Handbook of Electrical Components and Resistance

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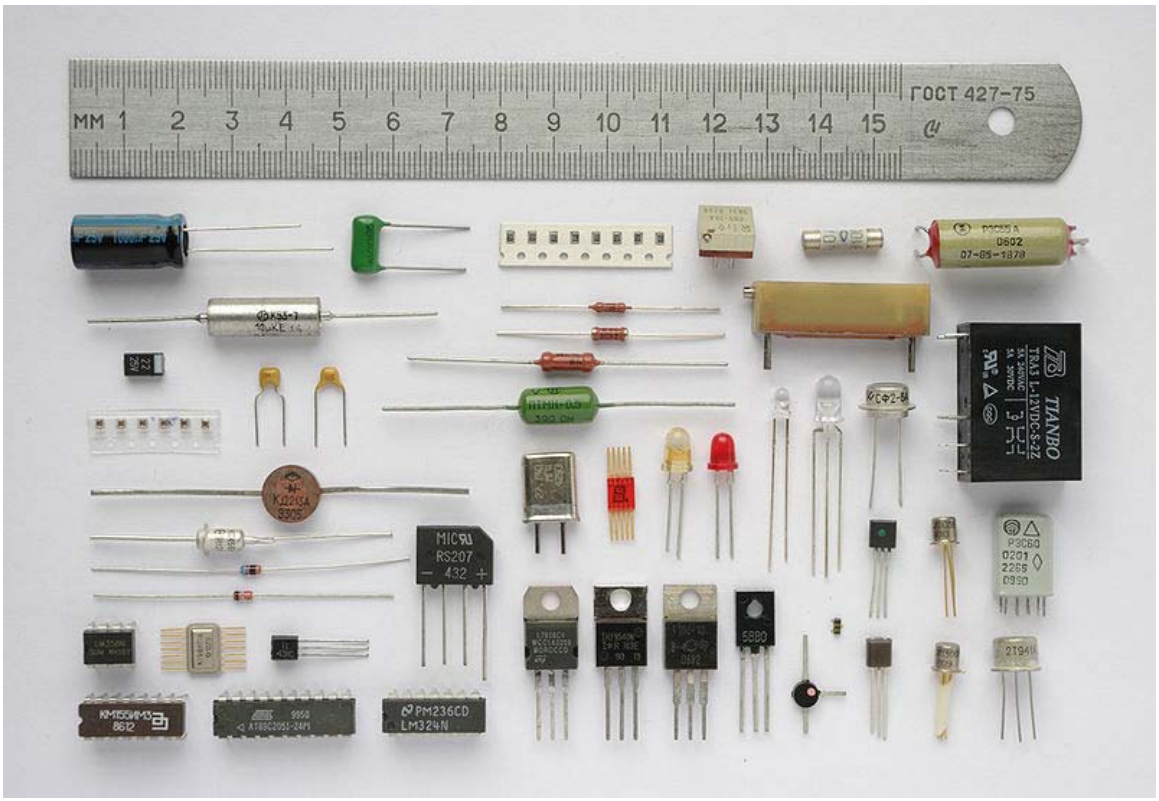
Electronic Component



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.

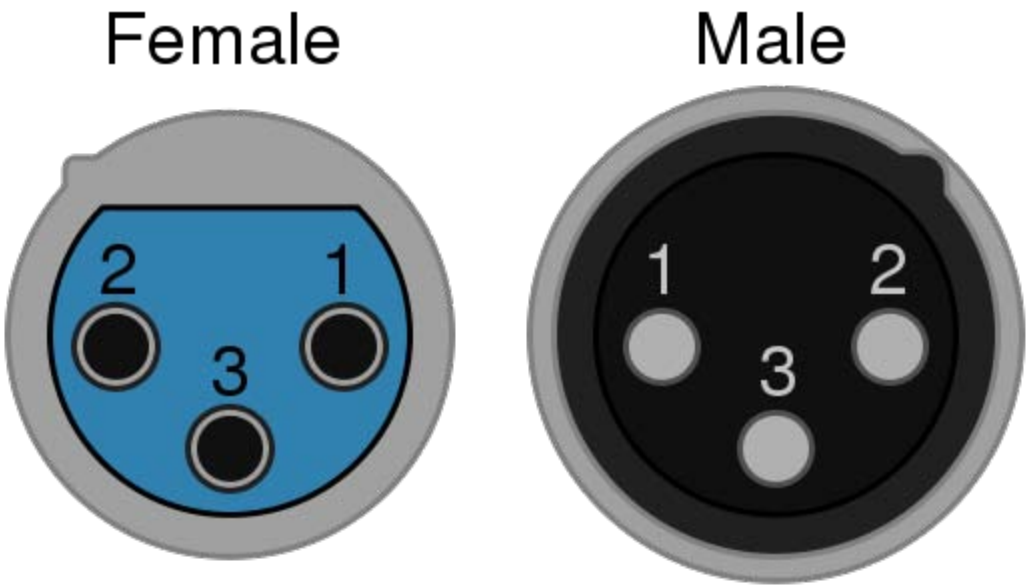
Properties of electrical connectors

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.

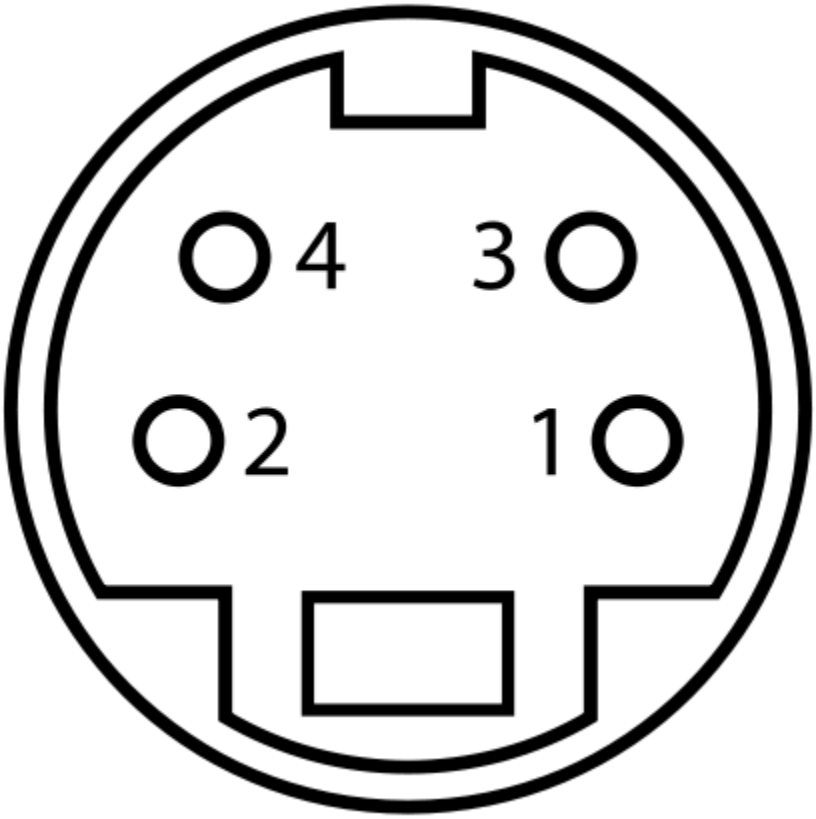
The safety ground in some power connectors, and certain crucial contacts in some hot swapping connectors, are designed to be first to mate / last to unmate.

Keying



XLR connector, showing the notch for alignment.

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

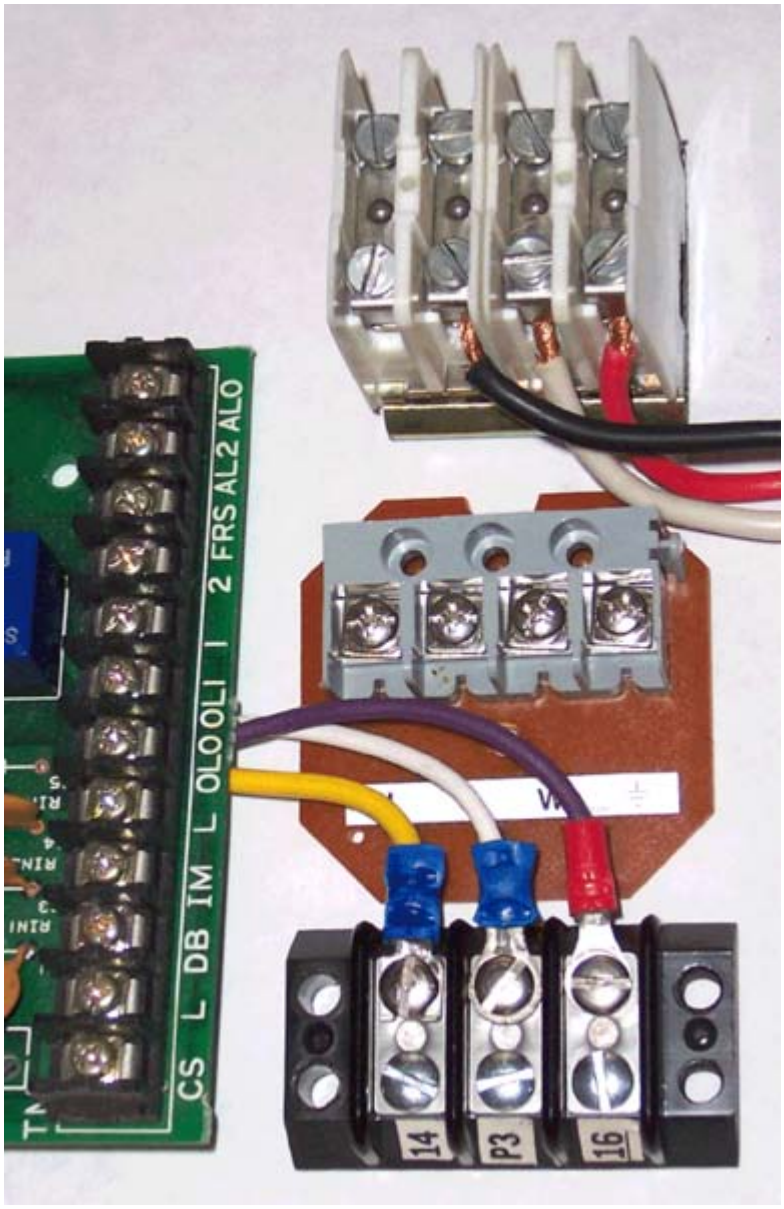


4-pin Mini-DIN pinout: the off-center rectangle and surrounding notches are a key.

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.

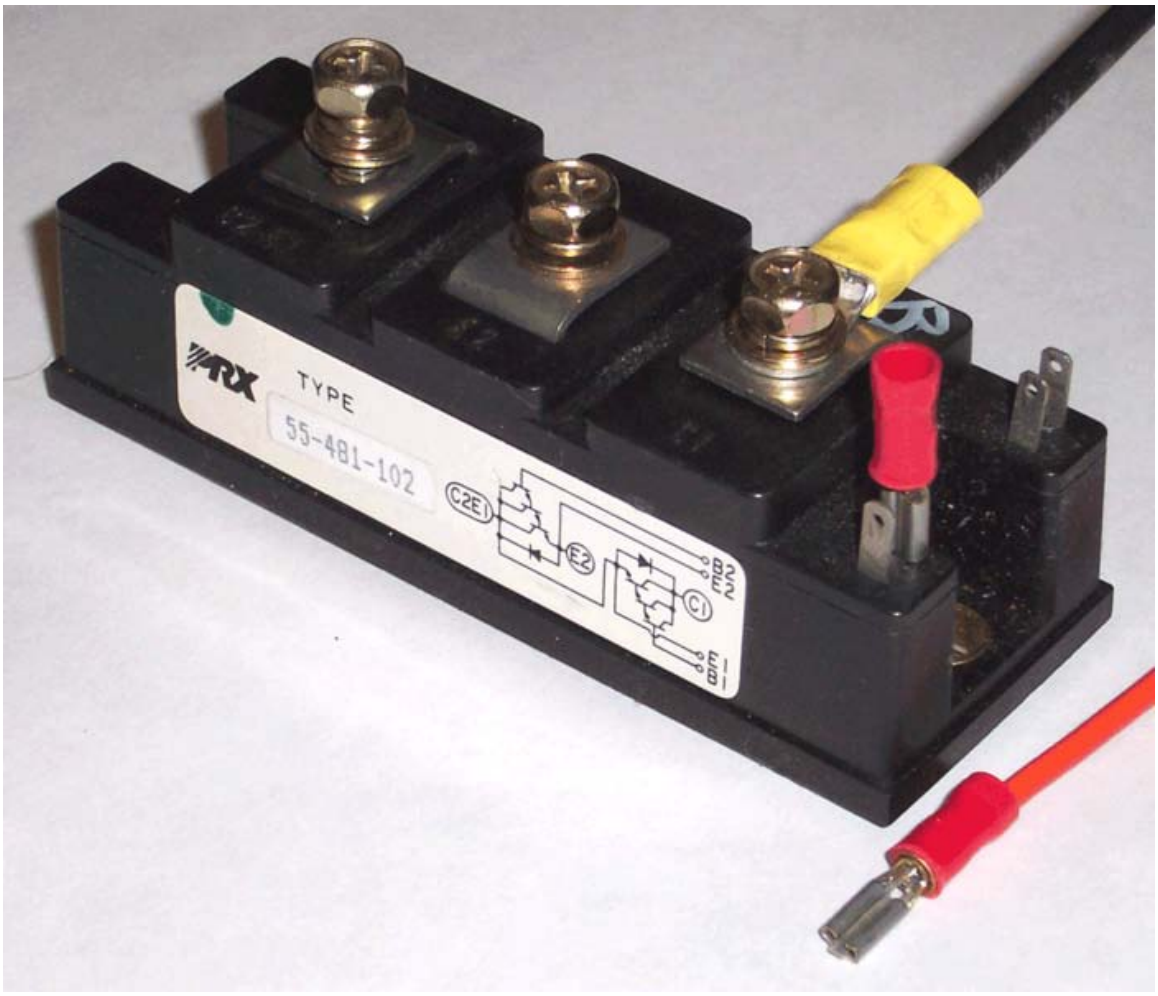
Plug and socket connectors

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

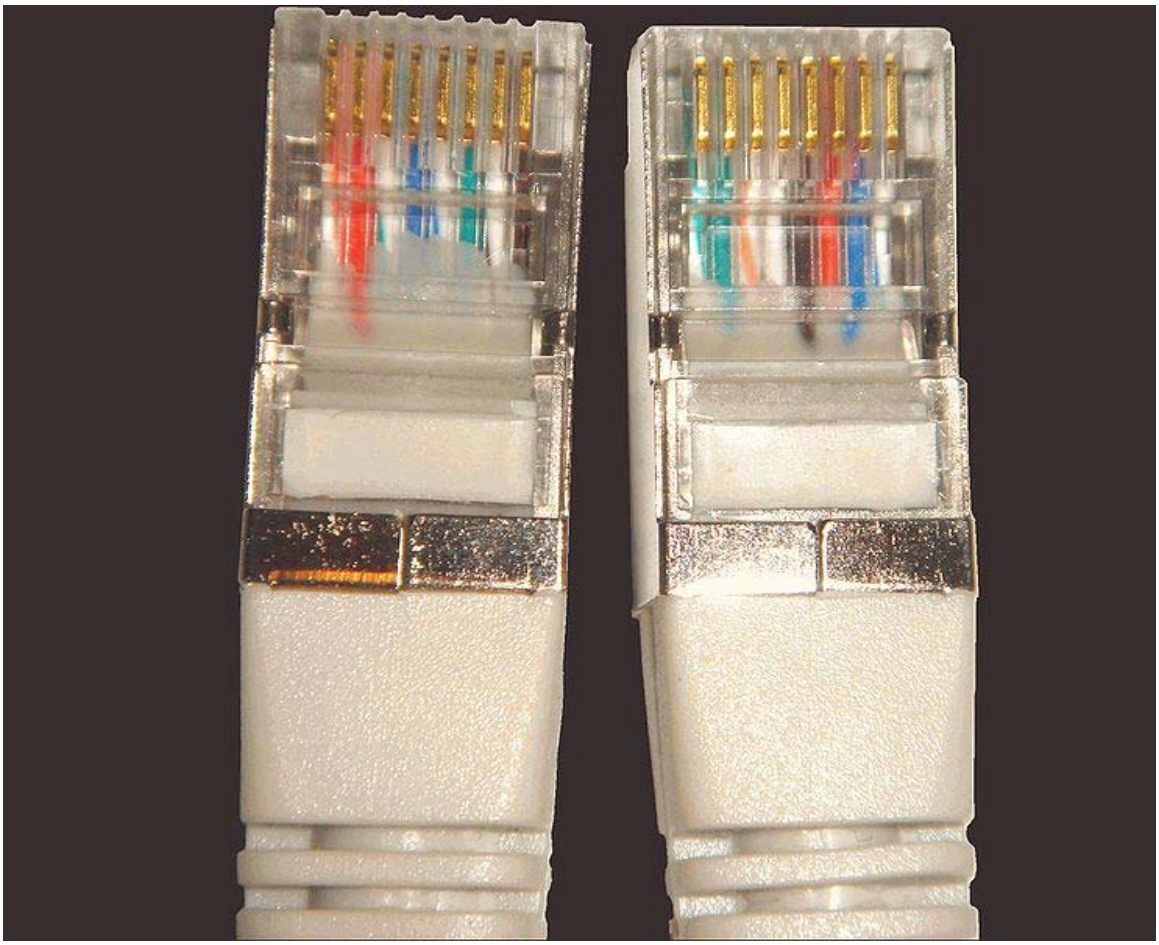
A DC connector is an electrical connector for supplying direct current (DC) power

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.

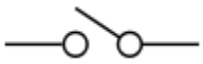
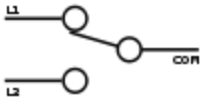
Switches are classified according to the arrangement of their contacts in electronics. Electricians installing building wiring use different nomenclature, such as "*one-way*", "*two-way*", "*three-way*" and "*four-way*" switches, which have different meanings in North American and British cultural regions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

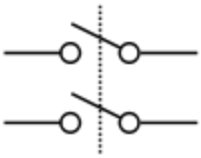
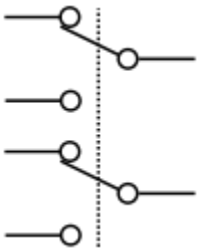
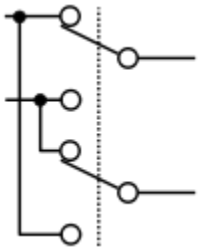
In a push-button type switch, in which the contacts remain in one state unless actuated, the contacts can either be *normally open* (abbreviated *"n.o." or "no"*) until closed by operation of the switch, or *normally closed* (*"n.c. or "nc"*) and opened by the switch action. A switch with both types 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.

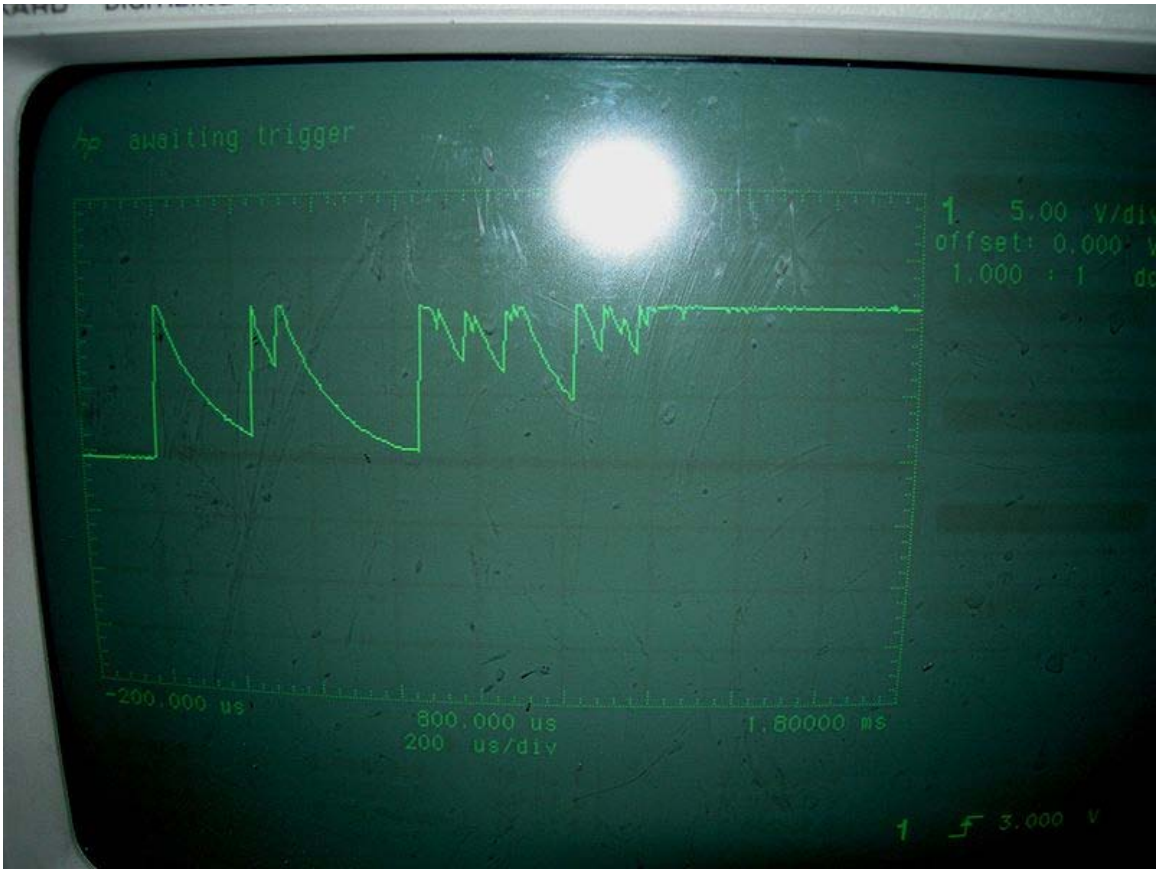
These terms give rise to abbreviations for the types of switch which are used in the electronics industry such as "*single-pole, single-throw*" (SPST) (the simplest type, "on or off") or "*single-pole, double-throw*" (SPDT), connecting either of two terminals to the common terminal. In electrical power 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

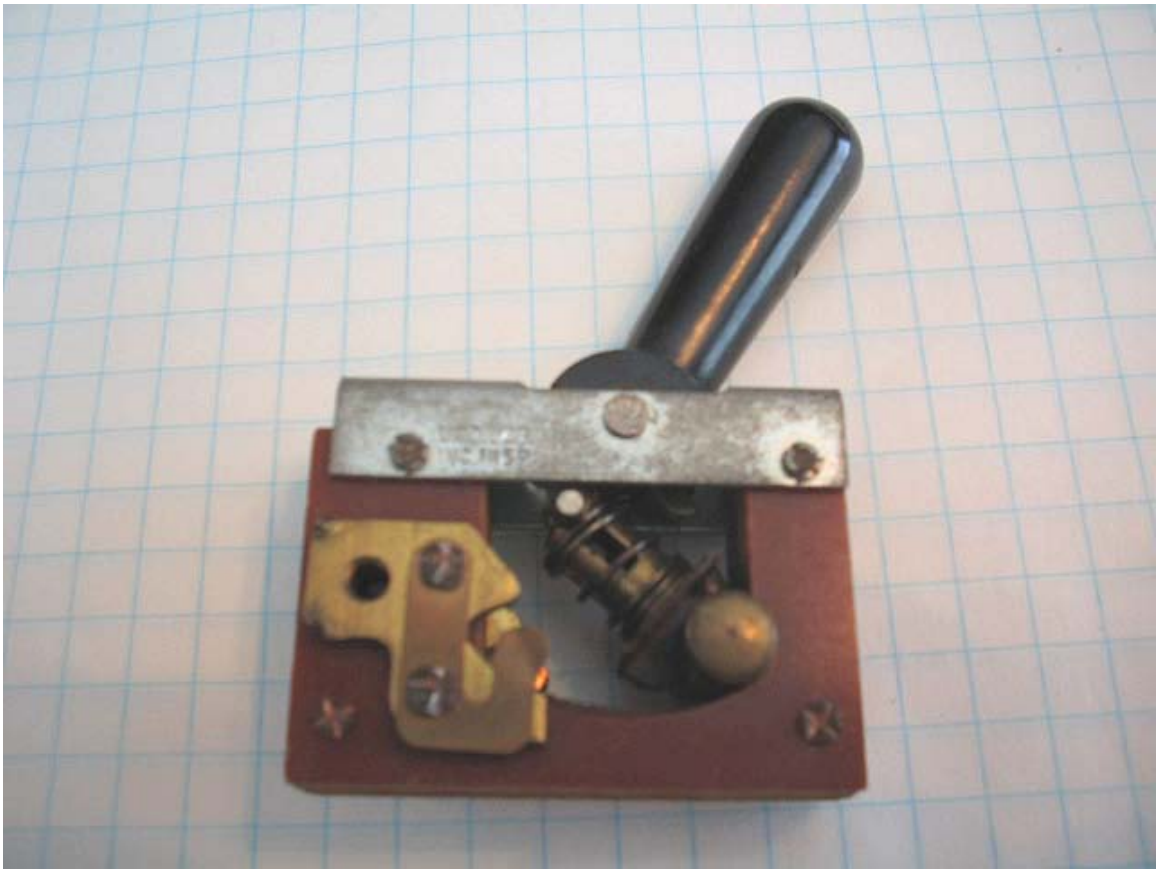
When a strongly inductive load such as an electric motor is switched off, the current cannot drop instantaneously to zero; a spark will jump across the opening contacts. Switches for inductive loads must be rated to handle these cases. The spark will cause electromagnetic interference if not suppressed;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



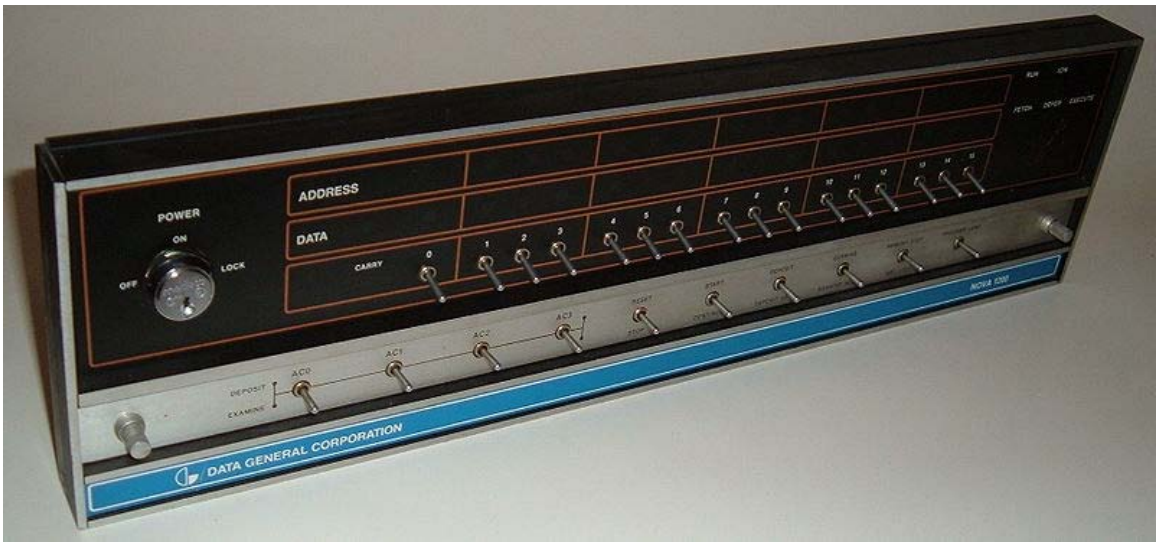
Large toggle switch, depicted in circuit 'open' position, electrical contacts to left; background is 1/4" square graph paper

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

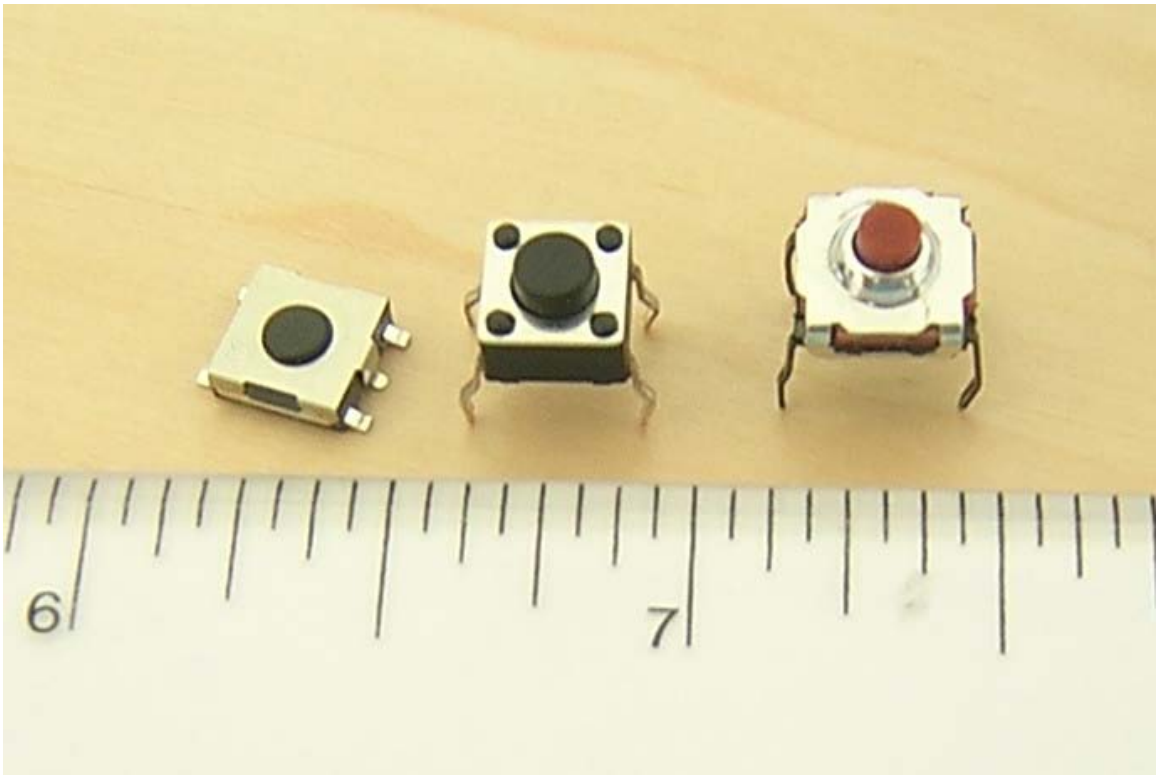
A footswitch is a ruged switch which is operated by foot pressure. An example of use is for the control of an electric sewing machine.

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*)

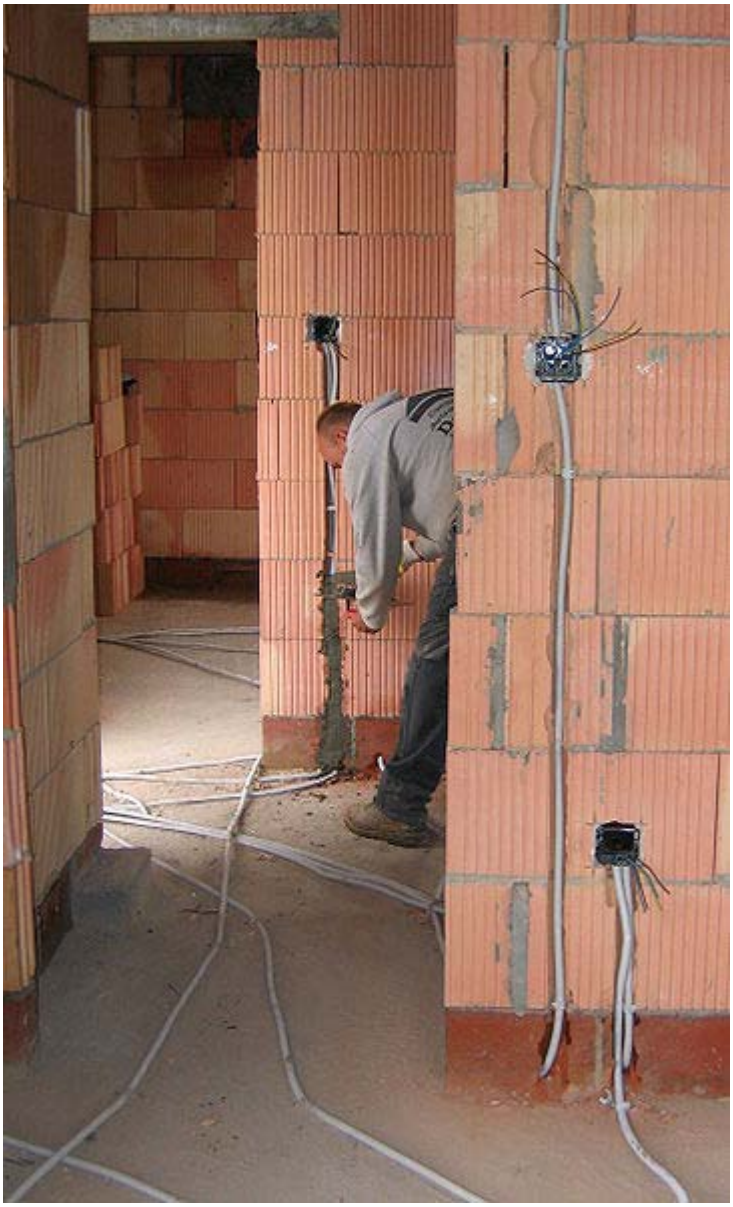
Standard wire colours for fixed cable
(In or behind the wall wiring cables)

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

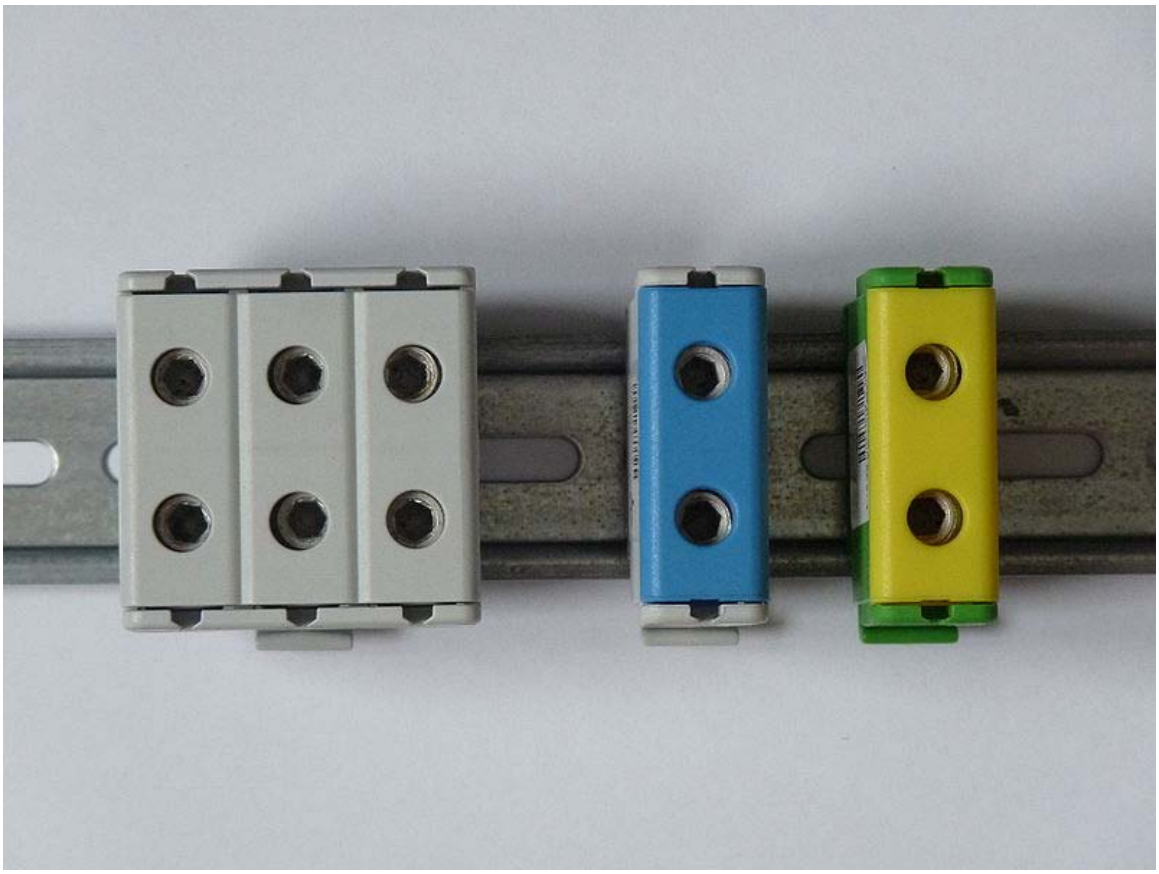
About 1950, PVC insulation and jackets were introduced, especially for residential wiring. About the same time, single conductors with a thinner PVC insulation and a thin nylon jacket became common.

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).

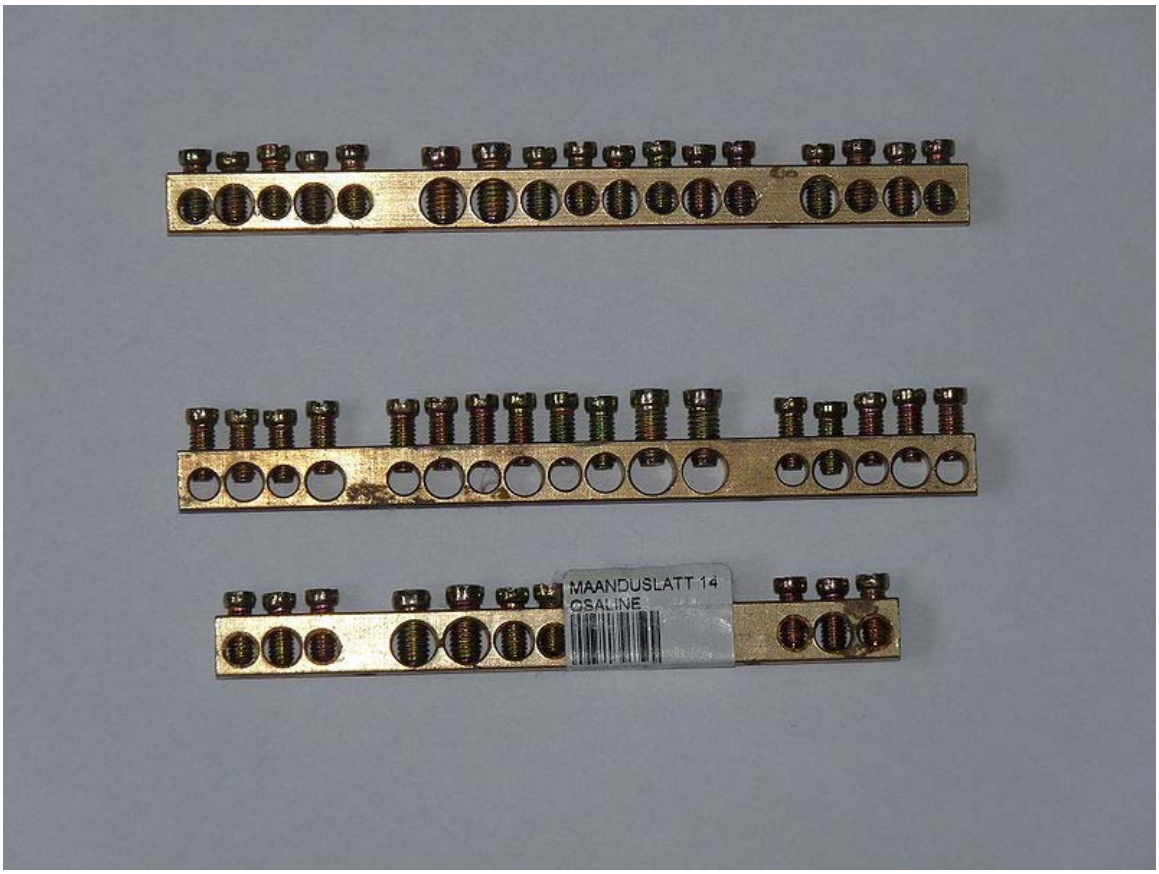
Special fittings are used for wiring in potentially explosive atmospheres.

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.

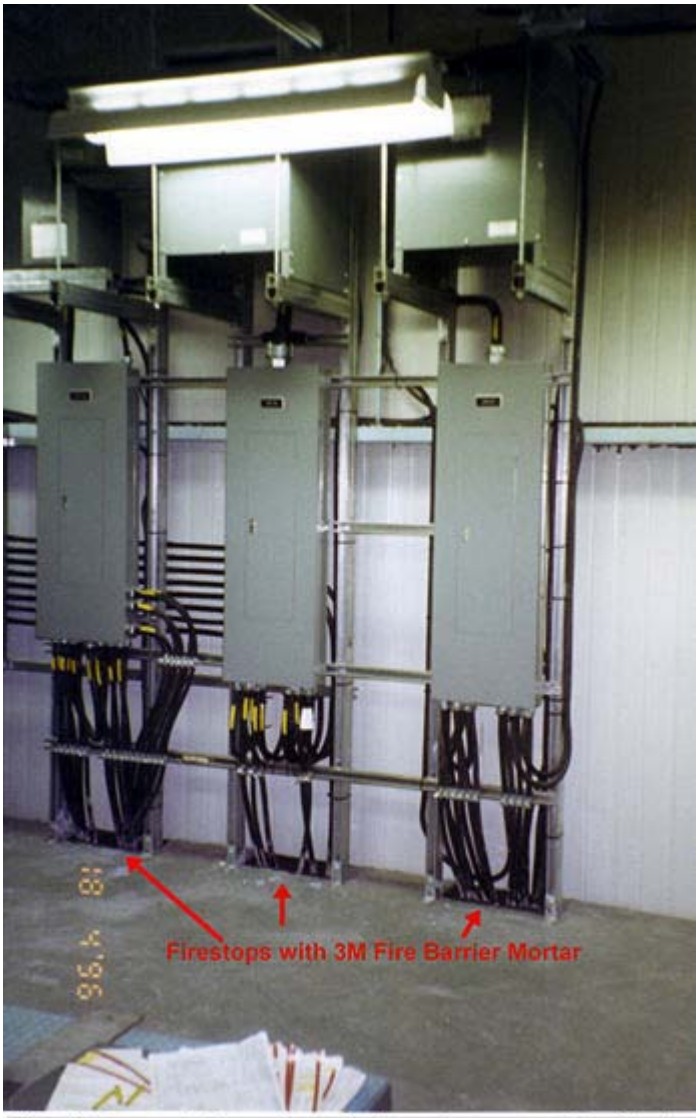
In industrial applications, conductor bars are assembled with insulators in grounded enclosures. This assembly, known as bus duct or busway, can be used for connections to large switchgear or for bringing the main power feed into a building. A form of bus duct known as plug-in bus is used to distribute 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



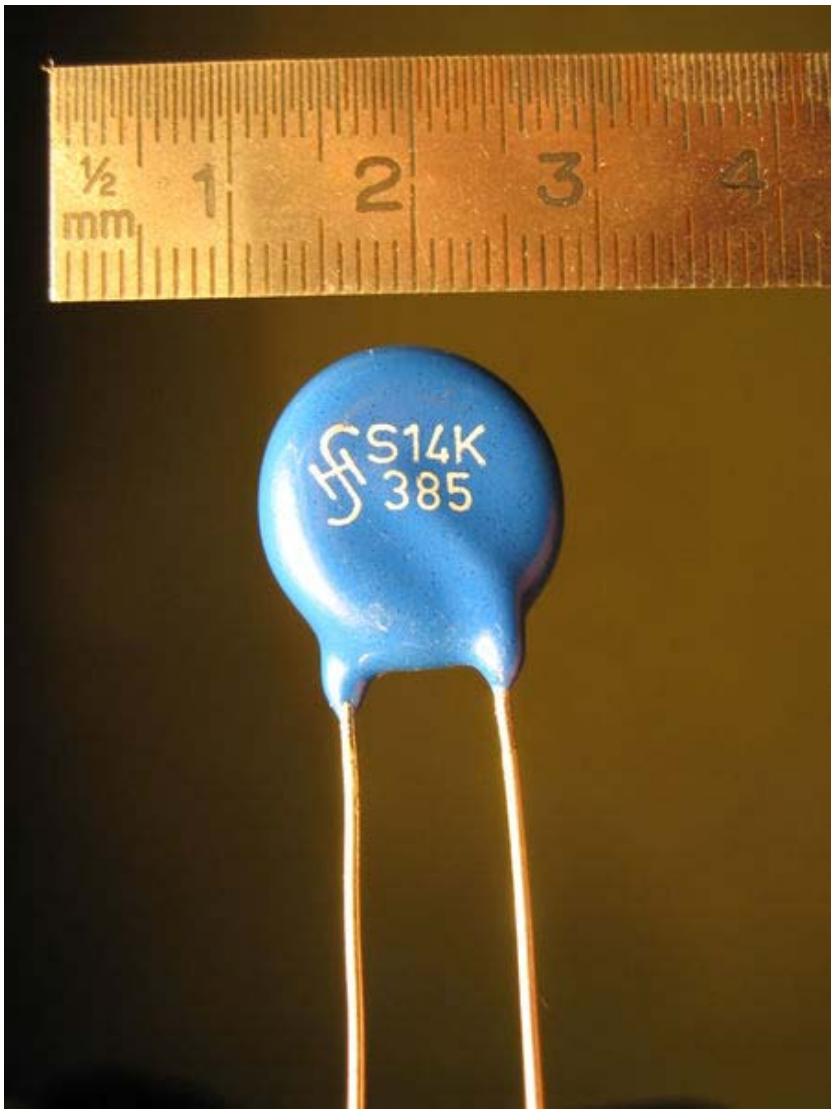
Electrical panels in an electrical service room at St. Mary's Pulp and Paper, Sault Ste. Marie, Ontario, Canada, April 1996

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



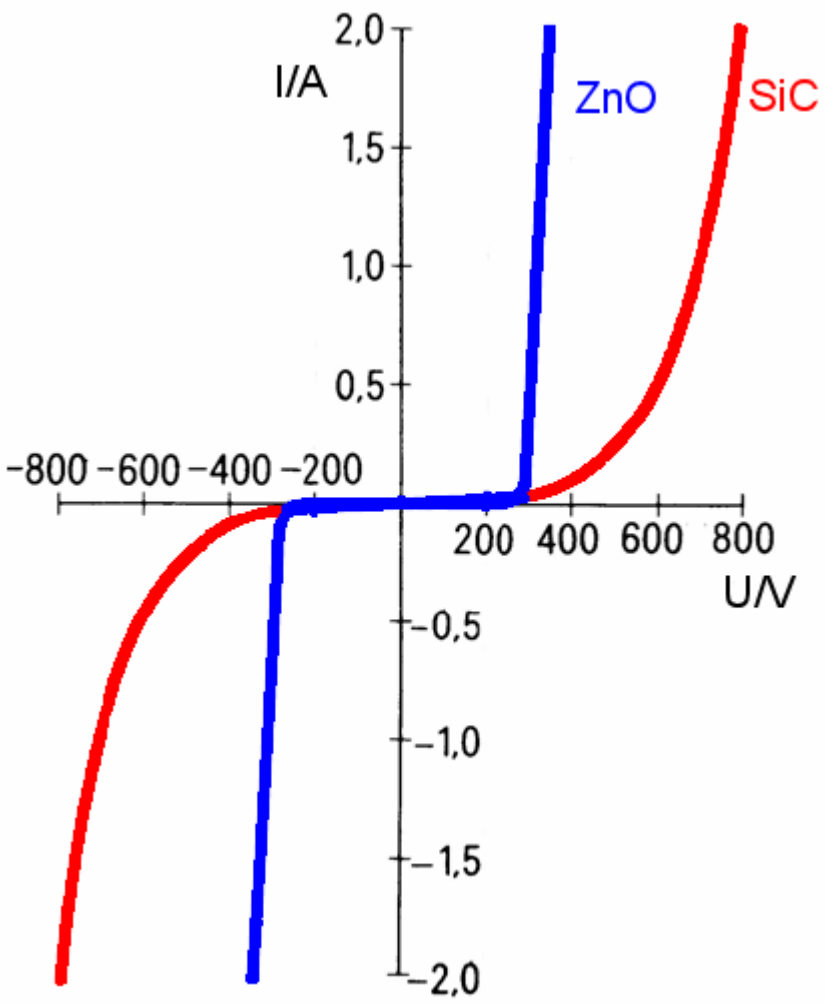
A 385-volt metal oxide varistor

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

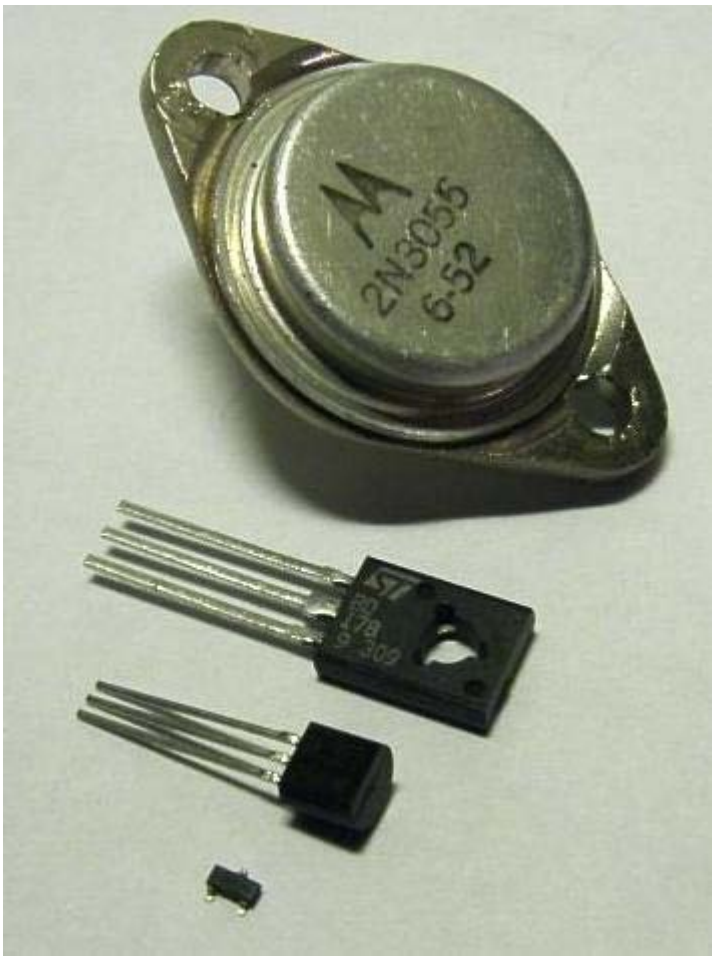
pF for microelectronic protection, such as in cellular phones. These low-capacitance varistors are, however, unable to withstand large surge currents simply due to their compact PCB-mount size.

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.

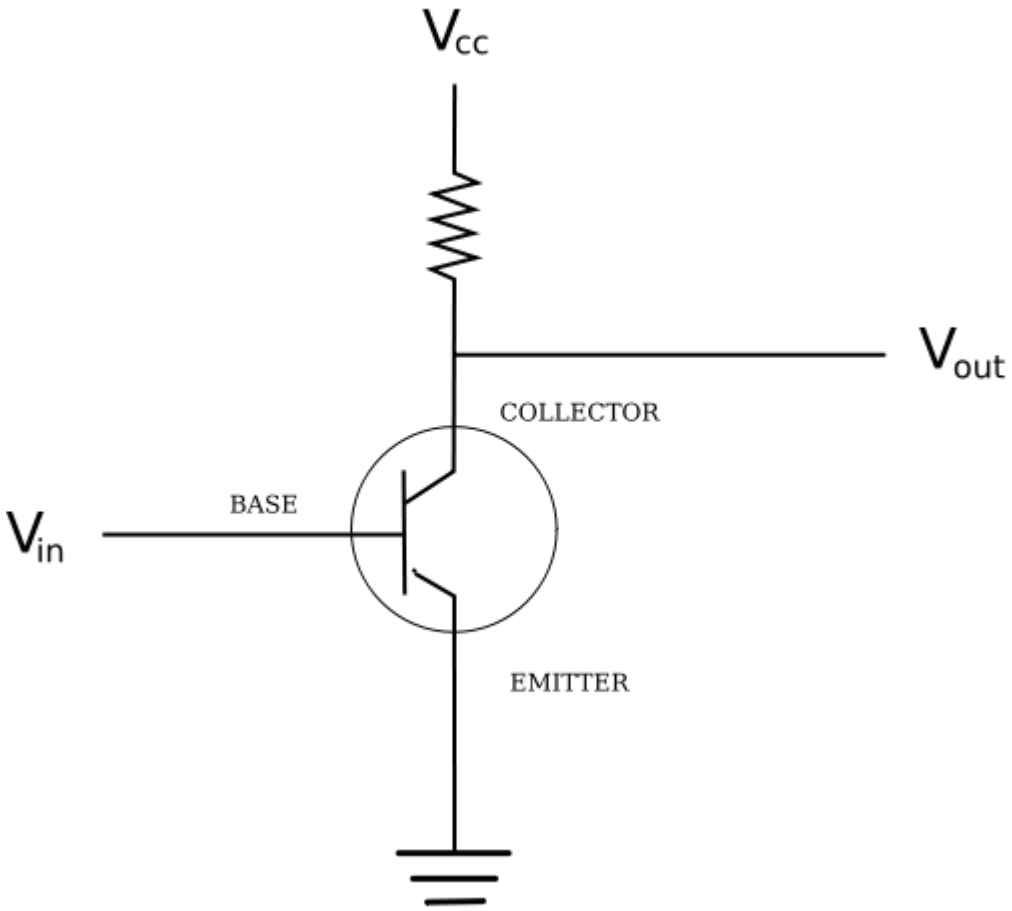
Although several companies each produce over a billion individually packaged (known as *discrete*) transistors every year, the vast majority of transistors now produced are in integrated circuits (often shortened to *IC*, *microchips* or simply *chips*), along with diodes, resistors, capacitors and other 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.

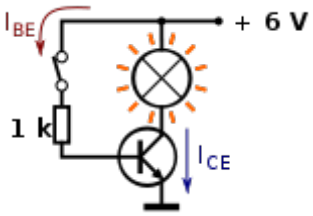
The essential usefulness of a transistor comes from its ability to use a small signal applied between one pair of its terminals to control a much larger signal at another pair of terminals. This property is called gain. A transistor can control its output in proportion to the input signal; that is, it 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.

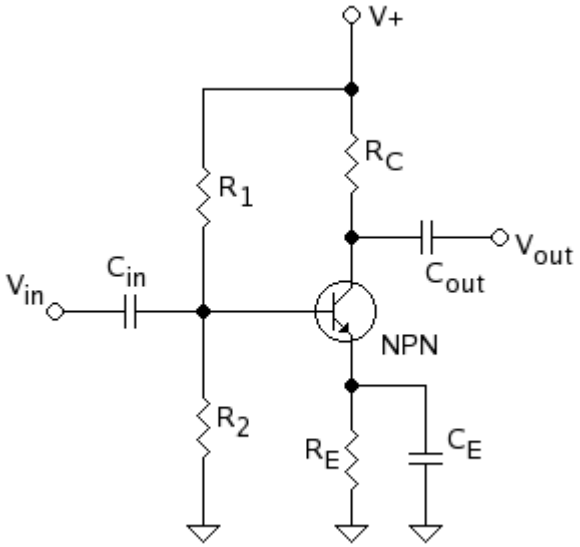
Transistors are commonly used as electronic switches, both for high-power applications such as switched-mode power supplies and for low-power applications such as logic gates.

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

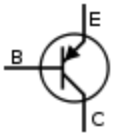
The key advantages that have allowed transistors to replace their vacuum tube predecessors in most applications are

- 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

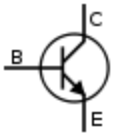
- Silicon transistors do not operate at voltages higher than about 1,000 volts (SiC devices can be operated as high as 3,000 volts). In contrast, vacuum tubes have been developed that can be operated at tens of thousands of volts.
- High-power, high-frequency operation, such as that used in over-the-air 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

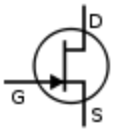


PNP

P-channel



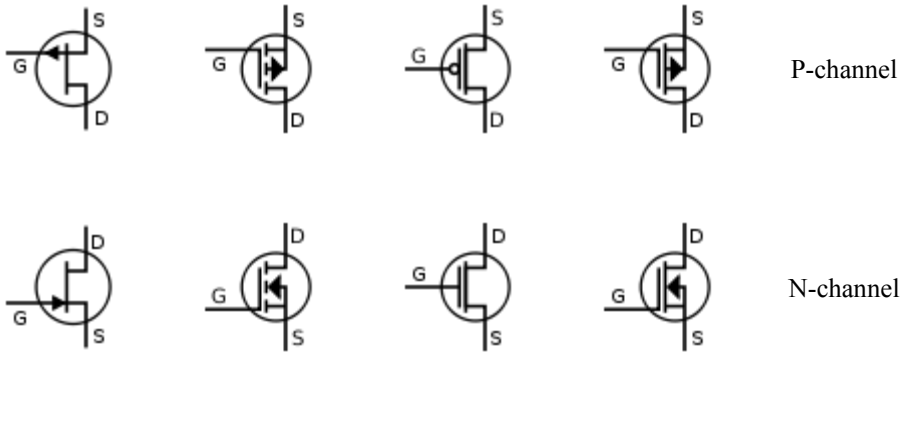
NPN



N-channel

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:

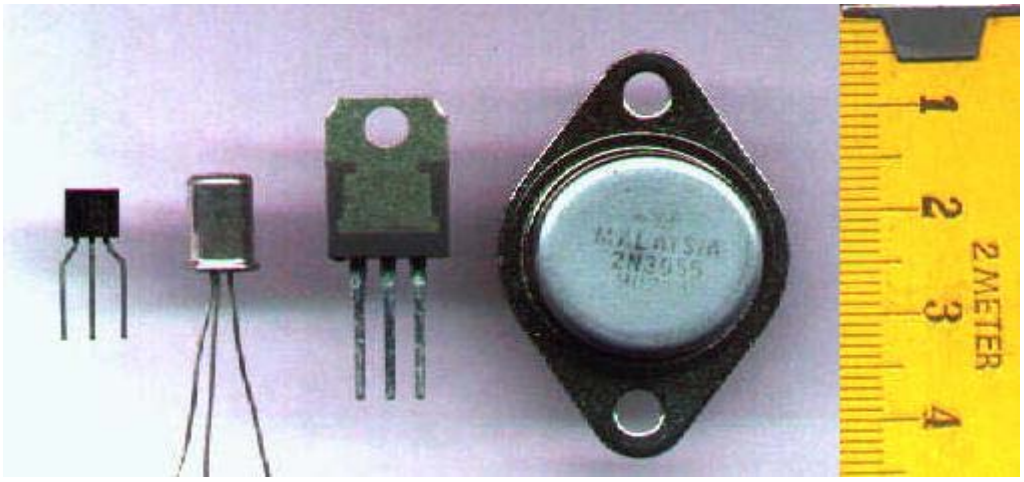
- Its maximum temperature is limited;
- it has relatively high leakage current;
- it cannot withstand high voltages;
- it is less suitable for fabricating integrated circuits.

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)

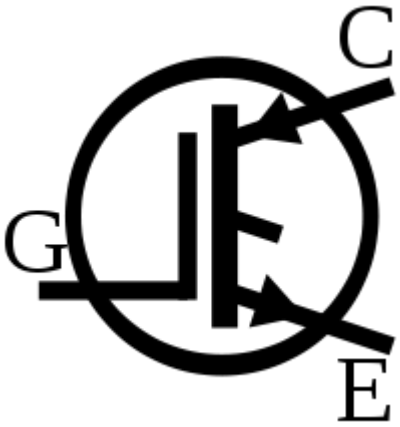
Transistors come in many different packages (semiconductor packages). The two main categories are *through-hole* (or *leaded*), and *surface-mount*, also known as *surface mount device* (SMD). The *ball grid array* (BGA) is the latest surface mount package (currently only for large *transistor arrays*). 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.

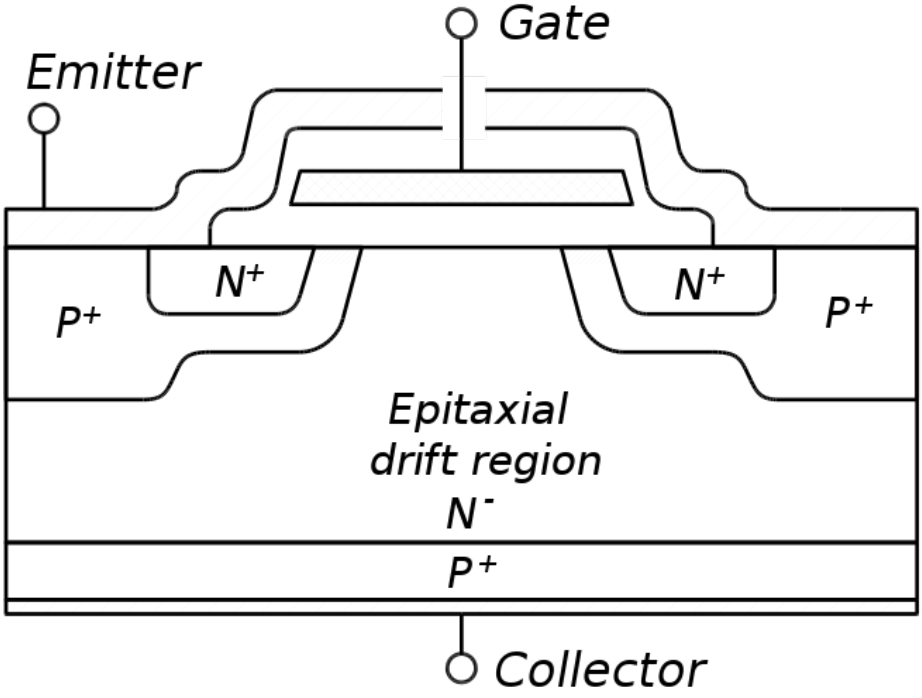
Often a given transistor type is available in sundry packages. Transistor packages are mainly standardized, but the assignment of a transistor's functions to the terminals is not: other transistor types can assign other functions to the package's terminals. Even for the same transistor type the terminal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

Chapter- 7

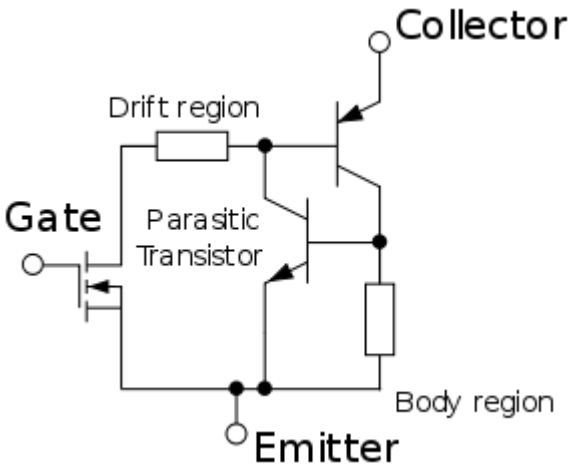
Insulated-gate Bipolar Transistor



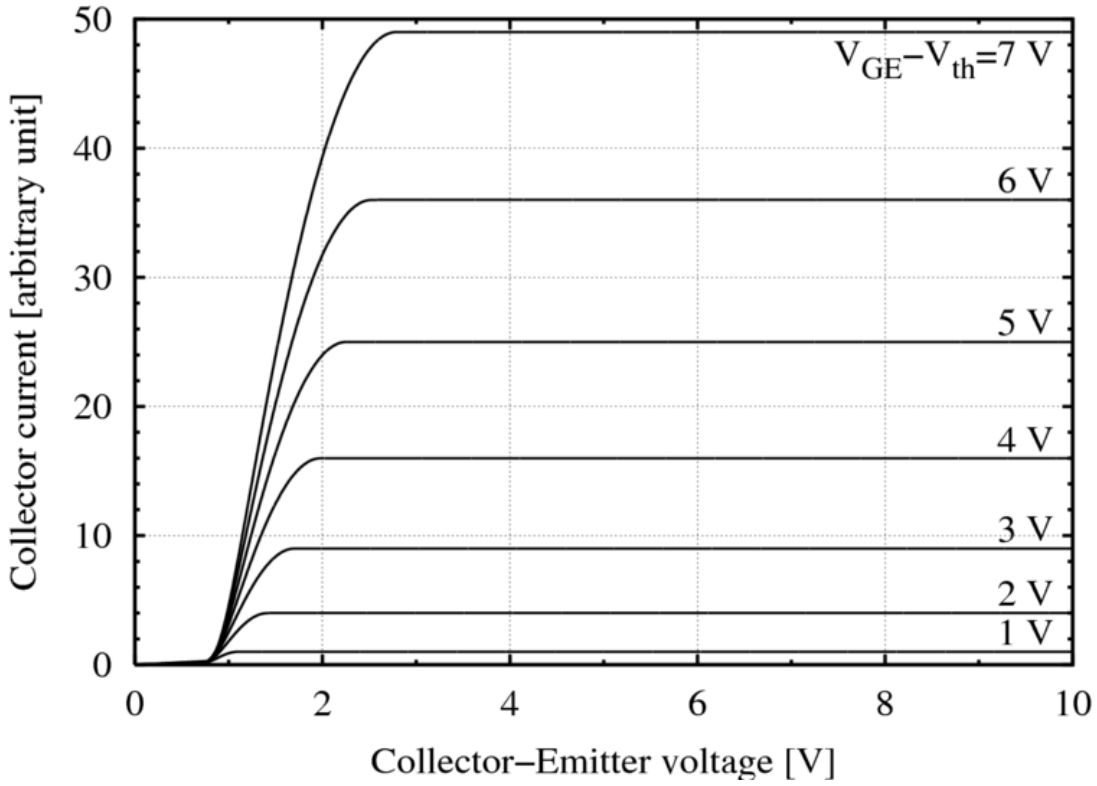
Electronic symbol for IGBT



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

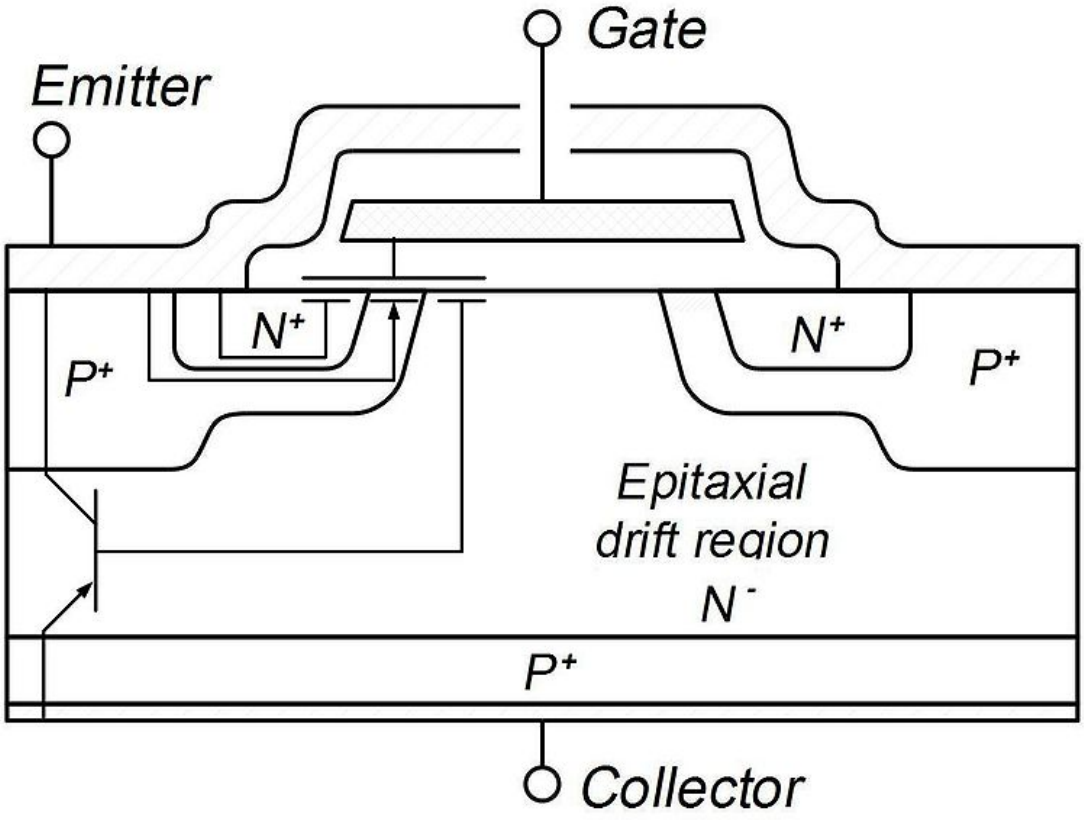
introduction of commercial devices in 1983, which could be utilized for a wide variety of applications.

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.

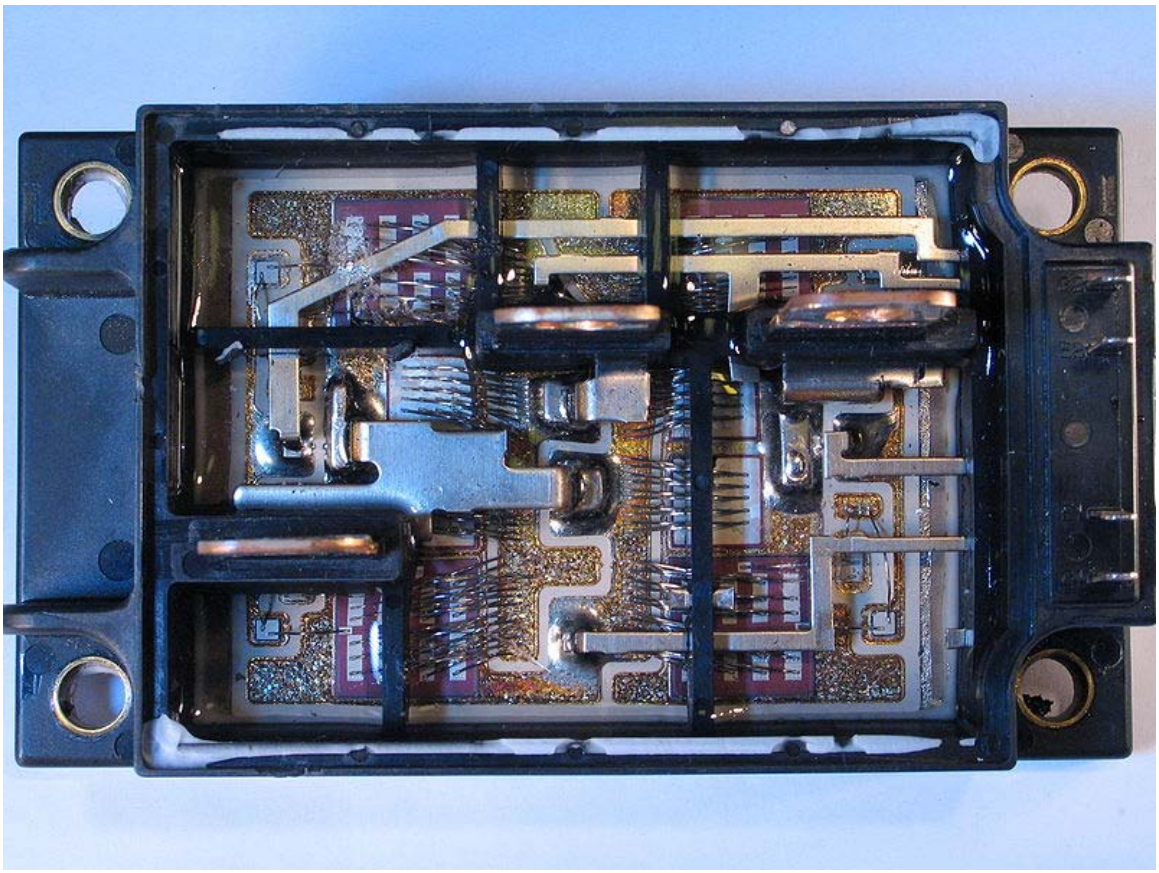
In general high voltage, high current and low switching frequencies favor IGBTs while low voltage, low current and high switching frequencies are the domain of the MOSFET.

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

Electrical Resistance and Conductance

The **electrical resistance** of an electrical element measures its opposition to the passage of an electric current; the inverse quantity is **electrical conductance**, measuring how easily electricity flows along a certain path. Electrical resistance shares some conceptual parallels with the mechanical notion of friction. The SI unit of electrical resistance is the ohm (Ω), while electrical conductance is measured in siemens (S).

An object of uniform cross section has a resistance proportional to its resistivity and length and inversely proportional to its cross-sectional area. All materials show some resistance, except for superconductors, which have a resistance of zero.

The resistance of an object is defined as the ratio of voltage across it to current through it:

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

For a wide variety of materials and conditions, the electrical resistance R is constant for a given temperature; it does not depend on the amount of current through or the potential difference (voltage) across the object. Such materials are called Ohmic materials. For objects made of ohmic materials the definition of the resistance, with R being a constant for that resistor, is known as Ohm's law.

In the case of a nonlinear conductor (not obeying Ohm's law), this ratio can change as current or voltage changes; the inverse slope of a chord to an I–V curve is sometimes referred to as a "chordal resistance" or "static resistance".

Conductors and resistors

A 65-Ω resistor, as identified by its electronic color code (blue–green–black). An ohmmeter could be used to verify this value.

Objects such as wires that are designed to have low resistance so that they transfer current with the least loss of electrical energy are called conductors. Objects that are designed to have a specific resistance so that they can dissipate electrical energy or otherwise modify how a circuit behaves are called resistors. Conductors are made of highly conductive materials such as metals, in particular copper and aluminium. Resistors, on the other hand, are made of a wide variety of materials depending on factors such as the desired resistance, amount of energy that it needs to dissipate, precision, and cost.

DC resistance

The resistance of a given resistor or conductor grows with the length of conductor and decreases for larger cross-sectional area. The resistance R and conductance G of a conductor of uniform cross section, therefore, can be computed as

$$R = \rho \frac{\ell}{A},$$
$$G = \frac{\sigma A}{\ell}.$$

where ℓ is the length of the conductor, measured in metres [m], A is the cross-sectional area of the conductor measured in square metres [m²], and ρ (rho) is the electrical resistivity (also called *specific electrical resistance*) of the material, measured in ohm-metres (Ωm). Resistivity is a measure of the material's ability to oppose electric current. For purely resistive circuits conductance is related to resistance R by:

$$G = \frac{1}{R}$$

For practical reasons, any connections to a real conductor will almost certainly mean the current density is not totally uniform. However, this formula still provides a good approximation for long thin conductors such as wires.

AC resistance

A wire carrying alternating current has a reduced effective cross sectional area because of the skin effect. Adjacent conductors carryng alternating current have a higher resistance than they would in isolation or when carrying direct current, due to the proximity effect. At commercial power frequency, these effects are significant for large conductors carrying large currents, such as busbars in an electrical substation, or large power cables carrying more than a few hundred amperes.

When an alternating current flows through the circuit, its flow is not opposed only by the circuit resistance, but also by the opposition of electric and magnetic fields to the current

change. That effect is measured by electrical reactance. The combined effects of reactance and resistance are expressed by electrical impedance.

Measuring resistance

An instrument for measuring resistance is called an ohmmeter. Simple ohmmeters cannot measure low resistances accurately because the resistance of their measuring leads causes a voltage drop that interferes with the measurement, so more accurate devices use four-terminal sensing.

Causes of resistance

In metals

A metal consists of a lattice of atoms, each with a shell of electrons. This is also known as a positive ionic lattice. The outer electrons are free to dissociate from their parent atoms and travel through the lattice, creating a 'sea' of electrons, making the metal a conductor. When an electrical potential difference (a voltage) is applied across the metal, the electrons drift from one end of the conductor to the other under the influence of the electric field.

Near room temperatures, the thermal motion of ions is the primary source of scattering of electrons (due to destructive interference of free electron waves on non-correlating potentials of ions), and is thus the prime cause of metal resistance. Imperfections of lattice also contribute into resistance, although their contribution in pure metals is negligible.

The larger the cross-sectional area of the conductor, the more electrons are available to carry the current, so the lower the resistance. The longer the conductor, the more scattering events occur in each electron's path through the material, so the higher the resistance. Different materials also affect the resistance.

In semiconductors and insulators

In metals, the Fermi level lies in the conduction band giving rise to free conduction electrons. However, in semiconductors the position of the Fermi level is within the band gap, approximately half-way between the conduction band minimum and valence band maximum for intrinsic (undoped) semiconductors. This means that at 0 kelvins, there are no free conduction electrons and the resistance is infinite. However, the resistance will continue to decrease as the charge carrier density in the conduction band increases. In extrinsic (doped) semiconductors, dopant atoms increase the majority charge carrier concentration by donating electrons to the conduction band or accepting holes in the valence band. For both types of donor or acceptor atoms, increasing the dopant density leads to a reduction in the resistance. Highly doped semiconductors hence behave metallic. At very high temperatures, the contribution of thermally generated carriers will

dominate over the contribution from dopant atoms and the resistance will decrease exponentially with temperature.

Small-signal device conductances

The term conductance applies to electronic devices such as transistors and diodes, where it usually refers to a small-signal model that is a linearization of the underlying device equations about a selected DC operating point or Q-point. This conductance is the reciprocal of the small-signal device resistance.

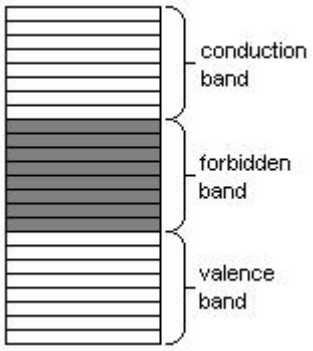
In ionic liquids/electrolytes

In electrolytes, electrical conduction happens not by band electrons or holes, but by full atomic species (ions) traveling, each carrying an electrical charge. The resistivity of ionic liquids varies tremendously by the concentration - while distilled water is almost an insulator, salt water is a very efficient electrical conductor. In biological membranes, currents are carried by ionic salts. Small holes in the membranes, called ion channels, are selective to specific ions and determine the membrane resistance.

Resistivity of various materials

Material	**Resistivity**, ρ ohm-metre
Metals	10^{-8}
Semiconductors	variable
Electrolytes	variable
Insulators	10^{16}
Superconductors	0 (exactly)

Band theory simplified



Electron energy levels in an insulator

Quantum mechanics states that the energy of an electron in an atom cannot be any arbitrary value. Rather, there are fixed energy levels which the electrons can occupy, and values in between these levels are impossible. The energy levels are grouped into two

bands: the **valence band** and the **conduction band** (the latter is generally above the former). Electrons in the conduction band may move freely throughout the substance in the presence of an electrical field.

In insulators and semiconductors, the atoms in the substance influence each other so that between the valence band and the conduction band there exists a forbidden band of energy levels, which the electrons cannot occupy. In order for a current to flow, a relatively large amount of energy must be furnished to an electron for it to leap across this forbidden gap and into the conduction band. Thus, even large voltages can yield relatively small currents.

Differential resistance

When the current–voltage dependence is not linear, **differential resistance**, **incremental resistance** or **slope resistance** is defined as the slope of the *V-I* graph at a particular point, thus:

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

This quantity is sometimes called simply *resistance*, although the two definitions are equivalent only for an ohmic component such as an ideal resistor. For example, a diode is a circuit element for which the resistance depends on the applied voltage or current.

If the *V-I* graph is not monotonic (i.e. it has a peak or a trough), the differential resistance will be negative for some values of voltage and current. This property is often known as *negative resistance*, although it is more correctly called *negative differential resistance*, since the absolute resistance *V*/*I* is still positive. An example of such an element is the tunnel diode.

Differential resistance is only useful to compare a nonlinear device with a linear source/load in some small interval; for example if it is necessary to evaluate a zener diode's voltage stability under different current values.

Temperature dependence

Near room temperature, the electric resistance of a typical metal increases linearly with rising temperature, while the electrical resistance of a typical semiconductor decreases with rising temperature. The amount of that change in resistance can be calculated using the temperature coefficient of resistivity of the material using the following formula:

$$R(T) = R_0[1 + \alpha(T - T_0)]$$

where T is its temperature, T_0 is a reference temperature (usually room temperature), R_0 is the resistance at T_0, and α is the percentage change in resistivity per unit temperature. The constant α depends only on the material being considered. The relationship stated is

actually only an approximate one, the true physics being somewhat non-linear, or looking at it another way, α itself varies with temperature. For this reason it is usual to specify the temperature that α was measured at with a suffix, such as α_{15} and the relationship only holds in a range of temperatures around the reference.

At lower temperatures (less than the Debye temperature), the resistance of a metal decreases as T^5 due to the electrons scattering off of phonons. At even lower temperatures, the dominant scattering mechanism for electrons is other electrons, and the resistance decreases as T^2. At some point, the impurities in the metal will dominate the behavior of the electrical resistance which causes it to saturate to a constant value. Matthiessen's Rule (first formulated by Augustus Matthiessen in the 1860s; the equation below gives its modern form) says that all of these different behaviors can be summed up to get the total resistance as a function of temperature,

$$R = R_{\mathrm{imp}} + aT^2 + bT^5 + cT$$

where R_{imp} is the temperature independent electrical resistivity due to impurities, and a, b, and c are coefficients which depend upon the metal's properties. This rule can be seen as the motivation to Heike Kamerlingh Onnes's experiments that led in 1911 to discovery of superconductivity.

Intrinsic semiconductors become better conductors as the temperature increases; the electrons are bumped to the conduction energy band by thermal energy, where they flow freely and in doing so leave behind holes in the valence band which also flow freely. The electric resistance of a typical intrinsic (non doped) semiconductor decreases exponentially with the temperature:

$$R = R_0 e^{-aT}$$

Extrinsic (doped) semiconductors have a far more complicated temperature profile. As temperature increases starting from absolute zero they first decrease steeply in resistance as the carriers leave the donors or acceptors. After most of the donors or acceptors have lost their carriers the resistance starts to increase again slightly due to the reducing mobility of carriers (much as in a metal). At higher temperatures it will behave like intrinsic semiconductors as the carriers from the donors/acceptors become insignificant compared to the thermally generated carriers.

The electric resistance of electrolytes and insulators is highly nonlinear, and case by case dependent, therefore no generalized equations are given.

Strain dependence

Just as the resistance of a conductor depends upon temperature, the resistance of a conductor depends upon strain. By placing a conductor under tension (a form of stress that leads to strain in the form of stretching of the conductor), the length of the section of conductor under tension increases and its cross-sectional area decreases. Both these

effects contribute to increasing the resistance of the strained section of conductor. Under compression (strain in the opposite direction), the resistance of the strained section of conductor decreases.

Chapter- 9

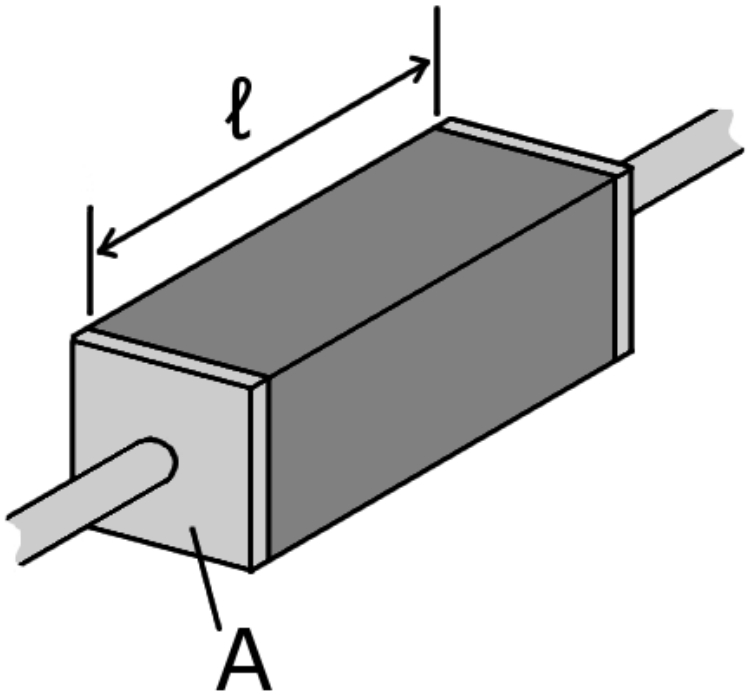
Electrical Resistivity and Conductivity

Electrical resistivity (also known as **resistivity**, **specific electrical resistance**, or **volume resistivity**) is a measure of how strongly a material opposes the flow of electric current. A low resistivity indicates a material that readily allows the movement of electric charge. The SI unit of electrical resistivity is the ohm metre [Ωm]. It is commonly represented by the Greek letter ρ (rho).

Electrical conductivity or **specific conductance** is the reciprocal quantity, and measures a material's ability to conduct an electric current. It is commonly represented by the Greek letter σ, but κ (esp. in electrical engineering) or γ are also occasionally used. Its SI unit is siemens per metre ($S \cdot m^{-1}$) and CGSE unit is reciprocal second (s^{-1}):

$$\sigma = \frac{1}{\rho}.$$

Definitions



A piece of resistive material with electrical contacts on both ends.

Electrical resistivity ρ (Greek: rho) is defined by,

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

where

ρ is the static resistivity (measured in ohm-metres, Ω-m)
E is the magnitude of the electric field (measured in volts per metre, V/m);
J is the magnitude of the current density (measured in amperes per square metre, A/m²).

Many resistors and conductors have a uniform cross section with a uniform flow of electric current and are made of one material. In this case, the above definition of ρ leads to:

$$\rho = R\frac{A}{\ell},$$

where

R is the electrical resistance of a uniform specimen of the material (measured in ohms, Ω)

ℓ is the length of the piece of material (measured in metres, m)
A is the cross-sectional area of the specimen (measured in square metres, m²).

The reason resistivity has the dimension units of ohm-metres can be seen by transposing the definition to make resistance the subject:

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

The resistance of a given sample will increase with the length, but decrease with greater cross-sectional area. Resistance is measured in ohms. Length over area has units of 1/distance. To end up with ohms, resistivity must be in the units of "ohms × distance" (SI ohm-metre, US ohm-inch).

In a hydraulic analogy, increasing the cross-sectional area of a pipe reduces its resistance to flow, and increasing the length increases resistance to flow (and pressure drop for a given flow).

Resistivity of various materials

- A conductor such as a metal has high conductivity and a low resistivity.
- An insulator like glass has low conductivity and a high resistivity.
- The conductivity of a semiconductor is generally intermediate, but varies widely under different conditions, such as exposure of the material to electric fields or specific frequencies of light, and, most important, with temperature and composition of the semiconductor material.

The degree of doping in semiconductors makes a large difference in conductivity. To a point, more doping leads to higher conductivity. The conductivity of a solution of water is highly dependent on its concentration of dissolved salts, and other chemical species that ionize in the solution. Electrical conductivity of water samples is used as an indicator of how salt-free, ion-free, or impurity-free the sample is; the purer the water, the lower the conductivity (the higher the resistivity). Conductivity measurements in water are often reported as *specific conductance*, the conductivity of the water at 25 °C. An EC meter is normally used to measure conductivity in a solution.

This table shows the resistivity, conductivity and temperature coefficient of various materials at 20 °C (68 °F)

Material	ρ [Ω·m] at 20 °C	σ [S/m] at 20 °C	Temperature coefficient [K^{-1}]
Silver	1.59×10^{-8}	6.30×10^{7}	0.0038
Copper	1.68×10^{-8}	5.96×10^{7}	0.0039

Annealed Copper		5.80×10^7	
Gold	2.44×10^{-8}	4.52×10^7	0.0034
Aluminium	2.82×10^{-8}	3.5×10^7	0.0039
Calcium	$3.36x10^{-8}$		0.0041
Tungsten	5.60×10^{-8}		0.0045
Zinc	5.90×10^{-8}		0.0037
Nickel	6.99×10^{-8}		0.006
Iron	1.0×10^{-7}		0.005
Platinum	1.06×10^{-7}		0.00392
Tin	1.09×10^{-7}		0.0045
Lead	2.2×10^{-7}		0.0039
Titanium	$4.20x10^{-7}$		X
Manganin	4.82×10^{-7}		0.000002
Constantan	4.9×10^{-7}		0.000008
Mercury	9.8×10^{-7}		0.0009
Nichrome	1.10×10^{-6}		0.0004
Carbon (amorphous)	$5\text{-}8\times10^{-4}$		−0.0005
Carbon (graphite)	$2.5\text{-}5.0\times10^{-6}$ ⊥ basal plane 3.0×10^{-3} // basal plane		
Carbon (diamond)	$\sim10^{12}$		
Germanium	4.6×10^{-1}		−0.048
Sea water	2×10^{-1}	4.8	
Drinking water		0.0005 to 0.05	
Deionized water		5.5×10^{-6}	
Silicon	6.40×10^{2}		−0.075
Glass	10^{10} to 10^{14}		?
Hard rubber	approx. 10^{13}		?
Sulfur	10^{15}		?
Air		3 to 8×10^{-15}	
Paraffin	10^{17}		?
Quartz (fused)	7.5×10^{17}		?
PET	10^{20}		?
Teflon	10^{22} to 10^{24}		?

The effective temperature coefficient varies with temperature and purity level of the material. The 20 °C value is only an approximation when used at other temperatures. For

example, the coefficient becomes lower at higher temperatures for copper, and the value 0.00427 is commonly specified at 0 °C.

The extremely low resistivity (high conductivity) of silver is characteristic of metals. George Gamow tidily summed up the nature of the metals' dealings with electrons in his science-popularizing book, *One, Two, Three...Infinity* (1947): "The metallic substances differ from all other materials by the fact that the outer shells of their atoms are bound rather loosely, and often let one of their electrons go free. Thus the interior of a metal is filled up with a large number of unattached electrons that travel aimlessly around like a crowd of displaced persons. When a metal wire is subjected to electric force applied on its opposite ends, these free electrons rush in the direction of the force, thus forming what we call an electric current." More technically, the free electron model gives a basic description of electron flow in metals.

Temperature dependence

In general, electrical resistivity of metals increases with temperature, while the resistivity of semiconductors decreases with increasing temperature. In both cases, electron–phonon interactions can play a key role. At high temperatures, the resistance of a metal increases linearly with temperature. As the temperature of a metal is reduced, the temperature dependence of resistivity follows a power law function of temperature. Mathematically the temperature dependence of the resistivity ρ of a metal is given by the Bloch–Grüneisen formula:

$$\rho(T) = \rho(0) + A\left(\frac{T}{\Theta_R}\right)^n \int_0^{\frac{\Theta_R}{T}} \frac{x^n}{(e^x - 1)(1 - e^{-x})} dx$$

where ρ(0) is the residual resistivity due to defect scattering, A is a constant that depends on the velocity of electrons at the Fermi surface, the Debye radius and the number density of electrons in the metal. Θ_R is the Debye temperature as obtained from resistivity measurements and matches very closely with the values of Debye temperature obtained from specific heat measurements. n is an integer that depends upon the nature of interaction:

1. n=5 implies that the resistance is due to scattering of electrons by phonons (as it is for simple metals)
2. n=3 implies that the resistance is due to s-d electron scattering (as is the case for transition metals)
3. n=2 implies that the resistance is due to electron–electron interaction.

As the temperature of the metal is sufficiently reduced (so as to 'freeze' all the phonons), the resistivity usually reaches a constant value, known as the **residual resistivity**. This value depends not only on the type of metal, but on its purity and thermal history. The value of the residual resistivity of a metal is decided by its impurity concentration. Some

materials lose all electrical resistivity at sufficiently low temperatures, due to an effect known as superconductivity.

An even better approximation of the temperature dependence of the resistivity of a semiconductor is given by the Steinhart–Hart equation:

$$1/T = A + B\ln(\rho) + C(\ln(\rho))^3$$

where *A*, *B* and *C* are the so-called **Steinhart–Hart coefficients**.

This equation is used to calibrate thermistors.

In non-crystalline semi-conductors, conduction can occur by charges quantum tunnelling from one localised site to another. This is known as variable range hopping and has the characteristic form of $\rho = Ae^{T^{-1/n}}$, where n=2,3,4 depending on the dimensionality of the system.

Complex resistivity and conductivity

When analyzing the response of materials to alternating electric fields, in applications such as electrical impedance tomography, it is necessary to replace resistivity with a complex quantity called **impeditivity** (in analogy to electrical impedance). Impeditivity is the sum of a real component, the resistivity, and an imaginary component, the **reactivity** (in analogy to reactance). The magnitude of Impeditivity is the square root of sum of squares of magnitudes of resistivity and reactivity.

Conversely, in such cases the conductivity must be expressed as a complex number (or even as a matrix of complex numbers, in the case of anisotropic materials) called the *admittivity*. Admittivity is the sum of a real component called the conductivity and an imaginary component called the susceptivity.

An alternative description of the response to alternating currents uses a real (but frequency-dependent) conductivity, along with a real permittivity. The larger the conductivity is, the more quickly the alternating-current signal is absorbed by the material (i.e., the more opaque the material is).

Resistivity density products

In some applications where the weight of an item is very important resistivity density products are more important than absolute low resistivity- it is often possible to make the conductor thicker to make up for a higher resistivity; and then a low resistivity density product material (or equivalently a high conductance to density ratio) is desirable. For example, for long distance overhead power lines— aluminium is frequently used rather than copper because it is lighter for the same conductance.

Material	Resistivity [nΩ·m]	Density [g/cm³]	Resistivity-density product [nΩ·m·g/cm³]
Sodium	47.7	0.97	46
Lithium	92.8	0.53	49
Calcium	33.6	1.55	52
Potassium	72.0	0.89	64
Aluminium	26.50	2.70	72
Copper	16.78	8.96	150
Silver	15.87	10.49	166

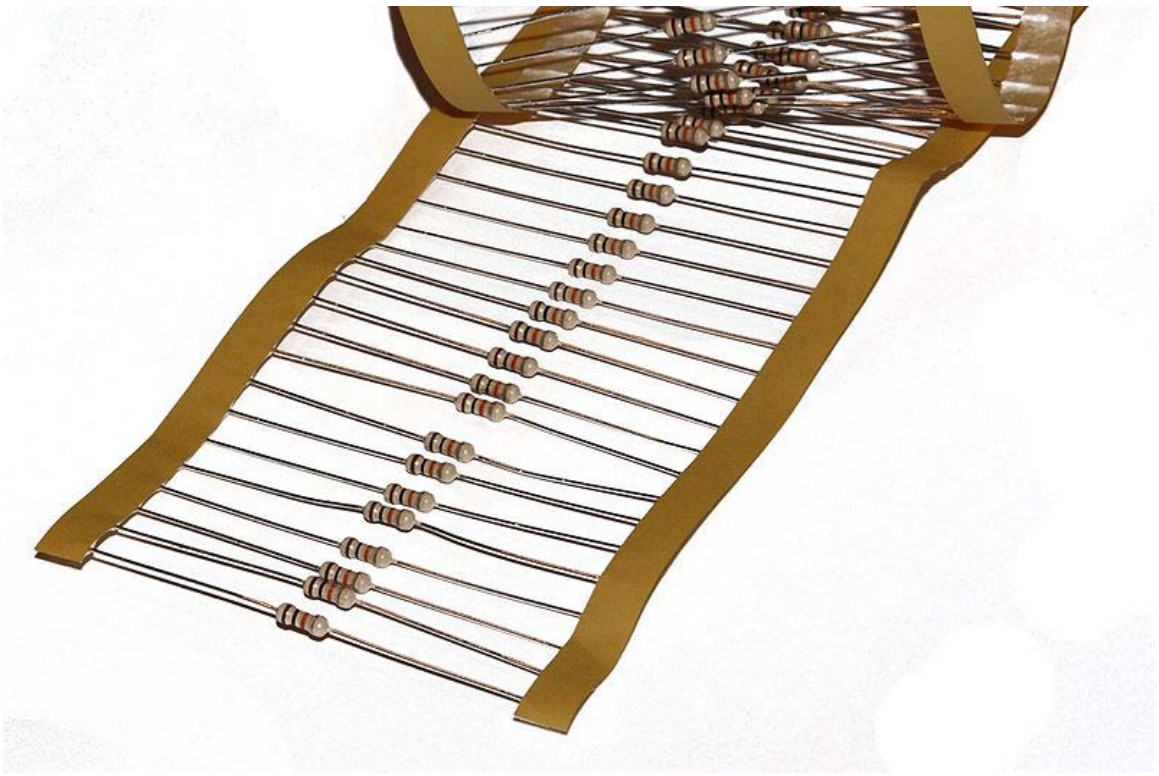
Silver, although it is the least resistive metal known, has a high density and does poorly by this measure. The calcium and the alkali metals have the best products, but are rarely used for conductors due to their high reactivity with water and oxygen. Aluminium is far more stable.

Chapter- 10

Resistor

A typical axial-lead resistor

Partially exposed Tesla TR-212 1 kΩ carbon film resistor



Axial-lead resistors on tape. The tape is removed during assembly before the leads are formed and the part is inserted into the board.

Three carbon composition resistors in a 1960s valve (vacuum tube) radio

A **resistor** is a two-terminal passive electronic component which implements electrical resistance as a circuit element. When a voltage V is applied across the terminals of a resistor, a current I will flow through the resistor in direct proportion to that voltage. The reciprocal of the constant of proportionality is known as the resistance R, since, with a given voltage V, a larger value of R further "resists" the flow of current I as given by Ohm's law:

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

Resistors are common elements of electrical networks and electronic circuits and are ubiquitous in most electronic equipment. Practical resistors can be made of various compounds and films, as well as resistance wire (wire made of a high-resistivity alloy, such as nickel-chrome). Resistors are also implemented within integrated circuits, particularly analog devices, and can also be integrated into hybrid and printed circuits.

The electrical functionality of a resistor is specified by its resistance: common commercial resistors are manufactured over a range of more than 9 orders of magnitude. When specifying that resistance in an electronic design, the required precision of the resistance may require attention to the manufacturing tolerance of the chosen resistor, according to its specific application. The temperature coefficient of the resistance may also be of concern in some precision applications. Practical resistors are also specified as having a maximum power rating which must exceed the anticipated power dissipation of that resistor in a particular circuit: this is mainly of concern in power electronics applications. Resistors with higher power ratings are physically larger and may require

heat sinking. In a high voltage circuit, attention must sometimes be paid to the rated maximum working voltage of the resistor.

The series inductance of a practical resistor causes its behavior to depart from ohms law; this specification can be important in some high-frequency applications for smaller values of resistance. In a low-noise amplifier or pre-amp the noise characteristics of a resistor may be an issue. The unwanted inductance, excess noise, and temperature coefficient are mainly dependent on the technology used in manufacturing the resistor. They are not normally specified individually for a particular family of resistors manufactured using a particular technology. A family of discrete resistors is also characterized according to its form factor, that is, the size of the device and position of its leads (or terminals) which is relevant in the practical manufacturing of circuits using them.

Units

The ohm (symbol: Ω) is the SI unit of electrical resistance, named after Georg Simon Ohm. An ohm is equivalent to a volt per ampere. Since resistors are specified and manufactured over a very large range of values, the derived units of milliohm (1 mΩ = 10^{-3} Ω), kilohm (1 kΩ = 10^{3} Ω), and megohm (1 MΩ = 10^{6} Ω) are also in common usage.

The reciprocal of resistance R is called conductance G = 1/R and is measured in Siemens (SI unit), sometimes referred to as a mho. Thus a Siemens is the reciprocal of an ohm: $S = \Omega^{-1}$. Although the concept of conductance is often used in circuit analysis, practical resistors are always specified in terms of their resistance (ohms) rather than conductance.

Theory of operation

Ohm's law

The behavior of an ideal resistor is dictated by the relationship specified in Ohm's law:

$$V = I \cdot R$$

Ohm's law states that the voltage (V) across a resistor is proportional to the current (I) passing through it, where the constant of proportionality is the resistance (R).

Equivalently, Ohm's law can be stated:

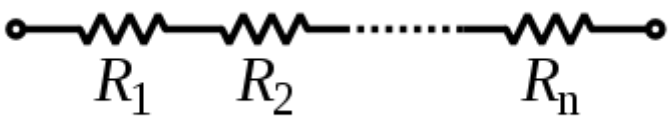
$$I = \frac{V}{R}$$

This formulation of Ohm's law states that, when a voltage (V) is present across a resistance (R), a current (I) will flow through the resistance. This is directly used in practical computations. For example, if a 300 ohm resistor is attached across the

terminals of a 12 volt battery, then a current of 12 / 300 = 0.04 amperes (or 40 milliamperes) will flow through that resistor.

Series and parallel resistors

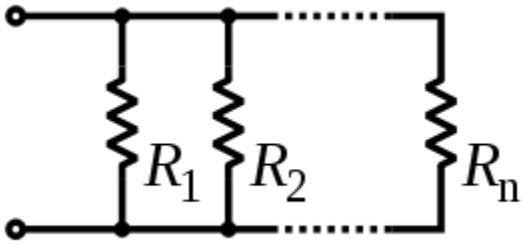
In a series configuration, the current through all of the resistors is the same, but the voltage across each resistor will be in proportion to its resistance. The potential difference (voltage) seen across the network is the sum of those voltages, thus the total resistance can be found as the sum of those resistances:



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

As a special case, the resistance of N resistors connected in series, each of the same resistance R, is given by NR.

Resistors in a parallel configuration are each subject to the same potential difference (voltage), however the currents through them add. The conductances of the resistors then add to determine the conductance of the network. Thus the equivalent resistance (R_{eq}) of the network can be computed:



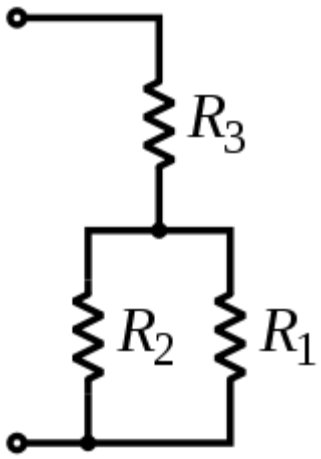
$$\frac{1}{R_{\text{eq}}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}$$

The parallel equivalent resistance can be represented in equations by two vertical lines "||" (as in geometry) as a simplified notation. For the case of two resistors in parallel, this can be calculated using:

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

As a special case, the resistance of N resistors connected in parallel, each of the same resistance R, is given by R/N.

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



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

However, some complex networks of resistors cannot be resolved in this manner, requiring more sophisticated circuit analysis. For instance, consider a cube, each edge of which has been replaced by a resistor. What then is the resistance that would be measured between two opposite vertices? In the case of 12 equivalent resistors, it can be shown that the corner-to-corner resistance is $^5/_6$ of the individual resistance. More generally, the Y-Δ transform, or matrix methods can be used to solve such a problem.

One practical application of these relationships is that a non-standard value of resistance can generally be synthesized by connecting a number of standard values in series and/or parallel. This can also be used to obtain a resistance with a higher power rating than that of the individual resistors used. In the special case of N identical resistors all connected in series or all connected in parallel, the power rating of the individual resistors is thereby multiplied by N.

Power dissipation

The power P dissipated by a resistor (or the equivalent resistance of a resistor network) is calculated as: $P = I^2R = IV = \frac{V^2}{R}$

The first form is a restatement of Joule's first law. Using Ohm's law, the two other forms can be derived.

The total amount of heat energy released over a period of time can be determined from the integral of the power over that period of time:

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

Practical resistors are rated according to their maximum power dissipation. The vast majority of resistors used in electronic circuits absorb much less than a watt of electrical power and require no attention to their power rating. Such resistors in their discrete form, including most of the packages detailed below, are typically rated as 1/10, 1/8, or 1/4 watt.

Resistors required to dissipate substantial amounts of power, particularly used in power supplies, power conversion circuits, and power amplifiers, are generally referred to as *power resistors*; this designation is loosely applied to resistors with power ratings of 1 watt or greater. Power resistors are physically larger and tend not to use the preferred values, color codes, and external packages described below.

If the average power dissipated by a resistor is more than its power rating, damage to the resistor may occur, permanently altering its resistance; this is distinct from the reversible change in resistance due to its temperature coefficient when it warms. Excessive power dissipation may raise the temperature of the resistor to a point where it can burn the circuit board or adjacent components, or even cause a fire. There are flameproof resistors that fail (open circuit) before they overheat dangerously.

Note that the nominal power rating of a resistor is not the same as the power that it can safely dissipate in practical use. Air circulation and proximity to a circuit board, ambient temperature, and other factors can reduce acceptable dissipation significantly. Rated power dissipation may be given for an ambient temperature of 25 °C in free air. Inside an equipment case at 60 °C, rated dissipation will be significantly less; a resistor dissipating a bit less than the maximum figure given by the manufacturer may still be outside the safe operating area and may prematurely fail.

Construction

A single in line (SIL) resistor package with 8 individual, 47 ohm resistors. One end of each resistor is connected to a separate pin and the other ends are all connected together to the remaining (common) pin - pin 1, at the end identified by the white dot.

Lead arrangements

Resistors with wire leads for through-hole mounting

Through-hole components typically have leads leaving the body axially. Others have leads coming off their body radially instead of parallel to the resistor axis. Other components may be SMT (surface mount technology) while high power resistors may have one of their leads designed into the heat sink.

Carbon composition

Carbon composition resistors consist of a solid cylindrical resistive element with embedded wire leads or metal end caps to which the lead wires are attached. The body of the resistor is protected with paint or plastic. Early 20th-century carbon composition resistors had uninsulated bodies; the lead wires were wrapped around the ends of the resistance element rod and soldered. The completed resistor was painted for color coding of its value.

The resistive element is made from a mixture of finely ground (powdered) carbon and an insulating material (usually ceramic). A resin holds the mixture together. The resistance is determined by the ratio of the fill material (the powdered ceramic) to the carbon. Higher concentrations of carbon, a weak conductor, result in lower resistance. Carbon composition resistors were commonly used in the 1960s and earlier, but are not so

popular for general use now as other types have better specifications, such as tolerance, voltage dependence, and stress (carbon composition resistors will change value when stressed with over-voltages). Moreover, if internal moisture content (from exposure for some length of time to a humid environment) is significant, soldering heat will create a non-reversible change in resistance value. Carbon composition resistors have poor stability with time and were consequently factory sorted to, at best, only 5% tolerance. These resistors, however, if never subjected to overvoltage nor overheating were remarkably reliable considering the component's size

They are still available, but comparatively quite costly. Values ranged from fractions of an ohm to 22 megohms. Because of the high price, these resistors are no longer used in most applications. However, carbon resistors are used in power supplies and welding controls.

Carbon film

A carbon film is deposited on an insulating substrate, and a helix cut in it to create a long, narrow resistive path. Varying shapes, coupled with the resistivity of carbon, (ranging from 90 to 400 nΩ m) can provide a variety of resistances. Carbon film resistors feature a power rating range of 0.125 W to 5 W at 70 °C. Resistances available range from 1 ohm to 10 megohm. The carbon film resistor has an operating temperature range of -55 °C to 155 °C. It has 200 to 600 volts maximum working voltage range. Special carbon film resistors are used in applications requiring high pulse stability.

Thick and thin film

Thick film resistors became popular during the 1970s, and most SMD (surface mount device) resistors today are of this type. The principal difference between thin film and thick film resistors is not the actual thickness of the film, but rather how the film is applied to the cylinder (axial resistors) or the surface (SMD resistors).

Thin film resistors are made by sputtering (a method of vacuum deposition) the resistive material onto an insulating substrate. The film is then etched in a similar manner to the old (subtractive) process for making printed circuit boards; that is, the surface is coated with a photo-sensitive material, then covered by a pattern film, irradiated with ultraviolet light, and then the exposed photo-sensitive coating is developed, and underlying thin film is etched away.

Thick film resistors are manufactured using screen and stencil printing processes.

Because the time during which the sputtering is performed can be controlled, the thickness of the thin film can be accurately controlled. The type of material is also usually different consisting of one or more ceramic (cermet) conductors such as tantalum nitride (TaN), ruthenium dioxide (RuO_2), lead oxide (PbO), bismuth ruthenate ($Bi_2Ru_2O_7$), nickel chromium (NiCr), and/or bismuth iridate ($Bi_2Ir_2O_7$).

The resistance of both thin and thick film resistors after manufacture is not highly accurate; they are usually trimmed to an accurate value by abrasive or laser trimming. Thin film resistors are usually specified with tolerances of 0.1, 0.2, 0.5, or 1%, and with temperature coefficients of 5 to 25 ppm/K.

Thick film resistors may use the same conductive ceramics, but they are mixed with sintered (powdered) glass and some kind of liquid so that the composite can be screen-printed. This composite of glass and conductive ceramic (cermet) material is then fused (baked) in an oven at about 850 °C.

Thick film resistors, when first manufactured, had tolerances of 5%, but standard tolerances have improved to 2% or 1% in the last few decades. Temperature coefficients of thick film resistors are high, typically ±200 or ±250 ppm/K; a 40 kelvin (70 °F) temperature change can change the resistance by 1%.

Thin film resistors are usually far more expensive than thick film resistors. For example, SMD thin film resistors, with 0.5% tolerances, and with 25 ppm/K temperature coefficients, when bought in full size reel quantities, are about twice the cost of 1%, 250 ppm/K thick film resistors.

Metal film

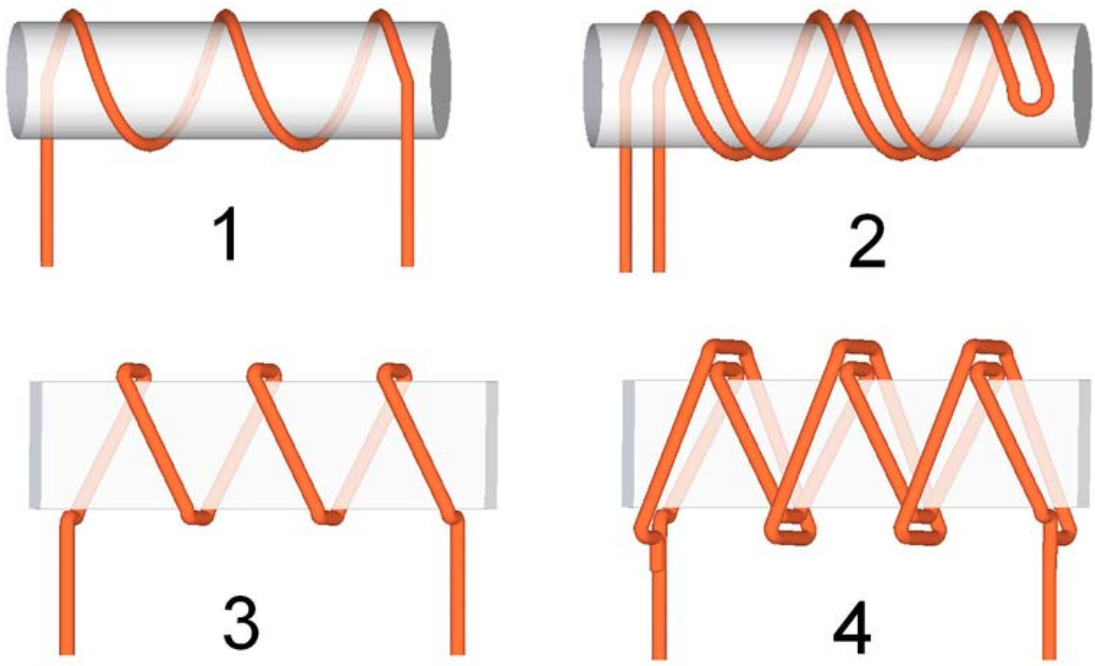
A common type of axial resistor today is referred to as a metal-film resistor. Metal electrode leadless face (MELF) resistors often use the same technology, but are a cylindrically shaped resistor designed for surface mounting. Note that other types of resistors (e.g., carbon composition) are also available in MELF packages.

Metal film resistors are usually coated with nickel chromium (NiCr), but might be coated with any of the cermet materials listed above for thin film resistors. Unlike thin film resistors, the material may be applied using different techniques than sputtering (though that is one such technique). Also, unlike thin-film resistors, the resistance value is determined by cutting a helix through the coating rather than by etching. (This is similar to the way carbon resistors are made.) The result is a reasonable tolerance (0.5, 1, or 2%) and a temperature coefficient that is generally between 50 and 100 ppm/K. Metal film resistors possess good noise characteristics and low non-linearity due to a low voltage coefficient. Also beneficial are the components efficient tolerance, temperature coefficient and stability.

Metal Oxide film

Metal-Oxide film resistors resemble Metal film types, but are made of metal oxides such as tin oxide. This results in a higher operating temperature and greater stability/reliability than Metal film. They are used in applications with high endurance demands.

Wirewound



Types of windings in wire resistors:
1 - common
2 - bifilar
3 - common on a thin former
4 - Ayrton-Perry

Wirewound resistors are commonly made by winding a metal wire, usually nichrome, around a ceramic, plastic, or fiberglass core. The ends of the wire are soldered or welded to two caps or rings, attached to the ends of the core. The assembly is protected with a layer of paint, molded plastic, or an enamel coating baked at high temperature. Because of the very high surface temperature these resistors can withstand temperatures of up to +450 °C. Wire leads in low power wirewound resistors are usually between 0.6 and 0.8 mm in diameter and tinned for ease of soldering. For higher power wirewound resistors, either a ceramic outer case or an aluminum outer case on top of an insulating layer is used. The aluminum-cased types are designed to be attached to a heat sink to dissipate the heat; the rated power is dependent on being used with a suitable heat sink, e.g., a 50 W power rated resistor will overheat at a fraction of the power dissipation if not used with a heat sink. Large wirewound resistors may be rated for 1,000 watts or more.

Because wirewound resistors are coils they have more undesirable inductance than other types of resistor, although winding the wire in sections with alternately reversed direction can minimize inductance. Other techniques employ bifilar winding, or a flat thin former (to reduce cross-section area of the coil). For most demanding circuits resistors with Ayrton-Perry winding are used.

Applications of wirewound resistors are similar to those of composition resistors with the exception of the high frequency. The high frequency of wirewound resistors is substantially worse than that of a composition resistor

Foil resistor

The primary resistance element of a foil resistor is a special alloy foil several micrometres thick. Since their introduction in the 1960s, foil resistors have had the best precision and stability of any resistor available. One of the important parameters influencing stability is the temperature coefficient of resistance (TCR). The TCR of foil resistors is extremely low, and has been further improved over the years. One range of ultra-precision foil resistors offers a TCR of 0.14 ppm/°C, tolerance ±0.005%, long-term stability (1 year) 25 ppm, (3 year) 50 ppm (further improved 5-fold by hermetic sealing), stability under load (2000 hours) 0.03%, thermal EMF 0.1 μV/°C, noise -42 dB, voltage coefficient 0.1 ppm/V, inductance 0.08 μH, capacitance 0.5 pF.

Ammeter shunts

An ammeter shunt is a special type of current-sensing resistor, having four terminals and a value in milliohms or even micro-ohms. Current-measuring instruments, by themselves, can usually accept only limited currents. To measure high currents, the current passes through the shunt, where the voltage drop is measured and interpreted as current. A typical shunt consists of two solid metal blocks, sometimes brass, mounted on to an insulating base. Between the blocks, and soldered or brazed to them, are one or more strips of low temperature coefficient of resistance (TCR) manganin alloy. Large bolts threaded into the blocks make the current connections, while much-smaller screws provide voltage connections. Shunts are rated by full-scale current, and often have a voltage drop of 50 mV at rated current. Such meters are adapted to the shunt full current rating by using an appropriately marked dial face; no change need be made to the other parts of the meter.

Grid resistor

In heavy-duty industrial high-current applications, a grid resistor is a large convection-cooled lattice of stamped metal alloy strips connected in rows between two electrodes. Such industrial grade resistors can be as large as a refrigerator; some designs can handle over 500 amperes of current, with a range of resistances extending lower than 0.04 ohms. They are used in applications such as dynamic braking and load banking for locomotives and trams, neutral grounding for industrial AC distribution, control loads for cranes and heavy equipment, load testing of generators and harmonic filtering for electric substations.

The term *grid resistor* is sometimes used to describe a resistor of any type connected to the control grid of a vacuum tube. This is not a resistor technology; it is an electronic circuit topology.

Special varieties

- Metal oxide varistor
- Cermet
- Phenolic
- Tantalum
- Water resistor

Variable resistors

Adjustable resistors

A resistor may have one or more fixed tapping points so that the resistance can be changed by moving the connecting wires to different terminals. Some wirewound power resistors have a tapping point that can slide along the resistance element, allowing a larger or smaller part of the resistance to be used.

Where continuous adjustment of the resistance value during operation of equipment is required, the sliding resistance tap can be connected to a knob accessible to an operator. Such a device is called a rheostat and has two terminals.

Potentiometers

A common element in electronic devices is a three-terminal resistor with a continuously adjustable tapping point controlled by rotation of a shaft or knob. These variable resistors are known as potentiometers when all three terminals are present, since they act as a continuously adjustable voltage divider. A common example is a volume control for a radio receiver.

Accurate, high-resolution panel-mounted potentiometers (or "pots") have resistance elements typically wirewound on a helical mandrel, although some include a conductive-plastic resistance coating over the wire to improve resolution. These typically offer ten turns of their shafts to cover their full range. They are usually set with dials that include a simple turns counter and a graduated dial. Electronic analog computers used them in quantity for setting coefficients, and delayed-sweep oscilloscopes of recent decades included one on their panels.

Resistance decade boxes

A resistance decade box or resistor substitution box is a unit containing resistors of many values, with one or more mechanical switches which allow any one of various discrete resistances offered by the box to be dialed in. Usually the resistance is accurate to high precision, ranging from laboratory/calibration grade accuracy of 20 parts per million, to field grade at 1%. Inexpensive boxes with lesser accuracy are also available. All types offer a convenient way of selecting and quickly changing a resistance in laboratory, experimental and development work without needing to attach resistors one by one, or

even stock each value. The range of resistance provided, the maximum resolution, and the accuracy characterize the box. For example, one box offers resistances from 0 to 24 megohms, maximum resolution 0.1 ohm, accuracy 0.1%.

Special devices

There are various devices whose resistance changes with various quantities. The resistance of thermistors exhibit a strong negative temperature coefficient, making them useful for measuring temperatures. Since their resistance can be large until they are allowed to heat up due to the passage of current, they are also commonly used to prevent excessive current surges when equipment is powered on. Similarly, the resistance of a humistor varies with humidity. Metal oxide varistors drop to a very low resistance when a high voltage is applied, making them useful for protecting electronic equipment by absorbing dangerous voltage surges. One sort of photodetector, the photoresistor, has a resistance which varies with illumination.

The strain gauge, invented by Edward E. Simmons and Arthur C. Ruge in 1938, is a type of resistor that changes value with applied strain. A single resistor may be used, or a pair (half bridge), or four resistors connected in a Wheatstone bridge configuration. The strain resistor is bonded with adhesive to an object that will be subjected to mechanical strain. With the strain gauge and a filter, amplifier, and analog/digital converter, the strain on an object can be measured.

A related but more recent invention uses a Quantum Tunnelling Composite to sense mechanical stress. It passes a current whose magnitude can vary by a factor of 10^{12} in response to changes in applied pressure.

Measurement

The value of a resistor can be measured with an ohmmeter, which may be one function of a multimeter. Usually, probes on the ends of test leads connect to the resistor. A simple ohmmeter may apply a voltage from a battery across the unknown resistor (with an internal resistor of a known value in series) producing a current which drives a meter movement. The current flow, in accordance with Ohm's Law, is inversely proportional to the sum of the internal resistance and the resistor being tested, resulting in an analog meter scale which is very non-linear, calibrated from infinity to 0 ohms. A digital multimeter, using active electronics, may instead pass a specified current through the test resistance. The voltage generated across the test resistance in that case is linearly proportional to its resistance, which is measured and displayed. In either case the low-resistance ranges of the meter pass much more current through the test leads than do high-resistance ranges, in order for the voltages present to be at reasonable levels (generally below 10 volts) but still measurable.

Measuring low-value resistors, such as fractional-ohm resistors, with acceptable accuracy requires four-terminal connections. One pair of terminals applies a known, calibrated current to the resistor, while the other pair senses the voltage drop across the resistor.

Some laboratory quality ohmmeters, especially milliohmmeters, and even some of the better digital multimeters sense using four input terminals for this purpose, which may be used with special test leads. Each of the two so-called Kelvin clips has a pair of jaws insulated from each other. One side of each clip applies the measuring current, while the other connections are only to sense the voltage drop. The resistance is again calculated using Ohm's Law as the measured voltage divided by the applied current.

Standards

Production resistors

Resistor characteristics are quantified and reported using various national standards. In the US, MIL-STD-202 contains the relevant test methods to which other standards refer.

There are various standards specifying properties of resistors for use in equipment:

- BS 1852
- EIA-RS-279
- MIL-PRF-26
- MIL-PRF-39007 (Fixed Power, established reliability)
- MIL-PRF-55342 (Surface-mount thick and thin film)
- MIL-PRF-914
- MIL-R-11
- MIL-R-39017 (Fixed, General Purpose, Established Reliability)
- MIL-PRF-32159 (zero ohm jumpers)

There are other United States military procurement MIL-R- standards.

Resistance standards

The primary standard for resistance, the "mercury ohm" was initially defined in 1884 in as a column of mercury 106 mm long and 1 square millimeter in cross-section, at 0 degrees Celsius. Difficulties in precisely measuring the physical constants to replicate this standard result in variations of as much as 30 ppm. From 1900 the mercury ohm was replaced with a precision machined plate of manganin. Since 1990 the international resistance standard has been based on the quantized Hall effect discovered by Klaus von Klitzing, for which he won the Nobel Prize in Physics in 1985.

Resistors of extremely high precision are manufactured for calibration and laboratory use. They may have four terminals, using one pair to carry an operating current and the other pair to measure the voltage drop; this eliminates errors caused by voltage drops across the lead resistances, because no current flows through voltage sensing leads. It is important in small value resistors (100–0.0001 ohm) where lead resistance is significant or even comparable with respect to resistance standard value.

Resistor marking

Most axial resistors use a pattern of colored stripes to indicate resistance. Surface-mount resistors are marked numerically, if they are big enough to permit marking; more-recent small sizes are impractical to mark. Cases are usually tan, brown, blue, or green, though other colors are occasionally found such as dark red or dark gray.

Early 20th century resistors, essentially uninsulated, were dipped in paint to cover their entire body for color coding. A second color of paint was applied to one end of the element, and a color dot (or band) in the middle provided the third digit. The rule was "body, tip, dot", providing two significant digits for value and the decimal multiplier, in that sequence. Default tolerance was ±20%. Closer-tolerance resistors had silver (±10%) or gold-colored (±5%) paint on the other end.

Four-band resistors

Four-band identification is the most commonly used color-coding scheme on resistors. It consists of four colored bands that are painted around the body of the resistor. The first two bands encode the first two significant digits of the resistance value, the third is a power-of-ten multiplier or number-of-zeroes, and the fourth is the tolerance accuracy, or acceptable error, of the value. The first three bands are equally spaced along the resistor; the spacing to the fourth band is wider. Sometimes a fifth band identifies the thermal coefficient, but this must be distinguished from the true 5-color system, with 3 significant digits.

For example, green-blue-yellow-red is 56×10^4 Ω = 560 kΩ ± 2%. An easier description can be as followed: the first band, green, has a value of 5 and the second band, blue, has a value of 6, and is counted as 56. The third band, yellow, has a value of 10^4, which adds four 0's to the end, creating 560,000 Ω at ±2% tolerance accuracy. 560,000 Ω changes to 560 kΩ ±2% (as a kilo- is 10^3).

Each color corresponds to a certain digit, progressing from darker to lighter colors, as shown in the chart below.

Color	1st band	2nd band	3rd band (multiplier)	4th band (tolerance)	Temp. Coefficient
Black	0	0	$\times10^0$		
Brown	1	1	$\times10^1$	±1% (F)	100 ppm
Red	2	2	$\times10^2$	±2% (G)	50 ppm
Orange	3	3	$\times10^3$		15 ppm
Yellow	4	4	$\times10^4$		25 ppm
Green	5	5	$\times10^5$	±0.5% (D)	
Blue	6	6	$\times10^6$	±0.25% (C)	
Violet	7	7	$\times10^7$	±0.1% (B)	

Gray	8	8	$\times 10^{8}$	±0.05% (A)	
White	9	9	$\times 10^{9}$		
Gold			$\times 10^{-1}$	±5% (J)	
Silver			$\times 10^{-2}$	±10% (K)	
None				±20% (M)	

There are many mnemonics for remembering these colors.

Preferred values

Early resistors were made in more or less arbitrary round numbers; a series might have 100, 125, 150, 200, 300, etc. Resistors as manufactured are subject to a certain percentage tolerance, and it makes sense to manufacture values that correlate with the tolerance, so that the actual value of a resistor overlaps slightly with its neighbors. Wider spacing leaves gaps; narrower spacing increases manufacturing and inventory costs to provide resistors that are more or less interchangeable.

A logical scheme is to produce resistors in a range of values which increase in a geometrical progression, so that each value is greater than its predecessor by a fixed multiplier or percentage, chosen to match the tolerance of the range. For example, for a tolerance of ±20% it makes sense to have each resistor about 1.5 times its predecessor, covering a decade in 6 values. In practice the factor used is 1.4678, giving values of 1.47, 2.15, 3.16, 4.64, 6.81, 10 for the 1-10 decade (a decade is a range increasing by a factor of 10; 0.1-1 and 10-100 are other examples); these are rounded in practice to 1.5, 2.2, 3.3, 4.7, 6.8, 10; followed, of course by 15, 22, 33, … and preceded by … 0.47, 0.68, 1. This scheme has been adopted as the **E6** range of the IEC 60063 preferred number series. There are also **E12**, **E24**, **E48**, **E96** and **E192** ranges for components of ever tighter tolerance, with 12, 24, 96, and 192 different values within each decade. The actual values used are in the IEC 60063 lists of preferred numbers.

A resistor of 100 ohms ±20% would be expected to have a value between 80 and 120 ohms; its E6 neighbors are 68 (54-82) and 150 (120-180) ohms. A sensible spacing, E6 is used for ±20% components; E12 for ±10%; E24 for ±5%; E48 for ±2%, E96 for ±1%; E192 for ±0.5% or better. Resistors are manufactured in values from a few milliohms to about a gigaohm in IEC60063 ranges appropriate for their tolerance.

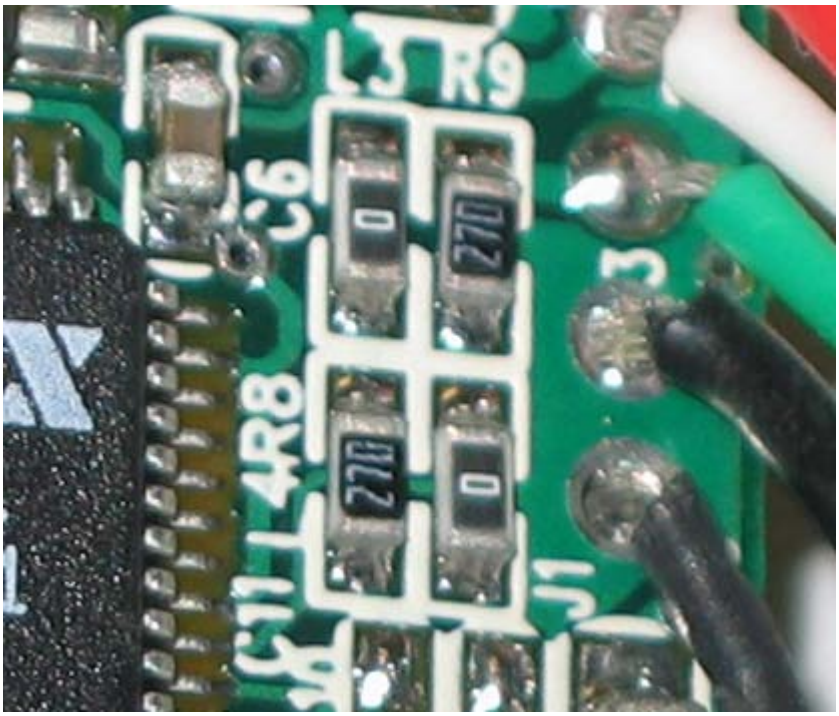
Earlier power wirewound resistors, such as brown vitreous-enameled types, however, were made with a different system of preferred values, such as some of those mentioned in the first sentence of this section.

5-band axial resistors

5-band identification is used for higher precision (lower tolerance) resistors (1%, 0.5%, 0.25%, 0.1%), to specify a third significant digit. The first three bands represent the significant digits, the fourth is the multiplier, and the fifth is the tolerance. Five-band

resistors with a gold or silver 4th band are sometimes encountered, generally on older or specialized resistors. The 4th band is the tolerance and the 5th the temperature coefficient.

SMD resistors



This image shows four surface-mount resistors (the component at the upper left is a capacitor) including two zero-ohm resistors. Zero-ohm links are often used instead of wire links, so that they can be inserted by a resistor-inserting machine. Of course, their resistance is non-zero, although quite low. *Zero* is simply a brief description of their function.

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

334 = 33 × 10^4 ohms = 330 kilohms
222 = 22 × 10^2 ohms = 2.2 kilohms
473 = 47 × 10^3 ohms = 47 kilohms
105 = 10 × 10^5 ohms = 1.0 megohm

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

100 = 10 × 10^0 ohm = 10 ohms
220 = 22 × 10^0 ohm = 22 ohms

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

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

4R7 = 4.7 ohms
R300 = 0.30 ohms
0R22 = 0.22 ohms
0R01 = 0.01 ohms

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

1001 = 100 × 10^1 ohms = 1.00 kilohm
4992 = 499 × 10^2 ohms = 49.9 kilohm
1000 = 100 × 10^0 ohm = 100 ohms

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

More recent surface-mount resistors are too small, physically, to permit practical markings to be applied.

Industrial type designation

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

	Power Rating at 70 °C			Tolerance Code		
Type No.	**Power rating (watts)**	**MIL-R-11 Style**	**MIL-R-39008 Style**	**Industrial type designation**	**Tolerance**	**MIL Designation**
BB	⅛	RC05	RCR05	5	±5%	J
CB	¼	RC07	RCR07	2	±20%	M
EB	½	RC20	RCR20	1	±10%	K
GB	1	RC32	RCR32	-	±2%	G
HB	2	RC42	RCR42	-	±1%	F
GM	3	-	-	-	±0.5%	D
HM	4	-	-	-	±0.25%	C

-	±0.1%	B

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

- Commercial grade: 0 °C to 70 °C
- Industrial grade: −40 °C to 85 °C (sometimes −25 °C to 85 °C)
- Military grade: −55 °C to 125 °C (sometimes -65 °C to 275 °C)
- Standard Grade -5 °C to 60 °C

Electrical and thermal noise

In amplifying faint signals, it is often necessary to minimize electronic noise, particularly in the first stage of amplification. As dissipative elements, even an ideal resistor will naturally produce a randomly fluctuating voltage or "noise" across its terminals. This Johnson–Nyquist noise is a fundamental noise source which depends only upon the temperature and resistance of the resistor, and is predicted by the fluctuation–dissipation theorem. Using a larger resistor produces a larger voltage noise, whereas with a smaller value of resistance there will be more current noise, assuming a given temperature. The thermal noise of a practical resistor may also be somewhat larger than the theoretical prediction and that increase is typically frequency-dependent.

However the "excess noise" of a practical resistor is an additional source of noise observed only when a current flows through it. This is specified in unit of μV/V/decade - μV of noise per volt applied across the resistor per decade of frequency. The μV/V/decade value is frequently given in dB so that a resistor with a noise index of 0 dB will exhibit 1 μV (rms) of excess noise for each volt across the resistor in each frequency decade. Excess noise is thus an example of 1/*f* noise. Thick-film and carbon composition resistors generate more excess noise than other types at low frequencies; wire-wound and thin-film resistors, though much more expensive, are often utilized for their better noise characteristics. Carbon composition resistors can exhibit a noise index of 0 dB while bulk metal foil resistors may have a noise index of -40 dB, usually making the excess noise of metal foil resistors insignificant. Thin film surface mount resistors typically have lower noise and better thermal stability than thick film surface mount resistors. However, the design engineer must read the data sheets for the family of devices to weigh the various device tradeoffs.

While not an example of "noise" per se, a resistor may act as a thermocouple, producing a small DC voltage differential across it due to the thermoelectric effect if its ends are at somewhat different temperatures. This induced DC voltage can degrade the precision of instrumentation amplifiers in particular. Such voltages appear in the junctions of the resistor leads with the circuit board and with the resistor body. Common metal film resistors show such an effect at a magnitude of about 20 μV/°C. Some carbon composition resistors can exhibit thermoelectric offsets as high as 400 μV/°C, whereas specially constructed resistors can reduce this number to 0.05 μV/°C. In applications where the thermoelectric effect may become important, care has to be taken (for

example) to mount the resistors horizontally to avoid temperature gradients and to mind the air flow over the board.

Failure modes

The failure rate of resistors in a properly designed circuit is low compared to other electronic components such as semiconductors and electrolytic capacitors. Damage to resistors most often occurs due to overheating when the average power delivered to it (as computed above) greatly exceeds its ability to dissipate heat (specified by the resistor's *power rating*). This may be due to a fault external to the circuit, but is frequently caused by the failure of another component (such as a transistor that shorts out) in the circuit connected to the resistor. Operating a resistor too close to its power rating can limit the resistor's lifespan or cause a change in its resistance over time which may or may not be noticeable. A safe design generally uses overrated resistors in power applications to avoid this danger.

When overheated, carbon-film resistors may decrease or increase in resistance. Carbon film and composition resistors can fail (open circuit) if running close to their maximum dissipation. This is also possible but less likely with metal film and wirewound resistors.

There can also be failure of resistors due to mechanical stress and adverse environmental factors including humidity. If not enclosed, wirewound resistors can corrode.

Variable resistors degrade in a different manner, typically involving poor contact between the wiper and the body of the resistance. This may be due to dirt or corrosion and is typically perceived as "crackling" as the contact resistance fluctuates; this is especially noticed as the device is adjusted. This is similar to crackling caused by poor contact in switches, and like switches, potentiometers are to some extent self-cleaning: running the wiper across the resistance may improve the contact. Potentiometers which are seldom adjusted, especially in dirty or harsh environments, are most likely to develop this problem. When self-cleaning of the contact is insufficient, improvement can usually be obtained through the use of contact cleaner (also known as "tuner cleaner") spray. The crackling noise associated with turning the shaft of a dirty potentiometer in an audio circuit (such as the volume control) is greatly accentuated when an undesired DC voltage is present, often implicating the failure of a DC blocking capacitor in the circuit.

Chapter- 11

Electrical Ballast

"Choke ballast" (inductor) used in older lighting. This example is from a tanning bed. Requires a lamp starter (below) and capacitor.

Lamp starter, required with some inductor type ballasts. Connects both ends of the lamp together to "preheat" the lamp ends for 1 second before lighting.

An **electrical ballast** (sometimes called **control gear**) is a device intended to limit the amount of current in an electric circuit.

Ballasts vary greatly in complexity. They can be as simple as a series resistor as commonly used with small neon lamps or light-emitting diodes (LEDs). For higher-power installations, too much energy would be wasted in a resistive ballast, so alternatives are used that depend upon the reactance of inductors, capacitors, or both. Finally, ballasts can be as complex as the computerized, remote-controlled electronic ballasts now often used with fluorescent lamps.

Current limiting

Ballasts stabilize the current through an electrical load. These are most often used when an electrical circuit or device presents a negative (differential) resistance to the supply. If such a device were connected to a constant-voltage power supply, it would draw an increasing amount of current until it was destroyed or caused the power supply to fail. To prevent this, a ballast provides a positive resistance or reactance that limits the ultimate current to an appropriate level. In this way, the ballast provides for the proper operation of the negative-resistance device by appearing to be a legitimate, stable resistance in the circuit.

An example of a negative-resistance device is a gas-discharge lamp, where after lamp ignition, increasing arc current reduces the voltage drop.

Ballasts can also be used simply to deliberately reduce the current in an ordinary, positive-resistance circuit.

Prior to the advent of solid-state ignition, automobile ignition systems commonly included a ballast resistor to regulate the voltage applied to the ignition system.

Although LEDs are positive resistance devices, they have insufficient resistance to regulate their current consumption when operated from a voltage controlled source, so ballasts are used to control the current through the LED. Because the power dissipation is minuscule, simple resistor ballasts are normally used.

Resistors

A **ballast resistor** compensates for normal or incidental changes in the physical state of a system. It may be a fixed or variable resistor.

Fixed resistors

For simple, low-powered loads such as a neon lamp or LED, a fixed resistor is commonly used. Because the resistance of the ballast resistor is large it dominates the current in the circuit, even in the face of negative resistance introduced by the neon lamp.

The term also refers to an automobile engine component that lowers the supply voltage to the ignition system after the engine has been started. Because cranking the engine causes a very heavy load on the battery, the system voltage can drop quite low during cranking.

To allow the engine to start, the ignition system must be designed to operate on this lower voltage. But once cranking is completed, the normal operating voltage is regained; this voltage would overload the ignition system. To avoid this problem, a ballast resistor is inserted in series with the supply voltage feeding the ignition system. Occasionally, this ballast resistor will fail and the classic symptom of this failure is that the engine runs while being cranked (while the resistor is bypassed) but stalls immediately when cranking ceases (and the resistor is re-connected in the circuit).

Modern electronic ignition systems do not require a ballast resistor as they are flexible enough to operate on the low cranking voltage or the ordinary operating voltage.

In some old AC/DC receivers (universal sets), the vacuum tube heaters are connected in series. Since the voltage drop across all the filaments in series is sometimes less than the full mains voltage, it was often necessary to get rid of the excess voltage. A ballast resistor was often used for this purpose, as it was cheap and worked with both AC and DC.

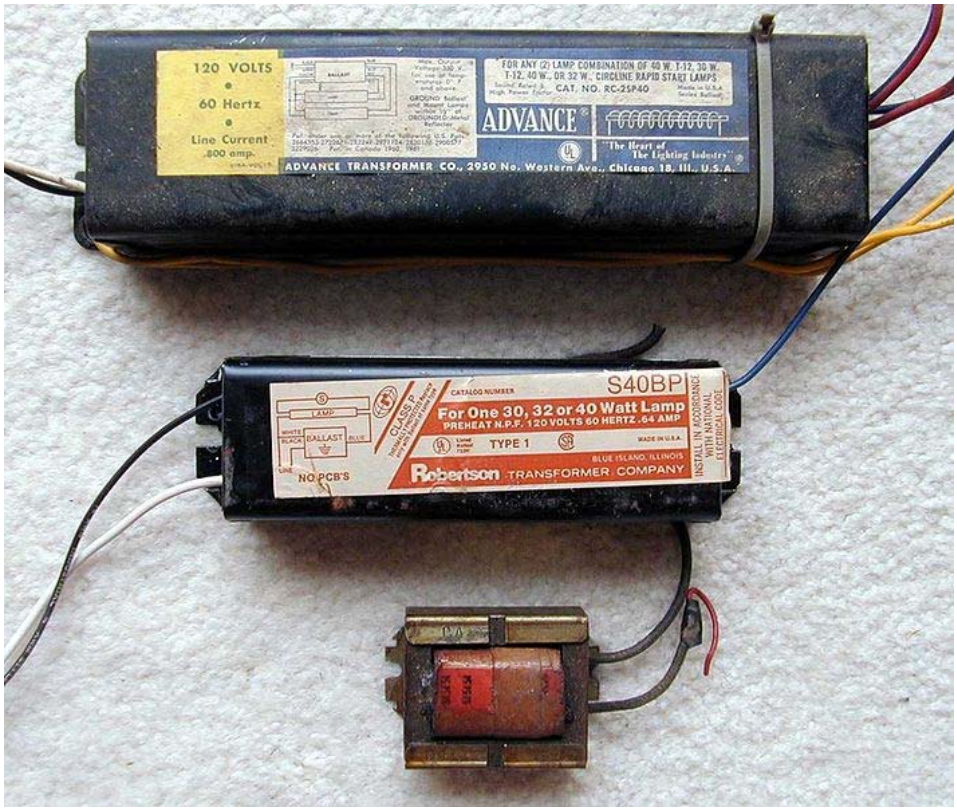
Self-variable resistors

Some ballast resistors have the property of increasing in resistance as current through them increases, and decreasing in resistance as current decreases. Physically, some such devices are often built quite like incandescent lamps. Like the tungsten filament of an ordinary incandescent lamp, if current increases, the ballast resistor gets hotter, its resistance goes up, and its voltage drop increases. If current decreases, the ballast resistor gets colder, its resistance drops, and the voltage drop decreases. Therefore the ballast resistor reduces variations in current, despite variations in applied voltage or changes in the rest of an electric circuit. These devices are sometimes termed barretters.

This property can lead to more precise current control than merely choosing an appropriate fixed resistor. The power lost in the resistive ballast is also reduced because a smaller portion of the overall power is dropped in the ballast compared to what might be required with a fixed resistor.

In times past, household clothes dryers sometimes incorporated a germicidal lamp in series with an ordinary incandescent lamp; the incandescent lamp operated as the ballast for the germicidal lamp. A commonly used light in the home in the 1960s in 220-240V countries was a circleline tube ballasted by an under-run regular mains filament lamp. Self ballasted mercury-vapor lamps incorporate ordinary tungsten filaments within the overall envelope of the lamp to act as the ballast, and it supplements the otherwise lacking red area of the light spectrum produced.

Reactive ballasts



Several typical magnetic ballasts for fluorescent lamps. The top is a high-power factor rapid start series ballast for two 30-40W lamps. The middle is a low power factor preheat ballast for a single 30-40W lamp while the bottom ballast is a simple inductor used with a 15W preheat lamp.

Because of the power that would be lost, resistors are not used as ballasts for lamps of more than about two watts. Instead, a reactance is used. Losses in the ballast due to its resistance and losses in its magnetic core may be significant, on the order of 5 to 25% of the lamp input wattage. Practical lighting design calculations must allow for ballast loss in estimating the running cost of a lighting installation.

An inductor is very common in line-frequency ballasts to provide the proper starting and operating electrical condition to power a fluorescent lamp, neon lamp, or high intensity discharge (HID) lamp. (Because of the use of the inductor, such ballasts are usually called *magnetic ballasts*.) The inductor has two benefits:

1. Its reactance limits the power available to the lamp with only minimal power losses in the inductor
2. The voltage spike produced when current through the inductor is rapidly interrupted is used in some circuits to first strike the arc in the lamp.

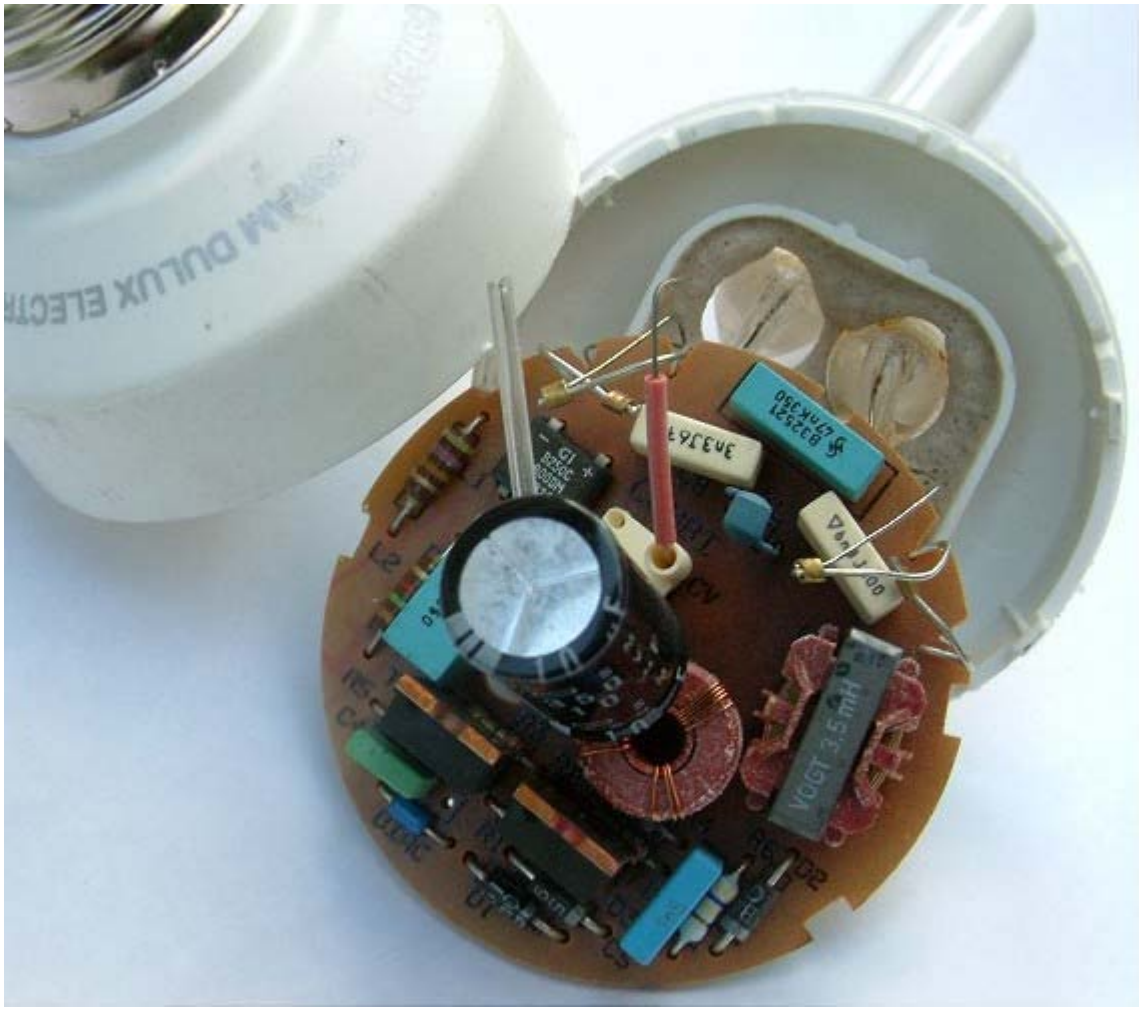
A disadvantage of the inductor is that current is shifted out of phase with the voltage, producing a poor power factor. In more expensive ballasts, a capacitor is often paired with the inductor to correct the power factor. In ballasts that control two or more lamps, line-frequency ballasts commonly use different phase relationships between the multiple lamps. This not only mitigates the flicker of the individual lamps, it also helps maintain a high power factor. These ballasts are often called *lead-lag* ballasts because the current in one lamp leads the mains phase and the current in the other lamp lags the mains phase.

For large lamps, line voltage may not be sufficient to start the lamp, so an autotransformer winding is included in the ballast to step up the voltage. The autotransformer is designed with enough leakage inductance so that the current is appropriately limited.

Because of the large inductors and capacitors that must be used, reactive ballasts operated at line frequency tend to be large and heavy. They commonly also produce acoustic noise (line-frequency hum).

Prior to 1980 in the United States, PCB-based oils were used as an insulating oil in many ballasts to provide cooling and electrical isolation.

Electronic ballasts



Electronic ballast of a compact fluorescent lamp

An **electronic lamp ballast** uses solid state electronic circuitry to provide the proper starting and operating electrical condition to power one or more fluorescent lamps and more recently HID lamps. Electronic ballasts usually change the frequency of the power from the standard mains (e.g., 60 Hz in U.S.) frequency to 20,000 Hz or higher, substantially eliminating the stroboscopic effect of flicker (a product of the line frequency) associated with fluorescent lighting. In addition, because more gas remains ionized in the arc stream, the lamps actually operate at about 9% higher efficacy above approximately 10 kHz. Lamp efficacy increases sharply at about 10 kHz and continues to improve until approximately 20 kHz. Because of the higher efficiency of the ballast itself and the improvement of lamp efficacy by operating at a higher frequency, electronic ballasts offer higher system efficacy for low pressure lamps like the fluorescent lamp. For HID lamps there is no improvement of the lamp efficacy in using higher frequency, but for these lamps the ballast losses are lower at higher frequencies and also the light depreciation is lower meaning more light after a given operating time of say 10 000 hours. Some HID lamp types like the Ceramic discharge metal halide lamp have reduced reliability when operated at high frequencies in the range of 20kHz to 200 kHz and for

these lamps a square wave low frequency current drive is mostly used with frequency in the range of 100 to 400 Hz, with the same advantage of lower light depreciation. Electronic ballasts are often based on the SMPS topology, first rectifying the input power and then chopping it at a high frequency. Advanced electronic ballasts may allow dimming via pulse-width modulation or via changing the frequency to a higher value and remote control and monitoring via networks such as LonWorks, DALI, DMX-512, DSI or simple analog control using a 0-10V DC brightness control signal. Recently also systems remotely controlling the dim level via a wireless mesh network have been introduced.

Fluorescent lamp ballasts

Instant start

An instant start ballast starts lamps without heating the cathodes at all by using high voltage (around 600 V). It is the most energy efficient type, but gives the least number of starts from a lamp as emissive oxides are blasted from the cold cathode surfaces each time the lamp is started. This is the best type for installations where lamps are not turned on and off very often.

Rapid start

A rapid start ballast applies voltage and heats the cathodes simultaneously. Provides superior lamp life and more cycle life, but uses slightly more energy as the cathodes in each end of the lamp continue to consume heating power as the lamp operates. A dimming circuit can be used with a dimming ballast, which maintains the heating current while allowing lamp current to be controlled.

Programmed start

A programmed-start ballast is a more advanced version of rapid start. This ballast applies power to the filaments first, then after a short delay to allow the cathodes to preheat, applies voltage to the lamps to strike an arc. This ballast gives the best life and most starts from lamps, and so is preferred for applications with very frequent power cycling such as vision examination rooms and restrooms with a motion detector switch.

Ballast factor

For a lighting ballast, the *ballast factor* is defined as the light output (in lumens) with a test ballast, compared to the light output with a laboratory reference ballast that operates the lamp at its specified nominal power rating. The ballast factor of practical ballasts must be considered in lighting design; a low ballast factor may save energy, but will produce less light. With fluorescent lamps, an electronic ballast may produce more light than the reference test ballast, which operates the lamp with line frequency current; such electronic ballasts have a ballast factor greater than one.

Chapter- 12

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

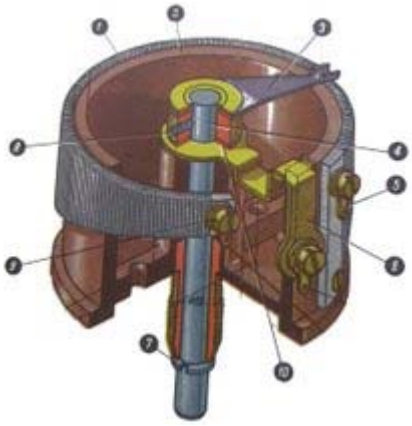
(one side and the wiper), it acts as a ***variable resistor*** or ***rheostat***. Potentiometers are commonly used to control electrical devices such as volume controls on audio equipment. Potentiometers operated by a mechanism can be used as position transducers, for example, in a joystick.

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

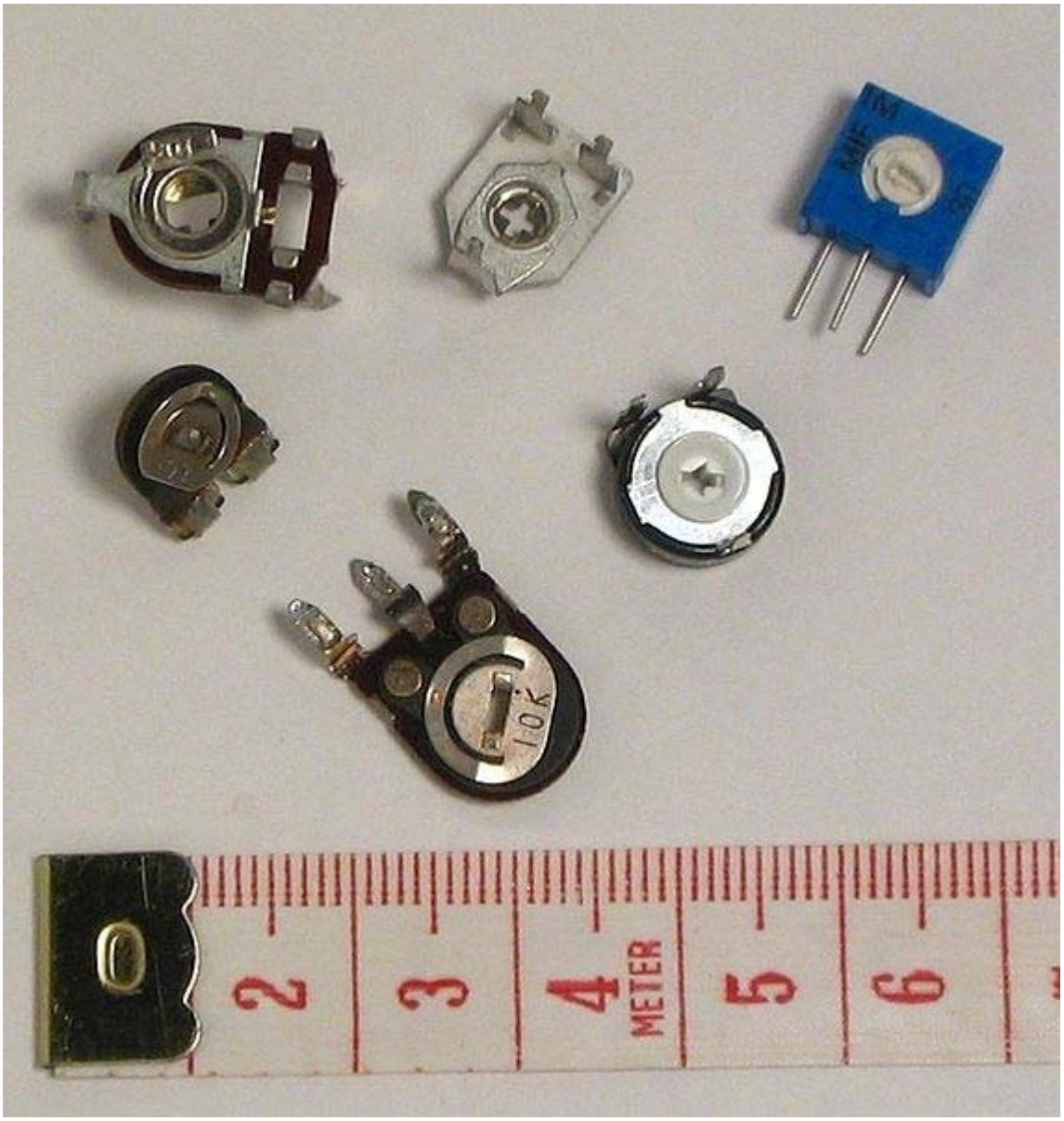
helical and the wiper may move 10, 20, or more complete revolutions, though multiturn potentimeters are usually constructed of a conventional resistive element wiped via a worm gear. Besides graphite, materials used to make the resistive element include resistance wire, carbon particles in plastic, and 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.

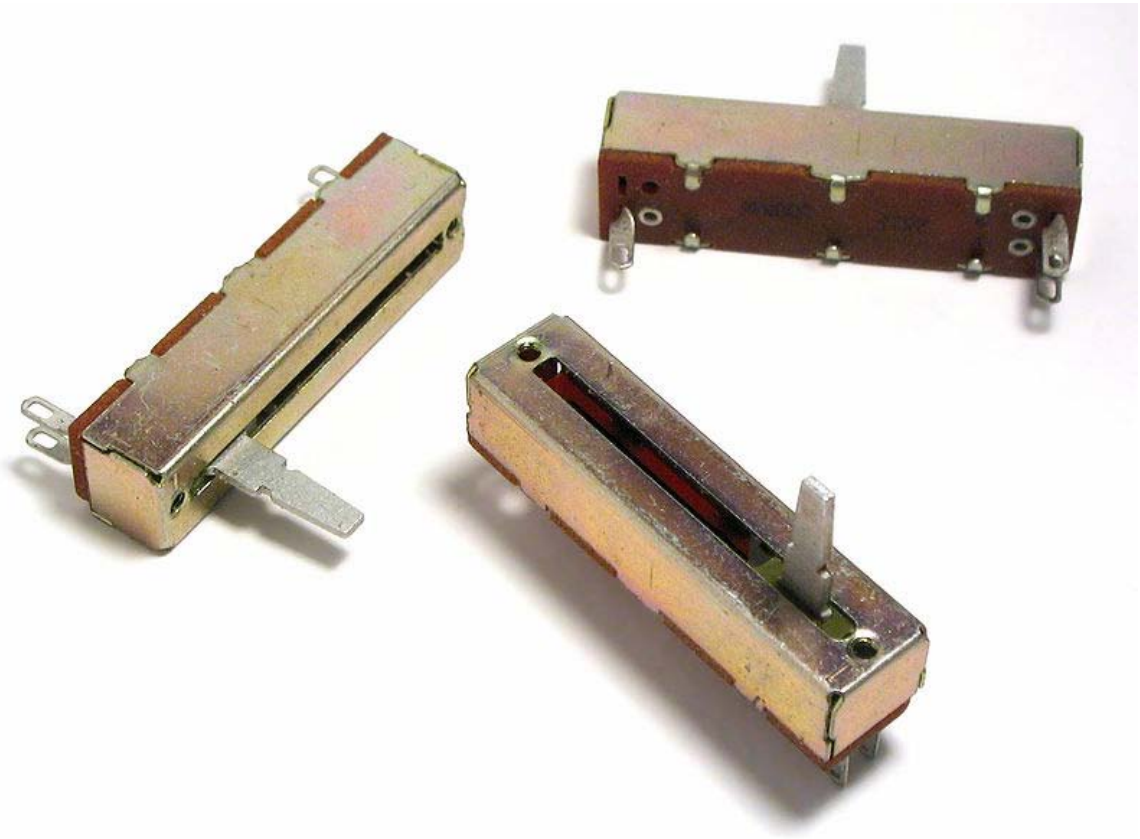
Membrane Potentiometer

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.

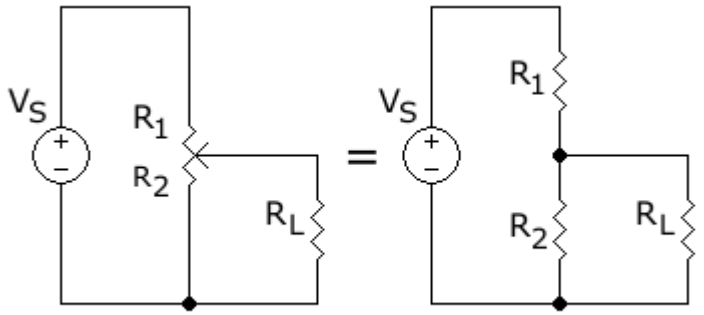
Transducers

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:

$$V_L = \frac{R_2 R_L}{R_1 R_L + R_2 R_L + R_1 R_2} \cdot V_s.$$

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:

$$V_L = \frac{R_2}{R_1 + R_2} \cdot V_s.$$

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.

Early patents

- US patent 131,334, Thomas Edison, "Coiled resistance wire rheostat", issued 1872-9-17
- Mary Hallock-Greenewalt invented a type of nonlinear rheostat for use in her visual-music instrument, the Sarabet (US patent 1,357,773)

Chapter- 13

Digital Potentiometer & Bleeder Resistor

Digital Potentiometer

A **digital potentiometer** is a digitally-controlled electronic component that mimics the analog functions of a potentiometer. It is often used for trimming and scaling analog signals by microcontrollers. It is either built using an R-2R integrated circuit or a Digital-to-analog converter. A digital potentiometer is an electronic component that is often controlled by digital protocols like I²C and SPI, as well as more basic Up/Down protocols. Some typical uses of digital potentiometers are in circuits requiring gain control of amplifiers (frequently instrumentation amplifiers), small-signal audio-balancing, and offset adjustment.

Sometimes this device is also referred to as an RDAC, Resistive Digital-to-Analog Converter.

Some Digipots come with non-volatile memory, so that they retain their last programmed position after they have been power cycled. Most, though, are volatile, i.e. after they are power cycled they will default to a standard value, which is usually the mid-point.

The former can be useful, but when they are controlled by a microprocessor, or even via a Field Programmable Gate Array (FPGA), these devices can retain, in other non-volatile memory, the value to initialise the Digipot with. In these circumstances, the need for non-volatile Digipots is less obvious.

Limitations

These devices are extremely useful in the modern, digitally controlled world, but have some limitations. While quite similar to a normal potentiometer, digital potentiometers are somewhat constrained by current limits in the tens of milliamperes. Also, most, if not all digital potentiometers limit the input voltage range to the digital supply range (often 0–5 VDC), so some ingenuity is often required when attempting to replace standard resistive potentiometers with digital potentiometers. Further, instead of the seemingly continuous control that can be obtained from a multiturn resistive potentiometer, digital

potentiometers have discrete steps in resistance. Eight-bit pots (256-steps) are most common, but potentiometers between 5 and 10 bits (32 to 1024 steps) are available. A fourth constraint is that special logic is often required to check for zero crossing of an analog AC signal to allow the resistance value to be changed without causing an audible click in the output for audio amplifiers.

The non-volatile Digipots also differ from their electro-mechanical cousins in that on power up, the resistance will default to (possibly) a different value after a power cycle.

Similarly, the Digipot resistance is only valid when the correct DC supply voltage(s) are present. When voltages are removed, the resistance between the two end points and the (nominal) Wiper are undefined. In an operational amplifier circuit, the Off-State impedance of a real potentiometer can help stabilise the DC operating point of the circuit during the power-up stage. This may not be the case when a Digipot is used.

Like their electro-mechanical counterparts, Digipots suffer similar weaknesses. Real potentiometers and Digipots generally have poor tolerances (typically +/- 20%), poor temperature coefficients (many hundreds of ppm per degree C), and a stop resistance that is typically about 0.5-1% of the full scale resistance. Note that Stop Resistance is the residual resistance when the terminal to wiper resistance is set to the minimum value.

Bleeder Resistor

A **bleeder resistor** is a resistor placed in parallel with a high-voltage supply for the purposes of discharging the energy stored in the power source's filter capacitors or other components that store electrical energy when the equipment is turned off.

It is a use for a standard resistor rather than a separate type of component.

Usage

DC power supplies

Power supplies, especially switchmode power supplies, use a bridge rectifier to convert mains AC power into a typical 340 volts DC for the chopper. A large filter capacitor typically stores enough energy at this high voltage to power the load during the zero crossings of the AC input. In fact, the capacitors in many supplies are large enough to support the load during AC outages lasting for a significant fraction of a second. This stored energy is clearly potentially lethal, and without a bleeder resistor it might remain long after the unit has been turned off. With a properly sized bleeder resistor, however, the voltage will quickly decay to safe levels when the supply is switched off, yet not consume too much power while the supply is on.

High voltage supply in television sets

The bleeder resistor commonly found inside a flyback transformer that supplies high voltage for a CRT is valued in the hundreds of megohms range, and can therefore not be measured with the common technician's multimeter.

Instead of a resistor inside the transformer, the focus and screen control array may be used for the same purpose, depending on the application and tolerances of the type of tube it is producing output for.

These bleeders discharge the focus supply, but not the high voltage final anode feed. The CRT itself forms a capacitor that can hold a sizable (and very dangerous) high voltage charge, so it is **always** advisable to momentarily ground a CRT's high voltage terminal before working on the unit.

Failure

The failure of a bleeder resistor prevents the discharge of the capacitors, resulting in dangerous voltages being retained for many days. This is one of several reasons for the typical warning on most equipment: "Warning - No user-serviceable parts inside". An un-suspecting user may get an electrical shock from opened equipment due to failure of a bleeder resistor, or the common practice of not fitting them.

Safe design suggests mounting a bleeder close to a dangerous capacitor, ideally directly to the capacitor terminals, and not through any connectors, so that it is difficult to disconnect the bleeder accidentally.

Despite the presence of a bleeder, it is wise to prove that any potentially dangerous capacitors are discharged, perhaps by shorting their terminals (or through a suitable low resistance for high energy capacitors), before working on any circuit.

Technical considerations

There is always a trade-off between the speed with which the bleeder operates and the amount of power wasted in the bleeder; a faster bleed-down rate wastes more power during normal, power-on operation.

The presence of a bleeder also guarantees a minimum load on the power source, which can help reduce the range of voltage change (regulation) when the normal load is changing and there is no active regulator. Use of a bleeder this way is a common design strategy for power supplies of vacuum tube power amplifiers, for instance.

Dual bleeder

Because of the speed/power tradeoff, high-powered circuits may use two separate bleeder circuits. A fast bleed circuit is switched out during normal operation so that no power is

wasted; when power is switched off, the fast bleeder is connected, rapidly bleeding down the voltage. The switch controlling the fast bleeder can fail, either by connecting when it shouldn't (and overheating) or by not connecting when it should (and thereby failing to bleed off the voltage quickly). To avoid the risk of not having an operational bleeder, a secondary, slower (and less lossy) bleeder is usually permanently connected so that there is always some bleed-down capability.

Chapter- 14

Attenuator (Electronics)

A 30dB 5W RF-attenuator, DC-18GHz, with N-type coaxial connectors

Coaxial Dynamics 100 Watt power attenuator

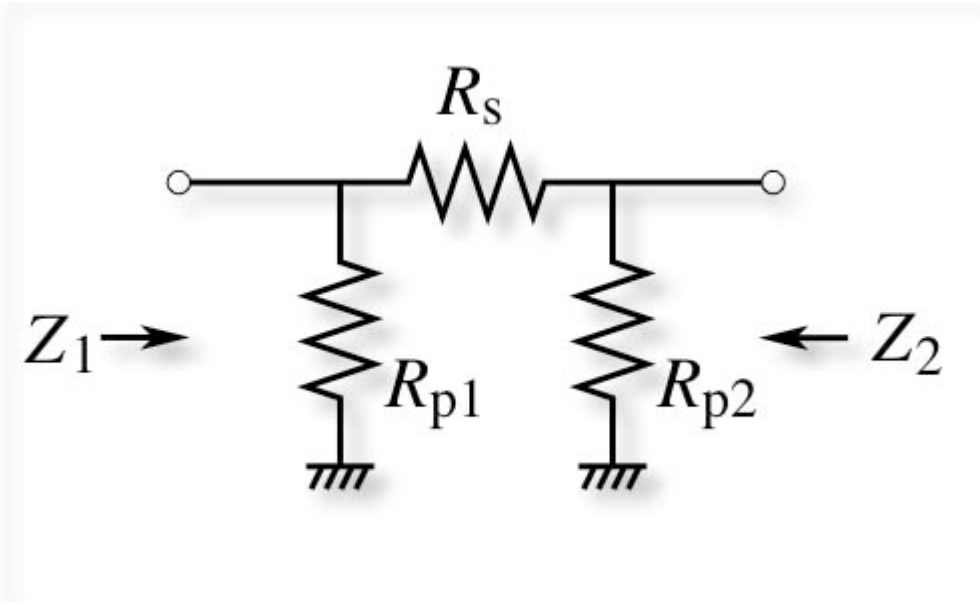
An **attenuator** is an electronic device that reduces the amplitude or power of a signal without appreciably distorting its waveform.

An attenuator is effectively the opposite of an amplifier, though the two work by different methods. While an amplifier provides gain, an attenuator provides loss, or gain less than 1.

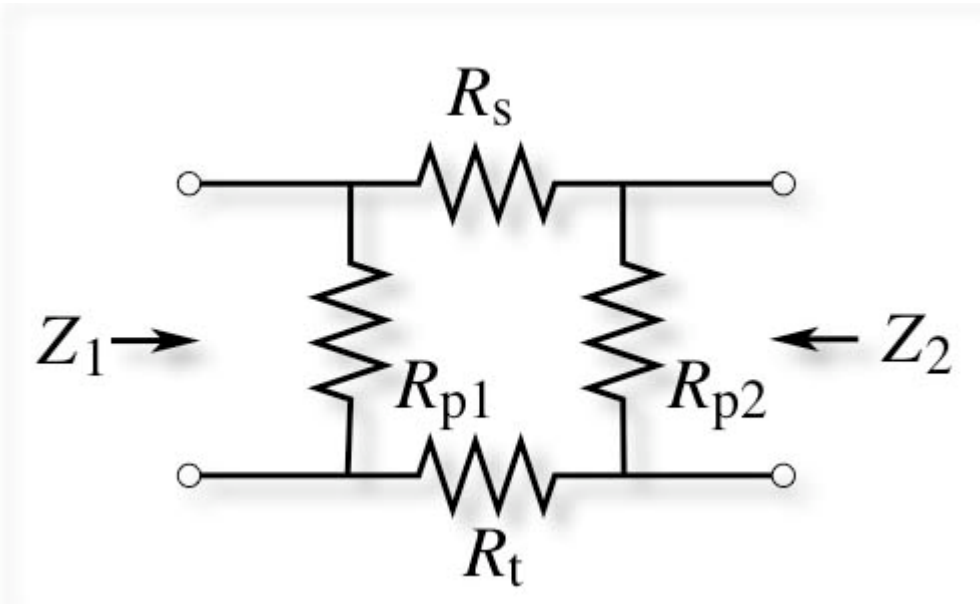
Attenuators are usually passive devices made from simple voltage divider networks. Switching between different resistances forms adjustable stepped attenuators and continuously adjustable ones using potentiometers. For higher frequencies precisely matched low VSWR resistance networks are used.

Fixed attenuators in circuits are used to lower voltage, dissipate power, and to improve impedance matching. In measuring signals, attenuator pads or adaptors are used to lower the amplitude of the signal a known amount to enable measurements, or to protect the measuring device from signal levels that might damage it. Attenuators are also used to 'match' impedances by lowering apparent SWR.

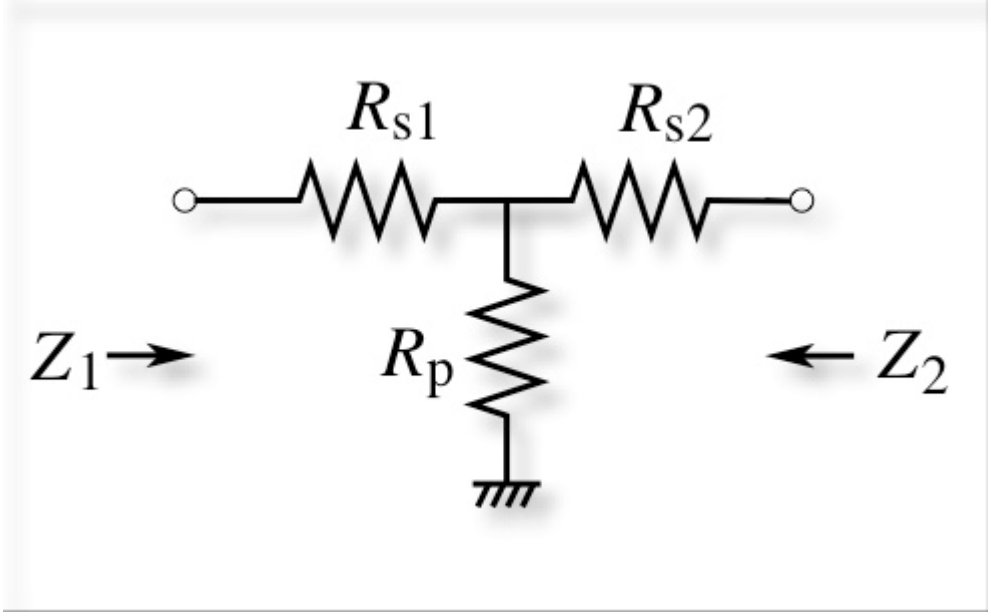
Attenuator circuits



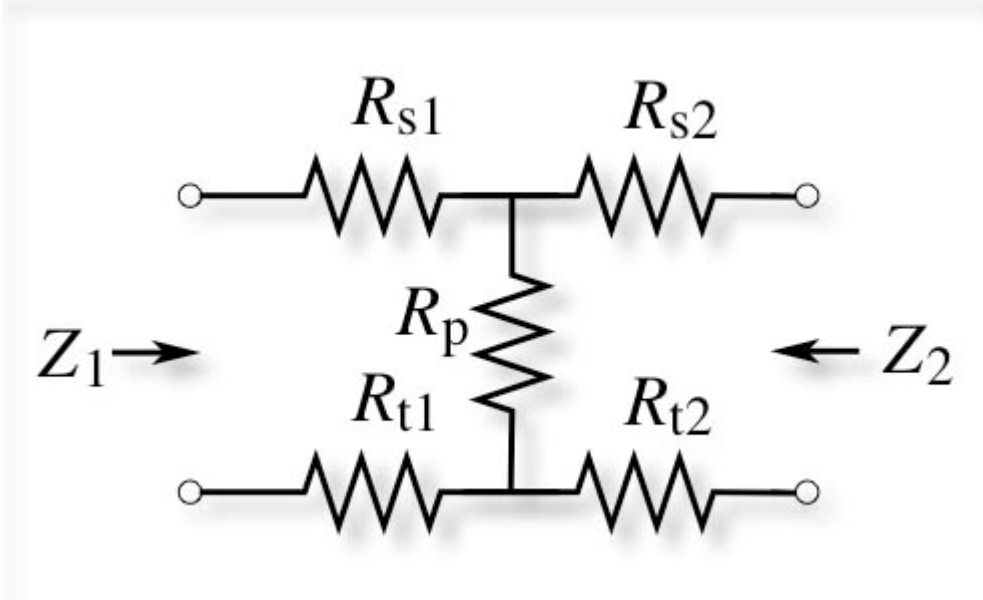
π-type unbalanced attenuator circuit



π-type balanced attenuator circuit



T-type unbalanced attenuator circuit

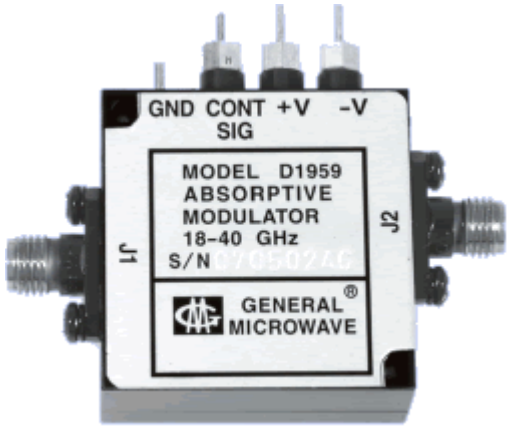


T-type balanced attenuator circuit

Basic circuits used in attenuators are pi pads (π-type) and T pads. These may be required to be balanced or unbalanced networks depending on whether the line geometry with which they are to be used is balanced or unbalanced. For instance, attenuators used with coaxial lines would be the unbalanced form while attenuators for use with twisted pair are required to be the balanced form.

Four fundamental attenuator circuit diagrams are given in the figures on the left. Since an attenuator circuit consists solely of passive resistor elements, it is linear and reciprocal. If the circuit is also made symmetrical (this is usually the case since it is usually required that the input and output impedances Z_1 and Z_2 are equal) then the input and output ports are not distinguished, but by convention the left and right sides of the circuits are referred to as input and output.

Attenuator characteristics



A RF Microwave Attenuator. Picture courtesy of Herley

Key specifications for attenuators are:

- **Attenuation** expressed in decibels of relative power. As a rule of thumb, a 3dB pad reduces power to one half, 6dB to one fourth, 10dB to one tenth, 20dB to one hundredth, 30dB to one thousandth and so on. For voltage you double the dBs so for example 6dB is half in voltage.
- **Frequency bandwidth**, for example DC-18 GHz
- **Power dissipation** depends on mass and surface area of resistance material as well as possible additional cooling fins.
- **SWR** is the standing wave ratio for input and output ports
- **Accuracy**
- **Repeatability**

RF attenuators

Radio frequency attenuators are typically coaxial in structure with precision connectors as ports and coaxial, microstrip or thin-film internal structure. Above SHF special waveguide structure is required.

Important characteristics are:

- accuracy,
- low SWR,

- flat frequency-response and
- repeatability.

The size and shape of the attenuator depends on its ability to dissipate power. RF attenuators are used as loads for and as known attenuations and protective dissipations of power in measuring RF signals.

Audio attenuators

A line-level attenuator in the preamp or a power attenuator after the power amplifier uses electrical resistance to reduce the amplitude of the signal that reaches the speaker, reducing the volume of the output. A line-level attenuator has lower power handling, such as a 1/2-watt potentiometer or voltage divider and controls preamp level signals, whereas a power attenuator has higher power handling capability, such as 10 watts or more, and is used between the power amplifier and the speaker.

- Power attenuator (guitar)
- Guitar amplifier

Component values for resistive pads and attenuators

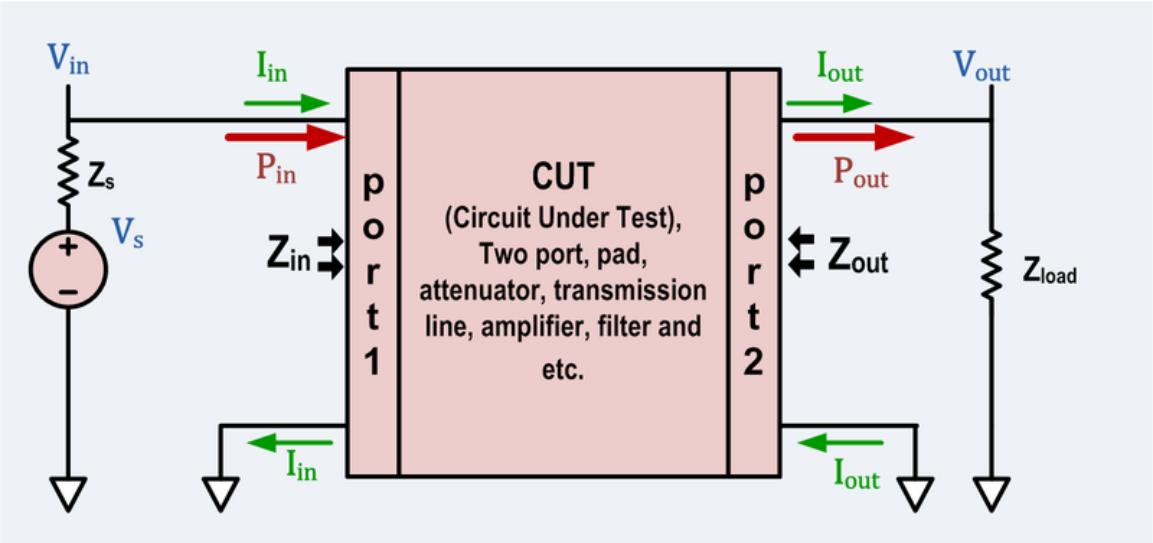
This section concerns pi-pads, T-pads and L-pads made entirely from resistors and terminated on each port with a purely real resistance.

- All impedances, currents, voltages and two-port parameters will be assumed to be purely real. For practical applications, this assumption is often close enough.

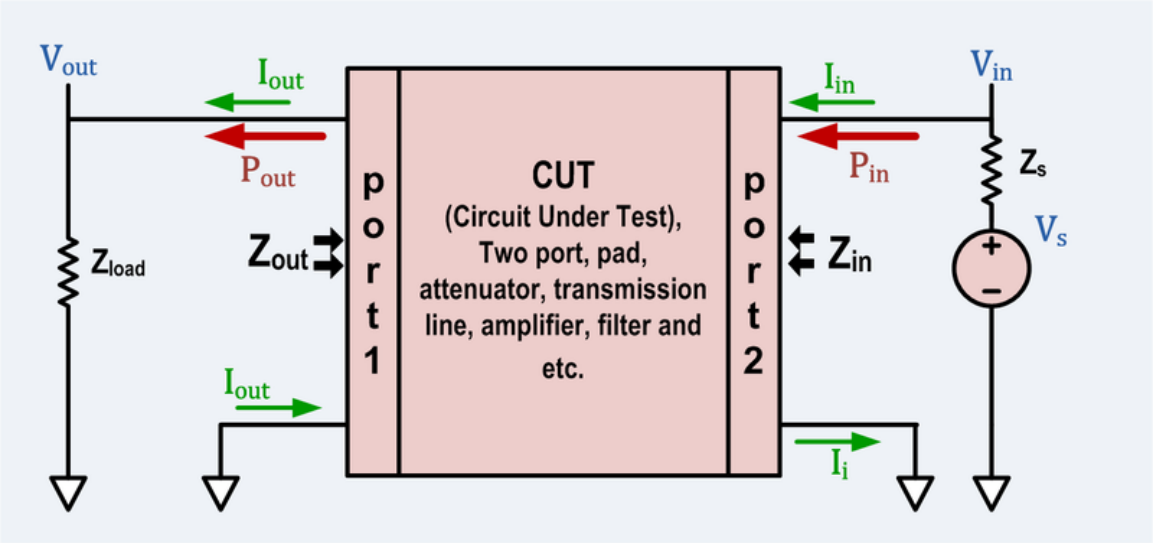
- The pad is designed for a particular load impedance, Z_{Load}, and a particular source impedance, Z_s.

    - The impedance seen looking into the input port will be Z_S if the output port is terminated by Z_{Load}.
    - The impedance seen looking into the output port will be Z_{Load} if the input port is terminated by Z_S.

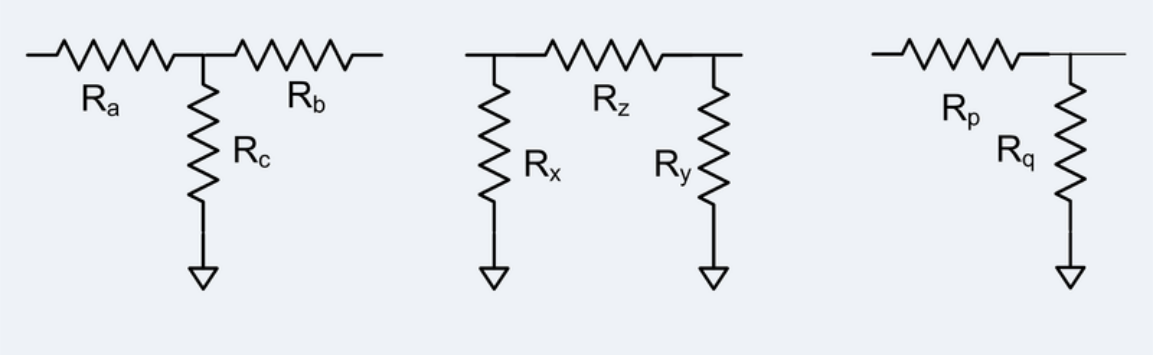
Reference figures for attenuator component calculation



This circuit is used for the general case, all T-pads, all pi-pads and L-pads when the source impedance is greater than or equal to the load impedance.



The L-pad computation assumes that port 1 has the highest impedance. If the highest impedance happens to be the output port, then use this figure.



Unique resistor designations for Tee, Pi and L pads.

The attenuator two-port is generally bidirectional. However here it will be treated as though it were one way. In general, either of the two figures above applies, but the figure on the left (which depicts the source on the left) will be tacitly assumed most of the time. In the case of the L-pad, the right figure will be used if the load impedance is greater than the source impedance.

Each resistor in each type of pad discussed is given a unique designation to decrease confusion.

The L-pad component value calculation assumes that the design impedance for port 1 (on the left) is equal or higher than the design impedance for port 2.

Terms used

- Pad will include pi-pad, T-pad, L-pad, attenuator, and two-port.
- Two-port will include pi-pad, T-pad, L-pad, attenuator, and two-port.
- Input port will mean the input port of the two-port.
- Output port will mean the output port of the two-port.
- Symmetric means a case where the source and load have equal impedance.
- Loss means the ratio of power entering the input port of the pad divided by the power absorbed by the load.
- Insertion Loss means the ratio of power that would be delivered to the load if the load were directly connected to the source divided by the power absorbed by the load when connected through the pad.

Symbols used

Passive, resistive pads and attenuators are bidirectional two-ports, but here they will be treated as unidirectional.

- Z_S = the output impedance of the source.

- Z_{Load} = the input impedance of the load.
- Z_{in} = the impedance seen looking into the input port when Z_{Load} is connected to the output port. Z_{in} is a function of the load impedance.
- Z_{out} = the impedance seen looking into the output port when Z_s is connected to the input port. Z_{out} is a function of the source impedance.
- V_s = source open circuit or unloaded voltage.
- V_{in} = voltage applied to the input port by the source.
- V_{out} = voltage applied to the load by the output port.
- I_{in} = current entering the input port from the source.
- I_{out} = current entering the load from the output port.
- $P_{in} = V_{in} I_{in}$ = power entering the input port from the source.
- $P_{out} = V_{out} I_{out}$ = power absorbed by the load from the output port.
- P_{direct} = the power that would be absorbed by the load if the load were connected directly to the source.
- $L_{pad} = 10 \log_{10} (P_{in} / P_{out})$ always. And if $Z_s = Z_{Load}$ then $L_{pad} = 20 \log_{10} (V_{in} / V_{out})$ also. Note, as defined, Loss ≥ 0 dB
- $L_{insertion} = 10 \log_{10} (P_{direct} / P_{out})$. And if $Z_s = Z_{Load}$ then $L_{insertion} = L_{pad}$.
- Loss $\equiv L_{pad}$. Loss is defined to be L_{pad}.

Symmetric T pad resistor calculation

$$A = 10^{-Loss/20} \qquad R_a = R_b = Z_S \frac{1-A}{1+A} \qquad R_c = \frac{Z_s^2 - R_b^2}{2R_b}$$

Symmetric pi pad resistor calculation

$$A = 10^{-Loss/20} \qquad R_x = R_y = Z_S \frac{1+A}{1-A} \qquad R_z = \frac{2R_x}{\left(\frac{R_x}{Z_0}\right)^2 - 1}]$$

L-Pad for impedance matching resistor calculation

If a source and load are both resistive (i.e. Z_1 and Z_2 have zero or very small imaginary part) then a resistive L-pad can be used to match them to each other. As shown, either side of the L-pad can be the source or load, but the Z_1 side must be the side with the higher impedance.

$$R_q = \frac{Z_m}{\sqrt{\rho - 1}} \qquad R_p = Z_m \sqrt{\rho - 1} \qquad Loss = 20 \log_{10} \left(\sqrt{\rho - 1} + \sqrt{\rho} \right) \quad \text{where} \quad \rho = \frac{Z_1}{Z_2} \quad Z_m = \sqrt{Z_1 Z_2}$$

Large positive numbers means loss is large. The loss is a monotonic function of the impedance ratio. Higher ratios require higher loss.

Converting T-pad to pi-pad

$$R_z = \frac{R_a R_b + R_a R_c + R_b R_c}{R_c} \qquad R_x = \frac{R_a R_b + R_a R_c + R_b R_c}{R_b} \qquad R_y = \frac{R_a R_b + R_a R_c + R_b R_c}{R_a}.$$

Converting pi-pad to T-pad

$$R_c = \frac{R_x R_y}{R_x + R_y + R_z} \qquad R_a = \frac{R_z R_x}{R_x + R_y + R_z} \qquad R_b = \frac{R_z R_y}{R_x + R_y + R_z}$$

Conversion between two-ports and pads

T-pad to impedance parameters

The impedance parameters for a passive two-port are

$$V_1 = Z_{11} I_1 + Z_{12} I_2 \qquad V_2 = Z_{21} I_1 + Z_{22} I_2 \qquad with \qquad Z_{12} = Z_{21}$$

It is always possible to represent a resistive t-pad as a two-port. The representation is particularly simple using impedance parameters as follows:

$$Z_{21} = R_c \qquad Z_{11} = R_c + R_a \qquad Z_{22} = R_c + R_b$$

Impedance parameters to T-pad

The preceding equations are trivially invertible, but if the loss is not enough, some of the t-pad components will have negative resistances.

$$R_c = Z_{21} \qquad R_a = Z_{11} - Z_{21} \qquad R_b = Z_{22} - Z_{21}$$

Impedance parameters to pi-pad

These preceding T-pad parameters can be algebraically converted to pi-pad parameters.

$$R_z = \frac{Z_{11} Z_{22} - Z_{21}^2}{Z_{21}} \qquad R_x = \frac{Z_{11} Z_{22} - Z_{21}^2}{Z_{22} - Z_{21}} \qquad R_y = \frac{Z_{11} Z_{22} - Z_{21}^2}{Z_{11} - Z_{21}}$$

Pi-pad to admittance parameters

The admittance parameters for a passive twp port are

$$I_1 = Y_{11} V_1 + Y_{12} V_2 \qquad I_2 = Y_{21} V_1 + Y_{22} V_2 \qquad with \qquad Y_{12} = Y_{21}$$

It is always possible to represent a resistive pi pad as a two-port. The representation is particularly simple using admittance parameters as follows:

$$Y_{21} = \frac{1}{R_z} \qquad Y_{11} = \frac{1}{R_x} + \frac{1}{R_z} \qquad Y_{22} = \frac{1}{R_y} + \frac{1}{R_z}$$

Admittance parameters to pi-pad

The preceding equations are trivially invertible, but if the loss is not enough, some of the pi-pad components will have negative resistances.

$$R_z = \frac{1}{Y_{21}} \qquad R_x = \frac{1}{Y_{11} - Y_{21}} \qquad R_y = \frac{1}{Y_{22} - Y_{21}}$$

General case, determining impedance parameters from requirements

Because the pad is entirely made from resistors, it must have a certain minimum loss to match source and load if they are not equal.

The minimum loss is given by

$$Loss_{min} = 20\ log_{10}\left(\sqrt{\rho - 1} + \sqrt{\rho}\ \right) \quad \text{where} \quad \rho = \frac{\max[Z_S, Z_{Load}]}{\min[Z_S, Z_{Load}]}$$

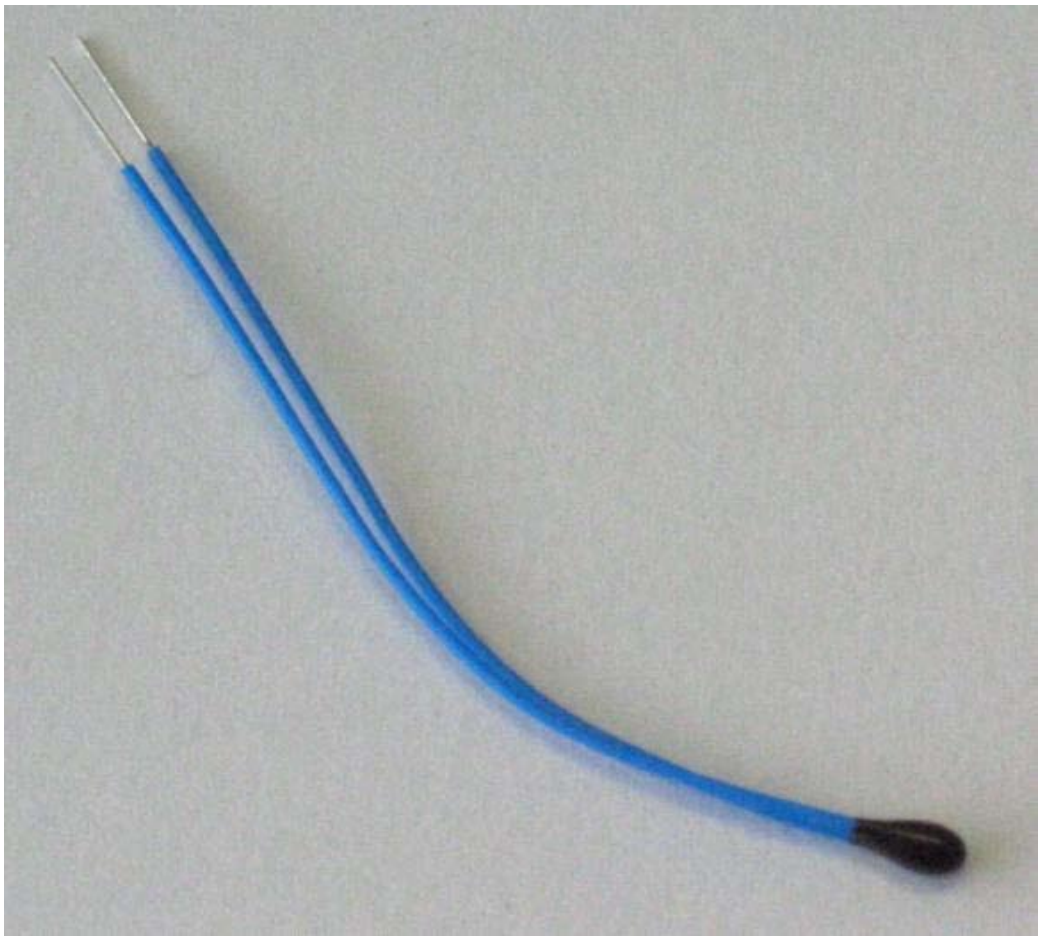
Although a passive matching two-port can have less loss, if it does it will not be convertible to a resistive attenuator pad.

$$A = 10^{-Loss/20} \qquad Z_{11} = Z_S \frac{1 + A^2}{1 - A^2} \qquad Z_{22} = Z_{Load} \frac{1 + A^2}{1 - A^2} \qquad Z_{21} = 2 \frac{A\sqrt{Z_S Z_{Load}}}{1 - A^2}$$

Once these parameters have been determined, they can be implemented as a T or pi pad as discussed above.

Chapter- 15

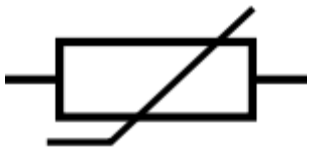
Thermistor



NTC thermistor, bead type, insulated wires

A **thermistor** is a type of resistor whose resistance varies significantly with temperature, more so than in standard resistors. The word is a portmanteau of *thermal* and *resistor*. Thermistors are widely used as inrush current limiters, temperature sensors, self-resetting overcurrent protectors, and self-regulating heating elements.

Thermistors differ from resistance temperature detectors (RTD) in that the material used in a thermistor is generally a ceramic or polymer, while RTDs use pure metals. The temperature response is also different; RTDs are useful over larger temperature ranges, while thermistors typically achieve a higher precision within a limited temperature range [usually −90 °C to 130 °C].



Thermistor symbol

Assuming, as a first-order approximation, that the relationship between resistance and temperature is linear, then:

$$\Delta R = k\Delta T$$

where

ΔR = change in resistance
ΔT = change in temperature
k = first-order temperature coefficient of resistance

Thermistors can be classified into two types, depending on the sign of k. If k is positive, the resistance increases with increasing temperature, and the device is called a positive temperature coefficient (**PTC**) thermistor, or **posistor**. If k is negative, the resistance decreases with increasing temperature, and the device is called a negative temperature coefficient (**NTC**) thermistor. Resistors that are not thermistors are designed to have a k as close to zero as possible(smallest possible k), so that their resistance remains nearly constant over a wide temperature range.

Instead of the temperature coefficient k, sometimes the *temperature coefficient of resistance* α (alpha) or α_T is used. It is defined as

$$\alpha_T = \frac{1}{R(T)}\frac{dR}{dT}.$$

For example, for the common PT100 sensor, α = 0.00385 or 0.385 %/°C. This α_T coefficient should not be confused with the α parameter below.

Steinhart-Hart equation

In practice, the linear approximation (above) works only over a small temperature range. For accurate temperature measurements, the resistance/temperature curve of the device must be described in more detail. The Steinhart-Hart equation is a widely used third-order approximation:

$$\frac{1}{T} = a + b\,\ln(R) + c\,\ln^3(R)$$

where *a*, *b* and *c* are called the Steinhart-Hart parameters, and must be specified for each device. *T* is the temperature in kelvin and *R* is the resistance in ohms. To give resistance as a function of temperature, the above can be rearranged into:

$$R = e^{\left(x-\frac{y}{2}\right)^{\frac{1}{3}} - \left(x+\frac{y}{2}\right)^{\frac{1}{3}}}$$

where

$$y = \frac{a - \frac{1}{T}}{c} \quad \text{and} \quad x = \sqrt{\left(\frac{b}{3c}\right)^3 + \frac{y^2}{4}}$$

The error in the Steinhart-Hart equation is generally less than 0.02 °C in the measurement of temperature. As an example, typical values for a thermistor with a resistance of 3000 Ω at room temperature (25 °C = 298.15 K) are:

$$a = 1.40 \times 10^{-3}$$
$$b = 2.37 \times 10^{-4}$$
$$c = 9.90 \times 10^{-8}$$

B *parameter equation*

NTC thermistors can also be characterised with the *B* parameter equation, which is essentially the Steinhart Hart equation with $a = (1 / T_0) - (1 / B)ln(R_0)$, $b = 1 / B$ and $c = 0$,

$$\frac{1}{T} = \frac{1}{T_0} + \frac{1}{B}\ln\left(\frac{R}{R_0}\right)$$

Where the temperatures are in kelvins and R_0 is the resistance at temperature T_0 (usually 25 °C = 298.15 K). Solving for *R* yields:

$$R = R_0 e^{B(1/T - 1/T_0)}$$

or, alternatively,

$$R = r_\infty e^{B/T}$$

where $r_\infty = R_0 e^{-B/T_0}$. This can be solved for the temperature:

$$T = \frac{B}{\ln\left(R/r_\infty\right)}$$

The B-parameter equation can also be written as $\ln R = B/T + \ln r_\infty$. This can be used to convert the function of resistance vs. temperature of a thermistor into a linear function of ln*R* vs. 1 / *T*. The average slope of this function will then yield an estimate of the value of the *B* parameter.

Conduction model

Many NTC thermistors are made from a pressed disc or cast chip of a semiconductor such as a sintered metal oxide. They work because raising the temperature of a semiconductor increases the number of electrons able to move about and carry charge - it promotes them into the *conduction band*. The more charge carriers that are available, the more current a material can conduct. This is described in the formula:

$$I = n \cdot A \cdot v \cdot e$$

I = electric current (amperes)
n = density of charge carriers (count/m³)
A = cross-sectional area of the material (m²)
v = velocity of charge carriers (m/s)
e = charge of an electron ($e = 1.602 \times 10^{-19}$ coulomb)

The current is measured using an ammeter. Over large changes in temperature, calibration is necessary. Over small changes in temperature, if the right semiconductor is used, the resistance of the material is linearly proportional to the temperature. There are many different semiconducting thermistors with a range from about 0.01 kelvin to 2,000 kelvins (−273.14 °C to 1,700 °C).

Most PTC thermistors are of the "switching" type, which means that their resistance rises suddenly at a certain critical temperature. The devices are made of a doped polycrystalline ceramic containing barium titanate ($BaTiO_3$) and other compounds. The dielectric constant of this ferroelectric material varies with temperature. Below the Curie point temperature, the high dielectric constant prevents the formation of potential barriers between the crystal grains, leading to a low resistance. In this region the device has a small negative temperature coefficient. At the Curie point temperature, the dielectric constant drops sufficiently to allow the formation of potential barriers at the grain

boundaries, and the resistance increases sharply. At even higher temperatures, the material reverts to NTC behaviour. The equations used for modeling this behaviour were derived by W. Heywang and G. H. Jonker in the 1960s.

Another type of PTC thermistor is the polymer PTC, which is sold under brand names such as "Polyswitch" "Semifuse", and "Multifuse". This consists of a slice of plastic with carbon grains embedded in it. When the plastic is cool, the carbon grains are all in contact with each other, forming a conductive path through the device. When the plastic heats up, it expands, forcing the carbon grains apart, and causing the resistance of the device to rise rapidly. Like the $BaTiO_3$ thermistor, this device has a highly nonlinear resistance/temperature response and is used for switching, not for proportional temperature measurement.

Yet another type of thermistor is a **silistor**, a thermally sensitive silicon resistor. Silistors are similarly constructed and operate on the same principles as other thermistors, but employ silicon as the semiconductive component material.

Self-heating effects

When a current flows through a thermistor, it will generate heat which will raise the temperature of the thermistor above that of its environment. If the thermistor is being used to measure the temperature of the environment, this electrical heating may introduce a significant error if a correction is not made. Alternatively, this effect itself can be exploited. It can, for example, make a sensitive air-flow device employed in a sailplane rate-of-climb instrument, the electronic variometer, or serve as a timer for a relay as was formerly done in telephone exchanges.

The electrical power input to the thermistor is just:

$$P_E = IV$$

where I is current and V is the voltage drop across the thermistor. This power is converted to heat, and this heat energy is transferred to the surrounding environment. The rate of transfer is well described by Newton's law of cooling:

$$P_T = K(T(R) - T_0)$$

where $T(R)$ is the temperature of the thermistor as a function of its resistance R, T_0 is the temperature of the surroundings, and K is the **dissipation constant**, usually expressed in units of milliwatts per degree Celsius. At equilibrium, the two rates must be equal.

$$P_E = P_T$$

The current and voltage across the thermistor will depend on the particular circuit configuration. As a simple example, if the voltage across the thermistor is held fixed,

then by Ohm's Law we have $I = V / R$ and the equilibrium equation can be solved for the ambient temperature as a function of the measured resistance of the thermistor:

$$T_0 = T(R) - \frac{V^2}{KR}$$

The dissipation constant is a measure of the thermal connection of the thermistor to its surroundings. It is generally given for the thermistor in still air, and in well-stirred oil. Typical values for a small glass bead thermistor are 1.5 mW/°C in still air and 6.0 mW/°C in stirred oil. If the temperature of the environment is known beforehand, then a thermistor may be used to measure the value of the dissipation constant. For example, the thermistor may be used as a flow rate sensor, since the dissipation constant increases with the rate of flow of a fluid past the thermistor.

Applications

- PTC thermistors can be used as current-limiting devices for circuit protection, as replacements for fuses. Current through the device causes a small amount of resistive heating. If the current is large enough to generate more heat than the device can lose to its surroundings, the device heats up, causing its resistance to increase, and therefore causing even more heating. This creates a self-reinforcing effect that drives the resistance upwards, reducing the current and voltage available to the device.
- PTC thermistors are used as timers in the degaussing coil circuit of most CRT displays and televisions. When the display unit is initially switched on, current flows through the thermistor and degaussing coil. The coil and thermistor are intentionally sized so that the current flow will heat the thermistor to the point that the degaussing coil shuts off in under a second. For effective degaussing, it is necessary that the magnitude of the alternating magnetic field produced by the degaussing coil decreases smoothly and continuously, rather than sharply switching off or decreasing in steps; the PTC thermistor accomplishes this naturally as it heats up. A degaussing circuit using a PTC thermistor is simple, reliable (for its simplicity), and inexpensive.
- NTC thermistors are used as resistance thermometers in low-temperature measurements of the order of 10 K.
- NTC thermistors can be used as inrush-current limiting devices in power supply circuits. They present a higher resistance initially which prevents large currents from flowing at turn-on, and then heat up and become much lower resistance to allow higher current flow during normal operation. These thermistors are usually much larger than measuring type thermistors, and are purposely designed for this application.
- NTC thermistors are regularly used in automotive applications. For example, they monitor things like coolant temperature and/or oil temperature inside the engine and provide data to the ECU and, indirectly, to the dashboard.
- NTC thermistors can be also used to monitor the temperature of an incubator.

- Thermistors are also commonly used in modern digital thermostats and to monitor the temperature of battery packs while charging.

History

The first NTC thermistor was discovered in 1833 by Michael Faraday, who reported on the semiconducting behavior of silver sulfide. Faraday noticed that the resistance of silver sulfide decreased dramatically as temperature increased. Because early thermistors were difficult to produce and applications for the technology were limited, commercial production of thermistors did not begin until the 1930s.