this instance, simply states that the more accurately we know a particle's position, the less accurately we can know its momentum, and vice versa.

The electron has spin ½ and is a fermion (it follows Fermi-Dirac statistics). In addition to its intrinsic angular momentum, an electron has an intrinsic magnetic moment along its spin axis.

Electrons in an atom are **bound** to that atom; electrons moving freely in vacuum, space or certain media are **free** electrons that can be focused into an electron beam. When free electrons move, there is a net flow of charge, this flow is called an electric current. The drift velocity of electrons in metal wires is on the order of mm/hour. However, the speed at which a current at one point in a wire causes a current in other parts of the wire is typically 75% of light speed.

In some superconductors, pairs of electrons move as Cooper pairs in which their motion is coupled to nearby matter via lattice vibrations called phonons. The distance of separation between Cooper pairs is roughly 100 nm. (Rohlf, J.W.)

A body has an electric charge when that body has more or fewer electrons than are required to balance the positive charge of the nuclei. When there is an excess of electrons, the object is said to be negatively charged. When there are fewer electrons than protons, the object is said to be positively charged. When the number of electrons and the number of protons are equal, their charges cancel each other and the object is said to be electrically neutral. A macroscopic body can develop an electric charge through rubbing, by the phenomenon of triboelectricity.

When electrons and positrons collide, they annihilate each other and produce pairs of high energy photons or other particles. On the other hand, high-energy photons may transform into an electron and a positron by a process called pair production, but only in the presence of a nearby charged particle, such as a nucleus.

The electron is currently described as a fundamental particle or an elementary particle. It has no substructure (although british physicist Humphrey Maris claims to have found a way to split the electron into "electrinos" using an Electron bubble). Hence, for convenience, it is usually defined or assumed to be a point-like mathematical point charge, with no spatial extension. However, when a test particle is forced to approach an electron, we measure changes in its properties (charge and mass). This effect is common to all elementary particlesCurrent theory suggests that this effect is due to the influence of vacuum fluctuations in its local space, so that the properties measured from a significant distance are considered to be the sum of the bare properties and the vacuum effects (see renormalization).

The classical electron radius is 2.8179×10^{-15} m. This is the radius that is inferred from the electron's electric charge, by using the classical theory of electrodynamics alone, ignoring quantum mechanics. Classical electrodynamics (Maxwell's electrodynamics) is the older concept that is widely used for practical applications of electricity, electrical engineering, semiconductor physics, and electromagnetics; quantum electrodynamics, on the other hand, is useful for applications involving modern particle physics and some aspects of optical, laser and quantum physics.

Based on current theory, the speed of an electron can approach, but never reach, *c* (the speed of light in a vacuum). This limitation is attributed to Einstein's theory of special relativity which defines the speed of light as a constant within all reference frames. However, when relativistic electrons are injected into a dielectric medium, such as water, where the local speed of light is significantly less than *c*, the electrons will (temporarily) be traveling faster than light in the medium. As they interact with the medium, they generate a faint bluish light, called Cherenkov radiation.

The effects of special relativity are based on a quantity known as γ or the Lorentz factor. γ is a function of *v*, the velocity of the particle, and *c*. It is defined as:

$$\gamma = 1/\sqrt{1-(v^2/c^2)}$$

The energy necessary to accelerate a particle is γ minus one times the rest mass. For example, the linear accelerator at Stanford can accelerate an electron to roughly 51GeV . This gives a gamma of 100,000, since the rest mass of an electron is $0.51 MeV/c^2$ (the relativistic mass of this electron is 100,000 times its rest mass). Solving the equation above for the speed of the electron (and using an approximation for large γ) gives:

$$v = \left(1 - \frac{1}{2}\gamma^{-2}\right)c = 0.999\,999\,999\,95\,c.$$

In practice

In the universe

Scientists believe that the number of electrons existing in the known universe is at least 10^{79}. This number amounts to an average density of about one electron per cubic metre of space. Astronomers have determined that 90% of all of the detectable mass in the universe is hydrogen, which is made of one electron and one proton.

Based on the classical electron radius and assuming a dense sphere packing, it can be calculated that the number of electrons that would fit in the observable universe is on the order of 10^{130}.

In industry

Electron beams are used in welding, lithography, scanning electron microscopes and transmission electron microscopes.

They are also at the heart of cathode ray tubes, which are used extensively as display devices in laboratory instruments, computer monitors and television sets. In photomultiplier tubes, one photon strikes the photocathode, initiating an avalanche of electrons that produces a detectable current.

In the laboratory

Electron microscopes are used to magnify details up to 500,000 times. Quantum effects of electrons are used in Scanning tunneling microscope to study features at the atomic scale.

In theory

In relativistic quantum mechanics, the electron can be described by the Dirac Equation which defines the electron as a (mathematical) point. In quantum field theory, the behavior of the electron can be described by quantum electrodynamics (QED), a U(1) gauge theory. In Dirac's model, an electron is defined to be a mathematical point, a point-like, charged "bare" particle surrounded by a sea of interacting pairs of virtual particles and antiparticles . These provide a correction of just over 0.1% to the predicted value of the electron's gyromagnetic ratio from exactly 2 (as predicted by Dirac's single-particle model). The extraordinarily precise agreement of this prediction with the experimentally determined value is viewed as one of the great achievements of modern physics.

In the Standard Model of particle physics, the electron is the first-generation charged lepton. It forms a weak isospin doublet with the electron neutrino; these two particles interact with each other through the both the charged and neutral current weak interaction. The electron is very similar to the two more massive particles of higher generations, the muon and the tau lepton, which are identical in charge, spin, interaction but differ in mass.

The antimatter counterpart of the electron is the positron. The positron has the same amount of electrical charge as the electron, except that the charge is positive. It has the same mass and spin as the electron. When an electron and a positron meet, they may annihilate each other, giving rise to two gamma-ray photons. If the electron and positron had negligible momentum, each gamma ray will have an energy of 0.511MeV. Electron-positron annihilation.

Electrons are a key element in electromagnetism, a theory that is accurate for macroscopic systems, and for classical modelling of microscopic systems.

History

The electron as a unit of charge in electrochemistry was posited by G. Johnstone Stoney in 1874, who also coined the term *electron* in 1894. During the late 1890s a number of physicists posited that electricity could be conceived of as being made of discrete units, which were given a variety of names, but their reality had not been confirmed in a compelling way.

The discovery that the electron was a subatomic particle was made in 1897 by J.J. Thomson at the Cavendish Laboratory at Cambridge University, while he was studying cathode ray tubes. A cathode ray tube is a sealed glass cylinder in which two electrodes are separated by a vacuum. When a voltage is applied across the electrodes, cathode rays are generated, causing the tube to glow. Through experimentation, Thomson discovered that the negative charge could not be separated from the rays (by the application of magnetism), and that the rays could be deflected by an electric field. He concluded that these rays, rather than being waves, were composed of negatively charged particles he called "corpuscles". He measured their mass-to-charge ratio and found it to be over a thousand times smaller than that of a hydrogen ion, suggesting that they were either very highly charged or very small in mass. Later experiments by other scientists upheld the latter conclusion.

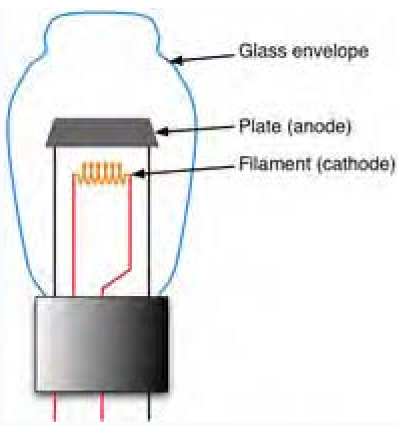
The electron's charge was carefully measured by Robert Millikan in his oil-drop experiment of 1909.

The periodic law states that the chemical properties of elements largely repeat themselves periodically and is the foundation of the periodic table of elements. The law itself was initially explained by the atomic mass of the elements. However, as there were anomalies in the periodic table, efforts were made to find a better explanation for it. In 1913, Henry Moseley introduced the concept of the atomic number and explained the periodic law in terms of the number of protons each element has. In the same year, Niels Bohr showed that electrons are the actual foundation of the table. In 1916, Gilbert Newton Lewis explained the chemical bonding of elements by electronic interactions.

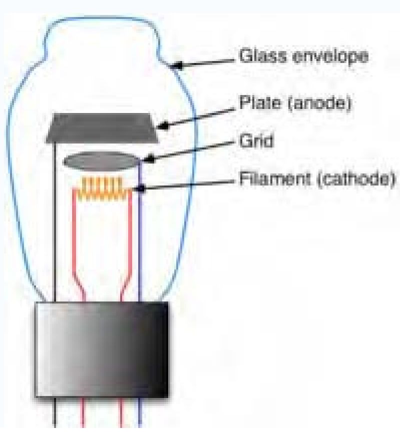
Vacuum tube

In electronics, a **vacuum tube** or **(thermionic) valve** (outside North America) is a device generally used to amplify, or otherwise modify, a signal by controlling the movement of electrons in an evacuated space. For most purposes, the vacuum tube has been replaced by the much smaller and less expensive transistor, either as a discrete device or in an integrated circuit. However, tubes are still used in several specialised applications such as audio systems and high power RF transmitters, as the display device in cathode ray tube television sets, and to generate microwaves in microwave ovens.

The vacuum tube is a *voltage-controlled device*, which means that the relationship between the input and output circuits is determined by a transconductance function. The solid-state device most closely analogous to the vacuum tube is the JFET, although the vacuum tube typically operates at far higher voltage (and power) levels than the JFET.



Diode



Explanation

Vacuum tubes, or *thermionic valves,* are arrangements of electrodes in a vacuum within an insulating, temperature-resistant envelope. Although the envelope was classically glass, power tubes often use ceramic and metal. The electrodes are attached to leads which pass through the envelope via an air tight seal. On most tubes, the leads are designed to plug into a tube socket for easy replacement.

The simplest vacuum tubes resemble incandescent light bulbs in that they have a filament sealed in a glass envelope which has been evacuated of all air. When hot, the filament releases electrons into the vacuuma process called **thermionic emission**. The resulting negatively-charged cloud of electrons is called a space charge. These electrons will be drawn to a metal "*plate*" inside the envelope if the plate (also called the anode) is positively charged relative to the filament (or cathode). The result is a current of electrons flowing from filament to plate. This cannot work in the reverse direction because the plate is not heated and cannot emit electrons. This very simple example described can thus be seen to operate as a diodea device that conducts current only in one direction.

History of development

Inside of a vacuum tube with plate cut open.

The 19th century saw increasing research with evacuated tubes, such as the Geissler and Crookes tubes. Scientists who experimented with such tubes included Eugen Goldstein, Nikola Tesla, Johann Wilhelm Hittorf, Thomas Edison, and many others. These tubes were mostly for specialized scientific applications, or were novelties, with the exception of the light bulb. The groundwork laid by these scientists and inventors, however, was critical to the development of vacuum tube technology.

Though the thermionic emission effect was observed as early as 1873, it is Thomas Edison's 1883 investigation of the "Edison Effect" that is the best known. He promptly patented it (U.S. Patent 307031), but as the particle nature of the electron was not known until 1897, he did not understand the process.

Diodes and triodes

John Ambrose Fleming had worked for Edison; in 1904, as scientific adviser to the Marconi company, he developed the "oscillation valve" or **kenotron**. Later known as the diode, it allowed electric current to flow in only one direction, enabling the rectification of alternating current. Its operation is described in greater detail in the previous section.

In 1906 Lee De Forest placed a bent wire serving as a screen between the filament and plate electrode, later known as the "grid" electrode. As the voltage applied to the grid was varied from negative to positive, the amount of electrons flowing from the filament to the plate would vary accordingly. Thus the grid was said to electrostatically "control" the plate current. The resulting three-electrode device was therefore an excellent and very sensitive amplifier of voltages. DeForest called his invention the "Audion". In 1907, DeForest filed U.S. Patent 879532 for a three-electrode version of the Audion for use in radio communications. The device is now known as the triode. De Forest's device was not strictly a vacuum tube, but clearly depended for its action on ionisation of the relatively high levels of gas remaining after evacuation. The De Forest company in its Audion leaflets warned against operation which might cause the vacuum to become too hard. The first true vacuum triodes were the Pliotrons developed by Irving Langmuir at the General Electric research laboratory (Schenectady, New York) in 1915. These were closely followed by the French 'R' Type which was in widespread use by the allied military by 1916. These two types were the first true **vacuum** tubes.

The non-linear operating characteristic of the triode caused early tube audio amplifiers to exhibit harmonic distortions at low volumes. This is not to be confused with the overdrive that tube amplifiers exhibit at high volume levels (known as the tube sound). To remedy the low volume overdrive problem, engineers plotted curves of the applied grid voltage and resulting plate currents, and discovered that there was a range of relatively linear operation. In order to use this range, a negative voltage had to be applied to the grid to place the tube in the "middle" of the linear area with no signal applied. This was called the idle condition, and the plate current at this point the "idle current". Today this current would be called the quiescent or standing current. The controlling voltage was superimposed onto this fixed voltage, resulting in linear swings of plate current for both positive and negative swings of the input voltage. This concept was called *grid bias*.

Batteries were designed to provide the various voltages required. "A" batteries provided the filament voltage. These were often rechargable - usually of the lead-acid type ranging from 2 to 12 volts (1-6 cells) with single, double and triple cells being most common. In portable radios, flashlight bateries were sometimes used.

The "B" batteries provided the plate voltage. These were generally of Dry cell construction, containing many small 1.5 Volt cells in series and typically came in ratings of 22.5, 45, 60, 90 or 135 volts. To this day, plate voltage is referred to as B^+.

Some sets used "C" batteries were used to provide grid bias, although many circuits used grid leak resistors, voltage dividers or Cathode bias to provide proper tube bias.

Direct and indirect heating

Many further innovations followed. It became common to use the filament to heat a separate electrode called the cathode, and to use the cathode as the source of electron flow in the tube rather than the filament itself. This minimized the introduction of hum when the filament was energized with alternating current. In such tubes, the filament is called a heater to distinguish it as an inactive element.

Tetrodes and pentodes

A two-tube homemade radio from 1958. The tubes are the two columns with the dark tops. The flying leads connect to the low-voltage filament and high-voltage anode supplies.

When triodes were first used in radio transmitters and receivers, it was found that they were often unstable and had a tendency to oscillate due to parasitic anode to grid capacitance. Many complex circuits were developed to reduce this problem (e.g. the Neutrodyne amplifier), but proved unsatisfactory over wide ranges of frequencies. It was discovered that the addition of a second grid, located between the control grid and the plate and called a *screen grid* could solve these problems. A positive voltage slightly lower than the plate voltage was applied to it, and the screen grid was bypassed (for high frequencies) to ground with a capacitor. This arrangement decoupled the anode and the first grid, completely eliminating the oscillation problem. This two-grid tube is called a *tetrode*, meaning four active electrodes.

Radio transmitter high power vacuum tube. The knitted copper leads provide heater current for the cathode. The tube also has a heat sink. Dubendorf museum of the military aviation.

However, the tetrode had a problem toothe positive voltage on the second grid accelerated the electrons, causing them to strike the anode hard enough to knock out secondary electrons. These could then be captured by the second grid, reducing the plate current and the amplification of the circuit. This effect was sometimes called "tetrode kink". Again the solution was to add another grid, called a suppressor grid. This third grid was biased at either ground or cathode voltage and its negative voltage (relative to the anode) electrostatically suppressed the secondary electrons by repelling them back toward the anode. This three-grid tube is called a pentode, meaning five electrodes.

Other variations

Frequency Conversion can be accomplished by many different methods in superheterodyne receivers. Tubes with 5 grids, called pentagrid converters, were generally used although alternative such as using a combination of a triode with a hexode were also used, even octodes have been used for frequency conversion The additional grids are either control grids, with different signals applied to each one, or screen grids. In many designs a special grid acted as a second 'leaky' plate to provide a built-in oscillator, which then coupled this signal with the incoming radio signal. These signals create a single, combined effect on the plate current (and thus the signal output) of the tube circuit. The heptode, or pentagrid converter, was the most common of these. 6BE6 is an example of a heptode (note that the first number in the tube ID indicates the filament voltage).

It was common practice almost everywhere in the world to combine more than one function, or more than one set of elements in the bulb of a single tube. The only constraint was where patents, and other licencing considerations required the use of multiple tubes. See British Valve Association

The RCA Type 55 for example was a double diode triode used as a detector, AVC rectifier and audio preamp in early AC powered radios. The same set of tubes often included the 53 Dual Triode Audio Output. A German firm actually built a multi-section tube with the coupling components inside the envelope. In that case the cost of individually sealing the parts in separate glass tubing to protect them from exposure to the vacuum ended up increasing the final cost.

Another early type of multi-section tube, the 6SN7, is a "dual triode" which, for most purposes, can perform the functions of two triode tubes, while taking up half as much space and costing less.

An RCA 12AX7 dual-triode tube (1947)

Currently the world's most popular vacuum tube is the 12AX7, with estimated annual worldwide sales of greater than 2 million units. The 12AX7 is a dual high-gain triode widely used in guitar amplifiers, audio preamps, and instruments.

The invention of the 9 pin miniature tube base, besides allowing the 12AX7 Family also allowed many other multi section tubes, such as the 6GH8 triode pentode which along with a host of simalar tubes was quite popular in television receivers. Some color TV sets even used exotic types like the 6JH8 which had two plates and beam deflection electrodes (known as 'sheet beam' tube). Vacuum tubes used like this were designed for demodulation of synchronous signals, an example of which is color demodulation for television receivers.

The desire to include many functions in one envelope resulted in the General Electric Compactron A typical unit, the 6AG11 Compactron tube contained two triodes and two diodes, but many in the series had triple triodes.

An early example of multiple devices in one envelope was the Loewe 3NF. this device had 3 triodes in a single glass envelope together with all the fixed capacitors and resistors required to make a complete radio receiver. As the Loewe set had only one tubeholder, it was able to substantially undercut the competition since, in Germany, state tax was levied by the number of tubeholders.

Loewe were to also offer the 2NF (two tetrodes plus passive components) and the WG38 (two pentodes, a triode and the passive components).

Vacuum tubes on a Philco model 20 tabletop radio set.

The beam power tube is usually a tetrode with the addition of beam-forming electrodes, which take the place of the suppressor grid. These angled plates focus the electron stream onto certain spots on the anode which can withstand the heat generated by the impact of massive numbers of electrons, while also providing pentode behavior. The positioning of the elements in a beam power tube uses a design called "critical-distance geometry", which minimizes the "tetrode kink", plate-grid capacitance, screen-grid current, and secondary emission effects from the anode, thus increasing power conversion efficiency. The control grid and screen grid are also wound with the same pitch, or number of wires per inch. Aligning the grid wires also helps to reduce screen current, which represents wasted energy. This design helps to overcome some of the practical barriers to designing high power, high efficiency power tubes. 6L6 was the first popular beam power tube, introduced by RCA in 1936. Corresponding tubes in Europe were the KT66, KT77 and KT88 by GEC (the KT standing for "Kinkless Tetrode").

An Electro-Harmonix 12Ax7EH Russian tube.

Variations of the 6L6 design are still widely used in guitar amplifiers, making it one of the longest lived electronic device families in history. Similar design strategies are used in the construction of large ceramic power tetrodes used in radio transmitters.

Special-purpose tubes

Some special-purpose tubes are intentionally constructed with various gases in the envelope. For instance, voltage regulator tubes contain various inert gases such as argon, helium or neon, and take advantage of the fact that these gases will ionize at predictable voltages. The thyratron is a special-purpose tube filled with low-pressure gas, for use as a high-speed electronic switch.

Tubes usually have glass envelopes, but metal, fused quartz (silica), and ceramic are possible choices. The first version of the 6L6 used a metal envelope sealed with glass beads, later a glass disk fused to the metal was used. Metal and ceramic are used almost exclusively for power tubes above 2 kW dissipation. The nuvistor is a tiny tube made only of metal and ceramic. In some power tubes, the metal envelope is also the anode. 4CX800A is an external anode tube of this sort. Air is blown through an array of fins attached to the anode, thus cooling it. Power tubes using this cooling scheme are available up to 150 kW dissipation. Above that level, water or water-vapor cooling are used. The highest-power tube currently available is the Eimac 8974, a water-cooled tetrode capable of dissipating 1.5 megawatts. (By comparison, the largest power transistor can only dissipate about 1 kilowatt). A pair of 8974s is capable of producing 2 megawatts of audio power. The 8974 is used only in exotic military and commercial radio-frequency installations.

Reliability

The chief reliability problem of a tube is that the filament or cathode is slowly "poisoned" by atoms from other elements in the tube, which damage its ability to emit electrons. Trapped gases or slow gas leaks can also damage the cathode or cause plate-current runaway due to ionization of free gas molecules. Vacuum hardness and proper selection of construction materials are the major influences on tube lifetime. Depending on the material, temperature and construction, the surface material of the cathode may also diffuse onto other elements. The resistive filaments that heat the cathodes may burn out as lamp filaments do, but usually not so quickly as they need not be so hot. Another important reliability problem is that the tube fails when air leaks into the tube. Usually oxygen in the air reacts chemically with the hot filament or cathode, quickly ruining it. Designers therefore worked hard to develop tube designs that sealed reliably. This was why most tubes were constructed of glass. Metal alloys (Cunife and Fernico) and glasses had been developed for light bulbs that expanded and contracted in similar amounts, as temperature changed. These made it easy to construct an insulating envelope of glass, and pass wires through the glass to the electrodes.

When a vacuum tube is overloaded or operated past its design dissipation, its anode (plate) may glow red. In consumer equipment, a glowing plate is universally a sign of an overloaded tube and must be corrected immediately. However, some large transmitting tubes are designed to operate with their anodes at red, orange or in rare cases, white heat.

Vacuum

It is very important that the vacuum inside the envelope be as perfect, or "hard", as possible. Any gas atoms remaining will be ionized at operating voltages, and will conduct electricity between the elements in an uncontrolled manner. This can lead to erratic operation or even catastrophic destruction of the tube and associated circuitry. Unabsorbed free air sometimes ionizes and becomes visible as a pink-purple glow discharge between the tube elements.

To prevent any remaining gases from remaining in a free state in the tube, modern tubes are constructed with "getters", which are usually small, circular troughs filled with metals that oxidize quickly, with barium being the most common. While the tube envelope is being evacuated, the internal parts except the getter are heated by RF induction heating to extract any remaining gases from the metal. The tube is then sealed and the getter is heated to a high temperature, again by Radio frequency induction heating causing the material to evaporate, absorbing/reacting with any residual gases and usually leaving a silver-colored metallic deposit on the inside of the envelope of the tube. The getter continues to absorb any gas molecules that leak into the tube during its working life. If a tube develops a crack in the envelope, this deposit turns a white color when it reacts with atmospheric oxygen. Large transmitting and specialized tubes often use more exotic getters. Early gettered tubes used phosphorous based getters and these tubes are easily identifiable as the phosphorous leaves a characteristic orange deposit on the glass. The use of Phosphorous was short lived and was quickly replaced by the superior barium getters. Unlike the barium getters, the phosphorous did not absorb any further gasses once it had fired.

British Broadcasting Corporation (BBC) research

Mazda of the UK produced a range of tubes for use in AC powered domestic receivers and other general purposes in around 1935 (the AC/ range). The British Broadcasting Corporation (BBC) used to maintain scrupulous records of equipment maintenence including the achieved life of all tubes. Their records show that a Mazda AC/HL (a triode) was removed from its equipment having achieved over 250,000 hours of service. When tested, the tube performed to the manufacturer's specification. The BBC did not claim any record for this as this order of longevity of life was typical for this range of tubes. Repair shops stocked up on spares to meet the anticipated demand for replacement tubes, but few were ever required. Any AC/ series tube encountered today is most likely unused (and may well be in its original carton).

Transmitting tubes

Large transmitting tubes have tungsten filaments containing a small trace of thorium. A thin layer of thorium atoms forms on the outside of the wire when heated, serving as an efficient source of electrons. The thorium slowly evaporates from the wire surface, while new thorium atoms diffuse to the surface to replace them. Such thoriated tungsten cathodes routinely deliver lifetimes in the tens of thousands of hours. The claimed record is held by an Eimac power tetrode used in a Los Angeles radio station's transmitter, which was removed from service after 80,000 hours (~9 years) of uneventful operation. Transmitting tubes are claimed to survive lightning strikes more often than transistor transmitters do.

Receiving tubes

Cathodes in small "receiving" tubes are coated with a mixture of barium oxide and strontium oxide, sometimes with addition of calcium oxide or aluminium oxide. An electric heater is inserted into the cathode sleeve, and insulated from it electrically. This complex construction causes barium and strontium atoms to diffuse to the surface of the cathode when heated to about 780 degrees Celsius, thus emitting electrons.

'Computer' vacuum tubes

'Colossus'

Colossus's designer, Dr Tommy Flowers, had a theory that most of the unreliability was caused during power down and (mainly) power up (nobody else believed him - but that didn't stop him). Once Colossus was built and installed, it was switched on and left switched on running from dual redundant diesel generators (the war time mains supply being considered too unreliable). The only time it was switched off was for conversion to the Colussus Mk2 and the addition of another 500 or so tubes. Another 9 Colossi Mk2 were built, and all 10 machines ran with a surprising degree of reliability. The only problem was that the 10 Colossi consumed 15 kilowatts of power each, 24 hours a day, 365 days a year - nearly all of it for the tube heaters.

Whirlwind

To meet the unique reliability requirements of the early digital computer Whirlwind, it was found necessary to build special "computer vacuum tubes" with extended cathode life. The problem of short lifetime was traced to evaporation of silicon, used in the tungsten alloy to make the wire easier to draw. Elimination of the silicon from the heater wire alloy (and paying extra for more frequent replacement of the wire drawing dies) allowed production of tubes that were reliable enough for the Whirlwind project. The tubes developed for Whirlwind later found their way into the giant SAGE air-defense computer system. High-purity nickel tubing and cathode coatings free of materials that can poison emission (such as silicates and aluminum) also contribute to long cathode life. The first such "computer tube" was Sylvania's 7AK7 of 1948. By the late 1950s it was routine for special-quality small-signal tubes to last for hundreds of thousands of hours rather than thousands, if operated conservatively. This reliability made mid-cable amplifiers in submarine cables possible.

World War II

A CV4501 subminiature tube designed for use in a military radio set. The tube is a special quality type based on the EF72. It is 35 mm long and 10 mm in diameter (excluding leads).

Near the end of World War II, to make radios more rugged, some aircraft and army radios began to integrate the tube envelopes into the radio's cast aluminum or zinc chassis. The radio became just a printed circuit with non-tube components, soldered to the chassis that contained all the tubes. Another WWII idea was to make very small and rugged glass tubes, originally for use in radio-frequency metal detectors built into artillery shells. These proximity fuzes made artillery more effective. Tiny tubes were later known as "subminiature" types. They were widely used in 1950s military and aviation electronics.

Applications

Tubes were ubiquitous in the early generations of electronic devices, such as radios, televisions, and early computers such as the Colossus which used 2000 tubes, the ENIAC which used nearly 18,000 tubes, and the IBM 700 series. Vacuum tubes inherently have higher resistance to the electromagnetic pulse effect of nuclear explosions. This property kept them in use for certain military applications long after transistors had replaced them elsewhere. Vacuum tubes are still used for very high-powered applications such as microwave ovens, industrial radio-frequency heating, and power amplification for broadcasting.

Tubes are also considered by many people in the audiophile, professional audio, and musician communities to have superior audio characteristics over transistor electronics, due to their warmer, more natural tone. There are many companies which still make specialized audio hardware featuring tube technology.

12AX7 tubes inside a modern guitar amplifier.

Tubes' characteristic sound when overloaded (interchangeable term with overdriven) is widely used in electric guitar amplification, and has defined the sound of some genres of music, including classic rock and rhythm and blues. In this regard, tube amplifiers are typically desired for the warmth and natural compression they can add to an input signal.

Cooling

All vacuum tubes produce heat while operating. Compared to semiconductor devices, larger tubes operate at higher power levels and hence dissipate more heat. The majority of the heat is dissipated at the anode, though some of the grids can also dissipate power. The tube's heater also contributes to the total, and is a source that semiconductors are free from.

In order to remove generated heat, various methods of cooling may be used. For low power dissipation devices, the heat is radiated from the anode - it often being blackened on the external surface to assist. Natural air circulation or convection may be required to keep power tubes from overheating. For larger power dissipation, forced-air cooling (fans) may be required.

High power tubes in large transmitters or power amplifiers are liquid cooled, usually with de-ionised water for heat transfer to an external radiator, similar to the cooling system of an internal combustion engine. Since the anode is usually the cooled element, the anode voltage appears directly on the cooling water surface, thus requiring the water to be an electrical insulator. Otherwise the high voltage can be conducted through the cooling water to the radiator system; hence the need for de-ionised water. Such systems usually have a built-in water conductance monitor which will shut down the high tension supply (often kilovolts) if the conductance gets too high.

Other vacuum tube devices

A vast array of devices were built during the 1920-1960 period using vacuum-tube techniques. Most such tubes were rendered obsolete by semiconductors; some techniques for integrating multiple devices in a single module, sharing the same glass envelope have been discussed above, such as the Loewe 3NF. Vacuum-tube electronic devices still in common use include the magnetron, klystron, photomultiplier, x-ray tube and cathode ray tube. The magnetron is the type of tube used in all microwave ovens. In spite of the advancing state of the art in power semiconductor technology, the vacuum tube still has reliability and cost advantages for high-frequency RF power generation. Photomultipliers are still the most sensitive detectors of light. Many televisions, oscilloscopes and computer monitors still use cathode ray tubes, though flat panel displays are becoming more popular as prices drop.

The fluorescent displays commonly used on VCRs and automotive dashboards are actually vacuum tubes, using phosphor-coated anodes to form the display characters, and a heated filamentary cathode as an electron source. These devices are properly called "VFDs", or Vacuum Fluorescent Displays. Because the filaments are in view, they must be operated at temperatures where the filament does not show a glow. Their big advantage is that it is relatively easy to create bespoke designs with all the legends required for a specific task. These devices are often found in automotive applications where their high brightness allows reading the display in daylight.

Some tubes, like magnetrons, traveling wave tubes, carcinotrons, and klystrons, combine magnetic and electrostatic effects. These are efficient (usually narrow-band) RF producers and still find use in radar, microwave ovens and industrial heating.

Gyrotrons or vacuum masers, used to generate high power millimetre band waves, are magnetic vacuum tubes in which a small relativistic effect, due to the high voltage, is used for bunching the electrons. Free electron lasers, used to generate high power coherent light and perhaps even X rays, are highly relativistic vacuum tubes driven by high energy particle accelerators.

Particle accelerators can be considered vacuum tubes that work backward, the electric fields driving the electrons, or other changed particles. (Like ordinary vacuum tubes many of their names end in "tron".) In this respect, a cathode ray tube is a particle accelerator.

A tube in which electrons move through a vacuum (or gaseous medium) within a gas-tight envelope is generically called an *electron tube*.

Vacuum tube can also literally mean a tube with a vacuum. It is e.g. used for demonstration of, and experiments with, free-fall.

Field emitter vacuum tubes

In the early years of the 21st century there has been renewed interest in vacuum tubes, this time in the form of integrated circuits. The most common design uses a cold cathode field emitter, with electrons emitted from a number of sharp nano-scale tips formed on the surface of a metal cathode.

Their advantages include greatly enhanced robustness combined with the ability to provide high power outputs at low power consumptions. Operating on the same principles as traditional tubes, prototype device cathodes have been constructed with emitter tips formed using nanotubes, and by etching electrodes as hinged flaps (similar to the technology used to create the microscopic mirrors used in Digital Light Processing) that are stood upright by a magnetic field.

Such integrated microtubes may find application in microwave devices including mobile phones, for Bluetooth and Wi-Fi transmission, in radar and for satellite communication. Presently they are being studied for possible application to flat-panel display construction.

Vacuum tube solar heaters

The term **vacuum tube** has recently been used to refer to the tubular elements of solar panels used for heating water. **Vacuum tube solar heaters** are becoming increasingly popular.

An **electrode** is an electrical conductor used to make contact with a nonmetallic part of a circuit (e.g. a semiconductor, an electrolyte or a vacuum). The word was coined by the scientist Michael Faraday from the Greek words *elektron* (meaning amber, from which the word electricity is derived) and *hodos*, a way.

Anode and cathode in electrochemical cells

An electrode in an electrochemical cell is referred to as either an *anode* or a *cathode*, words that were also coined by Faraday. The anode is defined as the electrode at which electrons come up from the cell and oxidation occurs, and the cathode is defined as the electrode at which electrons enter the cell and reduction occurs. Each electrode may become either the anode or the cathode depending on the voltage applied to the cell. A bipolar electrode is an electrode that functions as the anode of one cell and the cathode of another cell.

Primary cell

A primary cell is a special type of electrochemical cell in which the reaction cannot be reversed, and the identities of the anode and cathode are therefore fixed. The anode is always the negative electrode. The cell can be discharged but not recharged.

Secondary cell

A secondary cell, for example a rechargeable battery, is one in which the reaction is reversible. When the cell is being charged, the anode becomes the positive (+) electrode and the cathode the negative (−). This is also the case in an electrolytic cell. When the cell is being discharged, it behaves like a primary or voltaic cell, with the anode as the negative electrode and the cathode as the positive.

Other anodes and cathodes

In a vacuum tube or a semiconductor having polarity (diodes, electrolytic capacitors) the anode is the positive (+) electrode and the cathode the negative (−). The electrons enter the device through the cathode and exit the device through the anode.

In a three-electrode cell, a counter electrode, also called an auxiliary electrode, is used only to make a connection to the electrolyte so that a current can be applied to the working electrode. The counter electrode is usually made of an inert material, such as a noble metal or graphite, to keep it from dissolving.

Welding electrodes

In arc welding an electrode is used to conduct current through a workpiece to fuse two pieces together. Depending upon the process, the electrode is either consumable, in the case of gas metal arc welding or shielded metal arc welding, or non-consumable, such as in gas tungsten arc welding. For a direct current system the weld rod or stick may be a cathode for a filling type weld or an anode for other welding processes. For an alternating current arc welder the welding electrode would not be considered an anode or cathode.

Alternating current electrodes

For electrical systems which use alternating current the electrodes are the connections from the circuitry to the object to be acted upon by the electrical current but are not designated anode or cathode since the direction of flow of the electrons changes periodically, usually many times per second.

Types of electrode

- Electrodes for medical purposes, such as EEG, ECG, ECT, defibrillator
- Electrodes for electrophysiology techniques in biomedical research
- Electrodes for execution by the electric chair
- Electrodes for electroplating
- Electrodes for arc welding
- Electrodes for cathodic protection
- Inert electrodes for hydrolysis (made of platinum)

Semiconductor

A **semiconductor** is a solid whose electrical conductivity can be controlled over a wide range, either permanently or dynamically. Semiconductors are tremendously important technologically and economically. Semiconductors are essential materials in all modern electrical devices, from computers to cellular phones to digital audio players. Silicon is the most commercially important semiconductor, though dozens of others are important as well.

Summary

Semiconductors are very similar to insulators. The two categories of solids differ only in that insulators have larger band gaps -- energies that electrons must acquire to be free to flow. In semiconductors at room temperature, just as in insulators, very few electrons gain enough thermal energy to leap the band gap, which is necessary for conduction. For this reason, pure semiconductors and insulators, in the absence of applied fields, have roughly identical electrical properties. The smaller bandgaps of semiconductors, however, allow for many other means besides temperature to control their electrical properties.

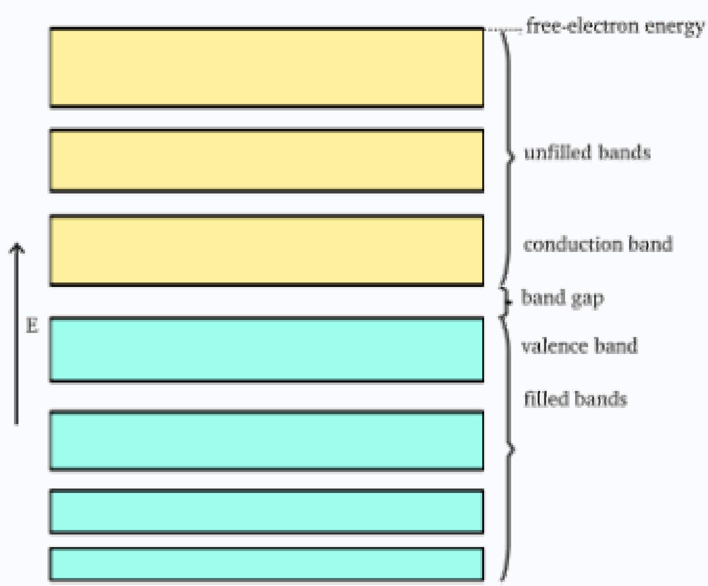
Semiconductors' intrinsic electrical properties are very often permanently modified by introducing impurities, in a process known as doping. Usually it is reasonable to approximate that each impurity atom adds one electron or one "hole" (a concept to be discussed later) that may flow freely. Upon the addition of a sufficiently large proportion of dopants, semiconductors conduct electricity nearly as well as metals. The junctions between regions of semiconductors that are doped with different impurities contain built-in electric fields, which are critical to semiconductor device operation.

In addition to permanent modification through doping, the electrical properties of semiconductors are often dynamically modified by applying electric fields. The ability to control conductivity in small and well-defined regions of semiconductor material, statically through doping and dynamically through the application of electric fields, has led to the development of a broad array of semiconductor devices, like transistors. Semiconductor devices with dynamically controlled conductivity are the building blocks of integrated circuits, like the microprocessor. These "active" semiconductor devices are combined with simpler passive components, such as semiconductor capacitors and resistors, to produce a variety of electronic devices.

In certain semiconductors, when electrons fall from the conduction band to the valence band (the energy levels above and below the band gap), they often emit light. This photoemission process underlies the light emitting diode (LED) and the semiconductor laser, both of which are tremendously important commercially. Conversely, semiconductor absorption of light in photodetectors excites electrons from the valence band to the conduction band, facilitating reception of fiber optic communications, and providing the basis for energy from solar cells.

Semiconductors may be elemental materials, such as silicon, *compound semiconductors* such as gallium arsenide, or alloys, such as silicon germanium or aluminium gallium arsenide.

Band structure



Band structure of a semiconductor showing a full valence band and an empty conduction band.

Like other solids, the electrons in semiconductors can have energies only within certain bands between the energy of the ground state, corresponding to electrons tightly bound to the atomic nucleii of the material, and the free electron energy, which is the energy required for an electron to escape entirely from the material. The energy bands each correspond to a large number of discrete quantum states of the electrons, and most of the states with low energy are full, up to a particular band called the *valence band*. Semiconductors and insulators are distinguished from metals because the valence band in the former materials is very nearly full under normal conditions.

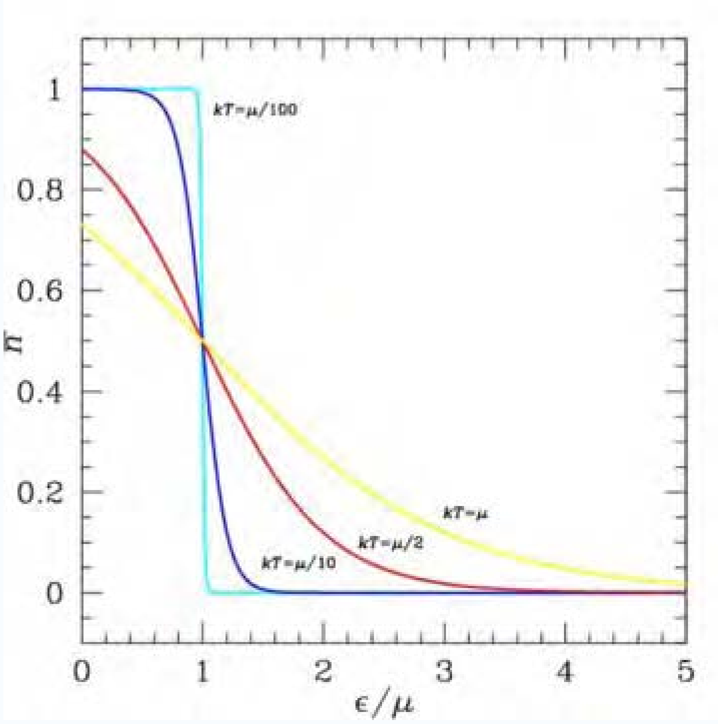
The ease with which electrons in a semiconductor can be excited from the valence band to the conduction band depends on the band gap between the bands, and it is the size of this energy bandgap that serves as an arbitrary dividing line (roughly 4 eV) between semiconductors and insulators.

The electrons must move between states to conduct electric current, and so due to the Pauli exclusion principle full bands do not contribute to the electrical conductivity. However, as the temperature of a semiconductor rises above absolute zero, the states of the electrons are increasingly randomized, or smeared out, and some electrons are likely to be found in states of the *conduction band*, which is the band immediately above the valence band. The current-carrying electrons in the conduction band are known as "free electrons", although they are often simply called "electrons" if context allows this usage to be clear.

Electrons excited to the conduction band also leave behind electron holes, or unoccupied states in the valence band. Both the conduction band electrons and the valence band holes contribute to electrical conductivity. The holes themselves don't actually move, but a neighbouring electron can move to fill the hole, leaving a hole at the place it has just come from, and in this way the holes appear to move, and the holes behave as if they were actual positively charged particles.

This behavior may also be viewed in relation to chemical bonding. The electrons that have enough energy to be in the conduction band have broken free of the covalent bonds between neighbouring atoms in the solid, and are free to move around, and hence conduct charge.

It is an important distinction between conductors and semiconductors that, in semiconductors, movement of charge (current) is facilitated by both electrons and holes. Contrast this to a conductor where the Fermi level lies *within* the conduction band, such that the band is only half filled with electrons. In this case, only a small amount of energy is needed for the electrons to find other unoccupied states to move into, and hence for current to flow.



Fermi-Dirac distribution. States with energy ε below the Fermi energy, here μ, have higher probability *n* to be occupied, and those above are less likely to be occupied. Smearing of the distribution increases with temperature.

The energy distribution of the electrons determines which of the states are filled and which are empty. This distribution is described by Fermi-Dirac statistics. The distribution is characterized by the temperature of the electrons, and the *Fermi energy* or *Fermi level*. Under absolute zero conditions the Fermi energy can be thought of as the energy up to which available electron states are occupied. At higher temperatures, the Fermi energy is the energy at which the probability of a state being occupied has fallen to 0.5.

The dependence of the electron energy distribution on temperature also explains why the conductivity of a semiconductor has a strong temperature dependency, as a semiconductor operating at lower temperatures will have fewer available free electrons and holes able to do the work.

Energy-momentum dispersion

In the preceding description an important fact is ignored for the sake of simplicitythe *dispersion* of the energy. The reason that the energies of the states are broadened into a band is that the energy depends on the value of the wave vector, or *k-vector*, of the electron. The k-vector, in quantum mechanics, is the representation of the momentum of a particle. The *E-k* relationship varies from material to material.

The dispersion relationship determines the effective mass, m^* -, of electrons or holes in the semiconductor, according to the formula:

$$m^* = \hbar^2 \cdot \left[\frac{d^2E(k)}{dk^2}\right]^{-1}$$

The effective mass is important as it effects many of the electrical properties of the semiconductor, such as the electron or hole mobility, which in turn influences the *diffusivity* of the charge carriers and the electrical conductivity of the semiconductor.

Typically the effective mass of electrons and holes are different. This affects the relative performance of *p-channel* and *n-channel* IGFETs, for example (Muller & Kamins 1986:427).

The top of the valence band and the bottom of the conduction band might not occur at that same value of k. Materials with this situation, such as silicon and germanium, are known as *indirect bandgap* materials. Materials in which the band extrema are aligned in k, for example gallium arsenide, are called *direct bandgap* semiconductors. Direct gap semiconductors are particularly important in optoelectronics because they are much more efficient as light emitters than indirect gap materials.

Carrier generation and recombination

When ionizing radiation strikes a semiconductor, it may excite an electron out of its energy level and consequently leave a hole. This process is known as *electron–hole pair generation*. Electron-hole pairs are constantly generated from thermal energy as well, in the absence of any external energy source.

Electron-hole pairs are also apt to recombine. Conservation of energy demands that these recombination events, in which an electron loses an amount of energy larger than the band gap, be accompanied by the emission of thermal energy (in the form of phonons) or radiation (in the form of photons).

In the steady state, the generation and recombination of electron-hole pairs are in equipoise. The number of electron-hole pairs in the steady state at a given temperature is determined by quantum statistical mechanics. The precise quantum mechanical mechanisms of generation and recombination are governed by conservation of energy and conservation of momentum.

Doping

The property of semiconductors that makes them most useful for constructing electronic devices is that their conductivity may easily be modified by introducing impurities into their crystal lattice. The process of adding controlled impurities to a semiconductor is known as *doping*. The amount of impurity, or dopant, added to an *intrinsic* (pure) semiconductor varies its level of conductivity. Doped semiconductors are often refered to as *extrinsic*.

Dopants

The materials chosen as suitable dopants depend on the atomic properties of both the dopant and the material to be doped. In general, dopants that produce the desired controlled changes are classified as either electron acceptors or donors. A donor atom that activates (that is, becomes incorporated into the crystal lattice) donates weakly-bound valence electrons to the material, creating excess negative charge carriers. These weakly-bound electrons can move about in the crystal lattice relatively freely and can facilitate conduction in the presence of an electric field. Conversely, an activated acceptor produces a hole. Semiconductors doped with donor impurities are called *n-type*, while those doped with acceptor impurities are known as *p-type*. The n and p type designations indicate which charge carrier acts as the material's majority carrier. The opposite carrier is called the minority carrier, which exists due to thermal excitation at a much lower concentration compared to the majority carrier.

For example, the pure semiconductor silicon has four valence electrons. In silicon, the most common dopants are IUPAC group 13 (commonly known as *column III*) and group 15 (commonly known as *column V*) elements. Group 13 elements all contain three valence electrons, causing them to function as acceptors when used to dope silicon.

Group 15 elements have five valence electrons, which allows them to act as a donor. Therefore, a silicon crystal doped with boron creates a p-type semiconductor whereas one doped with phosphorus results in an n-type material.

Carrier concentration

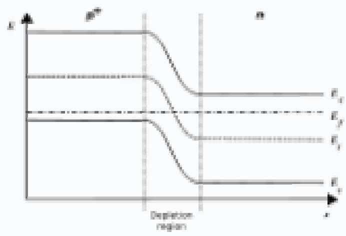
The concentration of dopant introduced to an intrinsic semiconductor determines its concentration and indirectly affects many of its electrical properties. The most important factor that doping directly affects is the material's carrier concentration. In an intrinsic semiconductor under thermal equilibrium, the concentration of electrons and holes is equivalent. That is,

$$n = p = n_i$$

Where n is the concentration of conducting electrons, p is the electron hole concentration, and n_i is the material's intrinsic carrier concentration. Intrinsic carrier concentration varies between materials and is dependent on temperature. Silicon's n_i, for example, is roughly 1×10^{10} cm^{-3} at 300 Kelvin (room temperature).

In general, an increase in doping concentration affords an increase in conductivity due to the higher concentration of carriers available for conduction. Degenerately (very highly) doped semiconductors have conductivity levels comparable to metals and are often used in modern integrated circuits as a replacement for metal. Often superscript plus and minus symbols are used to denote relative doping concentration in semiconductors. For example, n^+ denotes an n-type semiconductor with a high, often degenerate, doping concentration. Similarly, p^- would indicate a very lightly doped p-type material. It is useful to note that even degenerate levels of doping imply low concentrations of impurities with respect to the base semiconductor. In crystalline intrinsic silicon, there are approximately 5×10^{22} atoms/cm^3. Doping concentration for silicon semiconductors may range anywhere from 10^{13} cm^{-3} to 10^{18} cm^{-3}. Doping concentration above about 10^{18} cm^{-3} is considered degenerate at room temperature. Degenerately doped silicon contains a proportion of impurity to silicon in the order of parts per thousand. This proportion may be reduced to parts per billion in very lightly doped silicon. Typical concentration values fall somewhere in this range and are tailored to produce the desired properties in the device that the semiconductor is intended for.

Effect on band structure



Band diagram of a p^+n junction. The band bending is a result of the positioning of the Fermi levels in the p^+ and n sides.

Doping a semiconductor crystal introduces allowed energy states within the band gap but very close to the energy band that corresponds with the dopant type. In other words, donor impurities create states near the conduction band while acceptors create states near the valence band. The gap between these energy states and the nearest energy band is usually referred to as dopant-site bonding energy or E_B and is relatively small. For example, the E_B for boron in silicon bulk is 0.045 eV, compared with silicon's band gap of about 1.12 eV. Because E_B is so small, it takes little energy to ionize the dopant atoms and create free carriers in the conduction or valence bands. Usually the thermal energy available at room temperature is sufficient to ionize most of the dopant.

Dopants also have the important effect of shifting the material's Fermi level towards the energy band that corresponds with the dopant with the greatest concentration. Since the Fermi level must remain constant in a system in thermodynamic equilibrium, stacking layers of materials with different properties leads to many useful electrical properties. For example, the p-n junction's properties are due to the energy band bending that happens as a result of lining up the Fermi levels in contacting regions of p-type and n-type material.

This effect is shown in a *band diagram*. The band diagram typically indicates the variation in the valence band and conduction band edges versus some spatial dimension, often denoted x. The Fermi energy is also usually indicated in the diagram. Sometimes the *intrinsic Fermi energy*, E_i, which is the Fermi level in the absence of doping, is shown. These diagrams are useful in explaining the operation of many kinds of semiconductor devices.

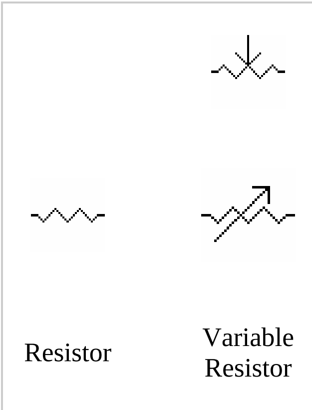
Preparation of semiconductor materials

Semiconductors with predictable, reliable electronic properties are necessary for mass production. The level of chemical purity needed is extremely high because the presence of impurities even in very small proportions can have large effects on the properties of the material. A high degree of crystalline perfection is also required, since faults in crystal structure (such as dislocations, twins, and stacking faults) interfere with the semiconducting properties of the material. Crystalline faults are a major cause of defective semiconductor devices. The larger the crystal, the more difficult it is to achieve the necessary perfection. Current mass production processes use crystal ingots between four and twelve inches (300 mm) in diameter which are grown as cylinders and sliced into wafers.

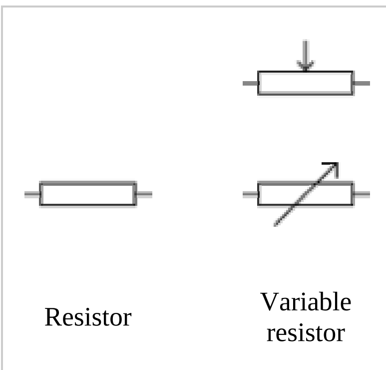
Because of the required level of chemical purity, and the perfection of the crystal structure which are needed to make semiconductor devices, special methods have been developed to produce the initial semiconductor material. A technique for achieving high purity includes growing the crystal using the Czochralski process. An additional step that can be used to further increase purity is known as zone refining. In zone refining, part of a solid crystal is melted. The impurities tend to concentrate in the melted region, while the desired material recrystalizes leaving the solid material more pure and with fewer crystalline faults.

In manufacturing semiconductor devices involving heterojunctions between different semiconductor materials, the lattice constant, which is the length of the repeating element of the crystal structure, is important for determining the compatibility of materials.

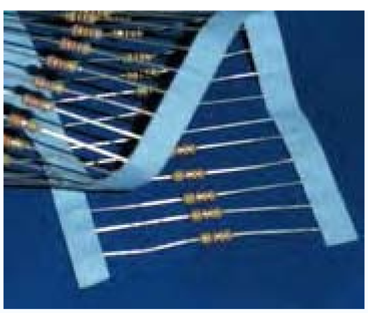
Resistor



Resistor symbols (US and Japan)



Resistor symbols (Europe, IEC)



A pack of resistors

A **resistor** is a two-terminal electrical or electronic component that resists an electric current by producing a voltage drop between its terminals in accordance with Ohm's law. (Certain ultra-precise resistors have 2 extra terminals, for a total of 4.)

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

The *electrical resistance* is equal to the voltage drop across the resistor divided by the current through the resistor. Resistors are used as part of electrical networks and electronic circuits.

Applications

- In general, a resistor is used to create a known voltage-to-current ratio in an electric circuit. If the current in a circuit is known, then a resistor can be used to create a known potential difference proportional to that current. Conversely, if the potential difference between two points in a circuit is known, a resistor can be used to create a known current proportional to that difference.
- Current-limiting. By placing a resistor in series with another component, such as a light-emitting diode, the current through that component is reduced to a known safe value.
- A series resistor can be used for speed regulation of DC motors, such as used on locomotives and trainsets.
- An **attenuator** is a network of two or more resistors (a voltage divider) used to reduce the voltage of a signal.
- A **line terminator** is a resistor at the end of a transmission line or daisy chain bus (such as in SCSI), designed to match impedance and hence minimize reflections of the signal.
- All resistors dissipate heat. This is the principle behind electric heaters.

The ideal resistor

The SI unit of electrical resistance is the ohm (Ω). A component has a resistance of 1 Ω if a voltage of 1 volt across the component results in a current of 1 ampere, or amp, which is equivalent to a flow of one coulomb of electrical charge (approximately 6.241506×10^{18} electrons) per second. The multiples kiloohm (1 kΩ = 1000 Ω) and megaohm (1 MΩ = 10^6 Ω) are also commonly used.

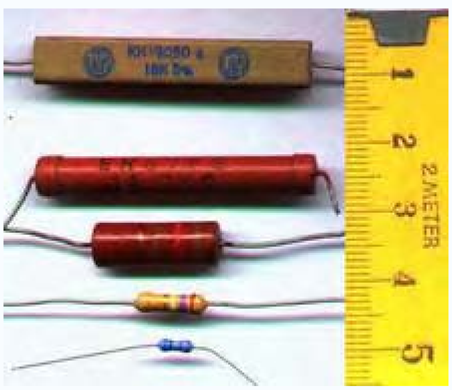
In an ideal resistor, the resistance remains constant regardless of the applied voltage or current through the device or the rate of change of the current. While real resistors cannot attain this goal, they are designed to present little variation in electrical resistance when subjected to these changes, or to changing temperature and other environmental factors.

Nonideal characteristics

A resistor has a maximum working voltage and current above which the resistance may change (drastically, in some cases) or the resistor may be physically damaged (overheat or burn up, for instance). Although some resistors have specified voltage and current ratings, most are rated with a maximum power which is determined by the physical size. Common power ratings for carbon composition and metal-film resistors are 1/8 watt, ¼ watt, and ½ watt. Metal-film and carbon film resistors are more stable than carbon resistors against temperature changes and age. Larger resistors are able to dissipate more heat because of their larger surface area. Wire-wound and resistors embedded in sand (ceramic) are used when a high power rating is required.

Furthermore, all real resistors also introduce some inductance and a small amount of capacitance, which change the dynamic behavior of the resistor from the ideal.

Types of resistor



A few types of resistors

Fixed resistors

Some resistors are cylindrical, with the actual resistive material in the centre (composition resistors, now obsolete) or on the surface of the cylinder (film) resistors, and a conducting metal lead projecting along the axis of the cylinder at each end(axial lead). There are carbon film and metal film resistors. The photo above right shows a row of common resistors. Power resistors come in larger packages designed to dissipate heat efficiently. At high power levels, resistors tend to be wire wound types. Resistors used in computers and other devices are typically much smaller, often in *surface-mount* packages without wire leads. Resistors can also be built into integrated circuits as part of the fabrication process, using the semiconductor material as a resistor. But resistors made in this way are difficult to fabricate and may take up a lot of valuable chip area, so IC designers alternatively use a transistor-transistor or resistor-transistor configuration to simulate the resistor they require.

Variable resistors

Construction of a wire-wound variable resistor. The effective length of the resistive element (1) varies as the wiper turns, adjusting resistance.

This 2 kW rheostat is used for the dynamic braking of a wind turbine.

The variable resistor is a resistor whose value can be adjusted by turning a shaft or sliding a control. They are also called **potentiometers** or **rheostats** and allow the resistance of the device to be altered by hand. The term *rheostat* is usually reserved for higher-powered devices, above about ½ watt. Variable resistors can be inexpensive single-turn types or multi-turn types with a helical element. Some variable resistors can be fitted with a mechanical display to count the turns. Variable resistors can sometimes be unreliable, because the wire or metal can corrode or wear. Some modern variable resistors use plastic materials that do not corrode and have better wear characteristics.

Some examples include:

- a *rheostat*a variable resistor with two terminals, one fixed and one sliding. It is used with high currents.
- a *potentiometer*a common type of variable resistor. One common use is as volume controls on audio amplifiers and other forms of amplifiers.

Other types of resistors

- A *metal oxide varistor* (**MOV**) is a special type of resistor that changes its resistance with rise in voltagea very high resistance at low voltage (below the trigger voltage) and very low resistance at high voltage (above the trigger voltage). It acts as a switch. It is usually used for short circuit protection in power strips or lightning bolt "arrestors" on street power poles, or as a "snubber" in inductive circuits.

- A *thermistor* is a temperature-dependent resistor. There are two kinds, classified according to the sign of their temperature coefficients
    - A *Positive Temperature Coefficient* (**PTC**) resistor is a resistor with a positive temperature coefficient. When the temperature rises the resistance of the PTC increases. PTCs are often found in televisions in series with the demagnetizing coil where they are used to provide a short-duration current burst through the coil when the TV is turned on. One specialized version of a PTC is the polyswitch which acts as a self-repairing fuse.
    - A *Negative Temperature Coefficient* (**NTC**) resistor is also a temperature-dependent resistor, but with a negative temperature coefficient. When the temperature rises the resistance of the NTC drops. NTCs are often used in simple temperature detectors and measuring instruments.
- A *sensistor* is a semiconductor-based resistor with a negative temperature coefficient, useful in compensating for temperature-induced effects in electronic circuits.
- *Light-sensitive resistors* are discussed in the *photoresistor* article.
- All wire except superconducting wire has some resistance, depending on its cross-sectional area and the conductivity of the material it is made of. Resistance wire has an accurately known resistance per unit length, and is used to make wire-wound resistors.

Identifying resistors

Most axial resistors use a pattern of colored stripes to indicate resistance. SMT ones follow a numerical pattern. Cases are usually brown, blue, or green, though other colors are occasionally found like dark red or dark gray.

One can use a multimeter to test the values of a resistor.

Resistor Standards

- MIL-R-11

- MIL-R-39008
- MIL-R-39017
- BS 1852
- EIA-RS-279

There are other MIL-R- standards.

Four-band axial resistors

Electronic color code

Four-band identification is the most commonly used color coding scheme on all resistors. It consists of four colored bands that are painted around the body of the resistor. The scheme is simpleThe first two numbers are the first two significant digits of the resistance value, the third is a multiplier, and the fourth is the tolerance of the value. Each color corresponds to a certain number, shown in the chart below. The tolerance for a 4-band resistor will be 2%, 5%, or 10%.

The Standard EIA Color Code Table per EIA-RS-279 is as follows:

Color	1st band	2nd band	3rd band (multiplier)	4th band (tolerance)	Temp. Coefficient
Black	0	0	$\times 10^0$		
Brown	1	1	$\times 10^1$	±1% (F)	100 ppm
Red	2	2	$\times 10^2$	±2% (G)	50 ppm
Orange	3	3	$\times 10^3$		15 ppm
Yellow	4	4	$\times 10^4$		25 ppm
Green	5	5	$\times 10^5$	±0.5% (D)	

Blue	6	6	$\times 10^6$	±0.25% (C)
Violet	7	7	$\times 10^7$	±0.1% (B)
Gray	8	8	$\times 10^8$	±0.05% (A)
White	9	9	$\times 10^9$	
Gold			×0.1	±5% (J)
Silver			×0.01	±10% (K)
None				±20% (M)

*Note*red to violet are the colors of the rainbow where red is low energy and violet is higher energy.

Resistors use specific values, which are determined by their tolerance. These values repeat for every exponent; 6.8, 68, 680, etc. This is useful because the digits, and hence the first two or three stripes, will always be similar patterns of colors, which make them easier to recognize.

Preferred values

Resistors are manufactured in values from a few milliohms to about a gigaohm; only a limited range of values from the IEC 60063 preferred number series are commonly available. These series are called **E6**, **E12**, **E24**, **E96** and **E192**. The number tells how many standarized values exist in each decade (e.g. between 10 and 100, or between 100 and 1000). So resistors confirming to the **E12** series, can have **12** distinct values between 10 and 100; while those confirming to the **E24** series would have **24** distinct values. In practice, the discrete component sold as a "resistor" is not a perfect resistance, as defined above. Resistors are often marked with their tolerance (maximum expected variation from the marked resistance). On color coded resistors the color of the rightmost band denotes the tolerance:

silver 10%
gold 5%
red 2%
brown 1%
green 0.5%.

Closer tolerance resistors, called *precision resistors*, are also available.

Manufacturers will measure the actual resistance of new resistors and sort them by tolerance according to how close they were to the intended value. Subsequently, if you buy 100 resistors of the same value with a tolerance of +/- 10%, you *won't* get some resistors with the correct value, some off by a little and the worst off by 10%... what you'll probably find if you measure them, is that about half of the resistors are between 5% and 10% too low in value, and the other half are between 5% and 10% too high in value. Those off by less than 5%, would've been marked and sold as more expensive 5% resistors. This is something to consider when calculating specifications on the components for a project, that *all* resistors will be "off" by the specified tolerance, and not just the "worse" of them.

E12 preferred values 10, 12, 15, 18, 22, 27, 33, 39, 47, 56, 68, 82

Multiples of 10 of these values are used, eg. 0.47Ω, 4.7Ω, 47Ω, 470Ω, 4.7k, 47k, 470k etc.

E24 preferred values, includes E12 values and 11, 13, 16, 20, 24, 30, 36, 43, 51, 62, 75, 91

5-band axial resistors

5-band identification is used for higher tolerance resistors (1%, 0.5%, 0.25%, 0.1%), to notate the extra digit. The first three bands represent the significant digits, the fourth is the multiplier, and the fifth is the tolerance. 5-band standard tolerance resistors are sometimes encountered, generally on older or specialized resistors. They can be identified by noting a standard tolerance color in the 4th band. The 5th band in this case is the temperature coefficient.

Mnemonic phrases for remembering codes

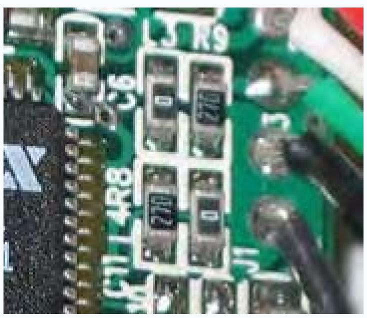
There are many mnemonic phrases used to remember the order of the colors.

They are, but are not limited to, and variations of:

- **B**ad **B**oys **R**avish **O**ur **Y**oung **G**irls **B**ut **V**iolet **G**ives **W**illingly
- **B**ad **B**eer **R**ots **O**ur **Y**oung **G**uts **B**ut **V**odka **G**oes **W**ell. **G**et **S**ome Now!
- **B**.**B**. **ROY** of **G**reat **B**ritain had a **V**ery **G**ood **W**ife
- **B**uffalo **B**ill **R**oamed **O**ver **Y**ellow **G**rass **B**ecause **V**istas **G**rand **W**ere **G**od's **S**anctuary
- **B**ully **B**rown **R**an **O**ver a **Y**odeling **G**oat, **B**ecause **V**iolet's **G**ranny **W**as **G**one **S**norkeling
- **B**uy **B**etter **R**esistance **O**r **Y**our **G**rid **B**ias **M**ay **G**o **W**rong

***B**lack **B**rown **R**ed **O**range **Y**ellow **G**reen **B**lue **V**iolet **G**ray **W**hite (**G**old **S**ilver)*

SMD resistors



This image shows some surface mosunt resistors, including two zero-ohm resistors. Zero-ohm links are often used instead of wire links, so that they can be inserted by a resistor-inserting machine.

Surface mounted resistors are printed with numerical values in a code related to that used on axial resistors. Standard-tolerance SMD resistors are marked with a three-digit code, in which the first two digits are the first two significant digits of the value and the third digit is the power of ten (the number of zeroes). For example:

"334" = 33 × 10,000 ohms = 330 kiloohms
"222" = 22 × 100 ohms = 2.2 kiloohms
"473" = 47 × 1,000 ohms = 47 kiloohms
"105" = 10 × 100,000 ohms = 1 megaohm

Resistances less than 100 ohms are written100, 220, 470. The final zero represents ten to the power zero, which is 1. For example:

"100" = 10 × 1 ohm = 10 ohms
"220" = 22 × 1 ohm = 22 ohms

Sometimes these values are marked as "10" or "22" to prevent a mistake.

Resistances less than 10 ohms have 'R' to indicate the position of the decimal point. For example:

"4R7"   = 4.7 ohms
"0R22" = 0.22 ohms
"0R01" = 0.01 ohms

Precision resistors are marked with a four-digit code, in which the first three digits are the significant figures and the fourth is the power of ten. For example:

"1001" = 100 × 10 ohms = 1 kiloohm
"4992" = 499 × 100 ohms = 49.9 kiloohm
"1000" = 100 × 1 ohm = 100 ohms

"000" and "0000" sometimes appear as values on surface-mount zero-ohm links, since these have (approximately) zero resistance.

Industrial type designation

Format*[two letters]<space>[resistance value (three digit)]<nospace>[tolerance code(numerical - one digit)]*

Power Rating at 70°C

Type No.	Power rating (Watts)	MIL-R-11 Style	MIL-R-39008 Style
BB	1/8	RC05	RCR05
CB	¼	RC07	RCR07
EB	½	RC20	RCR20
GB	1	RC32	RCR32
HB	2	RC42	RCR42
GM	3	-	-
HM	4	-	-

Tolerance Code

Industrial type designation	Tolerance	MIL Designation
5	±5%	J
2	±20%	-
1	±10%	K
-	±2%	G
-	±1%	F
-	±0.5%	D
-	±0.25%	C
-	±0.1%	B

The operational temperature range distinguishes commercial grade, industrial grade and military grade components.

- Commercial grade0°C to 70°C
- Industrial grade−40°C to 85°C (sometimes −25°C to 85°C)
- Military grade−55°C to 125°C

Calculations

Ohm's law

The relationship between voltage, current, and resistance through a metal wire, and some other materials, is given by a simple equation called Ohm's Law:

$V = IR$

where V (or U in some languages) is the voltage (or potential difference) across the wire in volts, I is the current through the wire in amperes, and R, in ohms, is a constant called the resistance. (In fact this is only a simplification of the original Ohm's law - see the article on that law for further details.) Materials that obey this law over a certain voltage or current range are said to be **ohmic** over that range. An ideal resistor obeys the law across all frequencies and amplitudes of voltage or current.

Superconducting materials at very low temperatures have zero resistance. Insulators (such as air, diamond, or other non-conducting materials) may have extremely high (but not infinite) resistance, but break down and admit a larger flow of current under sufficiently high voltage.

Power dissipation

The power dissipated by a resistor is the voltage across the resistor multiplied by the current through the resistor:

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

All three equations are equivalent. The first is derived from Joule's law, and other two are derived from that by Ohm's Law.

The total amount of heat energy released is the integral of the power over time:

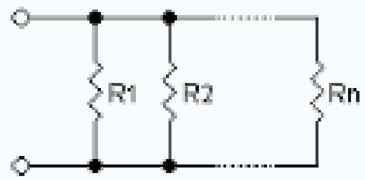
$$W = \int_{t_1}^{t_2} v(t) i(t) \, dt$$

If the average power dissipated exceeds the power rating of the resistor, then the resistor will first depart from its nominal resistance, and will then be destroyed by overheating.

Series and parallel circuits

Series and parallel circuits

Resistors in a parallel configuration each have the same potential difference (voltage). To find their total equivalent resistance (R_{eq}):



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

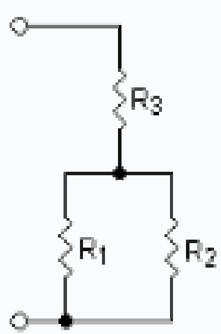
The parallel property can be represented in equations by two vertical lines "||" (as in geometry) to simplify equations. For two resistors,

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

The current through resistors in series stays the same, but the voltage across each resistor can be different. The sum of the potential differences (voltage) is equal to the total voltage. To find their total resistance:

$$R_{\mathrm{eq}} = R_1 + R_2 + \cdots + R_n$$

A resistor network that is a combination of parallel and series can sometimes be broken up into smaller parts that are either one or the other. For instance,



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

However, many resistor networks cannot be split up in this way. Consider a cube, each edge of which has been replaced by a resistor. For example, determining the resistance between two opposite vertices requires matrix methods for the general case. However, if all twelve resistors are equal, the corner-to-corner resistance is 5/6 of any one of them.

Technology

Carbon composition resistors consist of a solid cylindrical resistive element with embedded wire leadouts or metal end caps to which the leadout wires are attached, which is protected with paint or plastic. The solid cylindrical resistive element is made from a mixture of small particles of carbon and an insulating material (usually ceramic), the resistance is determined by the ratio of these, higher concentrations of carbon result in a lower resistance. Carbon composition resistors were commonly used in the 1960's and earlier, but are not so popular for general use now as other types have better specifications, such as tolerance.

The film resistors consist of a cylindrical ceramic body to which a carbon or metal oxide (eg. tin oxide) film is deposited. A spiral of the film is removed, leaving a spiral of film around the cylinder. A spiral is used to increase the length and decrease the width of the film which increases the resistance. The spiral trimming of the film is used to accurately set the value of the resistor and many different values can be made from the same film composition by altering the pitch of the spiral. Metal end caps with the leadout wires are attached to the ends of the cylinder. Or for surface mount types a nickel termination is deposited at either end of the rectangular chip. The film is protected with paint, enamel, epoxy or plastic.

Wirewound resistors are commonly made by winding a metal wire around a ceramic, plastic, or fiberglass core. The ends of the wire are soldered or welded to two caps, attached to the ends of the core. The assembly is protected with a layer of paint, molded plastic, or an enamel coating baked at high temperature. The wire leads are usually between 0.6 and 0.8 mm in diameter and tinned for ease of soldering. For higher power wirewound resistors either a ceramic outer case or an aluminium outer case ontop of an insulating layer is used. The aluminium cased types are designed to be attached to a heatsink to dissipate the heat, the rated power is dependant on being used with a suitable heatsink. eg. a 50W power rated resistor will overheat at around one fifth of the power dissipation if not used with a heatsink.

Types of resistors:

- Carbon composition
- Carbon film
- Metal film
- Metal oxide
- Wirewound (usually has higher parasitic inductance)
- Cermet
- Phenolic
- Tantalum

Foil resistor

Foil resistors have had the best precision and stability ever since they were introduced in 1958 by Berahard F. Telkamp. One of the important parameters influencing stability is the temperature coefficient of resistance (TCR). Although the TCR of foil resistors is considered extremely low, this characteristic has been further refined over the years.

Electronic engineering

Electronic engineering is a professional discipline that deals with the behavior and effects of electrons (as in electron tubes and transistors) and with electronic devices, systems, or equipment. The term now also covers a large part of electrical engineering degree courses as studied at most European universities. Its practitioners are called **electronics engineers** in Europe. In the Americas and some other parts of the world, the term electrical engineer is used to describe a person doing the same work.

In many areas, electronic engineering is considered to be at the same level as electrical engineering, requiring that more general programs be called **electrical and electronic engineering**. Both define a broad field that encompasses many subfields including those that deal with power, instrumentation engineering, telecommunications, and semiconductor circuit design amongst many others.

Terminology

The name electrical engineering is still used to cover electronic engineering amongst some of the older (notably American) universities and graduates there are called electrical engineers. In Europe, graduates of electronic engineering are known as *electronics engineers*.

Some people believe the term *electrical engineer* should be reserved for those having specialised in power and heavy current or high voltage engineering, while others believe that power is just one subset of electrical engineering (and indeed the term *power engineering* is used in that industry). Again, in recent years there has been a growth of new separate-entry degree courses such as *information and communication engineering*, often followed by academic departments of similar name.

History of electronic engineering

The modern discipline of electronic engineering was to a large extent born out of radio and television development and from the large amount of Second World War development of defence systems and weapons. In the interwar years, the subject was known as radio engineering and it was only in the late 1950s that the term **electronic engineering** started to emerge.

In the UK, the subject of electronic engineering became distinct from electrical engineering as a university degree subject around 1960. Students of electronics and related subjects like radio and telecommunications before this time had to enroll in the electrical engineering department of the university as no university had departments of electronics. Electrical engineering was the nearest subject with which electronic engineering could be aligned, although the similarities in subjects covered (except mathematics and electromagnetism) lasted only for the first year of the three-year course.

Early radio

In 1893, Nikola Tesla made the first public demonstration of radio communication. Addressing the Franklin Institute in Philadelphia and the National Electric Light Association, he described and demonstrated in detail the principles of radio communication. In 1896, Guglielmo Marconi made a wireless radio transmission and went on to develop a practical and widely used radio system. In 1904, John Ambrose Fleming , the first professor of electrical Engineering at University College London, invented the first radio tube, the diode. One year later, in 1906, Robert von Lieben and Lee De Forest independently developed the amplifier tube, called the triode.

In the interwar years the subject of electronics was dominated by the worldwide interest in *radio* and to some extent telephone and telegraph communications. The terms 'wireless' and 'radio' were then used to refer anything electronic. There were indeed few non-military applications of electronics beyond radio at that time until the advent of television. The subject was not even offered as a separate university degree subject until about 1960.

Prior to the second world war, the subject was commonly known as 'radio engineering' and basically was restricted to aspects of communications and RADAR, commercial radio and early television. At this time, study of radio engineering at universities could only be undertaken as part of a physics degree.

Later, in post war years, as consumer devices began to be developed, the field broadened to include modern TV, audio systems, Hi-Fi and latterly computers and microprocessors. In the mid to late 1950s, the term radio engineering gradually gave way to the name electronic engineering, which then became a stand alone university degree subject, usually taught alongside electrical engineering with which it had become associated due to some similarities.

Before the invention of the integrated circuit in 1959, electronic circuits were constructed from discrete components that could be manipulated by humans. These discrete circuits consumed much space and power and were limited in speed although they are still common in some applications. By contrast, integrated circuits packed a large number—often millions—of tiny electrical components, mainly transistors, into a small chip around the size of a coin. This allowed for the powerful computers and other electronic devices we see today.

Tubes or valves

The vacuum tube detector

The invention of the triode amplifier, generator, and detector enabled audio radio. On Christmas Eve, 1906, Reginald Fessenden (using his heterodyne principle) transmitted the first radio audio broadcast in history from Brant Rock, Massachusetts. Ships at sea heard a broadcast that included Fessenden playing O Holy Night on the violin and reading a passage from the Bible. The first known radio news program was broadcast 31 August 1920 by station 8MK, the unlicensed predecessor of WWJ (AM) in Detroit, Michigan. Regular wireless broadcasts for entertainment commenced in 1922 from the Marconi Research Centre at Writtle near Chelmsford, England.

While some early radios used some type of amplification through electric current or battery, through the mid 1920s the most common type of receiver was the crystal set. In the 1920s, amplifying vacuum tubes revolutionized both radio receivers and transmitters, examples may include human logic.

Phonographs and radiogrammes

This is the early name for record players or combined radios and record players that had some presence in the inter war years.

Television

In 1931 Manfred von Ardenne introduced the cathode ray tube and thus the electronic television. In the same year, the first successful transatlantic television transmission was made from London to New York. The broadcast television system adopted by the BBC in the UK was the EMI system which was chosen over the inferior mechanical system of John Logie Baird.

Radar and radio location

During WW2 many efforts were expended in the electronic location of enemy targets and aircraft. These included radio beam guidance of bombers, electronic counter measures, early radar systems etc. During this time very little if any effort was expended on consumer electronics developments.

Computers

In 1942, Konrad Zuse presented the Z3, the world's first functional computer. In 1946, the ENIAC (Electronic Numerical Integrator and Computer) of John Presper Eckert and John Mauchly followed, beginning the computing era. The arithmetic performance of these machines allowed engineers to develop completely new technologies and achieve new objectives. Early examples include the Apollo missions and the NASA moon landing.

Transistors

The invention of the transistor in 1947 by William B. Shockley, John Bardeen and Walter Brattain opened the door for more compact devices and led to the development of the integrated circuit in 1959 by Jack Kilby.

Microprocessors

In 1968, Marcian Hoff invented the microprocessor at Intel and thus ignited the development of the personal computer. Hoff's invention was part of an order by a Japanese company for a desktop computer, which Hoff wanted to build as cheaply as possible. The first realization of the microprocessor was the Intel 4004, a 4-bit processor, in 1969, but only in 1973 did the Intel 8080, an 8-bit processor, make the building of the first personal computer, the Altair 8800, possible.

Electronics

In the field of electronic engineering, engineers design and test circuits that use the electromagnetic properties of electrical components such as resistors, capacitors, inductors, diodes and transistors to achieve a particular functionality. The tuner circuit, which allows the user of a radio to filter out all but a single station, is just one example of such a circuit.

Electronics is often considered to have begun when Lee De Forest invented the vacuum tube in 1907. Within 10 years, his device was used in radio transmitters and receivers as well as systems for long distance telephone calls. Vacuum tubes remained the preferred amplifying device for 40 years, until researchers working for William Shockley at Bell Labs invented the transistor in 1947. In the following years, transistors made small portable radios, or transistor radios, possible as well as allowing more powerful mainframe computers to be built. Transistors were cooler, smaller and required lower voltages than vacuum tubes to work.

Before the invention of the integrated circuit in 1959, electronic circuits were constructed from discrete components that could be manipulated by hand. These non-integrated circuits consumed much space and power, were prone to failure and were limited in speed although they are still common in simple applications. By contrast, integrated circuits packed a large number — often millions — of tiny electrical components, mainly transistors, into a small chip around the size of a coin. This allowed for the powerful computers and other electrical devices we see today.

In designing an integrated circuit, electronics engineers first construct circuit schematics that specify the electrical components and describe the interconnections between them. When completed, VLSI engineers convert the schematics into actual layouts, which map the layers of various conductor and semiconductor materials needed to construct the circuit. The conversion from schematics to layouts can be done by software (see electronic design automation) but very often requires human fine-tuning to decrease space and power consumption. Once the layout is complete, it can be sent to a fabrication plant for manufacturing.

Integrated circuits and other electrical components can then be assembled on printed circuit boards to form more complicated circuits. Today, printed circuit boards are found in most electronic devices including televisions, computers and audio players.

Typical electronic engineering undergraduate syllabus

Apart from electromagnetics and network theory, other items in the syllabus are particular to *electronics* engineering course. *Electrical* engineering courses have other specialisms such as machines, power generation and distribution. Note that the following list does not include the large quantity of mathematics (maybe apart from the final year) included in each year's study.

Electromagnetics

Elements of vector calculusdivergence and curl; Gauss' and Stokes' theorems, Maxwell's equationsdifferential and integral forms. Wave equation, Poynting vector. Plane wavespropagation through various media; reflection and refraction; phase and group velocity; skin depth. Transmission linescharacteristic impedance; impedance transformation; Smith chart; impedance matching; pulse excitation. Waveguidesmodes in rectangular waveguides; boundary conditions; cut-off frequencies; dispersion relations. AntennasDipole antennas; antenna arrays; radiation pattern; reciprocity theorem, antenna gain.

Network theory

Network graphsmatrices associated with graphs; incidence, fundamental cut set and fundamental circuit matrices. Solution methodsnodal and mesh analysis. Network theoremssuperposition, Thevenin and Norton's maximum power transfer, Wye-Delta transformation. Steady state sinusoidal analysis using phasors. Linear constant coefficient differential equations; time domain analysis of simple RLC circuits, Solution of network equations using Laplace transformfrequency domain analysis of RLC circuits. 2-port network parametersdriving point and transfer functions. State equations for networks.

Electronic devices and circuits

Electronic Devices Energy bands in silicon, intrinsic and extrinsic silicon. Carrier transport in silicondiffusion current, drift current, mobility, resistivity. Generation and recombination of carriers. p-n junction diode, Zener diode, tunnel diode, BJT, JFET, MOS capacitor, MOSFET, LED, p-I-n and avalanche photo diode, LASERs. Device technologyintegrated circuits fabrication process, oxidation, diffusion, ion implantation, photolithography, n-tub, p-tub and twin-tub CMOS process.

Analog Circuits Equivalent circuits (large and small-signal) of diodes, BJTs, JFETs, and MOSFETs. Simple diode circuits, clipping, clamping, rectifier. Biasing and bias stability of transistor and FET amplifiers. Amplifierssingle-and multi-stage, differential, operational, feedback and power. Analysis of amplifiers; frequency response of amplifiers. Simple op-amp circuits. Filters. Sinusoidal oscillators; criterion for oscillation; single-transistor and op-amp configurations. Function generators and wave-shaping circuits. Power supplies.

Digital circuits Boolean algebra, minimization of Boolean functions; logic gates digital IC families (DTL, TTL, ECL, MOS, CMOS). Combinational circuitsarithmetic circuits, code converters, multiplexers and decoders. Sequential circuitslatches and flip-flops, counters and shift-registers. Sample and hold circuits, ADCs, DACs. Semiconductor memories. Microprocessor(8085)architecture, programming, memory and I/O interfacing.

Signals and systems

Definitions and properties of Laplace transform, continuous-time and discrete-time Fourier series, continuous-time and discrete-time Fourier Transform, z-transform. Sampling theorems. Linear Time-Invariant (LTI) Systemsdefinitions and properties; casuality, stability, impulse response, convolution, poles and zeros frequency response, group delay, phase delay. Signal transmission through LTI systems. Random signals and noiseprobability, random variables, probability density function, autocorrelation, power spectral density.

Control systems

Basic control system components; block diagrammatic description, reduction of block diagrams. Open loop and closed loop (feedback) systems and stability analysis of these systems. Signal flow graphs and their use in determining transfer functions of systems; transient and steady state analysis of LTI control systems and frequency response. Tools and techniques for LTI control system analysisroot loci, Routh-Hurwitz criterion, Bode and Nyquist plots. Control system compensatorselements of lead and lag compensation, elements of Proportional-Integral-Derivative (PID) control. State variable representation and solution of state equation of LTI control systems.

Communications

Analog communication systemsamplitude and angle modulation and demodulation systems, spectral analysis of these operations, superheterodyne receivers; elements of hardware, realizations of analog communication systems; signal-to-noise ratio (SNR) calculations for amplitude modulation (AM) and frequency modulation (FM) for low noise conditions. Digital communication systemspulse code modulation (PCM), differential pulse code modulation (DPCM), delta modulation (DM); digital modulation schemes-amplitude, phase and frequency shift keying schemes (ASK, PSK, FSK), matched filter receivers, bandwidth consideration and probability of error calculations for these schemes.

Education and training

Electronics engineers typically possess an academic degree with a major in electronic engineering. The length of study for such a degree is usually three or four years and the completed degree may be designated as a Bachelor of Engineering, Bachelor of Science or Bachelor of Applied Science depending upon the university.

The degree generally includes units covering physics, mathematics, project management and specific topics in electrical engineering. Initially such topics cover most, if not all, of the subfields of electronic engineering. Students then choose to specialize in one or more subfields towards the end of the degree.

Some electronics engineers also choose to pursue a postgraduate degree such as a Master of Engineering, a Doctor of Philosophy in Engineering or an Engineer's degree. The Master degree is being introduced in some European and American Universities as a first degree and the differentiation of an engineer with graduate and postgraduate studies is often difficult. In these cases, experience is taken into account. The Master and Engineer's degree may consist of either research, coursework or a mixture of the two. The Doctor of Philosophy consists of a significant research component and is often viewed as the entry point to academia.

In most countries, a Bachelor's degree in engineering represents the first step towards certification and the degree program itself is certified by a professional body. After completing a certified degree program the engineer must satisfy a range of requirements (including work experience requirements) before being certified. Once certified the engineer is designated the title of Professional Engineer (in the United States and

Canada), Chartered Engineer (in the United Kingdom, Ireland, India, South Africa and Zimbabwe), Chartered Professional Engineer (in Australia) or European Engineer (in much of the European Union).

Fundamental to the discipline are the sciences of physics and mathematics as these help to obtain both a qualitative and quantitative description of how such systems will work. Today most engineering work involves the use of computers and it is commonplace to use computer-aided design programs when designing electronic systems. Although most electronic engineers will understand basic circuit theory, the theories employed by engineers generally depend upon the work they do. For example, quantum mechanics and solid state physics might be relevant to an engineer working on VLSI but are largely irrelevant to engineers working with macroscopic electrical systems.

Licensure, certification, and regulation

Some locations require a license for one to legally be called an electronics engineer, or an engineer in general. For example, in the United States and Canada "only a licensed engineer may seal engineering work for public and private clients". This requirement is enforced by state and provincial legislation such as Quebec's Engineers Act. In other countries, such as Australia, no such legislation exists. Practically all certifying bodies maintain a code of ethics that they expect all members to abide by or risk expulsion. In this way these organizations play an important role in maintaining ethical standards for the profession. Even in jurisdictions where licenses are not required, engineers are subject to the law. For example, much engineering work is done by contract and is therefore covered by contract law. In cases where an engineer's work fails he or she may be subject to the tort of negligence and, in extreme cases, the charge of criminal negligence. An engineer's work must also comply with numerous other rules and regulations such as building codes and legislation pertaining to environmental law.

In locations where licenses are not required, professional certification may be advantageous.

Professional bodies

Professional bodies of note for electrical engineers include the Institute of Electrical and Electronics Engineers (IEEE) and the Institution of Electrical Engineers (IEE). The IEEE claims to produce 30 percent of the world's literature in electrical/electronic engineering, has over 360,000 members worldwide and holds over 300 conferences annually. The IEE publishes 14 journals, has a worldwide membership of 120,000, certifies Chartered Engineers in the United Kingdom and claims to be the largest professional engineering society in Europe.

Modern electronic engineering

Electronic engineering in Europe is a very broad field that encompasses many subfields including those that deal with, electronic devices and circuit design, control systems, electronics and telecommunications, computer systems, embedded software etc. Many European universities now have departments of Electronics that are completely separate from or have completely replaced their electrical engineering departments.

Subfields

Electronics engineering has many subfields. This section describes some of the most popular subfields in electronic engineering. Although there are engineers who focus exclusively on one subfield, there are also many who focus on a combination of subfields. For more information on each of the following, click the *read more...* link.

Overview of electronic engineering

Electronic engineering involves the design and testing of electronic circuits that use the electronic properties of components such as resistors, capacitors, inductors, diodes and transistors to achieve a particular functionality.

Before the invention of the integrated circuit in 1959, electronic circuits were constructed from discrete components. These non-integrated circuits consumed much space and power, and were limited in speed although they are still common in simple applications. By contrast, integrated circuits packed a large number — often millions — of tiny electrical components, mainly transistors, into a small chip around the size of a coin. This allowed for the powerful computers and other electronic devices we see today.

Signal processing deals with the analysis and manipulation of signals. Signals can be either analogue, in which case the signal varies continuously according to the information, or digital, in which case the signal varies according to a series of discrete values representing the information.

For analog signals, signal processing may involve the amplification and filtering of audio signals for audio equipment or the modulation and demodulation of signals for telecommunications. For digital signals, signal processing may involve the compression, error checking and error detection of digital signals.

Telecommunications engineering deals with the transmission of information across a channel such as a co-axial cable, optical fibre or free space.

Transmissions across free space require information to be encoded in a carrier wave in order to shift the information to a carrier frequency suitable for transmission, this is known as modulation. Popular analog modulation techniques include amplitude modulation and frequency modulation. The choice of modulation affects the cost and performance of a system and these two factors must be balanced carefully by the engineer.

Once the transmission characteristics of a system are determined, telecommunication engineers design the transmitters and receivers needed for such systems. These two are sometimes combined to form a two-way communication device known as a transceiver. A key consideration in the design of transmitters is their power consumption as this is closely related to their signal strength. If the signal strength of a transmitter is insufficient the signal's information will be corrupted by noise.

Control engineering has a wide range of applications from the flight and propulsion systems of commercial aeroplanes to the cruise control present in many modern cars. It also plays an important role in industrial automation.

Control engineers often utilize feedback when designing control systems. For example, in a car with cruise control the vehicle's speed is continuously monitored and fed back to the system which adjusts the engine's speed accordingly. Where there is regular feedback, control theory can be used to determine how the system responds to such feedback. *Read more...*

Instrumentation engineering deals with the design of devices to measure physical quantities such as pressure, flow and temperature. These devices are known as instrumentation.

The design of such instrumentation requires a good understanding of physics that often extends beyond electromagnetic theory. For example, radar guns use the Doppler effect to measure the speed of oncoming vehicles. Similarly, thermocouples use the Peltier-Seebeck effect to measure the temperature difference between two points.

Often instrumentation is not used by itself, but instead as the sensors of larger electrical systems. For example, a thermocouple might be used to help ensure a furnace's temperature remains constant. For this reason, instrumentation engineering is often viewed as the counterpart of control engineering. *Read more...*

Computer engineering deals with the design of computers and computer systems. This may involve the design of new hardware, the design of PDAs or the use of computers to control an industrial plant. Computer engineers may also work on a system's software. However, the design of complex software systems is often the domain of software engineering, which is usually considered a separate discipline.

Desktop computers represent a tiny fraction of the devices a computer engineer might work on, as computer-like architectures are now found in a range of devices including video game consoles and DVD players. *Read more...*

Project engineering

For most engineers not involved at the cutting edge of system design and development, technical work accounts for only a fraction of the work they do. A lot of time is also spent on tasks such as discussing proposals with clients, preparing budgets and determining project schedules. Many senior engineers manage a team of technicians or other engineers and for this reason project management skills are important. Most engineering projects involve some form of documentation and strong written communication skills are therefore very important.

The workplaces of electronics engineers are just as varied as the types of work they do. Electronics engineers may be found in the pristine laboratory environment of a fabrication plant, the offices of a consulting firm or in a research laboratory. During their working life, electronics engineers may find themselves supervising a wide range of individuals including scientists, electricians, computer programmers and other engineers.

Obsolescence of technical skills is a serious concern for electronics engineers. Membership and participation in technical societies, regular reviews of periodicals in the field and a habit of continued learning are therefore essential to maintaining proficiency. And these are mostly used in the field of consumer electronics products.

Electric power

Electric power is defined as the amount of work done by an electric current in a unit time.

Explanation

Electrical power is distributed via cables and electricity pylons like these in Brisbane, Australia.

When a current flows in a circuit with resistance, it does work. Devices can be made that convert this work into heat (electric heaters), light (light bulbs and neon lamps), or motion (electric motors). In our modern society, electrical power or electricity is a term not just for physical work but also for a public utility of modern infrastructure.

When a loss of electrical power occurs over a large region of a country, whether by the actions of people or nature, it is a disaster. Geomagnetic storms (solar storms) have previously caused power outages of this scale, and similar events can be anticipated in the future. More recent power outages have been primarily caused by human action and inaction . A few locations for power production and transmission facilities and hardware are classified in the United States, to prevent tampering or sabotage, because of the necessity of electrical power.

Mathematics of electric power

In circuits

Electric power, like mechanical power, is represented by the letter *P* in electrical equations, and is measured in units called watts (symbol W), named after Scottish engineer James Watt. The term **wattage** is used colloquially to mean 'electric power in watts'.

In resistive circuits, instantaneous electrical power is calculated using Joule's Law, which is named after the British physicist James Joule, who first showed that electrical and mechanical energy were interchangeable.

$$P = IV$$

where

P = power in watts
I = current in amperes
V = potential difference in volts

For example2 amperes × 12 volts = 24 watts.

Joule's law can be combined with Ohm's law to produce two more equations:

$$P = I^2 R$$

and

$$P = \frac{V^2}{R}$$

where

R = resistance in ohms.

For example:

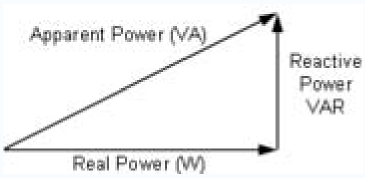
(2 amperes)^2 × 6 ohms = 24 watts

and

(12 volts)^2 / 6 ohms = 24 watts.

In reactive circuits, energy storage elements such as inductance and capacitance may result in periodic reversals of the direction of energy flow. The portion of power flow that, averaged over a complete cycle of the AC waveform, results in net transfer of energy in one direction is known as real power. That portion of power flow due to stored energy, that returns to the source in each cycle, is known as reactive power.

The unit for reactive power is given the special name *VAR*, which stands for volt-amperes-reactive. In reactive circuits, the watt unit (symbol W) is generally reserved for the real power component. The vector sum of the real power and the reactive power is called the *apparent power*. Apparent power is conventionally expressed in volt-amperes (V·A) since it is the simple multiple of rms voltage and current.



Power triangle

The relationship between real power, reactive power and apparent power can be expressed by representing the quantities as vectors. Real power is represented as a horizontal vector and reactive power is represented as a vertical vector. The apparent power vector is the hypotenuse of a right triangle formed by connecting the real and reactive power vectors. This representation is often called the *power triangle*. Using the Pythagorean Theorem, the relationship among real, reactive and apparent power is shown to be:

$$(\text{real power}/W)^2 + (\text{reactive power}/VAR)^2 = (\text{apparent power}/VA)^2.$$

In space

Electrical power flows wherever electric and magnetic fields exist in the same place. The simplest example of this is in electrical circuits, as the preceding section showed. In the general case, however, the simple equation $P = IV$ must be replaced by a more complex calculation, the integral of the vector cross-product of the electrical and magnetic fields over a specified area, thus:

$$\mathbf{P} = \int_S \mathbf{E} \times \mathbf{H} \cdot \mathbf{dA}$$

The result of this integral is a vector, since power has both magnitude and direction. For more information on this vector, see *Poynting vector*.

Power factor

The ratio between real power and apparent power in a circuit is called the power factor. Where the waveforms are purely sinusoidal, the power factor is the cosine of the phase angle (φ) between the current and voltage sinusoid waveforms. Equipment data sheets and nameplates often will abbreviate power factor as "cosφ" for this reason.

Power factor equals unity (1) when the voltage and current are in phase, and is zero when the current leads or lags the voltage by 90 degrees. Power factor must be specified as leading or lagging. For two systems transmitting the same amount of real power, the system with the lower power factor will have higher circulating currents due to energy that returns to the source from energy storage in the load. These higher currents in a practical system may produce higher losses and reduce overall transmission efficiency. A lower power factor circuit will have a higher apparent power and higher losses for the same amount of real power transfer.

Capacitive circuits cause reactive power with the current waveform leading the voltage wave by 90 degrees, while inductive circuits cause reactive power with the current waveform lagging the voltage waveform by 90 degrees. The result of this is that capacitive and inductive circuit elements tend to cancel each other out. By convention, capacitors are said to generate reactive power whilst inductors are said to consume it (this probably comes from the fact that most real-life loads are inductive and so reactive power has to be supplied to them from power factor correction capacitors).

In power transmission and distribution, significant effort is made to control the reactive power flow. This is typically done automatically by switching inductors (also commonly called reactors) or capacitor banks in and out, by adjusting generator excitation, and by other means. Electricity retailers may use electricity meters which measure reactive power to financially penalize customers with low power factor loads (especially larger customers).

Kilowatt-hour

When paired with a unit of time the term *watt* is used for expressing energy consumption. For example, a *kilowatt hour*, is the amount of energy expended by a one kilowatt device over the course of one hour; it equals 3.6 megajoules. A megawatt day (MWd or MW·d) is equal to 86.4 GJ. These units are often used in the context of power plants and home energy bills.

Electromagnetic field

Classically, the **electromagnetic field** is a physical influence (a field) that permeates through all of space, and which arises from electrically charged objects and describes one of the four fundamental forces of nature - electromagnetism. It can be viewed as the combination of an electric field and a magnetic field. The electric field is produced by non-moving charges and the magnetic field by moving charges (currents); these two are often described as the sources of the field. The way in which charges and currents interact with the electromagnetic field is described by Maxwell's equations and the Lorentz Force Law. From a non-classical quantum mechanical point of view, the electromagnetic field can be regarded as due to the exchange of virtual photons.

Nature of the electromagnetic field

As with many physical concepts, there are various ways of thinking about the electromagnetic field. The field may be viewed in two distinct ways.

Continuous structure

Classically, electric and magnetic fields are thought of as being produced by smooth motions of charged objects. For example, oscillating charges produce electric and magnetic fields that may be viewed in a 'smooth', continuous, wavelike manner. In this case, energy is viewed as being transferred continuously through the electromagnetic field between any two locations. For instance, the metal atoms in a radio transmitter appear to transfer energy continuously. This view is useful to a certain extent (radiation of low frequency), but problems are found at high frequencies (see ultraviolet catastrophe). This problem leads to another view.

Discrete structure

The electromagnetic field may be thought of in a more 'coarse' way. Experiments reveal that electromagnetic energy transfer is better described as being carried away in 'packets' or 'chunks' called photons with a fixed frequency. Planck's relation links the energy E of a photon to its frequency f through the equation:

$$E = h\,\nu$$

where *h* is Planck's constant, named in honour of Max Planck, and ν is the frequency of the photon . For example, in the photoelectric effect - the emission of electrons from metallic surfaces by electromagnetic radiation - it is found that increasing the intensity of the incident radiation has no effect and only the frequency of the radiation is relevant in ejecting electrons.

This quantum picture of the electromagnetic field has proved very successful, giving rise to quantum electrodynamics, a quantum field theory which describes the interaction of electromagnetic radiation with charged matter.

Dynamics

In the past, electrically charged objects were thought to produce two types of field associated with their charge property. An electric field is produced when the charge is stationary with respect to an observer measuring the properties of the charge and a magnetic field (as well as an electric field) is produced when the charge moves (creating an electric current) with respect to this observer. Over time, it was realised that the electric and magnetic fields are better thought of as two parts of a greater whole - the electromagnetic field.

Once this electromagnetic field has been produced from a given charge distribution, other charged objects in this field will experience a force (in a similar way that planets experience a force in the gravitational field of the Sun). If these other charges and currents are comparable in size to the sources producing the above electromagnetic field, then a new net electromagnetic field will be produced. Thus, the electromagnetic field may be viewed as a dynamic entity that causes other charges and currents to move and which is also affected by them. These interactions are described by Maxwell's equations and the Lorentz force law.

Mathematical description

There are different mathematical ways of representing the electromagnetic field.

Vector field approach

The electric and magnetic fields are usually described by the use of three-dimensional vector fields. These vector fields each have a value defined at every point of space and time and are thus often regarded as functions of the space and time coordinates. As such, they are often written as $\vec{E}(x, y, z, t)$ (electric field) and $\vec{B}(x, y, z, t)$ (magnetic field).

If only the electric field ($\vec{E}$) is non-zero, and is constant in time, the field is said to be an electrostatic field. Similarly, if only the magnetic field ($\vec{B}$) is non-zero and is constant in time, the field is said to be a magnetostatic field. However, if either the electric or magnetic field has a time-dependence, then both fields must be considered together as a coupled electromagnetic field using Maxwell's equations.

The behaviour of electric and magnetic fields, whether in cases of electrostatics, magnetostatics, or electrodynamics (electromagnetic fields), is governed in a vacuum by Maxwell's equations:

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$ (Gauss' Law - electrostatics)

$$\nabla \cdot \vec{B} = 0$$ (Gauss' Law - magnetostatics)

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$ (Faraday's Law)

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}$$ (Ampère-Maxwell Law)

where ρ is the charge density, which can (and often does) depend on time and position, ε_0 is the permittivity of free space, μ_0 is the permeability of free space, and $\vec{J}$ is the current density vector, also a function of time and position. The units used above are the standard SI units. Inside a linear material, Maxwell's equations change by switching the permeability and permitivity of free space with the permeability and permitivity of the linear material in question. Inside other materials which possess more complex responses to electromagnetic fields, these terms are often represented by complex numbers, or tensors.

Maxwell's equations, when they were first stated in their complete form in 1865, would turn out to be compatible with special relativity. Moreover, the apparent coincidences in which the same effect was observed due to different physical phenomena by two different observers would be shown to be not coincidental in the least by special relativity. In fact, half of Einstein's first paper on special relativity, On the Electrodynamics of Moving Bodies, is taken up by explanations of the transformation of Maxwell's equations.

The electric and magnetic fields transform under a Lorentz boost, a relativistic transformation of coordinates, in the direction $\vec{v}$ as:

$$\vec{E}' = \gamma\left(\vec{E} + \vec{v} \times \vec{B}\right) - \left(\frac{\gamma - 1}{v^2}\right)(\vec{E} \cdot \vec{v})\vec{v}$$
$$\vec{B}' = \gamma\left(\vec{B} - \frac{\vec{v} \times \vec{E}}{c^2}\right) - \left(\frac{\gamma - 1}{v^2}\right)(\vec{B} \cdot \vec{v})\vec{v}$$

Component by component, for relative motion along the x-axis, this works out to be the following:

$$E'_x = E_x$$
$$E'_y = \gamma\left(E_y - vB_z\right)$$
$$E'_z = \gamma\left(E_z + vB_y\right)$$
$$B'_x = B_x$$
$$B'_y = \gamma\left(B_y + \frac{v}{c^2}E_z\right)$$
$$B'_z = \gamma\left(B_z - \frac{v}{c^2}E_y\right)$$

Finally, one thing worth noting is that if one of the fields is zero in one frame of reference, that doesn't necessarily mean it is zero in all other frames of reference. This can be seen by, for instance, making the unprimed electric field zero in the transformation to the primed electric field. In this case, depending on the orientation of the magnetic field, the primed system could see an electric field, even though there is none in the unprimed system.

It should be stressed when stating this that this does not mean two completely different sets of events are seen in the two frames, but that the same sequence of events is described in two different ways. The classic example, and the one cited by Einstein in his paper the Electrodynamics of Moving Bodies, is that of a magnet and a conductor. If the conductor is held at rest, but the magnet moves, then there is a magnetic field which changes with time, which according to Faraday's Law produces an electric field, which in turn causes a current to flow in the conductor. However, if the magnet is held stationary but the conductor moves, the charges in the conductor that are moving with the conductor as a whole form a kind of current, which produces a magnetic field which then causes current to flow. Assuming that in these cases, the object in motion in one of these cases has a velocity that is identical in speed but opposite in direction to the velocity of the object in motion in the other case, then the results are identical. A current, with the same strength, direction and electromotive force, is induced in the conductor.

Potential field approach

Many times in the use and calculation of electric and magentic fields, the approach used first computes an associated potentialthe electric potential for the electric field, and the magnetic potential for the magnetic field. The electric potential is a scalar field, while the magnetic potential is a vector field. This is why sometimes the electric potential is called the scalar potential and the magnetic potential is called the vector potential. These potentials can be used to find their associated fields as follows:

$$\vec{E} = -\vec{\nabla}V - \frac{\partial \vec{A}}{\partial t}$$

$$\vec{B} = \vec{\nabla} \times \vec{A}$$

These relations can be plugged into Maxwell's equations to find them in terms of the potentials. Faraday's Law and Gauss's Law for magnetostatics reduce to identities (i.e. in the case of Gauss's Law for magnetostatics, 0 = 0). The other two of Maxwell's equations don't turn out so simply.

$$\nabla^2 V + \frac{\partial}{\partial t}\left(\vec{\nabla} \cdot \vec{A}\right) = -\frac{\rho}{\varepsilon_0}$$ (Gauss's Law for electrostatics)

$$\left(\nabla^2 \vec{A} - \mu_0\varepsilon_0 \frac{\partial^2 \vec{A}}{\partial t^2}\right) - \vec{\nabla}\left(\vec{\nabla} \cdot \vec{A} + \mu_0\varepsilon_0 \frac{\partial V}{\partial t}\right) = -\mu_0 \vec{J}$$ (Ampère-Maxwell Law)

These equations taken together are as powerful and complete as Maxwell's equations. Moreover, the problem has been reduced somewhat, as between the electric and magnetic fields, each had three components which needed to be solved for, meaning it was necessary to solve for six quantities. In the potential formulation, there are only four quantities, the electric potential and the three components of the scalar potential.

However, this improvement is contrasted with the equations being much messier than Maxwell's equations using just the electric and magnetic fields.

Fortunately, there is a way to simplify these equations that takes advantage of the fact that the potential fields are not what is observed, the electric and magnetic fields are. Thus there is a freedom to impose conditions on the potentials so long as whatever condition we choose to impose does not affect the resultant electric and magnetic fields. This freedom is called gauge freedom. Specifically for these equations, for any choice of a scalar function of position and time λ, we can change the potentials as follows:

$$\vec{A}' = \vec{A} + \vec{\nabla}\lambda$$
$$V' = V - \frac{\partial \lambda}{\partial t}$$

This freedom can be used to greatly simplify the potential formulation. Generally, two such scalar functions are chosen. The first is chosen in such a way that $\vec{\nabla} \cdot \vec{A} = 0$, which corresponds to the case of magnetostatics. In terms of λ, this means that it must satisfy the equation $\nabla^2 \lambda = -\vec{\nabla} \cdot \vec{A}$. This choice of function is generally called the Coloumb gauge, and results in the following formulation of Maxwell's equations:

$$\nabla^2 V = -\frac{\rho}{\varepsilon_0}$$
$$\nabla^2 \vec{A} - \mu_0 \varepsilon_0 \frac{\partial^2 \vec{A}}{\partial t^2} = -\mu_0 \vec{J} + \mu_0 \varepsilon_0 \nabla \left(\frac{\partial V}{\partial t} \right)$$

There are several things worth noting about Maxwell's equations in the Coloumb gauge. Firstly, solving for the electric potential is very easy, as the equation is a version of Poisson's equation. Secondly, solving for the magnetic vector potential is particularly hard to calculate. This is the big disadvantage of this gauge. The third thing to note, and something which is not immediately obvious, is that the electric potential changes instantly everywhere in response to a change in conditions in one locality.

For instance, if a charge is moved in New York at 1pm local time, then a hypothetical observer in Australia who could measure the electric potential directly would measure a change in the potential at 1pm New York time. This seemingly goes against the prohibition in special relativity of sending information, signals, or anything faster than the speed of light. The solution to this apparent problem lays in the fact that, as previously stated, no observer measures the potentials, they measure the electric and magnetic fields. So, the combination of ∇V and $\frac{\partial \vec{A}}{\partial t}$ used in determining the electric field restores the speed limit imposed by special relativity for the electric field, making all observable quantities consistent with relativity.

The second scalar function that is used very often is called the Lorenz gauge. This gauge chooses the scalar function λ such that $\vec{\nabla} \cdot \vec{A} = -\mu_0 \varepsilon_0 \frac{\partial V}{\partial t}$. This means λ must satisfy the equation $\nabla^2 \lambda = -\vec{\nabla} \cdot \vec{A} - \mu_0 \varepsilon_0 \frac{\partial V}{\partial t}$. The Lorenz gauge results in the following form of Maxwell's equations:

$$\nabla^2 \vec{A} - \mu_0 \varepsilon_0 \frac{\partial^2 \vec{A}}{\partial t^2} = \Box^2 \vec{A} = -\mu_0 \vec{J}$$
$$\nabla^2 V - \mu_0 \varepsilon_0 \frac{\partial^2 V}{\partial t^2} = \Box^2 V = -\frac{\rho}{\varepsilon_0}$$

The operator $\Box^2$ is called the d'Alembertian. These equations are inhomogenous versions of the wave equation, with the terms on the right side of the equation serving as the source functions for the wave. These equations lead to two solutionsadvanced potentials (which depend on the configuration of the sources at future points in time), and retarded potentials (which depend on the past configurations of the sources); the former are usually (and sensibly) dismissed as 'non-physical' in favor of the latter, which preserve causality.

It must be strongly emphasized that, as pointed out above, the Lorentz gauge is no more valid than any other gauge, as the potentials themselves are unobservable (with only a few loopholes, such as the Aharonov-Bohm effect, that still leave gauge invariance intact); any acausality exhibited by the potentials will vanish for the observable fields, which are the physically meaningful quantities.

Tensor field approach

The electric and magnetic fields can be combined together mathematically to form an antisymmetric, second-rank tensor, or a bivector, usually written as $F^{\mu\nu}$. This is called the electromagnetic field tensor, and it puts the electric and magnetic forces on the same footing. In matrix form, the tensor is as below.

$$F^{\mu\nu} = \begin{vmatrix} 0 & \frac{E_x}{c} & \frac{E_y}{c} & \frac{E_z}{c} \\ -\frac{E_x}{c} & 0 & B_z & -B_y \\ -\frac{E_y}{c} & -B_z & 0 & B_x \\ -\frac{E_z}{c} & B_y & -B_x & 0 \end{vmatrix}$$

where

```
   E is the electric field
   B the magnetic field and
   c the speed of light. When using natural units, the speed of light
is taken to equal 1.
```

There is actually another way of merging the electric and magnetic fields into an antisymmetric tensor, by replacing $\frac{\vec{E}}{c} \rightarrow \vec{B}$ and $\vec{B} \rightarrow -\frac{\vec{E}}{c}$, to get the dual tensor $G^{\mu\nu}$.

$$G^{\mu\nu} = \begin{vmatrix} 0 & B_x & B_y & B_z \\ -B_x & 0 & -\frac{E_z}{c} & \frac{E_y}{c} \\ -B_y & \frac{E_z}{c} & 0 & -\frac{E_x}{c} \\ -B_z & -\frac{E_y}{c} & \frac{E_x}{c} & 0 \end{vmatrix}$$

In the context of special relativity, both of these transform according to the Lorentz transformation like $F'^{\alpha\beta} = \Lambda^{\alpha}_{\mu}\Lambda^{\beta}_{\nu}F^{\mu\nu}$, where the Λ^{α}_{ν} are the Lorentz transformation tensors for a given change in reference frame. Though there are two such tensors in the equation, they are the same tensor, just used in the summation differently.

Examples

Here are two examples of transformations of the field tensor. Both are transformations due to observers moving with repect to each other on the x-axis. The first transformation shows how the unprimed observer can see an electric field, designated *E*, only in the positive z-axis direction, transform such that the primed observer, moving with velocity

$\beta = \frac{v}{c}$ along the x-axis with respect to the unprimed observer, sees both electric and magnetic fields.

$$F^{\mu\nu} = \begin{vmatrix} 0 & 0 & 0 & \frac{E}{c} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -\frac{E}{c} & 0 & 0 & 0 \end{vmatrix}$$
$$\Lambda^{\sigma}_{\mu} = \Lambda^{\tau}_{\nu} = \begin{vmatrix} \gamma & -\gamma\beta & 0 & 0 \\ -\gamma\beta & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$
$$F'^{\sigma\tau} = \Lambda^{\sigma}_{\mu}\Lambda^{\tau}_{\nu}F^{\mu\nu}$$

So, in the above, it's clear that the field tensor term is zero everywhere, except where μ = 0,ν = 3 or where μ = 3,ν = 0. The results are as below.

$$F'^{00} = \Lambda^{0}_{\mu}\Lambda^{0}_{\nu}F^{\mu\nu} = 0$$
$$F'^{01} = \Lambda^{0}_{\mu}\Lambda^{1}_{\nu}F^{\mu\nu} = 0$$
$$F'^{02} = \Lambda^{0}_{\mu}\Lambda^{2}_{\nu}F^{\mu\nu} = 0$$
$$F'^{03} = \Lambda^{0}_{\mu}\Lambda^{3}_{\nu}F^{\mu\nu} = \gamma\left(\frac{E}{c}\right)$$
$$F'^{10} = \Lambda^{1}_{\mu}\Lambda^{0}_{\nu}F^{\mu\nu} = 0$$
$$F'^{11} = \Lambda^{1}_{\mu}\Lambda^{1}_{\nu}F^{\mu\nu} = 0$$
$$F'^{12} = \Lambda^{1}_{\mu}\Lambda^{2}_{\nu}F^{\mu\nu} = 0$$
$$F'^{13} = \Lambda^{1}_{\mu}\Lambda^{3}_{\nu}F^{\mu\nu} = -\gamma\beta\left(\frac{E}{c}\right)$$
$$F'^{20} = \Lambda^{2}_{\mu}\Lambda^{0}_{\nu}F^{\mu\nu} = 0$$
$$F'^{21} = \Lambda^{2}_{\mu}\Lambda^{1}_{\nu}F^{\mu\nu} = 0$$
$$F'^{22} = \Lambda^{2}_{\mu}\Lambda^{2}_{\nu}F^{\mu\nu} = 0$$
$$F'^{23} = \Lambda^{2}_{\mu}\Lambda^{3}_{\nu}F^{\mu\nu} = 0$$
$$F'^{30} = \Lambda^{3}_{\mu}\Lambda^{0}_{\nu}F^{\mu\nu} = -\gamma\left(\frac{E}{c}\right)$$
$$F'^{31} = \Lambda^{3}_{\mu}\Lambda^{1}_{\nu}F^{\mu\nu} = \gamma\beta\left(\frac{E}{c}\right)$$

$$F'^{32} = \Lambda^3_\mu \Lambda^2_\nu F^{\mu\nu} = 0$$
$$F'^{33} = \Lambda^3_\mu \Lambda^3_\nu F^{\mu\nu} = 0$$

The result, in matrix form, looks like this:

$$F'^{\sigma\tau} = \begin{vmatrix} 0 & 0 & 0 & \gamma\frac{E}{c} \\ 0 & 0 & 0 & -\gamma\beta\frac{E}{c} \\ 0 & 0 & 0 & 0 \\ -\gamma\frac{E}{c} & \gamma\beta\frac{E}{c} & 0 & 0 \end{vmatrix}$$

As can be seen, if one compares this result with the general form of the field tensor shown above, two things have occurred. Firstly, the primed observer sees the electrical field as being stronger than the unprimed observer. Secondly, the primed observer sees a magnetic field in the positive y-axis direction that the unprimed observer does not see. This hints at the reason that magnetism is sometimes called a relativistic phenomenon.

However, it is not true that all Lorentz transformations on a field tensor with only an electric component will produce a magnetic component. The following example illustrates this, with the same two observers as above, but with the electric field being in the positive x-axis direction instead of the positive z-axis direction. This direction is in the same direction of the relative velocity between the two observers.

$$F^{\mu\nu} = \begin{vmatrix} 0 & \frac{E}{c} & 0 & 0 \\ -\frac{E}{c} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{vmatrix}$$
$$\Lambda^\sigma_\mu = \Lambda^\tau_\nu = \begin{vmatrix} \gamma & -\gamma\beta & 0 & 0 \\ -\gamma\beta & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$
$$F'^{\sigma\tau} = \Lambda^\sigma_\mu \Lambda^\tau_\nu F^{\mu\nu}$$

So, in the above, it's clear that the field tensor term zero everywhere except where $\mu = 0, \nu = 1$ or where $\mu = 1, \nu = 0$. The results are as below.

$$F'^{00} = \Lambda^0_\mu \Lambda^0_\nu F^{\mu\nu} = \Lambda^0_0 \Lambda^0_1 F^{01} + \Lambda^0_1 \Lambda^0_0 F^{10} = -\gamma^2\beta\frac{E}{c} + \gamma^2\beta\frac{E}{c} = 0$$

$$F'^{01} = \Lambda^0_\mu \Lambda^1_\nu F^{\mu\nu} = \Lambda^0_0 \Lambda^1_1 F^{01} + \Lambda^0_1 \Lambda^1_0 F^{10} = \gamma^2 \frac{E}{c} - \gamma^2 \beta^2 \frac{E}{c} = \frac{E}{c}$$
$$F'^{02} = \Lambda^0_\mu \Lambda^2_\nu F^{\mu\nu} = 0$$
$$F'^{03} = \Lambda^0_\mu \Lambda^3_\nu F^{\mu\nu} = 0$$
$$F'^{10} = \Lambda^1_\mu \Lambda^0_\nu F^{\mu\nu} = \Lambda^1_0 \Lambda^0_1 F^{01} + \Lambda^1_1 \Lambda^0_0 F^{10} = \gamma^2 \beta^2 \frac{E}{c} - \gamma^2 \frac{E}{c} = -\frac{E}{c}$$
$$F'^{11} = \Lambda^1_\mu \Lambda^1_\nu F^{\mu\nu} = \Lambda^1_0 \Lambda^1_1 F^{01} + \Lambda^1_1 \Lambda^1_0 F^{10} = -\gamma^2 \beta \frac{E}{c} + \gamma^2 \beta \frac{E}{c} = 0$$
$$F'^{12} = \Lambda^1_\mu \Lambda^2_\nu F^{\mu\nu} = 0$$
$$F'^{13} = \Lambda^1_\mu \Lambda^3_\nu F^{\mu\nu} = 0$$
$$F'^{20} = \Lambda^2_\mu \Lambda^0_\nu F^{\mu\nu} = 0$$
$$F'^{21} = \Lambda^2_\mu \Lambda^1_\nu F^{\mu\nu} = 0$$
$$F'^{22} = \Lambda^2_\mu \Lambda^2_\nu F^{\mu\nu} = 0$$
$$F'^{23} = \Lambda^2_\mu \Lambda^3_\nu F^{\mu\nu} = 0$$
$$F'^{30} = \Lambda^3_\mu \Lambda^0_\nu F^{\mu\nu} = 0$$
$$F'^{31} = \Lambda^3_\mu \Lambda^1_\nu F^{\mu\nu} = 0$$
$$F'^{32} = \Lambda^3_\mu \Lambda^2_\nu F^{\mu\nu} = 0$$
$$F'^{33} = \Lambda^3_\mu \Lambda^3_\nu F^{\mu\nu} = 0$$

In the above, the following relation was used less explicitly.

$$\gamma^2 - \gamma^2 \beta^2 = \frac{1}{\sqrt{1-\beta^2}^2} - \frac{\beta^2}{\sqrt{1-\beta^2}^2} = \frac{1-\beta^2}{1-\beta^2} = 1$$

The result, in matrix form, looks like this:

$$F'^{\mu\nu} = \begin{vmatrix} 0 & \frac{E}{c} & 0 & 0 \\ -\frac{E}{c} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{vmatrix}$$

Not only does no magnetic component show up, but the whole tensor is unchanged.

Maxwell's Equations in Tensor Notation

Using this tensor notation, Maxwell's equations have the following form.

$$F^{\alpha\beta}_{,\beta} = \frac{\partial F^{\alpha\beta}}{\partial x^\beta} = \mu_0 J^\alpha$$
$$G^{\alpha\beta}_{,\beta} = \frac{\partial G^{\alpha\beta}}{\partial x^\beta} = 0$$

In the above, the tensor notation $f_{,\alpha}$ is used to denote partial derivatives, $\frac{\partial f}{\partial x^\alpha}$. The four-vector J^α is called the current density four-vector, which is the relativistic analogue to the charge density and current density. This four-vector is as follows.

$$J^\alpha = \begin{pmatrix} c\rho & J_x & J_y & J_z \end{pmatrix}$$

The first equation listed above corresponds to both Gauss's Law (for $\alpha = 0$) and the Ampère-Maxwell Law (for $\alpha = 1,2,3$). The second equation corresponds to the two remaining equations, Gauss's Law for magnetism (for $\alpha = 0$) and Faraday's Law (for $\alpha = 1,2,3$).

This short form of writing Maxwell's equations illustrates an idea shared amongst some physicists, namely that the laws of physics take on a simpler form when written using tensors.

Properties of the field

Reciprocal behaviour of electric and magnetic fields

The two Maxwell equations, Faraday's Law and the Ampère-Maxwell Law, illustrate a very practical feature of the electromagnetic field. Faraday's Law may be stated roughly as 'a changing magnetic field creates an electric field'. This is the principle behind the electric motor.

The Ampère-Maxwell Law roughly states that 'a changing electric field creates a magnetic field'. Thus, this law can be applied to generate a magnetic field.

Light as an electromagnetic disturbance

Maxwell's equations take the following, free space, form in an area that is very far away from any charges or currents - that is where ρ and $\vec{J}$ are zero.

$$\nabla \cdot \vec{E} = 0$$
$$\nabla \cdot \vec{B} = 0$$
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$
$$\nabla \times \vec{B} = \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$

In the above, the substitution $\mu_0\epsilon_0 = \frac{1}{c^2}$ has been made, where *c* is the speed of light. Taking the curl of the last two equations, the result is as follows.

$$\nabla \times \nabla \times \vec{E} = \nabla\left(\nabla \cdot \vec{E}\right) - \nabla^2\vec{E} = \nabla \times \left(-\frac{\partial \vec{B}}{\partial t}\right)$$
$$\nabla \times \nabla \times \vec{B} = \nabla\left(\nabla \cdot \vec{B}\right) - \nabla^2\vec{B} = \nabla \times \left(\frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}\right)$$

However, the first two equations mean $\nabla\left(\nabla \cdot \vec{E}\right) = \nabla\left(\nabla \cdot \vec{B}\right) = 0$. So plugging this in, and moving the curls within the time derivates and then plugging in for the resultant curls, the result is as follows.

$$-\nabla^2\vec{E} = -\frac{\partial\left(\nabla \times \vec{B}\right)}{\partial t} = -\frac{\partial}{\partial t}\left(\frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}\right) = -\frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2}$$
$$-\nabla^2\vec{B} = \frac{1}{c^2}\frac{\partial\left(\nabla \times \vec{E}\right)}{\partial t} = \frac{1}{c^2}\frac{\partial}{\partial t}\left(-\frac{\partial \vec{B}}{\partial t}\right) = -\frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2}$$

Or:

$$\nabla^2\vec{E} = \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2}$$
$$\nabla^2\vec{B} = \frac{1}{c^2}\frac{\partial^2 \vec{B}}{\partial t^2}$$

Or even:

$$\Box^2 \vec{E} = 0$$
$$\Box^2 \vec{B} = 0$$

In this last form, the $\Box^2$ is the d'Alembertian, which is $\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}$, so the last two forms are the same thing written in two different ways. However, these equations are wave equations. That is valid electric fields and magnetic fields have an oscillatory form, such as a sinusoid, which result in wave behaviors. Moreover, the first two of the free space Maxwell's equations imply that the waves are transverse waves. The last two of the free space Maxwell's equations imply that the wave of the electric field is in phase with and perpendicular to the magnetic field wave. Moreover, the c^2 term represents the speed of the wave. So these electromagnetic waves travel at the speed of light. James Clerk Maxwell, after whom Maxwell's equations are named, suggested when he made these calculations that as these waves travel at the same speed as light, that light would actually be such a wave. His suggestion proved correct, and light is indeed an electromagnetic wave.

Relation to and comparison with other physical fields

Fundamental forces

Being one of the four fundamental forces of nature, it is useful to compare the electromagnetic field with the gravitational, strong and weak fields. The word 'force' is sometimes replaced by 'interaction'.

Electromagnetic and gravitational fields

Sources of electromagnetic fields consist of two types of charge - positive and negative. This contrasts with the sources of the gravitational field, which are masses. Masses are sometimes described as 'gravitational charges', the important feature of them being that there is only one type (no 'negative masses'), or, in more colloquial terms, 'gravity is always attractive'.

The relative strengths and ranges of the four interactions and other information are tabulated below:

Theory	Interaction	mediator	Relative Magnitude	Behavior	Range
Chromodynamics	Strong interaction	gluon	10^{38}	1	infinite
Electrodynamics	Electromagnetic interaction	photon	10^{36}	$1/r^2$	infinite
Flavordynamics	Weak interaction	W and Z bosons	10^{25}	$1/r^5$ to $1/r^7$	10^{-18} m
Geometrodynamics	Gravitation	graviton	10^0	$1/r^2$	infinite

Applications

Properties of the electromagnetic field are exploited in many areas of industry. The use of electromagnetic radiation is seen in various disciplines. For example, X-rays are high frequency electromagnetic radiation and are used in radio astronomy, radiography in medicine and radiometry in telecommunications. Other medical applications include laser therapy, which is an example of photomedicine. Applications of lasers are found in military devices such as laser-guided bombs, as well as more down to earth devices such as barcode readers and CD players. Something as simple as a relay in any electrical device uses an electromagnetic field to engage or to disengage the two different states of output (ie, when electricity is not applied, the metal strip will connect output A and B, but if electricity is applied, an electromagnetic field will be created and the metal strip will connect output A and C).

The electromagnetic field as a feedback loop

The behavior of the electromagnetic field can be resolved into four different parts of a loop(1) the electric and magnetic fields are generated by electric charges, (2) the electric and magnetic fields interact only with each other, (3) the electric and magnetic fields produce forces on electric charges, (4) the electric charges move in space.

The feedback loop can be summarized in a list, including phenomena belonging to each part of the loop:

- charges generate fields
  - Gauss's law Coulomb's lawcharges generate electric fields
  - Ampère's lawcurrents generate magnetic fields (★)
- the fields interact with each other

    - displacement currentchanging electric field acts like a current, generating 'vortex' (curl) of magnetic field
    - Faraday inductionchanging magnetic field induces (negative) vortex of electric field
    - Lenz's lawnegative feedback loop between electric and magnetic fields
    - Maxwell-Hertz equationssimplified version of Maxwell's equations
    - electromagnetic wave equation
- fields act upon charges
    - Lorentz forceforce due to electromagnetic field
        - electric forcesame direction as electric field
        - magnetic forceperpendicular both to magnetic field and to velocity of charge (★)
- charges move
    - continuity equationcurrent is movement of charges

Phenomena in the list are marked with a star (★) if they consist of magnetic fields and moving charges which can be reduced by suitable Lorentz transformations to electric fields and static charges. This means that the magnetic field ends up being (conceptually) reduced to an appendage of the electric field, i.e. something which interacts with reality only indirectly through the electric field.

Mechanics

Mechanics (Greek *Μηχανική*) is the branch of physics concerned with the behaviour of physical bodies when subjected to forces or displacements, and the subsequent effect of the bodies on their environment.

The discipline has its roots in the old Greece where people like Aristotle studied the way bodies behaved when they were thrown through the air (e.g. a stone). However it was Galileo, Kepler and especially Newton who lay the foundation for much of the so called Newtonian mechanics we know today.

A person working in the discipline is known as a **mechanician**.

Significance

Mechanics is the original discipline of physics, dealing with the macroscopic world that humans perceive. It is therefore a huge body of knowledge about the natural world. Mechanics encompasses the movement of all matter in the universe under the four fundamental interactions (or forces)gravity, the strong and weak interactions, and the electromagnetic interaction.

Mechanics also constitutes a central part of technology, the application of physical knowledge for humanly defined purposes. In this connection, the discipline is often known as engineering or applied mechanics. In this sense, mechanics is used to design and analyze the behavior of structures, mechanisms, and machines. Important aspects of the fields of mechanical engineering, aerospace engineering, civil engineering, structural engineering, materials engineering, biomedical engineering and biomechanics were spawned from the study of mechanics.

Classical vs. Quantum

The major division of the mechanics discipline separates classical mechanics from quantum mechanics.

Historically, classical mechanics came first, while quantum mechanics is a comparatively recent invention. Classical mechanics is older than written history, while quantum mechanics didn't appear until 1900. Both are commonly held to constitute the most certain knowledge that exists about physical nature. Classical mechanics has especially often been viewed as a model for other so-called exact sciences. Essential in this respect is the relentless use of mathematics in theories, as well as the decisive role played by experiment in generating and testing them.

Quantum mechanics is, formally at least, of the widest scope, and can be seen as encompassing classical mechanics, as a sub-discipline which applies under certain restricted circumstances. According to the correspondence principle, there is no contradiction or conflict between the two subjects, each simply pertains to specific situations. While it is true that historically quantum mechanics has been seen as having superseded classical mechanics, this is only true on the hypothetical or foundational level. For practical problems, classical mechanics is able to solve problems which are unmanageably difficult in quantum mechanics and hence remains useful and well used.

Einsteinian vs. Newtonian

Analogous to the quantum vs. classical reformation, Einstein's general and special theories of relativity have expanded the scope of mechanics beyond the mechanics of Newton and Galileo, and made small corrections to them. Relativistic corrections were also needed for quantum mechanics, although relativity is categorized as a classical theory.

There are no contradictions or conflicts between the two, so long as the specific circumstances are carefully kept in mind. Just as one could, in the loosest possible sense, characterize classical mechanics as dealing with "large" bodies (such as engine parts), and quantum mechanics with "small" ones (such as particles), it could be said that relativistic mechanics deals with "fast" bodies, and non-relativistic mechanics with "slow" ones. However, "fast" and "slow" are relative concepts, depending on the state of motion of the observer. This means that all mechanics, whether classical or quantum, potentially needs to be described relativistically. On the other hand, as an observer, one may frequently arrange the situation in such a way that this is not really required.

Types of mechanical bodies

Thus the often-used term **body** needs to stand for a wide assortment of objects, including particles, projectiles, spacecraft, stars, parts of machinery, parts of solids, parts of fluids (gases and liquids), etc.

Other distinctions between the various sub-disciplines of mechanics, concern the nature of the bodies being described. Particles are bodies with little (known) internal structure, treated as mathematical points in classical mechanics. Rigid bodies have size and shape, but retain a simplicity close to that of the particle, adding just a few so-called degrees of freedom, such as orientation in space.

Otherwise, bodies may be semi-rigid, i.e. elastic, or non-rigid, i.e. fluid. These subjects have both classical and quantum divisions of study.

For instanceThe motion of a spacecraft, regarding its orbit and attitude (rotation), is described by the relativistic theory of classical mechanics. While analogous motions of an atomic nucleus are described by quantum mechanics.

Sub-disciplines in mechanics

The following are two lists of various subjects that are studied in mechanics.

Note that there is also the "theory of fields" which constitutes a separate discipline in physics, formally treated as distinct from mechanics, whether classical fields or quantum fields. But in actual practice, subjects belonging to mechanics and fields are closely interwoven. Thus, for instance, forces that act on particles are frequently derived from fields (electromagnetic or gravitational), and particles generate fields by acting as sources. In fact, in quantum mechanics, particles themselves are fields, as described theoretically by the wave function.

Classical mechanics

The following are described as forming Classical mechanics:

- Newtonian mechanics, the original theory of motion (kinematics) and forces (dynamics)
- Lagrangian mechanics, a theoretical formalism
- Hamiltonian mechanics, another theoretical formalism
- Celestial mechanics, the motion of stars, galaxies, etc.
- Astrodynamics, spacecraft navigation, etc.
- Solid mechanics, elasticity, the properties of (semi-)rigid bodies
- Acoustics, sound in solids, fluids, etc.

- Statics, semi-rigid bodies in mechanical equilibrium
- Fluid mechanics, the motion of fluids
- Continuum mechanics, mechanics of continua (both solid and fluid)
- Hydraulics, fluids in equilibrium
- Applied / Engineering mechanics
- Biomechanics, solids, fluids, etc. in biology
- Statistical mechanics, large assemblies of particles
- Relativistic or Einsteinian mechanics, universal gravitation

Quantum mechanics

The following are categorized as being part of Quantum mechanics:

- Particle physics, the motion, structure, and reactions of particles
- Nuclear physics, the motion, structure, and reactions of nuclei
- Condensed matter physics, quantum gases, solids, liquids, etc.
- Quantum statistical mechanics, large assemblies of particles

Input is the term denoting either an entrance or changes which are inserted into a system and which activate/modify a process. It is an abstract concept, used in the modeling, system(s) design and system(s) exploitation. It is usually connected with other terms, *e.g.*, input variable, input parameter, input value, input signal and input device.

From the most general systemics perspective, input is a subjective concept and depends on how the system is used. In such sense, the same system can have different inputs in different applications.

In the case of a process description/model, the concept input is closely connected with the concept output. Here, what enters is called input and what exits is called output.

ExampleFor an abstract system $A(x,y,p)$, where x,y are variables and p is a parameter, x may denote input (variable) and y may denote the output for a process$y = f(p,x)$, but, for another goal/(system application), the system A can be the carrier of a process $x = g(p,y)$, where y is an input and x is an output.s

Usually, in the modeling of a problem/process, input are these variables which are known and output are those unknown to us yet.

In different contexts, **input** has several more concrete domain-dependent meanings.

Information processing

In information processing, **input** refers to either information received or the process of receiving it:

- In human-computer interaction, input is the information produced by the user with the purpose of controlling the computer program. The **user interface** determines what kinds of input the program accepts (for example, control strings or text typed with keyboard and mouse clicks).
- Input also comes from networks and storage devices such as disk drives.

Control theory

In control theory, the **inputs** of a system are the signals that can be observed or affected that feed into the system. Specifically, inputs are differentiated from states.

Equity theory

In equity theory, **inputs** are the skills, time, effort, expertise, experience or qualifications that an employee brings to his job.

Economic theory

In economics, inputs refer to priced or unpriced resources used in a production process, and outputs refer to the priced or unpriced results of that process. Normally, inputs are regarded as costs, and outputs as products. Outputs may be valued gross (before deduction of costs from sales) or net (after deduction of costs from sales). Input-output economics was popularised by the economist Wassily Leontief who devised an ingenious system of input and output accounts and matrices to analyse the flows of goods and services between different sectors of a national economy. In national accounts an attempt is made to value national inputs and outputs according to consistent valuation principles, to measure the creation and distribution of wealth.

Signal processing is the processing, amplification and interpretation of signals, and deals with the analysis and manipulation of signals. Signals of interest include sound, images, biological signals such as ECG, radar signals, and many others. Processing of such signals includes storage and reconstruction, separation of information from noise (e.g., aircraft identification by radar), compression (e.g., image compression), and feature extraction (e.g., speech-to-text conversion).

Signal classification

Signals can be either analog or digital, and may come from various sources.

There are various sorts of signal processing, depending on the nature of the signal, as in the following examples.

For analog signals, signal processing may involve the amplification and filtering of audio signals for audio equipment or the modulation and demodulation of signals for telecommunications. For digital signals, signal processing may involve the compression, error checking and error detection of digital signals.

- Analog signal processing—for signals that have not been digitized, as in classical radio, telephone, radar, and television systems
- Digital signal processing—for signals that have been digitized. Processing is done by digital circuits such as ASICs, FPGAs, general-purpose microprocessors or computers, or specialized digital signal processor chips.
- Statistical signal processing—analyzing and extracting information from signals based on their statistical properties
- Audio signal processing—for electrical signals representing sound, such as music
- Speech signal processing—for processing and interpreting spoken words
- Image processing—in digital cameras, computers, and various imaging systems
- Video signal processing—for interpreting moving pictures
- Array processing—for processing signals from arrays of sensors

'Information processing'

In information processing, **output** is the process of transmitting information by an object (verb usage).

Output may also be used as a noun for information transmitted by a source (object).

Human-computer interaction

In human-computer interaction, **output** is information produced by the computer program and **perceived** by the user. The kinds of output the program produces, and the kinds of input the program accepts, define the **user interface** of the program. In this context, feedback and output are often used interchangeably. However, output tends to refer specifically to explicit output, something that is intentionally provided for the user, whereas feedback also encompasses byproducts of operation that happen to contain information (see low-key feedback).

Telecommunications

In telecommunication, the term **output** can refer to:

1. Information retrieved from a functional unit or from a network, usually after some processing.

1. An output state, or sequence of states.

1. Pertaining to a device, process, or channel involved in the production of data by a computer or by any of its components.

Sourcefrom Federal Standard 1037C

Control theory

In control theory, the **outputs** of a system are what can be measured. Specifically, outputs are differentiated from states

Macro-economics

In Macro-economics, **output** is the produced goods and services in an economy. A distinction is drawn between Gross Output and Net output.

Equity theory

In equity theory, **output** is the benefits that an employee receives, including money, perquisites, power, status or variety.

Analog circuit

It has been suggested that this article or section be merged into *Analog electronics*.

An **Analog circuit** (or **analogue circuit**) is an electrical network designed to process signals that are continuously variable. Such signals are called analog signals. They differ from digital signals in that any fluctuation in the signal will change the value it represents. In digital circuits, quantisation means that a range of signal levels can represent the same value.

Origin of term

The word "analog" implies a direct analogy between the variations in the signal and variations in the phenomena that produce that signal. That is to say, the signal is analogous to the natural phenomena, unlike digital signals.

Analog signals

Analog signals are signals that have two characteristics. They can take ANY value from a given range, and each unique signal value represents different information. Simply put, any change in the signal is meaningful, and each level of the signal represents a different and unique level of the phenomenon that it represents.

For example, suppose the signal is being used to represent temperature, with one Volt representing one degree Celsius. In such a system 10 Volts would represent 10 degrees, and 10.1 Volts would represent 10.1 degrees. A similar digital circuit may only represent temperature to the nearest degree, so that 10.0 Volts and 10.1 Volts would both represent exactly 10 degrees.

In the analog circuit each voltage represents a unique temperature. In the digital circuit, different voltage levels can represent the same information(the same temperature), which is known as quantization.

In the example above, voltage was used to represent the information of interest, though any electrical property may have been used. Commonly voltage, current, frequency, and phase are used.

The basic building block of analog circuits is the operational amplifier, which is itself an analog circuit. It can perform a large number of functions useful in analog electronics, including addition, subtraction, multiplication, division, integration, differentiation and signal comparisons.

Analog and Digital Electronics

Since the information is encoded very differently in analog and digital electronics, the way they process a signal is consequently very different. However, most operations that can be performed with an analog signal can also be performed with a digital signal but in a different way.

The first electronic devices invented and mass produced were analog. However, as time progressed digital circuits have become predominant in electronics. It is important to note that analog and digital devices are the same, the only difference is the way they represent and process information. The same basic components can be used for analog or digital circuits.

The main diferences between analog and digital electronics are listed below:

NoiseBecause the way information is encoded in analog circuits, they are much more susceptible to noise than digital circuits, since a small change in the signal can represent a significant change in the information present in the signal and can cause the information present to be lost, corrupted or otherwise made useless. In digital electronics, because the information is quantized, as long as the signal stays inside a range of values, it represents the same information. This is one of the main reasons that digital electronic circuits are predominant. In fact, digital circuits use this principle to regenerate the signal at each logic gate, lessening or removing noise.

PrecisionA lot of factors afect how precise a signal is, mainly the noise present in the original signal and the noise added by processing. See Signal to Noise Ratio. In digital electronics it is much easier to have high precision signals than in analog electronics, because of the way information is represented and how noise affects digital and analog signals.

SpeedThis is where analog electronics really outshines digital electronics. Analog ciruits are several times faster than their digital counterparts. Depending on the operation, analog circuits can be several hundreds or hundreds of thousands of times faster digital circuits. This is because information in digital circuits is represented by bits, while in analog electronics it is represented by a property of the signal itself. For example, transmitting a value digitally may require sending 64 bits in succession. The same signal in analog electronics could easily be represented by a voltage, and transmiting that voltage takes the same time to transmit one bit, so the analog signal in this case is at least 64 times faster than digital.

BandwidthSimply put, bandwidth is the amount of information a given circuit can cope with. Again, analog circuits have much more bandwith than digital, and can process/transmit more information in the same time.

Design Dificulty Digital systems are much easier and smaller to design than comparable analog circuits. This is one of the main reasons why digital systems are more common than analog. An analog circuit must be designed by hand, and the process is much less automated than for digital systems. Also, because the smaller the integrated circuit (chip) the cheaper it is, and digital systems are much smaller than analog, digital is cheaper to manufacture.

Future of Analog Electronics

The field of analog electronics nowadays deals with high speed, high performance devices that need the unique advantages provided by analog circuits. Also, digital circuits are an abstraction of analog circuits, but remain analog circuits. As technology progressses and transistors get smaller and smaller, it becomes more and more important when designing digital circuits to account for effects usually present only in analog circuits, requiring expertise in analog circuits.

The range of applications of analog circuits will probably continue to reduce, being replaced by digital circuits because of their smaller size, cheaper cost and easier design. Analog circuits will never cease to exist, but will continue to exist as an speciality field for high performance circuits, or as a high performance part of a digital chip, as integrated circuits with analog and digital circuits in the same substrate become more popular.

Analog circuit functions

- Analog multipliers
- electronic amplifiers
- electronic filters
- electronic oscillators
- Phase-locked loops
- electronic mixers
- Power conversion
- Electronic power supply
- impedance matchers
- operational amplifiers
- comparators
- Voltage regulators

Electronic component

Various components

An **electronic component** is a basic electronic element usually packaged in a discrete form with two or more connecting leads or metallic pads. Components are intended to be connected together, usually by soldering to a printed circuit board, to create an electronic circuit with a particular function (for example an amplifier, radio receiver, or oscillator). Components may be packaged singly (resistor, capacitor, transistor, diode etc) or in more or less complex groups as integrated circuits (operational amplifier, resistor array, logic gate etc).

List of electronic components

There are many electronic components on the market today. Here is a list of some of them.

Interconnecting electronic components

- electrical connectors, plugs and sockets etc.
- printed circuit boards
- point-to-point construction
- wire-wrap
- breadboard

Passive components

- fuse

- capacitor
- inductor
- magnetic amplifier (toroid)
- piezoelectric crystal
- polyswitch
- resistor
- varistor
- transformer
- switch

Active components (solid-state)

- diode
  - light-emitting diode
  - photodiode
  - laser diode
  - Zener diode
  - Schottky diode
  - transient voltage suppression diode
  - variable capacitance diode
- transistor
  - field effect transistor
  - bipolar transistor
  - IGBT transistor
  - SIT/SITh (Static Induction Transistor/Thyristor)
  - Darlington transistor
  - Compound transistor
  - photo transistor
- integrated circuit
  - digital
  - analog
- other active components
  - triac
  - thyristor
  - unijunction transistor
  - Silicon Controlled Rectifier (SCR)

    - MOS composite static induction thyristor/CSMT
    - Field-emitter microtube

Active components (thermionic)

- thermionic valve
- cathode ray tube
- klystron
- magnetron

Display devices

- cathode ray tube
- liquid crystal display
- light-emitting diode
- nixie tube

Electromechanical sensors and actuators

- microphone
- loudspeaker
- strain gauge
- switch

Thermoelectric devices

- thermistor
- thermocouple
- thermopile
- Peltier cooler

Photoelectric devices

- photomultiplier tube
- light-dependent resistor
- photodiode
- photovoltaic cell (solar cell)

Antennas

- radio antenna
- elemental dipole
- biconical
- Yagi
- phased array
- magnetic dipole (loop)
- parabolic dish
- feedhorn, waveguide

Electronic test equipment

A Tektronix model 475A portable analogue oscilloscope

Electronic test equipment (sometimes called 'testgear') is used to create stimulus signals and capture responses from electronic Devices Under Test (DUTs). In this way, the proper operation of the DUT can be proven or faults in the device can be traced and repaired. Use of electronic test equipment is essential to any serious work on electronics systems.

Practical electronics engineering and assembly requires the use of many different kinds of electronic test equipment ranging from the very simple and inexpensive (such as a test light consisting of just a light bulb and a test lead) to extremely complex and sophisticated such as Automatic Test Equipment.

Generally, more advanced test gear is necessary when developing circuits and systems than is needed when doing production testing or when troubleshooting existing production units in the field.

Types of test equipment

Basic equipment

Commercial digital voltmeter checking a prototype

The following items are used for basic measurement of voltages, currents, and components in the circuit under test.

- Voltmeter (Measures voltage)
- Ohmmeter (Measures resistance)
- Ammeter, e.g. Galvanometer or Milliameter (Measures current)
- Multimeter e.g., VOM (Volt-Ohm-Milliameter) or DVM (Digital "Volt" Meter) (Measures all of the above)

The following are used for stimulus of the circuit under test:

- Power supplies
- Signal generator
- Pulse generator

Howard piA digital multimeter

The following are used to analyze the response of the circuit under test:

- Oscilloscope (Measures all of the above as they change over time)
- Frequency counter (Measures frequency)

And connecting it all together:

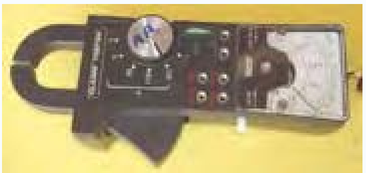
- Test probes

Advanced or less commonly used equipment

Meters

- Solenoid voltmeter (*Wiggy*)
- Clamp meter (current transducer)
- Wheatstone bridge (Precisely measures resistance)
- Capacitance meter (Measures capacitance)
- EMF Meter (Measures Electric and Magnetic Fields)
- Electrometer (Measures charge)

Probes



A multimeter with a built in clampfacility
Pushing the large button at the bottom opens the lower jaw of the clamp, allowing the clamp to be placed around a conductor (wire).

- RF probe
- Signal tracer

Analysers

- Logic analyzer (Tests digital circuits)
- Spectrum analyzer (SA) (Measures spectral energy of signals)
- Vector signal analyzer (VSA) (Like the SA but it can also perform many more useful digital demodulation functions)
- Time-domain reflectometer for testing integrity of long cables
- Waveform analyzer (An oscilloscope specialized for television waveforms)

Signal-generating devices

Leader Instruments LSG-15 signal generator

- Signal generator
- Frequency synthesiser
- Function generator
- Pulse generator
- Signal injector

Miscellaneous devices

- Continuity tester
- Cable tester
- Hipot tester

- Network analyzer (used to characterize components or complete computer networks)
- Test light
- Transistor tester

Mathematical methods in electronics

Mathematical methods are integral to the study of electronics. To become proficient in electronics it is also necessary to become proficient in mathematics.

Mathematics in Electronic Engineering careers

Electronic Engineering (EE) careers usually include courses in Calculus (single and multivariable), Complex Analysis, Differential Equations (both ordinary and partial), Linear Algebra and Probability. Fourier Analysis and Z-Transforms are also subjects which are usually included in EE programs.

Of these subjects, Calculus and Differential equations are usually prequisites for the Physics courses required in most Electronic Engineering programs (mainly Mechanics, Electromagnetism & Semiconductor Physics). Complex Analysis has direct applications in Circuit Analysis, while Fourier Analysis is needed for all Signals & Systems courses, as are Linear Algebra and Z-Transform.

Basic applications

A number of electrical laws apply to all electrical networks. These include

- Kirchhoff's current lawthe sum of all currents entering a node is equal to the sum of all currents leaving the node.
- Kirchhoff's voltage lawthe directed sum of the electrical potential differences around a circuit must be zero.
- Ohm's lawthe voltage across a resistor is the product of its resistance and the current flowing through it.
- the Y-delta transform
- Norton's theoremany two-terminal collection of voltage sources and resistors is electrically equivalent to an ideal current source in parallel with a single resistor.
- Thevenin's theoremany two-terminal combination of voltage sources and resistors is electrically equivalent to a single voltage source in series with a single resistor.
- Millman's theoremthe voltage on the ends of branches in parallel is equal to the sum of the currents flowing in every branch divided by the total equivalent conductance.

- Analysis of resistive circuits.

Circuit analysis is the study of methods to solve linear systems for an unknown variable.

- Circuit analysis

Electronic design automation

PCB Layout Program

Electronic design automation (**EDA**) is the category of tools for designing and producing electronic systems ranging from printed circuit boards (PCBs) to integrated circuits. This is sometimes referred to as ECAD (electronic computer-aided design) or just CAD. (Printed circuit boards and wire wrap both contain specialized discussions of the EDA used for those.)

Terminology

The term *EDA* is also used as an umbrella term for computer-aided engineering, computer-aided design and computer-aided manufacturing of electronics in the discipline of electrical engineering. This usage probably originates in the IEEE Design Automation Technical Committee.

This article describes EDA specifically for electronics, and concentrates on EDA used for designing integrated circuits. The segment of the industry that must use EDA are chip designers at semiconductor companies. Large chips are too complex to design by hand.

Growth of EDA

EDA for electronics has rapidly increased in importance with the continuous scaling of semiconductor technology. (See Moore's Law.) Some users are foundry operators, who operate the semiconductor fabrication facilities, or "fabs", and design-service companies who use EDA software to evaluate an incoming design for manufacturing readiness. EDA tools are also used for programming design functionality into FPGAs.

History

Before EDA, integrated circuits were designed by hand, and manually laid out. Some advanced shops used geometric software to generate the tapes for the Gerber photoplotter, but even those copied digital recordings of mechanically-drawn components. The process was fundamentally graphic, with the translation from electronics to graphics done manually. The best known company from this era was Calma, whose GDSII format survives.

By the mid-70s, developers were starting to automate the design, and not just the drafting. The first placement and routing tools were developed. The proceedings of the Design Automation Conference cover much of this era.

The next era began more or less with the publication of "Introduction to VLSI Systems" by Carver Mead and Lynn Conway in 1980. This groundbreaking text advocated chip design with programming languages that compiled to silicon. The immediate result was a hundredfold increase in the complexity of the chips that could be designed, with improved access to design verification tools that used logic simulation. Often the chips were not just easier to lay out, but more correct as well, because their designs could be simulated more thoroughly before construction.

The earliest EDA tools were produced academically, and were in the public domain. One of the most famous was the "Berkeley VLSI Tools Tarball", a set of UNIX utilities used to design early VLSI systems.

Another crucial development was the formation of MOSIS, a consortium of universities and fabricators that developed an inexpensive way to train student chip designers by producing real integrated circuits. The basic idea was to use reliable, low-cost, relatively low-technology IC processes, and pack a large number of projects per wafer, with just a few copies of each projects' chips. Cooperating fabricators either donated the processed wafers, or sold them at cost, seeing the program as helpful to their own long-term growth.

1981 marks the beginning of EDA as an industry. For many years, the larger electronic companies, such as Hewlett Packard, Tektronix, and Intel, had pursued EDA internally. In 1981, managers and developers spun out of these companies to concentrate on EDA as a business. Daisy Systems, Mentor Graphics, and Valid Logic Systems were all founded around this time, and collectively referred to as **DMV**. Within a few years there were many companies specializing in EDA, each with a slightly different emphasis.

In 1985, Verilog, a popular high-level design language, was first introduced as a hardware description language by Gateway. In 1987, the U.S. Department of Defense funded creation of VHDL as a specification language. Simulators quickly followed these introductions, permitting direct simulation of chip designsexecutable specifications. In a few more years, back-ends were developed to perform logic synthesis.

Many of the EDA companies acquire small companies with software or other technology that can be adapted to their core business. Most of the market leaders are rather incestuous amalgamations of many smaller companies. This trend is helped by the tendency of software companies to design tools as accessories that fit naturally into a larger vendor's suite of programs (the "tool flow").

While early EDA focused on digital circuitry, many new tools incorporate analog design, and mixed systems. This is happening because there is now a trend to place entire electronic systems on a single chip.

Current digital flows are extremely modular (see Integrated circuit design, Design closure, and Design flow (EDA)). The front ends produce standardized design descriptions that compile into invocations of "cells,", without regard to the cell technology. Cells implement logic or other electronic functions using a particular integrated circuit technology. Fabricators generally provide libraries of components for their production processes, with simulation models that fit standard simulation tools. Analog EDA tools are much less modular, since many more functions are required, they interact more strongly, and the components are (in general) less ideal.

Product areas

EDA is divided into many (sometimes overlapping) sub-areas. They mostly align with the path of manufacturing from design to mask generation. The following applies to chip/ASIC/FPGA construction but is very similar in character to the areas of printed circuit board design:

- Design and Architecturedesign the chip's schematics, output in Verilog, VHDL, SPICE and other formats.

- FloorplanningThe preparation step of creating a basic die-map showing the expected locations for logic gates, power & ground planes, I/O pads, and hard macros. (This is analogous to a city-planner's activity in creating residential, commercial, and industrial zones within a city block.)
- Logic synthesistranslation of a chip's abstract, logical RTL-description (often specified via a hardware description language, or "HDL", such as Verilog or VHDL) into a discrete netlist of logic-gate (boolean-logic) primitives.
- Behavioral Synthesis, High Level Synthesis or Algorithmic SynthesisThis takes the level of abstraction higher and allows automation of the architecture exploration process. It involves the process of translating an abstract behavioral description of a design to synthesizeable RTL. The input specification is in languages like behavioral VHDL, algorithmic SystemC, C++ etc and the RTL description in VHDL/Verilog is produced as the result of synthesis.
- IP coresprovide pre-programmed design elements.
- EDA databasesdatabases specialized for EDA applications. Needed since historically general purpose DBs did not provide enough performance.
- Simulationsimulate a circuit's operation so as to verify correctness and performance.
    - Transistor Simulation – low-level transistor-simulation of a schematic/layout's behavior, accurate at device-level.
    - Logic simulation – digital-simulation of an RTL or gate-netlist's digital (boolean 0/1) behavior, accurate at boolean-level.
    - **Behavioral Simulation** – high-level simulation of a design's architectural operation, accurate at cycle-level or interface-level.
    - Hardware emulation – Use of special purpose hardware to emulate the logic of a proposed design. Can sometimes be plugged into a system in place of a yet-to-be-built chip; this is called **in-circuit emulation**.
- Clock Domain Crossing Verification (CDC check)Similar to linting, but these checks/tools specialise in detecting and reporting potential issues like data loss, meta-stability due to use of multiple clock domains in the design.
- Formal verification, also model checkingAttempts to prove, by mathematical methods, that the system has certain desired properties, and that certain undesired effects (such as deadlock) cannot occur.
- Equivalence checkingalgorithmic comparison between a chip's RTL-description and synthesized gate-netlist, to ensure functional equivalency at the *logical* level.

- Power analysis and optimizationoptimizes the circuit to reduce the power required for operation, without affecting the functionality.
- Place and route, PAR(for digital devices) tool-automated placement of logic-gates and other technology-mapped components of the synthesized gate-netlist, then subsequent routing of the design, which adds wires to connect the components' signal and power terminals.
- Static timing analysisAnalysis of the timing of a circuit in an input-independent manner, hence finding a worst case over all possible inputs.
- **Transistor layout**(for analog/mixed-signal devices), sometimes called *polygon pushing* – a prepared-schematic is converted into a layout-map showing all layers of the device.
- Design for Manufacturabilitytools to help optimize a design to make it as easy and cheap as possible to manufacture.
- Design closureIC design has many constraints, and fixing one problem often makes another worse. Design closure is the process of converging to a design that satisfies all constraints simultaneously.
- Analysis of substrate coupling.
- Power network design and analysis
- Physical verification, PVchecking if a design is physically manufacturable, and that the resulting chips will not have any function-preventing physical defects, and will meet original specifications.
    - Design rule checking, DRC – checks a number of rules regarding placement and connectivity required for manufacturing.
    - Layout versus schematic, LVS – checks if designed chip layout matches schematics from specification.
    - Layout extraction, RCX – extracts netlists from layout, including parasitic resistors (PRE), and often capacitors (RCX), and sometimes inductors, inherent in the chip layout.
- Mask data preparation, MDPgeneration of actual lithography photomask used to physically manufacture the chip.
    - Resolution enhancement techniques, RET – methods of increasing of quality of final photomask.
    - Optical proximity correction, OPC – up-front compensation for diffraction and interference effects occurring later when chip is manufactured using this mask.
    - Mask generation – generation of flat mask image from hierarchical design.

- **Manufacturing Test**
    - Automatic test pattern generation, ATPG – generates pattern-data to systematically exercise as many logic-gates, and other components, as possible.
    - Built-in self-test, or BIST – installs self-contained test-controllers to automatically test a logic (or memory) structure in the design
    - Design For Test, DFT – adds logic-structures to a gate-netlist, to facilitate post-fabrication (die/wafer) defect testing.
- Technology CAD, or TCAD, simulates and analyses the underlying process technology. Semiconductor process simulation, the resulting dopant profiles, and electrical properties of devices are derived directly from device physics.
- Electromagnetic field solvers, or just field solvers, solve Maxwell's equations directly for cases of interest in IC and PCB design. They are known for being slower but more accurate than the layout extraction above.

Largest companies and their histories

Well before **Electronic Design Automation**, also called **Computer Aided Design**, the use of computers to help with drafting tasks was well established, and software commercially available. For example, Calma, Applicon, and Computervision, established in the late 1960s, sold digitizing and drafting software used for ICs. Zuken Inc. in Japan, established in 1976, sold similar software for PC boards. While these tools were valuable, they did not help with the design portion of the process, which was still done by hand. Design Automation software was developed in the 70s, in academia and within large companies, but it was not until the early 1980s that software to help with the design portion of the process became commercially available.

In 1981, Mentor Graphics was founded by managers from Tektronix, Daisy Systems was founded largely by developers from Intel, and Valid Logic Systems by designers from Lawrence Livermore National Laboratory and Hewlett Packard. Meanwhile companies such as Calma and Zuken attempted to expand into the design, as well as the drafting, portion of the market.

When EDA started, analysts categorized these companies as a niche within the “computer aided design” market, primarily mechanical design drafting tools for conceptualizing bridges, buildings and automobiles. In a few years these fields diverged, and today no companies specialize in both mechanical and electrical design automation.

Cadence Design Systems was founded in the mid 80s, specializing in physical IC design. Synopsys was founded about the same time frame to productize logic synthesis. Both have grown to be the largest full line suppliers of EDA tools. Magma Design Automation was founded in 1997 to take advantage of the simplifications possible by building an IC design system from scratch.

Company	Location	Market Value (12/2005)	Logo
Cadence Design Systems	San Jose, California	$5.17 billion	cadence
Synopsys	Mountain View, California	$2.95 billion	SYNOPSYS
Mentor Graphics	Wilsonville, Oregon	$729 million	Mentor Graphics
Magma Design Automation Inc	Santa Clara, California	$302 million	MAGMA
Zuken Inc.	Yokohama, Japan	$300 million	ZUKEN

Open source EDA tools

- Open Collector — a news site for Free EDA software
- OpenCores OpenTech CD ROM — collects several hundred tools
- gEDA — GPLed EDA tools
- Magic 7 — A popular open-source IC design tool
- Berkeley Chipmunk — A historic set of tools.

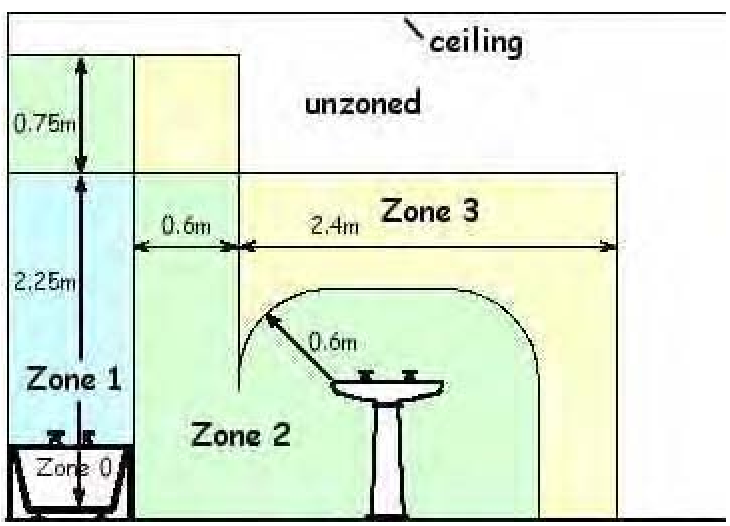
- The Electric VLSI Design System — a complete system for integerated-circuit design.
- LASI — Integrated Circuit CAD for Windows
- OpenCores — Predesigned, LGPLed intellectual property blocks for ICs
- Alliance — Complete set of RTL to layout EDA tools
- Kicad — Kicad is an open source (GPL) software for the creation of electronic schematic diagrams and printed circuit board artwork.
- For open source versions of logic design languages, see the languages, i.e. See VHDL, Verilog
- Signs — Signs (free eclipse-based hardware design and simulation environment)

Using electrical equipment in the bathroom

Using electrical equipment in bath or shower rooms has always needed care to ensure safety. Now the IEE Wiring Regulations (16th Edition) have identified particular zones within the bathroom to indicate what type of electrical equipment that can be installed.

The zones

The zones are identified from 0 to 3, with 0 being the wettest.



Zone 0
: The interior of the bath or shower which can hold water.

Zone 1
: The area directly above zone 0 limited vertically to 2.25m above the bottom of the bath or shower.

Zone 2
: The area beyond zones 0 and 1, 0.6m horizontally and up to 2.25m vertically. Zone 2 also included any window with a sill next to the bath.

Zone 3

The area beyond zones 2, 2.4m horizontally and up to 2.25m vertically.

Note

- Where ceiling heights exceed 2.25m, the zones are effectively up to 3m - beyond 3m, the walls are 'out of scope'.
- Basins are not covered, however they are usually considered to be Zone 2.
- Providing that the space under the bath cannot be accessed without using tools (i.e. screwdriver etc), that space is considered to be 'out of scope'.

Equipment for bathrooms

Electrical equipment may be identified as having a certain level of mechanical and moisture protection, these are quoted as 'Ingress Protection' (or IP) numbers - such as 'IPXY', where X and Y are numbers, the X showing the level of mechanical protection and Y showing the level of moisture protection - in both cases, the higher the number, the better the protection. If a piece of equipment does not have an IP number, it must not be used in zones 0, 1 or 2 (or elsewhere having a wet/damp environment).

Typical electrical items which are marked with IP numbers include

- Extractor fans
- Lighting
- Heaters
- Electrical shower units
- Shower pumps

Shaver power points are not IP rated, however, if they comply with BS EN 60742 Chapter 2, Section 1, they can be located in zone 2 (or beyond) providing they are unlikely be be the subject of direct spray from any shower.

As well as IP numbers, items may be classed as PELV or SELV.

- Protective Extra-Low Voltage (PELV) - As the name suggests, the item uses low voltage but it is connected to earth.
- Safety Extra-Low Voltage (SELV) - Again a low voltage system but the output is isolated from the input.

Standard electrical wall fittings (such as wall sockets, flexible cord outlets and fused switches etc) are not IP rated so cannot be installed within zones 0, 1 or 2. No standard socket outlets are allowed anywhere in the bathroom.

Use of Equipment

Any electrical item approved for use in a zone may be used in another zone with a higher number, but not in a lower number zone.

Zone 0
Requires electrical products to low voltage (max. 12 volts) and be IPX7 (the mechanical protection is unimportant).

Zone 1
Requires electrical products to be IPX4 or better, or SELV with the transformer located in zone 3 or beyond. If the fitting is 240v, a 30mA RCD must be used to protect the circuit.

Zone 2
Requires electrical products to be IPX4 or better, or SELV with the transformer located in zone 3 or beyond.

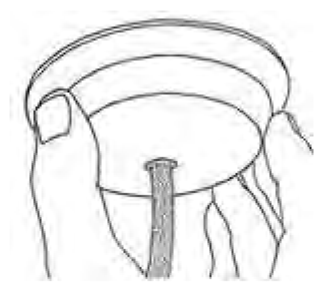
Zone 3
The regulations do not specify any IP number for zone 3, however reference should be made to the manufacturers data in case it indicates any exclusion. Portable electrical equipment is not permitted other than that using a SELV or shaver unit.

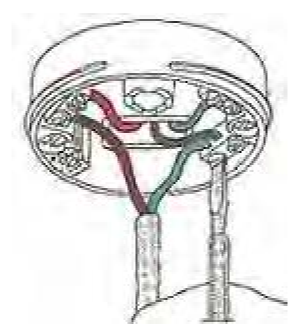
Beyond zone 3
When the size of bathroom extends beyond zone 3, portable equipment is allowed, however they should be positioned such that that their flex length does not enable them to be used in zone 3.

Replacing a ceiling rose for electric lighting

SafetyEnsure that the mains electricity to the light is completely isolated before starting the work. If you doubt your ability to undertake this work, seek assistance.

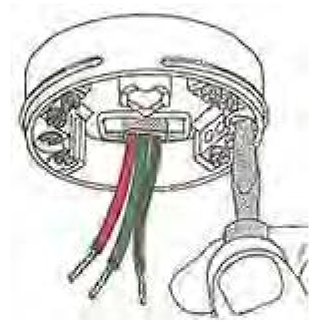
1. Unscrew the existing ceiling rose cover (normally anti-clockwise when looking up).





2. Note how the wires are connected. Unscrew the terminals holding the down flex and remove it.

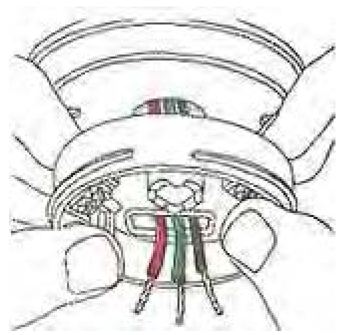
3. Unscrew the terminals holding the power cable and disconnect the individual wires. Carefully straighten the wires.



4. Unscrew the ceiling rose fitting from the ceiling and guide it down to clear the power cable.

5. Check the pitch of the mounting holes in the new rose against those in the old rose, if it is significantly different, you may need to rotate the new rose to avoid the existing holes.

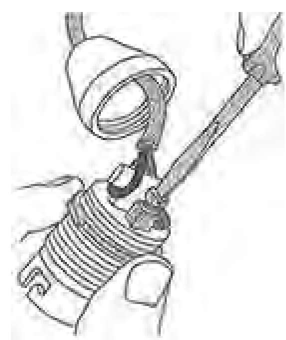
6. If necessary, carefully knock out the appropriate cable hole in the back of the new rose (these are normally areas which have thinner plastic than the rest of the rose).



7. Cut back or renew the power cable through the ceiling if the ends or complete cable is in poor condition. Older installations may not have had the earth wire connected to the rose, should this be the case, cut the cable back so that the earth wire can be connected to the new fitting.

8. Thread the new rose over the power cable and secure it to the ceiling making sure that the cable is not trapped - with the rose flat against the mounting surface, the cable should be free to move through the rose/ceiling.

9. Bend the wires from the power cable and connect them to the terminals in the rose. Ensure that the earth cable is connected and use a piece of earth sleeving to cover it.



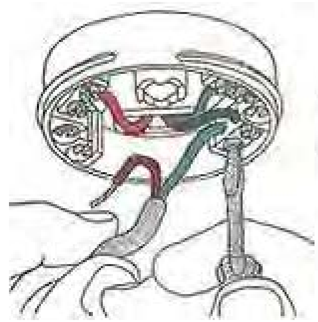
10. It is easier to connect the down flex to the light fitting before connecting the flex to the new rose on the ceiling. Unless the original down flex and lamp holder are relatively new, they should be discarded and new items used.

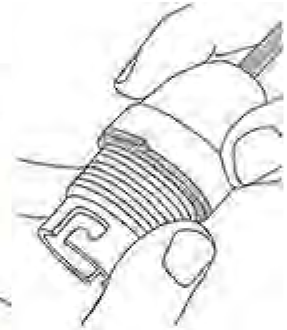
11. Strip back as necessary one end of the down flex and connect it to the light fitting, the end of the outer covering should be within the back of the fitting when it is finally secured. Make sure that the individual wires are wrapped around the staining lugs on the light fitting - these prevent the weight of the lamp being taking just by just the screw terminations.

12. Fit and secure the back of the light fitting.

13. Thread the down flex through the rose cover and secure the wires to the new ceiling rose as appropriate (Blue to Black, Brown to Red, normally the down flex does not include an earth wire).

14. Push the rose cover up the down flex and screw it onto the ceiling fixing.





15. Fit the lamp shade and lamp. Reconnect the mains electricity.

Down Lights (or recessed lighting)

Down lights, mounted in the ceiling, are becoming increasingly popular for lighting living areas, kitchens and bathrooms. A great advantage of down-lights is that they give even, gentle, low shadow lighting within a room.

The main part of the bulb is contained within a housing above the ceiling, the housing (or "can") is normally sealed to avoid the bulb acting as a chimney; if the can is not sealed, when the bulb gets warm, air is drawn up into the void above the ceiling.

Most modern cans are secured to the ceiling by simple clips which are engage when the fitting is pushed up into the ceiling from below. To remove the can, simply grip the inside of the can (having first removed the bulb) and pull down - the clips should work in reverse allowing the can to be pulled down clear of the ceiling to the extent of the cable.

As well as ordinary downlights with round bezels, other options are available

Downlight with adjustable bulb

Eyeball type spot downlight - mainly used to illuminate specific areas or items in the room

Square, adjustable downlight

Mains or low voltage

Downlights can be mains powered or low voltage (typically 12 volts) - 'low voltage' does not mean 'high efficiency', typically the transformer will waste energy, so overall a low voltage installation will use more electricity than a conventional mains installation - although low voltage bulbs do tend to last longer.

Transformers for low voltage downlights come in different electrical sizes (sometimes referred to as 'so many **va**' - simply the total of volts multiplied by amps - and this is the same as watts) so a 100 va transformer can handle 5 x 20 watt low voltage bulbs - it's best to match the transformer to the number of bulbs being used although a number of transformers can normally be connected to the same light switch so it shouldn't be apparent if more than one transformer is being used.

Most transformers for low voltage downlight incorporate a thermal cut-out so that if the transformer should overheat, it will cut off the supply before it caused damage. Transformers should only overheat if

- They are used to drive more bulbs (or higher wattage bulbs) than they are designed for.
  OR
- They do not surrounded by free air to allow heat to dissipate (could be they are covered by loft insulation).

Bulbs

Most recessed down lights use halogen bulbs, these give fairly good bulb life. LED lights are just becoming popular giving coloured lighting (great for children's rooms) but they do not really give enough light for ambient lighting. Typically mains bulbs used are 50 watt while low voltage systems use 20 watt - each giving similar levels of illumination.

Halogen bulb, mains downlights can be dimmed using normal light dimmers, low voltage need a special kit to dim.

Spotlights are different from ordinary downlights, often using 60 watt spotlight bulbs.

Downlights in Bathrooms

Be careful when choosing downlights for bathrooms, they need to conform to the electrical regulations which depends upon their actual position - see bathroom electrical zoning page.

Positioning downlights.

For general, ambient lighting, downlights should be positioned about 6 or 7 ft (1.8 to 2.1 m) apart in both directions (i.e. across the room as well as along the room). Before deciding on the spacing, check the position of the joists above the ceiling - you want to use a spacing which will position the downlights between joists. Keeping adjacent downlights between the same pair of joists will make running the cables easier.

Don't be tempted to position downlights close to walls; the down light will show up every imperfection - try to keep them 3 to 3 ft 6 in (0.9 to 1.05 m) from the ceiling/wall corner.

Don't overload your existing electrical wiring - most mains house lighting circuits can handle 400 watts per room, this allows for up to 8 downlights per room per circuit. If in doubt, consult a qualified electrician.

Electric power cables in the UK

general internal cable - three plus earth - armoured cable

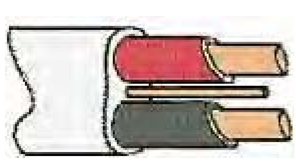
Domestic electric cable is usually available to British Standard BS 6004.

31st March 2004 saw the introduction of a new colour code (harmonised across the EU) for power cables (See this page for details of these changes). Until 31st March 2006, either the old colours or new colours may be used (but not mixed). Below we give both the old and new cable colours.

The standard UK domestic electricity supply is 230 volts AC.

Solid core cables should never be reused - although they can be bent into shape, they are not designed to be flexed and repeated movement can weaken the cores causing then to become weak, overheat or fail.

Twin core and earth (general internal power cables)



Consists of two insulated solid cores with a bare copper earth conductor between the inner cores and an overall PVC sheath. The colours being

	Pre March 2004	Post March 2004
Live	Red	Brown
Neutral	Black	Blue
Earth	Green and Yellow (see note)	

Notethe earth feed is normally bare copper in mains installation cable, the Green and Yellow applies to the coloured sleeving which needs to be fitted where the earth is connected to a fitting or appliance.

core size mm2	current (A) *see note	wattage (kW) at 240v *see note	typical applications
1.0	14	3.25	lighting
1.5	18	4.25	lighting
2.5	24	5.75	power circuit
4.0	32	7.75	power circuit, shower
6.0	40	9.75	shower, cooker
10	53	12.9	cooker

note

- The currents and wattages shown are for the cables in 'free air' installations, the cables should be derated if cables are run together or in such a way that the thermal rise of the cable is not free to dissipate.

Types of cables that may be found in older premises.

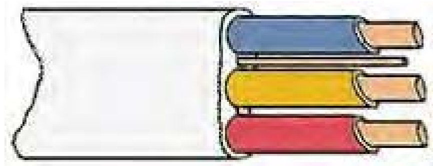
Rubber insulated, two core (multi strand) covered with an outer lead sheath. If there is any of this very old wiring still installed, it should be isolated and replaced immediately. With the age of this type of cable, it is almost guaranteed that the rubber insulation will be degraded and breaking down, any failure of the insulation can cause the outer covering to become live - an installation still using this type of wiring is unlikely to have modern trips fitted in the consumer unit or a master earth leakage trip.

Rubber insulated, two or three core (multi strand) covered with an outer rubber sheath. The danger with this type of cables is the degrading of the rubber especially where a terminal has become overheated. The wiring should be considered ready for replacement.

PVC insulated, three core (multi strand) covered with an outer PVC sheath, this may still be in good physical condition. Two points to watch for are

1. Broken individual strands - this will reduce the current carrying capacity of the cable and can cause the wire to overheat at screw terminals.
2. Earth wires which are just twisted together - this is not a function of the cable but the method of installation common at the time this type of cable was available.

3-core and earth (normally used for the connections between two way switches)

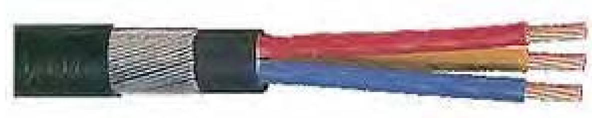


Consists of three insulated solid cores with a bare copper earth conductor between the inner cores and an overall PVC sheath. The colour codes are

Pre March 2004	Post March 2004
Blue	Grey
Yellow	Black
Red	Brown
Green and Yellow (see note)	

Core size mm2	current (A) *see note	wattage (kW) at 240v *see note	typical applications
1.0	12	2.75	lighting double pole switching

Armoured cable



Armoured cable is normally used to transfer power either underground or overhead. The construction is normally the inner cores (which are generally multi strand) being individually sheathed, then covered by an initial overall plastic sheath, followed by the protective wire armour with a final outer sheath to hold it all together. The inner cores may number two, three or four depending upon the application.

The wire protective armour should always be earthed at one end to ensure that it cannot become live if a fault should develop within the cable.

Installation of armour cable should be left to professional contractors, not so much because it is difficult but because of the safety implications if overhead or underground installations should fail to meet the exacting installation requirements.

The ratings below are typical for three core armoured cable but individual manufacturers will give specific ratings for their own cables which should be used in preference to the following.

Core size mm2	current (A) *see note	wattage (kW) at 240v *see note
1.5	18	4.25
2.5	24	5.75
6.0	41	9.9
10.0	56	13.5
16.0	85	20.5
25.0	104	25.25

Electric power cable colours in the UK

Harmonised cables

March 2004 saw amendment 2 to British Standard BS 7671 (Requirements for Electrical Installations). Probably the most significant change introduced for the diyer was the change of colour coding of electric cable. The new coloured cables are referred to as harmonised cables - the colours are harmonised across the EU.

'2 core and earth' cable

Pre March 2004 the UK standard for '2 core and earth' cable used in single phase (i.e. normal household) installation was:

Live Red
Neutral Black
Earth Green and Yellow (see note)

Notethe earth feed is normally bare copper in mains installation cable, the Green and Yellow applies to the coloured sleeving which needs to be fitted where the earth is connected to a fitting or appliance.

Post March 2004 the UK standard was changed to

Live Brown
NeutralBlue
Earth Green and Yellow (no change)

You may recognise that this new colour coding is the same as used for appliance flexes in the UK for many years.

'3 core and earth' cable (two way lighting)

Pre March 2004 the UK standard for '3 core and earth' cable used in two way lighting was blue, yellow and red with a bare copper earth.

Post March 2004 the UK standard was changed to Grey, Black and Brown with a bare copper earth.

Why the change ?

As with so very much these days, the change is the result of international standardisation (or harmonisation) with most of Europe already using this colour coding - the new colours are sometimes referred to as 'harmonised'.

How will the change come into effect ?

The new colours came into effect on 1st April 2004, however for there is a two year overlap between the old and new colour coding.

Until 31st March 2006, either the old colours or new colours may be used (but not mixed).

From 1st April 2006, the old colours will not be permissible in new installations or when making changes.

Where new colour cable is used to extend an existing 'old colour' installation before 1st April 2006, a warning notice (as right) must be fixed at the main distribution or consumer unit of the installation.

Lighting in the home

We all need some form of artificial lighting around our homes, but what type and where?

Lighting can be separated into three basic groups

- General lighting - the lamps which give the ambient light in an area, often a replacement for natural sunlight.
- Task lighting - used to illuminate an area for a particular task - cooking, reading etc. When not required for the task, the lamp is normally switched off.
- Accent lighting - the lighting for decorative purposes - to display a particular feature or item - ceiling beams or a picture on the wall.

General Lighting

General lighting is often provided by traditional pendant types, downlights, chandeliers, or ceiling mounted fixtures etc. The decor and aspect of the room will affect the amount of general lighting required.

Task Lighting

Task lighting is often provided by portable standard lamps, wall mounted spot lights, desk mounted lamps, standard lamps, or above worktops fixed lights.

Accent Lighting

Accent lighting is often provided by wall or ceiling mounted spot lights, or wall mounted coving lights.

Colour temperature

Different bulbs appear to give different types of light, this is usually referred to as the colour temperature of the lighting. Variations tend to be occur with fluorescent lamps, warm white or daylight fluorescents have a colour temperature of about 3000K (close to incandescent lamps) and are suitable for living areas. Cool white fluorescent tubes are about 5000K and are more suited to workshops and garages.

Different sorts of bulbs

Incandescent

The oldest of the bulb technologies, incandescent lamps work by heating a thin wire element within a glass bulb. They are cheap to buy, but expensive to use and don't last as long as other types.

Avoid using plain glass bulbs, they tend to produce glare.

Incandescent spotlight bulbs have a built in reflector to concentrate the light in one direction.

Halogen

Halogen bulbs are a form of incandescent bulb containing halogen gases, these increase the life of the bulb but they are more expensive to buy than ordinary incandescent bulbs.

Low voltage halogen bulbs are available, these tend to be more efficient than the 240 volt type, but this is often more than off set by the inefficiencies of the transformer. Low voltage bulbs do have the advantage that they run cooler.

Fluorescent

Fluorescent lamps are the most efficient bulb in common use, they do cost more than incandescent bulbs but they use a lot less electricity when used for long periods and last up to 10 times longer. They do take a lot of current when first switched on and take some minutes to warm up, they are not very efficient when used in places where the light is only switched on for short periods of time.

Most fluorescent lamps are not suitable for use with dimmers, however special lamps and dimmers are available if required.

Fluorescent lamps have come a long way since the 4 foot plus tube, these days they are available as direct replacements for incandescent bulbs - Compact Fluorescent Lamps (CFLs). One problem is choosing a CFL is that the wattage quoted is not the same as for incandescent lamps, as a rough guide:

CFL Wattage	9	13	18	25
Incandescent lamps rough equivalent wattage	40	60	75	100

This is a very rough guide, the packaging of CFLs normally show the incandescent equivalent wattage.

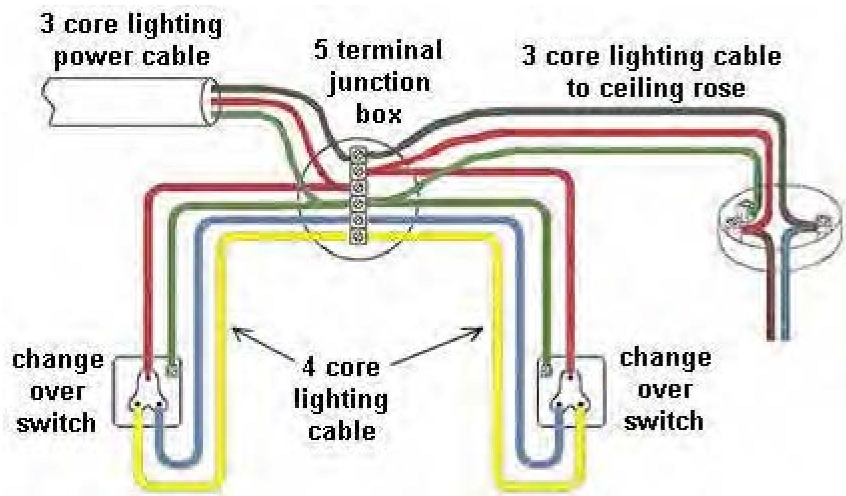
Wiring two way switches for lighting

Sometimes, a light circuit needs to be controlled from two positions - across a room, at each end of a corridor or at the top and bottom of a stairway. Such lighting circuits are commonly known as 'two way' light circuits and are quite easy to install.

The two switches need to be of a 'change-over' type. These have three terminals, a common terminal and one for each of the switch positions.

The cable to the switches needs to be 4 core lighting cable, 3 insulated cores and earth.

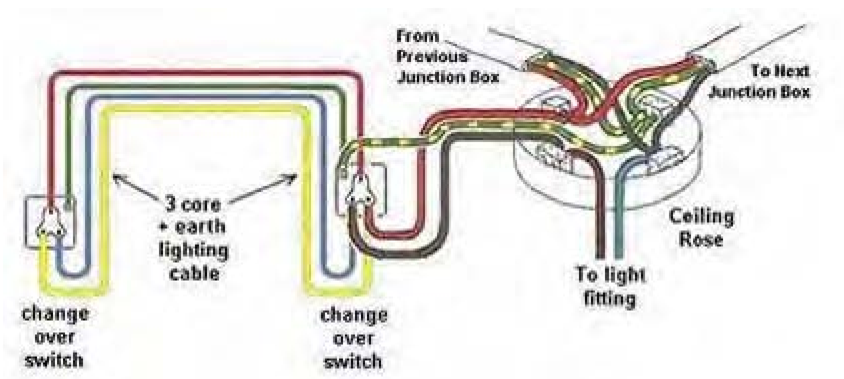
The circuit is shown below, the live feed is fed through both switches to the light and the switches are cross connected so that when a switch is operated, the state of the light is changed.



Because of the number of wires involved, it is easier to use a separate junction box (minimum of 5 terminals) rather than trying to make the connections in the ceiling rose.

An alternative method (contributed by Mike Pheysey)

Where space in the conduit to the switch allows, a simpler circuit can be used, this removes the need for the 5 terminal junction box but requires both a three core and a four cable to be connected to one of the switches. The circuit is shown below (thanks for your contribution mike)



Understanding domestic electric lighting circuits

lighting cable - switches - method of wiring

Please note that all electrical wiring and installation details given on diydata.com is for *information purposes only*. From 1st January 2005, the Building Regulations Part P requires, in

England and Wales, that only certified persons can carryout electrical installation work, or the work must be certified upon completion - see this page for more details.

In modern domestic properties in the UK, the main electric lighting circuits are separate from the power ring main circuit. Each house should ideally have at least two lighting circuits; each protected by a 5 amp fuse or 6 amp trip in the consumer unit. A single 5/6 amp circuit can cope with up to twelve 100 watt lamps, it is usual in a multi-storey house, to have at least one lighting circuit for each floor even if the number of lamps are less than 12 on each level.

Shaver units may also be connected to the lighting circuit (treat it as equivalent to one 100 watt lamp) - where installed in a bathroom or a room containing a shower, the shaver unit must incorporate an isolating transformer.

Lighting cable

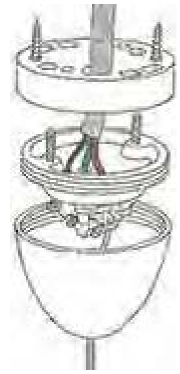
Unlike the ring power circuit, the lighting circuit does not form a loop returning to the consumer unit. The consumer unit is normally connected to the first lamp, which in turn is connected to the second lamp and so on.

The cable used is a 1sq mm PVC twin core and earth rated for up to 12 amps. It consists of a red insulated core for live, black insulated core for neutral with a bare earth conductor between them. The three conductors are laid side by side within a PVC sheath. When connecting the cable, the exposed earth connector must be covered with a sleeve coloured yellow and green (to denote that it's an earth).

The lighting cable is routed from the consumer unit to a series of lighting points for ceiling roses or wall light fittings. The power to each lamp is connected via a wall or ceiling mounted switch. Some light units incorporate their own switch, for these fittings, the power circuit is then connected directly to the fitting.

Light switches

Most room lights are controlled by wall mounted toggle switches (although alternatively touch sensitive or rotary light dimmers can be fitted), The cable normally runs down the wall within conduit within the plaster. A flush fitting wall box is sunk into the wall to take the switch, or alternatively a surface mounted box is fitted. Multi-switch units enable more than one light to be controlled from one position.



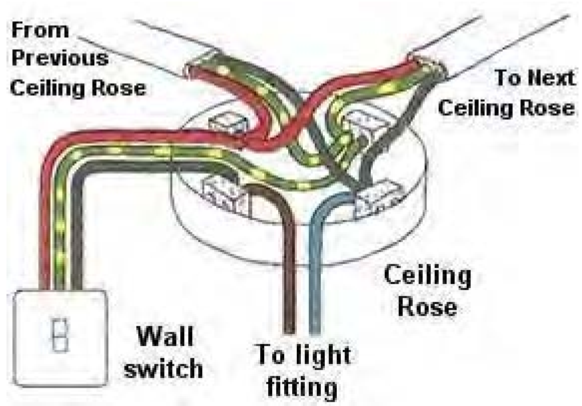
In bathrooms and shower rooms, the switch must be a 'pull string' type.

These switches can also be used when new lights are being installed - they can easily be screwed under a ceiling joist with minimal disturbance to the decorations. There is a tendency to feel that pull switches are only suitable for bathrooms etc., however this limits the opportunities and should be avoided. When a new light is to be positioned over a work surface or even an external light fitted, there is no reason why a pull switch should not be mounted in any convenient position.

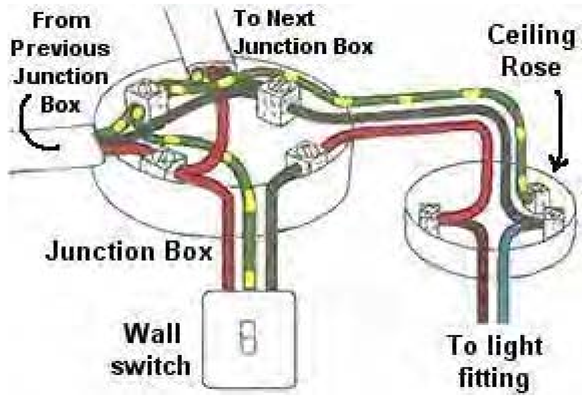
Two wiring methods

There are two basic methods of wiring lights - by ceiling rose and by junction box.

Systems using the ceiling roses make all the connections at the ceiling rose. While this removes the need for one junction box per lamp, it is often more awkward for the average diy'er.



With the junction box system (an old standard but still found in older installations), a cable is taken to a series of junction boxes, one for each light fitting/switch. The junction boxes are generally located between the ceiling joists or under floorboards close to the switch. Junction box type connections are required for fluorescent lights and other fittings that do not use a ceiling rose.



Wiring for electric appliances in domestic premises

ring circuit - fused outlets - high power - out of doors

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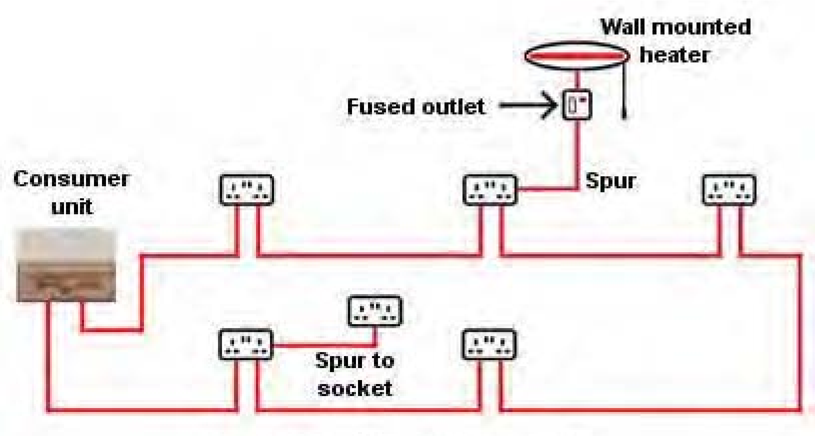
Ring circuit

The ordinary wall sockets around the house are normally connected to a ring circuit (also referred to as a ring main). The ring circuits of a domestic property supply the socket outlets and fixed appliances in the premises.

The 'ring' is formed by the cable going from the consumer unit to the first socket, then on to the second socket and then the next socket etc. until the cable returns to the consumer unit. This means (in simple terms) that every socket on the ring circuit has two cable routes back to the supply. The cable of the ring circuit consists of a red (live) wire, a black (neutral) wire and a bare copper earth wire, all three being enclosed by an outer PVC sheathing. The cable used in domestic ring circuits is either 2.5sq mm or 4.0sq mm twin core and earth, these are rated (in free air) at 24amps or 32amps respectively.



Basic Ring Circuit configuration

Each ring circuit is protected by a 32 amp fuse or trip fitted in the consumer unit. Modern installations incorporate a Residual Current Device (RCD) before the consumer unit which trips the whole system off if a fault is detected.

In older houses the cabling for ring circuits (and other circuits) may be fed through the wall cavity with the cables coming into the back of the wall mounted socket. This is unacceptable in new premises and extensions. It is now considered that cables within the cavity may become wet causing the insulation of the cable to break down and moisture running down the cable into the socket. When rewiring older houses, new cables should not be run through the cavity, they should be run through new ducting embedded in the inner wall surfaces or under floorboards.

A ring circuit is considered to be rated at 30amps (7200 watts). A ring may serve up to 100 m sq of floor area and, in theory, may have any number of sockets outlets or fused connection units connected to it. With each socket outlet is normally rated at 13 amps, as a 'rule of thumb', they are limited to under twenty outlets, it is unlikely that the variety of domestic appliances being used at any one time will exceed 30amps. The length of cable used in a ring circuit is limited to 50 metres for circuits protected by an MCB. The sockets are normally mounted flush with the wall although surface mounted boxes are often easier to fit when sockets are added to the circuit. .

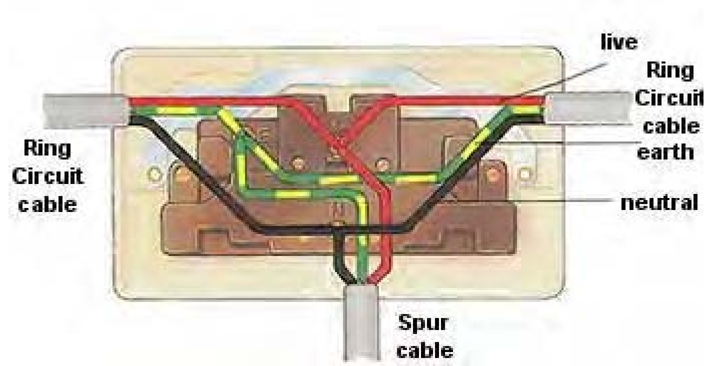
High power electrical appliances (such as cookers, showers etc.) should not be connected to a ring main even if they use less current that the 30 amp rating of the ring circuit. Connection of such appliances will reduce the number of other appliances that can be use simultaneously and will lead to nuisance trips at the consumer unit.

It is advisable to have at least two ring circuit in all premises, in multi floor houses, one for each floor. The kitchen may have a large number of electrical appliances so a separate ring circuit for the kitchen may also worthwhile, this has the added benefit that a freezer will not be affected if there is a fault elsewhere. A single ring circuit should serve a floor area no greater than 100sq m (or 120sq yd).

In the UK, plugs used on a modern ring circuit have square pins and each plug is fitted with either 3 or 13 amp fuses. The correct fuse should always be fitted to suit the appliance, 3 amp fuses for appliances rated up to 750 watts, (lamps and clock radios etc.) - 13amp fuses for larger appliances up to 3000 watts.

Spur extensions can be connected to the ring circuit. A spur is a socket connected into the ring by a single cable run so the socket does not have the full benefit of two cable routes to the consumer unit. Spurs are often used when a socket is added, it is easier to connect using a single cable rather than extending the ring circuit to include the new socket. A spur extension can be connected to the ring circuit provided that it supplies only 13 amp socket outlet (although that can be a double socket outlet) or one fixed appliance. Over the whole ring, the total number of spurs must not exceed the number of socket outlets directly on the main ring. No more than two separate spurs may be connected from each outlet on the ring.

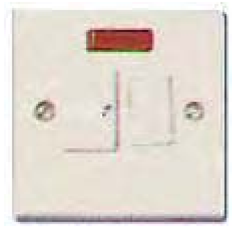
Removal of the front of a wall socket will give an indication of the circuit connected to it



- A single cable connected to the terminals indicates that it is an existing spur.
- Two cables may indicate either that it is on a main ring circuit OR that it is a spur with another spur connected to it. This is not a recognised configuration but possible if both spur sockets are single sockets.
- Three or four cables normally indicate a socket on a main ring circuit with one or two spurs running from it.

If the wiring has been changed by a previous diy'er, it may be possible to identify any added cables and then deduce the original circuit.

Ring circuit fused outlet units

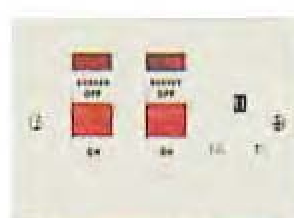


Where connection to a fixed appliance is required, a fused outlet unit may be fitted to the wall (rather than a plug socket) and connected into the ring main. These outlets require the correct fuse rating for the appliance and are connected to the appliance by a cable or flex. The outlet may be switched or unswitched and may be fitted with an indicator light to show when the supply is connected.

Where a flex is taken to a heater of any sort (e.g. night store heater) the flex must be of a special 'high temperature' type suitable for the elevated temperatures encountered. Use of ordinary flex will result in the insulation breaking down causing the flex to become dangerous.

A clock outlet is a similar type of unit, but with a small fuse fitted in a special plug connected to the flex. The plug may be retained in the socket by a screw or knurled thumbscrew. Though called a clock outlet, they are also suitable for other small low current appliances such as extractor fan units, door bells.

High Power circuits.



Typical cooker socket

Within domestic premises, there may be a number of high wattage appliances, the most common being an electric cooker, immersion heater and electric shower. Each of these appliances should be connected to the consumer unit using a dedicated fuse/trip and cable run. The installation instructions for the appliance should detail the wattage of the appliance (which will also normally be shown somewhere on the appliance), the amperage of the fuse/trip and the size of cable required. Any switches on these circuits must also be of a suitable current rating.

Power for out of doors.

When power is required for the shed, patio, garden pond or other out of doors purpose, a separate circuit from the consumer unit should be used. Where a Residual Current Device (RCD) is not already fitted before the consumer unit, one should be installed. The Residual Current Device will switch off the electricity almost instantaneously if a fault develops in the circuit.

Waterproof sockets must be used where an outside socket is required, an internal control switch is also recommended so that the outside socket can be isolated if necessary.

There are a number of alternatives to using mains electricity in the garden, low voltage garden lights and appliances are available to reduce the risk of using electricity out of doors.

10 Free ways to be more energy efficient around the home

8 low cost ways to be more energy efficient around the home

1. Check the room temperatures - a one degree Celsius reduction in the heat level can cut heating costs by 10%.

2. Check that the water in a hot water storage tank is not too hot - the recommended level is 60°C.

3. Always put a plug in the basin/sink when running hot water.

4. Take a shower instead of having a bath - a bath can use up to five times as much hot water as a shower.

5. When cooking, make sure that the cooker ring suits the saucepan. Use the saucepan lids. Gas hobs should only heat the base of saucepans, not the sides. Turn the ring down as soon as the water boils.

6. Keep the fridge/freezer full and only put cold food in them. If you don't have enough food to fill a fridge, put plastic bottles filled with water in it. (Every time the door of an upright fridge/freezer is opened, cold air rushes out, keeping the fridge/freezer full reduces the cold air which can rush out).

7. Don't put less than a full load into a washing machine, dryer, or dishwasher - but don't store dirty dishes as they will become harder to wash as the food dries. Use a short, low temperature washing machine programme if the load is lightly soiled. Use a low temperature dishwasher programme unless the dishes are extremely dirty.

8. Switch off the television and stereo rather than leave them on standby - a television on standby uses up to 75% of the energy it uses when switched fully on.

9. Don't leave lights switched on in empty rooms.

10. Draw the curtains at dusk to prevent heat loss through the windows (even double glazed). If there is a radiator under the window, make sure that the curtain tucks behind the radiator to keep the heat in the room.

8 Low cost ways to be more energy efficient around the home

10 free ways to be more energy efficient around the home

1. Fit reflective foil behind radiators fitted on outside walls to reduce heat loss.

2. Fit draught excluders to outside doors, inside doors, letter boxes, loft hatch, key holes.

3. Lag hot water pipes to stop heat escaping - especially important for pipes in the loft and under the ground floor floorboards (the latter are often overlooked).

4. Insulate any hot water tank with a jacket at least 3 inches (75mm) thick (modern hot water tanks are manufactured with highly efficient foam jackets).

5. Check the lost insulation, current regulations specify at least 8 inches (200mm) of fibre glass insulation, if the loft doesn't meet this requirement, add some more insulation material.

6. Fit energy efficient light bulbs - they cost more than ordinary light bulbs but use less than a quarter the energy and last approximately ten times as long - overall, giving a good saving.

7. Fix any dripping tap. In one day a dripping hot water tap (in a storage tank system) can use enough water to fill a bath - and that's EVERY day !

8. Use heavy lined curtains on all windows, make sure that the curtain does not cover any radiator under the window as this will deflect heat out of the room and through the windows.

General do it yourself safety comments

Safety do's - Safety don'ts

The home can be a highly dangerous area so every diy'er needs to take some precaution and, more importantly, use common sense. The following are some basic principles for the do it yourself person.

Do's

- Always keep safely in mind before you do any diy activity, use caution, care, and good judgement - if in doubt, don't !
- Always read the labels on cans containing paints, solvents, and other products; AND always follow the guidelines and any other warnings.

- Always read the manufacturer's instructions (especially the warnings) before using any tool, especially power tools with cutting blades/bits.
- Always pay deliberate attention to how a tool works, if you understand it's operation, you are less likely to cause injury.
- Always know and accept the limitations of your tools - use the appropriate tool for the task. Do not try to use a tool for anything it is not designed to do.
- Always remove the key from any drill chuck (hand or stand mounted) after you have removed/fitted a drill bit. Do not leave the key in the chuck even when the drill is switched off.
- Always wear the appropriate protection for the job in hand. This may involve gloves, facemasks (to filter dust etc.) and/or eye protection.
- Always keep your body (especially hands) away from the business ends of power tools using blades, cutters, and bits.
- Always make sure that any tool adjustment is secured before using the tool - it is always better to double check an adjustment - e.g., always check the fence on a saw bench - this will avoid possible injury and scraped material.
- Always be sure that the electrical supply is safe before using it; do not overload any circuit. Make sure all power tools, extension cables and electrical outlets are serviceable and undamaged. Do not use power tools in wet conditions.
- Always check for possible cables/pipework before drilling or cutting 'blind' into any wall or other surface. Take care when you cannot see the reverse side of what you are drilling or cutting.
- Always use special care when using a saw bench; older benches may not have the latest safest features (blade guard, safety cut-out etc.). Avoid sawing short pieces if you can, as these can be hard to keep a firm grip of..
- Always clamp small workpieces firmly to a bench or other work surface when using a power tool on them.
- Always remember that things can go wrong very quickly and the body's reaction will not always be quick enough.
- Always use both hands where a tool is designed to be used two handed.
- Always ensure that the work area is adequately lit.
- Always check your local building regulations before carrying out any new construction or major remodelling. The regulations are intended to avoid safety hazards and should be observed - they should not be considered obstructions to be circumvented.
- Always check ladders and steps before use, make sure the rungs and sides are undamaged.
- Always check the security of a ladder or set of steps before you start to climb.
- Always be aware and alert!

Don'ts

- Never wear loose clothing, hanging hair or jewellery when using power tools.
- Never try to use a tool (especially a power tool) for any task it was not designed to do.
- Never work with power tools when you are under the influence of alcohol or drugs or are tired. If in doubt - don't. Any of these factors can impair judgement of your ability, your physical state and general safety aspects - if always better to delay a job than risk serious injury.
- Never use a power tool which is damaged in any way (case, switch or cable etc.). If it starts to make an odd noise or emit smells - stop and investigate.
- Never cut small, loose pieces of wood, metal or other material using a power tool - small off-cuts which you cannot hold or secure, will tend to fly off with potential for injury.
- Never change a drill bit, router cutter or saw blade or make any adjustment to a 'cutting' power tool - until the power cable has been unplugged. Do not rely only upon the switch on the tool or outlet.

- Never use power tools is you are at risk of overbalancing, reposition any ladder, scaffold etc. to make the job comfortable.
- Never work with blunt tools (saws, drill bits, cutters etc.). Sharpen the tools yourself, have them sharpened, or throw them away and use a new tool.
- Never use a power tool on a workpiece which is not firmly secured.
- Never drill or cut 'blind' into a surface before checking the possible location of electrical cables or pipework.
- Never saw a large workpiece unless it is well supported both sides of the cut or there is someone else to support the off-cut.
- Never saw a workpiece supported on any part of your body (or anyone else's body !).
- Never carry sharp tools in your pocket. If you want to carry such tools, use a special-purpose tool belt.
- Never relay on your weight to stabilise a ladder or mobile steps, if necessary get someone to stand at the bottom or use stabilisers.
- Never overreach when working on a ladder or steps, always re-position the ladder/steps.

Smoke detectors and alarms

Properly installed smoke detectors/alarm will detect smoke from a fire and set off an alarm that will then warn of a fire and possible save lives. There are two types of smoke alarm

Ionisation Alarms. These detect all types of smoke that contain small particles, but they respond most rapidly to smoke caused by fires such as a chip pan fire.

The detector in these alarms consists a small amount of radioactive material that detects any invisible smoke particles that are floating in the air. When particles in the smoke are detected, the alarm is set off.

Optical Alarms. These detect all types of smoke, but are ideal for smoke with larger particles, such as burning furniture. In this alarm regular pulses of Ultra Violet light are sent to a detector, if the light is prevented from reaching the detector, the alarm will sound.

The two types can have identical external appearances, so check the packing it is supplied with or the label inside. As a rule of thumb use ionisation alarms for areas like halls and bedrooms and optical alarms in the kitchen or sitting room.

Before installing a smoke alarm always read the manufacturer's Instructions carefully.

Building Regulations require that at least one smoke alarm, wired directly to the mains, is installed in every new property. The regulations go on to say that smoke alarms should comply with BS5446. Even in existing buildings, all smoke detectors should be to British Standard BS5008 or BS5446 or BS kite marked. Other situations, such as properties of multiple occupation, B&Bs etc, require smoke detectors to building regulations - if in doubt, check with the local Building Control Office.

If installing mains operated smoke alarms then the installation must comply with the current IEE wiring regulations. It is worth incorporation a back-up battery in case there is a mains failure.

Smoke detectors/alarms are offered with a mixture of various features

- Some mains powered detectors are housed in the ceiling rose of ordinary lights (as shown right). This makes them rather unobtrusive.
- Most have some form of alarm that indicates when the battery needs replacing.
- Some have alarms that indicate when the sensor needs cleaning.
- Some alarms (specifically designed for kitchens) have a silencer that stops the alarm operating for about eight minutes while cooking. During this time they emit an intermittent bleep to indicate that the alarm has been silenced.
- Some alarms can be interconnected so that all of them will sound when any one alarm senses smoke.
- The alarm may have an emergency light which illuminates when the alarm goes off. The emergency light will help people escape.

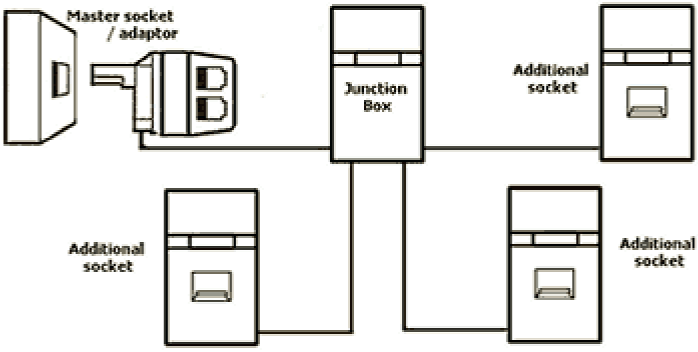
It is pointless having smoke alarms if the occupants of the building have no idea what to do when they operate. Escape routes should be established for every room and everyone in the building should be made aware of these routes. Escape routes must be unobstructed at any time, if window locks are fitted, make sure that a key is always located by each window.

REMEMBER

- Always follow the manufacturer's installation and maintenance requirements carefully.
- Remember to check the operation of each detector once a month and replace the batteries every year (or as directed by the manufacturers).
- Only the use the type of battery specified by the manufacturer.

Adding additional telephone sockets

It is very easy to wire your home with additional telephone sockets so that you can use a phone in almost any room. You can buy the individual parts you need for the work or kits



which will contain the relevant parts (i.e. cable with adapter converter, wall sockets and cable clips etc.) are available. NOTE that sockets for extensions need to be 'slave' sockets rather than 'master' sockets.

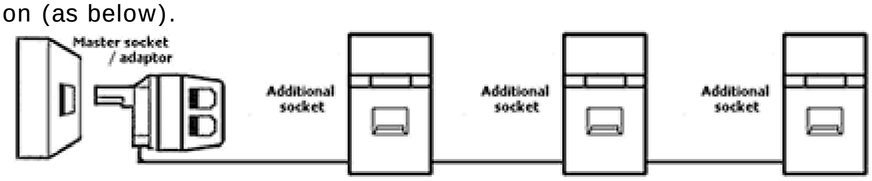
It is important that telephone extension sockets and cabling are added in such a way that they do not affect the public telephone network. The telephone service provider is entitled to check and test any socket and wiring connected to the exchange lines.

Each telephone exchange line coming into a home or office should be fitted with a special 'master socket' which must be installed by telephone service provider - some older houses may still have the telephone 'hard wired' - if you don't have a 'plug-in' telephone, you will need to get your telephone service provider to install one before you can start adding telephone sockets yourself. It is Illegal to tamper with the master socket and you cannot install one yourself or wire directly to it.

Planning the installation

There are two possible basic circuits for installing additional telephone sockets

- Spur wiring - where the adapter connected to the master socket goes to a junction box and then each socket is wired from the junction box (as right).
- Series wiring where the adapter connected to the master socket is wired to the first socket, which is wired to the second socket, which is wired to the third socket and so on (as below).



The choice of which is used will depend upon the position of the master socket and the required positions for the new sockets. You can mix the two forms as necessary, possibly using serial wiring to connect junction boxes on each floor, and then running spurs from each junction box to the socket positions on each floor.

A few basic guidelines are

1. No new socket should have more than 50 metres of cable between it and the master socket.
2. No matter how many sockets are on a telephone line, the number of actual telephone handsets which can be connected to it is limited to 4 REN (ringer equivalence

numbers) - each handset will have a REN, and the total of all the handsets must not exceed 4 REN. If any equipment is not marked with its 'REN', then check with supplier. If this is not possible, check that the equipment is approved for connection to the public telephone network (i.e. it carries a green circle on a label) and then assume a 'REN' of one.

3. Do not position extension sockets or junction boxes out of doors or where damp or condensation may occur (e.g. shower or bath room).
4. Only join telephone wiring within sockets or junction boxes. If 'spur" type layout is necessary, a junction box is essential.
5. Phone cable and sockets should be at least 2 inches from any mains electrical wiring and outlets to avoid electrical interference.
6. ALWAYS disconnect the adapter from the master socket before changing or adding wiring to the telephone circuit.

Fixing the sockets

The first thing is to decide upon the required positions for the sockets/junction boxes. Once decided upon, offer up the boxes and as appropriate depending upon the type of wall construction, temporarily secure the boxes to the wall.

Installing the cable

Starting at the master socket, and allowing enough cable to connect the adapter to it, run the cable to the junction box or the first socket. The cable can be run

- On the surface, simply using cable staples every 300mm or so. It is often easier to run it along the top of skirting and around door frames, this ensures the cable is unobtrusive.
- In surface mounted conduit, usually small profile square conduit with a removable front cover. Simply route and fix the conduit as necessary, feed the cable along it and fit the front cover of the conduit.
- Through conduit within the wall, it normally takes a bit of forward planning to put the conduit in place before you run the cable. It can however always be retrospectively installed the next time the room is decorated, just ensure that the necessary length of cable is available. When hiding conduit in walls, always run it vertically (up or down) from the socket.
- Through roof, floor or wall voids
    - In the roof, keep the cable away from other electrical wiring, you can 'snake' the cable over/under roof installation.
    - Under wooden floors, the joists may need to be drilled to run the cables, again keep the telephone cables away from other electrical wiring.
    - Wall voids are generally stud partitioning or similar, normally it easier to run cables within walls during their construction.

Where cables need to go between rooms, this can be done by a number of ways

- Drilling through a door frame.
- Drilling through the wall either just above the skirting board or at the top of a door frame.
- Taking the cable either below the floor or above the ceiling and through a hole in the wall and then down or up as appropriate within the next room.

Sockets/Junction boxes

When the cable has been run to the junction box/ socket

- Remove the cable entry/exit points from the back plate of the box.
- Pass the cable through the back plate from the rear, to the front.
- Securely mount the box in the required position.

Looking at the terminations on the socket, there are normally 6 (numbered 1 to 6) terminals in the socket or junction box, the wiring colour code is

terminal number		**wiring colour code**
1		green + white
2		blue + white
3		orange + white
4		white + orange
5		white + blue
6		white + green

There's no need to know what each wire does, just to know that the wiring is always the same colour to the same colour whether the cable comes from a master socket or goes to another socket.

For domestic installations, four core cable may be used, in this case these will be 2 to 5 above. If 6 core cable is available, the green and white cores can be cut back and not used.

The cable used for extending telephone systems is only designed to be used for fixed wiring to telephone socket or junction boxes, it is not designed to make extension leads or to have BT plugs fitted to it.

Two types of socket/junction box termination are available

1.Screw connection

- Carefully strip off the outer sheath from the cable without cutting the inner insulations.
- Strip back the inner cores and make the connections according to colour code.
- In a series circuit, two cables may enter the socket box and each terminal will have two inner cores (same colours) connected.
- Leave slack in the wire in case it has to be removed and the connection remade.
- Always use a cable tie to firmly secure the outer insulation to the socket/junction box cover.

- Ensuring that the socket is correctly positioned (the cover over the socket should need to be pushed up to connect a telephone), replace the cover.

2. IDC (insulation displacement connectors).

- Carefully strip off about 50mm of the outer sheath from the cable without cutting the inner insulations.
- Position an inner core (with its insulation in position) over the respectively numbered connector.
- Use the special tool (right) to push the inner core into the connector.
- Repeat for the remaining inner cores.
- In a series circuit, two cables may enter the socket box and each terminal will have two inner cores connected, each core being inserted individually.
- Leave slack in the wire in case it has to be removed and the connection remade.
- Always use a cable tie to firmly secure the outer insulation to the socket/terminal box.
- Ensuring that the socket is correctly positioned (the cover over the socket should need to be pushed up to connect a telephone), replace the cover.

Testing

First of all, with the adapter unconnected, use the original socket to make sure that your phone can make outgoing and incoming calls.

Repeat the test with the adapter plugged in to the master socket and the phone plugged into the adapter.

If all is working well, move along the new cable run and check each new socket in the same way.

If you have more than one telephone handset, leave the first in place and repeat the test in the first extension socket - ensure that when the bell rings, both phones operate together.

Add further handsets one at a time and repeat the test (up to a total of 4 REN loading). If you need to test more sockets than you have handsets or you reach the 4 REN loading, move the last handset from socket to socket until all sockets have been tested.

Problems ?

Two sorts of problems may be encountered:

1. When you plug the adapter into the the master socket, nothing works. This probably indicates a short circuit in the wiring.
   - If you have an electrical tester, unplug the adapter and check out the terminals for short circuits.

    - If you cannot find the problem, starting at the first socket or junction box after the master socket, remove the wires going into the socket and retest at the adapter - if the problem persists, the problem is in the adapter.
2. The handset works when plugged into the adapter but a socket further down the circuit does not work. This probably indicates an open circuit or poorly made connection.
    - Unplug the adapter and check the wiring within the appropriate socket and the last socket/junction boxes in the chain.
    - Check that the colours are in the correct places and that the wires are fully in position.
    - If in doubt, remake the connections.