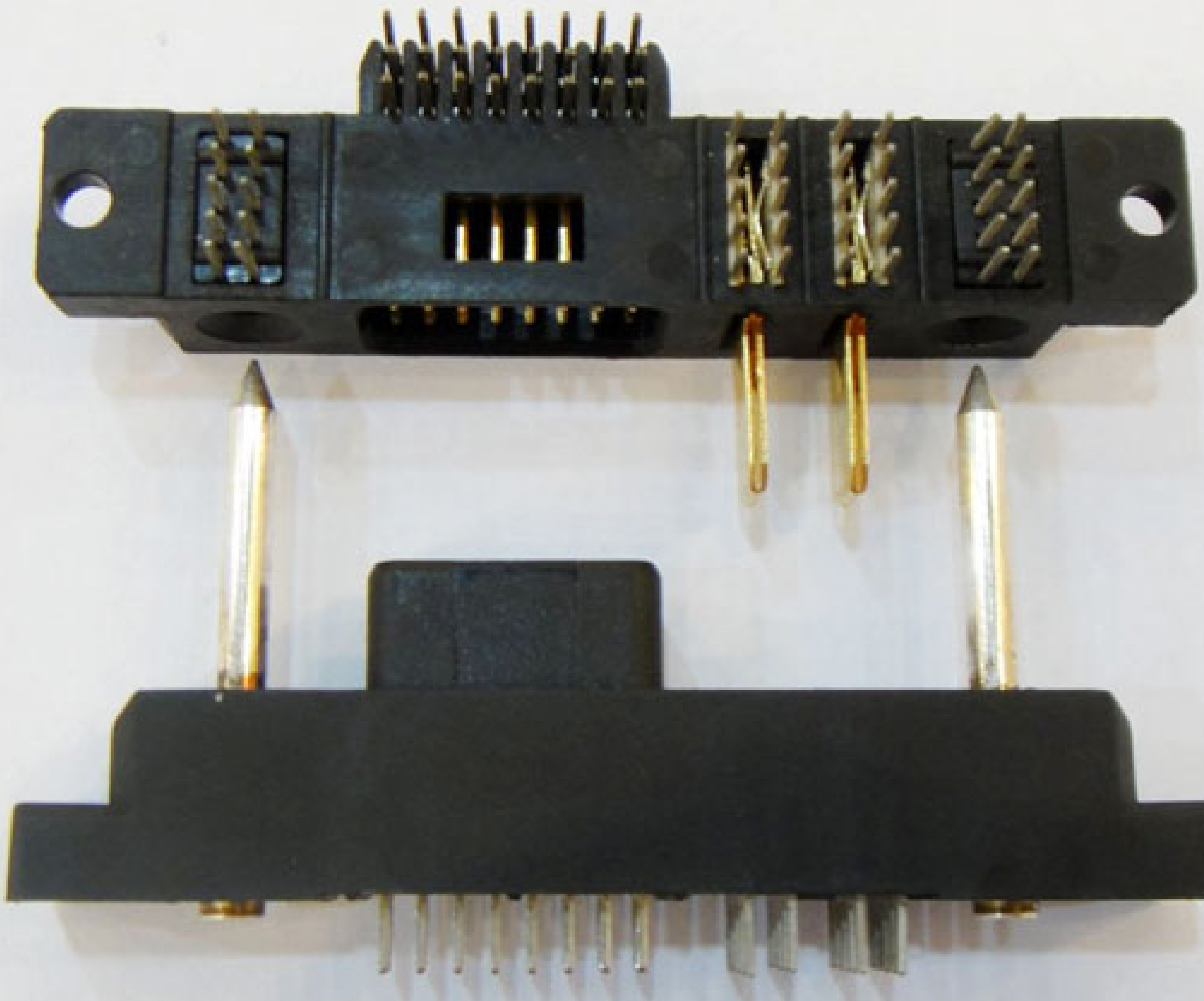
Electrical Components



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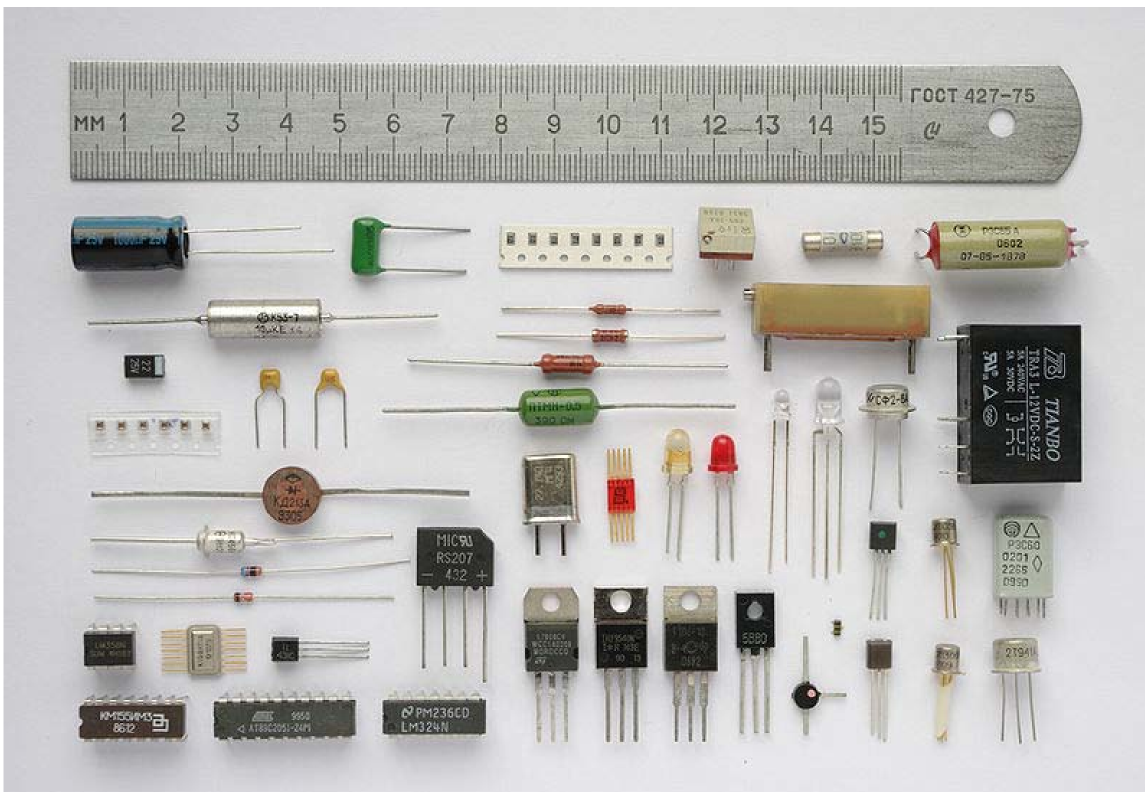
Electronic Component



Various components

An **electronic component** is a basic electronic element and may be available in a discrete form having two or more electrical terminals (or *leads*). These are intended to be connected together, usually by soldering to a printed circuit board, in order to create an electronic circuit with a particular function (for example an amplifier, radio receiver, or oscillator). Basic electronic components may be packaged discretely, as arrays or networks of like components, or integrated inside of packages such as semiconductor integrated circuits or thick film devices. The following list of electronic components focuses on the discrete version of these components, treating such packages as components in their own right.

Classification

A component may be classified as passive or active. The strict physics definition treats passive components as ones that cannot supply energy themselves, whereas a battery would be seen as an active component since it truly acts as a source of energy.

However electronic engineers performing circuit analysis use a more restrictive definition of passivity. When we are only concerned with the energy due to signals it is convenient to ignore the so-called DC circuit and pretend that the power supplying components such as transistors or integrated circuits is absent (as if each such component had its own battery built in) although it may in reality be supplied by the DC circuit which we are ignoring. Then the analysis only concerns the so-called AC circuit, an abstraction which ignores the DC voltages and currents (and the power associated with them) present in the real-life circuit. This fiction, for instance, allows us to view an oscillator as "producing energy" even though in reality the oscillator consumes even more energy from a power supply, obtained through the *DC circuit* which we have chosen to ignore. Under that restriction we define the terms as used in circuit analysis as follows:

- **Passive components** are ones which cannot introduce net energy into the circuit they are connected to. They also cannot rely on a source of power except for what is available from the (AC) circuit they are connected to. As a consequence they are unable to amplify (increase the power of a signal), although they may well increase a voltage or current such as is done by a transformer or resonant circuit. Among passive components are familiar two-terminal components such as resistors, capacitors, inductors, and most sorts of diodes.
- **Active components** rely on a source of energy (usually from the DC circuit, which we have chosen to ignore) and are usually able to inject power into a circuit although this is not part of the definition. This includes amplifying components such as transistors, triode vacuum tubes (valves), and tunnel diodes.

Passive components can be further divided into lossless and lossy components:

- **Lossless** components do not have a net power flow into or out of the component. This would include ideal capacitors, inductors, transformers, and the (theoretical) gyrator.
- **Lossy** or **dissipative** components do not have that property and generally absorb power from the external circuit over time. The prototypical example is the resistor. In practice all non-ideal passive components are at least a little lossy, but these are typically modeled in circuit analysis as consisting of an ideal lossless component with an attached resistor to account for the loss.

Most passive components with more than two terminals can be described in terms of two-port parameters satisfying the principle of reciprocity, although there are some rare exceptions. In contrast, active components (which have more than two terminals) generally lack that property.

Note that these distinctions only apply to components listed below which would be modeled as elements within circuit analysis. Practical items which act as transducers or have other connections to the outside world such as switches, cannot be subject to this form of classification since they defy the view of the electronic circuit as a closed system.

Components

Terminals and connectors

Devices to make electrical connection

- Terminal
- Connector
    - Socket
    - Screw terminal, Terminal Blocks
    - Header

Cable assemblies

Cables with connectors or terminals at their ends

- Power cord
- Patch cord
- Test lead

Switches

Components that can pass current ("closed") or break the flow of current ("open")

- Switch - Manually operated switch.
    - Electrical description: SPST, SPDT, DPST, DPDT, NPNT (general)
    - Technology: slide switches, toggle switches, rocker switches, rotary switches, pushbutton switches
- Keypad - Array of pushbutton switches
- DIP switch - Small array of switches for internal configuration settings
- Footswitch - Foot-operated switch
- Knife switch - Switch with unenclosed conductors
- Micro switch - Mechanically activated switch with snap action
- Limit switch - Mechanically activated switch to sense limit of motion
- Mercury switch - Switch sensing tilt
- Centrifugal switch - Switch sensing centrifugal force due to rate of rotation
- Relay - Electrically operated switch
- Reed switch - Magnetically activated switch

- Thermostat - Thermally activated switch
- Humidistat - Humidity activated switch
- Circuit Breaker - Switch opened in response to excessive current: a resettable fuse

Resistors

Pass current in proportion to voltage (ohms law).

- Resistor - fixed value
    - Power resistor - larger to safely dissipate heat generated
    - SIP or DIP resistor network - array of resistors in one package
- Variable resistor
    - Rheostat - Two terminal variable resistor (often for high power)
    - Potentiometer - Three terminal variable resistor (variable voltage divider)
    - Trim pot - Small potentiometer, usually for internal adjustments
- Heater - heating element
- Resistance wire, Nichrome wire - wire of high-resistance material, often used as heating element
- Thermistor - temperature-varied resistor
- Humistor - humidity-varied resistor
- Varistor, Voltage Dependent Resistor, MOV - Passes current when excessive voltage present

Protection devices

Passive components that protect circuits from excessive currents or voltages

- Fuse - Over-current protection, one time use
- Circuit Breaker - Resettable fuse in the form of a mechanical switch
- PolySwitch or Resettable fuse - Circuit breaker action using solid state device
- Ground-fault protection or Residual-current device - Circuit breaker sensitive to mains currents passing to ground
- Metal Oxide Varistor, Surge Absorber (MOV), TVS - Over-voltage protection.
- Inrush current limiter - Protection against initial Inrush current
- Gas Discharge Tube - Protection against high voltage surges
- Spark gap - Electrodes with a gap to arc over at a high voltage
- Lightning arrester - Spark gap used to protect against lightning strikes

Capacitors

Components that store and release electrical charge. Used for filtering power supply lines, for tuning resonant circuits, and for blocking DC voltages while passing AC signals, among numerous other uses.

- Capacitor - fixed capacitance
    - Capacitor network (array)

- Variable capacitor - Adjustable capacitance
    - Tuning capacitor - Variable capacitor for tuning a radio, oscillator, or tuned circuit
    - Trimmer capacitor - Small variable capacitor usually for internal adjustments
- Varicap diode - AC capacitance varies according to the DC voltage applied.

Magnetic (inductive) devices

Electrical components that use magnetism

- Inductor, coil, choke
- Variable inductor
- Saturable Inductor
- Transformer
- Magnetic amplifier (toroid)
- Ferrite impedances, beads
- Motor / Generator
- Solenoid
- Speaker / Microphone

Networks

Components that use more than one type of passive component

- RC network - forms an RC circuit, used in Snubbers
- LC Network - forms an LC circuit, used in tuneable transformers and RFI filters

Piezoelectric devices, crystals, resonators

Passive components that use piezoelectric effect

- Components that use the effect to generate or filter high frequencies
    - Crystal - Is a ceramic crystal used to generate precise frequencies
    - Ceramic resonator - Is a ceramic crystal used to generate semi-precise frequencies
    - Ceramic filter - Is a ceramic crystal used to filter a band of frequencies such as in radio receivers
    - Surface Acoustic Wave (SAW) filters
- Components that use the effect as mechanical Transducers.
    - Ultrasonic motor - Electric motor that uses the piezoelectric effect

Power sources

Sources of electrical power

- Battery - acid- or alkali-based power supply
- Fuel cell - an electrochemical generator
- Power supply - usually a mains hook-up
- Photo voltaic device - generates electricity from light
- Thermo electric generator - generates electricity from temperature gradients
- Electrical generator - an electromechanical power source

Transducers, sensors, detectors

1. Transducers generate physical effects when driven by an electrical signal, or vice-versa.
2. Sensors (detectors) are transducers that react to environmental conditions by changing their electrical properties or generating an electrical signal.
3. The Transducers listed here are single electronic components (as opposed to complete assemblies), and are passive.

- Audio
  - Loudspeaker - Magnetic or piezoelectric device to generate full audio
  - Buzzer - Magnetic or piezoelectric sounder to generate tones
- Position, motion
  - Linear variable differential transformer (LVDT) - Magnetic - detects linear position
  - Rotary encoder, Shaft Encoder - Optical, magnetic, resistive or switches - detects absolute or relative angle or rotational speed
  - Inclinometer - Capacitive - detects angle with respect to gravity
  - Motion sensor, Vibration sensor
  - Flow meter - detects flow in liquid or gas
- Force, torque
  - Strain gauge - Piezoelectric or resistive - detects squeezing, stretching, twisting
  - Accelerometer - Piezoelectric - detects acceleration, gravity
- Thermal
  - Thermocouple, thermopile - Wires that generate a voltage proportional to delta temperature
  - Thermistor - Resistor whose resistance changes with temperature, up PTC or down NTC
  - Resistance Temperature Detector (RTD) - Wire whose resistance changes with temperature
  - Bolometer
  - Thermal cutoff - Switch that is opened or closed when a set temperature is exceeded
- Magnetic field
  - Magnetometer, Gauss meter
- Humidity
  - Hygrometer
- Electromagnetic, light

    - Photo resistor - Light dependent resistor (LDR)

Semiconductors

Diodes

Conduct electricity easily in one direction, among more specific behaviors.

- Standard Diode, Rectifier, Bridge Rectifier
- Schottky Diode, Hot Carrier Diode - super fast diode with lower forward voltage drop
- Zener Diode - Passes current in reverse direction to provide a constant voltage reference
- Transient Voltage Suppression Diode (TVS), Unipolar or Bipolar - used to absorb high-voltage spikes
- Varactor, Tuning diode, Varicap, Variable Capacitance Diode - A diode whose AC capacitance varies according to the DC voltage applied.
- Light Emitting Diode (LED) - A diode which emits light
- LASER Diode - A semiconductor laser
- Photodiode - Passes current in proportion to incident light
    - Avalanche Photodiode Photodiode with internal gain
    - Solar Cell, photovoltaic cell, PV array or panel, produces power from light
- Diode for Alternating Current (DIAC, Trigger Diode, SIDAC) - Often used to trigger an SCR
- Constant current Diode
- Peltier cooler - A semiconductor heat pump

Transistors

Active components used for amplification.

- Bipolar transistors
    - Bipolar Junction Transistor (BJT, or simply "transistor") - NPN or PNP
        - Photo transistor - Amplified photodetector
    - Darlington transistor - NPN or PNP
        - Photo Darlington - Amplified photodetector
    - Sziklai pair (Compound transistor, complementary Darlington)
- Field effect transistor (FET)
    - Junction Field Effect Transistor (JFET) - N-CHANNEL or P-CHANNEL
    - Metal Oxide Semiconductor FET (MOSFET) - N-CHANNEL or P-CHANNEL
    - MEtal Semiconductor FET (MESFET)
    - High Electron Mobility Transistor (HEMT)
- Thyristors
    - Silicon Controlled Rectifier (SCR) - Passes current only after triggered by a sufficient control voltage on its gate

- TRIode for Alternating Current (TRIAC) - Bidirectional SCR
  - UniJunction Transistor (UJT)
  - Programmable UniJunction Transistor (PUT)
  - Static Induction Transistor/Thyristor (SIT, SITh)
- Composite transistors
  - Insulated Gate Bipolar Transistor (IGBT)

Integrated circuits

- Digital
- Analog
  - Hall effect sensor - Senses a magnetic field
  - Current sensor - Senses a current through it

Optoelectronic devices

- Optoelectronics
  - Opto-Isolator, Opto-Coupler, Photo-Coupler - Photodiode, BJT, JFET, SCR, TRIAC, Zero-crossing TRIAC, Open collector IC, CMOS IC, Solid State Relay (SSR)
  - Opto Switch, Opto Interrupter, Optical Switch, Optical Interrupter, Photo switch, Photo Interrupter
  - LED Display - Seven-segment display, Sixteen-segment display, Dot matrix display

Display technologies

Current:

- Filament lamp (indicator lamp)
- Vacuum fluorescent display (VFD) (preformed characters, 7 segment, starburst)
- Cathode ray tube (CRT) (dot matrix scan (e.g. computer monitor), radial scan (e.g. radar), arbitrary scan (e.g. oscilloscope)) (monochrome & colour)
- LCD (preformed characters, dot matrix) (passive, TFT) (monochrome, colour)
- Neon (individual, 7 segment display)
- LED (individual, 7 segment display, starburst display, dot matrix)
- Flap indicator (numeric, preprinted messages)
- Plasma display (dot matrix)

Obsolete:

- Filament lamp 7 segment display (aka 'minitron')
- Nixie Tube
- Dekatron (aka glow transfer tube)
- Magic eye tube indicator
- Penetron (a 2 colour see-through CRT)

Vacuum tubes (Valves)

Based on current conduction through a vacuum

- Diode or Rectifier tube

Amplifying tubes

- Triode
- Tetrode
- Pentode
- Hexode
- Pentagrid
- Octode
- Microwave tubes
    - Klystron
    - Magnetron
    - Traveling-wave tube

Optical detectors or emitters

- Phototube or Photodiode - tube equivalent of semiconductor photodiode
- Photomultiplier tube - Phototube with internal gain
- Cathode ray tube (CRT) or Television picture tube
- Vacuum fluorescent display (VFD) - Modern non-raster sort of small CRT display
- Magic eye tube - Small CRT display used as a tuning meter (obsolete)
- X-ray tube - Produces x-rays

Discharge devices

- Gas discharge tube

Obsolete:

- Mercury arc rectifier
- Voltage regulator tube
- Nixie tube
- Thyratron
- Ignitron

Antennas

Antennas transmit or receive radio waves

- Elemental dipole

- Yagi
- Phased array
- Loop antenna
- Parabolic dish
- Log-periodic dipole array
- Biconical
- Feedhorn

Assemblies, modules

Multiple electronic components assembled in a device that is in itself used as a component

- Oscillator
- Display devices
    - Liquid crystal display (LCD)
    - Digital voltmeters
- Filter

Prototyping aids

- Wire-wrap
- Breadboard

Mechanical accessories

- Enclosure
- Heat sink
- Heat sink paste & pads
- Fan

Other

- Printed circuit boards
- Lamp
- Waveguide
- Memristor

Obsolete:

- Carbon amplifier
- Carbon arc (negative resistance device)
- Dynamo (historic rf generator)

Standard symbols

On a circuit diagram, electronic devices are represented by conventional symbols. Reference designators are applied to the symbols to identify the component.

Chapter- 2

Electrical Connector

Interface of a 1987 RCA Dimensia, an advanced TV model of its time; note the European SCART connection

Back of TRM-800 audio amplifier

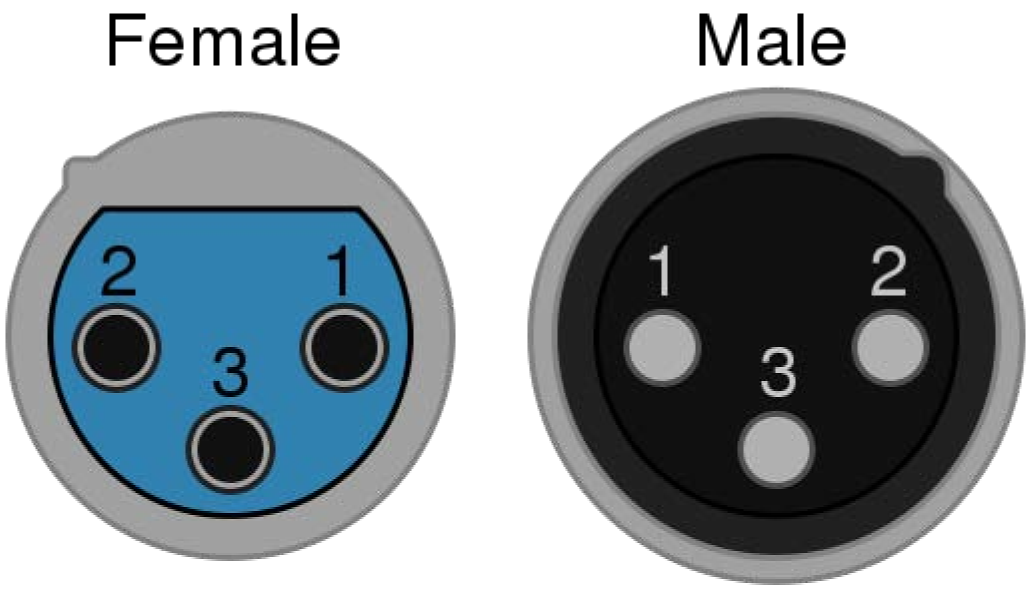
An **electrical connector** is a conductive device for joining electrical circuits together. The connection may be temporary, as for portable equipment, or may require a tool for assembly and removal, or may be a permanent electrical joint between two wires or devices. There are hundreds of types of electrical connectors. In computing, an electrical connector can also be known as a **physical interface** (compare Physical Layer in OSI model of networking). Connectors may join two lengths of flexible wire or cable, or may connect a wire or cable to an electrical terminal. Although cable glands are often called "connectors", a technical distinction can be made in the terminology, which differentiates them from quick-disconnect, conducting electrical connectors. The distinction is often not made.

Properties of electrical connectors

An ideal electrical connector would have a low contact resistance and high insulation value. It would be resistant to vibration, water, oil, and pressure. It would be easily mated/unmated, unambiguously preserve the orientation of connected circuits, reliable, carry one or multiple circuits. Desirable properties for a connector also include easy identification, compact size, rugged construction, durability (capable of many connect/disconnect cycles), rapid assembly, simple tooling, and low cost. No single connector has all the ideal properties. The proliferation of types is a reflection of the differing importance placed on the design factors.

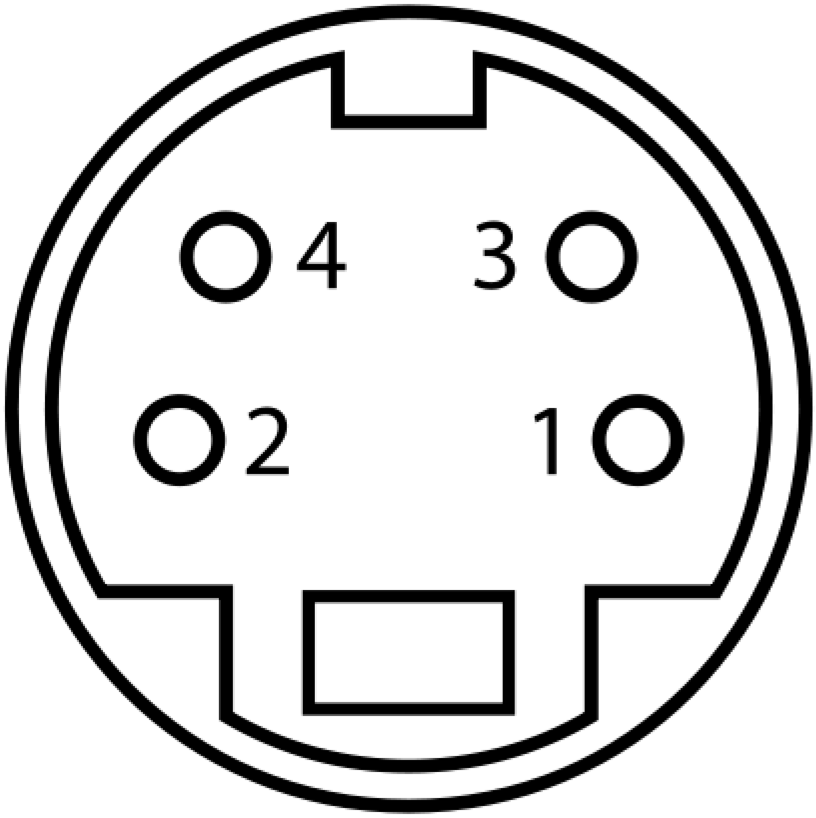
The safety ground in some power connectors, and certain crucial contacts in some hot swapping connectors, are designed to be first to mate / last to unmate.

Keying



XLR connector, showing the notch for alignment.

4-pin Mini-DIN S-Video cable: the notches are the keying showing the keying.

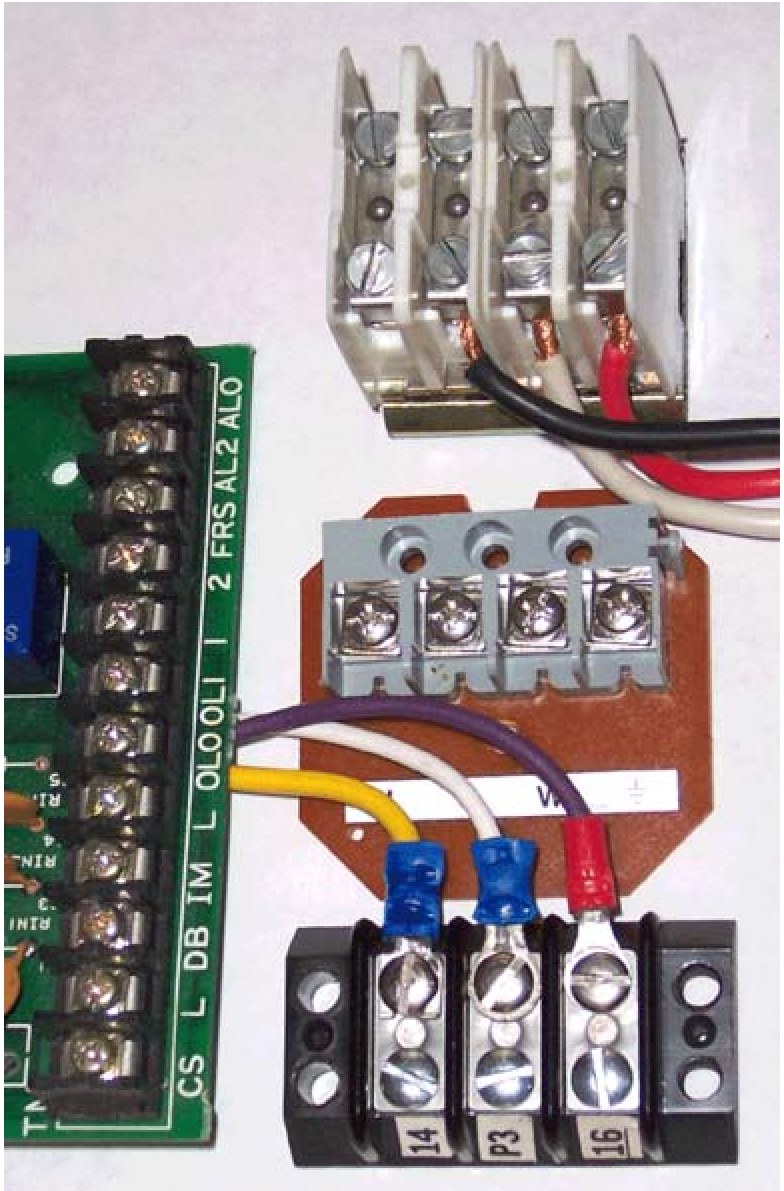


4-pin Mini-DIN pinout: the off-center rectangle and surrounding notches are a key.

Many connectors are **keyed,** meaning that they have some component which prevents mating except with specific connectors or in a specific orientation. This can be used to prevent incorrect or damaging interconnections, either preventing pins from being damaged by being jammed in at the wrong angle or fitting into imperfectly fitting plugs, or to prevent damaging connections, such as plugging an audio cable into a power outlet. For instance, XLR connectors have a notch to ensure proper orientation, while Mini-DIN plugs have a plastic projection, which fits into a corresponding hole in the socket and prevent different connectors from being pushed together (they also have a notched metal skirt to provide secondary keying).

Types of electrical connectors

A *terminal* is a simple type of electrical connector that connects two or more wires to a single connection point. Wire nuts are another type of single point connector.



Terminal blocks of various types.

Terminal blocks

Terminal blocks (also called terminal *boards* or *strips*) provide a convenient means of connecting individual electrical wires. They are usually used to connect wiring among various items of equipment within an enclosure or to make connections among individually enclosed items. Since terminal blocks are readily available for a wide range of wire sizes and terminal quantity, they are one of the most flexible types of electrical connector available. Some disadvantages are that connecting wires is more difficult than simply plugging in a cable and the terminals are generally not very well protected from contact with persons or foreign conducting materials.

One type of terminal block accepts wires that are prepared only by removing (*stripping*) a short length of insulation from the end. Another type accepts wires that have ring or spade terminal *lugs* crimped onto the wires. Printed circuit board (PCB) mounted terminal blocks allow individual wires to be connected to the circuit board. PCB mounted terminal blocks are soldered to the board, but they are available in a pull-apart version that allows the wire-connecting half of the block to be unplugged from the part that is soldered to the PCB.

Posts

A binding post (red and black) adaptor.

A general type of connector simply screws or clamps bare wire to a post; such connectors are frequently used in electronic test equipment and audio.

Crimp-on Connectors

A type of solderless connection.

Insulation displacement connectors

Since stripping the insulation from wires is time-consuming, many connectors intended for rapid assembly use insulation-displacement connectors so that insulation need not be removed from the wire. These generally take the form of a fork-shaped opening in the terminal, into which the insulated wire is pressed and which cut through the insulation to contact the conductor within. To make these connections reliably on a production line, special tools are used which accurately control the forces applied during assembly. If properly assembled, the resulting terminations are gas-tight and will last the life of the product. A common example is the multi-conductor flat ribbon cable used in computer disk drives; to terminate each of the many (approximately 40) wires individually would be slow and error-prone, but an insulation displacement connector can terminate all the wires in (literally) one stroke. Another very common use is so-called "punch down" blocks used for terminating telephone wiring.

Insulation displacement connectors are usually used with small conductors for signal purposes and at low voltage. Power conductors carrying more than a few amperes are more reliably terminated with other means, though "hot tap" press-on connectors find some use in automotive applications for additions to existing wiring.

Plug and socket connectors

A male plug made by Amphenol.

Plug and socket connectors are usually made up of a male plug and a female socket, although *hermaphroditic* connectors exist, such as the original IBM token ring LAN connector. Plugs generally have one or more pins or prongs that are inserted into openings in the mating socket. The connection between the mating metal parts must be sufficiently tight to make a good electrical connection and complete the circuit. When working with multi-pin connectors, it is helpful to have a pinout diagram to identify the wire or circuit node connected to each pin.

4-conductor hermaphrodite connector for token-ring attachment.

Detail of mating surfaces of hermaphrodite connector.

Transistor switch module with large screw connectors and small fast-on connectors.

Component and device connectors

Electrical and electronic components and devices sometimes have plug and socket connectors or terminal blocks, but individual screw terminals and fast-on or quick-disconnect terminals are more common. Small components have bare lead wires for soldering. They are manufactured using casting

Blade connector

Some blade connectors

A **blade connector** is a type of single wire connection using a flat blade which is inserted into a blade receptacle. Usually both blade connector and blade receptacle have wires attached to them either through soldering of the wire to the blade or crimping of the blade to the wire. In some cases the blade is a manufactured part of a component (such as a switch or a speaker unit) and a blade receptacle is pushed onto the blade to form a connection.

A common type of blade connector is the "Faston". While Faston is a trademark of Tyco Electronics, it has come into common usage. Faston connectors come in male and female types. They have been commonly used since 1970s.

Ring and Spade Terminals

The connectors in the top row of the image are known as **ring terminals** and **spade terminals** (sometimes called split ring terminals). Electrical contact is made by passing a screw or bolt through them. The spade terminal form factor facilitates connections since the screw or bolt can be left partially screwed in as the spade terminal is removed or attached. Their sizes can be determined by the size of the conducting wire AWG and/or the Screw/Bolt diameter size designation.

Commonly used connectors

8P8C connector

8P8C Connector crimped to cable

8P8C is short for "eight positions, eight conductors", and so an 8P8C modular connector (plug or jack) is a modular connector with eight positions, all containing conductors. The connector is probably most famous for its use in Ethernet and widely used on CAT5 cables.

The 8P8C modular plugs and jacks look very similar to the plugs and jacks used for FCC's registered jack RJ45 variants, although the true and extremely uncommon RJ45 is not really compatible with 8P8C modular connectors. It neither uses all eight conductors (but only two of them for wires plus two for shorting a programming resistor) nor does it fit into 8P8C because the true RJ45 is "keyed".

D-subminiature connectors

A male DE-9 plug.

The D-subminiature electrical connector is commonly used for the RS-232 serial port on modems and IBM compatible computers. The D-subminiature connector is used in many different applications, for computers, telecommunications, and test and measurement instruments. A few examples are monitors (MGA, CGA, EGA), the Commodore 64, MSX, Apple II, Amiga, and Atari joysticks and mice, and game consoles such as Atari and Sega.

USB connectors

A male USB series A plug

The **Universal Serial Bus** is a serial bus standard to interface devices, founded in 1996. It is currently widely used among PCs, Apple Macintosh and many other devices. There are several types of USB connectors, and some have been added as the specification has progressed. The most commonly used is the (male) series "A" plug on peripherals, when the cable is fixed to the peripheral. If there is no cable fixed to the peripheral, the peripheral always needs to have a USB "B" socket. In this case a USB "A" plug to a USB "B" plug cable would be needed. USB "A" sockets are always used on the host PC and the USB "B" sockets on the peripherals. It is a 4-pin connector, surrounded by a shield. There are several other connectors in use, the mini-A, mini- B and mini-AB plug and socket (added in the On-The-Go Supplement to the USB 2.0 Specification).

Power connectors

Power connectors must protect people from accidental contact with energized conductors. Power connectors often include a safety ground connection as well as the power conductors. In larger sizes, these connectors must also safely contain any arc produced when an energized circuit is disconnected or may require interlocking to prevent opening a live circuit.

Radio frequency connectors

Connectors used at radio frequencies must not change the impedance of the transmission line of which they are part, otherwise signal reflection and losses will result. A radio-frequency connector must not allow external signals into the circuit, and must prevent leakage of energy out of the circuit. At lower radio frequencies simple connectors can be used with success, but as the radio frequency increases, transmission line effects become more important, with small impedance variations from connectors causing the signal to reflect from the connector, rather than to pass through. At UHF and above, silver-plating of connectors is common to reduce losses.

For Wi-Fi antennas the R-TNC connectors are used. A BNC connector is common for radio and test equipment used up to about 1 GHz.

DC Connectors

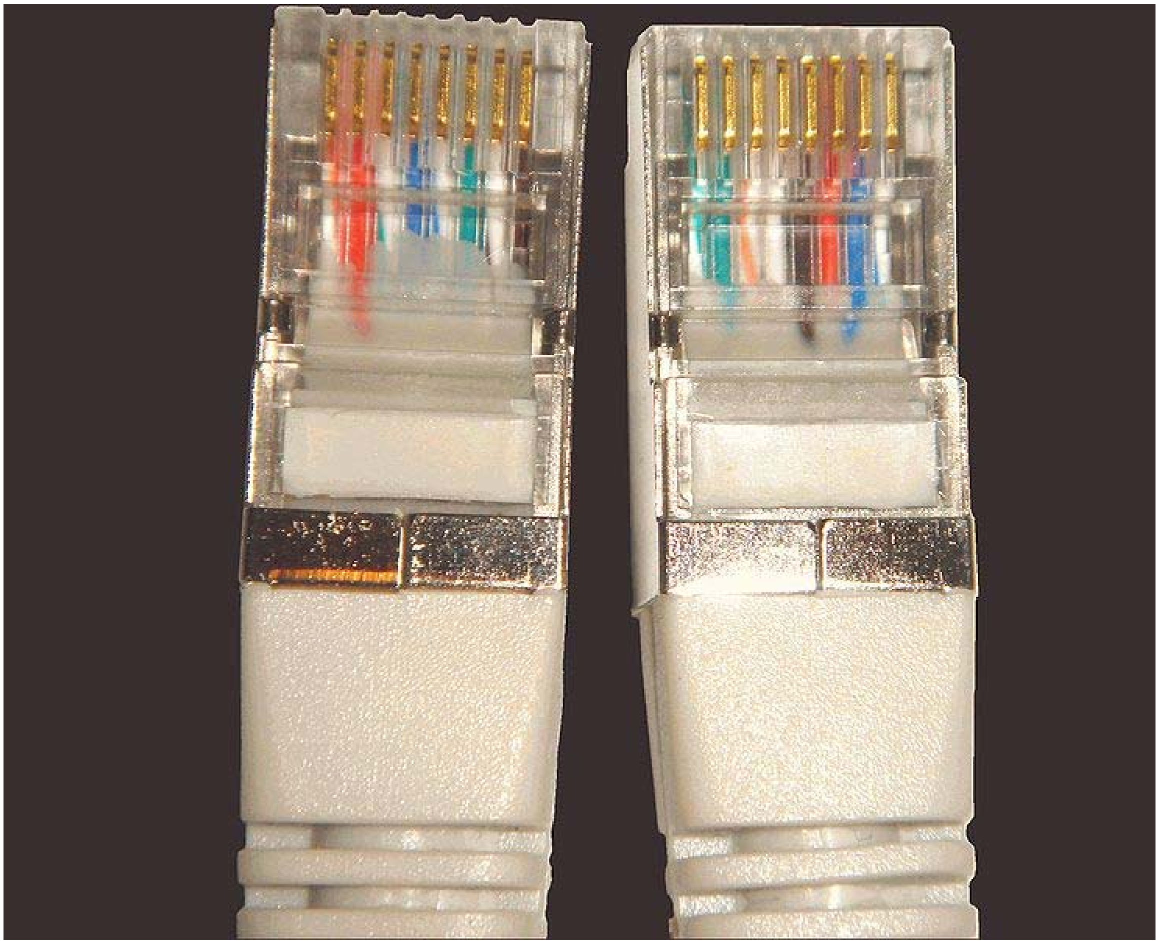
A DC connector is an electrical connector for supplying direct current (DC) power

Electrical cables

Termination and gender

When used to terminate cables, in some applications both ends of the cable are terminated using identical connectors (generally male), as in registered jack telephone cables or Ethernet over twisted pair network cables, while in other applications the two ends are terminated differently, either with male and female of the same connector (as in an extension cord), which ends can be connected to each other in a loop, or with incompatible connectors, in an adapter cable.

Wiring



Ethernet crossover cable, showing wiring at each end.

When a cable is terminated by a connector, the various wires in the cable are connected to contacts (pins) in the connector. If one has specified wires within a cable (for instance, the colored Ethernet cable wires in TIA/EIA-568-B), then which color wire connects to which number pin is the wiring. Different ways of wiring the two ends yield different cables which are superficially identical, but behave differently.

If both ends of a cable have the same connector, or male and female versions of a connector, or even similar connectors (such as RJ11 and BS 6312, both of which often have 6P4C (6 positions and 4 contacts)), there is a notion of **straight through cable** and **crossover cable:**

- in a **straight through cable,** pins on one end correspond exactly to the corresponding pins on the other end (pin 1 to pin 1, pin 2 to pin 2, etc.).

  Using the same wiring (a given color wire connects to a given number pin, the same at both ends) at each end yields a straight through cable.

- in a **crossover cable,** pins do not so correspond; most often in crossover cables some cables are swapped, meaning that if pin 1 on one end goes to pin 2 on the other end, then pin 2 on the first end goes to pin 1 on the second end, and not to pin 3 or some other: such crossover cables are symmetric, meaning that they work identically regardless of which way you plug them in (if you turn the cable around, it still connects the same pins as before).

  Using different wiring (a given color wire connects to one number pin at one end, and a different number pin at the other) at each end yields a crossover cable.

A well-known crossover cable is the Ethernet crossover cable, which converts between T568A and T568B termination.

What matters specifically is not "which contact corresponds to which wire", but rather "which contact on one connector corresponds to which contact on the other connector": to illustrate the distinction, T568A straight through cables and T568B straight through cables are electrically identical: pin 1 on one end corresponds to pin 1 on the other end, though in the T568A it is a green/white striped wire that connects them, while in T568B it is an orange/white striped wire that connects them. However, a cable wired with T568A at one end and T568B at the other is a crossover cable.

The name "straight through" is suggestive but slightly misleading: if one has a ribbon cable, such that all wires are in fact straight and in a line, the pinouts at the two ends are actually the *mirror* of each other: the left-most wire on one end is the right-most wire on the other.

Chapter- 3

Switch

Electrical switches. Top, left to right: circuit breaker, mercury switch, wafer switch, DIP switch, surface mount switch, reed switch. Bottom, left to right: wall switch (U.S. style), miniature toggle switch, in-line switch, push-button switch, rocker switch, microswitch.

In electronics, a **switch** is an electrical component that can break an electrical circuit, interrupting the current or diverting it from one conductor to another. The most familiar form of switch is a manually operated electromechanical device with one or more sets of electrical contacts. Each set of contacts can be in one of two states: either 'closed' meaning the contacts are touching and electricity can flow between them, or 'open', meaning the contacts are separated and nonconducting.

A switch may be directly manipulated by a human as a control signal to a system, such as a computer keyboard button, or to control power flow in a circuit, such as a light switch. Automatically-operated switches can be used to control the motions of machines, for example, to indicate that a garage door has reached its full open position or that a machine tool is in a position to accept another workpiece. Switches may be operated by process variables such as pressure, temperature, flow, current, voltage, and force, acting as sensors in a process and used to automatically control a system. For example, a thermostat is a temperature-operated switch used to control a heating process. A switch that is operated by another electrical circuit is called a relay. Large switches may be remotely operated by a motor drive mechanism. Some switches are used to isolate electric power from a system, providing a visible point of isolation that can be pad-locked if necessary to prevent accidental operation of a machine during maintenance, or to prevent electric shock.

In circuit theory

In electronics engineering, an ideal switch describes a switch that:

- has no current limit during its ON state
- has infinite resistance during its OFF state
- has no voltage drop across the switch during its ON state
- has no voltage limit during its OFF state
- has zero rise time and fall time during state changes
- switches only once without "bouncing" between on and off positions

Practical switches have loss and limitation. The ideal switch is often used in circuit analysis as it greatly simplifies the system of equations to be solved, however this can lead to a less accurate solution.

Contacts

A toggle switch in the "on" position.

In the simplest case, a switch has two conductive pieces, often metal, called *contacts* that touch to complete (make) a circuit, and separate to open (break) the circuit. The contact material is chosen for its resistance to corrosion, because most metals form insulating oxides that would prevent the switch from working. Contact materials are also chosen on the basis of electrical conductivity, hardness (resistance to abrasive wear), mechanical strength, low cost and low toxicity.

Sometimes the contacts are plated with noble metals. They may be designed to wipe against each other to clean off any contamination. Nonmetallic conductors, such as conductive plastic, are sometimes used.

Contact terminology

Triple Pole Single Throw (TPST or 3PST) knife switch used to short the windings of a 3 phase wind turbine for braking purposes. Here the switch is shown in the open position.

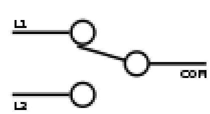
A pair of contacts is said to be "*closed*" when current can flow from one to the other. When the contacts are separated by an insulating air gap, they are said to be "*open*", and no current can flow between them at normal voltages.

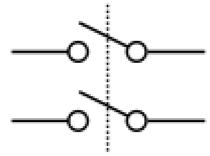
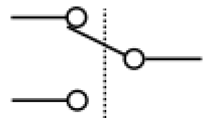
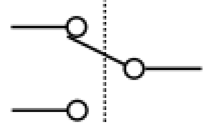
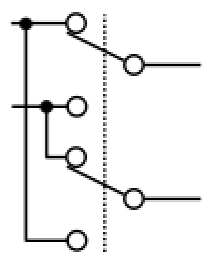
Switches are classified according to the arrangement of their contacts in electronics. Electricians installing building wiring use different nomenclature, such as "*one-way*", "*two-way*", "*three-way*" and "*four-way*" switches, which have different meanings in North American and British cultural regions as described in the table below.

In a push-button type switch, in which the contacts remain in one state unless actuated, the contacts can either be *normally open* (abbreviated *"n.o." or "no"*) until closed by operation of the switch, or *normally closed* (*"n.c. or "nc"*) and opened by the switch action. A switch with both types of contact is called a *changeover switch*. These may be "*make-before-break*" which momentarily connect both circuits, or may be "*break-before-make*" which interrupts one circuit before closing the other.

The terms *pole* and *throw* are also used to describe switch contact variations. The number of "*poles*" is the number of separate circuits which are controlled by a switch. For example, a "*2-pole*" switch has two separate identical sets of contacts controlled by the same knob. The number of "*throws*" is the number of separate positions that the switch can adopt. A single-throw switch has one pair of contacts that can either be closed or open. A double-throw switch has a contact that can be connected to either of two other contacts, a triple-throw has a contact which can be connected to one of three other contacts, etc.

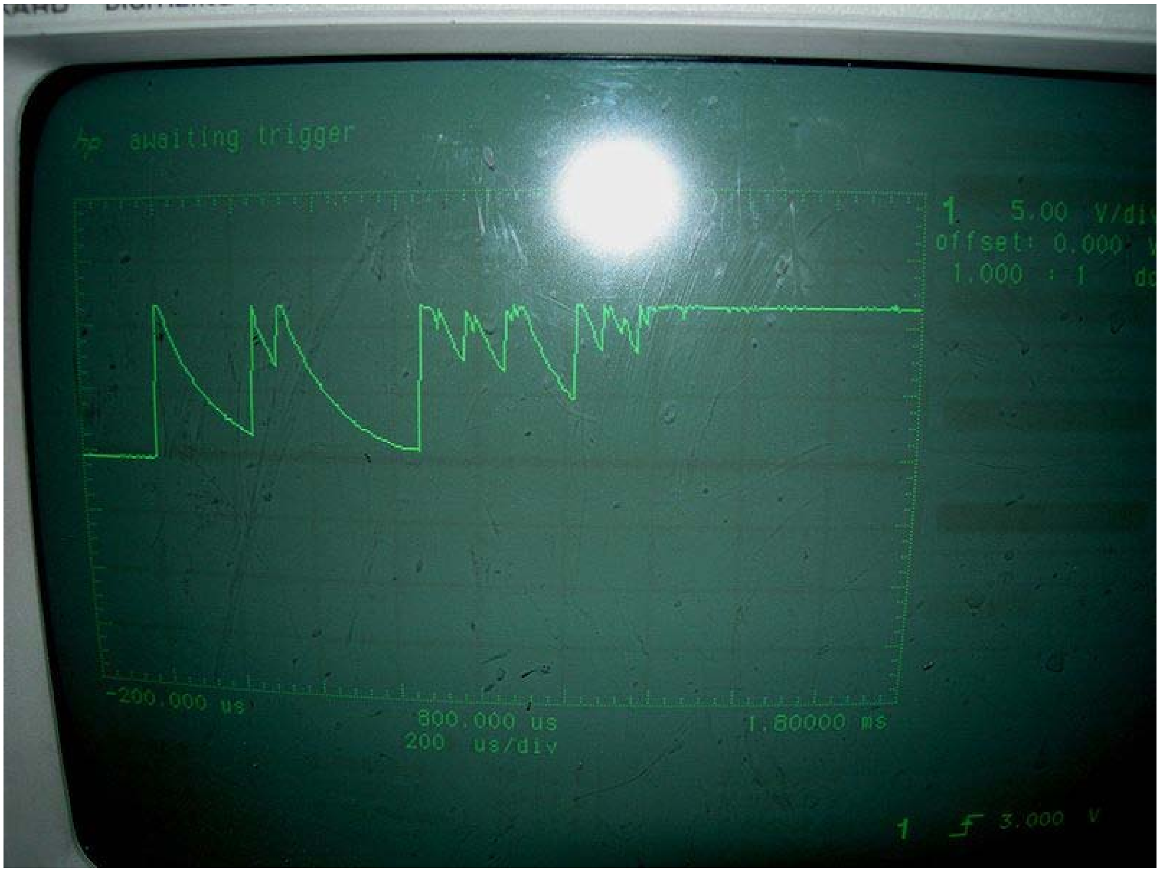
These terms give rise to abbreviations for the types of switch which are used in the electronics industry such as "*single-pole, single-throw*" (SPST) (the simplest type, "on or off") or "*single-pole, double-throw*" (SPDT), connecting either of two terminals to the common terminal. In electrical power wiring (i.e. House and building wiring by electricians) names generally involving the suffixed word *"-way"* are used; however, these terms differ between British and American English and the terms *two way* and *three way* are used in both with different meanings.

Electronics specification and abbreviation	Expansion of abbreviation	British mains wiring name	American electrical wiring name	Description	Symbol
SPST	Single pole, single throw	One-way	Two-way	A simple on-off switch: The two terminals are either connected together or disconnected from each other. An example is a light switch.	
SPDT	Single pole, double throw	Two-way	Three-way	A simple changeover switch: C (COM, Common) is connected to L1 or to L2.	
SPCO SPTT, c.o.	Single pole changeover *or* Single pole, centre off *or* Single Pole, Triple Throw			Similar to *SPDT*. Some suppliers use *SPCO/SPTT* for switches with a stable off position in the centre and *SPDT* for those	

				without.	
DPST	Double pole, single throw	Double pole	Double pole	Equivalent to two *SPST* switches controlled by a single mechanism	
DPDT	Double pole, double throw			Equivalent to two *SPDT* switches controlled by a single mechanism: A is connected to B and D to E, or A is connected to C and D to F.	
DPCO	Double pole changeover *or* Double pole, centre off			Equivalent to *DPDT*. Some suppliers use *DPCO* for switches with a stable off position in the centre and *DPDT* for those without.	
		Intermediate switch	Four-way switch	*DPDT* switch internally wired for polarity-reversal applications: only four rather than six wires are brought outside the switch housing; with the above, B is connected to F and C to E; hence A is connected to B and D to C, or A is connected to C and D to B.	

Switches with larger numbers of poles or throws can be described by replacing the "S" or "D" with a number or in some cases the letter "T" (for "triple").

Contact bounce



Snapshot of switch bounce on an oscilloscope. The switch bounces between on and off several times before settling.

Contact bounce (also called *chatter*) is a common problem with mechanical switches and relays. Switch and relay contacts are usually made of springy metals that are forced into contact by an actuator. When the contacts strike together, their momentum and elasticity act together to cause bounce. The result is a rapidly pulsed electric current instead of a clean transition from zero to full current. The effect is usually unimportant in power circuits, but causes problems in some analogue and logic circuits that respond fast enough to misinterpret the on-off pulses as a data stream.

The effects of contact bounce can be eliminated by use of mercury-wetted contacts, but these are now infrequently used because of the hazard of mercury release.

Contact circuits can be filtered to reduce or eliminate multiple pulses. In digital systems, multiple samples of the contact state can be taken or a time delay can be implemented so that the contact bounce has settled before the contact input is used to control anything. One way to implement this with an SPDT Switch is by using an SR Latch.

Arcs and quenching

When the power being switched is sufficiently large, the electron flow across opening switch contacts is sufficient to ionize the air molecules across the tiny gap between the contacts as the switch is opened, forming a gas plasma, also known as an electric arc. The plasma is of low resistance and is able to sustain power flow, even with the separation distance between the switch contacts steadily increasing. The plasma is also very hot and is capable of eroding the metal surfaces of the switch contacts.

Where the voltage is sufficiently high, an arc can also form as the switch is closed and the contacts approach. If the voltage potential is sufficient to exceed the breakdown voltage of the air separating the contacts, an arc forms which is sustained until the switch closes completely and the switch surfaces make contact.

In either case, the standard method for minimizing arc formation and preventing contact damage is to use a fast-moving switch mechanism, typically using a spring-operated tipping-point mechanism to assure quick motion of switch contacts, regardless of the speed at which the switch control is operated by the user. Movement of the switch control lever applies tension to a spring until a tipping point is reached, and the contacts suddenly snap open or closed as the spring tension is released.

As the power being switched increases, other methods are used to minimize or prevent arc formation. A plasma is hot and will rise due to convection air currents. The arc can be quenched with a series of nonconductive blades spanning the distance between switch contacts, and as the arc rises its length increases as it forms ridges rising into the spaces between the blades, until the arc is too long to stay sustained and is extinguished. A *puffer* may be used to blow a sudden high velocity burst of gas across the switch contacts, which rapidly extends the length of the arc to extinguish it quickly.

Extremely large switches in excess of 100,000 watts capacity often have switch contacts surrounded by something other than air to more rapidly extinguish the arc. For example, the switch contacts may operate in a vacuum, or immersed in mineral oil.

Power switching

When a switch is designed to switch significant power, the transitional state of the switch as well as the ability to stand continuous operating currents must be considered. When a switch is in the on state its resistance is near zero and very little power is dropped in the contacts; when a switch is in the off state its resistance is extremely high and even less power is dropped in the contacts. However when the switch is flicked the resistance must pass through a state where briefly a quarter (or worse if the load is not purely resistive) of the load's rated power is dropped in the switch.

For this reason, power switches intended to interrupt a load current have spring mechanisms to make sure the transition between on and off is as short as possible regardless of the speed at which the user moves the rocker.

Power switches usually come in two types. A momentary on-off switch (such as on a laser pointer) usually takes the form of a button and only closes the circuit when the button is depressed. A regular on-off switch (such as on a flashlight) has a constant on-off feature. Dual-action switches incorporate both of these features.

Inductive loads

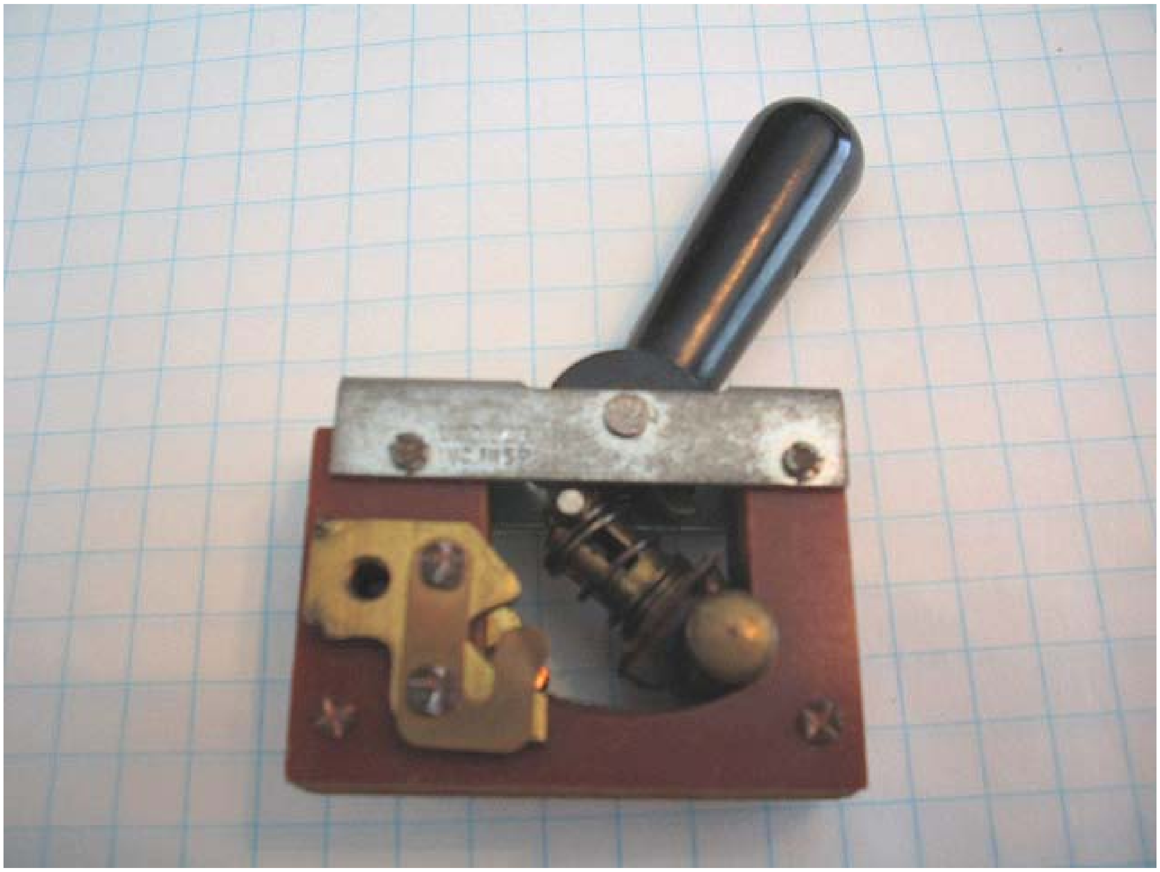
When a strongly inductive load such as an electric motor is switched off, the current cannot drop instantaneously to zero; a spark will jump across the opening contacts. Switches for inductive loads must be rated to handle these cases. The spark will cause electromagnetic interference if not suppressed; a snubber network of a resistor and capacitor in series will quell the spark.

Actuator

The moving part that applies the operating force to the contacts is called the *actuator*, and may be a **toggle** or *dolly*, a **rocker**, a **push-button** or any type of mechanical linkage.

Biased switches

The momentary push-button switch is a type of biased switch. The most common type is a "push-to-make" (or normally-open or NO) switch, which makes contact when the button is pressed and breaks when the button is released. Each key of a computer keyboard, for example, is a normally-open "push-to-make" switch. A "push-to-break" (or normally-closed or NC) switch, on the other hand, breaks contact when the button is pressed and makes contact when it is released. An example of a push-to-break switch is a button used to release a door held open by an electromagnet.



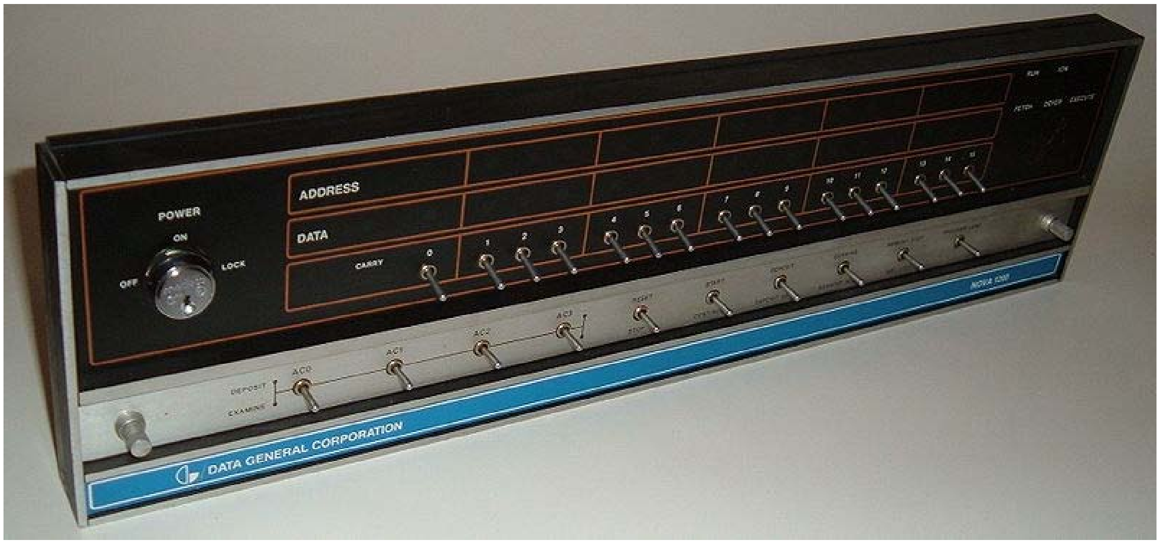
Large toggle switch, depicted in circuit 'open' position, electrical contacts to left; background is 1/4" square graph paper

Toggle switch

A toggle switch is a class of electrical switches that are manually actuated by a mechanical lever, handle, or rocking mechanism.

Toggle switches are available in many different styles and sizes, and are used in countless applications. Many are designed to provide, e.g., the simultaneous actuation of multiple sets of electrical contacts, or the control of large amounts of electric current or mains voltages.

The word "toggle" is a reference to a kind of mechanism or joint consisting of two arms, which are almost in line with each other, connected with an elbow-like pivot. However, the phrase "toggle switch" is applied to a switch with a short handle and a positive snap-action, whether it actually contains a toggle mechanism or not. Similarly, a switch where a definitive click is heard, is called a "positive on-off switch".



Bank of toggle switches on a Data General Nova minicomputer front panel

Special types

Opened float switch of a dirty water pump

Switches can be designed to respond to any type of mechanical stimulus: for example, vibration (the *trembler switch*), tilt, air pressure, fluid level (the *float switch*), the turning of a key (*key switch*), linear or rotary movement (the *limit switch* or *microswitch*), or presence of a magnetic field (the *reed switch*).

Mercury tilt switch

The mercury switch consists of a drop of mercury inside a glass bulb with 2 or more contacts. The two contacts pass through the glass, and are connected by the mercury when the bulb is tilted to make the mercury roll on to them.

This type of switch performs much better than the ball tilt switch, as the liquid metal connection is unaffected by dirt, debris and oxidation, it wets the contacts ensuring a very low resistance bounce-free connection, and movement and vibration do not produce a poor contact. These types can be used for precision works.

It can also be used where arcing is dangerous (such as in the presence of explosive vapour) as the entire unit is sealed.

Knife switch

Knife switches consist of a flat metal blade, hinged at one end, with an insulating handle for operation, and a fixed contact. When the switch is closed, current flows through the hinged pivot and blade and through the fixed contact. Such switches are usually not enclosed. The knife and contacts are typically formed of copper, steel, or brass, depending on the application. Fixed contacts may be backed up with a spring. Several parallel blades can be operated at the same time by one handle. The parts may be mounted on an insulating base with terminals for wiring, or may be directly bolted to an insulated switch board in a large assembly. Since the electrical contacts are exposed, the switch is used only where people cannot accidentally come in contact with the switch or where the voltage is so low as to not present a hazard.

Knife switches are made in many sizes from miniature switches to large devices used to carry thousands of amperes. In electrical transmission and distribution, gang-operated switches are used in circuits up to the highest voltages.

The disadvantages of the knife switch are the slow opening speed and the proximity of the operator to exposed live parts. Metal-enclosed safety disconnect switches are used for isolation of circuits in industrial power distribution. Sometimes spring-loaded auxiliary blades are fitted which momentarily carry the full current during opening, then quickly part to rapidly extinguish the arc.

Footswitch

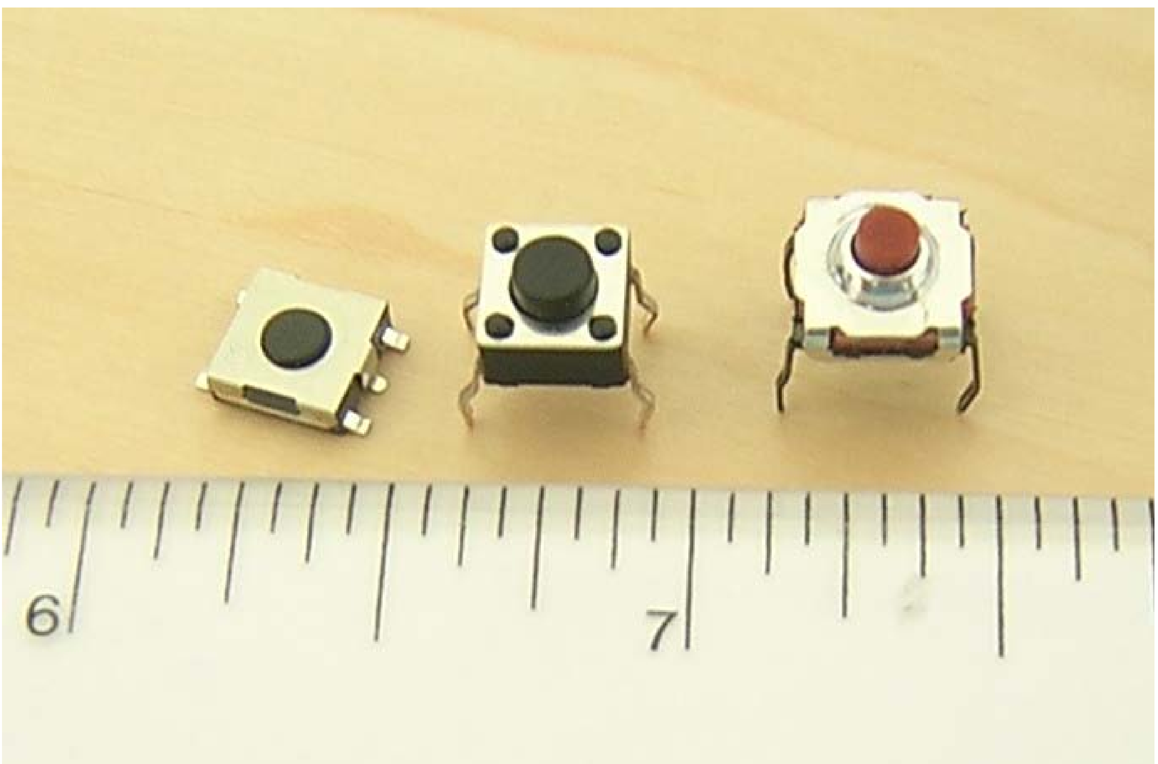
A footswitch is a ruged switch which is operated by foot pressure. An example of use is for the control of an electric sewing machine.

Reversing switch

A DPDT switch has six connections, but since polarity reversal is a very common usage of DPDT switches, some variations of the DPDT switch are internally wired specifically for polarity reversal. These crossover switches only have four terminals rather than six. Two of the terminals are inputs and two are outputs. When connected to a battery or other DC source, the 4-way switch selects from either normal or reversed polarity. Such switches can also be used as intermediate switches in a multiway switching system for control of lamps by more than two switches.

Light switches

In building wiring, light switches are installed at convenient locations to control lighting and occasionally other circuits. By use of multiple-pole switches, control of a lamp can be obtained from two or more places, such as the ends of a corridor or stairwell.



Three pushbutton switches (Tactile Switches). Major scale is inches.

Electronic switches

A relay is an electrically operated switch. Many relays use an electromagnet to operate a switching mechanism mechanically, but other operating principles are also used.

Solid-state relays control power circuits with no moving parts, instead using a semiconductor device to perform switching—often a silicon-controlled rectifier or triac.

The analogue switch uses two MOSFET transistors in a transmission gate arrangement as a switch that works much like a relay, with some advantages and several limitations compared to an electromechanical relay.

The power transistor(s) in a switching voltage regulator, such as a power supply unit, are used like a switch to alternately let power flow and block power from flowing.

Many people use metonymy to call a variety of devices "switches" that conceptually connect or disconnect signals and communication paths between electrical devices, analogous to the way mechanical switches connect and disconnect paths for electrons to flow between two conductors. Since the advent of digital logic in the 1950s, the term *switch* has spread to a variety of digital active devices such as transistors and logic gates whose function is to change their output state between two logic levels or connect different signal lines, and even computers, network switches, whose function is to provide connections between different ports in a computer network. The term 'switched' is also applied to telecommunications networks, and signifies a network that is circuit switched, providing dedicated circuits for communication between end nodes, such as the public switched telephone network. The common feature of all these usages is they refer to devices that control a binary state: they are either *on* or *off*, *closed* or *open*, *connected* or *not connected*.

Chapter- 4

Electrical Wiring

Electrical wiring in general refers to insulated conductors used to carry electricity, and associated devices. Here we, describes general aspects of electrical wiring as used to provide power in buildings and structures, commonly referred to as **building wiring**.

Wiring safety codes

Wiring safety codes are intended to protect people and buildings from electrical shock and fire hazards. Regulations may be established by city, county, provincial/state or national legislation, sometimes by adopting in amended form a model code produced by a technical standards-setting organization, or by a national standard electrical code.

Electrical codes arose in the 1880s with the commercial introduction of electrical power. Many conflicting standards existed for the selection of wire sizes and other design rules for electrical installations.

The first electrical codes in the United States originated in New York in 1881 to regulate installations of electric lighting. Since 1897 the U.S. National Fire Protection Association, a private nonprofit association formed by insurance companies, has published the National Electrical Code (NEC). States, counties or cities often include the NEC in their local building codes by reference along with local differences. The NEC is modified every three years. It is a consensus code considering suggestions from interested parties. The proposals are studied by committees of engineers, tradesmen, manufacturer representatives, fire fighters, and other invitees.

Since 1927, the Canadian Standards Association (CSA) has produced the Canadian *Safety Standard for Electrical Installations*, which is the basis for provincial electrical codes. The CSA also produces the Canadian Electrical Code, the 2006 edition of which references IEC 60364 (*Electrical Installations for Buildings*) and states that the code addresses the fundamental principles of electrical protection in Section 131. The Canadian code reprints Chapter 13 of IEC 60364, and it is interesting to note that there are no numerical criteria listed in that chapter whereby the adequacy of any electrical installation can be assessed.

Although the U.S. and Canadian national standards deal with the same physical phenomena and broadly similar objectives, they differ occasionally in technical detail. As part of the North American Free Trade Agreement (NAFTA) program, U.S. and Canadian standards are slowly converging toward each other, in a process known as harmonization.

In European countries, an attempt has been made to harmonize national wiring standards in an IEC standard, IEC 60364 *Electrical Installations for Buildings*. Hence national standards follow an identical system of sections and chapters. However, this standard is not written in such language that it can readily be adapted as a national wiring code. Neither is it designed for field use by electrical tradesmen and inspectors for testing compliance with national wiring standards. National codes, such as the NEC or CSA C22.1, exemplify the common objectives of IEC 60364, and provide rules in a form that allows for guidance of those installing and inspecting electrical systems.

DKE - the German Commission for Electrical, Electronic and Information Technologies of DIN and VDE - is the German organisation responsible for the promulgation of electrical standards and safety specifications. DIN VDE 0100 is the German wiring regulations document harmonised with IEC 60364.

In the United Kingdom wiring installations are regulated by the Institution of Engineering and Technology *Requirements for Electrical Installations: IEE Wiring Regulations, BS 7671: 2008,* which are harmonised with IEC 60364. The previous edition (16th) was replaced by the current 17th Edition in January 2008. The 17th edition includes new sections for microgeneration and solar photovoltaic systems. The first edition was published in 1882.

AS/NZS 3000 is an Australian/New Zealand standard, commonly known as the "wiring rules," that specifies the requirements for the selection and installation of electrical equipment and the design and testing of such installations. The standard is a mandatory standard in both New Zealand and Australia; therefore, all electrical work covered by the standard must comply.

The international standard wire sizes are given in the IEC 60228 standard of the International Electrotechnical Commission. In North America, the American Wire Gauge is used.

Colour code

To enable wires to be easily and safely identified all common wiring safety codes mandate a colour scheme for the insulation on power conductors. Many local rules and exceptions exist. Older installations vary in colour codes, and colours may shift with heat and age of insulation.

Standard wire colours for flexible cable
Such as Extension cords, power (line) cords and lamp cords

World Region, country or other entity(ies)	Hot (Live)	Neutral	Protective earth/ground
EU, Australia & South Africa (IEC 60446)	brown	blue	green & yellow
Australia & New Zealand (AS/NZS 3000:2007 3.8.1)	brown	light blue	green/yellow
United States and Canada	black (*brass*)	white (*silver*)	green (*green*)

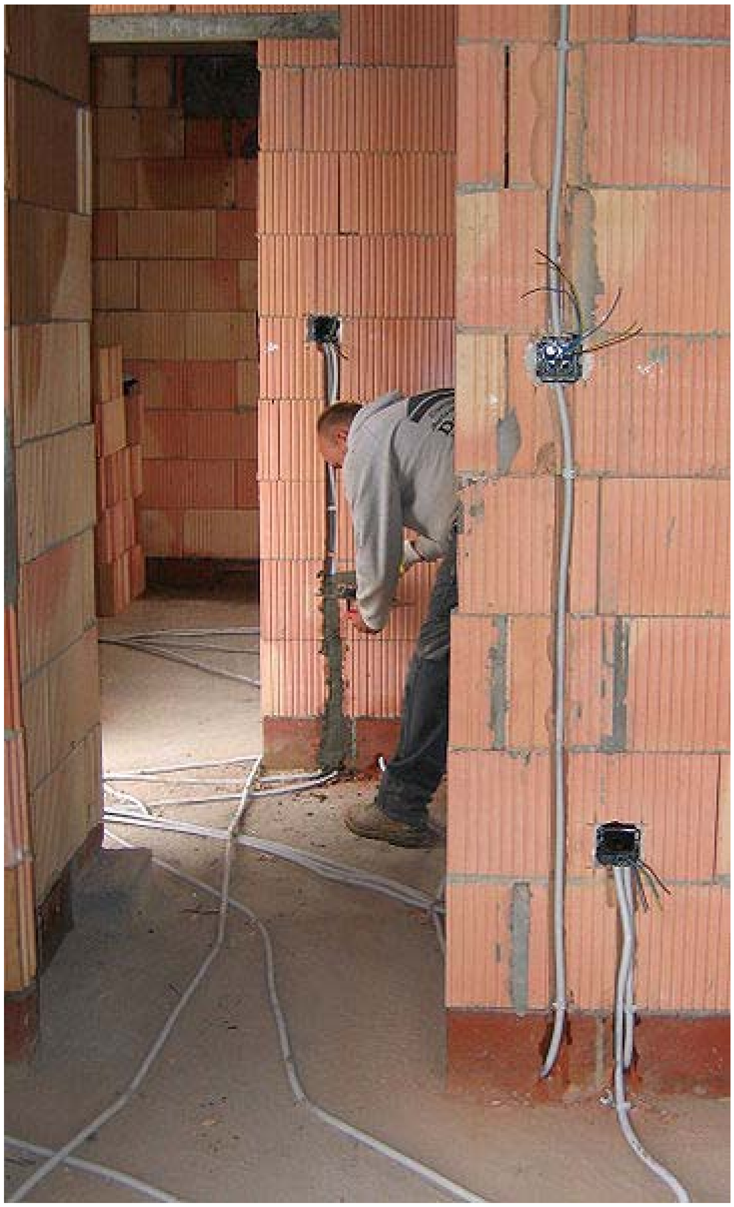
Standard wire colours for fixed cable
(In or behind the wall wiring cables)

Region	Phases	Neutral	Protective earth/ground
EU (IEC 60446) including UK from 31 March 2004	brown, black, grey	blue	green & yellow
Australia and South Africa	red	black	green & yellow (core is usually bare and should be sleeved at terminations. In Australia the earth core has been separately insulated with green or green/yellow plastic since about 1980.
United States	120/208/240V: black, red, blue (*brass*) 277/480V: brown, orange, yellow	120/208/240V: white (*silver*) 277/480V: grey	green (*green*) or bare copper wire Isolated ground: Green with yellow stripe
Canada	120/208/240V: red, black 600/347V: red, black, blue	120/208/240V: white 600/347V: white	green (*green*) or bare copper wire Isolated ground: Green
UK prior to 31	red, yellow, blue	black	green & yellow, formerly green (core is usually bare but is sleeved at

March 2004	terminations)

Note: the colours in this table represent the most common and preferred standard colours for single phase wiring however others may be in use, especially in older installations. Also the Canadian and American wiring standards are very similar with small differences and have different opperating voltages in ICI applications.

Wiring methods



Installing electrical wiring by cutting into the bricks of the building

Materials for wiring interior electrical systems in buildings vary depending on:

- Intended use and amount of power demand on the circuit
- Type of occupancy and size of the building
- National and local regulations
- Environment in which the wiring must operate.

Wiring systems in a single family home or duplex, for example, are simple, with relatively low power requirements, infrequent changes to the building structure and layout, usually with dry, moderate temperature, and noncorrosive environmental conditions. In a light commercial environment, more frequent wiring changes can be expected, large apparatus may be installed, and special conditions of heat or moisture may apply. Heavy industries have more demanding wiring requirements, such as very large currents and higher voltages, frequent changes of equipment layout, corrosive, or wet or explosive atmospheres. In facilities that handle flammable gases or liquids, special rules may govern the installation and wiring of electrical equipment in hazardous areas.

Wires and cables are rated by the circuit voltage, temperature rating, and environmental conditions (moisture, sunlight, oil, chemicals) in which they can be used. A wire or cable has a voltage (to neutral) rating, and a maximum conductor surface temperature rating. The amount of current a cable or wire can safely carry depends on the installation conditions.

Early wiring methods

The very first interior power wiring systems used conductors that were bare or covered with cloth, which were secured by staples to the framing of the building or on running boards. Where conductors went through walls, they were protected with cloth tape. Splices were done similarly to telegraph connections, and soldered for security. Underground conductors were insulated with wrappings of cloth tape soaked in pitch, and laid in wooden troughs which were then buried. Such wiring systems were unsatisfactory because of the danger of electrocution and fire and the high labour cost for such installations.

Knob and tube

Knob-and-Tube wiring

The earliest standardized method of wiring in buildings, in common use in North America from about 1880 to the 1930s, was *knob and tube* (K&T) wiring: single conductors were run through cavities between the structural members in walls and ceilings, with ceramic tubes forming protective channels through joists and ceramic knobs attached to the structural members to provide air between the wire and the lumber and to support the wires. Since air was free to circulate over the wires, smaller conductors could be used than required in cables. By arranging wires on opposite sides of building structural members, some protection was afforded against short-circuits that can be caused by driving a nail into both conductors simultaneously. By the 1940s, the labour cost of installing two conductors rather than one cable resulted in a decline in new knob-and-tube installations.

Metal-sheathed wires

In the United Kingdom, an early form of insulated cable, introduced in 1896, consisted of two impregnated-paper-insulated conductors in an overall lead sheath. Joints were soldered, and special fittings were used for lamp holders and switches. These cables were similar to underground telegraph and telephone cables of the time. Paper-insulated cables proved unsuitable for interior wiring installations because very careful workmanship was required on the lead sheaths to ensure moisture did not affect the insulation.

A system later invented in the UK in 1908 employed vulcanized-rubber insulated wire enclosed in a strip metal sheath. The metal sheath was bonded to each metal wiring device to ensure continuity.

A system developed in Germany called *Kuhlo wire* used one, two, or three rubber-insulated wires in a brass or lead-coated iron sheet tube, with a crimped seam. The enclosure could also be used as a return conductor. Kuhlo wire could be run exposed on surfaces and painted, or embedded in plaster. Special outlet and junction boxes were made for lamps and switches, made either of porcelain or sheet steel. The crimped seam was not considered as watertight as the *Stannos* wire used in England, which had a soldered sheath.

A somewhat similar system called "concentric wiring" was introduced in the United States around 1905. In this system, an insulated copper wire was wrapped with copper tape which was then soldered, forming the grounded (return) conductor of the wiring system. The bare metal sheath, at earth potential, was considered safe to touch. While companies such as General Electric manufactured fittings for the system, and a few buildings were wired with it, it was never adopted into the US National Electrical Code. Drawbacks of the system were that special fittings were required, and that any defect in the connection of the sheath would result in the sheath becoming energized.

Other historical wiring methods

Other methods of securing wiring that are now obsolete include:

- Re-use of existing gas pipes for electric lighting. Insulated conductors were pulled into the pipes feeding gas lamps.
- Wood mouldings with grooves cut for single conductor wires, covered by a wooden cap strip. These were prohibited in North American electrical codes by 1928. Wooden moulding was also used to some degree in England, but was never permitted by German and Austrian rules.
- A system of flexible twin cords supported by glass or porcelain buttons was used near the turn of the 20th century in Europe, but was soon replaced by other methods.
- During the first years of the 20th century various patented forms of wiring system such as Bergman and Peschel tubing were used to protect wiring; these used very thin fibre tubes or metal tubes which were also used as return conductors.
- In Austria, wires were concealed by embedding a rubber tube in a groove in the wall, plastering over it and then removing the tube and pulling in wires in the cavity.

Metal moulding systems, with a flattened oval section consisting of a base strip and a snap-on cap channel, were more costly than open wiring or wooden moulding, but could be easily run on wall surfaces. Similar systems are still available today.

Cables

Wiring in extremely-wet conditions

Armoured cables with two rubber-insulated conductors in a flexible metal sheath were used as early as 1906, and were considered at the time a better method than open knob-and-tube wiring, although much more expensive.

The first polymer-insulated cables for building wiring were introduced in 1922. These were two or more solid copper wires, with rubber insulation, woven cotton cloth over each conductor for protection of the insulation, with an overall woven jacket, usually impregnated with tar as a protection from moisture. Waxed paper was used as a filler and separator.

Rubber-insulated cables become brittle over time because of exposure to oxygen, so they must be handled with care, and should be replaced during renovations. When switches, outlets or light fixtures are replaced, the mere act of tightening connections may cause insulation to flake off the conductors. Rubber was hard to separate from bare copper, so copper was tinned, causing slightly more resistance.

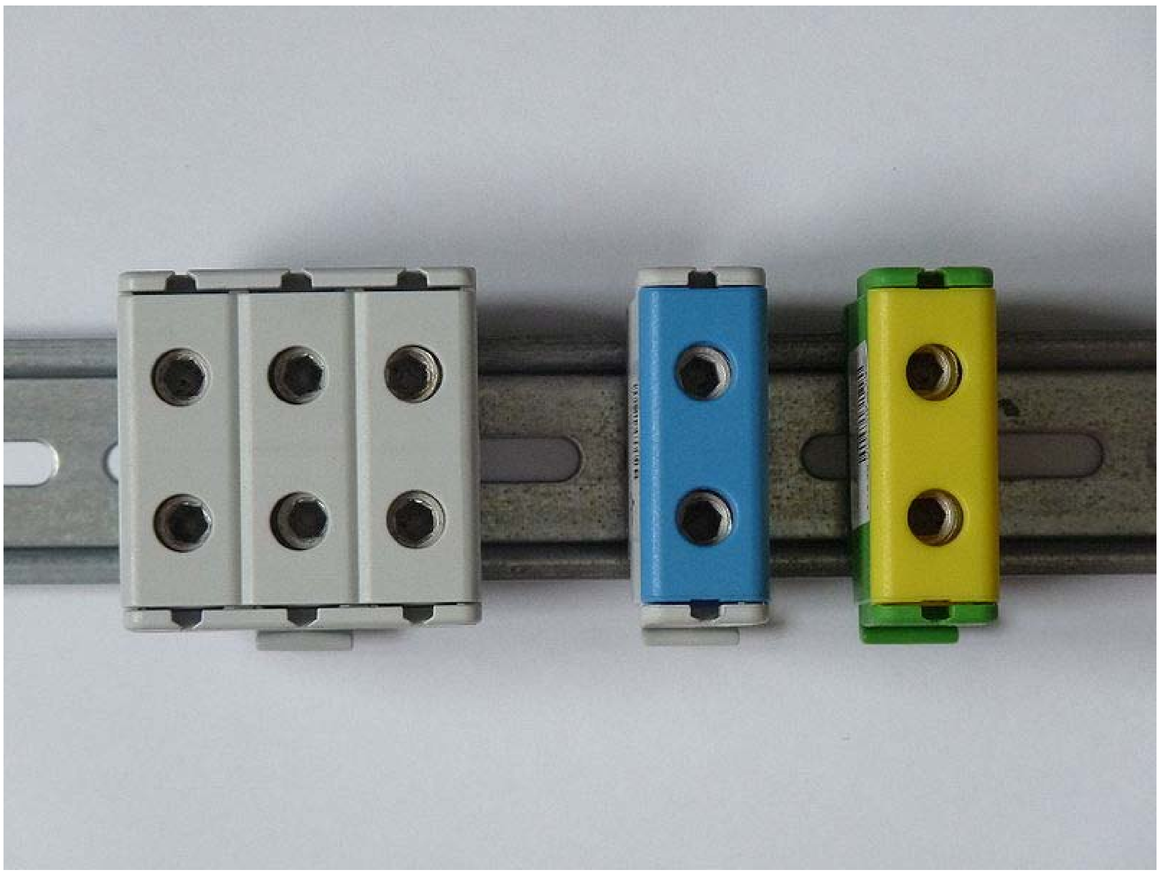
Three-phase copper cable TN-S 16mm² (5AWG) with PVC insulation

About 1950, PVC insulation and jackets were introduced, especially for residential wiring. About the same time, single conductors with a thinner PVC insulation and a thin nylon jacket became common.

The simplest form of cable has two insulated conductors twisted together to form a unit; such unjacketed cables with two or three conductors are used for low-voltage signal and control applications such as doorbell wiring. In North American practice, an overhead cable from a transformer on a power pole to a residential electrical service consists of three twisted (triplexed) wires, often with one being a bare copper wire (protective earth/ground) and the other two being insulated for the line voltage (hot/live wire and neutral wire).

Aluminium conductors

Aluminium wire was common in North American residential wiring from the late 1960s to mid 1970s due to the rising cost of copper. Because of its greater resistivity, aluminium wiring requires larger conductors than copper. For instance, instead of 14 AWG (American wire gauge) for most lighting circuits, aluminium wiring would be 12 AWG on a typical 15 ampere circuit, though local building codes may vary.



Terminal blocks for joining aluminium and copper conductors. The terminal blocks may be mounted on a DIN rail.

Aluminium conductors were originally used with wiring devices intended for copper wires. This can cause defective connections unless the aluminium was one of a special alloy, or all devices — breakers, switches, receptacles, splice connectors, i.e., wire nuts, etc. — were designed to address problems with junctions between dissimilar metals, oxidation on metal surfaces and mechanical effects that occur as different metals expand at different rates with increases in temperature. Unlike copper, aluminium has a tendency to cold-flow under pressure, so screw clamped connections may get loose over time. This can be mitigated by using spring-loaded connectors that apply constant pressure, applying high pressure cold joints in splices and termination fittings, and torquing the bolted connection. Unlike copper, aluminium forms an insulating oxide layer on the surface. This is sometimes addressed by coating aluminium wires with an antioxidant paste at joints, or applying a mechanical termination designed to break through the oxide layer during installation.

Because of improper design and installation, some junctions to wiring devices overheated under heavy current load and caused fires. Revised standards for wiring devices (such as the CO/ALR "copper-aluminium-revised" designation) were developed to reduce these problems. Nonetheless, aluminium wiring for residential use has acquired a poor reputation and has fallen out of favour.

Aluminium conductors are still used for power distribution and large feeder circuits, because they cost less than copper wiring, and weigh less, especially in the large sizes needed for heavy current loads. Aluminium conductors must be installed with compatible connectors.

Modern wiring materials

An electrical "3G" power cable found commonly in modern European houses. The cable consists of 3 wires (2 wires + 1 grounding in case if cable has "3G" name) and is double-insulated.

Modern nonmetallic sheathed cables (NMC), like (U.S. and Canadian) Type NM, consist of two to four wires covered with thermoplastic insulation and a bare wire for grounding (bonding) surrounded by a flexible plastic jacket. Some versions wrap the individual conductors in paper before the plastic jacket is applied. It is often called **Romex™** cable, since the first of its type was manufactured by Rome Cable Division of Cyprus Mines, Rome, New York. The trade name has been owned by Southwire since it purchased the electrical building wire assets of General Cable in 2001.

Rubber-like synthetic polymer insulation is used in industrial cables and power cables installed underground because of its superior moisture resistance.

Insulated cables are rated by their allowable operating voltage and their maximum operating temperature at the conductor surface. A cable may carry multiple usage ratings for applications, for example, one rating for dry installations and another when exposed to moisture or oil.

Generally, single conductor building wire in small sizes is solid wire, since the wiring is not required to be very flexible. Building wire conductors larger than 10 AWG (or about 6 mm^2) are stranded for flexibility during installation, but not stranded enough to be flexible enough to use as appliance cord.

Cables for industrial, commercial, and apartment buildings may contain many insulated conductors in an overall jacket, with helical tape steel or aluminium armour, or steel wire armour, and perhaps as well an overall PVC or lead jacket for protection from moisture and physical damage. Cables intended for very flexible service or in marine applications may be protected by woven bronze wires. Power or communications cables (e.g., computer networking) that are routed in or through air-handling spaces (plenums) of office buildings are required under the model code to be either encased in metal conduit or rated for low flame and smoke production.

For some industrial uses in steel mills and similar hot environments, no organic material gives satisfactory service. Cables insulated with compressed mica flakes are sometimes used. Another form of high-temperature cable is a mineral insulated cable, with individual conductors placed within a copper tube, and the space filled with magnesium oxide powder. The whole assembly is drawn down to smaller sizes, thereby compressing the powder. Such cables have a certified fire resistance rating, are more costly than non-fire rated cable, and have little flexibility and are effectively rigid to the user of the cable.

Mineral insulated cables at a panel board

Because multiple conductors bundled in a cable cannot dissipate heat as easily as single insulated conductors, those circuits are always rated at a lower "ampacity". Tables in electrical safety codes give the maximum allowable current for a particular size of conductor, for the voltage and temperature rating at the surface of the conductor for a given physical environment, including the insulation type and thickness. The allowable current will be different for wet or dry, for hot (attic) or cool (underground) locations. In a run of cable through several areas, the most severe area will determine the appropriate rating of the overall run.

Cables usually are secured by special fittings where they enter electrical apparatus; this may be a simple screw clamp for jacketed cables in a dry location, or a polymer-gasketed cable connector that mechanically engages the armour of an armoured cable and provides a water-resistant connection. Special cable fittings may be applied to prevent explosive gases from flowing in the interior of jacketed cables, where the cable passes through areas where inflammable gases are present. To prevent loosening of the connections of individual conductors of a cable, cables must be supported near their entrance to devices and at regular intervals through their length. In tall buildings special designs are required to support the conductors of vertical runs of cable. Usually, only one cable per fitting is allowed unless the fitting is otherwise rated.

Special cable constructions and termination techniques are required for cables installed in ocean-going vessels; in addition to electrical safety and fire safety, such cables may also be required to be pressure-resistant where they penetrate bulkheads of a ship.

Raceways

Electrical Conduit risers, seen inside fire-resistance rated shaft, as seen entering bottom of a firestop. The firestop is made of firestop mortar on top, rockwool on the bottom. Raceways are used to protect cables from damage.

Insulated wires may be run in one of several forms of a raceway between electrical devices. This may be a pipe, called a conduit, or in one of several varieties of metal (rigid steel or aluminum) or non-metallic (PVC or HDPE) tubing. Rectangular cross-section metal or PVC wire troughs (North America) or trunking (UK) may be used if many circuits are required. Wires run underground may be run in plastic tubing encased in concrete, but metal elbows may be used in severe pulls. Wiring in exposed areas, for example factory floors, may be run in cable trays or rectangular raceways having lids.

Where wiring, or raceways that hold the wiring, must traverse fire-resistance rated walls and floors, the openings are required by local building codes to be firestopped. In cases where the wiring has to be kept operational during an accidental fire, fireproofing must be applied to maintain circuit integrity in a manner to comply with a product's certification listing. The nature and thickness of any passive fire protection materials used in conjunction with wiring and raceways has a quantifiable impact upon the ampacity derating.

A cable tray can be used in stores and dwellings

Cable trays are used in industrial areas where many insulated cables are run together. Individual cables can exit the tray at any point, simplifying the wiring installation and reducing the labour cost for installing new cables. Power cables may have fittings in the tray to maintain clearance between the conductors, but small control wiring is often installed without any intentional spacing between cables.

Since wires run in conduits or underground cannot dissipate heat as easily as in open air, and adjacent circuits contribute induced currents, wiring regulations give rules to establish the current capacity (ampacity).

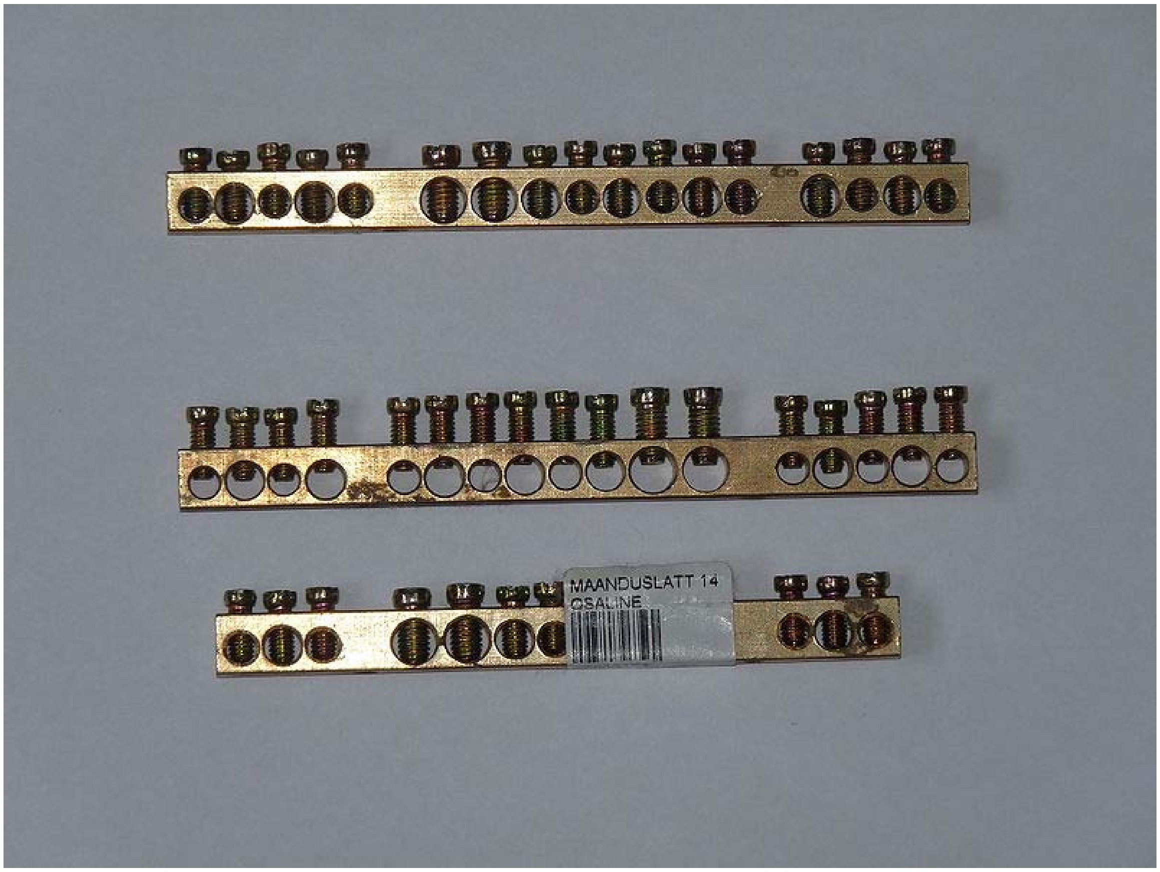
Special fittings are used for wiring in potentially explosive atmospheres.

Bus bars, bus duct, cable bus

Topside of firestop with penetrants consisting of electrical conduit on the left and a bus duct on the right. The firestop consists of firestop mortar on top and rockwool on the bottom, for a 2 hour fire-resistance rating.

For very heavy currents in electrical apparatus, and for heavy currents distributed through a building, bus bars can be used. Each live conductor of such a system is a rigid piece of copper or aluminium, usually in flat bars (but sometimes as tubing or other shapes). Open bus bars are never used in publicly accessible areas, although they are used in manufacturing plants and power company switch yards to gain the benefit of air cooling. A variation is to use heavy cables, especially where it is desirable to transpose or "roll" phases.

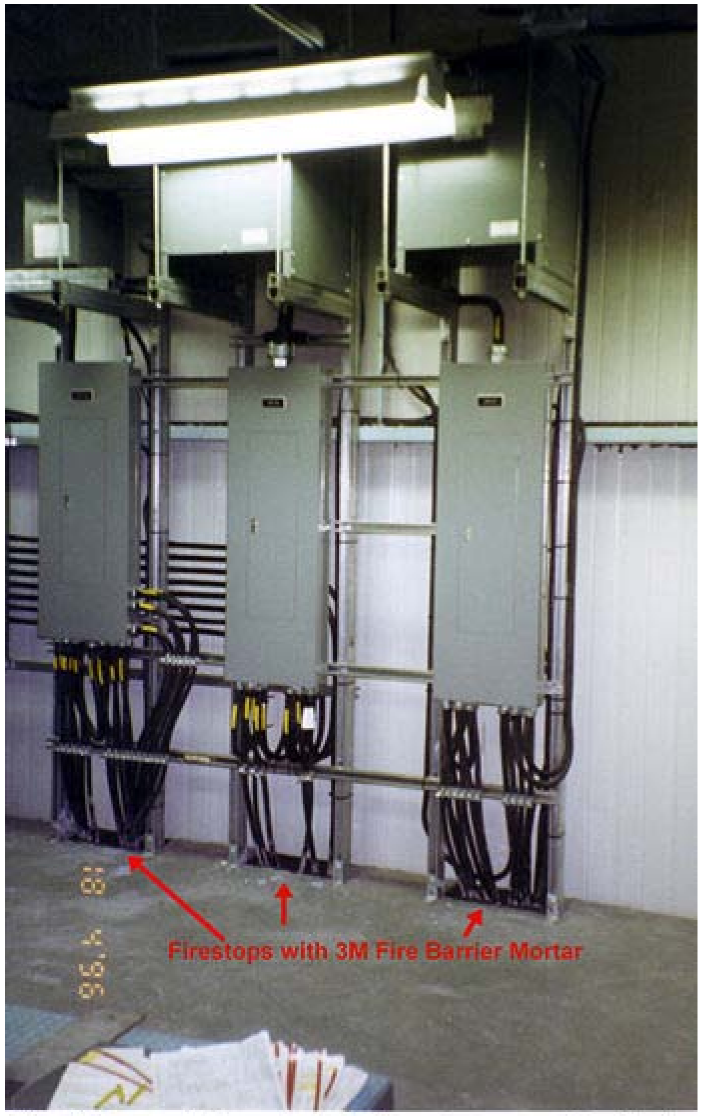
In industrial applications, conductor bars are assembled with insulators in grounded enclosures. This assembly, known as bus duct or busway, can be used for connections to large switchgear or for bringing the main power feed into a building. A form of bus duct known as plug-in bus is used to distribute power down the length of a building; it is constructed to allow tap-off switches or motor controllers to be installed at definite places along the bus. The big advantage of this scheme is the ability to remove or add a branch circuit without removing voltage from the whole duct.



Busbars for distributing PE (ground)

Bus ducts may have all phase conductors in the same enclosure (non-isolated bus), or may have each conductor separated by a grounded barrier from the adjacent phases (segregated bus). For conducting large currents between devices, a cable bus is used. For very large currents in generating stations or substations, where it is difficult to provide circuit protection, an isolated-phase bus is used. Each phase of the circuit is run in a separate grounded metal enclosure. The only fault possible is a phase-to-ground fault, since the enclosures are separated. This type of bus can be rated up to 50,000 amperes and up to hundreds of kilovolts (during normal service, not just for faults), but is not used for building wiring in the conventional sense.

Electrical panels



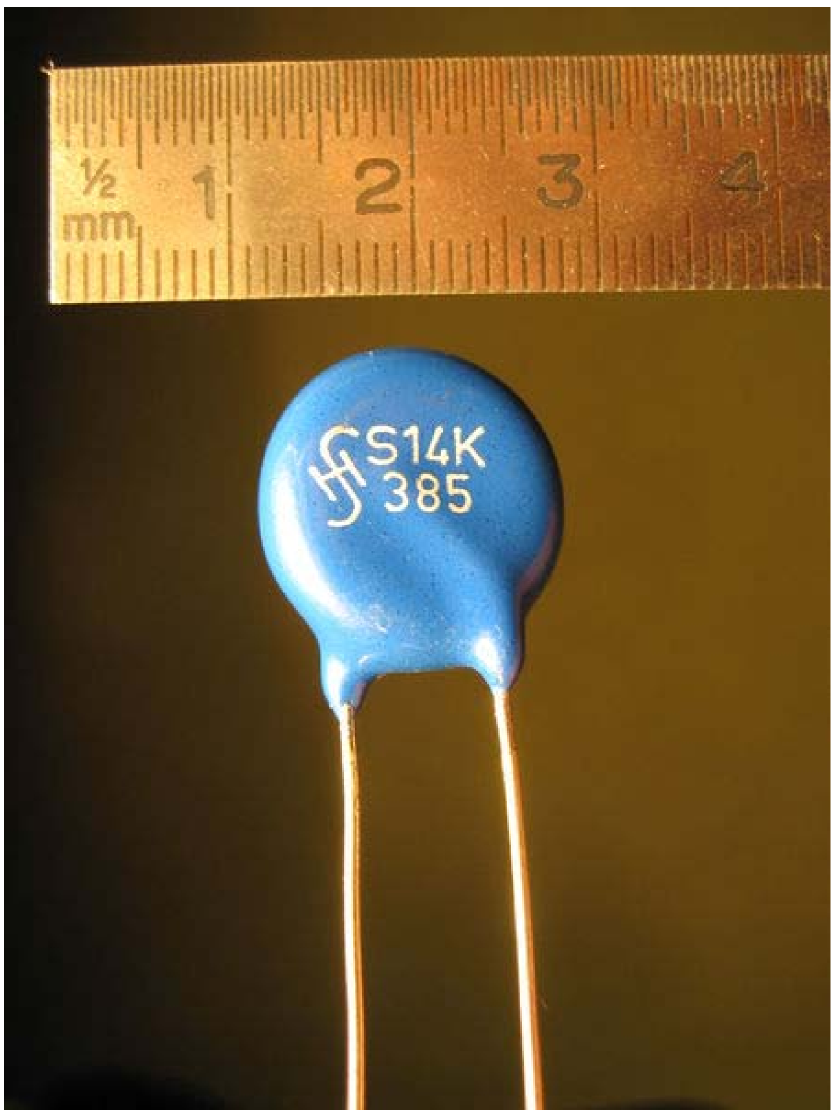
Electrical panels in an electrical service room at St. Mary's Pulp and Paper, Sault Ste. Marie, Ontario, Canada, April 1996

Electrical panels, cables and firestops in an electrical service room at St. Mary's Pulp and Paper, a paper mill in Sault Ste. Marie, Ontario, Canada.

Electrical panels are easily accessible junction boxes used to reroute and switch electrical services.

Chapter- 5

Varistor



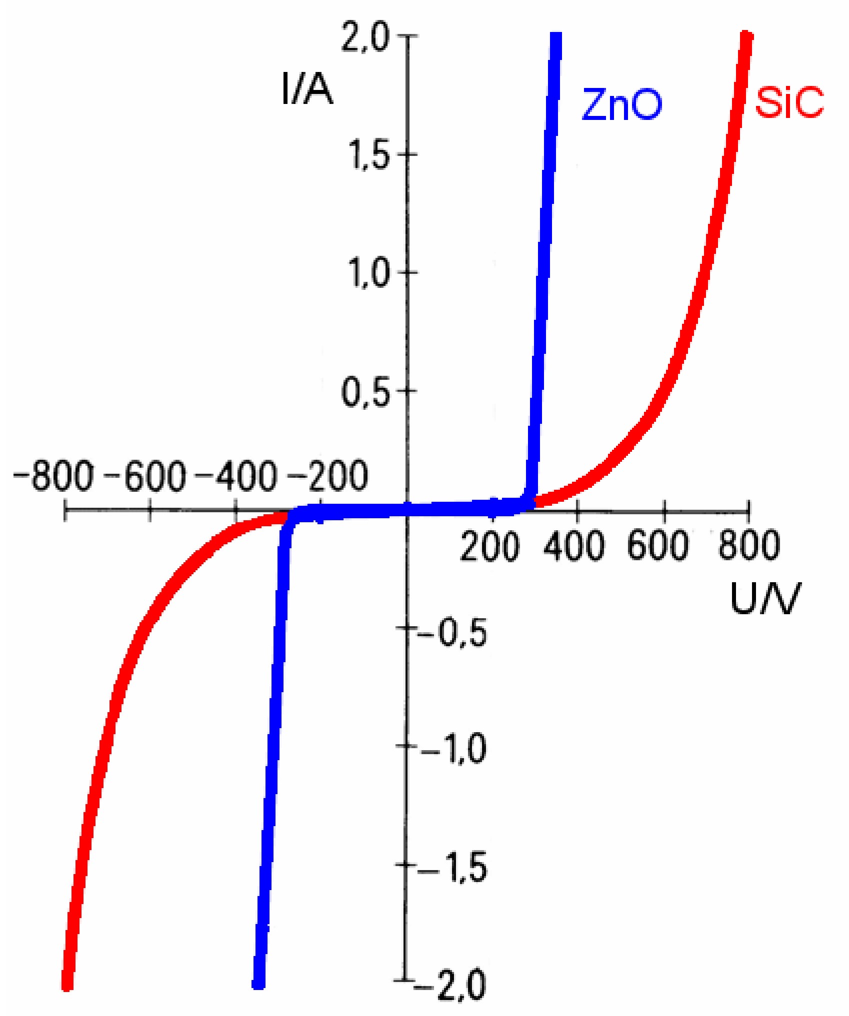
A 385-volt metal oxide varistor

A **varistor** is an electronic component with a "diode-like" nonlinear current–voltage characteristic. The name is a portmanteau of *variable resistor*. Varistors are often used to protect circuits against excessive transient voltages by incorporating them into the circuit in such a way that, when triggered, they will shunt the current created by the high voltage away from the sensitive components. A varistor is also known as *Voltage Dependent Resistor* or **VDR**. A varistor's function is to conduct significantly increased current when voltage is excessive.

Note: only non-ohmic variable resistors are usually called varistors*. Other, ohmic types of variable resistor include the potentiometer and the rheostat.*

Metal oxide varistor

The most common type of varistor is the **Metal Oxide Varistor** (MOV). This contains a ceramic mass of zinc oxide grains, in a matrix of other metal oxides (such as small amounts of bismuth, cobalt, manganese) sandwiched between two metal plates (the electrodes). The boundary between each grain and its neighbour forms a diode junction, which allows current to flow in only one direction. The mass of randomly oriented grains is electrically equivalent to a network of back-to-back diode pairs, each pair in parallel with many other pairs. When a small or moderate voltage is applied across the electrodes, only a tiny current flows, caused by reverse leakage through the diode junctions. When a large voltage is applied, the diode junction breaks down due to a combination of thermionic emission and electron tunneling, and a large current flows. The result of this behavior is a highly nonlinear current-voltage characteristic, in which the MOV has a high resistance at low voltages and a low resistance at high voltages.



Varistor current-voltage characteristic

Follow-through current as a result of a lightning strike may generate excessive current that permanently damages a varistor. In general, the primary case of varistor breakdown is localized heating caused as an effect of thermal runaway. This is due to a lack of conformality in individual grain-boundary junctions, which leads to the failure of dominant current paths under thermal stress.

Varistors can absorb part of a surge. How much effect this has on risk to connected equipment depends on the equipment and details of the selected varistor. Varistors do not absorb a significant percentage of a lightning strike, as energy that must be conducted elsewhere is many orders of magnitude greater than what is absorbed by the small device.

A varistor remains non-conductive as a shunt mode device during normal operation when voltage remains well below its "clamping voltage". If a transient pulse (often measured in joules) is too high, the device may melt, burn, vaporize, or otherwise be damaged or destroyed. This (catastrophic) failure occurs when "Absolute Maximum Ratings" in manufacturer's datasheet are significantly exceeded. Varistor degradation is defined by manufacturer's life expectancy charts using curves that relate current, time, and number of transient pulses. A varistor fully degrades typically when its "clamping voltage" has changed by 10%. A fully degraded varistor remains functional (no catastrophic failure) and is not visibly damaged.

Ballpark number for varistor life expectancy is its energy rating. As MOV joules increase, the number of transient pulses increases and the "clamping voltage" during each transient decreases. The purpose of this shunt mode device is to divert a transient so that pulse energy will be dissipated elsewhere. Some energy is also absorbed by the varistor because a varistor is not a perfect conductor. Less energy is absorbed by a varistor, the varistor is more conductive, and its life expectancy increases exponentially as varistor energy rating is increased. Catastrophic failure can be avoided by significantly increasing varistor energy ratings either by using a varistor of higher joules or by connecting more of these shunt mode devices in parallel.

Important parameters are the varistor's energy rating in joules, operating voltage, response time, maximum current, and breakdown (clamping) voltage. Energy rating is often defined using standardized transients such as 8/20 microseconds or 10/1000 microseconds, where 8 microseconds is the transient's front time and 20 microseconds is the time to half value.

To protect communications lines (such as telephone lines) transient suppression devices such as 3 mil carbon blocks (IEEE C62.32), ultra-low capacitance varistors or avalanche diodes are used. For higher frequencies such as radio communication equipment, a gas discharge tube (GDT) may be utilized.

A typical surge protector power strip is built using MOVs. A cheapest kind may use just one varistor, from hot (live, active) to neutral. A better protector would contain at least three varistors; one across each of the three pairs of conductors (hot-neutral, hot-ground, neutral-ground). A power strip protector in the United States should have a UL1449 3rd edition approval so that catastrophic MOV failure would not create a fire hazard.

High voltage varistor

Hazards

While a MOV is designed to conduct significant power for very short durations (≈ 8/20 microseconds), such as caused by lightning strikes, it typically does not have the capacity to conduct sustained energy. Under normal utility voltage conditions, this is not a problem. However, certain types of faults on the utility power grid can result in sustained over-voltage conditions. Examples include a loss of a neutral conductor or shorted lines on the high voltage system. Application of sustained over-voltage to a MOV can cause high dissipation, potentially resulting in the MOV device catching fire. The National Fire Protection Association (NFPA) has documented many cases of catastrophic fires that have been caused by MOV devices in surge suppressors, and has issued bulletins on the issue.

A series connected thermal fuse is one solution to catastrophic MOV failure. Varistors with internal thermal protection are also available.

There are several issues to be noted regarding behavior of transient voltage surge suppressors (TVSS) incorporating MOVs under over-voltage conditions. Depending on the level of conducted current, dissipated heat may be insufficient to cause failure, but may degrade the MOV device and reduce its life expectancy. If excessive current is conducted by a MOV, it may explode inside the case, keeping the load connected but now without any surge protection. A user may have no indication when the surge suppressor has failed. Under the right conditions of over-voltage and line impedance, it may be possible to cause the MOV to burst into flames, the root cause of many fires and the main reason for NFPA's concern. Properly designed TVSS devices should contain the flames, eventually resulting in the opening of a safety fuse.

What varistors don't do

A MOV inside a TVSS device does not provide equipment with complete power protection. In particular, MOV device provide no protection for the connected equipment from sustained over-voltages that may result in damage to that equipment as well as to the protector device.

A varistor provides no equipment protection from inrush current surges (during equipment startup), from overcurrent (created by a short circuit), or from voltage sags (also known as a brownout). A varistor neither senses nor controls such events. Susceptibility of electronic equipment to these other power disturbances is defined by equipment design. Protection from these power disturbances is installed inside that equipment or is provided by other external devices such as an UPS, some voltage regulators and Surge Protectors with built in overvoltage protection that make use of a voltage sensing circuit and a relay for disconnecting the AC input when voltage reaches a danger threshold.

Varistors compared to other transient suppressors

The response time of the MOV is largely ambiguous, as no standard has been officially defined. The sub-nanosecond MOV response claim is based on the material's intrinsic response time, but will be slowed down by other factors such as the inductance of component leads and the mounting method. That response time is also qualified as insignificant when compared to a transient having an 8 μs rise-time, thereby allowing ample time for the device to slowly turn-on. When subjected to a very fast, <1 ns rise-time transient, response times for the MOV are in the 40-60 ns range.

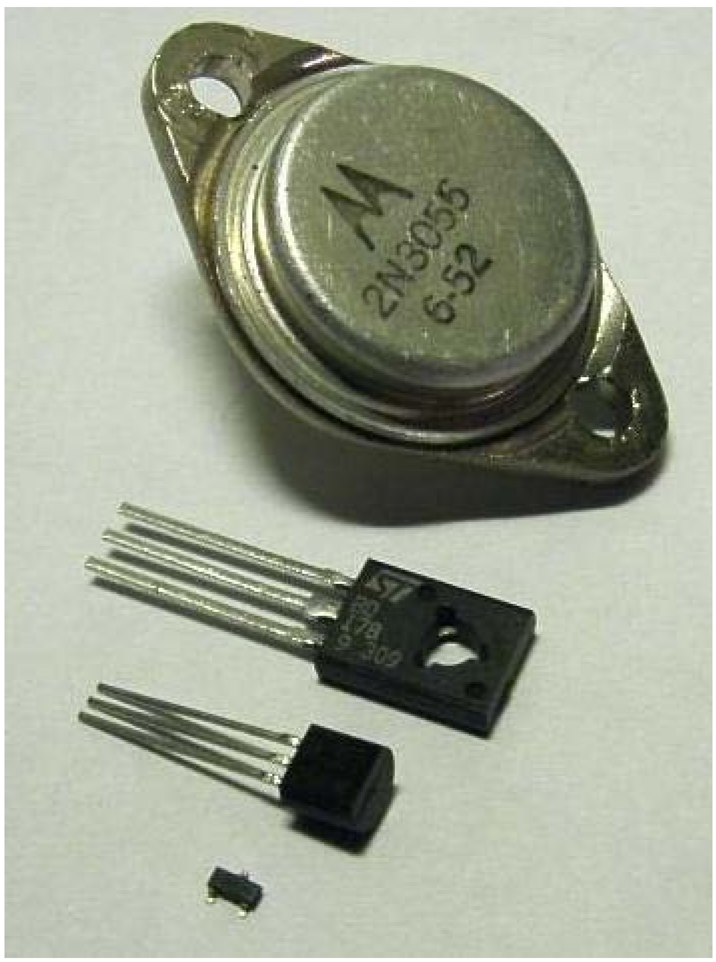
Typical capacitance for consumer-sized (7–20 mm diameter) varistors are in the range of 100-1,000 pF. Smaller, lower-capacitance varistors are available with capacitance of ~1 pF for microelectronic protection, such as in cellular phones. These low-capacitance varistors are, however, unable to withstand large surge currents simply due to their compact PCB-mount size.

Another method for suppressing voltage spikes is the transient voltage suppression diode (TVS). Although diodes do not have as much capacity to conduct large surges as MOVs, diodes are not degraded by smaller surges and can be implemented with a lower "clamping voltage". MOVs degrade from repeated exposure to surges and generally have a higher "clamping voltage" so that leakage does not degrade the MOV. Both types are available over a wide range of voltages. MOVs tend to be more suitable for higher voltages, because they can conduct the higher associated energies at less cost.

Another type of transient suppressor is the gas tube suppressor. This is a type of spark gap that may use air or an inert gas mixture and often, a small amount of radioactive material such as Ni-63, to provide a more consistent breakdown voltage and reduce response time. Unfortunately, these devices may have higher breakdown voltages and longer response times than varistors. However, they can handle significantly higher fault currents and withstand multiple high-voltage hits (for example, from lightning) without significant degradation.

Chapter- 6

Transistor



Assorted discrete transistors. Packages in order from top to bottom: TO-3, TO-126, TO-92, SOT-23

A **transistor** is a semiconductor device used to amplify and switch electronic signals. It is made of a solid piece of semiconductor material, with at least three terminals for connection to an external circuit. A voltage or current applied to one pair of the transistor's terminals changes the current flowing through another pair of terminals. Because the controlled (output) power can be much more than the controlling (input) power, the transistor provides amplification of a signal. Today, some transistors are packaged individually, but many more are found embedded in integrated circuits.

The transistor is the fundamental building block of modern electronic devices, and is ubiquitous in modern electronic systems. Following its release in the early 1950s the transistor revolutionized the field of electronics, and paved the way for smaller and cheaper radios, calculators, and computers, among other things.

History

A replica of the first working transistor.

Physicist Julius Edgar Lilienfeld filed the first patent for a transistor in Canada in 1925, describing a device similar to a field-effect transistor or "FET". However, Lilienfeld did not publish any research articles about his devices, nor did his patent cite any examples of devices actually constructed. In 1934, German inventor Oskar Heil patented a similar device.

From 1942 Herbert Mataré experimented with so-called *duodiodes* while working on a detector for a Doppler RADAR system. The duodiodes built by him had two separate but very close metal contacts on the semiconductor substrate. He discovered effects that could not be explained by two independently operating diodes and thus formed the basic idea for the later point contact transistor.

In 1947, John Bardeen and Walter Brattain at AT&T's Bell Labs in the United States observed that when electrical contacts were applied to a crystal of germanium, the output power was larger than the input. Solid State Physics Group leader William Shockley saw the potential in this, and over the next few months worked to greatly expand the knowledge of semiconductors. The term *transistor* was coined by John R. Pierce. According to physicist/historian Robert Arns, legal papers from the Bell Labs patent show that William Shockley and Gerald Pearson had built operational versions from Lilienfeld's patents, yet they never referenced this work in any of their later research papers or historical articles.

The name *transistor* is a portmanteau of the term "transfer resistor".

The first silicon transistor was produced by Texas Instruments in 1954. This was the work of Gordon Teal, an expert in growing crystals of high purity, who had previously worked at Bell Labs. The first MOS transistor actually built was by Kahng and Atalla at Bell Labs in 1960.

Importance

The transistor is the key active component in practically all modern electronics, and is considered by many to be one of the greatest inventions of the twentieth century. Its importance in today's society rests on its ability to be mass produced using a highly automated process (semiconductor device fabrication) that achieves astonishingly low per-transistor costs.

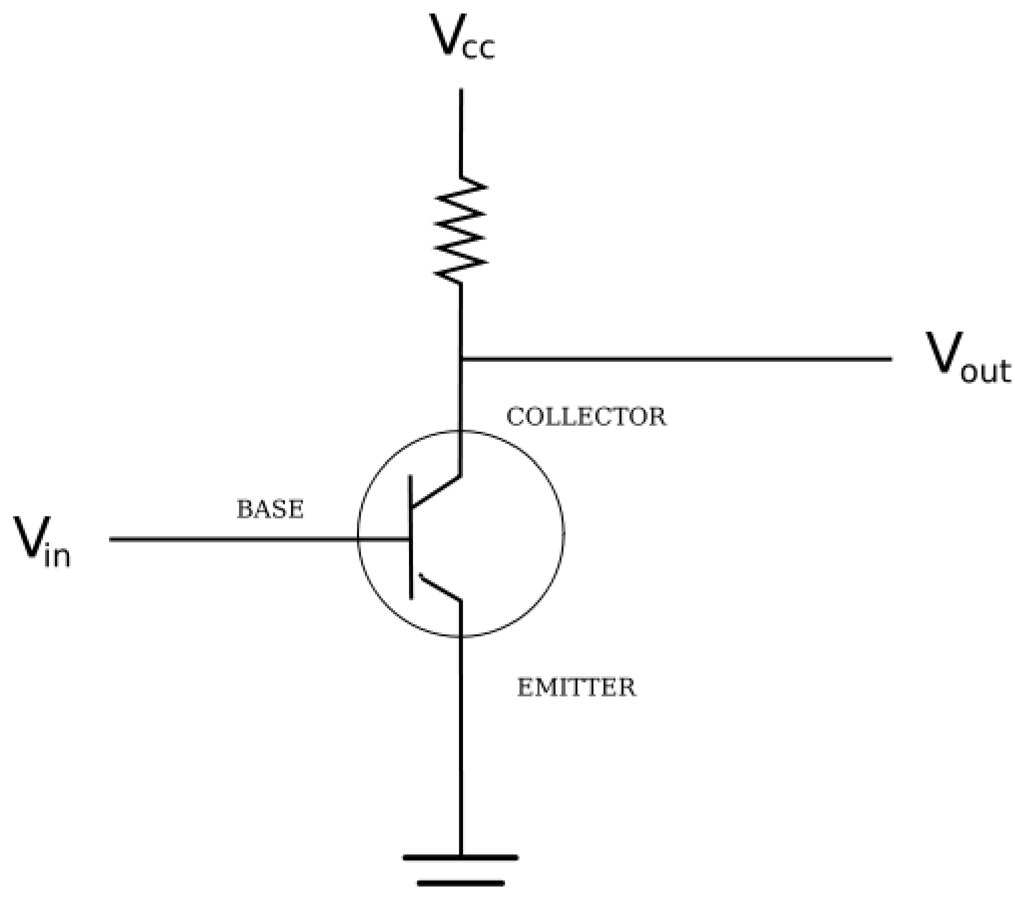
Although several companies each produce over a billion individually packaged (known as *discrete*) transistors every year, the vast majority of transistors now produced are in integrated circuits (often shortened to *IC*, *microchips* or simply *chips*), along with diodes, resistors, capacitors and other electronic components, to produce complete electronic circuits. A logic gate consists of up to about twenty transistors whereas an advanced microprocessor, as of 2011, can use as many as 3 billion transistors (MOSFETs). "About 60 million transistors were built this year [2002] ... for [each] man, woman, and child on Earth."

The transistor's low cost, flexibility, and reliability have made it a ubiquitous device. Transistorized mechatronic circuits have replaced electromechanical devices in controlling appliances and machinery. It is often easier and cheaper to use a standard microcontroller and write a computer program to carry out a control function than to design an equivalent mechanical control function.

Usage

The bipolar junction transistor, or BJT, was the most commonly used transistor in the 1960s and 70s. Even after MOSFETs became widely available, the BJT remained the transistor of choice for many analog circuits such as simple amplifiers because of their greater linearity and ease of manufacture. Desirable properties of MOSFETs, such as their utility in low-power devices, usually in the CMOS configuration, allowed them to capture nearly all market share for digital circuits; more recently MOSFETs have captured most analog and power applications as well, including modern clocked analog circuits, voltage regulators, amplifiers, power transmitters, motor drivers, etc.

Simplified operation



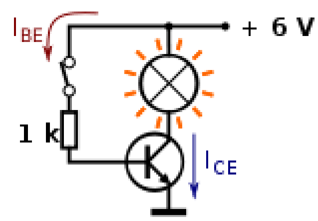
Simple circuit to show the labels of a bipolar transistor.

The essential usefulness of a transistor comes from its ability to use a small signal applied between one pair of its terminals to control a much larger signal at another pair of terminals. This property is called gain. A transistor can control its output in proportion to the input signal; that is, it can act as an amplifier. Alternatively, the transistor can be used to turn current on or off in a circuit as an electrically controlled switch, where the amount of current is determined by other circuit elements.

The two types of transistors have slight differences in how they are used in a circuit. A *bipolar transistor* has terminals labeled **base**, **collector**, and **emitter**. A small current at the base terminal (that is, flowing from the base to the emitter) can control or switch a much larger current between the collector and emitter terminals. For a *field-effect transistor*, the terminals are labeled **gate**, **source**, and **drain**, and a voltage at the gate can control a current between source and drain.

The image to the right represents a typical bipolar transistor in a circuit. Charge will flow between emitter and collector terminals depending on the current in the base. Since internally the base and emitter connections behave like a semiconductor diode, a voltage drop develops between base and emitter while the base current exists. The amount of this voltage depends on the material the transistor is made from, and is referred to as V_{BE}.

Transistor as a switch



BJT used as an electronic switch, in grounded-emitter configuration.

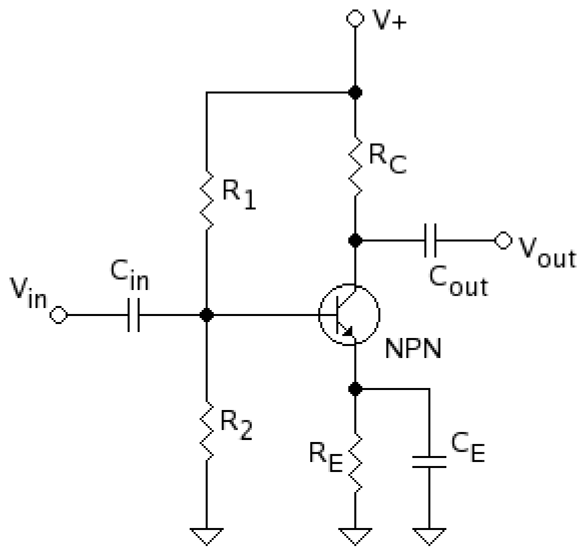
Transistors are commonly used as electronic switches, both for high-power applications such as switched-mode power supplies and for low-power applications such as logic gates.

In a grounded-emitter transistor circuit, such as the light-switch circuit shown, as the base voltage rises the base and collector current rise exponentially, and the collector voltage drops because of the collector load resistor. The relevant equations:

$V_{RC} = I_{CE} \times R_C$, the voltage across the load (the lamp with resistance R_C)
$V_{RC} + V_{CE} = V_{CC}$, the supply voltage shown as 6V

If V_{CE} could fall to 0 (perfect closed switch) then Ic could go no higher than V_{CC} / R_C, even with higher base voltage and current. The transistor is then said to be saturated. Hence, values of input voltage can be chosen such that the output is either completely off, or completely on. The transistor is acting as a switch, and this type of operation is common in digital circuits where only "on" and "off" values are relevant.

Transistor as an amplifier



Amplifier circuit, common-emitter configuration.

The common-emitter amplifier is designed so that a small change in voltage in (V_{in}) changes the small current through the base of the transistor and the transistor's current amplification combined with the properties of the circuit mean that small swings in V_{in} produce large changes in V_{out}.

Various configurations of single transistor amplifier are possible, with some providing current gain, some voltage gain, and some both.

From mobile phones to televisions, vast numbers of products include amplifiers for sound reproduction, radio transmission, and signal processing. The first discrete transistor audio amplifiers barely supplied a few hundred milliwatts, but power and audio fidelity gradually increased as better transistors became available and amplifier architecture evolved.

Modern transistor audio amplifiers of up to a few hundred watts are common and relatively inexpensive.

Comparison with vacuum tubes

Prior to the development of transistors, vacuum (electron) tubes (or in the UK "thermionic valves" or just "valves") were the main active components in electronic equipment.

Advantages

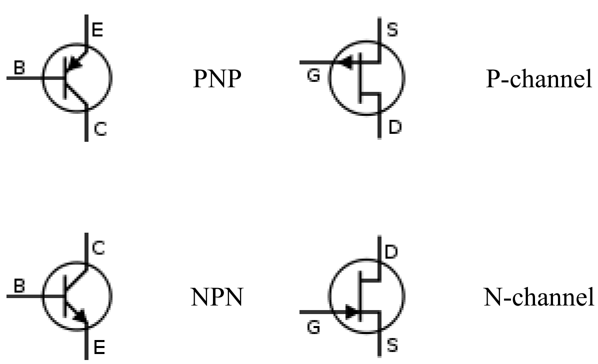
The key advantages that have allowed transistors to replace their vacuum tube predecessors in most applications are

- Small size and minimal weight, allowing the development of miniaturized electronic devices.
- Highly automated manufacturing processes, resulting in low per-unit cost.
- Lower possible operating voltages, making transistors suitable for small, battery-powered applications.
- No warm-up period for cathode heaters required after power application.
- Lower power dissipation and generally greater energy efficiency.
- Higher reliability and greater physical ruggedness.
- Extremely long life. Some transistorized devices have been in service for more than 50 years.
- Complementary devices available, facilitating the design of complementary-symmetry circuits, something not possible with vacuum tubes.
- Insensitivity to mechanical shock and vibration, thus avoiding the problem of microphonics in audio applications.

Limitations

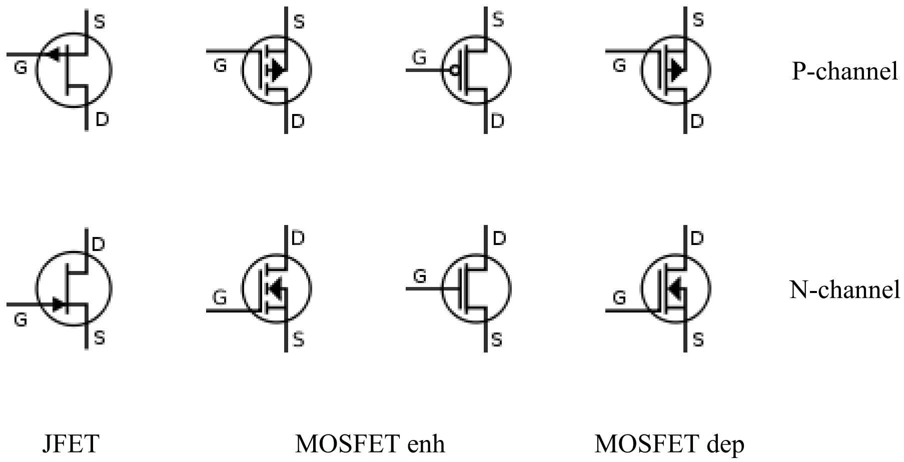
- Silicon transistors do not operate at voltages higher than about 1,000 volts (SiC devices can be operated as high as 3,000 volts). In contrast, vacuum tubes have been developed that can be operated at tens of thousands of volts.
- High-power, high-frequency operation, such as that used in over-the-air television broadcasting, is better achieved in vacuum tubes due to improved electron mobility in a vacuum.
- Silicon transistors are much more vulnerable than vacuum tubes to an electromagnetic pulse generated by a high-altitude nuclear explosion.

Types



BJT JFET

BJT and JFET symbols



JFET and IGFET symbols

Transistors are categorized by

- Semiconductor material: germanium, silicon, gallium arsenide, silicon carbide, etc.
- Structure: BJT, JFET, IGFET (MOSFET), IGBT, "other types"
- Polarity: NPN, PNP (BJTs); N-channel, P-channel (FETs)
- Maximum power rating: low, medium, high
- Maximum operating frequency: low, medium, high, radio frequency (RF), microwave (The maximum effective frequency of a transistor is denoted by the term f_T, an abbreviation for "frequency of transition". The frequency of transition is the frequency at which the transistor yields unity gain).
- Application: switch, general purpose, audio, high voltage, super-beta, matched pair
- Physical packaging: through hole metal, through hole plastic, surface mount, ball grid array, power modules
- Amplification factor h_{fe} (transistor beta)

Thus, a particular transistor may be described as *silicon, surface mount, BJT, NPN, low power, high frequency switch*.

Bipolar junction transistor

Bipolar transistors are so named because they conduct by using both majority and minority carriers. The bipolar junction transistor (BJT), the first type of transistor to be mass-produced, is a combination of two junction diodes, and is formed of either a thin layer of p-type semiconductor sandwiched between two n-type semiconductors (an n-p-n transistor), or a thin layer of n-type semiconductor sandwiched between two p-type semiconductors (a p-n-p transistor). This construction produces two p-n junctions: a base–emitter junction and a base–collector junction, separated by a thin region of semiconductor known as the base region (two junction diodes wired together without sharing an intervening semiconducting region will not make a transistor).

The BJT has three terminals, corresponding to the three layers of semiconductor – an *emitter*, a *base*, and a *collector*. It is useful in amplifiers because the currents at the emitter and collector are controllable by a relatively small base current." In an NPN transistor operating in the active region, the emitter-base junction is forward biased (electrons and holes recombine at the junction), and electrons are injected into the base region. Because the base is narrow, most of these electrons will diffuse into the reverse-biased (electrons and holes are formed at, and move away from the junction) base-collector junction and be swept into the collector; perhaps one-hundredth of the electrons will recombine in the base, which is the dominant mechanism in the base current. By controlling the number of electrons that can leave the base, the number of electrons entering the collector can be controlled. Collector current is approximately β (common-emitter current gain) times the base current. It is typically greater than 100 for small-signal transistors but can be smaller in transistors designed for high-power applications.

Unlike the FET, the BJT is a low–input-impedance device. Also, as the base–emitter voltage (V_{be}) is increased the base–emitter current and hence the collector–emitter current (I_{ce}) increase exponentially according to the Shockley diode model and the Ebers-Moll model. Because of this exponential relationship, the BJT has a higher transconductance than the FET.

Bipolar transistors can be made to conduct by exposure to light, since absorption of photons in the base region generates a photocurrent that acts as a base current; the collector current is approximately β times the photocurrent. Devices designed for this purpose have a transparent window in the package and are called phototransistors.

Field-effect transistor

The *field-effect transistor* (FET), sometimes called a *unipolar transistor*, uses either electrons (in *N-channel FET*) or holes (in *P-channel FET*) for conduction. The four terminals of the FET are named *source*, *gate*, *drain*, and *body* (*substrate*). On most FETs, the body is connected to the source inside the package, and this will be assumed for the following description.

In FETs, the drain-to-source current flows via a conducting channel that connects the *source* region to the *drain* region. The conductivity is varied by the electric field that is produced when a voltage is applied between the gate and source terminals; hence the current flowing between the drain and source is controlled by the voltage applied between the gate and source. As the gate–source voltage (V_{gs}) is increased, the drain–source current (I_{ds}) increases exponentially for V_{gs} below threshold, and then at a roughly quadratic rate ($I_{ds} \propto (V_{gs} - V_T)^2$) (where V_T is the threshold voltage at which drain current begins) in the "space-charge-limited" region above threshold. A quadratic behavior is not observed in modern devices, for example, at the 65 nm technology node.

For low noise at narrow bandwidth the higher input resistance of the FET is advantageous.

FETs are divided into two families: *junction FET* (JFET) and *insulated gate FET* (IGFET). The IGFET is more commonly known as a *metal–oxide–semiconductor FET* (MOSFET), reflecting its original construction from layers of metal (the gate), oxide (the insulation), and semiconductor. Unlike IGFETs, the JFET gate forms a PN diode with the channel which lies between the source and drain. Functionally, this makes the N-channel JFET the solid state equivalent of the vacuum tube triode which, similarly, forms a diode between its grid and cathode. Also, both devices operate in the *depletion mode*, they both have a high input impedance, and they both conduct current under the control of an input voltage.

Metal–semiconductor FETs (MESFETs) are JFETs in which the reverse biased PN junction is replaced by a metal–semiconductor Schottky-junction. These, and the HEMTs (high electron mobility transistors, or HFETs), in which a two-dimensional electron gas with very high carrier mobility is used for charge transport, are especially suitable for use at very high frequencies (microwave frequencies; several GHz).

Unlike bipolar transistors, FETs do not inherently amplify a photocurrent. Nevertheless, there are ways to use them, especially JFETs, as light-sensitive devices, by exploiting the photocurrents in channel–gate or channel–body junctions.

FETs are further divided into *depletion-mode* and *enhancement-mode* types, depending on whether the channel is turned on or off with zero gate-to-source voltage. For enhancement mode, the channel is off at zero bias, and a gate potential can "enhance" the conduction. For depletion mode, the channel is on at zero bias, and a gate potential (of the opposite polarity) can "deplete" the channel, reducing conduction. For either mode, a more positive gate voltage corresponds to a higher current for N-channel devices and a lower current for P-channel devices. Nearly all JFETs are depletion-mode as the diode junctions would forward bias and conduct if they were enhancement mode devices; most IGFETs are enhancement-mode types.

Other transistor types

- Point-contact transistor, first kind of transistor ever constructed
- Bipolar junction transistor (BJT)
    - Heterojunction bipolar transistor, up to several hundred GHz, common in modern ultrafast and RF circuits
    - Grown-junction transistor, first kind of BJT
    - Alloy-junction transistor, improvement of grown-junction transistor
        - Micro-alloy transistor (MAT), speedier than alloy-junction transistor
        - Micro-alloy diffused transistor (MADT), speedier than MAT, a diffused-base transistor

        - Post-alloy diffused transistor (PADT), speedier than MAT, a diffused-base transistor
        - Schottky transistor
        - Surface barrier transistor
    - Drift-field transistor
    - Avalanche transistor
    - Darlington transistors are two BJTs connected together to provide a high current gain equal to the product of the current gains of the two transistors.
    - Insulated gate bipolar transistors (IGBTs) use a medium power IGFET, similarly connected to a power BJT, to give a high input impedance. Power diodes are often connected between certain terminals depending on specific use. IGBTs are particularly suitable for heavy-duty industrial applications. The Asea Brown Boveri (ABB) *5SNA2400E170100* illustrates just how far power semiconductor technology has advanced. Intended for three-phase power supplies, this device houses three NPN IGBTs in a case measuring 38 by 140 by 190 mm and weighing 1.5 kg. Each IGBT is rated at 1,700 volts and can handle 2,400 amperes.
    - Photo transistor
- Field-effect transistor
    - Carbon nanotube field-effect transistor (CNFET)
    - JFET, where the gate is insulated by a reverse-biased PN junction
    - MESFET, similar to JFET with a Schottky junction instead of PN one
        - High Electron Mobility Transistor (HEMT, HFET, MODFET)
    - MOSFET, where the gate is insulated by a shallow layer of insulator
    - Inverted-T field effect transistor (ITFET)
    - FinFET, source/drain region shapes fins on the silicon surface.
    - FREDFET, fast-reverse epitaxial diode field-effect transistor
    - Thin film transistor, in LCDs.
    - OFET Organic Field-Effect Transistor, in which the semiconductor is an organic compound
    - Ballistic transistor
    - Floating-gate transistor, for non-volatile storage.
    - FETs used to sense environment
        - Ion-sensitive field effect transistor, to measure ion concentrations in solution.
        - EOSFET, electrolyte-oxide-semiconductor field effect transistor (Neurochip)
        - DNAFET, deoxyribonucleic acid field-effect transistor
- Spacistor
- Diffusion transistor, formed by diffusing dopants into semiconductor substrate; can be both BJT and FET
- Unijunction transistors can be used as simple pulse generators. They comprise a main body of either P-type or N-type semiconductor with ohmic contacts at each end (terminals *Base1* and *Base2*). A junction with the opposite semiconductor type is formed at a point along the length of the body for the third terminal (*Emitter*).

- Single-electron transistors (SET) consist of a gate island between two tunnelling junctions. The tunnelling current is controlled by a voltage applied to the gate through a capacitor.
- Nanofluidic transistor, controls the movement of ions through sub-microscopic, water-filled channels. Nanofluidic transistor, the basis of future chemical processors
- Multigate devices
    - Tetrode transistor
    - Pentode transistor
    - Multigate device
    - Trigate transistors (Prototype by Intel)
    - **Dual gate FETs** have a single channel with two gates in cascode; a configuration optimized for *high frequency amplifiers*, *mixers*, and oscillators.
- Junctionless Nanowire Transistor (JNT), developed at Tyndall National Institute in Ireland, was the first transistor successfully fabricated without junctions. (Even MOSFETs have junctions, although its gate is electrically insulated from the region the gate controls.) Junctions are difficult and expensive to fabricate, and, because they are a significant source of current leakage, they waste significant power and generate significant waste heat. Eliminating them held the promise of cheaper and denser microchips. The JNT uses a simple nanowire of silicon surrounded by an electrically isolated "wedding ring" that acts to gate the flow of electrons through the wire. This method has been described as akin to squeezing a garden hose to gate the flow of water through the hose. The nanowire is heavily n-doped, making it an excellent conductor. Crucially the gate, comprising silicon, is heavily p-doped; and its presence depletes the underlying silicon nanowire thereby preventing carrier flow past the gate.

Part numbers

The types of some transistors can be parsed from the part number. There are three major semiconductor naming standards; in each the alphanumeric prefix provides clues to type of the device:

Japanese Industrial Standard (JIS) has a standard for transistor part numbers. They begin with "2S", e.g. 2SD965, but sometimes the "2S" prefix is not marked on the package – a 2SD965 might only be marked "D965"; a 2SC1815 might be listed by a supplier as simply "C1815". This series sometimes has suffixes (such as "R", "O", "BL"... standing for "Red", "Orange", "Blue" etc.) to denote variants, such as tighter h_{FE} (gain) groupings.

Beginning of Part Number	**Type of Transistor**
2SA	high frequency PNP BJTs
2SB	audio frequency PNP BJTs
2SC	high frequency NPN BJTs
2SD	audio frequency NPN BJTs

2SJ	P-channel FETs (both JFETs and MOSFETs)
2SK	N-channel FETs (both JFETs and MOSFETs)

The Pro Electron part numbers begin with two letters: the first gives the semiconductor type (A for Germanium, B for Silicon, and C for materials like GaAs); the second letter denotes the intended use (A for diode, C for general-purpose transistor, etc.). A 3-digit sequence number (or one letter then 2 digits, for industrial types) follows (and, with early devices, indicated the case type – just as the older system for vacuum tubes used the last digit or two to indicate the number of pins, and the first digit or two for the filament voltage). Suffixes may be used, such as a letter (e.g. "C" often means high h_{FE}, such as in: BC549C) or other codes may follow to show gain (e.g. BC327-25) or voltage rating (e.g. BUK854-800A). The more common prefixes are:

Prefix class	**Usage**	**Example**
AC	Germanium small signal transistor	AC126
AF	Germanium RF transistor	AF117
BC	Silicon, small signal transistor ("allround")	BC548B
BD	Silicon, power transistor	BD139
BF	Silicon, RF (high frequency) BJT or FET	BF245
BS	Silicon, switching transistor (BJT or MOSFET)	BS170
BL	Silicon, high frequency, high power (for transmitters)	BLW34
BU	Silicon, high voltage (for CRT horizontal deflection circuits)	BU508

The JEDEC transistor device numbers usually start with 2N, indicating a three-terminal device (dual-gate field-effect transistors are four-terminal devices, so begin with 3N), then a 2, 3 or 4-digit sequential number with no significance as to device properties (although low numbers tend to be Germanium devices, because early transistors were mainly Germanium). For example 2N3055 is a silicon NPN power transistor, 2N1301 is a PNP germanium switching transistor. A letter suffix (such as "A") is sometimes used to indicate a newer variant, but rarely gain groupings.

Other schemes

Manufacturers of devices may have their own proprietary numbering system, for example CK722. Note that a manufacturer's prefix (like "MPF" in MPF102, which originally would denote a Motorola FET) now is an unreliable indicator of who made the device. Some proprietary naming schemes adopt parts of other naming schemes, for example a PN2222A is a (possibly Fairchild Semiconductor) 2N2222A in a plastic case (but a PN108 is a plastic version of a BC108, not a 2N108, while the PN100 is unrelated to other xx100 devices).

Military part numbers sometimes are assigned their own codes, such as the British Military CV Naming System.

Manufacturers buying large numbers of similar parts may have them supplied with "house numbers", identifying a particular purchasing specification and not necessarily a device with a standardized registered number. For example, an HP part 1854,0053 is a (JEDEC) 2N2218 transistor which is also assigned the CV number: CV7763

Naming problems

With so many independent naming schemes, and the abbreviation of part numbers when printed on the devices, ambiguity sometimes occurs. For example two different devices may be marked "J176" (one the J176 low-power Junction FET, the other the higher-powered MOSFET 2SJ176).

As older "through-hole" transistors are given Surface-Mount packaged counterparts, they tend to be assigned many different part numbers because manufacturers have their own systems to cope with the variety in pinout arrangements and options for dual or matched NPN+PNP devices in one pack. So even when the original device (such as a 2N3904) may have been assigned by a standards authority, and well known by engineers over the years, the new versions are far from standardised in their naming.

Construction

Semiconductor material

The first BJTs were made from germanium (Ge). Silicon (Si) types currently predominate but certain advanced microwave and high performance versions now employ the *compound semiconductor* material gallium arsenide (GaAs) and the *semiconductor alloy* silicon germanium (SiGe). Single element semiconductor material (Ge and Si) is described as *elemental*.

Rough parameters for the most common semiconductor materials used to make transistors are given in the table below; it must be noted that these parameters will vary with increase in temperature, electric field, impurity level, strain, and sundry other factors:

Semiconductor material characteristics

Semiconductor material	Junction forward voltage V @ 25 °C	Electron mobility $m^2/(V\cdot s)$ @ 25 °C	Hole mobility $m^2/(V\cdot s)$ @ 25 °C	Max. junction temp. °C
Ge	0.27	0.39	0.19	70 to 100

Si	0.71	0.14	0.05	150 to 200
GaAs	1.03	0.85	0.05	150 to 200
Al-Si junction	0.3	—	—	150 to 200

The *junction forward voltage* is the voltage applied to the emitter-base junction of a BJT in order to make the base conduct a specified current. The current increases exponentially as the junction forward voltage is increased. The values given in the table are typical for a current of 1 mA (the same values apply to semiconductor diodes). The lower the junction forward voltage the better, as this means that less power is required to "drive" the transistor. The junction forward voltage for a given current decreases with increase in temperature. For a typical silicon junction the change is −2.1 mV/°C. In some circuits special compensating elements (sensistors) must be used to compensate for such changes.

The density of mobile carriers in the channel of a MOSFET is a function of the electric field forming the channel and of various other phenomena such as the impurity level in the channel. Some impurities, called dopants, are introduced deliberately in making a MOSFET, to control the MOSFET electrical behavior.

The *electron mobility* and *hole mobility* columns show the average speed that electrons and holes diffuse through the semiconductor material with an electric field of 1 volt per meter applied across the material. In general, the higher the electron mobility the speedier the transistor. The table indicates that Ge is a better material than Si in this respect. However, Ge has four major shortcomings compared to silicon and gallium arsenide:

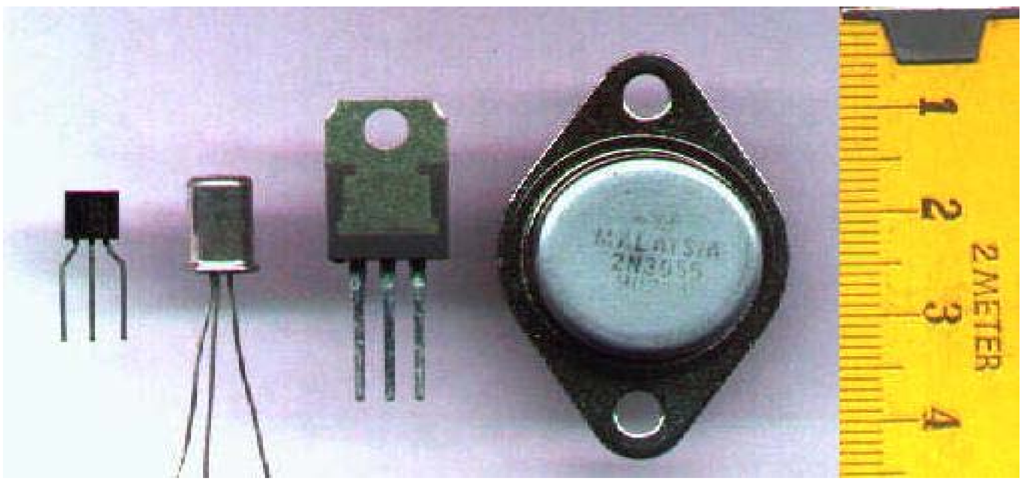
- Its maximum temperature is limited;
- it has relatively high leakage current;
- it cannot withstand high voltages;
- it is less suitable for fabricating integrated circuits.

Because the electron mobility is higher than the hole mobility for all semiconductor materials, a given bipolar NPN transistor tends to be swifter than an equivalent PNP transistor type. GaAs has the highest electron mobility of the three semiconductors. It is for this reason that GaAs is used in high frequency applications. A relatively recent FET development, the *high electron mobility transistor* (HEMT), has a heterostructure (junction between different semiconductor materials) of aluminium gallium arsenide (AlGaAs)-gallium arsenide (GaAs) which has twice the electron mobility of a GaAs-metal barrier junction. Because of their high speed and low noise, HEMTs are used in satellite receivers working at frequencies around 12 GHz.

Max. junction temperature values represent a cross section taken from various manufacturers' data sheets. This temperature should not be exceeded or the transistor may be damaged.

Al–Si junction refers to the high-speed (aluminum–silicon) semiconductor–metal barrier diode, commonly known as a Schottky diode. This is included in the table because some silicon power IGFETs have a *parasitic* reverse Schottky diode formed between the source and drain as part of the fabrication process. This diode can be a nuisance, but sometimes it is used in the circuit.

Packaging



Through-hole transistors (tape measure marked in centimetres)

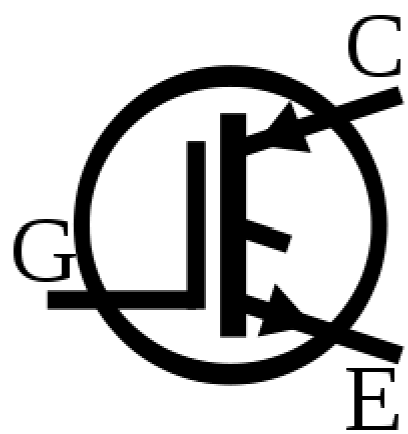
Transistors come in many different packages (semiconductor packages). The two main categories are *through-hole* (or *leaded*), and *surface-mount*, also known as *surface mount device* (SMD). The *ball grid array* (BGA) is the latest surface mount package (currently only for large *transistor arrays*). It has solder "balls" on the underside in place of leads. Because they are smaller and have shorter interconnections, SMDs have better high frequency characteristics but lower power rating.

Transistor packages are made of glass, metal, ceramic, or plastic. The package often dictates the power rating and frequency characteristics. Power transistors have larger packages that can be clamped to heat sinks for enhanced cooling. Additionally, most power transistors have the collector or drain physically connected to the metal can/metal plate. At the other extreme, some surface-mount *microwave* transistors are as small as grains of sand.

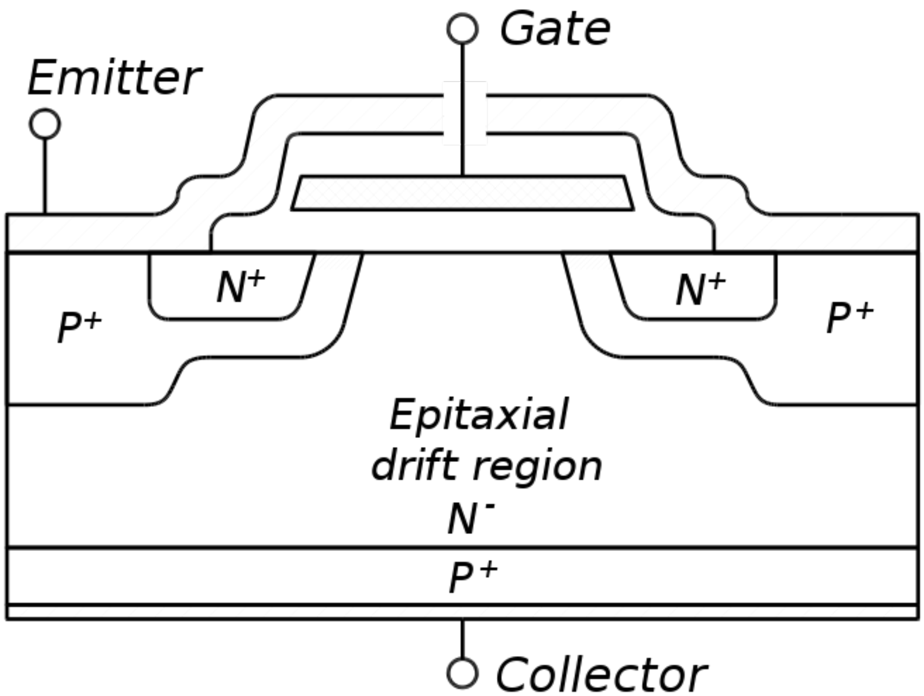
Often a given transistor type is available in sundry packages. Transistor packages are mainly standardized, but the assignment of a transistor's functions to the terminals is not: other transistor types can assign other functions to the package's terminals. Even for the same transistor type the terminal assignment can vary (normally indicated by a suffix letter to the part number, q.e. BC212L and BC212K).

Chapter- 7

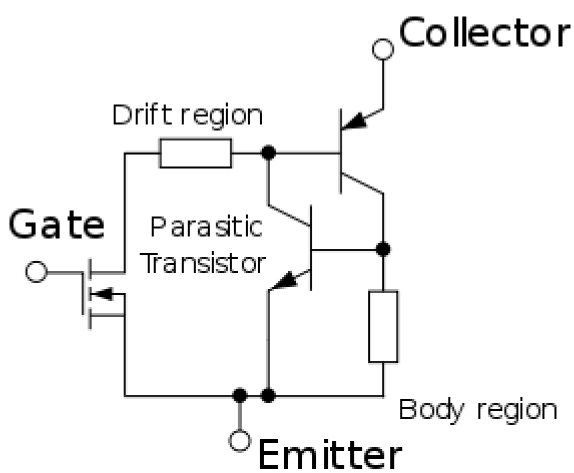
Insulated-gate Bipolar Transistor



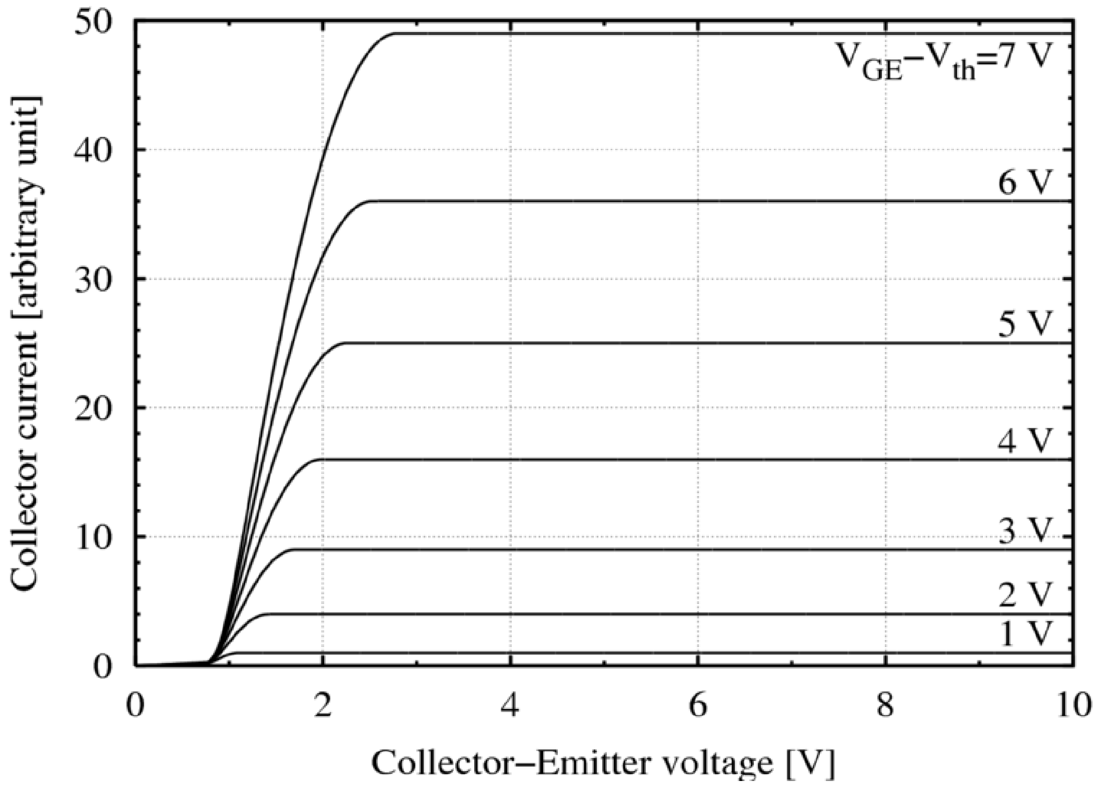
Electronic symbol for IGBT



Cross section of a typical IGBT cell. The illustration is not to scale.



Equivalent circuit for IGBT



Static characteristic of an IGBT.

The **insulated gate bipolar transistor** or **IGBT** is a three-terminal power semiconductor device, noted for high efficiency and fast switching. It switches electric power in many modern appliances: electric cars, trains, variable speed refrigerators, air-conditioners and even stereo systems with switching amplifiers. Since it is designed to rapidly turn on and off, amplifiers that use it often synthesize complex waveforms with pulse width modulation and low-pass filters.

The IGBT combines the simple gate-drive characteristics of the MOSFETs with the high-current and low–saturation-voltage capability of bipolar transistors by combining an isolated gate FET for the control input, and a bipolar power transistor as a switch, in a single device. The IGBT is used in medium- to high-power applications such as switched-mode power supply, traction motor control and induction heating. Large IGBT modules typically consist of many devices in parallel and can have very high current handling capabilities in the order of hundreds of amperes with blocking voltages of 6000 V, equating to hundreds of kilowatts.

The IGBT is a fairly recent invention. The first-generation devices of the 1980s and early 1990s were relatively slow in switching, and prone to failure through such modes as latchup and secondary breakdown. Second-generation devices were much improved, and the current third-generation ones are even better, with speed rivaling MOSFETs, and excellent ruggedness and tolerance of overloads.

The extremely high pulse ratings of second- and third-generation devices also make them useful for generating large power pulses in areas like particle and plasma physics, where they are starting to supersede older devices like thyratrons and triggered spark gaps.

Their high pulse ratings, and low prices on the surplus market, also make them attractive to the high-voltage hobbyist for controlling large amounts of power to drive devices such as solid-state Tesla coils and coilguns.

Availability of affordable, reliable IGBTs is a important enabler for electric vehicles and hybrid cars.

History

The IGBT is a semiconductor device with four alternating layers (P-N-P-N) that are controlled by a metal-oxide-semiconductor (MOS) gate structure without regenerative action. This mode of operation was first proposed by Yamagami in his Japanese patent S47-21739, which was filed in 1968. This mode of operation was first experimentally discovered by B. Jayant Baliga in vertical device structures with a V-groove gate region and reported in the literature in 1979. The device structure was referred to as a ‘V-groove MOSFET device with the drain region replaced by a p-type Anode Region’ in this paper and subsequently as the insulated gate rectifier (IGR), the insulated-gate transistor (IGT), the conductivity-modulated field-effect transistor (COMFET) and "bipolar-mode MOSFET".

Plummer found the same IGBT mode of operation in the four layer device (SCR) and he first filed a patent application for the device structure in 1978. USP No.4199774 was issued in 1980 and B1 Re33209 was reissued in 1995 for the IGBT mode operation in the four layer device (SCR).

Hans W. Becke and Carl F. Wheatley invented a similar device for which they filed a patent application in 1980, and which they referred to as "power MOSFET with an anode region". This patent has been called "the seminal patent of the Insulated Gate Bipolar Transistor." The patent claimed "no thyristor action occurs under any device operating conditions." This substantially means that the device exhibits non-latch-up IGBT operation over the entire device operation range.

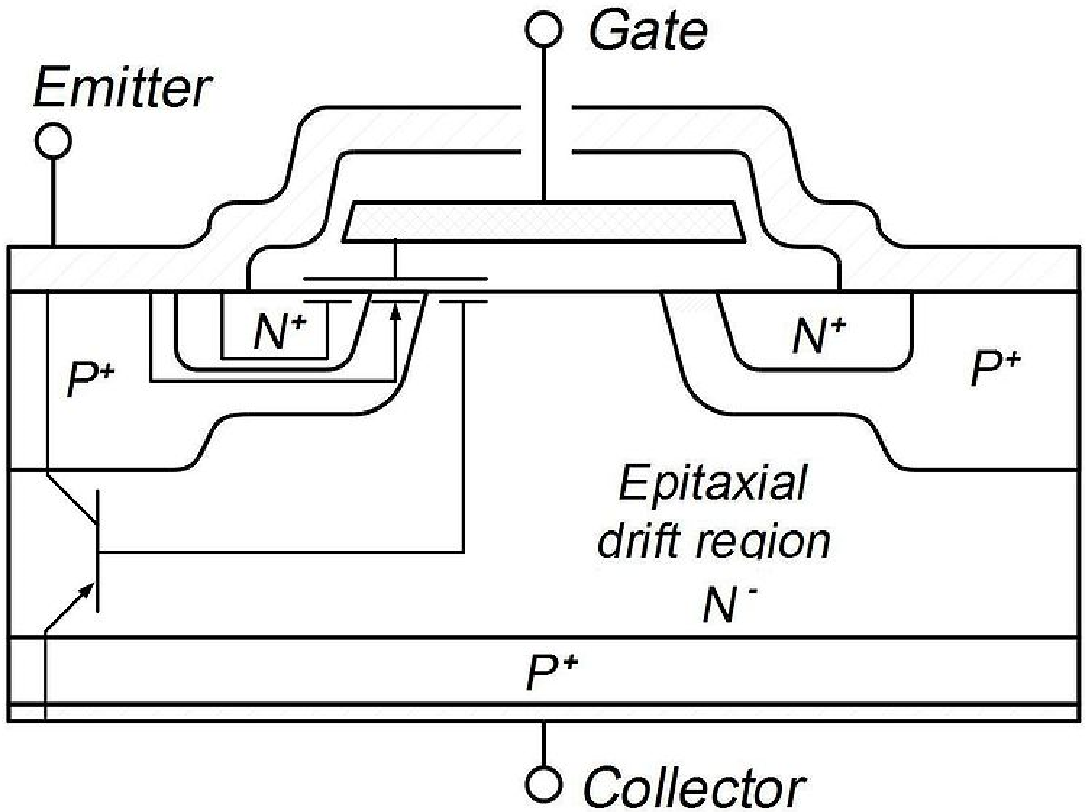
Devices capable of operating over an extended current range for use in applications were first reported by Baliga *et al.* in 1982. A similar paper was also submitted by J.P. Russel et al. to IEEE Electron Device Letter in 1982. The applications for the device were initially regarded by the power electronics community to be severely restricted by its slow switching speed and latch-up of the parasitic thyristor structure inherent within the device. However, it was demonstrated by Baliga and also by A.M. Goodman et al. in 1983 that the switching speed could be adjusted over a broad range by using electron irradiation. This was followed by demonstration of operation of the device at elevated temperatures by Baliga in 1985. Successful efforts to suppress the latch-up of the parasitic thyristor and the scaling of the voltage rating of the devices at GE allowed the introduction of commercial devices in 1983, which could be utilized for a wide variety of applications.

Complete suppression of the parasitic thyristor action and the resultant non-latch-up IGBT operation for the entire device operation range was achieved by A. Nakagawa et al. in 1984. The non-latch-up design concept was filed for US patents. To test the lack of latchup, the prototype 1200V IGBTs were directly connected without any loads across a 600V constant voltage source and were switched on for 25 microseconds. The entire 600V was dropped across the device and a large short circuit current flowed. The devices successfully withstood this severe condition. This was the first demonstration of so-called "short-circuit-withstanding-capability" in IGBTs. Non-latch-up IGBT operation was ensured, for the first time, for the entire device operation range. In this sense, the non-latch-up IGBT proposed by Hans W. Becke and Carl F. Wheatley was realized by A. Nakagawa et al. in 1984. Products of non-latch-up IGBTs were first commercialized by Toshiba in 1985.

Once the non-latch-up capability was achieved in IGBTs, it was found that IGBTs exhibited very rugged and a very large safe operating area. It was demonstrated that the product of the operating current density and the collector voltage exceeded the theoretical limit of bipolar transistors, $2x10^5 W/cm^2$, and reached $5x10^5 W/cm^2$.

Device structure

An IGBT cell is constructed similarly to a n-channel vertical construction power MOSFET except the n+ drain is replaced with a p+ collector layer, thus forming a vertical PNP bipolar junction transistor.



Cross section of a typical IGBT showing internal connection of MOSFET and Bipolar Device

This additional p+ region creates a cascade connection of a PNP bipolar junction transistor with the surface n-channel MOSFET.

Comparison With Power MOSFETS

An IGBT has a significantly lower forward voltage drop compared to a conventional MOSFET in higher blocking voltage rated devices. As the blocking voltage rating of both MOSFET and IGBT devices increases, the depth of the n- drift region must increase and the doping must decrease, resulting in roughly square relationship increase in forward conduction loss compared to blocking voltage capability of the device. By injecting minority carriers (holes) from the collector p+ region into the n- drift region during forward conduction, the resistance of the n- drift region is considerably reduced. However, this resultant reduction in on-state forward voltage comes with several penalties:

- The additional PN junction blocks reverse current flow. This means that unlike a MOSFET, IGBTs cannot conduct in the reverse direction. In bridge circuits where reverse current flow is needed an additional diode (called a freewheeling diode) is placed in parallel with the IGBT to conduct current in the opposite direction. The penalty isn't as severe as first assumed though, because at the higher voltages where IGBT usage dominates, discrete diodes are of significantly higher performance than the body diode of a MOSFET.

- The reverse bias rating of the N- drift region to collector P+ diode is usually only of tens of volts, so if the circuit application applies a reverse voltage to the IGBT, an additional series diode must be used.
- The minority carriers injected into the n- drift region take time to enter and exit or recombine at turn on and turn off. This results in longer switching time and hence higher switching loss compared to a power MOSFET.
- The on-state forward voltage drop in IGBTs behaves very differently to that in power MOSFETS. The MOSFET voltage drop can be modeled as a resistance, with the voltage drop proportional to current. By contrast, IGBT has a diode like voltage drop (typically of the order of 2V) increasing only with the log of the current. Additionally, MOSFET resistance is typically lower for smaller blocking voltages meaning that the choice between IGBTs and power MOSFETS depend on both the blocking voltage and current involved in a particular application, as well as the different switching characteristics mentioned above.

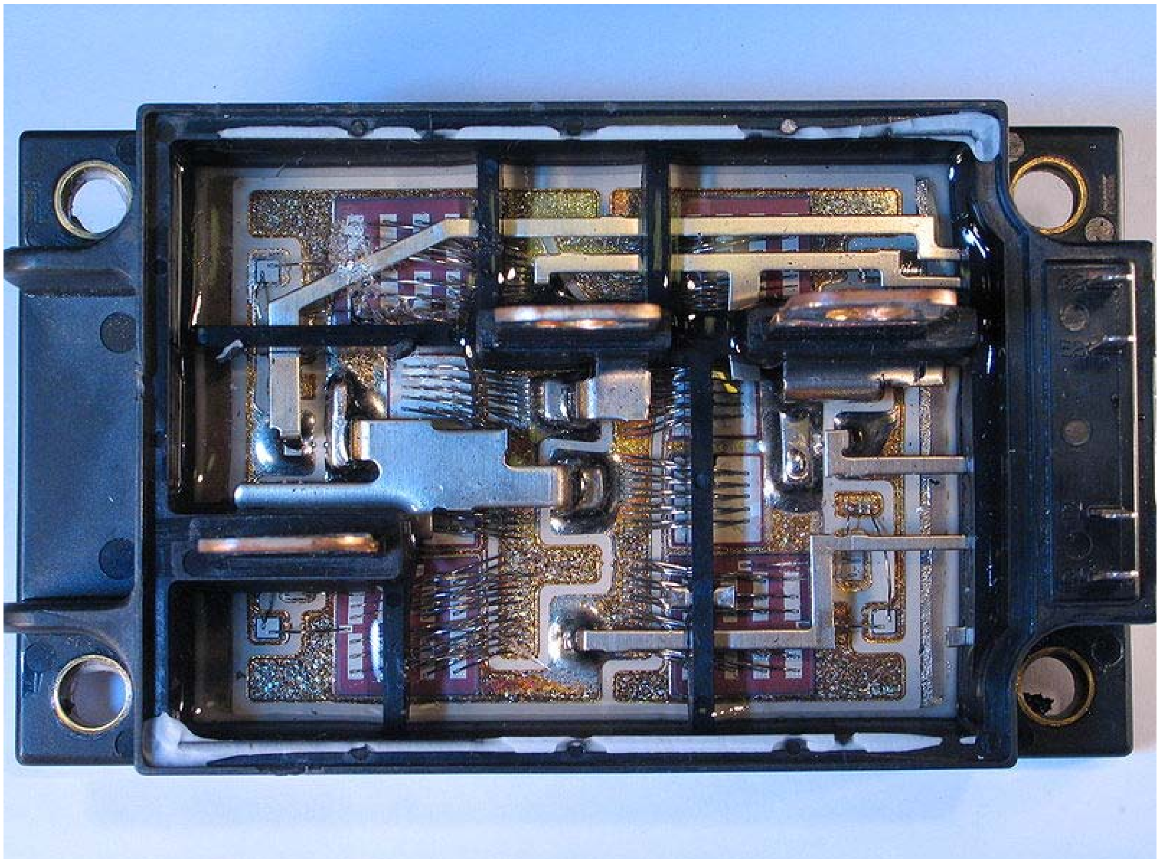
In general high voltage, high current and low switching frequencies favor IGBTs while low voltage, low current and high switching frequencies are the domain of the MOSFET.

IGBT models

Rather than using a device physics-based model, SPICE simulates IGBTs using Macromodels, a method that combines an ensemble of components such as FETs and BJTs in a Darlington configuration. An alternative physics-based model is the Hefner model, introduced by Allen Hefner of the NIST. It is a fairly complex model that has shown very good results. Hefner's model is described in a 1988 paper and was later extended to a thermo-electrical model and a version using SABER.

Usage

IGBT-Module (IGBTs and free wheeling diodes) with a rated current of 1,200 A and a maximum voltage of 3,300 V



Opened IGBT module with four IGBTs (half H-bridge) each rated for 400 A 600 V

Chapter- 8

Field-effect Transistor

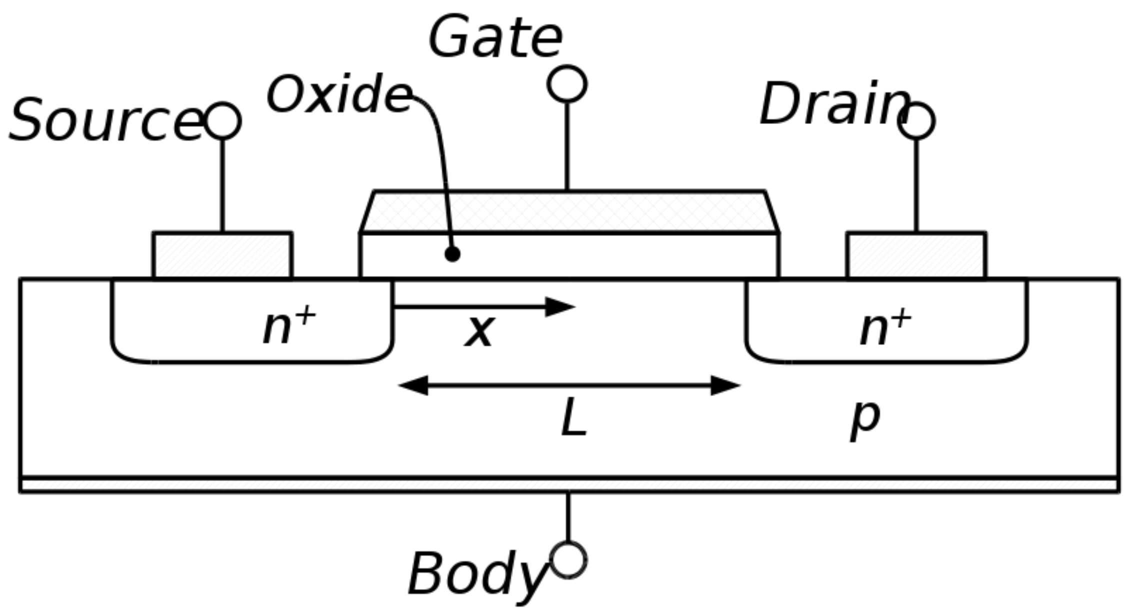
High-power N-channel field-effect transistor

The **field-effect transistor (FET)** relies on an electric field to control the shape and hence the conductivity of a channel of one type of charge carrier in a semiconductor material. FETs are sometimes called *unipolar transistors* to contrast their single-carrier-type operation with the dual-carrier-type operation of bipolar (junction) transistors (BJT). The *concept* of the FET predates the BJT, though it was not physically implemented until *after* BJTs due to the limitations of semiconductor materials and the relative ease of manufacturing BJTs compared to FETs at the time.

History

The principle of field-effect transistors was first patented by Julius Edgar Lilienfeld in 1925 and by Oskar Heil in 1934, but practical semi-conducting devices (the JFET, junction gate field-effect transistor) were only developed much later after the transistor effect was observed and explained by the team of William Shockley at Bell Labs in 1947. The MOSFET (metal–oxide–semiconductor field-effect transistor), which largely superseded the JFET and had a more profound effect on electronic development, was first proposed by Dawon Kahng in 1960.

Terminals

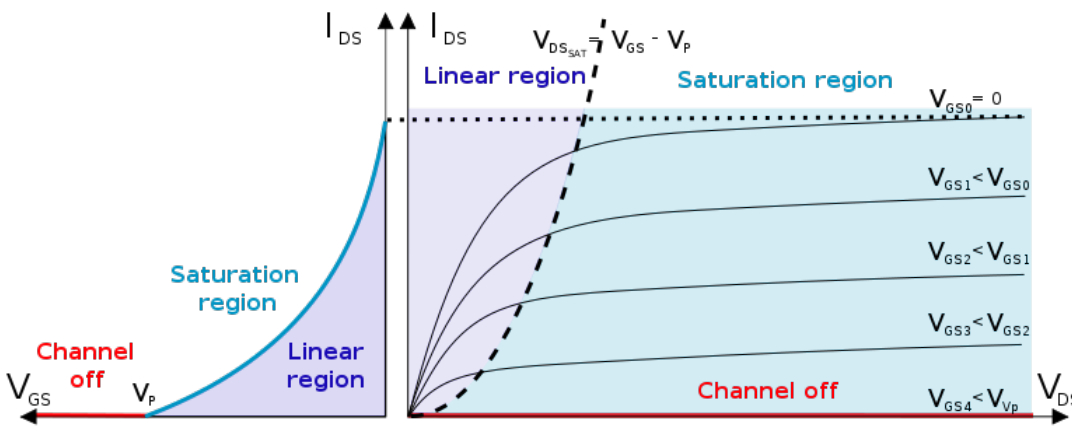


Cross section of an n-type MOSFET

All FETs have a *gate*, *drain*, and *source* terminal that correspond roughly to the *base*, *collector*, and *emitter* of BJTs. Aside from the JFET, all FETs also have a fourth terminal called the *body*, *base*, *bulk*, or *substrate.* This fourth terminal serves to bias the transistor into operation; it is rare to make non-trivial use of the body terminal in circuit designs, but its presence is important when setting up the physical layout of an integrated circuit. The size of the gate, length *L* in the diagram, is the distance between source and drain. The *width* is the extension of the transistor, in the diagram perpendicular to the cross section. Typically the width is much larger than the length of the gate. A gate length of 1 µm limits the upper frequency to about 5 GHz, 0.2 µm to about 30 GHz.

The names of the terminals refer to their functions. The gate terminal may be thought of as controlling the opening and closing of a physical gate. This gate permits electrons to flow through or blocks their passage by creating or eliminating a channel between the source and drain. Electrons flow from the source terminal towards the drain terminal if influenced by an applied voltage. The body simply refers to the bulk of the semiconductor in which the gate, source and drain lie. Usually the body terminal is connected to the highest or lowest voltage within the circuit, depending on type. The body terminal and the source terminal are sometimes connected together since the source is also sometimes connected to the highest or lowest voltage within the circuit, however there are several uses of FETs which do not have such a configuration, such as transmission gates and cascode circuits.

FET operation



I–V characteristics and output plot of a JFET n-channel transistor.

The FET controls the flow of electrons (or electron holes) from the source to drain by affecting the size and shape of a "conductive channel" created and influenced by voltage (or lack of voltage) applied across the gate and source terminals (For ease of discussion, this assumes body and source are connected). This conductive channel is the "stream" through which electrons flow from source to drain.

In an n-channel *depletion-mode* device, a negative gate-to-source voltage causes a *depletion region* to expand in width and encroach on the channel from the sides, narrowing the channel. If the depletion region expands to completely close the channel, the resistance of the channel from source to drain becomes large, and the FET is effectively turned off like a switch. Likewise a positive gate-to-source voltage increases the channel size and allows electrons to flow easily.

Conversely, in an n-channel *enhancement-mode* device, a positive gate-to-source voltage is necessary to create a conductive channel, since one does not exist naturally within the transistor. The positive voltage attracts free-floating electrons within the body towards the gate, forming a conductive channel. But first, enough electrons must be attracted near the gate to counter the dopant ions added to the body of the FET; this forms a region free of mobile carriers called a depletion region, and the phenomenon is referred to as the *threshold voltage* of the FET. Further gate-to-source voltage increase will attract even more electrons towards the gate which are able to create a conductive channel from source to drain; this process is called *inversion*.

For either enhancement- or depletion-mode devices, at drain-to-source voltages much less than gate-to-source voltages, changing the gate voltage will alter the channel resistance, and drain current will be proportional to drain voltage (referenced to source voltage). In this mode the FET operates like a variable resistor and the FET is said to be operating in a *linear mode* or *ohmic mode*.

If drain-to-source voltage is increased, this creates a significant asymmetrical change in the shape of the channel due to a gradient of voltage potential from source to drain. The shape of the inversion region becomes "pinched-off" near the drain end of the channel. If drain-to-source voltage is increased further, the pinch-off point of the channel begins to move away from the drain towards the source. The FET is said to be in *saturation mode*; some authors refer to it as *active mode*, for a better analogy with bipolar transistor operating regions. The saturation mode, or the region between ohmic and saturation, is used when amplification is needed. The in-between region is sometimes considered to be part of the ohmic or linear region, even where drain current is not approximately linear with drain voltage.

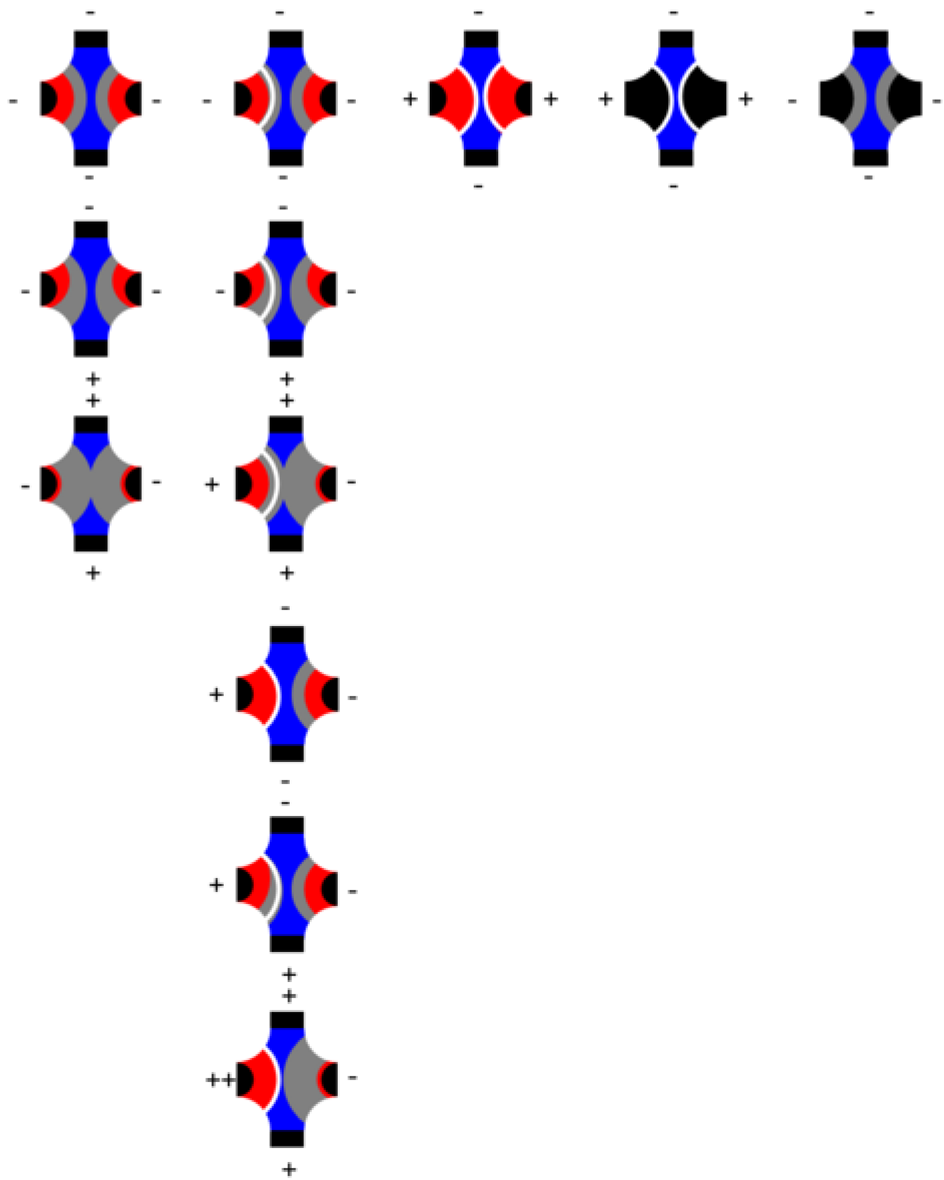
Even though the conductive channel formed by gate-to-source voltage no longer connects source to drain during saturation mode, carriers are not blocked from flowing. Considering again an n-channel device, a depletion region exists in the p-type body, surrounding the conductive channel and drain and source regions. The electrons which comprise the channel are free to move out of the channel through the depletion region if attracted to the drain by drain-to-source voltage. The depletion region is free of carriers and has a resistance similar to silicon. Any increase of the drain-to-source voltage will increase the distance from drain to the pinch-off point, increasing resistance due to the depletion region proportionally to the applied drain-to-source voltage. This proportional change causes the drain-to-source current to remain relatively fixed independent of changes to the drain-to-source voltage and quite unlike the linear mode operation. Thus in saturation mode, the FET behaves as a constant-current source rather than as a resistor and can be used most effectively as a voltage amplifier. In this case, the gate-to-source voltage determines the level of constant current through the channel.

Composition

The FET can be constructed from a number of semiconductors, silicon being by far the most common. Most FETs are made with conventional bulk semiconductor processing techniques, using the single crystal semiconductor wafer as the active region, or channel.

Among the more unusual body materials are amorphous silicon, polycrystalline silicon or other amorphous semiconductors in thin-film transistors or organic field effect transistors that are based on organic semiconductors and often apply organic gate insulators and electrodes.

Types of field-effect transistors



Depletion-type FETs under typical voltages. JFET, poly-silicon MOSFET, double-gate MOSFET, metal-gate MOSFET, MESFET. depletion, electrons, holes, metal, insulator. Top=source, bottom=drain, left=gate, right=bulk.

The channel of a FET is doped to produce either an N-type semiconductor or a P-type semiconductor. The drain and source may be doped of opposite type to the channel, in the case of depletion mode FETs, or doped of similar type to the channel as in enhancement mode FETs. Field-effect transistors are also distinguished by the method of insulation between channel and gate. Types of FETs are:

- CNFET

- The **DEPFET** is a FET formed in a fully-depleted substrate and acts as a sensor, amplifier and memory node at the same time. It can be used as an image (photon) sensor.
- The **DGMOSFET** is a MOSFET with dual gates.
- The **DNAFET** is a specialized FET that acts as a biosensor, by using a gate made of single-strand DNA molecules to detect matching DNA strands.
- The **FREDFET** (Fast Reverse or Fast Recovery Epitaxial Diode FET) is a specialized FET designed to provide a very fast recovery (turn-off) of the body diode.
- The **HEMT** (High Electron Mobility Transistor), also called an HFET (heterostructure FET), can be made using bandgap engineering in a ternary semiconductor such as AlGaAs. The fully depleted wide-band-gap material forms the isolation between gate and body.
- The **IGBT** (Insulated-Gate Bipolar Transistor) is a device for power control. It has a structure akin to a MOSFET coupled with a bipolar-like main conduction channel. These are commonly used for the 200-3000 V drain-to-source voltage range of operation. Power MOSFETs are still the device of choice for drain-to-source voltages of 1 to 200 V.
- The **ISFET** is an Ion-Sensitive Field Effect Transistor used to measure ion concentrations in a solution; when the ion concentration changes, the current through the transistor will change accordingly.
- The **JFET** (Junction Field-Effect Transistor) uses a reverse biased p-n junction to separate the gate from the body.
- The **MESFET** (Metal–Semiconductor Field-Effect Transistor) substitutes the p-n junction of the JFET with a Schottky barrier; used in GaAs and other III-V semiconductor materials.
- The **MODFET** (Modulation-Doped Field Effect Transistor) uses a quantum well structure formed by graded doping of the active region.
- The **MOSFET** (Metal–Oxide–Semiconductor Field-Effect Transistor) utilizes an insulator (typically SiO_2) between the gate and the body.
- The **NOMFET** is a Nanoparticle Organic Memory Field-Effect Transistor.
- The **OFET** is an Organic Field-Effect Transistor using an organic semiconductor in its channel.

Uses

IGBTs see application in switching internal combustion engine ignition coils, where fast switching and voltage blocking capabilities are important.

The most commonly used FET is the MOSFET. The CMOS (complementary-symmetry metal oxide semiconductor) process technology is the basis for modern digital integrated circuits. This process technology uses an arrangement where the (usually "enhancement-mode") p-channel MOSFET and n-channel MOSFET are connected in series such that when one is on, the other is off.

The fragile insulating layer of the MOSFET between the gate and channel makes it vulnerable to electrostatic damage during handling. This is not usually a problem after the device has been installed in a properly designed circuit.

In FETs electrons can flow in either direction through the channel when operated in the linear mode, and the naming convention of drain terminal and source terminal is somewhat arbitrary, as the devices are typically (but not always) built symmetrically from source to drain. This makes FETs suitable for switching analog signals between paths (multiplexing). With this concept, one can construct a solid-state mixing board, for example.

Chapter- 9

Capacitor

Capacitor

Modern capacitors, by a cm rule

Type Passive

Invented Ewald Georg von Kleist (October 1745)

Electronic symbol

A typical electrolytic capacitor

A **capacitor** (formerly known as **condenser**) is a passive electronic component consisting of a pair of conductors separated by a dielectric (insulator). When there is a potential difference (voltage) across the conductors, a static electric field develops in the dielectric that stores energy and produces a mechanical force between the conductors. An ideal capacitor is characterized by a single constant value, capacitance, measured in farads. This is the ratio of the electric charge on each conductor to the potential difference between them.

Capacitors are widely used in electronic circuits for blocking direct current while allowing alternating current to pass, in filter networks, for smoothing the output of power supplies, in the resonant circuits that tune radios to particular frequencies and for many other purposes.

The effect is greatest when there is a narrow separation between large areas of conductor, hence capacitor conductors are often called "plates", referring to an early means of construction. In practice the dielectric between the plates passes a small amount of leakage current and also has an electric field strength limit, resulting in a breakdown voltage, while the conductors and leads introduce an undesired inductance and resistance.

History

Battery of four Leyden jars in Museum Boerhaave, Leiden, the Netherlands.

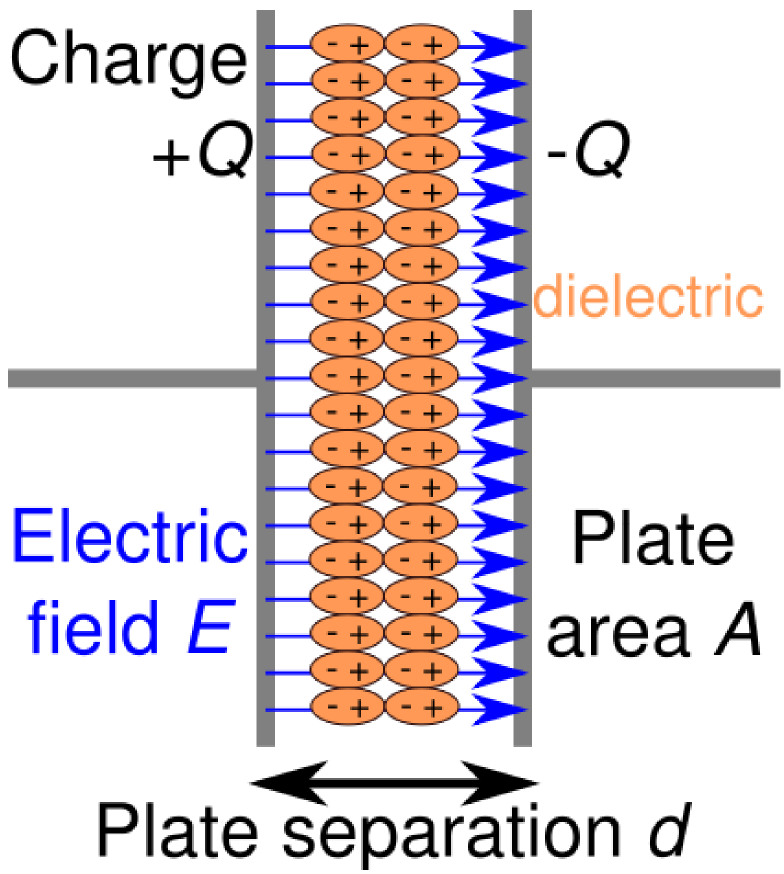
In October 1745, Ewald Georg von Kleist of Pomerania in Germany found that charge could be stored by connecting a high voltage electrostatic generator by a wire to a volume of water in a hand-held glass jar. Von Kleist's hand and the water acted as conductors and the jar as a dielectric (although details of the mechanism were incorrectly identified at the time). Von Kleist found, after removing the generator, that touching the wire resulted in a painful spark. In a letter describing the experiment, he said "I would not take a second shock for the kingdom of France." The following year, the Dutch physicist Pieter van Musschenbroek invented a similar capacitor, which was named the Leyden jar, after the University of Leiden where he worked.

Daniel Gralath was the first to combine several jars in parallel into a "battery" to increase the charge storage capacity. Benjamin Franklin investigated the Leyden jar and "proved" that the charge was stored on the glass, not in the water as others had assumed. He also adopted the term "battery", (denoting the increasing of power with a row of similar units as in a battery of cannon), subsequently applied to clusters of electrochemical cells. Leyden jars were later made by coating the inside and outside of jars with metal foil, leaving a space at the mouth to prevent arcing between the foils. The earliest unit of capacitance was the 'jar', equivalent to about 1 nanofarad.

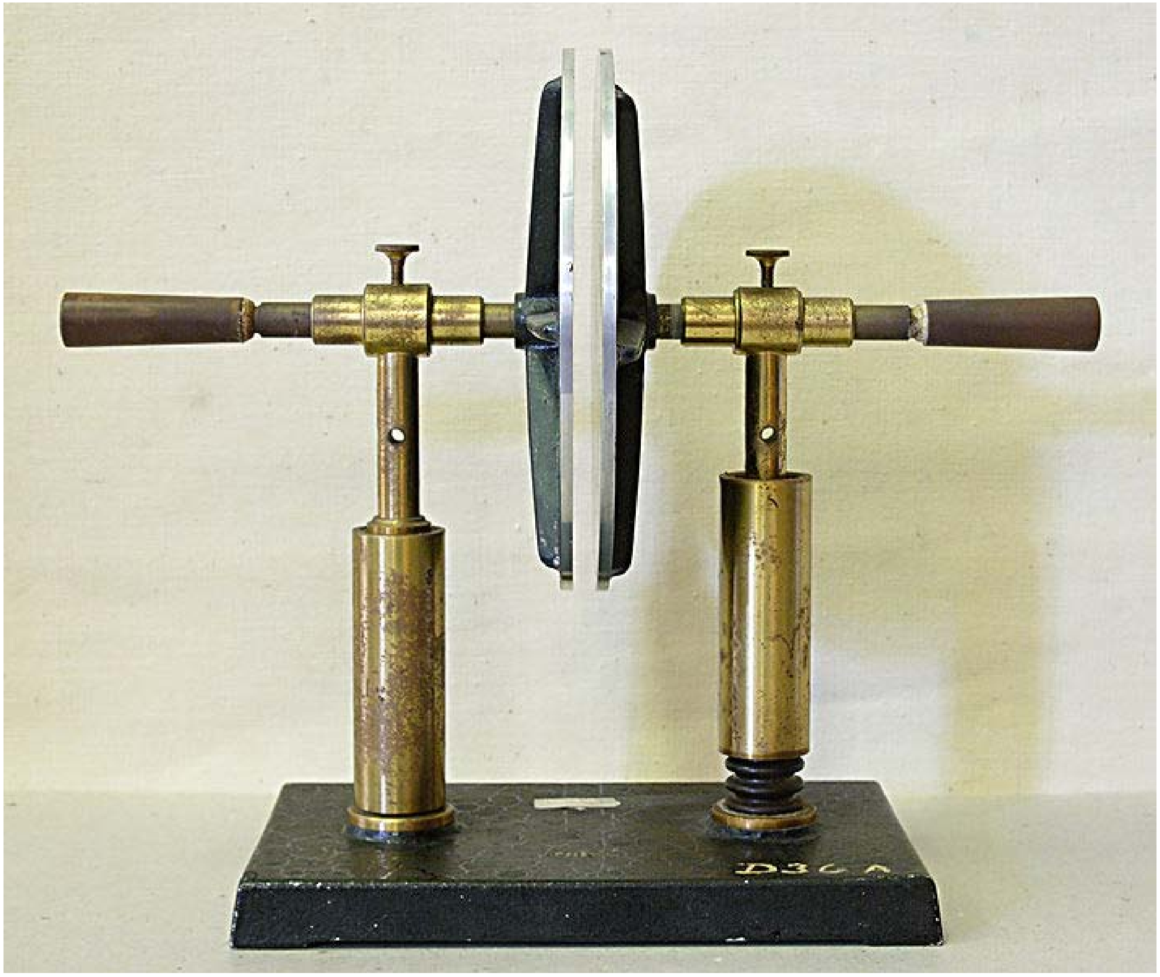
Leyden jars or more powerful devices employing flat glass plates alternating with foil conductors were used exclusively up until about 1900, when the invention of wireless (radio) created a demand for standard capacitors, and the steady move to higher frequencies required capacitors with lower inductance. A more compact construction began to be used of a flexible dielectric sheet such as oiled paper sandwiched between sheets of metal foil, rolled or folded into a small package.

Early capacitors were also known as *condensers*, a term that is still occasionally used today. The term was first used for this purpose by Alessandro Volta in 1782, with reference to the device's ability to store a higher density of electric charge than a normal isolated conductor.

Theory of operation



Charge separation in a parallel-plate capacitor causes an internal electric field. A dielectric (orange) reduces the field and increases the capacitance.



A simple demonstration of a parallel-plate capacitor

A capacitor consists of two conductors separated by a non-conductive region called the dielectric medium though it may be a vacuum or a semiconductor depletion region chemically identical to the conductors. A capacitor is assumed to be self-contained and isolated, with no net electric charge and no influence from any external electric field. The conductors thus hold equal and opposite charges on their facing surfaces, and the dielectric develops an electric field. In SI units, a capacitance of one farad means that one coulomb of charge on each conductor causes a voltage of one volt across the device.

The capacitor is a reasonably general model for electric fields within electric circuits. An ideal capacitor is wholly characterized by a constant capacitance C, defined as the ratio of charge $\pm Q$ on each conductor to the voltage V between them:

$$C = \frac{Q}{V}$$

Sometimes charge build-up affects the capacitor mechanically, causing its capacitance to vary. In this case, capacitance is defined in terms of incremental changes:

$$C = \frac{\mathrm{d}q}{\mathrm{d}v}$$

Energy storage

Work must be done by an external influence to "move" charge between the conductors in a capacitor. When the external influence is removed the charge separation persists in the electric field and energy is stored to be released when the charge is allowed to return to its equilibrium position. The work done in establishing the electric field, and hence the amount of energy stored, is given by:

$$W = \int_{q=0}^{Q} V \mathrm{d}q = \int_{q=0}^{Q} \frac{q}{C} \mathrm{d}q = \frac{1}{2} \frac{Q^2}{C} = \frac{1}{2} C V^2 = \frac{1}{2} V Q.$$

Current-voltage relation

The current $i(t)$ through any component in an electric circuit is defined as the rate of flow of a charge $q(t)$ passing through it, but actual charges, electrons, cannot pass through the dielectric layer of a capacitor, rather an electron accumulates on the negative plate for each one that leaves the positive plate, resulting in an electron depletion and consequent positive charge on one electrode that is equal and opposite to the accumulated negative charge on the other. Thus the charge on the electrodes is equal to the integral of the current as well as proportional to the voltage as discussed above. As with any antiderivative, a constant of integration is added to represent the initial voltage $v(t_0)$. This is the integral form of the capacitor equation,

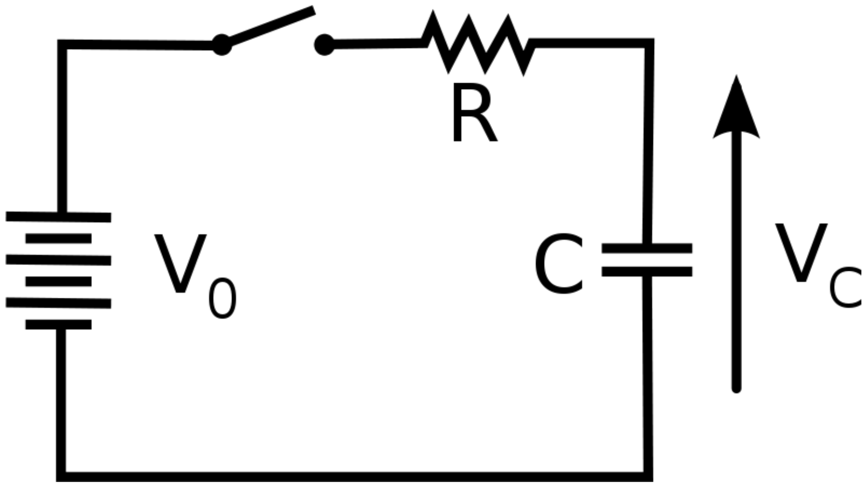
$$v(t) = \frac{q(t)}{C} = \frac{1}{C} \int_{t_0}^{t} i(\tau) \mathrm{d}\tau + v(t_0).$$

Taking the derivative of this, and multiplying by C, yields the derivative form,

$$i(t) = \frac{\mathrm{d}q(t)}{\mathrm{d}t} = C \frac{\mathrm{d}v(t)}{\mathrm{d}t}.$$

The dual of the capacitor is the inductor, which stores energy in the magnetic field rather than the electric field. Its current-voltage relation is obtained by exchanging current and voltage in the capacitor equations and replacing C with the inductance L.

DC circuits



A simple resistor-capacitor circuit demonstrates charging of a capacitor.

A series circuit containing only a resistor, a capacitor, a switch and a constant DC source of voltage V_0 is known as a *charging circuit*. If the capacitor is initially uncharged while the switch is open, and the switch is closed at $t = 0$, it follows from Kirchhoff's voltage law that

$$V_0 = v_{\text{resistor}}(t) + v_{\text{capacitor}}(t) = i(t)R + \frac{1}{C}\int_0^t i(\tau)\mathrm{d}\tau.$$

Taking the derivative and multiplying by C, gives a first-order differential equation,

$$RC\frac{\mathrm{d}i(t)}{\mathrm{d}t} + i(t) = 0.$$

At $t = 0$, the voltage across the capacitor is zero and the voltage across the resistor is V_0. The initial current is then $i\,(0) = V_0\,/R$. With this assumption, the differential equation yields

$$i(t) = \frac{V_0}{R}e^{-t/\tau_0}$$
$$v(t) = V_0\left(1 - e^{-t/\tau_0}\right),$$

where $\tau_0 = RC$ is the *time constant* of the system.

As the capacitor reaches equilibrium with the source voltage, the voltage across the resistor and the current through the entire circuit decay exponentially. The case of *discharging* a charged capacitor likewise demonstrates exponential decay, but with the initial capacitor voltage replacing V_0 and the final voltage being zero.

AC circuits

Impedance, the vector sum of reactance and resistance, describes the phase difference and the ratio of amplitudes between sinusoidally varying voltage and sinusoidally varying current at a given frequency. Fourier analysis allows any signal to be constructed from a spectrum of frequencies, whence the circuit's reaction to the various frequencies may be found. The reactance and impedance of a capacitor are respectively

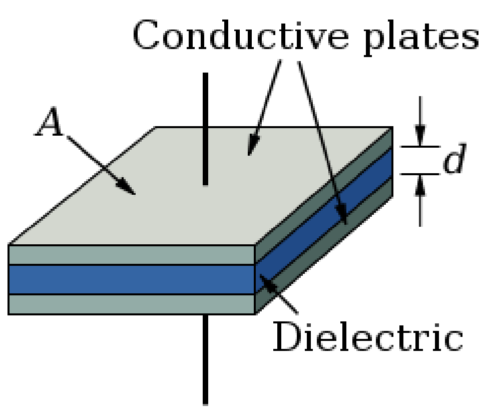
$$X = -\frac{1}{\omega C} = -\frac{1}{2\pi f C}$$
$$Z = \frac{1}{j\omega C} = -\frac{j}{\omega C} = -\frac{j}{2\pi f C}$$

where j is the imaginary unit and ω is the angular velocity of the sinusoidal signal. The $-j$ phase indicates that the AC voltage $V = Z I$ lags the AC current by 90°: the positive current phase corresponds to increasing voltage as the capacitor charges; zero current corresponds to instantaneous constant voltage, etc.

Note that impedance decreases with increasing capacitance and increasing frequency. This implies that a higher-frequency signal or a larger capacitor results in a lower voltage amplitude per current amplitude—an AC "short circuit" or AC coupling. Conversely, for very low frequencies, the reactance will be high, so that a capacitor is nearly an open circuit in AC analysis—those frequencies have been "filtered out".

Capacitors are different from resistors and inductors in that the impedance is *inversely* proportional to the defining characteristic, i.e. capacitance.

Parallel plate model



Dielectric is placed between two conducting plates, each of area A and with a separation of d.

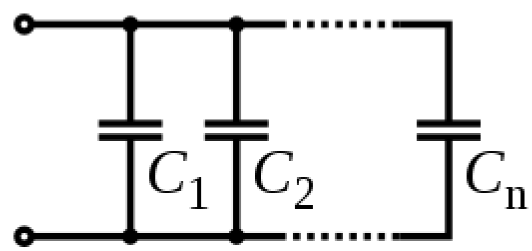
The simplest capacitor consists of two parallel conductive plates separated by a dielectric with permittivity ε (such as air). The model may also be used to make qualitative predictions for other device geometries. The plates are considered to extend uniformly over an area A and a charge density $\pm\rho = \pm Q/A$ exists on their surface. Assuming that the width of the plates is much greater than their separation d, the electric field near the centre of the device will be uniform with the magnitude $E = \rho/\varepsilon$. The voltage is defined as the line integral of the electric field between the plates

$$V = \int_0^d E \mathrm{d}z = \int_0^d \frac{\rho}{\varepsilon} \mathrm{d}z = \frac{\rho d}{\varepsilon} = \frac{Qd}{\varepsilon A}.$$

Solving this for $C = Q/V$ reveals that capacitance increases with area and decreases with separation

$$C = \frac{\varepsilon A}{d}.$$

The capacitance is therefore greatest in devices made from materials with a high permittivity.



Several capacitors in parallel.

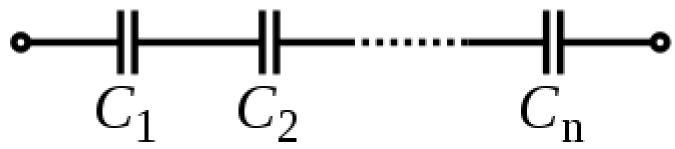
Networks

For capacitors in parallel

Capacitors in a parallel configuration each have the same applied voltage. Their capacitances add up. Charge is apportioned among them by size. Using the schematic diagram to visualize parallel plates, it is apparent that each capacitor contributes to the total surface area.

$$C_{eq} = C_1 + C_2 + \cdots + C_n$$

For capacitors in series



Several capacitors in series.

Connected in series, the schematic diagram reveals that the separation distance, not the plate area, adds up. The capacitors each store instantaneous charge build-up equal to that of every other capacitor in the series. The total voltage difference from end to end is apportioned to each capacitor according to the inverse of its capacitance. The entire series acts as a capacitor *smaller* than any of its components.

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots + \frac{1}{C_n}$$

Capacitors are combined in series to achieve a higher working voltage, for example for smoothing a high voltage power supply. The voltage ratings, which are based on plate separation, add up. In such an application, several series connections may in turn be connected in parallel, forming a matrix. The goal is to maximize the energy storage utility of each capacitor without overloading it. Series connection is also used to adapt electrolytic capacitors for AC use.

Non-ideal behaviour

Capacitors deviate from the ideal capacitor equation in a number of ways. Some of these, such as leakage current and parasitic effects are linear, or can be assumed to be linear, and can be dealt with by adding virtual components to the equivalent circuit of the capacitor. The usual methods of network analysis can then be applied. In other cases, such as with breakdown voltage, the effect is non-linear and normal (i.e., linear) network analysis cannot be used, the effect must be dealt with separately. There is yet another group, which may be linear but invalidate the assumption in the analysis that capacitance is a constant. Such an example is temperature dependence.

Breakdown voltage

Above a particular electric field, known as the dielectric strength E_{ds}, the dielectric in a capacitor becomes conductive. The voltage at which this occurs is called the breakdown voltage of the device, and is given by the product of the dielectric strength and the separation between the conductors,

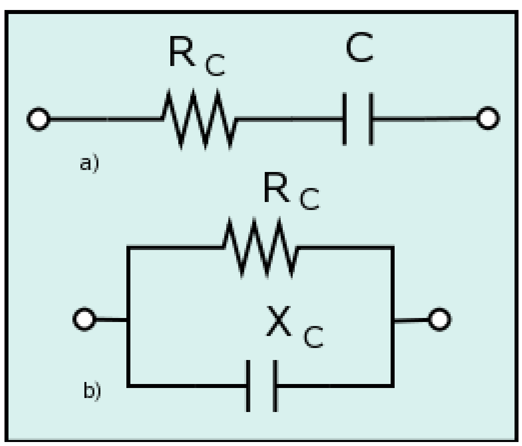
$$V_{\text{bd}} = E_{\text{ds}}d$$

The maximum energy that can be stored safely in a capacitor is limited by the breakdown voltage. Due to the scaling of capacitance and breakdown voltage with dielectric thickness, all capacitors made with a particular dielectric have approximately equal maximum energy density, to the extent that the dielectric dominates their volume.

For air dielectric capacitors the breakdown field strength is of the order 2 to 5 MV/m; for mica the breakdown is 100 to 300 MV/m, for oil 15 to 25 MV/m, and can be much less when other materials are used for the dielectric. The dielectric is used in very thin layers and so absolute breakdown voltage of capacitors is limited. Typical ratings for capacitors used for general electronics applications range from a few volts to 100V or so. As the voltage increases, the dielectric must be thicker, making high-voltage capacitors larger than those rated for lower voltages. The breakdown voltage is critically affected by factors such as the geometry of the capacitor conductive parts; sharp edges or points increase the electric field strength at that point and can lead to a local breakdown. Once this starts to happen, the breakdown will quickly "track" through the dielectric till it reaches the opposite plate and cause a short circuit.

The usual breakdown route is that the field strength becomes large enough to pull electrons in the dielectric from their atoms thus causing conduction. Other scenarios are possible, such as impurities in the dielectric, and, if the dielectric is of a crystalline nature, imperfections in the crystal structure can result in an avalanche breakdown as seen in semi-conductor devices. Breakdown voltage is also affected by pressure, humidity and temperature.

Equivalent circuit



Two different circuit models of a real capacitor

An ideal capacitor only stores and releases electrical energy, without dissipating any. In reality, all capacitors have imperfections within the capacitor's material that create resistance. This is specified as the *equivalent series resistance* or **ESR** of a component. This adds a real component to the impedance:

$$R_\mathrm{C} = Z + R_\mathrm{ESR} = \frac{1}{j\omega C} + R_\mathrm{ESR}$$

As frequency approaches infinity, the capacitive impedance (or reactance) approaches zero and the ESR becomes significant. As the reactance becomes negligible, power dissipation approaches $P_{RMS} = V_{RMS}^2 / R_{ESR}$.

Similarly to ESR, the capacitor's leads add *equivalent series inductance* or **ESL** to the component. This is usually significant only at relatively high frequencies. As inductive reactance is positive and increases with frequency, above a certain frequency capacitance will be canceled by inductance. High-frequency engineering involves accounting for the inductance of all connections and components.

If the conductors are separated by a material with a small conductivity rather than a perfect dielectric, then a small leakage current flows directly between them. The capacitor therefore has a finite parallel resistance, and slowly discharges over time (time may vary greatly depending on the capacitor material and quality).

Ripple current

Ripple current is the AC component of an applied source (often a switched-mode power supply) whose frequency may be constant or varying. Certain types of capacitors, such as electrolytic tantalum capacitors, usually have a rating for maximum ripple current (both in frequency and magnitude). This ripple current can cause damaging heat to be generated within the capacitor due to the current flow across resistive imperfections in the materials used within the capacitor, more commonly referred to as equivalent series resistance (ESR). For example electrolytic tantalum capacitors are limited by ripple current and generally have the highest ESR ratings in the capacitor family, while ceramic capacitors generally have no ripple current limitation and have some of the lowest ESR ratings.

Capacitance instability

The capacitance of certain capacitors decreases as the component ages. In ceramic capacitors, this is caused by degradation of the dielectric. The type of dielectric and the ambient operating and storage temperatures are the most significant aging factors, while the operating voltage has a smaller effect. The aging process may be reversed by heating the component above the Curie point. Aging is fastest near the beginning of life of the component, and the device stabilizes over time. Electrolytic capacitors age as the electrolyte evaporates. In contrast with ceramic capacitors, this occurs towards the end of life of the component.

Temperature dependence of capacitance is usually expressed in parts per million (ppm) per °C. It can usually be taken as a broadly linear function but can be noticeably non-linear at the temperature extremes. The temperature coefficient can be either positive or negative, sometimes even amongst different samples of the same type. In other words, the spread in the range of temperature coefficients can encompass zero.

Capacitors, especially ceramic capacitors, and older designs such as paper capacitors, can absorb sound waves resulting in a microphonic effect. Vibration moves the plates, causing the capacitance to vary, in turn inducing AC current. Some dielectrics also generate piezoelectricity. The resulting interference is especially problematic in audio applications, potentially causing feedback or unintended recording. In the reverse microphonic effect, the varying electric field between the capacitor plates exerts a physical force, moving them as a speaker. This can generate audible sound, but drains energy and stresses the dielectric and the electrolyte, if any.

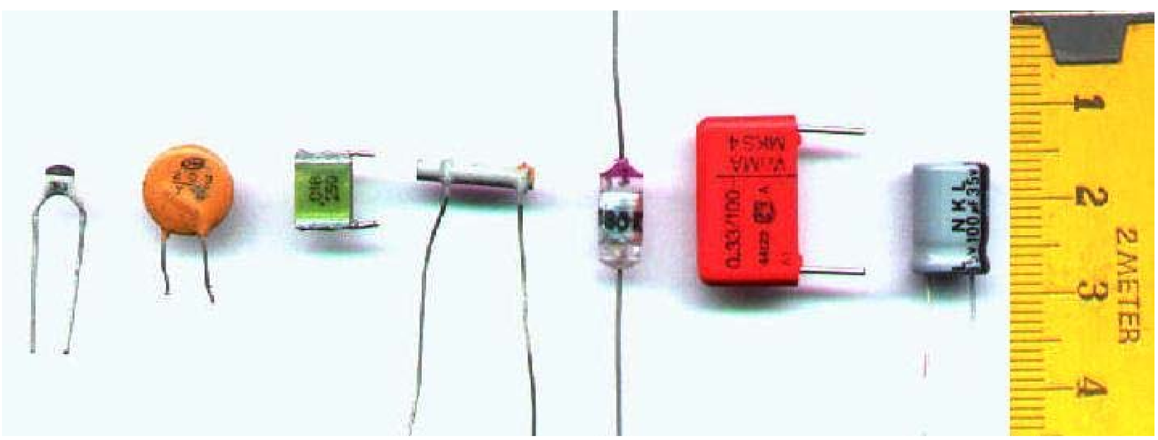
Capacitor types

Practical capacitors are available commercially in many different forms. The type of internal dielectric, the structure of the plates and the device packaging all strongly affect the characteristics of the capacitor, and its applications.

Values available range from very low (picofarad range; while arbitrarily low values are in principle possible, stray (parasitic) capacitance in any circuit is the limiting factor) to about 5 kF supercapacitors.

Above approximately 1 microfarad electrolytic capacitors are usually used because of their small size and low cost compared with other technologies, unless their relatively poor stability, life and polarised nature make them unsuitable. Very high capacity supercapacitors use a porous carbon-based electrode material.

Dielectric materials



Capacitor materials. From left: multilayer ceramic, ceramic disc, multilayer polyester film, tubular ceramic, polystyrene, metalized polyester film, aluminum electrolytic. Major scale divisions are in centimetres.

Most types of capacitor include a dielectric spacer, which increases their capacitance. These dielectrics are most often insulators. However, low capacitance devices are available with a vacuum between their plates, which allows extremely high voltage operation and low losses. Variable capacitors with their plates open to the atmosphere were commonly used in radio tuning circuits. Later designs use polymer foil dielectric between the moving and stationary plates, with no significant air space between them.

In order to maximise the charge that a capacitor can hold, the dielectric material needs to have as high a permittivity as possible, while also having as high a breakdown voltage as possible.

Several solid dielectrics are available, including paper, plastic, glass, mica and ceramic materials. Paper was used extensively in older devices and offers relatively high voltage performance. However, it is susceptible to water absorption, and has been largely replaced by plastic film capacitors. Plastics offer better stability and aging performance, which makes them useful in timer circuits, although they may be limited to low operating temperatures and frequencies. Ceramic capacitors are generally small, cheap and useful for high frequency applications, although their capacitance varies strongly with voltage and they age poorly. They are broadly categorized as class 1 dielectrics, which have predictable variation of capacitance with temperature or class 2 dielectrics, which can operate at higher voltage. Glass and mica capacitors are extremely reliable, stable and tolerant to high temperatures and voltages, but are too expensive for most mainstream applications. Electrolytic capacitors and supercapacitors are used to store small and larger amounts of energy, respectively, ceramic capacitors are often used in resonators, and parasitic capacitance occurs in circuits wherever the simple conductor-insulator-conductor structure is formed unintentionally by the configuration of the circuit layout.

Electrolytic capacitors use an aluminum or tantalum plate with an oxide dielectric layer. The second electrode is a liquid electrolyte, connected to the circuit by another foil plate. Electrolytic capacitors offer very high capacitance but suffer from poor tolerances, high instability, gradual loss of capacitance especially when subjected to heat, and high leakage current. Poor quality capacitors may leak electrolyte, which is harmful to printed circuit boards. The conductivity of the electrolyte drops at low temperatures, which increases equivalent series resistance. While widely used for power-supply conditioning, poor high-frequency characteristics make them unsuitable for many applications. Electrolytic capacitors will self-degrade if unused for a period (around a year), and when full power is applied may short circuit, permanently damaging the capacitor and usually blowing a fuse or causing arcing in rectifier tubes. They can be restored before use (and damage) by gradually applying the operating voltage, often done on antique vacuum tube equipment over a period of 30 minutes by using a variable transformer to supply AC power. Unfortunately, the use of this technique may be less satisfactory for some solid state equipment, which may be damaged by operation below its normal power range, requiring that the power supply first be isolated from the consuming circuits. Such remedies may not be applicable to modern high-frequency power supplies as these produce full output voltage even with reduced input.

Tantalum capacitors offer better frequency and temperature characteristics than aluminum, but higher dielectric absorption and leakage. OS-CON (or OC-CON) capacitors are a polymerized organic semiconductor solid-electrolyte type that offer longer life at higher cost than standard electrolytic capacitors.

Several other types of capacitor are available for specialist applications. Supercapacitors store large amounts of energy. Supercapacitors made from carbon aerogel, carbon nanotubes, or highly porous electrode materials offer extremely high capacitance (up to 5 kF as of 2010) and can be used in some applications instead of rechargeable batteries. Alternating current capacitors are specifically designed to work on line (mains) voltage AC power circuits. They are commonly used in electric motor circuits and are often designed to handle large currents, so they tend to be physically large. They are usually ruggedly packaged, often in metal cases that can be easily grounded/earthed. They also are designed with direct current breakdown voltages of at least five times the maximum AC voltage.

Structure

Capacitor packages: SMD ceramic at top left; SMD tantalum at bottom left; through-hole tantalum at top right; through-hole electrolytic at bottom right. Major scale divisions are cm.

The arrangement of plates and dielectric has many variations depending on the desired ratings of the capacitor. For small values of capacitance (microfarads and less), ceramic disks use metallic coatings, with wire leads bonded to the coating. Larger values can be made by multiple stacks of plates and disks. Larger value capacitors usually use a metal foil or metal film layer deposited on the surface of a dielectric film to make the plates, and a dielectric film of impregnated paper or plastic – these are rolled up to save space. To reduce the series resistance and inductance for long plates, the plates and dielectric are staggered so that connection is made at the common edge of the rolled-up plates, not at the ends of the foil or metalized film strips that comprise the plates.

The assembly is encased to prevent moisture entering the dielectric – early radio equipment used a cardboard tube sealed with wax. Modern paper or film dielectric capacitors are dipped in a hard thermoplastic. Large capacitors for high-voltage use may have the roll form compressed to fit into a rectangular metal case, with bolted terminals and bushings for connections. The dielectric in larger capacitors is often impregnated with a liquid to improve its properties.

Capacitors may have their connecting leads arranged in many configurations, for example axially or radially. "Axial" means that the leads are on a common axis, typically the axis of the capacitor's cylindrical body – the leads extend from opposite ends. Radial leads might more accurately be referred to as tandem; they are rarely actually aligned along radii of the body's circle, so the term is inexact, although universal. The leads (until bent) are usually in planes parallel to that of the flat body of the capacitor, and extend in the same direction; they are often parallel as manufactured.

Small, cheap discoidal ceramic capacitors have existed since the 1930s, and remain in widespread use. Since the 1980s, surface mount packages for capacitors have been widely used. These packages are extremely small and lack connecting leads, allowing them to be soldered directly onto the surface of printed circuit boards. Surface mount components avoid undesirable high-frequency effects due to the leads and simplify automated assembly, although manual handling is made difficult due to their small size.

Mechanically controlled variable capacitors allow the plate spacing to be adjusted, for example by rotating or sliding a set of movable plates into alignment with a set of stationary plates. Low cost variable capacitors squeeze together alternating layers of aluminum and plastic with a screw. Electrical control of capacitance is achievable with varactors (or varicaps), which are reverse-biased semiconductor diodes whose depletion region width varies with applied voltage. They are used in phase-locked loops, amongst other applications.

Capacitor markings

Most capacitors have numbers printed on their bodies to indicate their electrical characteristics. Larger capacitors like electrolytics usually display the actual capacitance together with the unit (for example, **220 μF**). Smaller capacitors like ceramics, however, use a shorthand consisting of three numbers and a letter, where the numbers show the capacitance in pF (calculated as $XY \times 10^{Z}$ for the numbers XYZ) and the letter indicates the tolerance (J, K or M for ±5%, ±10% and ±20% respectively).

Additionally, the capacitor may show its working voltage, temperature and other relevant characteristics.

Example

A capacitor with the text **473K 330V** on its body has a capacitance of 47 x 10^3 pF = 47 nF (±10%) with a working voltage of 330 V.

Applications

Capacitors have many uses in electronic and electrical systems. They are so common that it is a rare electrical product that does not include at least one for some purpose.

Energy storage

A capacitor can store electric energy when disconnected from its charging circuit, so it can be used like a temporary battery. Capacitors are commonly used in electronic devices to maintain power supply while batteries are being changed. (This prevents loss of information in volatile memory.)

Conventional capacitors provide less than 360 joules per kilogram of energy density, while capacitors using developing technologies could provide more than 2.52 kilojoules per kilogram.

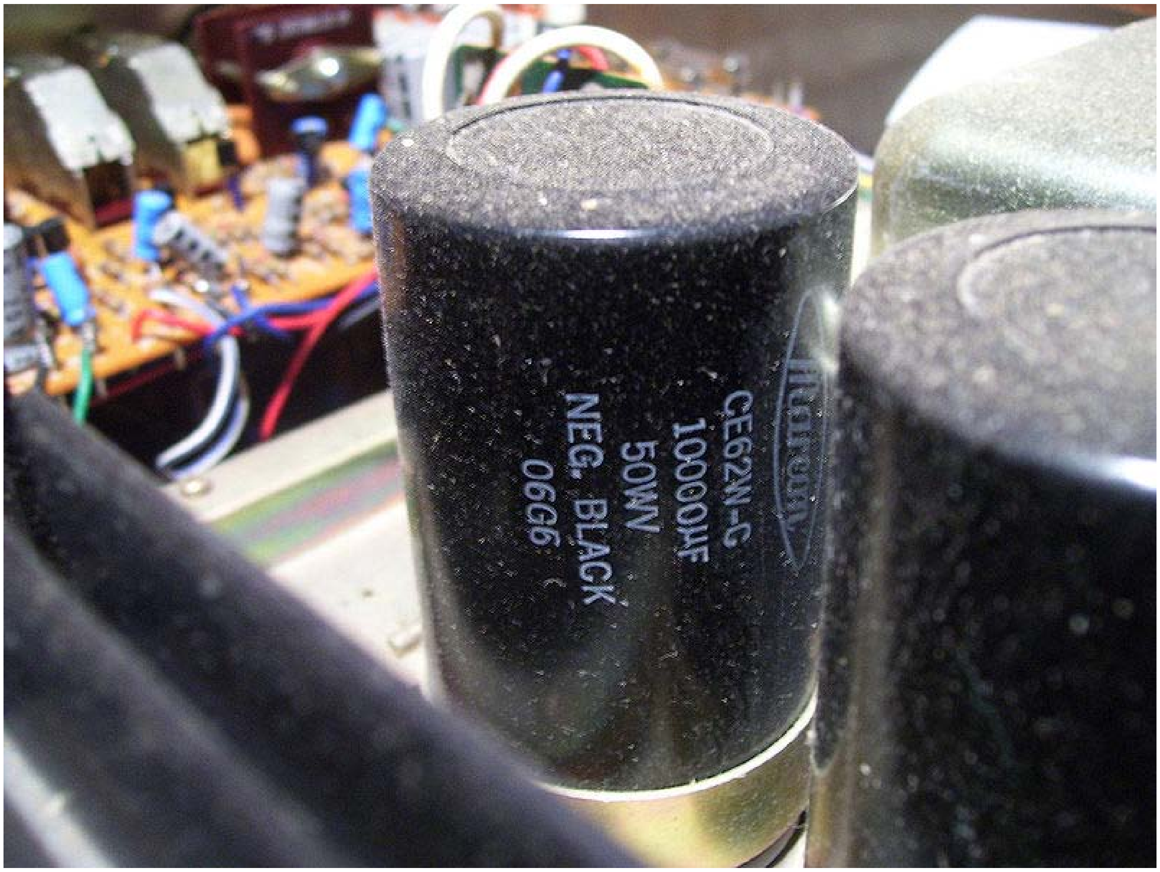
In car audio systems, large capacitors store energy for the amplifier to use on demand. Also for a flash tube a capacitor is used to hold the high voltage.

Pulsed power and weapons

Groups of large, specially constructed, low-inductance high-voltage capacitors (*capacitor banks*) are used to supply huge pulses of current for many pulsed power applications. These include electromagnetic forming, Marx generators, pulsed lasers (especially TEA lasers), pulse forming networks, radar, fusion research, and particle accelerators.

Large capacitor banks (reservoir) are used as energy sources for the exploding-bridgewire detonators or slapper detonators in nuclear weapons and other specialty weapons. Experimental work is under way using banks of capacitors as power sources for electromagnetic armour and electromagnetic railguns and coilguns.

Power conditioning



A 10,000 microfarad capacitor in a TRM-800 amplifier

Reservoir capacitors are used in power supplies where they smooth the output of a full or half wave rectifier. They can also be used in charge pump circuits as the energy storage element in the generation of higher voltages than the input voltage.

Capacitors are connected in parallel with the power circuits of most electronic devices and larger systems (such as factories) to shunt away and conceal current fluctuations from the primary power source to provide a "clean" power supply for signal or control circuits. Audio equipment, for example, uses several capacitors in this way, to shunt away power line hum before it gets into the signal circuitry. The capacitors act as a local reserve for the DC power source, and bypass AC currents from the power supply. This is used in car audio applications, when a stiffening capacitor compensates for the inductance and resistance of the leads to the lead-acid car battery.

Power factor correction

In electric power distribution, capacitors are used for power factor correction. Such capacitors often come as three capacitors connected as a three phase load. Usually, the values of these capacitors are given not in farads but rather as a reactive power in volt-amperes reactive (VAr). The purpose is to counteract inductive loading from devices like electric motors and transmission lines to make the load appear to be mostly resistive. Individual motor or lamp loads may have capacitors for power factor correction, or larger sets of capacitors (usually with automatic switching devices) may be installed at a load center within a building or in a large utility substation.

Supression and coupling

Signal coupling

Because capacitors pass AC but block DC signals (when charged up to the applied dc voltage), they are often used to separate the AC and DC components of a signal. This method is known as *AC coupling* or "capacitive coupling". Here, a large value of capacitance, whose value need not be accurately controlled, but whose reactance is small at the signal frequency, is employed.

Decoupling

A decoupling capacitor is a capacitor used to protect one part of a circuit from the effect of another, for instance to suppress noise or transients. Noise caused by other circuit elements is shunted through the capacitor, reducing the effect they have on the rest of the circuit. It is most commonly used between the power supply and ground. An alternative name is *bypass capacitor* as it is used to bypass the power supply or other high impedance component of a circuit.

Noise filters and snubbers

When an inductive circuit is opened, the current through the inductance collapses quickly, creating a large voltage across the open circuit of the switch or relay. If the inductance is large enough, the energy will generate a spark, causing the contact points to oxidize, deteriorate, or sometimes weld together, or destroying a solid-state switch. A snubber capacitor across the newly opened circuit creates a path for this impulse to bypass the contact points, thereby preserving their life; these were commonly found in contact breaker ignition systems, for instance. Similarly, in smaller scale circuits, the spark may not be enough to damage the switch but will still radiate undesirable radio frequency interference (RFI), which a filter capacitor absorbs. Snubber capacitors are usually employed with a low-value resistor in series, to dissipate energy and minimize RFI. Such resistor-capacitor combinations are available in a single package.

Capacitors are also used in parallel to interrupt units of a high-voltage circuit breaker in order to equally distribute the voltage between these units. In this case they are called grading capacitors.

In schematic diagrams, a capacitor used primarily for DC charge storage is often drawn vertically in circuit diagrams with the lower, more negative, plate drawn as an arc. The straight plate indicates the positive terminal of the device, if it is polarized.

Motor starters

In single phase squirrel cage motors, the primary winding within the motor housing is not capable of starting a rotational motion on the rotor, but is capable of sustaining one. To start the motor, a secondary winding is used in series with a non-polarized *starting capacitor* to introduce a lag in the sinusoidal current through the starting winding. When the secondary winding is placed at an angle with respect to the primary winding, a rotating electric field is created. The force of the rotational field is not constant, but is sufficient to start the rotor spinning. When the rotor comes close to operating speed, a centrifugal switch (or current-sensitive relay in series with the main winding) disconnects the capacitor. The start capacitor is typically mounted to the side of the motor housing. These are called capacitor-start motors, that have relatively high starting torque.

There are also capacitor-run induction motors which have a permanently connected phase-shifting capacitor in series with a second winding. The motor is much like a two-phase induction motor.

Motor-starting capacitors are typically non-polarized electrolytic types, while running capacitors are conventional paper or plastic film dielectric types.

Signal processing

The energy stored in a capacitor can be used to represent information, either in binary form, as in DRAMs, or in analogue form, as in analog sampled filters and CCDs. Capacitors can be used in analog circuits as components of integrators or more complex filters and in negative feedback loop stabilization. Signal processing circuits also use capacitors to integrate a current signal.

Tuned circuits

Capacitors and inductors are applied together in tuned circuits to select information in particular frequency bands. For example, radio receivers rely on variable capacitors to tune the station frequency. Speakers use passive analog crossovers, and analog equalizers use capacitors to select different audio bands.

The resonant frequency f of a tuned circuit is a function of the inductance (L) and capacitance (C) in series, and is given by:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

where L is in henries and C is in farads.

Sensing

Most capacitors are designed to maintain a fixed physical structure. However, various factors can change the structure of the capacitor, and the resulting change in capacitance can be used to sense those factors.

Changing the dielectric:

> The effects of varying the physical and/or electrical characteristics of the **dielectric** can be used for sensing purposes. Capacitors with an exposed and porous dielectric can be used to measure humidity in air. Capacitors are used to accurately measure the fuel level in airplanes; as the fuel covers more of a pair of plates, the circuit capacitance increases.

Changing the distance between the plates:

> Capacitors with a flexible plate can be used to measure strain or pressure. Industrial pressure transmitters used for process control use pressure-sensing diaphragms, which form a capacitor plate of an oscillator circuit. Capacitors are used as the sensor in condenser microphones, where one plate is moved by air pressure, relative to the fixed position of the other plate. Some accelerometers use MEMS capacitors etched on a chip to measure the magnitude and direction of the acceleration vector. They are used to detect changes in acceleration, e.g. as tilt sensors or to detect free fall, as sensors triggering airbag deployment, and in many other applications. Some fingerprint sensors use capacitors. Additionally, a user can adjust the pitch of a theremin musical instrument by moving his hand since this changes the effective capacitance between the user's hand and the antenna.

Changing the effective area of the plates:

> Capacitive touch switches are now used on many consumer electronic products.

Hazards and safety

Capacitors may retain a charge long after power is removed from a circuit; this charge can cause dangerous or even potentially fatal shocks or damage connected equipment. For example, even a seemingly innocuous device such as a disposable camera flash unit powered by a 1.5 volt AA battery contains a capacitor which may be charged to over 300 volts. This is easily capable of delivering a shock. Service procedures for electronic devices usually include instructions to discharge large or high-voltage capacitors. Capacitors may also have built-in discharge resistors to dissipate stored energy to a safe level within a few seconds after power is removed. High-voltage capacitors are stored with the terminals shorted, as protection from potentially dangerous voltages due to dielectric absorption.

Some old, large oil-filled capacitors contain polychlorinated biphenyls (PCBs). It is known that waste PCBs can leak into groundwater under landfills. Capacitors containing PCB were labelled as containing "Askarel" and several other trade names. PCB-filled capacitors are found in very old (pre 1975) fluorescent lamp ballasts, and other applications.

High-voltage capacitors may catastrophically fail when subjected to voltages or currents beyond their rating, or as they reach their normal end of life. Dielectric or metal interconnection failures may create arcing that vaporizes dielectric fluid, resulting in case bulging, rupture, or even an explosion. Capacitors used in RF or sustained high-current applications can overheat, especially in the center of the capacitor rolls. Capacitors used within high-energy capacitor banks can violently explode when a short in one capacitor causes sudden dumping of energy stored in the rest of the bank into the failing unit. High voltage vacuum capacitors can generate soft X-rays even during normal operation. Proper containment, fusing, and preventive maintenance can help to minimize these hazards.

High-voltage capacitors can benefit from a pre-charge to limit in-rush currents at power-up of high voltage direct current (HVDC) circuits. This will extend the life of the component and may mitigate high-voltage hazards.

Chapter- 10

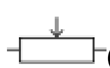
Potentiometer

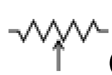
Potentiometer

A typical single-turn potentiometer

Type Passive

Electronic symbol

(Europe)

(US)

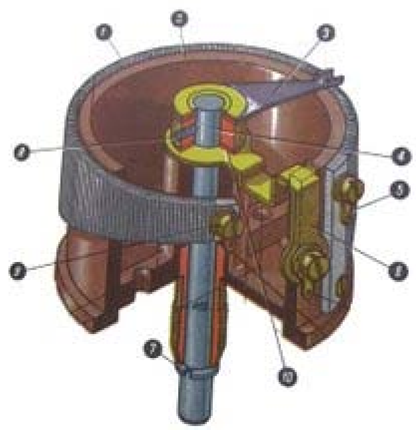
A **potentiometer** (colloquially known as a "**pot**") is a three-terminal resistor with a sliding contact that forms an adjustable voltage divider. If only two terminals are used (one side and the wiper), it acts as a ***variable resistor*** or ***rheostat***. Potentiometers are commonly used to control electrical devices such as volume controls on audio equipment. Potentiometers operated by a mechanism can be used as position transducers, for example, in a joystick.

Potentiometers are rarely used to directly control significant power (more than a watt), since the power dissipated in the potentiometer would be comparable to the power in the controlled load. Instead they are used to adjust the level of analog signals (e.g. volume controls on audio equipment), and as control inputs for electronic circuits. For example, a light dimmer uses a potentiometer to control the switching of a TRIAC and so indirectly control the brightness of lamps.

History

The slide-wire potentiometer was invented by Johann Christian Poggendorff (1796–1877) in 1841. Leeds and Northrup Type K model was a standard piece of apparatus in most college and university electrical measurements laboratories for the first half of the 20th century.

Potentiometer construction



Construction of a wire-wound circular potentiometer. The resistive element (1) of the shown device is trapezoidal, giving a non-linear relationship between resistance and turn angle. The wiper (3) rotates with the axis (4), providing the changeable resistance between the wiper contact (6) and the fixed contacts (5) and (9). The vertical position of the axis is fixed in the body (2) with the ring (7) (below) and the bolt (8) (above).

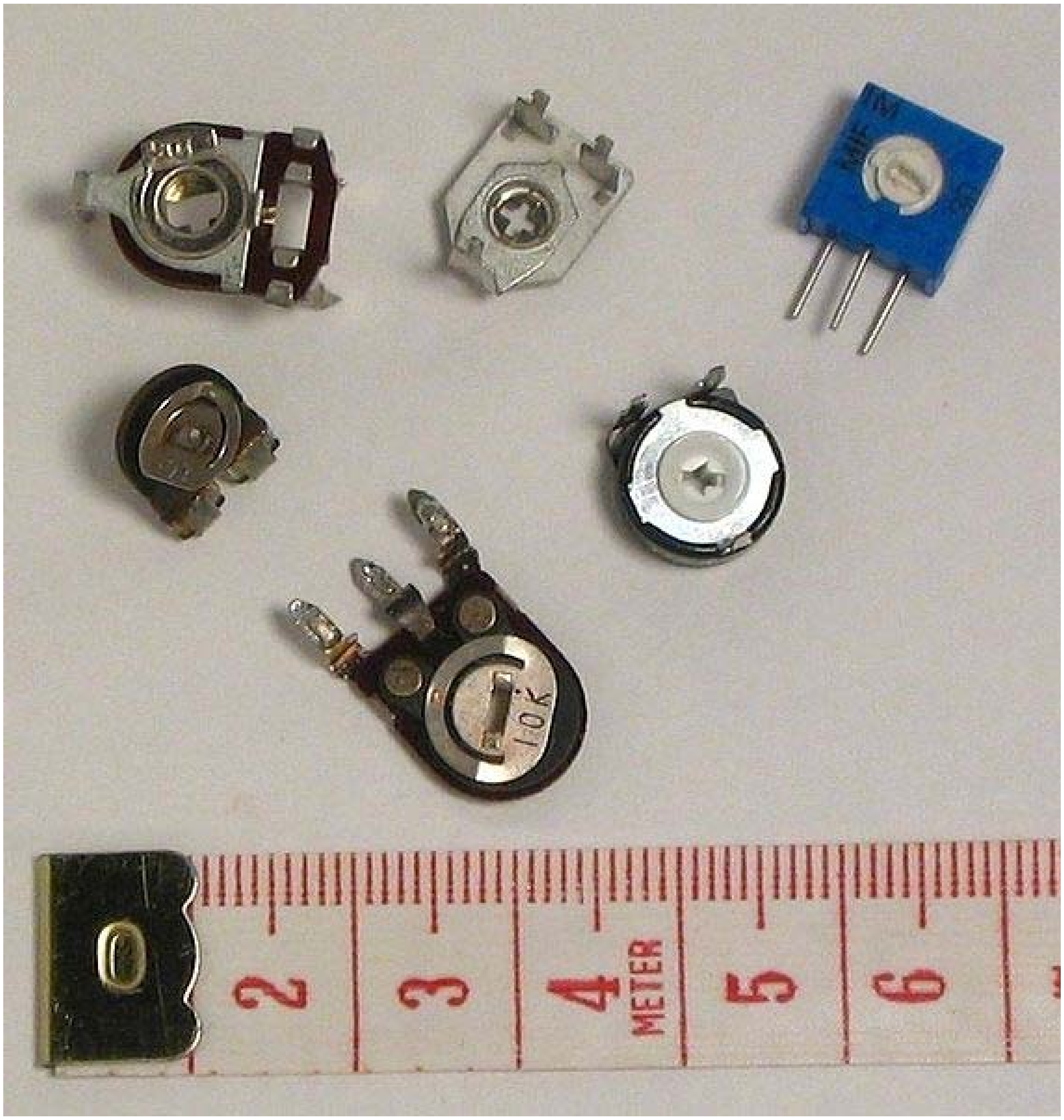
A potentiometer is constructed with a resistive element formed into an arc of a circle, and a sliding contact (wiper) travelling over that arc. The resistive element, with a terminal at one or both ends, is flat or angled, and is commonly made of graphite, although other materials may be used. The wiper is connected through another sliding contact to another terminal. On panel potentiometers, the wiper is usually the center terminal of three. For single-turn potentiometers, this wiper typically travels just under one revolution around the contact. "Multiturn" potentiometers also exist, where the resistor element may be helical and the wiper may move 10, 20, or more complete revolutions, though multiturn potentimeters are usually constructed of a conventional resistive element wiped via a worm gear. Besides graphite, materials used to make the resistive element include resistance wire, carbon particles in plastic, and a ceramic/metal mixture called cermet.

One form of rotary potentiometer is called a String potentiometer. It is a multi-turn potentiometer operated by an attached reel of wire turning against a spring. It is used as a position transducer.

In a linear slider potentiometer, a sliding control is provided instead of a dial control. The resistive element is a rectangular strip, not semi-circular as in a rotary potentiometer. Due to the large opening slot or the wiper, this type of potentiometer has a greater potential for getting contaminated.

Potentiometers can be obtained with either linear or logarithmic relations between the slider position and the resistance (potentiometer laws or "tapers"). A letter code ("A" taper, "B" taper, etc.) may be used to identify which taper is intended, but the letter code definitions are variable over time and between manufacturers.

Manufacturers of conductive track potentiometers use conductive polymer resistor pastes that contain hard wearing resins and polymers, solvents, lubricant and carbon – the constituent that provides the conductive/resistive properties. The tracks are made by screen printing the paste onto a paper based phenolic substrate and then curing it in an oven. The curing process removes all solvents and allows the conductive polymer to polymerize and cross link. This produces a durable track with stable electrical resistance throughout its working life.



PCB mount trimmer potentiometers, or "trimpots", intended for infrequent adjustment.

Linear taper potentiometer

A *linear taper potentiometer* has a resistive element of constant cross-section, resulting in a device where the resistance between the contact (wiper) and one end terminal is proportional to the distance between them. *Linear taper* describes the electrical characteristic of the device, not the geometry of the resistive element. Linear taper potentiometers are used when an approximately proportional relation is desired between shaft rotation and the division ratio of the potentiometer; for example, controls used for adjusting the centering of (an analog) cathode-ray oscilloscope.

Logarithmic potentiometer

A *logarithmic taper potentiometer* has a resistive element that either 'tapers' in from one end to the other, or is made from a material whose resistivity varies from one end to the other. This results in a device where output voltage is a logarithmic function of the mechanical angle of the potentiometer.

Most (cheaper) "log" potentiometers are actually not logarithmic, but use two regions of different resistance (but constant resistivity) to approximate a logarithmic law. A logarithmic potentiometer can also be simulated with a linear one and an external resistor. True logarithmic potentiometers are significantly more expensive.

Logarithmic taper potentiometers are often used in connection with audio amplifiers as human perception of audio volume is logarithmic.

A high power wirewound potentiometer. Any potentiometer may be connected as a rheostat.

Rheostat

The most common way to vary the resistance in a circuit is to use a variable resistor or a **rheostat** A rheostat is a two-terminal variable resistor. Often these are designed to handle much higher voltage and current. Typically these are constructed as a resistive wire wrapped to form a toroid coil with the wiper moving over the upper surface of the toroid, sliding from one turn of the wire to the next. Sometimes a rheostat is made from resistance wire wound on a heat-resisting cylinder with the slider made from a number of metal fingers that grip lightly onto a small portion of the turns of resistance wire. The "fingers" can be moved along the coil of resistance wire by a sliding knob thus changing the "tapping" point. They are usually used as variable resistors rather than variable potential dividers.

Any three-terminal potentiometer can be used as a two-terminal variable resistor by not connecting to the third terminal. It is common practice to connect the wiper terminal to the unused end of the resistance track to reduce the amount of resistance variation caused by dirt on the track.

Digital potentiometer

A digital potentiometer is an electronic component that mimics the functions of analog potentiometers. Through digital input signals, the resistance between two terminals can be adjusted, just as in an analog potentiometer.

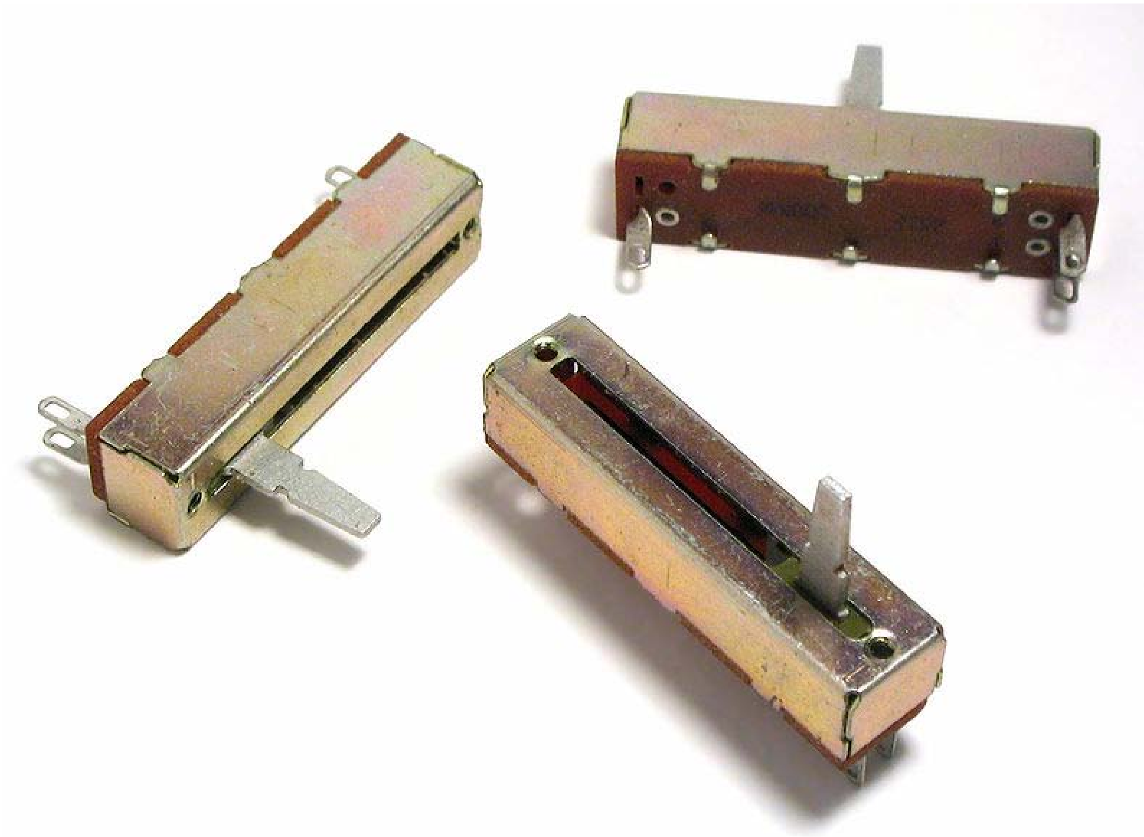
Membrane Potentiometer

A membrane potentiometer uses a conductive membrane that is deformed by a sliding element to contact a resistor voltage divider. Linearity can range from 0.5% to 5% depending on the material, design and manufacturing process. The repeat accuracy is typically between 0.1mm and 1.0mm with a theoretically infinite resolution. The service life of these types of potentiometers is typically 1 million to 20 million cycles depending on the materials used during manufacturing and the actuation method; contact and contactless (magnetic) methods are available. Many different material variations are available such as PET(foil), FR4, and Kapton. Membrane potentiometer manuafacturers offer linear, rotary, and application-specific variations. The linear versions can range from 9mm to 1000mm in length and the rotary versions range from 0° to 360°(multi-turn), with each having a height of 0.5mm. Membrane potentiometers can be used for position sensing.

Potentiometer applications

Potentiometers are widely used as user controls, and may control a very wide variety of equipment functions. The widespread use of potentiometers in consumer electronics has declined in the 1990s, with digital controls now more common. However they remain in many applications, such as volume controls and as position sensors.

Audio control



Linear potentiometers ("faders")

One of the most common uses for modern low-power potentiometers is as audio control devices. Both linear potentiometers and rotary potentiometers are regularly used to adjust loudness, frequency attenuation and other characteristics of audio signals.

The 'log pot' is used as the volume control in audio amplifiers, where it is also called an "audio taper pot", because the amplitude response of the human ear is also logarithmic. It ensures that, on a volume control marked 0 to 10, for example, a setting of 5 sounds half as loud as a setting of 10. There is also an *anti-log pot* or *reverse audio taper* which is simply the reverse of a logarithmic potentiometer. It is almost always used in a ganged configuration with a logarithmic potentiometer, for instance, in an audio balance control.

Potentiometers used in combination with filter networks act as tone controls or equalizers.

Television

Potentiometers were formerly used to control picture brightness, contrast, and color response. A potentiometer was often used to adjust "vertical hold", which affected the synchronization between the receiver's internal sweep circuit (sometimes a multivibrator) and the received picture signal.

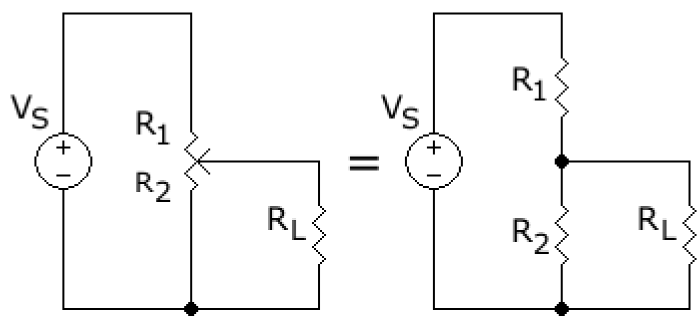
Transducers

Potentiometers are also very widely used as a part of displacement transducers because of the simplicity of construction and because they can give a large output signal.

Computation

In analog computers, high precision potentiometers are used to scale intermediate results by desired constant factors, or to set initial conditions for a calculation. A motor-driven potentiometer may be used as a function generator, using a non-linear resistance card to supply approximations to trigonometric functions. For example, the shaft rotation might represent an angle, and the voltage division ratio can be made proportional to the cosine of the angle.

Theory of operation



A potentiometer with a resistive load, showing equivalent fixed resistors for clarity.

The potentiometer can be used as a voltage divider to obtain a manually adjustable output voltage at the slider (wiper) from a fixed input voltage applied across the two ends of the potentiometer. This is the most common use of them.

The voltage across R_{L} can be calculated by:

$$V_{\mathrm{L}} = \frac{R_2 R_{\mathrm{L}}}{R_1 R_{\mathrm{L}} + R_2 R_{\mathrm{L}} + R_1 R_2} \cdot V_s.$$

If R_{L} is large compared to the other resistances (like the input to an operational amplifier), the output voltage can be approximated by the simpler equation:

$$V_{\mathrm{L}} = \frac{R_2}{R_1 + R_2} \cdot V_s.$$

As an example, assume

$$V_\mathrm{S} = 10\ \mathrm{V},\ R_1 = 1\ \mathrm{k\Omega},\ R_2 = 2\ \mathrm{k\Omega},\ \text{and}\ R_\mathrm{L} = 100\ \mathrm{k\Omega}.$$

Since the load resistance is large compared to the other resistances, the output voltage V_L will be approximately:

$$\frac{2\ \mathrm{k\Omega}}{1\ \mathrm{k\Omega} + 2\ \mathrm{k\Omega}} \cdot 10\ \mathrm{V} = \frac{2}{3} \cdot 10\ \mathrm{V} \approx 6.667\ \mathrm{V}.$$

Due to the load resistance, however, it will actually be slightly lower: ≈ 6.623 V.

One of the advantages of the potential divider compared to a variable resistor in series with the source is that, while variable resistors have a maximum resistance where some current will always flow, dividers are able to vary the output voltage from maximum (V_S) to ground (zero volts) as the wiper moves from one end of the potentiometer to the other. There is, however, always a small amount of contact resistance.

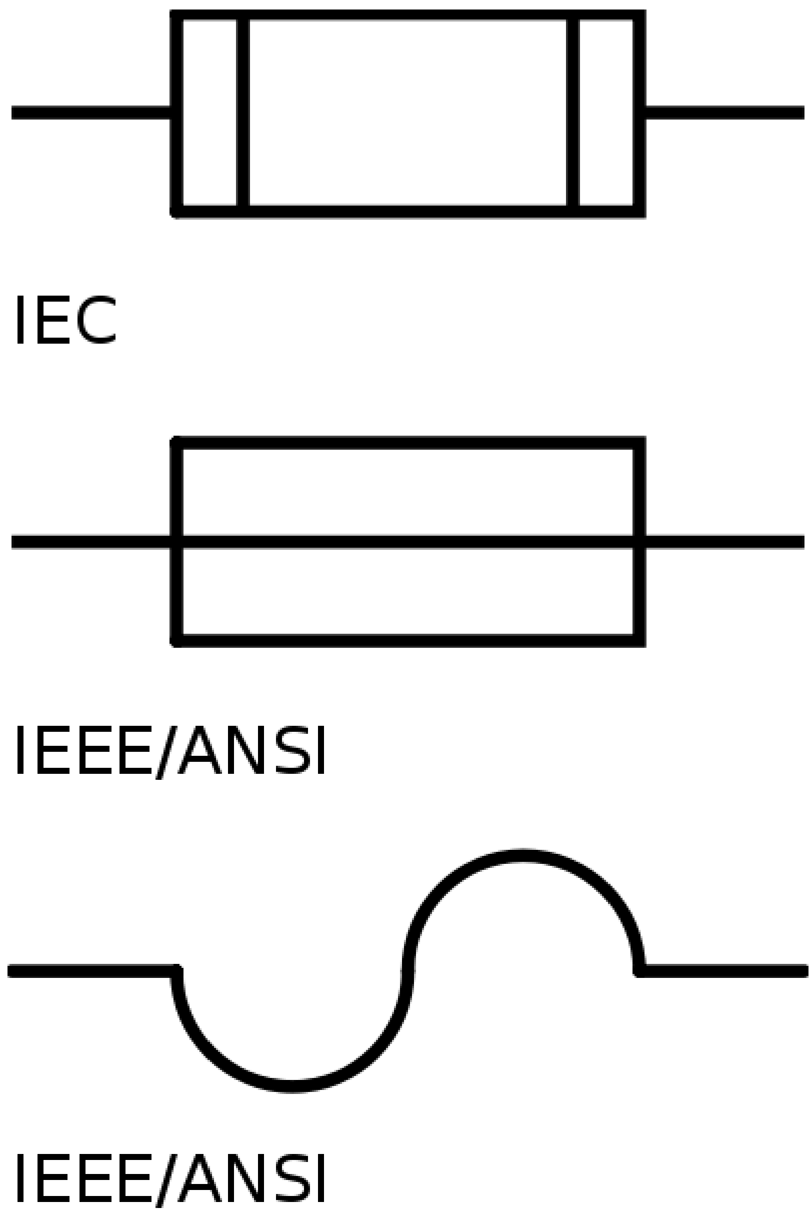
In addition, the load resistance is often not known and therefore simply placing a variable resistor in series with the load could have a negligible effect or an excessive effect, depending on the load.

Chapter- 11

Fuse

A miniature time-delay fuse used to protect electronic equipment, rated 3/10 amperes at 250 volts. 1 1/4 inches (about 32 mm) long.

200 A Industrial fuse. 80 kA breaking capacity.



Electronic symbols for a fuse. IEC (upper) and IEEE/ANSI American/Canadian (lower two) versions.

In electronics and electrical engineering a **fuse** (from the French *fusée*, Italian. *fuso*, "spindle") is a type of sacrificial overcurrent protection device. Its essential component is a metal wire or strip that melts when too much current flows, which interrupts the circuit in which it is connected. Short circuit, overload or device failure is often the reason for excessive current.

A fuse interrupts excessive current (blows) so that further damage by overheating or fire is prevented. Wiring regulations often define a maximum fuse current rating for particular circuits. Overcurrent protection devices are essential in electrical systems to limit threats to human life and property damage. Fuses are selected to allow passage of normal current and of excessive current only for short periods.

In 1847, Breguet recommended use of reduced-section conductors to protect telegraph stations from lightning strikes; by melting, the smaller wires would protect apparatus and wiring inside the building. A variety of wire or foil fusible elements were in use to protect telegraph cables and lighting installations as early as 1864.

A fuse was patented by Thomas Edison in 1890 as part of his successful electric distribution system.

Operation

A fuse consists of a metal strip or wire fuse element, of small cross-section compared to the circuit conductors, mounted between a pair of electrical terminals, and (usually) enclosed by a non-conducting and non-combustible housing. The fuse is arranged in series to carry all the current passing through the protected circuit. The resistance of the element generates heat due to the current flow. The size and construction of the element is (empirically) determined so that the heat produced for a normal current does not cause the element to attain a high temperature. If too high a current flows, the element rises to a higher temperature and either directly melts, or else melts a soldered joint within the fuse, opening the circuit.

When the metal conductor parts, an electric arc forms between the un-melted ends of the element. The arc grows in length until the voltage required to sustain the arc is higher than the available voltage in the circuit, terminating current flow. In alternating current circuits the current naturally reverses direction on each cycle, greatly enhancing the speed of fuse interruption. In the case of a current-limiting fuse, the voltage required to sustain the arc builds up quickly enough to essentially stop the fault current before the first peak of the AC waveform. This effect significantly limits damage to downstream protected devices.

The fuse element is made of zinc, copper, silver, aluminum, or alloys to provide stable and predictable characteristics. The fuse ideally would carry its rated current indefinitely, and melt quickly on a small excess. The element must not be damaged by minor harmless surges of current, and must not oxidize or change its behavior after possibly years of service.

The fuse elements may be shaped to increase heating effect. In large fuses, current may be divided between multiple strips of metal. A dual-element fuse may contain a metal strip that melts instantly on a short-circuit, and also contain a low-melting solder joint that responds to long-term overload of low values compared to a short-circuit. Fuse elements may be supported by steel or nichrome wires, so that no strain is placed on the element, but a spring may be included to increase the speed of parting of the element fragments.

The fuse element may be surrounded by air, or by materials intended to speed the quenching of the arc. Silica sand or non-conducting liquids may be used.

Characteristic parameters

Rated current I_N

A maximum current that the fuse can continuously conduct without interrupting the circuit.

Speed

The speed at which a fuse blows depends on how much current flows through it and the material of which the fuse is made. The operating time is not a fixed interval, but decreases as the current increases. Fuses have different characteristics of operating time compared to current, characterized as "fast-blow", "slow-blow" or "time-delay", according to time required to respond to an overcurrent condition. A standard fuse may require twice its rated current to open in one second, a fast-blow fuse may require twice its rated current to blow in 0.1 seconds, and a slow-blow fuse may require twice its rated current for tens of seconds to blow.

Fuse selection depends on the load's characteristics. Semiconductor devices may use a fast or *ultrafast* fuse since semiconductor devices heat rapidly when excess current flows. The fastest blowing fuses are designed for the most sensitive electrical equipment, where even a short exposure to an overload current could be very damaging. Normal fast-blow fuses are the most general purpose fuses. The time delay fuse (also known as anti-surge, or slow-blow) are designed to allow a current which is above the rated value of the fuse to flow for a short period of time without the fuse blowing. These types of fuse are used on equipment such as motors, which can draw larger than normal currents for up to several seconds while coming up to speed.

The I^2t value

A measure of energy required to blow the fuse element and so a measure of the damaging effect of overcurrent on protected devices; sometimes known as the let-through energy. Unique I^2t parameters are provided by charts in manufacturer data sheets for each fuse family. The energy is mainly dependent on current and time for fuses.

Breaking capacity

The breaking capacity is the maximum current that can safely be interrupted by the fuse. Generally, this should be higher than the prospective short circuit current. Miniature fuses may have an interrupting rating only 10 times their rated current. Some fuses are designated High Rupture Capacity (HRC) and are usually filled with sand or a similar material. Fuses for small, low-voltage, usually residential, wiring systems are commonly rated to interrupt 10,000 amperes. Fuses for larger power systems must have higher interrupting ratings, with some low-voltage current-limiting high interrupting fuses rated for 300,000 amperes. Fuses for high-voltage equipment, up to 115,000 volts, are rated by the total apparent power (megavolt-amperes, MVA) of the fault level on the circuit.

Rated voltage

Voltage rating of the fuse must be greater than or equal to what would become the open circuit voltage. For example, a glass tube fuse rated at 32 volts would not reliably interrupt current from a voltage source of 120 or 230 V. If a 32 V fuse attempts to interrupt the 120 or 230 V source, an arc may result. Plasma inside that glass tube fuse may continue to conduct current until current eventually so diminishes that plasma reverts to an insulating gas. Rated voltage should be larger than the maximum voltage source it would have to disconnect. This requirement applies to every type of fuse.

Rated voltage remains same for any one fuse, even when similar fuses are connected in series. Connecting fuses in series does not increase the rated voltage.

Medium-voltage fuses rated for a few thousand volts are never used on low voltage circuits, because of their cost and because they cannot properly clear the circuit when operating at very low voltages.

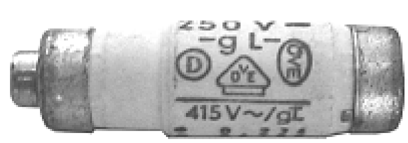
Voltage drop

A voltage drop across the fuse is usually provided by its manufacturer. Resistance may change when a fuse becomes hot due to energy dissipation while conducting higher currents. This resulting voltage drop should be taken into account, particularly when using a fuse in low-voltage applications. Voltage drop often is not significant in more traditional wire type fuses, but can be significant in other technologies such as resettable fuse (PPTC) type fuses.

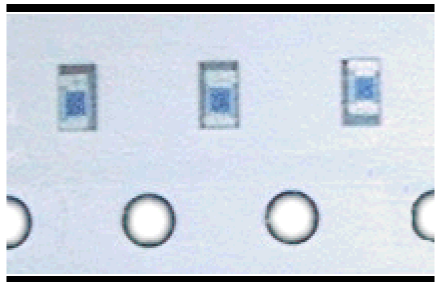
Temperature derating

Ambient temperature will change a fuse's operational parameters. A fuse rated for 1 A at 25°C may conduct up to 10% or 20% more current at -40°C and may open at 80% of its rated value at 100°C. Operating values will vary with each fuse family and are provided in manufacturer data sheets.

Markings



A sample of the many markings that can be found on a fuse.



Surface Mount Fuses on 8 mm tape. Each fuse measures 1.6 mm x 0.79 mm and has no markings.

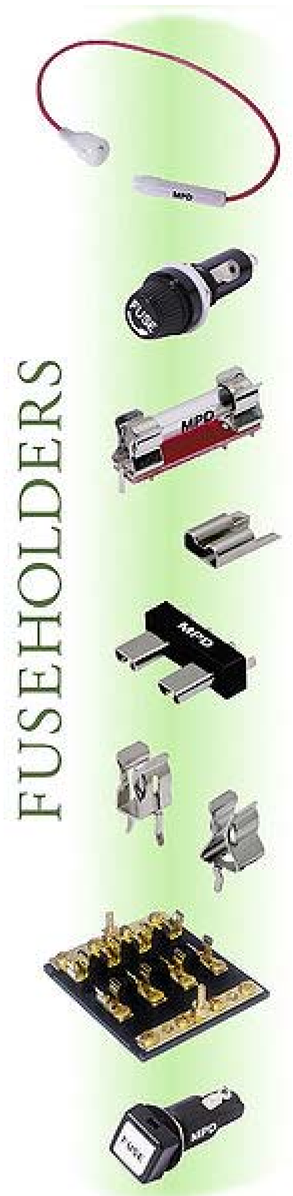
Most fuses are marked on the body or end caps with markings that indicate their ratings. Surface-mount technology "chip type" fuses feature few or no markings, making identification very difficult.

Similar appearing fuses may have significantly different properties, identified by their markings. Fuse markings will generally convey the following information, either explicitly as text, or else implicit with the approval agency marking for a particular type:

- Ampere rating of the fuse
- Voltage rating of the fuse
- Time-current characteristic, i.e. fuse speed
- Approvals by national and international standards agencies
- Manufacturer / Part number / Series
- Breaking capacity

Packages and materials

Fuses come in a vast array of sizes and styles to serve in many applications, manufactured in standardised package layouts to make them easily interchangeable. Fuse bodies may be made of ceramic, glass, plastic, fiberglass, molded mica laminates, or molded compressed fibre depending on application and voltage class.



Multiple fuseholders.

Cartridge (ferrule) fuses have a cylindrical body terminated with metal end caps. Some cartridge fuses are manufactured with end caps of different sizes to prevent accidental insertion of the wrong fuse rating in a holder, giving them a bottle shape.

Fuses for low voltage power circuits may have bolted blade or tag terminals which are secured by screws to a fuseholder. Some blade-type terminals are held by spring clips. Blade type fuses often require the use of a special purpose extractor tool to remove them from the fuse holder.

Renewable fuses have replaceable fuse elements, allowing the fuse body and terminals to be reused if not damaged after a fuse operation.

Fuses designed for soldering to a printed circuit board have radial or axial wire leads. Surface mount fuses have solder pads instead of leads.

High-voltage fuses of the expulsion type have fiber or glass-reinforced plastic tubes and an open end, and can have the fuse element replaced.

Semi-enclosed fuses are fuse wire carriers in which the fusible wire itself can be replaced. These are used in consumer units in some parts of the world, but are becoming less common.

While glass fuses have the advantage of a fuse element visible for inspection purposes, they have a low breaking capacity which generally restricts them to applications of 15 A or less at 250 V_{AC}. Ceramic fuses have the advantage of a higher breaking capacity, facilitating their use in circuits with higher current and voltage. Filling a fuse body with sand provides additional cooling of the arc and increases the breaking capacity of the fuse. Medium-voltage fuses may have liquid-filled envelopes to assist in the extinguishing of the arc. Some types of distribution switchgear use fuse links immersed in the oil that fills the equipment.

Fuse packages may include a rejection feature such as a pin, slot, or tab, which prevents interchange of otherwise similar appearing fuses. For example, fuse holders for North American class RK fuses have a pin that prevents installation of similar-appearing class H fuses, which have a much lower breaking capacity and a solid blade terminal that lacks the slot of the RK type.

Dimensions

Fuses can be built with different sized enclosures to prevent interchange of different ratings or types of fuse. For example, "Bottle style" fuses distinguish between ratings with different cap diameters. Automotive glass fuses were made in different lengths, to prevent high-rated fuses being installed in a circuit intended for a lower rating.

Special features

Glass cartridge and plug fuses allow direct inspection of the fusible element. Other fuses have other indication methods including:

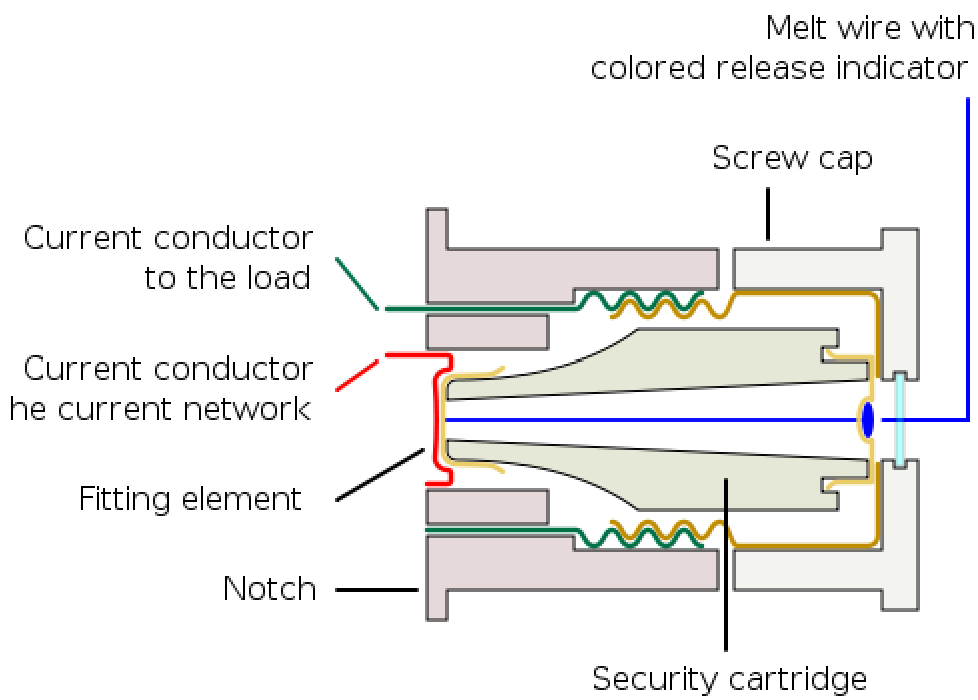
- Indicating pin or striker pin — extends out of the fuse cap when the element is blown.
- Indicating disc — a coloured disc (flush mounted in the end cap of the fuse) falls out when the element is blown.
- Element window — a small window built into the fuse body to provide visual indication of a blown element.
- External trip indicator — similar function to striker pin, but can be externally attached (using clips) to a compatible fuse.

Some fuses allow a special purpose micro switch or relay unit to be fixed to the fuse body. When the fuse element blows, the indicating pin extends to activate the micro switch or relay, which, in turn, triggers an event.

Some fuses for medium-voltage applications use two separate barrels and two fuse elements in parallel.

Fuse standards

IEC 60269 fuses



Cross section of a screw-type fuse holder with Diazed fuse

The International Electrotechnical Commission publishes standard 60269 for low-voltage power fuses. The standard is in four volumes, which describe general requirements, fuses for industrial and commercial applications, fuses for residential applications, and fuses to protect semiconductor devices. The IEC standard unifies several national standards, thereby improving the interchangeability of fuses in international trade. All fuses of different technologies tested to meet IEC standards will have similar time-current characteristics, which simplifies design and maintenance.

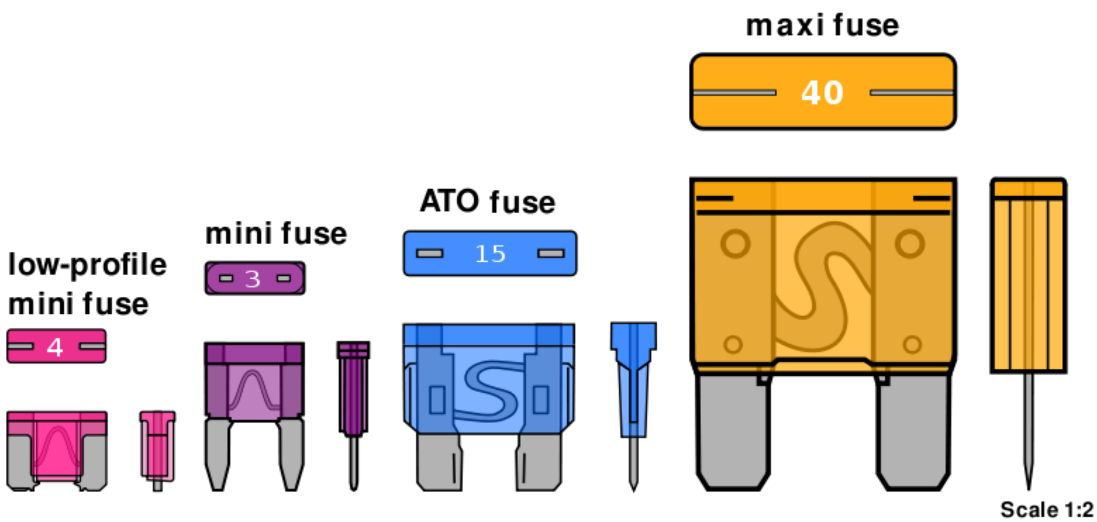
UL 248 fuses (North America)

In the United States and Canada, low-voltage fuses to 1000 v AC rating are made in accordance with Underwriters Laboratories standard UL 248 or the harmonized Canadian

Standards Association standard C22.2 No. 248. This standard applies to fuses rated 1000 V or less, AC or DC, and with breaking capacity up to 200 kA. These fuses are intended for installations following Canadian Electrical Code, Part I (CEC), or the National Electrical Code, NFPA 70 (NEC).

IEC and UL nomenclature varies slightly. IEC standards refer to a "fuse" as the assembly of a fuse link and fuse holder. In North American standards the "fuse" is the replaceable portion of the assembly, and a "fuse link" would be a bare metal element for installation in a fuse.

Automotive fuses



Blade type fuses come in four physical sizes: low-profile mini, mini, regular and maxi

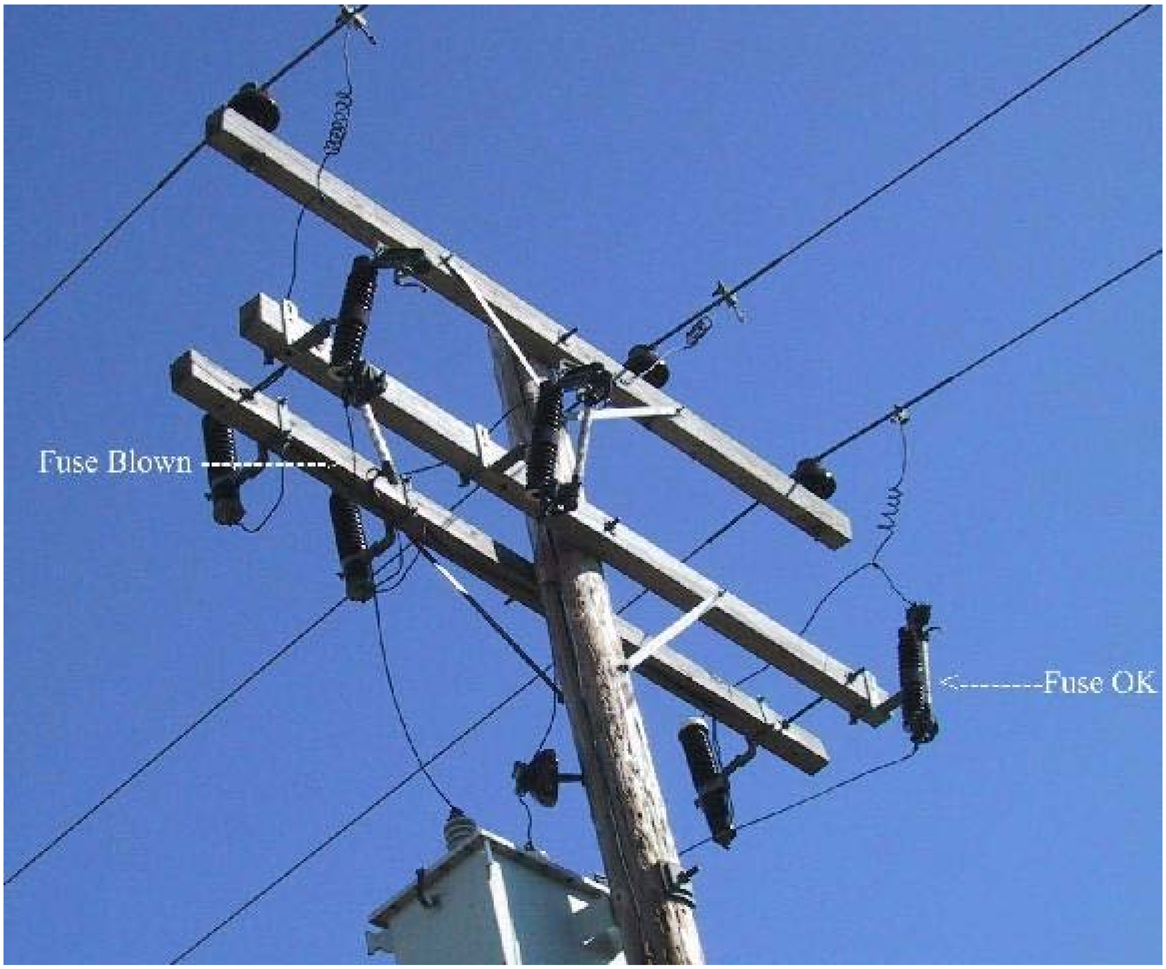
Automotive fuses are used to protect the wiring and electrical equipment for vehicles. There are several different types of automotive fuses and their usage is dependant upon the specific application, voltage, and current demands of the electrical circuit. Automotive fuses can be mounted in fuse blocks, inline fuse holders, or fuse clips. Some automotive fuses are occasionally used in non-automotive electrical applications. Standards for automotive fuses are published by SAE International (formerly known as the Society of Automotive Engineers).

Automotive fuses can be classified into four distinct categories:

- Blade Fuses
- Glass Tube or Bosch Type
- Fusible Links
- Fuse Limiters

Most automotive fuses rated at 32 volts are used on circuits rated 24 volts DC and below. Some vehicles use a dual 12/42 VDC electrical system that will require a fuse rated at 58 VDC.

High voltage fuses



A set of pole-top fusible cutouts with one fuse blown, protecting a transformer- the white tube on the left is hanging down

Fuses are used on power systems up to 115,000 volts AC. High-voltage fuses are used to protect instrument transformers used for electricity metering, or for small power transformers where the expense of a circuit breaker is not warranted. For example, in distribution systems, a power fuse may be used to protect a transformer serving 1-3 houses. A circuit breaker at 115 kV may cost up to five times as much as a set of power fuses, so the resulting saving can be tens of thousands of dollars. Pole-mounted distribution transformers are nearly always protected by a fusible cutout, which can have the fuse element replaced using live-line maintenance tools.

Large power fuses use fusible elements made of silver, copper or tin to provide stable and predictable performance. High voltage *expulsion fuses* surround the fusible link with gas-evolving substances, such as boric acid. When the fuse blows, heat from the arc causes the boric acid to evolve large volumes of gases. The associated high pressure (often greater than 100 atmospheres) and cooling gases rapidly quench the resulting arc. The hot gases are then explosively expelled out of the end(s) of the fuse. Such fuses can only be used outdoors.

A 115 kV high-voltage fuse in a substation near a hydroelectric power plant

Older medium-voltage fuse for a 20 kV Network

High voltage high power fuses are standalone protective switching devices used to 115 kV. They are used in power supply networks and for distribution uses. The most frequent application is in transformer circuits, with further uses in motor circuits and capacitor banks. These type of fuses may have an impact pin to operate a switch mechanism, so that all three phases are interrupted if any one fuse blows.

"High-power fuse" means that these fuses can interrupt several kiloamperes. Some manufacturers have tested their fuses for up to 63 kA cut-off current.

Fuses compared with circuit breakers

Fuses have the advantages of often being less costly and simpler than a circuit breaker for similar ratings. The blown fuse must be replaced with a new device which is less convenient than simply resetting a breaker and therefore likely to discourage people from ignoring faults. On the other hand, replacing a fuse without isolating the circuit first (most building wiring designs do not provide individual isolation switches for each fuse) can be dangerous in itself, particularly if the fault is a short circuit.

High rupturing capacity fuses can be rated to safely interrupt up to 300,000 amperes at 600 V AC. Special current-limiting fuses are applied ahead of some molded-case breakers to protect the breakers in low-voltage power circuits with high short-circuit levels.

"Current-limiting" fuses operate so quickly that they limit the total "let-through" energy that passes into the circuit, helping to protect downstream equipment from damage. These fuses open in less than one cycle of the AC power frequency; circuit breakers cannot match this speed.

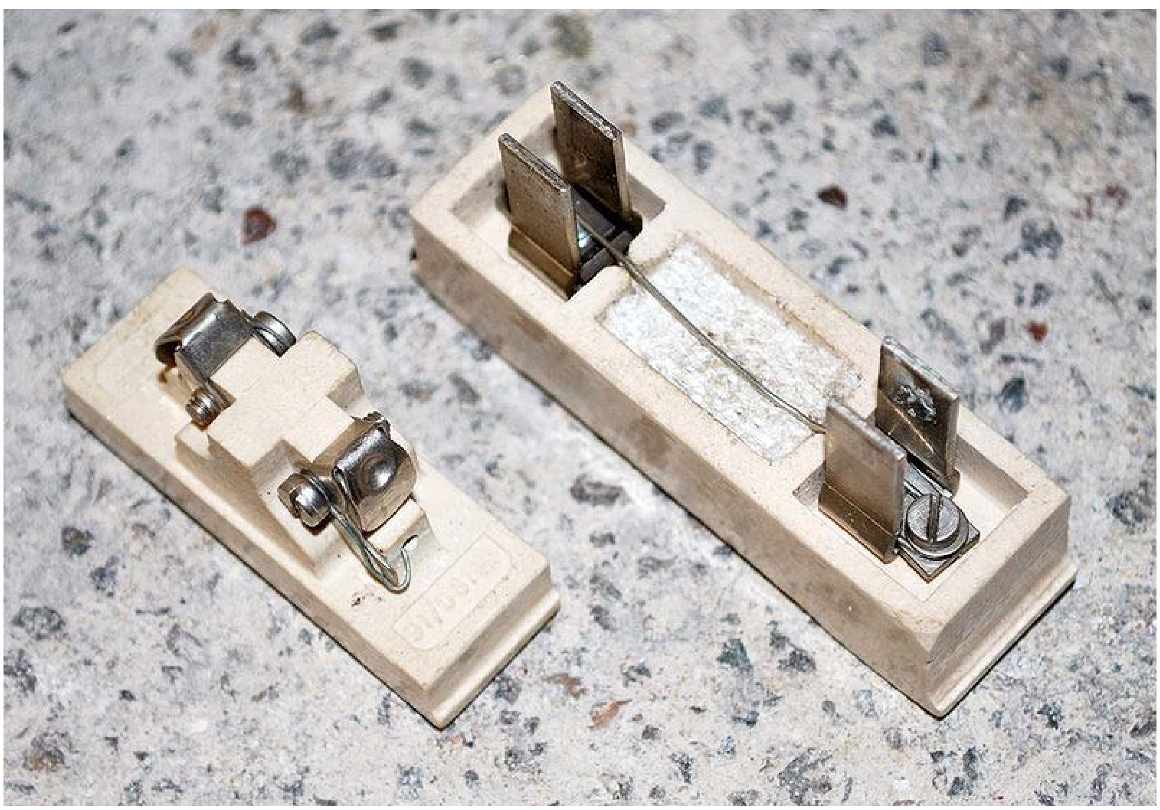
Some types of circuit breakers must be maintained on a regular basis to ensure their mechanical operation during an interruption. This is not the case with fuses, which rely on melting processes where no mechanical operation is required for the fuse to operate under fault conditions.

In a multi-phase power circuit, if only one fuse opens, the remaining phases will have higher than normal currents, and unbalanced voltages, with possible damage to motors. Fuses only sense overcurrent, or to a degree, over-temperature, and cannot usually be used independently with protective relaying to provide more advanced protective functions, for example, ground fault detection.

Some manufacturers of medium-voltage distribution fuses combine the overcurrent protection characteristics of the fusible element with the flexibility of relay protection by adding a pyrotechnic device to the fuse operated by external protective relays.

Fuse boxes

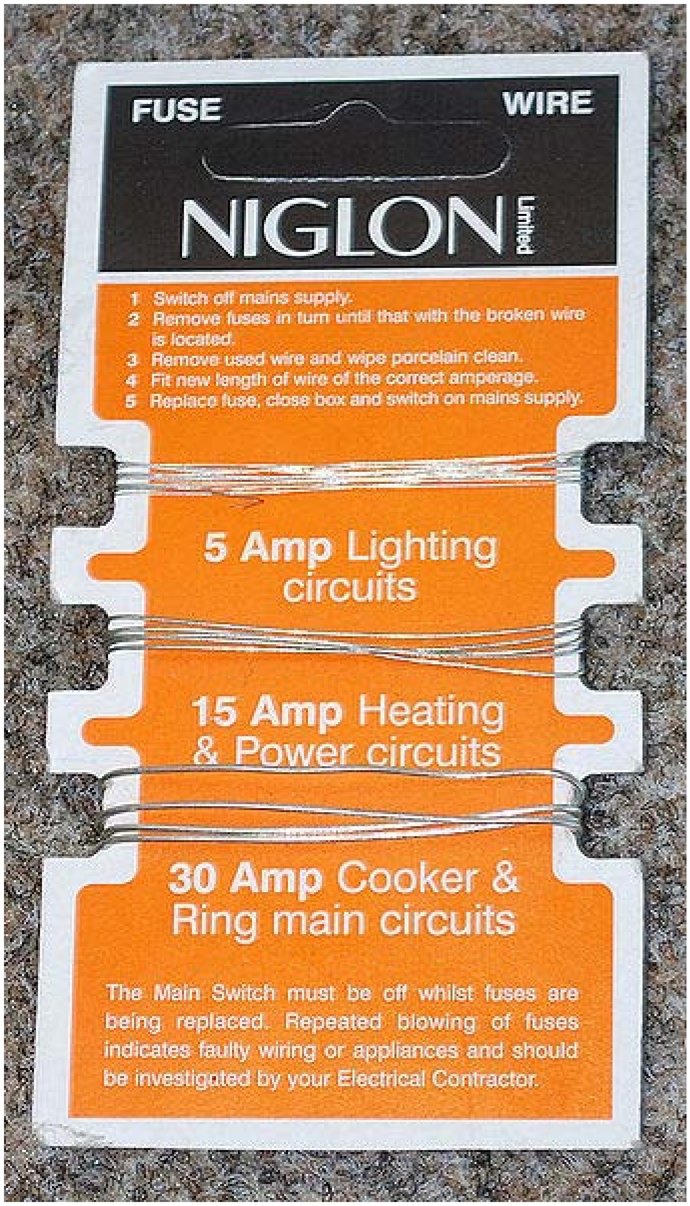
Rewirable fuses



MEM rewirable fuse holders (30A & 15A)

MEM rewirable fuse box

Wylex fuse box



fuse wire as sold to UK consumers

In the UK, older electrical consumer units (also called fuse boxes) are fitted either with semi-enclosed (rewirable) fuses (BS 3036) or cartridge fuses (BS 1361). (Fuse wire is commonly supplied to consumers as short lengths of 5A-, 15A- and 30A-rated wire wound on a piece of cardboard.) Modern consumer units usually contain miniature circuit breakers (MCBs) instead of fuses, though cartridge fuses are sometimes still used, as MCBs are prone to nuisance tripping.

Renewable fuses (rewirable or cartridge) allow user replacement, but this can be hazardous as it is easy to put a higher-rated or double fuse element (link or wire) into the holder ("overfusing"), or simply fitting it with copper wire or even a totally different type of conducting object (hairpins, paper clips, nails etc.) to the existing carrier. Such tampering will not be visible without full inspection of the fuse. Fuse wire was never used in North America for this reason, although renewable fuses continue to be made for distribution boards.

The fuse boxes pictured in this section are (right) a MEM consumer unit with four rewirable fuse holders (two 30A and two 15A) installed c. 1957 (cover removed); a "Wylex standard" unit with eight rewirable fuse holders.

The "Wylex standard" consumer unit was very popular in the United Kingdom until the wiring regulations started demanding Residual-Current Devices (RCDs) for sockets that could feasibly supply equipment outside the equipotential zone. The design does not allow for fitting of RCDs or RCBOs. Some Wylex standard models were made with an RCD instead of the main switch, but (for consumer units supplying the entire installation) this is no longer compliant with the wiring regulations as alarm systems should **not** be RCD-protected. There are two styles of fuse base that can be screwed into these units — one designed for rewirable fusewire carriers and one designed for cartridge fuse carriers. Over the years MCBs have been made for both styles of base. In both cases, higher rated carriers had wider pins, so a carrier couldn't be changed for a higher rated one without also changing the base. Cartridge fuse carriers are also now available for DIN-rail enclosures.

In North America, fuses were used in buildings wired before 1960. These "Edison Base" fuses would screw into a fuse socket similar to Edison-base incandescent lamps. Ratings were 5, 10, 15, 20, 25, and 30 amperes. To prevent installation of fuses with an excessive current rating, later fuse boxes included rejection features in the fuseholder socket. Some installations use resettable miniature thermal circuit breakers, which screw into a fuse socket.

One form of fuse box abuse was to put a penny in the socket, which defeated overcurrent protection and resulted in a dangerous condition.

In the 1950s, fuses in new residential or industrial construction for branch circuit protection were superseded by low voltage circuit breakers.

Coordination of fuses in series

Where several fuses are connected in series at the various levels of a power distribution system, it is desirable to blow (clear) only the fuse (or other overcurrent device) electrically closest to the fault. This process is called "coordination" and may require the time-current characteristics of two fuses to be plotted on a common current basis. Fuses are selected so that the minor, branch, fuse disconnects its circuit well before the supplying, major, fuse starts to melt. In this way, only the faulty circuit is interrupted with minimal disturbance to other circuits fed by a common supplying fuse.

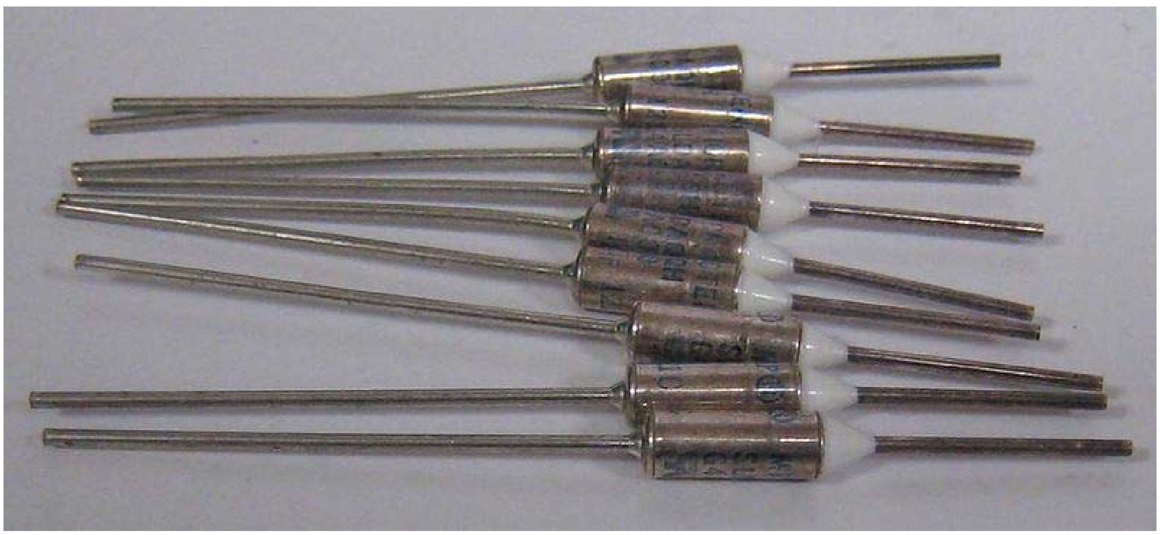
Where the fuses in a system are of similar types, simple rule-of-thumb ratios between ratings of the fuse closest to the load and the next fuse towards the source can be used.

Other fuse types

Resettable fuses

So-called "self-resetting" fuses use a thermoplastic conductive element known as a Polymeric Positive Temperature Coefficient (or PPTC) thermistor that impedes the circuit during an overcurrent condition (by increasing device resistance). The PPTC thermistor is self-resetting in that when current is removed, the device will cool and revert back to low resistance. These devices are often used in aerospace/nuclear applications where replacement is difficult, or on a computer motherboard so that a shorted mouse or keyboard does not cause motherboard damage.

Thermal fuses



Thermal Cutoff

A "thermal fuse" is often found in consumer equipment such as coffee makers or hair dryers or transformers powering small consumer electronics devices. They contain a fusible, temperature-sensitive alloy which holds a spring contact mechanism normally closed. When the surrounding temperature gets too high, the alloy melts and allows the spring contact mechanism to break the circuit. The device can be used to prevent a fire in a hair dryer for example, by cutting off the power supply to the heater elements when the air flow is interrupted (e.g. the blower motor stops or the air intake becomes accidentally blocked). Thermal fuses are a 'one shot', non-resettable device which must be replaced once they have been activated (blown).